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Search for a heavy narrow resonance decaying to $e\mu$, $e\tau$, or $\mu\tau$ with the ATLAS detector in $\sqrt{s} = 7$ TeV pp collisions at the LHC

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ABSTRACT

This Letter presents the results of a search for a heavy particle decaying into an $e^{\pm}\mu^{\mp}$, $e^{\pm}\tau^{\mp}$, or $\mu^{\pm}\tau^{\mp}$ final state in pp collisions at $\sqrt{s} = 7$ TeV. The data were recorded with the ATLAS detector at the LHC during 2011 and correspond to an integrated luminosity of 4.6 fb^{-1}. No significant excess above the Standard Model expectation is observed, and exclusions at 95% confidence level are placed on the cross section times branching ratio for the production of an R-parity-violating supersymmetric tau sneutrino. For a sneutrino mass of 500 (2000) GeV, the observed limits on the production cross section times branching ratio are 3.2 (1.4) fb, 42 (17) fb, and 40 (18) fb for the $e\mu$, $e\tau$, and $\mu\tau$ modes, respectively. These results considerably extend constraints from Tevatron experiments.

1. Introduction

Neutrino oscillations show that lepton-flavour quantum numbers are not conserved in Nature. On the other hand, lepton-flavour violation (LFV) has not been observed in the charged lepton sector, where neutrino-induced LFV is predicted to be extremely small in the Standard Model (SM) [1]. The study of possible LFV processes involving charged leptons is an important topic in the search for physics beyond the SM. One possible signature is the production of a particle that decays to a pair of different flavour, opposite-sign leptons $e^{\pm}\mu^{\mp}$ ($e\mu$), $e^{\pm}\tau^{\mp}$ ($e\tau$), or $\mu^{\pm}\tau^{\mp}$ ($\mu\tau$) (referred to generically as $\ell\ell'$).

Since the ATLAS detector identifies leptons with large transverse momenta with high purity, efficiently, and with good momentum resolution, it is well suited to a search for this signature. Many new physics models allow LFV in charged lepton interactions. For example, in R-parity-violating (RPV) models of supersymmetry (SUSY) [2], a sneutrino can have LFV decays to $\ell\ell'$. Models with additional gauge symmetry can accommodate an $\ell\ell'$ signature through LFV decays of an extra gauge boson Z' [3]. This signature is also produced in the SM framework, for example, $t\bar{t}$, WW, or $Z/\gamma^* \to \tau^-\tau^+$ production where the final-state particles decay to leptons of different flavour. These processes typically have small cross sections for $\ell\ell'$ pairs with invariant mass ($m_{\ell\ell'}$) in the high-mass range not already excluded for new physics signals.

This Letter reports on a search for a heavy particle decaying into the $e\mu$, $e\tau_{\text{had}}$, or $\mu\tau_{\text{had}}$ final state, where τ_{had} is a τ lepton that decays hadronically. The search uses 4.6 fb^{-1} of 7 TeV pp collision data taken with the ATLAS detector during 2011. The results are interpreted in terms of the production and subsequent decay of a tau sneutrino $\tilde{\nu}_\tau$ in RPV SUSY ($d\bar{d} \to \tilde{\nu}_\tau \to \ell\ell'$). This Letter presents results that supersede previous ATLAS results from a search for a high-mass resonance decaying to $e\mu$ based on 1 fb^{-1} of 2011 data [5] and extends the search to $e\tau_{\text{had}}$ and $\mu\tau_{\text{had}}$ final states. Both the CDF and D0 Collaborations at the Tevatron collider have reported searches for the RPV production and decay of a $\tilde{\nu}_\tau$ in the $e\mu$ channel [4]. The CDF Collaboration also reported searches in the $e\tau$ and $\mu\tau$ channels [4].

Precision low-energy searches, such as μ to e conversion on nuclei, rare muon decays, and rare tau decays, place limits on RPV couplings [6]. These limits often depend on masses of supersymmetric particles and on the assumption of the dominance of certain couplings or pairs of couplings. Direct searches, such as the one here, have different dependences on masses and couplings.

2. ATLAS detector

The ATLAS experiment at the LHC employs a multipurpose particle physics detector [7] with a forward-backward symmetric cylindrical geometry and near 4π coverage in solid angle.[1] The inner tracking detector covers the pseudorapidity region $|\eta| < 2.5$ and consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The inner tracking detector

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[1] 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 (x, y) plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

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is surrounded by a thin superconducting solenoid that provides a 2 T magnetic field and by a finely-segmented calorimeter with nearly full solid-angle coverage. The latter covers the pseudorapidity range $|\eta| < 4.9$ and provides three-dimensional reconstruction of particle showers. The electromagnetic compartment uses lead absorbers with liquid argon as the active material. This is followed by a hadronic compartment, which uses scintillating tiles with iron absorbers in the central region and 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 (each with eight coils), a system of precision tracking chambers ($|\eta| < 2.7$), and detectors for triggering.

