Searching for the Higgs Boson in Pairs of Tau Leptons in Data from the ATLAS Experiment

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Dissertation for the degree of Philosophiae Doctor (PhD)

Department of Physics and Technology
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Errata for
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Figure 9.5 and 9.6:

In these plots, instead of using the Higgs cross section and branching ratio listed in table 5.1, the effective Higgs cross sections were mistakenly taken from POWHEG+PYTHIA. This has a small effect on the expected number of Higgs events in the low Higgs mass range $m_H < 130$ GeV, but has a large effect for high Higgs masses.

Below is shown the corrected versions of figure 9.5 and 9.6 using the correct cross sections and branching ratios from table 5.1.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
$H^\rightarrow\tau^+_\text{had}\tau^-\text{had}$ & Expected CL$_{\text{b}}$ Limits & \\
\hline
$\int L dt = 4.7 fb^{-1}$ & Winter2012 & \\
$\sqrt{s} = 7$ TeV & New Limit (ggH+VBF) & \\
\hline
\end{tabular}
\end{table}

\begin{align*}
\text{SM} \sigma / \sigma_{95\% \text{ CL Limit on}} & \quad 5 \\ 
\text{Expected CL} & \quad 10 \\ 
\text{Winter2012} & \quad 15 \\ 
\text{New Limit (ggH+VBF)} & \quad 20 \\ 
\end{align*}

\begin{align*}
\text{Limit}_{\text{s}} & \quad 25 \\ 
\text{Expected CL} & \quad 30 \\ 
\text{Winter2012} & \quad 35 \\ 
\end{align*}

\begin{align*}
\text{New limits:} & \quad \pm 2\sigma \\
\text{Using } M_{\text{Boost-XYZ}} & \quad \pm 1\sigma \\
\text{Using } M_{\text{PC}} & \quad \text{Obs. limit (MMC)}
\end{align*}
Abstract

One of the key questions in particle physics today, is the origin of the electroweak symmetry breaking. The answer to this question will most likely be solved with the data provided by the Large Hadron Collider which started colliding protons in 2008. Many ideas have been posed to how particles gain their masses. The most promising of these ideas is the Higgs mechanism which predicts the existence of a new massive scalar boson, the Higgs boson.

Since the discovery of a new particle consistent with a Standard Model Higgs boson was made on July 4 by the ATLAS and CMS experiment, the solution for the puzzle of the electroweak symmetry breaking might be very near. However, in order to fully claim a discovery of the Standard Model Higgs boson, the new particle has to be proven to be a scalar boson and its decay has to be observed in both bosonic and fermionic final states with the corrected branching ratios predicted by the Standard Model. So far the new boson has only been seen in the bosonic $\gamma\gamma$, $ZZ$ and $WW$ final states, and the new particle is yet to be observed in any fermionic final state. Among the fermionic final states, the largest sensitivity is expected in $\tau^+\tau^-$ and $b\bar{b}$.

In this thesis, a search for the Standard Model Higgs boson in the fully hadronic $\tau^+\tau^-$ final state is presented. In the selection of Higgs candidate events, a technique for recreating the rest frame of the $\tau$-pairs is shown to be a powerful tool for discriminating between Higgs and background events. Using the reconstructed rest frame, a new mass estimation technique is developed and compared to the existing methods. Finally, an updated limit on the Higgs production cross section is derived using the data recorded by ATLAS during 2011, and compared to the existing ATLAS limit.

The thesis is structured as follows: In the first part a brief introduction to the Standard Model including the Higgs mechanism is given, followed by a description on the production of Higgs bosons at the LHC in the Standard Model. The second part describes the ATLAS experiment in general, but a special emphasis is put on the SCT prompt calibration loop, which a great deal of the work of this thesis has gone into developing. The last part describes in the analysis of $\tau$-pairs using the ATLAS detector. First, general description of the newly developed method for the rest frame reconstruction is given, followed by several chapters on the search for the Higgs boson in the $\tau^+\tau^-$ final state. Here, the attention is put on mass estimation, background normalisation and evaluation of the theoretical uncertainties related
to categorisation of events based on jet kinematics.
Acknowledgements

Needless to say that I could not have completed the work for this thesis without the help and support for a number of people. It would not be possible to mention all of them here and for that I apologise.

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Part I

The Higgs Boson
The present knowledge of Particle Physics has been put together in a model referred to as the Standard Model (SM). Although this model describes the data collected by current and past experiments to an extreme level of accuracy, it leaves many open questions. In this chapter, the features and principles in the SM is presented with special emphasis on the electroweak sector and Higgs mechanism.

1.1 Principles of the Standard Model.

One of the modern ways of describing quantum mechanical phenomena in high energy physics is using the path integral formulation. One of the major attractions with this formulation is that it gives an elegant and efficient way of handling the quantisation of gauge theories. The basic element in this theoretical framework is the Lagrangian, which contains all the known information on the system at hand. Normally knowing the Lagrangian will enable you to derive the equation of motion of the fields contained in the system and calculate any desired quantity of the system. Unfortunately, only solutions to the path integral of very idealised Lagrangians are known.

A way to get around this problem is perturbation theory. In perturbation theory, the Lagrangian is often split up into a free part and an interaction part where the interaction part is assumed to be weak and therefore is perturbed. If this is true, the interactions can be expanded in an infinite series, which might be solvable. If a system is solvable, a set of rules describing the transition amplitudes for the possible processes, can be constructed. These rules are known as the Feynman rules [2].

1.1.1 The gauge principle

Even before quantum mechanics, it was known that the physics of a given system was closely related to the symmetries of the system. The conservation of momentum, energy and angular momentum could be obtained by invariance of the Lagrangian under transformations such as translation, time displacement or rotation. In high energy physics the symmetries of a system are also important, e.g. the conservation of electric or colour
charge is connected to invariance under other types of transformations, which are called phase or gauge transformations.

Gauge theories are based on the Lagrangian being invariant under such transformations. An arbitrary phase transformation of a particle field $\psi$ has the form

$$\psi(x) \rightarrow e^{i\alpha} \psi(x)$$  \hspace{1cm} (1.1)

Since the theory should be invariant under this type of transformation, the phase $\alpha$ must be immeasurable and can be chosen arbitrarily. However, once it has been chosen, it has to remain fixed over all space and time. Therefore such transformation are also referred to as global phase transformations. Allowing $\alpha$ to be a function of space-time, $\alpha = \alpha(x)$ would lead to a larger group of transformations. These types of transformations are called local phase transformations. It is obvious that invariance under such types of transformations is a stronger requirement.

### 1.1.2 Quantum Electrodynamics and U(1) Gauge Invariance

A successful example of such a gauge theory is Quantum electrodynamics (QED), which is the relativistic quantum field theory of electrodynamics and part of the electroweak theory, which describes the electromagnetic and the weak force in a combined theory (see section 1.2.1). Due to the confirmations of the extraordinarily precise QED predictions, it has been used as a template of the construction of many other gauge theories.

QED is based on the theory of non-interacting electrons and positrons. As will be shown in this section, the interactions of electrons and photons will arise from requiring a gauge invariant Lagrangian. The electrons and positrons are described by a common spinor field $\psi(x)$. The Lagrangian for the non-interacting electrons and photons satisfying the Dirac equation is given by

$$\mathcal{L}_{\text{Dirac}}(x) = \bar{\psi}(x)(i\gamma^\mu \partial_\mu - m)\psi(x).$$  \hspace{1cm} (1.2)

It is easily verified that this Lagrangian is invariant under global phase transformations. However, this is not true in the case of local phase transformations, also called a U(1) gauge transformation. This type of transformation can be expressed as

$$\psi(x) \rightarrow e^{i\alpha(x)} \psi(x), \quad \text{and} \quad \bar{\psi}(x) \rightarrow e^{-i\alpha(x)} \bar{\psi}(x),$$  \hspace{1cm} (1.3)

Here the term $\partial_\mu \psi$ will not satisfy the invariance principle. However, the Lagrangian can be made invariant under U(1) gauge transformations by substituting our ordinary derivatives with new (covariant) derivatives, which are defined as

$$\partial_\mu \rightarrow D_\mu = \partial_\mu + ieQ A_\mu,$$  \hspace{1cm} (1.4)

This claims the existence of a new gauge field $A_\mu$, which has to transform in a manner that ensures the gauge invariance of the Lagrangian given in equation 1.2. This will lead to the following set of gauge transformations

$$\psi(x) \rightarrow e^{i\alpha(x)} \psi(x)$$  \hspace{1cm} (1.5)

$$A_\mu(x) \rightarrow A_\mu(x) - \frac{1}{eQ} \partial_\mu \alpha(x).$$  \hspace{1cm} (1.6)
1.2 The Standard Model

where $eQ$ is the coupling constant between fermions and the gauge field. Hence, the claim of local gauge invariance introduced interactions between the fermions and the gauge field. By rewriting the Lagrangian from equation 1.2, the new part due to the substitution of the derivatives can be identified as the interaction term

$$L_{\text{Int}}(x) = \bar{\psi}(x)(i\gamma^\mu D_\mu - m)\psi(x) - \bar{\psi}(x)(i\gamma^\mu \partial_\mu - m)\psi(x)$$

(1.7)

With our prior knowledge of particle physics, the gauge field $A_\mu$ is identified as the photon field. A part corresponding to the dynamics of this field has also to be added to our Lagrangian. Since this part has to be gauge invariant and can not contain second order derivatives, the part is determined to be

$$L_A(x) = -\frac{1}{4}F_{\mu\nu}^2(x),$$

(1.8)

where $F_{\mu\nu}(x) = \partial_\mu A_\nu(x) - \partial_\nu A_\mu(x)$.

Hence, the full Lagrangian for QED is given by

$$L_{\text{QED}}(x) = \bar{\psi}(x)(i\gamma^\mu \partial_\mu - m)\psi(x) - eQ\bar{\psi}(x)\gamma^\mu \psi(x)A_\mu(x) - \frac{1}{4}F_{\mu\nu}^2(x)$$

(1.9)

1.2 The Standard Model

Our present knowledge of particle physics has lead to a model, called the Standard Model (SM), which describes the elementary particles and the principal forces of nature, except for Gravity. The SM contains two types of particles; the matter particles and the force carriers.

The matter particles, which are point-like, spin one-half fermions, are divided into two groups; quarks and leptons. Both groups have three almost identical generations, that only differ in their masses. The heavier generations eventually decay into the lightest generation, leaving only this generation present in our every-day matter, e.g. atoms, molecules etc. The other generations have been discovered in cosmic rays studies or at collider experiments.

These particles interact due to three fundamental forces; the electromagnetic, the weak and the strong force. In quantum field theory (QFT), these forces mediate through point-like integer spin particles called the force carriers or gauge bosons. The large spread in the strengths and spacial extensions of these forces correspond to the fundamental quantities of their force carriers.

The force carrier of electromagnetism is the photon, which is massless and have neither electric nor colour charge. The photon couples to all electrically charged particles. Since the photon is massless, the electromagnetic force has an infinite range, which is why we are so familiar with this force in our every day life. The force carriers of the weak force are the $W^+, W^-$ and $Z^0$ bosons, which couples to particles with flavour, i.e. all fermions. They are all massive particles without colour charge, but they differ in their charge. The $W$ boson have electric charge of $\pm$ the electrons, while the $Z^0$ boson is neutral. Due to their masses, the weak force only works at very short ranges, e.g. inside the nucleus where it is responsible for radioactive decays.

The strong force have 8 force carries, called gluons, which couples to colour. This is the force that binds the nuclei together inside the nucleus, hence the name gluon.
The gluons are massless, but possess colour charge themselves, which makes them self interact. The massless gluons makes the strong force a long range force, but since it only couples to particles with colour charge and due to the colour confinement, the interactions between colours particles is only observed at very high energies or equivalent at very short distances.

The particle content of the SM and their properties is shown in figure 1.1.

Figure 1.1: Particle content of the Standard Model [3].

1.2.1 The Electroweak interaction and SU(2)×U(1) Gauge Theory

The standard theory of electroweak interactions is based on the Glashow-Weinberg-Salam model [2], in which four gauge bosons, the photon, the \( W^\pm \) and the \( Z^0 \) are introduced. Glashow unified the electromagnetic and the weak force by claiming that this theory could be derived from the SU(2)×U(1) gauge group. However, since the masses had to be put in by hand the gauge invariance was destroyed. The generation of masses by the Higgs mechanism[2] was introduced later on by Weinberg and Salam. However, the theory was first fully accepted when t’Hooft in 1971 showed that it was renormalisable.

The reason for choosing this particular gauge group to describe the electroweak interactions is not obvious. However, it has been shown to be extremely accurate in its predictions and it is the simplest group that reproduces the known features of the electroweak physics. Therefore it is widely accepted that the correct gauge group is SU(2)\( _T \)×U(1)\( _Y \), where \( T \) is the weak isospin and \( Y \) the hypercharge. Since the weak force acts differently on left and right-handed particles, the fermions fields are split into a left-handed \( \psi^L \) and a right-handed part \( \psi^R \). The weak isospin is then defined as \( \frac{1}{2} \) for left-handed fermions, which are grouped in SU(2) doublet, and 0 for right-handed fermions, grouped in SU(2) singlets. This transformation for the different field are given by

\[
\begin{align*}
\psi^L(x) &= \frac{1}{2}(1 - \gamma_5)\psi(x) \quad \rightarrow \quad e^{i\tau_j(x)+i\frac{1}{2}Y(x)}\psi^L(x) \\
\psi^R(x) &= \frac{1}{2}(1 + \gamma_5)\psi(x) \quad \rightarrow \quad e^{i\frac{1}{2}Y(x)}\psi^R(x)
\end{align*}
\]

(1.10)

where \( \tau_j, j = 1, 2, 3, \) are the three generators of SU(2) and \( Y \) is the one generator of U(1).

The conservation of the weak isospin and the hypercharge is ensured by the gauge invariance and for a given fermion these quantum numbers determines uniquely how the fermion interacts with other particles in the electroweak theory. Yet, the quantum
1.2 The Standard Model

<table>
<thead>
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<th>Particles</th>
<th>T</th>
<th>T&lt;sub&gt;3&lt;/sub&gt;</th>
<th>Q</th>
<th>Y</th>
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<td>(u, c&lt;sup&gt;′&lt;/sup&gt;)&lt;sub&gt;L&lt;/sub&gt;</td>
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<td>−1/3</td>
<td>1/3</td>
<td>1/3</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1.1: The fermion quantum number in the electroweak theory with hypercharge defined as \( Y = 2(Q - T_3) \).

number of electromagnetism, the electric charge \( Q \), has to be related to the generator \( \tau \) and \( Y \) in order to have a combined theory of the weak and electromagnetic force. Observations lead to the following relation

\[
Q = T_3 + \frac{Y}{2}.
\]

Furthermore, the fermions are given two additional quantum numbers, the baryon number \( B \) and lepton number \( L \). The quarks are given \( B = 1/3 \) and \( L = 0 \), while leptons are given \( B = 0 \) and \( L = 1 \). Hence, this allows us to specify the quantum numbers in the electroweak theory for the fermions as shown in table 1.1. Just as it was the case for QED, the Lagrangian for the electroweak theory can now be constructed by requiring SU(2) \( \times \) U(1) gauge invariance. The gauge invariance ensures the conservation of all the electroweak quantum numbers from electroweak interactions, which means that leptons and quarks cannot disappear or emerge. The gauge invariance leads to new covariant derivatives of the form

\[
\partial_\mu \rightarrow D_\mu = \partial_\mu + ig \tau_i W^i_\mu + ig' \frac{Y}{2} B_\mu
\]

where \( g, g' \) are the couplings between the fermions and the gauges fields. One gets the Lagrangian for the electroweak theory\(^1\)

\[
\mathcal{L}_{\text{EW}} = i \left( \bar{\psi}^L_i \gamma_\mu \psi^L_i + \bar{\psi}^R_i \gamma_\mu \psi^R_i \right) - \frac{1}{4} W^i_{\mu \nu} W^{i \mu \nu} - \frac{1}{4} B_{\mu \nu} B^{\mu \nu}
\]

where \( \psi^L \) and \( \psi^R \) denotes the left- and right-handed fermion fields, respectively, and \( \bar{\psi} = \gamma^\mu D_\mu \). Here, the first term is the kinetic energy and the interaction with the gauge field for left-handed fermions, while the second is the same for right-handed fermions. These two terms is henceforth denoted as \( \mathcal{L}_L \). The last two terms are the kinetic energy and the self-interaction of the gauges field, and will be denoted as \( \mathcal{L}_B \). The field strength tensors of these are given by

\[
B_{\mu \nu} = \partial_\mu B_\nu - \partial_\nu B_\mu
\]
\[
W^i_{\mu \nu} = \mathcal{F}^i_{\mu \nu} - g \epsilon_{ijk} W^j_\mu W^k_\nu
\]
\[
\mathcal{F}^i_{\mu \nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu
\]

\(^1\)Hereafter the \((x)\) argument is omitting in the expressions.
However, since the $W^i_{\mu\nu}$ and $B_{\mu\nu}$ is introduced as massless, they still need to be related to the observed physical particles $W$, $Z^0$ and $\gamma$. This is done by the following linear transformation determined by the Higgs mechanism

$$
\begin{pmatrix}
W^+_{\mu} \\
W^-_{\mu}
\end{pmatrix} = \begin{pmatrix}
1/\sqrt{2} & -i/\sqrt{2} \\
i/\sqrt{2} & 1/\sqrt{2}
\end{pmatrix} \cdot \begin{pmatrix}
W^1_{\mu} \\
W^2_{\mu}
\end{pmatrix},
$$

(1.15)

$$
\begin{pmatrix}
Z^0_{\mu} \\
A_{\mu}
\end{pmatrix} = \begin{pmatrix}
\cos \theta_W & -\sin \theta_W \\
\sin \theta_W & \cos \theta_W
\end{pmatrix} \cdot \begin{pmatrix}
W^3_{\mu} \\
B_{\mu}
\end{pmatrix},
$$

(1.16)

where $\theta_W$, called the weak mixing angle or the Weinberg angle, is defined as

$$
\cos \theta_W = \frac{g}{\sqrt{g^2 + g'^2}}, \quad \sin \theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}.
$$

Now, writing the Lagrangian from equation 1.13 as $L_L + L_B$, the boson interaction part can be rewritten as

$$
L_{LB} = -g\bar{\psi}^{L\gamma\mu}\tau_i W^i_{\mu}\psi^L - g'\bar{\psi}^{L\gamma\mu}\frac{Y}{2} B_{\mu}\psi
$$

$$
= - \left( \frac{g}{\sqrt{2}} \left( J^\mu_{cc} W^+_{\mu} + J^\dagger_{cc} W^-_{\mu} + g J^\mu_{em} A_{\mu} \right) + \sqrt{g^2 + g'^2} J^\mu_{nc} Z^0_{\mu} \right),
$$

(1.17)

where the neutral current $J_{nc}$, the charged currents $J_{cc}$ and the electromagnetic current $J_{em}$ can be expressed as the following by using the Pauli spin step operators $\tau^+ (\tau^-)$.

$$
J^\mu_{cc} = \bar{\psi}^{L\gamma\mu}\tau_i W^i_{\mu}\psi^L,
$$

$$
J^\mu_{em} = \bar{\psi}^{L\gamma\mu}Q\sin \theta_W \psi,
$$

$$
J^\mu_{nc} = \bar{\psi}^{L\gamma\mu} \left( \frac{1}{2} (1 - \gamma_5) T_3 - Q \sin^2 \theta_W \right) \psi
$$

(1.18)

Hence, the gauge field $A_{\mu}$ is identified as the photon, since it only couples to electric charge and does not distinguish between the left- and right-handed particles. Furthermore, the three remaining gauge fields couple to the fermions exactly the way they should for us to identify them as the experimentally discovered particles.

The $Z^0$ also couples to electric charge, but in addition it also couples to flavour, hence allowing it to decay into neutrinos. The $W$ only couples to the left-handed fermions and is responsible for the flavour changing decays (seen by the spin step operator), such as $d' \to u$. These types of decays can only take place inside the doublets, but since the weak isospin doublets is made of gauge eigenstates, that are slightly rotated with respect to the mass eigenstates, the weak interactions can cause decays between all types of flavours.

The relation between the mass eigenstates and the gauge eigenstates is given by introducing a $3 \times 3$ unitary matrix, $V_{CKM}$, known as the Cabbibo-Kobayashi-Maskawa matrix, $V_{CKM}$. This matrix connects the gauge eigenstates, denoted $d'$, $s'$, and $b'$, to the mass eigenstates, denoted $d$, $s$, and $b$.

$$
\begin{pmatrix}
d' \\
s' \\
b'
\end{pmatrix} = V_{CKM} \cdot \begin{pmatrix}
d \\
s \\
b
\end{pmatrix} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} \cdot \begin{pmatrix}
d \\
s \\
b
\end{pmatrix},
$$

(1.19)

2Provided that $e = g \sin \theta_W$
where the u, c, and t quarks by convention are unmixed. An element $V_{xy}$, where $x \in \{u, c, t\}$ and $y \in \{d, s, b\}$ in the $V_{\text{CKM}}$ matrix describes the transition amplitudes between the different quark eigenstates.

### 1.2.2 The Higgs Mechanism

Although the Lagrangian in equation 1.13 describes all the electroweak interactions some of which has been confirmed by observations to an extremely high precision, it is clearly not satisfactory since all particles are massless – in contrast to what has been observed by experiments. Adding mass terms to the Lagrangian by hand turns out to break gauge invariance. Furthermore, masses for the gauge bosons have to be added in a way which give masses to the $W$ and $Z^0$ while the photon remains massless.

A way to achieve this, is the Higgs mechanism. This consists of adding new Higgs fields, $\Phi$, arranged in a SU(2) doublet,

$$\Phi(x) = \begin{pmatrix} \phi_a(x) \\ \phi_b(x) \end{pmatrix} \tag{1.20}$$

with a non-vanishing vacuum expectation value $\langle 0 | \Phi | 0 \rangle \neq 0$. The $\Phi$ doublet is invariant under SU(2)$\times$U(1) gauge transformations, and transforms as the weak isospin doublet, $\psi^L$, following the transformations given in equation 1.10.

The $\Phi$ field will add an additional terms, $L_H$, to the electroweak Lagrangian given in equation 1.13 of the form

$$L_H = (D_\mu \Phi)^\dagger (D^\mu \Phi) - \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \tag{1.21}$$

The parameter $\lambda$ has to be positive for Higgs potential to be bounded from below. For $\lambda > 0$ and $\mu^2 < 0$, the ground state of $\Phi$ will be degenerate with a potential minimum at $\Phi^\dagger \Phi = \frac{\mu^2}{2\lambda}$. Hence, the ground state can be chosen as

$$\Phi_0 = \begin{pmatrix} \phi_0^a \\ \phi_0^b \end{pmatrix} = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \tag{1.22}$$

where $v = \sqrt{-\mu^2/\lambda}$, since any other choice of $\Phi_0$ can be transformed into $\Phi_0$ by a global phase transformation.

The ground state, $\Phi_0$, is not invariant under SU(2)$\times$U(1), and hence the gauge symmetry is broken spontaneously. However, $\Phi_0$ has to be invariant under U(1) in order to preserve conservation of electric charge and keep the photon massless. This can be done by assigning weak hypercharge 1 to $\Phi$, thus from equation 1.11 it follows that the lower component, $\phi_0^b$, has to be neutral.

The Higgs fields can now be expressed as expansion around the ground state in four real fields, $\sigma$, $\eta_1$, $\eta_2$ and $\eta_3$ as

$$\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} \eta_1(x) + i \eta_2(x) \\ v + \sigma(x) + i \eta_3(x) \end{pmatrix} \tag{1.23}$$

By substituting equation 1.23 into equation 1.21, it seems that upon quantisation of the Lagrangian we are left with four real fields. However, by studying the Lagrangian in the unitary gauge [4], it can be shown the only the field, $\sigma$ will give rise to a real massive
The Higgs potential: The Mexican hat, $\mu^2 > 0$.

Figure 1.2: The Higgs potential

Scalar whereas $\eta_1$, $\eta_2$ and $\eta_3$ are unphysical fields and will disappear. The massive scalar created by $\sigma$ is called the Higgs boson.

In the unitary gauge, $\mathcal{L}_B + \mathcal{L}_H$ expressed in the physical fields $Z$ and $W$, can now be written as

$$
\mathcal{L}_B + \mathcal{L}_H = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} F_{\mu\nu} F^{\mu\nu} + m_W^2 W^\dagger \! W^\mu - \frac{1}{2} Z_{\mu\nu} Z^{\mu\nu} + m_Z^2 Z^\dagger \! Z^\mu + \frac{i}{2} (\partial^\mu \sigma)(\partial^\nu \sigma) - \frac{1}{4} m_H^2 (\sigma)^2
$$

$$
+ \mathcal{L}_{BB} + \mathcal{L}_{HH} + \mathcal{L}_{HB} \tag{1.24}
$$

$\mathcal{L}_{BB}$, $\mathcal{L}_{HH}$ and $\mathcal{L}_{HB}$ terms incorporates the interactions among the bosons and $g = 2/\sin \theta_W$. Most notable are the Higgs self couplings given in

$$
\mathcal{L}_{HH} = -\frac{1}{4} \lambda \sigma^4 - \lambda v \sigma^3 \tag{1.25}
$$

and the Higgs coupling to the $Z^0$ and $W$ bosons given by

$$
\mathcal{L}_{HB} = \frac{1}{2} \frac{m_W^2}{v^2} W_{\mu} W_{\mu}^\dagger \! \sigma + \frac{1}{3} g W_{\mu} W_{\mu}^\dagger \! \sigma^2 + \frac{1}{2} \frac{m_Z^2}{v^2} Z_{\mu} Z_{\mu}^\dagger \! \sigma + \frac{1}{3} g Z_{\mu} Z_{\mu}^\dagger \! \sigma^2 \tag{1.26}
$$

which states that the Higgs coupling to the gauge bosons is proportional to the boson mass squared.

The mass parameters given in equation 1.24 are defined as

$$
m_W = \frac{1}{2} v g, \quad m_Z = \frac{m_W^2}{\sin \theta_W}, \quad m_H = 2v^2 \lambda \tag{1.27}
$$

Hence, the non-zero vacuum expectation value of $\Phi$ generates masses to the $W^\pm$ and $Z^0$ and leaves the photon massless. However, an additional term, $\mathcal{L}_{LH}$, has to added to the Lagrangian in order to generate masses for the leptons.

$$
\mathcal{L}_{LH} = -g_l \left( \bar{\psi}_l^L \psi_l^R \Phi + \Phi^\dagger \bar{\psi}_l^L \psi_l^R \right) \tag{1.28}
$$

$$
- g_{\nu_l} \left( \bar{\psi}_l^L \psi_{\nu_l}^R \Phi + \Phi^\dagger \bar{\psi}_l^L \psi_{\nu_l}^R \right) \tag{1.29}
$$
where $g_l$ and $g_{\nu_l}$ are dimensionless coupling constants and $\Phi$ is defined as

$$\Phi = \left( \begin{array}{c} \phi_b^* \\ -\phi_a^* \end{array} \right)$$

(1.30)

This way of generating masses to the fermions is called Yukawa interactions.

In the unitary gauge, the part of the Lagrangian describing interactions between the Higgs boson and fermions, can now be expressed in terms of the physical fields as

$$L_{HL} = -\frac{1}{v} m_l \bar{\psi}_l \psi_l \sigma - \frac{1}{v} m_{\nu_l} \bar{\psi}_{\nu_l} \psi_{\nu_l}$$

(1.31)

where $m_l$ and $m_{\nu_l}$ denotes the fermion masses. Hence the Higgs couplings to the fermions are proportional to the fermion mass.

The final Lagrangian of the EW theory including the Higgs mechanism can now be expressed as a free part $L_0$ and a series of interaction terms

$$L = L_0 + L_{LB} + L_{BB} + L_{HH} + L_{LH}$$

(1.32)

The existence of the Higgs boson is crucial to the success of the EW theory, since higher order Feynman diagrams containing Higgs bosons ensures the renormalisability of the theory. The size of these corrections depends on the Higgs mass, and therefore a theoretical upper limit on $m_H$ can be set around 1 TeV to explain the success of perturbative calculations of EW processes.

### 1.2.3 Quantum Chromo Dynamics

The basics of the EW theory has now been demonstrated, but we have not yet introduced the strong force. The gauge group of the strong force is SU(3), which means that the strong force have 8 gauge bosons, since there are 8 generators of SU(3). Hence, the gauge group of the full Standard Model Lagrangian is $U(1) \times SU(2) \times SU(3)$.

As mentioned earlier the gauge bosons of the strong force, called gluons, couples to colour. The quarks possess one of the three colours red, blue or green, while the anti-quarks possess anti-red, anti-blue or anti-green). The gluons possess both a colour and a anti-colour and cause the colour changing of the quarks. This also means that the gluons couple to themselves.

The theory of the strong force is called Quantum Chromo Dynamics (QCD). In QCD, the coupling constant that controls the interactions between coloured particles, $\alpha_S$ runs, i.e. $\alpha_S$ changes value as a function of the momentum transfer $Q^2$ in the interaction. For large values of $Q^2$ the coupling constant becomes weak, which means the quarks behaves like free particles, while for small values of $Q^2$ $\alpha_S$ diverges due to the self coupling of the gluon. The large value of $\alpha_S$ at low $Q^2$ causes perturbation theory to break down, hence a lower cut-off scale, $\Lambda$ has to be introduced. Below this cut-off perturbation theory is no longer valid. Experimental measurements show that $\Lambda \approx 200$ MeV, so perturbation theory will only be valid well above this scale. A typical limit for $\Lambda$ used in most generators is 1 GeV at which $\alpha_S \approx 0.4$.

Another feature of the strong force is colour confinement, which states that only colour neutral particles can be observed. Therefore no free quarks can be observed, but only bound states such as mesons, consisting of a coloured quark and an anti-quark with the corresponding anti-colour, or baryons, consisting of three quark (or anti-quarks) with different colours.
1.3 Open questions in the Standard Model.

In this chapter the SM has been presented. However, the SM still leaves many open questions to be examined:

- Of the four fundamental forces of nature, only three are included in the SM. In order for gravity in be properly included in the SM, it has to be described by QFT and hence quantised. This has so far not been done successfully. Luckily, gravity is so much weaker than the other forces that it can be neglected for all experimental purposes. Although going to increasingly higher energies and hence smaller distances, gravity will eventually become important and hence has to be included in our calculations.

- This leads to the question: Why is gravity so much weaker than the other forces of nature? From the scale of the electroweak symmetry breaking ($M_{EW} \leq 1 \text{ TeV}$) to the scale where gravity is expected to become as strong as the other tree forces, the Planck scale ($M_{Pl} \sim 10^{19} \text{ GeV}$), is a huge gap of many orders of magnitude. Moreover, if we assume the SM to be valid up to the Planck scale, we would expect the mass of the Higgs boson to receive large radiative corrections from vacuum polarisation. This would make the Higgs mass many orders of magnitude larger than the currently restricted value, unless there is an tremendous amount of fine-tuning cancellations among the quantum corrections. It should be noted that extensive fine-tuning is not prohibited by any fundamental principle, although thought be to unnatural. This problem is known as the Hierarchy problem.

- Another question is: Why do there exist exactly three generations of matter particles?

- The masses of the fermions are generated in the SM by the Yukawa couplings, but their values differ by many orders of magnitude and have to be put in by hand. The SM does not give any physical explanation why the masses of the fermions have such a large span.

- The mass of the neutrinos pose another problem. In the SM, the neutrinos are massless as shown in figure 1.1, however experiments [5] have discovered the neutrinos to indeed be massive particles by showing a mixing between the neutrino types. Yet, these types of measurements only determine the mass difference between the neutrinos with different flavour and not the precise mass. Several ways exist to give masses to the neutrinos, however which of them is the correct only experiments can tell.
CHAPTER 2

HIGGS PRODUCTION AT THE LHC

The discovery or exclusion of the Higgs boson has been named as one of the main goals of the LHC project [6]. At the startup of the LHC, the possible mass of the Higgs had a lower bound at 114 GeV set by the LEP experiments [7] and a theoretical upper limit around 1 TeV as mentioned in section 1.2.2. Recently, these bounds have been tighten significantly, leaving open only a small range in which a new particle consistent with the SM Higgs has been discovered as will be mentioned later. Figure 2.1 shows the recent exclusion plots from both ATLAS [8] and CMS [9] where the Higgs boson has been excluding for all mass points where the solid lines are below 1. The construction of these plots is described in section 9.1.

![ATLAS 2011 - 2012](a) ATLAS [8]

![CMS Preliminary](b) CMS [9]

Figure 2.1: Higgs exclusion limits combined across channels. Observed (solid) and expected (dashed) 95% CL upper limit on the Higgs cross section as a function of $m_H$, scaled to the SM Higgs cross section. The expected limits are derived under the background-only hypothesis, e.g. without the SM Higgs. The filled bands shows the 1 (2) $\sigma$ uncertainty bands on the expected limit.
2.1 Higgs production mechanisms

The production mechanism and decay of the Higgs boson is strongly dependent on its mass. As illustrated in figure 2.2(a) the inclusive cross section for \( pp \rightarrow H + X \) is rapidly decreasing with increasing \( m_H \). The inclusive cross section is also very dependent on the centre-of-mass energy in the collisions. In figure 2.2(b), the inclusive Higgs production is split into the most significant production mechanisms. The largest contribution comes from the gluon-fusion process, \( ggH \), where two gluons produces a Higgs boson through a quark-loop. Since the Higgs coupling to the quarks is proportional to the mass of the quark as illustrated in equation 1.31, the only significant contribution comes from the diagram with the top quark in the quark loop.

![Figure 2.2: Inclusive Higgs production cross section as function of the Higgs mass, \( m_H \).](image)

2.1.1 Gluon Fusion production

The leading-order Feynman diagram for \( ggH \) is shown in figure 2.3(a). Since this process is controlled by the strong dynamics, the next-to-leading-order contributions to this process are large which means that the Higgs is often produced in association with one or more jets when produced through gluon-fusion. It also means that the theoretical uncertainty on the cross section from QCD scales are large. This will be discussed in detail in chapter 8. Figure 2.3(b)-(d) shows the Feynman diagrams for Higgs+1jet production through \( ggH \).

2.1.2 Weak production

The second most dominant production mechanism for Higgs bosons at the LHC is the Vector-Boson-Fusion, VBF \([10, 11]\). The VBF is defined as the \( t- \) and \( u- \)channel Feynman diagrams shown in figure 2.4(a) and figure 2.4(b) where the Higgs boson is produced in
Figure 2.3: Feynman diagrams for Higgs production through gluon-fusion. The leading-order diagram is shown in (a) and the next-to-leading-order diagrams with real emission are shown in (b)-(d).
association with two hard forward jets through a pair of $W$ or $Z^0$-bosons. However this process is only gauge invariant if the $s$-channel diagram, shown in figure 2.4(c), is included as well.

![Feynman diagrams for Higgs production through weak interactions.](image1)

Figure 2.4: Feynman diagrams for Higgs production through weak interactions.

The two forwards jets in the VBF mode allow for a tagging signature of these events and can help discriminate VBF production from other processes [12]. Furthermore, the theoretical uncertainties associated with this process is much smaller than for $ggH$.

The VBF process is unique due to the colour-flow in the process as illustrated in figure 2.5. Both of the two associated jets will tend to be very forward in the detectors and each jet will be colour-connected with the beams remnants travelling in the same direction. This means that additional jets will tend to be produced in the forward regions and that the events will have a rapidity-gap in the central part of the detector without any hard jet activity.

