Search for scalar top quarks and higgsino-like neutralinos in pp collisions at a center-of-mass energy of 8 TeV with the ATLAS detector

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Abstract

Supersymmetry (SUSY) is a strong candidate of new physics beyond the Standard Model, which introduces new symmetry between bosons and fermions. It suppresses the known hierarchy problem of the Standard Model. In this thesis, a search for scalar top quark (stop) pair production has been performed in proton-proton collisions at a center-of-mass energy of 8 TeV at the Large Hadron Collider. The data collected with the ATLAS detector in 2012 corresponding to an integrated luminosity of 20.1 fb^{-1} are used. For a natural solution of the hierarchy problem, masses of stop and higgsino are required to be small. Most of the light stop signals are already excluded by the previous analyses at the LHC, but there remain some phase spaces not explored yet. The target decay mode is stop going into b quark and chargino. A 100 % decay branching ratio is assumed. If the lightest SUSY particle (LSP) has a higgsino component, the mass difference between chargino and the LSP (Δm) is expected to be small. In such a case, chargino decays in three body into low-momentum (soft) fermion pair and the LSP. Following the previous ATLAS analysis, two benchmark points of $\Delta m = 5 \text{ GeV}$ and 20 GeV are considered. The previous analysis has a strong sensitivity on signals with $\Delta m = 5 \text{ GeV}$, but it is weakened at $\Delta m = 20 \text{ GeV}$. This analysis requires the existence of a soft lepton as a probe of the signal and aims to improve the sensitivity at this phase space. If the mass difference between stop and the LSP (ΔM) is small in addition to the Δm , all of decay products are likely to be soft and a dedicated analysis is necessary. Therefore, two types of signal regions according to the event topologies are prepared: (1) the small ΔM channel and (2) the moderate ΔM channel. The small ΔM channel requires an initial state radiation jet with high transverse momentum in the event and the stop pair system produced in the boosted frame to the opposite direction to that is explored, which improves the acceptance to the soft particles. The moderate ΔM channel requires two b -quark-induced jets in the event and a variable sensitive to the stop mass am_{T2} is used as the signal discriminator. The Standard Model backgrounds are estimated by a semi-data-driven method. The normalization factors for the main background components of top quark pair production and W boson production associated with hadron jets are estimated in the dedicated control regions and extrapolated to the signal regions. The mis-identified lepton background is estimated by a pure data-driven method. The other backgrounds are estimated by the Monte Carlo simulation. No significant signals exceeding the estimated Standard Model background are observed in all signal regions. The results are interpreted as limits on the SUSY masses. In the signal hypothesis with $\Delta m = 20 \text{ GeV}$, the observation in the small ΔM channel excludes the region of $\Delta M < 70 \text{ GeV}$ for the first time in the range of stop masses less than 210 GeV . The moderate ΔM channel excludes stop masses in the range of 200 to 610 GeV for the LSP masses less than 280 GeV , which improves the previous ATLAS result by approximately 120 GeV to higher stop mass direction. The small ΔM channel also excludes stop pair production signals in which stop decays in four body into b quark, soft fermion pair, and the LSP, with stop masses less than 250 GeV for the first time. By taking combinations with other ATLAS stop searches, a wide range of stop masses below 600 GeV has been excluded.

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Chapter 1

Introduction

The table of particles predicted by the Standard Model has been completed after the discovery of a Higgs boson with a mass of approximately 125 GeV by the ATLAS [1] and CMS [2] experiments at the Large Hadron Collider (LHC) in July 2012. The Standard Model is an excellent approximation to describe the elementary particles and interactions among them, in particular up-to $O(100)$ GeV of energy scales. However, we know there are some problems with the Standard Model. Now we stand at the dawn of new physics beyond the Standard Model. In this chapter, the essence of the Standard Model and supersymmetry, one of the strong candidates of physics beyond the Standard Model, are explained and the goal of this thesis, why scalar top quark and higgsino-like neutrino are important, is clarified.

1.1 The Standard Model

Particle physics in the Standard Model (SM) is described by the following simple gauge invariant Lagrangian:

$$\mathcal{L}_{\text{SM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad (1.1)$$

$$+ i\bar{\psi}\gamma_{\mu}D^{\mu}\psi + \text{h.c.} \quad (1.2)$$

$$+ \psi_i y_{ij} \psi_j \phi + \text{h.c.} \quad (1.3)$$

$$+ |D_{\mu}\phi|^2 - V(\phi). \quad (1.4)$$

The first term Eq. (1.1) describes the kinetics of vector bosons; Eq. (1.2) describes the kinetics and interactions of fermions; Eq. (1.3) is a fermion mass term; and Eq. (1.4) is the Higgs sector. $F_{\mu\nu}$ is a field strength tensor for a particular gauge field. D_{μ} is the covariant derivative appropriately chosen for a given gauge symmetry. γ_{μ} ($\mu = 0, 1, 2, 3$) is the 4×4 gamma matrix in the Dirac expression (μ represents the dimension: t, x, y and z):

$$\gamma^0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \quad \gamma^{\mu} = \begin{pmatrix} 0 & \sigma_{\mu} \\ -\sigma_{\mu} & 0 \end{pmatrix},$$

where σ_{μ} ($\mu = 1, 2, 3$) is the 2×2 Pauli matrix:

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

The characters ψ and ϕ are the fermion and scalar fields, respectively. The chirality γ_5 is defined as:

$$\gamma_5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}.$$

Table 1.1: Fermions in the SM. The quantity S , Q , T , T^3 and Y indicate its spin, charge, weak isospin, third component of the weak isospin, and weak hypercharge, respectively. L and R indicate left- and right-handed chiral states, respectively. d' , s' and b' denote the weak interaction eigenstates of down-type quarks.

Category	Generation			S	Q ($ e $)	T	T^3	Y
	1st	2nd	3rd					
Quarks	$\begin{pmatrix} u \\ d' \end{pmatrix}_L$	$\begin{pmatrix} c \\ s' \end{pmatrix}_L$	$\begin{pmatrix} t \\ b' \end{pmatrix}_L$	1/2	$\begin{pmatrix} +2/3 \\ -1/3 \end{pmatrix}$	1/2	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$	1/3
	u_R	c_R	t_R	1/2	+2/3	0	0	4/3
	d'_R	s'_R	b'_R	1/2	-1/3	0	0	-2/3
Leptons	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$	1/2	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$	1/2	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$	-1
	e^-_R	μ^-_R	τ^-_R	1/2	-1	0	0	-2

Projection operators are defined using γ_5 as:

$$P_R = \frac{1}{2}(1 + \gamma_5) \quad (1.5)$$

$$P_L = \frac{1}{2}(1 - \gamma_5), \quad (1.6)$$

which decompose the Dirac spinor of a fermion to right- and left-handed components. y_{ij} in Eq. (1.3) is the Yukawa coupling constant matrix which gives masses to fermions. $V(\phi)$ in Eq. (1.4) is the potential of the scalar field.

First of all, let us see some details about the SM Lagrangian Eqs. (1.1)-(1.4). In our nature, four types of forces (interactions) are recognized:

1. electromagnetic force;
2. weak force;
3. strong force;
4. gravitational force.

Relative magnitudes of electromagnetic, weak and gravitational forces with respect to strong force are 10^{-2} , 10^{-7} and 10^{-39} , respectively. The gravity is the most familiar interaction for us, but it is too small for particle physics to compare with the other interactions and hence neglected in the framework of the SM.

Twelve types of fermions shown in Table 1.1 are considered in the SM. They are categorized into quarks and leptons. Leptons can only feel electromagnetic and weak forces, while quarks can feel all of three forces. They are further divided into three ‘generation’s (also known as ‘flavor’s). Fermions with different flavors in the same family¹ have the same properties with each other, except for their masses as shown in Table 1.1 and Fig. 1.1.

Quarks are forbidden to exist standalone in nature but form mesons (the resonance state of quark and anti-quark, like a pion) or baryons (the bound state of three quarks like proton and neutron) by quantum-chromo dynamics (QCD) described in Sec. 1.1.3. Mesons and baryons are collectively referred

¹We define e , μ and τ belong to charged lepton family, ν_e , ν_μ and ν_τ neutrino family; u , c and t up-type quark family; and d , s , and b down-type quark family.

Figure 1.1: The experimental measured masses of fermions versus generation. Charged lepton family is indicated by (red) circles, up-type quarks by (green) squares, and down-type quarks by (blue) triangles. $m_e = 510.998928 \pm 0.000011$ keV, $m_\mu = 105.6583715 \pm 0.0000035$ MeV, $m_\tau = 1776.82 \pm 0.16$ MeV, $m_u = 2.3^{+0.7}_{-0.5}$ MeV, $m_d = 4.8^{+0.5}_{-0.3}$ MeV, $m_s = 95 \pm 5$ MeV, $m_c = 1.275 \pm 0.025$ GeV, $m_b = 4.18 \pm 0.03$ GeV, and $m_t = 173.07 \pm 0.52 \pm 0.72$ GeV. Corrections from the perturbative QCD for quark masses are calculated by $\overline{MS}$ scheme. Only upper limit is measured for neutrino masses at 2 eV. The values are taken from Ref. [3].

as hadrons. Quantum numbers associated with the quark flavor, which are summarized in Table 1.2, are conserved except in the charged current weak interaction. Electric charge of a quark is described as:

$$Q = I^3 + \frac{1}{2}(B + S + C + B' + T),$$

where I^3 , B , S , C , B' and T are the third component of isospin, baryon number, strangeness, charmness, bottomness, and topness, respectively.

Leptons should also satisfy flavor number conservations: lepton number, and in general lepton flavor number. The lepton and lepton flavor numbers for each particle are summarized in Table 1.2. Since only left-handed helicity state of neutrinos has ever been observed, right-handed neutrino singlets are not considered in the SM. This fact leads masses of neutrinos to zero in the SM ².

The electromagnetism is a well-known interaction in our life. Electromagnetic force works between particles having electric charge, mediated by a massless, neutral gauge boson (photon). Coupling constant of electromagnetic interaction is called the fine structure constant: $\alpha = e^2/4\pi\hbar c = 1/137$.

Weak interaction is historically introduced to describe nucleon's β decay. First, four fermion interaction described by the Fermi coupling constant $G_F \approx 10^{-5}$ GeV⁻² was considered, but there was a known problem that the unitarity of weak interaction was broken at the high energy (> 300 GeV). To avoid the problem, the intermediate massive, charged vector boson $W^\pm$ was introduced. Processes violating quark

²We already know neutrino mass is not zero, since the neutrino oscillations are observed [4]. This is not mentioned in Sec. 1.1.5, but one of the typical problems of the SM.

Table 1.2: Lepton number L , lepton flavor number L_x (x : e , μ or τ), baryon number B , isospin I and its third component I^3 , strangeness S , charmness C , bottomness B' , and topness T for each fermion.

Particle	L	L_e	L_μ	L_τ	B	I	I^3	S	C	B'	T
e	1	1	0	0	0	0	0	0	0	0	0
μ	1	0	1	0	0	0	0	0	0	0	0
τ	1	0	0	1	0	0	0	0	0	0	0
ν_e	1	1	0	0	0	0	0	0	0	0	0
ν_μ	1	0	1	0	0	0	0	0	0	0	0
ν_τ	1	0	0	1	0	0	0	0	0	0	0
u	0	0	0	0	1/3	1/2	+1/2	0	0	0	0
d	0	0	0	0	1/3	1/2	-1/2	0	0	0	0
s	0	0	0	0	1/3	0	0	-1	0	0	0
c	0	0	0	0	1/3	0	0	0	1	0	0
b	0	0	0	0	1/3	0	0	0	0	-1	0
t	0	0	0	0	1/3	0	0	0	0	0	1

flavor number conservation are allowed only in the charged current weak interaction mediated by $W^\pm$ boson. The flavor mixing of quarks is described by the 3×3 unitary matrix (M_{CKM} : namely Cabibbo-Kobayashi-Maskawa (CKM) matrix)³, which makes the connection between the mass eigenstates of down-type quarks (d , s , b) and the weak interaction eigenstates (d' , s' , b') as:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = M_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \quad (1.7)$$

The magnitudes of all nine CKM elements determined by the global fit to the experimental measurements [3] are:

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97427 \pm 0.00014 & 0.225336 \pm 0.000061 & 0.00355 \pm 0.00015 \\ 0.22522 \pm 0.00061 & 0.97343 \pm 0.00015 & 0.0414 \pm 0.0012 \\ 0.0086^{+0.00033}_{-0.00032} & 0.0405^{+0.0011}_{-0.0012} & 0.99914 \pm 0.00005 \end{pmatrix}. \quad (1.8)$$

In order to keep the renormalizability of the weak interaction W^+W^- production, neutral current weak interaction was predicted, which is mediated by the massive, neutral Z^0 boson, and confirmed experimentally. Due to the properties of the unitary matrix (M_{CKM}), the flavor changing neutral currents (FCNCs) are strictly forbidden at the tree level in the SM (Glashow-Iliopoulos-Maiani (GIM) mechanism). Electromagnetic and weak interactions are then merged and called ‘electroweak’ interaction as described in Sec. 1.1.1. An additional scalar boson is necessary to give the massive W and Z bosons and masses to fermions by the spontaneous symmetry breaking, as described in Sec. 1.1.2.

Strong interaction is described by the QCD (see details in Sec. 1.1.3). The intermediate massless, neutral vector boson, gluon, carries the color charge of quarks. There are three types of color states, namely r (red), g (green) and b (blue). Mesons and baryons are formed to make ‘white’ color (colorless) state by a combination of color-anticolor pair and a combination of three primary colors (rgb), respectively. Since the gluon itself has color charge by the definition of the QCD Lagrangian, self-interaction of gluons is allowed. Quarks and gluon are collectively referred as partons.

The properties of the vector and scalar bosons in the SM are summarized in Table 1.3.

³The CKM matrix plays an important role to explain the observed CP violation [5], though it is not discussed in this thesis.

Table 1.3: Gauge and Higgs bosons in the SM. Masses [3] are represented in GeV. The quantity S^P , Q , T , T^3 and Y indicate its spin-parity, charge, weak isospin, third component of the weak isospin, and weak hypercharge, respectively.

	particles	mass	S^P	Q	T	T^3	Y
photon	γ	0	1^-	0	0	0	0
weak bosons	$W^\pm$	80.385 ± 0.015	1^-	± 1	1	± 1	0
	Z^0	91.1876 ± 0.0021	1^-	0	0	0	0
gluon	g	0	1^-	0	0	0	0
higgs	h	125.7 ± 0.4	0^+	0	1/2	-1/2	+1

1.1.1 Electroweak interaction

Before the discussion about electroweak interaction, for the simplicity, we start from electromagnetic interaction. The Lagrangian of the quantum electromagnetic dynamics (QED) is:

$$\begin{aligned}
 \mathcal{L}_{\text{QED}} &= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma^\mu D_\mu \psi - m\bar{\psi}\psi \\
 &= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma^\mu \partial_\mu \psi - e\bar{\psi}\gamma^\mu \psi A_\mu - m\bar{\psi}\psi
 \end{aligned} \tag{1.9}$$

by choosing the covariant derivative as:

$$D_\mu \equiv \partial_\mu - ieA_\mu, \tag{1.10}$$

where the vector field A_μ is introduced to satisfy the gauge invariance of the Lagrangian. A_μ is the photon field and its mass term $A_\mu A^\mu$ is forbidden since it breaks the local gauge symmetry. Therefore, the mass of photon is zero. $F_{\mu\nu}$ is defined using A_μ as:

$$F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu. \tag{1.11}$$

The first and second terms of Eq. (1.9) represent the photon and fermion kinetics, respectively. The third term represents electromagnetic interaction (e is the electric charge), which is re-written using an expression for the electromagnetic current $j_\mu^{\text{em}} \equiv \bar{\psi}\gamma^\mu \psi$ as:

$$-e\bar{\psi}\gamma^\mu \psi A_\mu = -ej_\mu^{\text{em}} A_\mu. \tag{1.12}$$

The fourth is the fermion mass term (m is the fermion mass).

Basically the same discussion takes place for electroweak interaction [6–8], embracing electromagnetic and weak interactions. Left- and right-handed fermions have independent weak isospin (T, T^3) and weak hypercharge $Y = 2(Q - T^3)$ as summarized in Table 1.1 i.e. different electroweak interactions occur to left- and right-handed fermions. Four massless bosons associated with the weak isospin T and weak hypercharge Y are introduced. Three of four bosons are $\mathbf{W}_\mu = \{W_\mu^1, W_\mu^2, W_\mu^3\}$, belonging to $T = 1$ triplet of the $SU(2)_L$ gauge group, while the fourth boson B_μ is $T = 0$ isosinglet belonging to the $U(1)_Y$ gauge group. Therefore, the theory is often denoted as $SU(2)_L \times U(1)_Y$. The electroweak sector of the

$\mathcal{L}_{\text{SM}}$ is:

$$\begin{aligned}
\mathcal{L}_{\text{EW}} &= -\frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + i\bar{\psi}\gamma^\mu D_\mu \psi \\
&= -\frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + i\bar{\psi}\gamma^\mu \partial_\mu \psi \\
&\quad - \frac{g}{2}\bar{\psi}_L\gamma^\mu \begin{pmatrix} W_\mu^3 & (W_\mu^1 - iW_\mu^2) \\ (W_\mu^1 + iW_\mu^2) & -W_\mu^3 \end{pmatrix} \psi_L - g'\bar{\psi}\gamma^\mu \frac{Y}{2}B_\mu \psi \\
&= -\frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + i\bar{\psi}\gamma^\mu \partial_\mu \psi \\
&\quad - \frac{g}{\sqrt{2}}(J_\mu^+ W^{-\mu} + J_\mu^- W^{+\mu}) - gJ_\mu^3 W^{3\mu} - \frac{g'}{2}J_\mu^Y B^\mu,
\end{aligned} \tag{1.13}$$

when D_μ is chosen as:

$$D_\mu \equiv \left(i\partial_\mu - g\boldsymbol{\tau} \cdot \mathbf{W}_\mu - g'\frac{Y}{2}B_\mu \right), \tag{1.14}$$

to require the gauge invariance of the Lagrangian. $\boldsymbol{\tau}$ is defined as:

$$\boldsymbol{\tau} \equiv \frac{1}{2} \{ \sigma_1, \sigma_2, \sigma_3 \}. \tag{1.15}$$

The $W_{\mu\nu}$ and $B_{\mu\nu}$ are defined as:

$$W_{\mu\nu} \equiv \partial_\mu W_\nu - \partial_\nu W_\mu - gW_\mu \times W_\nu \tag{1.16}$$

$$B_{\mu\nu} \equiv \partial_\mu B_\nu - \partial_\nu B_\mu. \tag{1.17}$$

g and g' are the coupling constants for weak isospin interaction and weak hypercharge interaction, respectively. ψ_L is the left-handed doublets of the fermion fields, defined as $\psi_L = P_L \psi$, where P_L is given by Eq. (1.6). As shown in Table 1.1, only left-handed fermions have weak isospin current, while both of left- and right-handed fermions have weak hypercharge current.

First to third terms of the last line of Eq. (1.13) represent the kinetics of vector bosons and fermions. Fourth term represents the charged current weak interaction; $W_\mu^\pm \equiv \frac{1}{\sqrt{2}}(W_\mu^1 \pm iW_\mu^2)$ are the fields of charged W bosons and $J_\mu^\pm$ are the raising and lowering operators for T^3 . $J_\mu^3 \equiv \bar{\psi}_L\gamma^\mu \tau_3 W_\mu^3 \psi_L$ in the fifth term is the third component of the weak isospin current, and $J_\mu^Y \equiv Y\bar{\psi}\gamma^\mu \psi$ in the sixth term is the weak hypercharge current. By the relation of $Y = 2(Q - T^3)$, the electromagnetic current can be written as:

$$j_\mu^{\text{em}} = J_\mu^3 + \frac{J_\mu^Y}{2}. \tag{1.18}$$

B_μ and neutral W_μ^3 bosons are mixed by Weinberg angle θ_W which is defined as

$$\tan \theta_W \equiv \frac{g'}{g}, \tag{1.19}$$

and form the Z^0 boson and photon fields (Z_μ and A_μ) as:

$$\begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_W & -\sin \theta_W \\ \sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix}. \tag{1.20}$$

Substituting J_μ^Y , W_μ^3 and B_μ derived by Eq. (1.18) and (1.20) for the fifth and sixth terms of Eq. (1.13), they are transformed to:

$$-gJ_\mu^3 W^{3\mu} - \frac{g'}{2}J_\mu^Y B^\mu = -g \sin \theta_W j_\mu^{\text{em}} A^\mu - \frac{g}{\cos \theta_W} (J_\mu^3 - \sin^2 \theta_W j_\mu^{\text{em}}) Z^\mu, \tag{1.21}$$

which describe the electromagnetic and neutral current weak interactions. By comparing Eq. (1.21) with Eq. (1.12), the electric charge is found to be related to the weak coupling constant by the Weinberg angle: $e = g \sin \theta_W$.

1.1.2 The spontaneous symmetry breaking

By comparing Eq. (1.9) and Eq. (1.13), we can see that the fermion mass term is not included in $\mathcal{L}_{EW}$. In addition, the mass terms of the weak bosons are forbidden in order to keep the gauge invariance of the Lagrangian, in spite of that they should be massive to describe the experimental results.

To solve these problems, an additional scalar field ϕ and its charge conjugation ϕ^c :

$$\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad \phi^c = \begin{pmatrix} \phi^{0\dagger} \\ -\phi^- \end{pmatrix} \quad (1.22)$$

are introduced [9, 10]. Considering the scalar particles that interact each other, the scalar sector of the Lagrangian can be defined by:

$$\mathcal{L}_{\text{Higgs}} = T - V = (\partial_\mu \phi)^\dagger (\partial_\mu \phi) - \left(\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \right). \quad (1.23)$$

Here, μ and λ are the mass and the self coupling constant of the scalar field ϕ . V is a rotation symmetric potential on ϕ_1 - ϕ_2 plane around $\phi = (0, 0)$. In the case of $\mu^2 < 0$ and $\lambda > 0$, as shown in Fig. 1.2, the field gets the minimum value of V if $v^2 = \phi_1^2 + \phi_2^2 = -\mu^2/2\lambda$ is satisfied. v is called the vacuum expected value (VEV). To make the Lagrangian to conserve the $SU(2)_L \times U(1)_Y$ gauge symmetry, appropriate choice of the scalar field is:

$$\phi(x) = \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}, \quad (1.24)$$

where $h(x)$ is the neutral Higgs boson field, which is the value of the field over and above the constant value v . The process $\phi \rightarrow \phi(x)$ is called a spontaneous symmetry breaking. If we substitute the scalar field ϕ in Eq. (1.23) by Eq. (1.24) and the operator $\partial_\mu \rightarrow D_\mu$ by Eq. (1.14), the mass terms of W and Z bosons appear in the Lagrangian and the values are calculated using the fact that photon is massless as:

$$m_W^2 = (gv)^2 \quad (1.25)$$

$$m_Z^2 = \frac{m_W^2}{\rho \cos^2 \theta_W}. \quad (1.26)$$

ρ is the parameter describing the effect of radiative corrections; $\rho = 1$ at the tree level. Indirect measurement of ρ is performed in the global fit to the electroweak parameters (see Sec. 1.1.4). The mass of the Higgs boson is obtained simultaneously in this process as:

$$m_h^2 = -2\mu^2. \quad (1.27)$$

From the measurement of the W and Z bosons' masses and Weinberg angle θ_W , the VEV is obtained to be $v \simeq 174$ GeV. Now we know that the measured Higgs boson mass is $m_h^2 \simeq (125 \text{ GeV})^2$, then we can obtain λ as:

$$\lambda = -\frac{\mu^2}{2v^2} = \frac{m_h^2}{4v^2} \simeq 0.13. \quad (1.28)$$

To give masses to fermions, we consider the interaction between fermion fields and the scalar field (Yukawa interaction). The effective Lagrangian is:

$$\mathcal{L}_{\text{Yukawa}} = -\bar{\psi}_{i,L} y_{ij}^a \phi \psi_{j,R} - \bar{\psi}_{i,R} y_{ij}^a \phi^\dagger \psi_{j,L}, \quad (1.29)$$

Figure 1.2: An effective potential $V(\phi)$ leading to the spontaneous symmetry breaking [11]. The vacuum (the lowest energy state) is randomly chosen around the bottom of the potential, when the field takes a non-zero VEV.

where $i, j = 1, 2, 3$ indicate the generations of fermions, and a corresponds to fermion's family ($a = \text{'lepton'}$, 'up' and 'down' denote charged lepton, up-type quark, and down-type quark families, respectively). y_{ij}^a is the 3×3 Yukawa coupling constant matrix for each fermion family. ψ_R is the right-handed component of the fermion field: $\psi_R = P_R \psi$, where P_R is defined in Eq. (1.5). We spontaneously break the symmetry and substitute Eq. (1.24) for Eq. (1.29).

For lepton masses, simply the diagonal matrix is chosen as the Yukawa constant i.e.:

$$y_{ij}^{\text{lepton}} = \begin{cases} y_k; k = e, \mu, \tau & (i = j) \\ 0 & (i \neq j). \end{cases} \quad (1.30)$$

For example, focussing on the electron mass and taking $\psi_L = (\nu_e, e)_L$ and $\psi_R = e_R$ from Table 1.1, the effective Lagrangian of the Yukawa interaction for electron is:

$$\begin{aligned} \mathcal{L}_{\text{Yukawa}}^e &= -(\bar{\nu}_e \quad \bar{e})_L y_e \begin{pmatrix} 0 \\ v+h \end{pmatrix} e_R - \bar{e}_R y_e \begin{pmatrix} 0 & v+h \end{pmatrix} \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \\ &= -y_e v (\bar{e}_L e_R + \bar{e}_R e_L) - y_e (\bar{e}_L e_R + \bar{e}_R e_L) h \\ &= -m_e \bar{e} e - y_e \bar{e} e h. \end{aligned} \quad (1.31)$$

The first term is the electron mass term and the second is the interaction between electron and the Higgs field. The coupling constant of electrons to the Higgs field is proportional to electron mass i.e. $y_e = m_e/v$. For the other charged leptons, the same mechanism can be considered.

For quark cases, again the same operation can be made. The flavor mixing should be considered additionally. The effective Lagrangian for quarks ($u_1 = u, u_2 = c, u_3 = t, d'_1 = d', d'_2 = s'$ and $d'_3 = b'$) is:

$$\begin{aligned} \mathcal{L}_{\text{yukawa}}^{\text{quarks}} &= -(\bar{u}_i \quad \bar{d}'_i)_L y_{ij}^{\text{down}} \begin{pmatrix} 0 \\ v+h \end{pmatrix} d'_{j,R} - (\bar{u}_i \quad \bar{d}'_i)_L y_{ij}^{\text{up}} \begin{pmatrix} v+h \\ 0 \end{pmatrix} u_{j,R} + h.c. \\ &= -(v+h) (\bar{d}'_{i,L} y_{ij}^{\text{down}} d'_{j,R} + \bar{u}_{i,L} y_{ij}^{\text{up}} u_{j,R}) + h.c. \\ &= -(v+h) \left[(\bar{d}' \quad \bar{s}' \quad \bar{b}')_L y^{\text{down}} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_R + (\bar{u} \quad \bar{c} \quad \bar{t})_L y^{\text{up}} \begin{pmatrix} u \\ c \\ t \end{pmatrix}_R \right] + h.c. \end{aligned} \quad (1.32)$$

For up-type quarks, charge conjugation ϕ^c is used instead of ϕ . We can choose the diagonal matrix y^{up} for up-type quark family as with the lepton case, since the flavor mixing is not considered. For down-type

quarks, by using the property of the unitary matrix (M_{CKM}), y^{down} is diagonalized and we get:

$$\begin{aligned}
\mathcal{L}_{\text{yukawa}}^{\text{quarks}} &= -(v+h) \left(\begin{pmatrix} \bar{d} & \bar{s} & \bar{b} \end{pmatrix}_L M_{\text{CKM}}^\dagger y^{\text{down}} M_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_R + \begin{pmatrix} \bar{u} & \bar{c} & \bar{t} \end{pmatrix}_L y^{\text{up}} \begin{pmatrix} u \\ c \\ t \end{pmatrix}_R \right) + h.c. \\
&= -(v+h) (y_d \bar{d}_L d_R + y_s \bar{s}_L s_R + y_b \bar{b}_L b_R + y_u \bar{u}_L u_R + y_c \bar{c}_L c_R + y_t \bar{t}_L t_R) + h.c. \\
&= -v y_i \bar{q}_i q_i - y_i \bar{q}_i q_i h \\
&= -m_i \bar{q}_i q_i - y_i \bar{q}_i q_i h.
\end{aligned} \tag{1.33}$$

Here, $q_i; i = 1, \dots, 6$ is each quark flavor and y_i is the diagonal component of y_{ij}^{up} and ($M_{\text{CKM}}^\dagger y_{ij}^{\text{down}} M_{\text{CKM}}$) corresponding to the quark flavor. The quark mass is defined to be $m_i = v y_i$ i.e. the coupling constant of a quark i to the Higgs boson is proportional to m_i .

From the above discussions, Eqs. (1.3) and (1.4) are introduced to $\mathcal{L}_{\text{SM}}$.

1.1.3 Quantum-chromo dynamics (QCD)

The QCD is described as the complete non-Abelian $SU(3)$ symmetry and not associated with spontaneous symmetry breaking. Representing the color triplet of a quark as $q = (r, b, g)$, the gauge invariant Lagrangian of the QCD is defined as:

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \bar{q} (i\gamma^\mu D_\mu - m) q, \tag{1.34}$$

where

$$D_\mu \equiv \partial_\mu + ig_s \sum_{k=1}^8 G_{k\mu} \frac{\lambda_k}{2}, \tag{1.35}$$

$$G_{\mu\nu} = \partial_\mu G_\nu - \partial_\nu G_\mu - g_s G_\mu \times G_\nu, \tag{1.36}$$

$$G_{\mu\nu} = (G_{k\mu\nu}; k = 1, \dots, 8). \tag{1.37}$$

g_s is the strong coupling constant and m is the fermion mass. The λ_k ($k = 1, \dots, 8$) are the 3×3 Hermite matrices to operate color current:

$$\begin{aligned}
\lambda_1 &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda_2 = -\frac{i}{\sqrt{2}} \begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda_3 = -\frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \\
\lambda_4 &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}, \lambda_5 = -\frac{i}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{pmatrix}, \lambda_6 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \\
\lambda_7 &= -\frac{i}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix}, \lambda_8 = -\frac{1}{\sqrt{6}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix},
\end{aligned} \tag{1.38}$$

corresponding to the color states of gluon.

The coupling constant of the QCD interaction is described by $\alpha_s = g_s^2/4\pi$, which is running as a function of the energy scale Q at the higher order calculation. In the leading order calculation of the renormalization group equation, it can be written as:

$$\alpha_s(Q) = \frac{4\pi\alpha_s(\mu_R)}{4\pi + \beta_0\alpha_s(\mu_R) \ln \frac{Q^2}{\Lambda_{\text{QCD}}^2}}, \tag{1.39}$$

where $\beta_0 = 11 - 2n_f/3$ (n_f is the active number of light flavors), μ_R is the renormalization scale and Λ_{QCD} is the cut-off scale at $O(200 \text{ MeV})$. For the non-Abelian gauge group, $\beta_0 > 0$ and $\alpha_s(Q)$ is the decreasing as a function of Q as shown in Fig. 1.3. This is called asymptotic freedom.

By the self-coupling term of gluons in Eq. (1.36), the QCD potential is a combination of the Coulomb-type potential and the potential in proportion to the distance. As a result of the latter term, quarks and gluons are not allowed to be standalone and color confinement occurs. Partons produced in the collider experiments are observed as bunches of multi-hadrons (jets) by the effect of the QCD color confinement.

These are important features of the QCD to describe kinetics of pp collisions at the LHC. More details are explained in Sec. 3.2.1.

Figure 1.3: Running coupling constant α_s as a function of the energy scale Q [12]. The QCD fit includes the measurements at the LHC (black filled circle), TEVATRON (blue triangle and red open circle), HERA (black square and purple diamond) and obtains $\alpha_s(m_Z) = 0.1148 \pm 0.0055$.

1.1.4 Test of the SM

The SM has been tested for a long time by many experiments. In particular, good prediction power is found in the electroweak sector. For example, the SM Higgs boson mass was predicted by the global fit to the precision electroweak measurements at the LEP and TEVATRON to be $94^{+29}_{-24} \text{ GeV}$ at 68% confidence level (CL) and less than 152 GeV at 95% CL [13]. The discovery of a Higgs boson at 125 GeV gives strong constraints to the indirect measurements of the SM parameters in the global fit. Fig. 1.4 shows the latest result of the global fit on the electroweak precision measurements. Blue and light blue contours show 68% and 95% CL allowed regions of m_W and top quark mass (m_t), by the fit including m_h measurement while m_W and m_t measurements are not used in the fit. The best fit result agrees with the direct measurements which are indicated by light green 1σ bands. It demonstrates the successful description of the electroweak theory even at the higher order calculation. If there are some loop contributions from new physics, small disagreement between the indirect and direct measurements will be found. To explore this, more precision measurements of the electroweak parameters are important at the future $e^+e^-/e^\pm p/pp$ collider experiments.

Measurements of the properties of the discovered new boson at 125 GeV are made by the ATLAS and CMS collaborations using all available data from the LHC until the end of 2012 and consistent properties with the Standard Model Higgs boson are reported. The spin-parity is favored to be $J^P = 0^+$ (scalar) [15, 16]. The coupling constants to each fermions/gauge bosons, including b and t quarks and τ lepton, are measured directly and indirectly [17–21] and show good agreements with the SM prediction

Figure 1.4: Contours of 68% and 95% CL obtained from scans of fixed W boson mass (M_W) and top quark mass (m_t) [14]. The blue (grey) areas illustrate the results when including (excluding) the Higgs boson mass measurements. The direct measurements of m_W and m_t are always excluded in the fit. The vertical and horizontal bands (green) indicate the 1σ regions of the direct measurements.

as shown in Fig. 1.5. These results strengthen the implication that the observed new particle is the SM Higgs boson.

Now, all particles predicted by the SM are completed and the SM is established as an accomplished theory.

1.1.5 Problems of the SM

The descriptions of our nature by the SM Lagrangian (Eqs. (1.1)-(1.4)) has succeeded as shown in Sec. 1.1.4, but we already know some problems not covered by the SM. For example:

Number of parameters

The simplest questions about the SM may be ‘what is the generation?’, ‘what is the origin of mass?’, ‘what is the origin of coupling constants?’ and so on. In the SM, these parameters are arbitrary and only constrained by the experimental observations. In general, the question is why there are so many parameters in the SM. If we can merge the $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetries to one unified gauge group, number of parameters can be reduced and more general theory can be established. The theory to describe electroweak and strong interactions in the same gauge group is called the Grand Unified Theory (GUT).

Gravity

Gravity is not included in the SM, but of course we know its existence. If we attempt to describe the gravitational interaction by the SM-like Lagrangian, we should introduce a spin-2 intermediate boson, graviton. Graviton is not discovered (yet).

Dark matter

The existence of unknown, invisible, neutral matters which feel the gravity (dark matters) is indicated by the cosmological observations that some luminous objects move faster than one would

Figure 1.5: Summary of the fits for deviations in the coupling as function of the particle mass, using the observations with CMS [21]. For the fermions, the values of the fitted Yukawa couplings hff are shown, while for vector bosons the square-root of the coupling for the hVV vertex divided by twice the vacuum expectation value of the Higgs boson field. Particle masses for leptons and weak bosons, and the vacuum expectation value of the Higgs boson are taken from the PDG. For the top quark, the same mass used in theoretical calculations is used (172.5 GeV) and for the bottom quark the running mass $m_b(m_b = 125.0 \text{ GeV}) = 2.76 \text{ GeV}$ is used. The solid black line with 68 % and 95 % bands are taken from the fit to the data, while the dashed line shows the SM prediction.

expect [22]. Indirect evidence for the existence of the dark matter was claimed by the measurements of the galaxy rotation curve [23, 24]. The fraction of dark matter in the universe is obtained by measurements of the power spectrum of the cosmic microwave background. In the latest result by a combination of the Planck+WMAP observations [25], the SM particles occupy only 4.9 % of the energy of the universe, while dark matter (26.6 %) and dark energy (68.5 %) which is the unknown energy to expand the universe, carry the remaining parts.

Hierarchy problem

The hierarchy problem is a question why the Higgs boson mass (125 GeV) is much smaller than the Planck scale (10^{19} GeV) where the gravitational interaction becomes comparable in magnitude to the gauge interactions, in spite of the fact that it receives quantum corrections from all particles which couple to the Higgs boson [26–29]. The single Higgs potential is generally described as:

$$V = m_H^2 |H|^2 + \lambda |H|^4. \quad (1.40)$$

In the SM, $m_H = \mu$ at the tree level as shown in Sec. 1.1.2. m_H^2 is negative and λ is positive, for the spontaneous symmetry breaking. By minimizing the potential, observable Higgs boson mass is given by $m_h^2 = 4\lambda v^2 = -2m_H^2$. Therefore, $|m_H|$ cannot be larger than m_h . One loop contribution of a fermion f with a term in the Lagrangian of $\lambda_f \bar{f}fH$ (which is a Yukawa interaction of the SM fermions as described in Sec. 1.1.2) as shown in Fig. 1.6 (a) yields a correction to m_H of:

$$\Delta m_H^2 = -\frac{\lambda_f^2}{8\pi^2} (\Lambda_{UV}^2 + \dots), \quad (1.41)$$

Figure 1.6: One-loop quantum corrections to the Higgs squared mass parameter m_H^2 from (a) a fermion f , and (b) a scalar particle S [30].

where Λ_{UV} is the ultra-violet momentum cutoff scale introduced to regulate the loop integral. The ellipses contain the terms proportional to m_f^2 growing at most logarithmically with Λ_{UV} . The largest correction comes from top quark, since $\lambda_t = y_t \sim 1$ is relatively larger than that for the other fermions. If Λ_{UV} is the Planck scale, Δm_H^2 is larger than m_h by an order 10^{32} GeV². To cancel out this large corrections, m_H ($= \mu$ in the SM) should take unnaturally large value. This is also known as the ‘fine-tuning’ problem. This fine-tuning problem is only for the Higgs boson, since radiative corrections to fermions and vector bosons are cancelled by the chiral and gauge symmetries, respectively.

1.2 Supersymmetry

The idea of supersymmetry (SUSY) [31–39] can explain several problems of the SM listed in Sec. 1.1.5. It introduces ‘superpartner’ for each SM particle which has spin varied by 1/2 i.e. the supersymmetry operator Q transforms bosons into fermions, and vice versa:

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle, Q|\text{Fermion}\rangle = |\text{Boson}\rangle. \quad (1.42)$$

One loop contribution for the Higgs boson mass from the scalar particle S with mass m_S is shown in Fig. 1.6 (b) with a Lagrangian term of $-\lambda_S S^2 H^2$. The diagram gives a correction:

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi} \left\{ \Lambda_{UV}^2 - 2m_S^2 \ln\left(\frac{\Lambda_{UV}}{m_S}\right) + \dots \right\}. \quad (1.43)$$

If there are two complex scalar contributions with $\lambda_S = \lambda_f^2$, the term proportional to Λ_{UV}^2 in Eq. (1.41) is cancelled out [40–45]. The remaining part is at most proportional to $\ln \Lambda_{UV}$. In the minimal supersymmetric extension of the Standard Model (MSSM) [40, 46–49], particle and its superpartner belong to one ‘super-multiplet’ satisfying the $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry, so they should have the same masses, couplings and quantum numbers. As shown in Sec. 1.2.1, superpartners of the left- and right-handed fermions provide two scalar fields contributing to the Higgs boson mass with the same strength. However, since any superpartners have not been observed yet, supersymmetry must be broken to enhance masses of SUSY particles at the electroweak symmetry breaking scale. The hierarchy problem can still be solved if the breaking of supersymmetry is ‘soft’ and supersymmetry-breaking mass parameters are not larger than a few TeV (see Sec. 1.2.3). This is a strong motivation to search for SUSY particles at the TeV energy scale.

Figure 1.7 shows the inverse coupling constants of the gauge interactions corresponding to $SU(3)_C$, $SU(2)_L$ and $U(1)_Y$ as a function of the energy scale calculated by the first order renormalization group

equation assuming the SM and the MSSM, respectively. Three forces are not merged at any energy scale if we assume the SM particles only. If there are new particles at the TeV scale which modify the running of the gauge couplings at the high energy close to the GUT scale (10^{16} GeV), the strength of three interactions can be merged. This is also a good motivation to consider supersymmetry at the TeV scale, although the MSSM is not complete unification because three gauge fields do not belong to one gauge group⁴. The GUT scale 10^{16} GeV is much lower than the Planck scale of 10^{19} GeV, so that there remains possibilities to establish further unified theory including gravity. In the MSSM, graviton and its superpartner gravitino play important roles in a mechanism of the SUSY breaking (see Sec. 1.2.3).

In most of the supersymmetry models, a new quantum number R -parity is required to be conserved (see details in Sec. 1.2.2). This leads to a consequence that the lightest neutral supersymmetric particle (LSP) is stable and can be a strong candidate of the dark matter [50, 51].

There are no particular models established containing supersymmetry. From next sections, let us discuss based on the MSSM.

Figure 1.7: Two-loop renormalization group evolution of the inverse gauge couplings $\alpha_a^{-1}(Q)$ in the SM (dashed lines) and the MSSM (solid lines) [30]. In the MSSM case, masses of the superpartners for the SM fermions are treated as a common threshold varies between 500 GeV and 1.5 TeV, and $\alpha_3(m_Z)$ is varied between 0.117 and 0.121 (blue and red lines, respectively). For both cases, the strengths of three forces are combined at the GUT scale (10^{16} GeV).

1.2.1 Minimum Supersymmetric Standard Model (MSSM)

Particles predicted in the MSSM are listed in Table 1.4. The tilde symbol is used to denote superpartners of the SM particles.

The gauge super-multiplets consist of the gluons and their ‘gluino’ fermionic superpartners and $SU(2)_L \times U(1)_Y$ gauge bosons and their ‘gaugino’ fermionic superpartners. The superpartners of W and B bosons are called ‘wino’ and ‘bino’, respectively.

Leptons and quarks have their scalar superpartners, ‘sleptons’ and ‘squarks’, respectively. Sleptons and squarks are collectively referred as ‘sfermions’. Conventionally, we put ‘s’ to each of the SM

⁴Some GUT models e.g. $SU(5)$ and $SO(10)$ reduces number of parameters of the SM. Some combined models of the GUT and supersymmetry are considered, but they are not explained in this thesis on account of limited space.

Table 1.4: List of the fields of the MSSM and their irreducible representations of the $SU(3)_C \times SU(2)_L \times U(1)_Y$ groups. For simplicity, only one generation of quarks and leptons is exhibited.

Super-multiplets		Boson fields	Fermionic partners	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
gluon/gluino	g	g	$\tilde{g}$	8	1	0
gauge/gaugino	W	$W^\pm, W^0$	$\tilde{W}^\pm, \tilde{W}^0$	1	3	0
	B	B^0	$\tilde{B}^0$	1	1	0
slepton/lepton	L	$(\tilde{\nu}_e, \tilde{e})_L$	$(\nu_e, e)_L$	1	2	-1
	e	$\tilde{e}_R$	e_R	1	1	-2
squark/quark	Q	$(\tilde{u}, \tilde{d})_L$	$(u, d)_L$	3	2	1/3
	u	$\tilde{u}_R$	u_R	3	1	4/3
	d	$\tilde{d}_R$	d_R	3	1	-2/3
Higgs/higgsino	H_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	1	2	1
	H_d	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$	1	2	-1

fermions to express their superpartners e.g. the superpartner of top quark is called ‘stop’, the superpartner of electron is called ‘selectron’, etc. Left-handed doublets and right-handed singlets have individual superpartners. They are denoted as for example $(\tilde{\nu}_e, \tilde{e})_L$ and $\tilde{e}_R$. Since a sfermion is spin 0 scalar, L and R are just for notations and do not stand for its helicity state.

The Higgs super-multiplet consists of the following two complex Higgs doublets and their supersymmetric fermionic ‘higgsinos’.

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}. \quad (1.44)$$

In the MSSM, the two Higgs fields are necessary to give masses to up-type quarks and down-type particles (down-type quarks and charged leptons), respectively. The VEVs for each Higgs field is defined as:

$$v_u = \langle H_u^0 \rangle, \quad v_d = \langle H_d^0 \rangle, \quad (1.45)$$

and the ratio of the two VEVs is conventionally written as:

$$\tan \beta \equiv \frac{v_u}{v_d}. \quad (1.46)$$

The VEV in the SM is considered as:

$$v^2 = v_u^2 + v_d^2 = \frac{4m_Z^2}{g^2 + g'^2}. \quad (1.47)$$

The masses and the CKM mixing angles of the quarks and leptons are determined by the Yukawa couplings and $\tan \beta$ in the MSSM e.g. the top and bottom quark masses are described by:

$$m_t = y_t v_u = y_t v \sin \beta, \quad (1.48)$$

$$m_b = y_b v_d = y_b v \cos \beta, \quad (1.49)$$

at the tree-level.

Number of quantum states in the $SU(3)_C$, $SU(2)_L$ and $U(1)_Y$ symmetries for each super-multiplet are summarized in Table 1.4. As shown in the table, particles and their superpartners have the same properties with each other, except for their spins and masses.

The total Lagrangian of the MSSM is written as:

$$\mathcal{L}_{\text{MSSM}} = -\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu} \quad (1.50)$$

$$-i\psi^\dagger \bar{\sigma}^\mu D_\mu \psi - i\lambda^{\dagger a} \bar{\sigma}^\mu D_\mu \lambda^a \quad (1.51)$$

$$-D^\mu \phi^* D_\mu \phi - V(\phi, \phi^*) \quad (1.52)$$

$$-\frac{1}{2}W^{ij}\psi_i\psi_j + h.c. \quad (1.53)$$

$$-\sqrt{2}g(\phi^* T^a \psi)\lambda^a + h.c. \quad (1.54)$$

$$+\mathcal{L}_{\text{soft}}^{\text{MSSM}}, \quad (1.55)$$

in Weyl's expression. It is basically a simple extension of the SM Lagrangian Eqs. (1.1)-(1.4), which is invariant under the gauge transformation. In addition, the MSSM Lagrangian is invariant under supersymmetry transformation except for the soft breaking term Eq. (1.55). ψ , ϕ and λ^a are the fields for fermions, scalar particles and gauginos, respectively, where $a = 1, \dots, 8$ for gluino, $a = 1, 2, 3$ for wino and $a = 1$ for bino. $F_{\mu\nu}^a$ is the field strength tensor for each vector boson field ($a = 1, 2, 3$ corresponds to $U(1)_Y$, $SU(2)_L$ and $SU(3)_C$), and D_μ is a covariance derivative appropriately chosen to keep the gauge invariance, which is the same with the SM. The first to forth terms of $\mathcal{L}_{\text{MSSM}}$ represents kinetics and interactions of gauge bosons, fermions, gauginos, and scalar particles, respectively. The fifth term $V(\phi)$ represents the scalar potential and the sixth term Eq. (1.53) describes interactions of fermions to scalar fields. W^{ij} is defined as:

$$W^{ij} = \frac{\delta^2}{\delta\phi_i\delta\phi_j}W,$$

where W is so-called superpotential. The scalar potential V is defined as:

$$V(\phi, \phi^*) = W^i W_i^* - \frac{1}{2}g^2(\phi^* T\phi)^2 \quad (1.56)$$

where W^i is:

$$W^i = \frac{\delta W}{\delta\phi_i}.$$

Let us start from the discussion about interactions described by the supersymmetric Lagrangian Eqs. (1.50)-(1.54) except for the soft breaking term Eq. (1.55), focusing on the third generation particles in particular stop. The definition of the superpotential for the MSSM is:

$$W_{\text{MSSM}} = \tilde{u}\mathbf{y}_u\tilde{Q}H_u - \tilde{d}\mathbf{y}_d\tilde{Q}H_d - \tilde{e}\mathbf{y}_e\tilde{L}H_d + \mu H_u H_d. \quad (1.57)$$

The H_u , H_d , $\tilde{Q}$, $\tilde{L}$, $\tilde{u}$, $\tilde{d}$ and $\tilde{e}$ are scalar fields corresponding to the Higgs and chiral supermultiplets in Table 1.4. The μ term is the supersymmetric version of the Higgs boson mass in the SM. In order to define the superpotential W_{MSSM} as a holomorphic function, at least two Higgs doublets are necessary i.e. terms $H_u^* H_u$ and $H_d^* H_d$ are forbidden and the term $\tilde{u}\tilde{Q}H_u$ cannot be replaced by $\tilde{u}\tilde{Q}H_d$. $\mathbf{y}_u$, $\mathbf{y}_d$ and $\mathbf{y}_e$ are the 3×3 Yukawa coupling matrices in family space, after the diagonalization using the CKM matrix as discussed in Sec. 1.1.2. For simplicity, it is useful to approximate $\mathbf{y}_u$, $\mathbf{y}_d$ and $\mathbf{y}_e$ as:

$$\mathbf{y}_u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_t \end{pmatrix}, \mathbf{y}_d = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_b \end{pmatrix}, \mathbf{y}_e = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_\tau \end{pmatrix} \quad (1.58)$$

since the top, bottom quarks and tau lepton are much heavier than the other fermions in each family. Then, W_{MSSM} can be re-written as:

$$W_{\text{MSSM}} = y_t(\tilde{t}\tilde{t}H_u^0 - \tilde{t}\tilde{b}H_u^+) - y_b(\tilde{b}\tilde{t}H_d^- - \tilde{b}\tilde{b}H_d^0) - y_\tau(\tilde{\tau}\tilde{\nu}_\tau H_d^- - \tilde{\nu}_\tau\tilde{\tau}H_d^0) + \mu(H_u^+ H_d^- - H_u^0 H_d^0) \quad (1.59)$$

Substituting Eq. (1.59) for Eq. (1.53), we can get the fermion mass terms in the same mechanism as the SM. For example, focussing on the terms containing y_t , the effective Lagrangian of scalar-fermion-fermion coupling is:

$$-\mathcal{L}_{\text{scalar-fermion-fermion}}^t = y_t \left(\tilde{t}_L t_R H_u^0 + \tilde{t}_L \tilde{H}_u^0 \tilde{t}_R + \tilde{H}_u^0 t_R \tilde{t}_L \right) - y_t \left(\tilde{t}_L b_R H_u^+ + \tilde{t}_L \tilde{H}_u^+ \tilde{b}_R + \tilde{H}_u^+ b_R \tilde{t}_L \right) + h.c. \quad (1.60)$$

Since spontaneous electroweak symmetry breaking occurs only for neutral Higgs fields (H_u^0 and H_d^0), we get top quark mass term and $\tilde{t}\tilde{H}_u^0$ interaction shown in the diagram in Fig. 1.8 (a). This Lagrangian leads to additional 5 scalar-fermion-fermion currents associated with y_t . Examples of diagrams for stop-higgsino-top interactions are shown in Fig. 1.8 (b) and (c). There is another diagram for each of the three diagrams with $H_u^0 \rightarrow H_u^+$ and $t_L \rightarrow -b_L$ with tildes where appropriate i.e. top-bottom-Higgs, stop-bottom-higgsino and sbottom-top-higgsino interactions, respectively. Also, if we focus on μ term of Eq. (1.59), we get:

$$-\mathcal{L}_{\text{higgsino mass}} = \mu \left(\tilde{H}_u^+ \tilde{H}_d^- - \tilde{H}_u^0 \tilde{H}_d^0 \right) + c.c., \quad (1.61)$$

from Eq. (1.53), which represents the mass terms of the charged and neutral higgsinos. Mass terms for gauginos do not appear due to the definition of the superpotential W_{MSSM} , which are generated only through the soft breaking term $\mathcal{L}_{\text{soft}}^{\text{MSSM}}$ as discussed in Sec. 1.2.3. Additionally, substituting Eq. (1.59) for the scalar potential Eq. (1.56), we get terms:

$$W^i W_i^* = \left| y_t (\tilde{t} H_u^0 - \tilde{b} H_u^+) \right|^2 + \left| y_t \tilde{t} H_u^0 - y_b \tilde{b} H_d^0 \right|^2 + \left| y_t \tilde{t} \tilde{t} - \mu H_d^0 \right|^2 + \left| y_t \tilde{t} \tilde{b} + \mu H_d^- \right|^2 + \dots, \quad (1.62)$$

and find (scalar)⁴, (scalar)³, and (scalar)² interactions. The only (scalar)⁴ and (scalar)³ interactions associated with y_t can be written as:

$$-\mathcal{L}_{(\text{scalar})^4}^t = y_t^2 \left(\left| \tilde{t}_L \right|^2 \left| \tilde{t}_R \right|^2 + \left| \tilde{t}_R \right|^2 \left| H_u^0 \right|^2 + \left| \tilde{t}_L \right|^2 \left| H_u^0 \right|^2 + \tilde{t}_L^* \tilde{b}_L \tilde{t}_R^* \tilde{b}_R \right) + h.c. \quad (1.63)$$

$$-\mathcal{L}_{(\text{scalar})^3}^t = \mu^* y_t \left(\tilde{t} \tilde{t} H_d^{0*} + \tilde{t} \tilde{b} H_d^{-*} \right) + c.c. \quad (1.64)$$

The first, second and third terms of Eq. (1.63) correspond to diagrams shown in Figs. 1.9 (a), (b) and (c), respectively. Figure 1.9 (b) and (c) are the $-\lambda_S |S|^2 |H|^2$ interactions, solving the hierarchy problem. The diagrams for (scalar)³ interactions are shown in Fig. 1.10. The supersymmetric Higgs mass terms:

$$-\mathcal{L}_{\text{Higgs mass}} = |\mu|^2 \left(\left| H_u^0 \right|^2 + \left| H_u^+ \right|^2 + \left| H_d^0 \right|^2 + \left| H_d^- \right|^2 \right) \quad (1.65)$$

appear as (scalar)² terms. More details about the MSSM Higgs sector including the soft breaking term are discussed in Sec. 1.2.4. There are also various scalar quartic interactions according to the second term of Eq. (1.56) including (Higgs)⁴ terms proportional to g^2 and g'^2 . They are the generalization of the Higgs self-coupling term in the SM.

