PROCEEDINGS OF SCIENCE

# Search for heavy resonances with the ATLAS detector

**Elizabeth CASTANEDA-MIRANDA*** **On behalf of the ATLAS Collaboration**
*Department of Physics, University of Johannesburg, South Africa*
*E-mail:* elizabeth.castaneda.miranda@cern.ch

We present a summary of recent results on the search for heavy resonances based on several different signatures and using the ATLAS detector at the LHC. The final states represented by dileptons, dijets, a photon plus a jet, a pair of leptons plus a photon and leptons plus missing transverse energy are robust signatures with which to look for new physics. The unprecedented center-of-mass energy (c.m.e) available allows the exploration of mass regions that are inaccessible to previous colliders. The aim of this work is to present the results of the search for physics beyond the Standard Model using up to 20 fb$^{-1}$ of integrated luminosity of proton-proton collisions at $\sqrt{s} = 8$ TeV.

*The European Physical Society Conference on High Energy Physics*
*18-24 July, 2013*
*Stockholm, Sweden*

*Speaker.

 

PoS(EPS-HEP 2013)268

## 1. Introduction

New heavy resonances are predicted by wider symmetry groups such as GUTs (Grand Unified Theories) [2], extra-dimensions (Kaluza-Klein, Randall-Sundrum) [3, 8], Compositeness (excited quarks and leptons [6]) or Technicolor (dynamic EWSB) [12], which are possible extensions of the Standard Model. We present the results from ATLAS studies to search for these particles, where all the event candidates satisfy the data-quality requirements of the ATLAS detector: proper functioning of the inner detector (ID), muon spectrometer (MS), solenoid, toroid, calorimeter and trigger subsystems, as well as stable LHC beam. All the events must be triggered by the trigger subsystems. These studies are performed using proton-proton collisions at $\sqrt{s} = 8$ TeV.

## 2. The dilepton signature

The neutral heavy gauge bosons are produced mainly by the Drell-Yan process. The dielectron and dimuon channels are the clearest signatures expected in the detector. The benchmark models used for this study are: $Z'_{SSM}$ [1], GUT's based-on $E_6$ model [2] and the spin-2 Randall-Sundrum $G^*$ [3].

For the dielectron channel, at least two electron candidates within $|\eta| < 2.47$ are required. The region $1.37 \leq |\eta| \leq 1.52$ is the transition region between barrel and end-cap calorimeters which exhibits degraded energy resolution. This region is excluded. The leading (sub-leading) electron must satisfy $E_T > 40$ GeV ($E_T > 30$ GeV). To suppress background from jets, the electron with the higher $E_T$ is isolated: $\sum E_T(\Delta R < 0.2) < 0.007 \times E_T + 5.0$ GeV, where $\sum E_T(\Delta R < 0.2)$ is the cluster transverse energy around the electron direction in a cone of $\Delta R < 0.2$. The sub-leading electron is required to satisfy $\sum E_T(\Delta R < 0.2) < 0.022 \times E_T + 6.0$ GeV [4].

For the dimuon channel, each muon must satisfy $p_T > 25$ GeV and $|\eta| < 2.4$. The selected muons are required to have at least three hits in each (inner, middle and outer) station of the MS, and at least one hit in two of the trigger chambers. To suppress background from cosmic rays, the muons are also required to have a transverse impact parameter $|d_0| < 0.2$ mm, and to have their the $z$ coordinate with respect to the primary vertex (PV), $|z_0 - z(PV)| < 1$ mm. To reduce the background from jets, each muon is isolated such that $\sum p_T(\Delta R < 0.3)/p_T < 0.05$, where $\sum p_T(\Delta R < 0.3)$ is the sum of the $p_T$ of the other tracks in a cone with $\Delta R < 0.3$ around the direction of the muon [4].

For the background estimation, the data driven method is used for multi-jets and W+jets. Drell-Yan, dibosons ($ZZ$, $WZ$, $WW$) and $t\bar{t}$ backgrounds are modeled with Monte Carlo (MC) simulation but normalised using data around the $Z$ peak in the region (80 GeV $-$ 110 GeV).

