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Search for Type-III SeeSaw heavy lepton with the ATLAS Detector at the LHC using $\sqrt{s} = 13$ TeV up to 140 fb–1

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Search for Type-III SeeSaw heavy lepton with the ATLAS Detector at the LHC using $\sqrt{s} = 13$ TeV up to 140 fb^{-1}

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Abstract. A search of heavy leptons N^0 and $L^{\pm}$ pair production predicted by the Type-III SeeSaw mechanism is presented. This mechanism extends the Standard Model, introducing at least two new triplets of fermionic fields with zero hypercharge in the adjoint representation of $\mathrm{SU(2)_L}$, resulting in two heavy Dirac charged leptons and a heavy Majorana neutral lepton.
This search uses data collected by the ATLAS detector at the Large Hadron Collider in proton-proton collision at a centre-of-mass energy of 13 TeV, with an integrated luminosity up to 140 fb^{-1} corresponding to the full Run-2 dataset recorded between 2015-2018.
The analysis focuses on all the possible production and boson decay channels of these heavy leptons, which are assumed to be degenerate in mass. The search is based on the separate optimization of each lepton multiplicity final state, considering 2, 3, 4 or more than 5 leptons. The power of the leptonic channels lies in the low expected background from Standard Model processes. Different control and signal regions are defined for each final state, designed to be orthogonal one each other. Good agreement between the number of events in data and Standard Model predictions is observed.
The results are translated into exclusion limits on heavy lepton masses with a 95% confidence level using statistical uncertainties only. Assuming the branching ratios to all lepton flavours to be equal, a lower limit of 560 GeV is obtained.

1. Introduction

The discovery of neutrino flavour oscillations implies non-null masses for these particles [1]. The smallness of neutrino masses is difficult to accommodate in a natural way through a pure Standard Model Yukawa coupling to the Higgs field [2].

In the SM all fermions acquire mass by Yukawa couplings with the Higgs field, involving both fermion chiralities [3]. The neutrino case is instead special because only left-handed neutrinos have been observed up to now. Furthermore, one of the most puzzling feature of particles physics is the lightness of neutrino masses with respect to those of the charged leptons. This peculiar mass hierarchy is a theory issue known as “naturalness problem”[4]. In this context, the Type-III SeeSaw mechanism [5] provides an elegant way to explain the origin of neutrino masses. This model predicts the existence of new heavy degrees of freedom, represented by a new heavy fermionic triplet with zero hypercharge in the adjoint representation of $\mathrm{SU}(2)_L$. If these new

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mediators are light enough, around the TeV scale, it is possible to observe their signature at the Large Hadron Collider (LHC) energies.

The ATLAS search presented at this conference uses a minimal Type-III SeeSaw model to optimize the analysis strategy and interpret the search results. This assumption allows to consider only 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. The simplified assumption of a single fermionic triplet has little impact on LHC physics as in most cases only the lighter states can be generated in TeV collider experiments.

The heavy leptons are assumed to be degenerate in mass [6] and the decay branching ratios are considered equal for all three lepton flavours, with $\mathrm{BR}_e = \mathrm{BR}_\mu = \mathrm{BR}_\tau = 1/3$.

These heavy leptons are mainly produced in pairs in the proton-proton (pp) collisions at the LHC through gauge coupling. The production mechanism happens via $q\bar{q}$ interaction mediated by a virtual boson, either Z, W or Higgs boson (see Fig 1 for an example of heavy leptons production). The search is performed on final states with at least two leptons, only electrons and muons are considered, including the ones coming from leptonic tau decays.

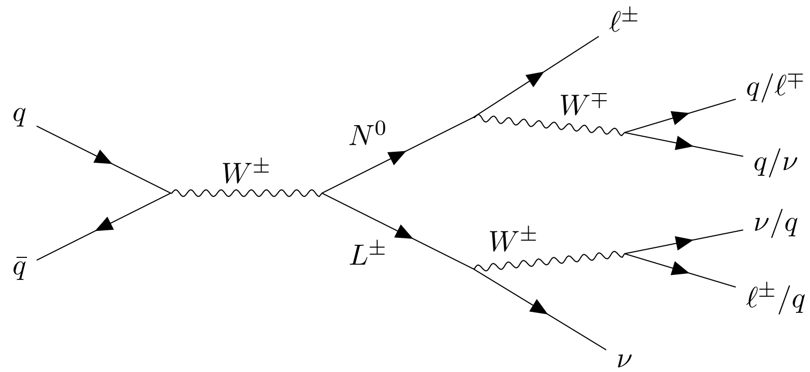

Figure 1. Feynman diagram for the dominant contribution to three-charged-leptons and three neutrinos final states in pair production of N^0 and $\mathrm{L}^\pm$ in the Type III SeeSaw mechanism.

