PROCEEDINGS OF SCIENCE

Search for charged Higgs bosons decaying via H$^{+} \rightarrow \tau + \nu$ in $t\bar{t}$ events with the ATLAS detector

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The results of a search for charged Higgs bosons are presented. The analysis is based on 4.6 fb^{-1}of proton-proton collision data at $\sqrt{s} = 7$ TeV collected by the ATLAS experiment at the Large Hadron Collider, using top quark pair events with a tau lepton in the final state. The data are consistent with the background expectation from Standard Model processes. Assuming a branching ratio $\mathscr{B}(H^{+} \rightarrow \tau\nu)$ = 100%, the upper limits at the 95% CL on $\mathscr{B}(t \rightarrow bH^{+})$ are determined to be between 5% m$_{H^{+}} = 90$ GeV and 1% m$_{H^{+}} = 160$ GeV.

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1. Introduction

The discovery of a charged Higgs boson[1] would herald the existence of Physics Beyond the Standard Model (BSM). The Higgs sector of the Standard Model (SM) has one complex Higgs doublet resulting in only one neutral Higgs boson. Many extensions of the SM scalar sector, such as the Two Higgs Doublet Models, include a charged Higgs boson. This search is looking for a charged Higgs boson produced in top decays, as shown in figure 1, with a mass range of 90–160 GeV. The assumption is made that the charged Higgs boson will decay into a τ lepton ($H^+ \to \tau\nu$) and throughout this note the $\mathscr{B}(H^+ \to \tau\nu)$ is assumed to be 1. The search presented is divided into three exclusive channels defined by the final state objects of the event. Their names and definitions are given in table 1. The search was performed on the proton-proton collisions data delivered by CERN's Large Hadron Collider (LHC) at a centre of mass energy of 7 TeV in 2011 and recorded by the ATLAS detector [1] resulting in an integrated luminosity of 4.6 fb^{-1}.

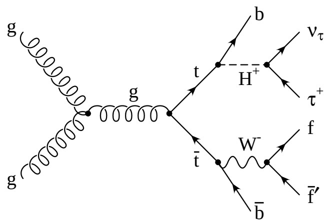


Figure 1: The Feynmann diargram for the main production process for a light charged Higgs boson. The Feynman diagram illustrates the three channels that comprise the search. The W boson decays hadronically as in either the lepton+jets or the τ+jets channel and leptonically as in the τ+leptons.

Channel	H^+	W
lepton+jets	leptonic τ (e or μ)	$q\overline{q}$
$\tau + lepton$	τ_{had}	e or μ or leptonic τ
$\tau + jets$	τ_{had}	$q\overline{q}$

Table 1: The channels employed in the search. These are defined by the final state objects from the H^+ and W decays as shown in figure 1. The τ lepton will decay leptonically (eg., $e^+\nu_e\overline{\nu}_\tau$ or $\mu^+\nu_\mu\overline{\nu}_\tau$) $\simeq$ 35% of the time and hadronically (eg., $\pi^+\overline{\nu}_\tau, \pi^+\pi^0\overline{\nu}_\tau, \pi^+\pi^-\pi^+\overline{\nu}_\tau$,...), referred to as a τ_{had}, $\simeq$ 65% of the time.

2. Data and simulated events

The SM processes that are background to the search together with signal processes ($t\overline{t} \to b\overline{b}H^+W^-$, $t\overline{t} \to b\overline{b}H^-W^+$ and $t\overline{t} \to b\overline{b}H^+H^-$) for 90 GeV $< m_{H+} <$ 160 GeV are listed in table 2. Their modelling is undertaken by different generators that are tuned by the ATLAS Collaboration [2] to describe the LHC data with their cross sections calculated to either Next-to-Next-to-Leading-Order (NNLO) or Next-to-Leading-Order (NLO) precision. The effect of multiple interactions taking place within or the neighbouring bunch crossing is included by superimposing a simulated minimum bias event on the hard process of each generated event. The response of the

[1] In this note, charged Higgs bosons are denoted H^+, with the charged-conjugate H^- always implied.