Interactions of gauginos are described by the terms in Eq. (1.54). g in Eq. (1.54) represents an appropriate coupling constant. Gauginos couple to (squark, quark), (slepton, lepton), (Higgs, higgsino) pairs. For example, each of the squark-quark-gluino couplings is given by $\sqrt{2}g_s (\tilde{q} T^a q \tilde{g} + c.c.)$ where $T^a = \lambda^a / \sqrt{2}$; $a = 1, \dots, 8$ are the matrix generators for $SU(3)_C$ defined in Eq. (1.38). Examples of the squark-quark-gaugino interactions are shown in Fig. 1.11.

1.2.2 R-parity

The MSSM superpotential Eq. (1.57) is defined to conserve the R -parity as:

$$R = (-1)^{3(B-L)+2S}. \quad (1.66)$$

Figure 1.8: The top-quark Yukawa coupling (a) and its supersymmetrizations (b), (c), all of strength y_t [30]

Figure 1.9: Some of the (scalar)⁴ interactions with strength proportional to y_t^2 [30]

B , L and S are baryon number, lepton number and spin for a given particle, respectively, summarized in Table 1.1 (Spin for SUSY particles is varied by $1/2$). All particles in the SM have $R = +1$, while their superpartners have $R = -1$. Since initial-state particles involve $R = +1$ in the collider experiment, SUSY particles must be generated in pair and decay into the lighter SUSY particle and the SM particle. Therefore, the LSP is stable and the strong candidate of the dark matter.

1.2.3 SUSY breaking

The soft breaking term $\mathcal{L}_{\text{MSSM}}$ can be written as:

$$\mathcal{L}_{\text{soft}}^{\text{MSSM}} = -\frac{1}{2} (M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B} + c.c.) \quad (1.67)$$

$$- (\tilde{u} \mathbf{a}_u \tilde{Q} H_u - \tilde{d} \mathbf{a}_d \tilde{Q} H_d - \tilde{e} \mathbf{a}_e \tilde{L} H_d + c.c.) \quad (1.68)$$

$$- \tilde{Q}^\dagger \mathbf{m}_{\tilde{Q}}^2 \tilde{Q} - \tilde{L}^\dagger \mathbf{m}_{\tilde{L}}^2 \tilde{L} - \tilde{u} \mathbf{m}_{\tilde{u}}^2 \tilde{u}^\dagger - \tilde{d} \mathbf{m}_{\tilde{d}}^2 \tilde{d}^\dagger - \tilde{e} \mathbf{m}_{\tilde{e}}^2 \tilde{e}^\dagger \quad (1.69)$$

$$- m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + c.c.). \quad (1.70)$$

M_1 , M_2 and M_3 in the first line Eq. (1.67) represent the masses of gauginos (bino, wino, and gluino, respectively). The (scalar)³ couplings are represented in Eq. (1.68). Each $\mathbf{a}_u$, $\mathbf{a}_d$, $\mathbf{a}_e$ is a complex 3×3 matrix in family space, which corresponds to the Yukawa couplings of the superpotential and only breaks the flavor symmetry. The third line Eq. (1.69) shows the mass terms of squarks and sleptons, which are invariant under the gauge transformation. Each $\mathbf{m}_{\tilde{Q}}^2$, $\mathbf{m}_{\tilde{u}}^2$, $\mathbf{m}_{\tilde{d}}^2$, $\mathbf{m}_{\tilde{L}}^2$ and $\mathbf{m}_{\tilde{e}}^2$ is a 3×3 matrix in family space. The fourth line Eq. (1.70) contains supersymmetry-breaking contributions to the Higgs potential, where $m_{H_u}^2$ and $m_{H_d}^2$ and b are the squared-mass parameter in the dimension of (mass)².

The MSSM has too many parameters of 124, after introducing the soft breaking term. To reduce parameters, some constrained MSSMs are proposed. It is desirable that supersymmetry breaks spontaneously, but it is very difficult to construct a realistic model. To achieve the SUSY breaking at the

Figure 1.10: Some of the supersymmetric (scalar)³ coupling proportional to $\mu^* y_t$, $\mu^* y_b$ and $\mu^* y_\tau$ [30]. When H_u^0 and H_d^0 get VEVs, those contribute to (a) $\tilde{t}_L$, $\tilde{t}_R$ mixing, (b) $\tilde{b}_L$, $\tilde{b}_R$ mixing, and (c) $\tilde{\tau}_L$, $\tilde{\tau}_R$ mixing.

Figure 1.11: Couplings of the gluino, wino, and bino to MSSM scalar-fermion pairs [30].

electroweak symmetry breaking scale, the MSSM consists of (at least) two distinct sectors: ‘a hidden’ sector and ‘a visible’ sector. A visible sector consists of the MSSM particles listed in Table 1.4, while a hidden sector consists of particles completely independent from the SM gauge groups. There are no tree-level interactions between particles in a visible and a hidden sector. Supersymmetry breaking is considered to occur in the hidden sector and the effects are mediated to the MSSM by some mechanism. As examples, two famous mechanisms are listed below:

Gravity mediated SUSY breaking (supergravity)

In the models so-called ‘supergravity (SUGRA)’, gravity is considered as the messenger to mediate the SUSY breaking. More precisely, SUSY breaking is mediated by effects of gravitational strength. It introduces the graviton and its spin-3/2 superpartner, gravitino. The mass of gravitino is of order at the electroweak symmetry breaking scale, and its coupling is gravitational in strength. Therefore, gravitino does not play an important role in SUGRA models. In the minimal SUGRA (mSUGRA) model [52–57], which is explained in details in Sec. 1.2.5, the number of parameters in addition to the SM is reduced to be five.

Gauge mediated SUSY breaking (GMSB)

In the gauge mediated SUSY breaking (GMSB) models [58–63], gauge interactions mediate the SUSY breaking to the MSSM. The models involve a hidden sector where supersymmetry is broken, a messenger sector consisting of messenger particles with non-trivial $SU(3) \times SU(2) \times U(1)$ quantum numbers, and the visible sector. SUSY breaking spectrum in the messenger sector occurs by the direct coupling of the messengers to the hidden sector, and then transmitted to the visible sector via the virtual exchange of the messenger. In this models, gravitino mass is in the eV range, which leads it to be the LSP.

In this thesis, we stand for a mSUGRA-like scenario. The LSP is assumed to be the neutralino ($\tilde{\chi}_1^0$).

1.2.4 The MSSM Higgs sector

Concerning the soft-breaking term, the total Higgs potential in the MSSM can be written as:

$$\begin{aligned}
 V = & \left(|\mu|^2 + m_{H_u}^2 \right) \left(|H_u^0|^2 + |H_u^\pm|^2 \right) + \left(|\mu|^2 + m_{H_d}^2 \right) \left(|H_d^0|^2 + |H_d^\pm|^2 \right) \\
 & + \left[b \left(H_u^+ H_d^- - H_u^0 H_d^0 \right) + c.c. \right] \\
 & + \frac{1}{8} (g^2 + g'^2) \left(|H_u^0|^2 + |H_u^\pm|^2 - |H_d^0|^2 - |H_d^\pm|^2 \right)^2 + \frac{1}{2} |H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2.
 \end{aligned} \quad (1.71)$$

We break the electroweak symmetry spontaneously and get:

$$V = \begin{pmatrix} v_u & v_d \end{pmatrix} \begin{pmatrix} |\mu|^2 + m_{H_u}^2 & -b \\ -b & |\mu|^2 + m_{H_d}^2 \end{pmatrix} \begin{pmatrix} v_u \\ v_d \end{pmatrix} + \frac{1}{8} (g^2 + g'^2) (v_u^2 - v_d^2)^2, \quad (1.72)$$

by choosing the phases of the Higgs fields such that b is real and non-negative. The vacuum minimization conditions are given by $\partial V / \partial v_u = \partial V / \partial v_d = 0$ to be:

$$\sin 2\beta = \frac{2b}{m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2}, \quad (1.73)$$

$$\frac{1}{2} m_Z^2 = -|\mu|^2 + \frac{m_{H_u}^2 - m_{H_d}^2 \tan^2 \beta}{\tan^2 \beta - 1}. \quad (1.74)$$

The degrees of freedom of the Higgs scalar fields in the MSSM is eight before the symmetry breaking. Three of them are eaten by the massive Z^0 and $W^\pm$ bosons as with the SM, and five Higgs scalar mass eigenstates are expected. They consist of two CP -even neutral scalars h^0 and H^0 , one CP -odd neutral scalar A^0 , and two charged scalar $H^\pm$. The masses of the Higgs bosons are obtained from the potential Eq. (1.72) and Eqs. (1.74)-(1.74):

$$m_{A^0}^2 = 2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2, \quad (1.75)$$

$$m_{h^0, H^0}^2 = \frac{1}{2} \left(m_{A^0}^2 + m_Z^2 \mp \sqrt{(m_{A^0}^2 + m_Z^2)^2 - 4m_Z^2 m_{A^0}^2 \cos^2(2\beta)} \right), \quad (1.76)$$

$$m_{H^\pm}^2 = m_{A^0}^2 + m_W^2 \quad (1.77)$$

at the tree level. Therefore, we can describe the MSSM Higgs sector by three independent parameters: m_{A^0} , $\tan \beta$ and sign of μ^2 . We can find in Eq. (1.76) that the lighter CP -even neutral Higgs boson should satisfy:

$$m_{h^0} \leq m_Z \cos 2\beta \leq m_Z, \quad (1.78)$$

at the tree level. Since the Higgs boson mass are affected by the radiative corrections as discussed in Sec. 1.2.6, it can be heavier than m_Z . The largest correction arises from top quark and stop, due to the large Yukawa coupling constant y_t . In the next-to-leading order calculation, m_{h^0} should be less than 135 GeV, depending on stop parameters. The observed Higgs boson mass is consistent with the above discussion.

1.2.5 SUSY spectrum

From here, for the simplicity, a discussion about the SUSY breaking takes place in the context of the mSUGRA. In the mSUGRA, we approximate:

$$M_1 = M_2 = M_3 = m_{1/2}, \quad (1.79)$$

$$m_{\tilde{Q}}^2 = m_{\tilde{L}}^2 = m_{\tilde{u}}^2 = m_{\tilde{d}}^2 = m_{\tilde{e}}^2 = m_0^2, \quad (1.80)$$

$$m_{H_u}^2 = m_{H_d}^2 = m_0^2, \quad (1.81)$$

Figure 1.12: Evolution of scalar and gaugino mass parameters in the MSSM with mSUGRA boundary conditions [30]. The parameters are $m_0 = 200$ GeV, $m_{1/2} = 600$ GeV, $A_0 = -600$ GeV, $\tan\beta = 10$ and $\text{sign}\mu > 0$.

at the GUT scale, where $m_{1/2}$ and m_0 are unified gaugino and sfermion masses, respectively, as shown in Fig. 1.12. $\mathbf{1}$ is the 3×3 identity matrix, which suppresses the FCNCs and CP -violating currents. In order to break supersymmetry in ‘soft’, m_0 and $m_{1/2}$ are at most $O(1)$ TeV. The (scalar)³ couplings in Eq. (1.68) are defined to be proportional to the corresponding Yukawa coupling matrix as:

$$\mathbf{a}_u = A_u \mathbf{y}_u, \mathbf{a}_d = A_d \mathbf{y}_d, \mathbf{a}_e = A_e \mathbf{y}_e. \quad (1.82)$$

Using the approximation Eq. (1.58), A_f for first and second generations are negligible i.e.

$$\mathbf{a}_u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_t A_u \end{pmatrix}, \mathbf{a}_d = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_b A_d \end{pmatrix}, \mathbf{a}_e = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_\tau A_e \end{pmatrix}. \quad (1.83)$$

In the mSUGRA, we put common A_f value at the GUT scale as $A_u = A_d = A_e = A_0$. Renormalization group evolution is employed to derive masses of gauginos and sfermions and A_f at the electroweak scale. Therefore, the MSSM spectrum and its interaction strengths are determined only by five parameters of:

$$\{m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu)\} \quad (1.84)$$

and an independent graviton mass, in addition to the SM parameters. The constrained MSSM (cMSSM) models like mSUGRA are useful to study the phenomenological behavior of the MSSM.

Gaugino masses

Gaugino masses are proportional to the strength of the interaction:

$$M_3 : M_2 : M_1 = g_s^2 : g^2 : \frac{5}{3} g'^2 = 6 : 2 : 1, \quad (1.85)$$

at the TeV scale, as shown in Figs. 1.7 and 1.12. This means gluino mass is much larger than the other gauginos at the TeV scale.

Masses of wino, bino and higgsino are mixed and form four charginos $\tilde{\chi}_{1,2}^\pm$ and four neutralinos $\tilde{\chi}_{1,2,3,4}^0$. The tree-level mixing of the $\tilde{W}^\pm$ and $\tilde{H}_u^\pm/\tilde{H}_d^\pm$ is described by the 2×2 complex mass matrix:

$$\begin{pmatrix} M_2 & \sqrt{2}m_W \sin\beta \\ \sqrt{2}m_W \cos\beta & \mu \end{pmatrix}, \quad (1.86)$$

where the M_2 comes from the soft breaking Lagrangian Eq. (1.67), μ comes from higgsino mass term Eq. (1.61), and terms proportional to m_W comes from Higgs-higgsino-wino couplings described by Eq. (1.54). Diagonalizing the matrix, one gets chargino masses as:

$$m_{\tilde{\chi}_{1,2}^\pm}^2 = \frac{1}{2} \left\{ (M_2^2 + \mu^2 + 2m_W^2) \mp \sqrt{(M_2^2 + \mu^2 + 2m_W^2)^2 - 4(\mu M_2 - m_W^2 \sin 2\beta)^2} \right\}. \quad (1.87)$$

The neutralino masses ($m_{\tilde{\chi}_{1,2,3,4}^0}$) can also be calculated by diagonalizing the following 4×4 mixing matrix:

$$\begin{pmatrix} M_1 & 0 & -\cos\beta \sin\theta_W m_Z & \sin\beta \sin\theta_W m_Z \\ 0 & M_2 & \cos\beta \cos\theta_W m_Z & -\sin\beta \cos\theta_W m_Z \\ -\cos\beta \sin\theta_W m_Z & \cos\beta \cos\theta_W m_Z & 0 & -\mu \\ \sin\beta \sin\theta_W m_Z & -\sin\beta \cos\theta_W m_Z & -\mu & 0 \end{pmatrix}. \quad (1.88)$$

As with the chargino case, M_1 and M_2 come from the soft breaking term, μ comes from higgsino mass term, and terms proportional to m_Z come from Higgs-higgsino-gaugino couplings.

In the case of $|\mu| \gg M_2, m_W, m_Z$, the LSP is bino-like i.e. $\tilde{\chi}_1^\pm \sim \tilde{W}^\pm$, $\tilde{\chi}_2^\pm \sim \tilde{H}^\pm$, $\tilde{\chi}_1^0 \sim \tilde{B}$ and $\tilde{\chi}_2^0 \sim \tilde{W}^0$. In this limit, the mass difference between chargino and the LSP is approximated to:

$$m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_2^0} \simeq 2m_{\tilde{\chi}_1^0}, \quad (1.89)$$

at the TeV scale, by using the relation in Eq. (1.85). On the other hand, in the case of $|\mu| \ll M_2, m_W, m_Z$, masses of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_{1,2}^0$ are close to masses of $\tilde{H}^\pm$, $\tilde{H}_u^0$ and $\tilde{H}_d^0$ (higgsino-like LSP). In this case, the mass differences are given as the following [64].

$$\Delta m = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \simeq \frac{m_Z^2}{2} \left(\frac{\cos^2\theta_W}{M_2} + \frac{\sin^2\theta_W}{M_1} \right). \quad (1.90)$$

The small Δm value depending on M_1 and M_2 is expected. If we assume $M_1 \simeq M_2 \simeq 1$ TeV, Δm is about 5 GeV.

Squark and slepton masses

Masses of squarks and sleptons can be written using the renormalization group equation as:

$$m_{\tilde{d}_L}^2 = m_0^2 + K_3 + K_2 + \frac{1}{36}K_1 + \Delta_{\tilde{d}_L}, \quad (1.91)$$

$$m_{\tilde{u}_L}^2 = m_0^2 + K_3 + K_2 + \frac{1}{36}K_1 + \Delta_{\tilde{u}_L}, \quad (1.92)$$

$$m_{\tilde{d}_R}^2 = m_0^2 + K_3 + \frac{1}{9}K_1 + \Delta_{\tilde{d}_R}, \quad (1.93)$$

$$m_{\tilde{u}_R}^2 = m_0^2 + K_3 + \frac{4}{9}K_1 + \Delta_{\tilde{u}_R}, \quad (1.94)$$

$$m_{\tilde{e}_L}^2 = m_0^2 + K_2 + \frac{1}{4}K_1 + \Delta_{\tilde{e}_L}, \quad (1.95)$$

$$m_{\tilde{\nu}_L}^2 = m_0^2 + K_2 + \frac{1}{4}K_1 + \Delta_{\tilde{\nu}_L}, \quad (1.96)$$

$$m_{\tilde{e}_R}^2 = m_0^2 + K_1 + \Delta_{\tilde{e}_R}, \quad (1.97)$$

where K_1 , K_2 and K_3 are the contributions from $U(1)_Y$, $SU(2)_L$ and $SU(3)_C$ interactions, respectively, which are approximated as:

$$K_1 \simeq 0.15m_{1/2}^2, \quad K_2 \simeq 0.5m_{1/2}^2, \quad K_3 \simeq (5.8 \pm 1.0)m_{1/2}^2.$$

m_0 terms come from the soft breaking term Eq. (1.69) with a mSUGRA assumption Eq. (1.80). Δ terms are given by:

$$\Delta_{\tilde{f}_L} = (T^3 - Q \sin^2 \theta_W) m_Z^2 \cos 2\beta + m_f^2 \quad (1.98)$$

$$\Delta_{\tilde{f}_R} = Q \sin^2 \theta_W m_Z^2 \cos 2\beta + m_f^2, \quad (1.99)$$

which depends on weak isospin, hypercharge, and the fermion mass, and resolve the degeneracy between up- and down-type left-handed sfermion masses. For the first and second generation sfermions, the effect of Δ is negligible, since effects from m_0 and gauge correction terms are much larger than that. This leads to that first and second generation sfermions are degenerated. In general, left-handed sfermions are heavier than right-handed sfermions due to the term associated with K_2 . In addition, squark masses are larger than slepton masses due to the term associated with K_3 .

Mass eigenstates of sfermions are obtained by L - R mixing. The (scalar)³ couplings $(\tilde{f}\tilde{f}H)$, which appear in both supersymmetric Lagrangian Eq. (1.64) and the soft breaking term Eq. (1.83), are considered as the off-diagonal term of the mass matrix. The (scalar)³ couplings $-\mu y_f \tilde{f} \tilde{f} H_d^*$ in Eq. (1.64) and $y_f A_f \tilde{f} \tilde{f} H_u$ in Eq. (1.68) become $-\mu^* y_f \tilde{f}_L \tilde{f}_R^* v \cos \beta$ and $y_f A_f v \tilde{f}_L \tilde{f}_R^* \sin \beta$, respectively, after the field gets the VEV. In the assumption of Eq. (1.83), these terms are negligible for the first and second generation sparticles i.e. there is no mixing in the first and second generations. It is enough to account for them only for third generation sfermions. For example, if we put focus on the stop mass, mass eigenstates ($\tilde{t}_1$, $\tilde{t}_2$) are given by diagonalizing the following 2×2 mass matrix:

$$\begin{pmatrix} m_{\tilde{t}_L}^2 & m_t (A_t - \mu \cot \beta) \\ m_t (A_t - \mu^* \cot \beta) & m_{\tilde{t}_R}^2 \end{pmatrix} \quad (1.100)$$

at the tree level ($m_t = y_t v \sin \beta$ as shown in Eq. (1.48)). The off-diagonal terms suppress masses of the third generation sfermions. As a result, one obtains $\tilde{t}_2 - \tilde{t}_1 \simeq O(m_t)$ and the lighter stop $\tilde{t}_1$ is the lightest squark.

1.2.6 Natural SUSY versus 125 GeV Higgs boson

From Eq. (1.76), the lighter CP -even neutral Higgs boson mass is described by:

$$m_{h^0}^2 = m_Z^2 \cos^2 2\beta + \delta_t^2, \quad (1.101)$$

in the decoupling limit ($m_{A^0} \gg m_Z$), where δ_t arises from loops of top quark and stop. At the large $\tan \beta$ limit, we need $\delta_t \simeq 85$ GeV to get the observed Higgs boson mass of 125 GeV. At the one loop calculation,

$$\delta_t^2 = \frac{3}{(4\pi)^2} \frac{m_t^4}{v^2} \left[\ln \frac{m_t^2}{m_{\tilde{t}}^2} + \frac{X_t^2}{m_{\tilde{t}}^2} \left(1 - \frac{X_t^2}{12m_{\tilde{t}}^2} \right) \right], \quad (1.102)$$

where $m_{\tilde{t}}^2 = m_{\tilde{t}_L} m_{\tilde{t}_R}$ and $X_t = A_t - \mu \cot \beta$ is the off-diagonal term of the mass matrix for stop. Allowed $m_{\tilde{t}}$ versus $X_t/m_{\tilde{t}}$ region to get 125 GeV Higgs boson is shown in Fig. 1.13 by the blue and red bands, corresponding to different renormalization prescriptions. The figure shows that heavy stop mass of greater than approximately 600 GeV is necessary to achieve 125 GeV Higgs boson mass. The minimum value

Figure 1.13: Contours of m_h in the MSSM as a function of a common stop mass $m_{\tilde{t}_L} = m_{\tilde{t}_R} = m_{\tilde{t}}$ and the stop mixing parameter X_t , for $\tan\beta = 20$ [65]. The red (light gray) and blue (deep gray) bands show the results from Suspect and FeynHiggs prescriptions, respectively, for m_h in the range of 124 to 126 GeV. All gaugino masses are fixed to 1 TeV, the Higgsino mass to $\mu = 200$ GeV, and $m_{A^0} = 1$ TeV. Purple lines show the fine-tuning of the Higgs mass, Δ_{m_h} . In order to boost the Higgs boson mass to 124 (126) GeV, we need $\Delta_{m_h} > 75$ (100).

of $m_{\tilde{t}}$ is obtained at the maximum mixing $X_t = \sqrt{6}m_{\tilde{t}}$. When X_t is varied to be absence, $m_{\tilde{t}}$ is required to be dramatically increased to a multi-TeV scale to achieve 125 GeV Higgs.

On the other hand, if we consider the degree of fine-tuning, stop mass is preferred to be light [64, 66, 67]. Let us recall a single Higgs field with the potential Eq. (1.40). In the context of the MSSM with large $\tan\beta$ ($m_{H_u} \gg m_{H_d}$), m_H^2 in Eq. (1.40) is written by:

$$m_H^2 = |\mu|^2 + m_{H_u}^2 + \delta m_{H_u}^2. \quad (1.103)$$

The amount of fine-tuning is determined by the size of the Higgs mass relative to the size of corrections to the quadratic term of the potential:

$$\Delta^{-1} = \frac{m_h^2}{2\delta m_{H_u}^2}. \quad (1.104)$$

Contributions to the quadratic term of the Higgs potential, $\delta m_{H_u}^2$, are written as:

$$\delta m_{H_u}^2 \simeq -\frac{3y_t^2}{8\pi^2} (m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + |A_t|^2) \ln\left(\frac{M_{\text{mess}}}{m_{\tilde{t}}}\right), \quad (1.105)$$

where M_{mess} is the messenger mass for supersymmetry breaking. If $\delta m_{H_u}^2$ becomes too large, the parameters of the theory must be tuned against each other to achieve the correct scale of electroweak symmetry

breaking. Assuming $m_h = 125$ GeV and requiring $\Delta^{-1} > 10\%$, the condition

$$\begin{aligned} m_{\tilde{t}}^2 &\leq \frac{2\pi^2}{3y_t^2 \left(1 + \frac{x^2}{2}\right)} \frac{m_H^2}{\Delta^{-1} \ln \frac{M_{\text{mess}}}{m_{\tilde{t}}}} \\ &\simeq (600 \text{ GeV})^2 \frac{1}{1 + \frac{x^2}{2}} \left(\frac{10\%}{\Delta^{-1}} \right) \left(\frac{3}{\ln \frac{M_{\text{mess}}}{m_{\tilde{t}}}} \right) \end{aligned} \quad (1.106)$$

is obtained [64], where $x \equiv |A_t|/m_{\tilde{t}}$. Unless extremely small $M_{\text{mess}} \leq 10$ TeV, the absence of fine-tuning requires $m_{\tilde{t}} \lesssim 600$ GeV. We would remark that large value of $|A_t|^2 = |X_t|^2 = 6m_{\tilde{t}}^2$ at large $\tan\beta$ also introduces fine-tuning as clearly found in Eq. (1.105). In addition, from the μ term of Eq. (1.103), higgsino mass is favored to be light [64]. If the fine-tuning parameter is defined as:

$$\Delta^{-1} = \frac{m_h^2}{2|\mu|^2} \quad (1.107)$$

and $\Delta^{-1} > 10\%$ is required,

$$|\mu| \lesssim 280 \text{ GeV} \left(\frac{10\%}{\Delta^{-1}} \right). \quad (1.108)$$

The light higgsino strengthens the higgsino-like LSP scenario. Another more complicated (general) parameter to describe the fine-tuning is defined in Ref. [65], by considering the sensitivity of the Higgs mass eigenvalue to variations of the fundamental parameters of the theory. It is defined to be maximum logarithmic derivative of the Higgs boson mass with respect to the fundamental parameters, p_i ,

$$\Delta_{m_h} = \max_i \left| \frac{\partial \ln m_h^2}{\partial \ln p_i} \right|, \quad (1.109)$$

where one takes the fundamental parameters, defined at the messenger scale M_{mess} , to be $\mu, b, m_{\tilde{t}_L}^2, m_{\tilde{t}_R}^2, A_t, m_{\tilde{H}_u}^2, m_{\tilde{H}_d}^2$. The value of Δ_{m_h} is computed at tree-level and the one-loop leading log contribution to $m_{\tilde{H}_u}^2$ is included given by Eq. (1.105), which allows to relate the value of $m_{\tilde{H}_u}^2$ at the cutoff to its value at the weak scale. Purple dashed lines in Fig. 1.13 show the contours of Δ_{m_h} values on the given parameter space of $m_{\tilde{t}}$ and $X_t/m_{\tilde{t}}$. One finds, even at the maximum mixing of $X_t = \sqrt{6}m_{\tilde{t}}$, at least $\Delta_{m_h} \simeq 100$ (i.e. order 1 % fine-tuning) is necessary. When X_t is varied to be absence, the value of the fine-tuning suddenly becomes quite large to be $\Delta_{m_h} = 1000$ or more.

Naturalness is improved in theories with a singlet superfield S coupled to the Higgs superfields via $\lambda S H_u H_d$, like next-to-minimum supersymmetric extension of the SM (NMSSM) [65]. If λ is perturbative up-to unified scales, the magnitude of fine-tuning is moderated to about 10 % with a low mediation scale. Figure 1.14 shows the possible region of $m_{\tilde{t}}$ and $X_t/m_{\tilde{t}}$ for 125 ± 1 GeV Higgs boson, in comparison with the contours of Higgs fine-tuning Δ_{m_h} in the NMSSM models with the different two $\tan\beta$ values. When $\tan\beta = 2$, the fine-tuning can be low, $\Delta_{m_h} < 15$ at $m_{\tilde{t}} < 500$ GeV and $X_t < 2m_{\tilde{t}}$, while for $\tan\beta = 5$, heavier stop masses are required.

As discussed above, now, we stand at a turning point in the development of the SUSY model. Some models give up the natural solution of the hierarchy problem and assume heavy sfermions at $O(100-1000)$ TeV [68–70]. If we stand for those models, large fine-tuning of at most $\Delta^{-1} = 0.1-1\%$ cannot be avoided. The analysis shown in this thesis makes, so to say, a last-gasp effort of search for the ‘natural’ SUSY. An example of the SUSY mass spectrum in the natural scenario is shown in Fig. 1.15. The stop pair production at the LHC is searched in the scenario assuming the higgsino-like LSP. Masses of the other SUSY particles except for $\tilde{t}_1, \tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ are set to be heavier than the stop mass $m_{\tilde{t}_1}$, for simplicity. The most of stop signals with $m_{\tilde{t}_1} < 600$ GeV have already been excluded by the previous direct measurements at the LHC as shown in Sec. 1.4.3, but there remain some phase spaces not explored yet due to the difficulty of the analysis. We aim to improve the sensitivity to those signals.

Figure 1.14: Contours of Higgs mass fine-tuning, Δm_h , in the NMSSM with the maximal value of $\lambda = 0.7$ for $\tan\beta = 2$ (left) and 5 (right), with $m_{\tilde{t}_L} = m_{\tilde{t}_R} = m_{\tilde{t}}$ and $m_{A^0} = 500$ GeV. Contours of $m_h = 124$ and 126 GeV are overlaid, including loop corrections from different prescriptions [65].

Figure 1.15: A spectrum for the SUSY particles which gives the correct scale for electroweak symmetry breaking without fine-tuning [64].

1.3 Productions and decay modes of SUSY particles at the LHC

In this section, the production and decay modes of the typical SUSY particles and the general strategy to search for SUSY particles at the LHC are presented. After that, possible decay modes of the stop $\tilde{t}_1$ are discussed.

Figure 1.16 shows examples of Feynman diagrams for productions of the SUSY particles at the LHC. The cross sections of the SUSY particles pair production calculated in the next-to-leading order in the context of the MSSM⁵ are shown in Fig. 1.17. Since gluon is the main parton contributing to the hard scattering in pp collisions at the LHC, the dominant processes are squark and gluino productions in the strong interactions. The cross sections of the color-less electroweak gauginos are much less than strong productions by an order of 10^{-3} .

A SUSY particle decays into a lighter SUSY particle and SM particles to conserve R -parity. As a result, the ‘cascade’ decay of the produced SUSY particle into the LSP with multi-SM particles is expected. The LSP does not interact with any detectors but it breaks the conservation of transverse energy and detected as the large missing transverse energy. Therefore, in general, the tools to search for SUSY particles at the LHC are:

- large missing transverse energy;
- multi high-transverse-energy hadron jets;
- several high-transverse-momentum isolated leptons.

Figure 1.16: Examples of gluino (a), squark (b) and gaugino (c)-(d) pair production at the LHC. Gauginos can be produced only in the electroweak interaction, while gluino and squarks can be produced in the strong interaction in addition.

⁵Procedure of the cross section calculation is explained in Sec. 3.2.1

Figure 1.17: Next-to-leading order MSSM SUSY production cross sections in pp collisions at the center-of-mass energy of 8 TeV as a function of the average final state mass [3].

Basically, a simple analysis can be made to search for inclusive squarks and gluinos by requiring high missing transverse energy and multi-jets, due to the large cross sections. Requirement of leptons can reduce the large QCD multi-jet background. On the other hand, in order to search for electroweak gauginos, multi-lepton requirement from the cascade decay of the SUSY particles is often imposed to enhance signals with small cross sections against the large background.

The lighter stop $\tilde{t}_1$ is mainly produced by the strong interaction. Enough large cross section with respect to the electroweak gaugino production is expected as shown in Fig. 1.17. Stop decays by the weak interaction. The possible decay modes of $\tilde{t}_1$ depend on the SUSY mass spectrum as illustrated in Fig. 1.18. Here, three types of decay modes of two-body, three-body and four-body decays are considered. The MSSM Lagrangian introduced in Sec. 1.2.1 allows the interactions of stop-top-higgsino, stop-bottom-higgsino, stop-top-wino, stop-bottom-wino, and stop-top-bino. As discussed in Sec. 1.2.5, wino, bino and higgsino are mixed and form charginos and neutralinos. Therefore, stop decays into heavy flavor quark and chargino or neutralino, assuming the R -parity conservation.

Figure 1.18: Illustration of stop decay modes in the plane spanned by the masses of stop and the LSP ($\tilde{\chi}_1^0$) [71].

Two-body decay

If the mass spectrum allows, stop can decay in two-body as:

- $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ (if $m_{\tilde{t}_1} > m_t + m_{\tilde{\chi}_1^0}$),
- $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$ (if $m_{\tilde{t}_1} > m_b + m_{\tilde{\chi}_1^\pm}$),
- $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ (if $m_{\tilde{t}_1} > m_c + m_{\tilde{\chi}_1^0}$).

The $b + \tilde{\chi}_1^\pm$ mode is the two-step decay, since chargino further decays into the LSP. If $\Delta m = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} > m_W$, it decays in two body via $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$. Otherwise, it decays in three body via $\tilde{\chi}_1^\pm \rightarrow (W^* \rightarrow ff')\tilde{\chi}_1^0$, where f and f' are different SM fermions. In the latter case, momenta of the final-state fermions are not constrained by the W boson mass and expected to be small depending on $\Delta m = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$. In this thesis, the small Δm is assumed by the higgsino-like LSP scenario, so the two-step decay mode $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow b(W^* \rightarrow ff')\tilde{\chi}_1^0$ is interesting to be focused on. The FCNC decay of $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ is allowed only through one-loop diagram as shown in Fig. 1.19. The branching ratio of the $c + \tilde{\chi}_1^0$ mode is expected to be very small, but it is dominant if $t + \tilde{\chi}_1^0$ and $b + \tilde{\chi}_1^\pm$ are forbidden due to the mass spectrum.

Figure 1.19: Example of the diagram of $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$.

Three-body decay

If $m_b + m_W + m_{\tilde{\chi}_1^0} < m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}_1^0}$, stop decays in three-body via $\tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0$.

Four-body decay

In the case of $m_{\tilde{t}_1} < m_b + m_W + m_{\tilde{\chi}_1^0}$, three-body decay is also forbidden and stop decays in four-body via $\tilde{t}_1 \rightarrow bff'\tilde{\chi}_1^0$.

In this thesis, we do not consider the decay modes via slepton/sneutrino, since we assume that slepton and neutrino masses are heavier than stop mass. Large missing transverse energy and multi-SM particles can be used as tools to search for stop, as with the standard SUSY analysis. In addition, existence of b quarks is expected in the final state. The b -quark-induced jet can be identified with the ATLAS detector. The requirement of the b quarks in the event enhances the signals from the SM backgrounds more.

1.4 Current status of SUSY searches

In this section, some direct search results for SUSY particles at the LEP and the LHC are reviewed. Generally, there are two types of analyses: one assumes specific SUSY models (e.g. mSUGRA/cMSSM)

and gives constraints on the parameter space; the other uses ‘simplified’ signals, which start from direct pair production of the target SUSY particles to study the sensitivity on the masses of SUSY particles and its decay kinematics without any other constraints. Here, mainly simplified results are shown. In the simplified approach, it is important to search for new physics independent of theoretical models as much as possible, but of course we need some hints by the theory.

For example, some precision measurements of low momentum physics constraints to SUSY models. Existence of heavy SUSY particles, in particular the stop-chargino loop, enhance the branching ratio of the FCNC decay of B_s^0 meson to di-muon, which is strictly forbidden at the tree-level in the SM by the GIM mechanism and allowed only at the higher order calculation to be $O(10^{-9})$, through a diagram shown in Fig. 1.20. The CMS and LHCb collaborations measured the branching ratio of $B_s^0 \rightarrow \mu^+\mu^-$ [72, 73], and the combined branching ratio is reported to be $(2.8^{+0.7}_{-0.6}) \times 10^{-9}$ [74], which is consistent with the SM expectation. Furthermore, no significant evidences are found in the other rare B meson decays sensitive to the SUSY parameters. To suppress them in the context of the cMSSM, $\tan\beta$ is preferable to be < 20 [75]. In addition, heavy stop mass is favored by this result in the context of the cMSSM, but the region of the stop mass $m_{\tilde{t}_1} \simeq 500$ GeV is still allowed, as shown in Fig. 1.21 (a). The constraints to SUSY parameters from the B -physics is relaxed in the non-minimal MSSM scenarios e.g. phenomenological MSSM (pMSSM) [76], as shown in Fig. 1.21 (b). Therefore, it is important to search for light stop

Figure 1.20: Example of diagrams to enhance the FCNC process $B_s^0 \rightarrow \mu^+\mu^-$ in the context of the MSSM.

Figure 1.21: 95 % (yellow) and 68 % (red) CL allowed parameter region of stop mass $M_{\tilde{t}_1}$ and CP -odd Higgs boson mass M_A from the global fit to the latest measurements of $B_s^0 \rightarrow \mu^+\mu^-$, $B \rightarrow K^*\mu^+\mu^-$, $b \rightarrow s\gamma$ and $B \rightarrow \tau\nu$, in the context of cMSSM (a) and pMSSM (b) [75]. All 5 (19) parameters for cMSSM (pMSSM) are floated in the fit. The region that both $M_{\tilde{t}_1}$ and M_A are small is excluded. The limit is relaxed in a more general model (pMSSM).

signals at the LHC.

In the simplified approach, the mass spectrum of SUSY particles are settled by hand and the decay modes of target particle are hypothesized by referring to theoretical expectations. We often assume 100 % decay branching fraction of the target mode and put upper limits on the cross section multiplied by branching fraction. Limits on parameters of some specific SUSY models can be obtained by combining results of simplified analyses.

1.4.1 Search for direct chargino pair production at the LEP

Chargino pair production have been searched in e^+e^- collisions at center-of-mass energies up to 208 GeV at the LEP [77–81]. If the small m_0 is assumed in the context of the mSUGRA, chargino decaying into the LSP via slepton ($\tilde{\chi}_1^\pm \rightarrow (\tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0) \nu$) and sneutrino ($\tilde{\chi}_1^\pm \rightarrow (\tilde{\nu} \rightarrow \nu \tilde{\chi}_1^0) \ell$) are allowed in addition to $\tilde{\chi}_1^\pm \rightarrow (W^{(*)} \rightarrow f f') \tilde{\chi}_1^0$. As a result, the leptonic branching ratio is expected to be increased. On the other hand, in the case of large m_0 , chargino decaying into the LSP via slepton/sneutrino are forbidden.

Three types of analyses requiring lepton, lepton+jet, and jets in the event are performed, according to target event topologies. Results from all four experiments at the LEP are combined. No significant signals are found and limits on chargino masses are obtained. At the region of sneutrino mass $m_{\tilde{\nu}} > 300$ GeV and the mass difference between chargino and the LSP (Δm) of greater than 10 GeV, masses of chargino are excluded up to the kinematic limit from center-of-mass energies at the LEP i.e. $m_{\tilde{\chi}_1^\pm} > 103.5$ GeV at 95 % CL not depending on sneutrino mass. In the case of $\Delta m < 10$ GeV, which is a limit of the higgsino-like LSP, chargino becomes long-lived and the SM fermions in the final state tend to have low momentum. Dedicated analyses using the initial state radiation (ISR) photon are performed ($e^+e^- \rightarrow \gamma \tilde{\chi}_1^+ \tilde{\chi}_1^-$) to recover the acceptance to low-momentum signals, yielding the lower limit on chargino mass at 91.9 GeV at 95 % CL not depending on Δm . For all phase spaces, chargino mass is constrained to be greater than approximately 100 GeV.

1.4.2 Search for direct production of electroweak gauginos at the LHC

As discussed in Sec. 1.3, due to the small cross sections, weaker sensitivity on the direct productions of the electroweak gauginos is found at the LHC, while $O(1)$ TeV limits are already set to masses of strongly produced squarks (first and second generations) and gluinos [82–86]. The current limits on gaugino masses using simplified signals of $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0$ and $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ are shown in Fig. 1.22. The searches are performed in several parameter spaces, above the lower limit by the LEP ($m_{\tilde{\chi}_1^\pm} \gtrsim 100$ GeV). As the signal signatures, analyses require the existence of multi-leptons in the event, according to the event topologies [89–94]. Assuming small m_0 , $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decay into the LSP via slepton/sneutrino. In this case, the gaugino masses up-to 700 GeV are excluded with various LSP masses by both the ATLAS and CMS experiments. In the case of large m_0 , $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decay via W/Z or the Higgs boson, yielding the limits on gaugino masses up-to 400 GeV. However, most of channels do not exclude signals on the line of $m_{\tilde{\chi}_1^\pm} = 2m_{\tilde{\chi}_1^0}$ (the bino-like LSP) and at the diagonal region (the higgsino-like LSP).

1.4.3 Search for scalar top quark pair production at the LHC

Motivated by the natural SUSY scenario, searches for direct stop pair production have been performed actively with both the ATLAS [71, 95–98] and CMS [99–102] experiments.

Figure 1.23 shows the 95 % CL exclusion region on $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ plane, assuming 100 % branching ratio of $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$, $\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0$ (two-body decays) and $\tilde{t}_1 \rightarrow b W \tilde{\chi}_1^0$ (three-body decay) corresponding to the kinematic ranges, as of March 2014 (ATLAS) and June 2014 (CMS). Analyses require 0-2 leptons in addition to b quarks and the missing transverse energy in the event. Both ATLAS and CMS exclude stop masses up-to 600 GeV. The limits on $\tilde{t}_1 \rightarrow b f f' \tilde{\chi}_1^0$ (four-body decay) are not set at that time due to the

Figure 1.22: Summary of ATLAS (a) and CMS (b) searches for electroweak production of charginos and neutralinos based on $\sqrt{s} = 8$ TeV data in 2012. Exclusion limits at 95 % CL are shown in the $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ plane. The dashed and solid lines show the expected and observed limits, respectively. Four decay modes of charginos and neutralinos are considered separately with 100 % branching fraction: (1) $\tilde{\chi}_1^\pm \rightarrow \tilde{\ell}\nu/\tilde{\nu}\ell \rightarrow \ell\nu\tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}\ell/\tilde{\nu}\nu \rightarrow \ell\ell\tilde{\chi}_1^0$, resulting in branching ratio for 3 leptons of 50 % and for 2 leptons of 100 % for $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ productions, respectively. The decays via sleptons and sneutrinos occur with 50 % probability each. Brown and blue lines with ATLAS and light green and light blue lines with CMS show the results. Orange line with CMS shows the 95 % CL exclusion limits for $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ production, decaying via right-handed slepton, assuming 100 % branching fraction to 2 leptons. (2) $\tilde{\chi}_1^\pm \rightarrow \tilde{\tau}\nu/\tau\tilde{\nu} \rightarrow \tau\nu\tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \rightarrow \tilde{\tau}\tau/\tilde{\nu}\nu \rightarrow \tau\tau\tilde{\chi}_1^0/\nu\nu\tilde{\chi}_1^0$, resulting in branching ratio of 3τ of 50 % and 2τ of 100 % for $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ productions, respectively. The decays via staus and tau sneutrinos occur with 50 % probability each. Purple, pink and light blue lines with ATLAS and green line with CMS show the results. (3) $\tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0$ (light green and dark blue lines with ATLAS and yellow line with CMS). (4) $\tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0$ (orange and yellow lines with ATLAS and dashed red line with CMS). In the case of $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ production, $m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm}$ is assumed and the masses of the sleptons, staus and sneutrinos are fixed at the mean of $m_{\tilde{\chi}_2^0}$ and $m_{\tilde{\chi}_1^\pm}$. Figures are taken by Ref. [87] and [88].

Figure 1.23: Summary of searches for stop pair production with ATLAS in March 2014 (a) and CMS in July 2014 (b). Exclusion limits at 95 % CL in the $\tilde{t}_1$ - $\tilde{\chi}_1^0$ plane are shown. The dashed and solid lines show the expected and observed limits, respectively. Three decay modes assuming 100 % branching ratio are considered: (1) $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$, (2) $\tilde{t}_1 \rightarrow b W \tilde{\chi}_1^0$ and (3) $\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0$. Figures are taken by Ref. [105] and [88].

difficulty of the analysis. At the kinematical boundary region between two-body and three-body decays, the signal kinematics are very similar to the SM top quark pair ($t\bar{t}$) production with additional missing transverse energy. It is therefore difficult to enhance signals from the background at this parameter space as shown in Fig. 1.23. Precision measurement of the $t\bar{t}$ cross section gives a constraint to the stop signals at this region [103]. In addition, stop signals can be distinguished from the SM top quark background through the measurement of angular correlations, using the difference of spins [104]. The measurement of the spin correlation between top and antitop quarks excludes stop masses between top quark mass and 191 GeV at 95 % CL assuming 100 % decay branching ratio of $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ and $m_{\tilde{\chi}_1^0} = 1$ GeV, as shown in Fig. 1.24.

Figure 1.25 shows the 95 % CL exclusion region set by ATLAS on $m_{\tilde{t}_1}$ - $m_{\tilde{\chi}_1^0}$ plane, assuming 100 % branching fraction of $\tilde{t}_1 \rightarrow b \tilde{\chi}_1^\pm \rightarrow b(W^{(*)} \rightarrow f f') \tilde{\chi}_1^0$. The region not excluded by the LEP has been searched ($m_{\tilde{\chi}_1^\pm} \gtrsim 100$ GeV). Several benchmark scenarios are taken up for interpretations. The bino-like LSP scenario is explored by setting $m_{\tilde{\chi}_1^\pm} = 2m_{\tilde{\chi}_1^0}$. The results of 1- and 2-lepton channels for this scenario are shown in Figs. 1.25 (a) and (b), respectively. Almost all regions up-to stop mass of 500 GeV are excluded by taking a combination of two results. The point around $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0}) = (175, 50)$ GeV cannot be excluded, since the signal topology is quite similar to the SM $t\bar{t}$ production. On the other hand, the higgsino-like LSP scenario is searched by requiring the absence of leptons (0-lepton) in the event. Two benchmark points of $\Delta m = 5$ GeV and 20 GeV are chosen. The mass distribution reconstructed by two b -quark-induced jets (m_{bb}) in 0-lepton channel is shown in Fig. 1.26. Data agree with the SM prediction within the uncertainty. The main background component in the signal region in $m_{bb} > 200$ GeV is $Z(\rightarrow \nu\nu)$ +heavy flavor jets, which is an irreducible background due to the physics-origin E_T^{miss} and b -quark-induced jets. Stop pair production signal with $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (500, 105, 100)$ GeV is overlaid by green dashed line in this figure. There is no significant excess on the SM prediction. The 95 % CL exclusion regions by this analysis are shown in Figs. 1.25 (c) and (d). At the phase space of $\Delta m = 5$ GeV,

Figure 1.24: Expected and observed limits at 95 % CL on the stop pair-production cross section as a function of $m_{\tilde{t}_1}$ from the measurement of the spin correlation between top and anti-top quarks, for pair-produced $\tilde{t}_1$ decaying with 100 % branching ratio via $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ to predominantly right-handed top quarks, assuming $m_{\tilde{\chi}_1^0} = 1$ GeV [104]. The black dotted line shows the expected limit with ± 1 (green) and ± 2 (green+yellow) standard deviation contours, taking into account all uncertainties. The red dashed line shows the theoretical cross section with uncertainties. The solid black line gives the observed limit.

the analysis excludes stop masses up-to 600 GeV with the various LSP masses. In $\Delta m = 20$ GeV case, however, exclusion reach is weakened due to the relatively large lepton branching ratio. In particular, no sensitivity is found at the diagonal region close to the kinematical bound, where masses of stop and the LSP (ΔM) is small in addition to Δm .

1.5 Target event topology of this work

Let us summarize the target signals in this thesis and tools to enhance them from the Standard Model background. This work stands for this natural SUSY scenario and search for stop pair production at the LHC. As shown in Fig. 1.15,

- light stop with $m_{\tilde{t}} \lesssim 600$ GeV and
- light higgsino with $|\mu| \lesssim 280$ GeV

are required if the fine-tuning of $\Delta^{-1} < 10\%$ is to be avoided. Enough large cross section of the stop pair production is expected, if stop is light, as shown in Fig. 1.17. Most of the signal models with stop masses less than 600 GeV are already excluded as discussed in Sec. 1.4.3, but there remain some phase spaces not covered by the previous analyses. Assuming the higgsino-like LSP from the prospect for the light higgsino, mass difference between $\tilde{\chi}_1^\pm$ and the LSP (Δm) is calculated to be small as discussed in Sec. 1.2.5. In order to use this information, we put focus on the decay mode of the stop:

$$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow b(W^* \rightarrow ff')\tilde{\chi}_1^0 + c.c.$$

The diagram of the target signal is shown in Fig. 1.27 (a). Following the previous ATLAS analysis requiring 0-lepton [95], two benchmark points of $\Delta m = 5$ GeV and 20 GeV are considered. The phase

Figure 1.25: Exclusion limits at 95 % CL by ATLAS for stop pair production in the $\tilde{t}_1$ - $\tilde{\chi}_1^0$ plane, assuming 100 % branching ratio of $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow b(W^{(*)} \rightarrow ff')\tilde{\chi}_1^0$. Concerning bino-like LSP, $m_{\tilde{\chi}_1^\pm} = 2m_{\tilde{\chi}_1^0}$ is assumed. Separate analyses requiring 1 lepton [71] (a) and 2 lepton [96] (b) are performed, which cover orthogonal phase spaces. Concerning higgsino-like LSP, small $\Delta m = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ of 5 GeV(c) and 20 GeV(d) are used as benchmark points. Analysis not requiring lepton [95] is sensitive for this phase space.

Figure 1.26: Mass distribution reconstructed by two b -tagged jets (m_{bb}) in a signal region of ATLAS stop analysis requiring absence of leptons [95]. Data (black dot) agree well with the SM background prediction (red line). The main component of the background is Z +jets at the high m_{bb} region, as indicated by dark blue histogram. A stop signal with $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^+}, m_{\tilde{\chi}_1^0}) = (500, 105, 100)$ GeV is indicated by dashed green line.

space of $\Delta m = 20$ GeV, in which the weaker sensitivity is found with the previous analysis, as shown in Fig. 1.25 (c) and (d), is the main target benchmark signal in this work.

Data collected with the ATLAS detector in 2012 corresponding to 20.1 fb^{-1} are used. Analysis is based on the simplified approach. A 100 % decay branching ratio of $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow b(W^{(*)} \rightarrow ff')\tilde{\chi}_1^0$ is assumed. The SUSY spectrum is defined by combinations of $m_{\tilde{t}_1}$, $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_1^0}$. Masses of the other SUSY particles are set to be much heavier than stop mass. Details of the signal hypotheses are shown in Sec. 3.2.3.

Assuming the small Δm , soft fermions are expected in the final state. Existence of the soft lepton is required as a probe of the signal in this work. The soft-lepton requirement suppresses $Z(\rightarrow \nu\nu)$ +jets background, which is the main source of the background in the previous analysis. The signal characteristics are thus:

- two b -quark-induced jets,
- large missing transverse energy from non-detected $\tilde{\chi}_1^0$, and
- exactly one soft lepton.

Additional soft hadronic activities from $W^* \rightarrow qq'$ from the other stop side are expected. Cuts on kinematical variables of reconstructed particles are optimized according to the target event topologies. Two types of analyses are performed, which are dedicated to the SUSY spectra shown in Fig. 1.28 left and right, respectively. For the signal models with the small mass difference between stop and the LSP (ΔM) in addition to small Δm (left panel of Fig. 1.28), all final-state activities tend to be soft and hence it is difficult to enhance the signals against the SM background. Therefore, such signals are not explored in the previous analyses. In this work, existence of the initial state radiation jet with high transverse momentum is required in the event and stop pair system in the boosted frame to that is explored. The Lorentz boost factor improves the acceptance to the soft final-state particles. Since the final-state topologies in this channel are quite similar to $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow b(W^* \rightarrow ff')\tilde{\chi}_1^0$, results are also interpreted in the signal model of the stop four-body decay:

$$\tilde{t}_1 \rightarrow bff'\tilde{\chi}_1^0 + c.c.$$

as shown in Fig. 1.27 (b), which is not explored in the previous analyses, either. For signals with the mass spectrum of the right panel of Fig. 1.28, two b quarks in the final state are expected to have high transverse momentum. We aim to achieve the better sensitivity at the higher stop mass region with respect to the previous analysis in this channel, by using a variable sensitive to the stop mass.

The LHC and the ATLAS experiment are explained in Chapter 2 and used data set and Monte-Carlo simulation are summarized in Chapter 3. Details of the particle reconstruction with the ATLAS detector are found in Chapter 4. The details of the event selection optimization are explained in Chapter 5. The criteria of the background estimation is discussed in Chapter 6. Finally, results are shown in Chapter 7 and conclusions are given in Chapter 8.

Figure 1.27: Diagrams illustrating the considered signal scenarios [71]. (a) stop two-step decay of $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow b(W^{(*)} \rightarrow ff')\tilde{\chi}_1^0$, and (b) stop four-body decay of $\tilde{t}_1 \rightarrow bff'\tilde{\chi}_1^0$.

