Searches for Charged Lepton Flavor Violation with the ATLAS Detector at the LHC*

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(Dated: April 19, 2016)

Abstract

ATLAS has searched for charged lepton flavor violation in several processes, including decays of Standard Model particles ($H \to \mu\tau$ and $Z \to e\mu$) and beyond the Standard Model physics (Z' or $\tilde{\nu}$ decay, $\tilde{t} \to \ell b$, neutralino decay in R-parity-violating supersymmetry theories, decays of Quantum Black Holes, and decays of heavy Majorana neutrinos). No significant excess of events over Standard Model expectations is seen and limits are set.

INTRODUCTION

Neutrino oscillations show that lepton flavor is not a good symmetry of Nature. An important and interesting question is whether charged leptons also exhibit lepton flavor violation (LFV).

ATLAS looked for several possible signatures of charged lepton flavor violation, including Higgs $\to \mu\tau$; $Z \to e\mu$; Z' or $\tilde{\nu} \to e\mu$, $e\tau$, or $\mu\tau$; $\tilde{t}$ decay in a B-L R-parity violating (RPV) supersymmetry (SUSY) theory; multilepton events or displaced vertices in RPV SUSY; decays of Quantum Black Holes; and production of heavy, Majorana neutrinos. No excess of events over Standard Model (SM) expectations was seen and limits were set. Some of these limits are compatible with or exceed limits on couplings from precision, low-energy experiments.

LHC AND THE ATLAS EXPERIMENT

The Large Hadron Collider (LHC) collides protons with protons at high energy. All the results in this article are from 20.3 fb^{-1} of data with a center-of-mass energy of 8 TeV taken during 2012 with the ATLAS detector.

ATLAS [1] is one of four major detectors at the LHC. It is a general purpose detector with roughly cylindrical symmetry. The inner tracking volume consists of silicon strip detectors, silicon pixel detectors, and transition radiation detectors surrounded by a 2 T superconducting solenoid. Outside the solenoid and in the endcap regions are lead-liquid Argon electromagnetic calorimeters followed by steel-scintillator hadronic calorimeters. Outside the calorimeters is the muon spectrometer consisting of trigger chambers, three layers of precision tracking chambers, and superconducting magnets giving a toroidal field.

The physics objects most important for the analyses presented here are electrons, muons, jets, and missing transverse momentum. Electrons are identified from a track in the inner detector associated with energy deposited in the electromagnetic calorimeter consistent with an electron. Muons are combined inner tracks and muon spectrometer tracks. Jets are identified from local energy clusters in the calorimeters by the anti-k_t algorithm with a distance parameter of 0.4. The missing tranverse momentum vector is the negative of the sum of the momentum vectors in the plane transverse to the beam of the physics objects (electrons, muons, photons, and jets) and any energy clusters in the calorimeters not associated with these objects. The magnitude of the missing transverse momentum vector is known as the missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$).

HIGGS $\rightarrow \mu\tau$

The observation of the Higgs boson completes the Standard Model (SM) but also raises many important questions, including "Is this the SM Higgs?" Observation of non-SM decays, such as LFV decays, would be direct evidence for physics beyond the SM.

Possible LFV Higgs decays include $H \rightarrow e\mu$, $H \rightarrow e\tau$, and $H \rightarrow \mu\tau$. The decay $H \rightarrow e\mu$ is constrained to have a branching ratio less than about 10^{-8} from low energy results limits on $\mu \rightarrow e\gamma$, but the decay $H \rightarrow \mu\tau$ could be as large as $\sim$10% and not be in conflict with low energy limits (Ref. [2] and references therein).

ATLAS searched for the decay $H \rightarrow \mu\tau$ [2] in events with a muon with transverse momentum $p_{\mathrm{T}} > 26$ GeV and a hadronic tau decay with $p_{\mathrm{T}} > 45$ GeV. Two signal regions and two control regions (one for W + jets and one for $t\bar{t}$ and single-top production) were defined based on the transverse masses of the muon-$E_{\mathrm{T}}^{\mathrm{miss}}$ and τ_{had}–$E_{\mathrm{T}}^{\mathrm{miss}}$ systems, the number of jets, and the number of b-tagged jets. The number of events in each region were simultaneously fit to constrain the backgrounds and search for a possible signal.