Process	**Generator**	**Cross Section (pb)**	
SM $t\bar{t}$ (with at least one lepton)	MC@NLO	91	NNLO
Single Top t-channel (with ℓ)	AcerMC	21	
Single Top s-channel (with ℓ)	MC@NLO	1.5	
Single Top quark Wt-channel (inclusive)	MC@NLO	16	
$W \to \ell\nu$	ALPGEN	3.1×10^4	
$Z/\gamma^* \to \ell\ell > 10$ GeV	ALPGEN	1.5×10^4	
WW	HERWIG	17	NLO
ZZ	HERWIG	1.3	
WZ	HERWIG	5.5	
H^+ signal with $\mathscr{B}(t \to bH^+) = 5\%$	PYTHIA 6	16	LO

Table 2: The simulated processes and their cross sections. MC@NLO, HERWIG and JIMMY used for the parton shower, hadronisation and underlying event. ALPGEN was interfaced to HERWIG and JIMMY.

Selection	**Channel**		
	lepton + jets	τ + *lepton*	τ + *jets*
Trigger	Single lepton		$\tau + E_{\mathrm{T}}^{\mathrm{miss}}$
Lepton	one isolated e/μ, p_{T} > 20/25 GeV		None
τ_{had}	None	one, p_{T} > 20 GeV	one, p_{T} > 40 GeV
Jets	≤ 4, p_{T} > 20 GeV 2 b-tagged	2, p_{T} > 20 GeV ≤ 1 b-tagged	≤ 4, p_{T} > 20 GeV ≤ 1 b-tagged
$\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$	> 40 GeV	None	> 65 GeV
Additional Requirement	None	Σp_{T} > 100 GeV	$\frac{E_{\mathrm{T}}^{\mathrm{miss}}}{0.5\mathrm{GeV}^{1/2}\sqrt{\Sigma p_{\mathrm{T}}}} > 13$

Table 3: A summary of the baseline selection criteria applied by the search on each channel.

ATLAS detector to each generated event is determined using a detailed GEANT4 simulation [3] of the detector and reconstructed with the same algorithms as data. These simulated events are collectively referred to as Monte Carlo (MC) and detailed information is available in [4].

3. Physics object and event selection

The study relies on reconstructed physics objects such as τ_{had} leptons, isolated leptons, jets originating from the hard scattering or initiated by b quarks as well as the momentum imbalance ($E_{\mathrm{T}}^{\mathrm{miss}}$) calculated in the transverse plane to the beam axis caused by particles escaping detection and instrumental effects. Details such as the algorithms used for the reconstruction and identification of τ_{had} leptons and b-jets, together with the working points chosen for efficiency and rejection factors are described in [4]. The different selection criteria applied on these objects in each channel for the subsequent event selection are listed in table 3.

4. Data driven methods

Data driven methods are applied to each channel, where appropriate, to determine the background contributions due to misidentified leptons, multi-jet events and events including true hadronic τ leptons. The measured probabilities are applied to the MC events used in each channel.

In the lepton+jets channel, the misidentified lepton contribution from non-isolated leptons arising from semileptonic decays is non-negligible. Using a control sample of $Z \to ll$ and looser identification criteria for the leptons, the misidentification rate is calculated from data and parametrized with respect to η and p_{T}. On average electron and muon misidentification probabilities are found to be 18% and 29% respectively.

In the $\tau + lepton$ channel, the misidentification studies also include electrons and jets faking a τ_{had}. The probability of an electron being misidentified as a tau is on average 0.2% and determined using a $Z \to ee$ control region in the data. While the probability of a jet being misidentified as a tau is determined with a control sample enriched in W+jets events. The difference in jet composition between W+jets and $t\bar{t}$, studied in simulation, are taken into account as systematic uncertainties.

