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Search for vector-boson resonances decaying to a top quark and a bottom quark with the ATLAS experiment at LHC

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Summary. — A recent search for heavy resonances, namely W' bosons, decaying to a top quark and a bottom quark with a lepton and missing transverse momentum plus jets in the final state is presented. The analysed data come from proton-proton collision and correspond to an integrated luminosity of 36.1 fb^{-1} collected with the ATLAS detector at the Large Hadron Collider at $\sqrt{s} = 13$ TeV. No significant excess of data over the Standard Model prediction is found and the results are expressed as upper limits on the $W' \to t\bar{b}$ production cross-section times branching ratio as a function of the W' boson mass. The production of right-handed W' bosons is excluded at 95% confidence level for masses below 3.15 TeV. A prospect for this search at the high luminosity LHC is also reported, showing the expected sensitivity for an integrated luminosity of 3000 fb^{-1} and a centre-of-mass of $\sqrt{s} = 14$ TeV.

1. – Introduction

1˙1. *Motivation.* – Various extensions of the Standard Model (SM) introduce new charged vector currents mediated by heavy gauge bosons, usually referred to as W' bosons. For instance W' bosons are predicted as Kaluza-Klein excitations of the SM W bosons in the universal extra dimensions [1-3], or as a right-handed version of the SM W boson in the models that extend the fundamental symmetries of the SM [4-6]. The W' bosons also appear in Little-Higgs [7] and Composite-Higgs theories [8, 9].

We present a search for W' bosons decaying to a top quark and a bottom quark, generally denoted as $W' \to t\bar{b}$(1). This decay channel is of particular interest. First, it explores models potentially inaccessible to searches where a W' boson decays into leptons. For example, in the right-handed sector, the W' boson cannot decay into a charged lepton and a hypothetical right-handed neutrino if the latter has a mass greater than the W' boson mass. Second, the W' boson is expected to couple more strongly

(1) The notation $t\bar{b}$ is used to describe both the $W'^{+} \to t\bar{b}$ and $W'^{-} \to \bar{t}b$ processes.

to the third generation of quarks than to the first and second generations according to several theories beyond the SM [10, 11].

1˙2. *$W' \to t\bar{b}$ search in an effective coupling approach.* – In order to achieve the most general approach with the theory we rely on an effective model describing the couplings of the W′ boson to the fermions, defined as follow:

$$\mathcal{L} = \frac{V'_{ij}}{2\sqrt{2}} g \bar{f}_i \gamma_\mu \left[g'_R(1+\gamma^5) + g'_L(1-\gamma^5) \right] W'^\mu f_j + h.c. \tag{1}$$

where the parameter g'_R (g'_L) represents the coupling constant of W' to left-(right-) handed fermions ($\bar{f}_i, f_j$), g is the SM weak coupling constant, and V'_{ij} is the Cabibbo-Kobayashi-Maskawa(δ_{ij}) matrix for quarks(leptons).

We search for right-handed W' bosons, W'_R, using data from proton collisions collected by the ATLAS detector [12] at the LHC.

2. – Search for $W' \to t\bar{b}$ in final states with an lepton plus jets using 36.1 fb^{-1}

2˙1. *Overview.* – This search is performed using data collected during the period 2015–2016 by the ATLAS detector at the LHC, corresponding to an integrated luminosity of 36.1 fb^{-1} at a centre-of-mass energy of 13 TeV. This search covers a mass range of 0.5 to 5.0 TeV. The W'_R bosons are searched in the semileptonic decay channel, where the W'_R decays into a top quark and a b-quark, the top quark decays into a W boson and a b-quark, and the W boson decays in turn into a lepton and a neutrino. The final-state signature therefore consists of two b-quarks, one charged lepton and a neutrino, which is undetected and results in missing transverse momentum, E_T^{miss}.

The dominant backgrounds come from the production of a pair of top quark ($t\bar{t}$) and W boson produced in association with jets (W + jets). Other considered backgrounds are productions of single top, Z boson in association with jets (Z + jets), pair of bosons (diboson), and multijet production. Every background is estimated using Monte Carlo (MC) simulation except for multijet, where a data-driven approach (matrix method) is used.

We reconstruct the W'_R boson mass using the invariant mass of the top and bottom quarks ($m_{t\bar{b}}$), and use the $m_{t\bar{b}}$ distributions to fit the expected prediction to data, and also to derive limits on the production cross section of the W'_R boson.

