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Search for a Heavy Neutral Particle Decaying to $e\mu$, $e\tau$, or $\mu\tau$ in pp Collisions at $\sqrt{s}=8$ TeV with the ATLAS Detector

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This Letter presents a search for a heavy neutral particle decaying into an opposite-sign different-flavor dilepton pair, $e^{\pm}\mu^{\mp}$, $e^{\pm}\tau^{\mp}$, or $\mu^{\pm}\tau^{\mp}$ using 20.3 fb^{-1} of pp collision data at $\sqrt{s}=8$ TeV collected by the ATLAS detector at the LHC. The numbers of observed candidate events are compatible with the standard model expectations. Limits are set on the cross section of new phenomena in two scenarios: the production of $\tilde{\nu}_{\tau}$ in R-parity-violating supersymmetric models and the production of a lepton-flavor-violating Z' vector boson.

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Lepton-flavor-violation (LFV) in the charged sector, if observed at present sensitivities, would be a clear signature of new physics. Such signatures occur in several new physics scenarios, including R-parity-violating supersymmetry (RPV SUSY) [1,2] and models with an additional heavy neutral gauge boson Z' [3] allowing for LFV couplings.

In RPV SUSY, the Lagrangian terms allowing LFV can be expressed as $\frac{1}{2}\lambda_{ijk}L_iL_j\bar{e}_k+\lambda'_{ijk}L_iQ_j\bar{d}_k$ [1], where L and Q are the $SU(2)$ doublet superfields of leptons and quarks; e and d are the $SU(2)$ singlet superfields of leptons and downlike quarks; λ and λ' are Yukawa couplings; and the indices i, j, and k denote fermion generations. A τ sneutrino ($\tilde{\nu}_{\tau}$) may be produced in pp collisions by $d\bar{d}$ annihilation and subsequently decay to $e\mu$, $e\tau$, or $\mu\tau$. Although only $\tilde{\nu}_{\tau}$ is considered here in order to compare with previous searches performed at the Tevatron, the results of our analysis apply to any sneutrino flavor.

The sequential standard model (SSM), where the Z' boson is often assumed to have the same quark and lepton couplings as the standard model (SM) Z boson, can be extended to include LFV couplings for the Z'. The $Z'\to e\mu$, $e\tau$, or $\mu\tau$ couplings (Q_{12}, Q_{13}, or Q_{23}) [4] are typically expressed as fractions of the SSM $Z'\to\ell^+\ell^-$ ($\ell=e,\mu,\tau$) coupling.

Strong limits on RPV couplings have been obtained by precision low-energy searches, such as μ to e conversion on nuclei [5], rare μ decays [6], and rare τ decays [7]. These limits often depend on masses of supersymmetric particles that occur in loop diagrams and assume the dominance of certain couplings. The CDF [8,9], D0 [10,11], and ATLAS [12] collaborations have searched for a $\tilde{\nu}_{\tau}$ in LFV final states and placed limits for various $\tilde{\nu}_{\tau}$ mass hypotheses. Both the CDF [13] and ATLAS [14] collaborations have placed limits on Q_{12} as a function of the Z' mass.

This Letter describes a search for a neutral heavy particle ($\tilde{\nu}_{\tau}$ or Z') decaying into $e^{\pm}\mu^{\mp}$ ($e\mu$), $e^{\pm}\tau^{\mp}_{\mathrm{had}}$ ($e\tau$), or $\mu^{\pm}\tau^{\mp}_{\mathrm{had}}$ ($\mu\tau$) using pp collision data collected at $\sqrt{s}=8$ TeV, where τ_{had} is a τ lepton that decays into hadrons. The ATLAS detector is described in detail elsewhere [15]. Events are selected with a three-level trigger system that requires one or two leptons (e or μ) with high transverse momentum (p_{T}). The data set has a total integrated luminosity of 20.3 ± 0.6 fb^{-1}, where the uncertainty is derived following the same methodology as that detailed in Ref. [16].

Electrons are required to have $p_{\mathrm{T}}>25$ GeV, $|\eta|<1.37$ or $1.52<|\eta|<2.47$ [17], and satisfy the "tight" selection in Ref. [18], which was modified in 2012 to reduce the impact of additional inelastic pp interactions, termed pileup. Muon candidates must have $p_{\mathrm{T}}>25$ GeV, $|\eta|<2.4$ and be reconstructed in both the inner tracker detector and the muon spectrometer. The muon momenta measured by the inner detector and muon spectrometer must match within five standard deviations of their combined uncertainty. Good quality reconstruction and p_{T} resolution at high momentum are ensured by requiring a minimum number of associated hits on the inner detector track [19] and in each of the three muon spectrometer stations.

