PROCEEDINGS OF SCIENCE

Search for new physics in final states with leptons with ATLAS

PoS(LHCP2018)273

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One of the main goals in the physics program of the ATLAS experiment at Large Hadron Collider is to discover hints for extensions to the Standard Model. Leptons provide experimentally clear signatures in the new physics searches with the ATLAS detector. This paper presents results of three new physics searches in final states characterized by leptons: a search for pair production of heavy leptons belonging to a new $SU(2)_{\mathrm{L}}$ triplet which is predicted by the type-III seesaw mechanism; a search for a new charged heavy gauge boson resonance (W') decaying into a charged lepton and a neutrino; and a search for lepton-flavor violating decays of Z bosons into a τ-lepton and an electron or a muon. They are based on 36.1-79.8 fb^{-1} of pp collision data recorded by the ATLAS detector at $\sqrt{s} = 13$ TeV. No statistically significant excess from the Standard Model expectation has been observed and upper limits for various new physics models have been set as the interpretation of the results.

ATL-PHYS-PROC-2018-092
03 September 2018

Sixth Annual Conference on Large Hadron Collider Physics (LHCP2018)
4-9 June 2018
Bologna, Italy

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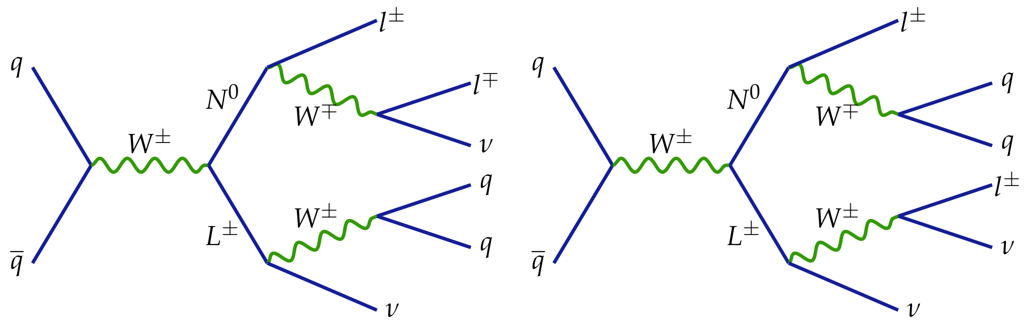
1. Introduction

One of the main goals in the physics program of the ATLAS experiment [1] at the Large Hadron Collider (LHC) [2] is to discover hints for extensions to the Standard Model (SM). The efficient reconstruction and triggering of leptons provide a wide acceptance in the new physics searches. Various new physics models can be efficiently probed via leptonic decays of new particles, such as heavy spin-1 bosons (W', Z') and heavy leptons of new $SU(2)_L$ multiplets, while a large amount of backgrounds can be discarded by the requirement on the presence of final state leptons. Furthermore, a new physics could introduce additional lepton flavor violating (LFV) couplings, which would give a unique indication of new physics.

The ATLAS detector covers nearly the entire solid angle around the collision point. It consists of an inner tracking detector surrounded by a thin superconducting solenoid magnet, electromagnetic and hadronic calorimeters, and an external muon spectrometer incorporating a large superconducting toroid magnet system. A two-level trigger system is used to select interesting events for recording and subsequent offline analysis. Electron candidates are reconstructed from energy deposits in the electromagnetic calorimeter matched to a charged-particle track measured in the inner tracking detector. Muon candidates are reconstructed by a combined measurement of track segments in the muon spectrometer and an inner detector track. Hadron jets are reconstructed from topological clusters of energy deposits in the calorimeter with the anti-k_{T} algorithm with the distance parameter of 0.4. In order to identify jets containing b-hadrons (b-jets), a multivariate classifier based on large impact parameters of the matched inner detector tracks with respect to the primary vertex, the presence of displaced secondary vertices, and the reconstructed flight paths of b- and c-hadrons associated with the jets is employed. Hadronically decaying τ leptons are typically characterized by one or three charged pions and up to two neutral pions and identified with the calorimeteric shower shapes and inner detector tracking information. The missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}}$, is calculated as the negative vectorial sum of the transverse momenta of all fully calibrated hard objects and soft contributions calculated with inner detector tracks.

