Searches for exotic particles in multileptonic final states with the ATLAS detector using full Run-2 data

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Summary. — Over the past years, the need for an extension of the Standard Model (SM) has become more and more clear, so high-energy physics experiments must explore Beyond the SM (BSM) scenarios, which now constitute an important part of the ATLAS experiment physics program. Searches for multileptonic final states have favourable signatures thanks to the low number of SM processes procuding events with high lepton multiplicity, as these would worsen the signal-to-background ratio. In the context of Left-Right Symmetric Model (LRSM) and the Type-III See-Saw mechanism, New Physics events are searched for in several processes, like the production of doubly charged Higgs bosons and the production of heavy neutral or charged leptons. The final states investigated can also involve same-sign light leptons, allowing lepton-number-violation foreseen by the LRSM. ATLAS BSM searches exploring these scenarios with full LHC Run-2 data, for a total luminosity of 139 fb^{-1} at a centre-of-mass energy of $\sqrt{s} = 13$ TeV in pp collisions, are here presented.

1. – Introduction

Multileptonic final states allow for searches of physics beyond the Standard Model with very high sensitivity. The SM predicts only few processes with multileptonic final states, making the study of new physics using these final states particularly advantageous thanks to the low number of SM background events. Here are presented two searches which exploited these topologies: production of doubly charged Higgs bosons $H^{\pm\pm}$ as predicted by the Type-II SeeSaw model [1] and production of heavy leptons as predicted by the Type-III SeeSaw model [2]. These analyses use proton-proton data collected by the ATLAS detector [3] during the entirety of Run 2 (2015-2018) at $\sqrt{s} = 13\,\text{TeV}$, for an integrated luminosity of $139\,\text{fb}^{-1}$.

SeeSaw mechanisms introduce new heavy particles to generate a small Majorana mass for neutrinos, providing coupling with lepton and Higgs doublets. Depending on the type of model, different new particles are predicted:

- In Type-II: a scalar triplet $A = (A^{++}, A^{+}, A^{0})$. In the context of the Left-Right Symmetric Model (LRSM), within which the SeeSaw Type-II mechanism can be applied, the Higgs multiplets contain doubly-charged Higgs: $H^{\pm\pm}_{L,R}$.
- In Type-III: a fermionic triplet $\Sigma = (\Sigma^{+}, \Sigma^{0}, \Sigma^{-})$. The derived physical particles are heavy leptons, called $L^{\pm}$ and N_0.

Figure 1 illustrates the production and decay processes for one of the final states of the Type-III SeeSaw analysis (T3SS) and the pair production of doubly charged Higgses (DCH).

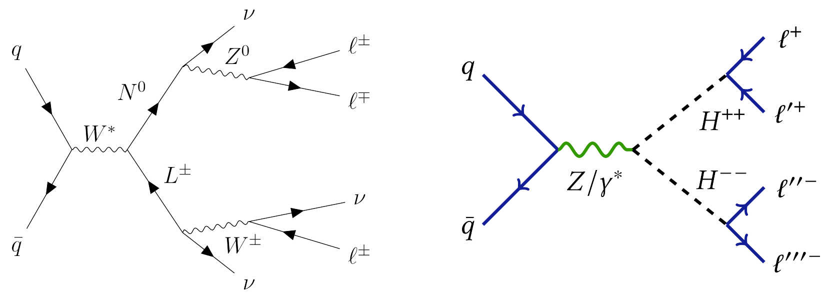

Fig. 1. – Left: Example of Feynman diagram for the considered T3SS model, producing three-lepton final state. Right: Feynman diagram of the process $pp \to H^{++}H^{--}$, target final state of the DCH analysis.

2. – Common analysis strategy

The primary goal of the presented analyses is to search for a signal in the form of excesses of events over the SM predictions or, otherwise, to set lower limits on the mass of heavy leptons, or $H^{\pm\pm}$ depending on the specific analysis, at 95% Confidence Level (CL). In the study of the discriminating variable to improve the signal over background ratio, different kinds of regions in the parameters space are defined. *Control Regions* (CRs) are rich of background processes and are used to normalize the contributions of the main backgrounds (diboson, top and Drell-Yan processes, in this context). *Signal Regions* (SRs) are rich in signal events and from these the signal strength is extracted through a 'likelihood fit', performed simultaneously also in the CR. *Validation Regions* (VRs) have a prevalence of background and are used to validate the background estimation performed in the CRs. The orthogonality of these regions is ensured by mutually-excluding cuts of the parameters space variables. Table 2 shows, as an example, the definition of CRs, SRs and VRs for the T3SS analysis, in the four-leptons channel.

Events considered in these analyses are required to have at least one collision vertex reconstructed with at least two tracks with transverse momentum, p_T, greater than 500 MeV. Identification and reconstruction criteria to single objects belonging to the selected events, like electrons, muons, jets and missing transverse energy, are then applied.