Figure 1.28: Illustration of the target signal spectra of the masses of stop ($m_{\tilde{t}_1}$), chargino ($m_{\tilde{\chi}_1^\pm}$) and neutralino ($m_{\tilde{\chi}_1^0}$). The mass difference between chargino and neutralino is defined as Δm , and the mass difference between stop and neutralino is defined as ΔM . Signals in highly compressed mass spectrum (left) and signals with moderate mass splitting between stop and chargino (right) are covered by the dedicated channels.

Chapter 2

The LHC and the ATLAS experiment

The big giant in current particle physics, the Large Hadron Collider (LHC) at CERN is the collider operated at the highest center-of-mass energy in the world. The ATLAS detector at the LHC is an apparatus to open up unknown physics at the energy frontier. In this chapter, technical details of the LHC and the ATLAS detector are described.

2.1 The Large Hadron Collider

The LHC [106] is a double-ring collider constructed at about 100 m underground at CERN and its neighborhood. The long circumference of 26.7 km and the strong magnetic field of 8.33 T produced by the superconductive dipole magnets achieve high center-of-mass energy proton-proton (pp) collisions at $\sqrt{s} = 14$ TeV at the designed value. Proton (or heavy ion) bunches are injected from the booster accelerator, the Super Proton Synchrotron (SPS). The bunches are accelerated in opposite directions in each ring, and collided at four bunch crossing points for the ATLAS, CMS, LHCb and ALICE experiments as shown in Fig. 2.1. The ATLAS and CMS are multi-purpose experiments which require high rate of

Figure 2.1: The overall view of the LHC experiment [107]. The proton beam is injected from the SPS and accelerated up-to 7 TeV (designed value). Heavy ion beam can also be accelerated. There are four points of bunch crossing, where the ATLAS, CMS, LHCb and ALICE experiments are located.

Table 2.1: Important parameters of the LHC recorded in 2012 (Run1) [108, 109] with the ATLAS detector in comparison with the expected values in 2015 (Run2) [109] and the designed values [106]. E_{CM} is the center-of-mass energy, N_b the number of particles per bunch, n_b^{max} the maximum number of bunches in each proton beam, ϵ_n the normalized transverse beam emittance, θ_c the full crossing angle, β^* the beta function, $\mathcal{L}$ the instantaneous luminosity, and $\langle\mu\rangle$ the averaged number of interactions per bunch crossing (number of pileup).

Parameter	Run1 recorded	Run2 expected	Designed
E_{CM} (TeV)	8	13	14
N_b (10^{11})	1.7	1.15-1.6	1.15
n_b^{max}	1374	1260-2760	2808
ϵ_n (μm)	2.5	1.6-3.75	3.75
β^* (cm)	60	60-70	55
θ_c (μrad)	290	230-380	285
$\mathcal{L}$ ($10^{34}\text{cm}^{-2}\text{s}^{-1}$)	0.77	1.6-2.3	1.0
Bunch space (ns)	50	25-50	25
$\langle\mu\rangle$	~ 35	up-to ~ 100	~ 23

pp collisions to study rare physics signatures; the LHCb detector is designed to study B -physics; and the ALICE is dedicated to study heavy ion collisions.

The expected number of events in pp collisions for a given period is described as

$$N_{\text{events}} = \sigma_{\text{process}} \int \mathcal{L} dt, \quad (2.1)$$

where σ_{process} is the cross section of the target physics process and $\mathcal{L}$ is an instantaneous luminosity. Assuming Gaussian beam distribution, the luminosity can be determined by beam parameters as:

$$\mathcal{L} = \frac{N_b^2 n_b f_{\text{rev}} \gamma_r}{4\pi \epsilon_n \beta^*} F, \quad (2.2)$$

where N_b is the number of particles per bunch, n_b the number of bunches per beam, f_{rev} the revolution frequency, γ_r the relativistic gamma factor, ϵ_n the normalized transverse beam emittance¹, β^* the beta function at the collision point², and F the geometric luminosity reduction factor due to the crossing angle at the interaction point given by:

$$F = \left(1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*} \right)^2 \right)^{-1}, \quad (2.3)$$

where θ_c is the full crossing angle at the interaction point and σ_z the RMS bunch length. The above expression assumes round beams, with $\sigma_z \ll \beta^*$, and with equal beam parameters for both beams. Thus, the $\mathcal{L}$ indicates the power of the collider. The designed instantaneous luminosity for the ATLAS and CMS experiments is $\mathcal{L} = 10^{34}\text{cm}^{-2}\text{s}^{-1}$.

During the period between 2009 and 2012, referred as the LHC Run1, the LHC was operated at $\sqrt{s} = 7-8$ TeV and the maximum instantaneous luminosity observed with the ATLAS detector³ was $\mathcal{L} = 7.7 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$. Figure 2.2 (a) shows the peak luminosity recorded with the ATLAS detector as

¹The normalized transverse beam emittance ϵ_n is the average of the beam spread normalized in transverse direction [108].

²The β^* is a parameter of how much the beam is squeezed at the interaction point i.e. the transverse RMS beam size at the interaction point $\sigma^* = \sqrt{\epsilon_n \beta^*} / \gamma_r$ [108].

³The criteria to measure the $\mathcal{L}$ and $\langle\mu\rangle$ is explained in Sec. 3.1.2.

a function of day in year 2012. Multiple interactions, what we call ‘pileup’, take place during one bunch crossing due to high luminosity and short bunch crossing space (50 ns in 2012). The averaged number of interactions per bunch crossing was $\langle\mu\rangle \simeq 35$ in 2012, as shown in Fig. 2.2 (b). It is challenging to reconstruct target physics while avoiding the effect of the pileup.

The LHC is shut down between 2013 and 2015 for the upgrade of the facilities to perform the higher center-of-mass energy and luminosity. The LHC Run2 will start from 2015, in which we expect $\sqrt{s} = 13$ TeV and $\mathcal{L} = 1.6\text{--}2.3 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$. Much higher luminosity than the designed value is scheduled, which leads to very high pileup environment (over 100 if the bunch spacing is 50 ns).

Recorded parameters in 2012 are summarized in Table 2.1 compared with the expected values in the LHC Run2 and the designed values.

(a)

(b)

Figure 2.2: (a) The maximum instantaneous luminosity versus day delivered to ATLAS [110]. Only the peak luminosity during stable beam periods is shown. (b) The maximum mean number of events per beam crossing (pileup) as a function of day in 2012, determined for each bunch [110]. The maximum pileup for any bunch is shown in green, as well as the maximum pileup averaged over all the colliding bunches shown in blue.

2.2 The ATLAS detector

ATLAS (A Troidal LHC ApparatuS) [111] is one of the pp colliding experiments at the LHC. Figure 2.3 illustrates the overall view of the ATLAS detector. The ATLAS detector is a multi-purpose apparatus whose height, length and weight are 25 m, 44 m, and 7,000 t, respectively. The detector consists of, from inside to outside, the inner detectors, electromagnetic and hadronic calorimeters, and muon spectrometers. The coverage of the detector is approximately 4π of the solid angle to detect secondary particles produced in pp collisions as much as possible to reconstruct the kinematics at the interaction point.

Figure 2.3: The overall view of the ATLAS detector [111]. It consists of the inner detectors (pixel detector, semiconductor tracker, and transition radiation tracker), electromagnetic and hadronic calorimeters, and muon chambers. Large toroid magnets provide magnetic fields to muon chambers.

The ATLAS detector is forward-backward asymmetric with respect to the interaction point. We take cylindrical coordinate system of (r, z, ϕ) , where z -axis is defined along beam pipe direction and the origin at the interaction point in the center of the detector, r -coordinate is orthogonal to that and ϕ is an azimuthal angle⁴. The rapidity y is defined as:

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right), \quad (2.4)$$

where E and p_z are the energy and z -component of the momentum of a given particle. The pseudo-rapidity, η , is defined using a polar angle θ as:

$$\eta = -\ln \left(\tan \frac{\theta}{2} \right), \quad (2.5)$$

which is an approximation of the rapidity at the massless limit.

The longitudinal component of energy and momentum of detected particles in the event is not conserved, while the transverse momentum of the initial partons is always zero. The conservation in the

⁴ATLAS uses a right-handed coordinate system: x -axis points to the ring center, y -axis points upward, and $\phi = 0$ is along x -axis so that the upper half of the detector is described by $0 < \phi < \pi$ and the lower half by $\pi < \phi < 2\pi$.

transverse direction is ensured so that usually we use transverse momentum $p_T = p \sin \theta$ and transverse energy $E_T = E \sin \theta$ to describe kinematical features of secondary particles. Secondary particles are assumed to be relativistic, of which the polar angle is described by η . The distance between two particles or two positions in the detector is defined in η - ϕ plane as:

$$\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}. \quad (2.6)$$

Particles produced in pp collisions can be identified by using a combination of sub-detectors. Figure 2.4 shows an example of the particle identification. Electrons⁵ and photons are detected as electromagnetic showers by the electromagnetic calorimeter: electron-induced showers can be distinguished from photon-induced ones by using inner detector information; hadrons deposit their energy at the hadronic calorimeter; muons can be detected at the outermost layer of the detector because of the long penetration length, and the momentum is reconstructed by both the inner detector and muon spectrometer; neutrinos do not interact with any detector materials, but consequently, existence of neutrinos are determined by the missing transverse energy, E_T^{miss} . The details of the reconstruction of each signature are described in Chapter 4.

The requirement for the ATLAS detector performance is summarized in Table 2.2. Each sub-detector is explained in the following sections.

Figure 2.4: An example of the particle identification with the ATLAS detector [107].

2.2.1 Inner detector

Inner detector plays an important role to reconstruct tracks of charged particles and the interaction point. The r - z view of the ATLAS inner detector (ID) is shown in Fig. 2.5. The cutting view of the ID system is illustrated in Fig. 2.6. The ATLAS ID system consists of three sub-detectors: silicon pixel detectors (Pixel); silicon micro-strip detectors (SCT); and transition radiation trackers (TRT). It can reconstruct

⁵The term electron refers to both electrons and positrons if not stated otherwise.

Table 2.2: Requirements for the ATLAS detector performance [111]. The units of E and p_T are in GeV. Calorimeter and muon spectrometer are used also as trigger detectors. The character $\oplus$ indicates the orthogonal direct sum.

Sub-detector	Required resolution	Coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\% p_T \oplus 1\%$	$ \eta < 2.5$	-
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	$ \eta < 3.2$	$ \eta < 2.5$
Hadronic calorimetry (jets) barrel and end-cap forward	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	$ \eta < 3.2$	$ \eta < 3.2$
	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \eta < 4.9$	$3.1 < \eta < 4.9$
Muon spectrometer	$\sigma_{p_T}/p_T = 10\%$ at $p_T = 1$ TeV	$ \eta < 2.7$	$ \eta < 2.4$

Figure 2.5: The r - z view of a quarter section of the ATLAS inner detectors with their active dimensions and envelopes [111]. The lower left part shows the zoom-up view of the Pixel detector.

the tracks and momenta of charged particles with $p_T > 0.5$ GeV and $|\eta| < 2.5$ ($9^\circ < \theta < 171^\circ$). The 2 T magnetic field provided by the central solenoid magnet bends the charged particle, and its momentum is reconstructed from the curvature measured from the hits at each ID layer. The magnetic field is approximately uniform in $|z| < 2$ m, with small r and z dependency; see Fig. 2.7.

High momentum resolution is required for the goal performance shown in Table 2.2. To perform the track reconstruction in the high pileup environment, a robust pattern recognition against the very large track density must be ensured. These are realized by high read-out granularity of the detectors. The precision measurements of charged particles make it possible to identify b -quark-induced jet, which is expected in the stop decay. Also electron identification against fake hadrons is performed for $|\eta| < 2.0$ ($15^\circ < \theta < 165^\circ$) using transition radiation photons at TRT.

The ID system is situated at the closest position to the beam pipe (about 5 cm) but the performance must be kept at the highest possible luminosity at the LHC and in high radiation environment. High-precision measurements of the detector alignments and amount of materials are also important to attain the required performance. Good understanding of the alignment for each sub-detector is made by a track-

Figure 2.6: Drawing of the ATLAS inner detector system at the barrel (a) and endcap (b) regions [111]. The infinite momentum lines for $\eta = 1.4$ and 2.2 are overlaid with red lines to (b).

based algorithm minimizing a χ^2 based on track-hit residuals [112]. Material distribution measured by the radiation length (X_0)⁶ and the nuclear interaction length (λ)⁷ at the exit of the ID envelope are shown in Fig. 2.8.

The criteria and performance of the track and vertex reconstruction are explained in Sec. 4.1. Here, the technical details of the ID system are presented.

⁶The radiation length X_0 is a characteristic of a material, related to the energy loss of electromagnetic interacting particles, which is defined as $E(x) = E_0 \exp\left(-\frac{x}{X_0}\right)$, where $E(x)$ is a particle energy at the distance x in the material and E_0 is its initial energy i.e. X_0 is the path length required to reduce the energy of electromagnetic interacting particles by factor $1/e$ in a material.

⁷The nuclear interaction length λ is also a characteristic of a material, to describe the path length required to reduce the number of relativistic charged particles by the factor $1/e$ while they pass through a matter, which is defined as: $N(x) = N_0 \exp\left(-\frac{x}{\lambda}\right)$, where $N(x)$ is the number of charged particles at the distance x , and N_0 is the initial number.

Figure 2.7: r and z dependency of the radial (Br) and the axial (Bz) magnetic field in the inner detector cavity, at fixed azimuth [111].

Figure 2.8: The material distributions measured by the radiation length (a) and the nuclear interaction length (b) at the exit of the inner detector envelope as a function of $|\eta|$ for the ATLAS detector simulation [111].

Pixel

The Pixel detector is placed at the innermost layer of the detector. In order to reconstruct primary and secondary vertices precisely, very high granularity of read-out cells and thinness of each Pixel layer are necessary. 1,744 oxygenated n -type silicon sensors with read-out pixel on the n^+ -implanted side of the detector are installed. Nominal pixel sensor size is $50 \times 400 \mu\text{m}^2$ with thickness of $250 \mu\text{m}$ and the number of channels per sensor is 46,080.

As shown in Fig. 2.5, there are three co-axial cylindrical layers of the Pixel at barrel region and three disk layers at both endcaps of the detector, which cover the range of $|\eta| < 2.5$ ($9^\circ < \theta < 171^\circ$). The innermost layer of the barrel Pixel detector, so-called b -layer, plays an important role to reconstruct secondary vertex. The intrinsic resolution is $10 \mu\text{m}$ in r - ϕ direction and $115 \mu\text{m}$ in z (r) direction for the barrel (endcap) region. The spacial resolution at each Pixel layer is measured using a test beam to be $12 \mu\text{m}$ in r - ϕ direction and it is found that approximately 80 % of the tracks have a single pixel hit.

SCT

There are four co-axial cylindrical SCT layers in the barrel region, and nine discs in both endcap regions, as shown in Figs. 2.5 and 2.6. Overall coverage of SCT is $|\eta| < 2.5$ ($9^\circ < \theta < 171^\circ$). A classic single-sided p -in- n technique with AC coupled read-out strip is employed for SCT. Total number of modules is 4,088 (2,112 in barrel and 1,976 in endcap region) and the number of read-out channels per each SCT module is 1,536. For noise suppression after radiation damage, the SCT must be kept at -5 to -10°C .

In the barrel region, a strip pitch of $80\mu\text{m}$ with daisy-chained 6 cm-long sensors are adapted. Each layer consists of two sensors at each on the top and bottom side, of which strips are rotated by $\pm 20\text{ mrad}$ around the geometrical center as shown in Fig. 2.9. This layout makes it possible to determine the two dimensional space-point of a particle across the layer. In the endcap region, radial strips of constant azimuth with a mean pitch of about $80\mu\text{m}$ are used. As with the barrel region, each module of nine discs has two sets of sensors glued back-to-back with a relative rotation of $\pm 20\text{ mrad}$ to measure the two coordinates of the hit. The spacial resolution of SCT is measured using a test beam to be $16\mu\text{m}$ in r - ϕ direction. The intrinsic accuracy in r - ϕ direction and z (r) direction for the barrel (endcap) region are $17\mu\text{m}$ and $580\mu\text{m}$, respectively. It is confirmed that the resolution is not affected by irradiation.

Figure 2.9: Schematic view of a barrel SCT module [111]. Two silicon sensors are glued back-to-back on a thermal pyrolytic graphite (TPG) base-board which provides a high thermal conductivity path between the coolant and the sensors.

TRT

TRT consists of 4 mm diameter polyimide-made drift tubes. The tubes work as a cathode and $31\mu\text{m}$ -diameter tungsten wires plated with 0.5 - $0.7\mu\text{m}$ gold inside the tubes work as an anode, which are directly connected to front-end electronics and kept at ground potential. The gas component inside the tubes is 70 % Xe, 27 % CO_2 and 3 % O_2 . The total number of read-out channels is approximately 351,000.

TRT covers the range of $|\eta| < 2.0$ ($15^\circ < \theta < 165^\circ$), with 73 layers in the barrel and 160 layers in the endcap region. The tube length is 144 cm in the barrel and 37 cm in the endcap region. The barrel tubes are laid in parallel with the beam pipe, side by side with an interval of 7 mm in each layer. There is small inefficient region of 2 cm at the center of tubes due to plastic insert to support the wires in each straw tube. In the endcap region, the TRT modules consist of two sets of individual wheels. For the inner region closer to the interaction point, twelve wheels with eight layers of straw tube strung by 8 mm pitch radially oriented are installed. For the outer set, eight wheels with eight straw layers are assembled with 15 mm pitch.

TRT can only measure space-points in r - ϕ direction, but charged particle with $p_T > 0.5\text{ GeV}$ traverses at least 36 tubes except for barrel-to-endcap transition region ($0.8 < |\eta| < 1.0$) which helps

improving p_T resolution of tracks. The intrinsic resolution for each tube is $130\ \mu\text{m}$.

As the transition radiation material, $19\ \mu\text{m}$ -diameter polypropylene fibers (barrel) and $15\ \mu\text{m}$ -thick polypropylene radiator foils separated by a polypropylene net (endcap) are inserted between tubes. Detection of transition radiation photon caused by materials with different refractive indices helps to distinguish electron tracks from hadrons for wide range of electron energy of $0.5 < E < 200\ \text{GeV}$. The energy of transition radiation photon is proportional to $\gamma = E/m$, where E and m are energy and mass of the charged particles, respectively. Transition radiation photon is absorbed by Xe inside tubes and the signal is detected at TRT. Figure 2.10 indicates the high-threshold hit probability as a function of γ derived by 7 TeV collision data with ATLAS in 2010. It is seen that response from electron is significantly higher than that for hadrons for the same momentum. Seven to ten high-threshold hits from transition radiation are expected by electrons with $E > 2\ \text{GeV}$.

Figure 2.10: The probability of a TRT high-threshold hit as a function of $\gamma = E/m$, for the TRT barrel (a) and endcap (b) regions, as measured in 7 TeV collision data collected in 2010 with the ATLAS detector [113].

2.2.2 Calorimetry

In this thesis, the calorimeter services are used to reconstruct the electron and hadronic jets from the stop decay. Good energy resolution of the electromagnetic calorimeter even in the low- E_T region is required to reconstruct the soft electron, which is the kinematic feature of the target signal. Signals at the calorimeters are also used to reconstruct the E_T^{miss} . The ATLAS sampling calorimeter system is illustrated in Fig. 2.11. It covers the range of $|\eta| < 4.9$ ($1^\circ < \theta < 179^\circ$) by using several techniques suited to the requirements at each η range. It consists of electromagnetic (EM) Liquid-Argon (LAr) calorimeter, hadronic tile calorimeter, hadronic endcap LAr calorimeter (HEC) and forward LAr calorimeter (FCal).

It is important that hadron jets must deposit all their energy inside the calorimetry service and not be detected in the muon chamber. The amount of materials for the EM calorimeter using radiation length is shown in Fig. 2.12 and that for whole calorimetry system using nuclear interaction length is shown in Fig. 2.13. Total active thickness of the EM calorimeter is greater than $24X_0$. At least 10λ is provided at the exit of the hadronic calorimeter in the whole η region.

Calorimeters are synchronized to the LHC clock every 25 ns at the trigger level to identify the bunch crossing. Pulse shape of the collected signals is recognized and cell energy is reconstructed by the optimal filtering algorithms [111]. Criteria to reconstruct e/γ and hadron jets are explained in Sec. 4.2 and 4.5. Here, only the technical details of ATLAS calorimeter system are presented.

Figure 2.11: The overview of the ATLAS electromagnetic and hadronic calorimeter [11]. It consists of lead-LAr electromagnetic calorimeter in the barrel and endcap regions (endcap LAr calorimeter is called as EMEC), hadronic endcap LAr calorimeter (HEC), barrel sampling hadron calorimeter using steel absorber and tile scintillator, and forward LAr calorimeter (FCal).

EM LAr calorimeter

Lead absorber and active LAr detector are employed for the EM calorimeter, with an accordion geometry to perform complete ϕ symmetry without azimuthal crack. It consists of two sets of barrel detector and two endcap detectors (EMECs) as shown in Fig. 2.11.

In the LAr calorimeters (EM and hadronic endcap calorimeter), ionization electrons produced by passing charged particles drift to electrodes and produce electrical currents proportional to the deposited energy. Signals are sent to the front-end board and the pre-amplifier is applied. LAr calorimeter has a better energy resolution in comparison with scintillator, but output triangular pulse has the base time of typically 600 ns, while that of signals from the Tile calorimeter is about 200 ns. Consequently, the LAr calorimeter is likely to be affected by the ‘out-of-time pileup’ from the other bunch crossing. To discriminate ‘in-time’ signals from the background, pulse shape from the LAr calorimeter is translated to be bipolar as shown in Fig. 2.14 using analogue filter, which allows the negative energy in the cell for the out-of-time background. The signals are then sampled at the LHC clock by analogue technique and sent to the ADC for the trigger (see Sec. 2.2.4). Only events accepted by the hardware-based trigger are read out and amplified by the optimal readout gain. Signals from all calorimeters are sent to the back-end system. At the back-end system, optimal filtering is applied to signals to reconstruct the energy of each calorimeter cell.

The barrel EM calorimeters cover $|\eta| < 1.475$ ($26^\circ < \theta < 164^\circ$). There is only small dead region at $z = 0$ by ~ 4 mm between two detectors for cabling. They are enclosed in cryostat vessels which maintain the LAr temperature at 88 K. Each module has three layers so-called Layer1, Layer2 and Layer3, from inside to outside. The depth of each layer is shown in Fig. 2.12 (a) using the radiation length X_0 . Schematic diagram of the barrel EM calorimeter positions is shown in the top panel of Fig. 2.15. The actual depth for each layer is optimized according to $|\eta|$ to fulfill uniform X_0 values with respect to η . Figure 2.16

Figure 2.12: The amount of materials at each service at the EM calorimeter divided into Layer1, Layer2 and Layer3 using radiation length as a function of η at barrel (a) and endcap (b) region, respectively [111].

Figure 2.13: The amount of materials of each the ATLAS calorimeter module as a function of η using nuclear interaction length [111].

shows a module of the barrel EM calorimeter. The figure shows that higher granularity of read-out cells along η direction at Layer1 is adapted (size of one read-out cell is $\Delta\eta \times \Delta\phi = 0.025/8 \times 0.1$) to measure η of reconstructed e/γ precisely. Most of the energy of the electromagnetic shower is dropped at Layer2, which has the longest depth among three layers. It has 8 times coarser read-out granularity in η direction than Layer1, but is divided into four sub-modules in ϕ direction ($\Delta\eta \times \Delta\phi = 0.025 \times 0.025$). Layer3 is used to measure the tail of electromagnetic shower and to distinguish e/γ from hadron jets. Layer3 has the coarser read-out granularity in η direction by factor 2 than Layer2 ($\Delta\eta \times \Delta\phi = 0.05 \times 0.025$).

The EMEC calorimeters at each side of the barrel EM calorimeters cover the range of $1.375 < |\eta| < 3.2$ ($5^\circ < \theta < 28^\circ$ and $152^\circ < \theta < 175^\circ$). Each EMEC has two co-axial wheels. Inner wheel covers $2.5 < |\eta| < 3.2$ ($5^\circ < \theta < 9.4^\circ$ and $171^\circ < \theta < 175^\circ$) and outer wheel covers $1.375 < |\eta| < 2.5$ ($9^\circ < \theta < 28^\circ$ and $152^\circ < \theta < 171^\circ$). There is a 3 mm gap region between two wheels at $|\eta| = 2.5$ for cabling. All wheels are further divided into 8 wedge-shaped modules. Illustrations of the inner and outer EMEC module are shown in bottom two panels of Fig. 2.15. As with the barrel region, the precision region of EMEC calorimeter (which can match the ID system: $1.5 < |\eta| < 2.5$) is divided into 3 layers in depth as shown in Fig. 2.12 (b). The front layer is segmented with strips along the η direction. The $\Delta\eta$ is optimized for each η region (at most 0.025 at the core region), and $\Delta\phi = 0.1$. The size of the read-out cell in the middle layer is $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$, except for barrel-to-endcap and endcap-

Figure 2.14: An example of the bipolar pulse shape in the ATLAS LAr calorimeter (barrel EM calorimeter) [111]. The sampling points every 25 ns are also shown.

to-forward boundaries. The back layer has a twice coarser granularity in η with respect to the middle layer ($\Delta\eta \times \Delta\phi = 0.05 \times 0.025$). The other regions ($|\eta| < 1.5$ and $2.5 < |\eta| < 3.2$) are divided into two longitudinal layers (see Fig. 2.12) and have a coarser transverse granularity ($\Delta\eta \times \Delta\phi = 0.1 \times 0.1$).

The transition region between the barrel and endcap EM calorimeters, $1.37 < |\eta| < 1.52$, has a large amount of material in front of the first calorimeter layer, ranging from $5X_0$ to $10X_0$. To improve energy measurement accuracy in this region, the LAr pre-sampler detectors are located in front of EM calorimeters, covering the range of $|\eta| < 1.52$ ($25^\circ < \theta < 155^\circ$) (barrel) and $1.5 < |\eta| < 1.8$ ($19^\circ < \theta < 25^\circ$ and $155^\circ < \theta < 161^\circ$) (endcap). The read-out granularity of the pre-sampler calorimeter is $\Delta\eta \times \Delta\phi = 0.025 \times 0.1$ and thickness is 11 mm (5 mm) for barrel (endcap).

The energy resolution of the EM calorimeter is measured using a test beam. The resolution is described after noise subtraction by the following formula:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E \text{ (GeV)}}} \oplus b, \quad (2.7)$$

where a is the statistical term and b is the constant term to take into account the local dependency of the pedestal of each calorimeter. The performance of barrel EM calorimeter is described by $a = (10.1 \pm 0.4) \%$ and $b = (0.2 \pm 0.1) \%$, which is compatible with the target performance described in Table 2.2.

Hadronic tile calorimeter

ATLAS uses steel absorber and scintillating tile as the active material for the barrel hadronic calorimeter. The tile calorimeter consists of one long module covering $|\eta| < 1.0$ ($40^\circ < \theta < 140^\circ$) and two extended modules covering $0.8 < |\eta| < 1.7$ ($21^\circ < \theta < 48^\circ$ and $132^\circ < \theta < 159^\circ$). They are divided azimuthally to 64 sub-modules. It is segmented into three layers in depth, by approximately 1.5λ , 4.1λ and 1.8λ for barrel, and 1.5λ , 2.6λ and 3.3λ for extended barrel as shown in Fig. 2.13. Segmentation of the hadronic tile calorimeter is illustrated in Fig. 2.17. Each cells have the dimensions of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ for first and second layers and 0.1×0.2 for third layer.

Scintillation light is collected by the wavelength-shifting fibers [111] placed in contact with the tile edge and converted to a longer wavelength. Each fiber collects light from tiles located at one or two

Figure 2.17: Segmentation in depth and η of the tile calorimeter modules in the central (left) and extended (right) barrels [111]. The bottom of the picture corresponds to the inner radius of the tile calorimeter. The tile calorimeter is symmetric with respect to the interaction point.

Figure 2.18: Schematic illustration of the mechanical assembly and the optical readout of the ATLAS hadronic tile calorimeter [111].

radial depths in the calorimeter and transmits it to the photomultiplier as shown in Fig. 2.18. Signals are transformed to unipolar pulse shape and amplified using analogue functions, and sent to the L1 trigger (see Sec. 2.2.4). Signals are digitalized every 25 ns by the ADC and only events passing the L1 trigger are recorded.

The fractional resolution $\sigma(E)/E$ of standalone tile calorimeter is measured using an isolated pion test beam. It is parameterized by Eq. (2.7) and found to be $a = (56.4 \pm 0.4) \%$ and $b = (5.5 \pm 0.1) \%$ at $\eta = 0.35$. It is improved to $a = (52.0 \pm 1.0) \%$ and $b = (3.0 \pm 0.1) \%$ by taking a combination with the EM calorimeter information.

Hadronic endcap LAr calorimeter (HEC)

In the endcap region, LAr calorimeter is adapted for the measurement of hadrons. Two wheels are located at both endcaps covering $1.5 < |\eta| < 3.2$ ($5^\circ < \theta < 25^\circ$ and $155^\circ < \theta < 175^\circ$) directly behind EMEC calorimeter sharing the LAr cryostat. Each wheel consists of 32 wedge-shaped modules. Each module is divided into two segments in depth, thus, there are 4 layers for each endcap. 25 mm (50 mm) copper plates laid in parallel are used for front (back) module as absorber. Number of copper plates is 24 (16) for the front (back). The 8.5 mm gap between copper plates provides the LAr active medium for the sampling calorimeter. The detector thickness of each HEC layer in λ is shown in Fig. 2.13. Total thickness of the HEC is about 10λ .

The read-out granularity of the HEC is $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ for $1.5 < |\eta| < 2.5$ and 0.2×0.2 for $2.5 < |\eta| < 3.2$. The resolution of the HEC is measured using a pion test beam with the same parameters as Eq. (2.7), resulting in $a = (70.6 \pm 1.5)\%$ and $b = (5.8 \pm 0.2)\%$. At the transition region to FCal ($|\eta| = 3.2$), $a \simeq 81\text{--}85\%$ is found. It is worse than the other regions, but meets well the designed value of $a = 100\%$ in Table 2.2.

Forward LAr calorimeter (FCal)

Another set of layers of calorimeter are arranged close to the beam axis to measure the secondary particles with small scattering angle. Figure 2.19 illustrates a schematic diagram for positions of the FCal. It covers the range of $3.1 < |\eta| < 4.9$ ($1^\circ < \theta < 5^\circ$ and $175^\circ < \theta < 179^\circ$). It consists of three modules and the depth is approximately 10λ as shown in Fig. 2.13. First module, made of copper, is optimized to electromagnetic measurements. The other two modules are made of tungsten, which measure hadronic interactions. The gap between materials as LAr active medium is 0.25 mm to avoid the effect of high particle flux and the radiation damage according to the small polar angle. In order to reduce the amount of neutron albedo in the inner detector cavity, the front face of the FCal is away from EM calorimeter front face by about 1.2 m.

The resolution of the FCal is estimated using a test beam. Two ways are tested. The first one uses single weight per module (flat weight) yielding $a = (28.5 \pm 1.0)\%$ and $b = (3.5 \pm 0.1)\%$ for electrons and $a = (94.2 \pm 1.6)\%$ and $b = (7.5 \pm 0.4)\%$ for pions, respectively, where a and b are defined in Eq. (2.7). The second one is more sophisticated technique using radial weights with fine transverse segmentation, improving a from 94% to 70% and b from 7.5% to 3.0% for the hadron measurement. The measured resolution of the FCal is acceptable in comparison with the designed value described in Table 2.2.

2.2.3 Muon spectrometer

Muon spectrometer is designed to measure wide range of muon momenta from a few GeV to about 3 TeV. Figure 2.20 shows the ATLAS muon detectors, which consist of four types of sub-detectors: monitored drift tubes (MDT), cathode strip chambers (CSC), resistive plate chambers (RPC) and thin gap chambers (TGC). Large and small chambers are located sided by side at each layer in both barrel and endcap

Figure 2.19: Schematic diagram of three forward LAr calorimeters located in the endcap cryostat [111]. FCal1 is used for electromagnetic measurements while FCal2 and FCal3 are used for hadronic measurements. Materials in front of the forward calorimeter and shielding plug behind that are also shown. Black region indicates structure of the cryostat.

regions, leading to a region overlapping in ϕ in order to gain the geometrical acceptance, as shown in Fig. 2.20 (a) for the barrel region. MDT and CSC are used for precision measurement, while RPC and TGC which are synchronized to the LHC clock to identify the bunch crossing are used for the trigger. The muon system is operated in the magnetic field, of typically 0.5 T provided by the barrel large toroidal magnet in $|\eta| < 1.4$ ($28^\circ < \theta < 152^\circ$), and 1 T by the endcap toroidal magnets for both endcaps of the detector in $1.6 < |\eta| < 2.7$ ($8^\circ < \theta < 23^\circ$ and $157^\circ < \theta < 172^\circ$). In the transition region ($1.4 < |\eta| < 1.7$), magnetic deflection is caused by a combination of barrel and endcap fields, as shown in Fig. 2.21. The magnetic fields forming 8-fold symmetry in ϕ are mostly orthogonal to muon directions. The muon track is bent by the magnetic field in η direction and its momentum and position are reconstructed using hits at muon chambers. The distance between the inner and outer layers of MDT is about 5 m and 14 m in barrel and endcap, respectively, as shown in Fig. 2.20 (b). Long baseline of the measurement leads to a better p_T -resolution for high- p_T muons. By taking a combination with ID tracks, more precise reconstruction of muon can be made, in particular in the low- p_T region. The muon identification criteria is described in detail in Sec. 4.3.

MDT

In the region $|\eta| < 2.7$ ($8^\circ < \theta < 172^\circ$), precision measurement of tracks is performed with MDT. MDT consists of 1,088 chambers and 339,000 read-out channels. There are three MDT layers both for the barrel and endcap regions as shown in Fig. 2.20. Each layer consists of 2×4 (inner MDT layer) or 2×3 (middle and outer MDT layer) drift-tube walls as illustrated in Fig. 2.22 (a). The diameter of a drift tube is ~ 30 mm and the gas component inside the tube is 93% Ar, 7% CO₂ and less than 1000 ppm H₂O. Small mixture of water is foreseen to improve high-voltage stability. The effect of water on the drift behavior is negligible. The electrons from ionization are collected at the central tungsten-rhenium wire with a diameter of $50 \mu\text{m}$. Maximum drift time is 700 ns. By making segments using combinations of multiple tubes per each layer as shown in Fig. 2.22 (b), it performs very high spacial resolution of $35 \mu\text{m}$, whereas average resolution of individual tubes is $80 \mu\text{m}$. MDT can measure only in z (r) direction for barrel (endcap). Secondary coordinate information (ϕ) is provided by RPC for barrel and TGC for endcap.

CSC

The limit for safe operation of the MDT is 150 Hz/cm^2 , which will be exceeded for $|\eta| > 2.0$ ($\theta > 165^\circ$ and $\theta < 15^\circ$) at the innermost layer. To cope with high muon rate in the forward region of $2.0 < |\eta| < 2.7$,

Figure 2.20: (a) Cross section of the ATLAS barrel muon system perpendicular to the beam axis [111]. In the barrel region, eight-fold ϕ symmetric structure is employed. Large and small chambers are located side by side, which lead to a region overlapping in ϕ to gain the acceptance. There are two feet to hold the detector up at sector 11-12 and 14-15, which lead to an acceptance loss. (b) r - z view of the ATLAS muon system [111]. Green and blue colors show barrel and endcap MDTs, respectively; yellow chamber is CSC; white chambers RPCs; and magenta TGCs. The barrel toroidal magnetic field and the endcap toroidal magnetic field are indicated with light green and blue shades, respectively.

Figure 2.21: Predicted magnetic field integral from innermost to outermost MDT layer in one troid octant, as a function of $|\eta|$, corresponding to the azimuthal angle $\phi = \pi/8$ (black) and $\phi = 0$ (red) [111].

CSC is used for the innermost layer of the muon system, which can be operated safely with a counting rate of 1000 Hz/cm^2 . There are 32 CSC chambers and the number of read-out channels is 31,000. Same as the MDT, CSC is segmented into large and small chambers side by side in ϕ direction. CSC is a multi-wire proportional chamber using cathode planes segmented into strips in orthogonal directions. This technique allows to measure both coordinates of muon tracks. Anode wire diameter is $30 \mu\text{m}$ and wire pitch is 2.5 mm. The cathode strip pitch is 5.31 mm and 5.56 mm for large and small chambers, respectively. The gas mixture is $\text{Ar} : \text{CO}_2 = 80 : 20$. The spacial resolution is $40 \mu\text{m}$ in r direction and 5 mm for R - ϕ direction. The time resolution is 7 ns.

RPC

The muon trigger chambers in the barrel region consist of three layers of RPC as shown in Fig. 2.20 (b). There are two RPC layers inside and outside of the middle MDT layer and one RPC layer outside of the outer MDT layer. RPC is a no-wire gas detector. Number of chambers is 544 and number of read-out channels is 359,000. The gas is enclosed between two phenolic-melaminic plastic laminate resistive plates located in parallel to each other at a distance of 2 mm. The gas mixture is 94.7% $\text{C}_2\text{H}_2\text{F}_4$, 5% $\text{Iso-C}_4\text{H}_{10}$ and 0.3% SF_6 . The electric field between the plates allows avalanches to form along the ionizing tracks towards the anode. The anode strips consist of $17 \mu\text{m}$ -thin copper on PET foil. Each strip has a width of 25-30 mm. Each RPC layer consists of two sub-layers, which have strips to measure η and ϕ , respectively. Spacial resolution is 1 mm, but the frequency response of the gas-amplifiers has a maximum at 100 MHz and a 60 MHz bandwidth. A time resolution of RPC is 1.5 ns.

TGC

TGC is a multi-wire proportional chamber covering $1.05 < |\eta| < 2.7$ ($8^\circ < \theta < 39^\circ$ and $141^\circ < \theta < 172^\circ$) in the endcap region. The gas mixture is $\text{CO}_2 : \text{n-pentane} = 55 : 45$. The wire pitch is 1.8 mm and the wire-to-cathode pitch is 1.4 mm, resulting in a spacial resolution of 2-6 mm. Number of chamber is 3,588 and number of read-out channels is 318,000. As shown in Fig. 2.20 (b), one layer of TGC is located in the innermost MDT layer (TGC I) and three TGC layers are in the middle MDT layer. Three TGC layers in the middle are used as trigger chambers in $|\eta| < 2.4$ ($\theta > 10^\circ$ and $\theta < 170^\circ$), because of the fast response (20 ns of the maximum drift time) and good time resolution (4 ns). Two-dimensional read-out is performed by the anode wires (in r) and the graphite cathode strips (in ϕ).

Figure 2.22: (a) The viewing of a MDT module [111] and (b) an example to reconstruct muon segment [114]. Two sets of three drift tube walls form one module (for middle and outer MDT layer). Drift tubes are shown in green outlined circles in (b). The charged particle trajectory is shown as the straight black line and the drift circles are shown in black. A linear fit on the drift circles is performed and the segment of the muon candidate is reconstructed.

2.2.4 Trigger and data acquisition system

As described in Sec. 2.1, the LHC has been operated typically with bunch spacing of 50 ns in 2012, corresponding to 20 MHz bunch crossing frequency. Concerning the pileup, we expect $O(1)$ GHz of pp collision rate. However, due to the limit of the computer facilities e.g. the disc access and the storage spaces, all of events produced in pp collisions cannot be recorded. Therefore, we need to apply tight event selection to collect rare signals against large background during data taking. This scheme is called trigger system. The acceptable trigger and data rate in 2012 was 700 Hz and 1 GB/s [115].

To cope with this challenging task, ATLAS employs three-level trigger system which consists of Level 1 (L1), Level 2 (L2) and Event Filter (EF) with increasing complexity and accuracy. The L2 and EF are collectively referred to as the Higher Level Trigger (HLT). The schematic view of the ATLAS trigger and data acquisition system is shown in Fig. 2.23. There are various event topologies that one wants to record depending on physics channels analyzed with ATLAS, so a signature-based trigger algorithm using e/γ , hadronic-decaying τ leptons, hadron jets, muons, and missing transverse energy, E_T^{miss} , is adapted. Combinations of each signature at the trigger level allow to define many variations of trigger logics based on event topology in parallel. Each logic is so-called a ‘trigger chain’. The band width is assigned to each trigger chain. Trigger chains exceeding the acceptable rate are pre-scaled. Pre-scaling factors can be determined individually and be changed during the data taking period, according to the beam situation of the LHC. For example, the trigger chain EF_μ4T, requiring at least one muon with $p_T > 4$ GeV, worked with high pre-scaling factor corresponding to 1.5 Hz of data-taking rate in 2012, in order to check the performance for the low- p_T muon signature.

In the LHC run1, the first running period of the experiment, there were some problems with the trigger system. I had applied some improvements on the muon reconstruction algorithm at the trigger level as an expert of the trigger system, as shown in Appendix G. My improvements suppressed the trigger rate while keeping the efficiency to events containing muons. It contributed to the ATLAS data taking in the LHC run1 with high efficiency of greater than 90 %.

Figure 2.23: The schematic view of the ATLAS trigger and data acquisition system [116]. The ATLAS physics data flow is indicated by blue lines and trigger information by red lines. In 2012, typical pp collision rate was 20 MHz corresponding to the output data stream of 1.6 MB/50 ns. The ATLAS three-level trigger system, applying tight event selection during the data taking, reduces the data taking rate to 700 Hz and 1 GB/s.

The L1 trigger

At the L1, fast and rough reconstruction of each signature is performed, using electromagnetic and hadronic calorimeters and fast muon trigger chambers (TGC and RPC). The L1 trigger defines the Region of Interest (RoI) and passes it to the HLT. By reading the signals from each sub-detector only around the RoI, faster reconstruction at the HLT can be realized. Acceptable output rate at the L1 in 2012 was 70 kHz and required latency was less than $2.5 \mu\text{s}$.

The e/γ candidates are reconstructed in the electromagnetic calorimeter based on ‘trigger tower’s with rough segmentation of the EM calorimeter in η and ϕ directions i.e. $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ and no segmentation in depth for faster read-out time; see Fig. 2.24. Combinations of 2×2 towers in which at least one of the four possible two tower sum (2×1 or 1×2) of the nearest neighbor towers exceeds predefined energy threshold form the RoI.

Jet reconstruction algorithm at L1 works with jet elements which are the sum of 2×2 trigger towers in the EM calorimeter added to 2×2 trigger towers at hadronic calorimeter. The E_T summed over 2×2 , 3×3 or 4×4 towers of hadronic calorimeter is compared with predefined E_T threshold and the jet candidate passing the threshold is defined as an RoI.

Missing transverse energy is reconstructed by vector-sum of all clusters reconstructed in the calorimeter. Correction from muons is not applied.

For muon candidates, RPC and TGC calculate p_T of muon tracks roughly using the predefined look-up-table from hit pattern at each detector layer. The typical dimensions of the muon RoI is $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ (0.03×0.03) for RPC (TGC).

Figure 2.24: The L1 electron/photon reconstruction algorithm [111].

The Higher Level Trigger (HLT)

At the HLT, software-based trigger algorithms run for each signature. More precise measurement of p_T and position can be made at L2 with respect to L1 using fine calorimeter segments and precise muon chamber (MDT). Moreover, ID track information by the fast reconstruction are available at the HLT which improves the resolution of p_T by a combination with the muon chamber and calorimeters. Tighter p_T threshold at L2 is therefore applied and EF input rate is reduced to about 5 kHz. Well-reduced EF input rate allows the EF algorithm to access to the full detector information, which can perform offline-like, with high p_T resolution and high spacial resolution for each trigger signature. Required latencies at L2 and EF were 75 ms and 1 s, respectively, in 2012.

Typical trigger chains in 2012

The typical non-pre-scaled trigger chains in 2012 are namely `EF_e24vhi_medium1`, `EF_mu24i_tight` and `EF_xe80(T)_tclcw_loose`. They are trigger chains based on simple logic, targeting to collect events with single signature of high- p_T isolated electron, high- p_T isolated muon and high missing transverse energy, respectively. Trigger logics for each chain are explained in the followings.

- `EF_e24vhi_medium1`: At least one electron candidate with $p_T > 18$ GeV at the L1 and $p_T > 24$ GeV at the HLT is required. In addition, a relative track isolation requirement $\sum_{\Delta R < 0.2} p_T^{\text{trk}} / E_T^e < 0.1$ is required at EF⁸, and a small hadronic leakage is applied at L1.
- `EF_mu24i_tight`: At least one muon candidate with $p_T > 15$ GeV at the L1 and $p_T > 24$ GeV and $\sum_{\Delta R < 0.2} p_T^{\text{trk}} / p_T^\mu < 0.12$ at the EF is required. The isolation requirement rejects muons from heavy quark decays.
- `EF_xe80(T)_tclcw_loose`: Both `EF_xe80_tclcw_loose` and `EF_xe80T_tclcw_loose` require calorimeter-base E_T^{miss} of > 40 GeV at L1, > 45 GeV at L2 and > 80 GeV at EF. `EF_xe80T_tclcw_loose` uses a complicated L1 algorithm, which does not take the first 3 bunch crossings in trains in order to cope with the out-of-time pileup contributions in the calorimeter pulse shape. `EF_xe80_tclcw_loose` was pre-scaled until May 2012. After May 2012, it was turned to be unpre-scaled for the signal acceptance. The out-of-time pileup contributions are corrected or reduced by the other criteria (see Sec. 4.5.3 and Sec. 4.5.5).

In 2012, successful operation of the trigger and data acquisition system was achieved. The trigger efficiency of `EF_e24vhi_tight` to events containing a reconstructed isolated electron candidate with $p_T > 24$ GeV is about 95 % at the barrel and 90 % at the endcap region [117]. The inefficiency of the electron trigger by 5-10 % occurs at the HLT, while about 99-100 % efficiency is achieved at the L1. The efficiency of `EF_mu24i_tight` to events containing a reconstructed isolated muon with $p_T > 24$ GeV is approximately 70 % at the barrel and 85 % at the endcap region [118]. The efficiency loss of the muon trigger is mainly caused by geometrical dead region of the L1 trigger chambers. The HLT efficiency with respect to L1 above the p_T threshold is about 98-99 %. The trigger efficiency of `EF_xe80_tclcw_loose` is about 100 % to events containing a jet with $p_T > 60$ GeV and $E_T^{\text{miss}} > 150$ GeV. The large E_T^{miss} of greater than 150 GeV and the soft muon (or electron) with $p_T > 6(7)$ GeV are expected in the target stop signal. The trigger efficiency to low- p_T leptons is not sufficient, as discussed in Appendix G for muons. Therefore, `EF_xe80(T)_tclcw_loose` is used to collect the data in this analysis. Performance of `EF_xe80(T)_tclcw_loose` is discussed in detail in Sec. 3.1.2.

Several combined-signature trigger chains are also prepared. For example:

⁸ $\sum_{\Delta R < 0.2} p_T^{\text{trk}}$ is the sum of all track's p_T within a cone of $R = 0.2$ around the lepton.

- EF_mu18_tight_mu8_EFFS requires one muon with $p_T > 18$ GeV passing all of L1, L2 and EF selection criteria and an additional muon with $p_T > 8$ GeV at EF;
- EF_e18vh_medium1_mu8 requires at least one electron with $p_T > 18$ GeV passing L1, L2 and EF requirements and at least one muon with $p_T > 8$ GeV passing L1, L2 and EF requirements.

These combined trigger chains will be more important in the LHC Run2, since higher event rate is expected.

Chapter 3

Data and Monte Carlo Simulation

We are looking for rare new physics signatures in the ‘big data’ collected with the ATLAS detector. For accurate modeling of the Standard Model background as well as signals, we use Monte Carlo simulation. In this chapter, the used dataset and Monte Carlo simulation samples in this analysis are presented.

3.1 The ATLAS pp collisions data in 2012

In this analysis, all available pp collisions data at $\sqrt{s} = 8$ TeV recorded with the ATLAS detector in 2012 are used. For the data quality, it is required that all of sub-detectors were fully working and stable beams were provided.

3.1.1 Data processing and online calibration

Data collected with the ATLAS detector are organized into different ‘stream’ based on trigger chains. In 2012, there were three physics streams:

- Egamma stream : containing events taken by electron or photon triggers;
- Muon stream : containing events taken by muon triggers;
- JetTauEtmiss stream : containing events triggered by jets, hadronic-decaying tau lepton or E_T^{miss} signatures.

The same event can appear in more than one stream, because trigger chains run in parallel. In addition, data are collected in the Express stream, which is a sub-set of the above physics streams, corresponding to 10 Hz of the data-taking rate.

The data are reconstructed in two-pass algorithm [119]. The data in Express stream are used for calibration and data quality assessment. Calibration constants are sent to physics streams after 48 hours (in 2012) from the data taking. Using the latest calibration from Express stream, raw data are translated into a data format containing variables for physics analysis. Both the raw and calibrated data in physics streams are stored at CERN computer facilities, which can be accessed from all over the world.

3.1.2 Luminosity measurement

The amount of used dataset is expressed with a time-integrated luminosity: $\int \mathcal{L} dt$. An instantaneous luminosity is derived with a measurement of the cross section and event rate of the inelastic scattering, σ_{inel} and R_{inel} , according to Eq. (2.1):

$$\mathcal{L} = \frac{R_{\text{inel}}}{\sigma_{\text{inel}}}. \quad (3.1)$$

By using the number of interaction per bunch crossing μ , number of bunches per beam n_b and the revolution frequency f_{rev} , it can be rewritten as:

$$\mathcal{L} = \frac{\mu n_b f_{\text{rev}}}{\sigma_{\text{inel}}} = \frac{\mu_{\text{vis}} n_b f_{\text{rev}}}{\sigma_{\text{vis}}}. \quad (3.2)$$

μ_{vis} is the observable interaction rate per bunch crossing, measured with the dedicated detector at the forward region [111]. The visible cross section of the inelastic scattering σ_{vis} can be determined using van der Mer scanning criteria [120]. n_b and f_{rev} are given by the LHC. Figure 3.1 shows the measured integrated luminosity delivered by the LHC, recorded by the ATLAS detector, and certified to be good quality data, as a function of day in 2012. After the data quality requirements, 20.3 fb⁻¹ data are available for physics. The uncertainty on the integrated luminosity is $\pm 2.8\%$ ¹. Once $\mathcal{L}$ is determined, we can measure the μ through Eq. (3.2), assuming the inelastic cross section to be $\sigma_{\text{inel}} = 71.5$ mb. The averaged number of interaction per bunch $\langle \mu \rangle$ as a function of day in 2012 is shown in Fig. 2.2 (b).

Figure 3.1: The integrated luminosity versus time delivered to (green), recorded by ATLAS (yellow), and certified to be good quality data (blue) during stable beams and for pp collisions at $\sqrt{s} = 8$ TeV in 2012. The delivered luminosity accounts for the luminosity delivered from the start of stable beams until the LHC requests ATLAS to put the detector in a safe standby mode to allow a beam dump or beam studies. The recorded luminosity reflects the data acquisition inefficiency.

3.1.3 Trigger efficiency measurement

As explained in Sec. 2.2.4, in high energy pp collision experiments, the trigger chain corresponding to the target signal topology must be prepared before the running of the experiment. As shown in Sec. 1.5, target signal characteristics of this thesis is two b -quarks, high E_T^{miss} , and one soft lepton. The high background rate of low- p_T leptons disables to collect the signals by the lepton trigger. Therefore, data collected by a missing transverse energy trigger: `EF_xe80(T)_tclcw_loose` is used in this analysis. As `EF_xe80_tclcw_loose` has been pre-scaled until May 2012 as mentioned to in Sec. 2.2.4,

¹It was derived in November 2012, following the same methodology as that detailed in Ref. [120], from a preliminary calibration of the luminosity scale derived from beam-separation scans.

Table 3.1: The used dataset for the analysis. Integrated luminosity for EF_xe80T.tclcw_loose is rescaled corresponding to the efficiency loss due to the trigger logic explained in the text.

Period	Trigger	Delivered (fb ⁻¹)	Rescaled (fb ⁻¹)
Apr. 2012 to May. 2012	EF_xe80T.tclcw_loose	2.1	1.9
May. 2012 to Dec. 2012	EF_xe80.tclcw_loose	18.2	18.2
Total in 2012		20.3	20.1

we used EF_xe80T.tclcw_loose instead for that period. Two trigger logics are basically the same, but EF_xe80T.tclcw_loose does not take events in the first 3 bunch crossing in trains, which leads to about 10 % efficiency loss. The integrated luminosity is rescaled to take into account this effect, which corresponds to 20.1 fb⁻¹, as described in Table 3.1.

The efficiency of EF_xe80.tclcw_loose to events containing significant missing transverse energy is evaluated by the Tag and Probe method, by which trigger efficiency can be measured independently to the trigger condition in the data taking. Data collected with the single muon trigger EF_mu24i_tight after May 2012, corresponding integrated luminosity of 18.2 fb⁻¹, are used to evaluate the efficiency. We select events containing a muonically decaying W boson by the following requirements:

- Exactly one `tight` isolated muon² with $p_T > 25$ GeV;
- No baseline electron³ exceeding $p_T = 10$ GeV;
- Transverse mass (see. Sec. 5.3) reconstructed by muon and E_T^{miss} should be greater than 40 GeV to enhance the Jacobian peak of the W boson.

In addition, in order to ensure the quality of E_T^{miss} reconstruction, existence of at least one jet with $p_T > 60$ GeV is required. Here, the definitions of muons, electrons, jets and E_T^{miss} used to the efficiency measurement are the same as those used in the SUSY analysis (see Chapter 4). Finally, as a ‘Tag’ of the event-taking trigger, the selected muon is required to geometrically match the muon track recognized at the EF in the trigger algorithm by $\Delta R < 0.05$. The E_T^{miss} reconstructed only from calorimeter informations (not corrected for muon momentum) is a trigger-bias-free variable, which is used as the ‘Probe’.

