Search for a heavy neutral particle decaying into an electron and a muon using 1 fb$^{-1}$ of ATLAS data

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Abstract A search is presented for a high mass neutral particle that decays directly to the $e^\pm \mu^\mp$ final state. The data sample was recorded by the ATLAS detector in $\sqrt{s} = 7$ TeV $pp$ collisions at the LHC from March to June 2011 and corresponds to an integrated luminosity of 1.07 fb$^{-1}$. The data are found to be consistent with the Standard Model background. The high $e^\pm \mu^\mp$ mass region is used to set 95% confidence level upper limits on the production of two possible new physics processes: tau sneutrinos in an $R$-parity violating supersymmetric model and $Z'$-like vector bosons in a lepton flavor violating model.

Short-lived particles that decay into two oppositely signed leptons of different flavors, $e^\pm \mu^\mp$ (e$\mu$), $e^\pm \tau^\mp$ (e$\tau$), or $\mu^\pm \tau^\mp$ (m$\tau$), are predicted by a number of extensions to the Standard Model (SM). Examples include sneutrinos in $R$-parity violating (RPV) supersymmetric (SUSY) models [1], and extra gauge $Z'$ bosons with lepton flavor violating (LFV) interactions [2]. This Letter reports a search for an excess of high invariant mass $e\mu$ ($m_{e\mu}$) events over SM predictions in $pp$ collisions at $\sqrt{s} = 7$ TeV at the LHC. The $e\mu$ final state is chosen due to its clean detector signature and low SM background in the high $m_{e\mu}$ region. Similar searches with the $e\mu$ final state have been reported previously by the CDF, D0 and ATLAS Collaborations [3–8]. In this Letter, we report an updated search with a data sample approximately 30 times larger than used for the previous ATLAS search [8] with improved sensitivity to new physics.

The ATLAS detector [9] is a multi-purpose particle physics apparatus with a forward-backward symmetric cylindrical geometry and near 4$\pi$ coverage in solid angle.$^1$

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 hermetic calorimeter system, which provides three-dimensional reconstruction of particle showers up to $|\eta| < 4.9$. For $|\eta| < 2.5$, the electromagnetic calorimeter is finely segmented and plays an important role in electron identification. The muon spectrometer (MS) is based on three large superconducting toroids arranged with an eight-fold azimuthal coil symmetry around the calorimeters. Three stations of drift tubes and cathode strip chambers enable precise muon track measurements, and resistive-plate and thin-gap chambers provide muon triggering capability.

The data sample used in this analysis was collected using single lepton ($e$ or $\mu$) triggers, between March and June 2011. The total integrated luminosity is 1.07 ± 0.04 fb$^{-1}$ [10, 11]. The trigger efficiency is measured to be 100%, with a precision of 1%, for e$\mu$ candidates that pass the default selection criteria described below.

To select $e\mu$ candidates, the electron candidate is required to have $p_T > 25$ GeV and to have pseudorapidity $|\eta| < 1.37$ or 1.52 < $|\eta|$ < 2.47. It is further required to pass the “medium” [12] quality definition, which is based on the calorimeter shower shape, track quality, and track matching with the calorimeter cluster. In addition, the electron is required to be isolated in the calorimeter with $E_T^{\Delta R<0.4} < 10$ GeV, where $E_T^{\Delta R<0.4}$ is defined as the transverse energy deposited in the calorimeter within a cone of radius $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.4$ around the electron cluster. Corrections have been applied to account for energy leakage from the electron and energy deposition inside the isolation cone due to additional $pp$ collisions. The muon candidate must be reconstructed in both the ID and the MS, and

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$^1$ 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, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. 

have $p_T > 25$ GeV and $|\eta| < 2.4$. Furthermore, the muon is required to be isolated in the ID with $p_T^{\Delta R<0.4} < 10$ GeV, where $p_T^{\Delta R<0.4}$ is defined as the scalar sum of the $p_T$ of tracks associated to the primary vertex, within a cone of radius $\Delta R = 0.4$ around the muon track. Only tracks with $p_T > 1$ GeV are used. Furthermore, only electrons separated from muons by $\Delta R > 0.2$ are considered.

