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Letter

Search for heavy neutrinos and right-handed W bosons in events with two leptons and jets in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

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Abstract This letter reports on a search for hypothetical heavy neutrinos, N, and right-handed gauge bosons, W_R, in events with high transverse momentum objects which include two reconstructed leptons and at least one hadronic jet. The results were obtained from data corresponding to an integrated luminosity of 2.1 fb^{-1} collected in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector at the CERN Large Hadron Collider. No excess above the Standard Model background expectation is observed. Excluded mass regions for Majorana and Dirac neutrinos are presented using two approaches for interactions that violate lepton and lepton-flavor numbers. One approach uses an effective operator framework, the other approach is guided by the Left–Right Symmetric Model. The results described in this letter represent the most stringent limits to date on the masses of heavy neutrinos and W_R bosons obtained in direct searches.

1 Introduction

The discovery of neutrino oscillations [1, 2] unambiguously establishes that neutrinos have non-zero mass and provides clear evidence for physics beyond the Standard Model (SM). One possible explanation for the mass of light neutrinos is provided by theoretical models based on a Grand Unified Theory (GUT). Such models often introduce one or more additional neutrino fields, which manifest themselves as new heavy particles that could be directly observable at the Large Hadron Collider (LHC). In the framework of GUT models, the mass of the light neutrinos could be explained via the see-saw mechanism [3–6]. This predicts $m_\nu \approx m_D^2/m_N$, where, for each generation, m_ν is the mass of a known light neutrino, m_D is the Dirac mass for charged fermions of the same generation, and m_N is the mass of a new heavy neutrino, N. If the see-saw mechanism were to explain the masses of the known neutrinos, both the light and the heavy neutrinos would have to be Majorana particles. This would violate lepton number conservation, and yield a striking signature of two leptons with the same charge at the LHC [7].

This letter reports on a search for new heavy neutrinos of either Majorana or Dirac type, with data corresponding to an integrated luminosity of 2.1 fb^{-1} recorded with the ATLAS detector at the LHC. Two approaches are employed. The first approach aims at exploring possible sources of new physics predicting heavy neutrinos using a Lagrangian of effective operators (referred to as HNEO hereafter) [8]. The theory is built on effective four-fermion operators ($q\bar{q}' \to N\ell$) with the N decaying promptly via a three-body decay, $N \to \ell jj$. The second approach is based on the concept of Left–Right Symmetry [9–11] which extends the electroweak part of the SM by a new gauge group. Its force particles (W_R and Z' bosons) could be produced at LHC energies. A particular implementation of left–right symmetry breaking [12], the Left–Right Symmetric Model (LRSM) with doubly charged Higgs bosons [13, 14] is used in the present analysis. According to this model, the heavy neutrinos would be produced in the decays of a W_R boson via $q\bar{q}' \to W_R \to \ell N$, with N decaying subsequently via $N \to \ell W_R^* \to \ell jj$. Thus, the final state signature for both models consists of two leptons and two jets with high transverse momenta (p_T). Only electrons and muons are considered in this analysis.

The N invariant mass can be fully reconstructed from the decay products in both approaches. Given the s-channel production in the LRSM, the W_R mass, m_{W_R}, can also be reconstructed in this model. The reconstructed W_R boson and N masses are used to perform the search in the context of the HNEO and LRSM models, respectively. Like the SM neutrinos, heavy neutrinos can mix if their masses are

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different. Both the scenarios of no mixing [15] and maximal mixing [16] between two generations of lepton flavors (electron and muon) are investigated assuming that the mass difference between the heavy neutrinos is much smaller than the experimental resolution of their reconstructed invariant mass. In the case of maximal mixing, a mass difference of 2 GeV is assumed. If the heavy neutrinos are of Majorana type, they would contribute to both the same-sign (SS) and opposite-sign (OS) channels, while heavy Dirac neutrinos would contribute solely to the OS channel.

Heavy neutrinos were previously searched for at LEP and excluded for masses up to ≈100 GeV [17–20]. The most stringent direct limits on W_R bosons [21, 22] come from the Tevatron, where $W_R \to tb$ decays were searched for. Assuming a branching ratio of 100 %, W_R boson masses below 825 GeV are excluded at 95 % confidence level (C.L.). Recently, the ATLAS collaboration published an inclusive search for new physics in the same-sign dilepton signature for an integrated luminosity of 34 pb^{-1} [23]. The 95 % C.L. limits presented exclude W_R masses up to about 1 TeV for the LRSM model and Majorana neutrino masses around 460 GeV for the HNEO model.

2 The ATLAS detector

The ATLAS detector [24] is a multipurpose particle physics apparatus with a forward-backward symmetric cylindrical geometry and nearly 4π coverage in solid angle.[1] The inner tracking detector (ID) covers the pseudorapidity range $|\eta| < 2.5$ and consists of: a silicon pixel detector, providing typically three measurements per track; a silicon microstrip detector (SCT), which provides typically four to five measurements; and, for $|\eta| < 2.0$, a transition radiation tracker (TRT), giving typically 30 straw-tube measurements per track. The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field. A high-granularity liquid-argon (LAr) sampling electromagnetic calorimeter covers the region $|\eta| < 3.2$. An iron-scintillator tile calorimeter provides hadronic coverage in the central rapidity range of $|\eta| < 1.7$. The end-cap and forward regions, spanning $1.5 < |\eta| < 4.9$, are instrumented with LAr calorimeters for both electromagnetic and hadronic measurements. The muon spectrometer (MS) surrounds the calorimeters and consists of a system of air-core superconducting toroid coils, precision tracking chambers up to $|\eta| < 2.7$, and detectors for triggering in the region of $|\eta| < 2.4$.

