Searches for Heavy Quark States at ATLAS

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Abstract. This talk highlights the latest results of heavy quark searches from the ATLAS collaboration, mainly on resonance searches and vector-like quarks (VLQs) searches. Searches for $t\bar{t}$ resonances using lepton-plus-jets events in proton-proton collisions at center-of-mass energy of 8 and 13 TeV are presented. Limits are set for BSM particles such as topcolor-assisted technicolor Z'_{TC}, Kaluza-Klein (K-K) gluons g_{KK} and K-K excitations of graviton G_{KK} in the Randall-Sundrum model of extra dimensions. VLQs arise naturally in many models such as Little Higgs and Composite Higgs and typically couple preferably to the third generation SM quarks and weak bosons. Limits are set for vector-like bottom (B) and top (T) quarks decay to lepton-plus-jets final states via Hb+X and Ht+X channels in two analyses using 8 and 13 TeV datasets from ATLAS.

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1. Introduction

There are two main categories of heavy quark searches at ATLAS [1]. Firstly, there are model-agnostic searches in which we look for resonances such as $X \to t\bar{t}$, $t\bar{b}$ or single $t+E_T^{miss}$. Secondly, there are vector-like quark (VLQ) searches in which we look for either a pair of VLQs or a single VLQ production. This talk intends to give an overview and describe several examples of these two categories of searches.

2. Resonance Searches

2.1. Overview of Resonance Searches at ATLAS

ATLAS has several searches for resonances with different final states. At $\sqrt{s} = 8$ TeV, there is a $t\bar{t}$ resonance search using the lepton-plus-jet final state [2], a $t\bar{b}$ resonance search using the lepton-plus-jet final state [3] and a $t\bar{b}$ resonance search using the $qqbb$ final state [4]. At $\sqrt{s} = 13$ TeV, there is a $t\bar{t}$ resonance search using the lepton-plus-jet final state looking for Z' [5]. The following sections focus on the two $t\bar{t}$ resonance searches using the lepton-plus-jet final state.

2.2. $t\bar{t}$ Resonance Searches: Motivations

Several benchmark models predict new resonances decaying into $t\bar{t}$. For example, the topcolor-assisted technicolor Z', which is a spin-1 color singlet, decays into $t\bar{t}$. In the Kaluza-Klein Randall-Sundrum model, the K-K excitation of gluon g_{KK} decays to $t\bar{t}$ and is a spin-1 color octet. Also, there is the excited graviton G_{KK} which is a spin-2 color singlet and decays to $t\bar{t}$. There are other color singlet scalar particles which also decay into $t\bar{t}$.

The general strategy here is to select $t\bar{t}$ events, then reconstruct the $t\bar{t}$ invariant mass $m_{t\bar{t}}$ and look for an excess or deviation from the Standard Model (SM) predicted $t\bar{t}$ background.

2.3. $t\bar{t}$ Resonance Searches at $\sqrt{s} = 8$ TeV

This analysis uses the 20.3 fb^{-1} of data collected at the ATLAS detector at a center-of-mass energy of 8 TeV in 2012. The events are categorized into two types depending on the topology.

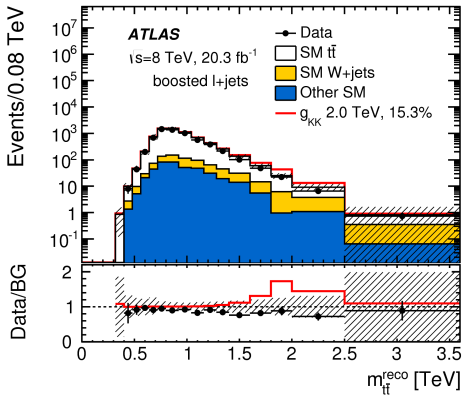

Figure 1. Reconstructed mass spectrum for the boosted topology overlaid with g_{KK} signal at 2.0 TeV. The ratio of data to SM background and signal is shown in the bottom. [2]

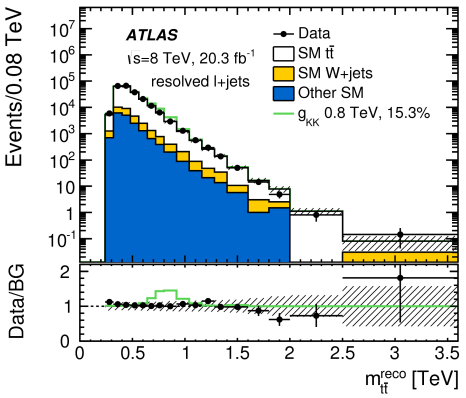

Figure 2. Reconstructed mass spectrum for the resolved topology overlaid with g_{KK} signal at 0.8 TeV. The ratio of data to SM background and signal is shown in the bottom. [2]

