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Search for tb Resonances in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector

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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 the data, and upper limits on the cross section times the branching ratio of W'_R resonances at 95% C.L. lie in the range of 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 $m_{W'_R} > 1.13$ TeV at 95% C.L.

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This Letter presents a search for tb ($t\bar{b}$ or $\bar{t}b$) resonances using data collected in 2011 by the ATLAS detector [1] at the Large Hadron Collider (LHC), corresponding to an integrated luminosity of 1.04 ± 0.04 fb^{-1} [2,3] 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 ℓ is a charged lepton, are the most sensitive. However, the $W' \to tb$ 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 ν_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 $W'_R \to tb$ decay channel has been searched for at the Tevatron [7,8]. 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 [9], 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 $tb \to \ell\nu bb$ decay channel, where the lepton ℓ 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].

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[15,16] 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 $t\bar{t}$ cross

TABLE I. NLO branching ratios, $\mathcal{B}(W'_R \to tb)$, and W'_R production cross section times the branching ratio value, $\sigma(pp \to W'_R) \times \mathcal{B}(W'_R \to tb)$, 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, α_s, NLO renormalization and factorization scales, and PDF uncertainties.

$m_{W'_R}$ [GeV]	$\mathcal{B}(W'_R \to tb)$	$\sigma \times \mathcal{B}$ [pb]
500	0.298 ± 0.002	54.6 ± 2.1
750	0.319 ± 0.001	10.9 ± 0.6
1000	0.326 ± 0.001	2.92 ± 0.18
1250	$0.328 < 0.001$	0.91 ± 0.07
1500	$0.330 < 0.001$	0.31 ± 0.03
1750	$0.331 < 0.001$	0.11 ± 0.01
2000	$0.332 < 0.001$	0.044 ± 0.005

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section is obtained from the approximate next-to-next-to-leading order (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 [22–24] 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 [25] program with the MSTW2008 PDFs. The MC samples simulated with the ACERMC and HERWIG MC generators use the MRST2007 LO* PDFs. Vector boson production in association with jets ($W+$ light jets, $Wb\bar{b}$, $Wc\bar{c}$, Wc, and $Z+$ jets with up to five additional partons) is simulated using the ALPGEN V2.13 [26] MC generator, coupled with the CTEQ6L1 PDFs [14] 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 [27]. A cross section correction factor is applied to the LO $W/Z+$ jet cross sections computed by comparing the LO and NLO predictions from the FEWZ [28] program. The Wc cross section correction factor is obtained using the MCFM [29] program with the CTEQ6.6 PDFs. All samples are passed through the full simulation of the ATLAS detector [30] based on GEANT4 [31] and are then reconstructed using the same procedure as collision data. The simulated samples include the effect of multiple pp collisions per bunch crossing (pileup) 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 the missing transverse momentum $E_T^{\rm miss}$ are required. The definition of the objects and details of a similar event selection, including lepton isolation requirements, are given in Ref. [32]. The reconstructed charged lepton is required to have a transverse momentum $p_T > 25$ GeV to ensure a constant trigger efficiency, $|\eta| < 2.5$ for a muon [33–35] and $|\eta| < 2.47$ for an electron [36] (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 [37] with a radius parameter $R = 0.4$ and calibrated to the hadronic energy scale [38]. Exactly two jets with $p_T > 25$ 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 [39]. 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 η, distributions, the b-tagging efficiency and the corresponding scaling factors to be applied to MC simulations are derived from data [40]. Events before applying any b tagging are referred to as *pretagged* events. Events where one or both jets are b tagged are referred to as *single-* or *double-tagged* events, respectively.

The $E_T^{\rm miss}$ is calculated using calorimeter energy clusters [41] calibrated according to the reconstructed physics object to which they are associated [42]; events are required to satisfy $E_T^{\rm miss} > 25$ 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 $m_{\rm T}(W)$ [43] and $E_T^{\rm miss}$: $m_T(W) + E_T^{\rm miss} > 60$ GeV [32]. After applying all selection criteria, the acceptance times efficiency for W'_R signal events with $m_{W'_R} = 1.0$ 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 $t\bar{t}$ 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 $Z+$ jet events.

Kinematic variable distributions for the $W+$ 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 tb invariant mass m_{tb}, which is described later, satisfying $m_{tb} > 500$ GeV. In each jet multiplicity bin, the number of $W+$ 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-$W+$ jet processes including the multijet process estimated from a data-driven method. The overall $W+$ jet normalization factor is the ratio of the number of $W+$ jet events in the data to the number of $W+$ jet events in simulation. The

TABLE II. Predicted signal event yields derived using the theoretical cross section times the branching ratio values for $W'_R \to tb$, for single- and double-tagged two-jet events in 1.04 fb^{-1} of data. The uncertainties correspond to the NLO cross section uncertainties [13].

