PROCEEDINGS OF SCIENCE

Search for $W' \to tb$ decays in the hadronic final state with the ATLAS detector

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A search for W' production with decay to a top quark and a bottom quark in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector is presented. The hadronic decay of the top quark is identified using DNN-based boosted-object techniques. The dominant background is obtained by a data-driven method with small systematic uncertainties. The results are presented as upper limits on the W' production cross-section times the top-bottom channel branching ratio for several W' masses ranging from 1.5 to 5 TeV.

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1. Introduction

A model-independent search for new physics Beyond the Standard Model (BSM) at the Large Hadron Collider is to select events with significant invariant mass in different combinations of jets and leptons, which is a signature of heavy resonance decay. One example is the W' boson. With its mass and couplings as free parameters, the W' can represent charged vector bosons seen in BSM scenarios such as the Little Higgs models [1], extra-dimensional models with Kaluza-Klein excitations of the W boson [2], and Topflavor models [3]. This analysis conducted by the ATLAS collaboration [4] focuses on a W' coupling exclusively to right-handed quarks (W'_R) with the electroweak coupling constant. It explores the decay $W' \to tb$ (meaning both $W'^+ \to t\bar{b}$ and $W'^- \to \bar{t}b$), motivated by models in which the W' couples preferentially to the third generation, as in the Topflavor model. The observation of the top-quark is through its decay to a bottom quark and a W boson. The two quarks from the subsequent W boson decay and the accompanying b quark (the hadronically decaying top) is the top quark decay channel focused by this analysis.

2. The W' reconstruction

The all-hadronic channel in the search for $W' \to tb$ consists of a b quark from the W' and a second b quark plus two light quarks from the top quark. According to QCD, final-state quarks and gluons undergo parton showers, giving rise to collimated hadrons traveling in close directions to the original quarks, thus leaving an image of a jet. At the ATLAS experiment, reconstructed jets are collections of hadronic calorimeter clusters within a radius parameter R. A small-R jet with R = 0.4 is used to cluster parton showers from a quark or a gluon. Since the mass range of interests for the W' in this analysis is at the TeV scale (much higher than the top quark mass), the three top-decay quarks are close in angles due to the Lorentz boost, and thus a large-R jet with an R of 1 is employed to contain the overlapping energy spread of the three quarks into one reconstructed jet.

With the Run-2 ATLAS data equivalent to 139 fb^{-1}, this search considers proton collision events with no leptons, one top-quark-like large-R jet with at least 500 GeV of transverse momentum (p_{T}), and a b-quark-like small-R jet with p_{T} > 500 GeV in the opposite direction, as viewed on the plane perpendicular to the clashing proton beams. The system of a t-associated jet plus a b-associated jet has a TeV-level invariant mass m_{tb}, the signal-probing parameter, where a smoothly falling distribution is expected for the SM backgrounds and a peaking structure around the W' mass for the signal.

3. The identification of jets associated with a top quark or a bottom quark

Thanks to the three contained quarks, a large-R jet originating from a top quark displays a three-prong energy profile, unlike the single-core structure in a large-R jet emitting by a light quark or a gluon. A Deep Neural Network (DNN) combines various jet substructure variables, jet mass, and jet p_{T} as input, outputting the top-tagging score for which a top-quark-emitted large-R jet assumes high scores [5]. Such a jet has a probability of 80% to pass a threshold called the 80% working point (80% WP) and then labeled as the **top-candidate jet**. We drop events with more than one top-candidate jet to reduce background events from top-quark pair production ($t\bar{t}$).

For the data-driven background estimation, discussed in the next section, the highest p_T small-R jet among those with a $\Delta\phi > 2$ from the top-candidate jet is declared the ***b*-candidate jet**. The identification of the b-candidate jet from b-quark is performed by a b-tagging algorithm considering charged particle tracks around small-R jets [6]. The hadrons formed by the hadronization of a b-quark travels a distance resolvable by the ATLAS inner detectors tracking charged particles from the b hadron decay.