In both these searches, the dominant uncertainty in the SRs, and in most of the other regions, is the statistical uncertainty, which varies from few % to $\sim 40\%$, depending on the signal region. The main contributions to the systematic uncertainty are related to the predictions of the background from *fake non-prompt leptons* (FNP) – defined as objects originated from in-flight decays of mesons (non-prompt leptons), jets reconstructed as

	Q0					**Q2**	
	DB-CR	RT-CR	DB-VR	RT-VR	SR	VR	SR
	$p_T(\ell_{1,2}) > 40$ GeV $p_T(\ell_3) > 15$ GeV $p_T(\ell_4) > 10$ GeV						
$\lvert\sum q_\ell\rvert$	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
$H_T + E_T^{\text{miss}}$ [GeV]	-	-	-	≥ 400	≥ 300	< 300	≥ 300
N_Z	-	-	-	-	≤ 1	-	-
$\mathcal{S}(E_T^{\text{miss}})$	-	-	-	≥ 5	≥ 5	-	-

Fig. 2. – Summary of the selection criteria used to define analysis regions in the four-leptons channel of the T3SS analysis. H_T is defined as the scalar sum of the p_T of all objects in the final state and N_Z is the number of leptonically reconstructed Z bosons. More details can be found in [2].

leptons and electron-photon conversion events – and from leptons with mis-reconstructed charge. FNP leptons are identified using a data-driven technique, the so-called *fake-factor*, based on the calculation of the probability for a fake lepton to be identified as prompt. Other main backgrounds are diboson production, rare processes involving the top quarks and Drell-Yan processes. To extract a possible signal, a maximum-likelihood fit is performed on different observables, depending on the search and channel, in the CRs and SRs.

3. – Type-III SeeSaw heavy leptons search

In this search, signal is defined as the pair-production of the neutral Majorana (N^0) and charged ($L^\pm$) heavy leptons, considered degenerate in mass and decaying in final states involving three or four SM leptons [6]. The allowed decays in this model are $L^\pm \to H\ell^\pm, Z\ell^\pm, W^\pm\nu$ and $N^0 \to Z\nu, H\nu, W^\pm\ell^\mp$ where $\ell = e, \mu, \tau$. For the three-lepton channel the regions are defined based on the decay modes – hadronic or leptonic – of the electroweak bosons. Furthermore, a specific Control Region is defined in order to estimate the contribution to the background events coming from FNP leptons. In the four-leptons channel, the main discriminating quality of the different analysis regions is the total charge of the leptons in the final state.

A likelihood fit is performed on the $m_{T,3\ell}$ and $H_T + E_T^{miss}$ (1) distributions, respectively for the three- and four-leptons channels. Event yields after the likelihood fit for the analysis regions are shown in Figure 3. Good agreement within statistical and systematic uncertainties between data and SM predictions is observed in all regions, demonstrating the validity of the background estimation procedure.

(1) The transverse mass of one or multiple objects N_{obj} is defined as: $m^2_{T,N_{\text{obj}}} = \left(\sum_i^{N_{\text{obj}}} E_{T,i} + E_T^{\text{miss}}\right)^2 - \left|\sum_i^{N_{\text{obj}}} \vec{p}_{T,i} + \vec{p}_T^{\text{ miss}}\right|^2$ with E_T^{miss} the magnitude of the $\vec{p}_T^{\text{ miss}}$ vector.

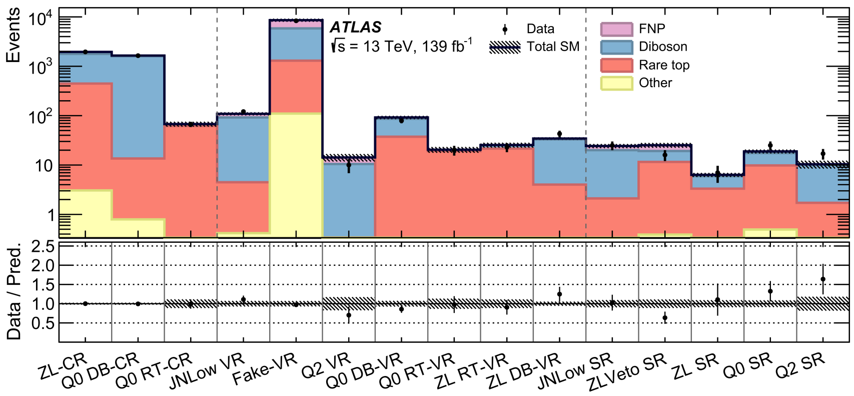

Fig. 3. – Observed and expected event yields in the CRs, VRs and SRs for the three- and four-leptons channels after the fit procedure for the Type-III SeeSaw analysis. More details can be found in [2].