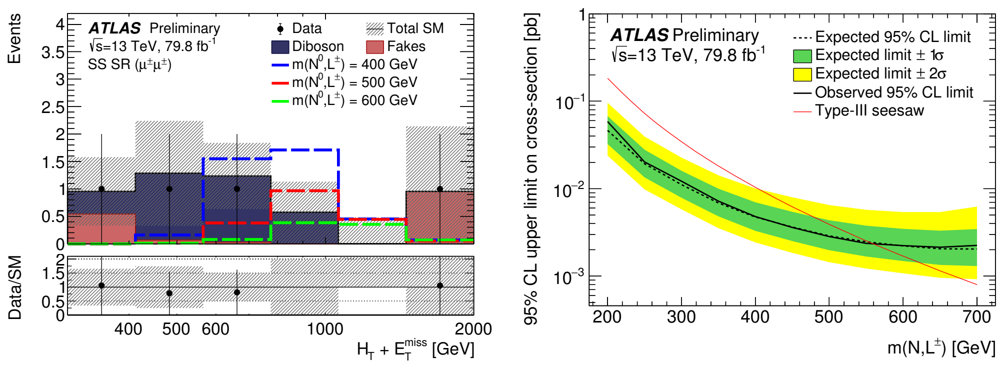
2. Search for type-III seesaw heavy leptons

The type-III seesaw mechanism for neutrino masses predicts new heavy leptons belonging to a new $SU(2)_{\mathrm{L}}$ triplet, N^0 and $L^{\pm}$. A search for pair productions of the heavy leptons is performed [3], using pp collision dataset with the single or double lepton triggers in 2015-17 at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 79.8 fb^{-1}. The analysis focuses on the pair production of N^0 and $L^{\pm}$ and their decays with intermediate W bosons. The candidate events can be characterized with two light leptons (electrons e and muons μ) in either of Opposite Sign (OS) or Same Sign (SS) charge combination, with at least two jets with high transverse momentum p_{T} from the hadronic W decay, and large missing transverse momentum for the neutrinos in the final states as shown in Figure 1. The search is optimized in the six channels distinguished by the combination of flavors (ee, $e\mu$, $\mu\mu$) and charge (OS, SS) of light leptons. The dominant background contribution in the OS channels is from the SM $t\bar{t}$ production, the normalization of which is estimated with the dedicated control regions. As the charge mis-reconstruction of electrons is the major background sources in SS channels, dedicated $Z+$jets validation samples are defined in order to validate the simulated charge mis-reconstruction modeling. Reducible backgrounds due to the hadron fake or non-prompt electron or muon, collectively called "fake", are estimated with a data-driven approach. Finally, the sum of the $E_{\mathrm{T}}^{\mathrm{miss}}$ and the scalar sum of the transverse momenta of selected objects, H_{T}, is examined for the signal extraction simultaneously in the six different regions. The $H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in the SS $\mu\mu$ channel is shown in Figure 2 (a) as an example. A good agreement is observed between the number of events in data and the SM predictions in all the signal regions. The results are translated into the exclusion limits on the heavy lepton mass, where N^0 and $L^{\pm}$ are mass-degenerate and equally coupling to the electrons, muons and taus. The observed lower limit on the mass of the type-III seesaw heavy leptons is 560 GeV as shown in Figure 2 (b).



(a) (b)

Figure 1: Feynman diagrams of the considered production and decays in the (a) OS and (b) SS final state cases.

