Exotic Physics at ATLAS

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Abstract. A number of proposed explanations to observed phenomena predict new physics that will be directly observable at the LHC. Each new theory is manifested in the experiments as an experimental signature that sets it apart from the many well understood Standard Model processes. Presented here is a summary of a selection of such searches performed using 8 TeV center of mass energy data produced by the LHC and collected with the ATLAS detector. As no significant deviations from the standard model are observed in any search channel presented here, the results are interpreted in terms of constraints on new physics in a number of scenarios including dark matter, sequential standard model extensions, and model independent interpretations depending on the given search channel.

1 Introduction

During 2012, the 20 fb^{-1} of proton proton collision data delivered by the LHC [1] at a center of mass energy of 8 TeV gave access to a new energy regime with higher statistics than before and allowed for ATLAS [2] to begin to more fully exploit the LHC as a discovery machine. Indeed, this was evidenced by the discovery of a new resonance [3], which has since been found to be described well in many ways by the standard model Higgs boson [4, 5]. But there are still many questions that remain in light of this. For instance, is the standard model as currently described just a limiting case of some larger grand unified theory? Do the fermions that we have currently found to be point-like (leptons and quarks) have underlying structure? What is dark matter and if it has a particle description, how well can we study it at the LHC?

These questions, and many more, span a very large space of models, each of which produces a distinct experimental signature when produced in LHC collisions. An efficient way to search for the presence of new physics is to search for deviations from the well understood Standard Model processes in unique, final-state signatures. To this end, the searches for exotic new physics at ATLAS can be categorized based on the final state and interpreted based on the multiple, new physics scenarios that may produce such a signature.

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2 Mono-X Signatures

The first category of signatures for new physics are those in which there is only a single visible object in the final state, called "Mono-X", where the single object can be representative of a quark or gluon, as in the mono-jet search [6], or vector boson, as in the mono-W/Z search [11]. In both of these searches, momentum is conserved in the transverse plane of the collision and the single detectable object is balanced by a large amount of missing transverse energy (MET) that is the primary signature of new physics, which is representative of a number of undetectable final state particles. The mono-jet search is focused on single high transverse momentum (p_T) jets produced primarily from initial state radiation of a quark or a gluon and reconstructed using the anti- k_T ($R=0.4$) jet algorithm [7]. The search is then divided into four regions based on the MET and the highest p_T jet to search for the contribution of new physics at different energy scales as in Figure 1(a). The data are well modelled by all known background processes, as shown in Figure 1(a), and the results are used to constrain models with large extra dimensions [8], weakly interacting massive particle (WIMP) dark matter [9], and gravitinos produced through gauge interactions [10] as in Figure 1(b).

Figure 1. From [6], shown in (a) is the MET spectrum for one kinematic signal region comparing stacked background predictions to data with several signal models overlayed. Shown in (b) is the interpretation of the combination of all kinematic signal regions for the 95% confidence level upper limits on the cross section times acceptance times efficiency for gauge mediated production of gravitinos as a function of squark/gluino mass.

On the other hand, the mono-W/Z search focuses on searching for a single hadronically decaying W/Z boson. These hadronic decays are identified as high p_T jets, reconstructed with the Cambridge-Aachen ($R=1.2$) algorithm [12], that pass a mass drop and filtering algorithm [13] in order to identify jets whose underlying constituents are consistent with the hard decay of a massive particle and whose mass is consistent with that of a W or Z boson. This jet is required to be balanced by a large amount of MET and events are further divided into two signal regions in which the search is performed. The data are observed to be well modelled by background processes (Figure 2(a)) and the results are used to constrain the production of dark matter interpreted in terms of an effective interaction with standard model particles. These results are transformed into limits on dark matter nucleon cross section as a function of WIMP mass such that the results can be directly compared to those found in direct detection experiments as in Figure 2(b).

Figure 2. From [11], shown in (a) is the comparison of the background prediction to data for the leading jet invariant mass spectrum for events with large MET with signal templates from the $D5$ dark matter effective operator overlayed. Shown in (b) is the interpretation of the search in terms of the WIMP-nucleon cross section as a function of WIMP mass.