No significant excess was found and exclusion limits at 95% C.L. on the $\sigma \times BR(Z'/G^*)$ were set [4]. These exclusion limits are the combination of the dielectron and dimuon channels exclusion limits (see Figure 1). From the observed limits for $Z'_{SSM}(G^*)$, masses below 2.86 TeV(2.47 TeV) are excluded using 20 fb$^{-1}$ of integrated luminosity [4].

We also search for the $Z'$ decaying into two hadronic taus using as a benchmark model the $Z'_{SSM}$ [1]. The $\tau_h$ is defined as a reconstructed jet with one or three associated tracks in the ID. The tau charge is reconstructed from the sum of the charges of the associated tracks and is required to be $\pm 1$. Events are required to have at least two taus (no muons, no electrons) with $p_T \geq 150$ GeV and to be within $|\eta| < 2.47$, where the region $1.37 \leq |\eta| < 1.52$ is excluded. The highest $p_T$

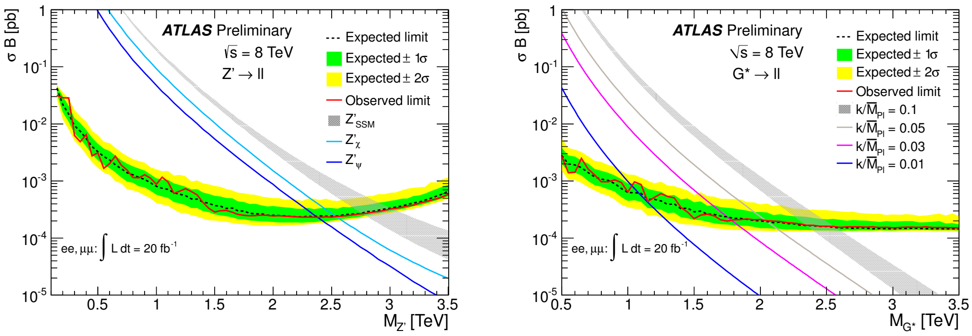


**Figure 1:** Combined exclusion limits from dielectron and dimuon channels. The 95% C.L. exclusion limits on the $\sigma \times BR(Z'/G^*)$ are indicated [4].

taus must be oppositely charged, back-to-back and they must pass the *loose* BDT tau ID [5]. The

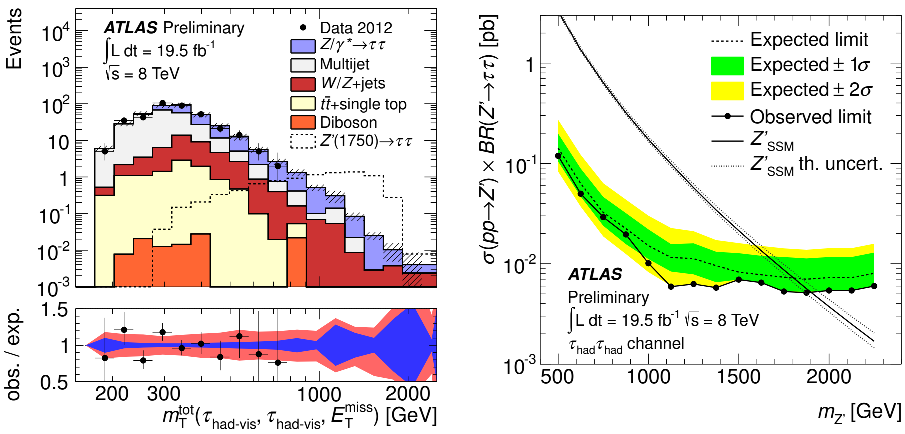


**Figure 2:** Transverse mass and exclusion limits for $Z' \to \tau_{had}\tau_{had}$. Left: the transverse mass data and background comparison. Right: the 95% C.L. exclusion limits on the $\sigma \times BR(Z'_{SSM})$ are indicated [5].

total transverse mass is defined as $m_T^{tot} = \sqrt{2p_{T1}p_{T2}C + 2|E_T^{miss}|p_{T1}C_1 + 2|E_T^{miss}|p_{T2}C_2}$, where the $p_{T1,T2}$ are the transverse momentum of the two taus; $C$ is defined as $1 - \cos\Delta\phi$, where $\Delta\phi$ is the angle in the transverse plane between the two taus; $C_{1,2}$ are defined analogously for the angles $E_T^{miss}$ and the first and second tau. A data-driven method was used for the multi-jets background estimation. MC simulation was used for Drell-Yan, diboson, $t\bar{t}$ and single top processes. The $W/Z+$ jets component is weighted with jet-to-tau fake rate [5].

