PROCEEDINGS OF SCIENCE

Searches for vector-like quarks and top-jet resonances with ATLAS

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Three distinct analyses, based on data collected in 2011 by the ATLAS detector with an LHC energy of $\sqrt{s} = 7$ TeV are summarized in the following proceedings. The first involves the search for pair production of vector-like quark singlets (VLS) b' decaying by neutral current, $b' \to Zb$. With 1.98 fb^{-1} of integrated luminosity, and using events with a least one b-tagged jet and a Z boson reconstructed from a pair of opposite charge electrons, a 95% confidence level exclusion is obtained for masses $m(b') < 400$ GeV, assuming that the VLS decays entirely to Zb. The second analysis discussed is the search for single production of vector-like quarks coupling to light generations. With 1.04 fb^{-1} of integrated luminosity, both the charged current (CC) and neutral current (NC) processes, $pp \to Qq \to Wqq'$ and $pp \to Qq \to Zqq'$ with leptonic decays of the vector gauge bosons were analysed. No evidence of heavy vector-like quarks is observed above the Standard Model expectations. For a coupling $\kappa_{Qq} = v/m_Q$, where v is the Higgs vacuum expectation value, limits of 900 GeV and 760 GeV are obtained in the CC and NC channels respectively at 95% confidence level. Finally, the third analysis presented here is a search for a new particle X produced singly in association with a $t(\bar{t})$ quark and decaying to a $\bar{t}(t)$ quark and a light quark. Using the full 2011 LHC luminosity of 4.7 fb^{-1}, the data are found to be in agreement with Standard Model expectation. At 95% confidence level, X masses below 350 (430) GeV for color singlet (triplet) resonances are excluded assuming unit right-handed coupling.

36th International Conference on High Energy Physics,
July 4-11, 2012
Melbourne, Australia

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PoS(ICHEP2012)151

1. Introduction

The results of two vector-like quark searches and one top-jet resonance search using the data of $\sqrt{s} = 7$ TeV pp collisions produced by the LHC and collected by ATLAS [1] will be presented.

Vector-like quarks (VLQ) are defined as quarks for which the left and right chiralities transform identically under the electroweak gauge group $SU(2) \times U(1)$. Various models related to Grand Unification, dynamical electroweak symmetry breaking, and even higher dimensions predict the existence of VLQs [2]. Given the wide range of potential models predicting the existence of VLQs, the two VLQ searches are performed here in a model-independent way by parametrizing their couplings and branching ratios to the known quarks. The first of these VLQ searches probes the existence of down-type vector-like quark singlets b' (VLS) produced in pair and decaying to Zb [3]. This analysis is outlined in section 2. Although precision electroweak and flavor observables generally require VLQs to couple mostly to the third generation, under certain symmetry assumptions, cancellations within the mixing with light quarks can occur alleviating these constraints [4]. VLQs coupling to light quark generations are searched for in the invariant mass spectrum of $W +$ jet and $Z +$ jet events, assuming single production through the exchange of a vector boson [2]. The details of this analysis are given in section 3. The top-quark's large mass, close to the weak scale, suggests that it may play an important role in electroweak symmetry breaking and possibly other new phenomena beyond the Standard Model. Moreover, the recent observation of forward-backward asymmetry in $t\bar{t}$ production at the Tevatron [5, 6] can be interpreted as resulting from the exchange of a top-jet resonance. The search shown in section 4 examines this possibility by probing the $t(\bar{t})$ + jet invariant mass spectrum [7].

2. Search for down-type vector-like quark singlets (VLS)

The search for pair production of a down-type vector-like quark singlet b' coupling to the third generation utilizes 1.98 ± 0.07 fb^{-1} of 2011 LHC data at $\sqrt{s} = 7$ TeV [3]. A b' of sufficient mass has three decay channels: Wt, Hb and Zb which, in the limit of high b' mass, have relative branching ratios scaling as $BR(b' \to Wt) : BR(b' \to Hb) : BR(b' \to Zb) \longrightarrow 2:1:1$. The probability that at least one b' decays to Zb is parametrized by

$$\beta = 2 \times BR(b' \to Zb) - [BR(b' \to Zb)]^2. \tag{2.1}$$

For the search of the decay $b' \to Zb$, with $Z \to e^+e^-$, events were selected using a single electron trigger with p_T exceeding 25 GeV and requiring two oppositely charged reconstructed electrons with an invariant mass within 15 GeV of the Z boson mass. Jets were reconstructed using the anti-k_t clustering algorithm [8] using a radius parameter $R = 0.4$. They were required to have $p_T > 25$ GeV and to be within a pseudorapidity range $|\eta| < 2.5$. A b-tagging algorithm is used to discriminate b-jets from jets originating from light quarks. Using a simulated $t\bar{t}$ sample, it was determined that this algorithm has an efficiency of 60% while its rejection factor for light quarks and gluons is ~ 300.