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 at least three associated tracks of $p_T > 500$ MeV.

The SM processes that can produce an $e\mu$ signature can be divided into two categories: processes such as $Z/\gamma^* \rightarrow \tau\tau$, $t\bar{t}$, single top, $WW$, $WZ$ and $ZZ$, which can produce electrons and muons in the final state, and processes, referred to as fake background in this Letter, such as $W/Z + \gamma$, $W/Z + $jets and multijet events where the photon or one or two jets are reconstructed as leptons.

The contributions from processes listed in the first category as well as photon-related backgrounds are estimated using Monte Carlo (MC) samples generated at $\sqrt{s} = 7$ TeV. The detector response simulation [13] is based on the GEANT4 program [14]. Lepton reconstruction and identification efficiencies, energy scales and resolutions in the MC are corrected to the corresponding values measured in the data in order to improve the modeling of the background. The MC predictions are normalized to the data sample based on the integrated luminosity and cross sections of various physics processes. Top production is generated with MC@NLO [15–17] for $t\bar{t}$ and single top, the Drell–Yan process is generated with PYTHIA [18], and the diboson processes are generated with HERWIG [19, 20]. Higher order corrections have been applied to the cross sections predicted by these generators [21–23]. The $W/Z + \gamma$ contribution in the fake background comes from the $W(\rightarrow \mu\nu)\gamma$ and $Z(\rightarrow \mu\mu)\gamma$ processes, where the photon is reconstructed as an electron. This background is estimated using events generated with MADGRAPH [24].

The uncertainties for the $t\bar{t}$ and single top cross sections are taken to be 10% [25, 26] and 9% [27], respectively. The cross sections for $W/Z + \gamma$, $Z/\gamma^* \rightarrow \tau\tau$, $WW$, $WZ$ and $ZZ$ are assigned uncertainties of 10%, 5%, 7%, 7%, and 5%, respectively; these uncertainties arise from the choice of PDF, from factorization and renormalization scale dependence and from $\alpha_s$ variations. The integrated luminosity uncertainty and other smaller systematic uncertainties from the lepton trigger, reconstruction and identification efficiencies, energy (momentum) scale and resolution have been added in quadrature and are included in the total uncertainty.

The remaining fake backgrounds arise from the $W/Z + $jets and multijet processes, where leptons are present from $b$- or $c$-hadron decays or at least one jet is misidentified as a lepton. Such lepton candidates are collectively referred to as “non-prompt leptons” in this Letter. These jet fake backgrounds account for $\sim30\%$ of the expected $e\mu$ data yield and are estimated from data using a $4 \times 4$ matrix background estimation method described below. A looser lepton quality selection (called loose lepton here) is defined for each lepton type in addition to the default quality selection (called tight lepton here). For loose muons, the isolation requirement is dropped. For loose electrons, the “loose” electron identification criteria as defined in Ref. [12] are used and the isolation requirement is also dropped. The tight and loose lepton selections are then used to classify events where both leptons pass the loose requirements into four categories, depending on whether both leptons subsequently pass the tight requirement ($N_{pp}$), only one lepton fails the tight requirement and the other lepton passes the tight requirement ($N_{pf}$ or $N_{fp}$), or both leptons fail the tight requirement ($N_{ff}$).

The sample composition can be estimated by solving a linear system of equations: $(N_{pp}, N_{pf}, N_{fp}, N_{ff})^T = \epsilon(N_{ee}, N_{e\mu}, N_{\mu e}, N_{\mu\mu})^T$, where $N_{ee}$ (or $N_{e\mu}$) is the number of events with two prompt leptons (or two non-prompt leptons), while $N_{e\mu}$ and $N_{\mu e}$ are the numbers of events with one prompt lepton and one non-prompt lepton.