Figure 3.2 shows the distributions of m_T and E_T^{miss} without muon correction after the event selections, before and after the requirement of EF_xe80.tclcw_loose trigger condition. Monte Carlo simulation of $W \rightarrow \ell\nu$ is overlaid, where ℓ denotes e, μ or τ . The simulated sample is normalized to the theoretical cross section and the integrated luminosity. Good agreement between the data and simulation is found i.e. high purity of $W \rightarrow \mu\nu$ is ensured, while the effect of mis-identified muon is found at the low E_T^{miss} region, where the data are a bit larger than the prediction. Trigger efficiency as a function of E_T^{miss} is shown in Fig. 3.3. A 100 % efficiency is found at $E_T^{\text{miss}} > 150$ GeV. It shows that the data in $E_T^{\text{miss}} > 150$ GeV and jet- $p_T > 60$ GeV agree well with the simulation, while avoiding the uncertainty associated with the resolution of the E_T^{miss} at the trigger and the effect of the mis-identified muon background. Systematic uncertainty associated with the E_T^{miss} trigger efficiency is assigned conservatively to be ± 5 %.

3.2 Monte Carlo Simulation

Monte Carlo (MC) simulation is used to model the SUSY signals and to evaluate the Standard Model (SM) background. Signal and the SM background samples are generated with various generators as explained in the following sections and processed with the ATLAS detector simulation.

²The `tight` isolation criteria is explained in Sec. 4.4.

³The baseline electron is defined in Sec. 4.2.

Figure 3.2: Distributions of the transverse mass m_T (a) and missing transverse energy E_T^{miss} without muon correction (b) after the selection criteria for $W \rightarrow \mu\nu$ are applied (at least one jet with $p_T > 60$ GeV is required). White (black) circle indicates data before (after) the requirement of the E_T^{miss} trigger (EF_xe80_tclcw_loose). The dashed and solid red lines indicate the Monte Carlo simulation of $W \rightarrow \ell\nu$ before and after the E_T^{miss} trigger is required, respectively. The data corresponding to an integrated luminosity of 18.2 fb^{-1} are used. The simulation is normalized to the cross section and luminosity. Errors only contain the statistical uncertainty.

Figure 3.3: The efficiency of EF_xe80_tclcw_loose to events with at least one jet with $p_T > 60$ GeV as a function of missing transverse energy E_T^{miss} without muon term. The efficiency derived by the data and $W \rightarrow \ell\nu$ Monte Carlo simulation are shown with black dots and red circles, respectively. The efficiency is approximately 100 % at $E_T^{\text{miss}} > 150$ GeV. At the plateau region, data agree well with Monte Carlo. The data corresponding to an integrated luminosity of 18.2 fb^{-1} are used. Errors contain only the statistical uncertainty.

3.2.1 Parton Distribution Function (PDF)

Figure 3.4 is a schematic illustration of a pp collision at the LHC. At a very high center-of-mass energy, the inelastic pp scattering is regarded as point-like interactions between partons, which are the constituents of proton: ‘valence’ quarks uud , ‘sea’ quarks from gluon radiation by the effect of QCD, and gluons themselves. Cross section of the physics process depends on the probability of the initial-state parton kinematics, which is described by parton distribution functions (PDFs).

Bjorken x is introduced to describe the fraction of the momentum p of a parton with respect to the proton momentum P , i.e.

$$p = xP. \quad (3.3)$$

The transverse momentum of partons in the proton-momentum frame is considered to be zero. In Fig. 3.4, a parton i with $x = x_i$ and j with $x = x_j$ contribute to the hard scattering. The cross section to produce hadron H in the pp collisions $\sigma_{pp \rightarrow HX}$ is schematically written by:

$$\sigma_{pp \rightarrow HX} = \sum_{ijk} \int dx_i dx_j dz_k f_i(x_i, \mu_F^2) \times f_j(x_j, \mu_F^2) \times \hat{\sigma}_{ij \rightarrow kX}(\alpha_s(\mu_R), x_i, x_j, \mu_F, \mu_R, Q^2) \times D_{k \rightarrow H}(z_k, \mu_F), \quad (3.4)$$

where k denotes a final-state parton and the sum is over all contributing parton sub-processes $ij \rightarrow kX$ contained in the perturbatively calculable cross sections $\hat{\sigma}_{ij \rightarrow kX}$. The μ_F is the factorization scale, which is thought as the scale that separates the long- and short-distance physics, and the μ_R is the renormalization scale for the QCD running coupling as introduced in Sec. 1.1.3. The μ_F and μ_R are usually chosen at the momentum scale of the hard-scattering process, and $\mu_F = \mu_R$ is assumed. The $D_{k \rightarrow H}$ is the fragmentation function to describe the transfer from the parton k to a hadron H . z_k denotes the collinear momentum fraction of k carried by the produced hadron H . The evolution of the PDF with Q^2 is understood by the DGLAP equation as:

$$\frac{df_a(x, Q^2)}{d \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \sum_b \int_x^1 dy P_{ab}\left(\frac{x}{y}\right) f_b(y, Q^2), \quad (3.5)$$

where P_{ab} is a parton-splitting probability of $b \rightarrow a$ transfer [121]. Therefore, we can calculate cross sections by using the PDFs at the arbitrary factorization scale. Uncertainties coming from the arbitrary choice of the factorization and renormalization scales are estimated by varying the scales within a factor of two around the default choice (see Sec. 6.3.2). However, x dependency of the PDFs needs to be obtained by the experimental measurements. Several collaborations have performed the global fit to data from some fixed target, $e^\pm p$, $p\bar{p}$ and pp collision experiments and provided PDFs available for MC simulation. Figure 3.5 shows the next-to-leading order (NLO) perturbative QCD calculation of the $xf(x, Q^2)$ by MSTW collaboration [122] as a function of x at two benchmark Q^2 values. The figure shows that the PDFs for valence quarks (u and d) peak at the higher x region, while gluons and sea quarks are dominant at the small x region, in particular at high Q^2 region which is the main phase space at the LHC. The experimental uncertainties on x distribution is taken into account in the SUSY analysis (see Sec. 6.3.2).

Cross sections for all kinds of physics processes at the LHC can be calculated in the same way. For productions of bosons and leptons, we do not need to consider the fragmentation function. Cross sections of SUSY particles (see Sec. 1.3) are also calculated in this method. Details of event generators and PDF sets used in this analysis for the SM background as well as signals are explained in the following sections.

3.2.2 The Standard Model backgrounds

Generators, PDF sets and cross sections for the SM background processes used in this analysis are summarized in Table 3.2.

Figure 3.4: The schematic illustration for the factorization of an inelastic scattering $pp \rightarrow HX$ at the LHC [123] at the factorization scale μ_F , where H denotes a hadron. In the lab-frame, protons with momentum P are collided at the centre of the picture. It is regarded as the scattering of a parton i with momentum of $x_i P$ and a parton j with $x_j P$. Species of the partons i and j are determined by the parton distribution function f_i and f_j . The hard scattering with the squared momentum transfer between two partons at Q^2 to produce a parton k occurs at the centre of the figure. The parton k is fragmented to a hadron H through the fragmentation function D_k . The total cross section of $pp \rightarrow HX$ is expressed by the superposition of all possible $ij \rightarrow kX$ combinations.

Figure 3.5: Parton distribution function versus Bjorken x at two squared momentum transfer benchmarks of $Q^2 = 10$ and 10^4 GeV^2 [122]. The blue and green lines are distributions for u - and d -quarks. Gluon, s -, c - and b -quarks are indicated by the red, pink, dark blue and light blue, respectively. $\bar{u}$, $\bar{d}$ and $\bar{s}$ are indicated by outlined blue, green and pink lines. $\bar{c}$ and $\bar{b}$ distributions are assumed to be the same with c and b . Contribution from b -quark arises above the energy scale greater than its mass. Color bands indicate uncertainties at 68 % CL. Gluon and sea quark distributions are divided by factor 10.

Table 3.2: Summary of Monte Carlo simulation for the Standard Model background processes.

Sample	Generator	PDF	Cross section [nb]
$t\bar{t}$	POWHEG+PYTHIA	CT10	253 (NNLO)
$(W \rightarrow \ell\nu)$ +jets	SHERPA	CT10	36.6×10^3 (NNLO)
$(Z \rightarrow \ell\ell)$ +jets			3.73×10^3 (NNLO)
Dibosons			
$WW \rightarrow \ell\ell\nu\nu$	SHERPA	CT10	5.61 (NLO)
$WZ \rightarrow \ell\ell\nu$	SHERPA	CT10	10.0 (NLO)
$WZ \rightarrow \ell\nu\nu$	SHERPA	CT10	1.47 (NLO)
$ZZ \rightarrow \ell\ell\nu\nu$	SHERPA	CT10	0.52 (NLO)
Others	SHERPA	CT10	43.2 (NLO)
Single top			
t -channel	ACERMC+PYTHIA	CTEQ6L1	28.4 (NLO+NNLL)
s -channel	POWHEG+PYTHIA	CT10	1.79 (NLO+NNLL)
Wt -channel	POWHEG+PYTHIA	CT10	22.3 (NLO+NNLL)
Zt -channel	MADGRAPH+PYTHIA	CTEQ6L1	0.03 (NLO)
$t\bar{t}+W$	MADGRAPH+PYTHIA	CTEQ6L1	0.23 (NLO)
$t\bar{t}+Z$			0.21 (NLO)
$t\bar{t}+WW$			0.001 (NLO)

Top quark pair production ($t\bar{t}$), the main background in this analysis, is generated with POWHEG-R2129 [124] interfaced to PYTHIA-6.426 [125] for fragmentation/hadronization, with a top quark mass of 172.5 GeV. The generator uses the NLO PDF set CT10 [126] and an underlying event tune by PERUGIA 2011C [127]. The $t\bar{t}$ cross section is calculated at next-to-next-to-leading order (NNLO) in QCD including resummation of next-to-next-to leading logarithmic (NNLL) soft gluon terms with top++2.0 [128–130] using MSTW2008 NNLO PDF set [122]. The normalization of $t\bar{t}$ is estimated by the fit (see Chapter 6) and the uncertainty on the cross-section calculation is not considered in this analysis. Top quark decays into a W boson and a b quark with a branching ratio of approximately 100 %. The $t\bar{t}$ sample is classified to three sub-channels corresponding to different decay modes of the W bosons. Semi-leptonic $t\bar{t}$, which is the case where one W boson decays directly or via an intermediate τ decay into an electron or a muon, is the dominant source of the background in this analysis. Di-leptonic $t\bar{t}$ is defined as the case where both W bosons decay into an electron or a muon. The other cases are classified as full-hadronic $t\bar{t}$. To account for discrepancies between data and simulated $t\bar{t}$ events at high p_T of the $t\bar{t}$ system ($p_T^{t\bar{t}}$), the MC is re-weighted as a function of $p_T^{t\bar{t}}$; re-weighting is based on the ATLAS measurement of the differential $t\bar{t}$ cross section at 7 TeV, following the method described in Ref. [131, 132] (see details in Appendix A). It is confirmed that the re-weighting of the $t\bar{t}$ MC does not affect the final results.

The sub-dominant source of the background in this analysis is W boson production associated with heavy quarks. Vector bosons (W and Z/γ^*) plus jets are generated with SHERPA-1.4.1 [133] containing four additional partons and the correct treatment of b and c quarks masses, using CT10 PDF set. SHERPA has an integrated underlying event tune and its own built-in fragmentation/hadronisation models. The cross sections for W/Z +jets are calculated with DYNLO [134]. The normalization of W +jets is estimated by the fit (see Chapter 6) so the uncertainty on the cross-section calculation is not considered in this analysis. The Z/γ^* with extra jets up to 5 partons (Drell-Yan process) for low dilepton invariant mass of 10-40 GeV is generated with ALPGEN [135] interfaced to HERWIG [136], but these backgrounds are found to be negligible after the event selections in the SUSY analysis. The electroweak diboson production processes (WW , WZ and ZZ) are also generated with SHERPA containing three additional parton.

The cross sections for the dibosons are calculated at NLO with MCFM [137, 138]. The uncertainties on the cross section calculation is 5 % for WW and ZZ productions and 7 % for WZ productions.

Single top quark production is categorized to the s -channel, the Wt -channel and the t -channel. The s -channel and Wt channel are generated with PowHEG interfaced to PYTHIA using CT10 PDF set, while the t -channel is generated with ACERMC-3.8 [139] connected to PYTHIA and CTEQ6L1 [140] PDF set. In Wt channel, the interference with $t\bar{t}$ at NLO in QCD calculation is treated by the diagram removal scheme [141, 142] (see also Sec. 6.3.2). The cross sections for single top quark production are calculated to approximate NLO+NNLL precision [143–145] using MSTW2008 PDF set. The cross section uncertainties on t -channel, s -channel and Wt -channel are 3.9 %, [+3.9, -2.2] %, and 6.8 %, respectively. Small contribution of Zt -channel is considered, which are generated by MADGRAPH-5.1.4.8 [146] using CTEQ6L1 PDF, interfaced to the ATLAS Underlying Event Tune 2B [147] and PYTHIA for the fragmentation/hadronisation. Conservative 50 % uncertainty is assigned to the cross section of Zt -channel.

The $t\bar{t}$ production in association with vector boson V (W or Z) are generated with MADGRAPH+PYTHIA with up to two additional partons. The cross sections for $t\bar{t}+V$ are calculated at NLO using MSTW2008 (for W) or CTEQ6.6M [148] (for Z) PDF set. Uncertainties on cross sections for $t\bar{t} + W/Z$ are 22 %. Small contribution of $t\bar{t} + WW$ is expected, and its cross section uncertainty is assigned to be 50 % conservatively.

3.2.3 Signals

Stop pair production signals are generated with MADGRAPH interfaced to PYTHIA for the fragmentation/hadronization. The SUSY mass spectrum is set by hand. In this analysis, the signal sample is characterized by a combination of masses of stop, chargino and neutralino, $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0})$. Masses of the other SUSY particles are set to be much heavier than $\tilde{t}_1$ for the simplicity. Simplified approach is employed assuming a 100 % branching ratio of $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$. The chargino decays as $\tilde{\chi}_1^\pm \rightarrow (W^{(*)} \rightarrow ff')\tilde{\chi}_1^0$. Two benchmark planes with relatively small Δm of 5 GeV and 20 GeV are chosen by following the previous ATLAS analysis [95]. Signals are generated in a grid across the plane of $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$ with a 50 GeV step of $m_{\tilde{t}_1}$. Figures 3.6 (a) and (b) show the signal grids for $\Delta m = 5$ GeV and 20 GeV. For the region $m_{\tilde{t}_1} < 300$ GeV in $\Delta m = 20$ GeV grid, finer granularity of the signal points is provided (typically 25 GeV step of $m_{\tilde{t}_1}$) to study the small $\Delta M = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ region in addition to the small Δm . A filter requiring $E_T^{\text{miss}} > 60$ GeV is applied at the generator level for all signal points. The filtering efficiency for each point is taken into account by correcting the cross section. Samples generated with tight E_T^{miss} filter requiring > 250 GeV are added to the region in $m_{\tilde{t}_1} \leq 300$ GeV in $\Delta m = 20$ GeV grid, to accumulate the signal statistics after the tight event selections are applied. Overlapping between two different filter samples are resolved by applying an upper cut on E_T^{miss} to samples with $E_T^{\text{miss}} > 60$ GeV.

In addition, in order to study the sensitivity of this analysis in several variations of Δm , signal samples are generated in three other orthogonal grids. Two planes fix the chargino mass at 106 GeV and 150 GeV and scan the variations of $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$, as shown in Figs. 3.6 (c) and (d). A generator-level filter requirement $E_T^{\text{miss}} > 60$ GeV is applied if the samples have a lepton with $p_T < 10$ GeV. As with signals in $\Delta m = 20$ GeV grid, signal samples with tighter E_T^{miss} filter requirement of greater than 250 GeV are generated in $m_{\tilde{t}_1} < 300$ GeV for the grid with fixed chargino mass of 150 GeV to increase the signal statistics at high E_T^{miss} tail. The other grid fixes the stop mass at 300 GeV. In this grid, signal points are generated in a $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ plane as shown in Fig. 3.6 (e). A generator-level filter requirement $E_T^{\text{miss}} > 60$ GeV is applied for events with a lepton with $p_T < 10$ GeV.

The one-step decay signal model of stop, in off-shell W phase space, so-called four-body decay grid: $\tilde{t}_1 \rightarrow bff'\tilde{\chi}_1^0$ is also interesting in this analysis, because the existence of low- p_T lepton is expected. Signals are generated in the $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ plane as shown in Fig. 3.6 (f) assuming a 100 % branching ratio of the four-body decay mode. Signal MC for one-step decay signals are generated separately with three

different E_T^{miss} regions: $80 < E_T^{\text{miss}} < 150$ GeV, $150 < E_T^{\text{miss}} < 300$ GeV and $E_T^{\text{miss}} > 300$ GeV to enhance signal statistics at high E_T^{miss} tail. Additional requirement for lepton ($p_T > 5$ GeV) is applied only for samples with $80 < E_T^{\text{miss}} < 150$ GeV filter.

For all signal grids, in the parameter region where W is on-shell, the full $\tilde{t}_1$ decay is simulated with MADGRAPH, while PYTHIA is used for the decay of $\tilde{t}_1$ in the off-shell W parameter region.

The cross sections of stop pair production are calculated at NLO including resummation of soft gluon emission at next-to-leading-logarithmic accuracy (NLO+NLL) [149–151]. The nominal cross section and the uncertainty are taken from an envelope of cross section predictions using different PDF sets and factorization and renormalisation scales, as described in Ref. [152] (see also Sec. 6.3). The stop pair production cross section as a function of $m_{\tilde{t}_1}$ is shown in Fig. 3.7.

3.2.4 Overlap removal between diagrams by matrix element and parton shower

Overlap of a diagram calculated with the higher order matrix element with the lower order diagram with additional parton from parton shower is removed carefully by omitting the diagram from parton shower. Two individual criteria are proposed to perform this operation [153]: MLM and CKKW. MLM is based on geometrical separation of partons between two diagrams. CKKW criteria removes parton based on k_T -measure [154, 155].

3.2.5 Detector simulation

After the tree-level generation and fragmentation/hadronization, MC samples are interfaced to the ATLAS detector simulation [156] based on GEANT4 [157] or a fast simulation framework, which simulates electromagnetic and hadronic showers using a parameterized simulation [158] and uses GEANT4 only for the rest of the detector. The validation of the fast simulation is performed against the full GEANT4 simulation for several samples [158]. Signals at each sub-detector is emulated here and the same online trigger algorithms run through the simulation samples. Finally MC samples are translated into the same format with data as described in Sec. 3.1.1 for physics analysis.

3.2.6 Pileup re-weighting

Various numbers of minimum-biased events generated with PYTHIA-8.160 [159] are overlaid to all MC samples to evaluate the impact of pileup. The MC samples are re-weighted to match the $\langle\mu\rangle$ distribution to data for each data-taking period. The $\langle\mu\rangle$ distribution in 2012 is shown in Fig. 3.8 (a) in comparison with Monte Carlo simulation before (dot-dash violet line) and after (solid red line) the pileup re-weighting. The Loose1B event selection defined in Sec. 6.6.2 is applied. The $\langle\mu\rangle$ distribution agrees well with MC after the pileup re-weighting. However, the criteria considers only ‘in-time’ pileup coming from the same bunch crossing and does not consider the effect of out-of-time pileup. Consequently, the number of vertices in the event (N_{vtx}) after the pileup re-weighting does not agree with data as shown in Fig. 3.8 (b). To correct the N_{vtx} distribution, the $\langle\mu\rangle$ distribution is rescaled by factor 1.11. Distributions of $\langle\mu\rangle$ and N_{vtx} after the rescale is shown by dashed blue lines in Fig. 3.8. This 11 % shape disagreement on the $\langle\mu\rangle$ distribution is considered as a systematic uncertainty associated with the pileup re-weighting.

Figure 3.6: Signal grids generated for this analysis. (a)-(e): Stop signals decaying into b -quark and soft fermion pair: $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow bff'\tilde{\chi}_1^0$. Generated signal points are shown in $m_{\tilde{t}_1}$ - $m_{\tilde{\chi}_1^0}$ plane with $\Delta m = 5$ GeV assumption (a), $\Delta m = 20$ GeV assumption (b), fixed $m_{\tilde{\chi}_1^\pm} = 106$ GeV assumption (c), and $m_{\tilde{\chi}_1^\pm} = 150$ GeV (d). Signal points with fixed $m_{\tilde{t}_1} = 300$ GeV are shown in $m_{\tilde{\chi}_1^\pm}$ - $m_{\tilde{\chi}_1^0}$ plane in (e). (f): Stop signals in the four-body decay scenario: $\tilde{t}_1 \rightarrow bff'\tilde{\chi}_1^0$ in $m_{\tilde{t}_1}$ - $m_{\tilde{\chi}_1^0}$ plane. A 100 % branching ratio are considered for all signals. The details of generator-level filters are explained in the text.

Figure 3.7: Cross section and its uncertainty of stop pair production in pp collisions at $\sqrt{s} = 8$ TeV as a function of stop mass.

Figure 3.8: The averaged interactions per bunch crossing $\langle\mu\rangle$ (a) and the number of vertices in the event N_{vtx} (b) after the selections of Loose1B (defined in Sec. 6.6.2). Dot-dash violet and solid red lines show Monte Carlo (MC) simulation before and after the pileup re-weighting, respectively, and blue dashed lines show those after the rescaling of $\langle\mu\rangle$ distribution by 11 %. MC simulation contains $t\bar{t}$, W/Z +jets, single top, $t\bar{t} + V$, dibosons samples as summarized in Table 3.2. Data-driven estimated mis-identified lepton background is added to MC distribution. The error bars contain only the statistical uncertainty.

Chapter 4

Particle Reconstruction

As mentioned in Sec. 2.2, particles produced in pp collisions are identified and their kinematics are reconstructed by a combination of signals at the sub-detectors. This chapter shows the methodology and performance of physics-signature reconstructions with the ATLAS detector.

4.1 Track and vertex reconstruction

Tracks of charged particles and primary vertices are recognized in the inner detector. Tracks are used in the electron, muon, and jet reconstruction algorithms as described in Sec. 4.2, 4.3 and 4.5, respectively. In addition, cuts on track parameters can be applied to each track, even if the track is not associated with a physics signature.

4.1.1 Track reconstruction

Tracks are reconstructed using the ATLAS tracking algorithm [160] from inside to outside. First, it finds three-dimensional representation of hits in the silicon detector (Pixel+SCT) easily reconstructed by two-coordinate read-out of the Pixel and SCT as described in Sec. 2.2.1 and collects hits along the track starting from the interaction point (IP) using a Kalman filter. Then, the reconstructed track candidate in the silicon detector is extended to TRT, after fake tracks are rejected by a χ^2 test and the ambiguities are resolved¹. The track parameters are optimized to minimize the χ^2 using the full inner detector information. In case that the track reconstruction quality at the silicon detector is higher than that for the combined track with TRT, the track calculated at the silicon detector is kept and the TRT hits are put as outlier measurements onto the track. Tracks reconstructed in TRT not combined with the silicon detectors are referred as TRT-standalone tracks and used to recover the failure in the silicon detector.

All reconstructed tracks are required to have $p_T > 400$ MeV. In addition, the inner detector quality cuts are introduced. For example, the following two conditions are used to evaluate the track and vertex reconstruction efficiencies.

- Default condition: at least 7 silicon hits and at most two holes² in the Pixel are required;
- Robust condition: at least 9 hits and no hole in the Pixel+SCT are required.

Figures 4.1 (a) and (b) show the track reconstruction efficiency, which is defined as the fraction of primary particles with $p_T > 400$ MeV and $|\eta| < 2.5$ matched to a reconstructed track, using a minimum

¹Tracks found in the crude silicon pattern recognition contains many fake tracks or overlapping track segments with shared hits. Such ambiguities are solved by a dedicated module [160] scoring the tracks in a reward/penalty schema with respect to another to finally achieve the best track collection.

²A hole of the detector is defined as a non-existing but expected measurement point caused by inactive modules.

bias MC simulation. The MC simulation is generated with $\sqrt{s} = 7$ TeV corresponding to 2011 run. The efficiencies in three pileup conditions of $\mu = 1, 21$ and 41 are compared, where μ is the number of interactions for each bunch crossing. The efficiency is not affected by the pileup with both default and robust conditions. The robust condition reduces the efficiency by about 5 % with respect to the default condition, while it suppresses the fake track fraction dramatically, as shown in Figs. 4.1 (c) and (d). It is important to optimize the track quality cuts for each signature (electrons, muons, or hadrons) according to the signal efficiency and fake probability. The track quality conditions for electrons and muons are explained in Sec. 4.2.4 and Sec. 4.3.5, respectively.

Figure 4.1: The primary track reconstruction efficiency as a function of p_T (a) and η (b) and the non-primary fraction as a function of p_T (c) and η (d) in the minimum bias MC simulation with pileup conditions of $\mu = 1$ (red), 21 (blue) and 41 (green) [161]. The setup of the MC simulation is for 2011 $\sqrt{s} = 7$ TeV. Dashed and solid lines show the efficiencies of the default and robust reconstruction conditions, respectively, which are explained in the text.

4.1.2 Vertex reconstruction

Primary vertices are reconstructed by an iterative vertex finding algorithm [162]. Vertex seeds are obtained from the track z -positions along the beam line. A robust χ^2 -base fit is performed to a seed track and tracks around it. Three-dimensional constraint from the beam position is made in the fit. Iteration to reconstruct vertices proceeds using a new seed track which is incompatible with the reconstructed vertex by more than approximately 7σ until there are no seed track remained. Among several vertices

reconstructed in the event, the one with the largest scalar sum of associated track p_T is chosen as the primary vertex for the hard scattering. For the reconstruction quality, at least 2 tracks associated with the primary vertex are required for the vertex reconstruction efficiency evaluation, whereas at least 5 tracks associated with the primary vertex are required in the SUSY analysis.

The vertex reconstruction efficiency as a function of μ is shown in Fig. 4.2 (a) derived by a MC simulation. The vertex reconstruction efficiency is evaluated using the same track-to-particle matching conditions as that used for the tracking efficiency evaluation. The figure shows two vertex reconstruction efficiencies using tracks passing the default and robust conditions. The efficiency depends on the pileup, but there are no significant difference between the default and robust track conditions. The denominator includes events containing only soft particles with $p_T < 400$ MeV, which leads to the efficiency of about 80 % at $\mu = 1$. The efficiency to events containing at least two particles with $p_T > 400$ MeV and $|\eta| < 2.5$ is shown by green line in the same figure, to be 90 % at $\mu = 1$. The robust condition can suppress the fake vertex probability in particular at high μ region, as shown in Fig. 4.2 (b).

Figure 4.2: The vertex reconstruction efficiency (a) and fake vertex probability (b) as a function of μ using a minimum bias MC sample [161]. The red (blue) lines show the efficiency using tracks reconstructed by the default (robust) condition, which are explained in the text. The MC simulation is generated at $\sqrt{s} = 7$ TeV. The vertex reconstruction efficiency to events containing at least two stable charged primary particles with $|\eta| < 2.5$ and $p_T > 400$ MeV is shown by green line in (a).

4.1.3 Impact parameter resolution

Primary particles are supposed to be produced at the IP and the position of the reconstructed vertex fluctuates around that. Therefore, the track impact parameter peaks at zero and the resolution of that indicates the performance of the track and vertex reconstruction. The transverse impact parameter d_0 is defined as the distance of the perpendicular line to a track from the IP in the x - y plane as shown in Fig. 4.3 (a). The longitudinal impact parameter z_0 is the one defined along z -axis and usually we use $z_0 \sin \theta$ where θ is a polar angle of the track, as shown in Fig. 4.3 (b). Figure 4.4 shows d_0 and $z_0 \sin \theta$ resolutions as a function of $1/\left(\sqrt{p^2 \sin^3 \theta}\right)$ which is a variable sensitive to multiple scattering. The resolution is defined as the width of the Gaussian fit and it depends on p_T and η . The d_0 resolution is better in small η , in particular at low p_T , while better $z_0 \sin \theta$ resolution is found in the high η , especially at high p_T . Data agree well with MC in almost all regions.

Figure 4.3: (a) Transverse (d_0) and (b) longitudinal (z_0) impact parameter definitions indicated by red lines. Black and white circles show the vertex and the interaction point, respectively.

4.2 Electron reconstruction

The electron reconstruction starts from the energy deposit (cluster) at the EM calorimeter. The clusters are then combined with the inner detector tracks. Energy calibration is applied based on the MC truth information and validated by using the data. Finally, a set of parameter cuts is applied to identify electrons for the physics analysis.

4.2.1 Cluster reconstruction at the EM calorimeter

The EM cluster is reconstructed by a combination of towers at the EM calorimeter. The size of the EM calorimeter tower is $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$, corresponding to the size of the read-out cell at the middle EM calorimeter layer. The tower energy is defined as the total energy of the cells in the all longitudinal layers. A cluster of 3×5 towers searched by a sliding-window criteria [163] exceeding $E_T = 2.5$ GeV forms a seed of an electron candidate. A duplicated cluster around the seed cluster is removed by the dedicated algorithm. Since it is difficult to estimate the cluster finding efficiency by data-driven method, it is evaluated by the MC simulation. Efficiencies are found to be 95 % at $E_T = 7$ GeV, 99 % at $E_T = 15$ GeV and 99.9 % at $E_T = 45$ GeV [164], which are sufficiently high.

4.2.2 Track matching

The region of interest for track finding algorithm with a cone size of $\Delta R = 0.3$ is defined around the EM cluster passing the loose shower shape requirements: $R_\eta > 0.65$ and $R_{\text{had}} < 0.1$, where R_η is the ratio of the energy in 3×7 cells over the energy in 7×7 cells centered at the electron cluster and R_{had} is the hadronic leakage defined by the ratio of E_T in the hadronic calorimeter to E_T of the EM calorimeter. If a reconstructed track (see Sec. 4.1.1) with $p_T > 1$ GeV but less than 7 hits at the inner detector fails matching the region of interest, the track is re-fitted by the new algorithm which allows energy loss due to bremsstrahlung in the detector. All matched tracks are required to have at least 4 silicon hits. The track parameters are then calculated precisely using an optimized electron track fitter using a Kalman filter [165]. The track is identified to match the EM cluster with the following conditions: $\Delta\phi < 0.1$ toward the direction track is bending or $\Delta\phi < 0.05$ in the opposite direction; $\Delta\eta < 0.05$ at the EM cluster. Additionally, the matching between TRT-standalone track and the EM cluster is tested with looser matching criteria in η ($|\Delta\eta| < 0.35$ in barrel and < 0.2 in endcap) and tighter in ϕ ($|\Delta\phi| < 0.03$ (0.02) on the (opposite) side the track is bending towards). If more than one tracks match an EM cluster, the closest track to the EM cluster in ΔR is selected. The EM clusters matched to the track are re-built in all

Figure 4.4: The impact parameter resolutions as a function of $1/\sqrt{p^2 \sin^3 \theta}$ in two different η regions estimated using the data taken in 2011 at $\sqrt{s} = 7$ TeV (black) and the corresponding minimum bias MC simulation (red). The resolutions of transverse (longitudinal) impact parameter d_0 ($z_0 \sin \theta$) are shown in (a) and (b) ((c) and (d)).

4 layers of the EM calorimeter sequentially, starting from the middle layer using 3×7 (5×5) cells in $\eta \times \phi$ in barrel (endcap) and the electron energy is calculated.

4.2.3 Energy calibration

Before the overall correction of the electron energy scale, the different longitudinal calorimeter layers are calibrated separately [166]. The intercalibration of the first and second layers of the EM calorimeter are performed in data by expected energy deposits of muons at the calorimeter from Z boson decay. The uncertainty associated with that is estimated to be 1-1.5 % depending on η , by varying the detector descriptions in the simulation. In addition, uncertainty on the energy scale at the first layer of the EM calorimeter coming from the gain instability is estimated to be 1-5 % at the specific η region. The energy scale of the pre-sampler calorimeter is determined from the ratio of the energies in data and MC and estimated by electrons from W and Z boson decays. The systematic uncertainty associated with the pre-sampler energy scale coming from the methodology is evaluated to be 2-3 % depending on η .

After the calibrations of the longitudinal layers, the cluster energy associated with the electron candidate is calibrated to the truth electron energy (E^{truth}) in the MC sample, using a multi-variate technique in 9×10 bins in E_T and η_{cluster} ; where η_{cluster} is the pseudo-rapidity of an electron candidate in the calorimeter. The multi-variate analysis is optimized to separate electron signals from photon conversion background. For the above multi-variate analysis based on the MC truth energy, the effects of detector geometry and interaction with materials must be correctively described in the simulation. The material

distribution is measured in data using the ratio of the first-layer energy to the second-layer energy of the EM calorimeter. The uncertainty on the modeling of the detector materials is evaluated by varying the parameters of the MC simulation describing them.

Further calibration of the electron energy scale and resolution is performed referring to the data. The correction factors are derived by comparing the peak position and width of the reconstructed invariant mass distribution of $Z^0 \rightarrow e^+e^-$ candidates between the data and MC. Since the energy response E/E^{truth} after the MC base calibration is confirmed to be stable with respect to ϕ and pileup condition, electron energy scale and resolution correction factors are derived only in η bins. The electron energy in the data E^{data} and resolution $(\sigma/E)^{\text{data}}$ are written using those in the MC (E^{MC} and $(\sigma/E)^{\text{MC}}$) as:

$$E^{\text{data}} = E^{\text{MC}} (1 + \alpha_i), \quad (4.1)$$

$$(\sigma/E)^{\text{data}} = (\sigma/E)^{\text{MC}} \oplus c_i, \quad (4.2)$$

where α_i and c_i are correction factors for the energy scale and resolution for i -th η bin. There are 34 and 24 η bins for α and c in $-2.47 < \eta < 2.47$. The α and c are propagated to the di-electron invariant mass for $Z^0 \rightarrow e^+e^-$ and width of the distribution, i.e.

$$m_{ij}^{\text{data}} = m_{ij}^{\text{MC}} (1 + \alpha_{ij}), \quad (4.3)$$

$$(\sigma_m/m)_{ij}^{\text{data}} = (\sigma_m/m)_{ij}^{\text{MC}} \oplus c_{ij}, \quad (4.4)$$

where i and j are η bins for two electrons and $\alpha_{ij} = (\alpha_i + \alpha_j)/2$ and $c_{ij} = (c_i \oplus c_j)/2$. The templates are prepared in pseudo-rapidity configurations (η_i, η_j) and constitute a two-dimensional grid along (α_{ij}, c_{ij}) . The best fit α and c are obtained by the χ^2 minimization in each (η_i, η_j) bin as shown in Fig. 4.5. The uncertainty on the electron energy scale and resolution coming from the above procedure is estimated to be a few %. The considered sources of the uncertainty are the fitting criteria, event selection, the incomplete description of the detector and the background modeling: the uncertainty coming from the fitting criteria is evaluated by performing the fit by the different method using the likelihood; the uncertainty coming from the event selection is evaluated by using a different electron identification criteria; the uncertainty coming from the detector descriptions is evaluated by varying the parameters in the simulation; the uncertainty coming from the background modeling is evaluated by varying the cross sections of the background in the fit. Additional systematic uncertainties for low- p_T electrons are considered in $p_T < 20$ GeV, which is derived by $J/\Psi \rightarrow e^+e^-$ sample.

Total systematic uncertainty on the electron energy scale, including the material uncertainty and the pre-sampler energy scale uncertainty depending on E_T and η is evaluated to be a few % at $E_T = 40$ GeV in the barrel region, while it rises up-to about 20 % in endcap. Relatively large uncertainties (several dozen %) at the other E_T regions are assigned: the main sources of the uncertainty at the lower- and the higher- E_T regions come from the material description and the gain instability of the calorimeter, respectively. The uncertainty on the energy resolution is less than 10 % for $E_T < 50$ GeV and asymptotically rises to about 40 % at high energy. A dominant source of the resolution uncertainty comes from the pileup modeling at the low- E_T , and the material modeling at the high- E_T .

4.2.4 Electron identification

Electrons are required to have $p_T > 7$ GeV and $|\eta| < 2.47$. After the energy calibrations, further requirements are applied to reject backgrounds coming from hadronic jets, photon conversions, Dalitz decays and semi-leptonic heavy flavor hadron decays. Two conditions of electron identification, namely **Medium** and **Tight** are used in this analysis. The **Medium** identification uses 13 discriminating variables shown in Table 4.1. The **Tight** identification additionally uses 3 more variables in Table 4.1 which require better agreement between the cluster and track and suppress photon conversion more. Cuts on each variable

Figure 4.5: The invariant mass (m_{ee}) reconstructed by two electrons from $Z^0 \rightarrow e^+e^-$ candidates in data compared with the MC simulation. Data collected with the ATLAS detector in 2012 at $\sqrt{s} = 8$ TeV, corresponding to 20.3 fb^{-1} are used. The templates of m_{ee} for different values of α for a fixed c (a) and different values of c for a fixed α (b) are overlaid. Events with one electron within $1.63 < \eta < 1.74$ and the other within $2.3 < \eta < 2.4$ [166] are shown.

are optimized in 10 bins for $|\eta|$ and 11 bins for E_T . Electron candidates passing Medium identification are defined as baseline electrons.

Electron candidates overlapped with the baseline jet defined in Sec. 4.5.6 by $\Delta R < 0.4$ are recognized as the mis-identified jet and removed from the event. The agreement of electron reconstruction and identification efficiencies between the data and MC simulation are not sufficient at the transition region between the barrel and endcap EM calorimeters ($1.37 < |\eta| < 1.52$), so events containing electrons in this region are not used in this analysis.

4.2.5 Reconstruction and identification efficiency

The total reconstruction and identification efficiency to electrons is evaluated by multiplying reconstruction efficiency and identification efficiency, which are derived individually [164].

The reconstruction efficiency of the EM cluster is estimated by the MC simulation to be $> 95\%$ at $E_T > 7$ GeV, as mentioned in Sec. 4.2.1. The track reconstruction efficiency to the EM cluster is evaluated by the data with the Tag and Probe method using $Z^0 \rightarrow e^+e^-$ sample to be 95-98 % depending on p_T and η . The EM cluster before the track matching are used as the probe.

The identification efficiency to the reconstructed electron is also estimated with the Tag and Probe method using $Z^0 \rightarrow e^+e^-$ events for high p_T and $J/\Psi \rightarrow e^+e^-$ for low p_T . About 80 % and 65 % efficiencies with Medium and Tight criteria, respectively, are found at low E_T (~ 10 GeV). For electrons with $20 < E_T < 50$ GeV, the efficiencies are evaluated to be $(88.1 \pm 0.2)\%$ and $(77.5 \pm 0.5)\%$ with the Medium and Tight criteria, respectively. The Medium condition gives a better efficiency than the Tight but the mis-identification probability to the background is $(1.11 \pm 0.02)\%$ for the Medium conditions whereas it is $(0.46 \pm 0.01)\%$ for Tight condition, for electron candidates with $20 < E_T < 50$ GeV.

Figure 4.6 shows the total efficiency to the electron candidates as a function of E_T and η . Disagreement between the data and MC is corrected by applying the scaling factor in E_T and η bins, as shown in the lower panels of Fig. 4.6. The pileup dependency on the electron reconstruction and identification efficiency is less than 4 %. The systematic uncertainties coming from the methodology of the tag and probe and the background modeling are considered. They are evaluated by varying the selection cuts in the procedure. Total systematic uncertainty on the electron reconstruction efficiency is below 0.5 % for

Table 4.1: Summary of the variables used in the Medium and Tight electron identification.

Type	Name	Description	Medium	Tight
Hadronic leakage	R_{HadI}	Ratio of E_T in the first layer of the hadronic calorimeter to E_T of the EM cluster (used over the range $ \eta < 0.8$ or $ \eta > 1.37$)	o	o
	R_{Had}	Ratio of E_T in the hadronic calorimeter to E_T of the EM cluster (used over the range $0.8 < \eta < 1.37$)	o	o
Back layer of EM calorimeter	f_3	Ratio of the energy in the back layer to the total energy in the EM calorimeter	o	o
Middle layer of EM calorimeter		Lateral shower width, $\sqrt{(\sum E_i \eta_i^2) / (\sum E_i) - ((\sum E_i \eta_i) / (\sum E_i))^2}$, where E_i is the energy and η_i is the pseudo-rapidity of cell i and the sum is calculated within a window of 3×5 cells		
	$W_{\eta/2}$	Ratio of the energy in 3×7 cells over the energy in 7×7 cells centered at the electron cluster position	o	o
	R_η		o	o
Strip layer of EM calorimeter		Shower width, $\sqrt{(\sum E_i (i - i_{\text{max}})^2) / (\sum E_i)}$, where i runs over all strips in a window of $\Delta\eta \times \Delta\phi \sim 0.0625 \times 0.2$, corresponding to typically to 20 strips in η , and i_{max} is the index of the highest-energy strip		
	w_{slot}	Ratio of the energy difference between the largest and second largest energy deposits in the cluster over the sum of these energies	o	o
Track quality	E_{ratio}			
	n_{Blayer}	Number of hits in the pixel b -layer	o	o
	n_{Pixel}	Number of hits in the pixel detector	o	o
	n_{Si}	Number of hits in the Pixel+SCT detectors	o	o
	d_0	Transverse impact parameter	o	o
TRT	n_{TRT}	Total number of hits in the TRT	o	o
	F_{HT}	Ratio of the number of high-threshold hits to the total number of hits in the TRT	o	o
Track-cluster matching	$\Delta\eta_1$	$\Delta\eta$ between the cluster position in the strip layer and the extrapolated track	o	o
	$\Delta\phi_2$	$\Delta\phi$ between the cluster position in the middle layer and the extrapolated track		o
	E/p	Ratio of the cluster energy to the track momentum		o
Conversions	isConv	Veto electron candidates matched to reconstructed photon conversions		o

Figure 4.6: The total electron reconstruction and identification efficiency as a function of E_T (a) and η (b) for the Medium (green) and Tight (red) identifications [164]. Efficiencies derived by the data collected with the ATLAS detector at $\sqrt{s} = 8$ TeV in 2012 corresponding to 20.3 fb^{-1} are shown with colored dots, while those by $Z^0 \rightarrow e^+e^-$ MC sample are shown with white dots. Loose (red) and Multilepton criteria (violet) are not used in this analysis.

$E_T > 25$ GeV and 0.5-1.5 % at the low- E_T region. On the other hand, total systematic uncertainty on the electron identification efficiency is 5-6 (1-2) % for electrons below (above) $E_T = 25$ GeV.

4.3 Muon reconstruction

Muon candidates are reconstructed in the muon spectrometer and inner detector, separately. An outside-in algorithm [167] is employed, which starts from the standalone muon candidate reconstructed at the muon spectrometer and combines it with the inner detector track. After the small corrections on the muon momentum scale and resolution between the data and MC are applied, some cuts on track parameters are applied to identify muons for the physics analysis.

4.3.1 Standalone muon reconstruction

As explained in Sec. 2.2.3, there are three layers of the precision muon measurement chamber (MDT and CSC) in both the barrel and endcap regions. The standalone muon reconstruction algorithm starts from the segment at the outermost layer and performs a track parameter fit including the inner and middle segments. Reconstructed tracks are back-extrapolated to the IP, taking into account the energy loss at the calorimeter. At least two segments are required to reconstruct the curvature of the muon track in the magnetic field (Assuming the IP, the fit can be performed if there are only two segments reconstructed).

4.3.2 Combined muon reconstruction

A statistical combination of the tracks reconstructed in the muon spectrometer and the inner detector (see Sec. 4.1.1) is performed using the corresponding covariant matrices [168]. The inner detector information improves the precision of the muon tracks at $p_T < 100$ GeV and suppresses mis-identified backgrounds from the in-flight decays of pions and kaons. The track combination is evaluated only for track pairs that show a reasonable matching in the η - ϕ plane at the closest approach to the beam line. The combination is accepted only if the global χ^2 is less than the predefined maximum value.

4.3.3 Segment-tagged muon reconstruction

To recover the acceptance for the low momentum muon which crosses only one muon spectrometer layer due to the small curvature, the segment-tagged muons are used in addition to combined muons. A inner detector track is classified as a muon, if it is matched to at least one segment at MDT or CSC.

4.3.4 Muon momentum scale and resolution

Small mis-modeling of the muon momentum scale and resolution caused by the incomplete description of the magnetic field, detector structure and so on in the MC simulation are corrected to better reproduce the data. As with the electron identification, the correction parameters are derived by a template fit using di-muon resonances. The correction factors for the muon momentum scale are evaluated separately for the muon spectrometer (MS) and the inner detector (ID). The corrected muon p_T are described as:

$$p_T^{\text{Cor,Det}} = \frac{p_T^{\text{MC,Det}} + \sum_{n=0}^1 s_n^{\text{Det}}(\eta, \phi) (p_T^{\text{MC,Det}})^n}{1 + \sum_{m=0}^2 \Delta r_m^{\text{Det}}(\eta, \phi) (p_T^{\text{MC,Det}})^{m-1} g_m} \quad (4.5)$$

($s_0^{\text{ID}} = 0$, $\Delta r_0^{\text{ID}} = 0$),

where Det=MS or ID. g_m are normally distributed random variables with mean 0 and width 1 and the terms $\Delta r_m^{\text{Det}}(\eta, \phi)$ and $s_n^{\text{Det}}(\eta, \phi)$ describe, respectively, the momentum resolution smearing and the scale corrections applied in a specific η and ϕ region. The Δr_m^{Det} corrects the each term of:

$$\frac{\sigma(p_T)}{p_T} = \frac{r_0}{p_T} \oplus r_1 \oplus r_2 p_T, \quad (4.6)$$

where $\oplus$ denotes a sum in quadrature. The first term accounts for fluctuations of the energy loss in the material, the second term multiple scattering, local magnetic field inhomogeneities and local radial displacements, and the third term intrinsic resolution effects caused by the spatial resolution of the hit measurements and residual misalignment. Momentum scale difference between the data and MC due to the mis-modeling of the magnetic field integral and radial dimension of the detector are corrected by s_1^{Det} . In addition, the s_0^{MS} term is introduced to model the p_T scale dependence discrepancy between the data and MC at the MS due to the energy loss of muons passing through the calorimeter and other materials. Energy loss fluctuations are negligible in the ID, so Δr_0^{ID} and s_0^{ID} are set to zero. As the energy loss fluctuations do not show significant disagreement between the data and MC in $|\eta| > 0.8$, Δr_0^{MS} is also fixed to zero in this region. A template fit to $J/\Psi \rightarrow \mu^+\mu^-$ at low p_T and $Z^0 \rightarrow \mu^+\mu^-$ at high p_T are performed, using the invariant mass distribution reconstructed by di-muon tracks. In the $Z^0 \rightarrow \mu^+\mu^-$ analysis, the distribution of the momentum balance between ID and MS is used as a template additionally:

$$\rho = \frac{p_T^{\text{MS}} - p_T^{\text{ID}}}{p_T^{\text{ID}}}. \quad (4.7)$$

Figure 4.7: Ratio of the fitted mean value of the dimuon invariant mass for data to $Z^0 \rightarrow \mu^+\mu^-$ (top), $\Upsilon \rightarrow \mu^+\mu^-$ (middle) and $J/\Psi \rightarrow \mu^+\mu^-$ (bottom) MC simulations as a function of the leading muon η , before (white) and after (black) the correction [169]. Yellow bands show the systematic uncertainties.

The evaluated scale correction factors by the fit are less than 0.1 % in all p_T and η regions for both MS and ID, except for the barrel large MS sector and specific MS regions with $1.25 < |\eta| < 1.5$. The s_0^{MS} is determined to be approximately 30 MeV. The momentum resolution smearing factors derived by the fit are less than 15 % for the MS and less than 10 % for the ID tracks, although they depend on the p_T .

The systematic uncertainty covers the imperfections in the models used for the momentum correction and in the fit procedure. It mainly comes from the background modeling, which is evaluated by varying the cut on the invariant mass distribution and by changing the modeling of the background. The total systematic uncertainty on the ID momentum scale is 0.02 % for $|\eta| < 1.0$ and 0.2 % for $|\eta| > 2.3$. The systematic uncertainty on the MS momentum scale is 0.03-0.1 % corresponding to the MS sectors.

The corrected muon momentum scale and resolution are validated using the di-muon mass distributions [169]. Figure 4.7 shows the ratio of the fitted mean value of the di-muon invariant mass in the data compared with the MC simulations as a function of the leading muon η , before and after the correction. The $Z^0 \rightarrow \mu^+\mu^-$, $\Upsilon \rightarrow \mu^+\mu^-$ and $J/\Psi \rightarrow \mu^+\mu^-$ samples are used to evaluate the systematic uncertainties. The total (ID+MS) muon momentum resolution is evaluated by the width of the di-muon mass distribution to be 1.7 % at low p_T in the central region, and 4 % at $p_T = 100$ GeV in the large $|\eta|$. The systematic uncertainty on the muon momentum resolution is estimated separately for the ID and MS tracks. The total (ID+MS) uncertainty on momentum scale is understood to be ± 0.05 % in $|\eta| < 1.0$ and less than 0.2 % in the other regions.

4.3.5 Muon identification

In this analysis, muons are required to have $p_T > 6$ GeV and $|\eta| < 2.5$. As the quality cuts for the inner detector tracks, we require:

- a hit at the Pixel b -layer, if it is expected.
- at least one hit at the Pixel detector (the malfunctioning pixel detector on the track is counted as a hit).
- at least 5 hits in the SCT (also the dead SCT sensor on the track is counted as a hit).
- at most 2 holes in the Pixel+SCT.
- at least 5 TRT hits if the track is in the core acceptance of the TRT ($0.1 < |\eta| < 1.9$).
- the number of outlier TRT tubes around the track not exceeding 90 % of the total number of TRT hits, if the track satisfies the one of the following conditions:
 - The track is in the core acceptance of the TRT ($0.1 < |\eta| < 1.9$);
 - The track is in the edge of the acceptance ($|\eta| > 1.9$ or $|\eta| < 0.1$) but having more than 5 hits in the TRT.

A muon which satisfies the above requirements is defined as a **baseline muon**.

Only muons in $|\eta| < 2.4$ are used in the SUSY analysis. Muons geometrically matched to **baseline jets** defined in Sec. 4.5.6 by $\Delta R < 0.4$ are removed from the event as a mis-identified hadron.

4.3.6 Reconstruction and identification efficiency

The muon reconstruction efficiency including the identification efficiency is measured by the Tag and Probe method using $Z^0 \rightarrow \mu^+\mu^-$ for high- p_T region and $J/\Psi \rightarrow \mu^+\mu^-$ for low- p_T region [169]. The inner detector track reconstruction efficiency with respect to the standalone muon and the standalone muon reconstruction efficiency with respect to the inner detector track are evaluated separately, and the combination of the two results are defined as the total reconstruction efficiency.

Figure 4.8 shows the combined and segment-tagged muon reconstruction efficiency as a function of p_T and $\langle\mu\rangle$. Approximately 99 % high efficiency in whole region above $p_T > 4$ GeV and very small dependency on $\langle\mu\rangle$ by about 1 % are confirmed. The difference between the data and MC simulation are corrected for by applying the scaling factor as functions of muon p_T , η and ϕ . The systematic uncertainties associated with the muon reconstruction efficiency come from the methodology of the tag and probe and the modeling of the background. They are estimated by varying the selection cuts and the function to describe the background in the procedure. An uncertainty coming from the difference of the kinematical distribution between data and MC is evaluated by re-weighting the distribution in the simulation to the data. Total systematic uncertainty is evaluated to be less than 1 %, depending on p_T , η , and ϕ .

4.4 Lepton isolation

Further requirements for leptons are applied to discriminate signals from the backgrounds. The lepton isolation requirement is effective to reject the mis-identified hadron backgrounds. Leptons from hadronic decay tend to have activities around the track due to other secondary particles such as pions and kaons, while the leptons in signal events are directly produced from leptonic decay of SUSY particle hence should be isolated.

Figure 4.8: The combined+segment-tagged muon reconstruction efficiency estimated by the Tag and Probe method [169], as a function of p_T (a) and the averaged number of interaction per bunch crossing $\langle \mu \rangle$ (b). Black dots are the observed data taken in 2012 corresponding to 20.3 fb^{-1} of the integrated luminosity after the selections for $Z^0 \rightarrow \mu^+\mu^-$. Red dots are the $Z^0 \rightarrow \mu^+\mu^-$ MC simulation. White and blue triangles in (a) are the $J/\Psi \rightarrow \mu^+\mu^-$ data and MC simulation, respectively. Slightly different inner detector quality cuts from those in the text are applied: at least 9 TRT hits for muons in the core TRT acceptance and no outlier requirements. For (b), $p_T > 10$ GeV is applied. The ratios of the data to MC simulation are shown in the lower panel.