The data along with the SM expectations and a possible Higgs signal are shown in Figure 1 for the two signal regions combined. No significant excess of events was seen, and a 95% confidence level (CL) limit was placed on the $H \rightarrow \mu\tau$ branching ratio of 1.92%, compared to an expected limit of 1.24%.

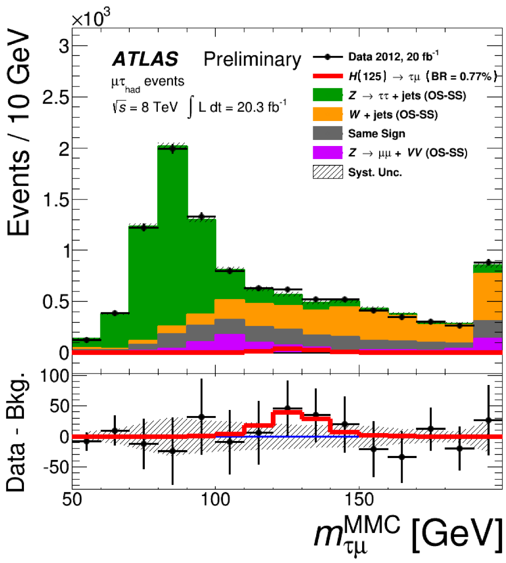

FIG. 1: The $\mu\tau$ invariant mass distribution for the combined signal regions showing the data, SM expected background, and a potential Higgs decay for BR = 0.77% (taken from Ref. [2]).

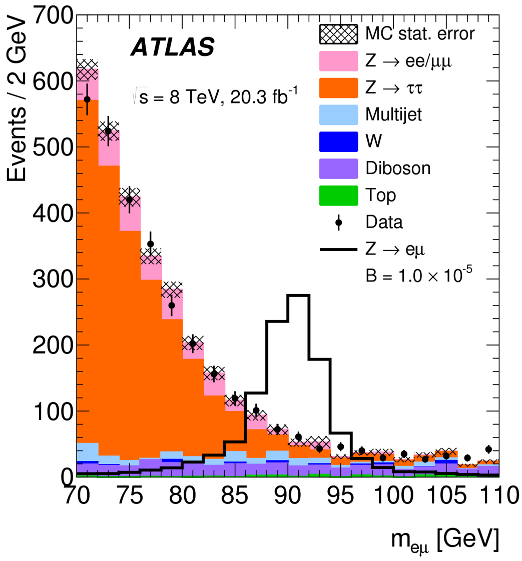

FIG. 2: The $e\mu$ invariant mass after all selections showing the data, expected backgrounds, and a potential signal for a branching ratio of 10^{-5} (taken from Ref. [3]).

$Z \to e\mu$

A search for the LFV decay $Z \to e\mu$ was done [3]. Events were required to have exactly one electron with $p_{\mathrm{T}} > 25$ GeV and exactly one muon with $p_{\mathrm{T}} > 25$ GeV and opposite sign. Events with a jet with $p_{\mathrm{T}} > 30$ GeV or $E_{\mathrm{T}}^{\mathrm{miss}} > 17$ GeV were rejected.

The resulting e-μ invariant mass distribution (Figure 2) was fit to a background distribution plus a signal contribution. No significant signal contribution was found, and the limit on the branching ratio was determined to be $\mathrm{BR}(Z \to e\mu) < 7.5 \times 10^{-7}$ at the 95% CL. This improves upon the previous limit from LEP of 1.6×10^{-6} but is not as low as the inferred limit of $\sim 10^{-12}$ from limits on the decay $\mu \to eee$.

