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Search for $tb$ resonances in proton-proton collisions at $\sqrt{s} = 7 \text{ TeV}$ with the ATLAS detector

The ATLAS Collaboration

Abstract

This Letter presents a search for $tb$ resonances in 1.04 fb$^{-1}$ of LHC proton-proton collision data collected by the ATLAS detector at a center-of-mass energy of 7 TeV. Events with a lepton, missing transverse momentum, and two jets are selected and the invariant mass of the corresponding final state is reconstructed. The search exploits the shape of the $tb$ invariant mass distribution compared to the expected Standard Model backgrounds. The model of a right-handed $W'_R$ with Standard Model-like couplings is chosen as the benchmark model for this search. No statistically significant excess of events is observed in data, and upper limits on the cross section times the branching ratio of $W'_R$ resonances at 95% CL lie in the range 6.1–1.0 pb for $W'_R$ masses ranging from 0.5 to 2.0 TeV. These limits are translated into a lower bound on the allowed right-handed $W'_R$ mass, giving $m_{W'_R} > 1.13 \text{ TeV}$ at 95% CL.
Search for $tb$ resonances in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

The ATLAS Collaboration

This Letter presents a search for $tb$ (or $\bar{t}\bar{b}$) resonances using data collected in 2011 by the ATLAS detector at the Large Hadron Collider (LHC), corresponding to an integrated luminosity of $1.04 \pm 0.04 \text{ fb}^{-1}$ from $pp$ collisions at a center-of-mass energy of 7 TeV. These resonances include new heavy gauge bosons such as the $W'$ boson. The $W'$ boson is a charged heavy gauge boson that is predicted in many extensions of the Standard Model (SM) such as universal extra dimensions [4] and little Higgs models [5]. If the $W'$ boson is assumed to have similar coupling strengths to those of the SM $W$ boson, searches in the $W' \to \ell\nu$ decay channel, where $\ell$ is a charged lepton, are the most sensitive. However, the $W' \to t\bar{b}$ channel is competitive if $W' \to \ell\nu$ decay is suppressed. For example, for a right-handed $W_R'$ this can happen if the right-handed neutrino, $\nu_R$, is heavy enough to prevent $W_R' \to \ell\nu_R$ decay [6]. The model of a right-handed $W_R'$ with SM-like couplings is chosen as the benchmark model for the analysis presented in this Letter. The $W_R' \to t\bar{b}$ decay channel has been searched for at the Tevatron [4, 5]. The best previous limit on a $W_R'$ with Standard Model-like couplings of the $W'$ to quarks was set by the D0 experiment and excludes a $W_R'$ mass below 890 GeV at 95% confidence level.

The innermost part of the ATLAS detector [6], a tracking system in a 2 T axial magnetic field, measures the momentum of the charged particles produced in the collisions. Outside of the solenoid are the calorimeter subsystems, which measure the electron, photon, and hadronic particle energies, and the muon spectrometer which is used to identify and measure the momentum of muons in a toroidal magnetic field. A three-level trigger system [10] reduces the event rate and selects the events for analysis.

The $tb$ resonances are searched for in the $t\bar{b}$ ($\ell\nu bb$ decay channel, where the lepton, $\ell$, is either an electron or a muon. $W_R'$ signal events are simulated to leading order (LO) with the PYTHIA v6.421 [11] Monte Carlo (MC) generator, using the MRST2007 LO* parton distribution functions (PDFs) [12]. Seven signal samples are simulated, with different $W_R'$ mass assumptions, ranging from 500 GeV to 2.0 TeV, as reported in Table I. The respective signal cross section times the branching ratio values are computed at next-to-leading-order (NLO) [13], using CTEQ6.6 PDFs [14].

