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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

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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 all R-parity violating couplings are zero except $\lambda'_{311} = 0.11$ and $\lambda_{312} = 0.07$. In a lepton flavor violating model, a Z'-like vector boson with masses of 0.70–1.00 TeV and corresponding cross sections times branching ratios of 0.175–0.183 pb is excluded. These results extend to higher mass R-parity violating sneutrinos and lepton flavor violating 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 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 $e\mu$ invariant mass ($m_{e\mu}$) lies below the range favored for new physics signals. This Letter reports a search for a heavy particle decaying into the $e\mu$ final state using data taken with the ATLAS detector. The results are interpreted in terms of the production and decay of a tau sneutrino $\tilde{\nu}_{\tau}$ and a Z'. Both the CDF and D0 Collaborations at the Tevatron collider have reported searches for the RPV production and decay of the $\tilde{\nu}_{\tau}$ [3–7]. The CDF Collaboration has also set limits on the LFV couplings as a function of the Z' mass [4].

The ATLAS detector [8] is a multipurpose particle physics apparatus with a forward-backward symmetric cylindrical geometry and near 4π 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 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 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 μ) triggers, which have nominal transverse momentum p_T thresholds up to 15 GeV for e and 13 GeV for μ. 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 electromagnetic 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 $E_T^{\Delta R<0.2}/E_T < 0.1$ is applied, where $E_T^{\Delta R<0.2}$ 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, excluding the core energy deposited by the electron, and E_T is the transverse energy of the electron.

The muon candidate must be reconstructed in both the ID and the muon spectrometer. A good match of the

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parameters of the ID and muon spectrometer 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 $p_T^{\Delta R<0.2}/p_T < 0.1$, where $p_T^{\Delta R<0.2}$ 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, excluding the muon track.

Jets are reconstructed by 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 considered only 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 $p_T > 150$ MeV.

The SM processes that can produce an $e\mu$ signature are predominantly $t\bar{t}$, $Z/\gamma^* \rightarrow \tau\tau$, $W/Z +$ jets, diboson, single top, and QCD multijet events. Among the processes listed above, $t\bar{t}$, $Z/\gamma^* \rightarrow \tau\tau$, single top, WW, WZ, and ZZ produce electrons and muons in the final state and amount to ~80% of the expected $e\mu$ data yield. The contributions from these processes are estimated by using Monte Carlo (MC) samples generated at $\sqrt{s} = 7$ TeV and processed with the standard chain of the ATLAS GEANT4 [13] simulation and reconstruction [14] using the ATLAS MC09 parameter tune [15]. The event generators used are PYTHIA 6.421 [16] (W and Z/γ^*), POWHEG 1.0 [17] ($t\bar{t}$), MADGRAPH 4 [18] ($W/Z + \gamma$), MC@NLO 3.4 [19] (single top), and HERWIG 6.510 [20] (WW, WZ, and ZZ). The MC samples are normalized to cross sections with higher order corrections applied, as follows. The cross section is calculated to next-to-next-to-leading-order accuracy for W and Z/γ^* [21], next-to-leading-order plus next-to-next-to-leading-log for $t\bar{t}$ [22], and next-to-leading-order for WW, WZ, and ZZ [23]. Single top and $W/Z + \gamma$ cross sections come from MC@NLO and MADGRAPH, respectively. 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 calculations to properly describe the data. The appropriate corrections are applied to the MC calculations in order to improve the modeling of the backgrounds.

The processes $W/Z + \gamma$, $W/Z +$ 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 ~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 by using data. The background component initiated by prompt photons, referred to as the photon instrumental background, is estimated from MC calculations.

The jet instrumental background is estimated by 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 $E_T^{\rm miss} <$ 15 GeV is applied to remove $W +$ 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^{+10}_{-5} events for candidates with one electron and one jet satisfying the muon selection criteria and 19^{+28}_{-7} 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 $1.3^{+5}_{-1.3}$ events from same-sign dilepton events in the data with the subtraction of contributions estimated from MC calculations for all physics processes except the QCD multijet. The overall jet instrumental background is found to be 29^{+30}_{-10} 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 $W(\rightarrow \mu\nu)\gamma$ 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 ± 0.7 events.