![Example on colour-flow in VBF production.](image2)

Figure 2.5: Example on colour-flow in VBF production. The colour-flows that appear between the upper and lower part of the diagram are separated which will result in a rapidity gap. Each of the two forward jets will be colour-connected with the beam remnants.
The final diagram in figure 2.4(c) where the Higgs boson is produced in association with a $Z^0$ or $W^-$-boson is referred to as *associated production*, $VH$. Since VH and VBF production leaves two distinct signatures in the detector they are usually separated in analyses as two production mechanisms, although they are closely connected. As seen from figure 2.2(b) the VH cross section, is well below that of VBF, but the possibility of reconstructing the weak boson creates a tagging signature for this channel as well.

### 2.2 Higgs branching ratios

![Higgs branching ratios graph](image)

Figure 2.6: Higgs branching ratios, BR, to different final states as a function of the Higgs mass, $m_H$. The filled areas around the curves indicate the total uncertainties on each BR. [13]

In figure 2.6 the Higgs branching ratios, BR, are shown as a function of $m_H$ in the low mass region. At higher values of $m_H$, only the decays to $Z^0Z^0$ and $WW$ are non-negligible. Both these channels have relatively low backgrounds in the leptonic final states. Furthermore, the $Z^0Z^0$ offers a very good mass resolution which enhances the discovery potential and is crucial for determining the Higgs mass in case an excess is observed.

In the low mass region, the decay to a pair of $\tau$-leptons or photons, $\gamma\gamma$, becomes important [14, 15, 12]. The $\gamma\gamma$ offers a very clean signature in the detector and like the $Z^0Z^0$ it has a good mass resolution. In the $\tau^+\tau^-$ channel the mass distribution is smeared due to the neutrinos, however the resolution is still better than in the $WW$ channel. The Higgs decay into $b\bar{b}$ also has a high BR in the low mass region, however this signature is very hard to separate from the huge swamp of QCD-jet background events. Figure 2.7 shows the expected sensitivity from ATLAS [8] for the different decay channels.

Even though the sensitivity across the different channels has a large variation, observing a possible Higgs in several channels is crucial for determining the properties of the Higgs boson. Especially, observing the Higgs boson in both vector boson and fermion final states is important for measuring the Higgs couplings [16] and hence for concluding that an observed particle is indeed a SM Higgs boson.
2.3 Recent discovery of a new Higgs-like particle

Recently, both CMS [17] and ATLAS [8] have announced the discovery of a new Higgs-like boson with a mass around 125 GeV. Figure 2.8 shows local \( p_0 \) value, i.e. the probability that the background through random fluctuations can produce larger signal than the excess observed in data. The local \( p_0 \) value is shown as a function of the \( m_H \), as it has been obtained by ATLAS over time. Clearly, the effect of the new particle is presently well above the 5\( \sigma \) value that by convention is needed to claim a discovery.

The statement that the observed new particle is a Higgs-like boson refers to following. First of all, it must be a boson since it has been seen decaying into two bosons (So far the \( WW, Z^0 Z^0 \) and \( \gamma \gamma \) have been used in the combination). Furthermore, it decays into two photons and therefore it must have spin 0 or 2. Secondly, the new boson has been observed in all the sensitive final states where a sensitive final state refers to a final state with an expected \( \mu \) below 1.

However, so far the new Higgs-like boson have only been observed bosonic final states\(^2\), and in order to conclude that the new particle indeed is the SM Higgs, we need to see it decays into fermions. And the most promising fermionic final states is the \( H \rightarrow \tau \tau \) search channel.

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\(^1\)Here a larger signal means a larger likelihood

\(^2\)Although, the new Higgs-like boson have only been observed in bosonic final states, the expected decay mode for \( \gamma \gamma \) is through a quark loop. Hence, one could argue that a fermionic decay has already been observed.
2.3 Recent discovery of a new Higgs-like particle

Figure 2.8: Combined search results: The observed (solid) local $p_0$ as a function of $m_H$ and the expectation (dashed) for a SM Higgs boson signal hypothesis at the given mass. [8]
Part II

The ATLAS Experiment
CHAPTER 3

THE ATLAS DETECTOR

The ATLAS (A Toroidal Lhc ApparatuS) experiment is the largest of the four main experiments located at the Large Hadron Collider (LHC) at European Organisation for Nuclear Research CERN. It is designed to be a multi-purposed experiment and therefore the requirements for the detector also have a wide range. In this chapter the layout if the ATLAS experiment is described. However a special emphasis is put on the Semi Conductor Tracker and its prompt calibration, since a large part of the thesis work has been implementing and operating this procedure. Also the ATLAS computer model is described. Here, part of the thesis work has been acting as Production Manager of the SCT.

3.1 The Large Hadron Collider

The LHC [18] has been designed to collide bunches of up to $10^{11}$ of protons (p) at a rate of 40 million times per second generating pp-collisions with a centre-of-mass energy of 14 TeV and a instantaneous luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$ extending the energy and luminosity frontier with a factor of $\sim 10$ and $\sim 100$ in comparison to the previous hadron colliders [19]. In addition to colliding protons, the LHC also has a heavy ions program which will not be covered here.

Currently, the LHC is not at the stage in its running program where the peak design criteria are reached. Instead the LHC is currently running with a centre-of-mass energy of 8 TeV and a peak luminosity $\sim 8 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$. Below, the major milestones from the start up of the LHC until now are sketched.

- 10 Sep 2008: First colliding protons at the LHC.
- 23 Nov 2009: First collisions at 450 GeV in all 4 detectors.
- 30 Nov 2009: First collisions at 1.18 TeV per beam.
- 30 Mar 2010: First collisions at 7 TeV.
- 5 Apr 2012: First collisions at 8 TeV.
- 4 July 2012: First announcement on the observation of a new boson consistent with the Higgs boson.

In figure 3.1 the integrated luminosity of the LHC in the three years of data taking is shown as measured by the ATLAS online monitoring.
The ATLAS Detector

The high interaction rates and the high beam energies at the LHC lead to a great potential for discovering new physics, but these also set the requirements to the detector in order to extract the few important events from the huge amount of background events. These requirement are:

- A high precision electromagnetic calorimeter for identification and reconstruction of electrons and photons
- A fully covering high precision hadronic calorimeter for identification and reconstruction of jets and missing transverse energy.
- A muon spectrometer for high-precision muon momentum measurements outside the calorimeters.
- A strong magnetic field to be increase the curvature of tracks from charge particles – especially muons.
- An efficient tracking for measuring the momentum and charge of high-$p_T$ particles and enable reconstruction of particle vertices.
- Fast and radiation-hard electronics.
- A fast triggering and data-acquisition system.

The overall layout of the ATLAS detector – shown in figure 3.2 – consists of an Inner Detector (ID) responsible for the tracking of charged particles, two calorimeters responsible for measuring energies of particles and an outside muon system responsible for tracking of muons. The ID is surrounded by a thin superconducting solenoid magnet generating the inner magnetic field while a large superconducting air-core toroid generates the magnet field in the outer part of the detector. A detailed description of the ATLAS detector is given in [20]
3.2 Coordinate System

In order to describe the detector in a consistent way, a common coordinate system is defined within the experiment. The origin of this coordinate system is taken to be the nominal interaction point. In cartesian coordinates, the z-axis is defined to be along the beam direction, the x-axis is pointing towards the centre of the LHC ring and the y-axis is pointing upwards. In spherical coordinates instead of the polar angle, $\theta$, it is often convenient to use the pseudo-rapidity, $\eta$, defined as $-\ln(\tan \theta/2)$. Unless stated otherwise, the transverse variables, e.g. transverse momentum, $p_T$, are defined as the component in the $x-y$ plane. The measure of object separation $\Delta R$ is defined in the pseudorapidity-azimuthal angle space as $\Delta R = \sqrt{\phi^2 + \eta^2}$.

3.3 The Magnet System

As mentioned earlier the ATLAS magnet system is divided in two parts, a central solenoid and an outer air-core toroid. The central solenoid, surrounding the ID, generates a magnetic field parallel to the beam axis with a slightly varying field strength of 2 T at the centre of detector and a peak value of 2.6 T at the solenoid. The solenoid has a length of 5.3 m, an inner diameter of 2.44 m and an outer diameter of 2.63 m. Due to its placement in front of the calorimeters, it has to contain as little material as possible to get as precise an energy measurement as possible.

The air-core toroid consists of two end-cap toroid magnets and the barrel toroid magnet. The barrel toroid part is placed in as large coils outside the calorimeters, while the end-cap toroids are placed at each end of the central solenoid magnet and inserted into the barrel part at each end. Both end-cap and barrel part consist of 8 coils placed in symmetrically around the beam pipe, therefore generating a strongly non-uniform field.
which has to be monitored and taken into account for the reconstruction of tracks.

The choice of a solenoid magnet in the central part of the detector ensures a small magnetic field in the calorimeter compared to the outer field, which is important for measuring the shower shapes in the calorimeter. The strong field in the outer part ensures a good momentum resolution in the muon spectrometer.

3.4 The Inner Detector

The ID [21], shown in figure 3.4, is responsible for the tracking of charged particles and consists of three sub-detectors using different technologies: closest to the beams the silicon pixel detector, next the Semi-Conductor Tracker (SCT) and farthest away from the beam axis the Transition Radiation Tracker (TRT). The outer dimensions of the ID are 5.6m (length) and 2.1m (diameter).
The main purpose of the ID is high precision tracking of charged particles providing a good reconstruction of the 4-momentum and the vertex of the tracks. The material budget in of the ID had to be minimised to reduce multiple scattering, worsening the momentum resolution, and to reduce energy loss before particles reaching the calorimeters. All the three sub-detectors of the ID, described in the following sections, are divided into barrel and end-cap parts.

### 3.4.1 The Pixel Detector

The pixel detector is the innermost detector in ATLAS providing the highest precision measurements for the tracking and vertex determination. It contains 80 million channels, placed in three concentric cylinders around the beam axis in the barrel part and in three disks perpendicular to the beam axis in each end-cap. The sensor size of $50 \times 400 \, \mu m^2$ generates a hit precision of $10 \, \mu m(r-\phi)$ and $115 \, \mu m(z)$ in the barrel regions and $10 \, \mu m(r-\phi)$ and $115 \, \mu m(r)$ in the end-caps. The pixel detector covers an $\eta$ range up to 2.5 as shown in figure 3.5.

### 3.4.2 The Semiconductor Trackers

The SCT, also depicted in figure 3.5, consists of 6.3 million silicon strip channels grouped in 4088 modules with 1536 channels per module [22]. In each module, the strips are placed in two back-to-back layers which are slightly rotated by a 40 mrad stereo angle wrt. each other. In this way, information on a measured hit is obtained along the strip
direction and a full 3D space point measurement is obtained. The modules are placed in 4 barrel cylinders and 18 end-cap disks, designed so particles will pass 8 layers on their way from the interaction point throughout the detector. Due to this the end-cap and barrel modules have different geometries. For the barrel modules the strip pitch is 80 $\mu$m while the pitch varies from 56.9 – 90.4 $\mu$m in the end-cap disks. The SCT covers a pseudo-rapidity range of $|\eta| < 2.5$ with a hit precision of 17 $\mu$m($r$-$\phi$) and 580 $\mu$m($z$) in the barrel modules and 17 $\mu$m($r$-$\phi$) and 580 $\mu$m($r$) in the end-caps.

### 3.4.3 Transition Radiation Tracker

The outermost part of the ID, the TRT has approximately 351,000 readout channels. Instead of few high precision measurements, the TRT, provides a series of tracking measurements by hits generated in 4 diameter straws tubes with a 30 $\mu$m tungsten wire in the centre and filled with a mixture of 70% Xe, 30% CO$_2$ and a small amount of O$_2$. A typical track has approximately 30 hits in the TRT, which allow for an almost continuous tracking of the particles in the region of $|\eta| < 2.0$. The TRT provides $r$-$\phi$ information with an intrinsic accuracy of 130 $\mu$m per straw. A third coordinate cannot be obtained since the space point coordinate along the wire direction can not be determined. In the barrel part, covering $|\eta| < 0.8$, the straws are placed parallel to the beam axis with the wires divided into two halves at $\eta = 0$, while in the end-caps, covering from $|\eta| = 0.8$ and up, the straws are arranged radially to maximise the numbers of straws passed by a particle coming from the interaction point.

The combination of the inner very precise trackers with the TRT at a larger radius gives very robust pattern recognition and high precision with a full set of track coordinates. Especially for high $p_T$ tracks the outer measurements by the TRT contributes significantly to the track resolution.

The TRT also provides a good electron identification. Due to the transition radiation produced by highly relativistic particles ($\gamma \geq 1000$) passed the material between in the TRT straws, good separation between electrons and charged pions is achieved.

### 3.5 Calorimeter

Outside the ID, the calorimeter system is placed as shown in figure 3.6. It consists of a fine granularity liquid-argon electromagnetic (EM) calorimeter and a coarser hadron calorimeter. The EM has a pseudo-rapidity range of $|\eta| < 3.2$, hereby fully covering the of the ID and providing valuable information on photons and electrons, while the hadronic calorimeter extents its range up to $|\eta| = 4.9$. Both calorimeters have an almost complete coverage in $\phi$ which together with the large $\eta$-range is crucial for the ability of reconstruct missing transverse energy, $E_{T}^{\text{miss}}$.

Calorimeters have to provide good containment for electromagnetic and hadronic showers and minimise the amount of particles faking muons by reaching the muon system. Therefore, the depth of each of the calorimeters has been an important design criteria.

#### 3.5.1 Electromagnetic calorimeter

The EM calorimeter consists of a barrel part, covering $|\eta| < 1.475$, and two end-cap parts, covering $1.375 < |\eta| < 3.2$. The barrel is divided into two half-barrels, which
are separated by a small gap of 6 mm in the middle. Each end-cap is divided into an inner wheel, covering $2.5 < |\eta| < 3.2$, and an outer wheel, covering $1.375 < |\eta| < 2.5$. This splitting is done to optimise the granularity and dimensions in each region. In the EM calorimeter the energies are measured by having alternating layers of absorbing material of high density (lead), which will make the particles start showering, and layers of active materials (LAr), that will detect the showering particles. To get a homogeneous response in $\phi$, each LAr cell is made in an accordion shape. The multilayer structure of the calorimeter allows for determination of the lateral and longitudinal shower shapes.

The layout of the magnet system and the material used in the calorimeter ensures that the magnetic field inside the EM calorimeter is small, which is important when determining the shape of showers made by incoming particles. A strong magnetic field inside the calorimeter would have caused an artificial broad shower shape. Unfortunately the solenoid adds extra material in front of the calorimeter, which can cause the particles to start showering before they reach the calorimeter and thereby make the energy measurements less precise.

**The presampler:** In order to correct for the energy loss in the ID and the solenoid, a single layer of LAr has been put in front of the EM barrel. This layer, called the presampler is not shown in figure 3.6. It only covers the region $|\eta| < 1.8$, since this is the region where particles pass most material in the ID due to the solenoid magnet.

**The first sampling:** The first layer in the longitudinal direction in the barrel and the end-caps has the finest granularity ($\Delta \eta \times \Delta \phi \approx 0.025 \times 0.1$) in order to best determine the impact point in the calorimeter and in order to separate neutral pions from single photons. The presence of additional neutral pions is important
for reconstruction of \( \tau \)-lepton which decays into hadrons. The depth of the first sampling is 4.3 radiation lengths (\( X_0 \)).

The second sampling: The second layer in the EM calorimeter is 16 \( X_0 \) deep, and is where most of the energy is deposited. In order to get a precise direction measurements in the EM calorimeter a fine granularity in both \( \eta \) and \( \phi \) in the second layer is needed. Although, the granularity in the second sampling is a factor \( \approx 5 - 10 \) worse in \( \eta \) and a factor \( \approx 2 \) in \( \phi \) than in the first sampling.

The third sampling: The third layer in the EM calorimeter only exists in the barrel and the outer wheels of the end-caps. It mainly has to measure leakage from the second sampling generated by very energetic particles. The resolution in \( \phi \) is the same as for the second sampling, but is reduced by a factor 2 in \( \eta \). The depth of the third sampling is 2 \( X_0 \).

3.5.2 Hadronic calorimeter

Surrounding the EM calorimeter is the hadronic calorimeter, divided into a barrel part, two extended-barrels and two end-caps. In order to achieve the required stopping power of particles and radiation hardness, the hadronic calorimeter consists of different types. The barrel, covering the region \(|\eta| < 0.8\), and the two extended-barrels, covering the range \(0.8 < |\eta| < 1.7\), are made up of samplings of steel and scintillating tiles. Both barrel and extended-barrel are divided azimuthally into 64 modules and in depth into three layers with an approximate thickness of 1.5, 4.1 and 1.8 interaction lengths in the barrel and 1.5, 2.6, and 3.3 in the extended barrels. The outer radius of the tile calorimeter is 4.25 m.

The two end-cap calorimeters are LAr calorimeters located directly in extension of the EM end-caps. Each of the end-caps consist of two wheels covering a range of \(1.5 < |\eta| < 3.2\) and hereby creating a small overlap with both the forward calorimeter, starting at \(|\eta| = 3.1\), and the barrels of the tile calorimeter. The wheels are divided into 32 modules in \( \phi \) and two segments in depth. The thickness of the steel layers are doubled in the outer wheels (50 mm) compared to the inner wheels (25 mm). Each layer of LAr has a depth of 8.5 mm in both wheels.

In addition to the Hadronic end-caps calorimeter a forward calorimeter covers the high density region \(3.1 < |\eta| < 4.9\). This calorimeter is also LAr based, but uses tungsten in two of its three layers as an absorbing material to make it more dense and more radiation hard. The depth of the forward calorimeter is approximately 10 interaction lengths.

3.6 Muon Spectrometer

The muon spectrometer is the outermost part of the ATLAS detector, and also the largest sub-detector. Due to the strong magnetic field, it enables a high-precision tracking of muons. Since mostly only muons reach the muon spectrometer, it also provides a high trigger efficiency on high-\( p_T \) muons.

The muon system consists of four different sub-detectors. The Monitored Drift Tubes (MDT), covering the \( \eta \)-range of up to 2.7 (2.0 for the innermost layer), are responsible for the precision tracking. The MDT’s are aluminium tubes of 3 cm in diameter with an
anode-wire in the middle. The tubes are filled with a gas consisting of $93\%$ Ar and $7\%$ CO$_2$. The average drift time in the MDT’s is 300 ns and the expected resolution on a single wire is $\sim 80 \mu m$.

In $\eta$-range of $2.0 - 2.7$, the precision tracking is done by the Cathode Strip Chambers (CSC), which are multi-wire proportional chambers, and provides an even higher granularity than the MDT to sustain the high radiation level expected in this region.

In order to provide extremely fast feedback for the trigger system, special subdetectors are needed for the muon system. In the barrel part, this is provided by the Resistive Plate Chambers (RPC), covering $|\eta| < 1.05$, while the Thin Gap Chambers (TGC) are covering in the end-cap region, $|\eta| < 2.7^3$. The RPC’s and TGC’s also measures the coordinate perpendicular to the wires in the MDT’s and CSC’s, hence providing an additional coordinate to the measured space points. The layout of the muon spectrometer with the different types of chambers can be seen in figure 3.7.

![Figure 3.7: An overview of the muon spectrometer with the different types of muon chamber [20].](image)

For precision measurements the Monitoring Drift Tubes and Cathode Strip Chambers are used, while the triggering uses the Resistive Plate Chambers and Thin Gap Chambers.

## 3.7 Trigger System

Even for the low luminosity runs in the first years of data-taking, the event rates are too high for all events to be recorded. Therefore, a coarse selection of which events to keep is needed. This triggering on events is designed to select potentially interesting events by

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$^3$The TGC covers an $\eta$-range up to 2.7, but only provides trigger information in the region up to $|\eta| = 2.4$. 


using increasing levels of information details. The triggering is divided into categories dependent on its signature, e.g. high-$p_T$-lepton or jet, or large $E_T^{\text{miss}}$, and later combined into menus.

At design peak luminosity, $\sim 10^9$ collisions will happen in the ATLAS detector each second. However, the maximal event rate which can be stored due to limitations in bandwidth, cpu and storage capacity, is $\sim 10^2$ events per second. This means that a reduction of $10^7$ is needed. Since the main part of the collisions will be soft interaction without interest for most studies at the LHC, most of the trigger menus are based on high-$p_T$ signatures of leptons. While most of the bandwidth in the trigger is used for these physics streams, dedicated calibration and random triggers also exist for performance studies.

Since getting clean signatures in most cases requires some computations with increasing cpu requirement dependent on the purity of the signature, the ATLAS trigger system is divided into three trigger levels, with increased event information available for processing at each level and increasing demands on the purity which each level lets through. The trigger and data-acquisition system can be seen in figure 3.8. Level 1

![Figure 3.8: Overview of the trigger design in ATLAS. Both design and present rates at each level of the triggering system is indicated.][23]

(LVL1) of the trigger system is designed to reduce the event rate to $< 75$ kHz. This is part of the trigger system is hardware-based due to the high demand on the decision time ($\sim 2.5\mu s$). The LVL1 makes a decision on whether to skip the event or send it to the
next level for further processing. This decision is based on the muon information from the muon trigger chambers as described in section 3.6 and a reduced information from the calorimeter. In the muon chambers the decision is based on candidates for high-$p_T$ muons, while in the calorimeter the signatures are high-$p_T$ objects, e.g. electrons, photon or jets, as well as large $E_T^{\text{miss}}$ or large total transverse energies.

During the LVL1 processing time, the full event information from all the sub-detectors are kept in the trigger readout pipelines. If an object passes the LVL1 trigger requirements, a region-of-interest (RoI), is defined as a suitable region in the detector around this object. When an event passes the LVL1 trigger, full detector informations from all RoI’s are send to the second trigger level (LVL2).

At LVL2, information from the RoI’s is processed using more sophisticated cuts, and the event rate is reduced to $\sim 3$ kHz. Normally, only a small fraction of the detector is selected as RoI. For the muons tracking information from the precision chambers is combined with the tracking information from the ID, hereby improving the $p_T$ measurement, and isolation information from the calorimeter is processed. For the electrons, the LVL2 matches calorimeter information to tracks in the ID as well as processing particle identification from the TRT.

Events that fulfill the requirement of the LVL2 are passed on the third level, the Event Filter (EF). At this level, the algorithms are very similar to the offline reconstruction algorithms. The designed output event rate of the EF is $\sim 200$ Hz, which corresponds to $\sim 200$ MB/s of stored data.

Figure 3.9 shows the output rate in ATLAS for different $\tau$-trigger menus in 2012. Section 5.3.2 describes the trigger menus used in the $H \rightarrow \tau\tau$ analysis in more detail.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{output_rate.png}
\caption{Output rate of different tau trigger menus during 2011 data taking [24].}
\end{figure}

\footnote{The energies in the calorimeter at LVL1 is calculated in towers by adding up the energy in all the samplings.}
3.8 ATLAS Computing Model

The design of the ATLAS Computing Model is described in the Computing Technical Design Report, C-TDR [1, 25]. The computing challenges foreseen in the C-TDR consist of the following

- An enormous amount of data. The foreseen size of the data from the ATLAS experiment amounts to many petabytes of raw and processed data every year.
- A diversity of different data formats with big variation of files sizes.
- A world-wide user community.

In order to cope with these challenges, a very hierarchical computing model is defined in order to ensure a stable and robust running. This structure should guarantee both that official data cannot be compromised by user interaction and that sufficient resources remain available for the offline reconstruction and processing of data and no bottle-necks occurs while constant resources also are accessible for single user analysis. The solution for this has been the Grid [26] and the Tiers-of-ATLAS structure which allows to maintain the both strict and yet flexible structure needed to meet the continuously updated requirements from the experiment.

3.8.1 Data formats

![Diagram](image)

(a) Data formats (b) Tiers-of-Atlas structure [25]. The Tier-3’s are left out.

Figure 3.10: ATLAS Computing Model.

The processing chain in ATLAS is depicted in figure 3.10(a). For full chain simulations, events from MC generators are converted to an Event-Summary-Data, ESD, through a GEANT4-simulation[27] of the particles interaction with the detector followed
by a digitalisation modelling of the detector response. This format is identical to the format produced by the offline reconstruction software for real data – except the truth record from the MC generator.

The ESD format contains almost all information from the reconstruction – including hits in the tracker and cell information in the calorimeters – and has a size of $\sim 1$ MB/event. From this format a chain of slimmed formats are derived keeping only a smaller and smaller fraction of information needed in the physics analyses. The final format used in most physics analysis is the D3PD format which is a ROOT ntuple.

For real data, events are split into blocks of a fixed integrated luminosity where each RAW file stored offline matches a single luminosity block. The block size is defined sufficiently small that detector and accelerator conditions can be assumed constant with one block. As data leaves the detector, it is split up into streams defined by their triggers, e.g. e-gamma stream, muon stream or ETmiss-Jet stream, which are kept separate throughout the full processing. The event overlap between different streams is $\sim 10\%$. A few special streams are also defined for detector calibration and monitoring purposes, but also an express stream which contains mixture of all physics streams.

### 3.8.2 The Tiers-of-ATLAS

The distributed computing model of ATLAS is divided into four level\(^5\), referred to as Tiers, as illustrated in figure 3.10(b).

#### Tier-0 and AF

The first level in the data processing model is the Tier-0 hosted at CERN. This centre is responsible for the first pass processing of the express streams and calibration streams from the RAW format into ESD’s and AOD’s. The Tier-0 is also responsible for exporting the RAW and derived data to the Tier-1 for improved reconstruction. Therefore large disk capacity is required at Tier-0. An integrated part of the Tier-0, is the Calibration and Alignment Facility, CAF, which takes care of the calibration and alignment tasks performed on the express and calibration streams. The Tier-0 also processes a fraction of the data from the physics streams in the bulk processing of data, while the rest of the data is shipped to the Tier-1’s.

#### Tier-1

There exist 10 Tier-1 centres around the world. Each receive a portion of the RAW data and is responsible for the reconstruction of this portion using the updated calibration and alignment constants. The Tier-1 is also responsible for the long-term storage of the derived data formats from its portion of data. In addition to the processing of real data, the Tier-1’s are also performing the main part of the processing of simulated data.

Furthermore, the Tier-1’s are providing a connection to the Tier-2’s. This means that all data transfers between Tier-2 centres goes through the Tier-1’s.

#### Tier-2 and Tier-3

The Tier-2 and Tier-3 are where the user analysis tasks are performed. All formats until D3PD production are derived by the ATLAS central production system. The Tier-2’s and Tier-3’s provide dedicated resources for user analysis.

\(^5\)Originally, the Tier-structure of ATLAS was defined as a three-level structure. However as the need for distributed storage of output from user analysis increased, a fourth level (Tier-3’s) where added
Since long-term storage for user generated data was not foreseen in the original computing model, a distinction is made between Tier-2’s and Tier-3’s depending on whether long-term storage for user data is available or not.

3.9 Calibration and Alignment

The ATLAS calibration and alignment tasks cover a wide variety of processes generating non-event data to be used for the reconstruction or monitoring of the detector [28]. The input data can come from one or more sub-detectors and the format ranges from dedicated readout on the individual sub-detectors to fully reconstructed event data. The output from all calibration and monitoring processing is stored in a conditions COOL database which can be accessed both by the online system as well in the reconstruction or analysis steps later on.

The calibrations tasks can be categorised in the following ways:

**Online calibration:** The purpose of the online calibration is to provide immediate feedback. Therefore these tasks are performed on resources at Point 1 very close to or on the detector. The online category is further divided depending on whether the processes are performed on subsystem readout (ROD) or in the Event Filter (EF) system. Both types of calibration need special triggers or dedicated calibration runs as well as dedicated resources in terms of CPU and disk spaces. However, whereas the ROD calibration tasks are limited by only having access to a partial event information, the EF system has access to the full event. The online calibration is very limited by both the time and resources available.

**Offline calibration:** The offline calibration runs on reconstructed events and its purpose is to further improve the reconstruction as much as possible. These tasks run either on Tier-0 at CERN or at the Tier-1’s outside CERN.

**Prompt calibration:** The prompt calibration sits in between the online and offline calibration. The purpose of these tasks are to process the express stream of the RAW data as fast as possible to provide the best possible detector status to the reconstruction before the reconstruction of the full physics data starts. These tasks are run on a dedicated part of the Tier-0 in order to optimise both the performance power and the feedback time.

3.10 Prompt Calibration Model

In figure 3.11, an overview of the Data Quality workflow is depicted. Once data is recorded the process of all physics streams, the *bulk* reconstruction, is delayed for 36 hours\(^6\). During this period the express stream and calibration streams are processed by the Prompt Calibration, and before the period has ended the new calibration and alignment data is uploaded to the central database. Once the bulk processing start, the updated detector conditions can be used.

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\(^6\)The initial delay period for the bulk reconstruction was 24 hours, but since some calibration task took longer than this, the period was extended to 36 hours.
3.10 Prompt Calibration Model

3.10.1 Task Management System

The Task Management System (TMS) is responsible for creating, monitoring, and controlling tasks running on Tier-0 as well as the staging of data to and from these tasks. The system was originally developed to handle bulk reconstruction tasks running at Tier-0, but as the need for more robust and automatic handling of the calibration tasks increased, its use was expanded to the prompt calibration tasks.

The SCT was the first sub-detector to deploy this system, but the use of TMS has later been deployed to several other sub-detectors including the Pixel and TRT.

In TMS, a task is defined as an entry in the Task Database (DB). Such an entry contains information on the task description, input and output datasets, associated jobs at Tier-0 and a global status. A single task will most commonly contain several jobs. An example from the reconstruction is the \texttt{ESD2AOD} task which converts ESD datasets into an AOD dataset. For each new ESD dataset a task will be created, however each ESD dataset contains many files and therefore each task will most likely contain several jobs, e.g. one job for each file in the dataset.

The typical workflow of the TMS system, sketched in figure 3.12, consists of following steps:

- The TOM daemon scans the central database for new datasets. In case a new dataset matches the task criterions defined in any of the tasks, a new task will be inserted in the Task DB. An example criterion for task creation could be the number of events in the dataset. Until the jobs associated to this task are defined, the task will have status \texttt{DEFINED}.

- The central Eowyn daemon scans the TMS DB for tasks. If a task with status
Figure 3.12: Overview of the Task Management System workflow. The TOM deamon handles all task management, while the central Eowyn deamon is responsible for the handling of individual jobs inside each task.

**DEFINED** is found, jobs are created according to the task description and submitted to Tier-0. The task status is then changed to **RUNNING**

- The Eowyn regularly scans the jobs status and update the task status accordingly. If jobs have failed they are automatically resubmitted. The Eowyn also handles the staging of input files and output files produced by each job.

- Once all jobs belonging to a task have finished, the TOM deamon changes the status of the task to **FINISHED**.

The TMS also provides a web service that allows user interaction with the Task DB. This enables users to manually abort or create tasks which can be useful both for testing purposes and for cases of special runs.

The webpage called the TaskLister, shown in figure 3.13, enables the user to easily monitor both current and past tasks. For each task the task name and type is listed together with the number of failed, running and successful jobs. In case a task has failing jobs, a link is provided to a copy of the log files which make quick debugging possible for the user.
Figure 3.13: Screenshot of the TaskLister webpage for monitoring of tasks. For each task the numbers of successful, running and failed jobs are shown. For failed jobs a link is provided to the log file of the job.
3.10.2 SCT Prompt Calibration

For the SCT Calibration, a special instance of the TOM daemon is running, controlling SCT calibration task, while the centrally managed Tier-0 Eowyn daemon controls all jobs running at the Tier-0 including the SCT calibration jobs. Upon initialisation, the TOM daemon reads in a configuration file with all the tasks description. Having a separate instance of the TOM daemon, enables easy change task parameters (both criteria and description) without affecting the rest of the Tier-0 workflow. The task criteria includes a search string for which datasets to process and a requirement on the minimal number of events in the dataset, while the task parameters contain more SCT specific settings.

Since TMS was initially developed to handle the bulk reconstruction workflow, several features needed to be implemented in order to facilitate the calibration tasks. In the reconstruction workflow the processing of datasets is split up into several identical sub-jobs running in parallel to allow faster processing. After all sub-jobs are done the output from all sub-jobs are merged into a new dataset which can be passed on to the next step in the reconstruction chain. For the SCT calibration, each dataset needs to be processed as a whole. This quickly generated problems as the size of datasets rose and the data became to large to be shipped to a single node on the Tier-0. In order to cope with these large datasets, a mechanism was developed to continuously stream data from the storage to the Tier-0 nodes. In addition to the space issues, the SCT calibration also needed to run several different tasks for each run – one for each calibration routine since these produce different output and in some cases take different input types.

\footnote{An example of a SCT TOM config file is given in appendix A}
Part III
Analysing Pairs of $\tau$-leptons
4.1 Reconstructing the $\tau^+\tau^-$ rest frame

At LHC energies, due to the short life time of the $\tau$-lepton, it is only possible to study $\tau$-leptons indirectly through their decay products. This introduces great challenges because of the neutrinos always present in the decays, which leads to an inconsistency between the visible 4-momentum of the decay products, the $\tau$-jet, and the 4-momentum of the true $\tau$-lepton.

This deviation in the 4-momentum makes it impossible to exactly calculate the rest frame, RF, of a resonance, decaying into a pair of $\tau$-leptons as well as accurately reconstruct the mass of the decaying resonance. Although, an approximation of the RF, is given by the centre-of-mass frame of the two visible $\tau$-jets, this frame will, by construction, always reconstruct the energy of the two $\tau$-jets to be equal. Hence this will give a poor frame to study helicity correlation of the two $\tau$-leptons.

Furthermore, the invariant mass of the two $\tau$-jets, $M_{\text{vis}}$, will greatly underestimate the invariant mass of the resonance as shown in figure 4.1 for $Z_0$-bosons.

In the RF of a heavy resonance, i.e. $Z_0$-bosons, decaying into a pair of $\tau$-leptons, the direction of the two $\tau$-jets will only deviate slightly from that of the $\tau$-leptons. Hence the two $\tau$-jets will appear nearly back-to-back in this frame. This can be exploited to find an approximation to the RF. For any given frame of reference the acollinearity – defined as angular difference for the two $\tau$-jets to be completely back-to-back, $\alpha = \pi - \angle(\tau_1, \tau_2)$ – is a well-defined number between zero and $\pi$. Hereafter, $\alpha$ denotes the acollinearity between the two $\tau$-jets and $\alpha_{\text{RF}}$ denotes the acollinearity in the resonance rest frame.

At LHC energies, $Z_0$-bosons (or possible light Higgs bosons) are produced with a large boost with respect to the detector frame predominately in the direction along the beam axis$^1$ as shown in figure 4.2. Therefore, the measured 4-momenta of the $\tau$-jets in the detector frame will deviate significantly from those in the RF.

As shown in figure 4.3, $\alpha_{\text{RF}}$ is expected to be small, with an average value of 0.28 rad. for $Z_0$-bosons and 0.50 rad. for 125 GeV $ggH$ Higgs bosons. This fact has been used

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$^1$In the case of a Higgs boson, both the size and direction of the boost will depend on the production mechanism.
Reconstructing the $\tau^+\tau^-$ rest frame

Figure 4.1: Visible mass distribution for $Z \to \tau\tau+\text{jets}$ in PYTHIA8+TAUOLA simulations pp-collisions at $\sqrt{s} = 7$ TeV.

Figure 4.2: Boost magnitudes and angles for $Z^0$ and Higgs bosons at different energies simulation using PYTHIA8. At both energies both $Z^0$ and Higgs bosons are created with a high boost predominantly along the beam axis.
to develop a technique for reconstructing the RF [29]. The technique is divided into two categories, depending on whether the transverse part of the boost should be estimated.