The main Z + jets backgrounds were simulated with ALPGEN and SHERPA. ALPGEN provided the baseline prediction while SHERPA was used to assess possible shape systematics between generators in their prediction of the $m(Zb)$ invariant mass distribution. Both however were

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normalized to cross-sections computed at NNLO. The $t\bar{t}$ events were simulated with MC@NLO and normalized to the approximate NNLO cross-section computed by HATHOR. $b'\bar{b}'$ signals in the 200 to 700 GeV mass range were generated with MADGRAPH together with the G4LHC extension. The signal cross-sections were also computed by HATHOR.

A further selection on the p_T of the Zb system, $p_T(Zb) > 150$ GeV, was used to enhance the search sensitivity. Once this selection was in place, the invariant mass of the Zb system was obtained and was found to be compatible with the background-only hypothesis. Therefore, limits were computed using a binned Poisson likelihood test for different signal masses and the obtained 95% C.L. limits on the cross-section times branching ratio are shown in figure 1. Hence, with

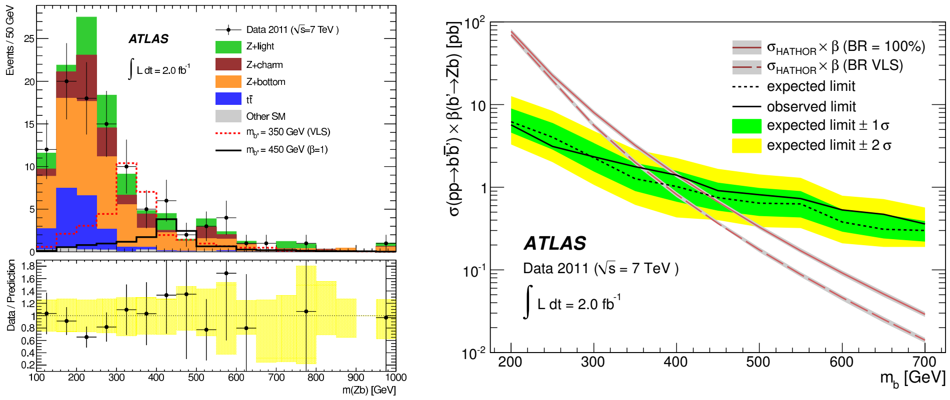

Figure 1: Left: Invariant mass of the Zb system in the signal region defined as events having $Z+\geq 1b$ with $p_T(Zb) > 150$ GeV. Right: upper limits on the $pp \to b'\bar{b}'$ cross-section times the probability β that at least one of the two b' decays to Zb [3].

the assumption that $\beta = 0.63$, an upper limit of $m_{b'} > 358$ GeV is obtained at 95% C.L. If b' decays entirely via $b' \to Zb$, then the upper limit becomes $m_{b'} > 400$ GeV. The main systematics taken into account were renormalization and factorization scales (14%), ALPGEN versus SHERPA shape difference (12%) and b-tagging efficiency (12%).

3. Search for vector-like quarks coupling to light quarks

Presented here is a model-independent search for vector-like quarks coupling to light quarks using 1.04 fb^{-1} of data collected by ATLAS in 2011 with $\sqrt{s} = 7$ TeV pp collisions [2].

The model-independent approach to this search was first outlined in [9], where the coupling of VLQs to light quarks is parametrized via $\kappa_{Qq} = (v/m_Q)\tilde{\kappa}_{Qq}$, where q is either an up or down quark, Q is the VLQ, and where $\tilde{\kappa}_{Qq}$ encodes all possible model dependencies. A baseline model [4] consists of two degenerate VLQ doublets having hypercharges 1/6 and 7/6. Because the doublets are degenerate, cancellations occur and mixings with light quarks do not induce any observable correction to the SM quark couplings. Finally, because these VLQs evade many electroweak precision measurements, the search for a W/Z+jet resonance in single production is favoured over pair production even for small values of κ.

The search is performed in both the charged current (CC) and neutral current (NC) channels and in the electron and muon W and Z boson decay channels. Single lepton triggers with p_T

thresholds of 20 and 18 GeV in the electron and muon channels respectively were used. Leptons were required to have a $p_T > 25$ GeV. As with the previous analysis, the anti-k_t algorithm with an $R = 0.4$ radius size was used to reconstruct jets.