$m_{W'_R}$ [GeV]	Single-tagged	Double-tagged
500	973 ± 37	455 ± 17
750	174 ± 9	77 ± 4
1000	42 ± 3	15 ± 1
1250	11 ± 1	3.9 ± 0.3
1500	3.2 ± 0.3	1.0 ± 0.1
1750	1.0 ± 0.1	0.26 ± 0.03
2000	0.36 ± 0.04	0.09 ± 0.01

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. All W + jet samples are scaled by the factors determined from data, with the uncertainties also derived from data. The multijet estimation is from the fitting method with a 50% (100%) uncertainty for single- (double-) tagged events. All the other predictions are derived using the theoretical cross sections and uncertainties.

Samples	Single-tagged	Double-tagged
W + jets	5970 ± 1000	290 ± 180
Multijets	1120 ± 560	47 ± 47
$t\bar{t}$	1560 ± 130	360 ± 30
Single top	1240 ± 90	120 ± 10
Diboson, Z + jets	320 ± 120	14 ± 2
Total prediction	10 200 ± 1200	830 ± 190
Data	10 428	844

flavor composition of the W + jet background is estimated by comparing the MC prediction to data while its dependence on jet and b-tagging multiplicity is modeled using MC simulations. The fractions of $Wb\bar{b}$, $Wc\bar{c}$, Wc, and W + light jet components of the total W + jet MC simulations are scaled such that the background sum equals the observed data in three separate samples: a single-tagged one-jet sample and the pretagged and single-tagged two-jet samples. The same scale factor is used for $Wb\bar{b}$ and $Wc\bar{c}$.

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 $E_T^{\rm miss}$ distribution in data in which the normalization of the W + jet and the multijet components is allowed to vary. The fit is performed separately in the pretagged, single-, and double-tagged samples, after applying all selection criteria except the $E_T^{\rm miss}$ cut. The uncertainty on the multijet rate is 50% for pretagged 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 $E_T^{\rm miss}$ distribution in the binned likelihood fit, and by using multijet background models built from data samples with low and high numbers of pp collisions per event.

The $t\bar{t}$, single top, Z + jet, 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 I, the numbers of single- and double-tagged W'_R signal events expected in 1.04 fb^{-1} are listed in Table II, as a function of $m_{W'_R}$. Table III lists the expected background yields.

The tb invariant mass is used as the observable to discriminate signal from background. The neutrino momentum in the decay $tb \to \ell\nu bb$ is computed assuming the transverse component to be equal to $E_T^{\rm miss}$, and extracting the longitudinal component (p_z) by constraining the ℓ-ν invariant mass to $m_W = 80.42$ GeV. This gives a quadratic equation in p_z and the solution with the smaller $|p_z|$ is used. If the solution is complex, only the real part is taken and the imaginary part is neglected.

Figure 1 shows the data and expected background distributions of m_{tb} for single- and double-tagged two-jet events. The data event with the highest m_{tb} value corresponds to a single-tagged event with $m_{tb} \simeq 2.0$ TeV. The BUMPHUNTER tool [44] is used to search for a local excess in the data due to the production of a tb resonance. This tool is used to test the consistency of the data with the SM background only hypothesis, comparing the data to the SM prediction over the spectrum of the tb invariant mass, scanning over sliding mass windows from 0.5 to 2.0 TeV. The width of the mass windows is chosen to be constant in $\log(m_{tb})$ as shown in Fig. 1 to deal with low background MC statistics in the higher mass bins. This comparison has been performed for single- and double-tagged events separately. The region with the highest data-background difference is 1024–1129 (764–842) GeV for single (double)-tagged events. The probability of observing the SM background fluctuating up to or above the number of observed data events in these regions is 0.66 for single-tagged events and 0.72 for double-tagged events. These values, which are based on the statistical error only, indicate that there is no significant evidence for tb resonances in the observed data.

Systematic uncertainties from various sources affecting the background and the signal acceptance (rate uncertainty), as well as shape changes in the invariant mass distribution (shape uncertainty) are considered.