No significant excess was found. From the observed limits, we excluded masses of the $Z'_{SSM}$ below 1.90 TeV using 19.5 fb$^{-1}$ of integrated luminosity (see Figure 2) [5].

## 3. The dijet signature

Collisions with the largest momentum transfer typically result in final states featuring two high transverse momentum ($p_T$) jets of particles. The benchmark model for this study is the excited quark ($q^*$) [6]. The events are required to have at least two jets with $p_T > 150$ GeV satisfying the rapidity requirement $|y| < 2.8$. The dijet invariant mass is computed with the two jets of the highest $p_T$. The current study is based on the analysis of the dijet invariant mass distribution for the selected events. The background is estimated using the observed dijet spectrum by fitting a smooth four-parameter function data [7]:

$$f(x \equiv m_{jj}/\sqrt{s}) = p_1(1-x)^{p_2} x^{p_3+p_4 \ln x} \tag{3.1}$$

This treatment of the background greatly reduces the effects of jet energy scale uncertainties, and the luminosity uncertainty [7]. Figure 3 (left) shows the data and background comparison dijet mass distribution.

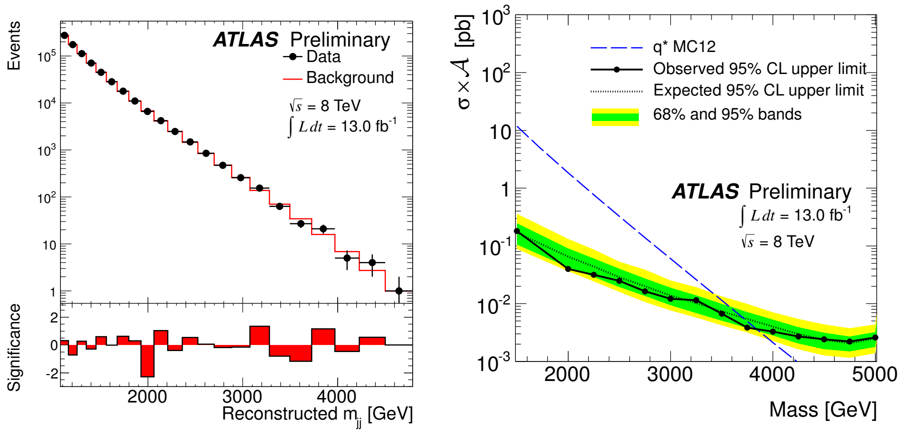


**Figure 3:** The dijet invariant mass data and background comparison (left) and the 95% C.L. exclusion limits on the $\sigma \times A$ for $q^*$ (right) [7].

The 95% C.L. exclusion limits on the $\sigma \times A$ for $q^*$ were set considering the lack of a significant excess. From the observed limits, we exclude $q^*$ masses below 3.84 TeV using 13 fb$^{-1}$ [7]. Figure 3 (right) shows the exclusion limits for the $q^*$.

## 4. The photon + jet signature

The direct photon + jet production can occur at tree level via Compton scattering of a quark and a gluon, or through quark-antiquark annihilation. The benchmark models used in this search are: the excited quark $q^*$ [6] and the Quantum Black Hole (QBH) [8].

For this study, events must have at least one photon and one jet with $p_T > 120$ GeV. The photon acceptance is restricted to the barrel calorimeter $|\eta_\gamma| < 1.37$ and requires $|\eta_\gamma - \eta_j| < 1.6$ between the photon and the jet. The highest $p_T$ candidates are selected to compute the photon+jet invariant mass $m_{\gamma j}$. The $m_{\gamma j}$ distribution is used to search for a peak over the SM background, estimated by fitting a smoothly falling function (Equation 3.1) to the $m_{\gamma j}$ distribution in the region $m_{\gamma j} > 426$ GeV [9].