3 Trigger and data

The data used in this analysis were recorded between March and August 2011 at a center-of-mass energy of 7 TeV. The application of beam, detector, and data quality requirements results in a total integrated luminosity of 2.1 fb^{-1} with an estimated uncertainty of ±3.7 % [25, 26]. The data were recorded with single lepton (e or μ) triggers [27]. At the last stage of the trigger decision, the electron trigger selects candidate electrons with transverse energy $E_T > 20$ GeV, satisfying shower-shape requirements and matching an ID track. For the last part of the dataset, corresponding to an integrated luminosity of 0.5 fb^{-1}, the threshold was raised to 22 GeV. The muon trigger selects candidate muons with $p_T > 18$ GeV and $|\eta| < 2.4$. These triggers reach full efficiency for electrons with $p_T > 25$ GeV and muons with $p_T > 20$ GeV. The typical trigger efficiencies measured from data for leptons selected for offline analysis are 99 ± 1 % for electrons, and 74 % and 91 % for muons in the barrel ($|\eta| < 1.05$) and end-cap ($1.05 < |\eta| < 2.4$) regions, respectively, with an uncertainty of about ±1 %.

4 Monte Carlo simulation

Fully simulated Monte Carlo (MC) event samples are used to develop and validate the analysis procedure, estimate the detector acceptance and reconstruction efficiency, and aid in the background determination. The simulation of background processes is described in detail in Ref. [28]. For the major backgrounds, $Z/\gamma^* +$ jets production and top quark pair production, ALPGEN [29] and MC@NLO [30–32] are used, respectively. The leading-order parametrization CTEQ6L1 [33] of the parton density functions (PDF) is used for the ALPGEN simulation, while the next-to-leading order parametrization CTEQ6.6 [33] is used for the MC@NLO simulation. Fragmentation and hadronization are performed in both cases with HERWIG [34–36], using JIMMY [37] for the underlying event modelling. Diboson (WW, WZ, and ZZ) event samples are generated using HERWIG, while MADGRAPH [38] interfaced to PYTHIA [39] is used for $W\gamma$ and $Z\gamma$ production. Single top-quark production is generated with MC@NLO. The production of W^+W^+ arising from a t-channel gluon exchange, resulting in two jets in the final state and two same-sign W bosons, are generated with MADGRAPH interfaced to PYTHIA. The associated production of a vector boson with a $t\bar{t}$ pair ($t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}\gamma$) is simulated with MADGRAPH interfaced with PYTHIA.

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector and the z-axis coinciding with the axis of the beam pipe. The x-axis points from the interaction point to the center of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = \ln\tan(\theta/2)$.

The HNEO signal MC samples are generated using CalcHEP [40] and the leading-order PDF CTEQ6L [33], and hadronization simulated with Pythia. All lepton combinations of e, μ or τ leading to lepton number violating (LNV) signatures, which produce SS or OS dilepton events, are included. The model is implemented via a Lagrangian of effective operators defined as

$$\mathcal{L} = \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \cdot \sum_i \alpha_i \mathcal{O}_i{}^{(n)}, \tag{1}$$

where n is the operator dimension, Λ is the scale of LNV interactions, α_i are the coupling constants between the neutrino N and the leptons, and $\mathcal{O}_i$ are the effective operators [8]. The signal samples are produced for four effective operator hypotheses: the four-fermion vector operator, $\mathcal{O}_V$, and four-fermion scalar operators, $\mathcal{O}_{s1}$, $\mathcal{O}_{s2}$, and $\mathcal{O}_{s3}$. The tree-level-generated dimension-6 operator $\mathcal{O}_V$ corresponds to *duNe*, while $\mathcal{O}_{s1}$ and $\mathcal{O}_{s2}$ correspond to *QuNL* and *LNQd*, respectively, and $\mathcal{O}_{s3}$ corresponds to *QNLd* (e, u, d and L, Q denote the right-handed SU(2) singlets and left-handed SU(2) doublets, respectively). The production via the effective operators $\mathcal{O}_{s1}$ and $\mathcal{O}_{s2}$ have the same cross section and lead to identical event kinematics, which makes them indistinguishable. The production cross sections for the Majorana and Dirac neutrinos in the framework of the effective Lagrangian are related to the energy scale of new physics and the coupling constant $\sigma \approx \alpha^2/\Lambda^4$, such that the coupling can be varied to scan for new physics at different Λ scales.

The LRSM signal MC samples are generated using an implementation of this model [14] in Pythia, with modified leading-order parton distribution functions MRST2008LO* [41]. The coupling constants for the W_R and left-handed W boson are assumed to be the same, including the CKM matrix for W_R boson couplings to right-handed chiral quark components. It is assumed that there is no mixing between the W_R boson and the SM W boson. The LRSM signal MC samples are generated constraining the decays to e or μ and with $m_N < m_{W_R}$. The branching fractions used are the ones predicted by Pythia. When the mass difference between the W_R and the N is large, the leptonic branching fractions are ≈8 %, and they decrease with decreasing mass difference.

Both Majorana and Dirac type heavy neutrinos are considered, assuming that the total production cross section is the same for both cases. The leading-order theoretical cross sections are used.

All signal and background samples are generated using the ATLAS underlying event tunes [42, 43] and processed through the ATLAS detector simulation [44] based on Geant4 [45]. The MC samples are produced including the simulation of multiple interactions per LHC bunch crossing (pile-up). Varying pile-up conditions and their dependence on the instantaneous luminosity of the LHC are taken into account by reweighting MC events to match the pile-up conditions measured in data.