Z' or $\tilde{\nu} \to e\mu$, $e\tau$, or $\mu\tau$

ATLAS searched for production of a resonance decaying to $e\mu$, $e\tau$, or $\mu\tau$ [4]. A spin-0 resonance was modeled as an RPV sneutrino. A spin-1 resonance was modeled as a Z' with the same couplings to quarks as the Z boson.

For this search, only 1-prong hadronic tau decays were used. The missing transverse

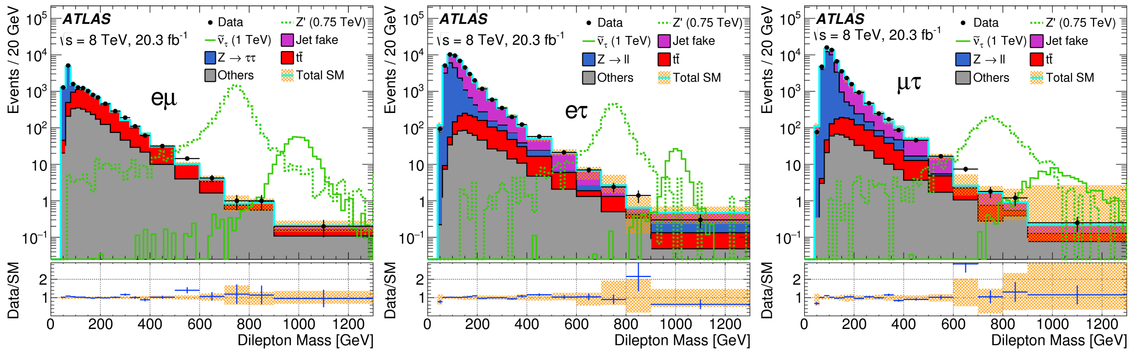

FIG. 3: The $e\mu$, $e\tau$, and $\mu\tau$ invariant mass distributions showing the data, expected SM backgrounds, and potential signals (taken from Ref. [4]).

momentum vector and the assumption that the neutrino in the tau decay is collinear with the visible tau decay products was used to correct the tau's momentum, which significantly improved the dilepton invariant mass resolution.

Events were selected with two leptons of different flavor and opposite sign. Each lepton had $p_{\mathrm{T}} > 25$ GeV. The dilepton invariant masses distributions are shown in Figure 3. No significant excesses above the SM expectations were seen, and the limits on cross sections times branching ratios at the 95% CL are shown in Figure 4.

In RPV SUSY, the sneutrino couples only to down-like quarks, d and s in this case. The coupling dependences and model assumptions are different for the ATLAS resonance search than for low-energy experiments, but the ATLAS limits are comparable or better than those from low-energy experiments for all the tau modes and for $s\bar{s} \to \tilde{\nu} \to e\mu$. The low-energy limits from μ-e conversion ($K_L \to e\mu$) are about an order of magnitude better than those from ATLAS for the production of $e\mu$ via $d\bar{d}$, $d\bar{s}$, or $s\bar{d}$.

STOP SQUARK $\tilde{t} \to \ell b$

A possible extension of supersymmetry is the addition of an R-parity violating (RPV) B-L U(1) symmetry which violates lepton number but not baryon number (Ref. [5] and references therein). In one such model, the stop squark $\tilde{t}$ is the lightest SUSY particle and decays to $b\ell$, where ℓ is a charged lepton.

ATLAS searched for $\tilde{t}$ pair production followed by decay to either be or $b\mu$ [5], giving events with two b-tagged jets and dileptons (ee, $\mu\mu$, or $e\mu$) of opposite sign. Events with

