

Search for type-III seesaw heavy leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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A search for the pair production of heavy leptons (N^0, L^\pm) as predicted by the type-III seesaw mechanism is presented. The search uses proton-proton collision data at a centre-of-mass energy of 13 TeV corresponding to 79.8 fb^{-1} of integrated luminosity recorded in 2015, 2016 and 2017 by the ATLAS detector at the Large Hadron Collider. The analysis focuses on the N^0 and L^\pm decays with intermediate W bosons and yielding two final-state light leptons (electrons or muons) of different flavor and charge combinations, with at least two jets and large missing transverse momentum in the final state. The search is optimized in six channels distinguished by the flavor combination and charge product of the final state lepton pair, where same charge or opposite charge final states are considered. Good agreement is observed between the number of events in data and Standard Model predictions. The results are translated into exclusion limits on heavy lepton $m(N^0, L^\pm)$ masses, where N^0 and L^\pm are considered mass-degenerate. The observed lower 95 % confidence level limit on the mass of the type-III seesaw heavy leptons, where the branching fractions to all lepton flavors are assumed to be equal, is 560 GeV.

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1. Introduction

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. [1] and references therein). The seesaw mechanism [2, 3] provides an elegant framework to explain the relative smallness of the neutrino masses, compared to other fundamental particles. The type-III model [4] introduces at least two extra triplets of heavy fermionic fields with zero hyper-charge in the adjoint representation of $SU(2)_L$ that couple to electroweak (EW) gauge bosons and generate neutrino masses through Yukawa couplings to the Higgs boson and neutrinos. Consequently, these new charged and neutral heavy leptons could be produced in EW processes in proton–proton collisions at the Large Hadron Collider (LHC).

The ATLAS search presented at this conference [5] uses a minimal type-III seesaw model [6] to optimize the analysis strategy and interpret the search results. This search focuses on the lightest 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 mass [7] and the decay branching ratios are considered equal for all three lepton flavors, with $BR_e = BR_\mu = BR_\tau = 1/3$.

The dominant production mechanism for type-III seesaw heavy leptons in pp collisions is pair-production through $pp \rightarrow W^* \rightarrow N^0 L^\pm$, and the largest branching fraction is the one with two W bosons in the final state. This search is optimized for the dominant processes $pp \rightarrow N^0 L^\pm \rightarrow W^\pm \ell^\mp W^\pm \nu$ and $pp \rightarrow N^0 L^\pm \rightarrow W^\mp \ell^\mp W^\pm \nu$, where one W boson decays leptonically and the other decays hadronically. Only final states containing electrons and muons are considered, also including those from leptonic tau decays.

In summary, the exclusive topology of the final state consists of two jets from the hadronically decaying 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.

2. Measured data and background composition

The ATLAS detector [8] at the LHC 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.

The data used in this analysis correspond to proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV recorded with the ATLAS detector at the LHC with proton bunches colliding every 25 ns and amounts to 79.8 fb^{-1} . The uncertainty on the combined 2015–2017 integrated luminosity is 2.0 % [9], where the results for 2017 are still preliminary.

Samples of signal and background processes are simulated using Monte Carlo (MC) generators. Simulated background samples include Drell–Yan ($q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+ \ell^-$ ($\ell = e, \mu, \tau$)), diboson (WW, ZZ, WZ), top quark pair ($t\bar{t}$) and single top quark production processes.

In general, the number of expected background events and the associated kinematic distributions are derived from a mixture of data-driven methods and simulation. Irreducible backgrounds containing real prompt leptons originate from SM processes producing opposite-sign and same-sign lepton pairs. Irreducible background and signal model predictions are obtained from Monte Carlo simulated samples.

The same MC samples also provide a source of reducible background due to charge misidentification (charge-flip) in channels that contain electrons. The effect of muon charge misidentification has been shown to be negligible. The modeling of charge misidentification in MC simulation deviates from data and consequently charge reconstruction scale factors are derived in a data-driven way to compensate for the differences, as explained more in detail in Ref. [5].

Another source of reducible background is given by events with at least one fake/non-prompt electron or muon, collectively called ‘fakes’. For both, electrons and muons, this contribution is caused by secondary decays into light leptons of light-flavor or heavy-flavor mesons, embedded within jets. For electrons, a significant component of fakes arises from jets which satisfy the electron reconstruction criteria and from photon conversions. A data-driven approach is used to assess this contribution from production of W +jets, $t\bar{t}$ and multi-jet events, using the so-called ‘fake factor’ method, as described in Ref. [10].