5 Object reconstruction and event selection

The criteria for electron and muon identification closely follow those described in Ref. [46]. Electrons are required to pass the "medium" selection criteria, with $p_T > 25$ GeV and $|\eta| < 2.47$, excluding the electromagnetic calorimeter transition region, $1.37 < |\eta| < 1.52$ [47]. To improve the background rejection for $|\eta| > 2.0$, more stringent requirements are placed on the track-cluster matching in η and shower shape. Electron tracks that pass through an active region of the innermost pixel detector are required to have a measurement in that layer in order to suppress electrons from photon conversions. Additionally, an electron whose track matches the ID track of a muon candidate is rejected.

Muons are required to be identified in both the ID and the MS systems. The ID track is required to have at least one pixel hit, more than five SCT hits, and a number of TRT hits that varies with η. Muon tracks that pass through an active region of the innermost pixel detector are required to have a measurement in that layer. The curvatures, as measured by the ID and MS systems, must have the same sign. Only muons with $p_T > 25$ GeV and $|\eta| < 2.4$ are considered. Selection criteria on the displacement of the muon relative to the primary vertex, selected as the one with the highest $\sum p_T^2$ of associated tracks, are required. The longitudinal (z_0) and transverse (d_0) impact parameters must satisfy $|z_0| < 5$ mm, $|d_0| < 0.2$ mm, and $|d_0/\sigma_{d_0}| < 5$, where σ_{d_0} is the uncertainty on d_0. These cuts reduce the cosmic ray muon background to a negligible level and also reduce the background from non-prompt muons.[2]

To reduce the background due to leptons from decays of hadrons (including heavy-flavor hadrons) produced in jets, requirements on the isolation of leptons are imposed. To evaluate the isolation energy for electrons, the transverse energies deposited in the calorimeter towers in a cone in η–ϕ space of radius $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.2$ around the electron direction are summed and corrected for energy deposition from pile-up events. In addition, the transverse energy of the electron, E_T, corrected for energy leakage into the neighboring towers, is subtracted. The isolation transverse energy is required to be less than 15 % of the electron E_T. An equivalent quantity, $E_T^{\Delta R=0.3}$, is calculated for the muon using a cone size of $\Delta R = 0.3$. If there is no jet with $p_T > 20$ GeV within $\Delta R < 0.4$ of the muon, $E_T^{\Delta R=0.3}$ is required to be less than 15 % of the muon p_T. Additionally, muons with $p_T < 80$ GeV should have no other track

[2] Leptons from W, Z and τ decays are classified as prompt leptons, while leptons any hadron decays are classified as non-prompt leptons.

with $p_{\mathrm{T}} > 1$ GeV originating from the primary vertex within a cone of $\Delta R = 0.3$ around the muon. Otherwise, if the muon has a jet nearby, it must satisfy $p_{\mathrm{T}} > 80$ GeV and $(E_{\mathrm{T}}^{\Delta R=0.3}/p_{\mathrm{T}} - 3)/p_{\mathrm{T}} > -0.02\ \mathrm{GeV}^{-1}$. These isolation requirements are powerful in rejecting background muons and highly efficient for selecting signal muons produced in the decays of heavy neutrinos and reconstructed near the signal jets in cases where the heavy neutrino is boosted.

Jets are reconstructed using the anti-k_{t} jet clustering algorithm [48, 49] with a radius parameter $R = 0.4$. The input to this algorithm is clusters of calorimeter cells seeded by cells with energies significantly above the measured noise. The energies and momenta of jets are evaluated by performing a four-vector sum over these clusters, treating each cluster as an $(E, \mathbf{p})$ four-vector with zero mass. Jets are corrected for calorimeter non-compensation, upstream material and other effects using p_{T} and η-dependent calibration factors [50] obtained from MC simulation [51], and validated with test-beam and collision-data studies. Only jets with $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.8$ are considered. To avoid double counting, the closest jet within $\Delta R < 0.5$ of an electron candidate is discarded. The selected jets must pass quality requirements based on their shower shape, and their calorimeter signal timing must be consistent with the timing of the beam crossings [52]. Events with any jet that fails the jet quality criteria are rejected. To suppress jets unrelated to the hard scattering of interest, at least 75 % of the summed p_{T} of all reconstructed tracks associated with a jet with $|\eta| < 2.8$ must come from tracks originating from the selected primary vertex. During a part of the data-taking period, corresponding to an integrated luminosity of 0.9 fb^{-1}, an electronic failure in a small η–ϕ region of the LAr EM calorimeter created a dead region. For this integrated luminosity, events in data and MC containing either an identified electron or a jet, with $p_{\mathrm{T}} > 40$ GeV, satisfying $-0.1 < \eta < 1.5$ and $-0.9 < \phi < -0.5$ are rejected, leading to a loss of signal efficiency of about 10 % for this portion of the data.