The first category is the boosted topology where the hadronic top is reconstructed using the largest p_T large-R jet. At least one small-R jet must be b-tagged and matched to at least one of the top candidates. The semi-leptonic top is reconstructed using E_T^{miss}, lepton, and the largest p_T small-R jet near jet. Events that failed to meet the requirement for the boosted topology will pass to the selection for the resolved topology where at least 4 small-R jets are required and at least one of them has to be b-tagged. In both categories, the b-tagged jet has to match to either the hadronic-top jet, the leptonic-top jet or both, otherwise it is discarded. The reconstructed mass $m_{t\bar{t}}^{reco}$ spectrum is scanned for deviations from the SM expectation as shown in figures 1 and 2. The search is performed on 6 boosted, 6 resolved and 6 combined channels and a deviation is required in all channels at the same place.

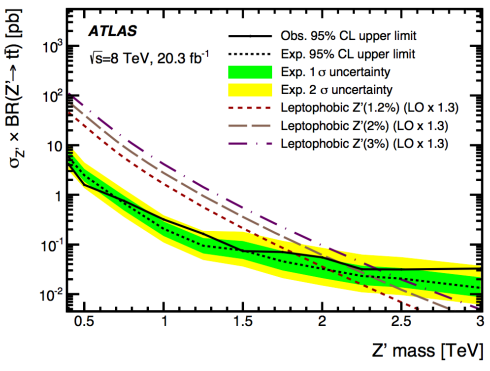

Figure 3. Limit plot for cross-section times branching fraction as a function of the Z' mass. [2]

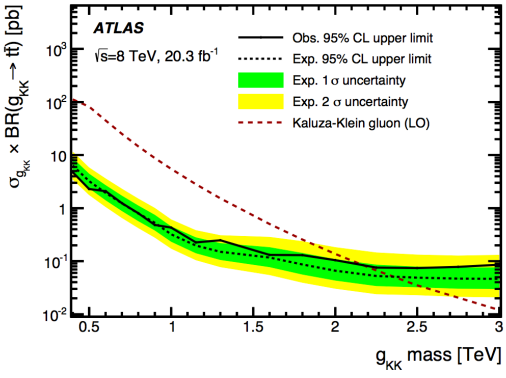

Figure 4. Limit plot for cross-section times branching fraction as a function of the g_{KK} mass. [2]

No excess above the SM prediction is observed. Cross-section limits are set for different benchmark models. In particular, the topcolor-assisted technicolor Z' has been excluded between 0.4 TeV and 1.8 TeV at 95% confidence level (CL). The K-K gluon in the R-S model g_{KK} has been excluded between 0.4 TeV and 2.2 TeV at 95% CL. The corresponding limit plots are shown in figures 3 and 4. This analysis is not sensitive enough to set any limit to the K-K graviton or the color singlet scalar particle.

2.4. $t\bar{t}$ Resonance Searches at $\sqrt{s} = 13$ TeV

This analysis uses 3.2 fb^{-1} data collected at the ATLAS detector at $\sqrt{s} = 13$ TeV in 2015. In each event, exactly one lepton is reconstructed and must match candidates that triggered the event. For the leptonic-top b-jet, at least one small-R jet is reconstructed in the $\Delta R(l, \text{jet}) < 1.5$ cone. For the hadronic-top jet, at least one top-tagged large-R jet is reconstructed in the $\Delta\phi(l,$ large-R jet$) > 2.3$ and $\Delta\phi($leptonic-top jet, large-R jet$) > 1.5$ region. In addition, at least one b-tagged small-R jet is reconstructed.

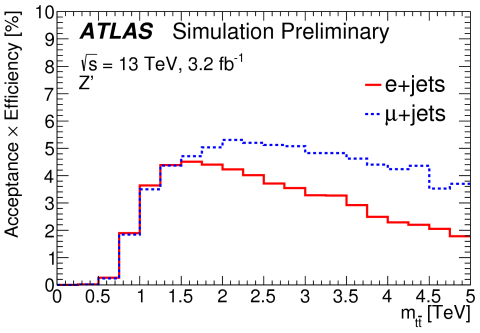

Figure 5. Acceptance times efficiency for the e+jets and μ+jets channels as a function of the Z' mass. [5]