<table>
<thead>
<tr>
<th>(m_{W_R'}) [GeV]</th>
<th>(B(W_R' \to t\bar{b}))</th>
<th>(\sigma \times B) [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>0.298 ± 0.002</td>
<td>54.6 ± 2.1</td>
</tr>
<tr>
<td>750</td>
<td>0.319 ± 0.001</td>
<td>10.9 ± 0.6</td>
</tr>
<tr>
<td>1000</td>
<td>0.326 ± 0.001</td>
<td>2.92 ± 0.18</td>
</tr>
<tr>
<td>1250</td>
<td>0.328 ± 0.001</td>
<td>0.91 ± 0.07</td>
</tr>
<tr>
<td>1500</td>
<td>0.330 ± 0.001</td>
<td>0.31 ± 0.03</td>
</tr>
<tr>
<td>1750</td>
<td>0.331 ± 0.001</td>
<td>0.11 ± 0.01</td>
</tr>
<tr>
<td>2000</td>
<td>0.332 ± 0.001</td>
<td>0.044 ± 0.005</td>
</tr>
</tbody>
</table>

TABLE I: NLO branching ratios, $B(\ell\nu bb \rightarrow t\bar{b})$, and $W_R'$ production cross section times the branching ratio value, $\alpha_{\gamma p \rightarrow W_R}' \times B(\ell\nu bb \rightarrow t\bar{b})$, in $pp$ collisions at 7 TeV center-of-mass energy [13]. The uncertainties on the branching ratios are due to the top quark mass uncertainty. The uncertainties on the cross sections include statistical, $\alpha_t$, NLO renormalization and factorization scales, and PDF uncertainties.

Data-driven methods and MC simulated samples are used to estimate and model backgrounds. The $t\bar{t}$ process is simulated with the MC@NLO v3.41 [13, 14] MC generator, assuming a top quark mass of 172.5 GeV, and using the CTEQ6.6 PDFs. The parton shower is added using the HERWIG [17] and JIMMY [18] MC generators. The $tt$ cross section is obtained from the approximate NNLO prediction calculated with the HATHOR program [19] using the MSTW2008 NNLO PDF sets [20]. The single top quark processes are simulated using the ACERMC v3.7 [21] MC generator and hadronization is performed with the PYTHIA MC generator; the cross section is calculated to approximate NNLO using the CTEQ6.6 PDFs. Diboson processes are simulated...
using the HERWIG v6.5 MC generator and their cross sections are obtained at NLO using the MCFM program with the MSTW2008 PDFs. The MC samples simulated with the A C E R M C and HERWIG MC generators use the MRST2007 LO* PDFs. 

Vector boson production in association with jets \( (W^+ \text{ light jets}, \ W \bar{b}, \ W \bar{c}, \ Wc \text{ and } Z+\text{jets with up to five additional partons}) \) is simulated using the ALPGEN v2.13 MC generator, coupled with the CTEQ6L1 PDFs and hadronization is performed with the HERWIG and JIMMY MC generators. In these samples, additional jets can be created from the parton shower. In order to avoid double counting between the inclusive \( W + n \) parton samples and the parton shower, overlaps are removed following the MLM matching prescription. A cross section correction factor is applied to the LO \( W/Z+\text{jet} \) cross sections computed by comparing the LO and NLO predictions from the FEWZ program. The \( Wc \) cross section correction factor is obtained using the MCFM program with the CTEQ6.6 PDFs. All samples are passed through the full simulation of the ATLAS detector based on GEANT4 and are then reconstructed using the same procedure as collision data. The simulated samples include the effect of multiple \( pp \) collisions per bunch crossing (pile-up) which on average is six events per bunch crossing. In order to ensure a good description of the energy scale and resolution, the trigger, the reconstruction and identification efficiency, corrections based on comparisons between data and MC events are applied to the simulated signal and background samples. The corresponding scale factors are obtained as a function of the object kinematics, resulting in final corrections of the order of a few percent.

