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Search for Type-III SeeSaw heavy leptons in leptonic final states in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

Giuseppe Carratta[a,b,*], **on behalf of the ATLAS Collaboration**

[a] *Dipartimento di Fisica e Astronomia "Augusto Righi", Alma Mater Studiorum Università di Bologna, Via Irnerio 46, 40126, Bologna, Italy*

[b] *INFN - Sezione di Bologna, Viale Carlo Berti Pichat 6/2, 40127, Bologna, Italy*

E-mail: carratta@bo.infn.it

Heavy leptons with masses ranging from GeV to TeV energies appear in several Beyond the Standard Model mechanisms, proposed to explain the neutrino mass generation. The SeeSaw mechanism provides an elegant extension of the Standard Model explaining the smallness of neutrino masses. In particular, it introduces at least one extra fermionic triplet field with zero hypercharge in the adjoint representation of $SU(2)_L$ which couples to the electroweak gauge bosons. These new charged and neutral heavy leptons could be produced via electroweak processes at the Large Hadron Collider. This search is performed using data collected by the ATLAS detector at $\sqrt{s}$ = 13 TeV with an integrated luminosity of 139 fb^{-1} corresponding to the full Run-2 dataset recorded in LHC Run 2 (2015-2018). The analysis is focused on final states with large lepton multiplicity, which allows to reject a significant part of background providing a large discovery power. For the first time, a result considering a combination of the most important Type-III SeeSaw heavy leptons decay modes is presented.

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*Speaker

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One of the most puzzling feature to be addressed in modern particle physics is represented by the smallness of neutrinos masses. Their extremely small mass values with respect to the other fermions is difficult to accommodate in a natural way in the Standard Model (SM) theory [1]. The Type-III SeeSaw mechanism [2] is a possible extension of the SM which provides an elegant way to give a very small mass value to each SM neutrino by introducing at least one extra heavy fermionic $SU(2)_L$ triplet field coupled to electroweak gauge bosons. This triplet is composed by a heavy Majorana neutral lepton (N^0) and two heavy Dirac charged leptons ($L^{\pm}$). The minimal Type-III SeeSaw model, which assumes the heavy leptons to be degenerate in mass, is considered in this analysis.

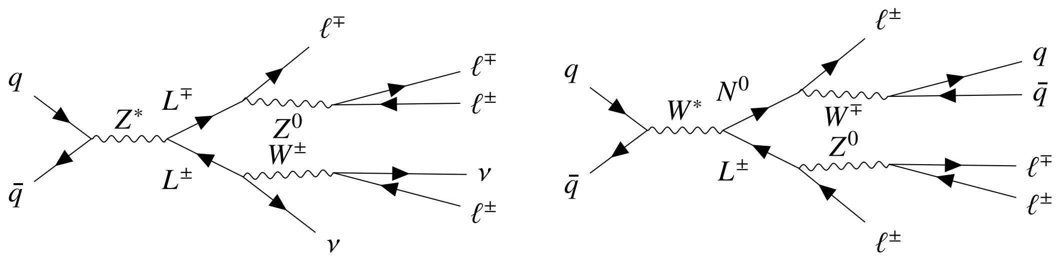
This analysis uses data collected by the ATLAS detector [3] during the full Run 2 period (2015-2018) in pp collisions at a center-of-mass energy $\sqrt{s} = 13$ TeV with an integrated luminosity of 139 fb^{-1}. The search is focused on all possible heavy lepton production and decay modes via electroweak and Higgs bosons, considering final states with three or four light leptons (electrons and muons, including the ones coming from leptonic τ decays) and large missing energy. Channels with large lepton multiplicity give clear signatures for new physics processes with low contribution of SM events and low systematic uncertainties due to objects reconstruction.