Track isolation variables are defined by the sum of the transverse momentum of all tracks (p_T^{trk}) in $\Delta R < 0.2$ or 0.3 around the lepton candidate except for lepton p_T itself:

$$I_{0.2}^{\text{trk}} = \sum_{\Delta R < 0.2} p_T^{\text{trk}}, \quad (4.8)$$

$$I_{0.3}^{\text{trk}} = \sum_{\Delta R < 0.3} p_T^{\text{trk}}. \quad (4.9)$$

For leptons with $p_T < 25$ GeV, in where the signal regions in this analysis are defined (see Chapter 5), the medium isolation requirement as:

- $I_{0.3} < 0.12 p_T$ for muon
- $I_{0.3} < 0.16 p_T$ for electron

is applied. The Medium electron identification criteria (see Sec. 4.2.4) is required for medium isolation. In addition, cuts on the longitudinal and transverse impact parameters are applied for the further suppression of backgrounds from in-flight decay of hadrons:

- $|z_0 \sin \theta| \leq 0.4 \text{ mm}$
- $|d_0| \leq 3\sigma(d_0)$,

where $\sigma(d_0)$ is the standard deviation of the d_0 assuming a Gaussian distribution.

For high- p_T muons with $p_T \geq 25$ GeV:

- $I_{0.2} < 1.8 \text{ GeV}$

Table 4.2: Definitions of the lepton isolation criteria used in this analysis. The high- p_T condition is defined to be consistent with the analysis using hard lepton with ATLAS [71].

condition	electron	muon
high- p_T	Tight identification $\sum_{\Delta R < 0.2} p_T^{\text{trk}} < 0.1 p_T$ $ d_0 < 1 \text{ mm}, z_0 < 2 \text{ mm}$	$\sum_{\Delta R < 0.2} p_T^{\text{trk}} < 1.8 \text{ GeV}$
medium	Medium identification $\sum_{\Delta R < 0.3} p_T^{\text{trk}} < 0.16 p_T^e$ $ z_0 \sin \theta \leq 0.4 \text{ mm}, d_0 \leq 3\sigma(d_0)$	$\sum_{\Delta R < 0.3} p_T^{\text{trk}} < 0.12 p_T^\mu$ $ z_0 \sin \theta \leq 0.4 \text{ mm}$ $ d_0 \leq 3\sigma(d_0)$
tight	Tight identification medium isolation + $\sum_{\Delta R < 0.3} E_T^{\text{cluster}} < 0.18 p_T^e$	medium isolation + $\sum_{\Delta R < 0.3} E_T^{\text{cluster}} < 0.12 p_T^\mu$

is applied for the consistency with the other ATLAS analysis using a high- p_T lepton [71]. As well as muon, the same isolation criteria with the previous analysis is required for electrons with $p_T \geq 25 \text{ GeV}$:

- Tight electron identification (see Sec. 4.2.4)
- $I_{0.2} < 0.1 p_T^e$
- $|z_0 \sin \theta| < 1 \text{ mm}$
- $|d_0| < 1 \text{ mm}$.

The tight isolation requirement is defined by the calorimeter-cluster-base isolation requirement:

- $\sum_{\Delta R < 0.3} E_T^{\text{cluster}} < 0.12 p_T$ for muon
- $\sum_{\Delta R < 0.3} E_T^{\text{cluster}} < 0.18 p_T$ for electron

in addition to the medium isolation. $\sum_{\Delta R < 0.3} E_T^{\text{cluster}}$ is the sum of the E_T of topological clusters at the calorimeters in $\Delta R < 0.3$ around the lepton candidate, except for energy deposits from the electron. The Tight electron identification criteria is required for tight isolation. The tight isolation requirement is used in the evaluation of the trigger efficiency (Sec. 3.1.3), but not in the SUSY analysis.

The isolation criteria for electrons and muons are summarized in Table 4.2. The isolation efficiency to baseline leptons is important to estimate the mis-identified lepton background. The efficiency is discussed in Sec. 6.4.

4.5 Jet reconstruction

Hadron jets are reconstructed based on clusters in the hadronic calorimeters. After the MC-based energy calibration, the effect of the pileup is subtracted and further energy and resolution calibrations are applied to reproduce the performance in the data. Finally, some cleaning cuts are applied to jets used in the physics analysis. The jet flavor can be determined by using the track information associated with the reconstructed jet. Since our signal regions are defined with b -tagged jets, the technique of jet flavor tagging is one of the keys of this analysis.

4.5.1 Calorimeter clustering criteria

Energy deposits detected at the hadronic calorimeter are clustered by Topo-cluster algorithm [163] with local cluster weighting (LCW) calibration [170]. The algorithm starts from seed calorimeter cells with

high signal-to-noise ratio exceeding 4. All neighboring cells around the seed are added to the cluster. If a neighboring cell is adjacent to more than one cluster, these clusters are merged. Neighboring cells with signal-to-noise ratio of greater than 2 but less than 4 are recorded as new seeds and the iteration proceeds until there are no neighboring cell with signal-to-noise ratio of greater than 2 around the cluster. The energy calibration factor is applied for each cluster, derived by the MC simulation of charged and neutral pions according to the cluster topology measured in the calorimeter.

4.5.2 anti- k_T algorithm

Hadronic jets are reconstructed by an anti- k_T algorithm [171]. It introduces a distance d_{ij} between two clusters i and j as:

$$d_{ij} = \min \left(\frac{1}{k_{t,i}^2}, \frac{1}{k_{t,j}^2} \right) \frac{\Delta_{ij}^2}{R^2}, \quad (4.10)$$

where $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ and $k_{t,i}$, y_i and ϕ_i are the transverse momentum, rapidity and azimuth angle of cluster i , respectively. R denotes the radius parameter, which represents the cone size of jets. The distance between a cluster i and the beam pile is defined as:

$$d_{iB} = \frac{1}{k_{t,i}^2}. \quad (4.11)$$

The pair with minimum d_{ij} are combined and form a new cluster, then, its k_t , y and ϕ are re-calculated. The iteration proceeds until the minimum d_{ij} becomes below d_{iB} . Then, the cluster i is called a jet and removed from the cluster list. The distances are re-calculated and the procedure is repeated until no entries are left in the cluster list. By taking the minimum value of $1/k_t$, soft clusters are likely to be combined with the hard cluster before it is combined with the other soft cluster. Thus, the anti- k_T algorithm tends to reconstruct conical jets with an approximate radius of R around the hard topo-cluster. In this analysis, jets reconstructed by the anti- k_T algorithm with $R = 0.4$ are used.

MC simulation truth jets are also reconstructed using anti- k_T algorithm with $R = 0.4$ from stable particles with proper lifetimes longer than 10 ps except for muons and neutrinos. The highest energy parton pointing to the truth jet defines the truth flavor of the jet.

4.5.3 Pileup subtraction

Jet energy is over-estimated due to the energy deposit from the pileup events. The effect of the pileup is subtracted from the reconstructed jet using the jet area method [172]. The jet area A is estimated by a dedicated algorithm [173], which is approximately πR^2 for an anti- k_T jet. The median p_T density in the event is defined as:

$$\rho = \text{median} \left(\frac{p_T^{\text{jet}_i}}{A^{\text{jet}_i}} \right), \quad (4.12)$$

where $p_T^{\text{jet}_i}$ and A^{jet_i} are p_T and A of the i -th jet. All of jet candidates including low-momentum ones are used to calculate ρ . Since the number of jets from pileup is expected to be much larger than that from the hard scattering, by taking median the averaged pileup contributions in the event can be estimated. Assuming uniform pileup density, jet p_T is corrected by:

$$p_T^{\text{corr}} = p_T - \rho A, \quad (4.13)$$

where p_T and p_T^{corr} are transverse momentum of the jet before and after the pileup subtraction, respectively. This method is effective in subtracting the in-time pileup, but not for the out-of-time pileup

detected as the negative energy at the HEC (see Fig. 2.14), spoiling the approximation of the unitarity of ρ and making the N_{PV} dependency of the reconstructed jet p_T . To improve this problem, additional corrections to eliminate $\langle\mu\rangle$ and N_{PV} dependency on the jet p_T are derived from comparison between the reconstructed and truth jets using MC simulation for each η bin. The correction factors are compared with those evaluated by the data using an in-situ method and the difference is assigned as the systematic uncertainty. The in-situ method uses the transverse momentum balance between the jet and a well-measurable particle e.g. photon and leptonic decaying Z^0 boson. For the validation of the pileup subtraction, photon is used as the reference in the in-situ method. Since a photon is detected at the EM calorimeter and the track information is not used in the reconstruction, it is not affected by hadrons from pileup. Independently, the sum of the all track- p_T matched to the jet is also used as the reference p_T . The estimated systematic uncertainty depends on $\langle\mu\rangle$, N_{PV} , η and jet p_T , but is typically less than 2 % at jet $p_T > 40$ GeV and up-to 7 % for low- p_T jets [174]. Uncertainties on the modelings of $\langle\mu\rangle$ and N_{PV} , p_T dependency and ρ topologies are derived separately.

4.5.4 Jet energy scale (JES) and resolution calibration

After the pileup subtraction, reconstructed jet energy is rescaled to match the truth jet energy using the MC. Figure 4.9 shows the averaged jet response $R = E_{jet}^{rec}/E_{jet}^{truth}$ as a function jet η , where E_{jet}^{rec} is the reconstructed jet energy and E_{jet}^{truth} is the matched truth jet energy, divided into several energy ranges. The R is the inverse of the jet energy calibration factor. The figure shows R derived by MC tuned for 2011 $\sqrt{s} = 7$ TeV run, whereas R values used in this thesis are optimized using MC tuned for 2012 $\sqrt{s} = 8$ TeV.

Furthermore, remaining differences on jet energy scale (JES) and jet energy resolution between the data and MC due to the mis-modeling of the detector materials, magnetic field etc. are corrected for using in-situ methods with several reference particles.

Jet energy resolution of the MC simulation is compared to the resolution observed in the data es-

Figure 4.9: Average response of simulated jets formed from topo-clusters shown separately for various truth-jet energies as a function of jet η , derived by MC simulation [174]. The different calorimeter regions are indicated.

timated by an in-situ method using di-jet events [175]. The smearing factor is randomly sampled as a

width of a Gaussian fit to the observed in data and applied to reconstructed jets in the MC simulation. The uncertainties associated with the jet energy resolution is estimated to be 10-20 % depending on p_T and rapidity.

In the central region ($|\eta| < 1.2$), the transverse momentum balance between a photon or a Z boson and a jet is used to correct the difference on the jet response between the data and MC. The γ +jet covers a jet p_T range of $25 < p_T < 800$ GeV while the Z+jets does a range of $15 < p_T < 200$ GeV. The photon is not affected by mis-identified tracks so the transverse momentum balance between a photon and all hadronic activities is used to study the hadronic recoil response. Multi-jet transverse momentum balance is used to study high- p_T jet response, where the reference low- p_T hadronic recoil jets are calibrated by the in-situ method using photons, which covers the jet p_T range up-to TeV scale. Systematic uncertainties are evaluated separately for reference particles. Main systematic uncertainty is due to the reconstruction of the reference particles. Finally, results from different reference particles are combined. The combined data-to-MC ratio is determined by the weighted average of each contribution, where the weights are chosen to give the minimum χ^2 of the response ratios in each p_T bin. The weights are therefore proportional to the square of the inverted uncertainties of the input measurements. Each systematic uncertainty is treated as fully correlated across p_T and η , while sources of the uncertainties are assumed to be independent of each other. Figure 4.10 shows the ratio of jet response derived by the data to that by the MC and the total systematic uncertainty coming from three in-situ methods as a function of jet p_T in $|\eta| < 0.8$ (corresponding to the barrel long tile calorimeter). The uncertainty on JES is evaluated to be about 2 % for $p_T < 200$ GeV and about 1 % above that. For convenience, the uncertainties and their correlations are preferable to be described by a reduced set of components in this analysis. The total covariance matrix of the uncertainties for JES correction factors is approximated to be written by 5 effective nuisance parameters and 1 constant parameter.

In the forward direction ($1.2 < |\eta| < 4.5$), statistics of γ /Z+jet is not sufficient, so the transverse momentum balance in di-jet events is exploited to evaluate the JES correction factors in addition to them. If we only use the topology with a well calibrated jet in the central region balanced against a jet in the forward region, statistics is limited in the forward region. To increase the statistics, we use full dijet

Figure 4.10: Ratio of the average jet response measured in data to that measured in MC for jets with $|\eta| < 1.2$ as a function of jet p_T [176]. The red, green and brown dots show the ratio derived by the in-situ method using Z+jet, γ +jet and multi-jet events, respectively. Blue and green bands show the total statistical and statistical+systematic uncertainty.

events including those with both jets in forward region and estimate η -intercalibration using the matrix method described in Ref. [177]. Systematic uncertainties associated with the intercalibration is evaluated to be less than 6 % depending on jet p_T and η [174].

In addition, difference of the jet response between quark- and gluon-induced jets is considered as the systematic uncertainty, if the jet is not b -tagged (details of the flavor tagging is explained in Sec. 4.5.7). The correction factors are evaluated by the MC and the systematic uncertainty associated with that is estimated by comparing different MC generators to be less than 3 %. The different correction factors are found for the tile and LAr calorimeters. For jets with $p_T = 40$ GeV, the flavor response uncertainty is about 2 % for the tile calorimeter ($|\eta| < 1.7$) and about 1 % for the LAr calorimeter ($1.5 < |\eta| < 3.2$), as shown in Fig. 4.11 (a).

Figure 4.11 shows the total fractional JES uncertainty as a function of jet η at $p_T = 40$ GeV (a) and p_T at $\eta = 0$ (b). Uncertainty on pileup subtraction described in Sec. 4.5.3 is also indicated.

Figure 4.11: Fractional jet energy scale systematic uncertainty components as a function of jet η at $p_T = 40$ GeV (a) and p_T at $|\eta| = 0.0$ (b) [176]. The total uncertainty is shown as a filled blue region. Red lines show the uncertainty estimated with absolute in-situ method using Z +jets, γ +jets and multijet events. Magenta dash-dot-dot lines show the uncertainty estimated by η -intercalibration technique. Blue dashed lines and green dot lines show the flavor composition and flavor response uncertainties, respectively. Gray dash-dot lines show the uncertainty coming from the pileup subtraction.

4.5.5 Jet vertex fraction (JVF)

Additional pileup suppression is made by the jet vertex fraction (JVF) [172] defined for each jet with respect to the primary vertex (PV_0). JVF for the jet i is defined as:

$$\text{JVF}(\text{jet}_i, PV_0) = \frac{\sum_k p_T(\text{track}_k^{\text{jet}_i}, PV_0)}{\sum_n \sum_l p_T(\text{track}_l^{\text{jet}_i}, PV_n)}, \quad (4.14)$$

where $p_T(\text{track}_k^{\text{jet}_i}, PV_n)$ is p_T of the track k from the n -th primary vertex PV_n matched to the jet i . The principle of the JVF is illustrated in Fig. 4.12. JVF approaches 1 if the jet purely constituents of tracks from primary vertex. Applying a cut on JVF, the background component from pileup can be suppressed as shown in Fig. 4.13 (a). Figure 4.13 (b) shows that JVF distribution derived from the data agrees with the MC in several pileup conditions. Since JVF for jets outside of the inner detector acceptance ($|\eta| \geq 2.5$) is not reliable ($\text{JVF} = -1$), a cut on JVF is applied only if $|\eta|$ of the jet is less than 2.4. The

Figure 4.12: Schematic representation of the JVF principle [172].

Figure 4.13: (a) JVF distribution for jets with $p_T > 20$ GeV from the hard scattering (blue) and pileup (red), derived by $Z \rightarrow ee$ MC simulation [172]. (b) JVF distribution for jets with $p_T > 20$ GeV and $|\eta| < 2.5$ in comparison between the data and MC in the several pileup conditions of $\mu \leq 15$, $15 < \mu \leq 25$ and $\mu \geq 25$ [172].

efficiency of the JVF cut depends on jet p_T , η and $\langle\mu\rangle$ and is greater than 95 % at $p_T = 20$ GeV and about 99 % at $p_T = 60$ GeV if $|JVF| > 0.25$ is required.

The contributions from pileup mainly appears for jets with low p_T . In this analysis, in order to retain the signal acceptance with high- p_T jet, the JVF requirement $|JVF| > 0.25$ is applied only if $p_T < 50$ GeV and $|\eta| < 2.4$. Systematic uncertainty associated with the JVF cut is estimated by changing the threshold of the cuts to the MC. For jets from hard scattering, the conditions $|JVF| > 0.22$ and $|JVF| > 0.28$ are required instead of 0.25, while $|JVF| > 0.1$ and $|JVF| > 1.1$ are required to jets from pileup events [172]. A requirement $|JVF| > 1.1$ means that all pileup jets are rejected by the cut.

4.5.6 Jet identification

Jets satisfying the following bad jet criteria are regarded as backgrounds from beam-gas, beam-halo, large calorimeter noise etc. Events containing a bad jet is rejected [177].

- If the fraction of the energy in the hadronic endcap calorimeter (HEC) is $f_{\text{HEC}} > 0.5$ and the fraction of the energy in the HEC with poor signal quality derived by comparison between measured and expected pulse shape at the cell satisfies $f_{\text{HEC}}^{\text{quality}} > 0.5$, the jet is recognized as the noise burst at the HEC.
- If the absolute value of the negative energy is $|E_{\text{neg}}| > 60$ GeV, the jet is also recognized as the noise at the HEC due to the out-of-time pileup.
- If the ratio of the energy deposit in the EM calorimeter in $|\eta| < 2.8$ to the total energy is $f_{\text{EM}} > 0.95$ and the fraction of the energy in the EM calorimeter with poor signal quality $f^{\text{quality}} > 0.8$, the jet is recognized as the coherent noise in the EM calorimeter.
- If $f_{\text{EM}} < 0.05$ and $f_{\text{ch}} < 0.05$, where f_{ch} is the ratio of the scalar sum of the track p_T associated with the jet to the jet p_T , the jet is recognized as non-collision background, because jets should have certain energy deposit at the EM calorimeter which is the closest layer with respect to the interaction point and certain associated charged tracks. In the region out of the TRT coverage in $|\eta| > 2.0$, jets are regarded as background, only if $f_{\text{EM}} < 0.05$.
- Jets with the jet time $|t_{\text{jet}}| > 25$ ns reconstructed by weighting the reconstructed time of calorimeter cells in the jet with square of the cell energy are recognized as cosmic or non-collision background.
- Jets with maximum energy fraction in any single calorimeter layer $f_{\text{max}} > 0.99$ are also regarded as non-collision background.

The efficiency of the quality cuts to jets from the hard scattering is evaluated to be approximately 100 % for all p_T and η regions. All jets for physics analyses are required to have $p_T > 20$ GeV and $|\eta| < 2.8$. Furthermore, if there is a baseline electron in the cone in $\Delta R < 0.2$ around the jet except for b -tagged jet, the jet is regarded as mis-identified electron and is removed from the event, while electrons around the b -tagged jet are removed prior to jet removal. Jets passing above requirements are used as baseline jets to resolve overlap removal with leptons and to reconstruct E_T^{miss} . Finally, only jets with $|\eta| < 2.5$ are used for the selection cuts in the SUSY signals.

4.5.7 Flavor tagging

b quark decays by weak interaction into c or u quark, but the decay is suppressed by the CKM matrix, which makes the lifetime of b particles much longer (typically 10^{-11} s) than that of c particles (typically 10^{-15} s), τ lepton (typically 10^{-15} ns) and strong interaction time scale (about 10^{-23} s) [3]. The displaced

secondary vertex associated with the jet originated by b quark can be reconstructed as shown in Fig. 4.14, which makes it possible to discriminate b -quark-induced jet from the others. Several algorithms to identify b -quark-induced jet are implemented. The relatively simple two algorithms, based on impact parameter and secondary vertex, and a sophisticated algorithm which exploits the topology of b - and c -hadron decays using a Kalman filter [178] are used. Jets recognized as b -quark-induced are called b -jets or b -tagged jets.

Figure 4.14: Drawing of variables for b -tagging [179].

Impact parameter-based algorithm

Tracks with $p_T > 1$ GeV satisfying the following inner detector quality cuts and matched to the jet by optimized ΔR according to jet p_T ($\Delta R < 0.45$ for $p_T = 20$ GeV and $\Delta R < 0.25$ for $p_T = 150$ GeV) are used to evaluate impact parameters for b -tagging.

- Hit at the Pixel b -layer;
- At least two hits in the Pixel;
- At least seven hits in the Pixel+SCT;
- $|d_0| < 1$ mm;
- $|z_0 \sin \theta| < 1.5$ mm.

The impact parameter-based algorithm combines the significance of the impact parameter for all tracks in the jet, weighted by the b -jet probability derived by a likelihood ratio technique in which input variables are compared to pre-defined distributions for the b - and light jet hypotheses obtained from the MC simulation. The cut is applied on two-dimensional space of $d_0/\sigma(d_0)$ and $z_0/\sigma(z_0)$, where $\sigma(z_0)$ is the standard deviation of the z_0 assuming the Gaussian distribution.

Secondary vertex-based algorithm

The condition of track quality cuts for the secondary vertex reconstruction are:

- $p_T > 400$ MeV;
- At least one hit in the Pixel (no requirement on the b -layer);
- No more than one hit on the track being shared with another track;
- $|d_0| < 3.5$ mm (no z_0 cut).

Secondary vertex reconstruction starts from all two-track pairs in the jet that form a good vertex at the position away from the primary vertex. Vertices matched to hypotheses of long-lived particle or material interaction are rejected. The remaining tracks forming the two-tracks vertices are combined into a single inclusive vertex, using an iterative procedure to remove the worst track until the χ^2 of the vertex fit becomes lower than the threshold.

The decay length L_{3D} is defined as distance between primary and secondary vertices measured in 3-dimensions (see Fig. 4.14). The significance of the decay length $L_{3D}/\sigma(L_{3D})$ is used as a discriminator of b -jet signals. To maximize the discrimination power, additional information is accounted using a likelihood ratio technique, which includes the invariant mass of all tracks associated with the vertex, the ratio of the sum of the energies of the tracks in the vertex to the sum of the energies of all tracks in the jet, the number of two-track vertices, and the ΔR between the jet axis and the line connecting the primary vertex and the secondary one.

Decay chain reconstruction algorithm

This algorithm exploits the topology of b - and c -hadron decays inside the jet. The nominal algorithm explained above reconstructs the single secondary vertex for successive b - and c -hadron decays. This leads to low rejection power to the background due to the random combination of tracks in light quark jets, showing large χ^2 of vertex fit as illustrated in Fig 4.15 (a). A Kalman filter is used to find a common line where the primary vertex and b - and c - vertices lie, as well as their position on this line to give an approximate flight path for the b -hadron as shown in Fig. 4.15 (b). The discriminating variable is a significance of the flight lengths of the b - and c -hadron candidates.

MV1 algorithm

The ATLAS default b -tagging algorithm MV1 [181] combines the results of above three algorithms by artificial neural networks. The output weight probability densities are estimated separately for b , c , τ and light-flavor jets. The training of the neural network is performed using b quark signals from $t\bar{t}$ MC and light flavor jets as the background [181, 182]. Calibration of b -tagging is performed at three benchmark working points, which correspond to 60 %, 70 % and 80 % efficiency to b -jet. The p_T and η dependence of the b -tagging efficiency are evaluated. Figure 4.16 shows the estimated MV1 b -tagging efficiency for b quark, c quark and τ lepton as a function of jet p_T and η . Three operation points are indicated by the different colors. The efficiency decreases with $|\eta|$ due to the acceptance of the inner detector. Lower efficiency is found at low p_T because of the short flight length and worse impact parameter resolution. The efficiency for light flavor jet is less than 1 % for 60 % and 70 % operation points and at most 5 % for 80 % operation point. About 30 % of c quarks and 20 % of τ leptons are mis-tagged as b -jet in the 80 % operation point, while about 10 % of c and 5 % of τ are mis-tagged in the 60 % operation point. The b -tagging operation point must be optimized for each analysis. The disagreement of the b -tagging efficiencies between the data and MC is eliminated by applying scaling factors derived from the data-to-MC ratio estimated for each (p_T, η) bin, which are determined for b -, c -, light-flavor quark and τ lepton,

Figure 4.15: Illustration of the decay chain reconstruction algorithm [180]. Standard secondary vertex reconstruction algorithm reconstructs only single vertex even if there are multi-vertices of b - and c -hadrons (a). On the other hand, the decay chain reconstruction algorithm can recognize both vertices in the jet (b).

separately. Relatively large uncertainty is assigned at low p_T , since $t\bar{t}$ MC is used to evaluate that, which typically have high- p_T b -jets.

Jet response uncertainty for b -tagged jet

Additional JES uncertainty is considered for b -tagged jets. The correction factor for b -jet is derived by the $t\bar{t}$ MC. Systematic uncertainties are evaluated by the MC, by comparing different MC generators, different b -tag calibrations, different material descriptions and so on to be about 3 %. The factor is validated by the data using sum of the track- p_T matched to the b -jet as the reference of the jet p_T . It is confirmed that the data agree with MC within the uncertainty.

4.6 Missing transverse energy reconstruction

Missing transverse energy (E_T^{miss}) is calculated by negative sum of the 2-component vectors of reconstructed objects described in the above sections after the calibration, projected on the x - y planes as:

$$\vec{E}_T^{\text{miss}} = - \sum \vec{E}_T^{\text{jet}} - \sum \vec{E}_T^e - \sum \vec{E}_T^\mu - \sum \vec{E}_T^{\text{soft}}, \quad (4.15)$$

where $\vec{E}_T^{\text{jet}}$, $\vec{E}_T^e$, $\vec{E}_T^\mu$, and $\vec{E}_T^{\text{soft}}$ represent the transverse energies of baseline jets, electrons, muons and soft components, respectively. Hadronic-decaying τ leptons are included in jet term. Soft component collects topo-clusters and tracks within $|\eta| < 4.9$ which are not associated with the physics objects. Usually E_T^{miss} denotes the norm of $\vec{E}_T^{\text{miss}}$.

Systematic uncertainty on each term estimated in the above sections are propagated to E_T^{miss} calculation. The uncertainty on the energy scale and resolution of the soft component is evaluated by the in-situ method using the Z^0 boson decaying into two muons, resulting in 8 % on the energy scale and 2.5 % on the energy resolution [183].

Jet area method (pileup subtraction technique) described in Sec. 4.5.3 improves the resolution of the reconstructed E_T^{miss} [184] as shown in Fig. 4.17.

We often decompose $\vec{E}_T^{\text{miss}}$ to x and y directions and define the azimuth of the missing transverse

Figure 4.16: The efficiency of MV1 for b -quark-induced (upper), c -quark-induced (middle) and τ -lepton-induced jets (bottom) as a function of jet p_T (left) and η (right) at 80 % (red), 70 % (violet), and 60 % (blue) working points. The p_T dependencies are shown in the bin $1.1 < |\eta| < 1.2$, and the η dependencies are in the bin for $p_T = 100$ GeV. Dots and shaded lines indicate data and MC, respectively. Bottom panels for each plot show the data-to-MC ratio. Both statistical and systematic uncertainties are included in the error bars.

energy as:

$$\tan \phi = \frac{E_y^{\text{miss}}}{E_x^{\text{miss}}}, \quad (4.16)$$

where E_x^{miss} and E_y^{miss} are the projection of $\vec{E}_T^{\text{miss}}$ on the x - and y -axis, respectively.

Figure 4.17: The resolution of the reconstructed E_T^{miss} evaluated by data (colored) and $Z^0 \rightarrow \mu^+ \mu^-$ MC (white), as a function of total transverse energy in the event [184]. Blue circle and red squares show before and after the pileup suppression using Jet Area method, respectively. Data agree well with MC as shown in the bottom panel.

Chapter 5

Event Selections

Event selections to enhance signals against the background are optimized corresponding to the target event topologies, using the MC simulation for the benchmark signals and the SM backgrounds. In this chapter, details of the signal region optimizations and the expected sensitivity of this analysis are discussed.

5.1 Preselection

First of all, background processes not coming from hard scattering, e.g. cosmic lay, hadronic halo events, are removed by the following event cleaning cuts. Background coming from detector noise, problems at the reconstruction and so on are also removed.

- As mentioned in Sec. 3.1, data taken in the period that all sub-detectors were not fully working are not used. Furthermore, event-by-event decisions to detect electronics failures are required.
- There should be at least 5 tracks associated with the primary vertex, as described in Sec. 4.1.2, to ensure the hard scattering and the quality of the primary vertex reconstruction.
- As described in Sec. 4.2.4, if there is an electron in the barrel-to-endcap transfer region ($1.37 < |\eta| < 1.52$), the event is rejected.
- If there is a cosmic-ray-like muon candidate which is defined by $|z_0| > 1$ mm and $|d_0| > 0.2$ mm, the event is rejected.
- If there is a muon with $Cov(Q/p)/(Q/p) > 0.2$, the event is rejected for the quality of the reconstructed muon, where $Cov(Q/p)$ is the covariance of the measured muon's Q/p ; Q and p are the electric charge and momentum of the muon.
- As described in Sec. 4.5.6, events containing a bad jet are rejected.
- If one of the jets satisfies the following criteria, the E_T^{miss} is judged to be mis-calculated and the event is rejected:
 - $p_T > 40$ GeV;
 - $B_{\text{jet}}^{\text{corr}} > 0.05$;
 - $\Delta\phi(E_T^{\text{miss}}, \text{jet}) < 0.3$;

where $B_{\text{jet}}^{\text{corr}}$ is a the fraction of the total missing energy due to a malfunctioning of the calorimeter cells in a jet to the total jet energy. The estimation of the missing energy is based on the geometrical shape of jets. If a cell has significantly small energy in the jet, the difference between the measured and the expected cell energy is counted as missing energy.

- In 2012, specific region of the HEC ($-1.85 < \eta < -1.55$ and $0.7363 < \phi < 0$) was not working due to a malfunction. Jets affected by this problem are removed from the event by the following criteria. The transverse momentum of the jet is corrected by using $B_{\text{cell}}^{\text{corr}}$ and $B_{\text{jet}}^{\text{corr}}$ as:

$$p_T^{\text{corr}} = p_T \frac{1 - B_{\text{cell}}^{\text{corr}}}{1 - B_{\text{jet}}^{\text{corr}}}, \quad (5.1)$$

where p_T is the transverse momentum of a reconstructed jet and $B_{\text{cell}}^{\text{corr}}$ is the fraction of the energy assigned to the bad calorimeter cells estimated from the average of the neighboring cells to the total jet p_T . The contribution of this problem to the total E_T^{miss} calculation is estimated as:

$$p_{T, \text{jet}}^{\text{miss}} = (p_T^{\text{corr}} - p_T) \cos \Delta\phi, \quad (5.2)$$

where $\Delta\phi$ is an azimuthal difference between the jet and E_T^{miss} . If the jet satisfies $p_{T, \text{jet}}^{\text{miss}} > 10$ GeV and the fraction of $p_{T, \text{jet}}^{\text{miss}}$ is greater than 10 % of the total E_T^{miss} , the jet is removed from the event.

Further preselection cuts according to the signal event topology are applied to reduce the data size. As discussed in Sec. 1.5, target signals are characterized by two b -jets, high E_T^{miss} , and exactly one soft lepton. As the common preselection, the following requirements are applied.

- The trigger `EF_xe80(T)_tc1cw_loose` is fired (see Sec. 3.1.3).
- $E_T^{\text{miss}} > 150$ GeV and at least one jet with $p_T > 60$ GeV are required, to ensure an approximately 100 % trigger efficiency as discussed in Sec. 3.1.3.
- Exact one lepton exists with $p_T > 7(6)$ GeV for electron (muon).
- No additional electron (muon) with $p_T > 7(6)$ GeV exists.

The high- p_T and the medium isolation conditions defined in Table 4.2 are required for leptons with $p_T > 25$ GeV and < 25 GeV, respectively. After the preselection, the dominant background processes are $W(\rightarrow \ell\nu)$ +jets (65 %) and semi-leptonic $t\bar{t}$ (22 %).

Figure 5.1 shows the lepton p_T distribution for some signal hypotheses having the same $m_{\tilde{l}_1}$ and $m_{\tilde{\chi}_1^+}$, with different Δm of 20 GeV, 50 GeV and 100 GeV, after the preselection. It is found that the p_T distribution depends on Δm values. A signal with $\Delta m = 20$ GeV distributes below $p_T = 50$ GeV, while in case of on-shell W boson with $\Delta m = 100$ GeV p_T reaches > 200 GeV. To enhance the small Δm signals from the backgrounds with on-shell W boson (e.g. W +jets and $t\bar{t}$), the upper cut on lepton p_T at 25 GeV is applied in the signal regions defined in Sec. 5.4. Events containing a high- p_T lepton ($p_T \geq 25$ GeV) are used to control the backgrounds as shown in Chapter 6.

5.2 Target signal topology

Signal samples with $\Delta m = 20$ GeV are used as the benchmark signal points to optimize the selection criteria. Two types of analyses corresponding to the target signal topologies defined in Sec. 1.5 of:

1. Small ΔM channel;

Figure 5.1: Lepton p_T distributions for signals after the preselection. Signals with the same $m_{\tilde{t}_1}$ but the different Δm of 20 GeV, 50 GeV and 100 GeV are compared. All samples are normalized to 1.0.

2. Moderate ΔM channel;

are performed. For the small ΔM channel, event selections are optimized to signals with small $\Delta M = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ in addition to the small Δm (as illustrated in Fig. 1.28 left), while signal region is designed to cover the broad ΔM region (see Fig. 1.28 right) for the moderate ΔM channel.

In the case of the small ΔM , not only the lepton but b -jets are expected to be soft. The b -tag efficiency is relatively low at the low p_T as discussed in Sec. 4.5.7. Furthermore, small E_T^{miss} is expected since all of the decay products of $\tilde{t}_1$ are soft. Since high- p_T multi SM particles and high E_T^{miss} are typical signal signatures in the standard SUSY analysis at the LHC as discussed in Sec. 1.3, the small ΔM channel is challenging. In order to compensate low- p_T b -jets and small E_T^{miss} of the signal, events containing very high- p_T initial state radiation (ISR) jet are selected. In this topology, the stop pair system and the decay products of stop are boosted to the opposite direction to the ISR jet as shown in Fig. 5.2, which increase transverse momentum of the stop pair system and help reconstructions of b -jets and E_T^{miss} .

In the moderate ΔM channel, two high- p_T b -jets are required. Stop pair is expected to be back-to-back in x - y plane if $m_{\tilde{t}_1}$ is relatively low (~ 200 GeV), so there are no additional hard hadronic activities in the event. To produce high mass stop pair (e.g. $m_{\tilde{t}_1} \sim 600$ GeV), higher probability to radiate high- p_T ISR jet is expected [185]. To account for the smaller cross section of high $m_{\tilde{t}_1}$ signals, events containing the ISR jet are also considered.

5.3 Tools for signal discrimination

Variables to discriminate signals in this analysis are summarized here.

Small ΔM channel

As mentioned in Sec. 5.1, the main sources of the background after the preselection are $W(\rightarrow \ell\nu)$ +jets and semi-leptonic $t\bar{t}$. Both backgrounds contain on-shell W boson decaying into lepton and neutrino, which makes a Jacobian peak at about 80 GeV on the transverse mass reconstructed by lepton and E_T^{miss} . On the other hand, the signal is expected to have high transverse mass due to high E_T^{miss} . The transverse

Figure 5.2: Illustration of the signal topology in the small ΔM channel in x - y plane. Stop pair generated to the opposite direction to the high- p_T ISR jet is selected, which leads to high E_T^{miss} . Soft b -jets are also boosted in this topology.

mass m_T is defined as:

$$m_T = \sqrt{2p_T^l E_T^{\text{miss}} (1 - \cos \Delta\phi)}, \quad (5.3)$$

where p_T^l is the transverse momentum of the lepton and $\Delta\phi$ is an azimuthal difference between the lepton and $\vec{E}_T^{\text{miss}}$.

W +jets backgrounds are strongly suppressed by requiring the existence of b -jets, while the fraction of the semi-leptonic $t\bar{t}$ background is enhanced as well as the stop signals. In addition, the QCD multi-jet events are considered as background if they pass the event selection, when a mis-identified lepton satisfies the isolation criteria, and large E_T^{miss} is observed due to mis-measured jets. The mis-identified lepton background is suppressed by the lepton isolation requirement but small contribution at low- p_T region is expected. These backgrounds are suppressed by a cut on $E_T^{\text{miss}}/m_{\text{eff}}$, where m_{eff} is the scalar sum of E_T^{miss} and the transverse momentum of all jets and lepton:

$$m_{\text{eff}} = \sum p_T^{\text{jet}} + p_T^l + E_T^{\text{miss}}. \quad (5.4)$$

E_T^{miss} coming from the un-detected $\tilde{\chi}_1^0$ has relatively larger fraction in m_{eff} than the $t\bar{t}$ and multi-jet backgrounds. In particular, $t\bar{t}$ background is expected to have lower $E_T^{\text{miss}}/m_{\text{eff}}$, since it has hard b -jets and on-shell W boson in the final-state.

Moderate ΔM channel

The requirement of two b -jets in the event suppresses large amount of the W +jets and mis-identified lepton background in the moderate ΔM channel. The remaining background mainly comes from the semi-leptonic $t\bar{t}$. Third and fourth jets from the decay of stop via off-shell W boson are expected to be

soft compared with those from top quark decay via on-shell W . The variable $H_{T,2}$ is defined by the scalar sum of the jet p_T except for the leading and second leading jets as:

$$H_{T,2} = \sum_{i=3}^{N_{\text{jets}}} p_T^{\text{jet}_i}, \quad (5.5)$$

where $p_T^{\text{jet}_i}$ is the transverse momentum of i -th jet and N_{jets} is the number of jets with $p_T > 25$ GeV in the event. Semi-leptonic $t\bar{t}$ background is suppressed by applying an upper cut on $H_{T,2}$. However, if high- p_T ISR jet exists in the 3rd jet, a cut on $H_{T,2}$ also reduces the signals. As discussed in Sec. 5.2, higher probability to contain the high- p_T ISR jet is expected at high $m_{\tilde{t}_1}$ region. It should be optimized whether a cut on $H_{T,2}$ is applied or not according to the stop mass.

Di-leptonic $t\bar{t}$ events are supposed to have two b -jets and high E_T^{miss} and high m_T due to two high p_T neutrinos. Therefore, it is difficult to distinguish this background from the signals if one of the leptons is not detected by the detector acceptance, inefficiency in the reconstruction, etc. The asymmetric m_{T2} variable, am_{T2} , is used to discriminate signals, which is a generalization of the transverse mass applied to signatures with two undetected particles. For an event characterized by two 1-step decay chains, a and b , each producing a missing particle C , m_{T2} is defined by $\vec{p}_{Ta}^C$ and $\vec{p}_{Tb}^C$ to minimize $m_{T,a}$ and $m_{T,b}$ [186] as:

$$m_{T2} = \min_{\vec{p}_{Ta}^C + \vec{p}_{Tb}^C = \vec{E}_T^{\text{miss}}} \{ \max(m_{T,a}, m_{T,b}) \}, \quad (5.6)$$

where $m_{T,a}$ and $m_{T,b}$ are the transverse mass of each decay chain a and b , respectively, for a given hypothetical allocation $(\vec{p}_{Ta}^C, \vec{p}_{Tb}^C)$ of the missing particle transverse momenta. The vector-sum of $\vec{p}_{Ta}^C$ and $\vec{p}_{Tb}^C$ is constrained to be observed $\vec{E}_T^{\text{miss}}$. There is an implicit use of an input mass for the missing particles when computing $m_{T,a}$ and $m_{T,b}$. The choice for this input mass is arbitrary, since for a given choice there is a known relationship between the mass of the parent particles and the endpoint of m_{T2} . The variable am_{T2} [187–189] is m_{T2} in which the missing particles for the branch a and b are different from each other. In this analysis, assuming di-leptonic $t\bar{t}$ events, the missing particle is the neutrino for the branch with the observed charged lepton and the W boson for the branch with the lost lepton, as shown in Fig. 5.3. The input masses are chosen such that am_{T2} of the di-leptonic $t\bar{t}$ background is bounded by the top quark mass. $m_{T,a}$ and $m_{T,b}$ are defined as:

$$\begin{aligned} m_{T,a}^2 &= (E_T^{b\text{-jet1}} + E_T^l + E_{Ta}^l)^2 - (\vec{p}_T^{b\text{-jet1}} + \vec{p}_T^l + \vec{p}_{Ta}^C)^2 \\ m_{T,b}^2 &= (E_T^{b\text{-jet2}} + E_{Tb}^l)^2 - (\vec{p}_T^{b\text{-jet2}} + \vec{p}_{Tb}^C)^2, \end{aligned}$$

where $E_T^{b\text{-jet1}}$, $E_T^{b\text{-jet2}}$ and E_T^l are the transverse energies of two b -jets and the lepton, and $\vec{p}_T^{b\text{-jet1}}$, $\vec{p}_T^{b\text{-jet2}}$ and $\vec{p}_T^l$ are the momenta of two b -jets and the lepton projected to the x - y plane. The masses of the missing particles are chosen to be m_ν and m_W i.e.

$$\begin{aligned} E_{Ta}^2 &= m_\nu^2 + \vec{p}_{Ta}^2, \\ E_{Tb}^2 &= m_W^2 + \vec{p}_{Tb}^2. \end{aligned}$$

The allocation of $(\vec{p}_{Ta}, \vec{p}_{Tb})$ is optimized by Eq. (5.6) under the constraint of $\vec{p}_{Ta} + \vec{p}_{Tb} = \vec{E}_T^{\text{miss}}$. The semi-leptonic $t\bar{t}$ is also expected to be bounded at the top quark mass, because $\vec{E}_{Ta} \sim \vec{E}_T^{\text{miss}}$ and $\vec{E}_{Tb} \sim 0$ are assigned if the procedure works well. Signals of the new physics have am_{T2} greater than the bound. It is known that the endpoint of the am_{T2} distribution for the signals is around the parent particle mass.

Furthermore, the invariant mass reconstructed by two b -jets is a useful variable, which is defined as:

$$m_{bb}^2 = (E^{b\text{-jet1}} + E^{b\text{-jet2}})^2 - (\vec{p}^{b\text{-jet1}} + \vec{p}^{b\text{-jet2}})^2, \quad (5.7)$$

where $E^{b\text{-jet1}(b\text{-jet2})}$ and $\vec{p}^{b\text{-jet1}(b\text{-jet2})}$ are the energy and momentum of the leading (2nd-leading) b -jets. The m_{bb} for the heavy stop signal is harder than that for the $t\bar{t}$ background.

Figure 5.3: Illustration of the am_{T2} reconstruction [71]. Dashed lines indicate the objects assumed to be undetected.

5.4 Optimization of signal regions

Signal regions are optimized to maximize the sensitivity at the benchmark signal point for each channel. The sensitivity is defined as:

$$\sigma_{\text{sig}} = \frac{s}{\sqrt{b + (0.3b)^2}}, \quad (5.8)$$

where s and b are the number of signals and background after the selections, respectively, assuming 30 % systematic uncertainty on the background estimation. The b -tag operation point (see Sec. 4.5.7) is also optimized for each channel, to maximize the σ_{sig} .

5.4.1 Small ΔM channel

This channel aims to cover the signals with small ΔM . The main target ΔM is less than about 100 GeV, which was not explored in the previous analysis [95]. Signal region is determined by optimizing thresholds for the variables listed below:

$$\{E_{\text{T}}^{\text{miss}}, p_{\text{T}}^{\text{jet1}}, N_{\text{jets}}, N_{b\text{-jets}}, m_{\text{T}}, \frac{E_{\text{T}}^{\text{miss}}}{m_{\text{eff}}}\}, \quad (5.9)$$

where $p_{\text{T}}^{\text{jet1}}$ is the transverse momentum of the leading jet, N_{jets} is the number of jets with $p_{\text{T}} > 25$ GeV and $N_{b\text{-jets}}$ is the number of b -jets.

To select the high- p_{T} ISR jet, the leading jet p_{T} is required to be greater than 180 GeV. Anti- b -tagging is required to the leading jet since it is assumed as the ISR jet. Number of b -jets in the event is optimized to be $N_{b\text{-jets}} \geq 1$, not $N_{b\text{-jets}} = 2$, to take the low b -tag efficiency for the low- p_{T} jet into account. The moderate b -tagging operation point with 70% efficiency is selected to keep signal acceptance and for tight anti- b -tagging requirement for the leading jet.

Figure 5.4 shows $E_{\text{T}}^{\text{miss}}$ distribution for the SM background after the preselection, soft lepton (lepton $p_{\text{T}} < 25$ GeV), ISR jet ($p_{\text{T}} > 180$ GeV) and at least one b -jet requirements. At this stage, the remaining backgrounds are $t\bar{t}$ (51 %) and W +jets (27 %). Two benchmark signal points at:

$$\mathbf{A} \quad m_{\tilde{t}_1} = 225 \text{ GeV}, m_{\tilde{\chi}_1^+} = 215 \text{ GeV}, m_{\tilde{\chi}_1^0} = 195 \text{ GeV};$$

Figure 5.4: The simulated distribution of the reconstructed missing transverse energy E_T^{miss} after the preselection, soft lepton, ISR jet and at least one b -jet requirement. Black line shows the total standard model background expectation. The $t\bar{t}$ and W +jets backgrounds are indicated by yellow and light green, respectively. The single- t , Z +jets, Drell-Yan, dibosons, $t\bar{t}$ +vector boson, mid-identified lepton backgrounds are considered in the ‘Other’ background. Two signal benchmark points of $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (225, 215, 195)$ GeV and $(225, 170, 150)$ GeV are overlaid by blue dashed line and red break line. All distributions are normalized to 20 fb^{-1} and the last bin contains over-flow. Signal cross sections are multiplied by factor 100.

$$\mathbf{B} \quad m_{\tilde{t}_1} = 225 \text{ GeV}, m_{\tilde{\chi}_1^\pm} = 170 \text{ GeV}, m_{\tilde{\chi}_1^0} = 150 \text{ GeV};$$

are overlaid. The same $m_{\tilde{t}_1}$ i.e. the same cross section, but different ΔM of 30 GeV for **A** and 75 GeV for **B** are assumed for these two signal hypotheses. The figure shows that with the larger ΔM , the smaller E_T^{miss} is expected when stop mass is fixed, since hard b -jets are balanced to the high- p_T ISR jet to cancel the E_T^{miss} , while soft b -jets do not contribute to E_T^{miss} calculation so much. Two sub-channels for a high compressed mass spectrum **A** and a moderate compressed mass spectrum **B** are defined, by requiring $E_T^{\text{miss}} > 370$ GeV and > 300 GeV, respectively. The sub-channels are named the small ΔM channel (high) and (low).

For more suppression of the W +jets background, events should have high jet multiplicity and high m_T . For small ΔM channel (low), the best sensitivity is found if $N_{\text{jets}} \geq 3$ and $m_T > 100$ GeV are required. These requirements are loosened for the small ΔM channel (high) to recover the signal acceptance loss caused by very tight E_T^{miss} requirement: $N_{\text{jets}} \geq 2$ and $m_T > 90$ GeV.

The remaining background is expected to be the semi-leptonic $t\bar{t}$ after all above selections are applied. The variable $E_T^{\text{miss}}/m_{\text{eff}}$ is used as the signal discriminator against the semi-leptonic $t\bar{t}$ background. Figures 5.5 (a) and (b) show the $E_T^{\text{miss}}/m_{\text{eff}}$ distributions in the small ΔM channel (high) and (low), respectively. Signals with the same $m_{\tilde{t}_1}$, but different ΔM of 75 GeV, 50 GeV and 30 GeV are overlaid. The figure shows that $E_T^{\text{miss}}/m_{\text{eff}}$ for signals is relatively high with respect to the SM backgrounds and the peak positions depend on ΔM . The threshold of the $E_T^{\text{miss}}/m_{\text{eff}}$ is optimized to be 0.35 and 0.3 for the small ΔM channel (high) and (low), respectively, to maximize the σ_{sig} for each benchmark signal. It is confirmed that the shape fit using $E_T^{\text{miss}}/m_{\text{eff}}$ distribution does not change the sensitivity. The 46 % and 60 % of the background comes from $t\bar{t}$ in the small ΔM channel (high) and (low), respectively, after the cut on $E_T^{\text{miss}}/m_{\text{eff}}$ is applied. Sub-dominant background processes are W +jets, single top and mis-identified lepton backgrounds (about 10-20 % for each).

Figure 5.5: The simulated distributions of $E_T^{\text{miss}}/m_{\text{eff}}$ for small ΔM channel (high) on left and (low) on right. Black lines indicate the total standard model background predictions. The $t\bar{t}$ and W +jets backgrounds are shown by yellow and light green, respectively. The single- t , Z +jets, Drell-Yan, dibosons, $t\bar{t}$ +vector boson, mis-identified lepton backgrounds are considered in the ‘Other’ background. Three signal points of $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^+}, m_{\tilde{\chi}_1^0}) = (225, 215, 195)$ GeV, $(225, 195, 175)$ GeV and $(225, 170, 150)$ GeV are overlaid. All distributions are normalized to 20 fb^{-1} . σ_{sig} as a function of the threshold of $E_T^{\text{miss}}/m_{\text{eff}}$ for each signal is shown in the bottom panels.

To investigate the sensitivity as a function of Δm , the shape fit on lepton p_T distribution in $6(7) < p_T < 50$ GeV is performed in the model-dependent fit configuration using CLs method (see details in Sec. 7.3). As shown in Fig. 5.1, lepton p_T distribution for signals is related to the Δm . Optimized number of bins to show the best sensitivity is 4 bins. Figure 5.6 shows the expected 95 % CL exclusion region of the masses of the stop and the LSP on the grid of $\Delta m = 20$ GeV (a) and $m_{\tilde{\chi}_1^+}$ at 150 GeV (b), derived by the CLs method with and without the shape fit on the lepton p_T . The small ΔM channel (high) and (low) are combined by taking the one showing the best expected CLs value at each point. The sensitivity to the stop signals at the target region of $\Delta M \leq 70$ GeV is expected in the grid (a). The shape fit on the lepton p_T improves the expected limit, in particular on the grid (b) from $15 < \Delta m < 70$ GeV to $15 < \Delta m < 100$ GeV at $m_{\tilde{t}_1} = 160$ GeV.

Event selections for the small ΔM channel (high) and (low) are summarized in the next chapter (Tables 6.2 and 6.3). Cut-flow charts for the SM backgrounds and the benchmark signals are found in Appendix B.

5.4.2 Moderate ΔM channel

This channel is designed to cover the moderate ΔM region, by requiring two high- p_T b -jets with $p_T > 60$ GeV. To ensure the performance of the E_T^{miss} trigger, jet p_T is required to be greater than 60 GeV. A sufficient b -tag efficiency is expected at $p_T = 60$ GeV, so the tight b -tag operation point with 60 % efficiency is used for the background suppression. Two jets having the highest and 2nd highest p_T in the event are required to be b -tagged. After the two b -jets requirement, W +light flavor jets and mis-identified lepton backgrounds are negligible and the remaining backgrounds are $t\bar{t}$ and W boson

Figure 5.6: Expected 95 % confidence level exclusion limit by the small ΔM channel on $\Delta M = 20$ GeV grid (a) and fixed $m_{\tilde{\chi}_1^{\pm}} = 150$ GeV grid (b), with (blue) and without (violet) shape fit on the lepton p_T distribution. Yellow band shows the uncertainty ($\pm 1\sigma$) on the exclusion limit with shape fit. The small ΔM channel (high) and (low) are merged by taking the better expected CLs value at each signal point. Shape fit gains the sensitivity, especially in the fixed $m_{\tilde{\chi}_1^{\pm}} = 150$ GeV grid at the large Δm region. The benchmark signal points: $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^{\pm}}, m_{\tilde{\chi}_1^0}) = (225, 215, 195)$ GeV **A** and $(225, 170, 150)$ GeV **B** are indicated by the black points. The shape fit recovers the sensitivity at the point **B**.

associated with heavy flavor quarks. For further suppression of the QCD multi-jet background with miscalculated E_T^{miss} , the leading two jets are required to be well-isolated from E_T^{miss} by $\Delta\phi > 0.4$, where $\Delta\phi$ is the azimuthal difference between the jet and E_T^{miss} . The signal region is optimized with respect to the following variables to maximize σ_{sig} at the benchmark signal points:

$$\{E_T^{\text{miss}}, am_{T2}, H_{T2}, m_{bb}\}. \quad (5.10)$$

Figure 5.7 shows the E_T^{miss} distribution after the preselection, soft lepton (lepton $p_T < 25$ GeV) and two high- p_T b -jets requirement are applied. At this stage, the background component is expected to be the semi-leptonic $t\bar{t}$ (73 %) and small contributions of di-leptonic $t\bar{t}$ (9 %) and W +jets (6 %). The following benchmark signals are overlaid:

C $m_{\tilde{t}_1} = 200$ GeV, $m_{\tilde{\chi}_1^\pm} = 120$ GeV, $m_{\tilde{\chi}_1^0} = 100$ GeV;

D $m_{\tilde{t}_1} = 600$ GeV, $m_{\tilde{\chi}_1^\pm} = 120$ GeV, $m_{\tilde{\chi}_1^0} = 100$ GeV.

As with the small ΔM channel, two sub-channels, namely the moderate ΔM channel (low) and (high), for the lower and higher stop mass regions are prepared. At the lower $m_{\tilde{t}_1}$ region, stop pair generated back-to-back in x - y plane is searched, which leads to a lower E_T^{miss} . Thus, the lowest threshold to ensure the E_T^{miss} trigger performance of greater than 150 GeV is required for the moderated ΔM channel (low). To reduce the semi-leptonic $t\bar{t}$ background, the upper cut on $H_{T,2}$ at 50 GeV is applied. At the higher $m_{\tilde{t}_1}$ region, signals generated with the ISR jet are also considered, which lead to the high E_T^{miss} . Therefore, tighter requirement of $E_T^{\text{miss}} > 250$ GeV is applied for the moderate ΔM channel (high). Concerning the ISR jet, a cut on $H_{T,2}$ is not applied.