![Graphs](image_url)

Figure 4.3: Acollinearity in the laboratory frame and the true rest frame for $Z^0$-bosons and Higgs at different energies.

### 4.1.1 The BoostZ-method

In the simplest method, the $p_T$ of the resonance is assumed to be negligible and therefore only the longitudinal boost, $\beta_z$ is reconstructed. The method, hereafter referred to as BoostZ-method [29], consists of searching for the $\beta_z$ that minimises $\alpha$. Since $\alpha$ is a well-defined positive number for any applied boost and $\alpha$ is a one-dimensional function of $\beta_z$ with a single minimum, this minimisation is highly reliable and the minimum can be found using a simple and fast binary search\(^2\).

In figure 4.4, $\alpha$ is shown as a function of applied $\beta_z$ for different $Z \rightarrow \tau\tau$ events in 7 TeV pp-collisions simulated using PYTHIA8 [30]. In all the events the minimum of the curves is close to the true $\beta_z$ of the $Z^0$-boson.

### 4.1.2 The BoostXYZ-method

The BoostZ-method works well for events with relative small $\beta_T$ which covers most part of both $Z^0$ and Higgs boson events produced at the LHC. On the other hand since events where the resonance is produced with a large $\beta_T$ are easier to trigger on at the LHC, it can be vital to extend this method to also be able to cope with such events.

In general, there always exists an infinitely set of frames of reference with $\alpha = 0$. Therefore it is not possible to do a sensible global minimisation of $\alpha$. Instead one has to restrict the allowed search directions – preferably to a subset of possible boosts which only contains a single minimum. This is exactly the strategy in searching for the boost along the beam axis in the BoostZ-method.

\(^2\)The minimisation procedure has also been cross checked using more sophisticated minimisation routines.
4.1.3 Performance using ATLAS simulations

In [29], the performance of both the BoostZ-method and the BoostXYZ-method is documented using generator level quantities. However, in order to fully test the performance of this technique, it is vital to do more complete studies using realistic detector reconstructed variables.

Since the BoostZ-method only relies on measured particles directions, its performance is not expected to be significantly degraded using reconstructed quantities. For the BoostXYZ-method the performance will depend heavily on the ability to estimate the transverse direction.

In the following the performance of the BoostZ-method and BoostXYZ-method is tested for reconstructed variables using full ATLAS detector Monte Carlo simulations listed in table 4.1. To get a realistic performance a loose preselection is applied on the events. The selection requires exactly two reconstructed $\tau$-leptons with $p_T > 15$ GeV and $|\eta| < 2.5$ to be within the detector resolution. Only $\tau$-leptons with 1 or 3 associated tracks are considered. Furthermore to be able to compare the reconstructed RF with the true boson RF both reconstructed $\tau$-leptons are required to be matched to a true lepton ($e, \mu$ or $\tau$) in the generator level event record.

Figure 4.5 shows the difference in reconstructed and generated $\beta_z$ for the different
4.1 Reconstructing the $\tau^+\tau^-$ rest frame

<table>
<thead>
<tr>
<th>Process</th>
<th>Generator</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ggH \rightarrow \tau\tau$</td>
<td>PowHEG+PYTHIA</td>
<td>250k</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>PYTHIA8</td>
<td>3M</td>
</tr>
</tbody>
</table>

Table 4.1: Dataset used to evaluate the rest frame reconstruction performance. For Higgs samples a Higgs mass of 120 GeV has been used.

samples divided into the decay mode of the $\tau^+\tau^-$-system. In both Higgs and $Z^0$ events, the performance of reconstructing the $\beta_z$ is good with an overall RMS$^3$ of 0.08 for $Z^0$ events and a RMS of 0.13 for Higgs events. Despite of presence of more neutrinos in the leptonic $\tau$-decays than in the hadronic decays, the distributions are slightly narrower close to zero but have much larger tails away from zero. The large spread around zero for hadronic decays, could be due to the large fraction of decays containing neutral hadrons.

![Figure 4.5](image)

(a) $Z \rightarrow \tau\tau$

(b) $ggH \rightarrow \tau\tau$

Figure 4.5: Reconstruction performance of the longitudinal boost using the BoostZ-method. The longitudinal boost reconstruction is identical to that in the BoostXYZ-method.

The worsening in performance for Higgs events is mainly due to the larger transverse boost in these events compared to the $Z^0$ events – as illustrated in figure 4.6(a) where the performance is shown as function of $\beta_T$ for $Z \rightarrow \tau\tau$ events. This fact clearly signal that an extension of the BoostZ-method is needed in case of large $\beta_T$.

To estimate the goodness of the full reconstruction, the vectorial difference of true and reconstruction boost vectors, $|\vec{\beta}_{\text{gen}} - \vec{\beta}_{\text{reco}}|$ is computed for both reconstruction methods. In [29] performance numbers based on generator level information have been derived for events with either leptonic or 1-prong $\tau$-decays. In table 4.2 the numbers from [29] are compared to the numbers derived here. Here the numbers are derived including all hadronic $\tau$-decays, but it is checked that the performance on 1-prong is very similar to that of multi-prongs.

As expected there is no significant difference between the generator level studies and full detector simulation Monte Carlo in the performance of BoostZ-method. However,

$^3$Here, the overall RMS is defined as the spread of the $\beta^\text{gen}_z - \beta^\text{recon}_z$ distribution.
Reconstructing the $\tau^+\tau^-$ rest frame

Figure 4.6: Dependence on transverse boost in the BoostZ reconstruction performance in $Z^0$ events. Neglecting the transverse component clearly has an effect for high transverse boost.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>BoostZ Gen. Level</th>
<th>Z$^0$</th>
<th>Det. Level</th>
<th>ggH</th>
<th>BoostXYZ Gen. Level</th>
<th>Z$^0$</th>
<th>Det. Level</th>
<th>ggH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_\ell\tau_\ell$</td>
<td>-</td>
<td>0.160</td>
<td>0.259</td>
<td>-</td>
<td>0.125</td>
<td>0.195</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_\ell\tau_{\text{had}}$</td>
<td>-</td>
<td>0.157</td>
<td>0.237</td>
<td>-</td>
<td>0.111</td>
<td>0.137</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_{\text{had}}\tau_{\text{had}}$</td>
<td>-</td>
<td>0.142</td>
<td>0.221</td>
<td>-</td>
<td>0.089</td>
<td>0.110</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td>0.149</td>
<td>0.148</td>
<td>0.234</td>
<td>0.076</td>
<td>0.098</td>
<td>0.132</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Comparison of rest frame reconstruction methods for different decay modes in $Z^0$ and Higgs events. For BoostZ, the performance is equally good at generator level and fully detector simulated objects while the performance is reduced for the BoostXYZ-method in full detector simulation.

for the BoostXYZ-method a reduction in the performance is seen in the detector simulation. For both methods, the best result is found in the fully hadronic final states as expected since only a single neutrino is generated in each decay. Although the bosons are predominantly longitudinally boosted, clear improvements are found when the search for the transverse boost is included in both $Z^0$ and Higgs events as also displayed in figure 4.7(a).

Since quantities such as particle momenta and energy transform highly non-linear as function of $\beta$, it is important to check how well the reconstruction works not just on an overall basis, but also in differential distributions. In figure 4.7(b), the performance of the BoostXYZ-method is shown as function of $\beta_z$ and although the most part of events is concentrated near high $\beta_z$, the spread is more or less constant over the whole range – except for a small subset near 1 where effects from the requirement $|\beta| < 1$ are resulting in a small spread.

Since the BoostZ-method does not try to estimate the transverse component, $|\vec{\beta}_{\text{gen}} - \vec{\beta}_{\text{reco}}|$
4.2 Mass Estimation

One of the applications for reconstructing the RF of resonances is a new technique for estimating the resonance mass. In $\tau^+\tau^-$ pair systems, a trivial reconstruction of the invariant mass of the decaying mother boson is in principle not possible due to the presence of neutrinos in the $\tau$-decays.

The visible invariant mass, $M_{\text{vis}}$, distribution peaks far below the real mass as demonstrated in figure 4.1. Although $M_{\text{vis}}$ can often be used as a powerful discriminator between bosons with different mass, it is insufficient when trying to estimate the mass of a new resonance.
Figure 4.8: Full rest frame reconstruction as function of transverse boost for $H \rightarrow \tau\tau$ events. The exclusion of the transverse component is clear visible in the BoostZ-method. Although the transverse boost is taken into account in the BoostXYZ-method it only managed to correct for this in a fraction of the events.

Figure 4.9: Estimation of the transverse direction heavily depend on the magnitude of the $E_{T}^{\text{miss}}$, but for most part of events summing the $\tau$-momenta and missing transverse momenta gives a reasonable estimate.
A method exists—called Collinear Approximation [31]—which corrects for the missing neutrinos by assuming that the neutrinos are collinear with the mother \( \tau \)-lepton. By doing this it can include \( E_T^{\text{miss}} \) by projecting it onto the \( \tau \)-jet directions. However, this projection is only possible and reliable in a fraction of the events with a large transverse boost and well aligned \( E_T^{\text{miss}} \) [32].

Due to the large fraction of events where the collinear mass approximation fails, most analyses involving pairs of \( \tau \)-leptons have switch to likelihood based techniques. In ATLAS, the most frequently used is called the missing mass calculator, MMC [33]. It uses probability density functions based on Monte Carlo simulations to assign a probability for the boson mass given the event topology of the visible particles—not just the two \( \tau \)-lepton— and \( E_T^{\text{miss}} \). In the process, it exploits a lot of assumptions from \( \tau \)-polarisations to object reconstruction and pileup activity in the detector. For most cases, these assumptions can be evaluated by studying control regions or pre-identified objects, but in searches for new particles, these assumptions rely heavily on Monte Carlo predictions. Furthermore, the constant re-tuning to new detector environment and the event-on-event calculations can be very computational intensive tasks.

A more detailed description of the present mass techniques is found in section 6.1. The technique presented here functions as an alternative way of estimating a boson mass.

### 4.2.1 Finding the kinematic edge

In the RF of a decaying boson the energy of either of \( \tau \)-jets cannot exceed half of the boson mass. Therefore the mass could be found by finding the end-point of twice the energy of the leading \( \tau \)-jet in the RF. A quantity which henceforth will be denoted, \( M_{\text{Boost}} \).

When both \( \tau \)-leptons decays into hadrons the distribution of \( M_{\text{Boost}} \)— shown in figure 4.10(a)— will accumulate towards the end-point due to the presence of a single neutrino in each \( \tau \)-decay, generating an almost triangular shape. Finding the kinematic edge of such a distribution is preferable to finding the end-point of a broad distribution, e.g. \( M_{\text{vis}} \), when including backgrounds distributions. The triangular shape is distorted by several effects, \( \tau \)-polarisation, the detector resolution and the width of the resonance all smear the distribution into a distribution which here is approximated with a triangle convoluted with gaussian.

For the final states involving leptonic \( \tau \)-decays, the peak of the \( M_{\text{Boost}} \)-distributions are shifted towards lower values, resulting in a less profound edge. However, estimating the edge in these events is still possible. The \( M_{\text{Boost}} \)-distributions for the leptonic final states are displayed in figure 4.10(b).

As opposed to the mass obtained from the collinear approximation, \( M_{\text{CA}} \), the \( M_{\text{Boost}} \) quantity can be calculated for all events without cpu intensive calculations since the both BoostZ and BoostXYZ methods are computational fast.

Fitting a triangle convoluted with a gaussian function to the distribution in figure 4.10(a) raises some numerical difficulties since such a fit is highly unstable due to the correlations between the gaussian width and the triangular end-point.

Numerical calculations in MATHEMATICA shows that taking the position of the steepest point in the \( M_{\text{Boost}} \) distribution as an estimator of the boson mass, \( \hat{m}_{\text{boost}} \), gives a reasonable agreement. Only a small offset towards a lower estimated mass is expected. The \( \hat{m}_{\text{boost}} \) is trivial to calculate, but will show disadvantages in low statistics scenarios.
Reconstructing the $\tau^+\tau^-$ rest frame

![Graph 1](image1.png)

(a) Fully hadronic final states

![Graph 2](image2.png)

(b) Fully leptonic final states

Figure 4.10: Distributions of $M_{\text{Boost}}$ in $ggH \rightarrow \tau\tau$ event with either the fully hadronic or fully leptonic final states. The $M_{\text{Boost}}$ distributions have been made both using both the BoostZ and BoostXYZ-method.

To evaluate the precision of $\hat{m}_{\text{boost}}$, a series of pseudo-experiments are performed. Using the shape from the distributions in figure 4.10, 1.000 pseudo-distributions are generated with a fixed number of events and $\hat{m}_{\text{boost}}$ is calculated using BoostXYZ. This is repeated with different numbers of events in each pseudo-distribution and the resulting mean and spread of $\hat{m}_{\text{boost}}$ as a function of the event statistic is shown in figure 4.11.

Instead of estimating the boson mass from the steepest point in the distribution, a more precise result might be achieved by fitting the $M_{\text{Boost}}$ distribution using templates. This approach is proposed for measuring the mass of the $W$-boson [34], but requires a huge amount of simulations in order to generate the templates. Therefore, an approach using of $\hat{m}_{\text{boost}}$ is more feasible.

### 4.3 Helicity correlations

The helicity of a particle is given as the projection of its spin onto its momentum. Since a $\tau$-lepton is a spin-$\frac{1}{2}$ fermion, it can have either -1 (left-handed) or +1 (right-handed) helicity. Information on the helicity is in principle achievable, since the decay of the $\tau$-lepton is affected by its helicity and the $\tau$-lepton decays inside the detector, but the information is hidden by the fact that the visible decay product cannot be compared to the originating $\tau$-lepton. Therefore, one cannot hope to reconstruct the polarisation for a single $\tau$-lepton. Instead the $\tau$-polarisation is defined on a statistical basis as the relative difference in cross sections for left-handed, $\sigma_L$, and right-handed,$\sigma_R$, $\tau$-leptons

$$P_\tau = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$ \hspace{1cm} (4.1)

At the LEP experiments, several powerful observables [35] were constructed for studying the polarisation of $\tau$-leptons in $Z^0$-decays. Since $Z^0$-bosons were produced at rest at
4.3 Helicity correlations

Figure 4.11: Performance of $\hat{m}_{\text{boost}}$ as a function of events in the distribution in simulated ggH events with $m_H = 120$ GeV. The performance is evaluated using 1000 pseudo-experiments for each point in the input statistics. The solid lines indicate the means and the filled areas indicate the spread of the distribution.

LEP, all these variables are defined in the RF of the $Z^0$-boson. As previously demonstrated, bosons producing pairs of $\tau$-leptons at the LHC will be highly boosted. Therefore a reconstruction of the RF is vital in order to use these observables at LHC.

The most dominant effect of $\tau$-polarisation is present in the single charge pion decay channel, $\tau^{\pm} \to \pi^{\pm} \nu_\tau$, hereafter referred to as the pion mode. Due to the single neutrino produced in the pion mode and that neutrinos have to be left-handed, a right-handed $\tau$-lepton will prefer to emit a neutrino in the direction of flight as pictured in figure 4.12.

In the $Z^0$ rest frame, the decay angle, i.e. direction of the visible $\tau$-jet, translates directly to the fraction of the $\tau$-lepton energy carried by the visible $\tau$-jet, e.g. $\frac{E_\tau^-}{E_\tau}$, as illustrated in figure 4.13(a) for the pion mode. In the Monte Carlo simulation format used in ATLAS, the helicity information is not stored. Therefore this plots are made using generator level quantities in PYTHIA8+TAUOLA [36].

Since one does not have access to the true energy of the $\tau$-lepton, the $\pi$-meson energy is normalised by the mass of the boson which in the correct RF should be twice $E_\tau$. Henceforth, $E_{\text{vis}}$ will denote energy of the visible $\tau$-jet.

The correlation between helicity and decay angle is also present in the other decay modes, although it is much weakened – in the leptonic modes due to the second neutrino and the $\tau^{\pm} \to \rho^{\pm} \nu \to h^{\pm} h^0 \nu$ decay, referred to as the rho mode, due to the non-zero spin of the $\rho$-meson. However in the rho mode, which constitutes $\sim 25\%$ of all $\tau$-decays, the decay of the $\rho$-meson can be used to estimate the polarisation. The decay directions for the neutral and charged pion correlates to the energy sharing between them in the $Z^0$ frame. As shown in figure 4.13(b), the charged energy fraction defined as

$$\Upsilon = \frac{E_{\text{ch}}^- - E_{\text{neu}}^-}{E_{\text{ch}}^- + E_{\text{neu}}^-}$$

in the $\tau$-jet correlates well to the helicity of the $\tau$-lepton. Since this quantity only compares an energy sharing of two very close objects, it only depends weakly on the frame of reference and it gives information on the $\tau$-helicity based on a single $\tau$-lepton without
Reconstructing the $\tau^+\tau^-$ rest frame

Table 2: Expected values of tau polarization for various processes

The method outlined in this note for extracting the tau polarization is independent of the mode of tau lepton production. The development of the method has valuable applications for discoveries of new phenomena at the LHC. In particular, $P_{\tau}$ may be used as a discriminating variable in searches for new particles. In the event of such a discovery, the tau polarization provides insight into the nature of the coupling to tau leptons.

2 Tau Polarization Observables

Parity is maximally violated in the charged current weak decays of tau leptons whereby the tau lepton always couples to a left-handed tau neutrino, $\nu_\tau$. Due to angular momentum conservation, the angular distribution of the tau lepton decay products depends strongly on the spin orientation of the tau lepton. The hadronic decay modes are particularly well suited to determine the tau spin orientation due to the presence of a single final state neutrino. Figure 1 illustrates the angular dependence of the charged pion in the $\tau_R$ channel. For right-handed taus, the charged pion is preferentially emitted along the line of flight of the tau whereas the opposite is true for left-handed tau leptons. In leptonic decays, the polarization dependence is obscured by the presence of two final state neutrinos.

(a) $E_{\text{vis}}/M_z$ for $\tau$-leptons decaying to $\pi^{\pm}\nu_\tau$.

(b) $\Upsilon$ for $\tau$-leptons decaying to $\rho^{\pm}\nu_\tau$.

Figure 4.12: Illustration of the preferred and suppressed decay distributions for $\tau \rightarrow h^{\pm}\nu_\tau$.

Figure 4.13: Polarisation variables for $\tau$-leptons with positive and negative helicities shown in the generated and reconstructed RF using the BoostXYZ-method as well as the laboratory frame. Improvements when going from laboratory to the reconstructed RF are only seen for the $\Upsilon$. 

- $P_{\tau}$
- $E_{\text{vis}}/M_z$
- $\Upsilon$
4.3 Helicity correlations

using the mass of the boson nor information about the mother \(\tau\)-lepton. Therefore this variable is very useful experimentally and was recently the primary variable used in the \(\tau\)-polarisation measurement \(W \rightarrow \tau \nu\) in ATLAS [37].

For a boson decaying to a pair of \(\tau\)-leptons, the helicity configuration of the \(\tau\)-leptons is determined by the spin of the boson. A spin 1 boson, e.g. \(Z^0\), will produce a set of \(\tau\)-leptons with same helicity while a spin 0 boson, e.g. a Higgs boson, will produce the opposite. Thus, if reconstructed well enough, the helicity correlations of the \(\tau\)-leptons can determine the spin of the boson. Figure 4.14 shows the normalised \(E_{\text{vis}}\) distributions for pairs of \(\tau\)-leptons coming from Higgs and \(Z^0\) bosons in the true RF of the boson. For Higgs bosons, the distributions are concentrated around (1,0) and (0,1) while for \(Z^0\) events the distribution are predominantly located at (0,0) and (1,1). The larger peak around (0,0) than at (1,1) is due to the axial-vector coupling of the \(Z^0\).

![Energy correlations](image)

(a) Spin 0 \((H)\)  
(b) Spin 1 \((Z^0)\).

Figure 4.14: Energy correlations of the visible \(\tau\)-jet observed in the true RF of the boson. Only events where both \(\tau\)-leptons decaying to \(h^\pm \nu_\tau\) are considered. To avoid effects coming from the mass differences all energies are scaled with the mass of the boson.

These correlations are mostly washed out when observing the \(\tau\) pair from the laboratory frame as seen in figures 4.15(a)-4.15(b), however some of the correlations are regained when reconstructing the RF as seen in figures 4.15(c)-4.15(d) for the BoostXYZ-method.
Figure 4.15: Energy correlations between the visible $\tau$-jets, observed in the detector frame (a,b) and in the reconstructed RF using the BoostXYZ-method (c,d). Only events where both $\tau$-leptons decaying to $h^\pm \nu_\tau$ are considered. To avoid effects coming from the mass differences all energies are scaled with the mass of the boson.
As described in section 2.1, the $H \rightarrow \tau \tau$ decay mode becomes an important search channel in the low Higgs mass range. In ATLAS the $\tau^+\tau^-$ channel is divided into three subchannels, the fully leptonic final states, $\tau_\tau\ell\ell$, where both $\tau$-leptons decay into leptons, the semi-leptonic final states, $\tau_\ell\tau_{\text{had}}$, where one $\tau$-lepton decays into leptons and the other into hadrons, and finally the fully hadronic final state, $\tau_{\text{had}}\tau_{\text{had}}$, where both $\tau$-leptons decay into hadrons.

In this chapter, a search for the Higgs boson in the $\tau_{\text{had}}\tau_{\text{had}}$ final state is presented. This final state suffers from a large background of QCD-jets which have a very similar signature in the detector. Furthermore, the QCD backgrounds are known not to be well described by simulations and therefore a urgent need for data-driven background estimations is present. However, as will be shown the different topology of QCD jet event compared to $Z^0$ and Higgs events, can be used quite effectively to suppress the QCD background, and in fact the irreducible background from $Z^0$ bosons will turn out to be the main obstacle.

On the other hand, the $\tau_{\text{had}}\tau_{\text{had}}$ final state gains by having a large branching ratio, $\text{BR}$, compared to the $\tau_\ell\tau_\ell$ and $\tau_\ell\tau_{\text{had}}$ final states. Table 5.1 summarises the cross sections for all production modes of the Higgs boson for different mass hypotheses in proton-proton collisions with a centre-of-mass energy of 7 TeV. The last column reports the branching ratio of the Higgs boson decaying to a pair of $\tau$-leptons. The $\tau_{\text{had}}\tau_{\text{had}}$ final state accounts for 42% of all $\tau$-pairs: $\text{BR}(\tau \rightarrow h) \times \text{BR}(\tau \rightarrow h) = 0.648^2 = 0.4199$.

The selection of Higgs candidates events is divided into two steps: a preselection step and a signal region selection. The preselection performs a minimal set of cuts to select any pair of real $\tau$-leptons. This stage in the selection also works as a control region where agreement between data and simulation is validated. Ideally, a guaranteed signal-free region would be the best control region, however as long as the mass of the Higgs boson is low or unknown, such a region is hard to obtain. Instead the preselection stage is used. At this stage, the contamination from Higgs events compared to the background processes is very low and therefore this region can serve as a control region.

After the preselection an optimised selection of Higgs events is performed. The optimised selection is split into a ggH and a VBF selection. The resulting events of each
Searching for the Higgs boson in the \( \tau \) channel

Table 5.1: NNLO cross sections for the SM Higgs production in proton-proton collision at 7 TeV and branching ratios for Higgs decaying in a pair of \( \tau \)-lepton [38, 39].

<table>
<thead>
<tr>
<th>( m_H ) [GeV]</th>
<th>( ggH ) ( [\text{pb}] )</th>
<th>VBF ( [\text{pb}] )</th>
<th>WH ( [\text{pb}] )</th>
<th>ZH ( [\text{pb}] )</th>
<th>( (H \to \tau\tau) ) ( [\text{pb}] )</th>
<th>( H \to \tau_{\text{had}}\tau_{\text{had}} ) ( [\text{pb}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>21.77</td>
<td>1.78</td>
<td>0.71</td>
<td>0.22</td>
<td>0.042</td>
<td>0.036</td>
</tr>
<tr>
<td>105</td>
<td>20.11</td>
<td>1.67</td>
<td>0.66</td>
<td>0.21</td>
<td>0.035</td>
<td>0.034</td>
</tr>
<tr>
<td>110</td>
<td>18.73</td>
<td>1.57</td>
<td>0.60</td>
<td>0.19</td>
<td>0.032</td>
<td>0.032</td>
</tr>
<tr>
<td>115</td>
<td>17.45</td>
<td>1.47</td>
<td>0.54</td>
<td>0.17</td>
<td>0.029</td>
<td>0.030</td>
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<tr>
<td>120</td>
<td>16.27</td>
<td>1.38</td>
<td>0.49</td>
<td>0.15</td>
<td>0.027</td>
<td>0.028</td>
</tr>
<tr>
<td>125</td>
<td>15.12</td>
<td>1.30</td>
<td>0.44</td>
<td>0.14</td>
<td>0.025</td>
<td>0.026</td>
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<tr>
<td>130</td>
<td>14.02</td>
<td>1.22</td>
<td>0.39</td>
<td>0.13</td>
<td>0.023</td>
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</tr>
<tr>
<td>135</td>
<td>13.00</td>
<td>1.16</td>
<td>0.35</td>
<td>0.12</td>
<td>0.021</td>
<td>0.023</td>
</tr>
<tr>
<td>140</td>
<td>12.04</td>
<td>1.09</td>
<td>0.31</td>
<td>0.11</td>
<td>0.019</td>
<td>0.022</td>
</tr>
<tr>
<td>145</td>
<td>11.14</td>
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<td>0.28</td>
<td>0.10</td>
<td>0.017</td>
<td>0.020</td>
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<tr>
<td>150</td>
<td>10.33</td>
<td>0.95</td>
<td>0.25</td>
<td>0.09</td>
<td>0.015</td>
<td>0.019</td>
</tr>
</tbody>
</table>

Table 5.2: Cross sections of Monte Carlo background processes. The cross sections for \( W \) and \( Z^0 \) includes a sum over the branching ratios indicated final states.

5.1 Background processes

Since the final state in this analysis consist of two hadronic final states, a large background arises from QCD-events, and the sensitivity of the analysis depends strongly on the ability to separate the huge amount of fake \( \tau \)-pairs from QCD events from real \( \tau \)-pairs.

Unfortunately, simulations does not describe QCD events very well. Therefore, a data-driven estimation of the QCD events is used. This method, described in section 7.2, consists in taking pairs where the \( \tau \)-candidates do not have opposite reconstructed electrical charge, referred to as not-opposite-sign events. Since the rate of not-opposite-sign and opposite-sign pairs coming from QCD events will not be identical, the number of not-opposite-sign events is normalised by the \( \Delta \eta(\tau_1, \tau_2) \) fit described in section 7.4.

The second large background is the irreducible background from \( Z \to \tau\tau \) events. This background process is estimated using the partly data-driven method of embedded \( Z \to \mu\mu \) events as described in section 7.1.

The background processes and their cross sections are listed in table 5.2.

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross section ( [\text{pb}] ) ( \times \text{BR} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W \to l\nu ) ( (l = e, \mu, \tau) ) + jets</td>
<td>( 10.46 \times 10^3 )</td>
</tr>
<tr>
<td>( Z^0 \to ll ) + jets ( (l = e, \mu) )</td>
<td>( 0.71 \times 10^3 )</td>
</tr>
<tr>
<td>( tt )</td>
<td>166.7</td>
</tr>
<tr>
<td>Single top ( t-, s- ) and ( Wt )-channel</td>
<td>58.7, 3.9, 13.1</td>
</tr>
<tr>
<td>( WW, WZ^0 ) and ( Z^0Z^0 )</td>
<td>46.2, 18.0, 5.6</td>
</tr>
</tbody>
</table>

of these categories are passed on to the limit setting described in chapter 9.
5.2 Input Samples

The analysis presented here uses data from proton-proton collisions with the centre-of-mass energy of 7 TeV recorded by the ATLAS experiment. All data taken in 2011 with all the subsystems of the ATLAS detector operating is used. This amounts to 4.7 fb$^{-1}$ of data.

The event generations of the Higgs samples are done with PowHeG [40, 41, 42] which is based on next-to-leading order (NLO) perturbative calculations. The parton shower, hadronisation and underlying event simulations are provided through an interface with PYTHIA8 [30]. The associated production samples are based on the leading order simulations using PYTHIA8. Several mass points have been produced and used in this analysis.

In the background processes, the $W/Z^0 +$ jets event generation is done with ALPGEN [43]. This generator employs the MLM matching scheme [44] between the hard process, calculated with leading-order matrix elements for up to five jets, and the parton shower. The $t\bar{t}$ and di-boson ($WW, WZ^0, Z^0Z^0$) samples are produced with MC@NLO [45] with NLO precision. Single-top events are simulated with AcerMC+PYTHIA [46]. The loop-induced $gg \rightarrow WW$ processes are generated using gg2WW [47].

In all the background Monte Carlo samples, the parton shower and the hadronisation are simulated using HERWIG [48] and the underlying event using JIMMY [49]. The $\tau$-decay is simulated using TAUOLA [36], and PHOTOS [50] is used to simulate additional photon radiation from the charged leptons.

The detector simulation in all the Monte Carlo samples is performed with GEANT4 [27] and the reconstruction is made with the same software as is used for data.

In order to get a correct modelling of the different pile-up conditions in all of the data taking periods, the Monte Carlo samples are reweighted according to the average number of interactions per bunch crossing. This reweighting is done by comparing distributions of the average number of interactions per bunch crossing in the recorded data and in the simulated events, and therefore the reweighting is dependent on the data periods used in each analysis.

Additional weights are applied on the simulations in order to correct for a mismodelling of the trigger efficiency [51]. These weights are derived as a function of $p_T$ and $\eta$ of the $\tau$-candidates, and are smaller than 5% over the full $p_T$ and $\eta$ range.

For the ggH signal samples a reweighting is also done as a function of the $p_T$ of the Higgs boson. This reweighting is done to incorporate NNLO effects of on the kinematics of the Higgs events.

5.3 Selection of $\tau$-pairs

In this section, the preselection of hadronic decaying $\tau$-pairs is described. The preselection aims to select a wide range of well reconstructed $\tau$-pairs, while filtering out regions in which simulations are known not to describe data accurately.

The preselection is divided into three step: The first step selects good events, i.e. events which has been selected by the triggering system and which satisfy some Data Quality cuts, the second step selects the individual objects, i.e. leptons, jets, by a series of quality cuts on the individual objects and the final step selects events with a suitable
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### 5.3.1 Identification of Hadronic $\tau$-decays

Since $\tau$-leptons decaying into leptons will be reconstructed as either an electron or a muon in the detector, reconstructed $\tau$-candidates only refers to the $\tau$-leptons decaying into hadrons. The $\tau$-reconstruction is performed using clusters in the electromagnetic and hadronic calorimeters [52] and is seeded by a jet with $p_T > 10$ GeV, reconstructed using the anti-$k_t$ jet-algorithm [53]. Reconstructed $\tau$-candidates are required to have $p_T > 20$ GeV and $|\eta| < 2.5$ to be within the reach of the tracking detectors. Furthermore, to avoid the transition regions from the barrel to end-cap, the leading track of the candidates are required not to be within $1.37 < |\eta| < 1.51$.

For the $\tau$-identification a Boosted Decision Tree (BDT) algorithm is used [52] to separate true $\tau$-leptons from fakes from QCD-jets. The BDT algorithm is based on input from shower profile in the calorimeter and topology of the associated tracks. Three standard cuts on the BDT score have been defined by the $\tau$-identification group, Loose, Medium and Tight, depending on the purity of the selection. Here both $\tau$-candidates are required to be Medium which corresponds to an efficiency of approximately 45%. Furthermore, a specific veto again electron and muon with is done each candidate using a cut-based approach for the muon veto and a BDT-based one for the electron rejection [52]. Finally, each candidates are required to be matched to the region of interest (RoI) where the trigger was fired. The selection criteria for $\tau$-leptons are summarised in Table 5.3.

### 5.3.2 Trigger

The first step of selecting $\tau$-pair is choosing the trigger from the ATLAS trigger menu described in section 3.7. In this analysis, different double hadronic triggers are chosen depending on the run period due to the increasing luminosity of the LHC. Usually the unprescaled trigger with the lowest $p_T$ requirement is chosen. All the used triggers are designed with an asymmetric $p_T$ requirement for the two candidates, which is lower at Level 1 than at Event Filter Level. The medium in the trigger name, refers to the tightness

---

<table>
<thead>
<tr>
<th>Selection criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster seeded</td>
</tr>
<tr>
<td>Electrical charge $= \pm 1$</td>
</tr>
<tr>
<td>BDT-Medium Identification</td>
</tr>
<tr>
<td>BDT-based Electron Veto</td>
</tr>
<tr>
<td>Cut-based Muon Veto</td>
</tr>
<tr>
<td>Matched to the EF Trigger within $\Delta R &lt; 0.2$</td>
</tr>
<tr>
<td>$</td>
</tr>
<tr>
<td>$p_T &gt; 20$ GeV</td>
</tr>
<tr>
<td>Leading track not within $1.37 &lt;</td>
</tr>
</tbody>
</table>

Table 5.3: Selection criteria for the tau candidates.

---

\(^1\)The highest $p_T$ track is referred to as the leading track.
of the identification at the trigger stage. Since less information is available during the trigger processing than in the offline reconstruction, this identification value will not match completely the BDT value in the offline identification. Some of the triggers also have a requirement on the number of associated tracks to be either 1, 2 or 3 which is marked with an 1 in the trigger name. The used triggers for the different periods are listed in table 5.4.

<table>
<thead>
<tr>
<th>EF Trigger</th>
<th>Periods</th>
<th>$\mathcal{L}$ [pb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EF_tau29_medium1_tau20_medium1 (loose)</td>
<td>B-E</td>
<td>222</td>
</tr>
<tr>
<td>EF_tau29_medium1_tau20_medium1 (default)</td>
<td>F-K</td>
<td>2047</td>
</tr>
<tr>
<td>EF_tau29T_medium1_tau20T_medium1</td>
<td>L-M</td>
<td>2400</td>
</tr>
</tbody>
</table>

Table 5.4: Summary of the triggers used through the 2011 data taking.

### 5.3.3 Event Cleaning

In order to only consider good quality data a set of event cleaning cuts is applied. The first of these cuts is is GoodRunsList(GRL) filtering provided by the ATLAS data quality group which guarantees that all parts of the detector have reported a green flag at the time of this event. To further remove non-collision events, e.g. beam halo and cosmic rays events, at least one reconstructed primary vertex is required with more than four associated tracks. These cuts are only applied to data. On top for this a cleaning cut is applied to the jets in both simulated events and in data. This cut provided by the JetEtMiss Performance group [54] rejects event poorly reconstructed or out-of-time jets.

### 5.3.4 Muons and Electrons

Since this analysis only focuses on events with two hadronic decaying $\tau$-leptons, a veto against events containing electrons or muon is done. Here the leptons are required to better reconstructed than in the lepton veto used on the individual $\tau$ objects.

The rejection of events containing reconstructed leptons also makes the combination with the semi-leptonic and fully-leptonic final states easier since an event cannot enter in both analysis and double counting is avoided.

The muons are chosen from the STACO algorithm [55] and required at be identify as Loose tag. The muon are required to have $p_T > 10$ GeV and be within $|\eta| < 2.5$. The muon are required to have at least certain number of hits in each subdetector in the ID, and no more the three holes-on-track$^2$. Additionally, a set of standard quality cuts is applied on the associated track. For the electrons is reconstruction is seeded by clusters in the electromagnetic calorimeter. Electrons are required to have an associated track and they are required to be tagged as MediumPP by the identification algorithm. They are required to have $p_T > 10$ GeV and $|\eta| < 2.47$, and not be in the transition region at $1.37 < |\eta| < 1.52$. As for the muons additional quality criteria made by the EGamma performance group is imposed.