The jet energy scale and the uncertainty on the b-tagging scale factors are the dominant systematic uncertainties for the signal. The background normalization yields are the dominant systematic uncertainty for the background

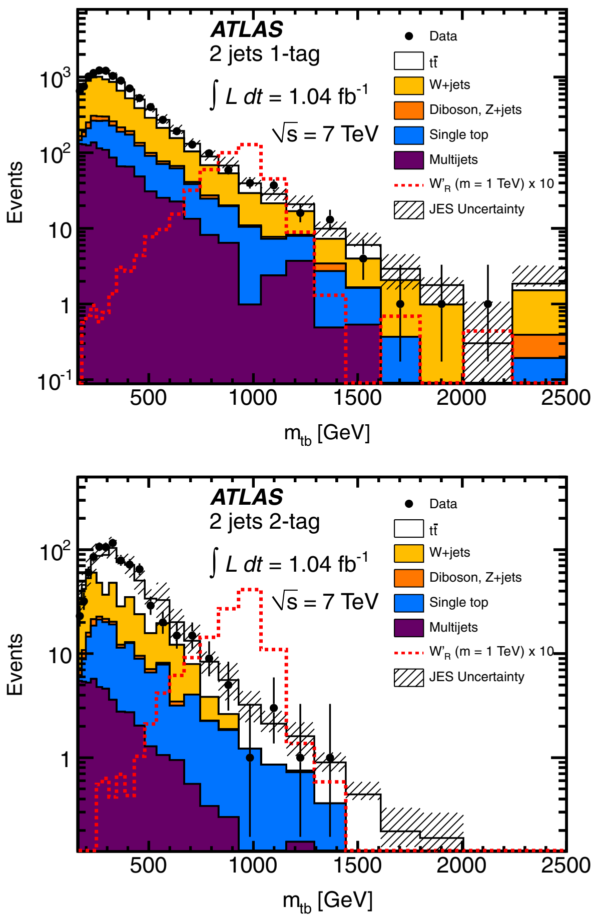

FIG. 1 (color online). The distribution of m_{tb} for single-tagged (top) and double-tagged (bottom) two-jet events in data compared to standard model expectations. The expected W_R' signal, normalized to the theoretical cross section times the $\mathcal{B}(W_R' \to tb)$ values from Table I, has been 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 $\log(m_{tb})$. The highest bin in each plot includes overflows.

contribution. The jet energy scale uncertainty is evaluated by scaling 1σ 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 + jets 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 ($t\bar{t}$ 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_{tb} distribution is evaluated using pretagged 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 $t\bar{t}$ and ACERMC and MC@NLO for single top events. The uncertainty in parton shower modeling is estimated by comparing two POWHEG $t\bar{t}$ 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 reweighting 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_{tb}, and an upper limit on the $W_R' \to tb$ production cross section (σ) times the $\mathcal{B}(W_R' \to tb)$ at 95% credibility-level (C.L.) is determined using a Bayesian approach assuming flat priors [47]. The likelihood function used is the product of the Poisson probabilities over all mass bins [48] per channel. The combination of single- and double-tagged events is done by extending the likelihood function; the joint likelihood is the product of Poisson probabilities for each individual bin in each channel. Systematic and statistical uncertainties are incorporated and treated as nuisance parameters with a Gaussian probability density function. Figure 2 shows the observed and the expected limits from single- and double-tagged events combined. Observed (expected) upper limits obtained on $\sigma(pp \to W_R') \times \mathcal{B}(W_R' \to tb)$ at 95% C.L. lie in the range

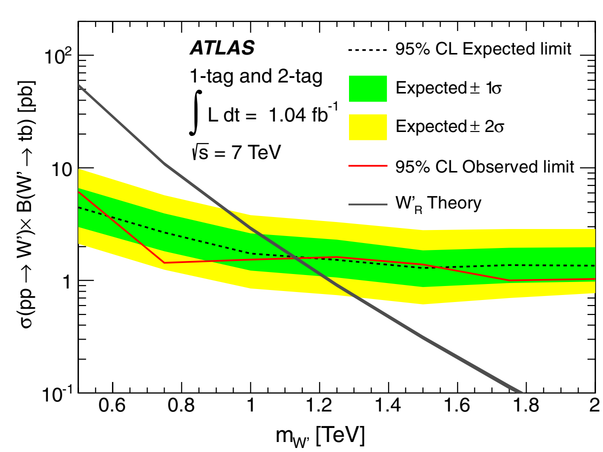

FIG. 2 (color online). 95% C.L. limit on the cross section, $\sigma(pp \to W_R')$, times branching ratio for $W_R' \to tb$ as a function of the W' boson mass. The theory curve is also shown.

6.1–1.0 (4.5–1.4) pb for W'_R masses ranging from 0.5 to 2.0 TeV. These $\sigma \times \mathcal{B}$ limits are also applicable to a left-handed W'. The $\sigma \times \mathcal{B}$ limits are converted into mass limits using the intersection between the theoretical $\sigma \times \mathcal{B}$ curve as a function of $m_{W'_R}$ and the expected and observed $\sigma \times \mathcal{B}$ limit curves. The corresponding observed (expected) 95% C.L. lower limit is $m_{W'_R} > 1.13(1.13)$ TeV. These are currently the most stringent direct limits on production of $W'_R \to tb$.

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