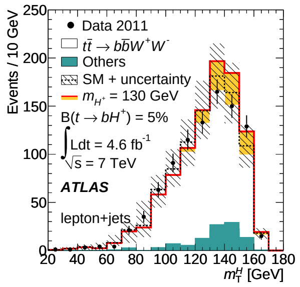
The $\tau + jets$ channel requires the estimate of the multi-jet background contribution (and other processes such as $t\bar{t}$ and W+jets) and the contribution of background processes featuring a correctly reconstructed hadronic τ. The first case is estimated by fitting the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution to data in a control and signal region. The method assumes that the shapes for the transverse mass between the τ_{had} and $E_{\mathrm{T}}^{\mathrm{miss}}$ (m_{T}) and $E_{\mathrm{T}}^{\mathrm{miss}}$ are the same in both regions. For the latter, an embedding method is chosen where a control sample of $t\bar{t}$-like μ+jets data events is modified by replacing the detector signature of the muon by a simulated τ_{had}. These events are then used for background prediction and they are selected using a looser selection criteria to avoid biasing the control sample. The shape of the m_{T} distribution is obtained by applying the baseline selection to the embedded sample and normalising the distribution to the estimated number of events with correctly reconstructed τ_{had} in the signal region of the sample.

5. Lepton+jets channel

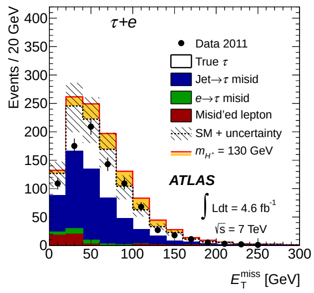
The main objectve of the cuts listed in table 3 for this channel is to enrich the lepton+jets events with $t\bar{t}$ events. They require to pass the single lepton triggers (E_{T} > 20–22 GeV for electrons and p_{T} > 18 GeV for muons). The signal region is defined using the invariant mass of the b jet and the charged lepton l given by $\cos\theta_l^* = (4\,p^b \cdot p^l)/(m_{\mathrm{top}}^2 - m_W^2) - 1$ and the transverse mass between the lepton and the $E_{\mathrm{T}}^{\mathrm{miss}}$ (m_{T}^W). Events featuring a charged Higgs boson will result in a $\cos\theta_l^*$ value closer to -1 and thus the signal region is defined by requiring $\cos\theta_l^* < -0.6$ and $m_{\mathrm{T}}^W < 60$ GeV. The discriminating variable is the charged Higgs boson transverse mass, $m_{\mathrm{T}}^H = \left(\sqrt{m_{\mathrm{top}}^2 + (\vec{p}_{\mathrm{T}}^{\,l} + \vec{p}_{\mathrm{T}}^{\,b} + \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})^2} - p_{\mathrm{T}}^b\right)^2 - \left(\vec{p}_{\mathrm{T}}^{\,l} + \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}\right)^2$ which gives the lower bound on the mass of the leptonically decaying charged boson produced in the top quark decay. The distribution of m_{T}^H from events satisfying the constraints is shown in figure 2(a).

6. τ+lepton channel

This channel employs the same single lepton triggers as the lepton+jets channel. The aim of



(a)



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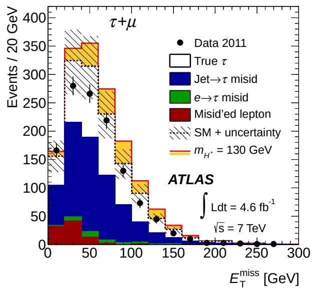
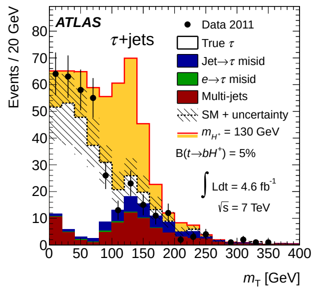


(c)



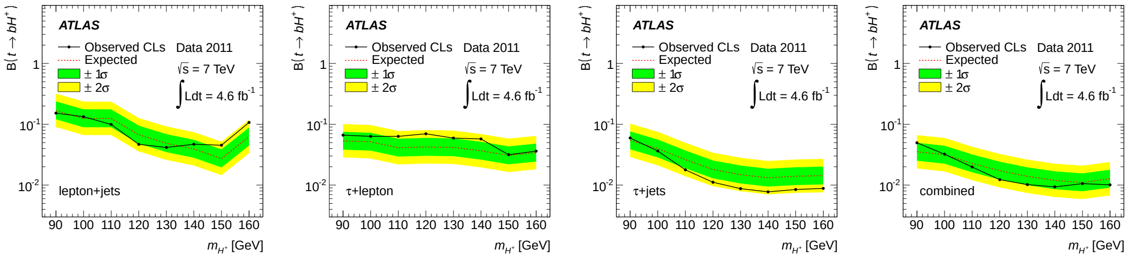
(d)