The lepton selection criteria are listed the table 5.5.

$^2$The number of holes-on-track are defined as the expected number of hits from the reconstruction track trajectory over the measured number of hits
5.3.5 Jets

In ATLAS jets are reconstructed jets using a set of different clustering algorithms. The default clustering algorithm in ATLAS – also used in here – is the anti-$k_t$-algorithm [53] with an cone size of $\Delta R \leq 0.4$. The input for the clustering is topological clusters [56] calibrated with the Local Hadronic Calibration scheme [57] which calibrates the energy deposit in the electromagnetic and hadronic calorimeters using weighting scheme based on different response for electrons and pions obtained by simulation and test-beam data. This calibration also takes into account the dead material and out-of-cluster cells to get the optimal response and noise suppression.

Only jets with $p_T > 20$ GeV and $|\eta| < 4.5$ are selected. Furthermore, jets which are within a cone of $\Delta R < 0.2$ of the $\tau$-candidates are removed.

5.3.6 Missing Transverse Energy

The missing transverse energy is reconstructed based on the energy deposited in calorimeters and on the muons reconstructed in the muon spectrometer [58]. The energy deposited in the cells is calibrated according to the reconstructed physics object to which they belong. The cells are associated to reconstructed objects in the following order: electrons, photons, hadronically decaying $\tau$-leptons, jets and muons. Also cells not associated to any of these objects are taken into account. All the calibrated energies are summed up to form a vector in the transverse plan. From all selected muons the summed $p_T$ is added to this vector.

5.3.7 Pair selection

Besides the trigger and event cleaning cuts, a series of cuts are used to define selected events of possible Higgs candidates. First of all, a veto against leptons selected by the criteria described in section 5.3.4 are performed. Exactly two $\tau$ candidates are required using the selection documented in section 5.3.1 with at least one of the two candidates have Tight identification. The two candidates are required to have $p_T$ above 35 GeV and 25 GeV. These $p_T$ requirements are mainly imposed to get rid of effects from the trigger turn-on which is known to be poorly modelled in the simulations. Furthermore, the two candidates are required to have opposite charges and no outlying tracks counted as described in section 7.3.1.
5.3 Selection of $\tau$-pairs

A cut on the visible mass of the selected $\tau$-pairs is imposed by removing events with $M_{\text{vis}} < 60$ GeV since the background modelling of QCD and $Z \rightarrow \tau\tau$ events is known to be inaccurate at low masses. For $Z \rightarrow \tau\tau$ events the inaccuracy comes from the fact that only $Z \rightarrow \mu\mu$ events above a certain threshold is used as input for the $Z \rightarrow \tau\tau$ modelling as described in section 7.1. Furthermore, since the direction of the $E_T^{\text{miss}}$-vector is used further on in the selection, a cut requiring $|E_T^{\text{miss}}| > 10$ GeV is imposed. This analysis tries to make minimal use of the $E_T^{\text{miss}}$, because large uncertainties are associated with the $E_T^{\text{miss}}$ reconstruction.

Finally, in order to reject QCD events only $\tau$-pairs with $\Delta\eta(\tau_1, \tau_2) < 2$ are selected. Figure 5.1 shows the $\Delta\eta(\tau_1, \tau_2)$ distribution before making this cut. Clearly, true $\tau$-jets are produced much closer in $\eta$ than fake $\tau$-jets from QCD.

![Figure 5.1: Normalised distributions of $\Delta\eta(\tau_1, \tau_2)$ for during preselection before cutting at $\Delta\eta(\tau_1, \tau_2) = 2$. The Higgs processes includes both ggH, VBF and VH events which are weighted by their cross sections before the normalisation.](image)

Table 5.6 summarised the expected and observed number of events surviving the steps in the preselection. Here both background and signal samples are kept split up to reflect the signal and background composition. Only the statistical uncertainties on the numbers are presented in table 5.6.

After applying the preselection cuts, the dominant background sources are $Z \rightarrow \tau\tau$ and QCD jets. Both of these background processes are normalised using the fit described in section 7.4. The normalisation is done before the $\Delta\eta(\tau_1, \tau_2)$-cut, and this normalisation are kept throughout the selection steps. For all other background and signal processes the cross sections listed in table 5.2 and table 5.1 are used.
Searching for the Higgs boson in the $\tau$ channel

### Events

<table>
<thead>
<tr>
<th>Cut</th>
<th>Data</th>
<th>Total</th>
<th>QCD-jets</th>
<th>$Z \rightarrow \tau\tau$</th>
<th>$W$</th>
<th>top</th>
<th>$Z \rightarrow \ell\ell$</th>
<th>Di-Bosons</th>
<th>Signal ($m_H = 125$ GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>-</td>
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<td>201130.0</td>
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<td>1200831.8</td>
<td>17013.4</td>
</tr>
<tr>
<td>Exactly 2 $\tau$-jets</td>
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<td>50289.7</td>
<td>41174.9</td>
<td>8050.6</td>
<td>966.3</td>
<td>53.4</td>
<td>23.6</td>
<td>20.9</td>
<td>37.2</td>
</tr>
<tr>
<td></td>
<td>$\pm$ 227.8</td>
<td>$\pm$ 83.8</td>
<td>$\pm$ 64.4</td>
<td>$\pm$ 27.6</td>
<td>$\pm$ 43.9</td>
<td>$\pm$ 2.0</td>
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<td>$\pm$ 3.9</td>
<td>$\pm$ 0.8</td>
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<tr>
<td>$M_{\text{vis}} &gt; 60$ GeV</td>
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<td>23.4</td>
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<tr>
<td></td>
<td>$\pm$ 222.2</td>
<td>$\pm$ 82.2</td>
<td>$\pm$ 63.0</td>
<td>$\pm$ 27.1</td>
<td>$\pm$ 43.0</td>
<td>$\pm$ 1.8</td>
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<td>$\pm$ 24.1</td>
<td>$\pm$ 41.8</td>
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<td>$\pm$ 3.9</td>
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<tr>
<td>$\Delta\eta(\tau_1, \tau_2) &lt; 2$</td>
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<td>6142.0</td>
<td>740.4</td>
<td>36.9</td>
<td>21.0</td>
<td>12.3</td>
<td>30.4</td>
</tr>
<tr>
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<td>$\pm$ 163.5</td>
<td>$\pm$ 65.7</td>
<td>$\pm$ 44.9</td>
<td>$\pm$ 24.1</td>
<td>$\pm$ 39.5</td>
<td>$\pm$ 1.5</td>
<td>$\pm$ 13.0</td>
<td>$\pm$ 0.7</td>
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</tbody>
</table>

### Cut Efficiencies

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<tr>
<th>Cut</th>
<th>Data</th>
<th>Total</th>
<th>QCD-jets</th>
<th>$Z \rightarrow \tau\tau$</th>
<th>$W$</th>
<th>top</th>
<th>$Z \rightarrow \ell\ell$</th>
<th>Di-Bosons</th>
<th>Signal ($m_H = 125$ GeV)</th>
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</thead>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>VH</td>
</tr>
<tr>
<td>Exactly 2 $\tau$-jets</td>
<td>0.005</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.005</td>
<td>0.001</td>
<td>&lt;0.001</td>
<td>0.001</td>
<td>0.189</td>
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<tr>
<td>$M_{\text{vis}} &gt; 60$ GeV</td>
<td>0.951</td>
<td>0.960</td>
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<td>0.852</td>
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<td>$</td>
<td>E_T^{\text{miss}}</td>
<td>&gt; 10$ GeV</td>
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</tr>
<tr>
<td>$\Delta\eta(\tau_1, \tau_2) &lt; 2$</td>
<td>0.754</td>
<td>0.750</td>
<td>0.693</td>
<td>0.996</td>
<td>0.864</td>
<td>0.841</td>
<td>0.972</td>
<td>0.707</td>
<td>0.990</td>
</tr>
</tbody>
</table>

Table 5.6: Cutflow table for preselection of $\tau$-pairs. At each step of the selection the number accepted events including statistical errors is shown for both simulations and data. In the bottom table the efficiencies of each cut wrt. the previous step in shown.
5.3.8 Validation

The purpose of validation procedure is to check if the variables used in the analysis behave according to expectation, and evaluate the level of disagreement in terms of systematic errors of the final results. In the procedure it is desirable to define signal free control regions where particular backgrounds can be studied and correction factors can be extrapolated to the signal region. However, no region has been found which is both guaranteed signal-free and in which all variables of interest can be validated. Therefore, the preselection stage is used as validation region. A validation of all variables used in the analysis is presented in appendix B.

Figure 5.2 shows the predicted and observed distributions of the mass variable $M_{\text{Boost-XYZ}}$, along with a ratio plot of the observed data over the expected background. Only statistical errors and errors from the normalisation procedure are included in the ratio plot, but even then good agreement is found between data and expectation. The expected signal in case of a 125 GeV Higgs boson is also included. For visual purposes the Higgs signal is enhanced by a factor 30.

Even though good agreement is found in the $M_{\text{Boost-XYZ}}$ presented here, discrepancies are found in some variables such as the $E_{\text{T}}^{\text{miss}}$.

5.4 Optimised Higgs Selections

After having preselection $\tau$-candidate pairs, an optimised selection of Higgs events are done. Since $ggH$ and VBF events have slightly different signatures, two different selection strategies are applied to the event, resulting in two signal regions or categories. The two strategies are optimised to select predominantly VBF or $ggH$ events. Since the expected sensitivity is highest for VBF due to the small theoretical uncertainty on VBF production, the VBF-selection is executed first. This means that only events which are not accepted in the VBF category, is passed on to the $ggH$ selection.

5.4.1 VBF category

Since VBF Higgs bosons will be more boosted in the transverse plan than $Z^0$ events as discussed in chapter 4, a cut is made on the reconstructed transverse boost of the $\tau$-pair system using the boost reconstruction method BoostXYZ. The reconstructed boost is required to have $\beta_T > 0.3$ and $\beta_z < 0.9$. Figure 5.3 shows the reconstructed $\beta_z$ and $\beta_T$ distributions for signal and two main background processes.

A cut is also put on the alignment of the $E_{\text{T}}^{\text{miss}}$-vector. In order to expressed the position of the $E_{\text{T}}^{\text{miss}}$-vector in the transverse plan relative to the $\tau$-jets, a continuous variable $E_{\text{T}}^{\text{miss}}$-centrality is defined by

$$E_{\text{T}}^{\text{miss}} - \text{centrality} = \frac{A + B}{\sqrt{A^2 + B^2}},$$

where

$$A = \frac{\sin(\phi_{E_{\text{T}}^{\text{miss}}} - \phi_{\tau_1})}{\sin(\phi_{\tau_1} - \phi_{E_{\text{T}}^{\text{miss}}})}, \quad B = \frac{\sin(\phi_{\tau_2} - \phi_{E_{\text{T}}^{\text{miss}}})}{\sin(\phi_{\tau_2} - \phi_{E_{\text{T}}^{\text{miss}}})},$$

which is above 1 when the $E_{\text{T}}^{\text{miss}}$-vector is in between the two $\tau$-jets in the transverse plan. The $E_{\text{T}}^{\text{miss}}$-centrality is defined in the range $[-\sqrt{2}, \sqrt{2}]$ with $\sqrt{2}$ being right between the
Searching for the Higgs boson in the $\tau$ channel

Figure 5.2: Validation plot of the $M_{\text{Boost-}XYZ}$ variable at preselection. Higgs signal which includes both $ggH$, VBF and VH events has been enhanced by a factor 30 in order to be visible. A ratio plot is shown between observed data and background predictions (labeled MC). Only statistical errors and uncertainties from the normalisation procedure are included in the ratio plot.

two $\tau$-jets. The normalised distributions at the preselection stage of the $E_T^{\text{miss}}$-centrality is shown in figure 5.4. Only events with $E_T^{miss}$-centrality above zero is selected.

The VBF event topology is characterised by having two forward jets in the detector with a large rapidity gap as mentioned in section 2.1.2. Therefore, events are required to have at least two jets with $p_T > 30$ GeV and with these two jets are satisfying $\Delta \eta(\text{jets}) > 2.5$ and $\eta_1 \times \eta_2 < 0$.

The event cutflow from the preselection to the VBF category is presented in table 5.7 for the background processes and 125 GeV Higgs samples. Table 5.7 also lists the efficiencies for each cut in the selection for the different samples.
Figure 5.3: Normalised distributions for the reconstructed boost variables at the preselection stage for the two main background and signal processes.

Figure 5.4: Normalised distributions (at logarithmic scale) of $E_{T}^{\text{miss}}$-centrality defined in equation 5.1 at the preselection stage. The Higgs processes includes both ggH, VBF and VH events which are weighted by their cross sections before the normalisation.
Searching for the Higgs boson in the $\tau$ channel

Figure 5.5: Normalised distribution of $\Delta \eta$ (jets) at preselection stage. The ggH and VBF Higgs processes are displayed separately to show the distinctive signature of VBF events.
Table 5.7: Cutflow table for the VBF category. At each step of the selection the number accepted events including statistical errors is shown for both simulations and data. In the bottom table the efficiencies of each cut wrt. the previous step in shown. The $\beta_T$ and $\beta_z$ are reconstructed using the BoostXYZ-method described in chapter 4. The cut efficiencies on in the first row are calculated wrt. the last of the preselection. table 5.6.
5.4.2 ggH category

The ggH category is optimised to mainly selected ggH events. The main discriminant in this selection is the $E_T^{\text{miss}}$ and the transverse boost of the $\tau$-pair system, which is not as dominant as for VBF production, but still higher than the background processes.

First, only events with a high $E_T^{\text{miss}}$ value is selected. This cut mainly suppressed QCD since neutrinos are also present in the $Z^0$ and $W$ events. Here a cut on $|E_T^{\text{miss}}|$ is chosen at 30 GeV.

In order to select boosted $\tau$-pairs, a cut is put on the reconstructed boost using the BoostXYZ-method is required to have $\beta_T > 0.2$ and $\beta_z < 0.9$.

Furthermore, the $E_T^{\text{miss}}$-vector is required to satisfy $E_T^{\text{miss,centrality}} > 0$, i.e. the $E_T^{\text{miss}}$-vector must point in the same $\phi$-hemisphere as the two $\tau$-jets. The two $\tau$-jets are required to be close in $\eta$ by requiring $\Delta\eta(\tau_1,\tau_2) < 1.5$. And finally, the two $\tau$-jets must be produced in associated with at least one hard jet ($p_T$ of the jet must be greater than 50 GeV).

With this selection the background have been greatly reduce ($\sim 5\%$) while keeping a much higher acceptance for the signal ($\sim 25\%$ for ggH at $m_H = 125$ GeV).
Table 5.8: Cutflow table for the ggH category. At each step of the selection the number accepted events including statistical errors is shown for both simulations and data. In the bottom table the efficiencies of each cut wrt. the previous step in shown. The $\beta_T$ and $\beta_z$ are reconstructed using the BoostXYZ-method described in chapter 4. The cut efficiencies on in the first row are calculated wrt. the last of the preselection.
Searching for the Higgs boson in the $\tau$ channel
As mentioned in chapter 4, reconstructing the mass of bosons decaying into $\tau$-pairs is highly non-trivial due to the escaping neutrinos in the $\tau$ decays. In this chapter, the performance of the mass reconstruction technique presented in section 4.2 is compared to some of the existing techniques given the selection of $\tau$-pairs presented in section 5.3. The performance of these methods all depends on the topologies of the events, and the performance is therefore specific to this selection.

6.1 Mass Reconstruction Techniques

In the following, a brief introduction to three of the most commonly used mass variables is given.

6.1.1 Visible Mass

The *visible mass* is simply the invariant mass of the sum of the two visible $\tau$-jets, $M_{\text{vis}} = \sqrt{(E_{\tau_1}\text{vis} + E_{\tau_2}\text{vis})^2 - (\vec{p}_{\tau_1}\text{vis} + \vec{p}_{\tau_2}\text{vis})^2}$, where $p_{\tau_i}\text{vis}$ denotes the four momenta of the $i^{th}$ $\tau$-jet.

6.1.2 Collinear Approximation Mass

The *Collinear Approximation*, CA, [31] is based on the assumption that the particles generated in the $\tau$-decay are emitted in a very narrow cone. This is true in most cases due to the large boost of the $\tau$-leptons. Using the four momenta of the two $\tau$-jets and the projection of $E_T^{\text{miss}}$ vector along the $\tau$-jet directions, it is possible to write down two equations which gives an estimation of the energy of the two $\tau$-leptons. The boson mass can then be easily evaluated.
The projection of the $E_T^{\text{miss}}$ onto the two $\tau$-jets can be written as

$$E_{x}^{\text{miss}} = E_{x,\nu_1} + E_{x,\nu_2} = E_{\nu_1} \frac{p_{x,\tau^{\text{vis}}_1}}{|p_{\tau^{\text{vis}}_1}|} + E_{\nu_2} \frac{p_{x,\tau^{\text{vis}}_2}}{|p_{\tau^{\text{vis}}_2}|}$$

$$E_{y}^{\text{miss}} = E_{y,\nu_1} + E_{y,\nu_2} = E_{\nu_1} \frac{p_{y,\tau^{\text{vis}}_1}}{|p_{\tau^{\text{vis}}_1}|} + E_{\nu_2} \frac{p_{y,\tau^{\text{vis}}_2}}{|p_{\tau^{\text{vis}}_2}|}$$

These equations can be inverted into

$$E_{\nu_1} = \frac{|p_{\tau^{\text{vis}}_1}|}{E_{x}^{\text{miss}}} (E_{x}^{\text{miss}} p_{y,\tau^{\text{vis}}_1} - E_{y}^{\text{miss}} p_{x,\tau^{\text{vis}}_1})$$

$$E_{\nu_2} = \frac{|p_{\tau^{\text{vis}}_1}|}{E_{x}^{\text{miss}}} (E_{x}^{\text{miss}} p_{y,\tau^{\text{vis}}_1} - E_{y}^{\text{miss}} p_{x,\tau^{\text{vis}}_1})$$

(6.1)

The two $\tau$-leptons four momenta, $p_{\tau_i}$, can then be expressed by summing up the $\tau$-jet four momenta with the reconstructed neutrinos as follows

$$p_{\tau_i} = \left(E_{\nu_i} + E_{\tau^{\text{vis}}_i}, (E_{\nu_i} + |p_{\tau^{\text{vis}}_i}|) \frac{p_{\tau^{\text{vis}}_i}}{|p_{\tau^{\text{vis}}_i}|} \right)$$

From here the collinear approximation mass, $M_{CA}$, can be constructed as the invariant mass of the two reconstructed $\tau$-leptons.

The drawback of this method is that it requires certain criteria on the event topology to be fulfilled. First of all, the two $\tau$-jets must not be completely back-to-back in the transverse plan, in order to keep the projection of the $E_T^{\text{miss}}$ onto the two $\tau$-jets unique. This is typically controlled by putting a cut on the $\phi$-angle between the two $\tau$-jets, $\cos \Delta \phi(\tau^{\text{vis}}_1, \tau^{\text{vis}}_2) > \text{cut value}$ where a typical cut value used in the ATLAS [59] is $-0.9$. This is a rather harsh cut on both $Z^0$ and Higgs events.

Another limitation with this method is that sometimes renders unphysical solutions to the neutrino energies given in equation 6.1. Therefore, it is convenient to define the fraction, $x$, of $\tau$-lepton’s energy carried by the visible $\tau$-jet

$$x = \frac{E_{\tau^{\text{vis}}_i}}{E_{\tau_i}} = \frac{E_{\tau^{\text{vis}}_i}}{E_{\tau^{\text{vis}}_i} + E_{\nu_i}}$$

(6.2)

which has to be in the range $[0, 1]$ for both $\tau$-jets in order to get a physical solution to the neutrino energies. This requirement is identical to requiring that in the transverse plan the $\phi$ of the $E_T^{\text{miss}}$ is in between the $\phi$ of the two $\tau$-jets.

### 6.1.3 Missing Mass Calculator

Another method for mass estimation is the Missing Mass Calculator, MMC [33]. This method does not have the same constrains on the phase space as CA. The MMC is a likelihood-based method, which takes the neutrino directions from probability distributions rather than assuming neutrinos are collinear with the visible decay products. In the $\tau$-pair system, the following four equations relate the known and unknown kinematic
quantities
\[
E_{x}^{\text{miss}} = p_{\nu 1} \sin \theta_{\nu 1} \cos \phi_{\nu 1} + p_{\nu 2} \sin \theta_{\nu 2} \cos \phi_{\nu 2} \\
E_{y}^{\text{miss}} = p_{\nu 1} \sin \theta_{\nu 1} \sin \phi_{\nu 1} + p_{\nu 2} \sin \theta_{\nu 2} \sin \phi_{\nu 2} \\
m_{\tau 1}^2 = m_{\tau 1}^2 + 2 \sqrt{p_{\tau 1}^2 + m_{\tau 1}^2} \cdot p_{\nu 1} - 2 p_{\tau 1} p_{\nu 1} \cos \Delta \theta_{\nu \tau 1} \\
m_{\tau 2}^2 = m_{\tau 2}^2 + 2 \sqrt{p_{\tau 2}^2 + m_{\tau 2}^2} \cdot p_{\nu 2} - 2 p_{\tau 2} p_{\nu 2} \cos \Delta \theta_{\nu \tau 2}
\]
(6.3)

where \( \theta_{\nu \tau i} \) denotes the angle between the \( \tau \)-jet and the neutrino. The mass of the \( \tau \)-lepton is known \( (m_{\tau} = 1.777 \text{ GeV}) \) and the mass of the \( \tau \)-jets are set to either the \( \pi \)-meson mass \( (m_{\pi} = 139 \text{ MeV}) \) or \( \rho \)-meson mass \( (m_{\rho} = 770 \text{ MeV}) \) depending on the number of tracks associated with the \( \tau \)-jet.

From these equations the most likely mass of the \( \tau \)-pair system can be estimated based on simulations. These simulations can also accounts for reconstruction performance of the \( \tau \)-jets and of the \( E_T^{\text{miss}} \).

6.1.4 Boost Mass

In section 4.2 an alternative way to estimating the mass of \( \tau \)-pair system are described. Two different versions of the mass estimator are presented based on whether the transverse component of the boost is neglected \( (M_{\text{Boost-Z}}) \) or if it is estimated using the direction of the \( E_T^{\text{miss}} \)-vector \( (M_{\text{Boost-XYZ}}) \).

As mentioned in section 4.2, which of these two mass estimators is best will depend on the size of the transverse boost and on the resolution of the \( E_T^{\text{miss}} \) direction. An easy way to combine the two mass estimator would be to choose a threshold based on the magnitude of \( E_T^{\text{miss}} \)-vector, and use the \( M_{\text{Boost-Z}} \) below this threshold and the \( M_{\text{Boost-XYZ}} \) above. In figure 6.1 the mixed \( M_{\text{Boost}} \) is shown on simulated \( Z \to \tau \tau \) events at preselection level for different threshold values of \( |E_T^{\text{miss}}| \).

Since no signification change in the mass distribution is observed in figure 6.1 and both the signal regions in the analysis target events with a high transverse boost of the Higgs, \( M_{\text{Boost-XYZ}} \) is chosen as the default mass estimator, and henceforth will be denoted \( M_{\text{Boost}} \).

6.2 Performance comparison

In order to compare the performance of the different mass estimation techniques a separation power, \( S \), is defined as

\[
S = \frac{|\mu_a - \mu_b|}{\sqrt{\frac{1}{2} (\sigma_a^2 + \sigma_b^2)}}
\]
(6.4)

where \( \sigma \) denotes the spread and \( \mu \) the mean of the distributions, and \( a,b \) denotes the two samples under test. Here, the performance is evaluated at the preselection level and the two samples will be the total background vs. the Higgs samples. These distributions along with the derived \( S \) are shown in figure 6.2 for the \( M_{\text{Boost}} \) mass estimator, in figure 6.3 for the visible mass and in figure 6.4 for the likelihood-based \( M_{\text{MMC}} \) variable.
Fig. 6.1: Combined $M_{\text{Boost}}-Z$ and $M_{\text{Boost}}-XYZ$ distribution for different threshold values of $E_T^{\text{miss}}$. The combined $M_{\text{Boost}}$ variable exploits the $M_{\text{Boost}}-XYZ$ when the $E_T^{\text{miss}}$ value is above the threshold and otherwise uses the $M_{\text{Boost}}-Z$ variable.

Fig. 6.2: Normalised distributions of $M_{\text{Boost}}$ at preselection for expected background and signal events. The separation power, $S$, is derived using equation 6.4.

It should be noted that the cut on $M_{\text{vis}}$ and the $p_T$ cuts on the $\tau$-objects truncates the $M_{\text{vis}}$ distribution and make the width unnatural small. Therefore the obtained values for the separation power will be biased, especially for the low Higgs masses. For two highest mass point, best separation is found using the $M_{\text{MMC}}$ variable, while the $M_{\text{vis}}$ variable has the worst separation.

6.3 Principal Component Analysis

As shown in [29], the $M_{\text{vis}}$ and $M_{\text{Boost}}$ are fairly correlated with a correlation factor of 0.67\(^1\), therefore using both variables should add information. However, it is possible to transform the correlated $M_{\text{vis}}$ and $M_{\text{Boost}}$ variables into a set of linearly uncorrelated variables. The Principal Component Analysis transforms input variables into linearly

\(^1\)This correlation factor were derived at generator level using $Z \rightarrow \tau\tau$ events.
Figure 6.3: Normalised distributions of $M_{\text{vis}}$ at preselection for expected background and signal events. The separation power, $S$, is derived using equation 6.4.

Figure 6.4: Normalised distributions of $M_{\text{MMC}}$ at preselection for expected background and signal events. The separation power, $S$, is derived using equation 6.4.
uncorrelated variables, referred to as principal components, by an orthogonal transformation. The new principal components are ranked by the variance of data in this variable. Hence a ranking of the expected importance of each principal component variable is achieved. Figure 6.5 shows the correlation between $M_{\text{vis}}$ and $M_{\text{Boost}}$ at preselection for the observed data, as well as the found principal components and their eigenvalues. Since the eigenvalue of the first component is much larger than the second eigenvalue, most of the information is stored in this variable and this component will hereafter be referred to as $M_{\text{PC}}$. In figure 6.6, the separation powers are calculated for the $M_{\text{PC}}$ variable as well. Only slightly better separation powers are found using the $M_{\text{PC}}$ over the $M_{\text{Boost}}$ variable.

The separation powers are summarised in table 6.1, although these numbers should not be used as proof of which variable is best in a search or exclusion scenario, they do contain some hint of the ranking of these variables. Therefore the $M_{\text{MMC}}$ is used as the default mass variable when setting a limit on the Higgs cross section in section 9.3.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$m_H = 110$</th>
<th>$m_H = 130$</th>
<th>$m_H = 150$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{vis}}$</td>
<td>0.156</td>
<td>0.408</td>
<td>0.886</td>
</tr>
<tr>
<td>$M_{\text{Boost}}$</td>
<td>0.024</td>
<td>0.520</td>
<td>0.976</td>
</tr>
<tr>
<td>$M_{\text{PC}}$</td>
<td>0.029</td>
<td>0.540</td>
<td>1.043</td>
</tr>
<tr>
<td>$M_{\text{MMC}}$</td>
<td>0.077</td>
<td>0.560</td>
<td>1.137</td>
</tr>
</tbody>
</table>

Table 6.1: Separation power for different mass variables.
Figure 6.6: Normalised distributions of $M_{PC}$ at preselection for expected background and signal events. The separation power, $S$, is derived using equation 6.4.
CHAPTER 7

BACKGROUND ESTIMATION

In this chapter, the modelling of the two main backgrounds, i.e. $Z \rightarrow \tau \tau$ and QCD jets, are described. In order to model the differential distributions of these processes, data-driven methods are used, as described in section 7.1 and section 7.2, while the normalisation of both samples is done using the track multiplicity fit described in section 7.3.

7.1 Embedded $Z \rightarrow \tau \tau$ events

Since $Z \rightarrow \tau \tau$ is a dominant background process for this analysis, getting the best possible prediction on its distribution is very important. The idea behind the embedding technique is to use $Z^0$ events from data to model the $Z^0$ background. By doing so one could get a low statistical uncertainty on the distributions (due to the large cross section of $Z^0$ events) and avoid systematics uncertainties related to the underlying events and jet kinematics in these events.

However, getting a clean and unbiased $Z^0 \rightarrow \tau_{\text{had}}\tau_{\text{had}}$ samples from data is not possible due to the large QCD background and possible contamination from Higgs events. Therefore, $Z \rightarrow \mu\mu$ events are used instead, where the muons from data are substituted with $\tau$-decays from Monte Carlo simulations. Due to the clean signatures and high energy resolution of muons in the detector, it is possible to select a almost un-contaminated $Z \rightarrow \mu\mu$ sample from data with an extremely good prediction on the $Z^0$-mass shape from data. By removing the muons from the events and replacing them with simulated $\tau$-decays, hybrid events can be constructed. Since $\tau$-decays are well understood and well modelled in simulations this procedure should be safe. However, global quantities, i.e. $E_T^{\text{miss}}$, have to be recomputed after inserting the $\tau$-decays.

In the following, the construction of the hybrid or embedded events is described:

- **Selection of $Z \rightarrow \mu\mu$ events:**
  $Z \rightarrow \mu\mu$ are selected from data by requiring exactly two well reconstructed and isolated muons with $p_T > 20$ GeV. The muons are required to have an invariant mass $m_{\mu\mu} > 55$ GeV and to come from the same primary vertex.

- **Extracting $Z \rightarrow \tau\tau$ information:**
  The $Z^0$ boson is reconstructed from the selected muons. In the rest frame of the $Z^0$ boson, the reconstructed muons are replace with $\tau$-leptons at generator level.
Background Estimation

Here the four-momenta of the $\tau$-leptons are scaled in order to account for the mass difference between the muon and $\tau$-lepton.

- **Simulation of $\tau$-decays**
  The generator level $\tau$-leptons and their decay are generated with TAUOLA and PHOTOS, in order to correctly simulate the polarisation and final state radiation of the $\tau$-leptons. The generator level event (containing only the two $\tau$-decays and their final state particles) is then processed by the full ATLAS detector simulation.

- **Merging data and simulation:**
  First, all tracks and calorimeter energy associated with the muons are subtracted from the events. The energy subtraction in the calorimeter cells is based on simulated $Z \rightarrow \mu\mu$ events where the kinematics have been fixed to match the $Z \rightarrow \mu\mu$ kinematics in this event. Subsequently, the tracks and energy deposited in the calorimeters from the $Z \rightarrow \tau\tau$ events are added to the original event.

- **Re-reconstruction of the hybrid event:**
  The resulting $Z \rightarrow \tau\tau$ hybrid event is then re-processed by the full event reconstruction to ensure that all global objects, e.g. $E_T^{\text{miss}}$, are correctly recomputed.

The *embedded* events have been thoroughly tested in ATLAS and have been shown to describe data well. However, no trigger information is available in the *embedded* samples. Therefore, additional weights provided by the ALTAS Tau Working Group are assigned to the events to incorporate the effects of the trigger as function of the $\eta$ and $p_T$ of the $\tau$-jets. The overall normalisation of the *embedded events* are done with the track fit described in section 7.3.

### 7.2 QCD modelling

Unfortunately, Monte Carlo simulations does not describe events only containing QCD-jets (QCD events) very well. Therefore, a data-driven estimation of the QCD events is used. This method consists of taking pairs of $\tau$-candidates with same reconstructed charge from data, referred to as same-sign events. A data-driven method of estimating QCD events, can therefore be achieved by taking same-sign events in data, and subtracting the small contamination of other background processes. However, the rate of same-sign and opposite-sign QCD events, is not guaranteed to be equal. Therefore a normalisation of the same-sign events is needed. This is done by the track-multiplicity fit described in section 7.3.

Although, the same-sign QCD events is assumed to describe well in most of the phase space, the statistical uncertainties on the predicted shapes become large when going to the tight signal regions. Therefore, the method is extended to use all events which does not satisfy the charge production $= -1$ requirement of the selection, i.e. the not-opposite-sign events. These events will have a higher contamination from other background processes, however these contaminations can still be estimated from simulations.

Hence, the QCD events are estimated from not-opposite-sign events from data with the not-opposite-sign events from the Monte Carlo samples subtracted. Figure 7.1 shows a comparison at preselection level of the shape of QCD events obtained from same-sign
and not-opposite-sign events. Using the not-opposite-sign events results increases the statistics for the QCD description by a factor of $\sim 12$.

7.3 Normalisation from Track Multiplicity Fit

A $\tau$-lepton decaying into hadrons typically creates a more collimated jet in the detector than jets originating from quarks or gluons, QCD-jets, and typically $\tau$-jets generate less tracks than QCD-jets, which is why these two features are central in the $\tau$-identification [52]. In most cases, a hadronic $\tau$-decay will generate one or three charged pions contained in a narrow cone around the direction of the $\tau$-lepton. Therefore, the

Figure 7.1: Comparison of QCD models using same-sign, SS, or not-opposite-sign, notOS, events. The comparison is done at the preselection stage.
Background Estimation

τ-reconstruction searches for tracks in a cone of \( \Delta R \leq 0.2 \) which can be associated to the τ-candidate. This cone size has been proven optimal for the τ-reconstruction. However, counting the number of tracks outside this cone, can help separating real τ-lepton from QCD-jets as well as give a way to estimate the fraction of selected real and fake τ-jet.

### 7.3.1 Track counting method

In addition to the standard τ-identification cuts further rejection against QCD-jets can be achieved by counting the tracks close to, but outside the cone used by the τ-reconstruction. Tracks with a distance in the range of \( 0.2 < \Delta R \leq 0.6 \) from the centre of the τ-jet is counted in an anti-\( k_t \)-like way, first used in [59], in order to be as independent of the underlying event and pileup-conditions as possible.

A real τ-jet will typically only have 1 or 3 associated tracks in the cone of \( \Delta R \leq 0.2 \), core tracks, and tracks in the outer cone \( \Delta R \leq 0.6 \), outer tracks, will most likely come from the underlying event or from pileup, and therefore be uncorrelated. In contrast, a QCD-jet faking a τ-jet will be likely to produce additional outer tracks which are correlated with the existing core tracks by the splitting kernels [60, 61].

Tracks are only selected as outer tracks if they satisfy certain quality criteria\(^1\) and have \( p_T > 500 \text{ MeV} \). In addition, outer tracks are required to have \( D_{\text{max}} < 4 \) where

\[
D_{\text{max}} = \max \sum_{\text{core}} \left( \frac{p_T^{\text{core}} \Delta R(\text{core, outer})}{p_T^{\text{outer}}} \right)
\]

The \( D_{\text{max}} \) distance measure mimics the distance measure used in the anti-\( k_t \)-clustering algorithm [53] and the requirement \( D_{\text{max}} < 4 \) has been found as that best threshold to filter out uncorrelated tracks [62, 63].

Figure 7.2 shows the core+outer track distribution for same-sign, SS, events in data and for real τ-jets obtained from \( Z \to \tau \tau \) simulations at the preselection level described in section 5.3, but before cutting on the number of tracks. These distributions are peaking at 1 and 3 due to the requirement that reconstructed electrical charge should be \( \pm 1 \) for both candidates. However, a clearly shift towards higher tracks multiplicities is seen for QCD-jet events compared to real τ-candidates.