Candidate events are identified using single high transverse momentum electron and muon triggers and stringent detector and data quality requirements. For each candidate, two jets, one isolated charged lepton, and missing transverse momentum, \( E_{T}^{\text{miss}} \), are required. The definition of the objects and details of a similar event selection including lepton isolation requirements are given in Ref. [31]. The reconstructed charged lepton is required to have a transverse momentum \( p_T > 25 \text{ GeV} \) to ensure a constant trigger efficiency, \(|\eta| < 2.5 \) for a muon and \(|\eta| < 2.47 \) for an electron (the calorimeter transition region \(1.37 < |\eta| < 1.52 \) is excluded), and to lie within \( \Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.15 \) of the corresponding triggered lepton. Jets are reconstructed from energy clusters in the calorimeters with the anti-k_t algorithm with a radius parameter \( R = 0.4 \) and calibrated to the hadronic energy scale. Exactly two jets with \( p_T > 25 \text{ GeV} \) and \(|\eta| < 2.5 \) are required in the event, and at least one of them must be tagged as a b-jet. The b-tagging algorithm uses measurements of the impact parameters of tracks and the properties of reconstructed vertices; these are combined in a neural network to extract a tagging decision for each jet. Based on a \( t\bar{t} \) MC sample, the working point is chosen at a b-tagging efficiency of 57%, leading to a light-quark tagging probability of 0.2% derived from the same sample. To account for the differences between observed and simulated jet \( p_T \) and \( \eta \) distributions, the b-tagging efficiency and the corresponding scaling factors to be applied to MC are derived from data. Events before applying any b-tagging are referred to as pre-tagged events. Events where one or both jets are b-tagged are referred to as single- or double-tagged events respectively.

The \( E_{T}^{\text{miss}} \) is calculated using calorimeter energy clusters calibrated according to the reconstructed physics object to which they are associated; events are required to satisfy \( E_{T}^{\text{miss}} > 25 \text{ GeV} \). The background contribution from multiple hadron jets (multijet background) is reduced by imposing a requirement on the sum of the \( W \) boson transverse mass \( m_{T}(W) \) and \( E_{T}^{\text{miss}} \): \( m_{T}(W) + E_{T}^{\text{miss}} > 60 \text{ GeV} \). After applying all selection criteria, the acceptance times efficiency for \( W \) signal events with \( m_{W}\nu = 1.0 \text{ TeV} \) is 1.38% for single-tagged events and 0.49% for double-tagged events.

One of the most important backgrounds for the \( tb \) resonance search comes from \( W \) production in association with either heavy-flavor jets, or light-flavor jets misidentified as b-jets. Multijet production is another source of background, when either a hadronic jet is misidentified as a lepton, or when a real high-\( p_T \) lepton from semileptonic decay of a heavy hadron within a jet fulfills the selection requirements. Another important background comes from \( tt \) pair production in the case that one \( W \) boson decays leptonically and the decay products of the other \( W \) boson are lost due to the detector acceptance. Other smaller backgrounds come from single top production, diboson production and \( Z+\text{jet} \) events.