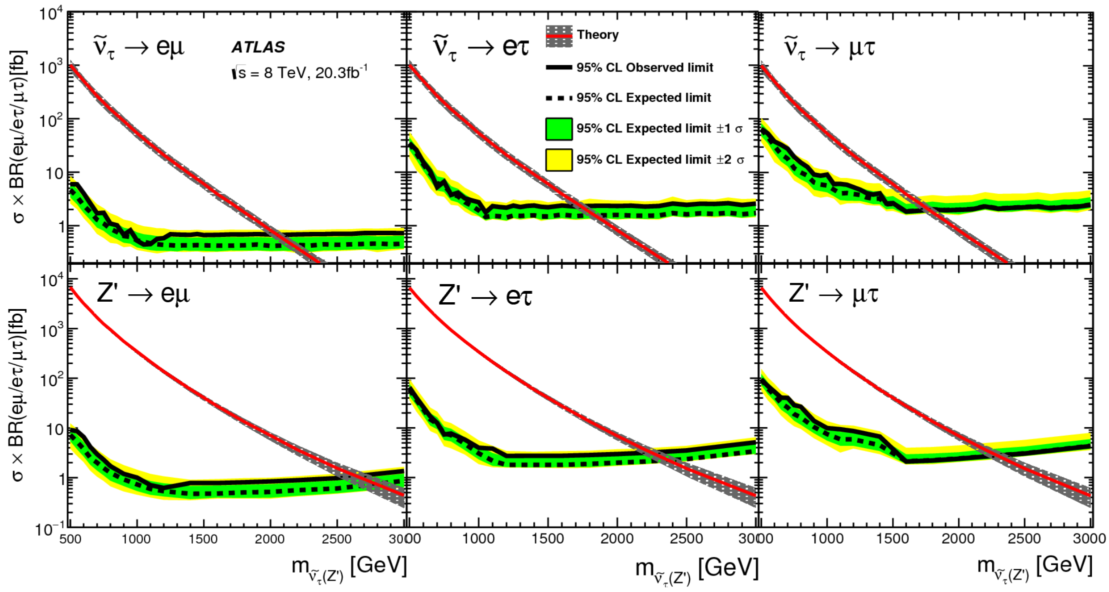

FIG. 4: The 95% CL limits on the cross section times branching ratio for $\tilde{\nu}$ (top) or Z' (bottom) decaying to $e\mu$, $e\tau$, or $\mu\tau$ (taken from Ref. [4]).

same flavor leptons with an invariant mass consistent with the Z mass were rejected. The jet-lepton pairing that gave the smallest difference between the masses of the two lepton-jet combinations was chosen. The lepton-jet invariant masses, their difference, and H_{T} (the scalar sum of the transverse momenta of the two b-jets and the two leptons) were used to define two signal regions and several control regions. Two events were observed, consistent with SM expectations. The 95% CL regions in the BR($\tilde{t} \to b\tau$) versus BR($\tilde{t} \to be$) plane (the sum of the branching ratios to be, $b\mu$, and $b\tau$ was constrained to one) is shown in Figure 5 for various $\tilde{t}$ masses.

MULTILEPTON EVENTS AND DISPLACED VERTICES IN RPV SUSY

In RPV SUSY, the lighest supersymmetric particle (LSP) (assumed to be a neutralino $\tilde{\chi}$ here) is not stable. ATLAS searched for neutralino decays with leptons ($\tilde{\chi} \to \ell\ell\nu$, $q\bar{q}\ell$, or $q\bar{q}\nu$) [6]. The neutralinos were assumed to be pair-produced either via gluinos ($q\bar{q} \to \tilde{g}\tilde{g} \to q\bar{q}\tilde{\chi}q\bar{q}\tilde{\chi}$) or squarks ($q\bar{q} \to \tilde{q}\bar{\tilde{q}} \to q\tilde{\chi}\bar{q}\tilde{\chi}$), leading to events with multiple leptons.