Table I shows the number of events selected in the data and the estimated background contributions with their uncertainties. A total of 160 $e\mu$ candidates are observed in the data, while the expectation from SM processes is 163^{+34}_{-18} events. The dominant sources of systematic uncertainty for the SM prediction arise from the uncertainty on

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

Process	Number of events
$Z/\gamma^* \to \tau\tau$	54 ± 7
$t\bar{t}$	57 ± 9
WW	13.4 ± 1.7
Single top	4.6 ± 0.9
WZ	0.79 ± 0.11
Instrumental background	33^{+30}_{-10}
Total background	163^{+34}_{-18}
Data	160

the probability for a jet to satisfy the lepton isolation requirement (70% for an electron and 30% for a 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 or momentum scale, and resolution have been included and are small.

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

The RPV production of $\tilde{\nu}_\tau$ by $d\bar{d}$ annihilation decaying into $e\mu$ is considered. By fixing all RPV couplings but λ'_{311} and λ_{312} to zero, the contributions to the $e\mu$ final state originate from the $\tilde{\nu}_\tau$ only. With these couplings, along with the assumption that $\tilde{\nu}_\tau$ is the lightest supersymmetric particle, the $\tilde{\nu}_\tau$ can decay only to $d\bar{d}$ or $e\mu$. The signal cross section depends on the $\tilde{\nu}_\tau$ mass ($m_{\tilde{\nu}_\tau}$), λ'_{311}, and λ_{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 nondiagonal lepton flavor couplings Z' [24]. 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]. By 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 [20,25] 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 [26] and 0.61 pb for $m_{Z'} = 700$ GeV [27]. The corresponding overall acceptance times efficiency is 55% for $\tilde{\nu}_\tau$ and 50% for Z'.

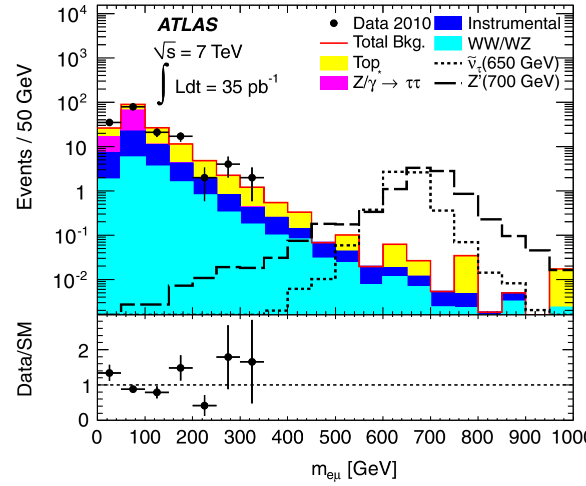

FIG. 1 (color online). Observed and predicted $e\mu$ invariant mass distributions. Signal simulations are shown for $m_{\tilde{\nu}_\tau} = 650$ GeV ($\lambda'_{311} = 0.11$ and $\lambda_{312} = 0.07$) and $m_{Z'} = 700$ GeV. The ratio plot at the bottom includes only statistical uncertainties.

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 σ is the expected $m_{e\mu}$ resolution (e.g., $\sigma \simeq 15$ 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 $\sigma(pp \to \tilde{\nu}_\tau) \times \mathrm{BR}(\tilde{\nu}_\tau \to e\mu)$ are calculated by using a Bayesian method [28] with a flat prior for the signal cross section as a function of $m_{\tilde{\nu}_\tau}$. Figure 2(a) 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 by using simulated pseudoexperiments containing only SM processes by evaluating the 95% C.L. upper limits for each pseudoexperiment 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 a mass of 100 GeV (1 TeV), the limit on the cross section times branching ratio is 0.951 (0.154) 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 by 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 λ'_{311} as a function of $m_{\tilde{\nu}_\tau}$ are shown in Fig. 2(b) for three values of λ_{312}, together with the exclusion region obtained from the D0 experiment [7]. The limits derived here are extended to a higher mass region than was available at D0,