Kinematic variable distributions for the \( W+\text{jet} \) background are taken from MC samples, while the overall normalization and flavor composition are derived from data; this is done after rejecting signal-like events with the \( t\bar{b} \) invariant mass, \( m_{tb} \) which is described later, satisfying \( m_{tb} > 500 \text{ GeV} \). In each jet multiplicity bin, the number of \( W+\text{jet} \) events in the data is assumed to be the difference between the number of observed data events and the number of events estimated for SM non-\( W+\text{jet} \) processes including the multijet process estimated from a data-driven method. The overall \( W+\text{jet} \) normalization factor is the ratio of the number of \( W+\text{jet} \) events in the data to the number of \( W+\text{jet} \) events in simulation. The flavor composition of the \( W+\text{jet} \) background is estimated by comparing the MC prediction to data while its dependence on jet and b-tagging multiplicity is modeled using MC. The fractions of \( Wb, Wc, Wc \) and \( Wc+\text{light jet} \) components of the total \( W+\text{jet} \) MC are scaled such that the background sum equals the observed data in three separate samples: a single-tagged one-jet sample and the pre-tagged and single-tagged two-jet samples. The same scale factor is used for \( Wb \) and \( WC \).
The multijet background normalization and the shape of each distribution are obtained from data. The shape of each multijet background distribution is taken from a data sample which requires a jet instead of an isolated lepton. This jet is required to have a detector signature similar to an electron: it must have $p_T > 25$ GeV and between 80% and 95% of its energy deposited in the electromagnetic section of the calorimeter. The jet must also be associated with at least four tracks. The normalization is estimated using a binned likelihood fit to the $E_T^{\text{miss}}$ distribution in data in which the normalization of the $W+J$ and the multijet components is allowed to vary. The fit is performed separately in the pre-tagged, single- and double-tagged samples, after applying all selection criteria except the $E_T^{\text{miss}}$ cut. The uncertainty on the multijet rate is 50% for pre-tagged and single-tagged events, while it amounts to 100% for double-tagged events. The uncertainty is estimated by using the $m_T(W)$ distribution instead of the $E_T^{\text{miss}}$ distribution in the binned likelihood fit, and by using multijet background models built from data samples with low and high numbers of $p\bar{p}$ collisions per event.

The $t\bar{t}$, single top, $Z+J$ and diboson events are normalized to the theoretical cross sections and the shape of each distribution is taken from the MC simulation.

Based on the theoretical predictions shown in Table II, the numbers of single- and double-tagged $W_T^\prime$ signal events expected in 1.04 fb$^{-1}$ are listed in Table II as a function of $m_{W_T^\prime}$. Table III lists the expected background yields.

### Table II: Predicted signal event yields derived using the theoretical cross sections.

<table>
<thead>
<tr>
<th>$m_{W_T^\prime}$ [GeV]</th>
<th>Single-tagged</th>
<th>Double-tagged</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>973 ± 37</td>
<td>455 ± 17</td>
</tr>
<tr>
<td>750</td>
<td>174 ± 9</td>
<td>77 ± 4</td>
</tr>
<tr>
<td>1000</td>
<td>42 ± 3</td>
<td>15 ± 1</td>
</tr>
<tr>
<td>1250</td>
<td>11 ± 1</td>
<td>3.9 ± 0.3</td>
</tr>
<tr>
<td>1500</td>
<td>3.2 ± 0.3</td>
<td>1.0 ± 0.1</td>
</tr>
<tr>
<td>1750</td>
<td>1.0 ± 0.1</td>
<td>0.26 ± 0.03</td>
</tr>
<tr>
<td>2000</td>
<td>0.36 ± 0.04</td>
<td>0.09 ± 0.01</td>
</tr>
</tbody>
</table>

### Table III: Predicted background event yields compared to the total observed event yields for single- and double-tagged two-jet events in 1.04 fb$^{-1}$ of data.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Single-tagged</th>
<th>Double-tagged</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W+J$</td>
<td>5970 ± 1000</td>
<td>290 ± 180</td>
</tr>
<tr>
<td>Multijets</td>
<td>1120 ± 560</td>
<td>47 ± 47</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>1560 ± 130</td>
<td>360 ± 30</td>
</tr>
<tr>
<td>Single top</td>
<td>1240 ± 90</td>
<td>120 ± 10</td>
</tr>
<tr>
<td>Diboson, $Z+J$</td>
<td>320 ± 120</td>
<td>14 ± 2</td>
</tr>
<tr>
<td>Total prediction</td>
<td>10200 ± 1200</td>
<td>830 ± 190</td>
</tr>
<tr>
<td>Data</td>
<td>10428</td>
<td>844</td>
</tr>
</tbody>
</table>