Candidate events must contain at least one primary interaction vertex reconstructed with more than three associated tracks with $p_{\mathrm{T}}>400$ MeV. If there is more than one such vertex, the one with the highest sum of p_{T}^2 of associated tracks is chosen. The longitudinal impact parameter is required to be smaller than 2 mm for candidate electrons and smaller than 1 mm for candidate muons. It is further required that the transverse impact parameter is less than six times its resolution for candidate electrons, and that the transverse impact parameter is smaller than 0.2 mm for candidate muons. A calorimeter isolation criterion $E_{\mathrm{T}}^{\Delta R<0.2}/E_{\mathrm{T}}<0.06$ and a tracker isolation criterion

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$p_{\mathrm{T}}^{\Delta R<0.4}/p_{\mathrm{T}} < 0.06$ are applied for both the electrons and muons, where $E_{\mathrm{T}}^{\Delta R<0.2}$ is the transverse energy deposited in the calorimeter within a cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ around the lepton, and $p_{\mathrm{T}}{}^{\Delta R<0.4}$ is the sum of the p_{T} of tracks with $p_{\mathrm{T}} > 1$ GeV within a cone size of 0.4 around the lepton. E_{T} and p_{T} are the lepton transverse energy and momentum, respectively.

Hadronic decays of τ leptons are characterized by one or three charged tracks associated with a narrow energy cluster in the calorimeters [20]. This search uses τ_{had} candidates with only one charged track due to reduced identification and reconstruction efficiency for high-p_{T} τ decays with three charged tracks. The identification efficiency of one track τ is around 50% and the fake rate is typically 2%–5%. Boosted-decision-tree multivariate discriminators, based on tracking and calorimeter information, are used to reject jets and electrons misidentified as τ_{had}. The τ_{had} candidates must have $|\eta| < 2.47$ and $E_{\mathrm{T}} > 25$ GeV. Candidates with $|\eta| < 0.03$ are removed to exclude a critical region where the incomplete coverage of the inner tracking detectors and calorimeters contribute to substantially increase the misidentification of electrons.

Jets are reconstructed from clusters of energy in the calorimeter using the anti-k_t algorithm [21] with radius parameter $R = 0.4$. Jet energies are calibrated using Monte Carlo (MC) simulation and a combination of several *in situ* calibrations [22]. The calculation of the missing transverse momentum vector $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ (with magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$) is based on the vector sum of the calibrated p_{T} of reconstructed jets, electrons, and muons, as well as calorimeter energy clusters not associated with reconstructed objects [23].

Candidate signal events are required to have exactly two leptons, of opposite charge and of different flavor, satisfying the above lepton selection criteria. The two leptons are required to be back-to-back in the azimuthal plane with $|\Delta\phi_{\ell\ell'}| > 2.7$, where $\Delta\phi_{\ell\ell'}$ is the ϕ difference between the two leptons. Because of the presence of the undetected neutrino in the τ decay, the E_{T} of the τ_{had} candidate is required to be less than the E_{T} (p_{T}) of the electron (muon) for the $e\tau_{\mathrm{had}}$ ($\mu\tau_{\mathrm{had}}$) channel. Veto on tagged b-jets, to suppress the contribution of final-state top quarks, is not applied since studies have shown no significant impact on the sensitivity of the search.

A collinear neutrino approximation is used to reconstruct the dilepton invariant mass ($m_{\ell\ell'}$) in the $e\tau_{\mathrm{had}}$ and $\mu\tau_{\mathrm{had}}$ channels. In the hadronic decay of a τ lepton from a heavy resonance, the neutrino and the resultant jet are nearly collinear. The four-vector of the neutrino is reconstructed from the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ and η of the τ_{had} jet. Four-vectors of the electron or muon, τ_{had} candidate and neutrino are then used to calculate $m_{\ell\ell'}$. For $e\tau_{\mathrm{had}}$ and $\mu\tau_{\mathrm{had}}$ signal events, the above technique significantly improves the mass resolution and search sensitivity.

