PROCEEDINGS OF SCIENCE

Searches for new physics with leptons using the ATLAS detector

Wasikul Islam*

On behalf of the ATLAS Collaboration

Department of Physics, University of Wisconsin, Madison, USA

E-mail: wasikul.islam@cern.ch

Many different theories beyond the Standard Model (SM) predict that new physics will manifest itself by decaying into final states involving leptons. Leptoquarks are predicted by many new physics theories to describe the similarities between the lepton and quark sectors of the SM. Right-handed W bosons and heavy-neutrinos are also predicted by many extensions of the SM in the gauge sector, and lepton flavour violation could manifest itself by decays of new gauge bosons into leptons of different flavours. This talk will present the most recent 13 TeV results on the searches for leptoquarks with the ATLAS detector, covering flavour-diagonal and cross-generational final states, as well as the latest searches for lepton-flavour violating Z' and heavy neutrinos arising from left-right symmetric models.

ATL-PHYS-PROC-2024-120
20 December 2024

Presented at the 43rd International Symposium on Physics in Collision (PIC), NCSR, Demokritos, Greece, 22-25 October 2024

*Speaker

1. Introduction

Leptons play an essential role in both precision measurements and searches for new physics at collider experiments, particularly the ATLAS experiment [1] at the CERN's Large Hadron Collider [2]. The clean signatures provided by leptons help minimize systematic uncertainties in detector resolution, making them invaluable for identifying subtle signals in the midst of background noise. Lepton triggers, used to reduce the multi-jet background, allow physicists to focus on events of interest. Events involving leptons exhibit a range of topologies, from leptonic and hadronic τ-decays to processes with b-jets and significant missing transverse energy (E_{T}^{miss}). These features make leptons a crucial probe in the exploration of new signatures, which could be linked to possibilities of new physics phenomena. In this report, we will share various lepton-based new physics searches using an integrated luminosity of 139 fb^{-1} of $\sqrt{s}$ = 13 TeV proton-proton collision data recorded by the ATLAS detector.

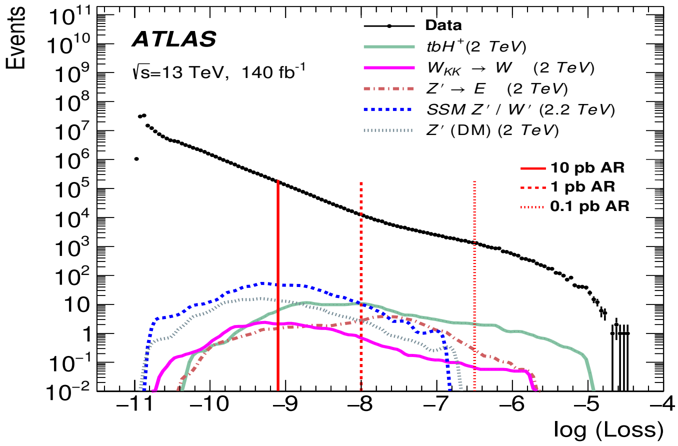


Figure 1: Distributions of the anomaly score from the AE for data and five benchmark BSM models.The vertical lines indicate the start of the three anomaly regions (ARs) [3].

2. Resonance Searches with Lepton Triggers

Lepton triggers are fundamental in resonance searches, where heavy particles decaying into leptons or jets are studied. For example, single electron or muon triggers with transverse momentum thresholds as low as 24 GeV help in the detection of low-mass resonances, starting from 0.22 TeV. Such triggers significantly suppress multi-jet events produced by the QCD processes, enhancing the sensitivity of these searches. In the search for dijet resonances [4] using a single lepton trigger with $p_{\mathrm{T}} > 60$ GeV set stringent limits for new particle masses, such as Z' and W', reaching exclusion limits at 95% confidence level (CL) up to 2 TeV. Incorporating leptons into the mass description alongside dijets, particularly in the context of 3 or 4-body invariant mass spectra, offers distinct advantages over relying solely on dijet invariant masses for many complex BSM models with novel decay modes. ATLAS searched for resonances in various invariant masses ($m_{jj\ell}$, $m_{jj\ell\ell}$, $m_{jb\ell}$, $m_{bb\ell}$) that include two jets (jj) and 1 or 2 leptons (electron or muon, denoted as ℓ), while requiring the isolated leading lepton to have $p_{\mathrm{T}} > 60$ GeV, and sub-leading lepton to have $p_{\mathrm{T}} > 30$ GeV [5]. This search extended the exclusion limit for W' up to 2.5 TeV and set limits for a new composite lepton.

