PROCEEDINGS OF SCIENCE

Search for light charged Higgs boson in $t \rightarrow H^{\pm} + b(H^{\pm} \rightarrow cb)$ decays with the ATLAS detector at LHC

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A search for light charged Higgs boson ($60 \leq m_{H^{\pm}} \leq 160$ GeV) in $t \rightarrow bH^{\pm}$ decay is presented. The analysis focuses on top-quark pair events in which one top quark decays to Wb, with the W boson decaying leptonically, and the other top quark decays to $bH^{\pm}$, with $H^{\pm}$ subsequently decaying to a charm quark and a bottom quark ($H^{\pm} \rightarrow cb$). The search is based on pp collisions at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the LHC and uses an integrated luminosity of 139 fb^{-1}. The process results in the lepton-plus-jets final state, characterized by an isolated electron or muon and at least four jets. The search exploits the high b-jet multiplicity in signal events and employs a neural network discriminant that uses the kinematic differences between the signal and the background, which is dominated by a top-quark pair production.

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1. Introduction

The Standard Model (SM) successfully describes many aspects of fundamental particle physics. However, it is known that it doesn't provide a complete description of nature and doesn't explain several phenomena found in particle physics and astrophysics (massless neutrinos, baryon asymmetry, nature of dark matter, etc.). To probe the new physics, the search for the particles that are predicted in the extensions of SM (BSM) is performed. These particles appear naturally in many BSM hypotheses, where more than one Higgs doublet is considered. For example, in the models with three Higgs doublets (3HDM) [1], the CP-even and two CP-odd neutral Higgs bosons, as well as two charged Higgs bosons, are featured.

In 3HDMs the lightest charged Higgs boson can be lighter than the top quark, so it will decay predominantly into a τ-lepton and a neutrino, a charm and a bottom quark, or a strange and a charm quark. If the charged Higgs is light enough, $m_{H^\pm} < m_t$, it can be produced in rare decays of the top quark, such as $t \to H^\pm b$. The study is performed in the 60 GeV to 160 GeV mass range for charged Higgs, where $H^\pm \to cb$ represents one of the dominant decay channels in 3HDM.

2. Analysis strategy

The search is centred on production of the charged Higgs boson via $t\bar{t} \to WbH^+b$, with $W \to l\nu$ ($l = e, \mu, \tau$) and $H^\pm \to cb$. The measurement is performed using the dataset of pp collisions collected at the center-of-mass energy $\sqrt{s} = 13$ TeV between 2015 and 2018 with the ATLAS detector [2] at the Large Hadron Collider, amounting to an integrated luminosity of 139fb^{-1}.

The dominant source of background comes from $t\bar{t} \to WbWb$ events. These events are split into $t\bar{t}$+ jets categories to improve the background modelling. The inclusively produced $t\bar{t}$ sample is classified based on the flavour of a jet that did not originate form the direct $t\bar{t}$ [3]. The procedure is done via matching between a jet and a hadron with $\Delta R < 0.3$. Events with at least one such match are labeled as $t\bar{t} \geq 1b$. Events that are already not recognized as $t\bar{t} \geq 1b$ but have a matched charm jet (not originating from W) are categorised as $t\bar{t} \geq 1c$. Both types of events are referred to as $t\bar{t}$+HF. The remaining events are labeled as $t\bar{t} + light$ events, including those with no additional jets. Apart from $t\bar{t}$, other sources of background are considered, such as $V + jets$, $t\bar{t} + V$, $t\bar{t}H + tH$, single top and di-bosons. Figure 1 shows the fractions of the different background components in the analysis regions. The $t\bar{t}$ contributes more than 80% to the total expected background.

To optimise the sensitivity of the search and disentangle different backgrounds, the selected events are categorised into nine different analysis regions depending on the number of jets (4j, 5j and 6j) and the number of b-tagged jets (2+1bl, 3b, $\geq 4b$[1]). The regions with (2+1bl) are used to derive data-based corrections in order to improve the $t\bar{t}$ modelling; the (4j,3b) and (5j,3b) regions are the main signal regions; (6j,3b) is used to improve the background modelling; (4j,4b) is used for recovering acceptance for signal events with a mis-tagged c-quark; (5j,$\geq$ 4b) and (6j, $\geq$ 4b) regions are used to control the $t\bar{t}$+b quark enhanced background.