Events with $m_{\ell\ell'} < 200$ GeV form a validation region to verify the background modeling, and events with $m_{\ell\ell'} > 200$ GeV are used as the search region.

The SM processes that produce $\ell^{\pm}\ell'^{\mp}$ final states can be divided into two categories: processes that produce two prompt leptons such as $Z/\gamma^* \to \tau\tau$, $t\bar{t}$, single-top Wt channel, diboson production, and processes where one or more photons or jets are misidentified as leptons, predominantly $W/Z + \gamma$, $W/Z +$ jets, and multijet events. The decay of a τ to an electron or a muon is considered as prompt production. For the $e\tau_{\mathrm{had}}$ ($\mu\tau_{\mathrm{had}}$) channel, additional background can originate from the $Z/\gamma^* \to ee(\mu\mu)$ process if one lepton is misidentified as a τ_{had} candidate. The contributions of these processes are even larger with respect to the $Z/\gamma^* \to \tau\tau$ background, since the final states e or μ are usually harder than those from leptonic τ decay.

Contributions from processes in the prompt two-lepton category, as well as photon-related and $Z/\gamma^* \to ee(\mu\mu)$ backgrounds, are estimated using MC simulation [24]. The detector response model is based on the GEANT4 program [25]. Lepton reconstruction and identification efficiencies, energy scales, and resolutions in the MC simulation are corrected to the corresponding values measured in the data. Pileup is included to match distributions observed in the data. Top quark production is generated with MC@NLO v4.06 [26–28] for $t\bar{t}$ and single-top, the Drell–Yan process ($Z/\gamma^* \to \ell\ell$) is generated with ALPGEN v2.14 [29], and diboson processes are generated with HERWIG v6.520.2 [30]. Samples of $W\gamma$ and $Z\gamma$ events are generated with SHERPA v1.04 [31–34]. These generated samples are normalized to the most accurate available cross-section calculations, and the uncertainties on the calculations have been included in the overall uncertainty for the SM predictions. For the dominant backgrounds, the Drell–Yan processes are corrected to next-to-next-to-leading order (NNLO) [35], and $t\bar{t}$ is corrected to NNLO, including soft-gluon resummation to next-to-next-to-leading-logarithm order [36,37].

Since it is difficult to model misidentification of jets as leptons, particularly at high p_{T}, the $W +$ jets and multijet backgrounds are determined from control regions in the data. The $W +$ jets background is determined in a control region selected with the same criteria as that used for the signal selection except requiring $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV (to enhance the W contribution) and requiring that the electron or muon p_{T} be less than 150 GeV (to eliminate potential signal). Simulation studies indicate there is negligible multijet background in this control region. For the $e\tau_{\mathrm{had}}$ and $\mu\tau_{\mathrm{had}}$ channels, the number of events in the control region is corrected for the other SM background sources using MC samples. For the $e\mu$ channel, the number of $W +$ jets events in the control region is too small to yield a statistically meaningful measurement. Instead, the control region is enlarged by removing the isolation criterion on one lepton, and the $W +$ jets contribution is estimated using the lepton $E_{\mathrm{T}}^{\Delta R<0.2}/E_{\mathrm{T}}$ distribution to fit the data with the MC predictions for other SM processes (dominant at low values of the isolation variable) and $W +$ jets (dominant at large values). For the $W +$ jets background in all three

TABLE I. Estimated SM backgrounds and observed event yields for the validation ($m_{\ell\ell'} < 200$ GeV) and search ($m_{\ell\ell'} > 200$ GeV) regions. Both the statistical and systematic uncertainties are included. $Z/\gamma^* \to \mu\mu$ background is larger in the validation region since the probability for muons to be misidentified as taus mainly depends on anomalously large calorimeter deposits that have a larger impact on low p_{T} muons. Because of correlations, particularly anitcorrelations of the $W+$jet and multijet contributions, the total uncertainties are not exactly the sum in quadrature of the components.