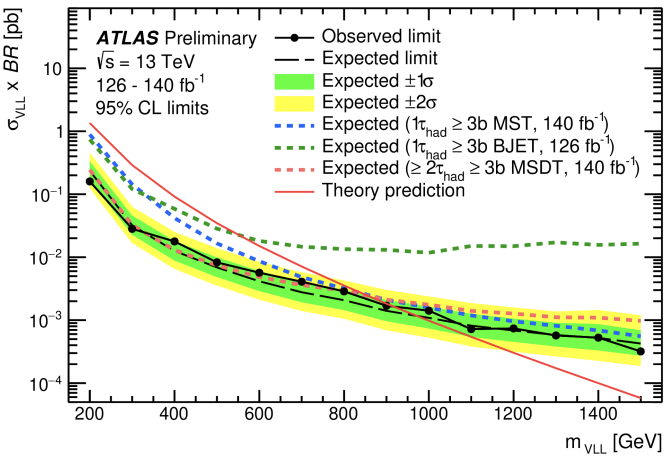


Figure 2: Observed (solid line with markers) and expected (dashed line) 95% CL upper limits on the VLL pair production cross-section (σ_{VLL}) times branching ratio (BR) to third generation quarks and leptons as a function of (m_{VLL}) [6].

3. New physics search using lepton triggers using Event-based Anomaly Detection

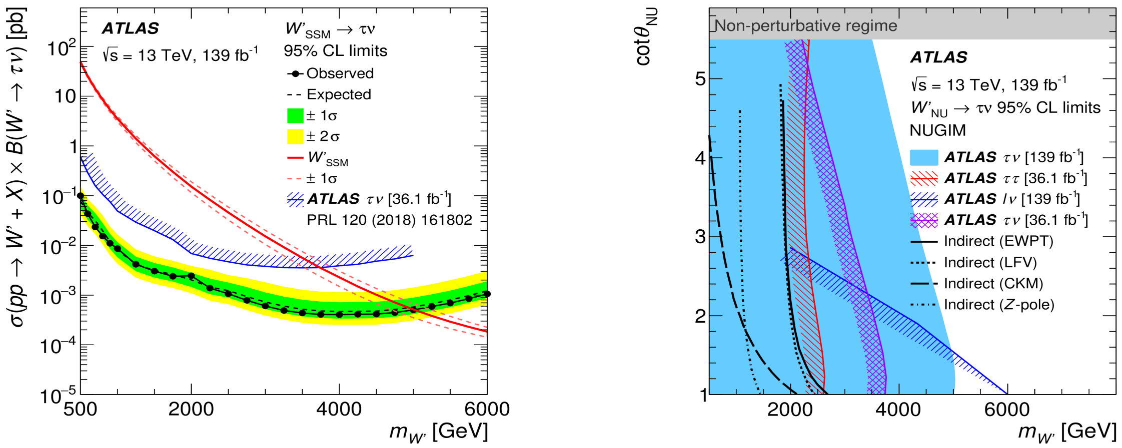
ATLAS has embraced innovative techniques like unsupervised machine learning to search for anomalies in data spanning invariant masses from 0.3 TeV to 8 TeV [3]. By analyzing events with reconstruction loss distributions from autoencoders (AE) algorithm (as shown in Figure 1) falling in the anomaly region, the experiment enhances sensitivity to subtle deviations from Standard Model predictions. Notably, for masses below 1 TeV, this approach achieves a two- to three-fold improvement in limits compared to traditional methods. Furthermore, the use of autoencoders significantly improves discovery sensitivity for various Beyond Standard Model (BSM) processes.

4. Vector-Like Leptons and Electroweak Production

Searches for vector-like leptons (VLLs), hypothetical spin-$\frac{1}{2}$ particles predicted by many BSM theories, represent a novel frontier in particle physics. ATLAS has conducted the first searches for electroweak production of VLL pairs decaying through $W^{\pm}$, Z, or γ^{*} [6]. Events are characterized by multiple τ-leptons and b-jets with no light leptons, using neural network-based scoring for classification. The analysis disfavored a 2.8σ excess observed by CMS at 600 GeV [7], setting stringent limits with lower observed (expected) exclusions of 910 GeV (970 GeV) for VLL masses, as shown in Figure 2. These results showcase ATLAS's ability to probe cutting-edge physics and provide robust constraints on new theories.

