The Compact Muon Solenoid Experiment

CMS Note

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Light Charged Higgs Discovery Potential of CMS in the $H^\pm \rightarrow \tau \nu_\tau$ Decay with Single Lepton Trigger

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Abstract

In this note the CMS discovery potential for the light charged Higgs boson in the Minimal Supersymmetric Standard Model framework is presented. Different Higgs boson production mechanisms were studied to cover the mass range $125 < m_{H^\pm} < 170 \text{ GeV}/c^2$. The analysis is based on the CMS full simulation and reconstruction. Systematic uncertainties on the background determination are included. It is shown that the systematic uncertainties reduce the observability of $H^\pm$ mainly at low $\tan\beta$. Finally the 5σ discovery contour for an integrated luminosity of 30fb^{-1} is presented.

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1 Introduction

The Minimal Supersymmetric extension to the Standard Model (MSSM) [1] requires the introduction of two Higgs doublets in order to preserve the supersymmetry. Five physical Higgs particles are predicted, two CP-even (h, H), one CP-odd (A) and two charged ones ($H^\pm$). All couplings and masses of the MSSM Higgs sector are determined at the lowest order by two independent parameters, which are generally chosen as $\tan\beta = v_2/v_1$, the ratio of the vacuum expectation values of the two Higgs doublets, and the pseudo-scalar Higgs boson mass m_A . Since the charged Higgs boson is a crucial signature of the MSSM, it is presently considered as one of the most interesting particles in the MSSM Higgs sector.

The latest results from the LEP Higgs working group concerning the indirect search for neutral MSSM Higgs bosons provide a mass lower limit of $125 \text{ GeV}/c^2$ for $m_{H^\pm}$ at $\tan\beta > 10$ [3]. Results from direct searches at LEP give instead a lower limit on the charged Higgs boson mass of $\sim 90 \text{ GeV}/c^2$ for $\text{BR}(H^\pm \rightarrow \tau\nu) \simeq 1$ [4]. Direct and indirect searches performed at the Tevatron lead to some exclusion region in the parameter space for $\tan\beta > 50$ and $\tan\beta < 1$ [5, 6].

In the study presented in this note the light charged Higgs ($m_{H^\pm} < m_t - m_b$) is searched for in the channel $H_{\text{MSSM}}^\pm \rightarrow \tau^+\nu_\tau, \tau \rightarrow \text{hadrons}$ in the mass range $125 < m_{H^\pm} < 170 \text{ GeV}/c^2$. The mass range chosen is the most critical since for Higgs boson masses close to the top mass the signal rate is low. Proving that the discovery is attainable in this mass range would imply that the light charged Higgs boson can be discovered also at lower masses. The analysis is based on full simulation and reconstruction of the CMS detector. All results are obtained according to the LEP $m_{h^0} - \text{max}$ benchmark scenario [3] with the following choice of the MSSM parameters: SU(2) gaugino mass $M_2 = 200 \text{ GeV}/c^2$, $\mu = -200 \text{ GeV}/c^2$, gluino mass $M_{\tilde{g}} = 800 \text{ GeV}/c^2$, SUSY breaking mass parameter $M_{\text{SUSY}} = 1 \text{ TeV}/c^2$ and stop mixing parameter $X_t = \sqrt{6} M_{\text{SUSY}}$ ($X_t = A_t + \mu \cot\beta$). The top quark mass is set to $175 \text{ GeV}/c^2$.

This document is organized as follows: Section 2 describes the signal and background channels considered for the analysis; cross sections and branching fractions are discussed. Event selection, reconstruction issues and selection efficiencies are described in Sections 3 and 4; additional contributions to signal and background not already discussed in Section 2, are presented in Section 5. Finally the results including the evaluation of systematic uncertainties are discussed in Section 6 and conclusions are drawn in Section 7.

2 Signal and background simulation, cross sections and branching ratios

The MSSM charged Higgs boson can be produced in top quark decays, $t \rightarrow H^\pm b$, if $m_{H^\pm} < m_t - m_b$. The signal channel $t\bar{t} \rightarrow H^\pm W^\mp b\bar{b}$ can have two different final states according to the $W^\pm$ leptonic or hadronic decay. In this study the $W^\pm$ leptonic decay (e or μ) is chosen. The background channels consist of $t\bar{t}$ events with at least a single lepton (e or μ) and τ -jets or jets which could fake τ -jets, $W^\pm + 3$ jets events and also single top events which have, however, a small contribution estimated later in the note.

A total NLO $t\bar{t}$ cross section of 850 pb was used in this note [10] for calculating the cross sections of the different final states. The cross section of $W^\pm + 3$ jets events was obtained with the MadEvent generator [15] with some preselection cuts: $E_T^{\text{jet}} > 20 \text{ GeV}$, $|\eta| < 2.5$ for all final state jets and $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.5$ for all pairs of final state jets.

The Higgs boson decay branching ratio to $\tau^+\nu_\tau$ was calculated with HDECAY [13] while TAUOLA [14] was used to evaluate the $\tau \rightarrow \text{hadrons}$ branching ratios. All others were calculated with PYTHIA 6.2 [8]. Signal and $t\bar{t}$ background events were generated with PYTHIA 6.2. In $t\bar{t}$ signal events the τ lepton was forced to decay to hadrons (TAUOLA) [14]. The $W^\pm + 3$ jets events were generated with MadEvent [15].

The branching ratio of top decay to charged Higgs depends on both $m_{H^\pm}$ and $\tan\beta$ as shown in Fig. 1a. The corresponding top decay to $W^\pm b$ (Fig. 1b) decreases with increasing $\tan\beta$ while keeping the sum of the branching ratios around one (for $m_{H^\pm} \simeq 170 \text{ GeV}/c^2$ the $t \rightarrow W^\pm b$ branching ratio is of the same order as that of $t \rightarrow H^\pm b$ therefore these two plots are not similar for $m_{H^\pm} = 170 \text{ GeV}/c^2$). While the top decay to $H^\pm$ or $W^\pm$ depends on $\tan\beta$, the light-charged Higgs decay to $\tau\nu$ is almost independent of $\tan\beta$ (for $\tan\beta > 10$ which is the region of interest in this study) and is $\sim 98\%$ for $m_{H^\pm} < m_t$. Such a large branching ratio has identified the light charged Higgs decay to τ leptons as the most promising decay channel for high $\tan\beta$. Figure 2 shows the $H^\pm$ decay branching ratio in different final states for $\tan\beta = 20$.