### 7.3.2 2-dimensional Fit of Track Multiplicities

In addition to rejecting QCD events, the track multiplicity distributions can also be used to estimate the fraction of real and fake τ-candidates in the selected ensemble. The fractions are found by creating 2-dimensional histograms of the track multiplicity of leading and sub-leading τ-candidates, before cutting on the number of tracks. These templates are generated for the following type of events: two real τ-candidates, \( T_{\text{real}} \), two fake τ-candidates, \( T_{\text{fake}} \), and one fake and one real τ-candidate, \( T_{\text{mixed}} \).

The \( T_{\text{real}} \) and \( T_{\text{mixed}} \) are generated from simulations of \( Z \to \tau \tau \) events and \( W \to \tau \nu \) and top events, while the \( T_{\text{fake}} \) template is mainly taken from same-sign events in data.

---

\(^1\)The standard track quality criteria consist of a minimum number of hits in each sub-detector in the ID and cuts on impact parameters.
Figure 7.2: Number of associated tracks – both core and outer – at normalisation stage for QCD and real taus. QCD event taken from from same-sign events in data, while real $\tau$-pairs are taken from $Z \rightarrow \tau\tau$ simulations.

Since, the $Z \rightarrow \tau\tau$ contamination of the $T_{\text{fake}}$ template due to the probability of charge misreconstruction is low, this effect is taken into account by subtracting these events from both data and the $T_{\text{fake}}$ template.

Each template is generated at the same stage of the selection, i.e. at the normalisation stage, to ensure the same kinematics in each templates. At this stage of the selection, the number of real and fake $\tau$-pairs can then be estimated, by fitting the ratio of the three templates to the observed data distributions. Since number of events from the third template is expected to be very small, the normalisation of this template is kept constant. In practice, the $T_{\text{mixed}}$ template is subtracted from data before fitting the two other templates to the remaining data.

The fraction of QCD events, $f_{\text{QCD}}$, is found using a binned maximum likelihood fit, with the log-likelihood function, $\log L$, defined as

$$
\log L = \sum_i \log \text{Poisson}(n_i | \mu_i)
$$

(7.2)

where for each bin $i$ in the 2-dimensional track multiplicity space, $n_i$ denotes the number of observed events and $\mu_i$ mean value given by the normalised $T_{\text{real}}$ and $T_{\text{fake}}$ using

$$
\mu_i = f_{\text{QCD}} T_{\text{fake}}(i) + (1 - f_{\text{QCD}}) T_{\text{real}}(i)
$$

(7.3)

Figure 7.3 shows the log-likelihood ratio, $q$, at the normalisation stage, defined as

$$
q = - \log \frac{L(f_{\text{QCD}})}{L(\hat{f}_{\text{QCD}})}
$$

(7.4)

where $\hat{f}_{\text{QCD}}$ is the value of $f_{\text{QCD}}$ that maximises $L(f_{\text{QCD}})$. The $q$ normalises $\log L$ to its maximal value. The $q$ shown in figure 7.3 clearly has a single minimum, and is well defined over a large range around it.

Figure 7.4 shows the fitted combination of two templates, $T_{\text{real}}$ and $T_{\text{fake}}$, to the observed data at the normalisation stage. Since the fit only evaluates the fraction of $T_{\text{fake}}$ vs. $T_{\text{real}}$ events, the overall normalisation of events are fixed by the number of events in data. The fit can easily be extended to also fitting the overall normalisation by
Background Estimation

Figure 7.3: Log Likelihood Ratio, $q$, for the track multiplicity likelihood function in equation 7.2.

Figure 7.4: Projections on track-multiplicity of leading and subleading $\tau$-candidates. Full line show the fitted combination of the real and fake $\tau$-pair templates, while the dashed lines shows the individual templates used in the combination. The points are the measured data points.
substituting the $f_{QCD}$ parameter with 2 parameters $N_{\text{fake}}$ and $N_{\text{real}}$ denoting the total number of QCD or real $\tau$-pair events. In this case the extended likelihood function is

$$\log \mathcal{L} = \sum_i \log \text{Poisson}(n_i|\mu_i) - \log \text{Poisson}(N_{\text{fake}} + N_{\text{real}}, N_{\text{observed}})$$

(7.5)

where

$$\mu_i = \frac{N_{\text{fake}}}{N_{\text{fake}} + N_{\text{real}}} T_{\text{fake}}(i) + \frac{N_{\text{real}}}{N_{\text{fake}} + N_{\text{real}}} T_{\text{real}}(i)$$

Fitting the 2-parameter likelihood given in equation 7.5, has been shown to give a consistent result with the one parameter fit in figure 7.4. And therefore the 1-parameter fit will be used here.

The ratio between QCD events and real $\tau$-pairs could in principle be determined at any stage of the selection. However, the number of events containing two real $\tau$-leptons might not be purely from $Z^0$, but can contain possible signal events. This would introduce a small bias of the on the $Z \rightarrow \tau\tau$ normalisation and possible hide a signal. Therefore the $Z \rightarrow \tau\tau$ samples has to be normalised at an early stage of the selection, i.e. the normalisation stage, where the bias is very small\(^2\) and therefore can be neglected. The normalisation of $Z \rightarrow \tau\tau$ events can hereafter be extrapolated from the normalisation stage to the signal regions.

### 7.4 Normalisation from $\Delta\eta(\tau_1, \tau_2)$ Fit

An alternative way of determining the amount of QCD and $Z^0$ events is to use the difference in the $\Delta\eta(\tau_1, \tau_2)$ distributions. The $\Delta\eta(\tau_1, \tau_2)$ distribution for $\tau$-pairs coming from $Z \rightarrow \tau\tau$ event is much more centred around 0 and has an upper limit at 2, while distribution for QCD-jets is much broader, as illustrated in Figure 5.1. This difference is already exploited in the selection of good $\tau$-pairs, however this difference also provides good way for estimating the ratio between QCD and $Z \rightarrow \tau\tau$ events.

By using the template distributions for QCD and $Z \rightarrow \tau\tau$ shown in figure 5.1, a maximum likelihood fit of the two distributions are performed to match the observed data at the normalisation stage. Just like for the track-multiplicity fit, the normalisation stage is defined as the preselection with the last cut on $\Delta\eta(\tau_1, \tau_2) < 2$. Before performing the fit, the other background processes are subtracted from the data points using the predicted distributions from simulations, so that the data only contains the two backgrounds of interest (and possibly a small contamination of signal events).

Figure 7.5 shows the observed and the fitted $\Delta\eta(\tau_1, \tau_2)$ distributions at normalisation stage, along with the QCD and $Z \rightarrow \tau\tau$ components of the fit. The obtained number of QCD events from fitting the $\Delta\eta(\tau_1, \tau_2)$ distributions is $\sim 100$ events more than from track multiplicity fit which is within the error of the fit. Hence, the two fit methods are consistent, but since the $\Delta\eta(\tau_1, \tau_2)$ fit give the best $\chi^2$, the normalisations further on are taken from this fit.

\(^2\)The signal contamination wrt. the number of $Z \rightarrow \tau\tau$ at the normalisation stage is $\approx 0.38\%$ (for $m_H = 125$ GeV)
Figure 7.5: Fit of $\Delta \eta(\tau_1, \tau_2)$ distribution to the observed data at the normalisation stage.
The theoretical uncertainties (THU) related to the Higgs production are often among the largest uncertainties in the Higgs searches at the LHC. The ability to claim either discovery or exclusion of the Higgs, is very dependent on getting the best prediction from theory on the expected signal yield in the analysis.

Three types of THU usually enter in the analysis in order to get the expected signal yield.

- The uncertainty on the inclusive cross section for a given production mode.
- The uncertainty on the branching ratios, BR, into different final states.
- The uncertainty on the differential cross section or on the kinematics in the Higgs event.

In order to get a consistent treatment of these uncertainties between ATLAS and CMS, the THU are evaluated by the LHC Higgs Cross Section Working Group, XSWG [38, 39] without taking experimental cuts or acceptance of the detector into account. This ensures a consistent use of THU across the different final states searches and across experiments, which is important when comparing the different results and crucial when trying to combine them.

The procedure of using values given by the Higgs XSWG, guarantees that the analyses use not only common, but also the most up-to-date numbers from theory both on the central values and on the associated uncertainties.

Since the THU’s listed above are derived without considering analysis cuts or detector acceptance, these still have to be evaluated by the individual analyses. Some recommendations on how to do this consistently is given in Handbook of LHC Higgs Cross Sections [39]. In the latter part of this chapter, a description of how these uncertainties are derived for the $H \rightarrow \tau\tau \rightarrow \tau_{\text{had}}\tau_{\text{had}}$ analysis is given.

### 8.1 Inclusive Cross Section Uncertainties

As described in section 2.1 the main Higgs production mechanism at the LHC is ggH where the Higgs boson is produced by two gluons through a heavy quark loop. Hence
this production mechanism is mainly controlled by the strong interaction and therefore one would expect sizeable QCD corrections.

The leading order, LO, cross section for ggH [64] is proportional to $\alpha_S^2$ which can be seen from the diagram in figure 2.3(a). The next-to-leading order, NLO, QCD corrections [65, 66, 67] enhances the cross section with $\sim 80 - 100\%$. These corrections are computed both with and without using the large-$m_t$ limit ($m_t \rightarrow \infty$), while the next-to-next-to-leading-order, NNLO [68, 69, 70], corrections are only computed in the large-$m_t$ limit. These corrections further increase the cross section with $\sim 25\%$. The NNLO cross section is improved by resumming the soft-gluon contributions [71] up to next-to-next-leading-log, NNLL which leads to an additional increase in the cross section of $7 - 9\%$.

In addition to the QCD corrections, also EW corrections has to be considered. Since the ggH is initiated by strong dynamics, the EW corrections are much smaller. Currently, two-loops EW corrections are computed [72, 73], and leads to a $\sim 5\%$ increase in the cross section for a low mass Higgs.

The uncertainties on the inclusive cross section comes from the following sources:

- Higher-order radiative corrections from both QCD and EW corrections
- Limited knowledge of the parton distribution functions, PDFs, and uncertainty on $\alpha_S$
- Effects of the large-$m_t$ approximation
- Uncertainties on the input quark masses, in particular the $m_t$ and $m_b$.
- Choice of the renormalisation scale, $\mu_R$, and factorisation scale, $\mu_F$

Of these uncertainties the two dominating sources are the uncertainties on the PDF+$\alpha_S$\(^1\) and uncertainties from QCD scales ($\mu_R, \mu_F$) which are comparable in size ($\sim 10\%$) for most of the $m_H$ range.

For the VBF and VH production modes also described in section 2.1, the QCD corrections are typically small since this production modes is controlled by weak interactions. The cross section have been calculated with both NLO QCD and EW corrections [10, 11]. These corrections also takes into account real photon emissions.

The main sources still comes from QCD scales and PDF+$\alpha_S$, however since the kinematics of this production mode is controlled by weak interaction, a large part of the uncertainties on the QCD scales are shifted to the PDF uncertainties.

The main THUs on the inclusive Higgs cross section taken from [38] are summarised in table 8.1.

### 8.2 Uncertainties on Jet Categories

Since the background composition often varies with the number of associated jets, the Higgs searches are often split up into categories based on the jet kinematics of the event in order to enhance sensitivity. Also these categories can be used to target ggH and

\(^1\) Since the uncertainties on $\alpha_S$ and the PDF’s are highly correlated it is customary to list these as a combined uncertainty.
8.2 Uncertainties on Jet Categories

<table>
<thead>
<tr>
<th>Source</th>
<th>ggH [%]</th>
<th>VBF [%]</th>
<th>VH [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDF+αS</td>
<td>+7.9</td>
<td>+2.7</td>
<td>+3.9</td>
</tr>
<tr>
<td></td>
<td>-7.7</td>
<td>-2.1</td>
<td>-3.9</td>
</tr>
<tr>
<td>QCD Scale</td>
<td>+13.3</td>
<td>+0.4</td>
<td>+0.7</td>
</tr>
<tr>
<td></td>
<td>-8.6</td>
<td>-0.4</td>
<td>-0.8</td>
</tr>
</tbody>
</table>

Table 8.1: Theoretical uncertainties on the inclusive Higgs cross section due to PDF+αS and QCD scale taken from [38].

VBF events separately. When splitting up the events into different jet categories, it becomes important to estimate the THU on the signal yield in each category. Since the uncertainty from PDF+αS does not modify the jet kinematics of the events, only the THU from QCD scales are considered important here.

Even for analyses which only have a single signal region, the uncertainty on the signal yield in this signal region still needs to be evaluated – especially if the jet kinematics is used to define the signal region. This was the case in the $H \rightarrow \tau \tau \rightarrow \tau_{\text{had}}\tau_{\text{had}}$ analysis for Moriond 2012 [51], where HNNLO [74, 75] was used to estimate the uncertainty on the Higgs $+ \geq 1$ jet cross section.

For analyses with multiple exclusive jet categories, a natural approach for estimating the uncertainties on the signal yield in each category would be to compute the exclusive cross section for the each jet category while varying the QCD scales, and treat the uncertainty for each category as uncorrelated. However, this approach has been shown to severely underestimate the uncertainty [39].

Instead, an improved prescription for estimating the uncertainties is given by Stewart and Tackman [76]. In the ATLAS $H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$ working group, the following three categories are proposed, VBF, Boosted and Rest with the cuts used to define the categories listed in Table 8.2. These categories do not entirely match the categories defined in section 5.4, but the VBF and Boosted category presented here have very similar definitions as the VBF and ggH categories, and therefore the THU are assumed to be the same.

<table>
<thead>
<tr>
<th>VBF</th>
<th>Boosted</th>
<th>Rest</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 2 jets with:</td>
<td>Not in the VBF</td>
<td>Not in the VBF</td>
</tr>
<tr>
<td>jet$_1$ $p_T \geq$ 50 GeV</td>
<td>≥ 1 jet with:</td>
<td>Not in Boosted</td>
</tr>
<tr>
<td>jet$_2$ $p_T \geq$ 30 GeV</td>
<td>Jet$_1$ $p_T \geq$ 50 GeV</td>
<td></td>
</tr>
<tr>
<td>$\eta_{\text{jet1}} \cdot \eta_{\text{jet2}} &lt; 0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta \eta_{\text{jet1,jet2}} &gt; 2.6$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_{jj} &lt; 350$ GeV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8.2: Proposed cuts to the define the jet categories in the $H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$ analysis.

For ggH production, the inclusive cross sections $\sigma_{\geq 2 \text{jets}}$, $\sigma_{\geq 1 \text{jets}}$ and $\sigma_{\text{Total}}$ have been computed using the Parton level Monte Carlo program, HNNLO, which is able to calculate the Higgs production at NNLO in QCD using a set of user-specific cuts on the associated jets. The $\sigma_{\geq 2 \text{jets}}$ cross section is computed using the cuts for the VBF category, while the $\sigma_{\geq 1 \text{jets}}$ cuts are defined as either the VBF or Boosted category. The uncertainties on the $\sigma_{\geq 2 \text{jets}}$, $\sigma_{\geq 1 \text{jets}}$ and $\sigma_{\text{Total}}$ are found by computing the cross sections...
while varying the QCD scales, $\mu_R$ and $\mu_F$, around the nominal value at $\mu_R = \mu_F = m_H$. The QCD scales are varied among the following values\(^2\)

$$\mu_R, \mu_F \in \{m_H/2, m_H, 2m_H\}$$  \hfill (8.1)

For any combination of $\mu_R$ and $\mu_F$, the HNNLO program is run for a sufficiently long time to make the statistical errors on the cross sections negligible\(^3\) (< 0.1%). The uncertainties, $\Delta \sigma_{\geq 2}$, $\Delta \sigma_{\geq 1}$ and $\Delta \sigma_{\text{Total}}$ on the inclusive cross sections are taken as the maximal variation from the nominal value.

From the inclusive cross sections, the exclusive cross section in each category is found by assuming

$$\sigma_{\text{VBF}} = \sigma_{\geq 2\text{jets}}, \quad \sigma_{\text{Boosted}} = \sigma_{\geq 1\text{jets}} - \sigma_{\geq 2\text{jets}}, \quad \sigma_{\text{Rest}} = \sigma_{\text{Total}} - \sigma_{\geq 1\text{jets}}$$  \hfill (8.2)

while the signal yield fractions in each category are defined as

$$f_{\text{VBF}} = \frac{\sigma_{\text{VBF}}}{\sigma_{\text{Total}}}, \quad f_{\text{Boosted}} = \frac{\sigma_{\text{Boosted}}}{\sigma_{\text{Total}}}, \quad f_{\text{Rest}} = \frac{\sigma_{\text{Rest}}}{\sigma_{\text{Total}}}$$  \hfill (8.3)

<table>
<thead>
<tr>
<th>$m_H$ [GeV]</th>
<th>$f_{\text{Rest}}$</th>
<th>$f_{\text{Boosted}}$</th>
<th>$f_{\text{VBF}}$</th>
<th>HNNLO $\delta \sigma_{\text{Total}}$</th>
<th>HNNLO $\delta \sigma_{\geq 1}$</th>
<th>HNNLO $\delta \sigma_{\geq 2}$</th>
<th>MCFM $\delta \sigma_{\geq 2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.615</td>
<td>0.377</td>
<td>0.008</td>
<td>23.2 %</td>
<td>22.5 %</td>
<td>75.1 %</td>
<td>25.7 %</td>
</tr>
<tr>
<td>110</td>
<td>0.577</td>
<td>0.414</td>
<td>0.009</td>
<td>22.6 %</td>
<td>22.4 %</td>
<td>74.0 %</td>
<td>27.0 %</td>
</tr>
<tr>
<td>120</td>
<td>0.545</td>
<td>0.446</td>
<td>0.009</td>
<td>24.3 %</td>
<td>22.2 %</td>
<td>73.0 %</td>
<td>27.3 %</td>
</tr>
<tr>
<td>130</td>
<td>0.514</td>
<td>0.476</td>
<td>0.010</td>
<td>22.3 %</td>
<td>22.5 %</td>
<td>72.2 %</td>
<td>27.7 %</td>
</tr>
<tr>
<td>140</td>
<td>0.485</td>
<td>0.505</td>
<td>0.010</td>
<td>22.6 %</td>
<td>22.5 %</td>
<td>71.5 %</td>
<td>27.2 %</td>
</tr>
<tr>
<td>150</td>
<td>0.461</td>
<td>0.528</td>
<td>0.011</td>
<td>23.1 %</td>
<td>23.0 %</td>
<td>70.8 %</td>
<td>27.4 %</td>
</tr>
</tbody>
</table>

Table 8.3: Fraction of signal yield in each jet category, $f$, for ggH Higgs production, along with the relative uncertainties on the cross sections in the inclusive jet bins, $\delta \sigma_{\text{Total}}$, $\delta \sigma_{\geq 1}$ and $\Delta \sigma_{\geq 2}$. Calculated using HNNLO and MCFM. The large uncertainties $\delta \sigma_{\geq 2}$ found by HNNLO are replaced by the uncertainties found by MCFM.

Table 8.3 shows the signal yield in each category and the associated relative uncertainties, $\delta \sigma_i = \Delta \sigma_i/\sigma_i$, on the inclusive cross sections obtained by HNNLO in the mass range of $m_H$ from 100 GeV to 150 GeV. Since HNNLO calculates ggH Higgs at NNLO, this means that the cross sections $\sigma_{\text{Total}}$, $\sigma_{\geq 1\text{jets}}$ and $\sigma_{\geq 2\text{jets}}$ are all calculated to same order in $\alpha_S$. However, the prediction for $H+ \geq 2$ jets is a LO prediction, and hence this cross section and its uncertainty are very sensitive to virtual corrections. Therefore, the uncertainty for the $\sigma_{\geq 2\text{jets}}$ is also computed using Monte Carlo event generator MCFM [77] which is able to calculate $H+ \geq 2$ jets at NLO. The results are also listed in table 8.3. As expected, the uncertainty on the $\sigma_{\geq 2\text{jets}}$ drops significantly when including the higher order corrections, and the high uncertainties found by HNNLO for $\sigma_{\geq 2\text{jets}}$ are replaced by the uncertainties found by MCFM.

Using the Stewart-Tackman (S.T.) approach, the uncertainties on the inclusive cross sections should be treated as correlated, and the uncertainties on the exclusive cross

\(^2\)Both the central values and the variation range of the QCD scales $\mu_R$ and $\mu_F$ are purely chosen by convention.

\(^3\)The cpu time for each cross section computation depends on the specific cuts, but a typical computation takes $\sim 10$ hours.
sections can be found from error propagation using the covariance matrix, \( C \), for the cross sections \( \{\sigma_{\text{Total}}, \sigma_{\text{Rest}}, \sigma_{\text{Boosted}}, \sigma_{\text{VBF}}\} \) [76]

\[
\begin{bmatrix}
\Delta\sigma^2_{\text{Total}} & \Delta\sigma^2_{\text{Total}} & 0 & 0 \\
\Delta\sigma^2_{\text{Total}} & \Delta\sigma^2_{\text{Total}} + \Delta\sigma^2_{\geq 1} & -\Delta\sigma^2_{\geq 1} & 0 \\
0 & -\Delta\sigma^2_{\geq 1} & \Delta\sigma^2_{\geq 1} + \Delta\sigma^2_{\geq 2} & -\Delta\sigma^2_{\geq 2} \\
0 & 0 & -\Delta\sigma^2_{\geq 2} & \Delta\sigma^2_{\geq 2}
\end{bmatrix}
\] (8.4)

When using THU in the likelihood fit described in section 9.1, the uncertainties are introduced as nuisance parameters, which are usually assumed to be gaussian distributed. However, due to the large values of the QCD scales uncertainties, these uncertainties are assumed to be distributed according to a log-normal distribution of width \( \kappa \). In practice, the uncertainties on the exclusive cross section are not used as nuisance parameters, because of their correlation. Instead, one or two nuisance parameters for the inclusive cross sections are given for each category. These nuisance parameters are derived as follows [78]

<table>
<thead>
<tr>
<th>Name</th>
<th>VBF</th>
<th>Boosted</th>
<th>Rest</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCDscale_ggH</td>
<td>( \kappa^{1/f_0}_{\text{tot}} )</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>QCDscale_ggH1in</td>
<td>( \kappa_{\geq 1}^{-f_1 + f_2/f_0} )</td>
<td>( \kappa_{\geq 1}^{-f_1 + f_2/f_1} )</td>
<td>-</td>
</tr>
<tr>
<td>QCDscale_ggH2in</td>
<td>-</td>
<td>( \kappa_{\geq 2}^{-f_2/f_1} )</td>
<td>( \kappa_{\geq 2} )</td>
</tr>
</tbody>
</table>

where the \( f \)'s are the fraction listed in table 8.3 and \( \kappa_i = 1 + \delta\sigma_i \). The value of \( \kappa_{\text{tot}} \) is taken from the Higgs XSWG [38].

For the VBF production mode, the cross sections are computed using the Monte Carlo generator HAWK [79], which is able to compute VBF production at NLO. Since the THU from QCD scales are much smaller in VBF than for ggH, the uncertainties on the exclusive cross section are not derived using the S.T. procedure, following the recommendations from the Higgs XSWG [39]. Instead, the exclusive cross sections are computed for different values of \( \mu_R \) and \( \mu_F \), and the uncertainties are taken as the maximal variation from the nominal value. Here, the nominal value is chosen for \( \mu_R = \mu_F = m_W \), and the QCD scales are varied independently between the following values \( \{1/2m_W, m_W, 2m_W\} \). The resulting relative uncertainties from HAWK are listed in table 8.4.

<table>
<thead>
<tr>
<th>( m_H ) [GeV]</th>
<th>( f_{\text{Rest}} )</th>
<th>( f_{\text{Boosted}} )</th>
<th>( f_{\text{VBF}} )</th>
<th>( \delta\sigma_{\text{Rest}} )</th>
<th>( \delta\sigma_{\text{Boosted}} )</th>
<th>( \delta\sigma_{\text{VBF}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>0.840</td>
<td>0.086</td>
<td>0.073</td>
<td>1.6%</td>
<td>3.2%</td>
<td>1.7%</td>
</tr>
<tr>
<td>120</td>
<td>0.822</td>
<td>0.091</td>
<td>0.086</td>
<td>5.6%</td>
<td>5.8%</td>
<td>2.8%</td>
</tr>
<tr>
<td>130</td>
<td>0.810</td>
<td>0.095</td>
<td>0.095</td>
<td>5.9%</td>
<td>3.0%</td>
<td>1.1%</td>
</tr>
<tr>
<td>140</td>
<td>0.813</td>
<td>0.089</td>
<td>0.097</td>
<td>5.7%</td>
<td>2.9%</td>
<td>1.8%</td>
</tr>
<tr>
<td>150</td>
<td>0.803</td>
<td>0.089</td>
<td>0.107</td>
<td>6.4%</td>
<td>4.2%</td>
<td>1.7%</td>
</tr>
</tbody>
</table>

Table 8.4: Fraction of signal yield in the different jet categories, \( f \), for VBF Higgs production and the associated relative uncertainties, \( \delta\sigma_{\text{Rest}} \), \( \delta\sigma_{\text{Boosted}} \) and \( \delta\sigma_{\text{VBF}} \) calculated using HAWK.
8.3 Background cross sections

The production cross section uncertainties for the $Z$ and $W$ background as well as diboson backgrounds are taken from [80] and listed in table 8.5.

For the cross-section uncertainty on top pair production, calculations have been used that approximates NNLO in QCD with Hathor 1.2 [81] using the MSTW2008 90% NNLO PDF sets [82] incorporating PDF+$\alpha_S$ uncertainties according to the MSTW prescription [83].

<table>
<thead>
<tr>
<th>Background</th>
<th>Total uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z^0$+jets</td>
<td>5.0</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>5.0</td>
</tr>
<tr>
<td>$WW$</td>
<td>$+5.5$</td>
</tr>
<tr>
<td>$WZ^0$</td>
<td>$-4.5$</td>
</tr>
<tr>
<td>$Z^0Z^0$</td>
<td>$+7.1$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$-5.9$</td>
</tr>
<tr>
<td>Single top</td>
<td>$+5.0$</td>
</tr>
<tr>
<td></td>
<td>$-4.1$</td>
</tr>
<tr>
<td></td>
<td>$+9.9$</td>
</tr>
<tr>
<td></td>
<td>$-10.7$</td>
</tr>
<tr>
<td></td>
<td>$+6.8$</td>
</tr>
<tr>
<td></td>
<td>$-2.2$</td>
</tr>
</tbody>
</table>

Table 8.5: Theoretical uncertainties for relevant background production cross sections.
CHAPTER 9

RESULTS

In this chapter, the results obtained from the $H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$ analysis in ATLAS from January 2012 is presented and compared to the sensitivity of the analysis presented in this thesis. The expected and observed limits on the Higgs cross section are presented for Higgs masses in the range $m_H \in [100, 150]$ GeV.

9.1 Limits Setting Technique

The exclusion limits on the Higgs production cross section is set using a binned profile likelihood fit based on methods described in [78]. It is customary to express the limits in terms of the signal strength parameter $\mu$ which normalises the limit on the cross section by the SM Higgs cross section, i.e. a limit on $\mu$ below 1 corresponds to an exclusion of the SM Higgs cross section at 95% Confidence Level, CL. It should be noted that $\mu$ only expresses a change in the cross section on the Higgs production while the Higgs BR are assumed fixed to the SM values.

The overall likelihood is given as the product of the likelihoods in each category. For a given category a likelihood is defined as

$$L(x_i|\mu, \theta) = \prod_i \text{Poisson}(x_i|\mu \cdot s_i(\theta) + b_i(\theta)) \cdot L(\theta)$$ \hspace{1cm} (9.1)

where

- $x_i$ denotes the number of events in each bin$^1$.
- $s_i$ and $b_i$ is expected signal and background yields in each bin.
- $\theta$ is the array of systematic uncertainties expressed as nuisance parameters.

In the following, a procedure for quantifying the compatibility of data, $x_i$ with the two hypotheses of $\text{background-only}$ and $\text{signal+background}$ for an assumed signal strength $\mu$ is described. In the limit setting procedure, this routine is performed as an iterative process in order to find an upper limit on $\mu$.

$^1$Here, these events can refers to both events from pseudo-data or from observed data
First, a test statistic, \( \tilde{q}_\mu \) [84], is defined as

\[
\tilde{q}_\mu = \begin{cases} 
-2 \ln \frac{\mathcal{L}(x_i|\mu, \hat{\theta})}{\mathcal{L}(x_i|0, \hat{\theta})} & \text{for } \hat{\mu} < 0 \\
-2 \ln \frac{\mathcal{L}(x_i|\mu, \hat{\theta}_\mu)}{\mathcal{L}(x_i|\hat{\mu}, \hat{\theta})} & \text{for } 0 \leq \hat{\mu} \leq \mu 
\end{cases}
\tag{9.2}
\]

where

- \( \hat{\theta}_\mu \) are the conditional Maximum Likelihood Estimators (MLE) of \( \theta \) given \( \mu \).
- \( \hat{\theta} \) and \( \hat{\mu} \) represent the MLE’s that globally maximises \( \mathcal{L} \).

From the observed data, the MLE’s for the nuisance parameters that best describe data under the background-only hypothesis, \( \hat{\theta}_\text{data}^0 \), and under the signal+background hypothesis, \( \hat{\theta}_\mu^\text{data} \), are found by maximising the likelihood in equation 9.1. From these MLE’s the probability density functions, p.d.f.’s, of the test statistics \( \tilde{q}_\mu \) are generated.

The p.d.f of the test statistic, \( f(\tilde{q}_\mu|\mu', \hat{\theta}_\text{data}^\mu) \), for the true value of \( \mu = \mu' \), is derived by generating a large ensemble of Monte Carlo pseudo-data with an input value of \( \mu = \mu' \) and evaluating \( \tilde{q}_\mu \). The corresponding p.d.f. of the test statistic under the background-only hypothesis, \( f(\tilde{q}_\mu|0, \hat{\theta}_\text{data}^0) \) is also derived by pseudo-data. It should be noted that in generating the pseudo-data for both hypothesis the nuisance parameters are fixed to MLE’s derived from the observed data, \( \hat{\theta}_\text{data}^\mu \) and \( \hat{\theta}_\text{data}^0 \).

Given the value of the test statistic derived from data \( \tilde{q}_\text{data}^\mu \), the two probabilities of getting an equal or large value of the test statistic is calculated: under the signal+background hypothesis, \( p_\mu \), and under the background-only hypothesis, \( p_0 \).

\[
p_\mu = P(\tilde{q}_\mu \geq \tilde{q}_\text{data}^\mu | \text{signal+background})
= \int_{\tilde{q}_\text{data}^\mu}^{\infty} f(\tilde{q}_\mu|\mu, \hat{\theta}_\text{obs}^\mu) \\
1 - p_0 = P(\tilde{q}_\mu \geq \tilde{q}_\text{data}^\mu | \text{background-only})
= \int_{\tilde{q}_\text{data}^\mu}^{\infty} f(\tilde{q}_\mu|0, \hat{\theta}_\text{obs}^0) \tag{9.3}
\]

With these definitions the probabilities, \( p_\mu \) and \( 1 - p_0 \) corresponds to the confidence levels, \( CL_{s+b} \) and \( CL_b \). From these, the confidence level ratio \( CL_s \) [85] is computed as

\[
CL_s = \frac{p_\mu}{1 - p_0} \tag{9.4}
\]

and the Higgs is said to be excluded at 95% CL if \( CL_s \leq 0.05 \) for \( \mu = 1 \).

Now, to set an upper limit on \( \mu \), this whole routine of pseudo-data generation and calculations is executed while modifying the input value of \( \mu \) until a \( \mu \) is found which correspond to a 95% CL exclusion.

**9.2 Current ATLAS Limit**

The current limit published by ATLAS in the \( H \to \tau\tau \to \tau_\text{had}\tau_\text{had} \) search channel [51](see attached papers) is based on a \( H + 1\text{jet} \) category similar to the \( ggH \) category presented
in section 5.4.2 with the collinear approximation mass as the discriminating variable. Figure 9.1 shows the $M_{CA}$ distribution in the $H+ \geq 1$jet category for both data and simulations.

Since no clear excess is observed an upper limit on the Higgs production cross section is set using the machinery described in section 9.1. Both the expected upper limit in case of the background-only hypothesis (no Higgs) and the observed upper limit are derived, and both limits are normalised to the SM Higgs cross section as described above.

The limits are derived using a limit setting tool, HistFactory [86], that ensures all limits in ATLAS are derived consistently across the Higgs search channels. Statistical and systematics uncertainties are taken into account as bin-by-bin fluctuations in the signal and background shapes. Four different shape are considered as input to the limit setting: signal, $Z \rightarrow \tau\tau$, QCD-jet event and other background (including $Z \rightarrow \ell\ell$, $W+\text{jets}$, top and di-boson events).

The QCD and $Z \rightarrow \tau\tau$ events are normalised using the fitted $\Delta\eta(\tau_1, \tau_2)$ distributions as described in section 7.4, while the normalisation of both signal and other backgrounds are taken from theoretical predictions. Uncertainties on the shape of templates are derived by varying the tau and jet energy scale and the $E_T^{\text{miss}}$ scale and resolution. Since the $Z \rightarrow \tau\tau$ are derived partly from data, the jet energy does not affect its shape. The tau and jet energy scale uncertainties are taken to be completely correlated. All uncertainties are considered uncorrelated between background and signal samples which will lead to a more conservative limit.

Figure 9.2 shows the expected and observed upper limits on the Higgs cross section in the mass range $m_H = [100, 150]$ GeV. The expected sensitivity is still far away from $\mu = 1$ at all mass points, hence the presence of a SM Higgs boson can not be excluded.
yet in the $\tau$-decay channel for any mass point.

Figure 9.2: Current ATLAS upper limit on the 95% CL exclusion of the Higgs production cross section from the fully hadronic $\tau$ final states. The limit on the cross section is normalised to the SM Higgs cross section. Plot taken from [51].

9.3 Exclusion Limits Comparison

In chapter 5, an alternative selection for $H \rightarrow \tau\tau$ events is presented. There are two main differences between this selection and the selection used in the previous section: the use of specific ggH and VBF categories and the selection of events based on the reconstructed boost of the Higgs candidates using the techniques developed in chapter 4.

Up until this point a blinded analysis has been carried out. Hence, the optimised selection has been derived using only the expected distributions from simulations and the data-driven background techniques. The true data has only been seen at the preselection level, and none of the cuts in the optimised part of the selection have been tuned by looking at the data. This is crucial for maintaining an unbiased selection.

Figure 9.3 shows the expected and observed $M_{MMC}$ distributions in the two signal regions, while figure 9.4 shows the equivalent distributions for the $M_{\text{Boost}}$ variable. In order to avoid empty bins due to fluctuations in the background samples, a bin width of 7 GeV has been chosen for the ggH category and 15 GeV for the VBF category.

A full evaluation of all systematic uncertainties is not done here, however the following uncertainties on the number of accepted events in each signal regions are considered for the processes based on Monte Carlo predictions: the uncertainty on the integrated luminosity delivered in ATLAS during the data taking period, uncertainties on the energy...
Figure 9.3: The expected and observed $M_{MMC}$ distributions in the signal regions for both background and signal processes.

Figure 9.4: The expected and observed $M_{Boost}$ distributions in the signal regions for both background and signal processes.
Table 9.1: Systematic uncertainties on the acceptance of events from simulated samples in the VBF signal region.