3. Data and event selection

The data used in this analysis were recorded in 2011 at a centre-of-mass energy of 7 TeV. Only data taken during stable run conditions and operational tracking, calorimetry, and muon subdetectors are used. This results in a data sample with an integrated luminosity of 4.6 fb^{-1} with an estimated uncertainty of 3.9% [8]. Events are required to satisfy a single-electron trigger for the $e\mu$ and $e\tau_{\text{had}}$ searches and a single-muon trigger for the $\mu\tau_{\text{had}}$ search. The nominal transverse momentum (p_{T}) threshold for the electron trigger was 20 or 22 GeV, depending on the instantaneous luminosity, and was 18 GeV for the muon trigger. The electron (muon) trigger is 98% (89%) efficient for events that pass the selection criteria below.

Further criteria are applied offline to select electron, muon, and tau candidates. An electron candidate is required to have $p_{\text{T}} > 25$ GeV and to lie in the pseudorapidity region $|\eta| < 2.47$, excluding the transition region ($1.37 < |\eta| < 1.52$) between the barrel and endcap calorimeters. The p_{T} of the electron is calculated from the calorimeter energy and the direction of the inner detector track. A set of electron identification criteria based on the calorimeter shower shape, track quality, transition radiation, and track matching with the calorimeter energy deposition, referred to as 'tight' in Ref. [9], is applied. These criteria correctly identify about 80% of electrons from Z decays and have a rejection factor of about 50,000 for generic jets. Two lepton isolation criteria are used to further reduce backgrounds from hadronic jets. The calorimetric isolation criterion requires that the transverse energy deposited within a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the electron cluster, excluding the core energy deposited by the electron, is less than 0.14 times the p_{T} of the candidate electron. The tracking isolation criterion requires the sum of the transverse momenta of tracks with $p_{\text{T}} > 1$ GeV within a cone of radius $\Delta R < 0.3$ around the electron track, excluding the electron track, is less than 0.13 times the p_{T} of the candidate.

A muon candidate must have reconstructed tracks in both the inner detector and the muon spectrometer. The inner detector track is required to have a pattern of hits consistent with a quality track. Furthermore, the muon candidate must have $p_{\text{T}} > 25$ GeV and be isolated, using similar criteria as for electrons: 0.14 times p_{T} for calorimetric isolation and 0.15 times p_{T} for tracking isolation.

Jets are reconstructed from calorimeter energy depositions using the anti-k_t jet clustering algorithm [10] with a radius parameter of 0.4. Only jets with $p_{\text{T}} > 20$ GeV and $|\eta| < 2.5$ are considered. Leptons are rejected if they lie within $\Delta R > 0.4$ of any jet. This is the only use of jets in this analysis.

For this search, tau leptons are reconstructed through their hadronic decays (τ_{had}). The tau reconstruction is seeded by anti-k_t jets [10] with cone size $\Delta R = 0.4$ and jet $p_{\text{T}} > 10$ GeV formed from calorimeter energy depositions. Tracks with $p_{\text{T}} > 1$ GeV are added to the tau candidate. Corrections depending on p_{T} and η are then applied to the tau energy. Since the reconstruction efficiency for hadronic tau decays with three tracks drops significantly at large transverse momentum as the tracks become more collimated, this analysis uses only tau candidates with one track, which comprise 75% of hadronic tau decays, that is, about 50% of all tau decays. For each tau, the track and each energy deposition not associated with the track is treated as coming from a massless particle. The four-momenta of these particles are summed to give the four-momentum of the tau candidate. The tau candidates must have $E_{\text{T}} > 20$ GeV and pseudorapidity in the range $0.03 < |\eta| < 2.5$. The lower limit excludes a region where there is reduced coverage from the inner detector and calorimeters, which greatly increases misidentification of electrons as hadronic tau decays.

A boosted decision tree discriminator [11] efficiently selects taus while rejecting backgrounds. The variables used in the discriminator are ΔR between the track and the tau candidate, the impact parameter significance of the track, the fraction of the p_{T} of the tau candidate carried by the track, the number of tracks ($p_{\text{T}} > 1$ GeV) in an isolation annulus of $0.2 < \Delta R < 0.4$, the rms width of the energy deposition in the cells of the calorimeter, energy isolation for cones of $\Delta R = 0.1$ and $\Delta R = 0.4$, and the invariant mass associated with the energy deposition. For this analysis, 'medium' selection criteria as described in Ref. [11] are used. This selection is about 60% efficient at retaining taus that decay hadronically, as measured in $Z \to \tau\tau$ decays, while accepting 1 of 20 to 1 of 50 ordinary hadronic jets misidentified as tau candidates. To retain only taus that decay hadronically, candidates consistent with being an electron or a muon are rejected.