4. – Doubly Charged Higgs boson search

In this analysis, the search for pair production of doubly charged Higgs bosons decaying in SM leptons is performed [5]. The relevant decays are $H^{\pm\pm} \to \ell^{\pm}\ell'^{\pm}$ with $\ell, \ell' = e, \mu, \tau$. Lepton flavour violating decays are allowed. The leading discriminant in the definition of the analysis regions is the number of leptons in the final states (two, three or four). Requirements on the leading leptons p_T, pseudorapidity η and invariant mass are also used to ensure the orthogonality of the analysis regions. The observed and expected yields in all CRs, SRs and VRs are shown in Figure 4. There is a good agreement between data and SM predictions. In the four-leptons signal region, potentially the most sensitive to new-physics, no data events are observed, accordingly to the expected yield.

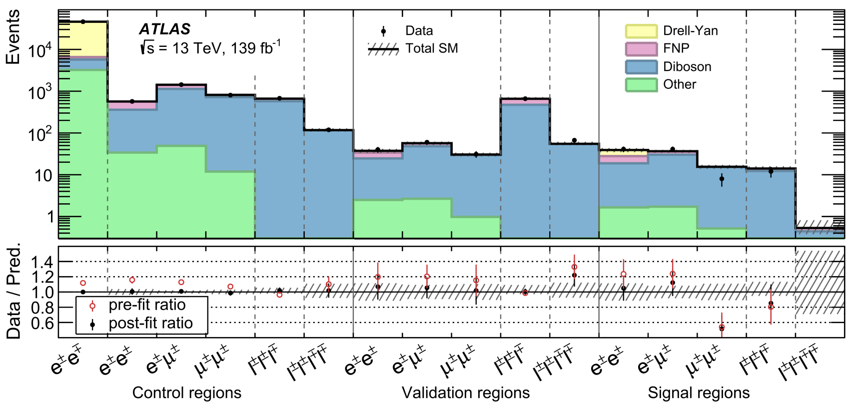

Fig. 4. – Number of observed and expected events in the control, validation and signal regions for all channels of the DCH search analysis, split by lepton flavour and electric charge combination. The symbol ℓ stands only for light leptons. The bottom part of the plot shows the agreement between data and prediction, both pre-fit (red) and post-fit (black). More details can be found in [1].

5. – Results

The searches presented in this work did not observe any significant excess with respect to the expected yield from SM processes, so lower limits on the masses of the heavy neutral leptons and the doubly charged Higgs are then set at 95% CL on the main observable. In the T3SS analysis, the heavy leptons masses have been constrained to $m(N, L^{\pm}) > 870\,\text{GeV}$ in the three- and four-leptons decay channels. The results have also been combined with a previous ATLAS analysis considering two-leptons final states [4], and this allowed to further improve the exclusion limit to 910 GeV. The 95% CL limits for three-, four-, and also two-leptons final states are shown in Figure 5 Left. In the DCH analysis, the lower limit on $m(H^{\pm\pm})$ varies between 520 and 1050 GeV depending on the leptonic multiplicity of the considered channel. The combination of all channels yields $m(H^{\pm\pm}) > 1080\,\text{GeV}$, as can be seen in Figure 5 Right.

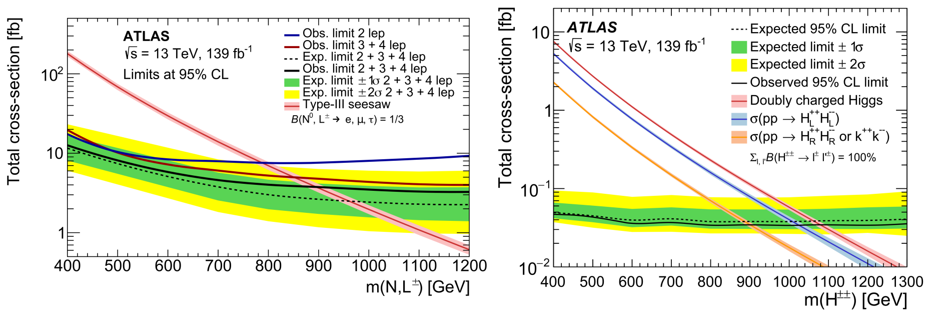

Fig. 5. – Left: Observed (solid line) and expected (dashed line) 95% CL exclusion limits in the two-lepton channel, the three- and four-leptons channels, and their combination for the Type-III SeeSaw process [2]. Right: Observed (solid line) and expected (dashed line) 95% CL upper limits on the $H^{\pm\pm}$ pair production cross-section as a function of $m(H^{\pm\pm})$ resulting from the combination of all analysis channels [1].

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