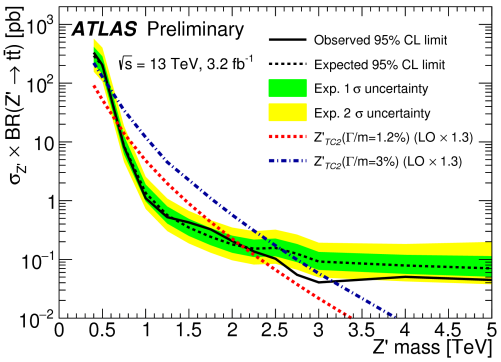

Figure 6. Limit plot for cross-section times branching fraction as a function of the reconstructed Z' mass. [5]

The acceptance times efficiency for e+jets and μ+jets channels as a function of reconstructed mass $m_{t\bar{t}}$ is shown in figure 5. The e+jets channel has lower acceptance times efficiency for $m_{t\bar{t}}$ above 1.5 TeV because of the inefficiency of e^- ID and overlap removal in highly boosted top quarks. The major sources of systematic uncertainties are the large-R jet energy scale, the light flavor and charm jet mistag rate and luminosity. No excess above the SM prediction is observed. The topcolor-assisted technicolor Z' has been excluded from 0.7 TeV to 2.7 TeV at 95% CL and the corresponding limit plot is shown in figure 6.

3. Vector-like Quark (VLQ) Searches

3.1. VLQ Searches: Motivations

VLQs that arise naturally in models alternative to supersymmetry such as the Little Higgs [6, 7] and the Composite Higgs [8, 9] have no Yukawa coupling to the newly discovered Higgs boson and are therefore not constrained by the recent Higgs measurements. They typically couple preferentially to the third generation quarks and can have flavor-changing neutral current decays. They can be pair-produced via QCD below 1 TeV and can be dominated by single production at high mass, depending on the weak couplings to the gauge bosons. Depending on the models, 4 types of VLQs exist. They include the vector-like T ($Q = +2/3$), B ($Q = -1/3$), X ($Q = +5/3$) and Y ($Q = -4/3$) quarks. The branching ratio of B and T quarks for different models are shown in figures 7 and 8.

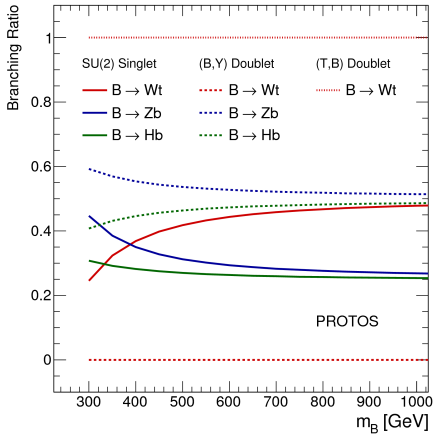

Figure 7. Branching ratio of $SU(2)$ singlet, (B, Y) and (T, B) doublet models as a function of the B quark mass. [10]

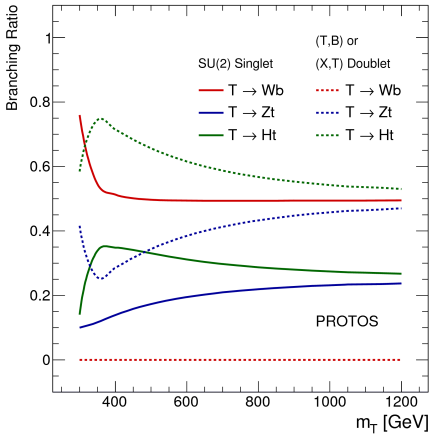

Figure 8. Branching ratio of $SU(2)$ singlet, (T, B) and (X, T) doublet models as a function of the T quark mass. [10]

3.2. Vector-like Bottom (B) and Top (T) Quark Searches at ATLAS

There are several searches for VLQs at ATLAS, each sensitive to different decay modes. At $\sqrt{s} = 8$ TeV, there is one for VLQs that decay into a Z boson and a third-generation quark [11] and another one for the final state of b-jets and a pair of leptons of the same charge [12]. In the following sections, searches for pair production of VLQ and of four top quarks in the lepton-plus-jets final state at 8 TeV [10] and 13 TeV [13] will be described.

3.3. B Quark Search using $Hb \to X$ Decay Mode at 8 TeV

The sample dominated by $t\bar{t}$ is selected and is sub-divided into 8 categories using jet multiplicity n_{jets}, b-multiplicity and the mass of the closest two jets. Background rich regions have low b-multiplicity and signal rich regions are dominated by high b-multiplicity events. The search is done in the distribution of the scalar sum of the transverse momentum of jets, $l^{\pm}$ and E_T^{miss} (H_T). The H_T distribution for the signal rich regions are shown in figure 9.

