PROCEEDINGS OF SCIENCE

ATLAS discovery prospects for the charged Higgs in the $H^+ \rightarrow \tau\nu$ final state

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In the Minimal Super-Symmetric model (MSSM), the decay $H^+ \rightarrow \tau\nu$ can be a dominant decay channel for the light ($m_{H^+} < m_{\text{top}}$) charged Higgs boson. Through this channel, the ATLAS detector at the Large Hadron Collider (LHC) could either discover the light H^+ or improve the current Tevatron upper limits on $\mathscr{B}(t \rightarrow bH^+)$. We evaluate the expected ATLAS upper limit for $\mathscr{B}(t \rightarrow bH^+)$, assuming $\mathscr{B}(H^+ \rightarrow \tau\nu) = 1$ and an integrated luminosity of 200 pb^{-1} gathered at $\sqrt{s} = 10$ TeV.

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1. Introduction

Many extensions of the SM, such as the MSSM, are based on so-called Two-Higgs Doublet Models (2HDM). Such models are characterized by two isodoublets of scalar fields in the Higgs sector, where the Electroweak Symmetry breaking through two complex Higgs doublets leads to five physical states, including two with an electric charge (H^+ and H^-). While at the tree level the Higgs sector is fully determined by two parameters, the mass m_{H^+} and the ratio of the two Higgs doublet vacuum expectation values $\tan\beta$, the values of these parameters are not predicted by the theory.

If the charged Higgs boson is light enough ($m_{H^+} < m_{\rm top}$), it can appear in the decay of an on-shell top quark. At the LHC, $t\bar{t}$ pairs will be produced in abundance via the gg or $q\bar{q}$ fusion processes. This paper presents the ATLAS discovery potential for the H^+ with a mass below the top quark mass. Additionally we assume $\mathscr{B}(H^+ \to \tau\nu) = 1$, motivated by scenarios with $\tan\beta > 3$ where $\mathscr{B}(H^+ \to \tau\nu)$ exceeds 90%. A discovery of a charged Higgs through this channel would present an ambiguous sign of physics beyond the SM.

Although dilepton $t\bar{t}$ events have an overall small branching ratio, the presence of two charged leptons in the final state provide an excellent trigger signature, as well as a cleaner analysis environment than other $t\bar{t}$ events with higher jet multiplicities. However, due to the presence of multiple undetectable neutrinos, the reconstruction of the invariant masses of both top quarks becomes impossible. In this paper [1] we present a search for charged Higgs bosons in dilepton decays of $t\bar{t}$ pairs with full simulations of the ATLAS detector, aided by the use of two new tools: the helicity angle $\cos\theta^*_\ell$ and the generalized transverse mass $m_{\rm T2}^{H^+}$ described in [2, 3]. The experimental sensitivity is estimated for an early data sample corresponding to an integrated luminosity of 200 pb^{-1}.

2. Event Selection

The dilepton $t\bar{t}$ candidate selection first relies on a positive decision by a single lepton (electron or muon) trigger with a $p_{\rm T}$ threshold of 15 GeV. This is followed by demanding a presence of two oppositely charged leptons with $p_{\rm T} > 10$ GeV and $|\eta| < 2.5$, with at least one of the leptons possessing $p_{\rm T} > 20$ GeV. The events must also have at least two jets with $p_{\rm T} > 15$ GeV and $|\eta| < 5$, including at least one jet with a positive b-jet identification. The two jets in the event with the highest likelihood of being b-jets are assumed to be the daughters of the top and anti-top quarks.