	$m_{\ell\ell'} < 200$ GeV			$m_{\ell\ell'} > 200$ GeV		
Process	$N_{e\mu}$	$N_{e\tau_{\mathrm{had}}}$	$N_{\mu\tau_{\mathrm{had}}}$	$N_{e\mu}$	$N_{e\tau_{\mathrm{had}}}$	$N_{\mu\tau_{\mathrm{had}}}$
$Z/\gamma^* \to \tau\tau$	6000 ± 400	11000 ± 900	11200 ± 700	28 ± 12	72 ± 21	99 ± 33
$Z/\gamma^* \to ee$	—	6100 ± 1100	—	—	430 ± 70	—
$Z/\gamma^* \to \mu\mu$	—	—	19500 ± 1300	—	—	410 ± 80
$t\bar{t}$	4220 ± 290	690 ± 60	580 ± 50	1640 ± 120	700 ± 60	550 ± 40
Diboson	1440 ± 80	321 ± 29	258 ± 17	474 ± 30	197 ± 17	141 ± 11
Single top quark	470 ± 40	87 ± 11	60 ± 7	202 ± 17	90 ± 10	73 ± 8
$W+$jets	54 ± 18	17000 ± 4000	14000 ± 4000	8 ± 4	3600 ± 700	2800 ± 600
Multijet	227 ± 32	4800 ± 1000	700 ± 800	58 ± 12	340 ± 210	100 ± 190
Total	12400 ± 600	40400 ± 2900	46000 ± 4000	2400 ± 130	5400 ± 500	4200 ± 400
Data	12954	41304	48304	2474	5336	4184

channels, the extrapolation factor from the control region to the signal region and the shape of the $m_{\ell\ell'}$ distribution are taken from the $W+$jets MC sample.

The contribution from multijet production is estimated from a control region with the same selection as the signal region except that the leptons are required to have the same electric charge, under the assumption that the probability of misidentifying a jet as a lepton is independent of the charge. The number of events in this same-sign control region is corrected for contributions from backgrounds with prompt leptons and from $W+$jets backgrounds using the procedure described above. The assumption of charge independence of the jet misidentification rates is tested in a multijet-enriched region with two nonisolated leptons. After subtraction of other SM backgrounds, the ratio of opposite-sign to same-sign events is found to be $1.07 \pm 0.06(\mathrm{stat}) \pm 0.02(\mathrm{syst})$.

The background estimates are verified in validation regions defined with the same selection criteria as for the signal regions but with $1.0 < |\Delta\phi_{\ell\ell'}| < 2.7$. In these validation regions, simulation studies show the backgrounds have compositions similar to the signal regions, and the predictions agree with the data within 20% over the entire $m_{\ell\ell'}$ range. An uncertainty of 20% is hence placed on the total background estimate that is used in the final results.

MC signal events are generated with HERWIG v6.520.2 for $\tilde{\nu}_\tau$ and PYTHIA v8.165 [38,39] for Z'. Samples are produced with $\tilde{\nu}_\tau$ and Z' masses ranging from 0.5 to 3 TeV. Signal cross sections are calculated to next-to-leading order for $\tilde{\nu}_\tau$ [40], and NNLO for Z' [35]. The theoretical uncertainties are taken from an envelope of cross-section predictions using different parton distribution function (PDF) sets and factorization and renormalization scales [41,42].

The signal selection efficiency (including τ decay branching ratio if τ is involved) for $m_{\tilde{\nu}_\tau} = 2$ TeV are 42%, 14%, and 10% in the $e\mu$, $e\tau$, and $\mu\tau$ channels, respectively. The corresponding numbers for a Z' boson with $m_{Z'} = 2$ TeV are 37%, 11%, and 9%. The systematic uncertainties on the signal efficiency vary from 3% to 6% depending on the resonance mass and decay mode. The primary contributions are due to the number of MC events, and the uncertainties related to the muon and τ p_{T} scales.

The observed and expected event yields in both the validation and search $m_{\ell\ell'}$ regions for all three final states are in good agreement, as summarized in Table I. The $m_{\ell\ell'}$ distributions (Fig. 1) show no significant excess above the SM expectation in any of the three modes. The dominant contributions to the uncertainty bands in Fig. 1 are due to the number of MC events, the MC cross-section uncertainties, the $E_{\mathrm{T}}^{\mathrm{miss}}$ scale and resolution, and the uncertainty in the shape of the $m_{\ell\ell'}$ distribution for $W+$jets.