5. High-Mass Resonance Searches with τ-Lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$

The high-mass resonance searches involving τ-leptons and missing transverse energy are a critical part of the ATLAS experiment's efforts to explore BSM physics. These searches target processes such as $W' \to \tau\nu$, which are predicted by models like the Sequential Standard Model



(a) (b)

Figure 3: (a) Observed (black markers) and expected (black dashed line) 95% CL upper limits on the cross-section times branching ratio ($\sigma\times B$) vs. W' mass in the SSM. (b) Observed 95% CL lower limit on the W' mass as a function of the parameter $\cot(\theta_{\rm NU})$ describing the coupling to the third generation [10].

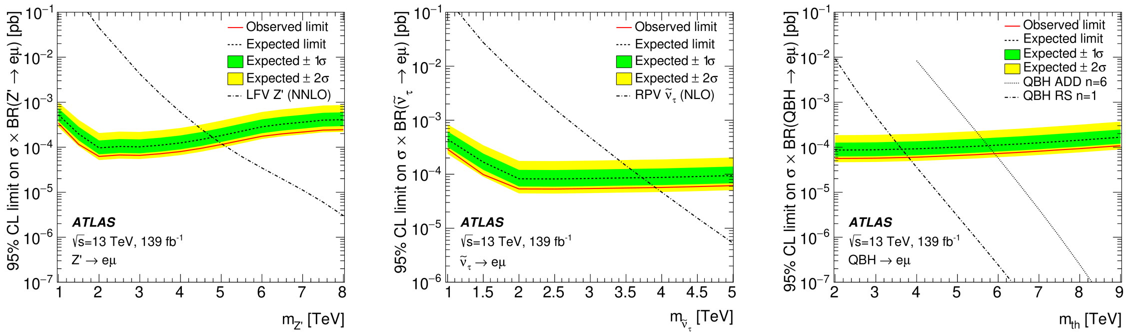
(SSM) and Non-Universal Gauge Interaction Models (NUGIM). The signatures of these processes in the detector are characterized by a τ-lepton with high momentum and significant missing transverse energy ($E_{\rm T}^{\rm miss}$), providing a clean and distinguishable signal from Standard Model processes. To enhance accuracy compared to a previous study [8, 9], the analysis employs a Recurrent Neural Network (RNN)-based algorithm to identify hadronic decays of τ-leptons. The transverse mass ($m_{\rm T}$) spectrum, defined as

$$m_{\rm T} = \sqrt{2E_{\rm T}^{\rm miss}p_{\rm T}^{\text{had-vis}}\left(1-\cos\Delta\phi_{\text{had-vis},E_{\rm T}^{\rm miss}}\right)},$$

is calculated using $E_{\rm T}^{\rm miss}$, the transverse momentum of the visible hadronic tau candidate ($p_{\rm T}^{\text{had-vis}}$), and the azimuthal angle difference ($\Delta\phi$) between them. It is used to identify resonances, with statistical analyses relying on profile-likelihood fits to distinguish signal from background. The results [10], as shown in Figure 3 demonstrate significant improvements over previous analyses, with a 95% confidence level exclusion of W'-bosons up to 5 TeV in the SSM. Moreover, the upper limits on the visible cross-section for these events have been improved by a factor of 5 for masses around 2 TeV, showcasing the robustness of the methodology. The NUGIM framework, which introduces non-universal couplings via mechanisms like the non-universality angle ($\theta_{\rm NU}$), shows enhanced sensitivity in these high-mass regions. These efforts underscore the experiment's capability to push the boundaries of current physics models and to provide stringent constraints on new theories involving τ-leptons and $E_{\rm T}^{\rm miss}$.