The missing transverse energy ($E_{\text{T}}^{\text{miss}}$) is calculated from the vector sum of the transverse momenta of all high-p_{T} objects (electrons, muons, photons, taus, and jets) and all calorimeter energy clusters with $|\eta| < 4.5$ not associated with those objects [12].

Events are required to have exactly two lepton candidates with opposite sign and different flavour, that is, $e\mu$, $e\tau_{\text{had}}$, or $\mu\tau_{\text{had}}$. In addition, each event must have at least one primary vertex with at least four tracks with $p_{\text{T}} > 400$ MeV. The two leptons are chosen to be back-to-back in ϕ by requiring that the azimuthal angle between them satisfies $\Delta\phi_{\ell\ell'} > 2.7$. Although the transverse momenta of the two leptons in an event are expected to be comparable, the missing neutrino reduces the measured E_{T} of tau candidates, so for the $e\tau_{\text{had}}$ and $\mu\tau_{\text{had}}$ events, the p_{T} of the electron or muon is required to be greater than the E_{T} of the tau.

For $e\tau_{\text{had}}$ and $\mu\tau_{\text{had}}$ signal events, the presence of only one tau with expected large momentum relative to the tau mass implies that the neutrino from the tau decay should point in nearly the same direction as the tau momentum and that there are no other significant sources of $E_{\text{T}}^{\text{miss}}$. The transverse components of the neutrino momentum are set equal to the components of the $E_{\text{T}}^{\text{miss}}$ vector and the polar angle of the neutrino momentum is set equal to the polar angle of the tau candidate's momentum. The momentum of the tau candidate is corrected for the momentum of the neutrino in the calculation of the $e\tau_{\text{had}}$ and $\mu\tau_{\text{had}}$ invariant masses. This significantly reduces the width of the invariant mass distribution for $e\tau_{\text{had}}$ and $\mu\tau_{\text{had}}$ pairs in the sneutrino signal simulation and improves the search sensitivity, while making no significant changes to the shape of the $m_{\ell\ell'}$ background distribution. For dilepton masses from 400 GeV to 2000 GeV, the mass resolutions range from 2.5% to 7.5%, 2.2% to 4.3%, and 6.3% to 9.0% for the $e\mu$, $e\tau_{\text{had}}$, and $\mu\tau_{\text{had}}$ decay modes, respectively. The mass resolutions are dominated by the resolution of the transverse momenta of the leptons. At high p_{T}, the transverse momentum resolution is best for electrons, whose p_{T} measurement is based primarily on energy deposited in the electromagnetic calorimeter. It is next best for taus, whose p_{T} measurement is based on electromagnetic and

Table 1
Estimated number of SM events and observed event yield for each signal category for the background ($m_{\ell\ell'} < 200$ GeV) and signal ($m_{\ell\ell'} > 200$ GeV) regions. The uncertainties given are the statistical and systematic uncertainties combined in quadrature.

Process	$m_{\ell\ell'} < 200$ GeV			$m_{\ell\ell'} > 200$ GeV		
	$N_{e\mu}$	$N_{e\tau_{had}}$	$N_{\mu\tau_{had}}$	$N_{e\mu}$	$N_{e\tau_{had}}$	$N_{\mu\tau_{had}}$
$Z/\gamma^* \to \tau\tau$	1880 ± 150	4300 ± 600	5300 ± 600	8 ± 1	24 ± 3	28 ± 4
$Z/\gamma^* \to ee$		1050 ± 80			44 ± 3	
$Z/\gamma^* \to \mu\mu$			3030 ± 290			29 ± 3
$t\bar{t}$	760 ± 110	96 ± 18	94 ± 14	251 ± 30	90 ± 15	70 ± 13
Diboson	260 ± 27	57 ± 8	60 ± 7	71 ± 8	26 ± 3	24 ± 3
Single top quark	87 ± 8	11 ± 2	9 ± 1	39 ± 4	10 ± 2	8 ± 1
$W +$ jets	420 ± 260	3500 ± 700	3200 ± 600	90 ± 40	370 ± 80	470 ± 110
Multijet	37 ± 13	2200 ± 700	730 ± 230	6 ± 2	150 ± 50	24 ± 18
Total background	3440 ± 300	$11\,200 \pm 900$	$12\,400 \pm 800$	460 ± 60	720 ± 80	650 ± 90
Data	3345	11 212	12 285	498	795	699

hadronic calorimeter energy depositions. It is the worst for muons, whose p_T measurement is from tracking.

4. Backgrounds

The SM processes that can produce an $\ell\ell'$ signature are divided into two categories: backgrounds that produce prompt-lepton pairs and jet backgrounds where one or both of the candidate leptons is from a misidentified jet. Data events with an $\ell\ell'$ invariant mass below 200 GeV constitute a control region to verify the background estimates, and events with masses above 200 GeV comprise the signal search region.