Upper limits are placed on the production cross section times branching ratio $[\sigma(pp \to \tilde{\nu}_\tau/Z') \times \mathrm{BR}(\tilde{\nu}_\tau/Z' \to \ell\ell')]$. For each $\tilde{\nu}_\tau$ or Z' mass, m, the search region is defined to be $m \pm 3\sigma_{\ell\ell'}$, where $\sigma_{\ell\ell'}$ is the standard deviation of the simulated signal $m_{\ell\ell'}$ distribution. The relative width of the signal $m_{\ell\ell'}$ distribution ranges from 3% to 17% for different mass points, channels, and models. To increase the signal efficiency, if the upper side of the search region is greater than 1 TeV, all events above 1 TeV are used. To further reduce the effect of fluctuations in the high-mass region due to low MC event counts, the number of background events in each mass window is estimated using a double exponential fit to the total background $m_{\ell\ell'}$ distribution. The fit uncertainty is taken into account in the limit-setting procedure, including a contribution from varying the fit function range.

A frequentist technique [43] is used to set the expected and observed upper limits as a function of $m_{\tilde{\nu}_\tau}$ and $m_{Z'}$. The likelihood of observing the number of events in data as a function of the expected number of signal and background events is constructed from a Poisson distribution for each

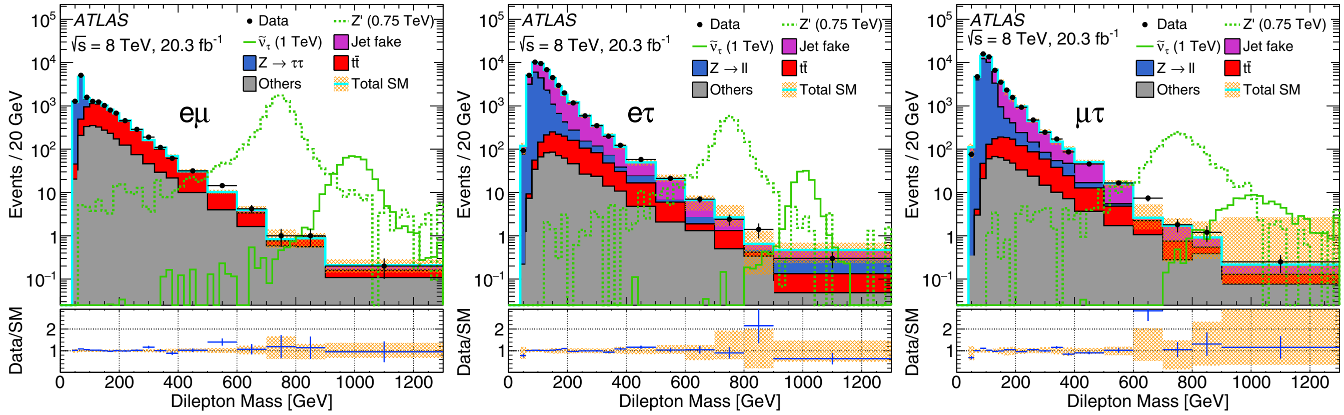

FIG. 1 (color online). Observed and predicted $e\mu$, $e\tau_{\rm had}$, $\mu\tau_{\rm had}$ invariant mass distributions. The contributions of the different processes are also shown: "Others" includes diboson and single-top while "Jet fake" refers to $W+$jets and multijet. All overflows are included in the rightmost bin. Signal simulations are shown for $m_{\tilde{\nu}_\tau}=1$ TeV and $m_{Z'}=0.75$ TeV. The couplings $\lambda'_{311}=0.11$ and $\lambda_{i3k}=0.07$ ($Q_{\ell\ell'}=1$) are used for the RPV (Z') model. The uncertainty bands include both the statistical and systematic uncertainties.

$m_{\ell\ell'}$ bin. Systematic uncertainties are taken into account with Gaussian-distributed nuisance parameters. A 95% confidence level (C.L.) limit is then determined. The expected exclusion limits are determined, using simulated pseudoexperiments containing only background processes, as the median of the 95% C.L. limit distributions for each set of pseudoexperiments at each value of $m_{\tilde{\nu}_\tau}$ or $m_{Z'}$, including systematic uncertainties. The ensemble of limits is also used to assess the 1σ and 2σ uncertainty envelopes of the expected limits.

Figure 2 shows the observed and expected cross section times branching ratio limits as a function of $m_{\tilde{\nu}_\tau}(m_{Z'})$, together with the $\pm1\sigma$ and $\pm2\sigma$ uncertainty bands. For a $\tilde{\nu}_\tau$ mass of 1 TeV, the observed limits on the production cross section times branching ratio are 0.5 fb, 2.7 fb, and 9.1 fb for the $e\mu$, $e\tau$, and $\mu\tau$ channels, respectively. The corresponding limits for a Z' boson mass of 1 TeV are 1.0 fb, 4.0 fb, and 9.9 fb for the $e\mu$, $e\tau$, and $\mu\tau$ channels, respectively.