Table 1 shows the cross section times branching ratio of $t\bar{t} \rightarrow H^\pm W^\mp b\bar{b}$ events for $\tan\beta = 20$. Due to the small cross section of $t\bar{t} \rightarrow H^+ H^- b\bar{b}$ as shown in Table 2 only $t\bar{t} \rightarrow H^\pm W^\mp b\bar{b}$ events were generated and simulated

Figure 1: a) Branching ratio of top decay to $H^\pm$ vs $\tan\beta$, b) Branching ratio of top decay to $W^\pm$ vs $\tan\beta$

Figure 2: Branching ratio of $H^\pm$ decays for different $m_{H^\pm}$ at $\tan\beta = 20$

Table 1: Cross section times branching ratio of $t\bar{t} \rightarrow H^\pm W^\mp b\bar{b} \rightarrow \tau\nu_\tau \ell\nu_\ell b\bar{b}, \tau \rightarrow \text{hadrons}$ for $\tan\beta = 20$

$m_{H^\pm} (\text{GeV}/c^2)$	140	150	160	170
Cross section [pb]	10.70	5.06	1.83	0.157

Table 2: Cross section times branching ratio of $t\bar{t} \rightarrow H^+ H^- b\bar{b} \rightarrow \tau^+ \nu_\tau \tau^- \bar{\nu}_\tau b\bar{b}, \tau^\pm \rightarrow \text{hadrons (leptons)}$ for $\tan\beta = 20$

$m_{H^\pm} (\text{GeV}/c^2)$	140	150	160
Cross section (pb)	0.91	0.19	0.02

as signal events for $m_{H^\pm} < 170 \text{ GeV}/c^2$. For the critical region ($m_{H^\pm} \simeq m_t$) two different strategies were used to achieve the best signal simulation. For $m_{H^\pm} \simeq m_t$ off-shell $t\bar{t}^*$ production contributing to the signal sample is possible. This can be simulated by adding on-shell $t\bar{t}$ events to $gb \rightarrow tH^\pm$ using NLO cross section for gb , or by using the process $gg \rightarrow t\bar{b}H^\pm$ which includes both on-shell $t\bar{t}$ and off-shell $t\bar{t}^*$ contributions and is available in PYTHIA 6.223 [8] or higher. The detailed comparison between cross sections and the procedure to avoid double counting is found in [9]. Here we only mention that for $m_{H^\pm} = 170 \text{ GeV}/c^2$ both $t\bar{t} + gb$ and $gg \rightarrow t\bar{b}H^\pm$ were used for comparison. The NLO cross section times branching ratio of signal events with $m_{H^\pm} \simeq m_t$ is listed in Table 3. Finally the cross section of the main background channels are shown in Table 4.

Table 3: Cross section times branching ratio of signal events for $m_{H^\pm} \simeq m_t$ according to NLO calculations in [9] for $\tan\beta = 20$.

Channel	$g\bar{b} \rightarrow tH^\pm \rightarrow \ell\nu_\ell b\tau\nu_\tau$ ($\tau \rightarrow \text{hadrons}$) $m_{H^\pm} = 170 \text{ GeV}/c^2$	$g\bar{g} \rightarrow t\bar{b}H^\pm \rightarrow \ell\nu_\ell b\bar{b}\tau\nu_\tau$ ($\tau \rightarrow \text{hadrons}$) $m_{H^\pm} = 170 \text{ GeV}/c^2$
Cross section [pb]	0.14	0.297

Table 4: Cross section times branching ratio of background events

Channel	$t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow \ell\nu_\ell \tau\nu_\tau b\bar{b}$ ($\tau \rightarrow \text{hadrons}$)	$t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow \ell\nu_\ell \ell'\nu_{\ell'} b\bar{b}$ $\ell, \ell' = e \text{ or } \mu$	$t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow \ell\nu_\ell j j b\bar{b}$	$W^\pm + 3 \text{ jets}$ $W^\pm \rightarrow e \text{ or } \mu$
Cross section [pb]	25.8	39.7	245.6	840

3 Event selection and reconstruction algorithms

Full simulation of the detector response was achieved with CMSIM [16] or OSCAR [17] including pile-up events corresponding to a luminosity of $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. The full reconstruction of the detector response and event analysis was performed with the ORCA package [18].

3.1 Event trigger

Events were triggered at Level 1 by the presence of a high- p_T single lepton ($p_T > 14 \text{ GeV}$, $|\eta| < 2.1$ for muons and $p_T > 29 \text{ GeV}$, $|\eta| < 2.4$ for electrons). At the High Level Trigger (HLT) [20] additional requirements were made on muons; a harder p_T cut ($p_T > 19 \text{ GeV}$) and isolation criteria in the tracker and calorimeters were applied to muons to suppress pile-up events and reduce the rate of events down to the level of tolerance of the data acquisition system. The parameters of the isolation criteria were studied in detail in [20]. Trigger efficiencies for signal and background events are listed in Table 5. Since in $t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow \ell\nu_\ell j j b\bar{b}$ background events, there are four jets in the final state, the lepton isolation requirement leads to a lower trigger efficiency. In the case of $W^\pm + 3 \text{ jets}$ events lower trigger efficiency compared to the case of $t\bar{t}$ events could be mainly due to the softer leptons in the $W^\pm$ decay compared to the corresponding leptons of $t\bar{t}$ events. In $t\bar{t}$ events with two leptons ($t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow \ell\nu_\ell \ell'\nu_{\ell'} b\bar{b}$) the trigger efficiency is higher than the signal events due to having two leptons in the events.

3.2 Jet reconstruction, selection and b-tagging

Jets were reconstructed with the Iterative Cone algorithm [20] with a cone size $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.5$. The energy of reconstructed jets is corrected, according to the algorithm described in [21], to better reproduce the generated jet energy. Jets were selected within $|\eta| < 2.4$ and requiring $E_T^{\text{jet}} > 40 \text{ GeV}$ (where E_T^{jet} is the jet corrected transverse energy). Events were accepted if $n_{\text{jets}} \geq 3$, aiming to select the signal final state, which contains two b-jets and a τ jet, and to reject $W^\pm + n \text{ jets}$ with $n < 3$.

The identification of b-quark jets was performed by exploiting the method based on the impact parameter significance ([22]). The b-tagging method is based on the evidence that tracks in jets originating from b hadrons decay carry information about long lifetime and have impact parameter larger than tracks belonging to light-quark jets. Accordingly, the impact parameter significance, defined as the ratio of the track impact parameter to its measurement error, can be used as tagging variable. Jets containing at least 3 tracks with transverse impact parameter significance greater than 2 were tagged as b-jets.

Events satisfying the requirement $n_{\text{jets}} \geq 3$ were subsequently required to contain only one b-jet. Jets from $t\bar{t}$ background are in general more energetic than jets in signal $H^\pm b$ events, because of different kinematics. Requiring only one b-jet in the event helps reducing the background, as will be discussed later in Section 5. The b-tagging efficiency and purity for signal and background events are listed in Table 6.

Table 5: Trigger efficiency for signal and background events. In the second column the HLT efficiency has been calculated relative to the L1 trigger efficiency. The third column shows the total L1 and HLT trigger efficiency.

	L1 efficiency	HLT rel. efficiency	L1+HLT efficiency
$t\bar{t} \rightarrow H^+W^-bb$ $m_{H^\pm} = 140\text{GeV}/c^2$	0.77	0.63	0.48
$t\bar{t} \rightarrow H^+W^-bb$ $m_{H^\pm} = 150\text{GeV}/c^2$	0.77	0.63	0.48
$t\bar{t} \rightarrow H^+W^-bb$ $m_{H^\pm} = 160\text{GeV}/c^2$	0.77	0.63	0.49
$t\bar{t} \rightarrow H^+W^-bb$ $m_{H^\pm} = 170\text{GeV}/c^2$	0.77	0.65	0.50
$g\bar{b} \rightarrow tH^-$ $m_{H^\pm} = 170\text{GeV}/c^2$	0.78	0.65	0.50
$gg \rightarrow tbH^-$ $m_{H^\pm} = 180\text{GeV}/c^2$	0.77	0.64	0.49
$t\bar{t} \rightarrow W^+W^-bb$ $\rightarrow \ell\nu_\ell\tau\nu_\tau b\bar{b}$	0.76	0.62	0.47
$t\bar{t} \rightarrow W^+W^-bb$ $\rightarrow \ell\nu_\ell\ell'\nu_{\ell'} b\bar{b}$	0.91	0.78	0.71
$t\bar{t} \rightarrow W^+W^-bb$ $\rightarrow \ell\nu_\ell jj b\bar{b}$	0.65	0.62	0.40
$W^\pm + 3\text{jets}$	0.59	0.56	0.33

