I. INTRODUCTION

Experiments show that neutrinos have much smaller masses than charged leptons (see Ref. [1] and references therein). While in the Standard Model (SM) the charged fermions acquire masses by coupling to the Higgs (H) boson, the neutrinos may become massive via new physics beyond the SM, e.g. via the introduction of Majorana mass terms [2]. These masses could be small due to the seesaw mechanism [3,4], which relies on new massive states that couple to a charged lepton and the Higgs field. Among different models for the seesaw mechanism, the type-III model [2,5] introduces at least two extra triplets of fermionic fields with zero hypercharge in the adjoint representation of SU(2)_L that generate neutrino masses and couple to gauge bosons. This model predicts new charged and neutral heavy leptons that could be produced in proton-proton collisions at the LHC.

A search by the CMS experiment [6] excluded the type-III seesaw heavy leptons with masses in the range of 100–210 GeV, depending on theoretical assumptions. A recent search by ATLAS [7] also sets complementary limits on heavy leptons using the three-lepton final state. Similar searches have also been done by the L3 experiment [8] ruling out charged heavy leptons with masses below 100 GeV.

In this paper, a search for heavy leptons predicted by the type-III seesaw mechanism is presented. The search explores the mass region above 100 GeV. A minimal type-III seesaw model [9] is used to optimize the analysis strategy and interpret the search results. The model introduces a triplet with one neutral and two oppositely charged leptons denoted by N^0 and L^±, respectively. The heavy leptons decay into a SM lepton and a W, Z, or Higgs boson. The heavy leptons are assumed to be degenerate in mass. This assumption does not affect the result because in the case of a small mass splitting due to radiative corrections, the decays within the heavy leptons are highly suppressed [10]. The dominant production mechanism for type-III seesaw heavy leptons in pp collisions is pair production through the weak coupling to the W boson propagator, \( pp \rightarrow W^* \rightarrow N^0 L^\pm \), and the largest branching fraction is the one with two W bosons in the final state, \( N^0 \rightarrow W^\pm f^\mp \) (\( f = e, \mu, \tau \)) and \( L^\pm \rightarrow W^\mp \nu \) (\( \nu = \nu_e, \nu_\mu, \nu_\tau \)). The production cross section does not depend on the mixing angles between the SM leptons and the new heavy lepton states \( V_{\alpha \beta} (\alpha = e, \mu, \tau) \), which enter only in the expressions for the L and N decay widths. The fraction of L and N decays to lepton flavor \( \alpha \) is proportional to \( b_\alpha = |V_{\alpha \beta}|^2 / (|V_{\alpha e}|^2 + |V_{\alpha \mu}|^2 + |V_{\alpha \tau}|^2) \). The limits obtained may be interpreted in terms of aken of mixing angles and Yukawa couplings [9], allowing tests of a range of models with different couplings to gauge bosons and cross section predictions [11,12]. In the type-III seesaw model considered here, a benchmark point is defined by setting \( V_{\nu e} \) to zero, so that \( b_e \) and \( b_\mu \) are determined only by the ratio \( V_{\nu e} / V_{\nu \mu} \), taken to be 0.87 based on the separately allowed maximum values of \( V_{\nu e} \) and \( V_{\nu \mu} \) in Refs. [13–15]. This choice results in values of \( b_e = 0.53 \), \( b_\mu = 0.43 \), and \( b_\tau = 0 \). The search is performed for the process \( pp \rightarrow N^0 L^\pm \rightarrow W^\pm \ell^\mp W^\pm \nu \), where one W boson decays leptonically and the other W boson decays hadronically, resulting in a lepton pair in the final state with either the same charge [same sign (SS)] or with the opposite charge [opposite sign (OS)].