The four-fold ambiguity in assigning the leptons and the b-jets to their parents is solved in two stages. At first, we select only the events with an easy-to-find incorrect pairing: pairs with either $\cos\theta^*_\ell \geq 1$ or no solution for $m_{\rm T2}^{H^+}$. For such events the other pairing gives the correct $\ell - b$ combinations, and the pair with the smallest $\cos\theta^*_\ell$ is presumed to originate from the $t \to bH^+$ decay (the "H^+ side"). For the remaining events we assign the pair with the highest $\cos\theta^*_\ell$ value to the $t \to bW$ decay (the "W side") and its partner pair to the $t \to bH^+$ decay (the "H side"). Although this method of pairing the leptons and jets causes a background bias towards smaller $\cos\theta^*_\ell$ values, the high purity for signal events potentially improves the ability to set the charged Higgs mass limit through the computation of the $m_{\rm T2}^{H^+}$. Furthermore, since no fit to the SM expected shape is performed, this bias does not hinder the rest of the analysis.

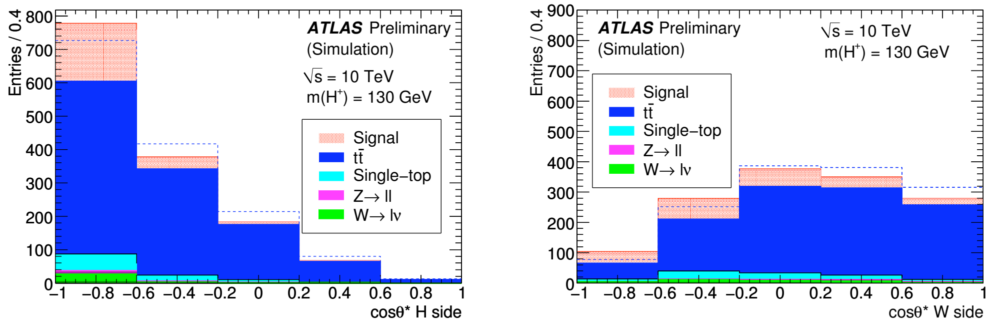

Figure 1: Comparison of the $\cos\theta_\ell^*$ distribution in the SM case (dashed line) and as obtained when assuming $m_{H^+} = 130$ GeV together with $\mathscr{B}(t \to bH^+) = 17\%$ (filled histogram). All selection cuts are applied, except the one on $\cos\theta_\ell^*$.

In addition, events are required to have missing transverse energy $E_\mathrm{T}^\mathrm{miss} > 50$ GeV. Figure 1 shows the resulting $\cos\theta_\ell^*$ distribution in the SM case (dashed line) or with $m_{H^+} = 130$ GeV and $\mathscr{B}(t \to bH^+) = 17\%$. The excess of events in the bin closest to -1 of the H^+ side can show evidence for the presence of a charged Higgs boson. Thus, we select signal events by requiring $\cos\theta_\ell^* < -0.6$.

3. Data Driven Methods

Although the background process cross sections can be estimated in theory, we refrain from relying on them due to both theoretical uncertainties and the potential contributions from new physics. Instead, we proceed to scale the number of Monte Carlo (MC) events to match the data in various sidebands that are insensitive to the signal. The scaling factors are determined by isolating each background type with a unique set of selection cuts in following variables: the b-jet likelihood, $E_\mathrm{T}^\mathrm{miss}$, the flavor and the invariant mass $m_{\ell\ell}$ of the two leptons, as well as $\cos\theta_\ell^*$. For example, Z+jets events are isolated by demanding $E_\mathrm{T}^\mathrm{miss} < 30$ GeV, 86 GeV $< m_{\ell\ell} < 96$ GeV, veto on b-jets, and selecting only ee or $\mu\mu$ events. Similarly, W+jets events are isolated by demanding $E_\mathrm{T}^\mathrm{miss} > 30$ GeV, veto on b-jets, and selecting only $e\mu$ events. The $t\bar{t}$ events are isolated by demanding a good b-jet candidate and $M_\mathrm{T}^\mathrm{miss} > 50$ GeV, but $\cos\theta_\ell^* > -0.4$.

