Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics B Proceedings Supplement 00 (2014) 1–6

Nuclear Physics B Proceedings Supplement

Searches for new physics in events with multiple leptons with the ATLAS detector

L. Fiorini[a]

[a] *on behalf of the ATLAS Collaboration.*
Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear, University of Valencia and CSIC, Catedràtic José Beltrán 2, E-46980 Paterna, Spain

Abstract

Events containing several leptons are useful probes of new phenomena due to the low background from Standard Model processes. We look for events with three or more leptons, as well as direct searches for WZ resonances, excited leptons and heavy fermions. The searches use data recorded in 2012 at $\sqrt{s}$=8 TeV centre-of-mass energy by the ATLAS experiment at the LHC. No evidence of excess above the Standard Model background predictions was observed and limits have been set accordingly.

Keywords: ATLAS, LHC, BSM searches

1. Introduction

Multiple leptons final states are of particular important in searches for new phenomena beyond the Standard Model at the LHC [1] hadron collider. Several models beyond the Standard Model predict decays of new particles in final states with multiple leptons and searches in multilepton final states benefit from low Standard Model backgrounds and high trigger efficiency at hadron colliders. Leptons are required to be energetic, isolated and originating from primary vertex interactions. The main backgrounds in multiple lepton searches originate from Standard Model processes such as WZ and ZZ production, where several energetic and isolated leptons are produced (irreducible backgrounds) and from processes where at least one of the identified leptons are produced by semileptonic heavy flavor decays, misidentified jets and photon conversions (reducible backgrounds).

Four searches in multiple lepton final states with the ATLAS detector [2] are described in the following. The searches use data recorded in 2012 at $\sqrt{s}$=8 TeV centre-of-mass energy by the ATLAS experiment at the LHC. First a model-independent search in final states with three or more leptons is described. Several final states and discriminant variables are investigated to provide sensitivity to a broad range of new phenomena with multiple lepton signatures.
The searches in specific final states are then described: the first analysis is searching for WZ resonances in final states with three leptons; the second search investigates the existence of excited leptons in a final state with two leptons and a photon; the third search is motivated by the type III seesaw mechanism and it looks for pair production of heavy fermions decaying to a four-lepton final state, including two leptons from an on-shell Z-boson.

2. Model-independent multi-lepton searches

ATLAS performed a model-independent search in final states with three or more leptons to provide sensitivity to a broad range of final states with multiple leptons. An integrated luminosity of 20.3 fb^{-1} of pp collisions at $\sqrt{s}$=8 TeV is used in this analysis. [3]

Email address: Luca.Fiorini@cern.ch (L. Fiorini)

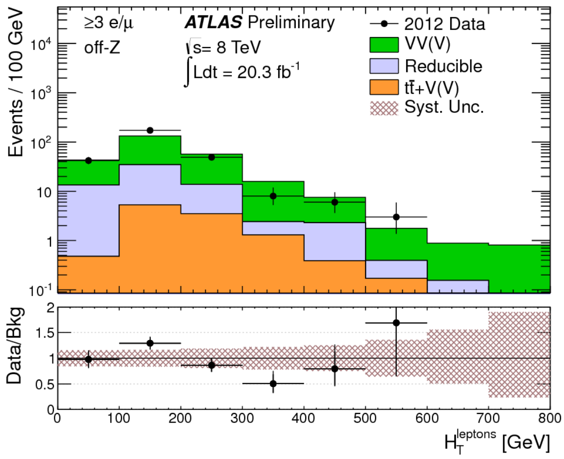

Figure 1: $H_{\mathrm{T}}^{\mathrm{leptons}}$ distribution for the off-Z 3 e/μ signal channel. The last bin shows the overflows. The bottom panel shows the ratio of events observed in data to those expected from background sources for each bin.[3]