II. DATA SAMPLE AND MONTE CARLO SIMULATION

The analysis uses data from \( \sqrt{s} = 8 \) TeV pp collisions at the LHC that were recorded by the ATLAS detector...
using single-electron and single-muon triggers. A detailed description of the ATLAS detector can be found elsewhere [16]. The data sample corresponds to 20.3 ± 0.6 fb−1 [17] of integrated luminosity. Data quality criteria are applied to ensure that events were recorded with stable beam conditions and with all relevant subdetector systems operational. The triggers [18] are fully efficient for leptons with $p_T > 25$ GeV, where transverse momentum $p_T$ is defined as the magnitude of the momentum component orthogonal to the beam axis. Events are required to have a reconstructed collision vertex with at least three associated tracks, each with $p_T > 400$ MeV. In events with multiple vertices, the vertex with the largest $\sum p_T^2$ of associated tracks is taken as the primary event vertex.

Monte Carlo (MC) samples are used to optimize the event selection and to model the kinematics and normalization of most background processes. Signal samples are generated for heavy lepton masses in the range 100–600 GeV. MadGraph 5 [19] is used to calculate the matrix elements for each process, while MadEvent [20] with the MSTW2008 parton distribution functions (PDFs) set [21] simulates the initial hard scattering and the $N$ and $L$ decay. Pythia 8.153 [22] is used to simulate the decays of $W$ bosons and the underlying physics by providing parton showers and hadronization, as well as adding initial- and final-state radiation (ISR and FSR) to the events simulated in MadEvent. The main background sources arise from the production of a $Z$ boson in association with jets ($Z +$ jets), single and pair production of top quarks, and diboson production ($WW$, $WZ$, $ZZ$). The $Z$+jets and diboson processes are simulated with Sherpa 1.4.1 [23], a generator based on a multileg matrix element calculation matched to the parton shower using the Catani-Krauss-Kuhn-Webber (CKKW) prescription [24], and using the CTEQ6L1 PDF set. For diboson production, both the electroweak and strong production processes are simulated [26]. Top-quark pair events and single-top-quark events in the $W$-channel and $s$-channel are simulated using MC@NLO 4.03 [27], which is interfaced to Herwig 6.520 [28] and Jimmy 4.31 [29] with the CT10 PDF set. Top pair production in association with a vector boson, $t\bar{t} + W/Z$, is simulated using MadGraph with the CTEQ6L1 PDF set [30], interfaced to Pythia 8.153 for parton showering and hadronization. Single-top-quark production in the $t$-channel is simulated using AcerMC v3.8 [31] with Pythia 6.426 [32] and the CTEQ6L1 PDF set.

All samples of simulated events include the effect of multiple $pp$ interactions in the same and neighboring bunch crossings (pileup) by overlaying simulated minimum-bias events on each generated signal and background event. The number of overlaid events is chosen to match the average number of interactions per $pp$ bunch crossing observed in the data as it evolved throughout the data-taking period (giving an average of 21 interactions per crossing for the whole data-taking period). The generated samples are processed through the Geant4-based detector simulation [33,34] or a fast simulation using a parameterization of the performance of the calorimeter and Geant4 for the other parts of the detector [35]. The standard ATLAS reconstruction software is used for both simulated and collision data.

III. OBJECT DEFINITIONS

The reconstructed objects used in this analysis are electrons, muons, jets, and missing transverse momentum. Electrons are reconstructed from clusters of energy depositions in the calorimeter that match a track reconstructed in the inner detector (ID) and satisfy the “tight” criteria defined in Ref. [36]. The electrons are required to have $p_T > 25$ GeV and pseudorapidity $|\eta| < 2.47$ [37], excluding the transition region between the barrel and end caps in the liquid argon calorimeter ($1.37 < |\eta| < 1.52$). Muons are reconstructed by combining ID and muon spectrometer tracks that are spatially matched and have consistent curvatures. The muon tracks are required to have $p_T > 25$ GeV and $|\eta| < 2.5$. In addition, leptons are required to be isolated from other tracks and calorimetric activity [38]. To ensure that leptons originate from the interaction point, requirements of $|d_0|/\sigma_d < 3$ and $|z_0\sin\theta| < 0.5$ mm are imposed on the electrons and muons, where $d_0$ ($z_0$) is the transverse (longitudinal) impact parameter of the lepton and $\sigma_d$ is the uncertainty on the measured $d_0$. The lepton impact parameters are measured with respect to the event primary vertex.