<table>
<thead>
<tr>
<th>Relative Uncertainties [%]</th>
<th>ggH</th>
<th>VBF</th>
<th>VH</th>
<th>MC Backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Energy Scale</td>
<td>7.9</td>
<td>12.0</td>
<td>0.6</td>
<td>+7.9</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>0.7</td>
<td>0.5</td>
<td>10.0</td>
<td>4.5</td>
</tr>
<tr>
<td>( E_{T}^{\text{miss}} )</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>( \tau)-ID</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>2.3</td>
</tr>
<tr>
<td>PDF</td>
<td>+7.6</td>
<td>2.3</td>
<td>+3.6</td>
<td>+4.7</td>
</tr>
<tr>
<td>QCD Scales</td>
<td>+29.8</td>
<td>-3.4</td>
<td>-4.1</td>
<td>-4.1</td>
</tr>
<tr>
<td>Underlying Event</td>
<td>-23.0</td>
<td>1.6</td>
<td>1.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

scale for both \( \tau \)-candidates and jets, the uncertainties on the energy resolution for both \( \tau \)-leptons and jets, the resolutions of the reconstructed \( E_{T}^{\text{miss}} \)-vector, the efficiencies on the used triggers and the efficiency of the \( \tau \)-identification methods. All these uncertainties are evaluated by tools or numbers provided by the performs groups. The uncertainties on the energy scales for \( \tau \)-leptons and jets have been taken to be 100% correlated.

Additionally, uncertainties from theory are evaluated as described in chapter 8. These uncertainties are among the largest for the signal samples. In addition to the theoretical uncertainties described in chapter 8, an uncertainties on the underlying event model is included. This uncertainty is determined by running the selection on samples generated with different models of the underlying event. The systematic uncertainties are summarised in table 9.1 for the VBF category and in Table 9.2 for the ggH category. In addition to the uncertainties on the simulated events, uncertainties on the normalisation of the data-driven samples for QCD-jets (17%) and \( Z \rightarrow \tau\tau \) events are also used. Besides the uncertainties on the normalisation, the embedded \( Z \rightarrow \tau\tau \) events also have an uncertainty from the energy scale of the reconstructed \( \tau \)-objects and an uncertainty from the embedding technique coming from the selection of \( Z \rightarrow \mu\mu \) events. The systematic uncertainties related to the \( Z \rightarrow \tau\tau \) sample are listed in table 9.3.

The obtained values for all systematic uncertainties are derived using a very similar re-optimised selection of events proposed in the \( H \rightarrow \tau_{\text{had}}\tau_{\text{had}} \) working group. The proposed re-optimised selection is described in appendix C. Since none of the deviations seen in the validation plots in appendix B exceeds the deviations found by using the re-optimised selection, the systematic uncertainties listed here are assumed to cover the uncertainties for this selection as well. However, no uncertainties on the mass shapes for either signal or background processes are included here.

Using the \( M_{\text{MMC}} \) distributions from figure 9.3 as the discriminating variable, an updated expected exclusion limit on the Higgs production cross section is shown in figure 9.5. This expected limit is achieved by combining the two signal regions. In addition to the combined expected limit, the updated expected limits using only events from the ggH or VBF categories are also shown. Despite the very different number of events in the two categories, similar sensitivity is achieve from the the two categories. The combined expected limit shows clear improvement compared to the current expected limit.
Figure 9.5: Current and updated expected upper limits on the 95% CL exclusion of the Higgs production cross section. The limits on the cross section are normalised to the SM Higgs cross section. For the updated limit the individual expected limits using only the ggH or VBF categories are also shown.
Table 9.2: Systematic uncertainties on the acceptance of events from simulated samples in the ggH signal region.

<table>
<thead>
<tr>
<th>Relative Uncertainties [%]</th>
<th>ggH</th>
<th>VBF</th>
<th>VH</th>
<th>MC Backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Energy Scale</td>
<td>1.5</td>
<td>0.4</td>
<td>1.9</td>
<td>6.8</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>3.4</td>
<td>0.7</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>$\tau$-ID</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>3.0</td>
</tr>
<tr>
<td>PDF</td>
<td>$+7.6$</td>
<td>$2.3$</td>
<td>$+3.6$</td>
<td>$+4.7$</td>
</tr>
<tr>
<td>$-7.1$</td>
<td>$-3.4$</td>
<td>$-4.1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QCD Scales</td>
<td>$19.0$</td>
<td>$+3.8$</td>
<td>$1.5$</td>
<td>$0.5$</td>
</tr>
<tr>
<td>Underlying Event</td>
<td>$6.9$</td>
<td>$6.9$</td>
<td>$6.9$</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 9.3: Systematic uncertainties on the acceptance of events from the $Z \rightarrow \tau\tau$ events in the ggH and VBF signal regions.

<table>
<thead>
<tr>
<th>ggH category</th>
<th>Energy Scale</th>
<th>Embedding Selection</th>
<th>Normalisation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9.5</td>
<td>$+6.0$</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>$+10.0$</td>
<td>$+6.1$</td>
<td>5.1</td>
</tr>
<tr>
<td>VBF category</td>
<td>$-8.0$</td>
<td>$-2.1$</td>
<td></td>
</tr>
</tbody>
</table>

In figure 9.5, the $M_{\text{MMC}}$ is used as discriminating variable, because most sensitivity is expected in this variable based on the separation power comparison done in section 6.2. Figure 9.6 shows the updated expected limits derived using $M_{\text{MMC}}$, $M_{\text{Boost}}$ and $M_{\text{MMC}}$ as the discriminating variable, along with the observed limit found using $M_{\text{MMC}}$. For all updated limits, the same selection of events is used, and the same set of systematic uncertainties are assign. As expected the $M_{\text{MMC}}$ variable gives the best limit, while the $M_{\text{Boost}}$ and $M_{\text{PC}}$ are right on top of each other and only deviating significantly at the last mass point. By checking the numerical results the $M_{\text{PC}}$ and $M_{\text{Boost}}$ do differ at the other mass points as well, however only very slightly. Hence, the ranking of the mass variables given in section 6.2 holds for the limits on the Higgs cross section. The observed limit shows only minor deviations from the expected limit. The small excess at the low mass points are within the $2\sigma$ errorband, and fluctuations of this size are to be expected.
Figure 9.6: Expected upper limits on the 95% CL exclusion of the Higgs production cross section for different discriminating variables, along with the observed limit when using the $M_{\text{MMC}}$. The 1\sigma and 2\sigma errorbands on the $\mu$ are shown for the expected limit using $M_{\text{MMC}}$. 

$$H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$$

$$\int L dt = 4.7 \text{fb}^{-1}$$

$$\sqrt{s} = 7 \text{ TeV}$$
CHAPTER 10

CONCLUSION

In this thesis, a new technique for reconstructing the rest frame of \( \tau \)-pair systems at hadron colliders is described. This technique is based on minimising the acollinearity of the \( \tau \)-pair by boosting the system along a given direction. No assumptions on the parton distribution functions in the hard collision or the spin of the resonance are used to derive the reconstructed rest frame, which should make the technique applicable for other final states as well.

Two sub-methods of the rest frame reconstruction are presented depending on whether the transverse boost of the system is neglected or not. Both sub-methods can be applied to all event topologies and have no or little dependence on the \( E^\text{miss}_T \) reconstruction. The methods were first presented in [29] where the performance was evaluated using generator level studies. In this thesis, an extensive study of the performance on \( Z^0 \) and Higgs events at the LHC is presented using full ATLAS detector simulation. The study demonstrates that the rest frame is well reconstructed and the performance from the generator level studies is only slightly worsened by including detector reconstruction.

The latter part of this thesis focuses on the search for the Higgs boson in the fully hadronic \( \tau \)-decay channel. This decay mode is very difficult due to the huge background from QCD-jet events, and the irreducible background from \( Z \rightarrow \tau \tau \). It is shown, that the reconstructed boost of the \( \tau \)-pair rest frame can be used to efficiently select \( \tau \)-pairs from both VBF and ggH Higgs bosons. Here, an alternative selection of Higgs candidate events is given, which deviates from both the latest ATLAS selection published last winter and the proposed re-optimised selection to be published by ATLAS. The biggest difference between the selection presented here and the other selections, is the use of the reconstructed boost of the Higgs candidate.

Using the reconstructed rest frame, a way of estimating mass of the \( \tau \)-pair system is also developed. Although, the mass estimation was originally intended as an estimation technique based on an ensemble distribution, the event-by-event mass estimator, \( M_{\text{Boost}} \), is shown to have comparable performance to the existing mass estimation methods. Two key features of this mass reconstruction techniques are that it works for all event topologies and only makes minimal use of the missing transverse energy, \( E^\text{miss}_T \). Using a principal component analysis, the new mass variable is combined with the visible invariant mass of the \( \tau \)-pair system, and a principal component mass variable is constructed. However, little or no sensitivity is gained by combining these variables in
the current search for Higgs boson.

An important issue in all searches in the \( \tau \)-pair channel, is the data-driven normalisation of the two main backgrounds. An alternative way of normalising the QCD and \( Z \to \tau \tau \) backgrounds using the \( \Delta \eta \) distribution between the two \( \tau \)-jets is presented. This method is shown to give a consistent result with the normalisation used in the current ATLAS analysis.

Using the new selection, an updated limit on the 95\% exclusion on the Higgs cross section is computed using three different mass estimator as the discriminating variable. The some preliminary systematic uncertainties have been taking from the very similar re-optimised selection. The largest uncertainties are coming from the theoretical predictions on the signal yield in each signal region. A part of this thesis work has gone into deriving these uncertainties both for analysis published last winter and for the proposed re-optimised selection. The uncertainties are computed through numerous calculations using the programs HNNLO and HAWK.

For all three mass variables, the updated limit on the Higgs cross section shows significant improvement over the current ATLAS limit. The best limit is found using the \( M_{\text{MMC}} \) with an upper limit on 2.9 times the Standard Model Higgs cross section for a Higgs mass of 125 GeV. However, no systematic uncertainties on the shapes of these mass variables have been included in the limit setting, and therefore a worsening the these limits is to be expected when including a full set of systematic uncertainties. Here it should be noted that since the \( M_{\text{Boost}} \) variable makes minimal use of the \( E_T^{\text{miss}} \)-vector and the production mechanism in the events, a larger uncertainties should be expected on the \( M_{\text{MMC}} \) than on the \( M_{\text{Boost}} \) distributions.

Also, an updated observed upper limit on the Higgs production cross section using the \( M_{\text{MMC}} \) variable is presented. For all mass points, the observed limit is consistent within 1.5\( \sigma \) deviations from the expected limit, and hence no significant excess is seen.

For a boson decaying into a pair of \( \tau \)-leptons, the spin of the boson will determine the polarisation configuration of the two \( \tau \)-leptons, which leads to distinct energy correlations between the visible \( \tau \)-objects. These correlations are hidden in the detector frame by large boost of the system. It is shown, how the rest frame reconstruction, regains part of the energy correlations in the \( \tau^{\pm} \to h^{\pm} \nu \tau \) decay mode. Unfortunately, the harsh requirement on the \( p_T \) of the \( \tau \)-candidates enforced by the trigger, is biasing these energy correlations and therefore these correlations has yet to be used in the full analysis.

Finally, this thesis documents the structure of the prompt calibration model for the Semi Conductor Tracker. The automation of these processes has guaranteed a consistent and robust processing of the calibration data, and helped save a huge amount of working hours.
Bibliography


APPENDIX A

CONFIGURATION FILE FOR THE SCT TOM DEAMON

```plaintext
### sctTOM.cfg
###
### sctcalibns (noisy strips RAW, c0 for BLK)
###

spp tom sctcalibns username sctcalib
spp tom sctcalibns bunchFion bunchByNumberSize
spp tom sctcalibns bunchsize 2000000000000

spp tom sctcalibns inputdsspecsignoff
  "type = 'CALRAW' AND runnr > 175333 AND "
  "datasetname like 'data11_%calibration_SCTNoisedaq.RAW\%' "
spp tom sctcalibns signoffmode on
spp tom sctcalibns inputdsspecautomatic
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  "datasetname like 'data11_%calibration_SCTNoisedaq.RAW\%' "
spp tom sctcalibns automaticmode on

spp tom sctcalibns taskstep sct_NoisyStrip

spp tom sctcalibns maxattempt 5
spp tom sctcalibns priority 2000
spp tom sctcalibns tasktype sctns
spp tom sctcalibns trfcpu 15000
spp tom sctcalibns tasktag 'c0'

spp tom sctcalibns tasktransinfo trfsetupcmd
  '/afs/cern.ch/user/s/sctcalib/testarea/latest/cmthome/setup.sh'

spp tom sctcalibns tasktransinfo trfpath
  '/afs/cern.ch/user/s/sctcalib/testarea/latest/
  InnerDetector/InDetCalibAlgs/SCT_CalibAlgs/scripts/sct_calib_trf.py'

spp tom sctcalibns trfname 'sct_calib_trf.py'
```
spp tom sctcalibns inputs input "!{'metatype': 'inputLFNlistDA'}"

spp tom sctcalibns outputs prefix \\n"!{'dstype': 'SCTCALIB', \\
'dsnamefion': 'replace daq.RAW sct_NoisyStrip.SCTCALIB', \\
}
"

spp tom sctcalibns phconfig SCTCalibConfig \\
"!{'value': \\
['/afs/cern.ch/user/s/sctcalib/testarea/latest/\\
 InnerDetector/InDetCalibAlgs/SCT_CalibAlgs/share/SCTCalibConfig.py'], \\
}
"

spp tom sctcalibns phconfig part \\
"!{'value': ['doNoisyStrip'],}"

spp tom sctcalibns phconfig doRunSelector "!{'value': 'True',}"

spp tom sctcalibns phconfig doRunInfo "!{'value': 'True',}"

spp tom sctcalibns eeconfig maxEvents "!{'value': -1,}"

addp1 tom sctcalibns 300

#~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
In the following, a comparison of variables between data and Monte Carlo predictions are performed at the preselection stage described in section 5.3. The two main backgrounds, $Z \rightarrow \tau \tau$ and QCD-jet events, are normalised using the fitted $\Delta \eta(\tau_1, \tau_2)$ distribution of the selection $\tau$-candidates as explained in section 7.4. The QCD jet events are modeled using not-opposite-sign events in data. Only statistical errors and the uncertainties from the normalisation procedure are included in the errorbars in the ratio plots.
Figure B.1: Mass variables
Figure B.2: MET and τ-pair variables
Validation at preselection

Figure B.3: Boost variables
Figure B.4: τ-candidate variables
Figure B.5: Jet variables
Figure B.6: Combined jet variables
Re-optimised Selection of $\tau$-pair

Good Events
- Trigger: EF$\tau_{29}$ medium1$\tau_{20}$ medium1
  or EF$\tau_{29T}$ medium1$\tau_{20T}$ medium1
- Same Event Cleaning and Data Quality cuts as in the present analysis

Preselection
- No muons or electrons in the event
- Exactly 2 $\tau$ candidates, $|\eta| < 2.5$, BDT Medium and matched to the trigger
- Leading $\tau$-jet $p_T \geq 40$ GeV and sub-leading $\tau$-jet with $p_T \geq 25$ GeV
- Product of the electric charges = -1 and 1 or 3 tracks in $\Delta R \leq 0.6$
- $\Delta R(\tau_1, \tau_2) \leq 3.2$

VBF
- Leading jet with $p_T > 50$ GeV and sub-leading jet with $p_T > 30$ GeV
- $\eta_{j1} \times \eta_{j2} < 0$, $\Delta \eta(j_{1},j_{2}) > 2.6$ and invariant mass $m_{jj} > 350$ GeV
- $\Delta R(\tau_1, \tau_2) < 2.8$, $\min(\eta_{\tau1}, \eta_{\tau2}) < \eta_{\tau1}, \eta_{\tau2} < \max(\eta_{\tau1}, \eta_{\tau2})$
- $E_T^{miss} > 20$ GeV
- ($E_T^{miss}$-vector pointing in between the two $\tau$-jets) OR
  $\min \{\Delta \phi(E_T^{miss}, \tau_1), \Delta \phi(E_T^{miss}, \tau_2)\} < 0.2\pi$

Booster
- Not accepted for the VBF category
- At least one jet with $p_T > 50$ GeV
- At least one of the two taus must be identified as tight and $\Delta R(\tau_1, \tau_2) < 1.9$
- $E_T^{miss} > 20$ GeV
- ($E_T^{miss}$-vector pointing in between the two $\tau$-jets) OR
  $\min \{\Delta \phi(E_T^{miss}, \tau_1), \Delta \phi(E_T^{miss}, \tau_2)\} < 0.1\pi$

Rest
- Not accepted for the VBF or Booster category
- At least one of the two $\tau$-candidates has to be identified as BDT Tight

Table C.1: Re-optimised selection proposed in the $H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$ working group.

<table>
<thead>
<tr>
<th>Process</th>
<th>VBF</th>
<th>Boosted</th>
<th>Rest</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>20.1</td>
<td>361</td>
<td>5410</td>
</tr>
<tr>
<td>QCD events</td>
<td>10</td>
<td>176</td>
<td>12090</td>
</tr>
<tr>
<td>Other Bkg.</td>
<td>3.13</td>
<td>13.3</td>
<td>340</td>
</tr>
<tr>
<td>Total Bkg.</td>
<td>33.5</td>
<td>551</td>
<td>17840</td>
</tr>
<tr>
<td>Total Higgs ($m_H = 130$ GeV)</td>
<td>1.45</td>
<td>3.18</td>
<td>34.3</td>
</tr>
</tbody>
</table>

Table C.2: Predicted number of events in all signal categories.
Part IV

Papers
The following papers has been included

   In this note the technique for reconstruction the rest frame of $\tau$-pairs was published for the first time. This note describes the method in general, and some of its applications such as the mass estimation and optimisation of spin sensitive variables.

2. The ATLAS Collaboration, Search for the Standard Model Higgs boson in the H to tau+ tau- decay mode in $\sqrt{s} = 7$ TeV pp collisions with ATLAS, [arXiv:1206.5971].
   This conference note present is most current results on the ATLAS search for the Higgs in the $\tau^+\tau^-$ channel. Here, I contributed in the fully hadronic final state. In particular I derived some of the theoretical uncertainties for both signal processes and on the $Z \rightarrow \tau\tau$.

   This is conference proceding from the 12th Pisa Meeting on Advanced Detector where I presented the general performance of the ATLAS Semi Conductor Tracker.
A method to estimate the boson mass and to optimise sensitivity to helicity correlations of $\tau^+\tau^-$ final states

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ABSTRACT: In proton-proton collisions at LHC energies, $Z^0$ and low mass Higgs bosons would be produced with high and predominantly longitudinal boost with respect to the beam axis. This note describes a new analysis tool devised to handle this situation in cases when such bosons decay to a pair of $\tau$-leptons. The tool reconstructs the rest frame of the $\tau^+\tau^-$ pair by finding the boost that minimises the acollinearity between the visible $\tau$ decay products. In most cases this gives a reasonable approximation to the rest frame of the decaying boson. It is shown how the reconstructed rest frame allows for a new method of mass estimation. Also a considerable gain in sensitivity to helicity correlations is obtained by analysing the $\tau$-jets in the reconstructed frame instead of using the laboratory momenta and energies, particularly when both $\tau$-leptons decay hadronically.

KEYWORDS: Hadron-Hadron Scattering

ArXiv ePrint: 1105.6003
1 Introduction

Experimental precision data strongly suggest that the Higgs boson should be relatively light. While experimental data exclude Standard Model Higgs, \( H \), masses below 114.4 GeV/c\(^2\), the lightest neutral supersymmetric Higgs can have a mass as low as 92.8 GeV/c\(^2\) [1], which is very close to the mass of the \( Z^0 \). In the mass range below 160 GeV/c\(^2\) the \( \tau^+\tau^- \) decay mode is of particular importance in searches for neutral \( H \), as demonstrated in Tevatron searches [2]. In this mass region, \( H \) production in proton-proton (pp) collisions at LHC energies is dominated by gluon-gluon fusion [3], and a search for \( gg \to H \to \tau^+\tau^- \) production at the LHC is very important, as emphasised in [4].

Together, these facts strongly motivates a careful study of the \( \tau^+\tau^- \) system as produced at the LHC, and the development of analysis tools that enhance sensitivity to measure properties of \( H \) bosons. Furthermore, since \( Z^0 \) production is an irreducible background for this channel it is also important to fully understand the behaviour of \( Z^0 \to \tau^+\tau^- \) events and to look for possible contributions from other processes in a selected sample of \( \tau^+\tau^- \) pairs. The sensitivity of such a study can be enhanced by exploiting the fact that the parity violating \( \tau \) decays carry helicity information. Thus, \( \tau \)-leptons can be used as spin analysers, and provide information that could be helpful in distinguishing the existence of a scalar \( H \) in a background of \( Z^0 \) decays.

In [5] some variables that could be used for a spin analysis are proposed. However, these are all defined in the rest frame of the decaying boson, a frame that cannot be found in any straightforward manner because of the escaping neutrinos produced in the \( \tau \)-decays.

Methods have been proposed to assign the measured missing transverse energy, \( \not{E}_T \), to the neutrinos to obtain unbiased estimates of \( \tau^+\tau^- \) mass [6, 7]. The resulting estimates of the neutrino momenta also gives access to an approximation of the rest frame of the decaying boson, but implications of this beyond mass estimation is not discussed. Further, these methods only work in a fraction of the events with a suitable topology whereas the technique proposed in this paper is applicable for all event topologies.
This note presents a new simple algorithm that finds an approximation to the rest frame of the decaying boson. This will be shown to result in an improved sensitivity to spin, and to an alternative variable that could be of use for the estimation of the mass of the decaying boson.

2 Reconstructing the $\tau^+\tau^-$ rest frame

Because of their short life time $\tau$-leptons are typically studied indirectly through their decay products. Due to the one or two neutrinos produced in the decay, the 4-momentum of the visible $\tau$-decay products, the $\tau$-jet, has a broad spectrum, often carrying less that half the energy of their mother $\tau$. Therefore, reconstructing the rest frame, RF, of a particle decaying into a $\tau^+\tau^-$ system is in principle not possible.

However, for a sufficiently massive particle decaying into a $\tau^+\tau^-$ pair, the directions of the $\tau$-jets are expected to be close to that of their mother $\tau$-leptons. Thus, one expects the $\tau$-jet pair to have only a slight deviation from being back-to-back in the rest frame of the massive particle. It is useful to define the acollinearity — the angular deviation of the $\tau$-jets from being back-to-back. This acollinearity is a well defined positive number in any frame of reference. Henceforth, $\alpha$ will denote the acollinearity between two $\tau$-jets, and furthermore $\alpha_{RF}$ the acollinearity in the heavy particle rest frame.

Simulations show that at 7 TeV pp-collisions, the $Z^0$ and a light $H$, are mostly produced with a high and predominantly longitudinal boost, $\beta_z$. Thus, measured 4-momenta will deviate significantly from those in the heavy particle RF. Exploiting that $\alpha_{RF}$ should be small and assuming that $\beta_T$ is small, the method proposed in this paper consists in searching for the $\beta_z$ that minimises $\alpha$. When restricting $\beta$ to be parallel to the beam axis, the $\alpha$ as a function of $\beta$ has a single minimum and hence can be reliably minimised.

The method can also be extended to look for the transverse component of the boost if one has a good estimate of the direction of the heavy particle in the transverse plan. The transverse direction of the heavy particle, can be estimated by summing up the transverse momenta of the $\tau$-jets and the reconstructed missing transverse energy, $E_T$. Our algorithm minimises $\alpha$ in two steps: first, by varying the longitudinal boost, $\beta_z$, secondly when a suitable minimum is found, the transverse boost is varied along the found transverse direction. In both steps the $\alpha$ is 1-dimensional function with a single global minimum and no secondary minima.

In this paper, we will denote the two search strategies as the Z- or XYZ-method depending on whether we only will try to estimate the longitudinal component of the boost of the heavy particle or estimate the transverse component as well.

Since particle directions are well measure quantities these methods are robust and can be applied in every collision event for any pair of measured particles or jets.

Performance. The performance of the methods were studied using $\tau^+\tau^-$ pairs from simulated $Z^0$ and 114 GeV/c$^2$ gluon-gluon fusion $H$ events produced in 7 TeV pp-collisions. Anticipating that backgrounds could be difficult to handle in multi-prong $\tau$ decays, only decays with exactly one charged particle in the final state were considered here. However,
the inclusion of \( \tau \) decays with more than one charged hadron is not expected to change the performance of this method significantly. \( 10^7 \) \( Z^0 \) and \( H \) events were generated with Pythia8 [8] and subsequent \( \tau \)-decays were done with TAUOLA [9] to correctly include spin and polarisation effects. Detector resolution effects were not included. However, an angular cut requiring the two jets to have \( |\eta| < 2.5 \) was imposed to match the acceptance of a typical tracker in an LHC experiment.

As shown in figure 1(a) the polar angle distributions for both \( H \) and \( Z^0 \) decays are predominantly parallel to the beam axis. Therefore, assuming a boost direction parallel to the beam seems to be a reasonable guess for a very large fraction of the events and we therefore only expect the XYZ-method to be slightly better in reconstructing the rest frame than the \( Z \)-method for these events. In figure 1(b) it is seen that the true \( \alpha_{RF} \) is concentrated at small values, with \( \langle \alpha_{RF} \rangle = 4.5^\circ \) for \( Z^0 \) events, while the acollinearity distributions in the reconstructed frames are peaked towards low acollinearities as expected. The effect of working in the collinear frame (\( \alpha = 0 \)) instead of in the true \( RF \) should have a small effect if the direction of the boost is correctly estimated. In the collinear frame closest to the true \( RF \), the momenta of the two \( \tau \)-jets will deviate with a factor \( \cos(\alpha_{RF}) \), meaning a typical deviation of 0.3\%.

Since the \( \alpha \) is always positive, it is easy to minimise with respect to the applied \( \beta_{z,T} \) of the two tau jets. For a selection of ranges in the generated \( \beta \) of a produced \( Z^0 \)-boson, figure 2 shows how, on average, \( \alpha \) varies as a function of an applied longitudinal boost to the two jets. The minimal acollinearity is always at a longitudinal boost that is close to the generated one. The actual value of \( \alpha \) is reflecting to which extent there might be a transverse boost present, ignored in figure 2.

To estimate the goodness of the reconstruction of the RF, the vectorial difference \( |\beta_{gen} - \beta_{reco}| \) is shown in figure 3(a) for both reconstruction methods. The reconstructed RFs are seen to be closer to the generated RF for the XYZ-method as expected. Figure 3(b) shows the difference in magnitude between the generated and reconstructed boost with a FWHM of the distribution of 0.010 for the XYZ-method.

\[ \text{Figure 1. Angular distributions for simulated heavy boson decays.} \]

\[ \text{(a) Polar angle, } \theta \text{, of the } Z^0 \text{ and } 114 \text{ GeV/c}^2 \text{ } H \text{ bosons. Typically the bosons are produced at small angles close to the beam axis.} \]

\[ \text{(b) Acollinearity, } \alpha \text{, for } Z^0 \rightarrow \tau^+ \tau^- \text{ in the generated and reconstructed RFs and in the laboratory frame of the } Z^0. \]
Figure 2. Average acollinearity as a function of attempted longitudinal boost for various ranges of true boost.

In conclusion both methods reconstructs the boost very reasonably, with a distribution around the true value with a mean deviation around 0.076 for the XYZ-method and 0.149 for the Z-method, when averaging over all events. Due to the exclusion of the transverse component, a small offset away from zero in the most probable value is seen in the Z-method. Although figure 1(a) shows that the bosons are mostly boosted longitudinally, improvements are found when also estimating the transverse components of the boost. However, these improvements will be very dependent on the ability to estimate the transverse direction of the bosons correctly in the detector. Therefore the two methods act complementary; for events with a small transverse boost and low precision on the $E_T$ the Z-method should be applied, whereas for events with good precision in $E_T$ and a high transverse boost, improvements will be gained by using the XYZ-method.
3 Estimating the boson mass

Due to the neutrinos in the $\tau$ decays, the visible invariant mass, $M_{\text{vis}}$, distribution peaks far below the real mass of the resonance produced. A method correcting for this is the so called collinear approximation [6]. This method assumes the neutrinos are collinear with the decaying $\tau$-lepton, and includes $E_T$ by projecting it to the $\tau$-jets. However, this projection is only possible and reliable in a fraction of events with large transverse boost and well aligned $E_T$ [10, 11].

In [7] the performance of a likelihood based technique is presented for simulations of Higgs and $Z^0$ events in antiproton-proton collisions at 1.96 TeV, and also for data collected by the CDF experiment. For fully hadronic decaying tau-leptons, unsmeared simulations show a mass reconstruction resolution of 8%, and more realistic simulation shows a mass resolution of 14%, and finally the CDF $Z^0 \rightarrow \tau^+\tau^-$ events show a resolution of 16% with this technique. The smeared results are obtained for events within $|\eta| < 1$, smearing of hadron momenta of 10% and of $E_T$ of 5 GeV in each of the transverse components.

At the LHC the events are much more boosted, and the experiments have larger $\eta$ coverage. In [12], CMS expects a likelihood mass resolution of 21% for a 130 GeV Higgs (for leptonic and semi-leptonic $\tau$-decays), in an analysis covering $|\eta| < 2.3$ for hadronic $\tau$ decays. This is approaching the width of the the $M_{\text{vis}}$ distribution which is reported to be 24%. A possible explanation for the poorer resolution in CMS could be that $E_T$ measures a smaller fraction of the full neutrino energies for $\tau$-jets with large $\eta$ than for transverse ones. Hence, estimates of the full neutrino energies from $E_T$ arises from correspondingly larger scale factors.

Another mass variable for $\tau$ pairs is the effective mass, $M_{\text{eff}} = \sqrt{(p_{\tau_1} + p_{\tau_2} + \not{p}_T)^2}$, where $p_{\tau}$ are the visible $\tau$-jet 4-momentum, and $\not{p}_T$ is the missing transverse momentum vector. In addition to the $M_{\text{vis}}$ and $M_{\text{eff}}$ recent result from the ATLAS collaboration [13] has also used a likelihood based method, whereas the recent result from the CMS collaboration [14] simply uses $M_{\text{vis}}$ in the analysis.

In the following an alternative variable for mass estimation is described and for simplicity comparisons have been made to distributions of $M_{\text{vis}}$ which is a straightforward robust alternative in use by all experiments.

Finding the kinematic edge. The mass of a particle decaying to $\tau^+\tau^-$ could be inferred by determining the kinematic endpoint of the distribution of twice the leading $\tau$-jet energy in the boson RF. This quantity will henceforth be named as $2E_{\text{RF}}^1$. As opposed to the collinear approximation this quantity can be calculated for all events. In figure 4 distributions of $2E_{\text{RF}}^1$ are compared to $M_{\text{vis}}$ distributions.

This way of estimating the mass becomes particularly useful when both $\tau$-leptons decay into hadrons, where only one neutrino is present in each $\tau$ decay. Figure 4 suggests that a first guess to the shape of $2E_{\text{RF}}^1$ could be a triangle convoluted with some resolution function, although it is clear that the inclusion of effects like the $Z^0/H$ width and helicity effects modifies such an assumption. Still the kinematic edge can be found be determining the point of steepest slopes of the distribution.
Figure 4. Distributions for $2E_{\text{RF}}^1$ calculated using the XYZ-method and invariant mass of the visible $\tau$-jets, $M_{\text{vis}}$, for $\tau^+\tau^-$ pairs both decaying to single charged hadrons. The dotted line marks the position of the steepest slope for the $2E_{\text{RF}}^1$ distribution.

Figure 4 is the result for all hadronic decaying events without any selection. As mentioned earlier, the decision on which boost reconstruction method to use should depend on the magnitude of the transverse boost. Therefore, the events have been divided into two classes; one with a large difference in azimuthal angle between the two jets, $\Delta\phi_{\text{jets}}$, compatible with no transverse boost, where the Z-method were used, and one with the rest of the event where the XYZ-method were applied. Here a threshold of $\Delta\phi_{\text{jets}} = 170^\circ$ were chosen to separate the two classes. The criterion for the choice of boosting method would have to be subject to study in a true experimental environment. Furthermore, a cut of 10 GeV on the $p_T$ for both $\tau$-jets were applied to both classes. In figure 5, it is shown that 24% of the $Z^0$-boson and 16% of the Higgs events can be reasonably subjected to the Z-method. Hence, without any use of $E_T$ an approximation of the centre of mass system is still available of these events.

Since the distributions of $2E_{\text{RF}}^1$ are clearly asymmetric and non-gaussian, the spread of the distributions calculated from the most likely value are therefore also asymmetric. For Higgs events with $\Delta\phi_{\text{jets}}$ above 170°, the spread from the peak position is found to be $\pm 17^{+9.7}_{-23.5}$%.

To evaluate the precision of retrieving the boson mass by finding the kinematic edge, $M_{\text{boost}}$, pseudo-experiments were performed. From the $2E_{\text{RF}}^1$ distribution shown in figure 4(a) several pseudo-distributions were generated with varying number of events and for each distribution the kinematic edge was found as the point of the steepest decent. In table 1, the found values and spread of $M_{\text{boost}}$ are listed as a function of the number of events in the pseudo-experiment for the two classes of events, where class 1 refers to the events in which the Z-method has been used, and class 2, refers to the events where the XYZ-method were used. For the simple kinematic edge-finder implemented for this analy-
Figure 5. Distributions for $2E_{RF}^1$ calculated for the two event classes using the Z and XYZ-method for $\tau^+\tau^-$ pairs both decaying to single charged hadrons.

Table 1. Mass estimation $M_{\text{boost}}$ as a function of number of events $n_{\text{evt}}$ as obtained from pseudo-experiments for the two classes of $Z^0$ events. Class 1 consists of events with $\Delta \phi^{\text{jets}} > 170^\circ$ where the Z-method have been applied and class 2 consists of events that has been subject to the XYZ-method.

<table>
<thead>
<tr>
<th>Number of events</th>
<th>Obtained values of $M_{\text{boost}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Class 1</td>
</tr>
<tr>
<td>250</td>
<td>88.3 ± 5.3</td>
</tr>
<tr>
<td>500</td>
<td>89.3 ± 3.1</td>
</tr>
<tr>
<td>1000</td>
<td>90.3 ± 2.3</td>
</tr>
<tr>
<td>2000</td>
<td>90.6 ± 1.8</td>
</tr>
<tr>
<td>4000</td>
<td>90.8 ± 1.4</td>
</tr>
</tbody>
</table>

Intuitively, constructing a mass variable that accumulates towards the real mass should help distinguishing different masses. One way to distinguish distributions is to compare the largest difference of the cumulative distributions, $D_L$ which is input to the Kolmogorov-Smirnov test. It is found that while $D_L$ between the calculated $2E_{RF}^1$ distributions (using...
the XYZ-method) for $Z^0$ and $H$ events is 0.35, it is only 0.24 when comparing the two $M_{\text{vis}}$ distributions. It is not clear if the tails towards high values of $2E_{\text{RF}}$ seen to be more important in figure 4 than figure 4(a) is helpful in a search scenario, because clearly the $Z^0$ contribution is non-negligible for values well beyond the kinematic edge. At present, it cannot be concluded that this variable will be better than any of the other proposition in a real experiment. However it seems to be worthwhile to consider the use this variable in an experimental search for the Higgs boson.

In figure 6, the correlation between $M_{\text{vis}}$ and $2E_{\text{RF}}$ is shown for $Z^0$ events. Thus, since the correlation is significantly lower than 1, the $2E_{\text{RF}}$ variable is adding information, and it should be studied for use in a search scenario.

4 Helicity correlations

Several powerful variables for studying $\tau$ polarisation in $Z^0$ decays were developed for the LEP experiments [15]. These variables are defined in the rest frame of the decaying boson. While this is close to identical to the laboratory frame at LEP, this is not true at the LHC, and this paper proposes to study these variables in a reconstructed RF instead.

