Search for a heavy particle decaying into an electron and a muon with the ATLAS detector in $\sqrt{s} = 7$ TeV $pp$ collisions at the LHC

The ATLAS Collaboration
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This Letter presents the first search for a heavy particle decaying into an $e^\pm \mu^\mp$ final state in $\sqrt{s} = 7$ TeV $pp$ collisions at the LHC. The data were recorded by the ATLAS detector during 2010 and correspond to a total integrated luminosity of 35 pb$^{-1}$. No excess above the Standard Model background expectation is observed. Exclusions at 95% confidence level are placed on two representative models. In an $R$-parity violating supersymmetric model, tau sneutrinos with a mass below 0.75 TeV are excluded, assuming single coupling dominance and the couplings $\lambda_{312} = 0.11$, $\lambda_{311} = 0.07$. In a lepton flavor violating model, a $Z'$-like vector boson with masses of 0.70 to 1.00 TeV and corresponding cross sections times branching ratios of 0.175 to 0.183 pb is excluded. These results extend to higher mass RPV sneutrinos and LFV $Z'$s than previous constraints from the Tevatron.

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Events with $e^\pm \mu^\mp$ ($e\mu$) in the final state, which played an important role in the discoveries of the tau lepton and the top quark, have a clean experimental signature and low background. Many new physics models allow an $e\mu$ signature. For example, in $R$-parity violating (RPV) Supersymmetric (SUSY) models [1] a sneutrino can decay to $e\mu$. Models with additional gauge symmetry can accommodate an $e\mu$ signature through lepton flavor violating (LFV) decays of an extra gauge boson $Z'$ [2]. Standard Model (SM) processes that can produce an $e\mu$ signature typically have small cross sections and the Standard Model background expectation is observed. Exclusions at 95% confidence level are placed on two representative models. In an $R$-parity violating supersymmetric model, tau sneutrinos with a mass below 0.75 TeV are excluded, assuming single coupling dominance and the couplings $\lambda_{312} = 0.11$, $\lambda_{311} = 0.07$. In a lepton flavor violating model, a $Z'$-like vector boson with masses of 0.70 to 1.00 TeV and corresponding cross sections times branching ratios of 0.175 to 0.183 pb is excluded. These results extend to higher mass RPV sneutrinos and LFV $Z'$s than previous constraints from the Tevatron.

The ATLAS detector [8] is a multipurpose particle physics apparatus with a forward-backward symmetric cylindrical geometry and near $4\pi$ coverage in solid angle [9]. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field, and by a finely-segmented, hermetic calorimeter. The latter covers $|\eta| < 4.9$ and provides three-dimensional reconstruction of particle showers using lead-liquid argon sampling for the electromagnetic (EM) compartment followed by a hadronic compartment which is based on iron-scintillating tiles sampling in the central region and on liquid argon sampling with copper or tungsten absorbers for $|\eta| > 1.7$. The muon spectrometer (MS) surrounds the calorimeters and consists of three large superconducting toroids, a system of precision tracking chambers, and detectors for triggering.

The data used in this analysis were recorded in 2010 at a center-of-mass energy $\sqrt{s} = 7$ TeV. Application of data-quality requirements results in a total integrated luminosity of 35 pb$^{-1}$ with an estimated uncertainty of 11% [10]. Events are required to satisfy one of the single lepton ($e$ or $\mu$) triggers, which have nominal transverse momentum, $p_T$, thresholds up to 15 GeV for $e$ and 13 GeV for $\mu$. The trigger efficiency is measured to be 100\%, with a precision of 1\%, for $e\mu$ candidates containing two leptons with transverse momentum $p_T > 20$ GeV.

To select $e\mu$ events, the electron candidate is required to have $p_T > 20$ GeV and to lie inside the pseudorapidity regions $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$. The event is rejected if the candidate cluster is located in a problematic region of the EM calorimeter. Electron identification and isolation requirements provide rejection against hadrons. A set of electron identification criteria based on the calorimeter shower shape, track quality and track matching with the calorimeter cluster, referred to as ‘medium’ in Ref. [11], is applied. In addition, a calorimeter isolation criterion $E_T^{R<0.2}/E_T < 0.1$ is applied, where $E_T^{R<0.2}$ is defined as the transverse energy deposited in the calorimeter within a cone of radius $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.2$ around the electron cluster, and $E_T$ is the transverse energy of the electron.

