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Searches for new phenomena in final states involving leptons and jets using the ATLAS detector

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Final states containing both leptons and jets can be used to probe for physics beyond the Standard Model. Searches for new physics models with these signatures, such as heavy neutrinos or leptoquarks, for example, are performed using the ATLAS experiment at the LHC. The results of the most recent searches on 13 TeV pp data will be presented.

Keywords: ATLAS; beyond the Standard Model; heavy neutrinos; leptoquarks; seesaw.

1. Introduction

Searches for physics beyond the Standard Model (SM) can be probed in various different final state topologies at collider experiments. Final states involving both leptons and jets are widely used for searching for specific models yielding increased sensitivity and allowing a larger phase space to be probed.

Several searches using either 36.1 fb^{-1} or 80 fb^{-1} of proton–proton collisions collected by the ATLAS detector¹ at the Large Hadron Collider (LHC) will be presented. ATLAS is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle around the collision point. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting toroidal magnets.

2. Excited Leptons

Excited leptons appear in a number of composite models² seeking to explain the existence of the three generations of quarks and leptons in the Standard Model. The composite models introduce new constituent particles called preons that bind at a high scale Λ to form SM fermions and their excited states. Excited leptons form vector-like states, SU(2) doublets and singlets, and acquire masses of the order of Λ .

The search for excited leptons³ uses 36.1 fb^{-1} of ATLAS data collected in 2015 and 2016. The focus of the analysis are excited electrons singly produced in pp

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collisions via a contact interaction $q\bar{q} \rightarrow ee^*$ and decaying either to an electron and a pair of quarks ($eq\bar{q}$) through a contact interaction or to a neutrino and a W boson (νW) via a gauge interaction, as illustrated in Figure 1. The first channel results in two energetic electrons and at least two hadronic jets j , denoted by $eejj$. In the second channel the W boson decays hadronically, yielding an $e\nu q\bar{q}$ final state. This yields final states with exactly one energetic electron, a large-radius (large- R) jet J produced by two collimated quarks, and missing transverse momentum, denoted by $e\nu J$.

Fig. 1. Feynman diagrams for (a) $ee^* \rightarrow eeq\bar{q}$ and (b) $ee^* \rightarrow e\nu W$.³

The dominant backgrounds in the $eejj$ and $e\nu J$ channels are from $Z/\gamma^* + \text{jets}$ and $W + \text{jets}$ production, respectively, and are estimated using Monte Carlo simulation. One of the background sources common to both channels is the misidentification of hadronic jets, photon conversions in the material or electrons from hadron decays as prompt electrons, referred to as the fake-electron background. This background is estimated in a data-driven way.

The signal regions for the $eejj$ channel are constructed using the invariant mass of the electron pair (m_{ee}), the scalar sum of the transverse momenta of the two electrons and the two jets with the highest p_T (H_T), and the invariant mass of the two electrons and the two jets with the highest p_T (m_{eejj}). For the $e\nu J$ channel different discrimination variables have been used, the transverse mass of the system of the missing transverse momentum and the W boson in signal events ($m_T^{\nu W}$), and the absolute value of the azimuthal angle between the neutrino and the electron in signal events ($|\Delta\phi(e, E_T^{\text{miss}})|$).

The statistical analysis of the search is based on a maximum-likelihood fit. The signal hypothesis test is performed using a likelihood-ratio test statistic in the asymptotic approach.⁴ No significant excess above the expected SM background is observed, and limits on the excited lepton model parameters are set at 95 % confidence level (CL), using the CL_s method. For excited electrons with $m_{e^*} < 1.5$ TeV, the lower limit on Λ is 11 TeV, and it decreases to 7 TeV at $m_{e^*} = 4$ TeV. In the special case of the excited lepton model where $m_{e^*} = \Lambda$, the values of $m_{e^*} < 4.8$ TeV are excluded. Combined lower limits on Λ as a function of m_{e^*} are displayed in Figure 2.