Events are preselected by requiring exactly two identified leptons with $p_{\mathrm{T}} > 25$ GeV originating from the primary vertex and at least one jet with $p_{\mathrm{T}} > 20$ GeV. At least one of the lepton candidates must match a triggered lepton at the last stage of the trigger selection. To reduce the number of background events from Drell–Yan production and misidentified leptons, the dilepton invariant mass, $m_{\ell\ell}$, is required to be greater than 110 GeV. The signal region is then subdivided into SS and OS dilepton events. In the OS dilepton channels, further background reduction is achieved by requiring that the scalar sum of the transverse energies of the two leptons and the leading two jets with $p_{\mathrm{T}} > 20$ GeV, denoted by S_{T}, is greater than 400 GeV. This event selection is referred to hereafter as the baseline selection. As mentioned previously, the mass of the N can be reconstructed from its decay products of one lepton and two jets. In the case where the N is boosted, the hadronic decay products can be reconstructed as one jet due to their proximity to each other. For scenarios with a large mass splitting between the W_{R} and N, up to half of the signal events have only one jet. The W_{R} boson invariant mass is reconstructed from the leptons and the two highest p_{T} jets in events with at least two jets, or a single jet in events with only one jet. Anti-k_{t} jets are massive, and therefore, the jet four-momenta are used in calculating the invariant mass. For the LRSM, the W_{R} boson invariant mass, $m_{\ell\ell j(j)}$, is required to be greater than 400 GeV for both SS and OS final states.

6 Background estimation

Several processes have the potential to contaminate the signal regions. The main background to the SS dilepton final state, which is referred to as "fake lepton" background, arises from SM $W+$jets, $t\bar{t}$, and multi-jet production where one or more jets are misidentified as prompt isolated leptons. This background is measured using a data-driven technique rather than using less accurate estimates from MC simulation. The other significant background arises from charge misidentification of a reconstructed electron as a result of hard bremsstrahlung followed by asymmetric conversion ($e^{\pm}_{\mathrm{hard}} \rightarrow e^{\pm}_{\mathrm{soft}}\gamma_{\mathrm{hard}} \rightarrow e^{\pm}_{\mathrm{soft}}e^{\pm}_{\mathrm{soft}}e^{\mp}_{\mathrm{hard}}$). This background is estimated with a combination of MC and data-driven techniques. Small contributions from diboson and single top-quark events are also accounted for using MC.

For the $e^{\pm}e^{\mp}$ and $\mu^{\pm}\mu^{\mp}$ final states, the dominant backgrounds are $Z/\gamma^{*}+$jets and $t\bar{t}$ events, with about equal contributions after all selection criteria are applied. The $e^{\pm}\mu^{\mp}$ final state is dominated by $t\bar{t}$ production. The backgrounds from $t\bar{t}$, single top-quark, and diboson production are estimated from MC simulation, while the estimation of the $Z/\gamma^{*}+$ jets background is extracted from a normalization to the data. The fake lepton background is estimated from data, using the same method as for the SS final states.

A data-driven approach, similar to the one described in Refs. [23, 28], is used to estimate the fake lepton background. The method uses "loose" leptons in addition to the candidate leptons. Loose muons are defined using the same identification criteria as the candidate muons, except for the isolation requirements, which are not applied. For the electrons, looser requirements on the shower shape variables, track-cluster matching, and track quality are used, and the isolation requirement is not applied. The method uses the fractions of these loose fake leptons, R_{fake}, and loose prompt leptons, R_{prompt}, which also pass the candidate lepton requirements. A 4×4 matrix is then employed on the "loose–loose" and "loose–tight" dilepton sample to predict the total fake lepton background contributing to the SS and OS dilepton final states. The R_{fake}

fractions are measured using fake lepton enriched control regions containing a single loose lepton. Additional criteria are imposed to reduce the true lepton contamination from electroweak processes to a negligible level. For events in the control regions, the transverse mass, $m_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{miss} \cdot (1 - \cos\Delta\phi(\ell, E_T^{miss}))}$, is required to be less than 40 GeV. E_T^{miss} is defined as the missing transverse momentum based on the calorimeter information and the transverse momenta of muons within $|\eta| < 2.7$ [46], while $\Delta\phi(\ell, E_T^{miss})$ is the azimuthal angle separation between the lepton and the E_T^{miss} vectors. Additionally, the following requirements are imposed: $\Delta\phi(\text{jet or } e, E_T^{miss}) < 0.1$ for the electron control region and $\Delta\phi(\mu, E_T^{miss}) < 0.5$ for the muon control region. For the muon control region, an additional requirement of at least one jet is imposed. After these criteria are applied, the remaining background from electroweak processes is estimated to be less than 5 %. The R_{prompt} fractions are measured using Z boson events satisfying 86 GeV $< m_{\ell\ell} <$ 96 GeV via a method referred to as the "tag-and-probe" method. The "tag" lepton is required to satisfy all lepton selection criteria, while the unbiased opposite charge "probe" lepton should satisfy the loose criteria. The R_{prompt} fractions are parametrized as a function of the lepton p_T and range from 89 % to 98 % for muons and 96 % to 99 % for electrons. To improve the accuracy of the prediction, the fractions are parametrized as a function of kinematic variables separately for leptons that pass the analysis trigger requirement and those that do not. The muon R_{fake} is measured separately for muons that originate from heavy flavor jets and those that do not, where the jet flavor is identified using a combination of the secondary vertex [53] and impact parameter-based [54] b-tagging algorithms. For muons, R_{fake} ranges from 5 % to 10 % (5 % to 40 %) for heavy flavor (light flavor) jets. For electrons, R_{fake} ranges from 45 % to 60 %.