3 Dijet Signatures

The next class of signatures focuses on new physics that would be observed decaying to pairs of hadronic jets. These searches benefit from high statistics and leverage the ability to fully reconstruct the invariant mass of the potentially new, resonantly-produced physics. The inclusive dijet resonance search [14] determines the mass of a central-jet pair with $|y^*| < 0.6$ that are reconstructed with the anti- k_T ($R=0.6$) algorithm.¹ The resulting spectrum is smoothly falling and modelled by the empirical function $f(m; p_{1,2,3,4}) = p_1(1-x)^{p_2} x^{p_3+p_3 \ln(x)}$ where x is the reconstructed dijet mass m (in units of 8 TeV) and $p_{1,2,3,4}$ are four free parameters. This background estimation is used to initially perform a search with the BUMP HUNTER algorithm [15] in all mass windows for the largest excess in data above the smooth background hypothesis as shown in Figure 3(a). As no significant resonant excess is observed, the results are interpreted as limits at 95% confidence level on cross section times acceptance for a benchmark excited quark model [16] in the mass range of 1 TeV to 5 TeV as well as simplified Gaussian models parametrized by the relative width, σ_G/M_G as in Figure 3(b).

In addition to the search for inclusive dijet resonances, a search is performed in which the dijet system is accompanied by an additional leptonically decaying W or Z boson [17]. This W/Z -tag is required to suppress the large multi-jet background present in the inclusive case and makes this search sensitive to other new physics, namely low scale technicolor (LSTC) [18]. To increase sensitivity, the W/Z boson is required to have $p_T > 50$ GeV and the dijet system, composed of the two highest p_T jets, is required to be central and back to back in azimuth by making requirements on $\Delta\eta(jj)$ and $\Delta\phi(jj)$ respectively. The dijet invariant mass spectrum (Figure 4(a)) is then inspected for deviations from the expected background. No such deviations are observed and 95% confidence level upper limits on cross section times branching ratio for the benchmark LSTC processes of a techni- ρ (ρ_T) decaying to a W/Z boson and a techni-pion (π_T), both as $\rho_T^{0\pm} \rightarrow W\pi_T^{0\pm}$ and $\rho_T^\pm \rightarrow Z\pi_T^\pm$, shown in Figure 4(b).

¹In an event, $|y^*| = \frac{1}{2}|y_1 - y_2|$ where y_1 and y_2 are the rapidities of the two highest p_T jets in the event.

Figure 3. From [14], shown in (a) is the comparison of the dijet invariant mass spectrum measured in data to the background estimate obtained from a smooth fit to data. Shown in (b) is the 95% confidence level upper limits on cross section times acceptance derived from the observed spectrum for a number of generic Gaussian signal templates.

Figure 4. From [17], shown in (a) is the dijet invariant mass spectrum in the signal region associated with the tag of a leptonically decaying $W \rightarrow \ell^\pm \nu$ boson. Shown in (b) are the 95% confidence level upper limits on cross section times branching ratio as a function of M_{π_T} assuming the relation $M_{\pi_T} = 3/2 * M_{\pi_T} + 55$ GeV. Note that the corresponding spectrum and exclusion limits exist for the neutral current $\rho_T^\pm \rightarrow Z \pi_T^\pm$ channel in [17].

4 Dilepton Signatures

The next class of experimental signatures that can be used to constrain a wide variety of new physics scenarios are those in which pairs of leptons are used to reconstruct an invariant mass spectrum. In the case of muon pairs, this provides a rich spectroscopy for resonances such as the J/Ψ , Υ , and Z boson and which, in the presence of new physics, may reveal resonant excesses in the high mass

tail. The search looks for resonant excesses in the Drell-Yan spectrum of pairs of well-reconstructed and isolated muons or electrons ² extending to masses of nearly 2 TeV [19]. This search benefits greatly from the reconstruction and identification of electrons and muons using the full detector information. The absence of any deviations from the background expectations make it possible to set 95% confidence level upper limits on cross section times branching ratio for a sequential standard model Z' boson [20], with a lower bound on the Z' mass of 2.86 TeV. A limit is also set on a spin-2 Randall-Sundrum graviton (G^*) [21], with a lower bound on the G^* mass of 2.47 TeV.

Figure 5. From [19], shown in (a) is the dilepton invariant mass spectrum for the $Z \rightarrow ee$ channel with multiple Z' signals overlayed. Shown in (b) is the 95% confidence level upper limit derived for the cross section times branching ratio for the Z' signal by combining the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ signal regions.

The second dilepton search has a very different final state as it searches for pairs of oppositely charged τ leptons that decay hadronically. The identification of hadronically decaying τ leptons is not as clean as compared to electrons and muons and requires a boosted decision tree to discriminate τ jets from quark and gluon-initiated jets. The charge of the τ is reconstructed as the sum of the charges of all tracks in the jet. The final state mass is not fully reconstructed due to the presence of neutrinos in the decay of the τ leptons and so only the reconstructed transverse mass of the visible decay products of the τ 's, m_T^{tot} , can be calculated for each event. Therefore, the resolution and sensitivity to signals such as those in the previous di-electron and di-muon search is not as great. Nonetheless, by requiring the τ identified jets to have high p_T allows for the $Z \rightarrow \tau\tau$ background to be clearly seen as in Figure 6(a) and as new physics need not obey lepton universality probing all lepton flavors is critical. However, no excess above the estimated background processes is observed and a 95% confidence level upper limit on the cross section times branching ratio for a sequential standard model Z' boson [23] is derived and a lower bound on the Z' mass is found to be 1.9 TeV.