3.3 Offline τ tagging

The τ reconstruction and selection is performed offline as described below, starting from the Level 1 τ -like energy deposits in the calorimeters ([20]). A regional jet reconstruction is performed around the direction of the Level 1 τ objects; the raw jet transverse energy is required to be $E_T^{\text{jet}} > 20$ GeV. Up to two jets are reconstructed around the direction of the first and second L1 τ objects. The contribution from electrons faking τ -jets can be reduced by requiring the hottest HCAL tower E_T to be larger than 2 GeV (only towers belonging to jets are considered). If this condition is satisfied by the first jet, it is used for the next steps otherwise the second reconstructed jet is used and this cut is applied. If none of the first two jets satisfies this requirement, the event is rejected. In the next step a matching cone with $\Delta R = 0.1$ is defined around the jet axis. Tracks with $p_T > 1$ GeV/c are searched for within the matching cone and the largest p_T track is identified and a signal cone with $\Delta R = 0.07$ is defined around its direction. The signal vertex is considered as the vertex from which the leading track originates. Then an isolation cone with $\Delta R = 0.4$ is defined around the leading track to check the tracker isolation requirement. If no track from the signal vertex is found with $p_T > 1$ GeV/c in the isolation cone except for those falling in the signal cone, the isolation is satisfactory.

Hadronic τ decays produce localized energy deposits in the electromagnetic calorimeter. The electromagnetic isolation parameter (Eq. 1) is used to suppress the contamination arising from quark and gluon jets [23]:

$$P_{\text{isol.}} = \sum_{\text{crystals}, \Delta R_{\text{crystal}, \tau\text{-jet}} < 0.4} E_{T\text{crystal}} - \sum_{\text{crystals}, \Delta R_{\text{crystal}, \tau\text{-jet}} < 0.13} E_{T\text{crystal}} < 5.6 \text{ GeV} \quad (1)$$

When a jet satisfies all requirements mentioned above, it is identified as a τ -jet candidate. Figure 3 shows the distribution of the transverse energy of τ jet candidates reconstructed with this procedure. A cut on the transverse energy of the τ jet, $E_{T\tau} > 40$ GeV, can be applied to suppress the background. The effect of cutting on the leading track p_T and on the number of τ decay prongs was checked after all other selection requirements were satisfied. The effect was proven to be negligible.

Figure 4 shows the number of reconstructed tracks in the signal cone 0.07 and the number of generated charged pions in τ decays for signal events as well as the number of reconstructed tracks in the signal cone for background events.

Since the leading track in the jst is more energetic in signal events than in background events, a cut on the τ energy carried by the leading track in the signal cone is applied by requiring $p_{\text{leading track}}/E_\tau > 0.8$. The distribution of the τ -jet energy fraction carried by the leading track and comparison with different background events is shown in Fig. 5.

Figure 3: The E_T distribution of τ jets in the signal and background events.

Figure 4: a) Number of tracks in the signal cone 0.07 defined around the leading track in the τ decay for signal ($m_{H^+} = 160 \text{ GeV}/c^2, \tan\beta = 20$), b) Number of charged pions in the τ decay in the same signal sample; Number of tracks in the signal cone 0.07 around the leading track: c) $t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow \ell\nu\tau\nu b\bar{b}$, d) $t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow \ell\nu\ell'\nu'b\bar{b}$, e) $t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow \ell\nu jj b\bar{b}$, f) $W^\pm + 3 \text{ jets}$

Table 6: b-tagging efficiency and purity for signal and background events.

	1 b-jet selection efficiency	b-jet purity
$t\bar{t} \rightarrow H^+W^-bb$ $m_{H^\pm} = 140\text{GeV}/c^2$	0.47	0.95
$t\bar{t} \rightarrow H^+W^-bb$ $m_{H^\pm} = 150\text{GeV}/c^2$	0.45	0.94
$t\bar{t} \rightarrow H^+W^-bb$ $m_{H^\pm} = 160\text{GeV}/c^2$	0.46	0.93
$t\bar{t} \rightarrow H^+W^-bb$ $m_{H^\pm} = 170\text{GeV}/c^2$	0.48	0.93
$g\bar{b} \rightarrow tH^-$ $m_{H^\pm} = 170\text{GeV}/c^2$	0.47	0.81
$g\bar{g} \rightarrow t\bar{b}H^-$ $m_{H^\pm} = 180\text{GeV}/c^2$	0.48	0.89
$t\bar{t} \rightarrow W^+W^-bb$ $\rightarrow \ell\nu_\ell\tau\nu_\tau b\bar{b}$	0.45	0.92
$t\bar{t} \rightarrow W^+W^-bb$ $\rightarrow \ell\nu_\ell\ell'\nu_{\ell'} b\bar{b}$	0.46	0.94
$t\bar{t} \rightarrow W^+W^-bb$ $\rightarrow \ell\nu_\ell jjb\bar{b}$	0.45	0.85
$W^\pm + 3\text{jets}$	0.16	0

The total charge of all tracks contained in the signal cone of an identified τ -jet gives an estimate of the τ -lepton charge. The sum of the charges of the event trigger lepton (e or μ) and of the τ -lepton is hence required to be $Q(\ell) + Q(\tau) = 0$, since they originate from mother particles of opposite charges ($H^\pm, W^\mp$). Figure 6 shows the reconstructed charge of τ -jets for one of the signal samples and also for the background events. Since in the signal $t\bar{t}$ events only H^- was generated, the reconstructed charge has a peak at a charge of -1. The τ jet tagging efficiency and purity are summarized in Table 7 for signal and background events. Because τ jets in signal events are more energetic than in the background $m_{H^\pm}$ is larger than ($m_{W^\pm}$), they are identified with a higher efficiency. The purity is greater than 90% for all signal samples.

Table 7: tau-tagging efficiency and purity for signal and background events.

	τ selection efficiency	purity of identified τ -jets
$t\bar{t} \rightarrow H^+W^-bb$ $m_{H^\pm} = 140\text{GeV}/c^2$	0.11	0.93
$t\bar{t} \rightarrow H^+W^-bb$ $m_{H^\pm} = 150\text{GeV}/c^2$	0.12	0.93
$t\bar{t} \rightarrow H^+W^-bb$ $m_{H^\pm} = 160\text{GeV}/c^2$	0.12	0.94
$t\bar{t} \rightarrow H^+W^-bb$ $m_{H^\pm} = 170\text{GeV}/c^2$	0.13	0.95
$g\bar{b} \rightarrow tH^-$ $m_{H^\pm} = 170\text{GeV}/c^2$	0.15	0.96
$g\bar{g} \rightarrow t\bar{b}H^-$ $m_{H^\pm} = 180\text{GeV}/c^2$	0.13	0.94
$t\bar{t} \rightarrow W^+W^-bb$ $\rightarrow \ell\nu_\ell\tau\nu_\tau b\bar{b}$	0.05	0.81
$t\bar{t} \rightarrow W^+W^-bb$ $\rightarrow \ell\nu_\ell\ell'\nu_{\ell'} b\bar{b}$	0.02	0
$t\bar{t} \rightarrow W^+W^-bb$ $\rightarrow \ell\nu_\ell jjb\bar{b}$	0.01	0
$W^\pm + 3\text{jets}$	0.01	0

Figure 5: τ -jet energy fraction carried by the leading track.