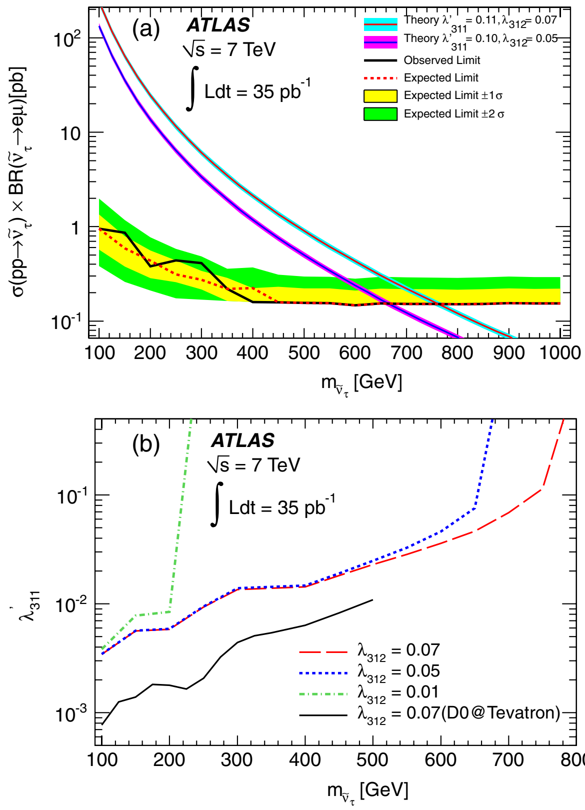

FIG. 2 (color online). (a) The observed 95% C.L. upper limits on $\sigma(pp \to \tilde{\nu}_\tau) \times \mathrm{BR}(\tilde{\nu}_\tau \to e\mu)$ as a function of $m_{\tilde{\nu}_\tau}$. The expected limits are also shown together with the ±1 and ±2 standard deviation uncertainty bands. The theoretical cross sections for $\lambda'_{311} = 0.11$, $\lambda_{312} = 0.07$ and $\lambda'_{311} = 0.10$, $\lambda_{312} = 0.05$ are also shown. For $m_{e\mu} > 400$ GeV, the total SM background is 0.67 ± 0.19, and the median of number of events expected from pseudoexperiments is 0; therefore, the -1σ and -2σ uncertainty bands cannot reach below this expectation. (b) The 95% C.L. upper limits on the λ'_{311} coupling as a function of $m_{\tilde{\nu}_\tau}$ for three values of λ_{312}. Regions above the three curves represent ranges of λ'_{311} values that are excluded. These results are compared to the exclusion region obtained from the D0 experiment.

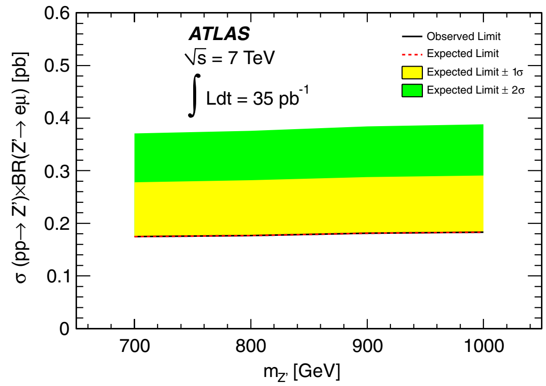

FIG. 3 (color online). The observed 95% C.L. upper limits on $\sigma(pp \to Z') \times \mathrm{BR}(Z' \to e\mu)$. The expected limits are also shown together with the ±1 and ±2 standard deviation uncertainty bands. The -1σ and -2σ uncertainty bands cannot reach below the expectation due to the same reason as in Fig. 2(a).

even though the limits are worse than those obtained by the D0 Collaboration in the low mass region due to limited statistics.

A similar method is used to set limits on the LFV Z'-like vector boson, by using only events with $m_{e\mu} > 400$ GeV. After finding no events in the data, the 95% C.L. upper limits on $\sigma(pp \to Z') \times \mathrm{BR}(Z' \to e\mu)$ 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 a 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.

In conclusion, a search has been performed for a heavy particle decaying into the $e^\pm\mu^\mp$ final state by 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 supersymmetric model, tau sneutrinos with a mass below 0.75 TeV are excluded, assuming single coupling dominance and coupling values $\lambda'_{311} = 0.11$ and $\lambda_{312} = 0.07$. Higher values of the RPV coupling are also excluded as a function of $m_{\tilde{\nu}_\tau}$. 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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