4. Data-driven background estimation

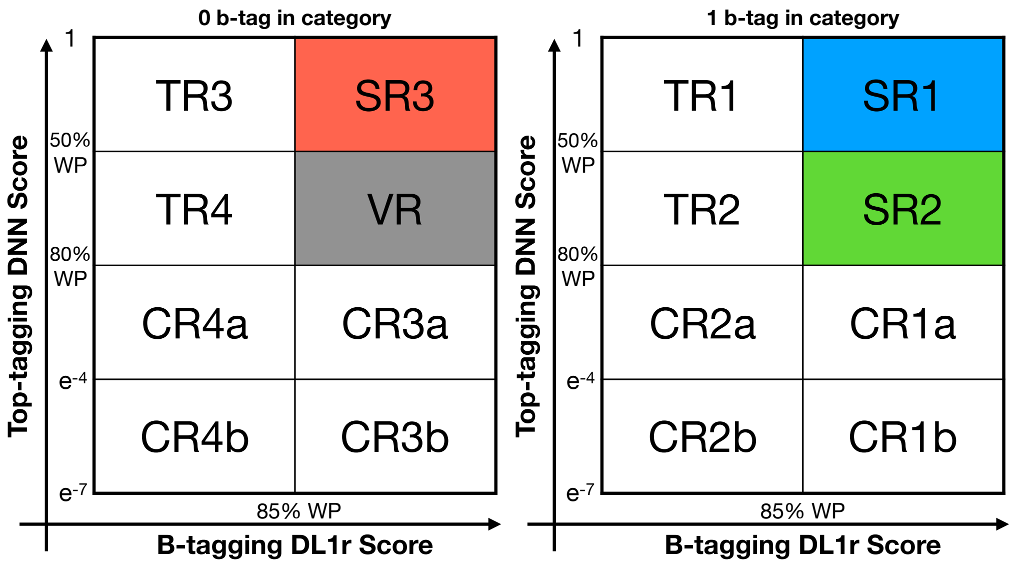

Figure 1: Signal Regions (SR1 to 3), Validation Region (VR), Template Regions (TR1 to 4), and Control Regions (CR1a to 4a and CR1b to CR4b) are defined by the top-tagging working points for the top-candidate jet (upper 2 rows), the associated DNN score for the top-proxy jets(lower 2 rows), the b-tagging status (2 columns), and whether or not there are b-tagged small-R jets inside the top-candidate or top-proxy jets (yes on the right grid, no on the left). Taken from Ref. [7].

With the abundant quarks and gluons produced in proton collisions, the dominant background to this analysis is the QCD production of multi-jet, estimated by a data-driven method. Events with only one top-candidate jet are divided into the signal and template regions with negligible signal events. The b-candidate jet in the former satisfies a threshold admitting about 85% of the b-quark-initiated small-R jets (b-tagged at the 85% WP). Control regions are constructed by considering events with no top-candidate jets but large-R jets with $p_T > 500$ GeV and a top-tagging DNN score $> e^{-7}$: the **top-proxy jets**. Each top-proxy jet is paired with a b-candidate jet like the top-candidate jet for separating control regions distinct ones by the same 85% WP. Given that the b-candidate jets in the multi-jet events are primarily due to light-quarks or gluons, the ratio between data in these two control regions measures the b-tag rates for the dominant multi-jet events as a function of m_{tb}, regardless of the large-R jet's top-tagging condition. By multiplying the rates bin-by-bin with the distribution of QCD multi-jet plus minor background in the template region (data subtracting the $t\bar{t}$ events), we obtain the data-driven background estimation for the signal region.

Figure 1 shows the final sets of regions after three steps of classification: b-tagged small-R jets counts inside the top-candidate or top-proxy jets duplicate the grid of the top-tagging versus b-tagging scores into two; the 50% working point doubles the number of signal regions and the corresponding template regions for the multi-jet background estimation; the control regions are subdivided by a top-tagging DNN requirement of e^{-4} on the top-proxy jets. The former two selections enhance the search sensitivities, while the last is used for systematic uncertainties in the data-driven method. According to simulation, the top-proxy-defining threshold of e^{-7} effectively restricts the composition of quarks and gluons among the b-candidate jets in data. The residual variation of b-tagging rates is thus treated as a systematic uncertainty, estimated by the double ratios among the control regions. The multi-jet background, which exhibits a rather flat shape in the top-tagging score, motivating the creation of the high score control regions by the score of e^{-4} for the nominal background estimation for each category. The region for cross-checking, the validation regions, are demoted from a signal region for its lack of signal events.