For $\tau^\pm \to \pi^\pm \nu_\tau$ events, the distribution of the decay angle in the $\tau$-lepton rest frame, that is the angle between the direction of the $\tau$-lepton and its visible decay product, is determined by the $\tau$ helicity. In the rest frame of the heavy boson producing a $\tau^+\tau^-$ pair this translates to a well determined distribution in the fraction of $\tau$ energy carried by $\pi$. The quantity used in the following figures is the energy of visible particles in the decay, $E_{\text{vis}}$, normalised to the kinematic endpoint (half the mass of the decaying boson). Weaker energy-energy correlations also shows for the $\tau^\pm \to \ell^\pm \nu_\ell$ and $\tau^\pm \to h^\pm \nu_\tau nh^0$ modes.

The $E_{\text{vis}}$ distributions for single $\pi$ decay modes shown in figure 7 for the generated and reconstructed heavy boson RFs show that the true correlations are partly recovered in the reconstructed RF using the XYZ-method proposed in section 2. Furthermore, it is shown that these correlations are much weakened in the laboratory frame.
Figure 7. $2E_{\text{vis}}^Z/M_Z$ for $\tau$-leptons with positive and negative helicities decaying into $\pi^\pm\nu_\tau$ shown in the generated and reconstructed RF using the XYZ-method as well as the laboratory frame.

(a) Spin 0 ($H$ sample).
(b) Spin 1 ($Z^0$ sample).

Figure 8. Energy correlations in the reconstructed RF using the XYZ-method of a $\tau^+\tau^-$ pair with both $\tau$-leptons decaying to $h^\pm\nu_\tau$. To avoid effects coming from the mass differences all energies are scaled with the mass of the decaying boson.

4.1 Analysis of the sensitivity to spin

Conservation of angular momentum leads to distinctly different helicity configurations when comparing the final states of $Z^0$ and $H$ decays in their rest frames. While the spin components along the direction of flight of the $\tau^+$ must add up to $\pm1$ for the $Z^0$, the sum must be 0 for the $H$ decays. Thus the spin effects can be studied by looking at the correlations in $E_{\text{vis}}$ of the two $\tau$-leptons as shown in figure 8.

To quantify the observed difference between spin 0 and spin 1 particles, the $Z^0$ and $H$ samples were split into training and test samples. Probability density functions for both spins, $P_0(E_{\tau^-}, E_{\tau^+})$ and $P_1(E_{\tau^-}, E_{\tau^+})$, were constructed as the fraction of events in a bin of $(E_{\tau^-}, E_{\tau^+})$ in the corresponding training sample. From this a likelihood, $\mathcal{L}$, is created for $N$ events from both training samples by

$$\log \mathcal{L} = \sum_{i=0}^{N} \left( \log(P^1_i) - \log(P^0_i) \right) / N$$

(4.1)
Figure 9. Log likelihood plot for energy-energy correlations in the reconstructed RF using the XYZ-method when both $\tau$-leptons decays into $h^{\pm} \nu_{\tau}$.

Table 2. Sensitivity to spin of the boson for different decay modes of the two $\tau$-leptons shown in the true and reconstructed RFs as well as in the laboratory frame.

<table>
<thead>
<tr>
<th>$\tau$ decay mode</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_1$</td>
<td>$\tau_2$</td>
</tr>
<tr>
<td>$\ell^{\pm} \nu_{\tau} \overline{\nu}_{\ell}$</td>
<td>$\ell^{\pm} \nu_{\tau} \overline{\nu}_{\ell}$</td>
</tr>
<tr>
<td>$\ell^{\pm} \nu_{\tau} \overline{\nu}_{\ell}$</td>
<td>$h^{\pm} \nu_{\tau}$</td>
</tr>
<tr>
<td>$\ell^{\pm} \nu_{\tau} \overline{\nu}_{\ell}$</td>
<td>$h^{\pm} \nu_{\tau}$</td>
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<tr>
<td>$h^{\pm} \nu_{\tau}$</td>
<td>$h^{\pm} \nu_{\tau}$</td>
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<td>$h^{\pm} \nu_{\tau}$</td>
<td>$h^{\pm} \nu_{\tau}$</td>
</tr>
<tr>
<td>$h^{\pm} \nu_{\tau}$</td>
<td>$h^{\pm} \nu_{\tau}$</td>
</tr>
</tbody>
</table>

Table 2 shows values obtained for $S$ in the reconstructed RFs using the Z- and XYZ-method as well as in the laboratory frame for the different $\tau$ decay modes. For all decay channels sensitivity is gained when using the reconstructed RF over the laboratory frame. When just applying the Z-method, differences in the transverse momentum of the bosons are kept in the distributions, while the XYZ-boost approximates the RF more correctly. The Z-method thus analyses a combination of the two effects, the boson $p_T$ and spin, while the sensitivities determined using the XYZ-method are largely only due to differences in spin.
Finally, further sensitivity would be gained by using ratios between neutral and charged energy for \( h^\pm \nu \), \( nh^0 \) final states. An exhaustive analysis of spin should probably make use of these ratios. These ratios remain almost unchanged in any boosted frame. The purpose of this note is to discuss the advantages of finding an approximate rest frame, so the sensitivities when using these variable are not reported here.

5 Conclusions and discussion

By minimising the acollinearity, two methods to reconstruct the rest frame of boosted heavy particles decaying to two \( \tau \)-leptons have been proposed, and it has been demonstrated that they both find the rest frame reasonably well. Whereas the XYZ-method requires an estimate of the transverse direction of the heavy particle, the Z-method can be used for analyses where one does not have a good estimate of this direction.

A new technique for mass estimation has been proposed using the end-point of the leading \( \tau \)-jet energy in the reconstructed rest frame. This technique does not introduce assumptions on transfer functions or production mechanisms of the heavy particle as more elaborate reconstruction techniques, and it can be applied to all events within the geometrical acceptance of the experiments. The method is complementary to existing methods in the sense that it can be applied without using information on the measured \( \not{E}_T \), and since it is not directly correlated with the visible mass it adds information, and thus the two can be combined to gain further sensitivity.

Furthermore, a scheme for an event-wise spin analysis of the \( \tau^+\tau^- \) system has been outlined, and it has been shown that enhanced sensitivity to spin is gained when transforming the 4-momenta as proposed in this paper. Both boost methods presented enhance sensitivity to spin when compared to an analysis in the laboratory frame. Which method to use depends on whether or not differences in production mechanism of the boson should be taken into account.

In summary, a tool has been developed to approximate the rest frame of \( \tau^+\tau^- \) systems, and two applications thereof have been illustrated. These applications could prove to be helpful in the analyses of \( Z^0 \) decays or in searches for new particles like \( H, Z' \) or SUSY particles. Additionally, it is possible that a transformation to the rest frame could be beneficial to other variables used in the study of \( \tau^+\tau^- \) systems.

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Search for the Standard Model Higgs boson in the $H \rightarrow \tau^+\tau^-$ decay mode in $\sqrt{s} = 7$ TeV $pp$ collisions with ATLAS

The ATLAS Collaboration

Abstract

A search for the Standard Model Higgs boson decaying into a pair of $\tau$ leptons is reported. The analysis is based on a data sample of proton-proton collisions collected by the ATLAS experiment at the LHC and corresponding to an integrated luminosity of 4.7 fb$^{-1}$. No significant excess over the expected background is observed in the Higgs boson mass range of 100–150 GeV. The observed (expected) upper limits on the cross section times the branching ratio for $H \rightarrow \tau^+\tau^-$ are found to be between 2.9 (3.4) and 11.7 (8.2) times the Standard Model prediction for this mass range.
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1 Introduction

The Higgs boson is the only fundamental particle in the Standard Model (SM) of particle physics that has not yet been observed. It is predicted by the Higgs mechanism [1–6], which in the SM gives mass to particles. The search for the Higgs boson is a centrepiece of the Large Hadron Collider (LHC) physics programme.

An indirect constraint on the Higgs boson mass of $m_H < 185$ GeV at the 95% confidence level (CL) has been set using global fits to electroweak precision data [7]. Direct searches at LEP and the Tevatron have placed exclusion limits at 95% CL for $m_H < 114.4$ GeV and in
the region $147 \text{ GeV} < m_H < 179 \text{ GeV}$ [8, 9], respectively. The results of searches in various channels using data corresponding to an integrated luminosity of up to $5 \text{ fb}^{-1}$ have recently been reported by both the ATLAS and CMS Collaborations [10, 11] excluding the mass range between $112.9 \text{ GeV}$ and $115.5 \text{ GeV}$ and the region between $127 \text{ GeV}$ and $600 \text{ GeV}$, again at the 95% CL.

In the Higgs boson mass range 100-150 GeV, the $H \rightarrow \tau^+\tau^-$ decay mode is a promising channel for the search at the LHC with branching ratios between 8% and 1.8%. The $H \rightarrow \tau^+\tau^-$ search is complementary to searches with other decays in the same mass range and enhances the overall sensitivity. Also, if the Higgs boson is discovered, the measurement of the $H \rightarrow \tau^+\tau^-$ decay rate provides a test of the SM prediction for the $\tau$ Yukawa coupling.

The process with the largest cross section to produce a SM Higgs boson at the LHC is gluon fusion $gg \rightarrow H$. However, Higgs boson production via vector boson ($WW$, $ZZ$) fusion $qq \rightarrow qqH$ (VBF) and via Higgs-strahlung $qq \rightarrow VH$, in association with a hadronically decaying vector boson ($V = W$ or $Z$), are highly relevant as well because they lead to additional jets in the final state, which provide distinct experimental signatures. In particular the VBF topology of two high-energy jets with a large rapidity separation offers a good discrimination against background processes. For all production processes above, the Higgs boson is typically more boosted in the transverse plane if there are additional high-$p_T$ jets in the event, which increases the transverse momentum of the $\tau$ decay products and thus facilitates the measurement of the $\tau^+\tau^-$ invariant mass and the discrimination of the signal from background processes.

This paper presents SM Higgs boson searches in the the $H \rightarrow \tau^+\tau^-\ell^+\ell^-$, $H \rightarrow \tau^+\tau^+\ell^+\ell^-$, and $H \rightarrow \tau^+\tau^-\ell^+\ell^-$ channels, where $\ell$ denotes a charged lepton. The data analyses use proton-proton ($pp$) collisions at $\sqrt{s} = 7 \text{ TeV}$ collected by the ATLAS experiment in 2011, which correspond to an integrated luminosity of 4.7 $\text{ fb}^{-1}$. In order to enhance the sensitivity of the search, the selected events are analysed in several separate categories according to the number and topology of reconstructed jets.

2 Data and Monte Carlo simulated samples

The ATLAS detector is a multipurpose apparatus with a forward-backward symmetric cylindrical geometry and nearly $4\pi$ coverage in solid angle [12]. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and an external muon spectrometer incorporating three large superconducting air-core toroid magnets. Electrons, muons, $\tau$ leptons and jets can be reconstructed and identified in the ATLAS detector. Only data taken with all sub-systems relevant to this analysis are used.

\footnote{Charge-conjugated decay modes are implied. Throughout the remainder of the paper, a simplified notation without the particle charges is used.}

\footnote{ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$-axis points upwards. Cylindrical coordinates ($r, \phi$) are used in the transverse plane,
operational are used. This results in an integrated luminosity of 4.7 fb$^{-1}$ for the full 2011 data sample.

The signal contributions considered here include the gluon fusion production process, the VBF production process, and the Higgs-strahlung $VH$ production in association with a hadronically-decaying vector boson $V = W, Z$. For the decay of the Higgs boson, the $H \to \tau\tau$ mode is considered. Next-to-next-to-leading-order (NNLO) Quantum Chromodynamics (QCD) corrections, soft-gluon resummations calculated in the next-to-next-to-leading-log-approximation and next-to-leading-order (NLO) electroweak (EW) corrections are applied to the signal cross sections for the $gg \to H$ production process \cite{13-24}. The cross sections of the VBF process are calculated with full NLO QCD and electroweak corrections \cite{25-27}, and approximate NNLO QCD corrections \cite{28}. The $WH/ZH$ processes are calculated with NLO QCD corrections \cite{29, 30} and NLO EW radiative corrections are applied \cite{31}. The Higgs boson decay branching ratios are calculated using HDECAY \cite{32}. The $gg \to H$ and VBF processes are modelled using the POWHEG \cite{33, 34} Monte Carlo (MC) generator, interfaced to PYTHIA \cite{35} for showering and hadronisation. In the $gg \to H$ process, the Higgs boson $p_T$ spectrum is reweighted to agree with the prediction of the HqT program \cite{36}. The associated $VH$ production process is modelled using PYTHIA.

ALPGEN \cite{37}, interfaced to HERWIG \cite{38}, with the MLM matching scheme \cite{39} is used to model the production of single $W$ and $Z/\gamma^*$ bosons decaying to charged leptons in association with jets. MC@NLO \cite{40} is used to model $t\bar{t}$, $WW$, $WZ$ and $ZZ$ production processes, using HERWIG for the parton shower and hadronisation and JIMMY \cite{41} for the underlying event modelling. AcerMC \cite{42} is used to model single top-quark production for all three production channels (s-channel, t-channel, and $Wt$ production). The TAUOLA \cite{43} and PHOTOS \cite{44} programs are used to model the decay of $\tau$ leptons and the Quantum Electrodynamics (QED) radiation of photons, respectively.

The set of parton distribution functions (PDF) CT10 \cite{45} is used for the MC@NLO samples, as well as CTEQ6L1 \cite{46} for the ALPGEN samples, and MRST2007 \cite{47} for the PYTHIA and HERWIG samples. Acceptances and efficiencies are based on a simulation of the ATLAS detector using GEANT4 \cite{48, 49}. Since the data are affected by the detector response to multiple interactions (pileup) occurring in the same or nearby bunch crossings, the simulation includes a treatment of the event pileup conditions present in the 2011 data.

The $Z/\gamma^* \to \tau\tau$ background processes are modelled with a $\tau$-embedded $Z/\gamma^* \to \mu\mu$ data sample as described in Section 6.

3 Selection and reconstruction of physics objects

Electron candidates are formed from an energy deposit in the electromagnetic calorimeter and associated to a track measured in the inner detector. They are selected if they have a transverse energy $E_T > 15$ GeV, lie within $|\eta| < 2.47$ but outside the transition region between $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln\tan(\theta/2)$. 

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- 3 -
the barrel and end-cap calorimeters (1.37 < |η| < 1.52), and meet quality requirements based on the expected shower shape [50].

Muon candidates are formed from a track measured in the inner detector and linked to a track in the muon spectrometer [51]. They are required to have a transverse momentum $p_T > 10$ GeV and to lie within $|\eta| < 2.5$. Additionally, the difference between the $z$-position of the point of closest approach of the muon inner detector track to the beam-line and the $z$-coordinate of the primary vertex is required to be less than 1 cm.\footnote{The primary vertex is defined as the vertex with the largest $\sum p_T^2$ of the associated tracks.} This requirement reduces the contamination due to cosmic ray muons and beam-induced backgrounds. Muon quality criteria based on, e.g., inner detector hit requirements are applied in order to achieve a precise measurement of the muon momentum and reduce the misidentification rate.

Identified electrons and muons are required to be isolated: the additional transverse energy in the electromagnetic and hadronic calorimeters must be less than 8% (4%) of the electron transverse energy (muon transverse momentum) in a cone of radius $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.2$ around the electron (muon) direction. The sum of the transverse momenta of all tracks with $p_T$ above 1 GeV located within a cone of radius $\Delta R = 0.4$ around the electron (muon) direction and originating from the same primary vertex must be less than 6% of the electron transverse energy (muon transverse momentum).

Jets are reconstructed using the anti-$k_t$ algorithm [52] with a distance parameter value of $R = 0.4$, taking as input three-dimensional noise-suppressed clusters in the calorimeters. Reconstructed jets with $p_T > 20$ GeV and within $|\eta| < 4.5$ are selected. Events are discarded if a jet is associated with out-of-time activity or calorimeter noise. After having associated tracks to jets by requiring $\Delta R < 0.4$ between tracks and the jet direction, a jet-vertex fraction (JVF) is computed for each jet as the scalar $p_T$ sum of all associated tracks from the primary vertex divided by the scalar $p_T$ sum of all tracks associated with the jet. Conventionally, $\text{JVF} = -1$ is assigned to jets with no associated tracks. Jets with $|\eta| < 2.4$ are required to have $|\text{JVF}| > 0.75$ in order to suppress pileup contributions. In the pseudorapidity range $|\eta| < 2.5$, $b$-jets are identified using a tagging algorithm based on the discrimination power of the impact parameter information and of the reconstruction of the displaced vertices of the hadron decays inside the jets [53]. The $b$-tagging algorithm has an average efficiency of 58% for $b$-jets in $t\bar{t}$ events [54]. The corresponding light-quark jet misidentification probability is 0.1–0.5%, depending on the jet $p_T$ and $\eta$ [55].

Hadronic decays of $\tau$ leptons are characterised by the presence of one or three charged hadrons accompanied by a neutrino and possibly neutral hadrons, which results in a collimated shower profile in the calorimeters and only a few nearby tracks. The visible decay products are combined into $\tau_{\text{had}}$ candidates. These candidates are reconstructed as jets, which are re-calibrated to account for the different calorimeter response to hadronic decays as compared to hadronic jets. The four-momentum of the $\tau_{\text{had}}$ candidates are reconstructed from the energy deposits in the calorimeters and the rejection of jets misidentified as hadronic $\tau$ decays is performed by a multivariate discriminator based on a boosted decision tree [56] that uses
both tracking and calorimeter information. The identification is optimised to be 50% efficient while the jet misidentification probability is kept below 1%. A $\tau_{\text{had}}$ candidate must lie within $|\eta| < 2.5$, have a transverse momentum greater than 20 GeV, one or three associated tracks (with $p_T > 1$ GeV) and a total charge of $\pm 1$ computed from the associated tracks. Dedicated electron and muon veto algorithms are used.

When different objects selected according to the above criteria overlap with each other geometrically (within $\Delta R < 0.2$), only one of them is considered for further analysis. The overlap is resolved by selecting muon, electron, $\tau_{\text{had}}$ and jet candidates in this order of priority.

The magnitude of the missing transverse momentum ($E_T^{\text{miss}}$) is reconstructed including contributions from muon tracks and energy deposits in the calorimeters. Calorimeter cells belonging to three-dimensional noise-suppressed clusters are used and they are calibrated taking into account the reconstructed physics object to which they belong.

4 Preselection

An initial selection of events is performed by requiring a vertex from the primary $pp$ collisions that is consistent with the beam spot position, with at least three associated tracks, each with $p_T > 500$ MeV. Overall quality criteria are applied to suppress events with fake $E_T^{\text{miss}}$, produced by non-collision activity such as cosmic ray muons, beam-related backgrounds, or noise in the calorimeters.

The $\ell\ell$, $\ell\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ final states considered in this search are defined in a mutually exclusive way: a requirement of exactly two, one, or zero electrons or muons is imposed, respectively.

4.1 $H \rightarrow \tau_{\text{lep}}\tau_{\text{lep}}$

Signal events in this channel are selected by requiring exactly two isolated and oppositely-charged light leptons (electrons and/or muons). Single lepton and di-lepton triggers are used to preselect the data. The trigger object quality requirements were tightened during the data-taking period to cope with increasing instantaneous luminosity. The single muon trigger requires $p_T > 18$ GeV; for the single electron trigger the $E_T$ threshold changes from 20 GeV to 22 GeV depending on the LHC instantaneous luminosity; the di-muon trigger requires $p_T > 15$ GeV for the leading muon and $p_T > 10$ GeV for the sub-leading muon; the di-electron trigger requires $E_T > 12$ GeV for each of the two electrons; the $e\mu$ trigger requires $E_T > 10$ GeV for the electron and $p_T > 6$ GeV for the muon. In addition to the trigger requirements, the preselection requires $E_T > 22$ GeV if the electron satisfies only the single electron trigger. The $E_T$ requirement is increased to 24 GeV when the trigger threshold is 22 GeV. If a muon is associated only with the single muon trigger object, it is required to have $p_T > 20$ GeV. For the $e\mu$ channel the di-lepton invariant mass is required to be in the range of $30$ GeV $< m_{\ell\ell} < 100$ GeV, whereas for the $ee$ and $\mu\mu$ channels $30$ GeV $< m_{\ell\ell} < 75$ GeV is required, reducing the contamination from $Z/\gamma^* \rightarrow \ell\ell$.

$^4$Here $\ell$ denotes an electron or a muon (also referred to below as light leptons).
4.2 $H \rightarrow \tau_{lep}\tau_{had}$

Signal events in this channel are characterised by exactly one isolated light lepton $\ell$, a $\tau_{had}$ candidate, and large $E_T^{miss}$ due to the undetected neutrinos. For the $e\tau_{had}$ ($\mu\tau_{had}$) final states, events are preselected using the single electron (muon) trigger described in Section 4.1. Exactly one electron with $E_T > 25$ GeV or one muon with $p_T > 20$ GeV, and one oppositely-charged $\tau_{had}$ candidate with $p_T > 20$ GeV are required in the event. Events with more than one electron or muon candidate are rejected to suppress events from $Z/\gamma^* \rightarrow \ell^+\ell^-$ decays and from $t\bar{t}$ or single top-quark production.\(^5\) The transverse mass of the lepton and $E_T^{miss}$ is calculated as

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

where $p_T^\ell$ denotes the magnitude of the transverse momentum of the lepton and $\Delta\phi$ is the angle between the lepton and $E_T^{miss}$ directions in the plane perpendicular to the beam direction.

In order to reduce contributions from the $W+\text{jets}$ and $t\bar{t}$ background processes, only events with $m_T < 30$ GeV are considered for further analysis. In addition, $E_T^{miss}$ is used for further event selection and categorisation, as described in Section 5.

4.3 $H \rightarrow \tau_{had}\tau_{had}$

Signal events in this channel are characterised by two identified hadronic $\tau$ decays and large $E_T^{miss}$ from the undetected neutrinos. The corresponding event selection starts with a double hadronic $\tau$ trigger, where the $p_T$ thresholds are 29 GeV and 20 GeV for the leading and sub-leading hadronic $\tau$ objects, respectively. A requirement of exactly zero charged light leptons, as defined in Section 3, is imposed. Two identified opposite charge $\tau_{had}$ candidates with $p_T > 35$ GeV and $p_T > 25$ GeV are required, each matching a $\tau$ trigger object $[58]$.\(^6\)

5 Analysis categories

For further analysis, the selected event samples are split into several categories according to the number and topology of reconstructed jets. The sensitivity of the search is usually higher for categories where the presence of one or more jets is required, as discussed in Section 1, but events without any reconstructed high-$p_T$ jets are also considered in order to maximise the sensitivity.

5.1 $H \rightarrow \tau_{lep}\tau_{lep}$

Four categories defined by their jet multiplicity and kinematics are used for this channel: $H + 2$-jet VBF, $H + 2$-jet $VH$, $H + 1$-jet and $H + 0$-jet. The first two categories require the presence of at least two jets and the cuts are optimised in one case for the VBF process $[59-61]$, and in the other for the $VH$ and $gg \rightarrow H$ processes $[62]$.

\(^5\)For the purpose of vetoing additional light leptons, the isolation requirements are removed from the muon selection and a looser identification requirement is used for electrons. The transverse momentum (energy) threshold for muons (electrons) is lowered to 10 GeV (15 GeV).
The $H + 0$-jet category uses an inclusive selection to collect part of the signal not selected by the categories with jets. In the $H + 0$-jet category, only the $e\mu$ final state is considered because of the overwhelming $Z/\gamma^* \to \ell\ell$ background in the $ee$ and $\mu\mu$ final states. In order to suppress the $t\bar{t}$ background, it is required that the di-lepton azimuthal opening angle be $\Delta\phi_{\ell\ell} > 2.5$ rad and that the leptonic transverse energy be $H_{T}^{lep} = p_{T}^{\ell_1} + p_{T}^{\ell_2} + E_{T}^{miss} < 120$ GeV, where $p_{T}^{\ell_1}$ and $p_{T}^{\ell_2}$ are the magnitudes of the transverse momenta of the leading and sub-leading leptons, respectively.

In categories with jets ($H + 2$-jet VBF, $H + 2$-jet $VH$ and $H + 1$-jet), the presence of a hadronic jet with a transverse momentum $p_T > 40$ GeV is required and to suppress the $t\bar{t}$ background, the event is rejected if any jet with $p_T > 25$ GeV is identified as a $b$-jet. In addition, $E_{T}^{miss} > 40$ GeV ($E_{T}^{miss} > 20$ GeV) for the $ee, \mu\mu$ (e$\mu$) channels is also required.

The collinear approximation technique [63] is used to reconstruct the kinematics of the $\tau\tau$ system. The approximation is based on two assumptions: that the neutrinos from each $\tau$ decay are nearly collinear with the corresponding visible $\tau$ decay products and that the $E_{T}^{miss}$ in the event is due only to neutrinos. In this case, the total invisible momentum carried away by neutrinos in each $\tau$ decay can be estimated from the polar and azimuthal angles of the visible products of each $\tau$ decay. Then, the invariant mass of the $\tau\tau$ system can be calculated as $m_{\tau\tau} = m_{\ell\ell}/|x_1 \cdot x_2|$, where $x_1$ and $x_2$ are the momentum fractions of the two $\tau$ candidates carried away by their visible decay products. Events that do not satisfy $0.1 < x_1, x_2 < 1.0$ are rejected. In categories with jets, there is an additional requirement that $0.5 \text{ rad} < \Delta\phi_{\ell\ell} < 2.5 \text{ rad}$ to suppress the $Z/\gamma^* \to \ell\ell$ background.

For the $H + 2$-jet categories, a subleading jet with $p_T > 25$ GeV is required in addition. For the $H + 2$-jet VBF category, a pseudorapidity difference between the two selected jets of $\Delta\eta_{jj} > 3$ and a di-jet invariant mass of $m_{jj} > 350$ GeV are required. Finally, the event is rejected in the $H + 2$-jet VBF category if any additional jet with $p_T > 25$ GeV and $|\eta| < 2.4$ is found in the pseudorapidity range between the two leading jets.

For the $H + 2$-jet $VH$ category, the requirement on the pseudorapidity separation of the jets and on the di-jet invariant mass are instead: $\Delta\eta_{jj} < 2$ and $50 \text{ GeV} < m_{jj} < 120 \text{ GeV}$. Only events failing the cuts for the $H + 2$-jet categories are considered in the $H + 1$-jet category. For the $H + 1$-jet category, the invariant mass of the two $\tau$ leptons and the leading jet is required to fulfil $m_{\tau\tau j} > 225$ GeV, where the $\tau$ momenta are taken from the collinear approximation. The main Higgs production mechanism in this category is the $gg \to H$ process plus a high-$p_T$ parton.

The $m_{\tau\tau}$ calculated with the collinear approximation (“collinear mass”) is used in categories with jets. Because this variable displays poor resolution in the $H + 0$-jet category due to the back-to-back configuration of the two leptons, the effective mass ($m_{\tau\tau}^{\text{eff}}$), defined as the invariant mass of the two leptons and the $E_{T}^{miss}$, is used instead.

5.2 $H \to \tau_{lep}\tau_{had}$

The selected data are split into seven categories based on jet properties and $E_{T}^{miss}$. 

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The $H+2$-jet VBF category includes all selected events with $E_{\text{miss}}^T > 20$ GeV and at least two jets with $p_T > 25$ GeV, where the two leading jets are found in opposite hemispheres of the detector ($\eta_{\text{jet}1} \cdot \eta_{\text{jet}2} < 0$), with $\Delta \eta_{jj} > 3$ and $m_{jj} > 300$ GeV. Both the lepton and the $\tau_{\text{had}}$ candidate are required to be found in the pseudorapidity range between the two leading jets. Due to the limited size of the selected event samples, the VBF category combines the $e\tau_{\text{had}}$ and $\mu\tau_{\text{had}}$ final states.

Two $H+1$-jet categories include all selected events with $E_{\text{miss}}^T > 20$ GeV and at least one jet with $p_T > 25$ GeV, that fail the VBF selection. The $e\tau_{\text{had}}$ and $\mu\tau_{\text{had}}$ final states are considered separately.

Four $H+0$-jet categories include all selected events without any jet with $p_T > 25$ GeV. The $e\tau_{\text{had}}$ and $\mu\tau_{\text{had}}$ final states are considered separately. In addition, the analysis is separated into events with $E_{\text{miss}}^T > 20$ GeV and $E_{\text{miss}}^T < 20$ GeV. The low-$E_{\text{miss}}^T$ region is included here because, in the absence of high-$p_T$ jets, the Higgs decay products, including the neutrinos, are typically less boosted than for events with additional jet activity.

For each category, the mass of the $\tau \tau$ system is reconstructed using the Missing Mass Calculator (MMC) [64]. This technique provides a full reconstruction of event kinematics in the $\tau \tau$ final state with 99% efficiency and 13–20% resolution in $m_{\tau \tau}$, depending on the event topology (better resolution is obtained for events with high-$p_T$ jets). Conceptually, the MMC is a more sophisticated version of the collinear approximation. The main improvement comes from requiring that relative orientations of the neutrinos and other decay products are consistent with the mass and kinematics of a $\tau$ lepton decay. This is achieved by maximising a probability defined in the kinematically allowed phase space region.

5.3 $H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$

In the $H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$ channel, only a single $H+1$-jet category is defined. After selecting two hadronic $\tau$ candidates, the collinear mass approximation cuts $0 < x_1, x_2 < 1$ are applied. Events at this stage are used as a control sample to derive the normalisation of the $Z/\gamma^* \rightarrow \tau \tau$ background. Then, events are selected if $E_{\text{miss}}^T > 20$ GeV and if the leading jet has a transverse momentum $p_T > 40$ GeV. The two $\tau$ candidates are required to be separated by $\Delta R(\tau, \tau) < 2.2$. Also, only events with an invariant mass of the $\tau \tau$ pair and the leading jet $m_{\tau\tau j} > 225$ GeV are considered for further analysis. The event selection criteria described here are effective against the multi-jet and $Z/\gamma^* \rightarrow \tau \tau$ backgrounds. The collinear mass approximation is used for the Higgs mass reconstruction.

6 Background estimation and modelling

The background composition and normalisation are determined using data-driven methods and the simulated event samples described in Section 2.

The main background to the Higgs boson signal in all selected final states is the largely irreducible $Z/\gamma^* \rightarrow \tau \tau$ process. While it is not possible to select a Higgs signal-free $Z/\gamma^* \rightarrow \tau \tau$ sample directly from the data, this background is still modelled in a data-driven way, by
choosing a control sample where the expected signal contamination is negligible. In a sample of selected $Z/\gamma^* \rightarrow \mu\mu$ data events, the muon tracks and associated calorimeter cells are replaced by $\tau$ leptons from a simulated $Z/\gamma^* \rightarrow \tau\tau$ decay with the same kinematics, where the $\tau$ polarisation and spin correlations are modelled with the TAUOLA program and the $\tau-\mu$ mass difference is taken into account as well. Thus, only the $\tau$ decays and the corresponding detector response are taken from the simulation, whereas the underlying event kinematics and all other properties—including pileup effects—are obtained from the data. These embedded data are used to model the shape of the relevant $Z/\gamma^* \rightarrow \tau\tau$ background distributions as well as the efficiency for selecting $Z/\gamma^* \rightarrow \tau\tau$ events from the preselected sample. The overall normalisation at the preselection level is obtained from simulation.

The procedure is extensively validated: example results for the $H \rightarrow \tau_\text{lep}\tau_\text{had}$ channel are shown in Figure 1. Systematic effects intrinsic to the method are studied by replacing the muons selected in data by simulated muons instead of $\tau$ decays. Figure 1(a) shows a comparison of the $E_T^{\text{miss}}$ distributions from the selected $Z/\gamma^* \rightarrow \mu\mu$ events in data before and after this muon embedding, demonstrating that the embedding procedure does not introduce any significant bias to the reconstruction of the event properties. Figure 1(b) compares the MMC mass distributions reconstructed from the $\tau$-embedded $Z/\gamma^* \rightarrow \mu\mu$ data and simulated $Z/\gamma^* \rightarrow \tau\tau$ events after the preselection described in Section 4; good agreement is found and similar studies for the other channels yield the same conclusions.

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Figure 1. (a) $E_T^{\text{miss}}$ distributions for the $Z/\gamma^* \rightarrow \mu\mu$ data before and after muon embedding and (b) MMC mass distributions (defined in Section 5) for the $\tau$-embedded $Z/\gamma^* \rightarrow \mu\mu$ data and simulated $Z/\gamma^* \rightarrow \tau\tau$ events. For (a) only statistical uncertainties are shown; (b) also includes systematic uncertainties associated with the embedding procedure as discussed in Section 7.
6.1 \( H \rightarrow \tau_\text{lep}\tau_\text{lep} \)

The \( Z/\gamma^* \rightarrow \tau\tau \) background is modelled using the embedding procedure described above. The contribution from \( Z/\gamma^* \rightarrow \ell^+\ell^- \) is determined by scaling the yields in the Monte Carlo simulation using correction factors obtained by comparing data to simulation in low- and high-\( E_\text{Tmiss} \) control regions enriched in these backgrounds. The correction factors are obtained separately for \( Z/\gamma^* \rightarrow ee \) and \( Z/\gamma^* \rightarrow \mu\mu \) and for the different analysis categories and are on the order of 10%.

The fake lepton background consists of events that have a reconstructed lepton that did not originate from the decay of a \( \tau \) lepton or the leptonic decay of a \( W \) or \( Z \) boson. The normalisation and shape of relevant distributions are obtained from data with a template method using a control region in which the lepton isolation requirement is reversed. The chosen template shape is the \( p_T \) distribution of the sub-leading lepton. For this method to be applied, it is first verified that the template shapes of the fake lepton distribution in the control and signal regions agree within uncertainties. This is performed at intermediate steps of the event selection where the data sample is dominated by background events and where the number of expected signal events is negligible.

After subtracting the simulated backgrounds, the template shape in a given distribution is obtained from the control region, while the normalisation is obtained from a fit of the distribution of the events in the signal region with the template shape. The uncertainty related to the estimation of backgrounds with fake leptons is calculated from the uncertainty on the subtraction of other processes from Monte Carlo simulation and from the difference in the \( p_T \) shape of the events in the control region and signal regions. Such systematic uncertainties lie in the range of 30–40%.

The contributions of the \( t\bar{t}, \) single top-quark and electroweak di-boson backgrounds are estimated from simulation. The Monte Carlo description of the top-quark backgrounds has been validated using data by selecting control regions enriched in top-quark background processes. The control regions are defined by inverting the \( b \)-jet selection for the \( H +2\)-jet VBF, \( H +2\)-jet \( VH \), \( H +1\)-jet categories and by inverting the \( H_\text{Tlep} \) selection for the \( H +0\)-jet category.

Table 1 displays the number of events expected and observed in the four categories after all selection criteria including all systematic uncertainties described in Section 7. The estimated combined background contributions are found to give a good description of all quantities relevant to the analysis. As examples, the distributions of the jet multiplicity, \( E_\text{Tmiss} \), the invariant mass of the two leading jets and their pseudorapidity difference are shown in Figure 2. Figure 3 displays the invariant mass spectra of the selected events for the four categories.
Table 1. Number of events after the $H \to \tau_\text{lep}\tau_\text{lep}$ selection for the four categories in data and predicted number of background events, for an integrated luminosity of 4.7 fb$^{-1}$. Expectations for the Higgs boson signal ($m_H = 120$ GeV) are also given. Statistical and systematic uncertainties are quoted, in that order.