Jets are reconstructed from three-dimensional topological clusters of energy depositions in the calorimeter using the anti-$k_t$ algorithm [39] with a radius parameter of $R = 0.4$. The energies of jets are calibrated to the hadronic energy scale by correcting for energy losses in passive material, the noncompensating response of the calorimeter, and extra energy due to multiple $pp$ interactions [40]. The jets are required to have $p_T > 30$ GeV and $|\eta| < 2.8$. For jets with $p_T < 50$ GeV and $|\eta| < 2.4$, the summed scalar $p_T$ of associated tracks from the reconstructed primary vertex is required to be at least 25% of the summed scalar $p_T$ of all tracks associated with the jet. In the pseudorapidity range $|\eta| < 2.5$, jets containing $b$-hadrons are identified using a $b$-tagging algorithm [41] with an efficiency of 70% and with a misidentification rate for selecting light-quark or gluon jets of less than 1%. The identification efficiency of the algorithm for jets containing $c$-hadrons is 20%. The efficiencies and misidentification rates are determined from $t\bar{t}$ MC events.

The missing transverse momentum vector (with its magnitude $E_T^{\text{miss}}$) is derived using the calorimeter cell energies within $|\eta| < 4.9$ and corrected on the basis of dedicated calibrations of the associated physics objects including muons [42]. Calorimeter cells containing energy depositions above noise and not associated with high-$p_T$ physics objects are also included.
IV. EVENT SELECTION

Events that contain exactly two reconstructed leptons (electrons or muons), at least two jets, and no $b$-tagged jets are selected. One of these leptons is required to match the object upon which the event was triggered. Different sets of optimized selection criteria are used for the events in the OS and SS final states. The optimization is done using simulated heavy lepton pair-production events at a benchmark mass of 300 GeV. For the OS (SS) final state, the leading and next-to-leading lepton candidates are required to have $p_T$ greater than 100 (70) GeV and 25 (40) GeV, respectively. The invariant mass of the two lepton candidates is required to be larger than 130 (90) GeV in order to suppress background from the production of $Z + \text{jets}$. The hadronically decaying $W$ candidate is formed by combining the two jets with highest $p_T$, and the $p_T$ of the first and second leading jets are, respectively, required to be larger than 60 (40) and 30 (25) GeV, for the OS (SS) final state. The invariant mass of the $W$ candidate, $m_{jj}$, is required to be between 60 and 100 GeV. Events selected in the OS (SS) final state are required to have a $E_T^{\text{miss}}$ of at least 110 (100) GeV and, for OS events, an angular separation $\Delta R_{jj} = \sqrt{\Delta\eta^2 + (\Delta\phi)^2} < 2$ between the two jets with highest $p_T$, where $\Delta\eta$ and $\Delta\phi$ are defined as the differences in pseudorapidity and azimuthal angle between the jets.

V. BACKGROUND ESTIMATE

The background in this search can be classified into two categories based on the origin of the charged lepton candidates. The first category of backgrounds consists of events in which two leptons are produced via the decays of $W$ or $Z$ bosons and are correctly reconstructed. This category of backgrounds includes the production of $Z + \text{jets}$, $t\bar{t}$, $Wt$ single-top-quark and diboson events. Smaller contributions originate from $t\bar{t} + W/Z$ events. Contributions from triboson events, such as $WWW$ and events containing a Higgs boson, are negligible. The number of events from this background category is estimated using the simulated samples described previously.