Fig. 2. Combined lower limits on Λ as a function of m_{e^*} . The $\pm 1(2)\sigma$ uncertainty bands around the expected limit represent all sources of systematic and statistical uncertainties. The limits for $m_{e^*} > 4$ TeV are the result of extrapolation.³

3. Heavy Neutrinos

Left-right symmetric models (LRSMs) attempt to explain the broken parity symmetry of the weak interaction in the Standard Model and can introduce, depending on the form of the LRSM, right-handed counterparts to the W and Z bosons (W_R and Z_R), and right-handed heavy neutrinos (N_R). A search for the W_R boson and N_R neutrino production in a final state containing two charged leptons and two jets ($lljj$) with $l = e, \mu$ was performed.⁵ The specific process of interest is the Keung-Senjanović (KS) process,⁶ shown in Figure 3. When the W_R boson is heavier than the N_R neutrino ($m_{W_R} > m_{N_R}$), the on-shell W_R mass can be reconstructed from the invariant mass of the $lljj$ system, whereas, when ($m_{W_R} < m_{N_R}$), the on-shell W_R mass can be reconstructed from the invariant mass of the jj system. No mixing between lepton flavours is assumed. In addition to the resolved regime a separate search was performed⁷ focusing on the regime where the W_R is very heavy compared with the N_R ($m_{N_R}/m_{W_R} \leq 0.1$). The heavy neutrinos are produced with large transverse momentum (i.e. are highly boosted) and their decay products are very collimated. Therefore a large-radius jet (large- R jet) can be used to reconstruct the N_R so the final state consists only of one lepton and one large-radius jet (lJ).

The resolved channel search used 36.1 fb^{-1} of ATLAS data recorded in 2015 and 2016. Heavy neutrinos can either be Dirac (only opposite-charge leptons) or Majorana particles (same-charge final state leptons allowed) which motivated the split of the channel in two sub-channels based on the lepton charge. For the opposite-charge channel, the dominant SM backgrounds are $Z + \text{jets}$ and $t\bar{t}$ processes, which are modelled using Monte Carlo simulation. A data-driven m_{jj} reweighting has been applied to improve the modelling of the $Z + \text{jets}$ background. Depending on the mass regime described above the reconstructed W_R was used in the fit. In the same-charge channel, the main backgrounds arise from misidentified leptons,

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Fig. 3. Feynman diagrams of the Keung-Senjanović process for (a) $m_{W_R} > m_{N_R}$ case and (b) $m_{W_R} < m_{N_R}$ case.⁵

electron charge misidentification, which are estimated in a data-driven way. The scalar sum of p_T of the two leptons and two leading jets (H_T) is used in the fit.

The boosted channel search also used 2017 data amounting to an integrated luminosity of 80 fb^{-1} . The signal events are selected if they contain exactly two same-flavour leptons (with no charge requirement) and at least one large- R jet with large transverse momentum $p_T > 200 \text{ GeV}$. The leading lepton should be back-to-back in azimuth with the jet, while the subleading lepton should be contained inside the jet. The latter causes 30 % uncertainty on electron identification which was estimated in a different-flavor validation region.

Binned maximum-likelihood fit was performed to obtain limits on masses of W_R and N_R . At 95 % confidence level W_R masses are excluded up to $m_{W_R} = 4.7 \text{ TeV}$ and N_R masses up to $m_{N_R} = 3.2 \text{ TeV}$ in the resolved channel. The boosted channel additionally improves the limits on m_{W_R} up to 5 TeV for low m_{N_R} as shown in Figure 4.