Events with 4ℓ, $3\ell\tau$, $2\ell 2\tau$, 3ℓ, or $\ell^{\pm}\ell^{\pm}$ were selected, where ℓ is e or μ. Any event consistent with coming from $Z \to \ell\ell$, $\ell\ell\gamma$, or $\ell\ell\ell\ell$ was rejected. The numbers of observed events were compatible with SM expections, and 95% CL limits were placed on various

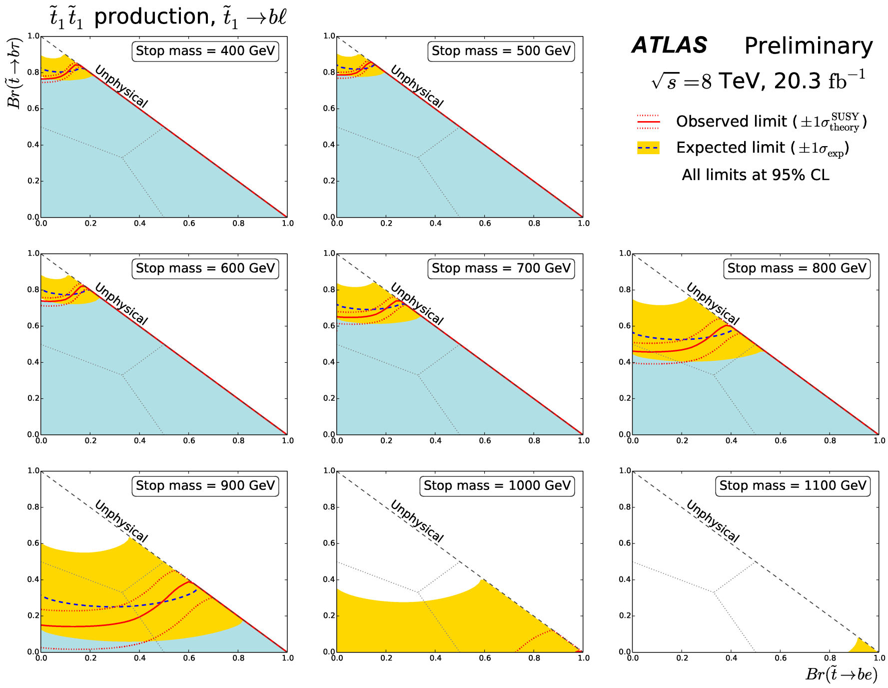

FIG. 5: Observed and expected limits on the $\tilde{t}$ leptonic branching ratios for various $\tilde{t}$ masses. The areas under the solid red curves are excluded at the 95% CL. The dashed lines are the expected limits (taken from Ref. [5]).

production mechanisms dependent on the gluino or squark mass. An example limit plot is shown in Figure 6, showing the limits on the gluino mass assuming $m_{\tilde{\chi}}/m_{\tilde{g}} = 0.1$ and using the $\ell\ell\ell$ and $\ell^{\pm}\ell^{\pm}$ events as a function of the neutralino branching ratios to taus for left-handed ($BR(\tau_L)$) and right-handed ($BR(\tau_R)$) superfields.

If the RPV SUSY couplings are sufficiently small, the LSP may live sufficiently long to give a displaced secondary vertex. ATLAS searched for displaced vertices with either one lepton (e or μ) or two leptons (ee, $\mu\mu$, or $e\mu$) [7]. Observed events were consistent with SM expectations. Limits depend on SUSY masses, the production mechanism, SUSY parameters. An example cross section limit is shown in Figure 7.

QUANTUM BLACK HOLES

In theories with large extra dimensions, it is possible to produce Quantum Black Holes at the LHC (Ref. [8] and references therein). For black holes, only quantum numbers associated with local gauge invariance (such as charge and color) are expected to be conserved, allowing for violation of both lepton flavor and lepton number. ATLAS searched for Quantum Black

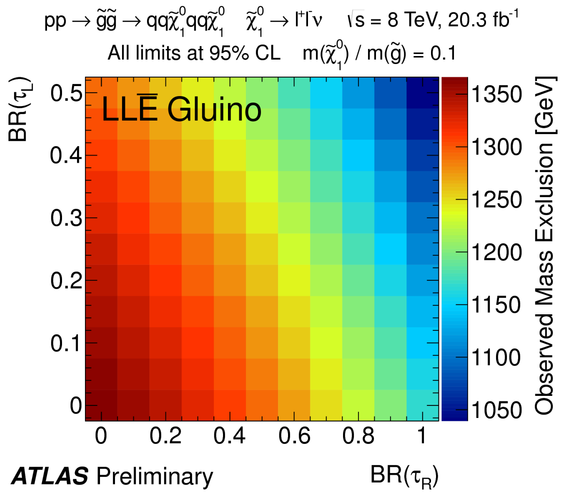

FIG. 6: Limits on the gluino mass assuming $m_{\tilde{\chi}}/m_{\tilde{g}} = 0.1$ and using $\ell\ell\ell$ and $\ell^{\pm}\ell^{\pm}$ events (taken from Ref. [6]).