Figure 5.7: The simulated E_T^{miss} distribution after the preselection, soft lepton, and two b -jets requirement with the leading two jets with $p_T > 60$ GeV. Black line shows the total standard model background expectation. The $t\bar{t}$ and W +jets backgrounds are indicated by yellow and light green, respectively. The single- t , Z +jets, Drell-Yan, dibosons, $t\bar{t}$ +vector boson, mis-identified lepton backgrounds are considered in the ‘Other’ background. Two signal benchmark points of $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (200, 120, 100)$ GeV and $(600, 120, 100)$ GeV are overlaid by blue dashed line and red broken line. All distributions are normalized to 20 fb^{-1} and the last bin contains over-flow. Signals are multiplied by factor 100.

For better signal-to-background ratio, $m_{bb} > 150$ GeV is required for both sub-channels. Finally, as the signal discriminator, am_{T2} variable is employed. Figures 5.8 (a) and (b) show the am_{T2} distributions in the moderate ΔM channel (low) and (high), respectively, after the all selection cuts described above. As discussed in Sec. 5.3, the $t\bar{t}$ background mainly distributes at $am_{T2} \lesssim 200$ GeV, while signals have an upper bound on am_{T2} at around the stop masses. As shown by the blue line in Fig. 5.8 (a), it is difficult to have a sensitivity for the benchmark signal **C** ($m_{\tilde{t}_1} = 200$ GeV) in the cut-base analysis, due to the quite similar signal topology to the $t\bar{t}$ background. The σ_{sig} for the benchmark signal **D** ($m_{\tilde{t}_1} = 600$ GeV) is maximized if an extreme high threshold on am_{T2} at about 400 GeV is taken as shown in the violet line in Fig. 5.8 (b), but the accuracy of the background modeling is not sufficient in this region due to the lack of the statistics¹. Therefore, cuts are optimized to be $am_{T2} > 170$ GeV for the moderate ΔM channel (low) and > 200 GeV for the moderate ΔM channel (high), to safely enhance stop signals against $t\bar{t}$ background for a wide range of signal region.

Figure 5.8: The am_{T2} distributions for moderate ΔM channel (low) and (high) channels. Black lines indicate the total standard model background predictions. The W +jets backgrounds are shown by light green. The semi-leptonic, di-leptonic, and full-hadronic $t\bar{t}$ are indicated by yellow, dark yellow and light brown, respectively. The single- t , Z +jets, Drell-Yan, dibosons, $t\bar{t}$ +vector boson, mid-identified lepton backgrounds are considered in the ‘Other’ background. Three signal points of $m(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^+}, m_{\tilde{\chi}_1^0}) = (200, 120, 100)$ GeV, $(250, 120, 100)$ GeV and $(300, 120, 100)$ GeV are overlaid for the moderate ΔM channel (low), and $(400, 120, 100)$ GeV, $(500, 120, 100)$ GeV and $(600, 120, 100)$ GeV are for the moderate ΔM channel (high). σ_{sig} as a function of the threshold of am_{T2} for each signal is shown in the bottom panels. All distributions are normalized to 20 fb^{-1} .

¹Concretely, the guard condition $b \geq 3$ is required in the signal region optimization for the accuracy of the background estimation.

The remaining backgrounds in the signal regions after the am_{T2} cut are expected to be semi-leptonic $t\bar{t}$ containing mis- b -tagged c quark from $W \rightarrow cs$ decay (46 % in the moderate ΔM channel (low) and 35 % in the moderate ΔM channel (high)). The sub-dominant processes are W +heavy flavor quarks and single top productions. These backgrounds show continuous distributions at the high am_{T2} region, since assumptions to compute the am_{T2} cannot be applied to them.

In the model-dependent fit configuration using CLs method (see Sec. 7.3), the shape fit on am_{T2} between 0 to 500 GeV in 6 bins (the cut on am_{T2} is omitted) is tried for both the moderate ΔM channel (low) and (high) to recover the sensitivity at the benchmark points **C** and **D**. Figure 5.9 shows the expected 95 % CL exclusion limit on masses of the stop and the LSP on $\Delta m = 20$ GeV grid derived by the CLs method, with and without the shape fit on am_{T2} . Two sub-channels are combined by taking the one with the best expected CLs value. Using the shape information, the sensitivity is gained by about 20 GeV towards both higher and lower $m_{\tilde{t}_1}$ directions and signal points **C** and **D** are covered by 1σ band.

Event selections for the small ΔM channel (high) and (low) are summarized in the next chapter (Tables 6.4 and 6.5). Cut-flow charts for the SM backgrounds and the benchmark signals are found in Appendix B.

Figure 5.9: Expected 95 % confidence level exclusion limit by the moderate ΔM channel on $\Delta M = 20$ GeV grid, with (blue) and without (violet) shape fit on the am_{T2} distribution. Yellow band shows the uncertainty ($\pm 1\sigma$) on the exclusion limit with shape fit. The moderate ΔM channel (low) and (high) are merged by taking the one with better expected CLs value at each signal point. The benchmark signal points: $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^+}, m_{\tilde{\chi}_1^0}) = (200, 120, 100)$ GeV **C** and $(600, 120, 100)$ GeV **D** are indicated by the black points. The shape fit makes it possible to cover the points **C** and **D** within the uncertainty.

5.4.3 Combination of two channels

The small and moderate ΔM channels are combined to take the one showing the best expected CLs value at each signal point. Figure 5.10 shows the expected 95 % CL exclusion region after the combination of two channels. Sub-channels taken at each point are also shown in the figure. Shape fits using the lepton p_T distribution for the small ΔM channel and am_{T2} for the moderate ΔM channel are performed. The small ΔM channel (high) covers the most compressed ΔM region at the diagonal; the small ΔM channel

(low) excludes the region at $30 < \Delta M < 70$ GeV and has the best sensitivity at $\Delta M < 120$ GeV; the moderate ΔM channel (low) excludes signals with $200 < m_{\tilde{t}_1} < 350$ GeV with $m_{\tilde{\chi}_1^0}$ less than approximately 200 GeV; and the sensitivity of the moderate ΔM channel (high) reaches to $m_{\tilde{t}_1} \simeq 600$ GeV with $m_{\tilde{\chi}_1^0} < 250$ GeV. Each sub-channel is confirmed to cover the target regions. No sensitivity is found at the gap region between two exclusion regions at $70 < \Delta M < 120$ GeV. This is due to that the sensitivity of the moderate ΔM channel (low) is suddenly lost at $\Delta M = 120$ GeV since the signal topology at this region is quite similar to the SM top quark pair production as discussed in Sec. 5.4.2.

Figure 5.10: Expected 95 % confidence level exclusion limit on $\Delta M = 20$ GeV grid, after the combination of four sub-channels. Yellow band shows the uncertainty ($\pm 1\sigma$). Sub-channels taken at each signal point are shown by black triangles (the small ΔM channel (high)), white triangles (the small ΔM channel (low)), black squares (the moderate ΔM channel (low)) and white circles (the moderate ΔM channel (high)).

Chapter 6

Background Estimation

Precise estimation of the SM background and the evaluation of the uncertainty on that are important to search for an excess of the SUSY signal. In this analysis, a simultaneous fit on the signal and backgrounds is performed to extract their normalizations. Systematic uncertainties are implemented as nuisance parameters in the fit to constrain the signal and background estimations. In this chapter, details of the fit procedure and considered systematic uncertainties and how to validate the background estimation are presented.

6.1 Overview

The maximum likelihood fit described in Sec. 6.2 is performed to estimate the SM background and search for an excess of the SUSY signal. There are three types of fit configurations:

Background only fit

The ‘background only’ fit configuration tests for the SM hypothesis without any signals.

Model-independent fit

The ‘model-independent’ fit configuration tests for an excess of events with respect to the background expectation.

Model-dependent fit

The ‘model-dependent’ fit configuration tests for a specific new physics model.

Here, for simplicity, the background estimation with the background only fit configuration is explained. As discussed in Chapter 5, the main sources of the background in this analysis are $t\bar{t}$ and W +jets. These backgrounds are estimated by a semi-data-driven method. Since the SUSY signals are searched in an extreme phase space defined by high E_T^{miss} and high m_T , where the tuning of event generators is not sufficient, the large uncertainty on the SM background has to be considered. To minimize the uncertainty, the fitting is performed to the data in dedicated control regions (CRs) where $t\bar{t}$ and W +jets are enriched, respectively. The fitting is carried out using the `HistFitter` framework [190]. The normalization factors for $t\bar{t}$ ($\mu_{t\bar{t}}$) and W +jets ($\mu_{W+\text{jets}}$) derived in the CRs are extrapolated into the signal region (SR) using MC shape information as:

$$N_{\text{bg,SR}}^{\text{data}} = \frac{N_{\text{bg,CR}}^{\text{data}}}{N_{\text{bg,CR}}^{\text{MC}}} \times N_{\text{bg,SR}}^{\text{MC}} = \mu_{\text{bg}} \times N_{\text{bg,SR}}^{\text{MC}} = \text{TF}_{\text{bg}} \times N_{\text{bg,CR}}^{\text{data}}, \quad (6.1)$$

$$\mu_{\text{bg}} = \frac{N_{\text{bg,CR}}^{\text{data}}}{N_{\text{bg,CR}}^{\text{MC}}}, \quad \text{TF}_{\text{bg}} = \frac{N_{\text{bg,SR}}^{\text{MC}}}{N_{\text{bg,CR}}^{\text{MC}}}, \quad (6.2)$$

where ‘bg’ denotes $t\bar{t}$ or W +jets. $N_{\text{bg,SR}}^{\text{data(MC)}}$ is the number of the background observed (expected by MC) in the signal region and $N_{\text{bg,CR}}^{\text{data(MC)}}$ is in the control region, respectively. A $t\bar{t}$ enriched control region (TR) and W +jets enriched control region (WR) are defined for each search channel by the similar selection cuts to SR as much as possible (details in Sec. 6.5) to minimize the uncertainty associated with the extrapolation. In the fitting, two normalization factors are floated as free parameters, simultaneously. The ratio of the number of events in the SR to those in the CR derived from the MC simulation, $\text{TF}_{\text{bg}} = N_{\text{bg,SR}}^{\text{MC}}/N_{\text{bg,CR}}^{\text{MC}}$, is called the transfer factor for a given sample (bg denotes $t\bar{t}$ or W +jets). It is a key of this procedure that the systematic uncertainties changing the normalization equally in the SR and CRs are implemented in the fit in terms of the transfer factors to reduce the systematic uncertainty (see Sec. 6.3.4). Almost the same procedures are performed with the model-dependent and model-independent fit configurations. The number of signals (model-independent fit) or the signal normalization factor μ (model-dependent fit) is treated as a free parameter in the fit as introduced in Sec. 6.2, in addition to $\mu_{t\bar{t}}$ and $\mu_{W\text{+jets}}$. A reliable prediction by the MC simulation is difficult of the QCD multi-jet events with mis-measured $E_{\text{T}}^{\text{miss}}$ and $Z(\rightarrow \nu\nu)$ +jets events, which are expected to be main sources of the mis-identified lepton background, due to the accuracy and statistics of the MC simulation. Therefore, the mis-identified lepton background is estimated by the data-driven method. Details of the criteria are described in Sec. 6.4. The other minor backgrounds containing lepton are estimated purely by the MC simulation. In Sec. 6.6, how to validate the estimated backgrounds and the results of the validation are shown.

6.2 Maximum likelihood fit

With the model-dependent fit configuration, the SRs for the small ΔM channel are divided into 4 bins using the lepton p_{T} distribution and the SRs for the moderate ΔM channel are divided into 6 bins using $am_{\text{T}2}$ distribution as defined in Sec. 5.4.1 and 5.4.2. The background only and model-independent fit configurations consider only the difference between observed and expected number of events in the SR and do not use the shape information (1 bin). The likelihood used in this analysis is defined as:

$$L(\mathbf{n}, \theta^0 | \mu, \mu_b, \theta) = \prod_{j=1}^{N_{\text{bins}}} P(n_{\text{SR},j} | \lambda_{\text{SR},j}(\mu, \mu_b, \theta)) \cdot P(n_{\text{TR}} | \lambda_{\text{TR}}(\mu, \mu_b, \theta)) \cdot P(n_{\text{WR}} | \lambda_{\text{WR}}(\mu, \mu_b, \theta)) \cdot F_{\text{nuis}}(\theta^0, \theta), \quad (6.3)$$

where j is the bin number and N_{bins} is the number of bins in the SR. $\mathbf{n} = \{n_{\text{SR}}, n_{\text{TR}}, n_{\text{WR}}\}$ is the vector for the number of observed events in SR, TR and WR. μ is the normalization factor for the signal (so-called signal strength) and $\mu_b = \{\mu_{t\bar{t}}, \mu_{W\text{+jets}}\}$ is the background normalization factors for $t\bar{t}$ and W +jets samples. The $P(k | \lambda)$ is the probability to observe an integral number k when λ is expected, described by the Poisson distribution function:

$$P(k | \lambda) = \frac{\lambda^k}{k!} e^{-\lambda}. \quad (6.4)$$

The expected number of events in SR ($\lambda_{\text{SR},j}$) and CRs ($\lambda_{t\bar{t}}$ and $\lambda_{W\text{+jets}}$) are defined as:

$$\lambda_{\text{SR},j} = \mu N_{\text{sig},j}^{\text{SR}}(\theta) + \mu_{t\bar{t}} N_{t\bar{t},j}^{\text{SR}}(\theta) + \mu_{W\text{+jets},j} N_{W\text{+jets}}^{\text{SR}}(\theta) + N_{\text{others},j}^{\text{SR}}(\theta), \quad (6.5)$$

$$\lambda_{\text{TR}} = \mu N_{\text{sig}}^{\text{TR}}(\theta) + \mu_{t\bar{t}} N_{t\bar{t}}^{\text{TR}}(\theta) + \mu_{W\text{+jets}} N_{W\text{+jets}}^{\text{TR}}(\theta) + N_{\text{others}}^{\text{TR}}(\theta), \quad (6.6)$$

$$\lambda_{\text{WR}} = \mu N_{\text{sig}}^{\text{WR}}(\theta) + \mu_{t\bar{t}} N_{t\bar{t}}^{\text{WR}}(\theta) + \mu_{W\text{+jets}} N_{W\text{+jets}}^{\text{WR}}(\theta) + N_{\text{others}}^{\text{WR}}(\theta), \quad (6.7)$$

where $N_{\text{sig}}^{\text{region}}$, $N_{t\bar{t}}^{\text{region}}$, $N_{W\text{+jets}}^{\text{region}}$ and $N_{\text{others}}^{\text{region}}$ are the expected number of the signal, $t\bar{t}$, W +jets, and the other backgrounds in a considered region (SR, TR, or WR) estimated by the MC. The normalization

factors are treated as free parameters within the positive values in the fit. The systematic uncertainties are considered in the fit as nuisance parameters:

$$F_{\text{nuis}}(\theta^0, \theta) = \prod_i \frac{1}{\sqrt{2\pi}\Delta_i} \exp\left(-\frac{(\theta_i - \theta_i^0)^2}{2\Delta_i^2}\right), \quad (6.8)$$

where $\theta = \{\theta_1, \theta_2, \dots\}$ is the vector of the nuisance parameters for all systematic uncertainties. Each parameter θ_i is assumed to follow the Gaussian probability distribution with the mean of the nominal value θ_i^0 and the width of the estimated systematic uncertainty Δ_i .

In the background only fit configuration, SR term is excluded from the likelihood Eq. (6.3) and μ is fixed to be zero i.e. background estimation in the SR is independent of the observed number of events in the SR. Nuisance parameters associated with the signal strength are also fixed to be zero. With the model-independent fit configuration, signal contamination in the CRs is fixed to be zero for conservative approach. μ is fixed to 1 in the SR and the number of signal events, $s = \mu N_{\text{sig}}^{\text{SR}}$, is used as a free parameter in the fit instead. Since model-independent interpretation of the signal excess is performed, nuisance parameters for signal strength are fixed to be zero. With the model-dependent fit configuration, a common value of μ is used in both the SR and CRs. For the stable fit, CRs should be defined to have small signal contamination. The nuisance parameters on signal strength are taken into account in the fit.

6.3 Systematic uncertainties

There are two types of systematic uncertainties coming from experimental sources (Sec. 6.3.1) and theoretical sources (Sec. 6.3.2). They are applied to all background and signal samples in the way described in Sec. 6.3.4.

6.3.1 Experimental sources

The systematic uncertainties coming from the experimental sources are already discussed in Chapter 3 and 4. A brief summary of them are listed below.

Luminosity measurement

As described in Sec. 3.1.2, $\pm 2.8\%$ uncertainty on the integrated luminosity measurement is assigned.

Trigger efficiency

As discussed in Sec. 3.1.3, conservatively 5% uncertainty is assigned on the trigger efficiency.

Pileup

To assess the uncertainty of the pileup modeling, the nominal scale factor to the averaged number of interaction per bunch crossing $\langle\mu\rangle$ is varied by $\pm 11\%$ (see Sec. 3.2.6). The difference of the number of events from the nominal value is assigned as the systematic uncertainty in each signal, control and validation region.

Lepton reconstruction

Systematic uncertainties associated with the lepton reconstruction are evaluated by varying the following 6 parameters for electron and 3 parameters for muon within the estimated uncertainties described in Sec. 4.2.3 and 4.3.4 in each signal, control, and validation region.

- Uncertainty on the electron energy scale derived by the data-driven $Z^0 \rightarrow e^+e^-$ events;
- Uncertainty on the electron energy resolution derived by the data-driven $Z^0 \rightarrow e^+e^-$ events;

- Uncertainty on the the modeling of the inner detector materials in the electron reconstruction;
- Uncertainty on the data-driven estimated energy scale of the pre-sampler calorimeter in the electron reconstruction;
- Uncertainty on low- p_T electron reconstruction, which is active only when $p_T < 20$ GeV;
- Uncertainty on the muon momentum resolution in the muon spectrometer, which is derived by di-muon resonances;
- Uncertainty on the muon momentum resolution in the inner detector, which is derived by di-muon resonances;
- Uncertainty on the momentum scale of the combined+segment-tag muon derived by di-muon resonances.

Lepton efficiency

Scaling factors are applied to account for the discrepancy of the lepton efficiencies between the data and MC as discussed in Sec. 4.2.5 and 4.3.6. The uncertainty associated with them are directly assigned as the systematic uncertainty.

Jet energy scale (JES)

The following 16 nuisance parameters are considered to account for the uncertainties on the jet energy scale (JES):

- Four nuisance parameters associated with the jet area method for the pileup subtraction, described in Sec. 4.5.3.
- Six nuisance parameters from absolute in-situ JES estimations after the reduction of the number of parameters; see Sec. 4.5.4.
- An uncertainty on the high- p_T jet estimated by in-situ method using multi-jets events; see Sec. 4.5.4.
- Two nuisance parameters associated with the η -intercalibration modeling and methodology; see Sec. 4.5.4.
- Two nuisance parameters on the flavor composition and energy response difference between flavors; see Sec. 4.5.4. For b -tagged jets, these uncertainties are not applied.
- Additional JES uncertainty for b -jet introduced in Sec. 4.5.7.

Jet energy resolution

Jet energy resolution is varied within the estimated uncertainty described in Sec. 4.5.4 and the difference of the number of events from the nominal value is assigned as the systematic uncertainty in each region.

Jet vertex fraction (JVF)

As discussed in Sec. 4.5.5, the uncertainty on the JVF cut is estimated by changing the threshold of JVF.

Flavor tagging

Scaling factors are applied to improve the data-to-MC ratio after the b -tagging. The uncertainty on the jets induced by b -, c - and the light-flavor-quark are estimated separately, as shown in Fig. 4.16, and assigned as independent nuisance parameters in the fit.

Soft term for E_T^{miss} calculation

The scale and resolution of the soft term in the E_T^{miss} calculation are varied within the estimated uncertainty described in Sec. 4.6 and the variations of the number of events are assigned as the systematic uncertainties.

6.3.2 Theoretical sources

Following systematic uncertainties associated with the theoretical calculations are considered.

Renormalization and factorization scales (Scale)

The uncertainty on a choice of the renormalization (μ_R) and factorization (μ_F) scales is evaluated by varying the scale up and down by a factor 2, independently (see Sec. 3.2.1).

Number of extra partons (N_{parton})

This uncertainty is considered for the MC generators calculating the multi-leg matrix elements (SHERPA). The uncertainty on the number of extra patrons (N_{parton}) is assessed by reducing the number of extra patrons N_{parton} to $N_{\text{parton}} - 1$.

Matrix element and parton shower matching parameters

The uncertainty on a choice of the matching parameter between matrix element and parton shower is considered, which is introduced in Sec. 3.2.4. In MADGRAPH interfaced to PYTHIA, the scale for the first emission in MLM matching (α_s) and the minimum k_T jet measure between patrons ($k_{\perp}^{\text{cut}}$) are varied while the CKKW merging cut is changed in SHERPA.

MC generator

The uncertainty on a choice of an event generator is assessed for $t\bar{t}$ MC by comparing POWHEG and ALPGEN. The MC generator difference on the dibosons sample is estimated by POWHEG and MS@NLO. For the other samples, this uncertainty is not considered.

Parton shower scheme

The uncertainty on a choice of a parton shower algorithm is assessed by comparing PYTHIA and HERWIG.

PDF modeling

The uncertainty associated with a choice of the PDF set is calculated, which are divided into inter- and intra-variations. The inter-variation is evaluated by comparing different PDF sets. MC samples using CT10 PDF set are compared with those using CTEQ6L1 and vice versa. Intra-variations are evaluated by MSTW PDF set using PDF4LHC prescription [191]. The MSTW package calculates 20×2 (up and down) variations of the PDF which span the range of the uncertainties coming from the experimental errors, in addition to one central value of the PDF, for the lightest 5 quarks and gluon. The effect of these uncertainties on the cross section is obtained by calculating the cross section for each of these variations (σ^{up} and σ^{down} for each) while keeping the other parameters fixed. This gives an asymmetric PDF uncertainty:

$$\begin{aligned}\Delta_{\text{PDF}}^{\text{up}} &= \sqrt{\sum (\max[\sigma^{\text{up}} - \sigma^0, \sigma^{\text{down}} - \sigma^0, 0])^2} \\ \Delta_{\text{PDF}}^{\text{down}} &= \sqrt{\sum (\max[\sigma^0 - \sigma^{\text{up}}, \sigma^0 - \sigma^{\text{down}}, 0])^2}\end{aligned}\tag{6.9}$$

where σ^0 is the cross section calculated using the nominal value of the PDF and the sum runs over all 20 variations.

Interference effect

As described in Sec. 3.2.2, the MC simulations for $t\bar{t}$ and single-top are generated separately. Therefore, the interference between single-top Wt -channel and $t\bar{t}$ production at NLO perturbative QCD calculation, as shown in Fig. 6.1, is not considered. It is resolved by the diagram removal scheme using the prescription in Ref. [141, 142]. The uncertainty associated with the interference is estimated by comparing nominal $t\bar{t}$ and single-top Wt sample with an inclusive ACERMC $WWbb$ sample.

Figure 6.1: (a) Tree-level diagram of the single top quark production in Wt channel. Diagrams of Wt production via $t\bar{t}$ in NLO calculation like (b) interfere with diagram (a). Diagram removal scheme simply do not use diagrams including $t\bar{t}$ for the production of the single-top quark Wt channel.

The fraction of heavy flavor quark production associated with a W boson (Wbb fraction)

As described in Sec. 6.5, the normalization of W +jets sample is estimated in an anti- b -tagged control region and extrapolated into the signal region containing b -jets. The uncertainty on the ratio of the heavy flavor quark production to the light flavor quark production associated with W boson (we call it Wbb fraction) is considered to be $\pm 24\%$ by following the ATLAS measurement [192].

6.3.3 Systematic uncertainty on the signal

As described in Sec. 3.2.3, the signal cross sections are calculated at next-to-leading-logarithmic accuracy in QCD [149–151]. The following systematic uncertainties on the cross-section calculation are estimated by the prescription in Ref. [152].

Renormalization and factorization scales (Scale)

The uncertainty on a choice of μ_R and μ_F are estimated in the same way as described in the previous section.

PDF modeling

The uncertainty associated with a choice of the PDF set is calculated in the same way as described in the previous section.

α_S uncertainty

Determination of PDF parameters has an overall uncertainty for the choice of α_S [193]. Two different cases are tested and the variations on cross-sections is taken as an uncertainty.

Additionally, the following uncertainties on kinematic acceptance are evaluated separately.

ISR and FSR parameters

Parameters for initial- and final-state radiation (ISR and FSR) are varied by a factor 2, and uncertainty on that is evaluated. The ISR uncertainty for signals is determined by the same way at several benchmark $m_{\tilde{t}_1}$ values. The uncertainty is parameterized as a function of ΔM as:

$$\Delta_{\text{ISR}}^{\text{signal}} = e^{-0.0073\Delta M - 1.93} \quad (6.10)$$

and applied to all signal points.

Matrix element and parton shower matching parameters

The uncertainty on a choice of the matching parameter between matrix element and parton shower is estimated in the same way as described in the previous section. The scale for the first emission in MLM matching (α_s) and the minimum k_T jet measure between patrons ($k_{\perp}^{\text{cut}}$) are varied.

These uncertainties are used as nuisance parameters in the model-dependent fit configuration.

6.3.4 Application of the systematic uncertainty

Minor systematic uncertainties are combined and treated as one nuisance parameter for each sample in the fit, in order to reduce the number of parameters and obtain a stable fit result. The largest upward and downward variations are taken as an overall uncertainty envelope. List of the theoretical uncertainties and those contained in the envelope for each background process as well as the signal are summarized in Table 6.1. Most of uncertainties on major background processes (W renormalization and factorization scale variations, $t\bar{t}$ generator and parton shower comparisons) are not included in the envelope, i.e. they are accounted in the fit as separated nuisance parameters.

Total systematic uncertainty on the number of the background in the SR (b) after the fit, Δb_{tot} , is calculated by a typical error propagation formula:

$$\Delta b_{\text{tot}}^2 = \sum_i \left(\frac{\partial b}{\partial \eta_i} \right)^2 \Delta_{\eta_i}^2 + \sum_i \sum_{j \neq i} \rho_{ij} \left(\frac{\partial b}{\partial \eta_i} \right) \left(\frac{\partial b}{\partial \eta_j} \right) \Delta_{\eta_i} \Delta_{\eta_j}, \quad (6.11)$$

where η_i are the floating fit parameters, containing normalization factors ($\mu_{t\bar{t}}$ and $\mu_{W+\text{jets}}$) and nuisance parameters (θ_l) and Δ_{η_i} is the estimated uncertainty. ρ_{ij} represents the correlation coefficient between η_i and η_j .

The uncertainties on $t\bar{t}$ and W +jets backgrounds that change the normalization equally between CRs and SR are implemented in terms of transfer factors ($\text{TF}_{t\bar{t}}$ and $\text{TF}_{W+\text{jets}}$). These uncertainties tend to cancel between CRs and SR i.e. for many uncertainties (e.g. luminosity measurement, part of JES) $\partial b / \partial \eta_i$ tends to be zero in Eq. (6.11). The statistic terms for TR and WR described by the Poisson function in Eq. (6.3) work as nuisance parameters for the normalization of these backgrounds instead. The other systematic uncertainties on $t\bar{t}$ and W +jets without cancellation between the CRs and SR, for example lepton uncertainties when transported from high to low lepton p_T in this analysis as explained in Sec. 6.5, and all systematic uncertainties on the other backgrounds are implemented separately in the CRs and SR.

The background processes except for $t\bar{t}$ and W +jets do not have dedicated control regions so the theoretical uncertainty has a direct impact on their event yields without constraint from the data. Samples to evaluate systematic uncertainties are normalized to nominal samples in a region defined with very loose selection in order to avoid undesired differences coming from different MC parameters, generator-level event filters etc. and double counting of the uncertainty on the cross section. The definition of the loose normalization region is:

- at least one lepton with $p_T > 6$ (7) GeV for muon (electron).

Even the preselection cuts are not applied in the loose normalization region.

The uncertainties on the cross section summarized in Sec. 3.2.2 are applied to all processes, except for $t\bar{t}$ and W +jets samples.

6.4 Mis-identified lepton estimation

Origins of the mis-identified lepton background is supposed to be semi-leptonic decay of heavy flavor hadrons and pion decaying into two photon (one of the photons is mis-identified as electron) in the QCD

Table 6.1: Summary of the systematic uncertainties considered for each background process and for signals.

Type	description
$t\bar{t}$	
MC generator	POWHEG+JIMMY vs ALPGEN+JIMMY
Parton shower	POWHEG+PYTHIA vs POWHEG+JIMMY
PDF	Explained in the text
Envelope	ISR/FSR and scale variations
W +jets	
Scale	Explained in the text
PDF	Explained in the text
N_{parton}	Number of extra patrons
Wbb fraction	Fraction of heavy flavor jets (24 %)
Z +jets	
Scale	Explained in the text
PDF	Explained in the text
N_{parton}	Number of extra patrons
dibosons	
Cross section	5 % for WW/ZZ , 7 % for WZ (see Sec. 3.2.2)
PDF	Explained in the text
Envelope	parton shower, MC generator, scales and matching
$t\bar{t}+V$	
Cross section	22 % for $t\bar{t} + W/Z$, 50 % for $t\bar{t} + WW$ (see Sec. 3.2.2)
PDF	Explained in the text
Envelope	parton shower, scales, matching and number of extra partons
Single t	
Cross section	3.9 % for s -channel, [+3.9, -2.2] % for t -channel, 6.8 % for Wt channel, 50 % for $Z+t$ (see Sec. 3.2.2)
PDF	Explained in the text
Envelope	ISR/FSR, interference, parton shower and MC generator
Signals	
Cross section	Containing scale variation and PDF variation uncertainties [152]
Matching	between matrix element and parton shower
ISR/FSR	Explained in the text

multi-jet and $Z(\rightarrow \nu\nu)$ +jets events. These backgrounds are suppressed by large E_T^{miss} requirement and the lepton isolation cut as discussed in Chapter 5, but small contamination especially at low- p_T region is expected due to the worse impact parameter resolution at low p_T as discribed in Sec. 4.1.3. Since our signal regions are defined by soft lepton, careful estimation of the mis-identified lepton is important. Data-driven estimation of the mis-identified lepton background using the matrix method is performed. The details of the criteria are found in Ref. [194, 195].

6.4.1 Matrix method

The number of events containing a baseline lepton (N_{baseline}) and the number of events containing an isolated lepton (N_{iso}) are related to the number of events containing a physics-origin (real) baseline lepton ($N_{\text{baseline}}^{\text{real}}$) and a mis-identified (fake) baseline lepton ($N_{\text{baseline}}^{\text{fake}}$) by 2×2 matrix as:

$$\begin{pmatrix} N_{\text{iso}} \\ N_{\text{baseline}} \end{pmatrix} = \begin{pmatrix} \epsilon_{\text{real}} & \epsilon_{\text{fake}} \\ 1 & 1 \end{pmatrix} \begin{pmatrix} N_{\text{baseline}}^{\text{real}} \\ N_{\text{baseline}}^{\text{fake}} \end{pmatrix}, \quad (6.12)$$

where ϵ_{real} is the efficiency of the isolation cut to events with the real baseline lepton, and ϵ_{fake} is that to events with the fake baseline lepton. As introduced in Sec. 4.4, medium isolation criteria for leptons with $p_T < 25$ GeV and high- p_T isolation criteria for $p_T > 25$ GeV are used to select isolated leptons. The number of fake lepton background passing the isolation cut ($\epsilon_{\text{fake}} N_{\text{baseline}}^{\text{fake}}$) can be described by multiplying inverse matrix to the both sides of Eq. (6.12) as:

$$\begin{aligned} \epsilon_{\text{fake}} N_{\text{baseline}}^{\text{fake}} &= \frac{\epsilon_{\text{fake}}}{\epsilon_{\text{real}} - \epsilon_{\text{fake}}} (\epsilon_{\text{real}} N_{\text{baseline}} - N_{\text{iso}}) \\ &= \frac{\epsilon_{\text{fake}}}{\epsilon_{\text{real}} - \epsilon_{\text{fake}}} (\epsilon_{\text{real}} N_{\text{fail}} - (1 - \epsilon_{\text{real}}) N_{\text{iso}}), \end{aligned} \quad (6.13)$$

where $N_{\text{fail}} = N_{\text{baseline}} - N_{\text{iso}}$ is the number of events containing the baseline lepton but rejected by the isolation cut. N_{fail} and N_{iso} are observable. ϵ_{real} and ϵ_{fake} are derived by the data in the dedicated control regions in which real and fake leptons are enriched, respectively, as functions of lepton p_T and η , considering the p_T and η dependencies of the impact parameter resolution.

Therefore, the amount of the mis-identified lepton background is estimated by applying the following event-by-event weight to the data.

$$w_{\text{iso}} = -\frac{\epsilon_{\text{fake}}(1 - \epsilon_{\text{real}})}{\epsilon_{\text{real}} - \epsilon_{\text{fake}}}, \quad (6.14)$$

$$w_{\text{fail}} = \frac{\epsilon_{\text{fake}} \epsilon_{\text{real}}}{\epsilon_{\text{real}} - \epsilon_{\text{fake}}}. \quad (6.15)$$

w_{iso} and w_{fail} are the weight for events containing the isolated lepton and for events containing the baseline lepton but failing the isolation requirement, respectively.

Statistical uncertainties associated with ϵ_{real} and ϵ_{fake} are calculated as:

$$\Delta \epsilon_{\text{real(fake)}}^{\text{stat}} = \sqrt{\frac{\epsilon_{\text{real(fake)}}(1 - \epsilon_{\text{real(fake)}})}{N_{\text{real(fake)}}^{\text{baseline}}}}. \quad (6.16)$$

Systematic uncertainties ($\Delta \epsilon_{\text{real(fake)}}^{\text{syst}}$) are evaluated by comparing $\epsilon_{\text{real(fake)}}$ derived by the data and MC. Additional uncertainties are added to $\Delta \epsilon_{\text{real}}$ at $p_T < 25$ GeV by comparing the different MC samples. Statistical and systematic uncertainties are propagated to w_{iso} and w_{fail} calculation, and used as nuisance parameters in the fit.

6.4.2 Measurement of isolation efficiency for real leptons

The isolation efficiency to events containing the real baseline lepton is estimated with the data by the Tag and Probe method using $Z \rightarrow \ell\ell$ events. Events satisfying the following selections are used in this procedure.

- One of electron or muon trigger chains¹ is fired.
- Exactly two baseline electrons or muons with opposite signs of an electric charge exist.
- There is at least one electron (or muon) with $p_T > 7$ (6) GeV, geometrically matched with tracks recognized in the trigger system (EF) by $\Delta R < 0.05$ (called a Tag).
- Both leptons should be isolated from any jets in the event by $\Delta R > 0.4$.
- The invariant mass calculated by two leptons should satisfy $80 < m_{ll} < 100$ GeV ($m_Z = 91.18$ GeV).

The opposite lepton to the Tag is used as a Probe to measure the isolation efficiency. Figures 6.2 (a) and (b) show the measured ϵ_{real} as functions of p_T and η for electron and muon, respectively. It should be noted that different isolation criteria (medium and high- p_T conditions) are used in $p_T < 25$ GeV and $p_T \geq 25$ GeV.

6.4.3 Estimation of isolation efficiency for fake leptons

The isolation efficiency to fake baseline leptons is estimated in the fake lepton enriched control region, which is defined by the following conditions.

- Data should be collected by one of the non-isolated lepton triggers².
- At least one baseline lepton exists.
- $E_T^{\text{miss}} < 30$ GeV.
- $m_T < 40$ GeV.
- At least one jet with $p_T > 60$ GeV exists.
- At least one b -jet in the event exists, since our SRs are defined by b -jets.

The fractions of real leptons in the fake lepton control region is subtracted by the $t\bar{t}$ and W +jets MC. The estimated ϵ_{fake} for electron and muon are shown in Figs. 6.2 (c) and (d).

Further study on the origin of the fake lepton is made using $t\bar{t}$ MC. Probability to mis-identify the heavy flavor quark as a lepton is higher than that for the light flavor quark by 10 % to 30 % depending on lepton p_T [196]. Fundamentally, the origin of the fake lepton cannot be recognized in the data. Conservatively constant 30 % uncertainty is added to $\Delta\epsilon_{\text{fake}}$ at $p_T < 25$ GeV.

¹Used trigger chains for the measurement of the isolation efficiency for real leptons are EF_e12Tvh_loose1, EF_e60_medium1, EF_2e12Tvh_loose1, EF_e12Tvh_medium1_mu8, EF_mu18_tight, EF_mu8_EFFS, EF_mu36_tight, or EF_mu18_tight_mu8_EFFS.

²Used trigger chains for the measurement of the isolation efficiency for fake leptons are EF_e5_medium1, EF_e15vh_medium1, EF_e24_medium1, EF_2e12Tvh_loose1, EF_mu6, EF_mu15, EF_e12Tvh_medium1_mu8, or EF_mu24_tight.

Figure 6.2: The isolation efficiency to events containing the real electron (a), real muon (b), fake electron (c) and fake muon (d), as a function of p_T . Efficiencies are evaluated by the data in several η ranges.

6.5 Control region and validation region definitions

Four signal channels are defined for the dedicated regions of ΔM in Chapter 5: the small ΔM channel (high), the small ΔM channel (low), the moderate ΔM channel (low) and the moderate ΔM channel (high). The control region definitions for each signal region are illustrated in Fig. 6.3 and summarized in Tables 6.2 - 6.5. Basically, TRs are defined by the same b -tag condition as the signal region, while WRs are defined by the anti- b -tag requirement i.e. W +jets sample in b -tagged signal region is extrapolated from b -vetoed control region. According to that, the uncertainty associated with the Wbb fraction ($\pm 24\%$) is considered in the fit as discussed in Sec. 6.3.2.

For the small ΔM channel, the backgrounds are controlled in the lower E_T^{miss} region of $200 < E_T^{\text{miss}} < 250$ GeV as illustrated in Fig. 6.3 (a) and described in Tables 6.2 and 6.3. To gain statistics, lepton p_T upper cut and $E_T^{\text{miss}}/m_{\text{eff}}$ cut are not applied in the control regions. It is confirmed that the lepton p_T and $E_T^{\text{miss}}/m_{\text{eff}}$ distributions in the data agree with the MC in the CRs (see Sec. 6.6.3). The purity of $t\bar{t}$ sample in the TR is improved by omitting $E_T^{\text{miss}}/m_{\text{eff}}$ cut, since $t\bar{t}$ background has lower $E_T^{\text{miss}}/m_{\text{eff}}$. For the orthogonality to the signal regions for the other ATLAS stop analyses requiring a hard lepton [71], the upper cut on m_T at 120 GeV is applied for the control region. The other cuts are the same with those for the signal region. To validate the extrapolation along the E_T^{miss} distribution, the validation region VR1 is defined in $250 < E_T^{\text{miss}} < 370$ GeV for the small ΔM channel (high) and $250 < E_T^{\text{miss}} < 300$ GeV for the small ΔM channel (low). The other cuts for VR1 except for $E_T^{\text{miss}}/m_{\text{eff}}$ are the same with those for the signal region. To check the extrapolation along $E_T^{\text{miss}}/m_{\text{eff}}$ distribution, alternative validation region VR2 is defined in $E_T^{\text{miss}}/m_{\text{eff}} > 0.35$ for the small ΔM channel (high) and $E_T^{\text{miss}}/m_{\text{eff}} > 0.3$ for the small ΔM channel (low), overlapping with VR1.

For the moderate ΔM channel, control regions are defined in $p_T > 25$ GeV to be orthogonal to the signal regions as illustrated in Fig. 6.3 (b) and summarized in Tables 6.4 and 6.5. For WR, $40 < m_T < 80$ GeV is required to enhance the Jacobian peak of W bosons. In order to accumulate the statistics, a cut on m_{bb} is omitted in the CRs and the cut on E_T^{miss} is loosened to > 150 GeV in the TR for the moderate ΔM channel (high). It is confirmed that E_T^{miss} and m_{bb} distributions in the CRs agree with the MC (see Sec. 6.6.3). The other cuts are the same with those for the signal region. A cut on am_{T2} is used to enhance signals from the $t\bar{t}$ backgrounds in the SRs. CRs are defined without am_{T2} cut, which leads to high purity of $t\bar{t}$ in the TR as discussed in Sec. 6.6.3. The validation region (VR) is defined in lepton $p_T < 25$ GeV and $m_{bb} < 150$ GeV to validate the extrapolation along lepton p_T .

6.6 Validation of the estimated background

The estimated backgrounds are validated in several regions, in which the mis-identified leptons are enriched (Sec. 6.6.1), with looser selection cuts (Sec. 6.6.2), and CRs and VRs for each channel (Sec. 6.6.3).

6.6.1 Validation for mis-identified lepton background

The mis-identified lepton background is estimated by the data-driven method described in Sec. 6.4. Figure 6.4 shows the E_T^{miss} and m_T distributions in the mis-identified lepton enriched validation region defined by:

- Preselection cuts described in Sec. 5.1 except for E_T^{miss} cut;
- $m_T < 30$ GeV;
- Existence of at least one b -jet defined by 70 % working point with $p_T > 25$ GeV,

(a)

(b)

Figure 6.3: Schematic illustration of the signal region (SR), control region (CR) and validation region (VR) definitions for the small ΔM channel (a) and the moderate ΔM channel (b). The $t\bar{t}$ control region (TR) is defined by the same b -tag requirement with SR, while the W +jets control region (WR) is defined by anti- b -tagging.

Table 6.2: Definitions of the signal region, $t\bar{t}$ and W +jets CRs (TR and WR) and VRs for the small ΔM channel (high). p_T^{lep1} and p_T^{lep2} are the leading and second leading lepton p_T , p_T^{jet1} is the leading jet p_T , E_T^{miss} is the missing transverse energy, m_T is the transverse mass reconstructed by lepton and E_T^{miss} , N_{jets} is number of jets with $p_T > 25$ GeV, m_{eff} is the effective mass, and $N_{b\text{-jets}}$ is the number of b -jets.

Small ΔM (high)	SR	TR	WR	VR1	VR2
p_T^{lep1}	Shape fit in [6(7), 50] GeV	$> 6(7)$ GeV		[6(7), 25] GeV	
p_T^{lep2}	$< 6(7)$ GeV for electron (muon)				
p_T^{jet1}	> 180 GeV				
E_T^{miss}	> 370 GeV	[200, 250] GeV		[250, 370] GeV	
m_T	> 90 GeV	[90, 120] GeV		> 90 GeV	
N_{jets}	≥ 2				
$E_T^{\text{miss}}/m_{\text{eff}}$	> 0.35	—		> 0.35	
$N_{b\text{-jets}}$	≥ 1 (jet1 is not b -tagged)		0	≥ 1 (jet1 is not b -tagged)	
Model-independent analysis	$p_T^{\text{lep1}} < 25$ GeV	-			

Table 6.3: Definitions of the signal region, $t\bar{t}$ and W +jets CRs (TR and WR) and VRs for the small ΔM channel (low). p_T^{lep1} and p_T^{lep2} are the leading and second leading lepton p_T , p_T^{jet1} is the leading jet p_T , E_T^{miss} is the missing transverse energy, m_T is the transverse mass reconstructed by lepton and E_T^{miss} , N_{jets} is number of jets with $p_T > 25$ GeV, m_{eff} is the effective mass, and $N_{b\text{-jets}}$ is the number of b -jets.

Small ΔM (low)	SR	TR	WR	VR1	VR2
p_T^{lep1}	Shape fit in [6(7), 50] GeV	$> 6(7)$ GeV		[6(7), 25] GeV	
p_T^{lep2}	$< 6(7)$ GeV for electron (muon)				
p_T^{jet1}	> 180 GeV				
E_T^{miss}	> 300 GeV	[200, 250] GeV		[250, 300] GeV	
m_T	> 100 GeV	[100,120] GeV		> 100 GeV	
N_{jets}	≥ 3				
$E_T^{\text{miss}}/m_{\text{eff}}$	> 0.3	—		> 0.3	
$N_{b\text{-jets}}$	≥ 1 (jet1 is not b -tagged)		0	≥ 1 (jet1 is not b -tagged)	
Model-independent analysis	$p_T^{\text{lep1}} < 25$ GeV	-			

Table 6.4: Definitions of the signal region, $t\bar{t}$ and W +jets CRs (TR and WR) and VRs for the moderate ΔM channel (low). p_T^{lep1} and p_T^{lep2} are the leading and second leading lepton p_T , E_T^{miss} is the missing transverse energy, p_T^{jet2} is the second leading jet p_T , $H_{T,2}$ is the scalar sum of the jet p_T except for the leading two jets, $N_{b\text{-jets}}$ is the number of b -jets, m_T is the transverse mass reconstructed by lepton and E_T^{miss} , and m_{bb} is the invariant mass reconstructed by two b -jets.

Moderate ΔM (low)	SR	TR	WR	VR
$p_{\text{T}}^{\text{lep1}}$	[6(7), 25] GeV	> 25 GeV		[6(7), 25] GeV
$p_{\text{T}}^{\text{lep2}}$	< 6 (7) GeV for electron (muon)			
$E_{\text{T}}^{\text{miss}}$	> 150 GeV			
$p_{\text{T}}^{\text{jet2}}$	> 60 GeV			
$H_{\text{T},2}$	< 50 GeV			
$N_{b\text{-jets}}$	2 (the leading two jets are b-tagged)	0		2
m_{T}	-		[40, 80]GeV	-
m_{bb}	> 150 GeV	No cut		< 150 GeV
$am_{\text{T}2}$	Shepe fit in [0, 500] GeV	-	-	-
Model-independent analysis	$am_{\text{T}2} > 170$ GeV	-		

Table 6.5: Definitions of the signal region, $t\bar{t}$ and W +jets CRs (TR and WR) and VRs for the moderate ΔM channel (high). p_T^{lep1} and p_T^{lep2} are the leading and second leading lepton p_T , E_T^{miss} is the missing transverse energy, p_T^{jet2} is the second leading jet p_T , $N_{b\text{-jets}}$ is the number of b -jets, m_T is the transverse mass reconstructed by lepton and E_T^{miss} , and m_{bb} is the invariant mass reconstructed by two b -jets.

Moderate ΔM (high)	SR	TR	WR	VR
$p_{\text{T}}^{\text{lep1}}$	[6(7), 25] GeV	> 25 GeV		[6(7), 25] GeV
$p_{\text{T}}^{\text{lep2}}$	< 6 (7) GeV for electron (muon)			
$E_{\text{T}}^{\text{miss}}$	> 250 GeV	> 150 GeV	> 250 GeV	
$p_{\text{T}}^{\text{jet2}}$	> 60 GeV			
$N_{b\text{-jets}}$	2 (the leading two jets are b-tagged)		0	2
m_{T}	-		[40, 80]GeV	-
m_{bb}	> 150 GeV	No cut		< 150 GeV
$am_{\text{T}2}$	Shepe fit in [0, 500] GeV	-	-	-
Model-independent analysis	$am_{\text{T}2} > 200$ GeV	-		

divided into electron- and muon-channel. All background processes considered in this analysis are indicated by the different colors. Normalizations for $t\bar{t}$ and W +jets backgrounds are estimated by background only fit described in Sec. 6.2 using CRs for the moderate ΔM channel (high)³. The other backgrounds are estimated by the MC. As shown in Fig. 6.4, the mis-identified leptons are enriched in the lower E_T^{miss} region, but we use the data collected with E_T^{miss} trigger which requires $E_T^{\text{miss}} > 80$ GeV at the trigger level and it is necessary to apply $E_T^{\text{miss}} > 150$ GeV to avoid the effect of the E_T^{miss} resolution at the trigger level. Because we do not consider the uncertainty on the E_T^{miss} resolution at the trigger level, the total systematic uncertainty on the background may be under-estimated in this region. However, data agree with the prediction within considered uncertainty. Large systematic uncertainty at low- m_T region mainly comes from additional 30 % uncertainty on ϵ_{fake} as introduced in Sec. 6.4.3. Since ϵ_{fake} for muon is higher than that for electron as shown in Fig. 6.2 by the definition of the isolation criteria, the expected number of mis-identified muons is larger than that of mis-identified electrons. It yields the larger uncertainty in the muon-channel at the mis-identified lepton enriched region (low- m_T).

6.6.2 Validation for MC samples with loose selection

The MC samples are validated with the looser event selections. Two loose regions requiring at least one b -jet and two b -jets are defined, namely Loose1B and Loose2B, respectively. For both regions, the preselection defined in Sec. 5.1 is required. Additionally, the following selection cuts are applied:

Loose1B (for the small ΔM channel)

- The leading jet is not b -tagged;
- The leading jet is required to have $p_T > 130$ GeV.
- At least two jets with $p_T > 25$ GeV exist;
- $m_T > 40$ GeV.

Loose2B (for the moderate ΔM channel)

- The leading two jets are b -tagged;
- At least two jets should have $p_T > 25$ GeV.

An upper cut on lepton p_T is not applied in the Loose1B and Loose2B in order to accumulate the statistics. Figure 6.5 shows the lepton p_T , $E_T^{\text{miss}}/m_{\text{eff}}$ and am_{T2} distributions after the Loose1B and Loose2B cuts are applied. Normalization factors for $t\bar{t}$ and W +jets are derived in CRs for the moderate ΔM channel (high). Mis-identified lepton background is estimated by the data-driven matrix method. The other backgrounds are estimated by the MC. The data agree with the prediction within the uncertainty. At this stages, the mis-identified lepton background is well-suppressed by E_T^{miss} and the lepton isolation requirements with respect to the total amount of the background. Although e - and μ -channels are combined in these figures, it is confirmed that data agree with the prediction in both sub-channels.

6.6.3 Validation in CRs and VRs

Figures 6.6 - 6.9 show the lepton p_T , $E_T^{\text{miss}}/m_{\text{eff}}$, E_T^{miss} , m_{bb} and am_{T2} distributions in CRs for the data and the SM backgrounds. The SM backgrounds are estimated by the maximum likelihood fit with the

³Since we do not apply any extreme cuts, we use the control regions for the moderate ΔM channel (high) for the validation in the mis-identified lepton validation region, Loose1B and Loose2B regions. Existence of high- p_T ISR jet is required for the small ΔM channel and 3rd jet veto is required using H_{T2} for the moderate ΔM channel (low).

Figure 6.4: m_T (top) and E_T^{miss} (bottom) distributions in mis-identified lepton validation region defined in the text, which is divided into electron- (left) and muon-channel (right). For m_T distributions, a cut $m_T < 30$ GeV is omitted. Shaded band indicates systematic uncertainty, which contains MC statistics, JES, jet energy resolution, lepton scale, resolution, and efficiency, resolution and scale of soft E_T^{miss} term, $\Delta\epsilon_{\text{real(fake)}}^{\text{stat}}$, $\Delta\epsilon_{\text{real(fake)}}^{\text{syst}}$ and b -tagging.

Figure 6.5: Lepton p_T (a) and $E_T^{\text{miss}}/m_{\text{eff}}$ (b) distributions after the Loose1B cuts are applied and lepton p_T (c) and am_{T2} (d) distributions after the Loose2B cuts are applied. The SM backgrounds estimated by the MC are overlaid. The normalization factors for $t\bar{t}$ and W+jets samples are extrapolated from CRs for the moderate ΔM channel (high), where the selection cut for TR is the loosest in all four channels. Shaded band indicates systematic uncertainty, which contains MC statistics, JES, jet energy resolution, lepton scale, resolution, and efficiency, resolution and scale of soft E_T^{miss} term, $\Delta\epsilon_{\text{real(fake)}}^{\text{stat}}$, $\Delta\epsilon_{\text{real(fake)}}^{\text{syst}}$ and b -tagging.

Table 6.6: Number of observed events (N_{obs}), the fraction of $t\bar{t}$ and W +jets samples, the normalization factors for $t\bar{t}$ ($\mu_{t\bar{t}}$) and W +jets ($\mu_{W+\text{jets}}$) in the TR and WR for each channel.

channel		N_{obs}	$t\bar{t}$	W +jets	$\mu_{t\bar{t}}$	$\mu_{W+\text{jets}}$
Small ΔM (high)	TR	336	57 %	22 %	0.76 ± 0.15	0.85 ± 0.07
	WR	1149	5 %	83 %		
Small ΔM (low)	TR	136	72 %	11 %	0.88 ± 0.16	0.65 ± 0.11
	WR	189	14 %	64 %		
Moderate ΔM (low)	TR	390	71 %	12 %	0.96 ± 0.11	0.94 ± 0.06
	WR	13724	6 %	86 %		
Moderate ΔM (high)	TR	1111	79 %	6 %	1.00 ± 0.11	0.78 ± 0.06
	WR	4089	13 %	77 %		

background only hypothesis. Since WRs are defined with anti- b -tagging, for the moderate ΔM channel the dijet mass distribution reconstructed by the leading two anti- b -tagged jets (m_{jj}) is presented instead of m_{bb} and am_{T2} is calculated by the leading two jets, lepton, and E_T^{miss} . The benchmark signals for each channel normalized to the cross section and luminosity are overlaid. Fractions of the signal samples in each CR are small compared to the SM background. Signal contamination at each signal point in the control regions are summarized in Appendix C. Data agree well with the SM background estimation in all distributions within the uncertainty. Statistics and the fractions of $t\bar{t}$ and W +jets in each CR are summarized in Table 6.6. The background normalization factors $\mu_{t\bar{t}}$ and $\mu_{W+\text{jets}}$ are shown in the same table. Basically, $\gtrsim 70\%$ high purity is achieved in all CRs. Purity of the $t\bar{t}$ background in the TR for the small ΔM channel (high) is relatively low, but very high purity of W +jets in the WR constrains the normalization of the W +jets sample strongly and allow to determine the normalization for $t\bar{t}$ background.