A partially data-driven approach is adopted to estimate $Z/\gamma^* \to ee$ and $Z/\gamma^* \to \mu\mu$ contributions to the OS dilepton channels. A control region is defined requiring 80 GeV $< m_{\ell\ell} <$ 100 GeV and $\geq$1 jets, where non-Z boson contributions are found to be negligible. Normalization factors between the observed number of events in data and the MC prediction are obtained as a function of jet multiplicity from this region and applied to the MC estimates in the signal region. All other backgrounds, including $Z/\gamma^* \to \tau\tau$, are estimated from MC simulation. The contribution of $Z/\gamma^* \to \tau\tau$ is found to be negligible after all selection criteria are applied. Table 1 summarises the background estimates for the OS channels. In the OS ee and $\mu\mu$ channels, Z/γ^* + jets and $t\bar{t}$ backgrounds dominate, while the $t\bar{t}$ production contributes more than 90 % in the $e\mu$ channel. Smaller contributions arise from diboson production and events with fake leptons.

The fraction of reconstructed electrons with charge misidentification due to hard bremsstrahlung is measured from simulated Z/γ^* + jets events, by comparing the MC generated charge of the electron originating from the Z to that of the reconstructed electron candidate. The fraction is parametrized as a function of the electron E_T and η and applied to $Z/\gamma^* \to e^+e^-$ and $t\bar{t} \to e^{\pm}\ell^{\mp}b\bar{b}$ MC backgrounds to obtain their contributions to the SS dilepton final state, thus benefiting from the large number of simulated OS events. Since the MC overestimates the charge misidentification as observed in the $Z/\gamma^* \to ee$ data sample, η-dependent scale factors between data and MC simulation are obtained using $Z/\gamma^* \to e^{\pm}e^{\pm}$ events with 80 GeV $< m_{\ell\ell} <$ 100 GeV. Both electrons are required to be within the same η range and with the same charge. These factors are applied to the MC estimates. The rate of charge misidentification due to tracking resolution is found to be negligible within the lepton transverse momentum range of interest and is well described by the MC simulation.

All other backgrounds are estimated from MC simulation and found to be small, as shown in Table 2. In the SS ee and $e\mu$ channels, the dominant background arises from fake leptons. The next most significant background is diboson production for the $e\mu$ channel and Z/γ^* production for the ee channel. The SS $\mu\mu$ channel is dominated by the diboson background with a smaller contribution from fake leptons.

7 Systematic uncertainties

The dominant contribution to the systematic uncertainties in the SS ee and $e\mu$ channels arises from the fake lepton background estimate. As a first step in validating the parametrization of R_{fake} and R_{prompt}, a closure test is performed in data. Measurements of R_{fake} and R_{prompt} are obtained by randomly sampling half of the control regions. The predicted values are then compared with the values measured in the other half of the data. The closure test yields an agreement for R_{fake} and R_{prompt} of, respectively, ±40 % and ±5 % for muons and, for electrons, ±5 % (±20 % for $1 < |\eta| < 1.9$) and ±2 %, which are propagated to the fake lepton background estimate. To evaluate the uncertainty on the overall fake lepton background estimate, the robustness of the procedure is tested against variations across samples. The estimated fake lepton background is compared to the observed background in SS events passing the same selection as events in the signal region but where the sub-leading lepton has a transverse momentum between 15 GeV and 25 GeV. The fake lepton background contributes between 65 % in $e^{\pm}e^{\pm}$ to 87 % in $e^{\pm}\mu^{\pm}$ of the total background. This study tests the reliability of both the parametrization and the use of R_{fake} and R_{prompt} to extract the background prediction. In this sample, the total background prediction agrees with the observed data within ±10 %. A ±30 % overall systematic uncertainty is assigned to cover for the differences between the predicted and the observed $m_{\ell\ell}$ spectra.

The uncertainties on the background due to the electron charge misidentification arise from the limited number of MC events used to parametrize the rate and the scale factors used to correct the simulation for differences between data and MC and contribute ±13 % and ±12 %, respectively.

The background and signal estimates derived from MC are affected by the jet energy scale (JES) calibration and the jet energy resolution (JER), theoretical and MC modelling uncertainties, and p_T and η dependent uncertainties on the lepton identification and reconstruction efficiencies (identification ±(0.2–3.3) %, p_T scale ±(0.2–2) % and resolution ±(0.4–10) %) [47, 55, 56]. The JES (±(2–6) %) and JER (±(5–12) %) uncertainties applied depend on jet p_T and η and are measured from the 2010 dataset [52]. An additional contribution of ±(2–7) % to the JES uncertainty is added in quadrature to account for the effect of high luminosity pile-up in the 2011 dataset. MC modelling uncertainties for $t\bar{t}$ production [28] are derived using different MC generators and varying, within their uncertainties, the parameters that control initial and final state radiation. The resulting uncertainties are ±15 % and ±(5–7) % for $t\bar{t}$ and diboson contributions, respectively.

Due to the limited knowledge of PDFs and α_s, the uncertainties are evaluated using a range of current PDF sets with the procedure described in Ref. [57]. The final uncertainty is taken from the outer bounds of the overall error bands. The PDF uncertainties are estimated to be ±9 % for the LRSM signal and ±12 % for the HNEO signals.