As a large portion of the non-$t\bar{t}$ background comes from lepton misidentification, the probability of lepton fake rate is estimated directly from data. This is accomplished by defining two lepton selection criteria: loose and tight. The fractions of real and fake leptons satisfying the tight selection is measured in the Z+jets sideband defined above, while the fake lepton fraction is measured from the W+jets sideband. These fractions, r and f respectively are defined as follows:

$$r = \frac{N_\mathrm{tight,real}}{N_\mathrm{tight,real} + N_\mathrm{loose,real}} \text{ and } f = \frac{N_\mathrm{tight,fake}}{N_\mathrm{tight,fake} + N_\mathrm{loose,fake}}, \tag{3.1}$$

where the sum of N_tight and N_loose may not be the total number of leptons in the sample. The values of N_tight and N_loose are measured using a "tag & probe" approach: for each event with a tight lepton

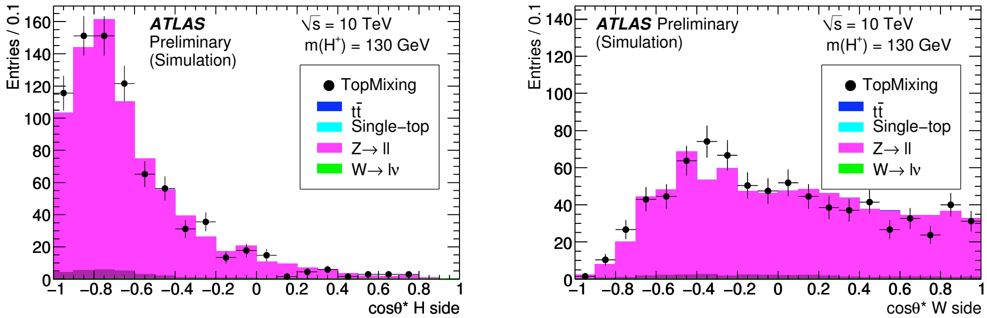

Figure 2: Comparison of the $\cos\theta_\ell^*$ distribution, as obtained from the scaled MC samples and the TopMixing pseudo-data sample in the Z+jets sideband.

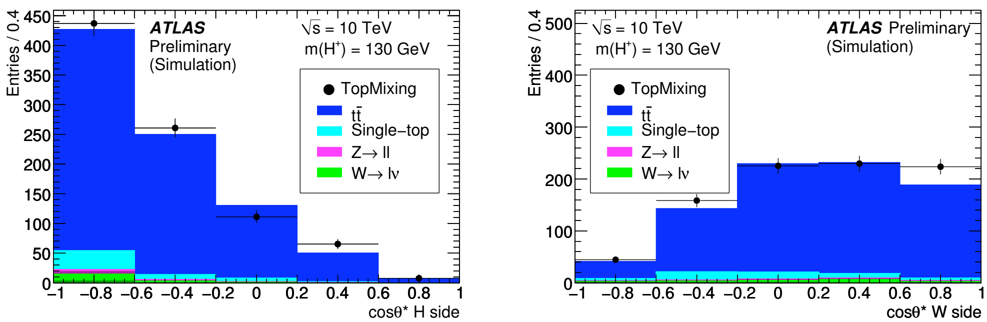

Figure 3: Comparison of the $\cos\theta_\ell^*$ distribution, as obtained from the scaled MC samples and the TopMixing pseudo-data sample in the $t\bar{t}$ sideband.

("tag"), we count how often the other lepton ("probe") satisfies the tight and loose criteria. The number of real and fake leptons passing the tight and loose selection can be expressed as:

$$\begin{bmatrix} N_{\text{tight}} \\ N_{\text{loose}} \end{bmatrix} = \begin{bmatrix} rr & rf \\ r(1-r) & r(1-f) \end{bmatrix} \begin{bmatrix} N_{\text{real}} \\ N_{\text{fake}} \end{bmatrix}. \tag{3.2}$$

leading to the number of selected events with a fake lepton, N_{RF}:

$$N_{\text{fakes}} = N_{\text{RF}} = \frac{N_{\text{TL}} + \frac{r-1}{r} N_{\text{TT}}}{r-f}. \tag{3.3}$$

After measuring N_{TT} and N_{TL} from data, we can determine if the MC fake lepton background expectation is accurate.