2˙2. *Reconstruction of the W'_R candidate* . – The particular feature of a W' signal is a resonant structure in the $t\bar{b}$ invariant mass. The top quark is reconstructed from the combination of the charged lepton, the neutrino, and the jet that gives the best top quark mass reconstruction. We assume that all of the missing energy of the selected event is carried by one single neutrino, hence the E_T^{miss} is used to obtain the xy-components of the neutrino momentum. Constraining the invariant mass of the neutrino and associated charged lepton to the W boson mass (80.4 GeV) provides a quadratic equation for the z-component of neutrino momentum. The four-momentum of the top quark candidate is reconstructed by adding the four-momenta of the W boson candidate and the jet that yields the invariant mass closest to the top quark mass. The jet used to form the top quark candidate is referred to as "b_2". Finally, the four-momentum of the candidate W' boson is reconstructed by adding the four-momentum of the reconstructed top quark candidate and the four-momentum of the highest p_T remaining jet (referred to as "b_1").

TABLE I. – *Event selection criteria used to define signal and validation regions.*

SR	$\mathrm{VR}_{\mathrm{pretag}}$	$\mathrm{VR}_{t\bar{t}}$	$\mathrm{VR}_{\mathrm{HF}}$
2 or 3 jets 1 or 2 b-tag $\Delta R(\ell, b_2) < 1.0$ $m_{tb} > 500$ GeV	2 or 3 jets ≥ 0 b-tag (pretag)	4 jets 1 or 2 b-tag	2 or 3 jets 1 b-tag $\Delta R(\ell, b_2) > 2.0$ $\Delta R(b_1, b_2) > 1.5$

2˙3. *Event selection.* – Candidate events are required to have exactly one charged lepton, two to four jets with at least one of them b-tagged and a minimum E_T^{miss} threshold that depends on the lepton flavor. A set of category based on the number of jets and b-tagged jets is used to define a signal region (SR) and three validation regions (VR) enriched with background events: W+jets ($\mathrm{VR}_{\mathrm{pretag}}$), $t\bar{t}$ ($\mathrm{VR}_{t\bar{t}}$), and heavy flavour ($\mathrm{VR}_{\mathrm{HF}}$). The SR and VR are labelled as X-jet Y-tag, where X = 2,3,4 and Y = pretag,1,2 and separated for electron and muon channel selections. An event selection common to all signal and validation regions is defined as: $p_T(\ell) > 50$ GeV, $p_T(b_1) >$ 200 GeV, $p_T(\mathrm{top}) > 200$ GeV, E_T^{miss} >30 GeV, $m_T^W + E_T^{miss} > 100$ GeV, where m_T^W is the transverse mass of the W boson. To suppress the multijet background coming from misindentified electrons, the E_T^{miss} threshold is raised to 80 GeV in the electron channel. Additional selections used to define the SR and VR are given in table I.

The efficiency in selecting events in SR for a W'_R signals is shown in fig. 1. The maximum SR signal efficiency, 11.3%, is obtained for a mass of 1.5 TeV, then the efficiency decreases for higher masses to 5.3% at 5 TeV. This decrease is due to the loss of b-tagging efficiency for high p_T jets and the higher boost at higher mass where leptons and jets get close to each other. The muon channel outperforms the electron channel due to overlap removal requirements, as they are relaxed by using a variable ΔR cone size. The

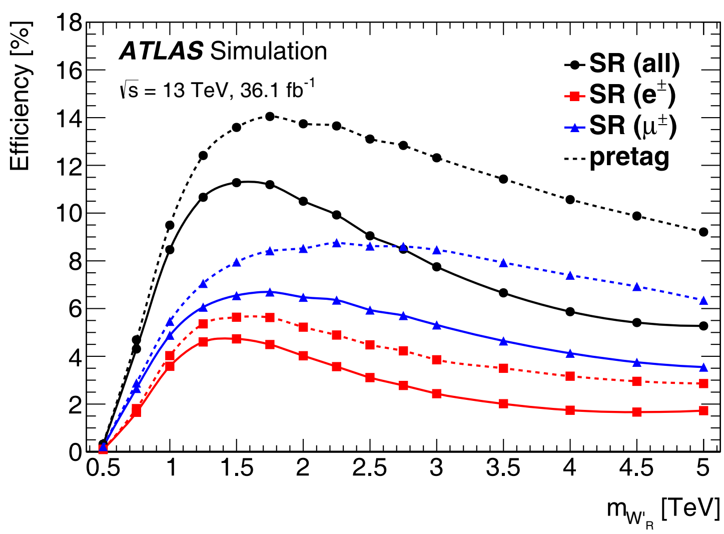

Fig. 1. – Signal selection efficiencies [13].