The dominant prompt-lepton backgrounds are $t\bar{t}$, $Z/\gamma^* \to \ell\ell$, diboson (WW, ZZ, and WZ), and single top quark (Wt). Since these processes are well understood and modelled, their contributions are estimated using Monte Carlo samples generated at $\sqrt{s} = 7$ TeV and processed with the full ATLAS GEANT4 [13] simulation and reconstruction. The event generators used are PYTHIA 6.421 [14] (W and Z/γ^*), POWHEG 1.0 [15] ($t\bar{t}$), MADGRAPH 4 [16] ($W/Z + \gamma$), MC@NLO 3.4 [17] (single top quark) and HERWIG 6.510 [18] (WW, WZ and ZZ). The parton distribution functions are CTEQ6L1 [19] for W and Z production and CT10 [20] for $t\bar{t}$, single top quark, and diboson production. The Monte Carlo samples are normalised to cross sections with higher-order corrections applied. The cross section is calculated to next-to-next-to-leading order 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 quark and $W/Z + \gamma$ cross sections are calculated with MC@NLO and MADGRAPH, respectively. The effects of QED radiation are generated with PHOTOS [24]. Hadronic tau decays are simulated with TAUOLA [25]. Studies of leptons in Z/γ^*, W, and J/ψ events [26] have shown that the lepton reconstruction and identification efficiencies, energy scale, and energy resolution need small adjustments in the Monte Carlo simulation to describe the data properly. The appropriate corrections are applied to the Monte Carlo samples to improve the modelling of the backgrounds. The effect of additional pp interactions per bunch crossing as a function of the instantaneous luminosity is modelled by overlaying simulated minimum bias events with the same distribution in number of events per bunch crossing as observed in the data.

The processes $W/Z + \gamma$, $W/Z +$ jets, and multijet production give rise to backgrounds from jets misidentified as leptons, electrons from photon conversions, and leptons from hadron decays (including b- and c-hadron decays). The dominant component of these backgrounds is from events with one prompt lepton and one jet misidentified as a lepton. There is an additional, small contribution from events with two misidentified jets. These backgrounds are estimated using data. The background component coming from prompt photons is estimated from Monte Carlo samples and found to be negligible.

The jet backgrounds, including semileptonic decays in bottom and charm jets, are greatly reduced by the lepton isolation and high-p_T requirements but are still significant. The dominant jet background is due to $W +$ jets production, whose contribution is estimated using data from a subsample selected with the same criteria as signal events but with the additional requirement $E_T^{miss} > 30$ GeV. This subsample is enriched in $W +$ jets events, whose contribution is about 60%, while the multijet background is reduced to about 3% and the prompt-lepton background to about 37%. The potential effect of the multijet contribution is included in the systematic uncertainty. There could be signal events in this subsample, but from examination of the p_T spectra of the leptons, E_T^{miss} distributions, and, for the $e\tau$ and $\mu\tau$ modes, distributions of the difference in azimuthal angle between the tau direction and the E_T^{miss} vector, this contamination must be significantly less than 1%. The contribution from prompt-lepton backgrounds in the subsample is determined from Monte Carlo simulation and is subtracted to give the number of $W +$ jets events. This number is extrapolated to the number in the full data sample without the E_T^{miss} criterion using the $W +$ jets Monte Carlo samples. The shapes of the $W +$ jets background in various kinematic variables, including $m_{\ell\ell'}$, are taken from $W +$ jets Monte Carlo samples.

Studies of event samples dominated by multijet events show that the probability that a jet is misidentified as a lepton is independent of its charge [27], with a 10% uncertainty. A same-sign sample is selected using the same criteria as for the signal sample but with the sign requirement reversed. The multijet background in the opposite-sign sample is taken to be equal to its contribution in the same-sign sample. Prompt-lepton backgrounds produce more opposite-sign than same-sign events, so the same-sign sample is enriched in multijet background. Contributions to the same-sign sample by the prompt-lepton backgrounds are determined from Monte Carlo simulation. The $W +$ jets contamination of the same-sign sample is determined by selecting only same-sign events with $E_T^{miss} > 30$ GeV and then extrapolating to the full same-sign sample using Monte Carlo simulation. The prompt-lepton background and $W +$ jets contributions are subtracted from the observed same-sign sample to give the expected distribution and normalisation of the multijet background in the opposite-sign sample.

Table 1 shows the number of events selected in data and the estimated background contributions with their uncertainties (statistical and systematic combined in quadrature). The expected number of events in the control region agrees well with the observed number of events for all three signatures ($e\mu$, $e\tau_{had}$, and $\mu\tau_{had}$).