2. Data collected and MC samples

The data used in this analysis corresponds to pp collision at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector, between 2015-2018, at the LHC with an average number of pp interactions per bunch crossing of 33.7 and an integrated luminosity up to 140 fb^{-1}. The uncertainty in the combined 2015-2018 integrated luminosity is 1.7% [7].

The ATLAS detector [8] is a multi-purpose particle detector placed ~ 100 meters underground at the Point-1 site along the LHC tunnel. ATLAS has a cylindrical symmetry and it is composed of many different sub-detectors to reconstruct particles from pp collisions: inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting toroidal magnets.

Samples of signal and background processes are simulated using Monte Carlo (MC) generators. The Type-III SeeSaw simplified model is simulated using MadGraph5_aMC@NLO [9] generator which is interfaced to Pythia 8.212 [10] for parton showering, in a range of mass from 300 GeV to 1200 GeV. The simulated *irreducible* background samples, which represent SM processes, include di- and multi-boson (ZZ, WW, WZ, WWW, ZZZ, WWZ, WZZ), Drell-Yan ($Z/\gamma^* \to \ell^+\ell^-(\ell = e, \mu, \tau)$), top quark pair ($t\bar{t}$), rare top ($3t, 4t$) and single top quark production processes. This kind of background contains the real *prompt* leptons from SM processes producing opposite-sign and same-sign lepton pairs.

Besides the prompt background contribution described in above, another source of background comes from mis-reconstructed objects; these are:

- *Fake leptons*, objects originated from in-flight decays of mesons (*non-prompt leptons*), jets reconstructed as leptons and electron-photon conversions;
- *Charge-flipped leptons*, events where an electron is reconstructed with the wrong charge. This effect is negligible for muons [11].

3. Analysis Strategy

In order to perform a statistical interpretation of the data, two hypotheses are needed: one consistent with only SM background expectation, the other matching the background plus signal hypothesis. These two kinds of hypothesis are fitted using two regions where different categories of events are defined satisfying different sets of requirements, the so-called *analysis regions*.

The region of the phase space where the signal is expected to produce an excess over the SM expectation is defined as *signal region* (SR). A *control region* (CR) is defined to constrain a specific background, while a *validation region* (VR) can be used to prove the goodness of the background estimation before applying it to the signal region.

A first selection level is obtained by leptonic pre-selection cut, which allows to consider only events with the required number of leptons in the final state (2, 3, 4 or more than 5). Only charged and light leptons, then electrons and muons, are considered. In the Tab 1-3, criteria to define analysis regions for each final state are reported.

	OS ($\ell^+\ell^- = e^+e^-$, $e^\pm\mu^\mp$, $\mu^+\mu^-$)		**SS** ($\ell^\pm\ell^\pm = e^\pm e^\pm$, $e^\pm\mu^\pm$, $\mu^\pm\mu^\pm$)	
	Top CR	SR	m_{jj} CR	SR
N(jet)	≥ 2	≥ 2	≥ 2	≥ 2
$N(bjet)$	≥ 2	0	0	0
$m_{jj}\,[GeV]$	$[60, 100)$	$[60, 100)$	$[0, 60) \cup [100, 300)$	$[60, 100)$
$m_{\ell\ell}[GeV]$	$[110, \infty)$	$[110, \infty)$	$[100, \infty)$	$[100, \infty)$
Sig(E_T^{miss})	≥ 5	≥ 10	≥ 5	≥ 7.5
$\Delta\phi(E_T^{miss}, \ell)_{\min}$		$[1, \infty)$		
$p_T(jj)$ [GeV]		$[100, \infty)$		$[60, \infty)$
$p_T(\ell\ell)$ [GeV]		$[100, \infty)$		$[100, \infty)$
$H_T + E_T^{miss}$ [GeV]	$[300, \infty)$	$[300, \infty)$	$[300, 500)$	$[300, \infty)$

Table 1. Summary of 2-lepton regions defined in the analysis. Only control and signal regions are reported in this table.