The second category corresponds to all other sources, such as events containing at least one particle that is incorrectly identified as a lepton, or a lepton which originates from secondary interactions and decays, which are together denoted as "fakes," and events with a lepton whose charge is incorrectly determined. Fake electrons originate primarily from jets that have a large electromagnetic energy fraction passing the electron selection requirements, photon conversions, and electrons from semileptonic decays of charm or bottom hadrons. Fake muons include muons arising from semileptonic decays of charm or bottom hadrons, in-flight decays of pions or kaons, or energetic particles that reach the muon spectrometer.

For the OS final state, the background contribution is dominated by events of the first category. For the SS final state, the expected background is very small and is also primarily from the first category. Events from $Z + \text{jets}$ production can mimic the SS signal if the charge of one of the electrons is incorrectly determined. The background events from this contribution are modeled by simulation, with correction factors derived using $Z \rightarrow ee$ events in data. The probability of misidentifying the muon charge is negligible.

The background contribution in the second category (i.e. fake leptons) is estimated using an in situ technique [38] that relies minimally on simulation. This is done by reweighting a complementary set of events, selected by changing the electron identification criterion from tight to "loose" [43] and by loosening the muon $|d_0|/\sigma_{d_0}$ and the electron and muon isolation requirements, while keeping the event selection otherwise identical. The reweighting factors are defined as the ratio of the number of events containing a lepton that satisfies the nominal criteria to the number of events containing a lepton that only fulfills the relaxed criteria.
uncertainties of the measured scale factors in the control samples. They are the dominant systematic uncertainties (∼35%) on the background estimates. For top-quark production, an additional systematic uncertainty is considered to account for a potential difference between scale factors in the control region and the signal region. This is done by comparing the nominal \( t\bar{t} \) sample to alternative \( t\bar{t} \) MC samples. These samples include events that are generated using POWHEG-BOX 1.0 (patch 4) [44–46] and the leading-order, multileg generator ALPGEN v2.13 [47]. The POWHEG-BOX generator is interfaced to the PYTHIA 6.426 showering routines with either CT10 or HERAPDF [48] PDF sets and with the POWHEG \( R_{\text{damp}} \) parameter set to either the mass of the top quark or infinity [49]. ALPGEN is interfaced to HERWIG 6.520 and used to simulate top pair events with up to four additional partons in the matrix element. The uncertainties due to QCD ISR and FSR modeling are estimated with samples generated with ACERMC v3.8 interfaced to PYTHIA 6.426 in which the parton shower parameters are varied in a range consistent with a measurement of additional hadronic activity in \( t\bar{t} \) events [50]. The differences observed in the signal region by using different MC simulations are about 35%.

For the \( Z + n \)-jets (\( n \geq 2 \)) background estimate, the dominant systematic uncertainty in the OS final state is from the uncertainty on its production cross section (∼50%) [51]. For the SS final state, the systematic uncertainty is dominated by the statistical uncertainty on the measured electron charge misidentification rate.

Uncertainties on the background estimate due to fake leptons are determined in dedicated studies using a combination of simulation and data. They account for potential biases in the method used to extract the reweighting factors and for the dependency of the reweighting factors on the event topology.

For both the predicted signal and background event yields, uncertainties resulting from detector effects from jet energy scale and resolution [40], lepton reconstruction and identification efficiencies [36,52], lepton momentum scales and resolutions [52,53], and missing transverse momentum [42] are considered. They are typically small (1%–5%). The theoretical uncertainties on the signal production cross section and acceptance, such as PDF choice and ISR and FSR modeling, are found to be negligible.

The background estimates and their uncertainties are tested in two other regions: a \( Z + \) jets control region and a \( Z + n \)-jets (\( n \geq 2 \)) control region. The differences observed in the signal region by using different MC simulations are about 35%.