<table>
<thead>
<tr>
<th>Source</th>
<th>ee $+\mu\mu$</th>
<th>ee $+\mu\mu$</th>
<th>ee $+\mu\mu$</th>
<th>ee $+\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H +2-jet VBF</td>
<td>H +2-jet VH</td>
<td>H +1-jet</td>
<td>H +0-jet</td>
</tr>
<tr>
<td>$gg \to H$</td>
<td>0.26±0.06±0.10</td>
<td>0.8 ±0.1 ±0.2</td>
<td>3.9 ±0.2 ±1.0</td>
<td>23 ±1 ±3</td>
</tr>
<tr>
<td>VBF $H$</td>
<td>1.08±0.03±0.11</td>
<td>0.10±0.01±0.01</td>
<td>1.15±0.03±0.01</td>
<td>0.75±0.03±0.06</td>
</tr>
<tr>
<td>VH</td>
<td>0.01±0.01±0.01</td>
<td>0.53±0.02±0.07</td>
<td>0.40±0.02±0.03</td>
<td>0.52±0.02±0.04</td>
</tr>
<tr>
<td>$Z/\gamma^* \to \tau\tau$</td>
<td>24 ±3 ±2</td>
<td>107 ±12 ±9</td>
<td>(0.52±0.01±0.04)·10$^3$</td>
<td>(9.68±0.05±0.07)·10$^3$</td>
</tr>
<tr>
<td>$Z/\gamma^* \to \ell^+\ell^-$ ($\ell=e,\mu$)</td>
<td>2 ±1 ±1</td>
<td>25 ±4 ±9</td>
<td>83 ±10 ±30</td>
<td>185 ±11 ±14</td>
</tr>
<tr>
<td>$tt$ +single top</td>
<td>7 ±1 ±2</td>
<td>42 ±2 ±6</td>
<td>98 ±3 ±12</td>
<td>169 ±4 ±14</td>
</tr>
<tr>
<td>WW/WZ/ZZ</td>
<td>0.9±0.3±0.3</td>
<td>6 ±1 ±1</td>
<td>21 ±1 ±3</td>
<td>221 ±3 ±18</td>
</tr>
<tr>
<td>Fake leptons</td>
<td>1.3±0.8±0.6</td>
<td>13 ±2 ±5</td>
<td>30 ±4 ±12</td>
<td>(1.2±0.5)·10$^3$</td>
</tr>
<tr>
<td>Total background</td>
<td>35 ±3 ±4</td>
<td>193 ±7 ±20</td>
<td>(0.75±0.01±0.05)·10$^3$</td>
<td>(11.4±0.5)·10$^3$</td>
</tr>
<tr>
<td>Observed data</td>
<td>27</td>
<td>185</td>
<td>702</td>
<td>11420</td>
</tr>
</tbody>
</table>
Figure 2. Distributions of (a) the jet multiplicity, (b) the $E_T^{\text{miss}}$, (c) the invariant mass of the two leading jets and (d) the $\eta$ difference of the two leading jets in the $H \rightarrow \tau_\ell \tau_\ell$ channel for the selection criteria described in the text. Simulated samples are normalised to an integrated luminosity of $4.7 \text{ fb}^{-1}$. For illustration only, the signal contributions have been scaled by factors given in the legends. $30 \text{ GeV} < m_{\ell\ell} < 100 \text{ GeV}$ is required for the $ee$ and $\mu\mu$ channels and $30 \text{ GeV} < m_{\ell\ell} < 75 \text{ GeV}$ for the $e\mu$ channel. For the $E_T^{\text{miss}}$ distribution the presence of a leading jet with $p_T > 40 \text{ GeV}$ is required; for the invariant mass and for the $\eta$ difference of the two leading jets, the presence of a sub-leading jet with $p_T > 25 \text{ GeV}$ is required in addition.
Figure 3. Reconstructed $m_{\tau\tau}$ of the selected events in the $H \rightarrow \tau \ell \tau \ell$ channel for the four categories described in the text. Simulated samples are normalised to an integrated luminosity of 4.7 fb$^{-1}$. Predictions from the Higgs boson signal ($m_H = 120$ GeV) and from backgrounds are given. In the case of the $H +0$-jet category $m_{\text{eff}}$ is used. For illustration only, the signal contributions have been scaled by factors given in the legends.
6.2 $H \to \tau_{lep}\tau_{had}$

In order to estimate the background contributions to the selected $H \to \tau_{lep}\tau_{had}$ candidate events, a control sample in data is obtained by applying the signal selection described in Section 5.2 but now requiring that the light lepton and the $\tau_{had}$ candidate have the same charge. This control sample is referred to as the same-sign (SS) sample here, in contrast to the opposite-sign (OS) signal sample. The number of OS background events in the signal region ($n_{bkg}^{OS}$) can be expressed as

$$n_{bkg}^{OS} = n_{all}^{SS} + n_{W+jets}^{OS-SS} + n_{Z\to\tau\tau}^{OS-SS} + n_{other}^{OS-SS},$$

where $n_{all}^{SS}$ is the sum of all SS backgrounds in the signal region and the remaining terms are the differences between the number of OS and SS events for $W$ + jets, $Z/\gamma^* \to \tau\tau$ and other backgrounds, respectively. Due to their large production cross sections, multi-jet processes provide a significant background if quark/gluon jets are misidentified as hadronic $\tau$ decays. The ratio of OS to SS events for the multi-jet background ($r_{QCD}^{OS/SS}$) is expected to be close to unity and therefore $n_{QCD}^{OS-SS} = 0$ is assumed. This assumption is validated with a control sample that is dominated by low-$p_T$ jets from multi-jet processes. This sample is selected by replacing the requirement $E_T^{miss} > 20$ GeV with $E_T^{miss} < 15$ GeV and removing the isolation criteria of the electron or muon candidate. After subtraction of the other backgrounds using simulation, a value of $r_{QCD}^{OS/SS} = 1.10 \pm 0.01(\text{stat.}) \pm 0.09(\text{syst.})$ is obtained. The observed deviation of $r_{QCD}^{OS/SS}$ from unity is taken into account as a systematic uncertainty for the final result.

The $Z/\gamma^* \to \tau\tau$ contribution is estimated from the $\tau$-embedded $Z/\gamma^* \to \mu\mu$ sample in the data, as described previously. For the $W$ + jets background, a significant deviation of the ratio of OS and SS events ($r_{OS/SS}^{W}$) from unity is expected since $W$ + jets production is dominated by $gu/gd$-processes that often give rise to a jet originating from a quark, the charge of which is anti-correlated with the $W$ boson charge. The predicted number of $W$ + jets background events is obtained from the simulation after applying a normalisation correction factor determined from $W$-dominated data control samples. The remaining contributions $n_{other}^{OS-SS}$ are taken from the simulation.

Table 2 displays the number of events expected and observed in the seven categories after the full signal selection, including all systematic uncertainties as described in Section 7. The estimated combined background contributions are found to give a good description of all quantities relevant to the analysis. As examples, the distributions of $E_T^{miss}$, the transverse mass of the lepton-$E_T^{miss}$ system as well as the invariant mass of the two leading jets and their pseudorapidity difference are shown in Figure 4. Figure 5 shows the corresponding $\tau\tau$ invariant mass spectra, where the electron and muon categories have been combined for illustration purposes. The data are found to be consistent with the estimated combined background contributions in both normalisation and shape within the uncertainties.

---

6 These control samples are defined by replacing the $m_T < 30$ GeV requirement in the nominal selection with $m_T > 50$ GeV.
Table 2. Predicted number of signal events (for $m_H = 120$ GeV) and predicted backgrounds obtained as described in the text, together with the observed number of events in data for the $H \to \tau_\tau \tau_\tau$ categories. The total background yield predicted by the alternative estimation method is given as well for comparison. The listed uncertainties are statistical and systematic, in that order.

<table>
<thead>
<tr>
<th></th>
<th>$H +0$-jet (low $E_T^{miss}$)</th>
<th>$H +0$-jet (high $E_T^{miss}$)</th>
<th>$H +1$-jet</th>
<th>$H +2$-jet VBF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electron</td>
<td>Muon</td>
<td>Electron</td>
<td>Muon</td>
</tr>
<tr>
<td>$ggH$ signal</td>
<td>11 ± 1</td>
<td>± 2</td>
<td>17 ± 1</td>
<td>± 4</td>
</tr>
<tr>
<td>VBF $H$ signal</td>
<td>0.08 ± 0.02 ± 0.12</td>
<td>0.01</td>
<td>± 0.03 ± 0.03</td>
<td>0.09 ± 0.02 ± 0.02</td>
</tr>
<tr>
<td>$VH$ signal</td>
<td>0.07 ± 0.02 ± 0.05</td>
<td>0.10 ± 0.03 ± 0.01</td>
<td>0.08 ± 0.02 ± 0.01</td>
<td>0.08 ± 0.02 ± 0.01</td>
</tr>
<tr>
<td>$n_{ggH}^{jet}$</td>
<td>(3.7 ± 9.0 ± 0.8 · 10^3)</td>
<td>(2.0 ± 0.1 ± 0.4 · 10^3)</td>
<td>(0.69 ± 0.06 ± 0.14) · 10^3</td>
<td>(0.47 ± 0.04 ± 0.09) · 10^3</td>
</tr>
<tr>
<td>$n_{ggH}^{SS}$</td>
<td>(3.0 ± 9.0 ± 0.8 · 10^3)</td>
<td>(5.0 ± 0.2 ± 0.07 · 10^3)</td>
<td>(0.15 ± 0.01 ± 0.02 · 10^3)</td>
<td>(0.18 ± 0.01 ± 0.03 · 10^3)</td>
</tr>
<tr>
<td>$n_{ggH}^{VS}$</td>
<td>(3.2 ± 9.0 ± 0.8 · 10^3)</td>
<td>(7.29 ± 0.06 ± 1.21 · 10^3)</td>
<td>(1.49 ± 0.04 ± 0.23 · 10^3)</td>
<td>(2.80 ± 0.04 ± 0.42 · 10^3)</td>
</tr>
<tr>
<td>$n_{ggH}^{SS}$</td>
<td>(0.97 ± 0.04 ± 0.22 · 10^3)</td>
<td>(0.59 ± 0.04 ± 0.14 · 10^3)</td>
<td>(0.27 ± 0.02 ± 0.08 · 10^3)</td>
<td>(0.14 ± 0.02 ± 0.04 · 10^3)</td>
</tr>
<tr>
<td>Total background</td>
<td>(8.2 ± 9.0 ± 0.8 · 10^3)</td>
<td>(10.4 ± 0.2 ± 1.2 · 10^3)</td>
<td>(2.59 ± 0.07 ± 0.26 · 10^3)</td>
<td>(3.59 ± 0.07 ± 0.43 · 10^3)</td>
</tr>
<tr>
<td>Observed data</td>
<td>8363</td>
<td>10911</td>
<td>2545</td>
<td>3570</td>
</tr>
<tr>
<td>Altern. estimate</td>
<td>(8.7 ± 9.0 ± 0.8 · 10^3)</td>
<td>(10.7 ± 0.1 ± 1.0 · 10^3)</td>
<td>(2.76 ± 0.05 ± 0.33 · 10^3)</td>
<td>(3.75 ± 0.05 ± 0.47 · 10^3)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$H +1$-jet</th>
<th>$H +2$-jet VBF</th>
<th>Electron</th>
<th>Muon</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ggH$ signal</td>
<td>8.1 ± 0.7 ± 1.6</td>
<td>10.8 ± 0.8 ± 2.2</td>
<td>0.9 ± 0.2 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>VBF $H$ signal</td>
<td>1.6 ± 0.1 ± 0.1</td>
<td>1.9 ± 0.1 ± 0.1</td>
<td>2.2 ± 0.1 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>$VH$ signal</td>
<td>1.1 ± 0.1 ± 0.1</td>
<td>1.4 ± 0.1 ± 0.1</td>
<td>0.02 ± 0.01 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>$n_{ggH}^{jet}$</td>
<td>(0.93 ± 0.03 ± 0.19) · 10^4</td>
<td>(0.49 ± 0.04 ± 0.10) · 10^4</td>
<td>45 ± 7 ± 9</td>
<td></td>
</tr>
<tr>
<td>$n_{ggH}^{SS}$</td>
<td>(0.25 ± 0.01 ± 0.03) · 10^3</td>
<td>(0.26 ± 0.01 ± 0.03) · 10^3</td>
<td>5 ± 1 ± 2</td>
<td></td>
</tr>
<tr>
<td>$n_{ggH}^{VS}$</td>
<td>(1.23 ± 0.03 ± 0.17) · 10^3</td>
<td>(1.76 ± 0.03 ± 0.25) · 10^3</td>
<td>54 ± 6 ± 8</td>
<td></td>
</tr>
<tr>
<td>$n_{ggH}^{SS}$</td>
<td>(0.28 ± 0.02 ± 0.04) · 10^3</td>
<td>(0.24 ± 0.01 ± 0.03) · 10^3</td>
<td>20 ± 3 ± 5</td>
<td></td>
</tr>
<tr>
<td>Total background</td>
<td>(2.69 ± 0.08 ± 0.26) · 10^3</td>
<td>(2.75 ± 0.05 ± 0.27) · 10^3</td>
<td>124 ± 10 ± 13</td>
<td></td>
</tr>
<tr>
<td>Observed data</td>
<td>3610</td>
<td>2711</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td>Altern. estimate</td>
<td>(2.63 ± 0.05 ± 0.25) · 10^3</td>
<td>(2.72 ± 0.04 ± 0.28) · 10^3</td>
<td>131 ± 11 ± 23</td>
<td></td>
</tr>
</tbody>
</table>
In order to validate these results, an alternative background estimation is performed. This second method provides an estimate of the multi-jet background using control samples that are defined by separately inverting the light-lepton isolation and the τ_{had-ℓ} charge cor-

**Figure 4.** (a) Missing transverse momentum, (b) transverse mass of the lepton-\(E_T^{\text{miss}}\) system as well as (c) invariant mass and (d) pseudorapidity difference of the two leading jets in the \(H \to \tau_{\text{lep}}\tau_{\text{had}}\) channel. The preselection criteria and an \(E_T^{\text{miss}} > 20\) GeV requirement are applied except those for the displayed quantity; for (c) and (d) the presence of at least two jets with \(p_T > 25\) GeV is required in addition. Simulated samples are normalised to an integrated luminosity of 4.7 fb\(^{-1}\). The selected events in data are shown together with the predicted Higgs boson signal (\(m_H = 120\) GeV) stacked above the background contributions (see text). For illustration only, the signal contributions have been scaled by factors given in the legends.
relation requirements, respectively. In addition to the signal region (A) this results in three background-dominated regions B (SS $\ell_\text{had}^\tau$, $\ell_\text{isolated}$), C (OS $\ell_\text{had}^\tau$, $\ell_\text{anti-isolated}$) and D (SS $\ell_\text{had}^\tau$, $\ell_\text{anti-isolated}$). The shape of the MMC mass distribution for multi-jet contributions in the signal region A is taken from the control region B and the normalisation is derived from the relation $n_A = n_C/n_D \times n_B$. Here, $n_B$, $n_C$ and $n_D$ denote the event yields in regions.
B, C and D, after subtracting the contribution from non-multi-jet backgrounds in all control regions. The $Z/\gamma^* \rightarrow \tau\tau$ contribution is estimated from the $\tau$-embedded $Z/\gamma^* \rightarrow \mu\mu$ data and the estimate of the $W +$ jets background is obtained from the simulation after applying normalisation correction factors determined from $W$-dominated (high-$m_T$) OS and SS data control samples. The remaining contributions are obtained from the simulation. The resulting total background estimates are also included in Table 2 and are found to be consistent with both the observed number of data events and the predictions of the default background estimate within the uncertainties.

Further studies of specific background contributions are performed by estimating the probability to misidentify jets as $\tau_{\text{had}}$ candidates in the signal region and using data control regions for the background from $t\bar{t}$ production processes. Results are consistent with the background estimates in Table 2 in both cases.

### 6.3 $H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$

The dominant backgrounds in the $H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$ channel are $Z/\gamma^* \rightarrow \tau\tau$ and multi-jet production. For both, the normalisation and shape of the mass distribution are estimated using data-driven methods.

The normalisation of the $Z/\gamma^* \rightarrow \tau\tau$ background is obtained by using collision data events at an early stage of the event selection. This data-driven control sample is defined by requiring that events contain two $\tau_{\text{had}}$ candidates that pass the hadronic selections including the collinear approximation cuts ($0 < x_{1,2} < 1$ and $\Delta R(\tau\tau) < 2.8$). To avoid signal contamination in this control sample, a requirement that $m_{\tau\tau} < 100$ GeV is applied; this results in a SM Higgs signal contamination of less than 0.2%. The $Z/\gamma^* \rightarrow \tau\tau$ contribution is obtained by fitting the track multiplicity of the two $\tau$ candidates simultaneously. The tracks associated to the $\tau_{\text{had}}$ candidates are counted in the cone defined by $\Delta R < 0.6$, as motivated by the momentum correlation between tracks in $\tau_{\text{had}}$ candidates [56]. A two-dimensional distribution of the track multiplicities for these two $\tau$ candidates is formed, and a track multiplicity fit is performed. The multi-jet template is modelled from the same-sign (SS) candidates in the data while the $Z/\gamma^* \rightarrow \tau\tau$ contribution is modelled by the simulation. The less significant backgrounds are estimated from the simulation and subtracted before the fit is performed.

The result of the fit is used to normalise the $\tau$-embedded $Z/\gamma^* \rightarrow \mu\mu$ sample described above, and then this sample is used to model the acceptance of the later cuts and the mass shape in the signal region.

The multi-jet contribution is estimated by the same two-dimensional track multiplicity fitting technique, where the fit is now performed in the signal region. The contribution from di-$\tau$ events is allowed to float in the fit, where the shape comes from the simulation. It is assumed that the shape of the two-dimensional track multiplicity in the $Z/\gamma^* \rightarrow \tau\tau$ and Higgs boson signal processes are the same.

The systematic uncertainties considered for the background prediction arise from the jet template statistics, alternative multi-jet track multiplicity templates, the presence of non-di-$\tau$
background, signal contamination, charge misidentification probability and variations in the pileup conditions.

Instead of using the SS events for the multi-jet track template, the alternative multi-jet track multiplicity template is built from events with one additional electron or muon which enhances the contribution of $W$+jets events, where two jets are misidentified as the hadronic

Figure 6. (a) $\Delta R$ of the two $\tau$ candidates, (b) missing transverse momentum, (c) collinear mass and (d) invariant mass of the reconstructed Higgs boson and the leading jet in the $H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$ control region. Expectations from the Higgs boson signal ($m_{H} = 120$ GeV) and from backgrounds are given. The error band indicates the total background uncertainty. For illustration only, the signal contributions, which are expected to be small in this control region, have been scaled by factors given in the legends.
taus. This provides a different mix of quark- and gluon-initiated jets from the inclusive multi-jet sample, addressing a possible flavour dependence of the track multiplicity distribution.

The overall systematic uncertainties are 11.6% and 22% for $Z/\gamma^* \rightarrow \tau\tau$ and multi-jet backgrounds, respectively.

The mass shape from the multi-jet events is modelled by dropping the opposite-sign and $\tau_{\text{had}}$ track multiplicity requirements. In order to obtain a data sample that is enriched with the multi-jet background, events are accepted if they are same-sign events or if the sum of the charges of the products of a single $\tau$ decay is 0 or $\pm 2$. This mass shape model is tested against several other hypothesis obtained, e.g., from pure SS samples or events selected with looser $\tau$ identification criteria.

Figure 6 shows the kinematic distributions of (a) the $\Delta R$ of the two $\tau$ candidates, (b) the missing transverse momentum, (c) the collinear mass and (d) the invariant mass of the reconstructed Higgs boson and the leading jet in the $H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$ control region.

Table 3 presents the event yields after the full event selection, where the yields are normalised to 4.7 fb$^{-1}$. The collinear mass distribution after full selection is presented in Figure 7.

<table>
<thead>
<tr>
<th>Event Category</th>
<th>$H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$ (3.1 ± 0.2 ± 0.6)</th>
<th>$H + 1$-jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \rightarrow H$ signal</td>
<td>3.1 ± 0.2 ± 0.6</td>
<td></td>
</tr>
<tr>
<td>VBF $H$ signal</td>
<td>1.51 ± 0.05 ± 0.18</td>
<td></td>
</tr>
<tr>
<td>$VH$ signal</td>
<td>0.61 ± 0.04 ± 0.06</td>
<td></td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \tau^+\tau^-$</td>
<td>287 ± 23 ± 34</td>
<td></td>
</tr>
<tr>
<td>W+jets / Z+jets</td>
<td>6.1 ± 1.3 ± 1.4</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}$ + single top</td>
<td>1.9 ± 0.3 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>$WW/WZ/ZZ$</td>
<td>2.1 ± 0.4 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>Multi-jet</td>
<td>54 ± 21 ± 12</td>
<td></td>
</tr>
<tr>
<td>Total background</td>
<td>348 ± 31 ± 36</td>
<td></td>
</tr>
<tr>
<td>Observed data</td>
<td>317</td>
<td></td>
</tr>
</tbody>
</table>
Figure 7. Reconstructed $m_{\tau\tau}$ of the selected events in the $H \to \tau_{\text{had}}\tau_{\text{had}}$ channel. Expectations from the Higgs boson signal ($m_H = 120$ GeV) and from backgrounds are given. Results are shown after all selection criteria (see text). For illustration only, the signal contribution has been scaled by a factor given in the legend.
Systematic uncertainties on the normalisation and shape of the signal and background mass distributions are taken into account. These are treated either as fully correlated or uncorrelated across categories. In the case of partial correlations, the source is separated into correlated and uncorrelated components. The dominant correlated systematic uncertainties are those on the measurement of the integrated luminosity and on the theoretical predictions of the signal production cross sections and decay branching ratios, as well as those related to detector response that impact the analyses through the reconstruction of electrons, muons, hadronic $\tau$ decays, jets, $E_T^{\text{miss}}$ and $b$-tagging.

Theoretical uncertainties: The Higgs boson cross section, branching ratios and their uncertainties are compiled in Refs. [65, 66]. The QCD scale uncertainties on the signal cross sections depend on $m_H$ and are of the order of 1% for the VBF and $VH$ production modes and in the range of 8–25% for $gg \rightarrow H$ depending on jet multiplicity [67, 68]. An uncertainty of 4–5% is assumed for the inclusive cross section of the single vector boson and di-boson production mechanisms and a relative uncertainty of 24% is added in quadrature per additional jet. For both $tt$ production and single top-quark production, the QCD scale uncertainties are in the range of 3–6% [69–71]. The uncertainties related to the PDF amount to 8% for the predominantly gluon-initiated processes, $gg \rightarrow H$ and $tt$, and 4% for the predominantly quark-initiated processes, VBF, $VH$, single vector boson and di-boson production [72–75]. The systematic uncertainty arising from the choice of different sets of PDF is included. In addition to the theoretical errors considered in Ref. [66], other effects are taken into account. Uncertainties related to hadronisation effects are estimated by replacing PYTHIA with HERWIG. Effects due to initial and final state radiation are assessed with PYTHIA samples where the gluon emission is changed according to Ref. [76]. The effect of a different choice of parton shower and underlying event parametrisation yields a total uncertainty of about 10% on the acceptance of the Higgs boson produced via the VBF mechanism in the $H+2\text{jet}$ VBF channel.

Detector-related uncertainties: The uncertainty on the integrated luminosity is considered as fully correlated across all analysis categories and amounts to 3.9% [77, 78]. The effect of pileup on the signal and background expectations is modelled in the Monte Carlo simulations and the corresponding uncertainty is taken into account.

Appropriate scale factors for the trigger efficiencies of electron, muon and hadronic $\tau$ triggers are obtained from data and applied to the Monte Carlo simulations. The associated systematic uncertainties are typically 1–2%. Differences between data and Monte Carlo simulations in the reconstruction and identification efficiencies of $\tau$ leptons, electrons and muons are taken into account, as well as the differences in the momentum scales and resolutions.

The systematic uncertainties on the hadronic $\tau$ decay identification efficiency are estimated from data samples enriched in $W \rightarrow \tau\nu$ and $Z/\gamma^* \rightarrow \tau\tau$ events and they are less than 4%. The energy scale uncertainties on the hadronic $\tau$ and jets are evaluated based on the single hadron response in the calorimeters [79]. In addition, the $\tau_{\text{had}}$ energy scale is validated.
in data samples enriched in \(Z/\gamma^* \rightarrow \tau\tau\) events. The systematic uncertainties related to the \(\tau\) and jet energy scale, resolution and \(b\)-veto are modelled as functions of \(\eta\) and \(p_T\). The jet and \(\tau\) energy scale and resolution uncertainties are treated as correlated and propagated to the \(E_T^{\text{miss}}\) calculation. Uncertainties associated with the remaining pileup noise and cluster activity in the calorimeters are also considered as independent \(E_T^{\text{miss}}\) uncertainties.

The detector-related uncertainties depend on the event topology and are typically small compared to the theoretical uncertainties. The main exceptions are the jet energy scale uncertainty, which reaches up to 12\%, and the \(\tau\) energy scale uncertainty, which is in the range 2–5\%.

**Background modelling uncertainties:** The modelling of the \(Z/\gamma^* \rightarrow \tau\tau\) background is performed with the data, as described in Section 2. Corresponding uncertainties are obtained by propagating variations of the \(Z/\gamma^* \rightarrow \mu\mu\) event selection and the muon energy subtraction procedure through the \(\tau\)-embedding procedure. Backgrounds with misreconstructed leptons and \(\tau\) had candidates are estimated with data and the uncertainty in the estimation lies in the range of 6–40\%. The uncertainty takes into account the dependence on the number of jets. The treatment of the other background processes varies across channels and the uncertainties related to the modelling are taken into account as described in Section 6.

8 Statistical analysis

The statistical analysis of the data employs a binned likelihood function constructed as the product of the likelihood terms for each category. A total of twelve categories are considered from the \(H \rightarrow \tau\text{lep}\tau\text{lep}, H \rightarrow \tau\text{lep}\tau\text{had}\) and \(H \rightarrow \tau\text{had}\tau\text{had}\) channels. The likelihood in each category is a product over bins in the distributions of the MMC mass, collinear mass or effective mass shown in Figs. 3, 5 and 7.

The expected signal and background, as well as the observed number of events, in each bin of the mass distributions enter in the definition of the likelihood function \(\mathcal{L}(\mu, \theta)\). A “signal strength” parameter (\(\mu\)) multiplies the expected signal in each bin. The signal strength is a free parameter in the fit procedure. The value \(\mu = 0\) (\(\mu = 1\)) corresponds to the absence (presence) of a Higgs boson signal with the SM production cross-section. Signal and background predictions (\(s\) and \(b\)) depend on systematic uncertainties that are parametrised by nuisance parameters \(\theta\), which in turn are constrained using Gaussian functions. The correlation of the systematic uncertainties across categories are taken into account:

\[
\mathcal{L}(\mu, \theta) = \prod_{\text{bin}} \text{Poisson}(N_j|\mu(s_j) + b_j) \prod_{\theta} \text{Gaussian}(\theta|0, 1).
\]  

(8.1)

The expected signal and background event counts in each bin are functions of \(\theta\). The parametrisation is chosen such that the rates in each channel are log-normally distributed for a normally distributed \(\theta\).

The test statistic \(q_\mu\) is defined as:

\[
q_\mu = -2 \ln \left( \frac{\mathcal{L}(\mu, \hat{\theta})}{\mathcal{L}(\hat{\mu}, \hat{\theta})} \right),
\]  

(8.2)
where $\hat{\mu}$ and $\hat{\theta}$ refer to the global maximum of the likelihood (with the constraint $0 \leq \hat{\mu} \leq \mu$) and $\hat{\theta}_\mu$ corresponds to the conditional maximum likelihood of $\theta$ for a given $\mu$. This test statistic is used to compute exclusion limits following the modified frequentist method known as CL$_s$ \cite{80}. The asymptotic approximation \cite{81} is used to evaluate the Gaussian probability density functions rather than performing pseudo-experiments and the procedure has been validated using ensemble tests.

The profile likelihood formalism used in this statistical analysis incorporates the information on the observed and expected number of events, nuisance parameters, probability density functions and parameters of interest. The statistical significance of an excess is evaluated in terms of the same profile likelihood test statistic. The expected sensitivity and the $\pm 1, 2\sigma$ bands are obtained for the background expectation in the absence of a Standard Model Higgs boson signal. The consistency with the background-only hypothesis is quantified using the $p$-value, the probability that the test statistic of a background-only experiment fluctuates to at least the observed one.

9 Results

No significant excess is observed in the data compared to the SM expectation in any of the channels studied here. Exclusion limits at the 95\% confidence level, normalised to the Standard Model cross section times the branching ratio of $H \rightarrow \tau^+\tau^-$ ($\sigma_{SM}$), are set as a function of the Higgs boson mass. Figure 8 shows expected and observed limits for the individual channels and for the combined result. The combined expected limits vary between 3.4 and 8.2 times the predicted Standard Model cross section times branching ratio for the mass range 100–150 GeV. The most sensitive categories are the $H + 1$-jet category in the $\tau_{\text{had}}\tau_{\text{had}}$ channel, the $H + 2$-jet VBF category in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel and the $H + 2$-jet VBF category in the $\tau_{\text{lep}}\tau_{\text{lep}}$ channel. The observed limits are in the range between 2.9 and 11.7 times the predicted Standard Model cross section times branching ratio for the same mass range. The most significant deviation from the background-only hypothesis is observed in the combined limit for $m_H = 150$ GeV with a local $p$-value of 10\%, corresponding to a significance of 1.3 $\sigma$.

10 Conclusions

A search for a Higgs boson decaying in the $H \rightarrow \tau\tau$ channel has been performed with the ATLAS detector at the Large Hadron Collider. It uses the full 2011 data sample of 4.7fb$^{-1}$ collected at a centre-of-mass energy of 7 TeV. The $H \rightarrow \tau_{\text{lep}}\tau_{\text{lep}}$, $H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$ and $H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$ decays are considered in this search. No significant excess is observed in the mass range of 100–150 GeV. The observed (expected) upper limits on the cross section times the branching ratio of $H \rightarrow \tau\tau$ are between 2.9 (3.4) and 11.7 (8.2) times the SM prediction. These limits are similar to results recently reported by the CMS experiment \cite{82}.
Figure 8. Observed (solid) and expected (dashed) 95% confidence level upper limits on the Higgs boson cross section times branching ratio, normalised to the Standard Model expectation, as a function of the Higgs boson mass. Expected limits are given for the scenario with no signal. The bands around the dashed line indicate the expected statistical fluctuations of the limit. Results are given for the $H \rightarrow \tau_{\text{lep}}\tau_{\text{lep}}$, $H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$, and $H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$ channels independently and for all channels combined.
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ATLAS Silicon Microstrip Tracker Operation and Performance

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Abstract

The Semi-Conductor Tracker is a silicon microstrip detector at the heart of the ATLAS experiment at the CERN Large Hadron Collider. Together with the rest of the ATLAS Inner Detector it provides vital precision tracking information of charged particles. In this paper the performance and operational status of the Semi-Conductor Tracker in the last two years of ATLAS data taking are reviewed.

1. Introduction

The ATLAS Inner Detector (ID) is responsible for the tracking of charged particles and consists of three sub-detectors using different technologies: closest to the beams the silicon pixel detector, next the Semi-Conductor Tracker (SCT) and furthest away from the beam axis the Transition Radiation Tracker (TRT). The ID is located in a solenoidal 2T magnetic field. The outer dimensions of the ID are 5.6m (length) and 2.1m (diameter).

The 6.3 million silicon strip channels of the SCT are grouped in 4088 modules with 1536 channels per module\cite{1}. The modules are placed in 4 barrel cylinders and 18 end-cap disks, designed so particles will pass 4 SCT layers on their way from the interaction point through the detector. Modules are constructed with back-to-back layers of strips, rotated with a stereo angle of 40 mrad with respect to each other to provide tracking information in the longitudinal (beam) direction. The strip pitch for barrel modules is 80 $\mu$m.

In 2010 and 2011, LHC delivered 47pb\textsuperscript{−1} and 5.6fb\textsuperscript{−1} integrated luminosity of 7 TeV proton-proton collision data. During these periods the SCT recorded good quality data in 99.9% and 99.6% of the time.

In the typical operation configuration of the SCT during data taking 99.3% of the SCT modules have been in operation. Only very few (\textsim 30) modules have been disabled from operation due to either problems in a cooling loop, HV connectivity failures or failures of the optical transmitters.

2. Lorentz Angle

Due to the strong magnetic field the drift direction of the charge carriers in the strips is affected by the Lorentz force.\textsuperscript{47} The number of strips which is collecting charges from a track,\textsuperscript{48} also referred to as the cluster width, varies with the incident angle of the track. The angle with the smallest cluster width is called the Lorentz angle. This angle depends on both the strength of the magnetic field, the module temperatures and the bias voltage, which makes this quantity important to monitor.

By plotting by the cluster width as function of the incident angle for different layers of the SCT barrel, Lorentz angle can be extracted as the minimum of each curves. The obtained values of Lorentz angles, listed in figure 1, show good agreement with model predictions.

![Figure 1: Measured and predicted Lorentz angles for the SCT Barrel layers.](image)

3. Calibration

The online calibration of the SCT monitors the noise level in two different ways \cite{2}: through a response curve test and through a noise occupancy test. The response curve test measures the noise level via charge injection in the front end chip and fitting the number of hits from the binary readout as function of the discriminator threshold. The alternative method of noise occupancy test monitors the hit occupancy in events where no particle activity in the detector is expected. Noise occupancies obtained by this method for 2010 data is shown in figure 2. Both methods give a noise occupancy below the design criteria of $5 \times 10^{-4}$ at a threshold of 1fC.
4. Intrinsic Hit Efficiency

As shown in figure 3 the strip hit efficiencies of the SCT are well above the design criteria of 99%. The hit efficiency is derived as the measured fraction of hits on a track per possible hits along the track trajectory, and is derived both using SCT standalone tracks and tracks from the full ID. For the SCT standalone tracks, efficiencies for the innermost and outermost layer will be biased since holes on tracks are only counted from the first to the last measured point.

5. Alignment

The alignment of the SCT modules is done by minimising a $\chi^2$ based on the track-hit residuals of tracks reconstructed in the ID [3]. A track-hit residual is defined as the distance from the trajectory of the reconstructed track to the measured space point. The alignment is constantly improving over time. During 2010, the residuals measured in the direction across the strips in the local module frame for barrel and endcap modules changed from 42$\mu$m and 44$\mu$m in the spring to 36$\mu$m and 38$\mu$m in the autumn. In comparison, simulations of a perfectly aligned detector have shown to give residuals for barrel and endcap of 34$\mu$m and 38$\mu$m.

6. Radiation Damage

The effects of radiation damage in the SCT are monitored through the leakage current in the HV supplies. As expected significant increases in leakage currents have been observed. In figure 4 the measured leakage currents for barrel modules are shown together with the LHC luminosity and sensor temperatures since these are directly correlated [4]. Simulations of the expected effects from radiation damage have been carried out using the Hamburg model[5] and the foreseen dose of radiation predicted by FLUKA [6]. The mode predictions, also shown in figure 4, are found to be in excellent agreement with the measured leakage currents.

7. Conclusion

During the last two years of ATLAS data taking, the SCT has been delivering vital tracking data with an extremely high data acquisition efficiency. Both the alignment, hit efficiency and the noise level of the SCT have been found to be well within design limits. The effects of radiation damage are monitored and shown to be in agreement with the model predictions based on the luminosity and temperature profiles.

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