Figure 2: The distribution of the discriminating variables employed by the different channels. These include all the events satisfying the selection criteria specified for each channel. The dashed line corresponds to the SM-only hypothesis while the hatched area around it illustrates the total uncertainty associated with the SM backgrounds. The solid line shows the predicted contribution of signal+background in the presence of a 130 GeV charged Higgs boson with $\mathscr{B}(t \to bH^+) = 5\%$ and $\mathscr{B}(H^+ \to \tau\nu) = 100\%$.

the additional cut (see table 3) on the sum of the transverse momenta of all the tracks associated with the primary vertex ($\sum p_{\mathrm{T}}$), is to suppress the multi-jet events. The $E_{\mathrm{T}}^{\mathrm{miss}}$ associated with each event is used to discriminate between SM $t\bar{t}$ events and those where a charged Higgs boson mediates the decay of the top quark. The $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in the two scenarios will be different because in the latter the neutrino tends to be more energetic. The resulting distributions from the selected events, $\tau + e$ or $\tau + \mu$, are shown in figure 2(b and c).

7. τ+jets channel

The events analysed in this channel are selected by the $\tau + E_{\mathrm{T}}^{\mathrm{miss}}$ trigger. It applies a threshold of 29 GeV to the τ object and 35 GeV on the $E_{\mathrm{T}}^{\mathrm{miss}}$ of the event. The selection criteria applied on the reconstructed final state objects are listed in table 3. The additional requirement is a ratio based on the $\sum p_{\mathrm{T}}$ as defined in section 6 to reject events whose large reconstructed $E_{\mathrm{T}}^{\mathrm{miss}}$ is due to the limited resolution of the energy measurement. In this channel, m_{T}, related to either the W boson in the case of the SM $t\bar{t}$ process or the charged Higgs boson in the case of signal is the discriminating variable. In figure 2(d) the m_{T} distribution is shown for selected events in data and MC. It illustrates the contribution from true τ, misidentified τ obtained from data driven methods and a hypothetical signal process featuring a 130 GeV charged Higgs boson.



(a) (b) (c) (d)

Figure 3: The observed and expected 95% CL exclusion limits on $\mathscr{B}(t \rightarrow bH^+)$ for charged Higgs boson production from top quark decays as a function of its mass (m_{H^+}) assuming $\mathscr{B}(H^+ \rightarrow \tau\nu) = 100\%$. The graphs shown are from the individual channels: (a) lepton+jets, (b) τ+lepton and (c) τ+jets. Graph (d) is the combination from the three channels. It shows upper limits at the 95% CL on $\mathscr{B}(t \rightarrow bH^+)$ between 5% $m_{H^+} = 90$ GeV and 1% $m_{H^+} = 160$ GeV.

8. Results and conclusion

The compatibility of the data with background-only and signal+background hypothesis is tested using a profile likelihood that includes the discriminating variables from each channel. The systematic uncertainties of the shape and normalisation are incorporated via nuisance parameters which are listed in [4]. No significant deviation from the SM prediction is observed in any of the channels studied in 4.6 $\text{fb}^{-1}$of ATLAS data. Exclusion limits are set on the branching ratio $\mathscr{B}(t \rightarrow bH^+)$ for the individual channels together with a combined limit (see figure 3). By assuming a $\mathscr{B}(H^+ \rightarrow \tau\nu) = 100\%$ the upper limits at the 95% confidence level are set on the branching ratio $\mathscr{B}(t \rightarrow bH^+)$ between 5% $m_{H^+} = 90$ GeV and 1% $m_{H^+} = 160$ GeV. This is a significant improvement over limits obtained by previous searches [5, 6].

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