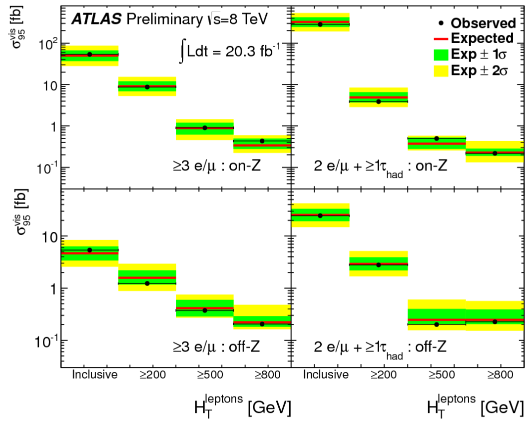

Figure 2: Example of observed and expected 95% CL limit on the visible cross section in the different signal channels, as functions of increasing lower bounds on $H_{\mathrm{T}}^{\mathrm{leptons}}$. The $\pm 1\,\sigma$ and $\pm 2\,\sigma$ uncertainties on the median expected limit are indicated by green and yellow bands, respectively.[3]

2.1. Selection Criteria

The analysis requires at least three energetic, prompt and isolated leptons, where the two leptons of highest p_{T} are electrons or muons and the third lepton is an electron, muon or hadronically decaying tau. The leading lepton is required to have $p_{\mathrm{T}} > 26$ GeV. The other leptons are required to have $p_{\mathrm{T}} > 15$ GeV, in the case of hadronically decaying tau, it is required to have $p_{\mathrm{T}} > 20$ GeV. Events are separated in four categories, depending on whether the third lepton is a hadronically decaying tau and whether two of the leptons with the same flavour and different charge are consistent with the decay of an on-shell Z-boson (on-Z and off-Z categories). Figure 1 shows the $H_{\mathrm{T}}^{\mathrm{leptons}}$ distribution for the off-Z 3 e/μ signal category.

Five variables are used to define the signal regions, resulting in a total of 92 inclusive signal regions are defined to be sensitive to a range of production and decay modes resulting in multiple lepton final states:

- $H_{\mathrm{T}}^{\mathrm{leptons}}$: sum of the p_{T} of the three leptons;
- $E_{\mathrm{T}}^{\mathrm{miss}}$: missing transverse energy of the event;
- m_{eff} : sum of $H_{\mathrm{T}}^{\mathrm{leptons}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$ and the p_{T} of the jets in the event;
- min p_{T}^{ℓ} : lowest p_{T} of the leptons;
- b-tags: number of b-tagged jets.

2.2. Backgrounds and Results

The irreducible backgrounds of this analysis are WZ, ZZ and $t\bar{t}+W/Z$. Monte Carlo simulation is used to estimate them. Reducible backgrounds originate mainly from $t\bar{t}$ and W/Z+jets and they are estimated with data-driven techniques in control regions where the the lepton selection criteria are relaxed. The nature of the dominant backgrounds depend on the category and signal region: the backgrounds in the categories with only electrons or muons are mainly from irreducible processes, while the backgrounds in categories with a hadronically decaying tau lepton are in majority of reducible nature. No significant excesses with respect to Standard Model predictions are observed. The results are presented as 95% CL limits on the visible cross-section for each of the signal region. As an example $H_{\mathrm{T}}^{\mathrm{leptons}}$ limits are shown in Figure 2. Fiducial efficiencies (ϵ_{fid}) are also given as a function of p_{T} and pseudo-rapidity[1] of all the leptons for model testing.

3. *WZ* resonances searches

The search for diboson resonances is an essential tool in the investigation of the source of the electroweak symmetry breaking mechanism. A number of theories predict the existence of high mass resonances decaying to WZ final states. ATLAS performed a direct search of $WZ \to \ell' \nu \ell\ell$ resonances [4], where the vector bosons

[1] The pseudo-rapidity is defined as a function of the azimuthal angle $\eta = -\ln(\mathrm{tg}\frac{\theta}{2})$

decay to leptons (ℓ,ℓ'=e or μ). The analysis employs 20.3 fb^{-1} of data at $\sqrt{s}$ = 8 TeV and the results are then interpreted in the context of the production of an extended gauge model W and a simplified model of heavy vector triplets.