8 Results and interpretation

The expected and observed numbers of events in each dilepton final state for the baseline selection and the LRSM selections are compared in Tables 1 and 2 for the OS and

Table 1 Summary of the expected background yields and observed numbers of events for the OS dilepton channels. The top part of the table shows the numbers obtained for events with two leptons, ≥1 jet, $m_{\ell\ell} > 110$ GeV, and $S_T > 400$ GeV. The bottom part of the table shows the numbers for the final LRSM selection, where an additional requirement $m_{\ell\ell j(j)} \geq 400$ GeV is imposed. The quoted uncertainties include statistical and systematic components, excluding the luminosity uncertainty of ±3.7 %. The latter is relevant for all backgrounds except for the fake lepton(s) background, which is measured using data

Physics processes	$e^{\pm}e^{\mp}$	$\mu^{\pm}\mu^{\mp}$	$e^{\pm}\mu^{\mp}$	Total
Z/γ^* + jets	136.1 ± 12.5	173.2 ± 15.1	0.8 ± 0.8	310 ± 20
Diboson	4.3 ± 1.8	7.3 ± 1.9	5.9 ± 1.6	18 ± 3
Top	103.1 ± 12.3	100.9 ± 12.0	199.4 ± 23.3	403 ± 46
Fake lepton(s)	12.5 ± 8.1	-0.2 ± 0.7	6.1 ± 4.2	18 ± 9
Total background	256.0 ± 26.2	281.2 ± 27.9	212.3 ± 33.8	750 ± 78
Observed events	248	245	247	740
	$m_{\ell\ell j(j)} \geq 400$ GeV			
Total background	254.8 ± 25.8	279.7 ± 27.6	210.9 ± 33.4	745 ± 77
Observed events	246	241	244	731

Table 2 Summary of the expected background yields and observed numbers of events for the SS dilepton channels. The top part of the table shows the numbers obtained for events with two leptons, ≥ 1 jet and $m_{\ell\ell} > 110$ GeV. The bottom part of the table shows the numbers for the final LRSM selection, where an additional requirement $m_{\ell\ell j(j)} \geq 400$ GeV is imposed. The quoted uncertainties include statistical and systematic components, excluding the luminosity uncertainty of ±3.7 %. The latter is relevant for all backgrounds except for the fake lepton(s) background, which is measured using data

Physics processes	$e^{\pm}e^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}\mu^{\pm}$	Total
Z/γ^* + jets	26.1 ± 5.6	$0.0^{+1.6}_{-0}$	1.2 ± 0.7	27 ± 6
Diboson	12.7 ± 2.3	7.2 ± 1.7	18.8 ± 3.0	39 ± 6
Top	5.8 ± 1.3	0.7 ± 0.3	6.8 ± 1.6	13 ± 3
Fake lepton(s)	93.6 ± 35.7	3.1 ± 1.6	53.8 ± 20.3	151 ± 50
Total background	138.3 ± 36.5	$11.0^{+2.9}_{-2.5}$	80.7 ± 20.8	230 ± 52
Observed events	155	14	99	268
	$m_{\ell\ell j(j)} \geq 400$ GeV			
Total background	48.4 ± 16.1	$4.4^{+2.1}_{-1.3}$	24.6 ± 7.6	77 ± 21
Observed events	59	8	39	106

SS events, respectively. Additionally, the reconstructed masses of the N and W_R candidates, $m_{\ell j(j)}$ and, $m_{\ell\ell j(j)}$ respectively, are examined in each dilepton channel. Figures 1 and 2 show those distributions for the OS and SS channels (ee, $\mu\mu$, and $e\mu$ combined).

Given the good agreement between the data and the expectations from SM processes, the results are used to set limits at 95 % C.L. on the visible cross section, $\sigma\mathcal{A}\epsilon$, where σ is the cross section for new phenomena, $\mathcal{A}$ is the acceptance (i.e. the fraction of events passing geometric and kinematic selection requirements at the particle level), and ϵ is the efficiency (i.e. the detector reconstruction and identification efficiency). For the HNEO model, $\mathcal{A}\epsilon$ is about 10 % for $m_N = 0.1$ TeV and reaches a plateau value of about 28 % at around $m_N = 0.8$ TeV, for all six dilepton channels. For the LRSM, $\mathcal{A}\epsilon$ varies between 40 % and 65 % across the (m_{W_R}, m_N) plane. The lowest $\mathcal{A}\epsilon$ occurs for small m_N. It should be noted that the difference in $\mathcal{A}\epsilon$ between the two models is dominated by the fact the decays to τ leptons are included in generating the HNEO samples, while only decays to e and μ are included in the LRSM samples. Table 3 quotes the limits obtained for each channel, after the baseline selection.

The resulting limits for the interpretation of the data in terms of the HNEO and LRSM models are derived using as templates the reconstructed masses of the N and W_R candidates in each dilepton channel. The baseline selection is used for the HNEO model, while the additional cut of $m_{\ell\ell j(j)}$ is applied for the LRSM model. Systematic uncertainties