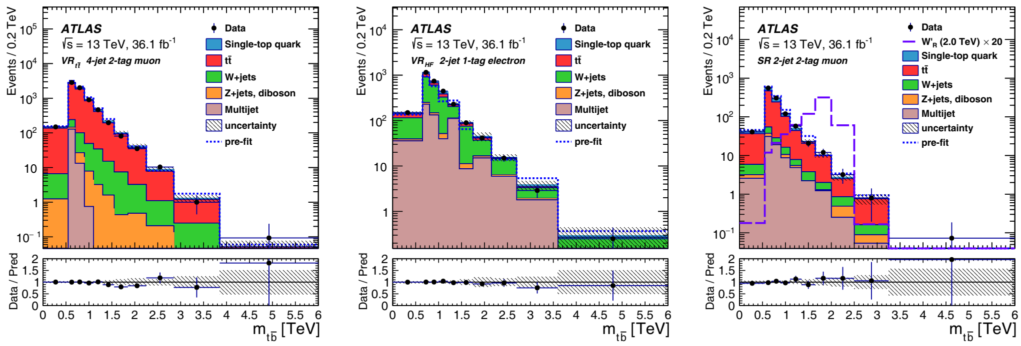

Fig. 2. – Reconstructed $m_{t\bar{b}}$ distributions in the (left) 4-jet 2-tag muon $\mathrm{VR}_{t\bar{t}}$, (middle) 2-jet 1-tag electron $\mathrm{VR}_{\mathrm{HF}}$, and (right) 2-jet 2-tag muon SR [13].

variable ΔR cone size is not used for electrons because of the possible double counting of the energies of electron and jet. Figures 2 show the $m_{t\bar{b}}$ distribution in different regions.

2˙4. *Results and interpretations.* – The $m_{t\bar{b}}$ distributions from signal and background simulated events are fitted to data in the eight SR (simultaneously) using binned maximum-likelihood (ML) approach, including statistical and systematic uncertainties as nuisance parameters. The normalizations of the $t\bar{t}$ and W+jets backgrounds are free parameters in the fit and their fitted rates relative to their nominal predictions are found to be 0.98 $\pm$ 0.04 and 0.78 $\pm$ 0.19, respectively. For a W'_R boson with a mass of 2 TeV the total expected uncertainty in estimating the signal strength([2]) is 12%. The largest systematic uncertainties come from MC generator choice for $t\bar{t}$ events (4.0%), jet energy scale (2.8%), $t\bar{t}$ showering (2.8%). The total systematic uncertainty is 9%. For resonances with a mass of 2.5 TeV or above, the data Poisson uncertainty becomes the largest uncertainty, while the total systematic uncertainty is dominated by the uncertainty on the b-tagging efficiency.

Figure 2 on the right shows an agreement between data and the Standard Model expectation within uncertainties after the fit. The binning of the $m_{t\bar{b}}$ distribution is chosen to optimise the search sensitivity while minimising statistical fluctuations. As no significant excess of events is observed above the predictions, upper limits at the 95% confidence level (CL) are set. The limits on the production cross section multiplied by the branching fraction for $W'_R \to t\bar{b}$ are set assuming the W'_R coupling g' is equal to the SM weak coupling constant g. The existence of W'_R bosons with masses below 3.15 TeV is excluded at 95% CL. The result is shown in the left side of fig. 3. The right side of fig. 3 shows limits on the ratio of couplings g'/g as a function of the W'_R boson mass, derived from the limits on the W'_R boson cross section. The effect of increasing W'_R width for coupling values of $g'/g > 1$ is included for signal acceptance and differential distributions. Above $g'/g \approx 5$, the W' model is no more perturbative. The lowest observed limit on g'/g, obtained for a W'_R boson mass of 0.75 TeV, is 0.13. More details can be found in ref. [13].

([2]) The signal strength is defined as the ratio of the signal cross section estimated using the data to the predicted signal cross section.

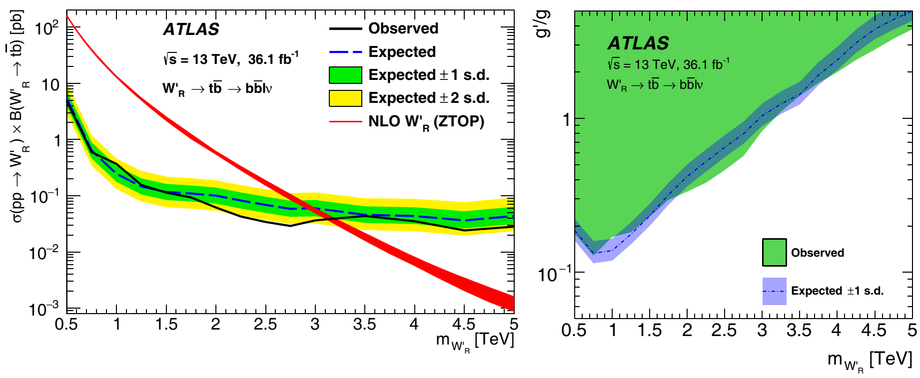

Fig. 3. – Left: Upper limits at the 95% CL on the W'_R production cross section times the $W'_R \to t\bar{b}$ branching fraction as a function of resonance mass, assuming $g'/g = 1$ [13]. Right: Observed and expected 95% CL limit on the ratio g'/g, as a function of resonance mass, for right-handed W'_R coupling [13].

