PROCEEDINGS OF SCIENCE

Tests of neutrino mass models with the ATLAS detector

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Multiple theories beyond the Standard Model predict the existence of heavy neutrinos, such as the type-I or type-III seesaw mechanisms that can explain the light neutrino masses, or left-right symmetric models that restore parity symmetry in weak interactions at a higher energy scale and predict right-handed counterparts to the weak gauge bosons. Searches for such heavy Majorana or Dirac neutrinos with the ATLAS detector, which can lead to boosted or displaced signatures, are presented using proton-proton data from the LHC at a center-of-mass energy of 13 TeV.

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1. Introduction

The discovery of neutrino oscillations confirmed that at least two neutrinos have non-zero mass. Extensions of the Standard Model are needed to fully describe it. The seesaw mechanism might explain the relative smallness of the neutrino masses by connecting Standard Model left-handed neutrino masses with the masses of new right-handed neutrino-like particles. There are three types of the seesaw mechanism: type-I seesaw introducing at least two fermionic singlets [1–5], type-II seesaw introducing a scalar $\mathrm{SU}(2)_L$ triplet [6–8] and type-III seesaw introducing at least two fermionic $\mathrm{SU}(2)_L$ triplets [9]. Combinations of the seesaw models are also possible.

A generalisation of this are the left–right symmetric models (LRSMs) that introduce right-handed counterparts to the W and Z bosons (W_R and Z_R), and right-handed heavy neutrinos (N_R) [1, 3, 5, 8]. Heavy neutrinos can either be Dirac or Majorana particles.

In this document, several searches using the Run 2 dataset of proton–proton collisions collected by the ATLAS [10] detector at the Large Hadron Collider (LHC) will be presented.

2. Type-I seesaw

The type-I seesaw introduces a right-handed Majorana neutrino N, also called Heavy Neutral Lepton (HNL). Depending on the mixing and mass parameters, the HNL may decay promptly or be long-lived. The ATLAS search reported in the Ref. [11] explores the HNL mass range $4.5 < m_N < 50\,\mathrm{GeV}$ produced in a leptonic W boson decay where a Standard Model neutrino oscillates into a heavy neutrino. An example Feynman diagram is shown in Figure 1.

The prompt signature requires three leptons produced at the interaction point (either $\mu\mu e$ or $ee\mu$) with a veto on same-flavour opposite-charge lepton pairs. The displaced signature comprises a prompt muon from the W boson decay and the requirement of a dilepton vertex (either $\mu\mu$ or μe) displaced in the transverse plane by 4–300 mm from the interaction point. Both lepton number conserving and lepton number violating final states are possible. The prompt channel uses $36.1\,\mathrm{fb}^{-1}$ of ATLAS data recorded in 2015 and 2016 while the displaced channel uses only 2016 data with $32.9\,\mathrm{fb}^{-1}$.

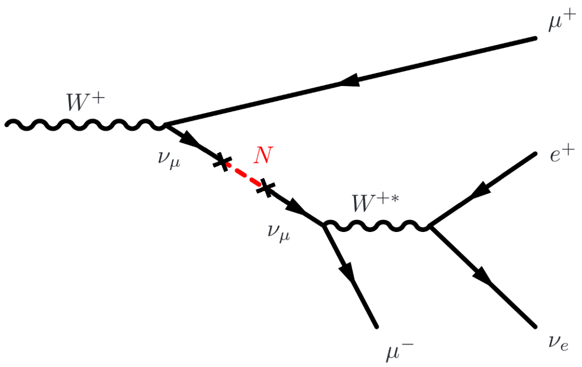


Figure 1: Feynman diagrams for N production and decay in a channel with μ mixing probed by the displaced signature. Taken from Ref. [11].

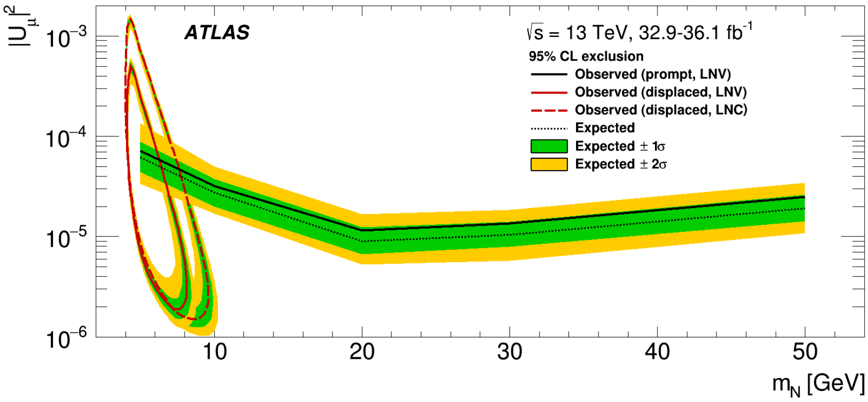


Figure 2: Observed 95% confidence-level exclusion in $|U_\mu|^2$ versus the HNL mass for the prompt signature (the region above the black line is excluded) and the displaced signature (the region enclosed by the red line is excluded). Taken from Ref. [11].