5. Reconstructed W' mass

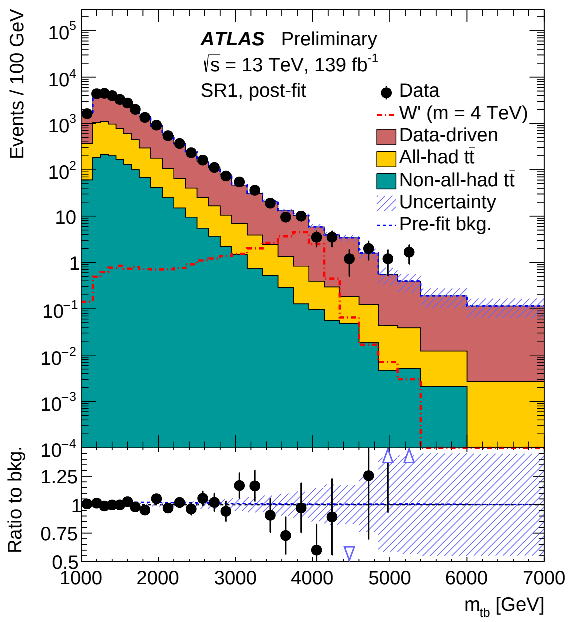

Figure 2: Invariant mass distribution in the signal region SR1 after a profile-likelihood fit of the background model with data. A right-handed W' with 4 TeV, shown by a red dashed histogram has an area given by the predicted cross-section times branching ratio, multiplied by the acceptance, efficiencies and the integrated luminosity. Thee blue dashed lines shows the total background pre-fit. The hatched bands include the background systematic plus statistical uncertainties. Taken from Ref. [7].

Figure 2 compares data to the predicted background distribution in region SR1 (with the highest signal-to-background ratio) after a background-only fit. The background shown by the stacked histogram is dominated by the data-driven estimate (pale red), seconded by the $t\bar{t}$ events with two hadronically top quarks (green). The yellow band shows the $t\bar{t}$ background with at least one leptonically-decaying top quark. The bottom panel shows that the ratio of data to the total background is consistent with the systematic plus statistical uncertainties.

6. Exclusion upper limit

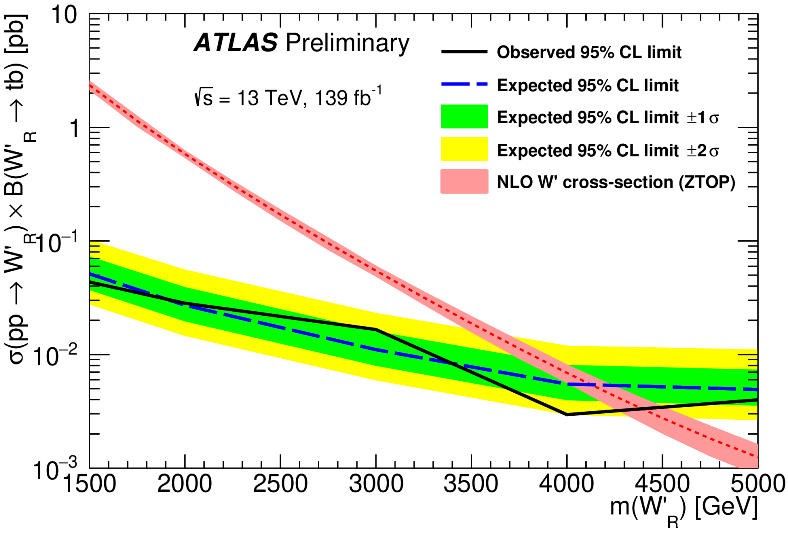

Figure 3: The exclusion upper limit on the W'_R production times the tb decay branching ratio at the 95% confidence level as a function of the W'_R mass. The red band include the theory uncertainties from Parton Distribution Functions, the strong coupling constant, renormalization and factorization scale, and the top quark mass. Taken from Ref. [7].

We compute the exclusion upper limit for different W' masses from 1.5 to 5 TeV to interpolate a limit curve, as depicted in Figure 3. The black line is the observed limit calculated with data; the blue dashed lines is obtained by treating the total background distribution as data, surrounded by yellow (green) bands of one-sigma (two-sigma) uncertainties. The intersection of the black curve with the red theory curve allows us to exclude a right-handed W', having the same coupling to quarks as the SM W boson while not interacting with leptons, up to 4.4 TeV. The theoretical cross-section is computed by the ZTOP framework [8, 9]. For more details about this analysis, please refer to the conference note [7].

7. Summary

A search for a right-handed W' boson is performed in the final state of a hadronically-decaying top quark plus a bottom quark, using the 139 fb^{-1} data collected by the ATLAS experiment at the LHC. No excess from the SM background is observed. The W'_R production cross-section times branching ratio limit is set, excluding the W' mass up to 4.4 TeV.

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