The largest backgrounds in the signal region ($m_{\ell\ell'} > 200$ GeV) are $W+$jets events, arising primarily from the leptonic decay of the W and the misidentification of a jet as a lepton, and $t\bar{t}$ events, arising primarily from semileptonic decays of both the t and $\bar{t}$. For the $e\tau_{\text{had}}$ mode, there is a significant contribution from multijet events where two jets are misidentified as leptons. There is also a significant contribution to the $e\mu$ mode from WW diboson production where one W decays to an electron and the other to a muon. Blank entries indicate an insignificant contribution to the background.

The dominant sources of systematic uncertainty for the background predictions arise from the statistical uncertainty on the $W+$jets and multijet background determinations from data, a 10% uncertainty on extrapolation from the subsample to the full sample in the calculation of the $W+$jets backgrounds, theoretical uncertainties on the cross sections of the prompt-lepton background processes (5% to 10%), and the integrated luminosity uncertainty (3.9%). Other systematic uncertainties from the lepton trigger (1%), the product of reconstruction and identification efficiencies (1%, 2%, and 5% for e, μ, and τ, respectively), and the energy/momentum scale and resolution (1%, 1%, and 3% for e, μ, and τ, respectively) are small and have been included. The total systematic uncertainties are calculated for each bin in the $\ell\ell'$ invariant mass, including variations in background compositions, Monte Carlo statistics, uncertainties on performance as a function of kinematics. There are small correlations between the background estimates (for example, from the luminosity), which are included when setting limits.

5. Signal simulation

The production of an RPV $\tilde{\nu}_\tau$ followed by a lepton-flavour-violating decay into $e\mu$, $e\tau$, or $\mu\tau$ is considered in the interpretation of the data. The $\tilde{\nu}_\tau$ may be produced by either $d\bar{d}$ or $s\bar{s}$ but not $u\bar{u}$ annihilation. This search is performed assuming exclusively $d\bar{d}$ production, since $s\bar{s}$ production is expected to be a factor of 10 to 60 lower than $d\bar{d}$ production for the same couplings for sneutrino masses from 400 GeV to 2000 GeV.

In RPV SUSY, the LFV terms of the effective Lagrangian are given by $L = \frac{1}{2}\lambda_{ijk}L_iL_je_k + \lambda'_{ijk}L_iQ_jd_k$ [2,6], where L and Q are the lepton and quark SU(2) supermultiplets, e and d are the lepton and down-like quark singlet supermultiplets, and $i, j, k = 1, 2, 3$ refer to fermion generation number. The theory requires $\lambda_{ijk} = -\lambda_{jik}$. The λ' terms include coupling of downlike quark–antiquark pairs to sneutrinos, and the λ terms include couplings of the sneutrino to distinct charged leptons. For the interpretation of this measurement, the sneutrino is produced with coupling λ'_{311} and decays to $\ell\ell'$ with couplings λ_{132}, λ_{133}, and λ_{233} for $e\mu$, $e\tau$, and $\mu\tau$, respectively.

The signal cross sections are calculated to next-to-leading order [2] using CTEQ6L1 parton distribution functions [19] and depend on the $\tilde{\nu}_\tau$ mass ($m_{\tilde{\nu}_\tau}$), λ'_{311} and λ_{i3k}, where $i \neq k$ are the final-state lepton generations. For the range of couplings considered in this Letter, the width is always less than 5% of the mass. If the couplings are significantly larger than our benchmarks, the use of perturbation theory is not valid. The measurement here is sensitive to the production coupling λ'_{311} and the branching ratio $\tilde{\nu}_\tau \to \ell\ell'$. Monte Carlo events with $\tilde{\nu}_\tau$ decaying into $e\mu$, $e\tau$, and $\mu\tau$ are generated with HERWIG 6.520 [18,28] with sneutrino masses in steps of 50 GeV from 400 GeV to 700 GeV, 100 GeV from 700 GeV to 1600 GeV, and 200 GeV from 1600 GeV to 2000 GeV.

From precision low-energy experiments [6], the best limit on λ'_{311} is $0.012 \times (m_{\tilde{d}}/100\ \text{GeV}) = 0.12$ for the current lower limit on $m_{\tilde{d}}$. The limit on λ_{i3k} is $0.05 \times (m_{\tilde{e}_k}/100\ \text{GeV})$, where $\tilde{e}_k$ is the kth generation slepton. Couplings of $\lambda'_{311} = 0.11$, $\lambda_{i3k} = 0.07$ and $\lambda'_{311} = 0.10$, $\lambda_{i3k} = 0.05$ are used as benchmarks in this Letter. These are consistent with current limits and benchmarks used in previous searches [4,5].

6. Results

The $\ell\ell'$ invariant mass distributions in the signal region are presented in Fig. 1 for data, SM background contributions, and a $\tilde{\nu}_\tau$ with $m_{\tilde{\nu}_\tau} = 500$ GeV and with couplings $\lambda'_{311} = 0.11$ and $\lambda_{i3k} = 0.07$.