In the prompt channel a requirement is imposed on the three-lepton invariant mass $40 < m(\ell, \ell, \ell') < 90\,\text{GeV}$. To reduce the contribution of electron pairs from Z boson decays a cut on invariant mass $m(e, e) < 78\,\text{GeV}$ is applied. The missing transverse momentum $E_{\text{T}}^{\text{miss}}$ must be less than 60 GeV.

In the displaced channel the most important part is to estimate backgrounds as accurately as possible as no events are observed in the signal region, where displaced vertices with two lepton tracks are selected. Two track displaced vertices can occur due to hadronic interactions in material, decays of bottom, charm, and strange hadrons, accidental crossings of charged particles produced in the collisions, or cosmic-ray muons.

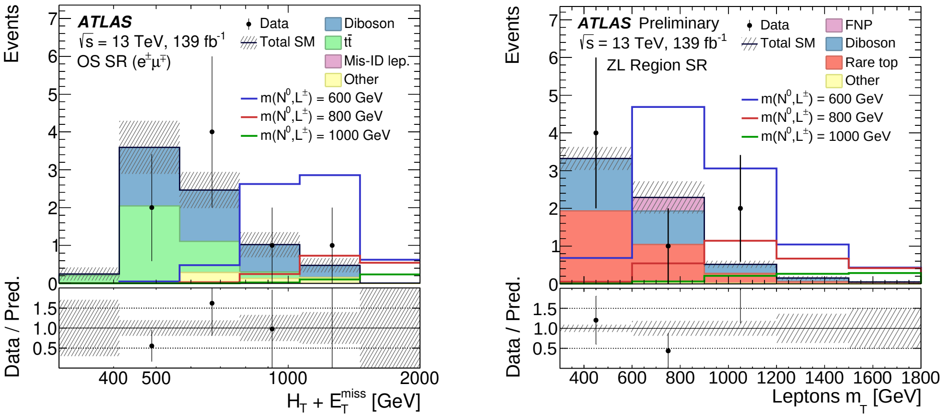
Upper limits on coupling strengths of the HNL with electrons and muons $|U_e|^2$ and $|U_\mu|^2$ are set. The prompt signature shows highest sensitivity in the mass range 20–30 GeV, where the regions with $|U_e|^2$ and $|U_\mu|^2$ above 1.4×10^{-5} are excluded. The displaced signature can improve the limits for masses below 10 GeV and exclude regions down to $|U_\mu|^2 \approx 1.5 \times 10^{-6}$. The limits for the muon channels are displayed in Figure 2.

3. Type-III seesaw

The ATLAS searches reported in Refs. [12] and [13] use the full Run 2 dataset with an integrated luminosity 139 fb^{-1} and target a minimal type-III seesaw model [14] focusing on the lightest fermionic triplet of unknown masses at the order of 1 TeV 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.

Signal regions are first split by light lepton multiplicity. Six dilepton signal regions probe all flavour and charge combinations, and require at least two hadronic jets to be present. In the trilepton case, two regions also requiring at least two jets are split by the presence of a leptonically decaying Z boson, and one region covers events with no or one jets. Two four-lepton signal regions are defined based on the total sum of lepton charge being either zero or two. Two examples of signal regions are shown in Figure 3. As the signal process contains neutrinos in the final state, one of the most important selection criteria is based on the $E_{\mathrm{T}}^{\mathrm{miss}}$ significance $\mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}})$ [15].

A binned maximum-likelihood fit of the $H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$ variable distribution, the sum of the $E_{\mathrm{T}}^{\mathrm{miss}}$ and the scalar sum of the transverse momenta H_{T} of the selected leptons and jets, is used to interpret the observations in dilepton and four lepton signal regions, whereas in trilepton regions the transverse mass of three leptons is used. Combining dilepton, trilepton and four-lepton channels from Refs. [12] and [13] masses of type-III seesaw $L^{\pm}$ and N^{0} below 910 GeV are excluded.