²Only muon pairs are required to be of opposite charge due to the higher rate of bremsstrahlung and subsequent charge misidentification for electrons.

Figure 6. From [22], shown in (a) is the $\tau^+\tau^-$ invariant mass spectrum comparing the background expectation to data with a Z' signal overlayed for comparison. Shown in (b) is the 95% confidence level upper limit on $\sigma(pp \rightarrow Z') \times BR(Z' \rightarrow \tau^+\tau^-)$ as a function of Z' mass.

5 Photon+X Signatures

The “photon+X” class of searches cover new states that decays to a photon and a jet or a photon and a lepton. The photon-jet search [24], is very similar to the inclusive dijet search but selects a with a well-reconstructed, isolated photon in addition to an anti- k_T ($R=0.6$) jet to reconstruct the invariant mass spectrum. Both the photon and the jet are required to have high p_T and be in the central region of the detector. Similar to the dijet search, a selection is made on $|\Delta\eta(j, \gamma)|$ to help identify s -channel production of the pair. The photon-jet mass spectrum (Figure 7(a)) is then scanned with the BUMP HUNTER algorithm and no signal is observed so the background is modelled by the same function as in the dijet search. This background prediction is used to set 95% confidence level upper limits on cross section times branching ratio for benchmark models of excited quarks [16], quantum black holes [25], and model independent limits on general Gaussian signals. Shown in Figure 7(b) is the interpretation of the search in terms of the quantum black hole signal.

The second such “photon+X” search focuses on searching for excited leptons [26] (ℓ^* is limited to e^* or μ^*) produced through an effective field theory description [27]. The effective field theory production mechanism requires the emission of an additional Standard Model electron or muon with the excited lepton then decays via emission of a single photon to a Standard Model lepton of the same flavor. Thus the search is carried out by selecting events with a single photon produced in association with a pair of well-reconstructed electrons or muons, where $M(\ell\ell)$ is required to be greater than 110 GeV to suppress Drell-Yan background. However, when reconstructing the $\ell^* \rightarrow \ell\gamma$ decay, it is ambiguous as to which Standard Model lepton is a result of the decay of the excited lepton and which came from the production mechanism. Thus, the search is performed by reconstructing the total invariant mass of the three-body ($e\ell\gamma$ or $\mu\mu\gamma$) as shown in (Figure 8(a)). In the absence of a signal, exclusion limits at 95% confidence level are set in the two dimensional plane of the excited lepton mass and the scale of the new physics present in the effective field theory description (Λ) as in Figure 8(b).

Figure 7. From [24], shown in (a) is the comparison of data and background estimate from the smooth fit of the photon-jet invariant mass spectrum with several quantum black hole signals overlayed. Shown in (b) is the 95% confidence level upper limit on cross section times branching ratio times acceptance times efficiency for the quantum black hole signal as a function of the black hole production energy threshold.

Figure 8. From [26], shown in (a) is the comparison of the background prediction to data for the $M(\mu\gamma)$ spectrum with the 95% confidence level exclusion limit in the two dimensional plane of the excited muon (μ^*) mass and the scale of the new physics present in the effective field theory description (Λ). Note that the corresponding spectrum and exclusion limit exists for the excited electron (e^*) channel in [26].

6 Multi-Lepton Signatures

The next class of searches involving a more complex final state is that of the multi-lepton search [28]. In the Standard Model, the production of events with three or more real leptons is very rare. Thus, the production of multiple leptons by new physics, such as fourth generation quarks [29], supersymmetry [30], and models with doubly charged Higgs bosons [31], will be clearly visible as an excess on the small background. Therefore, the analysis selects well-reconstructed, isolated electrons or muons and leptonically and hadronically decaying τ leptons in addition to jets reconstructed with the anti- k_T ($R=0.4$) algorithm. Events are then classified based on the number of electrons, muons and τ 's. They are further subdivided into regions based on the number of b -tagged jets and whether there is an electron or muon pair present which can reconstruct an on-shell Z boson. In the case of an on-shell Z boson the effective mass of the MET and the highest p_T lepton in the event (meant as a proxy for the

presence of a W boson). Events are divided into kinematic regimes based on the MET and the scalar sum of the energy of leptons or jets (H_T^{leptons} and H_T^{jets} respectively) as in Figure 9(a).