The invariant mass spectra above 400 GeV are examined for the presence of an RPV sneutrino. No significant excess of events above the SM expectation is observed, and limits are placed on the production cross section times branching ratio. For each sneutrino mass, the search region is defined to be within $\pm 3\sigma_m$ of the sneutrino mass, where σ_m is the mass resolution, except for $m_{\tilde{\nu}_\tau}$ above 800 GeV, where all events with $m_{\ell\ell'} > 800$ GeV are used. The probability of observing a number of events as a function of the cross section times branching ratio, efficiency, luminosity, and background expectation is constructed from a Poisson distribution. The systematic uncertainties are included by convolving Gaussian distributions, one for each source, with the Poisson distribution. The expected and observed 95% confidence level (CL) upper limits on $\sigma(pp \to \tilde{\nu}_\tau) \times \text{BR}(\tilde{\nu}_\tau \to \ell\ell')$ are calculated as a function of $m_{\tilde{\nu}_\tau}$ using a Bayesian method [29] with a flat prior for the signal cross section times branching ratio and integrating over the nuisance parameters. 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% CL upper limits for each pseudo-experiment at each value of $m_{\tilde{\nu}_\tau}$, including systematic uncertainties. The expected limit is calculated as the median of the distribution of limits. The ensemble of limits is also used to find the 1σ and 2σ envelopes of the expected limits as a function of $m_{\tilde{\nu}_\tau}$. For a sneutrino mass of 500 (2000) GeV, the observed limits on the production cross section times branching ratio are 3.2 (1.4) fb, 42 (17) fb, and 40 (18) fb for the $e\mu$, $e\tau$, and $\mu\tau$ modes, respectively. The $e\tau$ and $\mu\tau$ limits are weaker because (1) the 1-track tau hadronic branching ratio is about 50%, (2) the tau reconstruction efficiency is lower due to criteria needed to reduce jet backgrounds, and (3) the jet backgrounds are significantly larger than for the $e\mu$ mode.

In order to extract mass and coupling limits, it is assumed that only $d\bar{d}$ and $\ell\ell'$ couple to the sneutrino. The theoretical cross sections times branching ratios for $\lambda'_{311} = 0.11$, $\lambda_{i3k} = 0.07$ and $\lambda'_{311} = 0.10$, $\lambda_{i3k} = 0.05$ are also shown in Fig. 2. The branching ratio (in lowest order) for each $\ell\ell'$ mode is $2|\lambda_{i3k}|^2/(2|\lambda_{i3k}|^2 + N_c|\lambda_{311}|^2$, where $N_c = 3$ is the number of colours and the factor of 2 is for the two charge states ($\ell^{\pm}\ell'^{\mp}$). This gives branching ratios of 21% for $\lambda'_{311} = 0.11$, $\lambda_{i3k} = 0.07$ and 14% for $\lambda'_{311} = 0.10$, $\lambda_{i3k} = 0.05$. The uncertainties on the theoretical cross sections are evaluated by varying the factorisation and renormalisation scales (set equal to each other) from $m_{\tilde{\nu}_\tau}/2$ to $2m_{\tilde{\nu}_\tau}$ and varying the parton distribution functions. These uncertainties are indicated as bands in Fig. 2 and are small (only slightly larger than the width of the central line). For couplings $\lambda'_{311} = 0.10$, $\lambda_{i3k} = 0.05$, the lower limits on the $\tilde{\nu}_\tau$ mass are 1610 GeV, 1110 GeV, and 1100 GeV for $e\mu$, $e\tau$, and $\mu\tau$, respectively. These lower limits are a factor of two to three higher than the best limits from the Tevatron for the same couplings [4].

The limits on the cross section times branching ratio are converted to limits on the couplings under the assumption that there are no other significant couplings that contribute to the decay of the $\tilde{\nu}_\tau$. In this case, the dependence of the cross section times branching ratio on the couplings is $|\lambda'_{311}|^2|\lambda_{i3k}|^2/(N_c|\lambda'_{311}|^2 +$