3.1. Selection Criteria

The event are required to have three isolated and prompt leptons with p_T > 25 GeV and E_T^{miss} > 25 GeV. Events with an additional lepton with p_T > 20 GeV are rejected. The two leptons of same flavour and opposite charge are required to have $|m_Z - m_{\ell\ell}| < 20$ GeV. In case two possible combination satisfying the above criteria exist, the one having a mass closest to the Z-boson pole mass is chosen. In case the lepton associated to the W boson is an electron, a tighter identification criteria is required in order to reduce the background from Z+jets process. A requirement on the difference of rapidity[2] between the W- and Z-boson is applied to improve the sensitivity to resonant signals, $\Delta y(W, Z) < 1.5$. A low (high) mass signal region is then defined by the requirement on the angles in the transverse plane between the lepton attributed to the W-boson and the E_T^{miss} : $\Delta\phi(\ell, E_T^{miss}) > 1.5$ (< 1.5).

3.2. Backgrounds and Results

The main background is the irreducible WZ Standard Model process, which is modelled by Monte Carlo simulation. Its agreement with data is verified in a control region defined by reverting the requirement on $\Delta y(W, Z)$ and removing the request on $\Delta\phi(\ell, E_T^{miss})$. Other backgrounds modelled by Monte Carlo simulation are the $t\bar{t}$ +W/Z and Z+γ. Contributions from $\ell\ell'$+jets backgrounds where a jet is misidentified as lepton, such as Z+jets and $t\bar{t}$ processes, are estimated with data-driven techniques.

Figure 3 shows the m_{WZ} distribution for events in the high-mass signal region. The m_{WZ} spectrum of the two signal regions is scrutinised for an excess over the expected Standard Model background. No significant deviation from the Standard Model predictions is observed and upper limits on the production cross sections of WZ resonances from an extended gauge model W' and from a simplified model of heavy vector triplets are derived. A corresponding observed (expected) lower mass limit of 1.52 (1.49) TeV is derived for the W' at a 95% confidence level. Figure 4 shows the 95% CL upper limits on $\sigma(pp \to X) \times \mathcal{B}(X \to WZ)$ as a function of the mass of the resonance X.

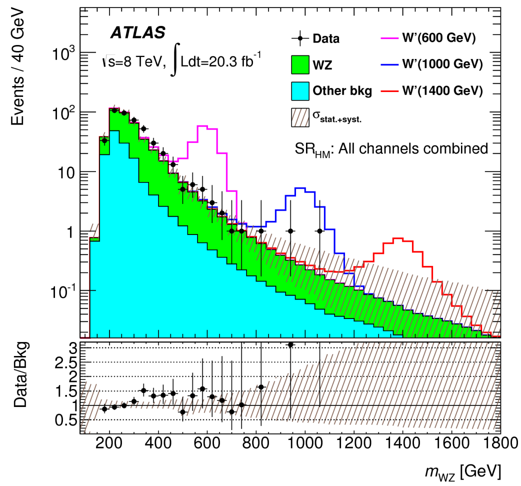

Figure 3: Observed and predicted WZ invariant mass (m_{WZ}) distribution for events in the high-mass signal region. Predictions from W' samples with masses of 600 GeV, 1000 GeV and 1400 GeV are also shown, stacked on top of the expected backgrounds. The uncertainty bands upon the expected background include both the statistical and systematic uncertainties in the MC simulation and the fake-background estimation added in quadrature.[4]

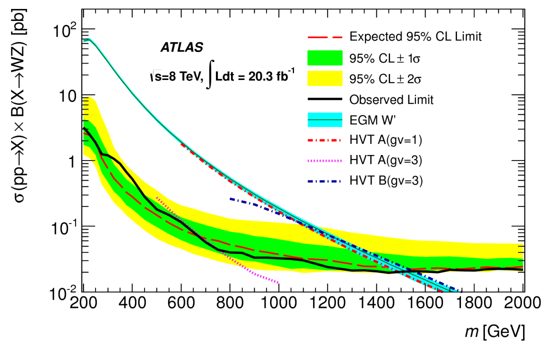

Figure 4: The observed 95% CL upper limits on $\sigma(pp \to X) \times \mathcal{B}(X \to WZ)$ as a function of the signal mass m, where X stands for the signal resonance. The expected limits are also shown together with the ± 1 and ± 2 standard deviation uncertainty bands. Theoretical cross sections for the EGM W' and the HVT benchmark models are also shown. The uncertainty band around the EGM W' cross-section line represents the theoretical uncertainty on the NNLO cross-section calculation using ZWPROD [5].[4]