In the absence of a signal we have the 95% C.L. exclusion limits on $\sigma \times BR(q^*/QBH) \times A \times \varepsilon$. For $q^*$, masses below 3.5 TeV are excluded and for QBH, masses below 4.6 TeV are excluded using 20.3 fb$^{-1}$ of integrated luminosity (see Figure 4). The results quoted are observed limits [9].

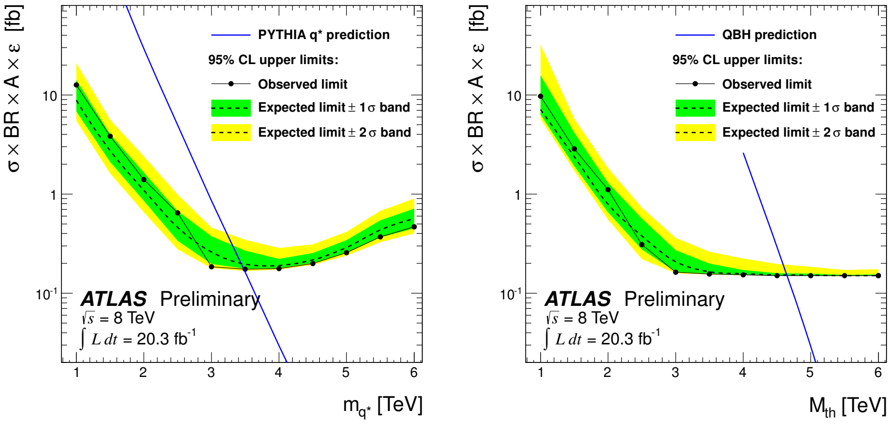


**Figure 4:** The 95% C.L. exclusion limits on the $\sigma \times BR(q^*/QBH) \times A \times \varepsilon$ [9].

## 5. The excited leptons

The excited leptons may be produced via $q\bar{q} \to l^*\bar{l}$ or in pairs via $q\bar{q} \to l^*\bar{l}^*$. As the cross-section for pair production is much less than for single production this search is based on events with two same-flavor leptons (muons or electrons) and a photon ($ll\gamma$ final state). The excited lepton ($l^*$) is the benchmark model for this search [6].

For $e^*$ and $\mu^*$ searches, the selection criteria are similar to those described in section 2. Only the electron isolation is applied to the leading electron and is required to be $\sum E_T(\Delta R < 0.2) <$ 7 GeV [10]. The presence of at least one photon with $p_T > 30$ GeV and $|\eta| < 2.37$ is required in both channels. The region $1.37 < |\eta| < 1.52$ is excluded. For the background estimation the MC was used for $Z+\gamma$, $Z$+jets, $t\bar{t}$ and diboson. A scale factor was applied to the $Z$+jets backgrounds in a region of (70 GeV, 110 GeV). The $Z+\gamma$ and $Z$+jets backgrounds were fitted and extrapolated in the region of 150 GeV $< m_{ll\gamma} <$ 1050 GeV. This was due to the poor statistics from MC [10].

No evidence of $l^*$ was found. The 95% C.L. limits on the $\sigma \times BR(l^* \to l\gamma)$ was set using 13 fb$^{-1}$ of integrated luminosity [10] (see Figure 5).