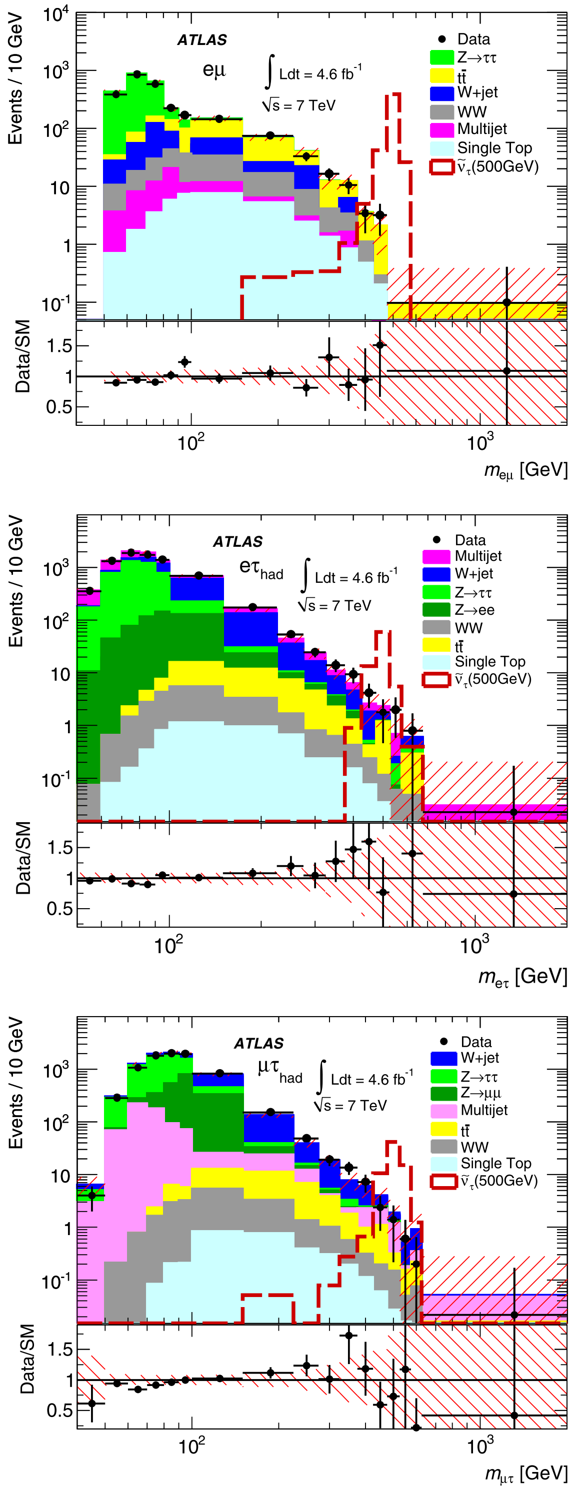

Fig. 1. Observed and predicted $\ell\ell'$ invariant mass distributions for $e\mu$ (top), $e\tau_{\text{had}}$ (middle), and $\mu\tau_{\text{had}}$ (bottom). Signal simulations are shown for $m_{\tilde{\nu}_\tau} = 500$ GeV ($\lambda'_{311} = 0.11$, $\lambda_{i3k} = 0.07$). The region with $m_{\ell\ell'} < 200$ GeV is used to verify the background estimation. The lower plot for each decay mode shows the ratio of the data to the SM backgrounds. The red hatching represents the uncertainty on the total background in all plots. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