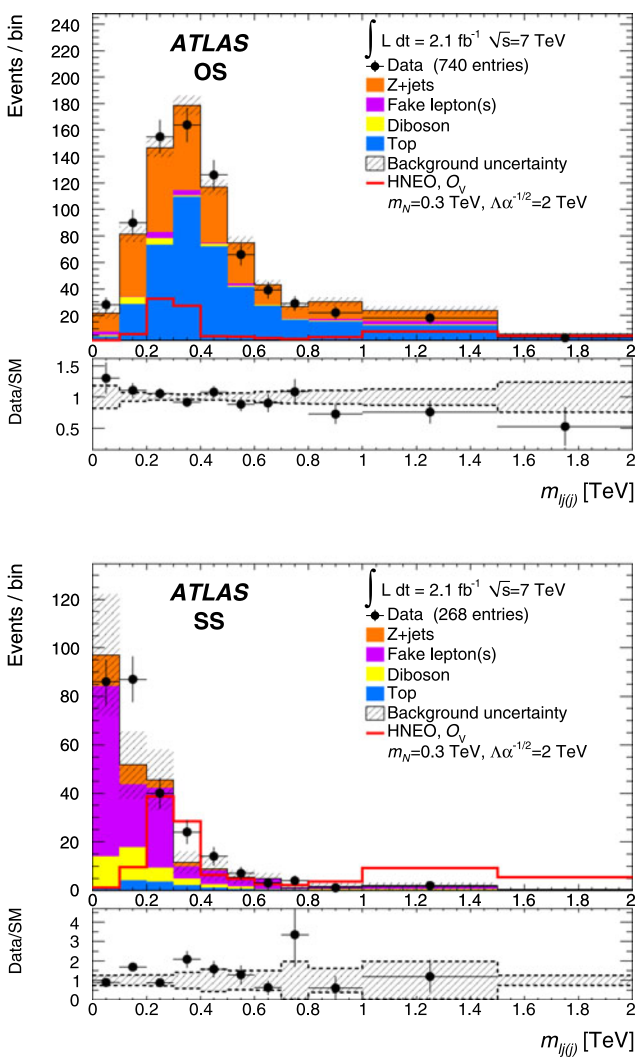

Fig. 1 Distributions of the reconstructed N invariant mass, $m_{\ell j(j)}$, for OS (*top*) and SS (*bottom*) dilepton events with ≥ 1 jets and $m_{\ell\ell} > 110$ GeV. A selection criterion $S_T \geq 400$ GeV is used for the OS selection. The hypothetical signal distributions for $m_N = 0.3$ TeV for $\mathcal{O}_V$ and $\Lambda/\sqrt{\alpha} = 2$ TeV are superimposed

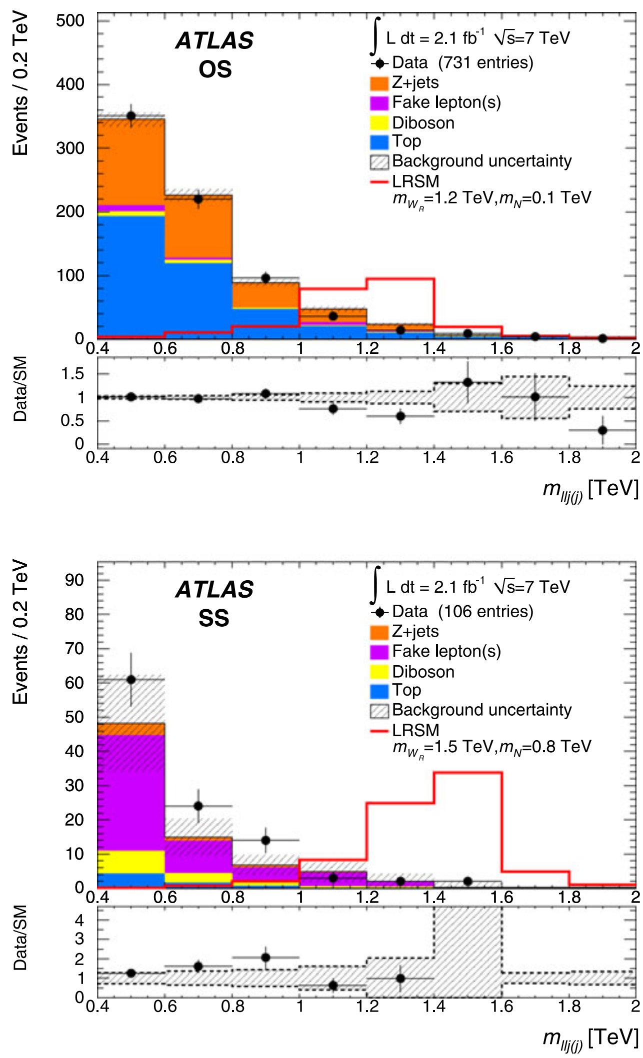

Fig. 2 Distributions of the reconstructed W_R invariant mass, $m_{\ell\ell j(j)}$, for OS (*top*) and SS (*bottom*) dilepton events with ≥ 1 jets, $m_{\ell\ell} > 110$ GeV, and $m_{\ell\ell j(j)} \geq 400$ GeV. A selection criterion $S_T \geq 400$ GeV is used for the OS selection. The hypothetical signal distributions for $m_{W_R} = 1.2$ TeV and $m_N = 0.1$ TeV ($m_{W_R} = 1.5$ TeV and $m_N = 0.8$ TeV) for the case of maximal mixing, are superimposed to the OS (SS) distribution

Table 3 Observed (obs) and expected (exp) 95 % C.L. upper limits on the visible cross section, $\langle\sigma\mathcal{A}\epsilon\rangle^{95}$, for each OS and SS dilepton channel after the baseline selection

Channels	$\langle\sigma\mathcal{A}\epsilon\rangle^{95}_{\text{obs}}$ [fb]	$\langle\sigma\mathcal{A}\epsilon\rangle^{95}_{\text{exp}}$ [fb]
$e^{\pm}e^{\mp}$	28.6	31.0
$\mu^{\pm}\mu^{\mp}$	25.1	36.7
$e^{\pm}\mu^{\mp}$	50.9	36.4
$e^{\pm}e^{\pm}$	37.6	29.6
$\mu^{\pm}\mu^{\pm}$	6.1	4.6
$e^{\pm}\mu^{\pm}$	25.4	16.2