Depending on the heavy lepton decay modes, multiple regions of interest have been defined which are further divided into *analysis regions* with a different categorization of events. These regions are used to perform a statistical interpretation of the data under two types of hypotheses: one consistent with the only SM background expectations, the other with the background plus signal hypothesis. The former is studied in *control regions* (CR), while the latter in *signal regions* (SR). CRs are used to constrain a specific background by comparing the data and Monte Carlo (MC) yields to extrapolate a normalization factor (NF). The goodness of the estimated NF is then evaluated in the *validation regions* (VRs) before being applied in the SRs. Commonly, a SR is enriched with signal events which are expected to produce excesses with respect to SM predictions.

Events are first selected by requiring transverse momentum p_{T} larger than 40 GeV for the two more energetic leptons, $p_{\mathrm{T}} > 15$ GeV for the third lepton, and $p_{\mathrm{T}} > 10$ GeV for a fourth lepton if it is there. In the three-lepton channel three kinds of phase-space regions are considered: **ZL** region where a Z decaying leptonically in the final state is required, **ZLveto** region where the leptonically decaying Z's are vetoed and **JNLow** region with low jet multiplicity (< 1). The Z boson is selected by looking at the invariant mass of the opposite-sign same-flavour lepton pair ($m_{\ell\ell}(OSSF)$).

Two types of four-lepton final states are targeted: **Q0** (Figure 1a) looking for two same-sign lepton pairs with a total charge of the system equal to zero, and **Q2** (Figure 1b) with one lepton of different sign giving a total charge of 2. Since high energy objects are searched, the most important requirements on the SRs definition are related to the scalar sum of the objects p_{T} (H_{T}), the missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$, and the invariant mass of the three (four) leptons system $m_{\ell\ell\ell}$ ($m_{\ell\ell\ell\ell}$). In Table 1, additional selection criteria are listed.

The main background contributions, estimated using MC samples, come from diboson processes (WZ and ZZ) and rare top events due to top quarks associated with vector boson production and



(a) Example of Feynman diagram for the Q0 region. **(b)** Example of Feynman diagram for the Q2 region.

Three-leptons	**ZL**					**ZLveto**	**JNLow**	
	Fake-VR	CR	DB-VR	RT-VR	SR	SR	VR	SR
$\mathcal{S}\,(E_{\mathrm{T}}^{\mathrm{miss}})$	< 5	≥ 5						
N(jet)	-	≥ 2					≤ 1	
N(bjet)	-	-	0	≥ 1	-	-	-	-
$m_{\ell\ell}(OSSF)$ [GeV]	-	80 – 100				≥ 115	≥ 80	
$H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	-	-	-	-	-	≥ 600	-	-
$m_{\ell\ell\ell}$ [GeV]	-	-	≥ 300			≥ 300	-	-
H_{T} (SS) [GeV]	-	-	-	-	-	≥ 300	-	-
m_{jj} [GeV]	-	-	-	-	-	< 300	-	-
H_{T} $(\ell\ell\ell)$ [GeV]	-	-	-	-	-	-	≥ 230	
m_{T} (ℓ_1) [GeV]	-	-	≥ 200			-	< 240	≥ 240
m_{T} (ℓ_2) [GeV]	-	< 200	≥ 200			-	≥ 150	
$\Delta R(\ell_1, \ell_2)$	-	-	< 1.2		1.2 – 3.5	-	≥ 1.3	

Four-leptons	**Q0**					**Q2**	
	DB-CR	RT-CR	DB-VR	RT-VR	SR	VR	SR
$\lvert\sum q_\ell\rvert$	0					2	
$N_{b\text{-jet}}$	0	≥ 2	1	1	0	-	-
$m_{\ell\ell\ell\ell}$ [GeV]	170 – 300	< 500	170 – 300	300 – 500	≥ 300	< 200 OR	≥ 300
$H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	-	-	-	≥ 400	≥ 300	< 300	≥ 300
N_Z	-	-	-	-	≤ 1	-	-
$\mathcal{S}\,(E_{\mathrm{T}}^{\mathrm{miss}})$	-	-	-	≥ 5	≥ 5	-	-

Table 1: Summary of the selection criteria used to define analysis regions in the three- and four-lepton channel [4].