Figure 6: Reconstructed τ jet charge: a) Signal ($m_{H^+} = 160 \text{ GeV}/c^2$, $\tan\beta = 20$), b) $t\bar{t} \rightarrow WWbb \rightarrow \ell\nu\tau\nu bb$, c) $t\bar{t} \rightarrow WWbb \rightarrow \ell\nu\ell'\nu bb$, d) $t\bar{t} \rightarrow WWbb \rightarrow \ell\nu jjbb$, e) $W^\pm + 3 \text{ jets}$.

3.4 Missing E_T reconstruction

The missing transverse energy reconstruction is performed by summing all the Ecal energy deposits plus the Hcal towers and correcting for muons (if any in the event). The raw energy jets of jets involved in the E_T^{miss} reconstruction are corrected [24] to improve their energy resolution. Only jets with raw jet $E_T > 30$ GeV are used; this cut is optimized to improve the E_T^{miss} resolution (Figure 7). Figure 8 shows E_T^{miss} for $t\bar{t}$ signal with $m_{H^\pm} = 160$ GeV/ c^2 and $\tan\beta = 20$ and different background channels. A cut at $E_T^{\text{miss}} > 70$ GeV is applied to increase the signal to background ratio.

Figure 7: The difference between reconstructed and generated E_T^{miss} in signal and different background samples: a) Signal ($m_{H^\pm} = 160$ GeV/ c^2 , $\tan\beta = 20$), b) $t\bar{t} \rightarrow WWb\bar{b} \rightarrow l\nu\tau\nu b\bar{b}$, c) $t\bar{t} \rightarrow WWb\bar{b} \rightarrow l\nu l' \nu b\bar{b}$, d) $t\bar{t} \rightarrow WWb\bar{b} \rightarrow l\nu jj b\bar{b}$, e) $W^\pm + 3$ jets

4 Signal and background selection efficiencies

The summary of all event selection requirements together with the corresponding efficiencies is given in Tables 8, 9 (signal) and Table 10 (background). As mentioned in Section 2 the number of signal events from $t\bar{t}$ and gb fusion for $m_{H^\pm} = 170$ GeV/ c^2 should actually be added together and then compared to gg fusion process. No significant difference is seen between $t\bar{t}$ +gb and gg.

The one b-jet requirement mentioned in Section 3.2 is decomposed into two different steps: firstly events with at least one b-jet are accepted, secondly events with more than one b-jet are rejected. The first requirement has a higher selection efficiency for background events, however, the second cut rejects background events reasonably (more than $\sim 30\%$) at the expense of losing $\sim 5 - 20\%$ of signal events. The efficiency of the second cut for signal events increases with larger $m_{H^\pm}$, i.e. with lower signal cross section. Hence there is little loss where the signal rate is low.

Results can be extrapolated to other $\tan\beta$ values by using the branching ratios of Figs. 1a, 1b and 2. The effect of a larger $\tan\beta$ appears only as some increase in the signal rate and no kinematic effect is expected. Selection

Figure 8: The reconstructed E_T^{miss} and comparison between signal and background events.

efficiencies are then expected to be independent from $\tan\beta$. Different $\tan\beta$ values were investigated in this study for different masses of charged Higgs. In the next sections the results are presented and the final conclusions are drawn.

5 Contribution of other signal and background final states

Before calculating the signal statistical significance the contribution of other signal and background events is estimated. In this study only $t\bar{t} \rightarrow H^\pm W^\mp b\bar{b} \rightarrow \tau\nu_\tau \ell\nu_\ell b\bar{b}$ was considered as signal for $m_{H^\pm} < 170 \text{ GeV}/c^2$. Other final states, however, should be also taken into account if their cross sections have sizable effects in the discovery. Table 11 lists all other signal final states which could be added to the signal events which were studied in this note, as well as their cross section times branching ratios for three charged Higgs masses of $m_{H^\pm} = 140, 150, 160 \text{ GeV}/c^2$ at $\tan\beta = 20$.

As shown in Table 11, the cross section of these channels is not negligible. The dominant channel (channel III) has a cross section times branching ratio of 17.8 pb with $m_{H^\pm} = 140 \text{ GeV}/c^2$ and the other channels have a cross section of ~ 2 pb. If the difference between the lepton p_T distributions from τ decay and $W^\pm$ is taken into account (Fig. 9), considering a factor of two reduction in the selection efficiency of channel III compared to the selection efficiency of $t\bar{t} \rightarrow W^+ W^- b\bar{b} \rightarrow \ell\nu_\ell jj b\bar{b}$ (~ 0.00013), a total number of 12, 5 and 2 events is obtained after 10 fb^{-1} for $m_{H^\pm} = 140, 150, 160 \text{ GeV}/c^2$ respectively. This corresponds to $\sim 2\%$ additional contribution to the signal events and considered to be negligible.

An available sample of events containing $Wt \rightarrow \ell\nu_\ell \tau\nu_\tau b$ was used in this analysis and the single top background contribution was estimated to be small on the base of the following argument. The cross section times branching ratio of $Wt \rightarrow \ell\nu_\ell \tau\nu_\tau b$ considering the largest possible theoretical cross section within the theoretical uncertainty of the cross section calculation is 1.8 pb [10]. Table 12 shows the chain of selection cuts and their efficiencies. A total number of ~ 20 events is expected to survive the selection after 10 fb^{-1} .

There are also single top final states containing a lepton (e or μ) and jets which could be mistagged as τ -jets and could contribute to the background. These channels are $Wt \rightarrow \ell\nu_\ell jj b$ and $tq + t\bar{b} \rightarrow \ell\nu_\ell bq + \ell\nu_\ell b\bar{b}$ and they have a total cross section times branching ratio of 78.1 pb [10]. This cross section is also the largest possible value taking into account the theoretical uncertainty.

Table 8: List of selection cuts and their efficiencies for signal events with $m_{H^\pm} < 170 \text{ GeV}/c^2$ for $\tan\beta = 20$. Numbers in each row show the remaining cross section after applying the corresponding cut. Numbers in parentheses are relative efficiencies in percent.