The muon candidate must be reconstructed in both the ID and the MS. A good match of the parameters of the ID and MS tracks is required, and the $p_T$ values measured by these two systems must be compatible. Furthermore, the muon candidate must have $p_T > 20$ GeV, $|\eta| < 2.4$, and be isolated in the ID with $\Delta p_T^{R<0.2}/p_T < 0.1$, where $\Delta p_T^{R<0.2}$ is defined as the sum of the $p_T$ of tracks with $p_T > 1$ GeV within a cone of radius $\Delta R < 0.2$ around the muon track.

Jets are reconstructed using the anti-$k_t$ jet clustering algorithm [12] with a radius parameter of 0.4. Only jets with $p_T > 20$ GeV and $|\eta| < 2.5$ are considered. If such a
jet and an electron lie within $\Delta R = 0.2$ of each other, the jet is discarded. Leptons are only considered if they are separated from all of the remaining jets by $\Delta R > 0.4$. Electrons and muons are also required to be separated from each other by $\Delta R > 0.2$.

The $e\mu$ candidate events are required to have exactly one electron and one muon with opposite charge satisfying the above selection criteria. Furthermore, events have to contain at least one primary vertex reconstructed with more than four associated tracks with $p_T > 150 \text{ MeV}$.

The SM processes that can produce an $e\mu$ signature are predominantly $t\bar{t}$, $Z/\gamma^* \rightarrow \tau\tau$, $W/Z + \text{jets}$, diboson, single top and QCD multijet events. Among the final state and amount to $80\%$ of the expected $e\mu$ data yield. The contributions from these processes are estimated using Monte Carlo (MC) samples generated at $\sqrt{s} = 7 \text{ TeV}$ and processed with the standard chain of the ATLAS GEANT4 simulation and reconstruction using the ATLAS MC09 parameter tune. The event generators used are PYTHIA 6.421, POWHEG 1.0 (invariant mass $\sim 7 \text{ TeV}$ and processed with the standard chain of the ATLAS GEANT4 simulation and reconstruction using the ATLAS MC09 parameter tune). The event generators used are PYTHIA 6.421, POWHEG 1.0 (invariant mass $\sim 7 \text{ TeV}$ and processed with the standard chain of the ATLAS GEANT4 simulation and reconstruction using the ATLAS MC09 parameter tune).

Studies of $Z/\gamma^* \rightarrow \ell\ell$ ($\ell = e, \mu$) events have shown that the lepton reconstruction and identification efficiencies, energy scale and resolution need to be adjusted in the MC to properly describe the data. The appropriate corrections are applied to the MC in order to improve the modeling of the backgrounds.

The processes $W/Z + \gamma$, $W/Z + \text{jets}$ and pure QCD jet production give rise to background in addition to prompt leptons, which come from $W$ and $Z$ decay. Jets misidentified as leptons, electrons from photon conversions, and leptons from hadron decays (including $b$- and $c$-hadron decays) are classified as instrumental background. The instrumental background accounts for $\sim 20\%$ of the expected $e\mu$ data yield. The dominant component of the instrumental background comes from events with one prompt lepton and one jet identified as a lepton, with an additional contribution from events with two misidentified jets. These sources are referred to as jet instrumental background, and are estimated using data. The background component initiated by prompt photons, referred to as the photon instrumental background, is estimated from MC.