The matrix $\epsilon$ contains the probabilities for a loose quality lepton to pass the tight quality selection for both prompt and non-prompt leptons. The probability for prompt leptons (non-prompt leptons) is estimated by applying the loose and tight selections on $Z/\gamma^* \rightarrow ee/\mu\mu$ events (a sample of dijet events). To take into account the lepton $p_T$ dependence of the two probabilities, the matrix equation is inverted for each event, giving four weights, corresponding to the four combinations of prompt and non-prompt leptons. These weights are then summed over all events to yield the total number of events with one or more non-prompt leptons. The overall jet fake background is found to be $1175 \pm 250$ events.

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Table 1: Estimated backgrounds in the selected sample, together with the observed event yield. The total integrated luminosity is 1.07 fb$^{-1}$

<table>
<thead>
<tr>
<th>Process</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>1580±170</td>
</tr>
<tr>
<td>Jet fake</td>
<td>1175±120</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \tau\tau$</td>
<td>750 ± 60</td>
</tr>
<tr>
<td>WW</td>
<td>380 ± 31</td>
</tr>
<tr>
<td>Single top</td>
<td>154 ± 16</td>
</tr>
<tr>
<td>W/Z + $\gamma$</td>
<td>82 ± 13</td>
</tr>
<tr>
<td>ZZ</td>
<td>22.4±2.3</td>
</tr>
<tr>
<td>Total background</td>
<td>4145±250</td>
</tr>
<tr>
<td>Data</td>
<td>4053</td>
</tr>
</tbody>
</table>

Table 2: Estimated total backgrounds in the selected sample, together with the observed event yields for 11 high $e\mu$ mass regions

<table>
<thead>
<tr>
<th>$m_{e\mu}$</th>
<th>Data</th>
<th>SM prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;200 GeV</td>
<td>286</td>
<td>288 ± 22</td>
</tr>
<tr>
<td>&gt;250 GeV</td>
<td>152</td>
<td>136 ± 11</td>
</tr>
<tr>
<td>&gt;300 GeV</td>
<td>70</td>
<td>67 ± 6</td>
</tr>
<tr>
<td>&gt;350 GeV</td>
<td>35</td>
<td>34.0 ± 3.0</td>
</tr>
<tr>
<td>&gt;400 GeV</td>
<td>22</td>
<td>17.7 ± 1.7</td>
</tr>
<tr>
<td>&gt;450 GeV</td>
<td>10</td>
<td>10.5 ± 1.2</td>
</tr>
<tr>
<td>&gt;500 GeV</td>
<td>7</td>
<td>6.8 ± 0.9</td>
</tr>
<tr>
<td>&gt;550 GeV</td>
<td>3</td>
<td>4.3 ± 0.6</td>
</tr>
<tr>
<td>&gt;600 GeV</td>
<td>3</td>
<td>2.4 ± 0.4</td>
</tr>
<tr>
<td>&gt;650 GeV</td>
<td>1</td>
<td>1.49 ± 0.31</td>
</tr>
<tr>
<td>&gt;700 GeV</td>
<td>0</td>
<td>1.07 ± 0.25</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 and $m_{Z'} = 700$ GeV. The couplings $\lambda'_{311} = 0.10$ and $\lambda'_{312} = 0.05$ are used for the RPV $\tilde{\nu}_\tau$ model. The production cross section is assumed to be the current published limit of 0.178 pb for the LFV $Z'$ model [8]. The ratio plot at the bottom includes only statistical uncertainties.

An $e\mu$ resonance also appears in models containing a heavy neutral gauge boson, $Z'$ [33], with non-diagonal lepton flavor couplings. Rare muon decay searches have placed extremely stringent limits on the combination of the mass and the coupling to $e\mu$ in such models [2]. The $e\mu$ searches at hadron colliders are not able to match the sensitivity of dedicated $\mu \rightarrow e$ conversion experiments. A limit on the production cross section times branching ratio to $e\mu$ is placed on the $Z'$-like boson model to represent the production of vector particles that can decay to the $e\mu$ final state. To calculate the efficiency and acceptance, the $Z'$ is assumed to have the same quark and lepton couplings as the SM $Z$ except a non-zero $Z'$ to $e\mu$ coupling, which is assumed to be the same as the $Z'$ to $ee$ coupling. The cross section is 0.61 pb for $m_{Z'} = 700$ GeV [34]. MC samples with $Z'$ masses ranging from 0.7 to 2 TeV are generated with PYTHIA [19, 20, 32].