The differences observed in the signal region by using different MC simulations are about 35%.
要求的中微子质量为35 < \mu_j < 60 \text{ GeV} 或 100 < \mu_j < 125 \text{ GeV}。这个选择提供了样本，其中背景事件由具有相似 kinematic properties 的信号事件主导。在这个区域，预测的数量为 34 ± 7 事件，其中错误包括两个统计学和系统不确定性的贡献，以及在数据中观察到的 18 事件。这些数据与预测在 1.9 标准偏差内一致。

VII. RESULTS AND INTERPRETATION

表 I 列出了预测的数量和背景事件以及在信号区域的数据。数据与假设背景的假设一致。图 2 显示了模拟信号和背景事件以及在数据中观察到的事件。在任何显著的数据缺失的区域，上部极限在生产率为 \( p p \rightarrow N^0 L^\pm \rightarrow W^\pm \ell^\mp W^\pm \nu_l \) 的 95% 的置信水平下，这些上部极限是通过使用 CLs 方法计算的 [54]。结果计算的限制考虑了在 OS 和 SS 终态中的观察，如图 3 和图 4 所示。将其他假设考虑进来，重正则的事件质量不超过 335 GeV 被排除在分析之外，而质量不超过 475 GeV 也在其中。在所有可能的假设中，如在 OS 和 SS 终态中观察到的事件，对于比较，上部极限也用于计算，适用于不同的假设。此外，除信息可能对两个主导的事件质量的假设外，重正则的质量不超过 475 GeV 也在其中。

图 3（左）显示了在重正则的重正派中的重正化质量为 0 的预测的 95% 的上部极限。在重正派的质量为 0 的领域，命中的数个事件和数据事件在信号区域。数据与预期的信号一致，图 5 显示了预测的信号和背景事件。在数据中观察到的事件，其中错误包括两个统计学和系统不确定性的贡献，以及在数据中观察到的 18 事件。这些数据与预测在 1.9 标准偏差内一致。

图 4（右）显示了在重正化质量为 0 的重正派中的重正化质量为 0 的预测的 95% 的上部极限。在重正派的质量为 0 的领域，命中的数个事件和数据事件在信号区域。数据与预期的信号一致，图 5 显示了预测的信号和背景事件。在数据中观察到的事件，其中错误包括两个统计学和系统不确定性的贡献，以及在数据中观察到的 18 事件。这些数据与预测在 1.9 标准偏差内一致。
are excluded for exclusive electron (muon) coupling. Heavy leptons with a mass below $400\ (325)\ \text{GeV}$ can be ruled out by the data in the case of exclusive coupling to muons (electrons). Masses less than $540\ (470)\ \text{GeV}$ are excluded in the scenario in which heavy leptons can only decay to the $W\ell$ or $W\nu$ final state.

**VIII. CONCLUSIONS**

A search for the pair production of heavy leptons predicted by the type-III seesaw model is presented. The analysis is performed using a final state that contains two leptons, two jets from a hadronically decaying $W$ boson, and a large missing transverse momentum. The data used in the search correspond to an integrated luminosity of $20.3\ \text{fb}^{-1}$ of $pp$ collisions at $\sqrt{s} = 8\ \text{TeV}$ collected by the ATLAS detector at the LHC. No evidence of heavy lepton production is observed. Heavy leptons with masses below $325\sim 540\ \text{GeV}$ are excluded at the 95% confidence level, depending on the considered theoretical scenarios.

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[26] Production mechanisms involving weak interactions at the Born level (order $\alpha^2_{EW}$ without considering the boson decay, where $\alpha_{EW}$ is the electroweak coupling constant) are referred to as electroweak production [55]. Production mechanisms involving both the strong and electroweak interactions at Born level (order $\alpha^2\alpha^2_{EW}$, where $\alpha_s$ is the strong coupling constant) are referred to as strong production.
[37] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the $z$ axis along the beam pipe. The $x$ axis points from the IP to the center of the LHC ring, and the $y$ axis points upward. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, where $\phi$ is the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln\tan(\theta/2)$.


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