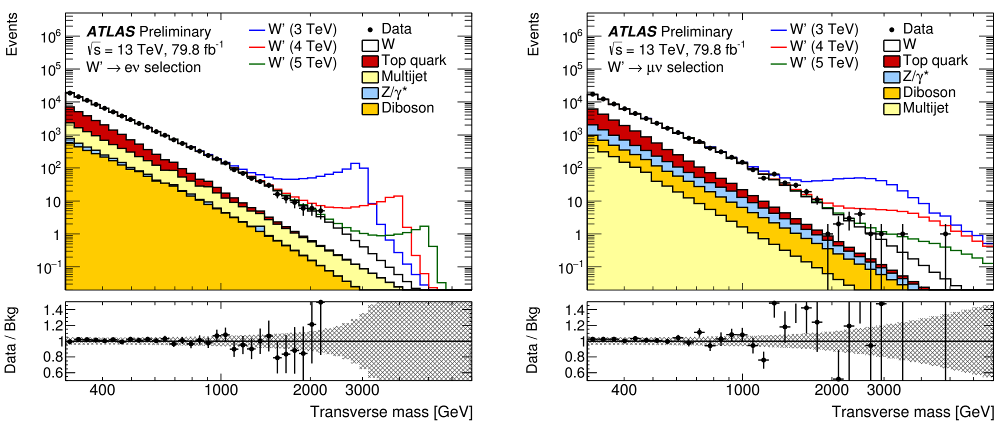


(a) (b)

Figure 2: (a) Distributions of $H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$ in SS $\mu\mu$ signal regions after the background-only fit. The hatched bands include all systematic uncertainties post-fit with the correlations between various sources taken into account. The dashed colored lines show benchmark signal samples with the N^0 and $L^{\pm}$ mass marked in the legend. (b) Expected and observed 95% confidence level exclusion limit on the cross-section of N^0 and $L^{\pm}$ pair-production in the Type-III seesaw models with the signal hypothesis mentioned in the text [3].

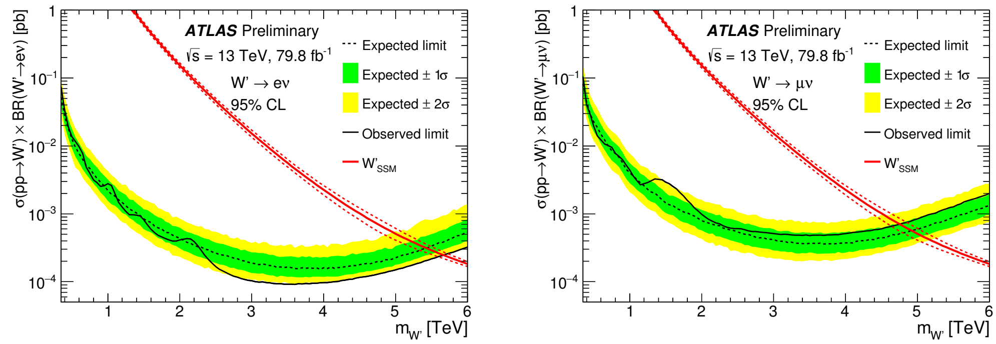
3. Search for a new charged heavy gauge boson resonance decaying into a charged lepton and a neutrino

Extensions to the SM may include heavy gauge bosons that could be discovered at the LHC. A heavy W' signal would appear as an excess of events above the SM backgrounds in energetic charged lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ final states. A search for W' decaying into an e or μ, collectively denoted to as ℓ, and a neutrino is performed, based on 79.8 fb^{-1} of pp collision data recorded by the single lepton triggers in 2015-17 at $\sqrt{s} = 13$ TeV [4]. The events must satisfy the $E_{\mathrm{T}}^{\mathrm{miss}} > 55$ GeV and $p_{\mathrm{T}}^{\mu} > 55$ GeV in the muon channel, and $E_{\mathrm{T}}^{\mathrm{miss}} > 65$ GeV and $p_{\mathrm{T}}^{e} > 65$ GeV in the electron channel. To ensure optimal muon resolution at high p_{T} and avoid p_{T} mis-measurements, a set of tight quality requirements are applied in the muon selection. The backgrounds from $W \to \ell\nu$, $Z/\gamma^* \to \ell\ell$, $W \to \tau\nu$, $Z/\gamma^* \to \tau\tau$ are estimated based on the simulations, while the multi-jet backgrounds with fake leptons are estimated with a data-driven technique. W' signals would be seen as an excess above the SM background prediction with a high transverse mass $m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\phi_{\ell\nu})}$, where $\phi_{\ell\nu}$ is the azimuthal angle between the direction of the lepton p_{T} and $E_{\mathrm{T}}^{\mathrm{miss}}$. Examining transverse mass spectrum in $m_{\mathrm{T}} > 300$ GeV, no significant excess above the expected SM background is observed as shown in Figure 3. Exclusion limit at 95% confidence level upper limits on the $\sigma \times BR$ are set with respect to the Sequential Standard Model (SSM) signal hypothesis as shown in Figure 4. The figure also shows the predicted $\sigma \times BR$ for the SSM hypothesis. The comparison between the observed (expected) limits and the SSM prediction of $\sigma \times BR$ can exclude the hypothesis of W' in the SSM with the mass below 5.7 (5.4) TeV in the electron channel, and 4.8 (4.9) TeV in the muon channel, respectively. The combined limit of the two channels is 5.6 (5.5) TeV.