To increase the signal sensitivity in both the CC and NC channels, a set of kinematic requirements were imposed: (i) in the CC channel, a missing transverse momentum $E_T^{\text{miss}} > 50$ GeV, suppressing the multijet background, (ii) one jet with $p_T > 50$ GeV, and (iii) a minimum pseudo-rapidity separation of $|\Delta\eta| > 1.0$ between the highest p_T jet and the second or third jet, since the presence of a forward jet is expected in the dominant t-channel single process, (iv) a transverse mass $m_T(l, E_T^{\text{miss}}) = \sqrt{2E_T^l E_T^{\text{miss}}(1 - \cos\Delta\phi_{l,E_T^{\text{miss}}})} > 40$ GeV since the W boson is expected to be boosted, being the decay product of a heavy VLQ, and (v) an azimuthal angle between the lepton p_T and E_T^{miss} smaller than 2.4 rad. In order to obtain the invariant mass of the lepton + E_T^{miss} + jet system, the longitudinal momentum is calculated by fixing the invariant mass of the W decay products to precisely the mass of the W. For the NC process, the invariant mass of the two opposite sign leptons must be within 25 GeV of the Z mass, and the summed transverse momenta of the two leptons must obey $p_T(l,l) > 50$ GeV since we also expect a boosted Z boson. Applying these requirements on events produces the W/Z + jet invariant mass distributions found in figure 2 for both the charged and neutral current channels. A linear fit is then applied to correct the background from

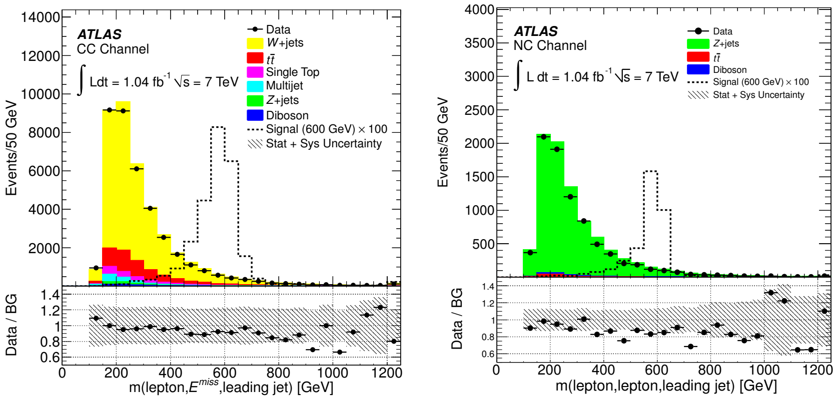

Figure 2: Invariant mass distributions of the $W(Z)+$ highest p_T jet is shown on the left (right) [2].

mis-modeling by Monte Carlo. Since no evidence of a peak over the background was observed, the CL$_S$ method was used to compute upper limits on both the CC and NC process cross-sections. The results are shown in figure 3. The primary uncertainties taken into account were those of the linear fit correction($\sim$ 10%), renormalization/factorization scales (4% to 12% depending on signal mass), and jet energy scale ($\sim$ 20%).

4. Search for t+jet and $\bar{t}$+jet resonances

A hypothetical resonance X coupling to a $t(\bar{t})$ + jet could explain the top anti-top asymmetry measured at the Tevatron if it appears within a t-channel production process. The resonant signal is assumed to not be self-conjugate, thereby evading limits from same sign top quark searches. Two types of signals are probed for in $t\bar{t}$ + jet events. Because quarks dominate over antiquarks at the

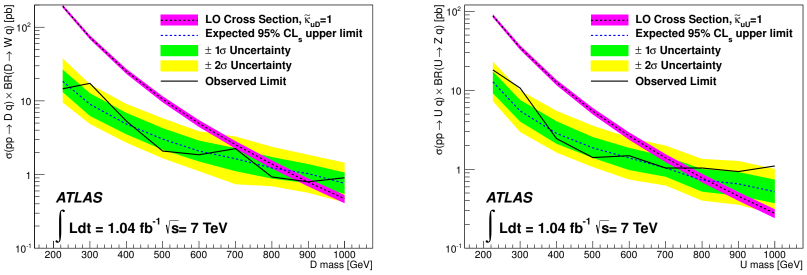

Figure 3: Left: The upper limits on the cross-section times branching ratio $\sigma(pp \to Qq) \times \mathrm{BR}(Q \to Wq)$. The predicted LO signal cross-section assumes $\tilde{\kappa}_{uD} = 1$. Right: The upper limits on the cross-section times branching ratio $\sigma(pp \to Qq) \times \mathrm{BR}(Q \to Zq)$. Similarly, the LO signal cross-section assumes $\tilde{\kappa}_{uU} = 1$ [2].