[2] The rapidity is defined as $y = \frac{1}{2} ln \frac{E+p_z}{E-p_z}$

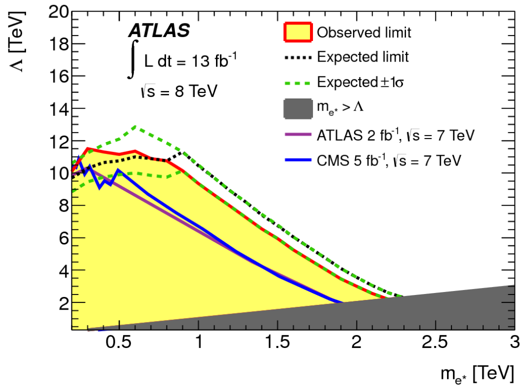

Figure 5: Exclusion limit in the compositeness scale (Λ) vs excited-lepton mass (m_{ℓ^*}) parameter space for the electron channel. The filled area is excluded at 95% CL. No limits are set in the dark shaded region $m_{\ell^*} > \Lambda$ where the model is not applicable.[6]

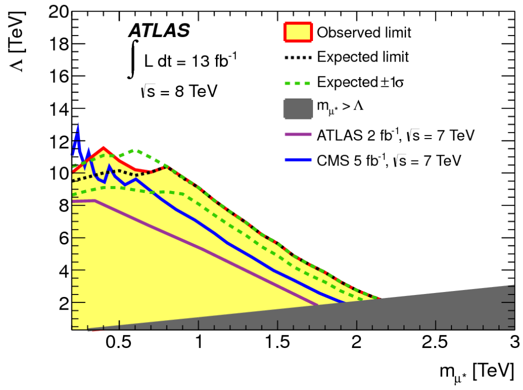

Figure 6: Exclusion limit in the compositeness scale (Λ) vs excited-lepton mass (m_{ℓ^*}) parameter space for the muon channel. The filled area is excluded at 95% CL. No limits are set in the dark shaded region $m_{\ell^*} > \Lambda$ where the model is not applicable.[6]

4. Excited leptons searches

Excited quarks and leptons are possible in models of composite fermions, where the Standard Model fermions are supposed to be bound states of more fundamental constituents. As a consequence, new interactions among fermions can happen near the compositeness scale, including the possibility of excited states with a mass below the compositeness scale Λ. ATLAS analysed the first 13 fb^{-1} of data at $\sqrt{s}$= 8 TeV searching for the production of excited leptons in a four-particle contact interaction, $pp \rightarrow \ell\ell^*$, where the excited lepton decays via $\ell^* \rightarrow \ell\gamma$. [6]

4.1. Selection Criteria

Events are required to have one photon and two leptons of same flavour and opposite sign. The p_T requirement is to be > 30 GeV for the photon, > 25 GeV for the muons and > 40 (30) GeV for the leading (sub-leading) electron. Additional isolation and identification criteria are imposed to the leptons and photon. The invariant mass of the two leptons has to be $m_{\ell\ell}$ > 110 GeV to reduce the background of the Z-boson decays, while the $m_{\ell\ell\gamma}$ invariant mass is required to be > 1050 GeV for m_{ℓ^*} > 900 GeV searches and m_{ℓ^*}+150 GeV for m_{ℓ^*} < 900 GeV searches.