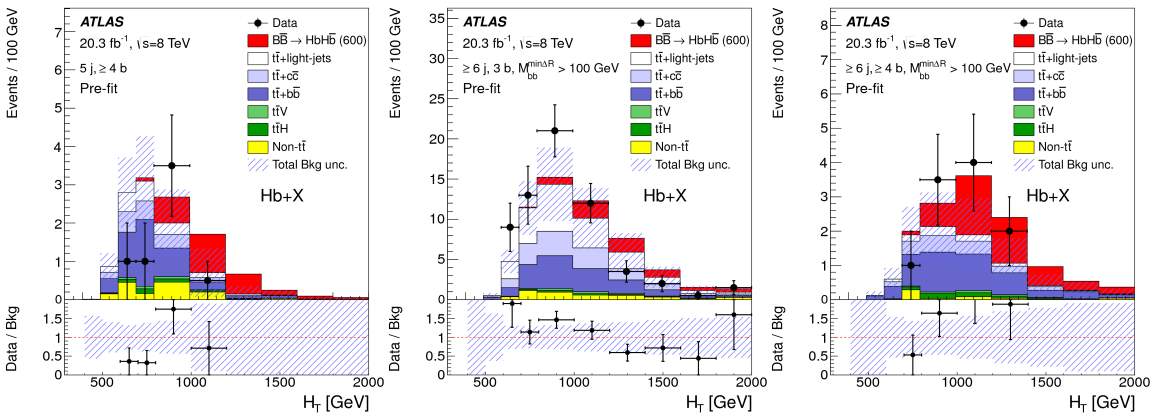

Figure 9. H_T distribution of the signal rich regions. [10]

The major systematic uncertainties are the jet energy scale and the theoretical cross-section. No excess above the SM prediction is observed. Assuming $\mathcal{BR}(B \to Hb) = 1$, m_B is excluded

from 350 GeV to 580 GeV and from 635 GeV to 700 GeV at 95% CL with expected exclusion region below 625 GeV. In the SU(2) singlet model, m_B is excluded below 735 GeV at 95% CL with expected exclusion region below 635 GeV. The results are summarized in the exclusion limit plots as shown in figure 10.

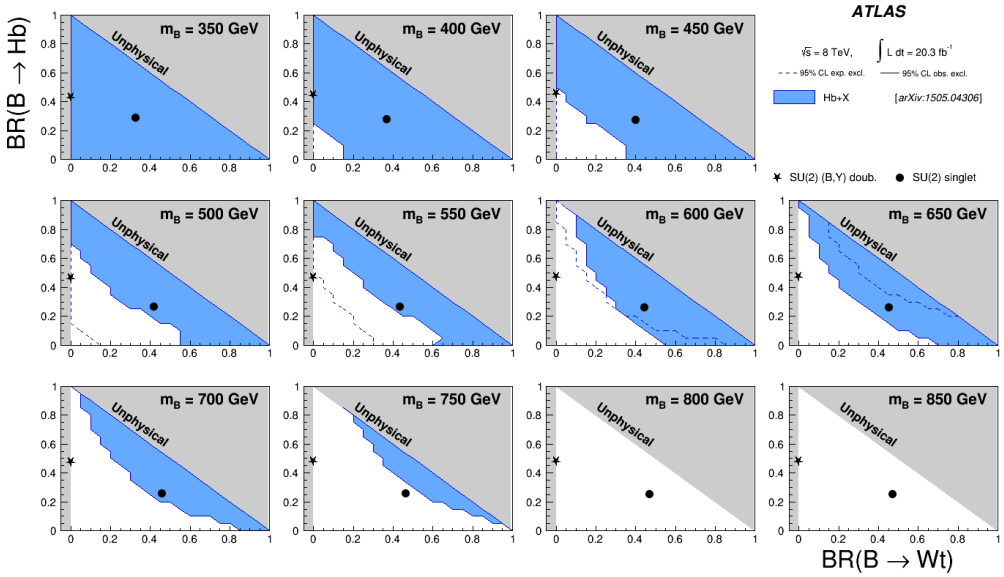

Figure 10. 2D exclusion limit plots of $\mathcal{BR}(B \to Hb)$ vs $\mathcal{BR}(B \to Wt)$ for the B quark mass m_B ranging from 350 GeV to 850 GeV. [10]

3.4. T Quark Search using $Ht \to X$ Decay Mode at 13 TeV

The sample is sub-divided into 20 categories using jet multiplicity n_{jets}, b-multiplicity, the mass of the two closest jets and the number of large-R jets with mass greater than 100 GeV. The background rich regions have low b-multiplicity while the signal rich regions have high b-multiplicity. The search is done using the distribution of the scalar sum of the transverse momentum of jets, $l^{\pm}$ and E_T^{miss} (m_{eff}) using a binned likelihood fit under the background-only hypothesis. The m_{eff} distribution of the signal-sensitive regions are shown in figure 11.