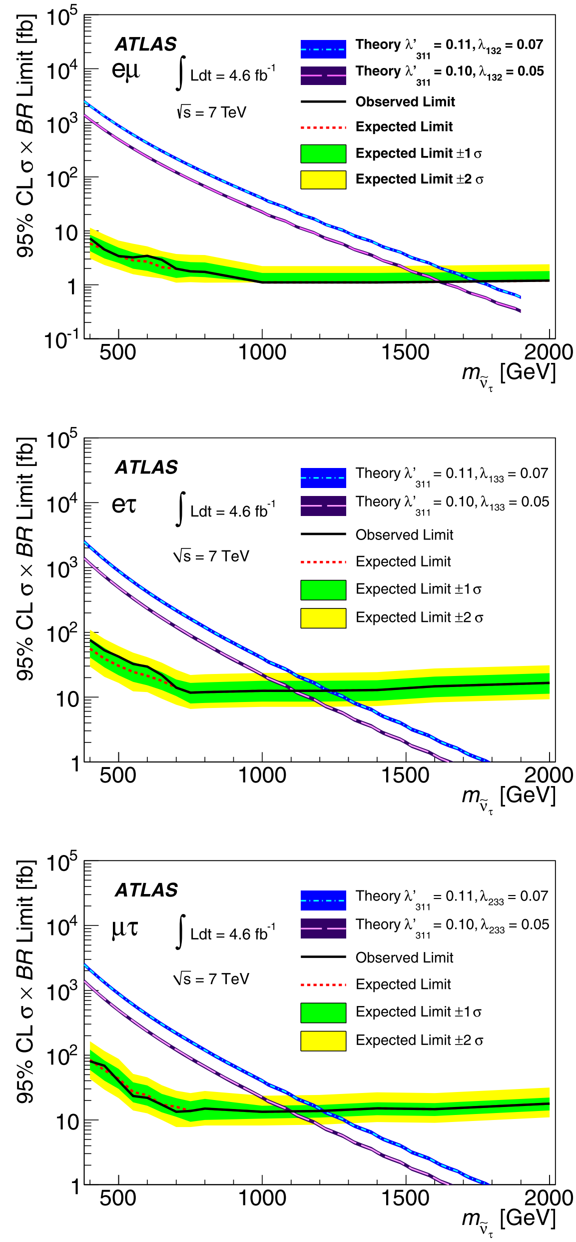

Fig. 2. The 95% CL upper limit on the production cross section times branching ratio as a function of sneutrino mass for $e\mu$ (top), $e\tau$ (middle), and $\mu\tau$ (bottom) modes. The red dotted curve is the expected limit, the black solid curve is the observed limit, and the yellow and green bands give ± 1 and ± 2 standard deviations in the expected limit. The expected theoretical curves for $\lambda'_{311} = 0.11$, $\lambda_{i3k} = 0.07$ (light blue dot-dashed) and $\lambda'_{311} = 0.10$, $\lambda_{i3k} = 0.05$ (light magenta dashed) are also plotted with their uncertainties. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

$2|\lambda_{i3k}|^2$), where the $|\lambda'_{311}|^2$ in the numerator is from the production and the rest is from the branching ratio. The factor $N_c = 3$ is from colour, and the 2 in the denominator comes from accepting both charge states, that is, $\ell^+\ell'^-$ and $\ell^-\ell'^+$. Fig. 3 shows contours of the limit on λ'_{311} as a function of the sneutrino mass for various values of λ_{i3k}. For each curve, the area above the curve is excluded. The previous limit from ATLAS for the $e\mu$ mode, based on 1 fb^{-1} of 7 TeV data [5], is also shown.

7. Summary

A search has been performed for a narrow heavy particle decaying to $e\mu$, $e\tau_{\text{had}}$, or $\mu\tau_{\text{had}}$ final states using 4.6 fb^{-1} of pp collision data at $\sqrt{s} = 7$ TeV recorded by the ATLAS detector at the LHC. The

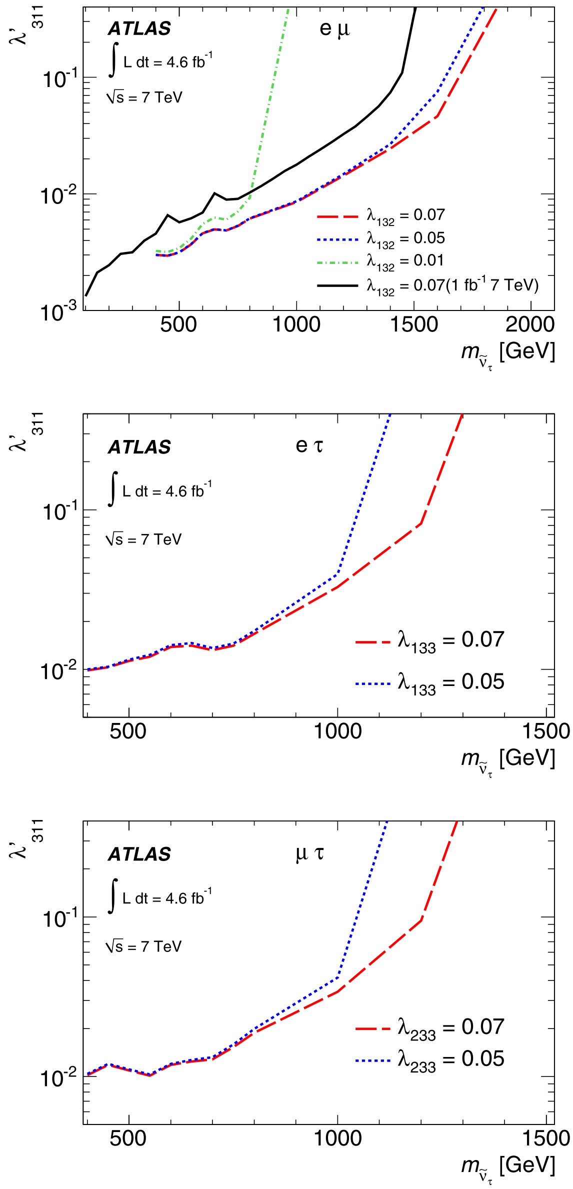

Fig. 3. The 95% CL limits on λ'_{311} as a function of sneutrino mass for assumed values of λ_{i3k} for the $e\mu$ (top), $e\tau$ (middle), and $\mu\tau$ (bottom) modes. For the $e\mu$ mode, the black solid curve is the previous ATLAS result based on 1 fb^{-1} of data at 7 TeV.

data are found to be consistent with SM predictions. Limits are placed on the cross section times branching ratio for an RPV SUSY sneutrino. These results considerably extend previous constraints from ATLAS [5] and the Tevatron experiments [4].

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