The fit results are extrapolated into VRs, which validates the extrapolation along E_T^{miss} distribution for the small ΔM channel, and along lepton p_T distribution for the moderate ΔM channel. Figure 6.10 shows the distributions of signal discriminators in each VR. The ratio of the difference between number of observed and expect events in the VR to the total statistical and systematic uncertainty (σ_{tot}) are shown in Fig 6.11. Data agree well with the SM background within $1\sigma_{\text{tot}}$ for all VRs.

Number of observed and expected events and breakdown of the background components in each CR/VR are summarized in the next chapter (Tables 7.1 - 7.2 and 7.5 - 7.6).

Figure 6.6: Lepton p_T and $E_T^{\text{miss}}/m_{\text{eff}}$ distributions for TR (left) and WR (right) for the small ΔM channel (high). The SM backgrounds estimated by the maximum likelihood fit is overlaid. $t\bar{t}$ and W +jets are indicated by yellow and light green histograms, respectively. The ‘other’ background contains the single- t , Z +jets, Drell-Yan, dibosons, $t\bar{t}$ +vector boson and mis-identified lepton backgrounds. The benchmark signal $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (225, 215, 195)$ GeV is overlaid. Negligible fraction of the signal is confirmed in CRs. Shaded band indicates systematic uncertainty, which contains MC statistics, JES, jet energy resolution, lepton scale, resolution, and efficiency, resolution and scale of soft E_T^{miss} term, $\Delta\epsilon_{\text{real(fake)}}^{\text{stat}}$, $\Delta\epsilon_{\text{real(fake)}}^{\text{syst}}$ and b -tagging.

Figure 6.7: Lepton p_T and $E_T^{\text{miss}}/m_{\text{eff}}$ distributions for TR (left) and WR (right) for the small ΔM channel (low). The SM backgrounds estimated by the maximum likelihood fit is overlaid. $t\bar{t}$ and W +jets are indicated by yellow and light green histograms, respectively. The ‘other’ background contains the single- t , Z +jets, Drell-Yan, dibosons, $t\bar{t}$ +vector boson and mis-identified lepton backgrounds. The benchmark signal $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^{\pm}}, m_{\tilde{\chi}_1^0}) = (225, 170, 150)$ GeV is overlaid. Shaded band indicates systematic uncertainty, which contains MC statistics, JES, jet energy resolution, lepton scale, resolution, and efficiency, resolution and scale of soft E_T^{miss} term, $\Delta\epsilon_{\text{real(fake)}}^{\text{stat}}$, $\Delta\epsilon_{\text{real(fake)}}^{\text{syst}}$ and b -tagging.

Figure 6.8: E_T^{miss} , m_{bb} and am_{T2} distributions for TR (left) and WR (right) for the moderate ΔM channel (low). The SM backgrounds estimated by the maximum likelihood fit is overlaid. $t\bar{t}$ and W +jets are indicated by yellow and light green histograms, respectively. The ‘other’ background contains the single- t , Z +jets, Drell-Yan, dibosons, $t\bar{t}$ +vector boson and mis-identified lepton backgrounds. The benchmark signal $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^{\pm}}, m_{\tilde{\chi}_1^0}) = (200, 120, 100)$ GeV is overlaid. Shaded band indicates systematic uncertainty, which contains MC statistics, JES, jet energy resolution, lepton scale, resolution, and efficiency, resolution and scale of soft E_T^{miss} term, $\Delta\epsilon_{\text{real(fake)}}^{\text{stat}}$, $\Delta\epsilon_{\text{real(fake)}}^{\text{syst}}$ and b -tagging.

Figure 6.9: E_T^{miss} , m_{bb} and am_{T2} distributions for TR (left) and WR (right) for the moderate ΔM channel (high). The SM backgrounds estimated by the maximum likelihood fit is overlaid. $t\bar{t}$ and W +jets are indicated by yellow and light green histograms, respectively. The ‘other’ background contains the single- t , Z +jets, Drell-Yan, dibosons, $t\bar{t}$ +vector boson and mis-identified lepton backgrounds. The benchmark signal $(m_{t\bar{t}}, m_{\chi^\pm}, m_{\chi^0}) = (600, 120, 100)$ GeV is overlaid. Shaded band indicates systematic uncertainty, which contains MC statistics, JES, jet energy resolution, lepton scale, resolution, and efficiency, resolution and scale of soft E_T^{miss} term, $\Delta\epsilon_{\text{real(fake)}}^{\text{stat}}$, $\Delta\epsilon_{\text{real(fake)}}^{\text{syst}}$ and b -tagging.

Figure 6.10: $E_T^{\text{miss}}/m_{\text{eff}}$ distributions in VR1 for the small ΔM channel (high) (a) and (low) (b), and am_{T_2} distributions in VR for the moderate ΔM channel (low) (c) and (high) (d). The SM backgrounds estimated by the maximum likelihood fit is overlaid. $t\bar{t}$ and W +jets are indicated by yellow and light green histograms, respectively. The ‘other’ background contains the single- t , Z +jets, Drell-Yan, dibosons, $t\bar{t}$ +vector boson and mis-identified lepton backgrounds. The benchmark signals $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (225, 215, 195)$ GeV, $(225, 170, 150)$ GeV, $(200, 120, 100)$ GeV and $(600, 120, 100)$ GeV are overlaid for each channel. Shaded band indicates systematic uncertainty, which contains MC statistics, JES, jet energy resolution, lepton scale, resolution, and efficiency, resolution and scale of soft E_T^{miss} term, $\Delta\epsilon_{\text{real(fake)}}^{\text{stat}}$, $\Delta\epsilon_{\text{real(fake)}}^{\text{syst}}$ and b -tagging.

Figure 6.11: The ratio of the difference between observed and expected number of events in each VR to the total statistical and systematic uncertainties. In all VRs, observed data agree well with the SM background estimation within 1σ .

Chapter 7

Results

Discussions about the observations in the signal regions take place in this chapter. The observed number of events in each signal region is compared with the Standard-Model-only hypothesis in Sec. 7.1. A model-independent limit on excesses against the Standard Model background is shown in Sec. 7.2. Finally, limits on the specific SUSY models are discussed in Sec. 7.3.

7.1 Observations in signal regions

After the careful checking of the fit configurations, the estimation of the systematic uncertainties, and data/MC agreements in the control and validation regions in Chapter 6, observed numbers of events in the signal regions are compared with the SM expectations by the fit.

7.1.1 Small ΔM channel

Numbers of observed events in the signal regions for the small ΔM channel (high) and (low) are presented in Tables 7.1 and 7.2, respectively, in comparison with those in the control and validation regions. The expected number of the SM backgrounds obtained by the maximum likelihood fit with the background only configuration (see Sec. 6.2) and the breakdown in each region are also summarized in the tables. Figure 7.1 shows the lepton p_T and $E_T^{\text{miss}}/m_{\text{eff}}$ distributions in the small ΔM channel (high) and (low). The expected signal at the benchmark point of $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0})$ for each channel is overlaid. The signals are normalized to the same luminosity as the background. In the small ΔM channel (high), 11 events are observed while 6.54 ± 1.52 events are expected in lepton $p_T < 25$ GeV and $E_T^{\text{miss}}/m_{\text{eff}} > 0.35$, yielding an excess of ~ 4.5 events. However, the number of observed data agree with the expectation in the range of 1.5σ , where σ is the total statistical plus systematic uncertainties. The dominant source of the background is $t\bar{t}$ (42 %). The W +jets (16 %), dibosons (16 %), and single top (13 %) are sub-dominant background processes. In the small ΔM channel (low), 20 events are observed in lepton $p_T < 25$ GeV and $E_T^{\text{miss}}/m_{\text{eff}} > 0.3$, which agree well with the prediction of 17.34 ± 4.28 . The significance of the observed excess is 0.4σ . The dominant background process is $t\bar{t}$ (60 %). The mis-identified lepton background (14 %) is not negligible in this sub-channel, and W +jets, single top and dibosons are sub-dominant processes (5-10 % for each). The main components of the systematic uncertainties are summarized in Tables 7.3 and 7.4. Signal uncertainties are not considered in the background only fit configuration. The dominant systematic uncertainty is on the main source of the background, $t\bar{t}$ ($\mu_{t\bar{t}}$, the choice of the MC generator and the parton shower scheme, etc.). The uncertainty on $\mu_{t\bar{t}}$ mainly comes from the statistical uncertainty in the TR (see Sec. 6.3.4). Large uncertainty on the mis-identified lepton background is due to a conservative 30 % additional uncertainty on ϵ_{fake} (see Sec. 6.4.3). However, it is confirmed that the

impact of this uncertainty is not significant on the upper limit calculations shown in Sec. 7.2 and 7.3 (see details in Appendix D). Most of the experimental systematic uncertainties are suppressed less than 4 %.

Table 7.1: Number of observed events and the expected number of events obtained by the maximum likelihood fit with the background only configuration (see text for details), in W +jets control region (WR), $t\bar{t}$ control region (TR), validation regions (VR1, VR2) and signal region (SR) for the small ΔM channel (high) for an integrated luminosity 20.1 fb^{-1} . The errors shown are the systematic uncertainty only.

Small ΔM channel (high)	WR	TR	VR1	VR2	SR
Observed events	1149	336	74	33	11
Expected events	1149.08 ± 33.91	336.00 ± 18.33	73.96 ± 12.53	36.07 ± 9.53	6.54 ± 1.52
$t\bar{t}$	59.68 ± 16.89	190.36 ± 35.45	42.99 ± 10.12	16.18 ± 7.50	2.76 ± 0.89
W +jets	949.62 ± 54.70	73.80 ± 21.38	12.12 ± 2.17	8.76 ± 1.75	1.07 ± 0.49
Z +jets	19.66 ± 6.83	1.46 ± 0.96	0.23 ± 0.14	$0.17^{+0.19}_{-0.17}$	0.02 ± 0.02
Single- t	22.35 ± 5.73	43.11 ± 11.85	7.47 ± 2.24	2.81 ± 0.76	0.86 ± 0.42
$t\bar{t}+V$	0.63 ± 0.30	2.32 ± 0.68	1.05 ± 0.33	0.39 ± 0.14	0.23 ± 0.09
Dibosons	87.37 ± 26.70	10.45 ± 5.13	3.93 ± 1.32	3.19 ± 1.22	1.04 ± 0.61
Mid-id. lepton	$9.77^{+24.62}_{-9.77}$	$14.50^{+15.25}_{-14.50}$	$6.17^{+8.25}_{-6.17}$	$4.56^{+5.53}_{-4.56}$	$0.55^{+0.99}_{-0.55}$

Table 7.2: Number of observed events and the expected number of events obtained by the maximum likelihood fit with the background only configuration (see text for details), in W +jets control region (WR), $t\bar{t}$ control region (TR), validation regions (VR1, VR2) and signal region (SR) for the small ΔM channel (low) for an integrated luminosity 20.1 fb^{-1} . The errors shown are the systematic uncertainty only.

Small ΔM channel (low)	WR	TR	VR1	VR2	SR
Observed events	189	136	29	18	20
Expected events	189.18 ± 13.75	135.95 ± 11.68	27.37 ± 5.87	17.86 ± 5.15	17.47 ± 4.28
$t\bar{t}$	25.80 ± 7.40	97.72 ± 17.00	19.03 ± 5.06	11.10 ± 4.19	10.49 ± 3.15
W +jets	121.80 ± 19.57	15.10 ± 4.94	1.69 ± 0.51	0.97 ± 0.39	1.19 ± 0.48
Z +jets	5.05 ± 2.36	0.36 ± 0.34	0.10 ± 0.09	$0.10^{+0.13}_{-0.10}$	$0.02^{+0.14}_{-0.02}$
Single- t	5.22 ± 1.97	14.10 ± 7.92	1.78 ± 0.70	1.05 ± 0.40	1.75 ± 0.92
$t\bar{t}+V$	0.33 ± 0.15	1.20 ± 0.38	0.34 ± 0.14	0.19 ± 0.09	0.47 ± 0.17
Dibosons	27.64 ± 9.56	$2.21^{+3.97}_{-2.21}$	3.00 ± 1.73	2.66 ± 1.49	1.07 ± 0.58
Mid-id. lepton	$3.35^{+4.68}_{-3.35}$	$5.26^{+5.37}_{-5.26}$	$1.44^{+2.19}_{-1.44}$	$1.78^{+2.16}_{-1.78}$	$2.48^{+2.67}_{-2.48}$

Table 7.3: Breakdown of the dominant (top 20) systematic uncertainties on background estimates in the small ΔM channel (high) signal region. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the total expected background.

Small ΔM channel (high)	SR
Total background expectation	6.54
Total statistical ($\sqrt{N_{\text{exp}}}$)	± 2.56
Total background systematic	± 1.52 [23.27%]
Mis-identified lepton background	± 0.99 [15.1%]
MC statistical uncertainty in the SR	± 0.60 [9.1%]
$\mu_{t\bar{t}}$	± 0.56 [8.6%]
Dibosons theory (envelope)	± 0.53 [8.1%]
$t\bar{t}$ theory (envelope)	± 0.37 [5.7%]
$t\bar{t}$ generator difference	± 0.37 [5.7%]
Single- t theory (envelope)	± 0.34 [5.1%]
Trigger efficiency	± 0.30 [4.5%]
Lepton reconstruction efficiency	± 0.28 [4.3%]
W +jets N_{parton}	± 0.28 [4.2%]
$t\bar{t}$ parton shower	± 0.27 [4.2%]
W +heavy flavor to light flavor ratio	± 0.25 [3.9%]
b -tag efficiency on b quarks	± 0.20 [3.1%]
Pileup	± 0.17 [2.6%]
Single- t PDF uncertainty	± 0.14 [2.1%]
Scale of the $E_{\text{T}}^{\text{miss}}$ soft term	± 0.13 [2.0%]
b -tag efficiency on c quarks	± 0.13 [1.9%]
b -tag efficiency on light-flavor quarks and gluons	± 0.12 [1.9%]
Jet energy resolution	± 0.11 [1.6%]
Dibosons PDF uncertainty	± 0.10 [1.5%]

Table 7.4: Breakdown of the dominant (top 20) systematic uncertainties on background estimates in the small ΔM channel (low) signal region. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the total expected background.

Small ΔM channel (low)	SR
Total background expectation	17.47
Total statistical ($\sqrt{N_{\text{exp}}}$)	± 4.18
Total background systematic	± 4.28 [24.50%]
Mis-identified lepton background	± 2.67 [15.3%]
$\mu_{\tilde{t}\tilde{t}}$	± 1.95 [11.1%]
$t\bar{t}$ parton shower	± 1.93 [11.1%]
Jet energy resolution	± 1.30 [7.5%]
MC statistical uncertainty in the SR	± 0.84 [4.8%]
Single- t theory (envelope)	± 0.83 [4.8%]
$t\bar{t}$ theory (envelope)	± 0.83 [4.8%]
$t\bar{t}$ generator difference	± 0.79 [4.5%]
Trigger efficiency	± 0.74 [4.3%]
Resolution of the $E_{\text{T}}^{\text{miss}}$ soft term	± 0.53 [3.1%]
JES (flavor composition)	± 0.53 [3.0%]
Pileup	± 0.50 [2.9%]
JES (for b -jets)	± 0.41 [2.3%]
JES (flavor response)	± 0.36 [2.1%]
b -tag efficiency on b quarks	± 0.33 [1.9%]
Lepton reconstruction efficiency	± 0.28 [1.6%]
W +heavy flavor to light flavor ratio	± 0.28 [1.6%]
JES (effective nuisance parameter 2)	± 0.28 [1.6%]
JES (effective nuisance parameter 1)	± 0.24 [1.4%]
W +jets theory (envelope)	± 0.24 [1.3%]

Figure 7.1: Lepton p_T and $E_T^{\text{miss}}/m_{\text{eff}}$ distributions in the signal regions for the small ΔM channel (high) (left) and (low) (right). Lepton p_T upper cut at 25 GeV is not applied to the lepton p_T distributions and a cut $E_T^{\text{miss}}/m_{\text{eff}} > 0.35$ for the small ΔM channel (high) and > 0.3 for the small ΔM channel (low) is not applied to the $E_T^{\text{miss}}/m_{\text{eff}}$ distributions. Normalization of the $t\bar{t}$ and W+jets samples are obtained by the maximum likelihood fit with the background only configuration. The ‘other’ background contains the single- t , Z+jets, Drell-Yan, dibosons, $t\bar{t}$ +vector boson and mid-identified lepton backgrounds. The benchmark signal $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (225, 215, 195)$ GeV for the small ΔM channel (high) and $(225, 170, 150)$ GeV for the small ΔM channel (low) is overlaid. Shaded band shows the systematic uncertainties, which contains MC statistics, JES, jet energy resolution, lepton scale, resolution, and efficiency, resolution and scale of soft E_T^{miss} term, $\Delta\epsilon_{\text{real(fake)}}^{\text{stat}}$, $\Delta\epsilon_{\text{real(fake)}}^{\text{syst}}$ and b -tagging.

7.1.2 Moderate ΔM channel

Number of observed and expected events in the signal regions for the moderate ΔM channel (low) and (high), compared with those in control and validation regions, are shown in Tables 7.5 and 7.6, respectively. The expected number of events are obtained by the maximum likelihood fit with the background only configuration. am_{T2} distributions in the signal regions are shown in Fig. 7.2. The number of observed events in $am_{T2} > 170$ GeV in the moderate ΔM channel (low) is 41, while 32.1 ± 5.1 events are expected. The agreement between the data and the expectation is 1.2σ . The main components of the background are $t\bar{t}$ (47 %), W +jets (30 %) and single top (19 %). In the moderate ΔM channel (high), 7 events are observed which is smaller than the expectation (9.8 ± 1.6 events). Agreement between the data and prediction is -0.8σ . The background components are $t\bar{t}$ (42 %), single top (30 %) and W +jets (25 %). Main systematic uncertainties on the background estimation are summarized in Tables 7.7 and 7.8. As with the small ΔM channel, the dominant source of the uncertainty is coming from the $t\bar{t}$ estimation e.g. $\mu_{t\bar{t}}$ and choice of the parton shower scheme and MC generator. The uncertainty on the fraction of W +heavy-flavor quark (Wbb fraction) has a large impact in the moderate ΔM channel, although it is negligible in the small ΔM channel. This is because W +jets background is one of the dominant backgrounds in this channel. The uncertainty on the estimation of the mis-identified lepton background is sub-dominant, due to a conservative systematic uncertainty on ϵ_{fake} , although it is strongly suppressed in the signal regions. It is confirmed that this large uncertainty on ϵ_{fake} does not affect the final results on the upper limits.

Table 7.5: Number of observed events and the expected number of events obtained by the maximum likelihood fit with the background only configuration (see text for details), in W +jets control region (WR), $t\bar{t}$ control region (TR), validation regions (VR) and signal region (SR) for the small ΔM channel (high) for an integrated luminosity 20.1 fb^{-1} . The errors shown are the systematic uncertainty only.

Moderate ΔM channel (low)	WR	TR	VR	SR
Observed events	13724	390	76	41
Fitted bkg events	13724.18 ± 117.50	390.01 ± 19.75	75.99 ± 11.78	32.10 ± 5.08
$t\bar{t}$	832.14 ± 192.78	277.39 ± 27.93	45.39 ± 10.22	15.20 ± 3.97
W +jets	11786.76 ± 300.14	47.36 ± 12.79	22.01 ± 3.33	9.53 ± 2.77
Z +jets	74.49 ± 25.87	1.55 ± 0.62	0.63 ± 0.32	0.23 ± 0.13
Single- t	229.39 ± 34.06	53.09 ± 9.42	4.66 ± 1.11	6.22 ± 1.20
$t\bar{t}+V$	1.47 ± 0.43	1.30 ± 0.38	0.16 ± 0.07	0.13 ± 0.04
Dibosons	756.40 ± 138.13	6.11 ± 1.95	3.14 ± 2.36	0.06 ± 0.02
Mid-id. lepton	$42.49^{+124.67}_{-42.49}$	$3.20^{+5.34}_{-3.20}$	0.00 ± 3.64	$0.74^{+2.79}_{-0.74}$

Table 7.6: Number of observed events and the expected number of events obtained by the maximum likelihood fit with the background only configuration (see text for details), in W+jets control region (WR), $t\bar{t}$ control region (TR), validation regions (VR) and signal region (SR) for the small ΔM channel (high) for an integrated luminosity 20.1 fb^{-1} . The errors shown are the systematic uncertainty only.

Moderate ΔM channel (high)	WR	TR	VR	SR
Observed events	4089	1111	12	7
Fitted bkg events	4088.77 ± 64.00	1111.23 ± 33.36	15.11 ± 3.52	9.80 ± 1.61
$t\bar{t}$	533.22 ± 92.86	878.58 ± 52.00	10.46 ± 3.21	3.75 ± 0.78
W+jets	3132.25 ± 135.05	64.14 ± 18.07	2.91 ± 0.70	2.47 ± 0.85
Z+jets	20.42 ± 8.83	2.95 ± 1.27	0.02 ± 0.01	0.10 ± 0.06
Single- t	100.31 ± 24.84	137.59 ± 26.44	0.86 ± 0.38	2.94 ± 0.78
$t\bar{t}+V$	5.34 ± 1.66	8.26 ± 2.38	0.14 ± 0.08	0.27 ± 0.10
Dibosons	291.54 ± 47.91	8.74 ± 2.43	0.47 ± 0.24	0.08 ± 0.02
Mid-id. lepton	$5.69^{+32.90}_{-5.69}$	$10.98^{+15.43}_{-10.98}$	$0.26^{+1.21}_{-0.26}$	$0.18^{+0.64}_{-0.18}$

Figure 7.2: The am_{T2} distributions in signal regions for the moderate ΔM channel (low) (left) and (high) (right). A cut $am_{T2} > 170 \text{ GeV}$ for the moderate ΔM channel (low) and $> 200 \text{ GeV}$ for the moderate ΔM channel (high) is not applied. Normalization of the $t\bar{t}$ and W+jets samples are obtained by the maximum likelihood fit with the background only configuration. The ‘other’ background contains the single- t , Z+jets, Drell-Yan, dibosons, $t\bar{t}$ +vector boson and mid-identified lepton backgrounds. The benchmark signal $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (200, 120, 100) \text{ GeV}$ for the moderate ΔM channel (low) and $(600, 120, 100) \text{ GeV}$ for the moderate ΔM channel (high) is overlaid. Shaded band shows the systematic uncertainties, which contains MC statistics, JES, jet energy resolution, lepton scale, resolution, and efficiency, resolution and scale of soft E_T^{miss} term, $\Delta\epsilon_{\text{real(fake)}}^{\text{stat}}$, $\Delta\epsilon_{\text{real(fake)}}^{\text{syst}}$ and b -tagging.

Table 7.7: Breakdown of the dominant (top 20) systematic uncertainties on the background estimates in the moderate ΔM channel (low) signal region. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the total expected background.

Moderate ΔM channel (low)	SR
Total background expectation	32.10
Total statistical ($\sqrt{N_{\text{exp}}}$)	± 5.67
Total background systematic	± 5.08 [15.82%]
Mis-identified lepton background	± 2.79 [8.7%]
Wbb	± 2.27 [7.1%]
$\mu_{\bar{t}\bar{t}}$	± 1.78 [5.5%]
$t\bar{t}$ parton shower	± 1.70 [5.3%]
Trigger efficiency	± 1.56 [4.9%]
Jet energy resolution	± 1.51 [4.7%]
JES (η -intercalibration modeling)	± 1.30 [4.1%]
$t\bar{t}$ generator difference	± 1.18 [3.7%]
Lepton reconstruction efficiency	± 1.17 [3.6%]
b -tag efficiency on b quarks	± 1.14 [3.5%]
JES (effective nuisance parameter 1)	± 1.08 [3.4%]
JES (effective nuisance parameter 2)	± 0.93 [2.9%]
Resolution of the $E_{\text{T}}^{\text{miss}}$ soft term	± 0.71 [2.2%]
b -tag efficiency on c quark	± 0.69 [2.2%]
Single- t PDF uncertainty	± 0.66 [2.0%]
$\mu_{W+\text{jets}}$	± 0.57 [1.8%]
$W+\text{jets } N_{\text{parton}}$	± 0.57 [1.8%]
Jet area method (ρ uncertainty)	± 0.52 [1.6%]
$W+\text{jets}$ scale uncertainty	± 0.47 [1.5%]
JES (flavor composition)	± 0.41 [1.3%]

Table 7.8: Breakdown of the dominant (top 20) systematic uncertainties on the background estimates in the moderate ΔM channel (high) signal region. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the total expected background.

Moderate ΔM channel (high)	SR
Total background expectation	9.80
Total statistical ($\sqrt{N_{\text{exp}}}$)	± 3.13
Total background systematic	± 1.61 [16.42%]
MC statistical uncertainty	± 0.65 [6.7%]
Mis-identified lepton background	± 0.64 [6.5%]
Single- t theory (envelope)	± 0.61 [6.3%]
Wbb	± 0.59 [6.0%]
b -tag efficiency on b quarks	± 0.55 [5.6%]
Lepton reconstruction efficiency	± 0.51 [5.2%]
Trigger efficiency	± 0.48 [4.9%]
$t\bar{t}$ generator difference	± 0.45 [4.6%]
b -tag efficiency on c quarks	± 0.45 [4.6%]
$\mu_{t\bar{t}}$	± 0.41 [4.2%]
Jet energy resolution	± 0.29 [3.0%]
Single- t PDF uncertainty	± 0.28 [2.8%]
JES (effective nuisance parameter 1)	± 0.27 [2.8%]
$t\bar{t}$ parton shower	± 0.20 [2.1%]
W +jets N_{parton}	± 0.20 [2.0%]
$\mu_{W+\text{jets}}$	± 0.18 [1.8%]
b -tag efficiency on light-flavor quarks and gluons	± 0.17 [1.8%]
JES (effective nuisance parameter 2)	± 0.17 [1.7%]
Single- t Wt channel cross section	± 0.16 [1.6%]
$t\bar{t}$ theory (envelope)	± 0.13 [1.3%]

7.2 Model-independent upper limit

As shown in Sec. 7.1, no significant excesses are not observed in all four channels. In this section, the upper limit on the observed signals obtained with the model-independent fit configuration in each region is presented. As defined in Sec. 6.2, with the model-independent fit configuration, the signal strength μ is fixed to 1 in the SR and the expected signal contamination in CRs is fixed to 0. The number of signal yields in the signal region (s) is introduced as a free parameter in the fit instead. The likelihood (Eq. (6.3)) is rewritten as:

$$L(\mathbf{n}, \theta^0 | s, \mu_b, \theta) = P(n_{\text{SR}} | s + \lambda_{\text{SR}}(\mu_b, \theta)) \cdot P(n_{\text{TR}} | \lambda_{\text{TR}}(\mu_b, \theta)) \cdot P(n_{\text{WR}} | \lambda_{\text{WR}}(\mu_b, \theta)) \cdot F_{\text{nuis}}(\theta^0, \theta). \quad (7.1)$$

Definitions of the other variables and functions are the same as in Sec. 6.2.

7.2.1 Profile-likelihood method

The profile-log-likelihood ratio is defined to test a signal hypothesis s for the observation $\mathbf{n}, \theta^0$ as follows:

$$\Lambda(s) = -2 \ln \frac{L(\mathbf{n}, \theta^0 | s, \hat{\mu}_b, \hat{\theta})}{L(\mathbf{n}, \theta^0 | \hat{s}, \hat{\mu}_b, \hat{\theta})}, \quad (7.2)$$

where $\hat{s}, \hat{\mu}_b, \hat{\theta}$ are chosen to maximize the likelihood, and $\hat{\mu}_b, \hat{\theta}$ are optimized for each values of s in the fit. s is constrained to be a non-negative value i.e. if $\hat{s} < 0$ is observed, the log-likelihood Eq. (7.2) is:

$$\Lambda(s) = -2 \ln \frac{L(\mathbf{n}, \theta^0 | s, \hat{\mu}_b, \hat{\theta})}{L(\mathbf{n}, \theta^0 | 0, \hat{\mu}_b, \hat{\theta})}. \quad (7.3)$$

The minimum value of $\Lambda(s)$ is always 0 in case $s = \hat{s}$. A probability density function to observe $\Lambda(s)$ with a given hypothesis s , $f(\Lambda(s))$, is obtained by throwing multiple pseudo-experiments that randomize the number of observed events ($\mathbf{n}$) and the central values of the auxiliary measurements (θ^0). With enough large statistics, the $f(\Lambda(s))$ has a χ^2 distribution with one degree of freedom. In this analysis, a χ^2 approximation using the prescription defined in Ref. [197] is employed. It is confirmed that the results are consistent with the results using multiple pseudo-experiments (see Appendix E). The p -value describing the agreement between signal hypothesis s and the observed data is defined as:

$$p = \int_{\Lambda(s)_{\text{obs}}}^{\infty} f(\Lambda(s)) d\Lambda(s), \quad (7.4)$$

where $\Lambda(s)_{\text{obs}}$ is the observed $\Lambda(s)$ in the experimental data. Models with p -value smaller than 0.05 are said to be excluded with 95 % confidence level (CL). For the upper limit setting, if $\hat{s} > s$, $\Lambda(s)$ is constrained to 0 i.e. $p = 1$. Conventionally, we put the upper limit on p -value at 0.5.

For instance, let us consider the hypothesis that we observed $\hat{s} = 5.5$ at an experiment. if we want to test a signal hypothesis $s = 10$, we get the value $\Lambda(10)_{\text{obs}}$ like Fig. 7.3 (a). Then, the pseudo-experiments are performed several-thousand times with the mean value of randomized observed number of events in the signal region at $s + b$. s is settled to be 10 and b is the estimated number of the background in the fit to the experimental data. For each pseudo-experiment, we obtain the $\Lambda(10)$ value in the same way as the experiment, like the red line in Fig. 7.3 (c), and get the probability density function $f(\Lambda(10))$ like Fig. 7.3 (b). The shaded area shown in Fig. 7.3 (b) is the p -value for signal hypothesis $s = 10$. Expected sensitivity for the signal model of $s = 10$ is determined by running pseudo-experiments that randomize the observed number of events at the central value of b ($s = 0$). It is defined as the fraction of pseudo-experiments with $s = 10$ hypothesis of which $\Lambda(10)$ exceeds the median of $\Lambda(10)$ with $s = 0$ hypothesis, as illustrated in Figs. 7.3 (c) and (d).

Figure 7.3: Illustration of the profile-log-likelihood ratio ($\Lambda(s)$) (a) and the probability density function $f(\Lambda(s))$ (b), in the case that a signal hypothesis $s = 10$ is tested for observed number of signal at $\hat{s} = 5.5$. The definition of p -value is indicated by the shaded area in (b). The $f(\Lambda(10))$ shown in (b) is obtained by running thousands pseudo-experiments that randomize the observed events at the mean value of $s = 10$, as illustrated by the red line in (c). The $f(\Lambda(10))$ can also be obtained by analytical method assuming χ^2 distribution. Expected sensitivity is determined by the probability density function for the background only hypothesis, which is obtained by thousands pseudo-experiments that randomize the observed events at the mean value of $s = 0$, as illustrated by the blue line in (c). The area above the median $\Lambda(10)$ derived by the pseudo-experiments with $s = 0$ hypothesis is defined as the expected p -value, as shown in (d). The uncertainty on the expected p -value is evaluated by the standard deviation of the probability density function for $s = 0$ hypothesis as indicated by broken lines in (d). Input systematic uncertainties are irresponsible for all illustrations.

Table 7.9: Left to right: 95% CL upper limits on the visible cross section ($\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$), the number of signal events (s_{obs}^{95}) and the number of signal events given the expected number of background events and $\pm 1\sigma$ excursions on the expectation (s_{exp}^{95}). The last two columns show the CL_b value, i.e. the confidence level observed for the background-only hypothesis, and the discovery p -value ($p(s=0)$). The p -value in the last column has been constrained to be $p \leq 0.5$ in the case of asymptotic calculation.

Signal channel		$\langle\epsilon\sigma\rangle_{\text{obs}}^{95} [\text{fb}]$	s_{obs}^{95}	s_{exp}^{95}	CL_b	$p(s=0)$
Small ΔM channel	(high)	0.58	11.8	$7.9^{+3.6}_{-2.2}$	0.86	0.10
	(low)	0.71	14.4	$12.5^{+5.4}_{-3.5}$	0.65	0.34
Moderate ΔM channel	(low)	1.15	23.4	$17.6^{+6.8}_{-4.9}$	0.81	0.16
	(high)	0.30	6.0	$7.9^{+3.7}_{-2.3}$	0.23	0.5

7.2.2 Limits on the signal hypotheses

Table 7.9 shows the 95 % CL upper limits on the visible cross section ($\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$), the observed and expected number of signals in the signal region (s_{obs}^{95} and s_{exp}^{95}), CL_b and the discovery p -value derived with $s=0$ hypothesis. The visible cross section is defined as the products of acceptance, reconstruction efficiency and production cross section: $\langle\epsilon\sigma\rangle_{\text{obs}}^{95} = s_{\text{obs}}^{95} / \int \mathcal{L} dt$. CL_b is the confidence level observed for the background only hypothesis, which is defined in Sec. 7.3.1. Excesses of 4.5 and 8.9 events are observed in the small ΔM channel (high) and the moderate ΔM channel (low), respectively. The local p -value with $s=0$ assumption in these channels are 0.10 and 0.16, respectively.

7.3 Model-dependent limits

With the model-dependent fit configuration, the signal strength μ is treated as a free parameter in the fit. The likelihood used in the fit is defined in Eq. (6.3). The same approach with Sec. 7.2 (the profile-likelihood method) using the signal strength μ instead of s can be made but the method has a possibility to over-estimate the sensitivity. In order to avoid this, the CLs method [198] is employed conservatively to set the limit on each signal point.

7.3.1 CLs method

The log-likelihood ratio between signal plus background hypothesis (L_{s+b}) with a given signal strength μ and background only hypothesis (L_b) with $\mu=0$ is defined as:

$$q(\mu) = -2 \ln \frac{L_{s+b}}{L_b} = -2 \ln \frac{L(\mathbf{n}, \boldsymbol{\theta}^0 | \mu, \hat{\mu}_b, \hat{\boldsymbol{\theta}})}{L(\mathbf{n}, \boldsymbol{\theta}^0 | 0, \hat{\mu}_b, \hat{\boldsymbol{\theta}})}. \quad (7.5)$$

As with Sec. 7.2, the fit parameters to maximize the likelihood are denoted as $(\hat{\mu}, \hat{\mu}_b, \hat{\boldsymbol{\theta}})$ and $(\hat{\mu}_b, \hat{\boldsymbol{\theta}})$ are optimized in the fit to maximize the likelihood for each value of μ . An example of the observed q distribution as a function of μ and the observed q value for the signal hypothesis $\mu=1$, $q(1)_{\text{obs}}$, are illustrated in Fig. 7.4 (a) when the observed signal strength is $\hat{\mu}=0.3$.

The probability density functions for the signal plus background hypothesis (f_{s+b}) and for the background only hypothesis (f_b) are obtained by running several pseudo-experiments with $\mu=1$ and $\mu=0$, respectively. In contrast to Eq. (7.2), the minimum value of $q(\mu) = q(\hat{\mu})$ is not fixed to 0. Figure 7.4

Table 7.10: The observed and expected ($\pm 1\sigma$) 95% CL upper limits on signal strength μ (μ^{95}) for the benchmark points of each sub-channel.

Signal channel		benchmark (GeV) ($m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}$)	Obs. μ^{95}	Exp. μ^{95}
Small ΔM channel	(high)	(225, 215, 195)	1.81	$1.16^{+0.75}_{-0.41}$
	(low)	(225, 170, 150)	1.20	$1.00^{+0.52}_{-0.50}$
Moderate ΔM channel	(low)	(200, 120, 100)	1.47	$1.23^{+0.69}_{-0.39}$
	(high)	(600, 120, 100)	0.88	$1.30^{+0.85}_{-0.46}$

(b) shows examples of $q(1)$ value extracted from pseudo-experiments with the signal plus background hypothesis and the background only hypothesis. The figure shows the signal plus background hypothesis tends to show the negative value of $q(1)$, while the background only hypothesis the positive value. CL_{s+b} and CL_b are defined as:

$$CL_{s+b} = \int_{q(1)_{\text{obs}}}^{\infty} f_{s+b} dq(1) \quad (7.6)$$

$$CL_b = \int_{-\infty}^{q(1)_{\text{obs}}} f_b dq(1) \quad (7.7)$$

as shown in Fig. 7.4 (c) and CL_s is defined as:

$$CL_s = \frac{CL_{s+b}}{CL_b}. \quad (7.8)$$

If $CL_s < 0.05$, the signal hypothesis is said to be excluded at 95 % CL. Expected CL_s value is obtained by the median of the f_b distribution and errors are estimated by the standard deviation of the f_b distribution. Strictly speaking, the CL_s value does not represent the probability. However, by constraint from the background only hypothesis it can prevent from overestimating the upper limit. According to Ref. [197], f_{s+b} and f_b can be approximated using the Gaussian distribution. In this thesis, we use this approximation after it is confirmed that the results are consistent with those using pseudo-experiments.

7.3.2 Limits on stop pair production models

Figure 7.5 shows the observed CL_s , CL_{s+b} and CL_b values as a function of the tested signal strength μ for each benchmark point for the sub-channel. The observed and expected 95 % CL upper limits on the signal strength (μ^{95}) obtained as μ -value at $CL_s = 0.05$ for each signal point are summarized in Table 7.10.

If the μ -value for the test is fixed to 1, the 95 % CL exclusion regions for the masses of SUSY particles are obtained for various models of stop pair production. From here, all four channels are combined by choosing the one providing the best expected CLs value at each signal point. The channel chosen at each point is summarized in Appendix F.

Figure 7.6 shows the exclusion limits in the $m_{\tilde{t}_1}$ - $m_{\tilde{\chi}_1^0}$ plane for a signal model: $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow b(W^* \rightarrow ff')\tilde{\chi}_1^0$ with mass splitting between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ (Δm) of 20 GeV and 5 GeV, respectively. In the case of $\Delta m = 20$ GeV, stop masses in the range of approximately 200 to 600 GeV are excluded by the moderate ΔM channel for a variety of $\tilde{\chi}_1^0$ mass. The small ΔM channel improves the sensitivity in the highly compressed mass region close to the diagonal i.e. small mass difference between $\tilde{t}_1$ and $\tilde{\chi}_1^0$ (ΔM)

Figure 7.4: (a) The observed log-likelihood ratio as a function of μ in the experimental data in the case of $\hat{\mu} = 0.3$. (b) The log-likelihood ratio as a function of μ in pseudo-experiments with the signal plus background hypothesis (red) and the background only hypothesis (blue). Probability density functions for the signal plus background hypothesis and the background only hypothesis are obtained by running several pseudo-experiments. (c) The probability density functions in pseudo-experiments for the signal plus background hypothesis (f_{s+b}) and the background only hypothesis (f_b), and definitions of CL_{s+b} and $(1 - CL_b)$.

Figure 7.5: Observed CL_s (red), CL_{s+b} (blue) and CL_b (black) as a function of the signal strength μ for the benchmark signal points of each sub-channel: (a) the small ΔM channel (high), (b) the small ΔM channel (low), (c) the moderate ΔM channel (low) and (d) the moderate ΔM channel (high). The benchmark point for each sub-channel is $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (225, 215, 195)$ GeV for (a), $(225, 170, 150)$ GeV for (b), $(200, 120, 100)$ GeV for (c) and $(600, 120, 100)$ GeV for (d). The expected CL_s value $\pm 1\sigma$ (green) and 2σ (yellow) bands are overlaid. The upper values of CL_{s+b} and CL_b are set to be 0.5 in the asymptotic calculation.

in addition to the small Δm . The region in $\Delta M < 70$ GeV is excluded for $m_{\tilde{t}_1} < 210$ GeV. Exclusion limits are set on this region for the first time. It is confirmed that statistical combination of two channels cannot gain the sensitivity in the gap region between two channels ($70 < \Delta M < 125$ GeV). This is due to the fact that two channels are based on completely different strategies: one requires very high- p_T ISR jet and the other requires two high- p_T b -jets from the stop decays and absence of the ISR jet. In particular, the moderate ΔM channel suddenly loses the sensitivity at $\Delta M \approx 125$ GeV, since the signal has quite similar topology to the $t\bar{t}$ background and discrimination power using am_{T2} distribution is weakened (see Fig. 5.8). For the signal models with $\Delta m = 5$ GeV, stop masses in the range of approximately 230 to 600 GeV are excluded by the moderate ΔM channel for a variety of $\tilde{\chi}_1^0$ masses. The small Δm of 5 GeV weaken the sensitivity at the diagonal region with the small ΔM channel, due to the lower lepton p_T acceptance.

Figure 7.7 shows the exclusion limits in the $m_{\tilde{t}_1}$ - $m_{\tilde{\chi}_1^0}$ plane for a signal model: $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow b(W^{(*)} \rightarrow ff')\tilde{\chi}_1^0$ with the fixed $m_{\tilde{\chi}_1^\pm}$ at 150 GeV and 106 GeV, respectively. For signals with $m_{\tilde{\chi}_1^\pm} =$

150 GeV, stop masses in the range of 260 to 610 GeV are excluded by the moderate ΔM channel for a variety of $\tilde{\chi}_1^0$ masses. The small ΔM channel improves the sensitivity in the low stop mass region at $m_{\tilde{t}_1} < 200$ GeV. For the case of $m_{\tilde{\chi}_1^\pm} = 106$ GeV, stop masses in the range of 210 - 610 GeV are excluded by the moderate ΔM channel for a variety of $\tilde{\chi}_1^0$ masses. The small ΔM channel has a sensitivity at the low stop mass region, but any signal point in this grid is not excluded by the observed data.

Figure 7.8 shows the exclusion limit in the $m_{\tilde{\chi}_1^\pm}$ - $m_{\tilde{\chi}_1^0}$ plane for a signal model: $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow b(W^{(*)} \rightarrow ff')\tilde{\chi}_1^0$ with the fixed $m_{\tilde{t}_1} = 300$ GeV. The region of $m_{\tilde{\chi}_1^\pm} < 180$ GeV is excluded by the moderate ΔM channel. The region around the signal point $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (300, 250, 200)$ is excluded by the small ΔM channel. Figure 7.6 shows that the small ΔM channel does not have the sensitivity at $m_{\tilde{t}_1} = 300$ GeV in $\Delta m = 20$ GeV grid due to the small cross section but it is improved by the shape fit on lepton p_T distribution at $\Delta m = 50$ GeV and enough high LSP mass of 200 GeV leading to high E_T^{miss} .

Finally, Fig. 7.9 is the exclusion limit for a four-body decay model of stop: $\tilde{t}_1 \rightarrow b(W^* \rightarrow ff')\tilde{\chi}_1^0$ in the plane of $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$. Due to the high compression of mass spectrum in this phase space, only the small ΔM channel has a sensitivity. Stop masses up to 250 GeV are excluded with mass differences between the stop and LSP down to 30 GeV. Exclusion limits on this phase space is set for the first time. The sensitivity is weakened in the region of $m_{\tilde{\chi}_1^0} < 60$ GeV due to the small E_T^{miss} of the signals.

7.3.3 Comparison with other ATLAS stop analyses

The results requiring a soft lepton presented in this thesis are compared with the results of other ATLAS stop searches.

Figures 7.10 (a)-(c) shows the 95 % CL exclusion regions on $m_{\tilde{t}_1}$ - $m_{\tilde{\chi}_1^0}$ plane for $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow b(W^* \rightarrow ff')\tilde{\chi}_1^0$ signals with fixed $\Delta m = 20$ GeV (a), $\Delta m = 5$ GeV (b) and fixed $m_{\tilde{\chi}_1^\pm} = 150$ (c). Figure 7.10 (d) shows the limit on the fixed $m_{\tilde{t}_1} = 300$ GeV grid.

Soft-lepton analysis improves the exclusion limits on $\Delta m = 20$ GeV grid by approximately 120 GeV for the higher stop mass direction with respect to the ATLAS analysis requiring the absence of leptons (0L) [95], while the 0L analysis excludes wide range of parameter space on the $\Delta m = 5$ GeV grid. The 0L analysis and the soft-lepton analysis (the moderate ΔM channel) compensate each other at the small Δm region. It is clearly seen on the $m_{\tilde{\chi}_1^\pm} = 150$ GeV grid (Fig. 7.10 (c)); we can see that the 0L analysis has a better sensitivity at the region in which the soft-lepton analysis does not have a sensitivity around $160 < m_{\tilde{t}_1} < 580$ GeV at $\Delta m < 10$ GeV. The region with larger Δm (> 50 GeV) is excluded by the previous ATLAS analysis requiring hard one lepton (1L) [71]. Soft-lepton analysis (the small ΔM channel) gains the sensitivity at low $m_{\tilde{t}_1}$ region of less than 200 GeV. The same things can be confirmed in the fixed $m_{\tilde{t}_1} = 300$ GeV grid (Fig. 7.10 (d)). The 0L analysis has the best sensitivity at the diagonal region ($m_{\tilde{\chi}_1^\pm}$ is close to $m_{\tilde{\chi}_1^0}$), while large Δm regions are excluded by the 1L analysis. Soft-lepton analysis excludes the transition region between two analyses. In particular, a region excluded by the small ΔM channel at $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (300, 250, 200)$ GeV is not covered by other two analyses.

Figure 7.11 shows the combined 95 % CL exclusion limits on the stop decays $\tilde{t}_1 \rightarrow bff'\tilde{\chi}_1^0$ (four-body decay), $\tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ (three-body decay), $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ and $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ (two-body decay) on $m_{\tilde{t}_1}$ - $m_{\tilde{\chi}_1^0}$ plane. The two- and three-body decay signals are excluded by 0-2L analyses up-to $m_{\tilde{t}_1} = 650$ GeV [71, 95, 96]. Soft-lepton analysis (the small Δm channel) excludes the four-body decay signals (shown by dark gray) as shown in Fig. 7.9. Again, soft-lepton analysis and the mono-jet analysis (light-gray) play complementary roles in this phase space. Highly compressed signals on the four-body decay grid are excluded by the mono-jet analysis [95], where the sensitivity of the soft-lepton analysis is weakened. By taking a combination, wide range of the stop signals with $m_{\tilde{t}_1} < 600$ GeV are excluded.

Figure 7.6: Expected (blue dashed with yellow band showing the the uncertainty) and observed (red solid with dashed showing the uncertainty) 95 % CL excluded region in the plane of $m_{\tilde{\chi}_1^0}$ v.s. $m_{\tilde{t}_1}$, assuming the branching fraction of $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow bff'\tilde{\chi}_1^0$ is 100 % with fixed $\Delta m = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} = 20\text{ GeV}$ (top) and 5 GeV (bottom).

Figure 7.7: Expected (blue dashed with yellow band showing the the uncertainty) and observed (red solid with dashed showing the uncertainty) 95 % CL excluded region in the plane of $m_{\tilde{\chi}_1^0}$ v.s. $m_{\tilde{t}_1}$, assuming the branching fraction of $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow bff'\tilde{\chi}_1^0$ is 100 % with fixed $m_{\tilde{\chi}_1^\pm} = 150\text{ GeV}$ (top) and 106 GeV (bottom).

Figure 7.8: Expected (blue dashed with yellow band showing the the uncertainty) and observed (red solid with dashed showing the uncertainty) 95 % CL excluded region in the plane of $m_{\tilde{\chi}_1^0}$ v.s. $m_{\tilde{\chi}_1^\pm}$, assuming the branching fraction of $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow bff'\tilde{\chi}_1^0$ is 100 % with fixed $m_{\tilde{t}_1} = 300$ GeV.

Figure 7.9: Expected (blue dashed with yellow band showing the the uncertainty) and observed (red solid with dashed showing the uncertainty) 95 % CL excluded region in the plane of $m_{\tilde{\chi}_1^0}$ v.s. $m_{\tilde{t}_1}$, assuming the branching fraction of $\tilde{t}_1 \rightarrow bff'\tilde{\chi}_1^0$ is 100 % (four-body decay).

Figure 7.10: 95 % CL exclusion regions in comparison with 0L analysis [95] (green) and 1L analysis [71] (violet) on $\Delta m = 20\text{ GeV}$ (a) 5 GeV (b) $m_{\tilde{\chi}_1^+} = 150\text{ GeV}$ (c) and $m_{\tilde{t}_1} = 300\text{ GeV}$ (d) grids. 0L analysis excludes the region inside the green lines. In (c) and (d), 1L analysis excludes the region below the violet lines.

Figure 7.11: Summary of the dedicated ATLAS searches for top squark (stop) pair production based on 20 fb^{-1} of pp collision data taken at $\sqrt{s} = 8 \text{ TeV}$, and 4.7 fb^{-1} of pp collision data taken at $\sqrt{s} = 7 \text{ TeV}$ [87]. Exclusion limits at 95 % CL are shown in the $m_{\tilde{t}_1}$ - $m_{\tilde{\chi}_1^0}$ plane. The dashed and solid lines show the expected and observed limits, respectively, including all uncertainties except the theoretical signal cross section uncertainty (PDF and scale). Three decay modes are considered separately with 100 % branching ratio: $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$, $\tilde{t}_1 \rightarrow b W \tilde{\chi}_1^0$ (3- body decay for $m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}_1^0}$ and $\tilde{t}_1 \rightarrow b f f' \tilde{\chi}_1^0$ (four-body decay). Dark gray region is excluded by the soft-lepton analysis shown in this thesis.

Chapter 8

Conclusions

Supersymmetry (SUSY), one of the strong candidates of new physics beyond the Standard Model, introduces new symmetry between bosons and fermions, which predicts new particles having different spin by 1/2 from the Standard Model particles. For the natural solution of the hierarchy problem, masses of scalar top quark (stop) and higgsino are expected to be light. On the other hand, heavy stop of greater than $O(1)$ TeV is favored in order to boost the Higgs boson mass to 125 GeV in the context of the minimum supersymmetric extension of the Standard Model. Furthermore, some indirect measurements of the stop mass also favors the heavy stop. Now we stand at the cross road of the development of the SUSY model. Light stop with $m_{\tilde{t}_1} < 600$ GeV is not completely excluded by these results, depending on the other SUSY parameters. The most of the stop signals with $m_{\tilde{t}_1} < 600$ GeV have been excluded by the previous direct measurements at the Large Hadron Collider (LHC), but there remain some phase spaces with the light stop not explored due to the difficulty of the analysis. This thesis has presented the result of a search for stop pair production in pp collisions at $\sqrt{s} = 8$ TeV at the LHC, in the natural SUSY scenario assuming light stop and higgsino-like lightest supersymmetric particle (LSP). A 100 % decay branching ratio of stop into b -quark and chargino is assumed. If the LSP has a higgsino component, the mass difference between chargino and the LSP (Δm) is expected to be small. In such a case, chargino decays in three-body into low-momentum (soft) fermion pair and the LSP.

The ATLAS detector is a multi-purpose apparatus at the LHC, which reconstructs and identifies particles produced in pp collisions by a combination of several particle detection techniques. Since the detector acceptance to the soft fermions are low, signals with small Δm have not been explored actively with the previous analyses. In this analysis, existence of one soft lepton in the event is required as a probe of the signal, to suppress the QCD multi-jet and ($Z \rightarrow \nu\nu$)+jets background. Characteristics of the target signals are thus one soft lepton, high missing transverse energy E_T^{miss} coming from non-detected LSP and two b -quark-induced jets (b -jets). Event selections are optimized to have a sensitivity with respect to the SUSY signals against the Standard Model backgrounds in a wide range of the SUSY masses. In the region with small mass difference between the stop and the LSP (ΔM) in addition to small Δm , all final-state activities are expected to be soft, which makes the acceptance to the signals much smaller. Two analysis channels, each having two signal regions, are defined. (1) The small ΔM channel requires high- p_T initial state radiation jet in the event to detect the stop pair system produced in the boosted frame to the opposite direction to that. It improves the acceptance to the signals with small ΔM . (2) The other channel, the moderate ΔM channel, requires two high- p_T b -jets. It provides the better sensitivity in higher stop mass region than the previous ATLAS analysis requiring the absence of leptons.

The Standard Model backgrounds are estimated by the maximum likelihood fit. The normalization factors of the MC simulations for the main sources of the background, $t\bar{t}$ and W +jets, are extracted in the dedicated control regions and extrapolated to the signal regions. Likelihood used in this analysis is designed to cancel some common systematic uncertainties between a signal region and control regions.

The mis-identified lepton backgrounds are estimated in a data-driven way. The other backgrounds are estimated by the MC. It is confirmed that the estimated Standard Model background represents the observed data in all control regions. Validations for the distributions used in the extrapolation are made in dedicated validation regions. In all validation regions, data agree well with the prediction.

No significant signal against the Standard Model prediction has been observed in all signal regions. The results are interpreted as limits on the SUSY masses. In the signal hypothesis with $\Delta m = 20$ GeV, the moderate ΔM channel has excluded stop masses in the range of 200 to 600 GeV for LSP masses less than 280 GeV. The limits on stop masses settled by the previous ATLAS analyses are updated by approximately 120 GeV in the higher $m_{\tilde{t}_1}$ direction. The small ΔM channel has excluded the region with $\Delta M < 70$ GeV in the range of stop mass less than 210 GeV with $\Delta m = 20$ GeV. Exclusion limits are set on this region for the first time. Interpretation assuming stop four-body decay $\tilde{t}_1 \rightarrow bff'\tilde{\chi}_1^0$ is performed in addition and the first exclusion limits are set in the region with $m_{\tilde{t}_1} < 250$ GeV. By taking a combination with other ATLAS stop searches, a wide range of the stop signals has been excluded below 600 GeV of stop mass.