The large number of b-tagged jets in the final state causes ambiguities in the calculation of a kinematic variables that are used to discriminate signal from background events. For this reason,

[1]The regions with 3 and more b-tagged jets use tight b-tagging operation point with 60% efficiency of b-tagger, while 2+1bl region has 2 tight b-tagged jets and one loose at 70% efficiency

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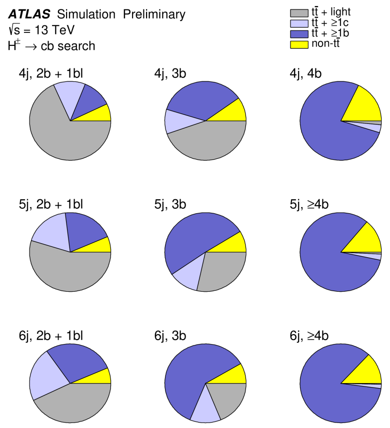

Figure 1: Fractional contributions of the various processes to the total background prediction in each analysis region [4].

a neural network discriminant (DNN) has been developed. A feed-forward NN is used to separate the $H^{\pm}$ signal from the large $t\bar{t}$ background. A low-level kinematic information from jets and leptons (p_T, η and ϕ), E_T^{miss}, invariant masses of jet pair permutations, and pseudo-continuous b-tagging scores are fed into the NN input layer. The NN is parameterised as a function of $m_{H^{\pm}}$ by incorporating the signal mass information as a label in the training [5]. The training is done for all signal mass points in (≥4j, ≥3b) regions. Figure 2 compares the distribution of the NN output between the signal, for $m_{H^{\pm}}$ = 70 GeV and $m_{H^{\pm}}$ = 130 GeV, and the $t\bar{t}$ in (5j, 3b) region.

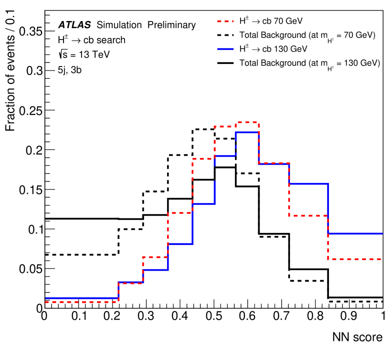

Figure 2: Comparison of the distributions of the NN score of the $m_{H^{\pm}}$ signal with $m_{H^{\pm}}$ = 70 GeV (red dashed) and $m_{H^{\pm}}$ =130 GeV (blue solid), and the total SM background evaluated at the same masses (black dashed and black solid, respectively) in the (5j, 3b) analysis regions [4].

The $t\bar{t}$ simulation is well known for not properly describing data at high jet multiplicities. This results in discrepancy between the data and the Monte Carlo (MC), which increases with the jet multiplicity. In order to improve the data/MC agreement in jet multiplicity and p_T^{jet}, data-driven reweighting procedure [6] is used in (2bex+1bl) regions for all jet multiplicities and applied to the $t\bar{t}$ MC. The correction factors are given by

$$C(H_T^{all,i}, j^i) = \frac{N^{data}(H_T^{all,i}, j^i) - N^{non-t\bar{t}}(H_T^{all,i}, j^i)}{N^{t\bar{t}}(H_T^{all,i}, j^i)} \tag{1}$$

where $N^{data}(H_T^{all,i}, j^i)$, $N^{non-t\bar{t}}(H_T^{all,i}, j^i)$ and $N^{t\bar{t}}(H_T^{all,i}, j^i)$ represent the yields observed in data, predicted non-$t\bar{t}$ and $t\bar{t}$ yields in the H_T^{all}[2] bins for all jet multiplicities. Since the $t\bar{t}$ mismodelling is

[2] H_T^{all} is defined as the scalar sum of the transverse momenta of all selected objects in the event and E_T^{miss}

assumed to be mainly due to the additional radiation in the parton shower, these reweighting factors are expected to improve the data/MC agreement in the 3b and $\geq$ 4b regions (Figure 3).

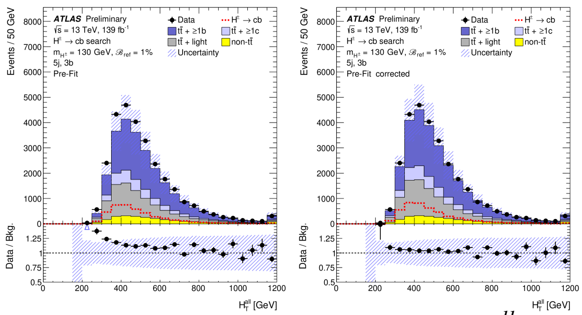

Figure 3: Comparison between the data and MC prediction for the H_T^{all} distribution before and after the inclusion of the $t\bar{t}$ correction, prior to the likelihood fit to data. The bottom panels display the ratios of data to the SM background prediction [4].