(a) (b)

Figure 3: Transverse mass distributions for events satisfying all selection criteria in the (a) electron and (b) muon channels. The distributions in data are compared to the stacked sum of all expected backgrounds. As examples, expected signal distributions for three different SSM W' boson masses are shown on top of the SM prediction. The bin width is constant in $\log(m_{\mathrm{T}})$. The lower panels show the ratios of the data to the adjusted expected background (post-fit) that results from the statistical analysis. The bands in the ratio plots indicate the total systematic uncertainty, including the integrated luminosity [4].

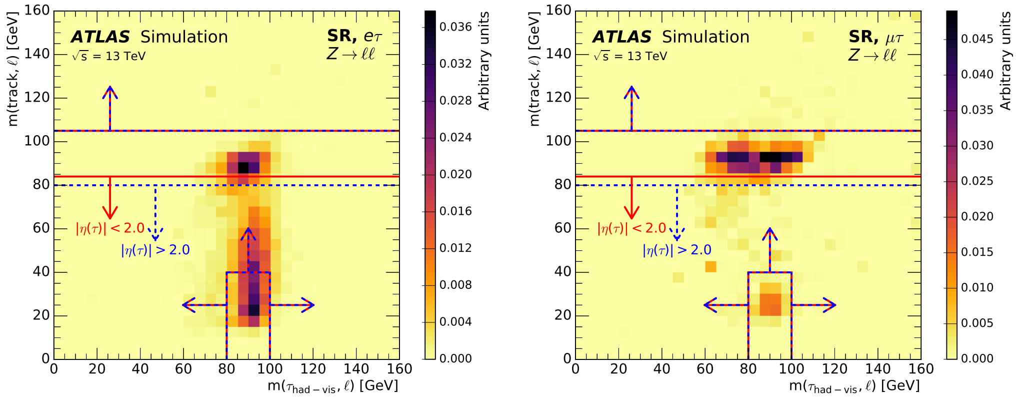


(a) (b)

Figure 4: Observed (solid black line) and expected (dashed black line) upper limits on cross-section times branching ratio ($\sigma \times$ BR) as a function of the SSM W' boson mass in the (a) electron, (b) muon and (c) combined electron and muon channels. The 1σ (green) and 2σ (yellow) expected limit bands are also shown. The predicted $\sigma \times$ BR for SSM W' production is shown as a red solid line. For illustration the uncertainties in $\sigma \times$ BR from the PDF, α_s and the renormalization and factorization scales are also shown as red-dashed lines [4].