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The $m_{\mu}$ spectrum is examined for the presence of a new heavy particle. For each assumed $m_\tilde{\nu}_\tau$ value in the range 100 GeV to 2 TeV, a search region, which depends on the simulated $e\mu$ mass resolution, is used. The number of observed and predicted background and signal events in each search range are used to set an upper limit on $\sigma(pp \rightarrow \tilde{\nu}_\tau) \times \text{BR}(\tilde{\nu}_\tau \rightarrow e\mu)$. A Bayesian method is used with a uniform prior for the signal cross section for a given $m_\tilde{\nu}_\tau$. Figure 2a shows the expected and observed 95% confidence level (C.L.) limits, as a function of $m_\tilde{\nu}_\tau$, together with the limits previously published by ATLAS, which were based on 35 pb$^{-1}$ of data, and the expected ±1 and ±2 standard deviation uncertainty bands. For a $\tilde{\nu}_\tau$ with a mass of 100 GeV (1 TeV), the limit on the cross section times branching ratio is 135 (4.5) fb. The limits obtained extend 7 (34) times beyond the previous ATLAS results. The theoretical cross sections for $\lambda_{311} = 0.10$, $\lambda_{312} = 0.05$ and $\lambda_{311}' = 0.11$, $\lambda_{312}' = 0.07$ are also shown. Tau sneutrinos with a mass below 1.32 (1.45) TeV are excluded, assuming coupling values $\lambda_{311} = 0.10$ and $\lambda_{312} = 0.05$ ($\lambda_{311}' = 0.11$ and $\lambda_{312}' = 0.07$). The limits are significantly better than the limits from the previous ATLAS analysis using 35 pb$^{-1}$ of data. The 95% C.L. observed upper limits on $\lambda_{311}$ as a function of $m_\tilde{\nu}_\tau$ are shown in Fig. 2b for three values of $\lambda_{312}$, together with the exclusion region obtained from the D0 experiment and previously by the ATLAS experiment. The limits on $\lambda_{311}'$ are shown in Fig. 3. The expected limit is the same as the observed limit for the high mass points because both the median background event count expectation and the observed number of events are zero. For a $Z'$ with mass of 0.7 TeV (1.0 TeV), the limit on the cross section times branching ratio is 9.6 fb (4.8 fb). This result improves upon previous ATLAS limits by roughly a factor of 20 (40).

In conclusion, a search has been performed for high mass $e\mu$ events using $pp$ collision data at $\sqrt{s} = 7$ TeV recorded by the ATLAS detector. The observed $m_{e\mu}$ distribution is found to be consistent with SM predictions. With no evidence for new physics, 95% C.L. exclusion limits are placed on the production cross sections and RPV coupling values of the tau sneutrinos in an RPV SUSY model, and tau sneutrinos with a mass below 1.32 (1.45) TeV are excluded, assuming coupling values $\lambda_{311} = 0.10$ and $\lambda_{312} = 0.05$ ($\lambda_{311}' = 0.11$ and $\lambda_{312}' = 0.07$). The results presented here are the most stringent results to date for $m_\tilde{\nu}_\tau > 270$ GeV. More stringent constraints are also set on the production cross sections of $Z'$ bosons in an LFV model. These two benchmark models can be used to represent the production of any narrow scalar and vector particles that can decay to the $e\mu$ final state.
Fig. 3 The observed 95% C.L. upper limits on $\sigma(pp \rightarrow Z') \times \text{BR}(Z' \rightarrow e\mu)$. The expected limits are also shown together with the expected ±1 and ±2 standard deviation uncertainty bands. The observed and expected limits overlap as discussed in the text.

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