	$\sum \mathbf{Q}_\ell = \mathbf{0}$			$\sum \mathbf{Q}_\ell = \mathbf{1}$		**5 leptons**
	Diboson CR	Rare Top CR	SR	VR	SR	SR
N_{bjet}	0	≥ 2	0			
$m_{\ell\ell\ell\ell}\,[GeV]$	$[170, 300)$	$[170, 300)$	≥ 300	< 300	≥ 300	
N_Z			≤ 1			
SigE_T^{miss}			≥ 5			
No cuts						✓

Table 2. Summary of 4- and 5-lepton regions defined in the analysis.

	ZL		**ZLveto**		**jVeto**	
	CR	SR	CR	SR	CR	SR
$p_T(\ell_1) > 50$ GeV	✓		✓		✓	
$p_T(\ell_2) > 0,5 \cdot (l_1)$	✓		✓		✓	
$p_T(\ell_3) > 15$ GeV	✓		✓		✓	
$\mathrm{Sig}(E_T^{miss}) > 5$	✓		✓		✓	
$N(jet)$	≥ 2		≥ 2		0	
$m_{\ell\ell}(OSSF)[GeV]$	$[80, 100]$		≥ 115		≥ 80	
H_T+E_T^{miss} [GeV]	< 500	≥ 500	< 500	≥ 500		
$m_{\ell\ell\ell}$ [GeV]	< 230	≥ 300		≥ 300		
m_{jj} [GeV]		< 500		< 300		
$H_T(SS)$ [GeV]				≥ 200		
$H_T(\ell\ell\ell)$ [GeV]					< 230	≥ 230
$m_T(\ell_1)$ [GeV]					< 240	≥ 240
$m_T(\ell_2)$ [GeV]		≥ 150			< 150	≥ 150
$\Delta R(\ell_1, \ell_2)$		< 1.7				< 1.3
$\Delta R(\ell_1, \ell_3)$		< 3.7				

Table 3. Summary of 3-lepton regions defined in the analysis. Only control and signal regions are reported in this table.

As the signal process predicts high mass heavy leptons, kinematics variables (as H_T, $H_T + E_T^{miss}$[1], leptons or jets p_T) allow to isolate signal events in high energy regions. Due to the presence of neutrinos in the final state with 2 (2L) and 3 (3L) leptons, one of the most important selection criteria is based on the E_T^{miss} significance, $\mathrm{Sig}(E_T^{miss})$[2] [12]. Angular distributions, as $\Delta\phi$ for 2L and ΔR for 3L, guarantee a very good separation power, exploiting the different nature of E_T^{miss} and of leptons emission between signal and background processes.

For 4 (4L) and 5 (5L) leptons topologies, simple selections are required due to the few SM events containing high lepton multiplicities. For 4L final states, cut on invariant mass of the four-lepton system ($m_{\ell\ell\ell\ell} > 300$ GeV) is enough to reduce the diboson contribution. For 5L topology no additional cuts are applied as very small SM background is expected.

4. Signal extraction technique

For the statistical data analysis, the statistical framework `HistFitter` [13] was used to implement a binned maximum-likelihood fit of the $H_T + E_T^{miss}$ variable distribution (see Fig 2) which has a good signal-to-background discrimination power. It was used in all CRs and SRs designed for each different final state to obtain the numbers of signal and backgrounds events. Two kinds of fit are used in this analysis: the *background only fit*, which evaluates the background in CR to extrapolate a normalization factor applied to the SR, and the *exclusion fit* which sets the limits on the production cross-section of new particles combining CR and SR. A good agreement between data and MC simulation is observed before the fitting procedure in the SR (Fig 2). The SR is fitted under the hypothesis of a signal strength for heavy lepton production with $\mu_{SIG} = 1$. All heavy leptons masses with a fitted μ_{SIG} parameter below one can be excluded.

At the moment, only statistical fit for 2 leptons final states using 2015, 2016 and 2017 datasets,

[1] Where H_T is the scalar sum of the transverse momenta of all objects in the final state and E_T^{miss} is the missing energy transverse.

[2] It is defined as the log-likelihood ratio quantifying how likely the reconstructed E_T^{miss} is consistent with the true E_T^{miss}.