The performance of both data driven methods were tested with a pseudo-data sample, where the relative background process cross-sections were varied from the expected SM values. The background scaling factors, as well as the lepton fake rates as determined by the data-driven methods, were found to be consistent with the MC truth values. Figures 2 and 3 show sample distributions for the isolated Z+jets and $t\bar{t}$ backgrounds, for the MC and pseudo-data samples.

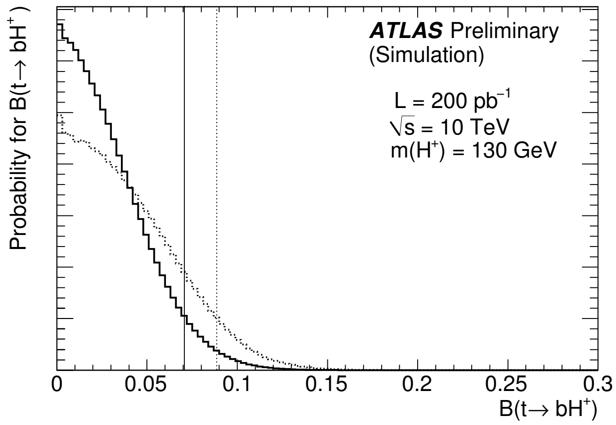

Figure 4: Determination of the branching ratio upper limit with (dashed line) and without (solid line) systematic uncertainties, for a 130 GeV charged Higgs boson.

4. Upper Limit Estimation

The branching ratio upper limits are evaluated according to:

$$\mathscr{B} = \frac{N_{\text{obs}} - N_{\text{bg}}}{2 \times \sigma_{t\bar{t}} \times L_{\text{int}} \times \varepsilon_{\text{sig}}}, \tag{4.1}$$

where N_{obs} and N_{bg} are the number of observed events and the number of expected background events respectively, $\sigma_{t\bar{t}}$ is the $t\bar{t}$ cross section, L_{int} is the integrated luminosity, and ε_{sig} is the signal selection efficiency. We evaluate the branching ratio for 10000 toy MC experiments, while varying the input parameters by their uncertainties. The probability weight for each branching ratio is determined by $W_{\mathscr{B}}(N_{\text{bg}}, N_{\text{obs}}, \varepsilon_{\text{sig}}) = P(N_{\text{bg}}) \times P(N_{\text{obs}}) \times P(\varepsilon_{\text{sig}})$, where P(x) are Gaussian probability density functions for each parameter. The width of the N_{obs} distribution is the Poisson uncertainty $\sqrt{N_{\text{obs}}}$, and the widths of the N_{bg} and ε_{sig} are determined by the MC statistics and systematic uncertainties. Figure 4 shows a typical resulting branching ratio distribution with and without systematic uncertainties, along with the 95% confidence level upper limit on the branching ratio (vertical line).