LHC, higher sensitivity is obtained for a color singlet W' in the $\bar{t}q$ channel and for a color triplet di-quark in the tq final state. The analysis used the full ATLAS 2011 dataset (4.7 fb^{-1}) at $\sqrt{s} = 7$ TeV [7].

The $t\bar{t}$ baseline modeling was obtained using MC@NLO although POWHEG and ACERMC were studied to ascertain various systematics. Vector boson + jet events were also simulated with ALPGEN. Several control regions were defined to verify the modeling of the backgrounds.

The basic event selection requires one of the two W bosons to decay leptonically and the other hadronically, therefore requiring minimally one lepton and five jets in $t\bar{t}$ + jet events. The signal region is defined as also requiring at least one b-tagged jet, $E_T^{\mathrm{miss}} > 30$ GeV (20 GeV) in the electron (muon) channel and one well reconstructed electron (muon) with $p_T > 25$ (20) GeV. Anti-k_t jets with radius $R = 0.4$ are used and are selected if their $E_T > 25$ GeV and $|\eta| < 2.5$. Finally, events must have a $m_T(W) > 30$ GeV in the electron channel and $E_T^{\mathrm{miss}} + m_T(W) > 60$ GeV in the muon channel.

The resulting $m_{\bar{t}j}$ and m_{tj} distributions optimized for a color singlet resonance search are shown in figure 4. Very similar distributions for the case of a color triplet resonance was observed. Given that no excess was found, limits were computed for both the color singlet and color

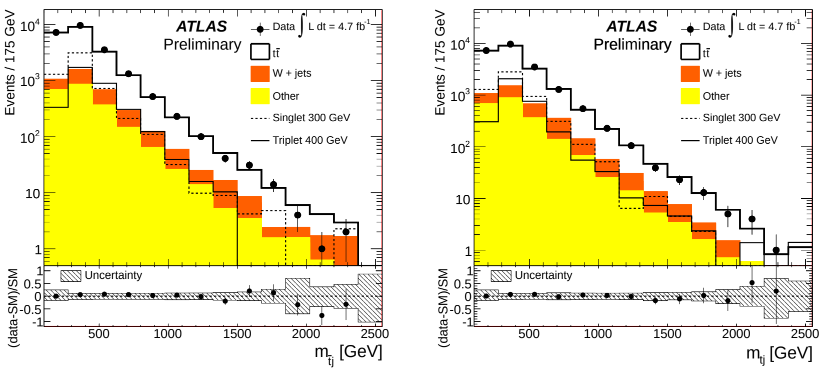

Figure 4: Expected and observed $m_{\bar{t}j}$ (left) and m_{tj} (right) distribution in the signal region. The shown signal assumes unit coupling with the hypothetical X particle. Error bands cover both statistical and systematic uncertainties [7].

triplet type resonances at 95% confidence level. The results of these CL_S based limits are shown in figure 5. The main systematics of the analysis include jet energy scale (21%) and b-tagging

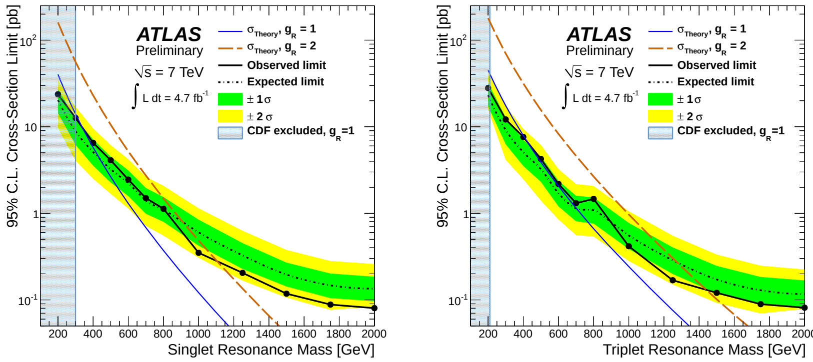

Figure 5: On the left are the 95% C.L. upper limits on the W' singlet cross-section. On the right are 95% C.L. upper limits on the di-quark triplet cross-section [7]. In both cases, two theoretical lines with couplings $g_R = 2$ and $g_R = 1$ are shown as reference along with the previously obtained CDF limits [5].

efficiency (16%).

5. Conclusion

The three ATLAS analyses just described here have pushed the boundaries of existing limits and have very successfully laid the groundwork for future analyses pursuing the search for vector-like quarks and top-jet resonances.

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