The jet instrumental background is estimated using data in the following way. Two selections are defined, both requiring at least one lepton satisfying all lepton criteria. The selections are defined by the second lepton candidate: the “tight” selection requires the second candidate to pass all lepton criteria, while the “loose” selection does not enforce the lepton isolation requirement. The probability for a lepton to satisfy the lepton isolation requirement is estimated by applying the loose and tight selections on $Z/\gamma^* \rightarrow \ell\ell$ events. The probability for a jet to satisfy the lepton isolation requirement is estimated by applying the loose and tight selections on a sample of QCD dijet events to which a cut on the missing transverse energy $E_T^{\text{miss}} < 15 \text{ GeV}$ is applied to remove $W + \text{jets}$ events. These two probabilities, along with numbers of events selected in the loose and tight samples, are used to estimate the background in the final selected sample. The background is estimated to be $12_{-5}^{+6}$ events for candidates with one electron and one jet satisfying the muon selection criteria, and $19_{-28}^{+28}$ events for candidates with one muon and one jet satisfying the electron selection criteria. The dominant uncertainty on the jet instrumental background estimation comes from the $p_T$ dependence of the probability for a jet to pass the lepton isolation criterion. The background due to two jets satisfying the lepton requirements is estimated to be $1.3_{-1.3}^{+5}$ events from same-sign dilepton events in data with the subtraction of contributions estimated from MC for all physics processes except the QCD multijet. The overall jet instrumental background is found to be $29_{-10}^{+30}$ events. This background level has been checked in simulated samples, which agree with the data driven estimates.

The dominant photon instrumental background comes from the $W(\rightarrow \nu\ell\gamma)$ and $Z(\rightarrow \mu\mu\gamma)$ processes where the photon is reconstructed as an electron. A photon can be reconstructed as an electron if it lies close to a charged particle track or the photon converts to $e^+e^-$ after interacting with the material in front of the calorimeter. The photon instrumental background is found to be $4.0 \pm 0.7$ events.

Table I shows the number of events selected in data and the estimated background contributions with their uncertainties. A total of 160 $e\mu$ candidates are observed in data while the expectation from SM processes is $163_{-18}^{+34}$ events. The dominant sources of systematic uncertainty for the SM prediction arise from the uncertainty on the probability for a jet to satisfy the lepton isolation requirement ($70\%$ for electron, $30\%$ for muon), theoretical cross sections on the physics background processes ($5\% - 15\%$), and the integrated luminosity ($11\%$). Other systematic uncertainties from the lepton trigger, reconstruction and identification efficiencies, energy/momentum scale and resolution have been included and are small.

Since no excess is observed in data, limits are set for the production of $\tilde{\nu}_\tau$ in RPV SUSY models and an LFV $Z'$-like vector boson.

The RPV production of $\tilde{\nu}_\tau$ by $d\bar{d}$ annihilation decay-
ing into $e\mu$ is considered. With the assumption of single coupling dominance [24], fixing all RPV couplings but $\lambda'_{311}$ ($\tilde{\nu}_\tau$ to $d\bar{d}$) and $\lambda'_{312}$ ($\tilde{\nu}_\tau$ to $e\mu$) to zero, and that $\tilde{\nu}_\tau$ is the lightest supersymmetric particle, the contributions to the $e\mu$ final state originate from the $\tilde{\nu}_\tau$ only. The signal cross section depends on the $\tilde{\nu}_\tau$ mass ($m_{\tilde{\nu}_\tau}$), $\lambda'_{311}$ and $\lambda'_{312}$. The third-generation $\tilde{\nu}_\tau$ is considered since stringent limits exist on the electron sneutrino and muon sneutrino [1]. The couplings $\lambda'_{311} = 0.11$ and $\lambda'_{312} = 0.07$, compatible with the current indirect limits [1], are chosen as a benchmark point.

An $e\mu$ resonance can be generated in models containing a heavy neutral gauge boson with non-diagonal lepton flavour couplings, $Z'$ [25]. Very stringent limits on the combination of the mass and the coupling to $ee$ and $e\mu$ of such models have been inferred from searches for rare muon decay [2]. Using the data presented in this Letter, a limit on the production cross section times branching ratio to $e\mu$ can be placed on a $Z'$-like vector boson. To calculate the acceptance and efficiency, the $Z'$ is assumed to have the same quark and lepton couplings as the SM $Z$

MC events with $\tilde{\nu}_\tau$ or $Z'$ decaying into $e\mu$ are generated with HERWIG [20, 26] or PYTHIA, respectively. Samples are produced with sneutrino masses ranging from 0.1 to 1 TeV, and $Z'$ masses from 0.7 to 1 TeV.