3. Analysis strategy and event selection

Selected events are then categorized into exclusive categories called *analysis regions* based on different sets of requirements on reconstructed objects. These regions are grouped according to their purpose: in control regions (CR) one fits the background normalizations to the data; in validation regions (VR) one can validate the background estimation methods by comparing the background model with data; finally, signal regions (SR), with enhanced signal-to-background ratios, are used to compare data to the expected signal-and-background hypothesis using statistical methodology detailed in Section 4.

The six OS and SS analysis channels are defined, according to the flavor combination ee , $e\mu$, $\mu\mu$. Different selection criteria are applied to ensure the highest possible signal and background separation.

For each signal event, the invariant dijet mass (m_{jj}) of the two leading (highest p_T) jets is expected to be close to the W mass. The dijet invariant mass is thus required to be in a window $60\text{ GeV} < m_{jj} < 100\text{ GeV}$.

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 $\text{Sig}(E_T^{\text{miss}})$ [11]. The value of $\text{Sig}(E_T^{\text{miss}})$ is calculated using a maximum likelihood ratio method considering the direction of the E_T^{miss} and the calibrated objects as well their respective resolutions. The values of $\text{Sig}(E_T^{\text{miss}}) > 10$ for the OS channels and $\text{Sig}(E_T^{\text{miss}}) > 7.5$ for SS channels are required to maximize the analysis sensitivity.

In the OS channels the azimuthal angle $\Delta\phi(E_T^{\text{miss}}, l)_{\min}$ between the directions of four 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, where the latter tends to have a spurious component due to misreconstructed jets. For this variable, a requirement $\Delta\phi(E_T^{\text{miss}}, l)_{\min} > 1$ is used.

To further increase the expected signal significance additional selection criteria on the invariant mass of the lepton pair ($m_{\ell\ell}$), the dijet transverse momentum $p_T(jj)$ and the dilepton transverse momentum $p_T(\ell\ell)$ are imposed.

4. Statistical analysis and results

The statistical analysis package HISTFITTER [12] was used to implement 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 , in all control and signal regions to obtain the numbers of signal and background events. The likelihood is the product of a Poisson probability density function describing the observed number of events and Gaussian distributions to constrain the nuisance parameters associated with the systematic uncertainties.

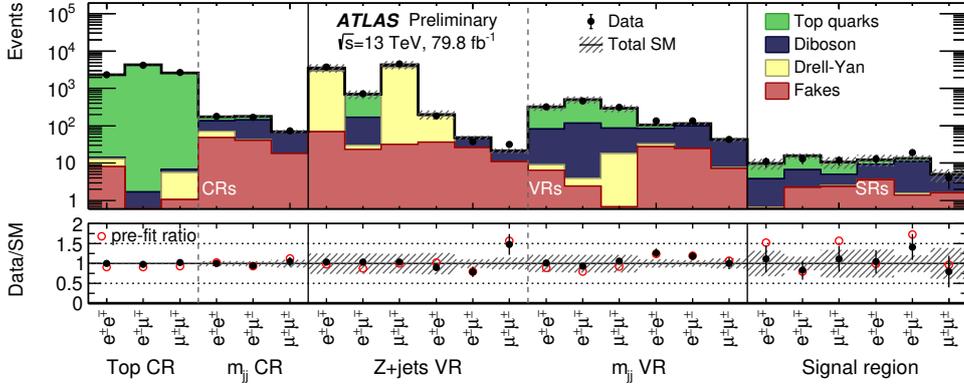


Figure 1: Number of observed and expected events in the control, validation, and signal regions for all considered channels, split by flavor and electric charge combination. The background expectation is the result of the background-only fit described in the text. The hatched bands include all post-fit systematic uncertainties with the correlations between various sources taken into account.

Several sources of systematic uncertainty are accounted for in the analysis. These correspond to experimental and theoretical sources affecting both background and signal predictions. The impact of systematic uncertainties on both the total event yields as well as the changes in the shape of kinematic distributions is taken into account when performing the statistical analysis.

Additional free parameters are introduced for the $t\bar{t}$ and the diboson background contributions, to fit their yields in the analysis Top and m_{jj} control regions, respectively. Fitting the yields of the largest backgrounds reduces the systematic uncertainty in the predicted yield from SM sources. The fitted normalizations are compatible with their SM predictions within the uncertainties. Figure 1 (taken from Ref. [5]) shows a good agreement within the uncertainties between expected background and observed events in all the regions and channels considered in the analysis.