	$t\bar{t} \rightarrow H^\pm W^\mp b\bar{b} \rightarrow \ell\nu_\ell\tau\nu_\tau b\bar{b}$ $m_{H^\pm} = 140 \text{ GeV}/c^2$	$t\bar{t} \rightarrow H^\pm W^\mp b\bar{b} \rightarrow \ell\nu_\ell\tau\nu_\tau b\bar{b}$ $m_{H^\pm} = 150 \text{ GeV}/c^2$	$t\bar{t} \rightarrow H^\pm W^\mp b\bar{b} \rightarrow \ell\nu_\ell\tau\nu_\tau b\bar{b}$ $m_{H^\pm} = 160 \text{ GeV}/c^2$
$\sigma \times \text{BR}[\text{fb}]$	10.7×10^3	5060.	1830.
L1 + HLT	5170.5(48.3)	2456.3(48.5)	888.9(48.6)
≥ 3 jets	1889.7(36.5)	795.0(32.4)	264.3(29.7)
≥ 1 b jet	1103.5(58.4)	427.4(53.8)	131.4(49.7)
< 2 b jets	883.0(80.0)	358.7(83.9)	119.2(90.7)
Having L1 τ	878.4(99.5)	357.4(99.6)	119.0(99.8)
τ -jet reconstruction	875.0(99.6)	356.5(99.7)	118.8(99.8)
Hottest HCAL tower $E_T > 2 \text{ GeV}$	778.0(88.9)	316.1(88.6)	105.9(89.1)
Tracker isolation	378.2(48.6)	163.5(51.7)	52.7(49.8)
Ecal isolation	292.9(77.4)	134.2(82.1)	43.1(81.8)
τ $E_T > 40 \text{ GeV}$	244.3(83.4)	113.0(84.2)	36.5(84.7)
$p_{\text{leading track}}/E_\tau > 0.8$	102.3(41.9)	50.7(44.8)	16.8(45.9)
$Q(\ell) + Q(\tau) = 0$	88.0(86.0)	42.4(83.6)	14.6(87.0)
$E_T^{\text{miss}} > 70 \text{ GeV}$	51.0(58.0)	25.4(59.9)	9.2(63.3)
Expected Number of events after 10 fb^{-1}	510	254	92

Figure 9: Muon p_T distribution from $W^\pm$ and τ decays.

All single top channels which could be considered as background have a single lepton, a neutrino, mainly two jets ($\sim 20\%$ of events have three jets in the final state) and the kinematics of the jets is almost the same (the s-channel $t\bar{b}$ has a very small contribution of 3% of single top events and the remaining events are t-channel).

Therefore the contribution of single top channels with final states containing jets which could be mistagged as τ -jets is estimated by assuming that all selection efficiencies is the same as that for the single top signal. Exceptions would be the τ selection efficiency because of the possibility of having a real or fake τ -jet depending on the final state and the selection efficiency of the cut on the sum of the charges of the lepton and the τ -jet in the event (in events with fake τ -jet the efficiency of this cut is smaller because there is no correlation between the charge of the jet which is mistagged as a τ -jet and the charge of the lepton in the event).

Therefore the same L1+HLT and ≥ 3 jets selection and b-tagging and missing E_T cut efficiency of $Wt \rightarrow \ell\nu_\ell\tau\nu_\tau b$ is assumed for single top events with fake τ jets ($Wt \rightarrow \ell\nu_\ell jjb$ and tq and $t\bar{b}$). Assuming that the τ mistagging rate is the same in these events as in $t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow \ell\nu_\ell jjb\bar{b}$ events (~ 0.013) and taking the same efficiency of the cut on the sum of the charges of the lepton and the τ -jet in above $t\bar{t}$ events (~ 0.21) for single top events with fake τ -jet, the total selection efficiency of these single top events is estimated by using the selection efficiencies of

Table 9: List of selection cuts and their efficiencies for signal events with $m_{H^\pm} = 170 \text{ GeV}/c^2$ for $\tan\beta = 20$. Numbers in each row show the remaining cross section after applying the corresponding cut. Numbers in parentheses are relative efficiencies in percent.

	$t\bar{t} \rightarrow H^\pm W^\mp b\bar{b} \rightarrow \ell\nu_\ell\tau\nu_\tau b\bar{b}$ $m_{H^\pm} = 170 \text{ GeV}/c^2$	$g\bar{b} \rightarrow tH^\pm \rightarrow \ell\nu_\ell\tau\nu_\tau b$ $m_{H^\pm} = 170 \text{ GeV}/c^2$	$g\bar{g} \rightarrow t\bar{b}H^\pm \rightarrow \ell\nu_\ell\tau\nu_\tau b\bar{b}$ $m_{H^\pm} = 170 \text{ GeV}/c^2$
$\sigma \times \text{BR}[\text{fb}]$	157.	140.	297.
L1 + HLT	78.0(49.7)	70.5(50.4)	145.4(48.9)
≥ 3 jets	23.2(29.7)	21.7(30.7)	55.3(38.0)
≥ 1 b jet	11.5(49.4)	11.7(54.1)	31.9(57.7)
< 2 b jets	10.9(94.8)	10.0(85.5)	25.8(80.9)
Having L1 τ	10.8(99.8)	10.0(99.6)	25.7(99.4)
τ -jet reconstruction	10.8(99.9)	10.0(99.9)	25.5(99.1)
Hottest HCAL tower $E_T > 2\text{GeV}$	9.6(88.4)	8.9(88.8)	22.6(88.9)
Tracker isolation	4.9(51.3)	5.1(57.2)	11.4(50.5)
Ecal isolation	4.2(84.9)	4.3(84.5)	9.6(84.4)
τ $E_T > 40\text{GeV}$	3.8(90.9)	3.9(90.6)	8.6(89.2)
$p_{\text{leading track}}/E_\tau > 0.8$	1.6(41.7)	1.8(45.9)	3.4(39.6)
$Q(\ell) + Q(\tau) = 0$	1.3(84.4)	1.6(87.2)	2.8(82.6)
$E_T^{\text{miss}} > 70 \text{ GeV}$	0.8(61.7)	1.0(65.2)	1.6(55.3)
Expected Number of events after 10 fb^{-1}	8	10	16

Table 12 and replacing the τ tagging efficiency and the efficiency of the cut on the sum of the charges of the lepton and the τ -jet by their corresponding values taken from $t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow \ell\nu_\ell jj b\bar{b}$ events using Table 10.

A total selection efficiency of 5.0×10^{-5} is obtained for single top events with single lepton and jets in the final state. Since these events have a total cross section times branching ratio of 78.1 pb, a total number of ~ 43 events is obtained after 10 fb^{-1} which should be added to 20 events containing real τ -jets. The contribution of single top events is about 5% of the total background and also partially compensated by the additional signal events which were described earlier.

The contribution of these events is included in the significance calculation by taking into account the theoretical uncertainties on their cross section calculation: $\sim 17\%$ for the Wt channel and $\sim 11\%$ for $tq + t\bar{b}$ according to [10]. The contribution of other possible background events such as $W^\pm b\bar{b}$ with $W^\pm \rightarrow e\nu_e$ or $\mu\nu_\mu$ and $Zb\bar{b}$ followed by the decay $Z \rightarrow ee$ or $\tau\tau$ were also estimated. The cross section of $W^\pm b\bar{b} \rightarrow \ell\nu_\ell b\bar{b}$ with $\ell = e$ or μ is 70 pb which was calculated with TopReX [11]. The cross section of $Zb\bar{b}$ with $Z \rightarrow ee$ or $\tau\tau$ is 26.3 pb as calculated with CompHEP in [12]. The $Zb\bar{b}$ events with $m_{ee} > 100 \text{ GeV}/c^2$ or $m_{\tau\tau} > 100 \text{ GeV}/c^2$ were also analyzed and after all selection cuts no event survived after 10 fb^{-1} .

6 Results with systematic uncertainties

Because the $t\bar{t} \rightarrow H^\pm W^\mp b\bar{b} \rightarrow \ell\nu_\ell\tau\nu_\tau b\bar{b}$ signal events are characterized by a final state containing two neutrinos, the charged Higgs mass cannot be reconstructed. The presence of signal must be thus inferred by observing an excess of events over the Standard Model expectation. Once the charged Higgs existence is inferred with this search strategy, the corresponding channel with $W^\pm \rightarrow jj$ can be used for transverse mass reconstruction.