Figure 9. From [28], shown in (a) is the comparison of the background estimation to data for the MET spectrum for the signal region containing $\geq 3e/\mu$ with a pair that is off-shell from the Z boson mass. Shown in (b) is an example of the interpretation of the final results in terms of the 95% confidence level upper limits on visible cross section (σ_{95}^{vis}) for four of the final signal region categories.

In these numerous signal regions, no deviations from the background estimation is observed and the results are reported as 95% confidence level upper limits on the visible cross section (σ_{95}^{vis}) in each region as in Figure 9(b). In addition to these limits on the visible cross section, detector level efficiencies (ϵ_{fid}) for the identification of the reconstructed objects in the event are reported to allow for new models at particle level to be constrained by transforming the limit on visible cross section to a limit on fiducial cross section as $\sigma_{95}^{\text{fid}} = \sigma_{95}^{\text{vis}} / \epsilon_{fid}$.

7 Diboson Signatures

The last class of experimental signatures covered is that in which new physics couples to pairs of W and Z bosons, that form an intermediate state before decaying to leptons, neutrinos, or jets in the final state. One search that focuses on the WZ intermediate state identifies the presence of three well-reconstructed, isolated leptons (electrons or muons) in addition to a neutrino (reconstructed as large MET) in the final state [32]. The four possible signature combinations ($eeve$, $ee\nu\mu$, $\mu\mu\nu\mu$, $\mu\mu\nu e$) are all required to have an oppositely charged lepton pair whose invariant mass is near the Z boson mass. The longitudinal momentum of the neutrino is reconstructed using the W boson mass constraint with the third lepton. The resulting WZ boson pair is required to be central and back to back in the transverse plane by making selections on $\Delta\eta(W, Z)$ and $\Delta\phi(W, Z)$ respectively. The total invariant mass of the four body system is then reconstructed, as shown in Figure 10(a), and in the absence of a resonant excess, 95% confidence level upper limits on cross section times branching ratio are obtained for a benchmark extended gauge model W' [33] as in Figure 10(b).

The second search of this type focuses on the semi-leptonic ($\ell\ell q\bar{q}$) final state which can be representative of the ZZ or ZW (indistinguishable due to the resolution of the measurement of the hadronic decay of the W/Z boson) intermediate state pair [34]. The final state is identified by first reconstructing a leptonic Z boson decay to a pair of well-reconstructed and isolated electrons or muons. The hadronic side of the event, although it is dominated by quark and gluon initiated jets from Standard

Figure 10. From [32], shown in (a) is the comparison of the background estimation to data for the combination of all signal regions. Figure (b) shows the expected and observed 95% confidence level upper limits on $\sigma(pp \rightarrow W') \times BR(W' \rightarrow WZ)$.

Model production of Z +jets, is used to identify the decay of the second boson. For the case of low signal mass, this W/Z boson is reconstructed with two high p_T anti- k_T ($R=0.4$) jets whose combined invariant mass is near the Z boson. However, in the case of very massive signals (above 1 TeV), the $q\bar{q}$ pair coming from the W/Z boson decay are so heavily boosted that they are indistinguishable in the calorimeter and thus identified as a single high- p_T , massive anti- k_T ($R=0.4$) jet. The invariant mass of the boson pair is then reconstructed as either $m(\ell\ell jj)$ (Figure 11(a)) or $m(\ell\ell j)$ (Figure 11(b)) depending on whether the selection is made in the low mass or high mass regime. By using these two distinct event topologies, maximal sensitivity can be obtained across a broad range of reconstructed signal masses. In the absence of any clear excess, 95% confidence level upper limits on cross section times branching ratio are obtained for a benchmark Randall-Sundrum graviton (G^*) [21] decaying to a pair of Z bosons, and a lower limit on the G^* mass found to be 850 GeV (Figure 11(c)).

Figure 11. From [34], shown in (a) and (b) are the comparisons of the Monte Carlo estimated backgrounds to data for combined electron and muon channels for the low mass and high mass selections respectively with theoretical signal predictions overlaid. Figure (c) shows the expected and observed 95% confidence level upper limits on $\sigma(pp \rightarrow G^*) \times BR(G^* \rightarrow ZZ)$ obtained in the absence of signal.

8 Conclusion

The data delivered by the LHC during Run 1, and the tremendous effort put towards understanding the performance of ATLAS detector, has allowed direct searches for new physics to cover a wide array of experimental signatures. Although no clear signs of exotic physics have been found, the data put direct constraints on many scenarios including technicolor, grand unified theories, fermion compositeness, the production of quantum black holes, and even dark matter couplings to the Standard Model. Many of these constraints are pushing the TeV scale of new physics and with the increased energy of the LHC and the upgraded ATLAS detector to begin taking data during Run 2 in 2015, the prospects for such future searches are very exciting.

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