6. Heavy Majorana Neutrinos in Same-Sign Dilepton States

Searches for heavy Majorana neutrinos explore lepton-number-violating processes predicted by mechanisms like Type-1 Seesaw. ATLAS analyzed same-sign dilepton final states with $\mu\mu$ pairs [11] and with ee or $e\mu$ final states [12]. Combining statistical data across multiple channels improved



(a) (b) (c)

Figure 4: The observed and expected 95% CL upper limits on the (a) Z' boson, (b) RPV τ-sneutrino ($\bar{\nu}_\tau$) and (c) QBH production in Arkani-Hamed–Dimopoulos–Dvali (ADD) and Randall–Sundrum (RS) models for cross-section times branching ratio for decays into an $e\mu$ final state [9].

sensitivity by 27% compared to individual analysis with $\mu\mu$ channel. The study's exclusion limits, such as 24 GeV for m_{ee}, provide valuable constraints on BSM scenarios involving heavy neutrinos. Most stringent exclusion limits on mass of heavy Majorana neutrino was found at 500 GeV. These findings enhance our understanding of neutrino mass-generation mechanisms and offer a pathway to test lepton-number violation.

7. Lepton Flavor Violation in High-Mass Dilepton States

Lepton flavor violation (LFV) in high-mass dilepton states is investigated in $e\mu$, $e\tau$, and $\mu\tau$ channels, probing theories like R-parity-violating SUSY, quantum black holes (QBH), and heavy gauge bosons [9]. Mild excesses above the background were observed at 2.0–2.3 TeV in $\ell\tau$ channels, while stringent 95% CL limits were set using profile-likelihood fits on invariant masses. Figure 4 shows results in $e\mu$ channel for 3 BSM scenarios. These searches refine our understanding of LFV processes, providing key insights into theories that challenge the Standard Model.

8. Leptoquark Searches

Leptoquarks, particles connecting quarks and leptons, were searched for in both single and pair-production modes [13]. For pair production, parameterized neural networks (PNNs) enhanced sensitivity, setting mass exclusions up to 1.75 TeV for b-quark decays and 1.64 TeV for scalar leptoquarks decaying into $t\mu$ final states. In the Yang-Mills (minimal coupling) scenario, vector leptoquarks are excluded for masses below 1.58 TeV (1.35 TeV) at a gauge coupling of 1.0, and below 2.05 TeV (1.99 TeV) at a gauge coupling of 2.5. For scalar leptoquarks, masses are excluded below 1.28 TeV for a Yukawa coupling of 1.0 and below 1.53 TeV for a Yukawa coupling of 2.5. Figure 5 shows exclusion limits for one of the many scenarios considered in the analysis. A combination of decay channels [14] revealed improvements in mass exclusions for both up-type and down-type leptoquarks. These results highlight innovative approaches of ATLAS in probing leptoquark interactions.

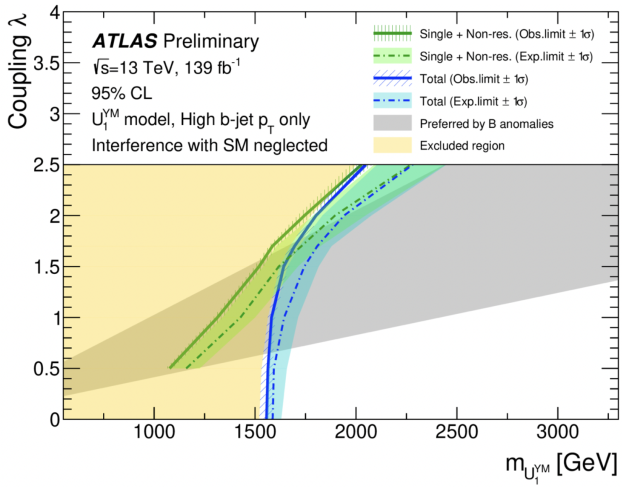


Figure 5: The two-dimensional 95% CL exclusion limits in the λm_{LQ} plane for singly plus non-resonant produced vector LQ (green lines) and for the sum, referred as Total, of single plus non-resonant plus pair vector LQ production (blue lines) with $\kappa = 0$ [13].

9. Summary and Future Prospects

The ATLAS experiment has conducted a comprehensive suite of searches for new physics using leptons, targeting a range of Beyond Standard Model phenomena. Resonance searches with lepton triggers have set stringent mass limits on heavy gauge bosons like W' and Z', achieving exclusions up to 5 TeV in specific models. Anomaly detection with unsupervised machine learning has significantly enhanced sensitivity to subtle deviations from the Standard Model, particularly for masses below 1 TeV. Searches for vector-like leptons and heavy Majorana neutrinos have provided robust constraints on their masses and mixing parameters, with ATLAS leading in disfavoring anomalies reported by other experiments. High-mass resonance searches involving τ-leptons and missing transverse energy have improved cross-section limits by a factor of 5 at 2 TeV, while studies of lepton flavor violation in dilepton final states have yielded mild excesses and tighter limits on processes like R-parity-violating SUSY and quantum black holes. Lastly, leptoquark searches in both pair and single-production modes have excluded masses up to 2 TeV depending on the coupling strengths and decay channels.