4.2. Backgrounds and Results

The Drell-Yan background is suppressed by the $m_{\ell\ell}$ > 110 GeV requirement. The background from $Z + \gamma$ production is irreducible and is the dominant background. It is modelled by Monte Carlo simulation. The reducible background from Z+jets contributes to a lower extent. It is estimated from simulation and normalised in a control region to account for the misidentification of jets as photons. Background contributions from $t\bar{t}$, di-boson processes are modelled from Monte Carlo simulation. No significant excesses are observed, so limits are set on electron and muon final states. Figures 5 and 6 show the exclusion limits in the parameter space defined by the compositeness scale (Λ) and the excited-lepton mass (m_{ℓ^*}).

5. Type III seesaw heavy fermions searches

A number of theoretical models have been proposed to explain not only how neutrinos acquire mass, but also the reason why their mass is so small compared to other fermions. Type III Seesaw mechanism [7, 8, 9] introduces additional fermionic triplets to the Standard Model, generating neutrino masses. The lightest triplet is composed of two charged heavy fermions $N^{\pm}$ and a neutral heavy fermion N^0, whose masses are approximately degenerate and producing a reciprocal seesaw mechanism.
At LHC, the heavy fermions could be produced in pairs $N^0N^{\pm}$ and $N^{\pm}N^{\mp}$. The heavy fermions can then decay into W, Z and H bosons. This direct search is performed in final states with electron and muons where the charged fermion can be fully reconstructed, $N^{\pm} \rightarrow Z\ell^{\pm}$, and $N^0 \rightarrow W^{\pm}\ell^{\mp}$ ($\ell = e, \mu$).
The analysis is performed using the first 5.8 fb^{-1} of pp collisions at $\sqrt{s}$= 8 TeV. [10]

5.1. Selection Criteria

Events are required to have four or more electrons and muons. The p_T of the leading lepton must be >

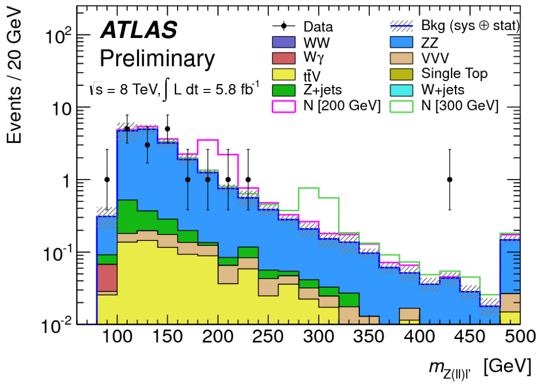

Figure 7: Invariant mass distribution of the $N^{\pm}$ candidates, $Z(\ell\ell)\ell'$, in the signal region, for data (black points), and the expected total background (solid histograms). The rightmost bin includes overflow events. The shape and normalisation are in agreement with the SM expectation.[10]

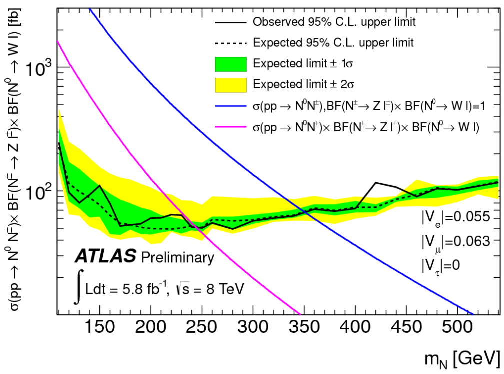

Figure 8: The expected (dashed line) and observed (solid line) exclusion limits at 95% confidence level on $\sigma \times \mathcal{B}$ as a function of the fermion mass m_N assuming $|V_e|$=0.055, $|V_\mu|$=0.063 and $|V_\tau|$=0 and for $\mathcal{B}$=1 (theory LO). The dark(green) and light (yellow) shaded areas represent the 1 standard deviation (68% CL) and 2 standard deviations (95% CL) limits on the expected, respectively. At m_N=420 GeV, the probability to have equal to or more than the observed number of events with a background only hypothesis, p_0, is found to be 0.20.[10]

25 GeV, while the p_T of the remaining three leptons must be > 10 GeV. The $N^{\pm} \rightarrow Z\ell^{\pm}$ kinematic is reconstructed by selecting the pair of same flavour and opposite sign leptons with $|m_Z - m_{\ell\ell}| < 10$ GeV. The third lepton originating from the $N^{\pm}$ decay is chosen to be closest one in the transverse plan to the reconstructed Z candidate. Events with a second reconstructed Z candidate are rejected to reduce the ZZ background.