Since the number of background events after all selection cuts is large enough (more than 1000 events), the significance can be defined as

$$S = \frac{N_{\text{obs.}}^{\text{MSSM}} - (N_{W+3 \text{ jets}}^{\text{SM}} + N_{t\bar{t}}^{\text{SM}})}{\sqrt{N_{W+3 \text{ jets}}^{\text{SM}} + N_{t\bar{t}}^{\text{SM}} + (\Delta N_{W+3 \text{ jets}}^{\text{SM}})^2 + (\Delta N_{t\bar{t}}^{\text{SM}})^2}} \quad (2)$$

The systematic uncertainties on the signal statistical significance calculation include the experimental uncertainty on the selection of background events as well as the theoretical uncertainty on the cross section of the $t\bar{t}$ and single top background. In the next sections the approach used for including the systematic uncertainties is described, for

Table 10: List of selection cuts and their efficiencies for background events. Numbers in each row show the remaining cross section after applying the corresponding cut. Numbers in parentheses are relative efficiencies in percent.

	$t\bar{t} \rightarrow W^+W^-bb \rightarrow \ell\nu_\ell\tau\nu_\tau b\bar{b}$	$t\bar{t} \rightarrow W^+W^-bb \rightarrow \ell\nu_\ell\ell'\nu_{\ell'}b\bar{b}$	$t\bar{t} \rightarrow W^+W^-bb \rightarrow \ell\nu_\ell jjb\bar{b}$	$W^\pm + 3 \text{ jets}$ $W^\pm \rightarrow \ell\nu_\ell$
$\sigma \times \text{BR}[\text{fb}]$	25.8×10^3	39.8×10^3	245.6×10^3	$840. \times 10^3$
L1 + HLT	12101.2(46.9)	28429.1(71.4)	99506.6(40.5)	287280(34.2)
≥ 3 jets	5105.2(42.2)	11306.6(39.8)	66038.6(66.4)	114050(39.7)
≥ 1 b jet	3428.3(67.1)	7622.0(67.4)	43433.0(65.8)	24292.7(21.3)
< 2 b jets	2325.7(67.8)	5262.7(69.0)	29003.4(66.8)	21207.5(87.3)
Having L1 τ	2310.7(99.3)	5233.7(99.4)	28698.8(98.9)	20613.7(97.2)
τ -jet reconstruction	2303.6(99.7)	5224.4(99.8)	28465.0(99.2)	19438.7(94.3)
Hottest HCAL tower $E_T > 2\text{GeV}$	2034.1(88.3)	3850.6(73.7)	26635.1(93.6)	17125.5(88.1)
Tracker isolation	798.7(39.3)	1120.6(29.1)	6653.3(25.0)	5411.7(31.6)
Ecal isolation	545.6(68.3)	519.5(46.3)	2952.8(44.4)	2554.3(47.2)
τ $E_T > 40\text{GeV}$	405.8(74.4)	341.8(65.8)	1946.8(65.9)	1312.9(51.4)
$p_{\text{leading track}}/E_\tau > 0.8$	123.5(30.4)	131.9(38.6)	377.9(19.4)	224.5(17.1)
$Q(\ell) + Q(\tau) = 0$	95.7(77.5)	56.7(43.0)	78.8(20.9)	27.1(12.1)
$E_T^{\text{miss}} > 70 \text{ GeV}$	51.6(53.9)	29.3(51.8)	36.6(46.4)	10.7(39.3)
Expected Number of events after 10 fb^{-1}	516	293	366	107

Table 11: Additional signal channels and their cross section times branching ratio for $\tan\beta = 20$.

	Process	$m_{H^+} = 140 \text{ GeV}/c^2$	$m_{H^+} = 150 \text{ GeV}/c^2$	$m_{H^+} = 160 \text{ GeV}/c^2$
I	$t\bar{t} \rightarrow H^+W^-bb$ $H^+ \rightarrow t\bar{b}, c\bar{s}, s\bar{u}, c\bar{b}$ $W^- \rightarrow \ell\bar{\nu}_\ell$	0.35 pb	0.17 pb	0.06 pb
II	$t\bar{t} \rightarrow H^+W^-bb$ $H^+ \rightarrow t\bar{b}, c\bar{s}, s\bar{u}, c\bar{b}$ $W^- \rightarrow \tau\bar{\nu}_\tau, \tau \rightarrow \text{leptons}$	0.06 pb	0.03 pb	0.01 pb
III	$t\bar{t} \rightarrow H^+W^-bb$ $H^+ \rightarrow \tau^+\nu_\tau, \tau^+ \rightarrow \text{leptons}$ $W^- \rightarrow jj$	17.83 pb	8.44 pb	3.05 pb
IV	$t\bar{t} \rightarrow H^+W^-bb$ $H^+ \rightarrow \tau^+\nu_\tau, \tau^+ \rightarrow \text{leptons}$ $W^- \rightarrow \tau\bar{\nu}_\tau, \tau \rightarrow \text{hadrons}$	1.87 pb	0.88 pb	0.32 pb
V	$t\bar{t} \rightarrow H^+W^-bb$ $H^+ \rightarrow \ell\bar{\nu}_\ell$ $W^- \rightarrow jj$	0.18 pb	0.08 pb	0.03 pb
VI	$t\bar{t} \rightarrow H^+W^-bb$ $H^+ \rightarrow \ell\bar{\nu}_\ell$ $W^- \rightarrow \tau\bar{\nu}_\tau, \tau \rightarrow \text{hadrons}$	0.018 pb	0.008 pb	0.003 pb

example, for $W^\pm + 3 \text{ jets}$ and $t\bar{t}$ events. For single top events the same approach as for $t\bar{t}$ events is used for taking into account the theoretical cross section uncertainty. We rely on the current theoretical predictions of the Standard Model $t\bar{t}$ cross section rather than on its measurement from the data. The measurement of the $t\bar{t}$ cross section from the data would be affected by possible contributions from SUSY events and needs a dedicated study. In the real experiment any existence of SUSY events would appear as a source of background in the search for the signal and this also needs a separated study.

The experimental uncertainty on the background event selection was added quadratically to the background statistical fluctuation in the denominator of the significance formula (Eq. 2). The $t\bar{t}$ theoretical cross section uncertainty, $\delta = \frac{\Delta\sigma_{t\bar{t}\text{theo.}}}{\sigma_{t\bar{t}\text{theo.}}}$, is also added quadratically to the terms related to the experimental selection uncertainty of these events. Thus the $N_{t\bar{t}}^{\text{SM}}$ term refers to the number of standard model $t\bar{t}$ events calculated according to the central

Table 12: Selection cuts and their efficiencies for $Wt \rightarrow \ell\nu_\ell\tau\nu_\tau b$ events.