The $t\bar{t}$, single top, $Z+J$ and diboson events are normalized to the theoretical cross sections and uncertain ties. The background acceptance (rate uncertainty) is evaluated by scaling $1\sigma$ up or down the energy of each jet. The $b$-tagging scale factors are $p_T$-dependent and have an uncertainty between 8% and 20%. The multijet background uncertainty has already been described. The uncertainty on the normalization of the $W+J$ background and its flavor composition include...
both systematic contributions and a statistical contribution from the limited size of the sample. The $W+$jet flavor uncertainties are treated as fully correlated between $Wb\bar{b}$ and $Wc\bar{c}$ and uncorrelated otherwise. Theoretical cross section uncertainties for the top ($tt\bar{t}$ and single top), diboson and $Z+$jet backgrounds of 10%, 5% and 60% are assigned, respectively. The $Z+$jet theoretical cross section uncertainty is estimated based on the variation of ALPGEN parameters, and a relative uncertainty of 50% on the heavy-quark contributions, but it has a very small impact on the result due to the small contribution of $Z+$jet events. Systematic uncertainties due to the residual differences between data and MC simulation for the reconstruction and energy calibration of jets, electrons and muons are estimated to have a small impact on the result. The uncertainty on the integrated luminosity is 3.7% [3]. The uncertainty on the background modeling in the $m_t\bar{t}$ distribution is evaluated using pre-tagged data and found to be negligible.

An uncertainty due to the MC event generator is estimated by comparing MC@NLO and POWHEG [45, 46] for $tt\bar{t}$ and AcerMC and MC@NLO for single top events. The uncertainty in parton shower modeling is estimated by comparing two POWHEG $tt\bar{t}$ samples for which the hadronization is performed by PYTHIA or HERWIG. Uncertainties from modeling the amount of initial and final-state QCD radiation are also taken into account. The uncertainty due to the specific choice of PDFs in the simulated events is determined by re-weighting the MC events using the NNPDF20, MSTW2008 and CTEQ6.6 [20] eigenvector PDF sets. Finally, an uncertainty to account for the limited MC sample sizes is also included.

No significant data excess is identified for any value of $m_t\bar{t}$, and an upper limit on the $W' \rightarrow t\bar{b}$ production cross section ($\sigma$) times the $B(W'_R \rightarrow t\bar{b})$ values from Table I has been scaled by a factor of 10. The effect of the jet energy scale (JES) uncertainty on the predicted background is shown, as are the data statistical uncertainties. The bin width is constant in $\log(m_t\bar{t})$. The highest bin in each plot includes overflows.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The distribution of $m_{t\bar{t}}$ for single-tagged (top) and double-tagged (bottom) two-jet events in data compared to Standard Model expectations. The expected $W'_R$ signal, normalized to the theoretical cross section times the $B(W'_R \rightarrow t\bar{b})$ values from Table I, has been scaled by a factor of 10. The effect of the jet energy scale (JES) uncertainty on the predicted background is shown, as are the data statistical uncertainties. The bin width is constant in $\log(m_{t\bar{t}})$. The highest bin in each plot includes overflows.}
\end{figure}

\textbf{ACKNOWLEDGEMENTS}

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We thank Z. Sullivan for discussions on the $W'$ model and for providing NLO signal cross section calculations.

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FIG. 2: 95% CL limit on the cross section, $\sigma(pp \rightarrow W'_R)$, times branching ratio for $W'_R \rightarrow tb$ as a function of the $W'$ boson mass. The theory curve is also shown.

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[9] In the ATLAS coordinate system the pseudorapidity, $\eta$, is defined as $\eta = -\ln[tan(\theta/2)]$, where $\theta$ is measured with respect to the $z$-axis, defined to be parallel to the beam. The azimuthal angle, $\phi$, is measured with respect to the $x$-axis, which points towards the center of the LHC ring, and the $y$-axis points upwards.

[42] The W boson transverse mass is defined as $m_T(W) = \sqrt{2p_T^l E_T^{miss}(1 - \cos \Delta \phi)}$, where $p_T^l$ is the $p_T$ of the lepton and $\Delta \phi$ is the azimuthal angle separation between the lepton and $E_T^{miss}$.
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