5. Systematic Uncertainties

Since the background MC samples are normalized to data, many of the overall scaling uncertainties (e.g. luminosity) do not affect the expected number of background events. Although the data driven MC normalization works for many of the backgrounds, we rely on the relative theoretical cross sections between some background processes (e.g. $t\bar{t}$ and single-top). The theoretical uncertainty on the single-top cross section is 3-8% [4] resulting in an additional uncertainty below 1% for the total number of background events. The uncertainty in the trigger and reconstruction efficiencies for leptons are both assumed to be 1%, as estimated in [5] for 100 pb^{-1} at 14 TeV. The energy scale uncertainty is 1% for leptons. The dominant uncertainty when estimating the number of jets faking electrons comes from defining the control sidebands. The uncertainty is estimated by varying the $E_{\mathrm{T}}^{\mathrm{miss}}$ cut, and taking twice the largest variation as the systematic uncertainty. The jet energy scale uncertainty is 7% for $|\eta| \leq 3.2$, and 15% for $|\eta| \geq 3.2$. In addition to the p_{T} requirements, the energy scale has an effect on the $\cos\theta_\ell^*$ selection efficiency, which depends on the assumed mass of the charged Higgs boson. The missing transverse energy is affected by the lepton and jet energy scale measurements described above. Since we normalize the dominant $t\bar{t}$ process only after having applied the $E_{\mathrm{T}}^{\mathrm{miss}}$ cut, any other effects due to mis-modeling are estimated to be negligible. Using the b-tagger at the default operating point (60% efficiency), the uncertainty in the efficiency is estimated to be 4%. The fake rejection rate affects mainly the Z/W+jets and QCD backgrounds, for which we assign an additional uncertainty of 10% on the number of background events. The dominant $t\bar{t}$ process is studied with both AcerMC and MC@NLO samples, and we observe no differences in the distribution shapes beyond statistical fluctuations. The uncertainties coming from ISR/FSR are negligible, since we place upper limit on the jet multiplicity. The total systematic uncertainties on the number of background events and the signal efficiency are determined to be 10% and 6% respectively.

6. Summary and Conclusion

We have described the ATLAS sensitivity prospect for a search of a light charged Higgs boson. For the channel $H^+ \to \tau\nu \to \ell + \nu$s in dilepton $t\bar{t}$ events, two new tools have been used: the helicity angle $\cos\theta_\ell^*$ and the generalized transverse mass $m_{\mathrm{T2}}^{H^+}$. After selecting the dilepton $t\bar{t}$ topology, both $\cos\theta_\ell^*$ and $m_{\mathrm{T2}}^{H^+}$ are used to determine the correct lepton and b-jet pairing. Having normalized the background MC samples to data in signal free regions, the $\cos\theta_\ell^*$ distribution is used to search for an excess of events over the SM prediction for nonzero $\mathscr{B}(t \to bH^+)$. The expected 95% CL upper limits on $\mathscr{B}(t \to bH^+)$ assuming $\mathscr{B}(H^+ \to \tau\nu) = 1$ were evaluated in toy MC experiments where the expected signal and background are fluctuated according to their systematic uncertainties. The 95% CL upper limits with 200 pb^{-1} of integrated luminosity at $\sqrt{s} = 10$ TeV are expected to substantially improve on the current limits at the Tevatron experiments, see Figure 5.

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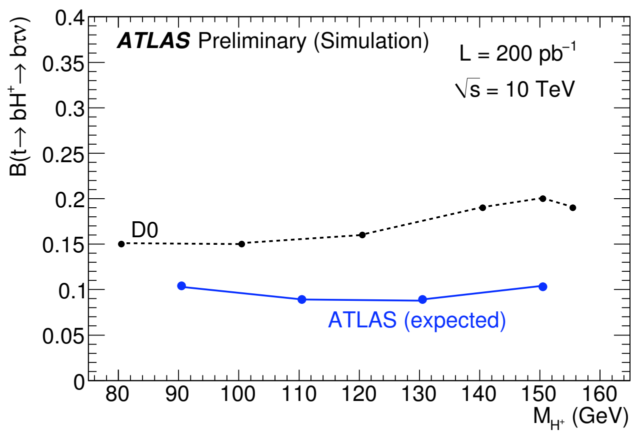

Figure 5: Expected 95% CL upper limits for $\mathscr{B}(t \rightarrow bH^+)$ as a function of m_{H^+}, using the early ATLAS data (i.e. integrated luminosity of 200 pb^{-1} gathered at $\sqrt{s} = 10$ TeV). Also shown for reference are the current Tevatron upper limits on $\mathscr{B}(t \rightarrow bH^+)$ [6]. No pile-up is included here.