	$Wt \rightarrow \ell\nu_\ell\tau\nu_\tau b$	$W^\pm bb$ $W^\pm \rightarrow e \text{ or } \mu$	Zbb $Z \rightarrow ee$	Zbb $Z \rightarrow \tau\tau$
$\sigma \times BR[\text{fb}]$	1800	70000	26300	26300
L1 + HLT	887.4(49.3)	16660.(23.8)	5549.3(21.1)	4891.8(18.6)
≥ 3 jets	147.3(16.6)	216.6(1.3)	1942.2(35.0)	102.7(2.1)
≥ 1 b jet	74.7(50.7)	94.2(43.5)	588.5(30.3)	50.2(48.9)
< 2 b jets	66.2(88.7)	79.7(84.6)	559.1(95.0)	43.7(87.0)
Having L1 τ	66.2(99.9)	78.7(98.7)	558.5(99.9)	42.6(97.5)
τ -jet reconstruction	66.1(99.9)	78.6(99.9)	558.0(99.9)	42.4(99.6)
Hottest HCAL tower $E_T > 2$ GeV	56.5(85.5)	62.0(78.9)	238.2(42.7)	32.8(77.4)
Tracker isolation	28.0(49.5)	21.7(35.0)	83.4(35.0)	8.5(25.8)
Ecal isolation	23.3(83.3)	9.3(42.9)	49.4(59.2)	3.4(40.4)
τ $E_T > 40$ GeV	17.9(76.8)	4.1(44.4)	39.5(80.0)	1.8(52.6)
Pleading track/ $E_T > 0.8$	5.5(31.0)	2.1(50.0)	12.3(31.2)	0.4(20.3)
$Q(\ell) + Q(\tau) = 0$	4.1(73.7)	0.2(10.0)	4.9(40.0)	0.03(9.7)
$E_T^{\text{miss}} > 70$ GeV	2.0(49.4)	0.05(24.4)	0.6(12.5)	0.005(14.3)
Expected Number of events after 10 fb^{-1}	20	0	6	0

value of NLO value of 850 pb as the cross section of these events.

For the $W^\pm + 3$ jets no theoretical cross section uncertainty was introduced as their cross section is assumed to be measured in the real experiment, however the effect of variation of the cross section was studied by changing the cross section by a factor of $\pm 50\%$ which led to negligible change in the signal significance. The experimental uncertainty was estimated starting from a cross section given by MadEvent package (Table 4) and evaluating this background in the signal free region and then estimating their contribution in the signal area. In this section since the results are dominated by the systematic uncertainties, all results are presented at 30 fb^{-1} where the systematic uncertainties are well understood. Details about the evaluation of the systematic uncertainties for $t\bar{t}$ and $W^\pm + 3$ jets are described in the next two sections.

6.1 The $t\bar{t}$ background contribution uncertainty

The experimental uncertainty on the $t\bar{t}$ background event selection (Table 10) is expected to receive contributions from the uncertainty on the b-jet tagging, the τ -tagging and the lepton reconstruction efficiencies. An additional source of systematic uncertainty is due to the requirement $n_{\text{jets}} \geq 3$ with $E_T > 40$ GeV because of the uncertainty on the jet energy scale. The luminosity uncertainty has also been taken into account with a value of 5% which is added quadratically to other terms. The systematic error on the b-tagging efficiency was discussed in [25] leading to an assumption of 2%. In this study a more conservative value of 5% is assumed at 30 fb^{-1} . The uncertainty on the τ -tagging efficiency is taken to be 4% at 30 fb^{-1} which is more conservative than the estimate given in [25]. The preliminary studies on the uncertainty of the lepton reconstruction efficiency show $\sim 1\%$ uncertainty per lepton ([26]), however in this note a more conservative value of 2% at 30 fb^{-1} is assumed. The average jet energy scale uncertainty was assumed to be 3% for LHC after 30 fb^{-1} . This leads to an asymmetric uncertainty of $\Delta_{\geq 3 \text{ jet}}^+ = 5.3\%$ and $\Delta_{\geq 3 \text{ jet}}^- = 5.6\%$ where $\Delta_{\geq 3 \text{ jet}}^+$ ($\Delta_{\geq 3 \text{ jet}}^-$) refer to the uncertainty of selecting ≥ 3 jets with corrected jet $E_T^{\text{jet}} > 40$ GeV due to increase (decrease) in the absolute jet energy scale by 3%. Hence an average value of 5.5% was assumed for ≥ 3 jet selection uncertainty in this study.

Finally the total systematic uncertainty on the $t\bar{t}$ background can be expressed as

$$\Delta_{\text{sys}}^{t\bar{t}} = \Delta_{\text{lepton reconstruction}} \oplus \Delta_{\geq 3 \text{ jet selection}} \oplus \Delta_{1 \text{ b-jet tagging}} \oplus \Delta_{1 \tau \text{ tagging}} \oplus \Delta_{\text{lumi.}} \oplus \Delta_{\text{theo}}^{t\bar{t}} \quad (3)$$

In $t\bar{t}$ channels with no real tau, the uncertainty of tagging a tau jet is replaced by the uncertainty of mistagging a jet as a tau jet.

The total error on the theoretical NLO cross section for $t\bar{t}$ events consists of the uncertainty due to energy scale variation as well as to the choice of PDF. The uncertainty on the energy scale is considered to be 5% according to [27]. The recent results [28] on the uncertainty on the $t\bar{t}$ cross section at LHC due to the PDF suggests an uncertainty of $\sim 2.5\%$. For this analysis $\delta = 5.6\%$ was used.

6.2 The $W^\pm + 3$ jets background contribution uncertainty

The cross section of $W^\pm + 3$ jets events is assumed to be measured in the real experiment and a simple approach was tried in this note. The value 840 pb, calculated with the MadEvent package after generator level preselection cuts, as described earlier, was used for the total cross section of $W^+ + 3$ jets and $W^- + 3$ jets ($W^\pm \rightarrow e$ or μ).

A set of selection cuts was devised in order to isolate an event sample dominated by $W+3$ jets events which in the following will be referred to as "signal free area". The contribution of these events in the signal free region is estimated by first applying the L1 + HLT single lepton trigger selections. If the triggering lepton is an electron, an isolation requirement in the tracker is applied. Tracks seeds are reconstructed in the pixel detector; for the isolation it is required that no pixel seeds with $p_T > 1$ GeV are present in the cone of $\Delta R = 0.2$ around the electron direction. This isolation requirement is applied to reject QCD multi-jet events. Then ≥ 3 jets are required with $E_T^{\text{jet}} > 40$ GeV (after jet energy correction). The $t\bar{t} \rightarrow \ell\nu_{\ell}jjb\bar{b}$ component present in the sample is reduced by requiring no b-jet in the event. The non-b-jets are identified by requiring an anti-b-tag with the impact parameter significance method used in this analysis. Table 13 shows the full list of selection cuts and their efficiencies and the final cross section of events which pass all selection cuts.

Table 13: Selection efficiencies for $W^\pm + 3$ jets and $t\bar{t} \rightarrow \ell\nu_{\ell}jjb\bar{b}$ events.

	$W^\pm + 3$ jets	$t\bar{t} \rightarrow \ell\nu_{\ell}jjb\bar{b}$
$\sigma \times \text{BR}[\text{pb}]$	840	245.6
L1+HLT	287.3(34.2)	99.5(40.5)
Electron pixel isolation	248.8(86.6)	83.1(83.6)
≥ 3 jets, $E_{T\text{corrected jet}} > 40$ GeV	79.8(32.1)	53.4(64.2)
3 non-b-jets, $E_{T\text{corrected jet}} > 40$ GeV	52.7(66.0)	21.0(39.3)
Number of events after 10 fb^{-1}	52.7×10^4	21.0×10^4

The total number of observed events after the selection described before is the sum of the real $W^\pm + 3$ jets events and $t\bar{t}$ contamination leading to a statistical uncertainty of $\sim 0.07\%$ at 30 fb^{-1} which is much smaller compared to other systematic uncertainties related to the experimental selection of these events.