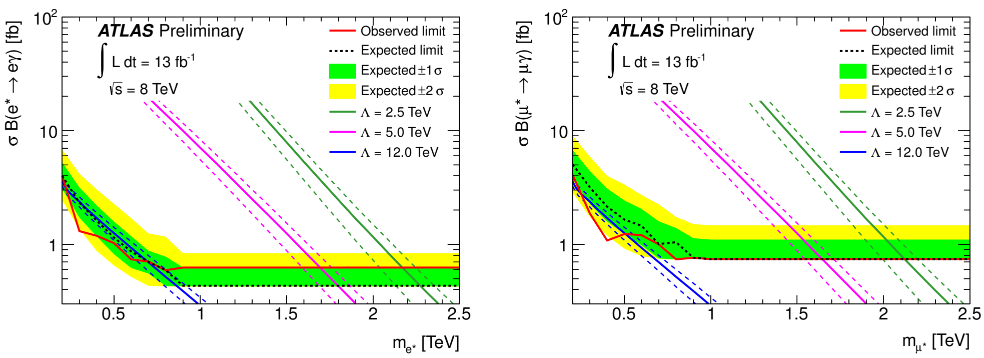


**Figure 5:** The 95% C.L. exclusion limits on the $\sigma \times BR(l^* \to l\gamma)$ [10].

## 6. Diboson: $WZ \to l\nu ll$ and $ZZ \to llqq$

Direct searches for heavy resonances that decay to vector boson pairs have been conducted at the LHC. We cover the search for resonances decaying to $WZ$ and $ZZ$ where the extended gauge model (EGM) [11], dynamic (EWSB) [12] and the bulk Randall-Sundrum graviton [14] are the benchmark models used for these searches.

For the resonances decaying to WZ, events with exactly 3 leptons with $p_T > 25$ GeV and no fourth lepton with $p_T > 20$ GeV are required. Amongst the three leptons, a pair must have the same flavor and opposite sign, and have an invariant mass within 20 GeV of the $Z$ boson mass. They are classified as: $e\nu ee$, $\mu\nu ee$, $e\nu\mu\mu$ and $\mu\nu\mu\mu$. A value of the $E_T^{miss}$ above 25 GeV is required. The backgrounds from diboson final states ($WZ$, $ZZ$ and $Z\gamma$) are estimated by MC simulation. The reducible background from $ll$+jets ($Z$+jets, $t\bar{t}$ and $Wt$) involves objects known as 'fake' leptons. The rate of the such fake leptons is evaluated by a data-driven method [13].

No significant excess of events is observed, and exclusion limits on the $\sigma \times BR(WZ)$ were set using 13 fb$^{-1}$ of integrated luminosity. From the observed limits, we excluded $W'$ [11] masses below 1.18 TeV and $\rho_T$ [12] masses below 0.92 TeV. Figure 6 shows the exclusion limit plots for $W'$ (left) and $\rho_T$ (right).

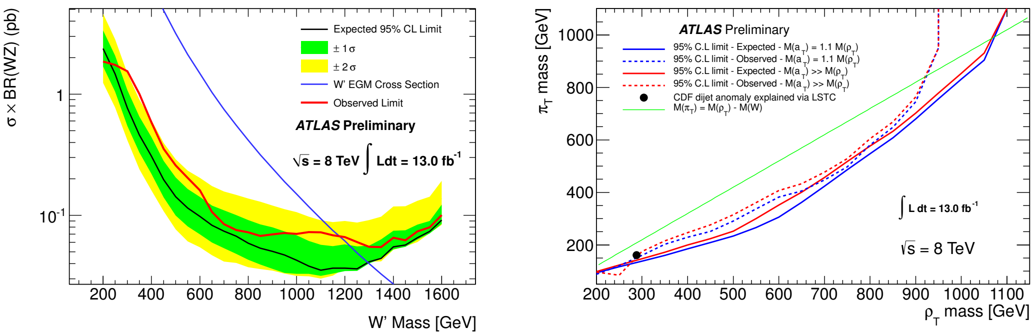


**Figure 6:** The 95% C.L. exclusion limits on the $\sigma \times BR(WZ)$ for $W'$ (left) and the exclusion mass region on($\pi_T, \rho_T$) plane (right) [13].

For the bulk RS $G^*$ [14] resonance decaying to $ZZ$, events with exactly two leptons with same flavor are required and the invariant mass of the pair of leptons must be between 66 GeV and 116 GeV to be sure that the two leptons are coming from the $Z$ boson. Muon pair events are further required to be of opposite charge. Electrons are required to have $E_T > 25$ GeV within $|\eta| < 2.47$ (excluding the region $1.37 < |\eta| < 1.52$) and muons must have $p_T > 25$ GeV within ($|\eta| < 2.4$). The isolation requirement is a combination of track and calorimeter isolation $\frac{\sum E_T(p_T)(\Delta R<0.2)}{E_T(p_T)} < 0.3(0.15)$. Jets are required to have $p_T > 30$ GeV and $|\eta| < 2.1$. Two signal regions are defined for good acceptance over the wide mass range: $m_{lljj}$ for signal below 1 TeV (resolved selection) and $m_{llj}$ for signal above 1 TeV (merged selection) [15]. The background is estimated by fitting $m_{lljj}(m_{llj})$ in the data after the resolved(merged) signal selection is applied. The function used is Equation 3.1.