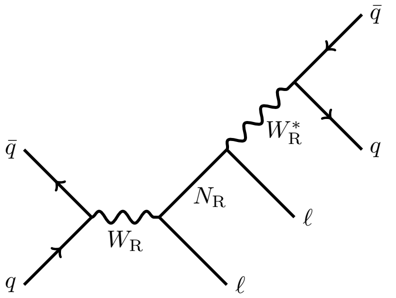
(a) **(b)**

Figure 3: Distributions of (a) $H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$ in the opposite-sign electron–muon signal region and (b) $m_{\mathrm{T}}(3\ell)$ in the trilepton signal region containing leptonically decaying Z boson. Taken from Refs. [12] and [13].

4. Heavy Neutrinos

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 [16]. The specific process of interest is the Keung-Senjanović (KS) process [17], shown in Figure 4. When the W_{R} boson is heavier than the N_{R} neutrino ($m_{W_{\mathrm{R}}} > m_{N_{\mathrm{R}}}$), the on-shell W_{R} mass can be reconstructed from the invariant mass of the $\ell\ell jj$ system, whereas when ($m_{W_{\mathrm{R}}} < m_{N_{\mathrm{R}}}$), 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 performed [18] focusing on the regime where the W_{R} is very heavy compared with the N_{R} ($m_{N_{\mathrm{R}}}/m_{W_{\mathrm{R}}} \leq 0.1$). As heavy neutrinos are produced with large transverse momentum and their decay products are very collimated, a large-radius jet can be used to reconstruct and identify them. The final state consists only of one lepton and one large-radius jet (lJ).

The resolved channel search uses 36.1 fb^{-1} of ATLAS data recorded in 2015 and 2016. It is split in two sub-channels based on the lepton charge. For the opposite-charge channel, the dominant SM backgrounds are Z + jets and $t\bar{t}$ processes, which are modelled using Monte Carlo simulation. A data-driven m_{jj} reweighting is applied to improve the modelling of the Z + jets background. Depending on the mass regime described above the reconstructed W_{R} is used in the fit. In the same-charge channel, the main backgrounds arise from misidentified leptons and electron charge



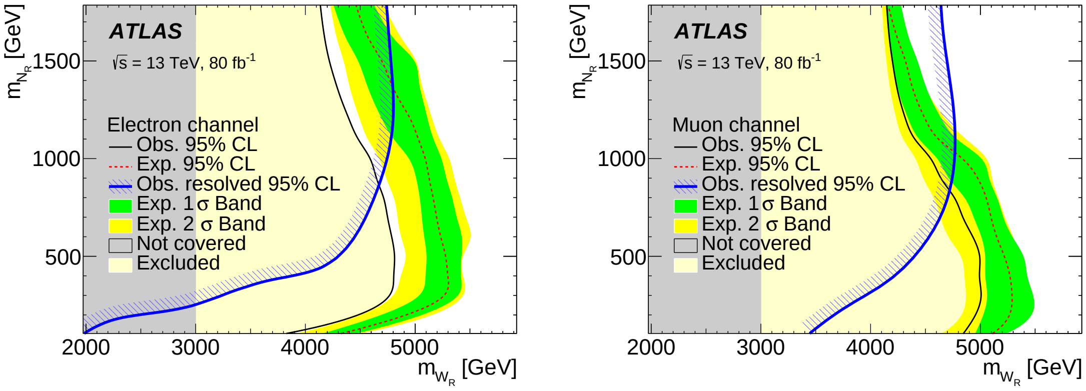
(a) **(b)**

Figure 4: Feynman diagrams of the Keung-Senjanović process for (a) $m_{W_\mathrm{R}} > m_{N_\mathrm{R}}$ case and (b) $m_{W_\mathrm{R}} < m_{N_\mathrm{R}}$ case. Taken from Ref. [16].

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

The boosted channel search additionally uses 2017 data, that leads to a total 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-radius jet with large transverse momentum $p_\mathrm{T} > 200\,\mathrm{GeV}$. 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 is estimated in a different-flavor validation region.

A binned maximum-likelihood fit is performed to obtain limits on masses of W_R and N_R. At 95% confidence level W_R masses are excluded up to $m_{W_\mathrm{R}} = 4.7\,\mathrm{TeV}$ and N_R masses up to $m_{N_\mathrm{R}} = 3.2\,\mathrm{TeV}$ 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 5.



(a) (b)

Figure 5: Observed (black solid line) and expected (red dashed line) 95% CL exclusion contours in the $(m_{W_\mathrm{R}}, m_{N_\mathrm{R}})$ 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. Taken from Ref. [18].

5. Conclusions

The ATLAS experiment at the LHC has performed many searches for new paricles proposed in various neutrino mass models. 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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