4. Search for lepton-flavor violating decays of the Z boson in to a τ-lepton and a light lepton

An observation of lepton flavor violation (LFV) in decays of Z bosons, such as $Z \to e\tau$ and $Z \to \mu\tau$, would give a clear indication for new physics. A search for the decays of the Z into a τ-lepton and electron or muon is performed with a hadronically decaying τ (τ_{had}) considered [5]. This search analyzes pp collision data recorded by the ATLAS detector during 2015 and 2016 at $\sqrt{s} = 13$ TeV, the corresponding integrated luminosity of 36.1 fb^{-1}. The candidate events are selected by the single lepton triggers in both $e\tau$ and $\mu\tau$ channels. The events are required to contain exactly one isolated electron or muon and at least one τ_{had} candidate that passes identification selection criteria. Events with b-tagged jets are removed to reject backgrounds with top quarks. To reduce the $Z \to \ell\ell$ backgrounds due to mis-identification of electrons or muons as τ_{had}, events with 1-prong τ_{had} with $|\eta_{\tau_{\text{had}}}| > 2.2$ in $e\tau$ search or $|\eta_{\tau_{\text{had}}}| < 0.1$ in $\mu\tau$ channel are discarded, where higher mis-identification rates are expected. Furthermore, selection criteria on the invariant mass of the track for 1-prong τ_{had} and the light lepton ($m(\text{track}, \ell)$) and invariant mass of the 1-prong τ_{had} and the light lepton ($m(\tau_{\text{had}}, \ell)$) can suppress remaining $Z \to \ell\ell$ backgrounds as shown in Figure 5. The selected events are examined using neural networks (NNs) trained to discriminate signals ($Z \to e\tau$, $Z \to \mu\tau$) from backgrounds of $Z \to \tau\tau$, $Z \to \ell\ell$ and $W \to \ell\nu +$jets. Three different classifiers are trained for the three background processes and combined into a NN output score. A binned maximum-likelihood fit is used to compare the observed binned distributions of the combined NNs to extract evidence of signal events. The background contribution from events where a τ_{had} candidate arises from a mis-identified jet are evaluated by a data-driven "fake factor" technique. Fake factors are measured for major physics processes of fake backgrounds such as $W +$jets and $t\bar{t}$ using four data samples. The backgrounds from process with a true hadronically



(a) (b)

Figure 5: Expected distributions of m(track,ℓ) versus m(τ_{had}, ℓ) $Z \to \ell\ell$ events with 1-prong τ_{had} candidates in the (a) $e\tau$ (b) $\mu\tau$ channels for the remaining $Z \to \ell\ell$ backgrounds after selections applied except for the cuts on these two variables [5].

decaying τ-lepton and from light leptons mis-identified as τ_{had} candidate are estimated from simulations. Results of the fit on the NN outputs are shown in Figure 6. A simultaneous fit is performed between 1-prong and 3-prong samples, separately for $e\tau$ and $\mu\tau$ channels. The best-fit values of the branching fraction is consistent with zero in the $\mu\tau$ channel $BR(Z \to \mu\tau) = (-0.1^{+1.2}_{-1.2}) \times 10^{-5}$, and the slightly fluctuating to positive values in the $e\tau$ channel $BR(Z \to e\tau) = (3.3^{+1.5}_{-1.4}) \times 10^{-5}$. The observed (expected) upper limits at 95% confidence level are $BR(Z \to e\tau) < 5.8 \times 10^{-5} (2.8 \times 10^{-5})$ and $BR(Z \to \mu\tau) < 2.4 \times 10^{-5} (2.4 \times 10^{-5})$. The significance of the excess from the background only hypothesis is 2.3σ.

5. Conclusions

The ATLAS collaboration has performed searches for new physics in final states characterized by leptons at $\sqrt{s} = 13$ TeV. This paper presents three of new results with 36.1-79.8 fb^{-1} of pp collision data taken in 2015, 2016 and 2017 at $\sqrt{s} = 13$ TeV. No statistically significant excess from the background expectation has been observed and upper limits for large classes of new physics have been set as the interpretation of the results.