The $e\mu$ invariant mass distribution is presented in Fig. 1 for data, background contributions and two possible new physics signals: a $\tilde{\nu}_\tau$ with $m_{\tilde{\nu}_\tau} = 650$ GeV and a $Z'$ with $m_{Z'} = 700$ GeV. The cross section is 0.31 pb for $m_{\tilde{\nu}_\tau} = 650$ GeV [27] and 0.61 pb for $m_{Z'} = 700$ GeV [28]. The corresponding overall acceptance times efficiency is 55% for $\tilde{\nu}_\tau$ and 50% for $Z'$.

The $m_{e\mu}$ spectrum is examined for the presence of a new heavy particle. For $m_{\tilde{\nu}_\tau} < 500$ GeV, the search region for specific $m_{\tilde{\nu}_\tau}$ is defined to be $(m_{\tilde{\nu}_\tau} - 3\sigma, m_{\tilde{\nu}_\tau} + 3\sigma)$, where $\sigma$ is the expected $m_{e\mu}$ resolution (e.g., $\sigma \approx 15$ GeV for $m_{\tilde{\nu}_\tau} = 400$ GeV). For higher $m_{\tilde{\nu}_\tau}$, the region $m_{e\mu} > 400$ GeV is used. The expected and observed 95% C.L. upper limits on $\sigma(pp \rightarrow \tilde{\nu}_\tau) \times \text{BR}(\tilde{\nu}_\tau \rightarrow e\mu)$ are calculated using a Bayesian method [29] with flat prior for signal cross section as a function of $m_{\tilde{\nu}_\tau}$. Fig. 2 shows the expected and observed limits, as a function of $m_{\tilde{\nu}_\tau}$, together with the ±1 and ±2 standard deviation uncertainty bands. The expected exclusion limits are determined using simulated pseudo-experiments containing only SM processes by evaluating the 95% C.L. upper limits for each pseudo-experiment at each value of $m_{\tilde{\nu}_\tau}$. The median of the distribution of limits is shown as the expected limit. The ensemble of limits is also used to find the 1σ and 2σ envelope of the expected limits as a function of $m_{\tilde{\nu}_\tau}$. For a sneutrino with mass of 100 GeV (1 TeV), the limit on the cross section times branching ratio is $0.951 (0.057)$ pb. The theoretical cross sections for $\lambda'_{311} = 0.11$, $\lambda'_{312} = 0.07$ and $\lambda'_{311} = 0.10$, $\lambda'_{312} = 0.05$ are also shown. Sneutrinos with masses below 0.75 (0.65) TeV are excluded using $\lambda'_{311} = 0.11$ and $\lambda'_{312} = 0.07$ ($\lambda'_{311} = 0.10$ and $\lambda'_{312} = 0.05$). The results improve on the previous CDF 95% C.L. limit of 0.56 TeV assuming $\lambda'_{311} = 0.10$ and $\lambda'_{312} = 0.05$. The 95% C.L. observed upper limits on $\lambda'_{311}$ as a function of $m_{\tilde{\nu}_\tau}$ are shown in Fig. 2 for three values of $\lambda'_{312}$, together with the exclusion region obtained from the D0 experiment [7]. The limits derived here extend to higher mass regions.

A similar method is used to set limits on the LFV $Z'$-like vector boson, using only events with $m_{e\mu} > 400$ GeV. Finding no events in the data, the 95% C.L. upper limits on $\sigma(pp \rightarrow Z') \times \text{BR}(Z' \rightarrow e\mu)$ are set, as shown in Fig. 3. The expected limit is the same as the observed limit because the median background event count expectation is also zero. For a $Z'$ with mass of 700 GeV (1 TeV), the limit on the cross section times branching ratio is 0.175 (0.183) pb. This result improves upon previous CDF limits by probing a higher mass range of $Z'$-like vector particles.