After the fit, the compatibility between the data and the expected background is assessed and good agreement is observed, with a p-value of 0.5 for the background-only hypothesis. In absence of a significant deviation from expectations within uncertainties, 95 % confidence level (CL) upper limits were derived as a function of the heavy lepton mass on the signal strength μ_{SIG} and hence

on the signal production cross section, using the CL_s method [13]. The resulting exclusion limits on both the μ_{SIG} and signal cross section are shown in Figure 2 (taken from Ref. [5]). The type-III seesaw heavy leptons N^0 and L^\pm expected limit is at 550_{-77}^{+68} GeV, where the uncertainties on the limit are extracted from the $\pm 1\sigma$ band, while the observed limit has been placed at 560 GeV, excluding the mass values below this point.

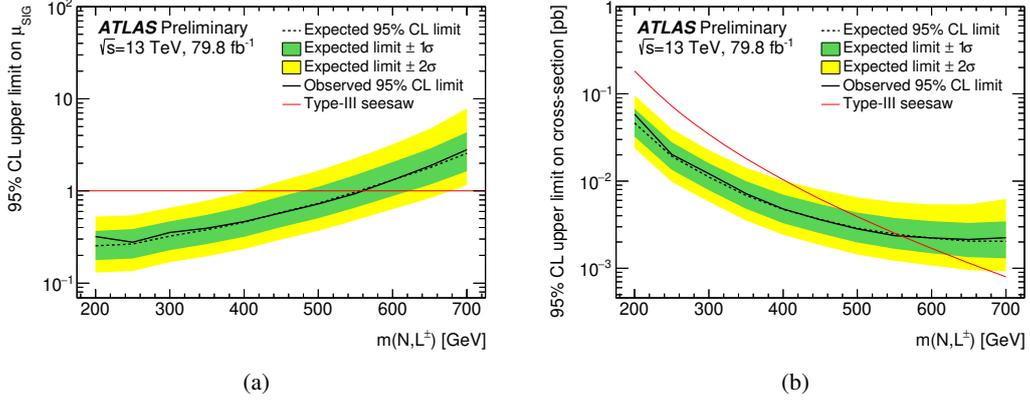


Figure 2: Expected and observed 95 % CL_s exclusion limits for the type-III seesaw process with the corresponding one and two standard deviation bands, (a) showing 95 % CL upper limit on the signal strength μ_{SIG} , (b) showing 95 % CL upper limit on cross-section.

References

- [1] PARTICLE DATA GROUP collaboration, C. Patrignani et al., *Review of Particle Physics*, *Chin. Phys. C* **40** (2016) 100001.
- [2] P. Minkowski, $\mu \rightarrow e\gamma$ at a Rate of One Out of 10^9 Muon Decays?, *Phys. Lett.* **67B** (1977) 421.
- [3] R. N. Mohapatra and G. Senjanovic, *Neutrino Mass and Spontaneous Parity Violation*, *Phys. Rev. Lett.* **44** (1980) 912.
- [4] R. Foot, H. Lew, X. G. He and G. C. Joshi, *Seesaw Neutrino Masses Induced by a Triplet of Leptons*, *Z. Phys.* **C44** (1989) 441.
- [5] ATLAS Collaboration, *Search for type-III seesaw heavy leptons in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, ATLAS-CONF-2018-020, 2018. <https://cds.cern.ch/record/2621484>.
- [6] C. Biggio and F. Bonnet, *Implementation of the Type III Seesaw Model in FeynRules/MadGraph and Prospects for Discovery with Early LHC Data*, *Eur. Phys. J. C* **72** (2012) 1899 [1107.3463].
- [7] R. Franceschini, T. Hambye and A. Strumia, *Type-III see-saw at LHC*, *Phys. Rev.* **D78** (2008) 033002 [0805.1613].
- [8] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, *JINST* **3** (2008) S08003.
- [9] ATLAS Collaboration, *Luminosity determination in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector at the LHC*, *Eur. Phys. J. C* **76** (2016) 653 [1608.03953].

- [10] ATLAS Collaboration, *Search for doubly charged Higgs boson production in multi-lepton final states with the ATLAS detector using proton–proton collisions at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J. C* **78** (2018) 199 [1710.09748].
- [11] ATLAS Collaboration, *Performance of missing transverse momentum reconstruction with the ATLAS detector using proton–proton collisions at $\sqrt{s} = 13$ TeV*, 1802.08168.
- [12] M. Baak, G. J. Besjes, D. Côte, A. Koutsman, J. Lorenz and D. Short, *HistFitter software framework for statistical data analysis*, *Eur. Phys. J.* **C75** (2015) 153 [1410.1280].
- [13] A. L. Read, *Presentation of search results: The $CL(s)$ technique*, *J. Phys.* **G28** (2002) 2693.