Fig. 4. Observed (black solid line) and expected (red dashed line) 95 % CL exclusion contours in the (m_{W_R}, m_{N_R}) plane, along with the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands (green and yellow) around the expected exclusion contour in the (a) electron and (b) muon channels. The exclusion limits in the resolved topology are shown by the blue line.⁷

4. Scalar Leptoquarks

Leptoquarks (LQs) are features of a number of extensions of the Standard Model and may provide an explanation for the similarities between the quark and lepton sectors in the SM. They are colour-triplet bosons with fractional electric charge and possess non-zero baryon and lepton number.⁸ Scalar and vector LQs have been proposed and are expected to decay directly into lepton–quark pairs. The lepton can be either electrically charged or neutral. The benchmark signal model used for this search is the minimal Buchmüller–Rückl–Wyler (BRW) model.⁹ LQs belong to three families, corresponding to the three SM generations, such that only leptons and quarks within a given generation can interact. The couplings are determined by two parameters: a model parameter β and the coupling parameter λ . The coupling to the charged lepton is given by $\sqrt{\beta}\lambda$, and the coupling to the neutrino by $\sqrt{1-\beta}\lambda$. The branching ratio B into charged leptons is for first and second generations directly proportional to β , but it also has leptoquark mass dependence for third generation due to sizeable top-quark mass.

The search focused on pair production of scalar leptoquarks using 36.1 fb^{-1} of ATLAS data. It was split into several channels primarily split between first and second generations,¹⁰ and third generation leptoquarks.¹¹ The light generations channel is focusing on two different final state topologies, one consisting of two leptons and at least two jets $\ell\ell jj$, and the other of exactly one lepton, missing transverse momentum and at least two jets $\ell\nu jj$. The electron and muon channels are treated separately as they correspond to LQs of different generations.

The third generation searches are all reinterpretations of existing ATLAS searches. One is based on a search for pair-produced Higgs bosons decaying into two b -jets and two τ -leptons, and four are reinterpretation searches for supersymmetric particles. They cover topologies with two top-quark decays and E_T^{miss} , two τ -leptons one b -jet and E_T^{miss} , and two b -jets and E_T^{miss} . Supersymmetric particles can have similar or even identical experimental signatures and very similar kine-

Fig. 5. Limits on the branching ratio into charged leptons for scalar third generation (a) up-type leptoquark pair production and (b) down-type leptoquark pair production as a function of the leptoquark mass.¹¹

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ematics to pair-produced LQs.

The observed and expected lower limits on the leptoquark mass at 95 % confidence level extend up to 1.25 TeV for first and second generation leptoquarks. A separate limit was set for each of the channels of the third generation search as shown in Figure 5. LQ masses below 0.8 TeV are excluded independently of the branching ratio B . For the special cases of $B = 0$ and $B = 1$ third generation scalar leptoquarks are excluded up to 1 TeV.

5. Dijet Resonances in Events With an Isolated Lepton

Searches for resonances in dijet invariant mass distributions provide a means to investigate a wide range of theories beyond the Standard Model (BSM). Such searches are sensitive to heavy particles that decay into two partons which, following hadronization, form two jets. Selecting events with a final-state lepton in addition to dijets increases sensitivity to a different range of exotic models. In addition, exploitation of the lepton in event selection gives an opportunity to probe smaller dijet invariant masses than in the previous dijet searches based on jet triggers.

The study presented focuses on a generic search¹² for BSM resonances in the dijet invariant mass distribution constructed from events with at least one isolated lepton (muon or electron) and uses an integrated luminosity of 80 fb^{-1} of ATLAS data. The presence of a new resonance with mass m_X may lead to an excess of events at $m_{jj} = m_X$ in an otherwise smooth and monotonically decreasing dijet invariant mass distribution. The background shape was fitted with a function

$$f(x) = p_1(1-x)^{p_2}x^{p_3+p_4 \ln x + p_5 \ln^2 x},$$

where $x \equiv m_{jj}/\sqrt{s}$ and the p_i are five free parameters to be estimated.