**TABLE I:** Estimated backgrounds in the selected sample, together with the observed event yield.

<table>
<thead>
<tr>
<th>Process</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z/\gamma^* \rightarrow \tau\tau$</td>
<td>54 ± 7</td>
</tr>
<tr>
<td>$tt$</td>
<td>57 ± 9</td>
</tr>
<tr>
<td>WW</td>
<td>13.4 ± 1.7</td>
</tr>
<tr>
<td>Single top</td>
<td>4.6 ± 0.9</td>
</tr>
<tr>
<td>WZ</td>
<td>0.79 ± 0.11</td>
</tr>
<tr>
<td>Instrumental background</td>
<td>33 ± 30</td>
</tr>
<tr>
<td>Total background</td>
<td>163 ± 18</td>
</tr>
<tr>
<td>Data</td>
<td>160</td>
</tr>
</tbody>
</table>

**FIG. 1:** Observed and predicted $e\mu$ invariant mass distributions. Signal simulations are shown for $m_{\tilde{\nu}_\tau} = 650$ GeV ($\lambda'_{311} = 0.11$, $\lambda'_{312} = 0.07$) and $m_{Z'} = 700$ GeV. The ratio plot at the bottom includes only statistical uncertainties.
In conclusion, a search has been performed for a heavy particle decaying into the $e^±\mu^±$ final state using $pp$ collision data at $\sqrt{s} = 7$ TeV recorded by the ATLAS detector. The data are found to be consistent with the SM prediction. Exclusions are placed on two representative models at 95% C.L. In an RPV SUSY model, tau sneutrinos with a mass below 0.75 TeV are excluded, assuming single coupling dominance and coupling values $\lambda_{311} = 0.11, \lambda_{312} = 0.07$. Higher values of the RPV coupling are also excluded as a function of $m_\nu$. In an LFV model, extra $Z'$-like gauge bosons are excluded with a cross section times branching ratio above 0.183 pb, assuming $m_{Z'} = 1$ TeV. These results extend to higher mass RPV sneutrinos and LFV $Z$'s than previous constraints from the Tevatron.

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9. ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre 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 η = − ln tan(θ/2).

Institute of Physics, Academia Sinica, Taipei, Taiwan
Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel
Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Department of Physics, University of Toronto, Toronto ON, Canada
Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan
Science and Technology Center, Tufts University, Medford MA, United States of America
Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
INFN Gruppo Collegato di Udine; ICTP, Trieste; Dipartimento di Fisica, Università di Udine, Udine, Italy
Department of Physics, University of Illinois, Urbana IL, United States of America
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
Department of Physics, University of British Columbia, Vancouver BC, Canada
Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
Waseda University, Tokyo, Japan
Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison WI, United States of America
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Department of Physics, Yale University, New Haven CT, United States of America
Yerevan Physics Institute, Yerevan, Armenia
Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France
Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal
Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Also at TRIUMF, Vancouver BC, Canada
Also at Department of Physics, California State University, Fresno CA, United States of America
Also at Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
Also at Department of Physics, University of Coimbra, Coimbra, Portugal
Also at Università di Napoli Parthenope, Napoli, Italy
Also at Institute of Particle Physics (IPP), Canada
Also at Louisiana Tech University, Ruston LA, United States of America
Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada
Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
Also at Manhattan College, New York NY, United States of America
Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
Also at High Energy Physics Group, Shandong University, Shandong, China
Also at California Institute of Technology, Pasadena CA, United States of America
Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
Also at Section de Physique, Université de Genève, Geneva, Switzerland
Also at Departamento de Física, Universidade de Minho, Braga, Portugal
Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
x Also at Institute of Physics, Jagiellonian University, Krakow, Poland
y Also at Department of Physics, Oxford University, Oxford, United Kingdom
z Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France
aa Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
ab Also at Department of Physics, Nanjing University, Jiangsu, China
* Deceased