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Appendix A

Impact of $t\bar{t}$ re-weighting

There are known discrepancy between data and $t\bar{t}$ MC samples at the high p_T region of the $t\bar{t}$ system ($p_T(t\bar{t})$) [131, 132]. Figure A.1 shows the differential cross section of $t\bar{t}$ as a function of $p_T(t\bar{t})$ measured with the ATLAS data at $\sqrt{s} = 7$ TeV in 2011 [132]. The data is compared with several MC generators. As mentioned in Sec. 3.2.2, to improve the agreement, the $t\bar{t}$ MC is corrected by re-weighting factors as a function of $p_T(t\bar{t})$, which is calculated by the vector-sum of the generated-level momenta of two top quarks. The weights are derived using 2012 data following the method described in Ref. [131] as shown in Fig. A.2. The same binning with Ref. [131, 132] is chosen. In order to reproduce the data, large correction up-to 45 % is applied to events with $p_T^{t\bar{t}} > 340$ GeV.

Impact of this operation to the final result is checked by performing the fit without the weights on $t\bar{t}$. Table A.1 shows the observed number of events in each signal region compared with the expected number of events with and without $t\bar{t}$ re-weighting in the background only fit. The expected numbers of $t\bar{t}$ and normalization factors derived by the fit ($\mu_{t\bar{t}}$ and $\mu_{W+\text{jets}}$) are also shown in the table. In all signal regions, expected numbers of events with and without $t\bar{t}$ re-weighting agree within the uncertainties, since control regions for $t\bar{t}$ are defined to be robust against the $t\bar{t}$ re-weighting. In the small ΔM channel, extrapolation from the control region to the signal region is used along the E_T^{miss} distribution, which is correlated to $p_T(t\bar{t})$. However, by using the control regions defined by enough high $E_T^{\text{miss}} (> 250 \text{ GeV})$ close to the signal region, $t\bar{t}$ re-weighting does not affect the extrapolation. Control regions for the moderate ΔM channel are defined as lepton $p_T > 25$ GeV, which is a variable independent of $p_T(t\bar{t})$.

It is found that the best fit $\mu_{t\bar{t}}$ becomes to be closer to 1 by the re-weighting, in particular in the small ΔM channel which looks at the high- $p_T(t\bar{t})$ region due to the requirement of high- p_T ISR jet. The moderate ΔM channel favors the phase space of which top quarks are generated in back-to-back, so $p_T(t\bar{t})$ is likely to be low and the impact of the re-weighting on $\mu_{t\bar{t}}$ is limited. Figure A.3 shows the leading jet p_T and E_T^{miss} distributions in $t\bar{t}$ control regions for the small ΔM channel and moderate ΔM channel, respectively. The data is compared with the MC with and without $t\bar{t}$ re-weighting. The normalization factors $\mu_{t\bar{t}}$ and $\mu_{W+\text{jets}}$ derived by the fit with each configuration (shown in Table A.1) are applied. No significant differences are found between with and without $t\bar{t}$ re-weighting in all our control regions.

Table A.2 shows the obtained 95 % CL upper limits on visible cross section, observed and expected number of signals in the signal regions, CL_b and discovery p -values with $t\bar{t}$ re-weighting (nominal result), compared with those without $t\bar{t}$ re-weighting. Consistent results are obtained with and without $t\bar{t}$ re-weighting in all sub-channels.

Figure A.1: Differential cross section of $t\bar{t}$ as a function of $t\bar{t}$ -system p_T ($p_T^{t\bar{t}}$) measured with ATLAS using 7 TeV data collected in 2011 [132]. Predictions by four different MC generators are overlaid. Bottom panel shows the ratio of MC prediction to the observed data in each bin.

Figure A.2: Weights applied to $t\bar{t}$ sample in this thesis. Weights are derived with 8 TeV data in 2012, following the criteria in Ref. [131].

Figure A.3: The leading jet p_T distributions in $t\bar{t}$ control regions for the small ΔM channel (high) (a) and (low) (b), and the E_T^{miss} distributions in $t\bar{t}$ control regions for the moderate ΔM channel (low) (c) and (high) (d). Colored histograms show the nominal estimation of the SM background by the maximum likelihood fit with background only configuration. Magenta lines show the total SM background prediction also estimated by the fit, but not applying $t\bar{t}$ re-weighting.

Table A.1: Number of observed events (N_{obs}) compared with expected number of events ($N_{\text{exp}}^{\text{total}}$) estimated by the background only fit with nominal configuration and the configuration without $t\bar{t}$ re-weighting and number of expected $t\bar{t}$ component ($N_{\text{exp}}^{t\bar{t}}$). The normalization factors for $t\bar{t}$ and W +jets derived by the fit ($\mu_{t\bar{t}}$ and $\mu_{W+\text{jets}}$) are also shown.

	Small ΔM channel		Moderate ΔM channel	
	(high)	(low)	(low)	(high)
N_{obs}	11	20	41	7
$N_{\text{exp}}^{\text{total}}$ (nominal)	6.54 ± 1.52	17.47 ± 4.28	32.10 ± 5.08	9.80 ± 1.61
$(N_{\text{exp}}^{t\bar{t}})$	2.76 ± 0.89	10.49 ± 3.15	15.20 ± 3.97	3.75 ± 0.78
$\mu_{t\bar{t}}$	0.76 ± 0.15	0.87 ± 0.16	0.95 ± 0.11	1.00 ± 0.11
$\mu_{W+\text{jets}}$	0.85 ± 0.07	0.65 ± 0.11	0.94 ± 0.06	0.78 ± 0.06
$N_{\text{exp}}^{\text{total}}$ (w/o $t\bar{t}$ re-weighting)	7.02 ± 1.58	19.10 ± 4.58	32.17 ± 5.13	10.10 ± 1.65
$(N_{\text{exp}}^{t\bar{t}})$	3.24 ± 1.02	12.11 ± 3.57	15.29 ± 4.04	4.12 ± 0.87
$\mu_{t\bar{t}}$	0.57 ± 0.12	0.64 ± 0.12	0.93 ± 0.11	0.95 ± 0.10
$\mu_{W+\text{jets}}$	0.85 ± 0.07	0.65 ± 0.11	0.94 ± 0.06	0.76 ± 0.06

Table A.2: Comparison of model-independent upper limits between nominal configuration and the configuration without $t\bar{t}$ re-weighting.

Signal channel		$\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$ [fb]	s_{obs}^{95}	s_{exp}^{95}	CL_b	$p(s=0)$	
Small ΔM channel	(high)	(nominal)	0.58	11.8	$7.9^{+3.6}_{-2.2}$	0.86	0.10
		(w/o $t\bar{t}$ re-weighting)	0.56	11.4	$8.0^{+3.7}_{-2.3}$	0.83	0.13
	(low)	(nominal)	0.71	14.4	$12.5^{+5.4}_{-3.5}$	0.65	0.34
		(w/o $t\bar{t}$ re-weighting)	0.67	13.7	$12.9^{+5.4}_{-3.6}$	0.55	0.44
Moderate ΔM channel	(low)	(nominal)	1.15	23.4	$17.6^{+6.8}_{-4.9}$	0.81	0.16
		(w/o $t\bar{t}$ re-weighting)	1.15	23.1	$17.7^{+6.8}_{-4.9}$	0.81	0.16
	(high)	(nominal)	0.30	6.0	$7.9^{+3.7}_{-2.3}$	0.23	0.5
		(w/o $t\bar{t}$ re-weighting)	0.29	6.0	$8.0^{+3.8}_{-2.3}$	0.21	0.5

Appendix B

Cut-flow chart

Cut-flow charts for the Standard Model backgrounds and the benchmark signals for each sub-channel are summarized in Tables B.1-B.4. The normalization factors for $t\bar{t}$ and W +jets backgrounds derived by the fit (see Sec. 6.1) are not applied to these numbers.

In Tables B.1 and B.2, it is confirmed that the cut on m_T reduces large amount of backgrounds, in particular W +jets component. Requirement of b -jets and the cut on $E_T^{\text{miss}}/m_{\text{eff}}$ improve the signal-to-background ratio. Finally, the upper cut on lepton p_T at 25 GeV for the model-independent analysis enhances the signals with $\Delta m = 20$ GeV.

In Tables B.3 and B.4, we can find the two b -jets requirement improves the signal-to-background ratio. The cut on $H_{T,2}$ and m_{bb} are useful to reduce $t\bar{t}$ background, while keeping the signals with lower stop mass. Since the am_{T2} for the signal point (200,120,100) GeV distributes typically at < 200 GeV as shown in Fig. 5.8, no sensitivity is expected after the cut on $am_{T2} > 170$ GeV in Table B.3. This signal point is searched by using the shape fit on am_{T2} distribution. For the signals with stop mass greater than 200 GeV, such as the last column of Table B.3, a cut on am_{T2} works to discriminate signals from the background.

Table B.1: Cutflow chart for the small ΔM channel (high). ‘Others’ includes $t\bar{t} + V$, Drell-Yan, Z+jets, and Di-bosons. Errors are only MC statistical uncertainties. Those for signal benchmark points of $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0})=(225,215,195)$ GeV is also shown.

cut	background					signal (225, 215, 195) GeV
	$t\bar{t}$	W+jets	Single t	Fake	Others	Total
Trig+lepton	2.10×10^5	2.66×10^6	4.88×10^4	2.50×10^5	1.55×10^5	3.32×10^6
$E_{\text{T}}^{\text{miss}} > 370$ GeV	222 ± 3	2.58×10^3	64.2 ± 2.2	27.9 ± 6.6	221 ± 16	3.12×10^3
$m_{\text{T}} > 90$ GeV	25.6 ± 1.0	83.3 ± 2.8	6.65 ± 0.60	12.3 ± 2.5	27.2 ± 1.5	155 ± 4
$p_{\text{T}}^{\text{jet1}} > 180$ GeV	25.3 ± 1.0	82.0 ± 2.8	6.55 ± 0.60	12.1 ± 2.5	26.5 ± 1.5	152 ± 4
$N_{\text{jets}} \geq 2$	25.2 ± 1.0	64.2 ± 2.4	6.41 ± 0.59	10.0 ± 2.3	21.8 ± 1.3	106 ± 4
$N_{b\text{-jets}} \geq 1$	20.4 ± 0.9	6.51 ± 0.67	4.56 ± 0.46	2.21 ± 1.16	3.63 ± 0.59	37.3 ± 1.8
jet1 is not b	17.5 ± 0.8	4.32 ± 0.52	3.18 ± 0.42	1.46 ± 0.96	3.02 ± 0.58	29.5 ± 1.5
$E_{\text{T}}^{\text{miss}}/m_{\text{eff}} > 0.35$	7.73 ± 0.57	3.35 ± 0.46	1.88 ± 0.31	0.85 ± 0.84	2.36 ± 0.53	16.2 ± 1.3
$p_{\text{T}}^{\text{lep1}} < 25$ GeV	3.63 ± 0.39	1.25 ± 0.26	0.86 ± 0.23	0.55 ± 0.62	1.29 ± 0.47	7.58 ± 0.94
						7.54 ± 1.0

Table B.2: Cutflow chart for the small ΔM channel (low). ‘Others’ includes $t\bar{t} + V$, Drell-Yan, Z+jets, and Di-bosons. Errors are only MC statistical uncertainties. Those for signal benchmark points of $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0})=(225,170,150)$ GeV is also shown.

cut	background					signal (225, 170, 150) GeV
	$t\bar{t}$	W+jets	Single t	Fake	Others	Total
Trig+lepton	2.10×10^5	2.66×10^6	4.88×10^4	2.50×10^5	1.55×10^5	3.32×10^6
$E_{\text{T}}^{\text{miss}} > 300$ GeV	849 ± 7	7.99×10^3	193 ± 4	82.6 ± 12.1	616 ± 25	9.73×10^3
$m_{\text{T}} > 100$ GeV	71.2 ± 1.7	171 ± 6	12.3 ± 0.8	24.1 ± 3.5	54.0 ± 3.0	333 ± 8
$p_{\text{T}}^{\text{jet1}} > 180$ GeV	66.4 ± 1.7	161 ± 6	11.8 ± 0.8	20.6 ± 3.3	50.2 ± 2.9	310 ± 8
$N_{\text{jets}} \geq 3$	60.2 ± 1.6	67.1 ± 4.8	9.63 ± 0.72	15.0 ± 2.6	25.6 ± 2.6	178 ± 6
$N_{b\text{-jets}} \geq 1$	49.7 ± 1.4	9.20 ± 0.91	7.37 ± 0.58	6.91 ± 1.80	5.01 ± 0.59	78.2 ± 2.6
jet1 is not b	43.3 ± 1.3	6.09 ± 0.68	4.76 ± 0.51	4.54 ± 1.48	3.79 ± 0.51	62.5 ± 2.2
$E_{\text{T}}^{\text{miss}}/m_{\text{eff}} > 0.3$	28.4 ± 1.1	5.08 ± 0.63	3.72 ± 0.47	3.40 ± 1.31	3.12 ± 0.51	43.7 ± 2.0
$p_{\text{T}}^{\text{lep1}} < 25$ GeV	11.9 ± 0.7	1.83 ± 0.34	1.75 ± 0.37	2.48 ± 1.01	1.56 ± 0.44	19.8 ± 1.4
						13.7 ± 1.2

Table B.3: Cutflow chart for the moderate ΔM channel (low). ‘Others’ includes $t\bar{t} + V$, Drell-Yan, Z+jets, and Di-bosons. Errors are only MC statistical uncertainties. Those for signal benchmark point of $(m_{T1}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0})=(200,120,100)$ GeV an $(300,120,100)$ GeV are also shown.

cut	background					signal	
	$t\bar{t}$	W+jets	Single t	Fake	Others	Total	(200, 120, 100) GeV (300, 120, 100) GeV
Trig+lepton	9.88×10^4	1.28×10^6	2.53×10^4	1.92×10^5	7.72×10^4	1.67×10^6	1.7×10^4 4.13×10^3
$E_T^{\text{miss}} > 150$ GeV	1.85×10^4	1.45×10^5	3.60×10^3	636 ± 64	7.94×10^3	1.76×10^5	3.8×10^3 2.11×10^3
$p_T^{2\text{nd jet}} > 60$ GeV	1.32×10^4	3.73×10^4	1.83×10^3	779 ± 39	3.16×10^3	5.63×10^4	2.4×10^3 1.67×10^3
3rd jet veto	4.75×10^3	2.72×10^4	1.02×10^3	294 ± 30	2.00×10^3	3.53×10^4	1.02×10^3 830 ± 20
$N_{b\text{-jets}} = 2$	237 ± 4	41.4 ± 1.8	40.3 ± 1.5	8.65 ± 3.93	5.91 ± 0.90	333 ± 6	54.4 ± 13.3 263 ± 11
$H_{T,2} < 50$ GeV	150 ± 3	38.1 ± 1.8	32.3 ± 1.4	7.97 ± 3.47	4.96 ± 0.87	233 ± 5	42.4 ± 11.3 211 ± 10
$\Delta\phi > 0.4$	137 ± 3	36.9 ± 1.7	28.0 ± 1.3	4.29 ± 2.99	4.81 ± 0.86	211 ± 5	39.6 ± 11.0 209 ± 10
$m_{bb} > 150$ GeV	89.8 ± 2.2	13.6 ± 1.0	23.3 ± 1.2	4.37 ± 2.67	0.88 ± 0.28	132 ± 4	39.6 ± 11.0 136 ± 8
$am_{T2} > 170$ GeV	15.8 ± 0.9	10.1 ± 0.81	6.22 ± 0.62	0.74 ± 1.49	0.41 ± 0.13	33.3 ± 2.0	4.79 ± 2.04 114 ± 7

Table B.4: Cutflow chart for the moderate ΔM channel (high). ‘Others’ includes $t\bar{t} + V$, Drell-Yan, Z+jets, and Di-bosons. Errors are only MC statistical uncertainties. Those for signal benchmark point of $(m_{T1}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0})=(600,120,100)$ GeV is also shown.

cut	background					signal	
	$t\bar{t}$	W+jets	Single t	Fake	Others	Total	(600, 120, 100)
Trig+lepton	9.88×10^4	1.28×10^6	2.53×10^4	1.92×10^5	7.72×10^4	1.67×10^6	57.5 ± 1.7
$E_T^{\text{miss}} > 250$ GeV	1.34×10^3	1.15×10^4	268 ± 4	147 ± 18	767 ± 28	1.40×10^4	34.2 ± 1.3
$p_T^{2\text{nd jet}} > 60$ GeV	1.20×10^3	4.83×10^3	190 ± 4	104 ± 13	445 ± 19	6.77×10^3	33.3 ± 1.3
$N_{b\text{-jets}} = 2$	39.6 ± 1.4	7.32 ± 0.62	7.01 ± 0.57	-0.06 ± 1.09	1.24 ± 0.30	55.1 ± 2.3	6.11 ± 0.48
$\Delta\phi > 0.4$	29.5 ± 1.2	7.08 ± 0.61	5.67 ± 0.49	0.16 ± 1.00	1.16 ± 0.30	43.6 ± 1.8	6.09 ± 0.48
$m_{bb} > 150$ GeV	19.0 ± 1.0	3.36 ± 0.41	4.80 ± 0.46	-0.10 ± 0.65	0.542 ± 0.010	27.6 ± 1.3	5.82 ± 0.47
$am_{T2} > 200$ GeV	3.76 ± 0.44	3.17 ± 0.40	2.94 ± 0.36	0.18 ± 0.45	0.449 ± 0.095	10.5 ± 0.8	5.57 ± 0.46

Appendix C

Signal leaks to control regions

Signal leaks to control regions are shown in Fig. C.1-C.2 when $\Delta m = 20$ GeV is assumed. Expected 95 % CL exclusion regions are indicated by blue lines. For $t\bar{t}$ control regions (TRs), at most 20 % signal contaminations are found at the lowest stop mass region, due to the large cross section of the signal. In such a case, the SM background may be under-estimated in the fit. However, the signal contaminations are suppressed to be less than 10 % at the edge of the exclusion curves, in which a careful estimation of the SM background is required to exclude the weaker signals. Larger contaminations of the signal in TRs than W +jets control regions (WRs) are found, because $t\bar{t}$ backgrounds have the similar characteristics with the signals. For WRs, signal contaminations are less than 5 % at almost all signal points in all sub-channels.

Figure C.1: Signal-to-background ratio at the each signal point in TR for the small ΔM channel (high) (a), WR for the small ΔM channel (high) (b), TR for the small ΔM channel (low) (c) and WR for the small ΔM channel (low) (d). Expected 95 % CL exclusion regions are shown by the blue dashed lines.

Appendix D

Impact of additional uncertainty on ϵ_{fake}

Uncertainty on mis-identified lepton background estimation is sub-dominant source of the systematic uncertainty in the final results as shown in Sec. 7.1. As explained in Sec. 6.4.3, additional uncertainty coming from the origin of the fake lepton ($\Delta\epsilon_{\text{fake}}^{\text{add}}$) is assigned to ϵ_{fake} to be conservatively 30 %. The impact of this on the final results is confirmed by performing the fit in absence of $\Delta\epsilon_{\text{fake}}^{\text{add}}$. Table D.1 shows the fit results with the background only fit configuration without $\Delta\epsilon_{\text{fake}}^{\text{add}}$, in comparison with the nominal fit results. The mean values of the mis-identified lepton background are not changed and the uncertainties are decreased with respect to the nominal ones. The model-independent upper limits at 95 % CL on visible cross section, observed and expected number of signals in the signal regions, CL_b values and discovery p -values are summarized in Table D.2, also compared with the nominal results. Results with and without additional uncertainty on ϵ_{fake} are consistent with each other in all sub-channels.

Table D.1: Number of observed events (N_{obs}) compared with expected number of events ($N_{\text{exp}}^{\text{total}}$) estimated by the background only fit with nominal configuration and the configuration without additional uncertainty on ϵ_{fake} ($\Delta\epsilon_{\text{fake}}^{\text{add}}$). Expected number of mis-identified lepton background ($N_{\text{exp}}^{\text{mis-id}}$) with both configurations are also shown. The additional uncertainty does not change the mean value of the mis-identified lepton background.

	Small ΔM channel		Moderate ΔM channel	
	(high)	(low)	(low)	(high)
N_{obs}	11	20	41	7
$N_{\text{exp}}^{\text{total}}$ (nominal)	6.54 ± 1.52	17.47 ± 4.28	32.10 ± 5.08	9.80 ± 1.61
$(N_{\text{exp}}^{\text{mis-id}})$	$0.55^{+0.99}_{-0.55}$	$2.48^{+2.67}_{-2.48}$	$0.74^{+2.79}_{-0.74}$	$0.18^{+0.64}_{-0.18}$
$N_{\text{exp}}^{\text{total}}$ (w/o $\Delta\epsilon_{\text{fake}}^{\text{add}}$)	6.54 ± 1.41	17.48 ± 3.88	32.10 ± 4.75	9.80 ± 1.57
$(N_{\text{exp}}^{\text{mis-id}})$	$0.55^{+0.81}_{-0.55}$	2.48 ± 1.99	$0.74^{+2.12}_{-0.74}$	$0.18^{+0.52}_{-0.18}$

Table D.2: Comparison of model-independent upper limits between nominal configuration and the configuration without additional uncertainty on ϵ_{fake} ($\Delta\epsilon_{\text{fake}}^{\text{add}}$).

Signal channel			$\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$ [fb]	s_{obs}^{95}	s_{exp}^{95}	CL_b	$p(s=0)$
Small ΔM channel	(high)	(nominal)	0.58	11.8	$7.9^{+3.6}_{-2.2}$	0.86	0.10
		(w/o $\Delta\epsilon_{\text{fake}}^{\text{add}}$)	0.58	11.7	$7.6^{+3.4}_{-2.2}$	0.87	0.09
	(low)	(nominal)	0.71	14.4	$12.5^{+5.4}_{-3.5}$	0.65	0.34
		(w/o $\Delta\epsilon_{\text{fake}}^{\text{add}}$)	0.69	14.1	$12.2^{+5.1}_{-3.6}$	0.66	0.33
Moderate ΔM channel	(low)	(nominal)	1.15	23.4	$17.6^{+6.8}_{-4.9}$	0.81	0.16
		(w/o $\Delta\epsilon_{\text{fake}}^{\text{add}}$)	1.14	23.1	$16.7^{+6.7}_{-4.6}$	0.83	0.14
	(high)	(nominal)	0.30	6.0	$7.9^{+3.7}_{-2.3}$	0.23	0.5
		(w/o $\Delta\epsilon_{\text{fake}}^{\text{add}}$)	0.30	6.0	$7.9^{+3.7}_{-2.3}$	0.22	0.5

Appendix E

Confirmation of statistical approximations

As explained in Sec. 7.2.1 and 7.3.1, we use the statistical approximations to describe probability density functions following the criteria in Ref. [197] in model-independent and model-dependent upper limit settings. It is confirmed that results using the approximations are consistent with those using pseudo-experiments. Table E.1 shows the model-independent upper limits at 95 % CL on visible cross section, observed and expected number of signals in the signal regions, CL_b values and discovery p -values, using probability density function derived by 3000 times pseudo-experiments (denoted as ‘Toy ($N_{\text{toy}} = 3000$)’) and those using the statistical approximation (nominal, denoted as ‘Asimov’). The consistent results between Asimov and Toy configurations are found.

Table E.1: Comparison of model-independent upper limits between nominal configuration using the statistical approximation (Asimov) and the configuration pseudo-experiments (Toy).

Signal channel			$\langle\epsilon\sigma\rangle_{\text{obs}}^{95} [\text{fb}]$	s_{obs}^{95}	s_{exp}^{95}	CL_b	$p(s = 0)$
Small ΔM channel	(high)	Asimov (nominal)	0.58	11.8	$7.9^{+3.6}_{-2.2}$	0.86	0.10
		Toy ($N_{\text{toy}} = 3000$)	0.59	12.1	$8.4^{+2.7}_{-2.1}$	0.90	0.08
	(low)	Asimov (nominal)	0.71	14.4	$12.5^{+5.4}_{-3.5}$	0.65	0.34
		Toy ($N_{\text{toy}} = 3000$)	0.76	15.4	$13.1^{+5.0}_{-3.9}$	0.67	0.20
Moderate ΔM channel	(low)	Asimov (nominal)	1.15	23.4	$17.6^{+6.8}_{-4.9}$	0.81	0.16
		Toy ($N_{\text{toy}} = 3000$)	1.19	24.2	$18.9^{+5.8}_{-5.0}$	0.82	0.16
	(high)	Asimov (nominal)	0.30	6.0	$7.9^{+3.7}_{-2.3}$	0.23	0.5
		Toy ($N_{\text{toy}} = 3000$)	0.30	6.1	$8.1^{+3.3}_{-2.2}$	0.24	0.93

Appendix F

Combination of sub-channels for the exclusion limit setting

When the model-dependent limits are set on SUSY masses, results of 4 sub-channels are merged by taking one showing the best expected CL_s value, as shown in Sec. 7.3.2. Figure F.1 shows sub-channels taken at each signal point on $\Delta m = 20$ GeV and 5 GeV, fixed $m_{\tilde{\chi}_1^\pm} = 150$ GeV and 106 GeV, fixed $m_{\tilde{t}_1} = 300$ GeV and stop four-body decay grids, respectively. It is found that the small ΔM channel (high) covers the most diagonal region of $\Delta m = 20$ GeV and 5 GeV grids and four-body decay grid, and the $m_{\tilde{t}_1} = 160$ GeV on the fixed $m_{\tilde{\chi}_1^\pm} = 150$ GeV grid. The small ΔM channel (low) covers the region at $40 < \Delta M < 70$ GeV on $\Delta m = 20$ GeV grid, and plays main roles to exclude signal points in the four-body decay grid. This channel excludes a point at $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (300, 250, 200)$ GeV on fixed $m_{\tilde{t}_1} = 300$ GeV grid, which is excluded only by this analysis even if it is merged with other ATLAS stop analyses, as shown in Fig. 7.10. The moderate ΔM channel (low) covers the region from $m_{\tilde{t}_1} \simeq 200$ GeV to $\simeq 350$ GeV, while the moderate ΔM channel (high) covers $400 < m_{\tilde{t}_1} < 600$ GeV on $\Delta m = 20$ GeV, $\Delta M = 5$ GeV, fixed $m_{\tilde{\chi}_1^\pm} = 150$ GeV and $m_{\tilde{\chi}_1^\pm} = 106$ GeV grids. Corresponding to that, the moderate ΔM channel (low) excludes broad region with $m_{\tilde{\chi}_1^\pm} < 180$ GeV on fixed $m_{\tilde{t}_1} = 300$ GeV grid.

Observed and expected CLs values for each signal point are summarized in Fig. F.2 and F.3, respectively.

Figure F.1: Sub-channel selected for each signal point showing the best expected CLs value for grids with $\Delta m = 20$ GeV (top-left) 5 GeV (top-right), $m_{\tilde{\chi}_1^\pm} = 150$ GeV (middle-left), 106 GeV (middle-right), $m_{\tilde{t}_1} = 300$ GeV (bottom-left) and four-body decay grid (bottom-right). Black inverse triangle shows the small ΔM channel (high); white triangle the small ΔM channel (low); black square the moderate ΔM channel (low); and white circle the moderate ΔM channel (high). Observed (red lines) and expected (blue dashed lines with yellow bands) 95 % CL exclusion region curves are also shown.

Figure F.2: Observed CL_s value for each signal point of the sub-channel showing the best expected CL_s value for grids with $\Delta m = 20$ GeV (top-left) 5 GeV (top-right), $m_{\tilde{\chi}_1^\pm} = 150$ GeV (middle-left), 106 GeV (middle-right), $m_{\tilde{t}_1} = 300$ GeV (bottom-left) and four-body decay grid (bottom-right). Points with observed $CL_s < 0.05$ are indicated by red color.

Figure F.3: Expected CL_s value for each signal point of the sub-channel showing the best expected CL_s value for grids with $\Delta m = 20$ GeV (top-left) 5 GeV (top-right), $m_{\tilde{\chi}_1^\pm} = 150$ GeV (middle-left), 106 GeV (middle-right), $m_{\tilde{t}_1} = 300$ GeV (bottom-left) and four-body decay grid (bottom-right).

Points with expected $CL_s < 0.05$ are indicated by blue color.

Appendix G

Improvements on the ATLAS muon trigger system

G.1 Introduction

Muon with high transverse momentum ($p_T = p \sin \theta$) is an important probe in many physics channels e.g. searches for physics beyond the Standard Model such as scalar top quark pair production [71] as well as precision measurements of the Standard Model processes such as a Higgs boson decaying into four leptons [18]. Low- p_T muon is also used as a physics signature, for instance in a search for the rare decay of $B_s^0 \rightarrow \mu^+ \mu^-$ [199]. Triggering data sufficiently by using the muon signals in wide range of p_T from a few GeV to $O(1)$ TeV is an important key of the physics program with ATLAS. This chapter reports a part of improvements on the ATLAS muon trigger system in 2010 and 2011 and its performance evaluated with the data collected in 2012.

G.2 Improvements on the ATLAS muon trigger system

G.2.1 The ATLAS muon trigger system

As shown in Sec. 2.2.3, the muon spectrometer (MS) is located at the outermost layer of the detector. It consists of monitored drift tubes (MDT), cathode strip chambers (CSC), resistive plate chambers (RPC) and thin gap chambers (TGC). For both barrel ($|\eta| < 1.05$) and endcap ($|\eta| > 1.05$) regions, *Large* and *Small* chambers are located side-by-side, as illustrated in Fig. 2.20 (a) for barrel, to gain the geometrical coverage. The 8-fold symmetry of the detector in ϕ is assumed. In barrel, there are two feet to hold the detector up as shown in Fig. 2.20 (a), yielding an acceptance loss in a specific ϕ region. *Large Special* and *Small Special* chambers are located instead at these regions, which break the 8-fold symmetry in the barrel region. RPC and TGC are custom-made trigger chambers synchronized to the LHC clock to identify the bunch crossing. MDT and CSC are used in the precision measurements of the muon tracks, which have better spacial resolution than the trigger chambers. There are three layers of the precision muon chambers in both the barrel and endcap regions as shown in Fig. 2.20 (b). At each MDT layer, a muon track traverses 6-8 drift tubes. Linear fit to drift circles at several tubes is performed to reconstruct position and direction of the muon track at each MDT layer. MDT can measure only z (r) coordinate of the muon trajectories in the barrel (endcap) region. Azimuth of the muon track is compensated by the measurements at RPC, TGC and CSC.

About 0.5 T and 1 T strong magnetic fields are applied to the barrel and endcap regions, respectively, indicated by the green and blue shaded regions in Fig. 2.20 (b). Momentum of the muon is calculated from the curvature of the track in the magnetic field, which is reconstructed from hits at each layer of

the muon spectrometer. Tracks reconstructed at the muon spectrometer are combined with those at the inner detector (ID). The combined muon candidates are calibrated by the dedicated criteria after the data taking as explained in Sec. 4.3, which are called *offline* muons in this chapter.

As described in Sec. 2.2.4, ATLAS employs the three-level trigger algorithm of Level 1 (L1), Level 2 (L2) and Event Filter (EF) with increasing complexity and accuracy. The L2 and EF triggers are collectively referred as Higher Level Trigger (HLT). The ATLAS trigger system is based on physics signatures e.g. electron, muon, hadron jets and missing transverse energy. Combinations of signatures at the trigger level allow to define many trigger logics in parallel. Each logic is called *trigger chain*. For example:

- The trigger chain to collect events containing one isolated high- p_T muon with $p_T > 24$ GeV was called *EF_mu24i_tight*. It was used as the default single muon trigger requiring the lowest p_T threshold in 2012 without pre-scaling. It required at least one muon candidate with $p_T > 15$ GeV at L1, > 24 GeV at each stage of L2 and EF, and $\sum_{\Delta R < 0.2} p_T^{\text{trk}} < 0.12 p_T$ at EF¹.
- The trigger chain to collect $B_s^0 \rightarrow \mu^+ \mu^-$ candidates in early 2011 was called *EF_2mu4_Bmumu*. It required at least two muons with $p_T > 0$ GeV at L1 and > 4 GeV at each level of L2 and EF. In addition, the invariant mass reconstructed by two muons was required to be around the mass of B_s^0 meson at each stage of L2 and EF.

The band width for each physics signature is settled at each trigger level according to the physics program with ATLAS. Events satisfying the one of the pre-defined trigger chains are recorded. The trigger menu can be modified every running periods.

Maximum instantaneous luminosity recorded with ATLAS is shown in Fig. G.1. It increased dramatically in 2011 up-to $3.5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ and reached to $7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ in 2012. As the expected proton-proton collision rate was going up according as the luminosity, the trigger system had to be improved immediately in 2011. I worked as an expert of the ATLAS muon trigger system from 2010. In the following sections, improvements on the ATLAS muon trigger system that I applied are explained.

Figure G.1: Maximum instantaneous luminosity recorded by ATLAS versus month during 2010 and 2012.

¹The condition $\sum_{\Delta R < 0.2} p_T^{\text{trk}} < 0.12 p_T$ requires the muon well-isolated from the other tracks, where p_T is the muon transverse momentum, p_T^{trk} is track p_T except for the muon track itself and sum runs over all of tracks within the cone of $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.2$ centering around the muon track.

G.2.2 Development of the new L1 trigger logic for low- p_T muons

At the L1 muon trigger, RPC and TGC define *Region of Interest (RoI)* and pass it to the HLT. The typical dimension of RoI in barrel (endcap) is $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ (0.03×0.03). In the endcap region, three TGC layers located in the middle MDT layer (see Fig. 2.20 (b)) are used for the trigger. From inside to outside, the TGC layers are called M1, M2 and M3, respectively. Figure G.2 (a) illustrates an octant module of the TGC. Each sub-sector of the TGC is defined to contain 8 wires and 8 strips, corresponding to the definition of RoI. In the forward region ($2.0 < |\eta| < 2.4$), the coarser read-out granularity in ϕ is adapted. The algorithm to reconstruct muon candidate starts from a hit at M3 layer. The straight line between the hit at M3 and the interaction point is assumed to be a pseudo muon track having infinite momentum. For each layer of M1 and M2, dedicated *coincidence window* is pre-defined in r - ϕ plane centering around the intersection point between the infinite-momentum track and the detector surface. Hits at M1 and M2 layers are explored within the windows. Track p_T is roughly estimated in 6 steps ($p_T > 0$ (4), 6, 10, 11, 15 and 20 GeV) according to the distance of the hit from the central point of the window. An example of coincidence window is shown in Fig. G.2 (b). Coincidence window is optimized for each RoI assuming 8-fold ϕ symmetry using the Monte-Carlo simulation and validated using the data [200]. The condition to require hits at all of three layers (three-station coincidence) is employed for high- p_T muon candidates ($p_T > 6$ GeV, 11 GeV, 15 GeV and 20 GeV). Since the curvature of the low- p_T muon track ($p_T > 0$ GeV) is expected to be large and the hit at the M1 layer is possible to be out of the window, two-station coincidence of M2 and M3 was required until July 2011 to keep the efficiency. Two-station coincidence is required also in the condition for $p_T > 10$ GeV to study the

Figure G.2: (a) Illustration of the TGC octant [200]. Sub-sectors are defined by 8 wires and 8 strips, corresponding to the definition of RoIs. (b) An example of the coincidence window for a sub-sector of the TGC defined in r - ϕ plane [200]. The central point at $(\Delta\phi, \Delta R) = (0,0)$ is the intersection point of the line between the hit at third TGC layer and the interaction point and the detector surface. The muon transverse momentum is calculated by the distance of the hit from the origin. It roughly estimated in 5 steps of $p_T > 0$ GeV (black), 6 GeV (blue), 10 GeV (green), 15 GeV (red) and 20 GeV (pink). Two-station coincidence is required for $p_T > 0$ GeV and $p_T > 10$ GeV, while three-station coincidence is used for the others. The trigger condition for $p_T > 11$ GeV is defined by taking three-station coincidence in the window for $p_T > 10$ GeV. The window is optimized using the Monte-Carlo simulation for each RoI.

impact of three-station coincidence at the high- p_T region. Although a single muon trigger requiring $p_T > 0$ GeV at L1 was highly pre-scaled due to the large background processes, a trigger requiring two muons with $p_T > 0$ GeV at L1 (*di-muon L1 trigger*) worked without pre-scaling and it was used in the chain EF_2mu4_Bmumu to collect $B_s^0 \rightarrow \mu^+\mu^-$. After July 2011, however, di-muon L1 trigger was also expected to exceed the acceptable rate. In order to claim the rare decay of $B_s \rightarrow \mu^+\mu^-$ (the branching ratio is predicted to be $O(10^{-9})$ by the Standard Model), an analysis using large amount of data as much as possible is important. Suppression of the trigger rate at the low- p_T region had to be made immediately, while keeping the efficiency to the signals. The simplest solution to suppress the rate was to apply the tighter p_T threshold and it was made in the barrel region to define the new threshold for $p_T > 4$ GeV at L1. However, it was not able to optimize the p_T threshold in the endcap region due to the technical reason. If three-station coincidence was required for low- p_T muons, the rate of di-muon L1 trigger could be reduced by 90 % in the endcap region, but serious efficiency loss was expected at the lowest p_T region. Figure G.3 shows the ratio between the efficiencies of three-station and two-station triggers to the events containing one offline muon with $p_T > 4$ GeV as a map of η and ϕ . The strong position dependency on the efficiency of three-station trigger was found in my study i.e. relatively high efficiency of about 90 % of two-station was found in the region A defined in the figure. I defined a new endcap L1 trigger condition for low- p_T muons by requiring three-station coincidence only in the region A and still two-station in the other regions. The new trigger condition were defined to say $p_T > 4$ GeV at L1². It could reduce the rate of di-muon L1 trigger by about 40 %, which was sufficient to tolerate the expected luminosity in 2011. The relative efficiency of the new trigger to $B_s^0 \rightarrow \mu^+\mu^-$ signal was confirmed by the Monte-Carlo simulation to be > 90 % with respect to the original EF_2mu4_Bmumu chain. The performance

Figure G.3: Ratio of the endcap L1 muon trigger efficiency requiring three-station coincidence to event containing single muon with $p_T > 4$ GeV to the efficiency requiring two-station coincidence, as a map of detector position in η and ϕ . The data collected by two-station trigger in early 2011 is used for the optimization. The efficiency of three-station trigger is estimated by emulating the additional coincidence of M1 TGC layer in offline analysis. The 8-fold symmetry in ϕ is assumed. Relatively high efficiency is found in the region A. Individual TGC modules are overlapped in $\phi = \pi/8$, yielding high rate of the di-muon trigger by the fake hit. Therefore, more suppression of the di-muon trigger rate is expected if three-station coincidence is required in regions B, C and D in addition to A.

²Actually, the original efficiency of the L1 trigger for $p_T > 0$ GeV is about 55 % at $p_T = 4$ GeV of the offline muon and about 90 % at $p_T > 8$ GeV due to the definition of coincidence windows. Therefore, the efficiency of the new L1 trigger for $p_T > 4$ GeV is about 40 % at $p_T = 4$ GeV. Only a few % efficiency loss is expected at the plateau.

of the new trigger was validated by the data collected in 2011 using the resonance of $J/\Psi \rightarrow \mu^+\mu^-$ (further validation using the 2012 data is shown in Sec. G.3) and implemented online from July 2011. Consequently, the full statistics delivered from the LHC in 2011 corresponding to about 5 fb^{-1} of the integrated luminosity could be used for the $B_s^0 \rightarrow \mu^+\mu^-$ analysis while avoiding the pre-scale [199].

G.2.3 Improvements on the L2 muon trigger algorithm

Software-based trigger algorithms are employed at HLT. Signals at the precision muon chambers (MDT and CSC) and the tracks reconstructed at the inner detector can be used at this stage. More precision measurements of the track parameters can be performed, which enable to apply the tighter selection cuts.

Fast reconstruction of the muon track is required at L2 to cope with the acceptable rate. It is achieved by reading out the detector information only around the RoI. The ATLAS L2 muon trigger algorithm consists of two steps. Each step is called *L2 Muon Standalone* and *L2 Muon Combined*, respectively. L2 Muon Standalone reconstructs muon tracks using the signals only at the muon spectrometer. The muon p_T is estimated by the curvature of the track in the magnetic fields roughly measured from hits at MDT layers. By giving the constraint from the interaction point, the muon can be reconstructed even if there are only two hits among three MDT layers. Events with muon candidates satisfying the pre-defined p_T threshold at L2 Muon Standalone are passed to L2 Muon Combined in each trigger chain. At this stage, the track reconstructed at L2 Muon Standalone is extrapolated to the interaction point and combined with the inner detector track. The transverse momentum of the combined muon is calculated by taking the weighted average of two tracks' p_T by the inverse of the uncertainties on p_T parameterized as a 2D-functions of p_T and η . The inner detector track improves the precision of the measurement at the low- p_T region and reduces the hadronic backgrounds from the in-flight decays of pion and kaon at the calorimeter. A tighter cut on p_T is applied at L2 Muon Combined. Basically, only events passing the requirement at L2 Muon Combined are handled at EF. The EF algorithm can access to the full detector and perform a-la offline reconstruction of the muon track. If the rate allows, it can reconstruct muon at EF without L2 information (*EF full-scan trigger*) in some trigger chains.

At L2 Muon Standalone, the magnetic fields and the momentum deficits of the muon in the detector materials are parameterized in advance in η - ϕ bins to estimate p_T from the curvature, in order to reduce the calculation time [201]. Number of bins at the barrel (endcap) region is $\eta \times \phi = 30 \times 30$ (12×30) assuming 8-fold ϕ symmetry of the detector. Parameters for Large Special and Small Special chambers are estimated separately. In 2010, the first year of the LHC, the parameters were optimized with the Monte-Carlo simulation tuned before the start of the experiment. Due to the incomplete descriptions about the magnetic fields, detector materials and the detector alignments, p_T resolution at L2 Muon Standalone was not good [201, 202]. In addition, there was known issue in the endcap region that p_T calculated at L2 Muon Standalone was biased depending on p_T itself [201, 202]. As shown in Fig. G.1, the instantaneous luminosity was well suppressed in 2010 up-to $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ and it was allowed to apply very loose p_T cut at L2 to avoid the inefficiency caused by these problems. From 2011, however, the instantaneous luminosity was expected to be increased dramatically and the rate reduction at L2 was to be important to suppress the input rate at EF. Therefore, the improvement of the p_T resolution at L2 Muon Standalone had to be done before data taking in 2011. After the detector alignments were corrected, I studied the relation between the curvature of the muon track calculated at L2 Muon Standalone and the offline muon p_T precisely, using the data collected in 2010. All parameters to describe the magnetic fields and the detector materials were optimized to describe the data in each η - ϕ bin. The bias of the p_T calculation in endcap was caused due to that the function to transform the curvature to p_T did not represent the data behavior well. I introduced the new equation to calculate p_T from the curvature by taking a polynomial function. Figure G.4 (a) shows the mean value of the Gaussian fit to the residual r

Figure G.4: The p_T bias (a) and resolution (b) of L2 Muon Standalone as a function of offline muon p_T in the specific endcap region in 2010 (blue triangles) and 2011 (blue circles). The latest alignment correction are applied for both. Those derived by $Z^0 \rightarrow \mu^+\mu^-$ Monte-Carlo simulation are overlaid.

distribution as a function of the offline muon p_T , which is defined as:

$$r = \frac{1/p_T^{\text{offline}} - 1/p_T^{\text{L2 SA}}}{1/p_T^{\text{offline}}}, \quad (\text{G.1})$$

where p_T^{offline} and $p_T^{\text{L2 SA}}$ are the transverse momenta of the muon calculated offline and at L2 Muon Standalone, respectively. The p_T bias was found to be about 30 % at $p_T = 4$ GeV and depended on p_T in the 2010 data, but it was eliminated to be less than 1 % by using my new function in 2011. The p_T resolution is defined as the width of the Gaussian fit to r distribution. It was improved by about factor 2 in all regions, as shown in Fig. G.4 (b) for the specific endcap region as an example, by re-optimizing the parameters. As a result, finally the p_T cut could be tightened at the L2 Muon Standalone. I optimized the p_T -threshold values to collect the data of greater than 99 % above the thresholds. All of the improvements on L2 Muon Standalone explained above were implemented online from the beginning of the 2011 run. The rates of the trigger chains requiring at least one muon with $p_T > 4$ GeV and > 6 GeV at L2 Muon Standalone were reduced by factor 5 and 2, respectively, with respect to those without any improvements. I parameterized the uncertainty on the muon p_T at L2 Muon Standalone as a function of p_T and η , which was used in the combination at L2 Muon Combined. Better p_T resolution at L2 Muon Standalone improves the performance at L2 Muon Combined.

During 2011, the alignment corrections for the MDT chambers at the barrel Large Special sector were found to be still wrong in the L2 Muon Standalone algorithm. The different behavior on p_T bias depending on the electric charge of the muon multiplied by its η ($Q \times \eta$) was found in this region as shown by blue points in Fig. G.5 (a) and (b), coming from the alignment mis-modeling. The inefficiency caused by this problem was occurred at this region in 2011, but the impact was limited since the coverage of the Large Special chamber was very small with respect to the other chambers. For 2012, I developed the patch tool to give the alignment correction factors for the barrel Large Special chamber as arguments from the outside of the function. The alignment correction factors were estimated from the 2011 data in each η - ϕ bin for the p_T calculation, by using an assumption that the curvature of the muon track

Figure G.5: The p_T bias (top) and resolution (bottom) at L2 Muon Standalone algorithm at the barrel Large Special chambers, divided into $Q \times \eta < 0$ (left) and > 0 (right), as a function of offline muon p_T . The data collected in 2011 at the center-of-mass energy of 7 TeV are analyzed. Results with and without the alignment correction factors are indicated by red and blue dots, respectively.

became to be zero at the enough high- p_T region not depending on the electric charges. After the new alignment correction, the bias on p_T depending on $Q \times \eta$ was improved to be at most 6 % at $p_T = 40$ GeV as shown by red points in Fig. G.5 (a) and (b). Parameters to calculate p_T were re-optimized after the application of the new alignment corrections. The p_T resolution at the Large Special sector was improved by approximately factor 3 as shown in Fig. G.5 (c) and (d) to be about 10 %, which was comparable to the other barrel regions. Validation of the new alignment corrections at the Large Special sector was made carefully using the early 2012 data, since the detector alignment might be changed again. After the confirmation of the quite better performance with the new alignment corrections in the data, it was turned on in the default online trigger system from May 2012.

G.3 Trigger efficiency measurements

G.3.1 Tag and probe method

The performance of the muon trigger have been studied using the data collected in 2010 [202, 203], 2011 [204] and 2012 [118] separately, since the different trigger menus were used at each period. *Tag and probe* method was employed to estimate the muon trigger efficiency. For high- p_T muons, rich statistics from $Z^0 \rightarrow \mu^+\mu^-$ were available for tag and probe method. In 2012 analysis [118], it uses the data mainly collected by the trigger chain EF_mu24i_tight (see the definition in Sec. G.2.1). The analysis requires two offline muons with opposite electric charges in the event and the invariant mass reconstructed by them around Z^0 mass. One muon is required to match the track reconstructed at EF geometrically (called the tag muon). The other muon can be used to estimate the efficiency not affected by the data-taking trigger (called the probe muon). Using muons from Z^0 decay, physics-induced muons are ensured. The plateau efficiency of EF_mu24i_tight was found to be about 70 % in barrel and 80 % in endcap [118]. Data agree well with the Monte-Carlo simulation and the result was stable against the pileup condition. The muons from $W \rightarrow \mu\nu$ and top quark pair were used to validate the result. Tag and probe using a low-mass di-muon resonances e.g. $J/\Psi \rightarrow \mu^+\mu^-$ must be made as well for the performance study of the low- p_T muon triggers. However, the trigger chain to collect events with at least one low- p_T muon was highly pre-scaled at L1 as discussed in Sec. G.2.2. Therefore, simple tag and probe using $J/\Psi \rightarrow \mu^+\mu^-$ cannot be made, due to the poor statistics. The trigger chain to collect $J/\Psi \rightarrow \mu^+\mu^-$ candidates by requiring two muons at the trigger level were available in 2012, but the data collected with this trigger could not be used because the trigger condition was applied to the probe muon absolutely, leading to an over-estimation of the efficiency. There are two keys to use $J/\Psi \rightarrow \mu^+\mu^-$ events for the trigger efficiency measurement while suppressing the data-taking rate:

1. to use J/Ψ mesons produced in the boosted frame;
2. to estimate the trigger efficiency at each stage of L2 and EF, separately.

In this section, the criteria to measure the trigger efficiency to low- p_T muons using 2012 data is explained.

G.3.2 Development of the dedicated criteria for low- p_T muons

Reconstruction of the boosted J/Ψ meson

The events with two muons with opposite electric charges are selected. The invariant mass reconstructed by two muons are required to be around the mass of J/Ψ meson. In order to suppress the trigger rate, a tag muon was required to have $p_T > 18$ GeV. Requirement of the high- p_T tag muon leads to the high transverse momentum of the J/Ψ meson i.e. J/Ψ produced in the boosted frame is likely to be selected. Differential cross section of the inclusive prompt and non-prompt J/Ψ meson production at the LHC have been measured with ATLAS [205]. Enough large cross section and

high signal-to-background ratio were expected even if the transverse momentum of J/Ψ meson was high. In such a case, the probe muon distributes at a few GeV, which can be used to estimate the trigger efficiency at the low- p_T region. However, it makes the spacial angle between two muons small, as illustrated in Fig. G.6, yielding the under-estimation of the L1 trigger efficiency. If two muons bended by the magnetic field to the same direction as shown in Fig. G.6 (a), the L1 trigger might issue only one RoI due to the read-out granularity of RPC and TGC. The isolation requirement between two muons to avoid this problem using ΔR calculated at the interaction point reduces the most of the statistics. In my study, offline muon tracks were extrapolated to the detector surface of the middle MDT layer, in which RoIs were defined, and two muons were required to be isolated with each other by $\Delta R > 0.2$ at that plane, as shown in Fig. G.6 (b). As a result, about 75 % of the all events can be used for tag and probe method. The J/Ψ candidates from non-prompt interaction such as the decay of b -particles were increased with the p_T of J/Ψ [205]. Fraction of the non-prompt interaction was found to be 60 % at $p_T > 30$ GeV. The effect of the non-prompt J/Ψ production was subtracted in my study by re-weighting the impact parameter distribution to the prompt sample (see details in [118]).

Using special trigger chains

Further suppression of the trigger rate was necessary to require $p_T > 18$ GeV to the tag muon. The following two trigger chains dedicated to this analysis were implemented in 2012:

- One required at least one muon with $p_T > 15$ GeV at L1 and $p_T > 18$ GeV at each stage of L2 and EF and additional one muon with $p_T > 4$ GeV reconstructed by EF full-scan trigger. The invariant mass reconstructed by two muons at EF was required to be around J/Ψ mass.
- The other required at least two muons at L1 with asymmetric thresholds of $p_T > 15$ GeV and > 4 GeV. The tighter thresholds of $p_T > 18$ GeV and $p_T > 4$ GeV were required at L2. The invariant mass reconstructed by two muons at L2 were required to be around the mass of J/Ψ . At EF, it required at least one muon with $p_T > 18$ GeV.

The trigger efficiency of L1 and L2 could be estimated with the data collected by the former trigger chain. The EF efficiency with respect to L2 were estimated with the data collected by the latter chain. Finally, the total efficiency was calculated by multiplying both results.

G.3.3 Results

Figure G.7 shows the trigger efficiencies to the low- p_T muons, estimated by the above criteria, as a function of the offline muon p_T . Efficiencies at each stage of L1, L2 and EF are multiplied. Efficiencies of the different trigger chains requiring at least one muon with $p_T > 4$ GeV (mu4), > 6 GeV (mu6) and > 8 GeV (mu8) are overlaid. The plateau efficiency of the low- p_T muon trigger chains are about 80 % in both barrel and endcap regions. Since two-station coincidence at L1 is required in barrel for low- p_T muon trigger chains, about 10 % higher efficiency than the high- p_T trigger chains are found. On the other hand, three-station coincidence is required in endcap for mu6 and mu8. The new L1 trigger requiring $p_T > 4$ GeV in endcap developed in Sec. G.2.2 was used in the mu4 chain and the better efficiency of mu4 than the other chains by about 5 % was found. At L2 Muon Standalone, sufficient high efficiency of greater than 99 % with respect to L1 was found for all trigger chains. The results show the data agree well with Monte-Carlo simulation even in the low- p_T region. Small disagreements between the data and simulation is corrected by applying the scaling factor. The uncertainty associated with that is estimated precisely and provided as an input of the physics analyses.

Figure G.6: Illustration of the di-muon in the decay of the boosted J/Ψ meson. Purple line shows the momentum-vector of the J/Ψ meson. Red and blue lines indicate tracks of minus- and plus-charged muons from the decay of J/Ψ . The spacial angle of two muons at the interaction points are likely to be small. If both muons are bended to the same direction (a),

Figure G.7: The low- p_T muon trigger efficiency as a function of the offline muon p_T , divided into barrel (a) and endcap (b) regions [118]. The efficiencies of the trigger chains requiring at least one muon with $p_T > 4$ GeV (mu4, black circles), 6 GeV (mu6, red squares) and 8 GeV (mu8, blue triangles) are overlaid. The data collected in 2012 corresponding to 19.2 fb $^{-1}$ are used. The $J/\Psi \rightarrow \mu^+\mu^-$ candidates are selected in the dedicated criteria explained in the text. Results derived by the Monte-Carlo simulation are overlaid.