The experimental uncertainty on the event selection mentioned above receives contributions from the uncertainty on the lepton reconstruction efficiency, the ≥ 3 jet selection and the identification of 3 non-b-jet.

The contribution of the $W^\pm + 3$ jets events in the signal area is estimated then using Eq. 4,

$$N_S^{W^\pm + 3 \text{ jets}} = \epsilon_{W^\pm + 3 \text{ jets}}^S \frac{N_B^{\text{obs.}} - N_B^{t\bar{t}}}{\epsilon_{W^\pm + 3 \text{ jets}}^B} \quad (4)$$

where $N_S^{W^\pm + 3 \text{ jets}}$ is the number of $W^\pm + 3$ jets events in the signal area, $N_B^{\text{obs.}}$ is the total number of events which pass the $W^\pm + 3$ jets selection cuts in the background area, $N_B^{t\bar{t}}$ is the number of $t\bar{t}$ contamination in the background area which is subtracted from the observed number of events, and $\epsilon_{W^\pm + 3 \text{ jets}}^S$ ($\epsilon_{W^\pm + 3 \text{ jets}}^B$) is the total selection efficiency for $W^\pm + 3$ jets events in the signal (background) area. The selection efficiency in the background area corresponds to the total selection efficiency as shown in Table 13 while the selection efficiency in the signal area corresponds to the total selection efficiency as shown in Table 10.

The experimental uncertainty on the event selection in the signal area is due to the uncertainty on the lepton reconstruction efficiency, the uncertainty on the ≥ 3 jet selection, the uncertainty on the 3 non-b-jet identification and the uncertainty on the τ -jet mis-tagging.

Terms common to the numerator and denominator in Eq. 4 cancel out, so that the only uncertainties which remain are the statistical uncertainty of $W^\pm + 3$ jets events, the uncertainty of anti-tagging 3 non-b-jets, the uncertainty of mistagging a non-b-jet as a b-jet and mistagging a jet as a τ -jet as in Eq. 5. The systematic uncertainty of $t\bar{t}$ contribution is also taken into account in the second term of Eq. 5 which includes the lepton reconstruction uncertainty, ≥ 3 jet selection uncertainty and 3 non-b-jet selection uncertainty.

$$\Delta_{\text{sys.}}^{W^\pm + 3 \text{ jets}} = \Delta_{\text{stat.}} \oplus \frac{\Delta N_B^{t\bar{t}}}{N_B^{W^\pm + 3 \text{ jets}}} \oplus \Delta_{3 \text{ non-b-jet}} \oplus \Delta_{\text{b-jet mistagging}} \oplus \Delta_{\tau \text{ mistagging}} \quad (5)$$

In Eq. 5, $\Delta N_B^{t\bar{t}}$ is the uncertainty of the number of $t\bar{t}$ events in the background area and $N_B^{W^\pm + 3 \text{ jets}}$ is the number

of $W^\pm + 3$ jets events in the background area.

The three non-b-jet uncertainty should be evaluated considering a factor of $\sqrt{3}$ multiplied by the uncertainty of identifying a single non-b-jet. In this study the uncertainty of non-b-jet identification (anti-b-tagging) and mistagging a non-b-jet as a b-jet were assumed to be 5% at 30fb^{-1} and the uncertainty of mistagging a jet as a τ -jet (the last term in Eq. 5) was assumed to be 2% at 30fb^{-1} . Table 14 shows the values of individual uncertainties which were used in the signal significance calculation for 30fb^{-1} . These are the minimum values of uncertainties in the duration of an integrated luminosity of 30fb^{-1} which would be reached at the end of this period.

Table 14: The values of different experimental and theoretical uncertainties used for $t\bar{t}$ and $W^\pm + 3$ jets background events at 30fb^{-1} .

Scale uncertainty of $t\bar{t}$ cross section	5%
PDF uncertainty of $t\bar{t}$ cross section	2.5%
b-tagging	5%
τ -tagging	4%
Lepton identification	2%
Jet energy scale	3%
Mistagging a non-b-jet as a b-jet	5%
Mistagging a jet as a τ -jet	2%
Non-b-jet identification (anti-b-tagging)	5%
Luminosity uncertainty	5%

6.3 Final result and the 5σ discovery contour with systematic uncertainties

Equation 2 is used to calculate the signal statistical significance at 30fb^{-1} for different $\tan\beta$ values. Table 15 shows the signal significance for different $m_{H^\pm}$ and $\tan\beta$ values at 30fb^{-1} . The extrapolation to large $\tan\beta$ values shows that a 5σ significance for $m_{H^\pm} = 170\text{GeV}/c^2$ is obtained only for $\tan\beta \geq 100$.

Table 15: The signal significance for different $m_{H^\pm}$ and $\tan\beta$ values at 30fb^{-1} including systematic uncertainties.

	$\tan\beta = 10$	$\tan\beta = 20$	$\tan\beta = 30$	$\tan\beta = 40$	$\tan\beta = 50$
$m_{H^\pm} = 140\text{GeV}/c^2$	1.60	5.02	9.43	15.00	20.17
$m_{H^\pm} = 150\text{GeV}/c^2$	0.96	2.50	4.70	8.61	12.71
$m_{H^\pm} = 160\text{GeV}/c^2$	0.33	0.93	1.66	3.76	5.98
$m_{H^\pm} = 170\text{GeV}/c^2$	0.07	0.21	0.46	0.75	1.19

The results listed in Table 15 are shown in the form of a 5σ discovery contour in Figs. 10, 11. In Fig. 11 the Pythagorean relation at tree level between $m_{H^\pm}$ and m_A ($m_{H^\pm} = \sqrt{m_A^2 + m_{W^\pm}^2}$) has been used. The result of introducing the systematic uncertainties in calculation of the signal significance reduces the observability of $m_{H^\pm}$ for $\tan\beta < 50$. For $\tan\beta > 50$ the signal cross section increases and the effect of the uncertainties becomes small.

7 Conclusions

The light charged Higgs discovery potential at CMS was studied with full detector simulation and reconstruction in the $t\bar{t} \rightarrow H^\pm W^\mp b\bar{b} \rightarrow \ell\nu_\ell \tau\nu_\tau b\bar{b}$ ($\tau \rightarrow \text{hadrons}$) channel. Results were obtained for an integrated luminosity of 30fb^{-1} including low uminosity pile-up events. The systematic uncertainties were evaluated considering all uncertainties except the jet energy scale since it is expected to improve with increasing luminosity. It was shown that the effect of the systematic uncertainties is to decrease by 5-10 GeV/c^2 the observable charged Higgs mass for $\tan\beta < 50$. Since for $m_{H^\pm} > 160\text{GeV}/c^2$ the signal rate becomes small the 5σ discovery contour shows a small growth for $m_{H^\pm} \geq 160\text{GeV}/c^2$ and the charged Higgs mass of $170\text{GeV}/c^2$ is observable at $\tan\beta \simeq 100$.

Figure 10: The 5σ contour in $(m_{H^\pm}, \tan\beta)$ plane for the light charged Higgs discovery including the effect of systematic uncertainties.

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Figure 11: The 5σ contour in $(m_{A^0}, \tan\beta)$ plane for the light charged Higgs discovery including the effect of systematic uncertainties.

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