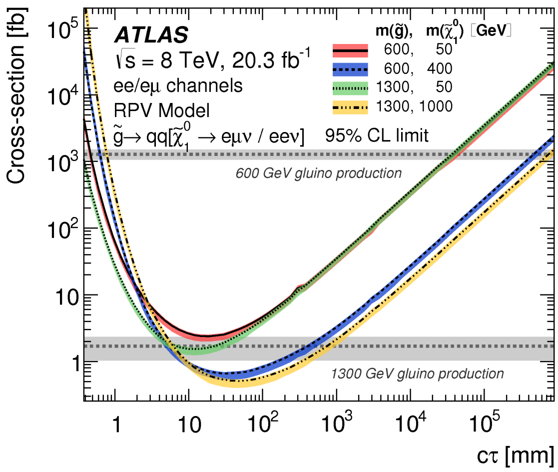

FIG. 7: Limit on the cross section as a function of $c\tau$ for displaced vertices with ee or $e\mu$ (taken from Ref. [7]).

Holes decaying to a lepton (e or μ) plus a jet [8]. Figure 8 shows the e-jet and μ-jet invariant mass distributions for the data, expected SM backgrounds, and potential Black Hole signals. Limits were placed on the cross section times branching ratio as a function of the model parameter M_{th} (Figure 9).

ATLAS also searched for Black Holes in other modes that have LFV in the model but where it would not be manifest in the signal [9, 10].

HEAVY MAJORANA NEUTRINOS

A very important question in neutrino physics is whether they are Dirac or Majorana particles. In some theories, such as those with a see-saw mechanism or left-right symmetric models, the partner to a Majorana neutrino is expected to be heavy (Ref. [11] and references therein). Furthermore, different flavor heavy neutrinos can in principle mix, giving rise to lepton flavor violation.

ATLAS searched for heavy neutrinos in events with two same-sign leptons ($e^{\pm}e^{\pm}$ or $\mu^{\pm}\mu^{\pm}$) with at least two jets that might be produced in processes such as those shown in Figure 10 [11]. No excess of events was seen over SM expectations, and limits were placed at the 95% CL. The limits depend on the mode and the masses of the additional gauge bosons in the model. An example of an excluded region in the mass of the heavy neutrino (m_N) versus the mass of a right-handed W (m_{W_R}) plane for the $\mu\mu$ is shown in Figure 11.

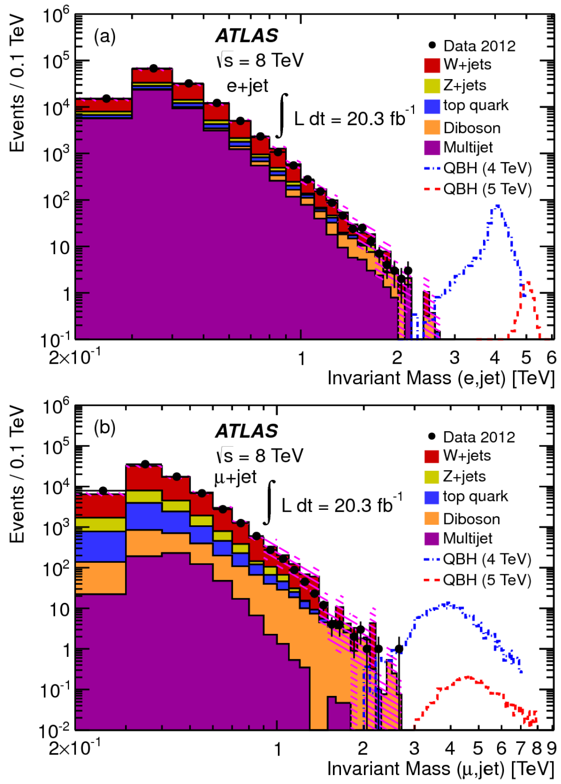

FIG. 8: Invariant mass distributions for e-jet (left) and μ-jet (right) showing the data, SM backgrounds, and potential Black Hole signals (taken from Ref. [8]).