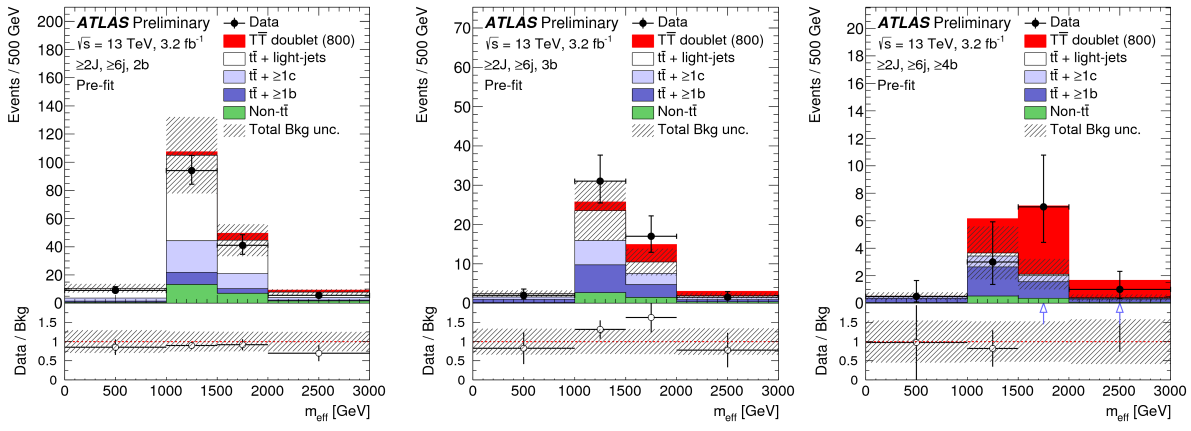

Figure 11. m_{eff} distribution of the signal-sensitive regions. [13]

The main systematic uncertainties include background production cross-section, which includes factorization and renormalization scales and parton distribution function uncertainty both at NLO and NNLO, luminosity and the jet energy scale. No excess above the SM prediction is observed. Under the $\mathcal{BR}(T \to Ht) = 1$ hypothesis, m_T is excluded below 900 GeV with an expected exclusion region below 980 GeV at 95% CL. In the SU(2) singlet model, m_T is excluded below 750 GeV with an expected exclusion region below 780 GeV at 95% CL. In the SU(2) doublet model, m_T is excluded below 800 GeV with an expected exclusion region below 900 GeV at 95% CL. The cross-section limits as a function of the T quark mass are shown in figure 12. The 13 TeV analysis sensitivity reaches 950 GeV, exceeding that of 8 TeV analysis. However, the observed limits are weaker than expected above 700 GeV due to statistical fluctuations in data.

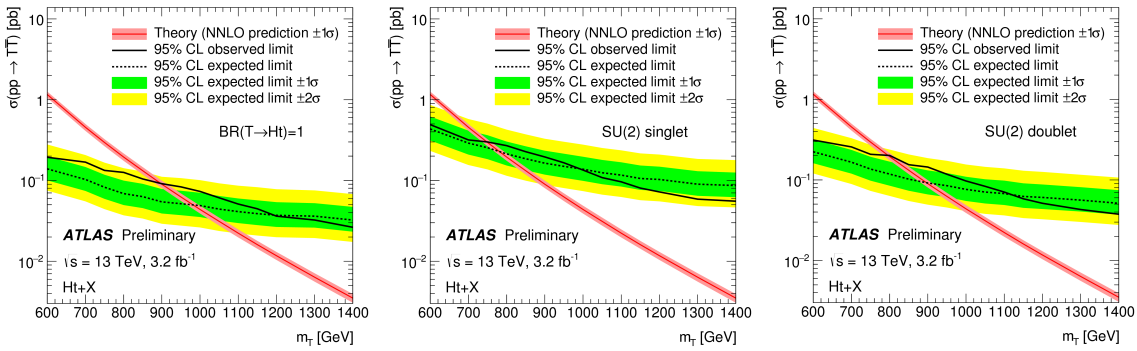

Figure 12. Cross-section limit plots as a function of the T quark mass m_T under $\mathcal{BR}(T \to Ht) = 1$, SU(2) singlet and SU(2) doublet hypotheses. [13]

4. Acknowledgement

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