3. – Prospect for $W' \to t\bar{b}$ search in final states with an lepton plus jets at HL-LHC

We now present prospects for $W' \to t\bar{b}$ resonance searches at the high luminosity (HL) with 3000 fb^{-1} proton-proton collision data at a centre-of-mass energy of 14 TeV. The analysis strategy used in this prospect study is very similar to the data analysis explained in sect. **2** and relies on MC simulation. All MC simulated processes are considered. The multijet background is also present but it is very small and further suppressed by applying dedicated selections, and it will be neglected in the following.

The presence of a massive resonance is tested by simultaneously fitting the $m_{t\bar{b}}$ templates of the signal and background simulated event samples using a binned ML approach.

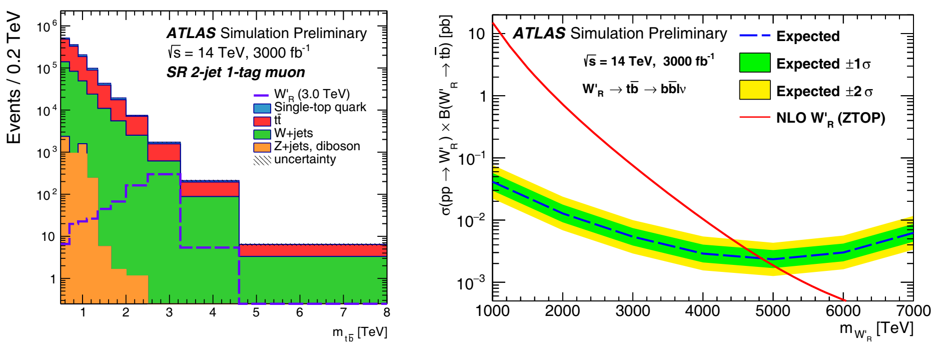

Fig. 4. – Right: Post-fit distributions of the reconstructed mass of the W'_R boson candidate in the 2-jet 2-tag signal region, muon channel [14]. An expected signal contribution corresponding to a W'_R boson mass of 3 TeV is shown.Uncertainty bands include all the systematic uncertainties. Left: Upper limits at the 95% CL on the W'_R production cross section times branching fraction as a function of resonance mass [14]. The dashed curve and shaded bands correspond to the limit expected in the absence of signal and the regions enclosing one/two standard deviation (σ) fluctuations of the expected limit. The theory prediction is also shown.

Systematic uncertainties are evaluated following the analysis of 36.1 fb^{-1} (sect. **2**) and then scaled according to the ATLAS recommendations to match HL-LHC conditions. As an example, the $m_{t\bar{b}}$ distribution for one of the eight signal regions after the ML fit is shown in fig. 4 on the left for the expected background and signal contribution corresponding to a W'_R boson with a mass of 3 TeV.

The existence of W'_R bosons with masses below 4.9 TeV is expected to be excluded at 95% CL, as can be seen in fig. 4 on the right, assuming that the coupling of W'_R to fermions, g' , is equal to the SM weak coupling constant g. This would increase the limit obtained with the analysis of 36.1 fb^{-1} by a factor of 1.8. More details can be found in ref. [14].

4. – Conclusions

A search for $W'_R \to t\bar{b}$ in the lepton and missing transverse momentum plus jets final state is performed using data from $\sqrt{s} = 13$ TeV proton collisions, corresponding to 36.1 fb^{-1} collected with the ATLAS detector at the LHC. No significant excess of events is observed above the SM predictions, thus the upper limits are placed at the 95% CL on the cross section times branching fraction. W'_R masses below 3.15 TeV are excluded. Exclusion limits are also calculated for the ratio of the couplings g'/g and the lowest observed limit, obtained for a W'_R boson mass of 0.75 TeV, is 0.13. The prospect studies at HL-LHC which is expected to run at $\sqrt{s} = 14$ TeV and collect 3000 fb^{-1} of data show that W'_R bosons with masses below 4.9 TeV are expected to be excluded.

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