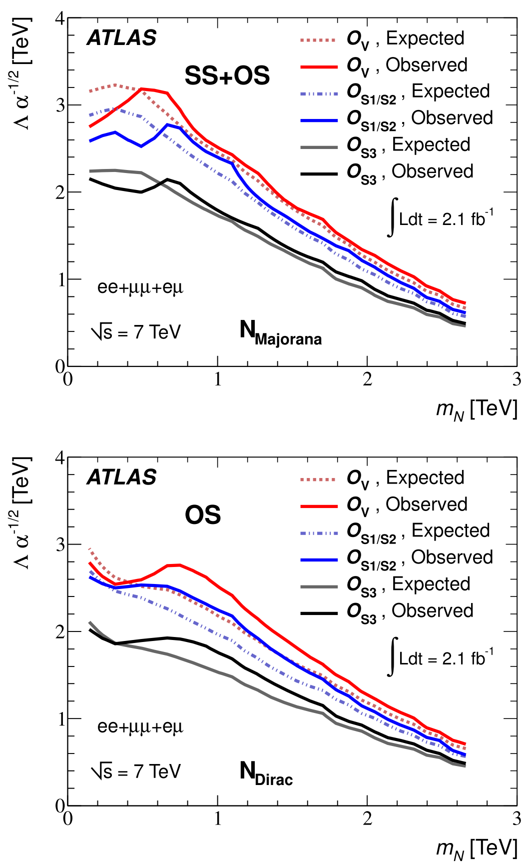

Fig. 3 Expected and observed 95 % C.L. upper limits on $\Lambda/\sqrt{\alpha}$ as a function of the mass of a heavy neutrino, for the operators $\mathcal{O}_V$, $\mathcal{O}_{s1}/\mathcal{O}_{s2}$, and $\mathcal{O}_{s3}$, using the formalism of Lagrangian of effective operators, for the Majorana (*top*) and Dirac (*bottom*) scenarios

from JES and JER are included as variations in the signal and background templates. The uncertainties on the measurement of R_{fake} and R_{prompt} are included as variations in the fake lepton background templates. All other uncertainties have no significant kinematic dependence. Correlations of uncertainties between signal and background, as well as across channels, are taken into account.

The 95 % C.L. exclusion limits on the mass of the heavy neutrino in the HNEO model and their dependence

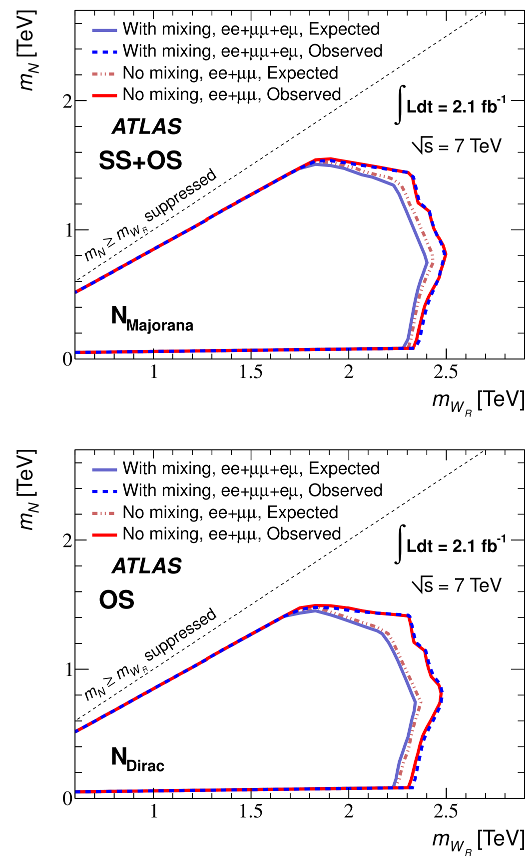

Fig. 4 Expected and observed 95 % C.L. upper limits on the heavy neutrino and W_R masses for the Majorana (*top*) and Dirac (*bottom*) cases, in the no-mixing and maximal-mixing scenarios

on $\Lambda/\sqrt{\alpha}$ are shown in Fig. 3 for the Majorana and Dirac scenarios using various effective operator hypotheses. Figure 4 shows the exclusion limits for the masses of heavy neutrinos and the W_R boson in the LRSM interpretation, for the no-mixing and maximal-mixing scenarios between N_e and N_μ neutrinos, for both the Majorana and Dirac heavy neutrinos hypotheses.

The above results are obtained with a Bayesian [58] approach, where systematic uncertainties are treated as nuisance parameters with a truncated Gaussian as a prior shape. The prior shape on the parameters of interest, $\sigma\times$ BR, is assumed to be flat.

9 Conclusions

A dedicated search for hypothetical heavy Majorana and Dirac neutrinos, and W_R bosons in final states with two high-p_T same-sign or opposite-sign leptons and hadronic jets has been presented. In a data sample corresponding to an integrated pp luminosity of 2.1 fb^{-1} at $\sqrt{s}=7$ TeV, no significant deviations from the SM expectations are observed, and 95 % C.L. limits are set on the contributions of new physics. Excluded mass regions for Majorana and Dirac neutrinos are presented for various operators of an effective Lagrangian framework and for the LRSM. The latter interpretation was used to extract a lower limit on the mass of the gauge boson W_R. For both no-mixing and maximal-mixing scenarios, W_R bosons with masses below ≈1.8 TeV (≈2.3 TeV) are excluded for mass differences between the W_R and N masses larger than 0.3 TeV (0.9 TeV). In the effective Lagrangian interpretation, considering the vector operator and Majorana-type heavy neutrinos, the lower limit on $\Lambda/\sqrt{\alpha}$ ranges from ≈2.5 TeV to ≈0.7 TeV for heavy neutrino masses ranging from 0.1 TeV to 2.7 TeV. Comparable limits are obtained for Dirac-type neutrinos in both models. The results described represent the most stringent limits to date on the masses of heavy neutrinos and W_R boson obtained in direct searches.

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