Theoretical predictions of cross section times branching ratio are also shown, assuming $\lambda'_{311}=0.11$ and $\lambda_{i3k}=0.07$ for the $\tilde{\nu}_\tau$ and $Q_{ij}=1$ for the Z', consistent with benchmark couplings used in previous searches.

For these benchmark couplings, the lower limits on the $\tilde{\nu}_\tau$ mass are 2.0 TeV, 1.7 TeV, and 1.7 TeV for the $e\mu$, $e\tau$, and $\mu\tau$ channels, respectively. The corresponding lower

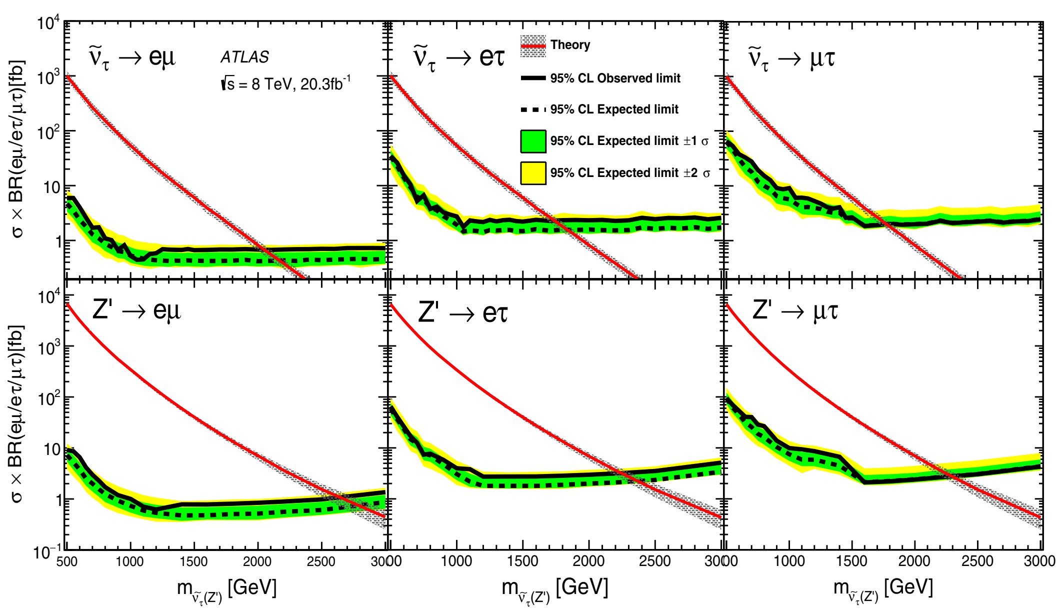

FIG. 2 (color online). The 95% C.L. limits on cross section times branching ratio as a function of $\tilde{\nu}_\tau$ mass (top plots) and Z' mass (bottom plots) for $e\mu$ (left), $e\tau$ (middle), and $\mu\tau$ (right). Theory curves are for the arbitrary choice of couplings $\lambda'_{311}=0.11$ and $\lambda_{i3k}=0.07$ for $\tilde{\nu}_\tau$ and $Q_{\ell\ell'}=1$ for Z'. The gray band around the theory curve represents the theoretical uncertainty from the PDFs and factorization and renormalization scales.

limits on the Z' mass are 2.5 TeV, 2.2 TeV, and 2.2 TeV for the $e\mu$, $e\tau$, and $\mu\tau$ channels, respectively. The observed lower mass limits are a factor of three to four higher than the best limits from the Tevatron [8–11] and 1.5 to 2 times better than the previous limits from ATLAS [12] for the same couplings.

In summary, a search has been performed for a heavy particle decaying to $e\mu$, $e\tau_{\rm had}$, or $\mu\tau_{\rm had}$ final states using 20.3 fb^{-1} of pp collision data at $\sqrt{s} = 8$ TeV recorded by the ATLAS detector at the LHC. The data are found to be consistent with SM predictions. Limits are placed on the cross section times branching ratio for an RPV SUSY $\tilde{\nu}_\tau$ and a LFV Z' boson. These results considerably extend previous constraints from the Tevatron and LHC experiments.

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