In order to determine the most significant deviation from the background only hypothesis, the BumpHunter¹³ (BH) test is used. In the BH procedure, for each of the N possible intervals in m_{jj} , a local p -value is calculated from the background-only hypothesis test statistic. The result of the background fit and the BH procedure is shown on Figure 6 with the highest deviation at $m_{jj} = 3.56 \text{ TeV}$ corresponding to a significance of 2.5 standard deviations. In the absence of any significant excess, upper limits have been calculated for different resonance widths, from a narrow width to 15 % of the mean mass. The resulting limits range from 50 fb to 0.1 fb in the mass range from 0.25 to 6 TeV and are presented in Figure 7.

6. Type-III seesaw heavy leptons

The experimental observation of neutrino oscillation shows that neutrinos have non-zero masses, which are much smaller than those of the charged leptons (see Ref. 14 and references therein). The ATLAS search using 80 fb^{-1} of data presented at this conference¹⁵ uses a minimal type-III seesaw model¹⁶ focusing on the lightest

Fig. 6. The dijet mass distribution for events with leptons of $p_T > 60$ GeV. The data are shown together with the background fit (shown with the red line). The fit corresponds to $\chi^2/\text{ndf} = 1.02$ in the considered mass range. The lower panel shows the bin-by-bin significances of the data-fit differences considering only statistical uncertainties.¹²

fermionic triplet of unknown (heavy) masses with one neutral and two oppositely-charged leptons denoted by (L^+, L^-, N^0) . Here L^+ is the antiparticle of L^- and N^0 is a Majorana particle. These heavy leptons decay into a SM lepton and a W , Z or H boson. The heavy leptons are assumed to be degenerate in mass¹⁷ and the decay branching ratios are considered equal for all three lepton flavors. Pair-production through $pp \rightarrow W^* \rightarrow N^0 L^\pm$ with one of the two W bosons decaying leptonically and the other decaying hadronically was considered, as illustrated in Figure 8. The

Fig. 7. Comparisons of the 95 % credibility-level upper limits for a BSM signal approximated by Gaussian contributions with different widths. The limits are weaker for broader resonances for which Gaussian contributions span more m_{jj} bins.¹²

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Fig. 8. Feynman diagrams of the considered type-III seesaw production process in the (a) OS and (b) SS final state cases.¹⁵

exclusive topology of the final state consists of two jets from the W boson, large missing transverse momentum (E_T^{miss}) and a lepton pair with either the same-sign charge (SS) or with the opposite-sign charge (OS) and with either same-flavor (ee or $\mu\mu$) or different-flavor ($e\mu$) combinations.

The six OS and SS analysis channels are defined according to the flavor combination. Different selection criteria are applied to ensure the highest possible signal and background separation. The invariant dijet mass (m_{jj}) of the two leading jets is expected to be close to the W mass. As the signal process contains neutrinos in the final state, one of the most important selection criteria is based on the E_T^{miss} significance $\text{Sig}(E_T^{\text{miss}})$.¹⁸ In the OS channels the azimuthal angle $\Delta\phi(E_T^{\text{miss}}, l)_{\min}$ between the directions of transverse momenta of E_T^{miss} and closest lepton has a very good separation power, exploiting the different nature of E_T^{miss} between signal and background.

A binned maximum-likelihood fit of the $H_T + E_T^{\text{miss}}$ variable distribution, the sum of the E_T^{miss} and the scalar sum of the transverse momenta H_T , was used to

Fig. 9. Expected and observed 95% CLs exclusion limits on the type-III seesaw cross section with the corresponding one and two standard deviation bands.¹⁵

obtain the numbers of signal and background events. The compatibility between the data and the expected background is assessed and good agreement is observed. 95% confidence level upper limits were derived as a function of the heavy lepton mass and are shown on Figure 9. The type-III seesaw heavy leptons observed limit has been placed at 560 GeV, excluding the mass values below this point.

7. Conclusions

The ATLAS experiment at the LHC has performed many searches with leptons and jets in the final state using 36.1 fb^{-1} and 80 fb^{-1} of collected data. No significant excess from the Standard Model has been observed and limits on production cross sections of various theories beyond the Standard Model have been set.

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