References

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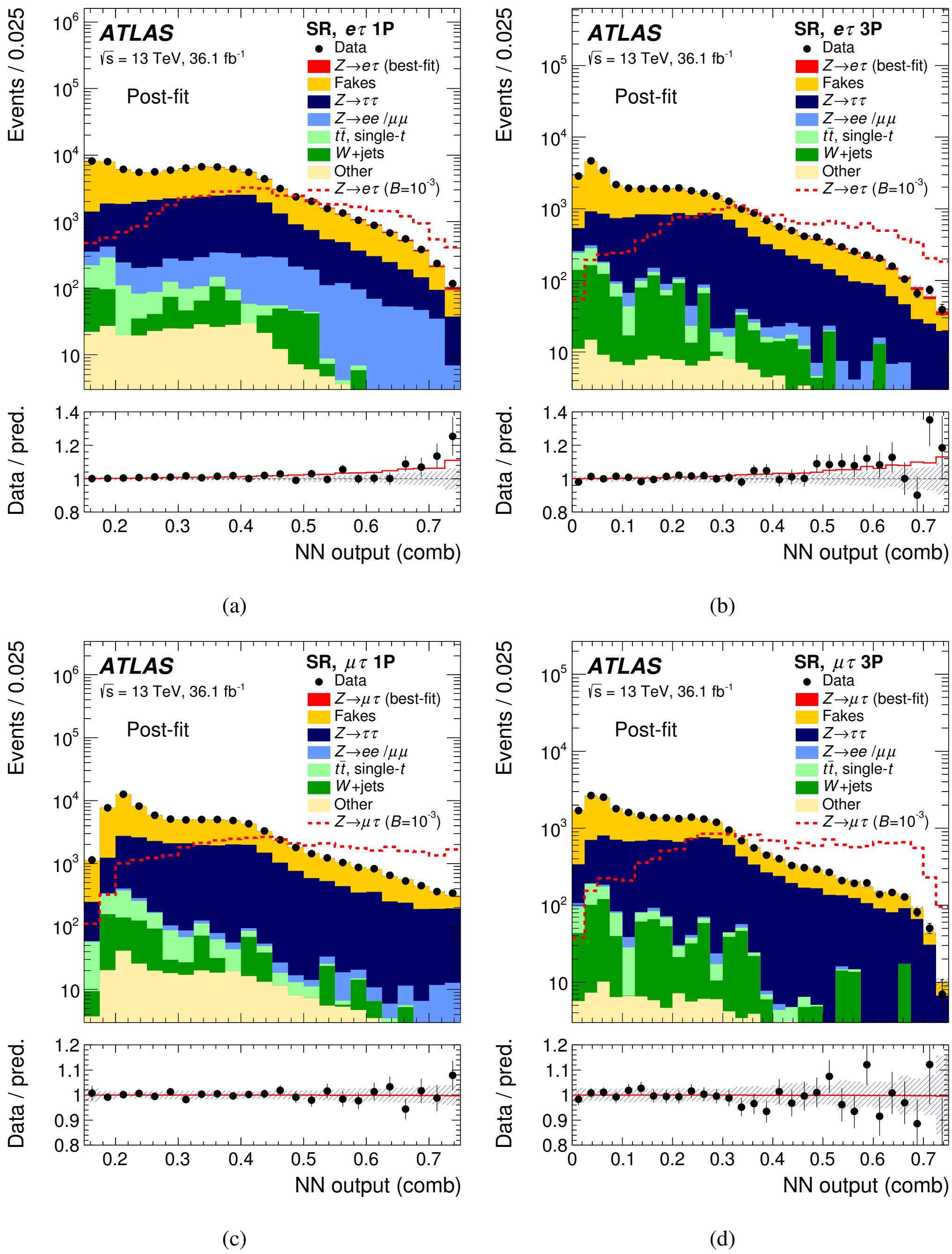

Figure 6: Observed and expected post-fit distributions of the combined NN output in SR for the $e\tau$ (top) and $\mu\tau$ (bottom) channels, for 1-prong (left) and 3-prong (right) τ_{had} candidates. The filled histogram stacked on top of the backgrounds represents the signal normalized to the best-fit $BR(Z \to \ell\tau)$. The overlaid dashed line represents the expected distribution for the signal normalized to $B(Z \to \ell\tau) = 10^{-3}$. In the bottom panels, the ratios of the observed data (dots) and the post-fit background plus signal (solid line) to the post-fit background are shown. The hatched error bands represent the combined statistical and systematic uncertainties. The first and last bins include underflow and overflow events, respectively [5].