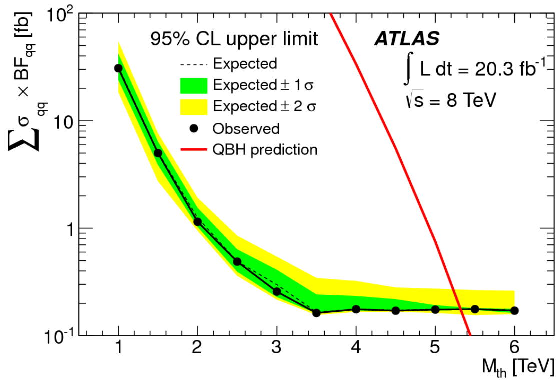

FIG. 9: Limit on the cross section times branching ratio for production of a Black Hole decaying to lepton + jet as a function of the model paramter M_{th} (taken from Ref. [8]).

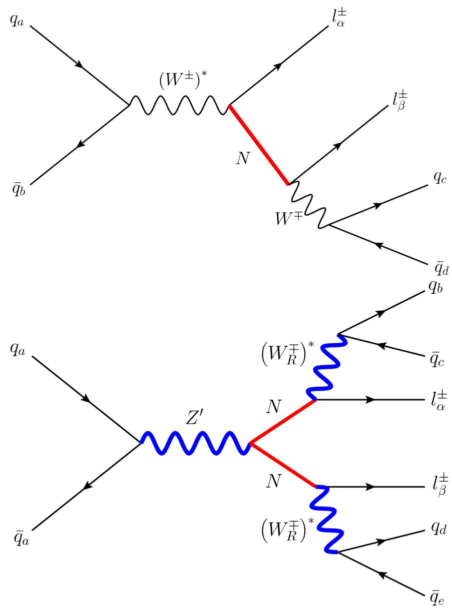

FIG. 10: Possible processes for producing same-sign dilepton events via heavy neutrinos (taken from Ref. [11]).

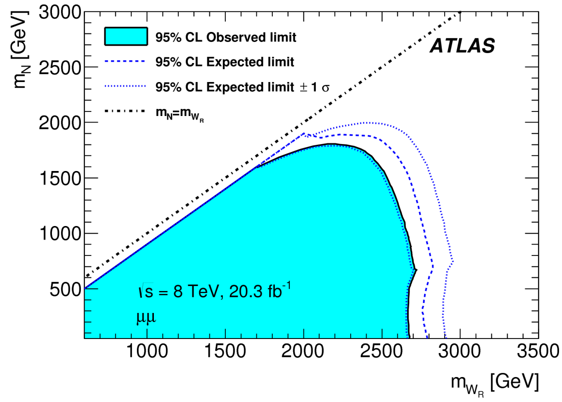

FIG. 11: Excluded region in the heavy neutrino mass versus right-handed W mass plane for the $\mu\mu$ mode (taken from Ref. [11]).

CONCLUSIONS

ATLAS has searched for LFV signatures in both SM particle decays (H and Z) and in processes from beyond the SM physics. No excess of events over SM expectations was seen, and limits were placed, some of which are comparable or better than those from precision, low-energy experiments. Since the coupling dependences and model assumptions for limits from the LHC and from low-energy experiments are often different, these measurements complement each other.

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* *Presented at NuFact15, 10-15 Aug 2015, Rio de Janeiro, Brazil [C15-08-10.2]*

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