The analysis event selection requires to have exactly one reconstructed and trigger matched lepton (muon or electron) with p_T >28 GeV, at least 4 jets with p_T >24 GeV, where at least two of them are required to be b-tagged. Further requirements on E_T^{miss} or transverse mass of the lepton and E_T^{miss} (m_T^W)[3] are applied. An event is selected if $E_T^{miss} \geq 20$ GeV and $E_T^{miss} + m_T^W \geq 60$ GeV; the requirements are the same for the muon and electron channels.

3. Results

The NN score across all fit regions is jointly analysed to test for the presence of a signal. The statistical analysis is based on a binned likelihood (LH) function $\mathcal{L}(\mu, \theta)$, that is build as a product of Poisson probability terms across all bins considered. This function depends on the signal strength parameter μ, a multiplicative factor for the branching ratio $t \to H^+ b$ [4] and θ, a set of nuisance parameters that encode the effect of systematic uncertainties on the signal and background expectations. These variables are implemented in the LH function as Gaussian or log-normal priors.

In the absence of a significant excess of data events above the background expectation, 95% CL limits are set on the product of branching fractions B. Figure 4 shows the observed (expected) 95% CL upper limits on B as a function of $m_{H^\pm}$. They vary between 0.15% (0.09%) and 0.42% (0.25%) depending on $m_{H^\pm}$. The predictions from 3HDM are superimposed on the upper limits, corresponding to three benchmark values for the parameters X, Y and Z, which are functions of the Higgs doublet vacuum expectation values and the mixing angle between the charged Higgs bosons. The best-fit B[5] varies between 0.06% and 0.19% with a relative uncertainty ranging from about 100% to 38% depending on $m_{H^\pm}$. The most precise best-fit B is measured to be 0.16 $\pm$ 0.06% for $m_{H^\pm} = 130$ GeV. The total uncertainties of the measured μ are dominated by systematic uncertainties. The observed exclusion limits are consistently weaker than the expectation. The largest excess in the data corresponds to about 3σ for $m_{H^\pm}$ =130 GeV. A global probability of the

[3] $m_T^W = \sqrt{2 p_T^l E_{miss}^T (1 - \cos\Delta\phi)}$, where p_T^l is the transverse momentum (energy) of the muon (electron) and $\Delta\phi$ is the azimuthal angle separation between the lepton and the direction of the missing transverse momentum.

[4] normalised to a reference branching ratio $B_{\rm ref}(t \to H^+ b) = 1.0\%$

[5] The branching ratio B is defined as $B = 1\% \times \mu$

most significant excess to be observed anywhere in the considered $m_{H^\pm}$ range is estimated to be approximately 1.6σ.

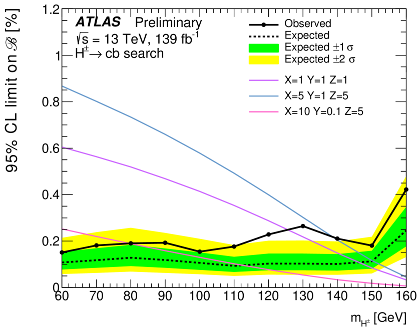

Figure 4: The observed (solid) 95% CL upper limits on $B = B(t \to H^\pm b) \times B(H^\pm \to cb)$ as a function of $m_{H^\pm}$ and the expectation (dashed) under the background-only hypothesis. The green and yellow shaded bands show the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties on the expected limits. The predictions from 3HDM are also shown [4].

4. Summary

A search for $H^\pm \to cb$ in top-quark decays is presented. The search uses a dataset of pp collisions collected at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC with total integrated luminosity of 139 fb^{-1}. In the absence of a significant excess of data events above the background expectation, model-independent exclusion limits at 95% CL on $B = B(t \to H^\pm b) \times B(H^\pm \to cb)$ are reported. The observed (expected) limits vary between 0.15% (0.09%) and 0.42% (0.25%) for $m_{H^\pm}$ between 60 GeV and 160 GeV. The largest excess in data corresponds to about 3σ for $m_{H^\pm} = 130$ GeV and a global p-value corresponding to 1.6σ in the considered $m_{H^\pm}$ range.

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References

[1] A. G. Akeroyd and et al., *Light charged Higgs boson scenario in 3HDMs*, PoS (2016) 024 [1612.05194].

[2] ATLAS collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** (2008) S08003. 437 p.

[3] ATLAS collaboration, *Search for charged Higgs bosons decaying into a top quark and a bottom quark at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, JHEP **06** (2021) 145 [2102.10076].

[4] ATLAS Collaboration. *ATLAS-CONF-2021-037* [https://cds.cern.ch/record/2779169].

[5] ATLAS collaboration, *Jet energy scale measurements and their systematic uncertainties in proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, Phys. Rev. D **96** (2017) .

[6] ATLAS collaboration, *Measurement of the $t\bar{t}t\bar{t}$ production cross section in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector*, 2106.11683.