Higgs boson decaying leptonically. Another source of background events is due to *fake non-prompt* leptons representing misreconstructed or misidentified objects, estimated through an *ad hoc* data-driven technique [4].

A NF for each main background, i.e. WZ, ZZ and rare top processes, is extrapolated by a statistical likelihood fit considering all the defined CRs, while SRs are included in this technique to extract the signal strength and to find possible excesses of the signal with respect to SM predictions. In Figure 2 the number of observed and expected events in each CR, VR and SR after the normalization procedure, are reported. An overall good agreement in each region inside the error bands is present. No significance excess of the Type-III SeeSaw heavy leptons with respect to the SM predictions is found, then an exclusion limit for each mass point is set at 95% of confidence level (CL). The observed (expected) lower mass limit of the N^0 and $L^{\pm}$ heavy lepton is 870 GeV (900^{+80}_{-80} GeV). The three- and four-lepton channel results are also combined with the already published two leptons

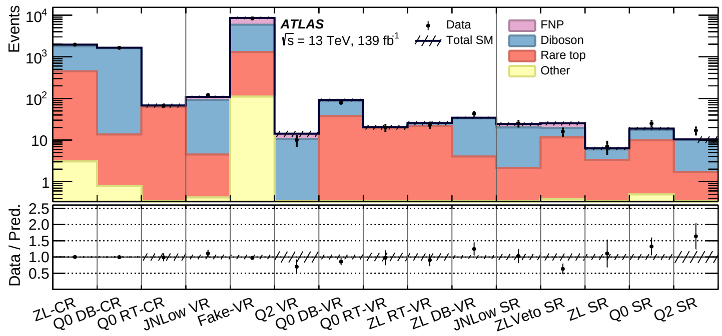


Figure 2: Number of observed and expected events in each analysis region [4].

plus two jets channel [5] with the same model, providing for the first time a comprehensive search considering the most important Type-III SeeSaw production and decays modes. The combined observed (expected) exclusion limits on the total cross-section are shown in Figure 3 excluding heavy lepton masses lower than 910 GeV (960^{+90}_{-80} GeV) at 95% CL.

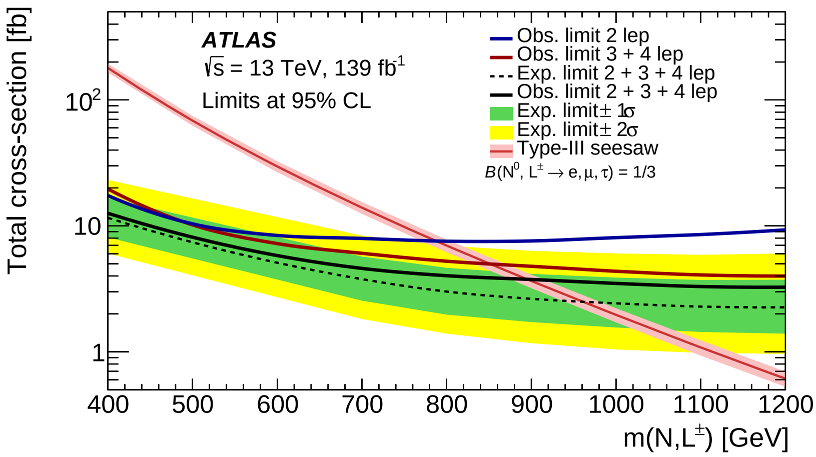


Figure 3: Expected (dashed lines) and observed (solid lines) 95% CLs exclusion limits for the production cross-section of the two- (from [5]), three- and four-lepton channels of Type-III SeeSaw heavy leptons with the corresponding one (green) and two (yellow) standard-deviation uncertainty bands. The theoretical cross-sections for heavy lepton production are presented with a red line [4].

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