Despite no significant deviations from the Standard Model so far, Run-3 improvements, including increased luminosity, enhanced detector performance, and higher collision energy, promise to expand discovery potential. The High-Luminosity LHC (HL-LHC) will further elevate the capabilities of ATLAS, offering unprecedented opportunities to uncover new physics with leptons. The experiment's ongoing efforts ensure it remains at the forefront of high-energy physics, with exciting results anticipated in the near future.

References

[1] ATLAS Collaboration. "The ATLAS Experiment at the CERN Large Hadron Collider". *JINST* 3 (2008), S08003. DOI: 10.1088/1748-0221/3/08/S08003.

[2] Lyndon R Evans and Philip Bryant. “LHC Machine”. *JINST* 3 (2008), p. S08001. DOI: 10.1088/1748-0221/3/08/S08001.

[3] ATLAS Collaboration. “Search for New Phenomena in Two-Body Invariant Mass Distributions Using Unsupervised Machine Learning for Anomaly Detection at $\sqrt{s}$ = 13 TeV with the ATLAS Detector”. *Phys. Rev. Lett.* 132.8 (2024), p. 081801. DOI: 10.1103/PhysRevLett.132.081801.

[4] ATLAS Collaboration. “Search for dijet resonances in events with an isolated charged lepton using $\sqrt{s}$ = 13 TeV proton-proton collision data collected by the ATLAS detector”. *JHEP* 06 (2020), p. 151. DOI: 10.1007/JHEP06(2020)151.

[5] ATLAS Collaboration. “Search for new phenomena in multi-body invariant masses in events with at least one isolated lepton and two jets using $\sqrt{s}$ = 13 TeV proton–proton collision data collected by the ATLAS detector”. *JHEP* 07 (2023), p. 202. DOI: 10.1007/JHEP07(2023)202.

[6] ATLAS Collaboration. “Search for electroweak production of vector-like leptons in multiple tau and b-jets final states in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector”. *ATLAS-CONF-2024-008* (2024). URL: https://cds.cern.ch/record/2904563.

[7] CMS Collaboration. “Search for pair-produced vector-like leptons in final states with third-generation leptons and at least three b quark jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV”. *Phys. Lett. B* 846 (2023), p. 137713. DOI: 10.1016/j.physletb.2023.137713.

[8] ATLAS Collaboration. “Search for a heavy charged boson in events with a charged lepton and missing transverse momentum from pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector”. *Phys. Rev. D* 100.5 (2019), p. 052013. DOI: 10.1103/PhysRevD.100.052013.

[9] ATLAS Collaboration. “Search for lepton-flavour violation in high-mass dilepton final states using 139 fb^1 of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector”. *JHEP* 23 (2020), p. 082. DOI: 10.1007/JHEP10(2023)082.

[10] ATLAS Collaboration. “Search for high-mass resonances in final states with a τ-lepton and missing transverse momentum with the ATLAS detector”. *Phys. Rev. D* 109.11 (2024), p. 112008. DOI: 10.1103/PhysRevD.109.112008.

[11] ATLAS Collaboration. “Search for Majorana neutrinos in same-sign WW scattering events from pp collisions at $\sqrt{s}$ = 13 TeV”. *Eur. Phys. J. C* 83.9 (2023), p. 824. DOI: 10.1140/epjc/s10052-023-11915-y.

[12] ATLAS Collaboration. “Search for heavy Majorana neutrinos in $e^\pm e^\pm$ and $e^\pm \mu^\pm$ final states via WW scattering in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector”. *Phys. Lett. B* 856 (2024), p. 138865. DOI: 10.1016/j.physletb.2024.138865.

[13] ATLAS Collaboration. “Search for leptoquarks decaying into the $b\tau$ final state in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector”. *JHEP* 10 (2023), p. 001. DOI: 10.1007/JHEP10(2023)001.

[14] ATLAS Collaboration. “Combination of searches for pair-produced leptoquarks at $\sqrt{s}$ = 13 TeV with the ATLAS detector”. *Phys. Lett. B* 854 (2024), p. 138736. DOI: 10.1016/j.physletb.2024.138736.