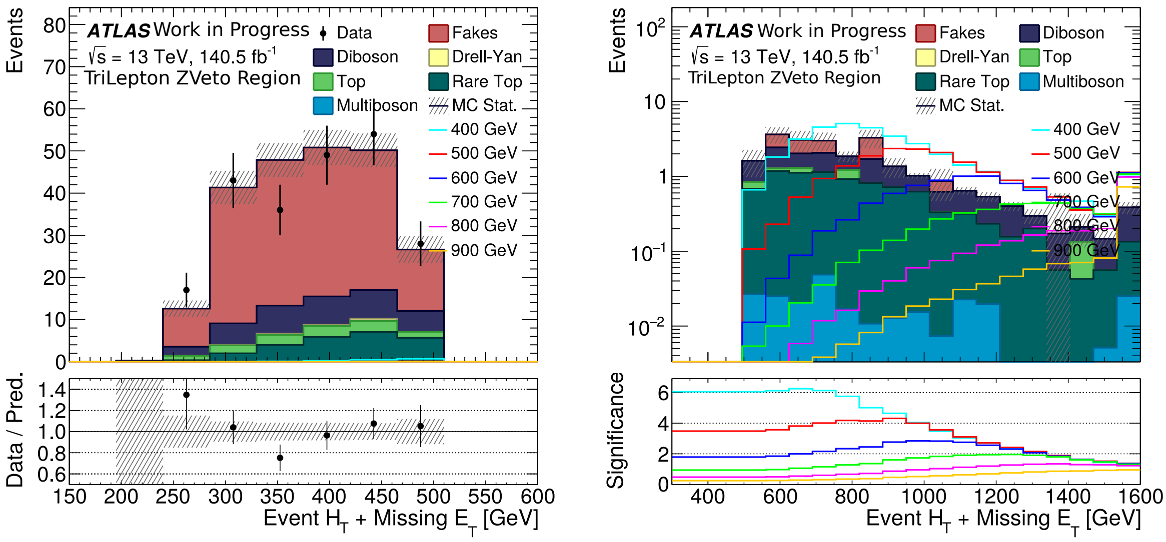

Figure 2. Distribution of $H_T + E_T^{miss}$ variable of the 3 leptons final state in the ZVeto Region for CR (left) and SR (right). A good agreement between data and MC simulation is shown into the CR distribution.

corresponding to an integrated luminosity of 79.8 fb^{-1}, is performed [11]. Since no excess over the SM predictions are found, a limit on the heavy lepton cross section can be derived. The expected 95% CL exclusion plot with one and two standard deviation bands superimposed is shown in Fig 3 with dashed lines. The theoretical cross-sections for both the heavy leptons are presented in red lines. The point in which the theoretical cross-section curve crosses the observed limit sets the lower mass limit. The observed lower mass limit of the Type-III Seesaw heavy leptons is about 560 GeV.

Increasing the statistics up to an integrated luminosity of 140 fb^{-1}, an improvement on this limit is expected. This mainly includes all lepton multiplicities and considers all the decay and production channels of the heavy leptons.

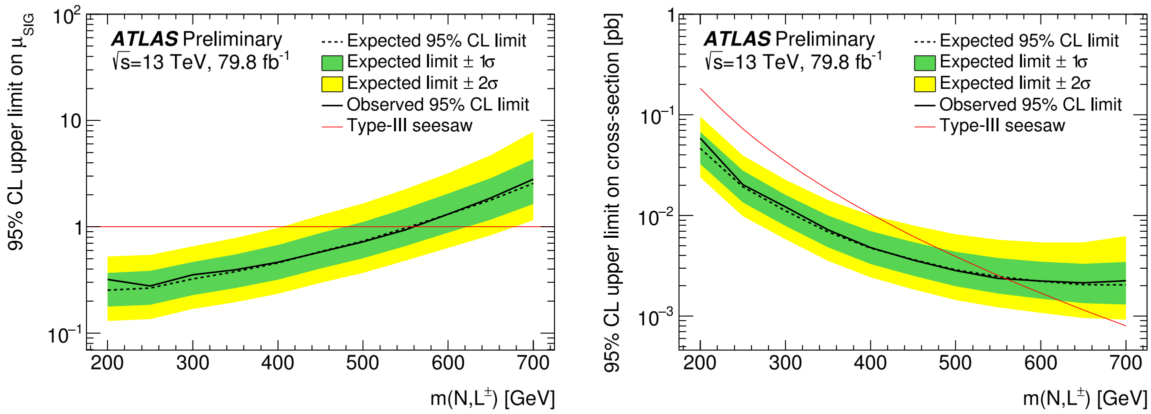

Figure 3. Expected 95% CLs exclusion limits for the Type-III SeeSaw process with the corresponding one and two standard deviation bands, showing 95% CL upper limit on the signal strength μ_{SIG} (left), showing 95% CL upper limit on cross section (right) [11].

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