5.2. Backgrounds and Results

The requirement of four lepton suppresses backgrounds from WZ and Z+jets production. After the selection criteria are applied, the dominant background is the irreducible ZZ background, with smaller contributions from $t\bar{t}+W/Z$, Z+jets, ZZZ and ZWW processes. All backgrounds are modelled from Monte Carlo simulation; in the case of the irreducible ZZ background, the simulation is normalised in a ZZ control region defined by reverting the veto on the second Z-boson. Figure 7 shows the invariant mass distribution of the $N^{\pm}$ candidates in the signal region.

No significant excess is observed above the background expectations, allowing to set limits on $\sigma \times \mathcal{B}$ production rate. Figure 8 shows the exclusion limits at 95% confidence level on $\sigma \times \mathcal{B}$ as a function of the fermion mass m_N assuming $|V_e|$=0.055, $|V_\mu|$=0.063 and $|V_\tau|$=0 and for $\mathcal{B}$=1 (theory LO). In the scenario of maximum allowed mixing angles with Standard Model leptons the exclusion limit on m_N is of 245 GeV.

6. Summary

ATLAS performed model-independent as well as direct searches for New Physics particles in final states with prompt isolated leptons with 8 TeV data. Four ATLAS searches for new phenomena have been presented: a model-independent search requiring three or more leptons and analysing a large variety of signal regions; a search for WZ resonances employing the full 8 TeV statistics; a search for excited leptons in final states with two leptons and a photon and a search for type III seesaw heavy fermions. No evidence of excess above the Standard Model background predictions was observed and limits have been set accordingly.

References

[1] L. Evans and P. Bryant (editors), "LHC Machine", *JINST* **3** (2008), S08001.
[2] ATLAS Collaboration, "The ATLAS Experiment at the CERN Large Hadron Collider", *JINST* **3** (2008), S08003.
[3] ATLAS Collaboration, "Search for New Phenomena in Events with Three Charged Leptons at a Center-of-Mass Energy of 8 TeV with the ATLAS detector", ATLAS-CONF-2013-070, CERN, Geneva. `http://cdsweb.cern.ch/record/1562898`
[4] ATLAS Collaboration, "Search for WZ resonances in the fully leptonic channel using pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector", *Phys. Lett.* **B** (2014), pp. 223-243
[5] R. Hamberg, W. van Neerven, T. Matsuura, "A Complete calculation of the order $\alpha - s^2$ correction to the Drell-Yan K factor", Nucl. Phys. **B359** (1991) 343405. `doi:10.1016/0550-3213(91)90064-5`.

[6] ATLAS Collaboration, "Search for excited electrons and muons with proton-proton collisions at s =8 TeV with the ATLAS detector ", *New J. Phys.* **15** (2013), 093011.

[7] R. Foot, H. Lew and X.-G. He and G.C. Joshi, "See-saw neutrino masses induced by a triplet of leptons", Z. Phys. **C 44** (1989) 441.

[8] R. Franceschini, T. Hambye, and A. Strumia, " Type-III see-saw at LHC", Phys.Rev. **D78** (2008) 033002, `arXiv:0805.1613 [hep-ph]`.

[9] F. del Aguila and J. Aguilar-Saavedra, " Distinguishing seesaw models at LHC with multi-lepton signals", Nucl.Phys. **B813** (2009) 2290, `arXiv:0808.2468 [hep-ph]`.

[10] ATLAS Collaboration, "Search for Type III Seesaw Model Heavy Fermions in Events with Four Charged Leptons using 5.8/fb of sqrt(s) = 8 TeV Data with the ATLAS Detector", ATLAS-CONF-2013-019, CERN, Geneva. http://cdsweb.cern.ch/record/1525526