No significant excess is observed, and 95% C.L. limits are set on $\sigma \times BR(G^*)$ using 7.2 fb$^{-1}$ of integrated luminosity. From observed limits, for masses below 850 GeV, a bulk RS $G^*$ with a coupling parameter $\kappa/\bar{m}_{Pl} = 1.0$ is excluded (see Figure 6).

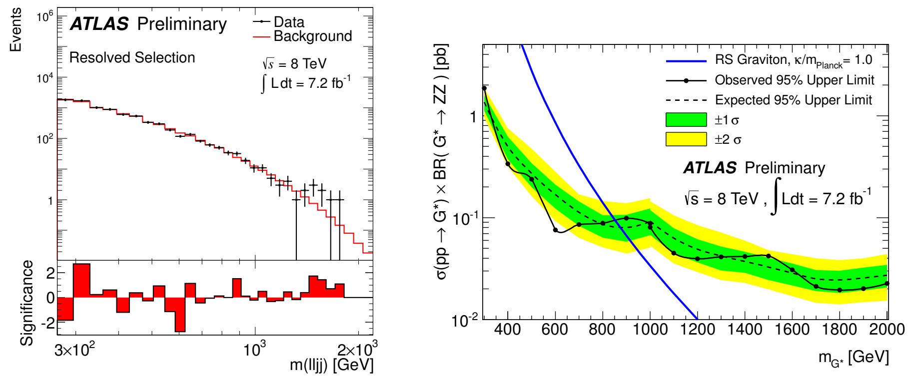


**Figure 7:** The $m_{lljj}$ data and background comparison (left) and 95% C.L. exclusion limits on the $\sigma \times BR(G^* \to ZZ)$ (right) [15].

## 7. Conclusions

We presented six different signatures at 8 TeV c.m.e., constraining nine models of new phenomena, with the ATLAS detector.

The ATLAS Collaboration continues the search for the physics beyond the Standard Model expecting much improved reach with 14 TeV c.m.e.

## References

[1] P. Langacker, *The Physics of Heavy Z' Gauge Bosons*, *Rev. Mod. Phys.* **81** (2009) 1199

[2] D. London and J. L. Rosner, *Extra Gauge Bosons in E(6)*, *Phys. Rev.* **D34** (1986) 1530.

[3] L. Randall and R. Sundrum, *A large mass hierarchy from a small extra dimension Phys. Rev. Lett.* **83** (1999) 3370

[4] The ATLAS Collaboration, (2013) [ATLAS-CONF-2013-017].

[5] The ATLAS Collaboration, (2013) [ATLAS-CONF-2013-083].

[6] U. Baur, M. Spira and P. M. Zerwas, *Excited-Quark and -Lepton Production at Hadron Colliders*, *Phys. Rev.* **D42** (1990) 815.

[7] The ATLAS Collaboration, (2012) [ATLAS-CONF-2012-148].

[8] P. Meade and L. Randall, *Black Holes and Quantum Gravity at the LHC*, *JHEP* **05** (2008) 003.

[9] The ATLAS Collaboration, (2013) [ATLAS-CONF-2013-059].

[10] The ATLAS Collaboration, (2012) [ATLAS-CONF-2012-146].

[11] G. Altarelli, B. Mele and M. Ruiz-Altaba, *Searching for new heavy vector bosons in p anti-p colliders*, *Z. Phys.* **C45** (1989) 109.

[12] E. Eichten and K. Lane, *Low-scale technicolor at the Tevatron and LHC*, *Phys. Lett.* **B669** (2008) 235

[13] The ATLAS Collaboration, (2013) [ATLAS-CONF-2013-015].

[14] K. Agashe et al., *Warped Gravitons at the LHC and Beyond*, *Phys. Rev.* **D76** (2007) 036006

[15] The ATLAS Collaboration, (2012) [ATLAS-CONF-2012-150].