LFV searches by ATLAS and CMS experiments

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Abstract

The appearance of lepton-flavour-violating processes in LHC proton-proton collisions is one of the possible ways that new physics beyond the Standard Model could manifest itself. This proceeding summarizes the most recent searches for lepton-flavour-violating processes and tests of lepton flavour universality with the ATLAS and CMS detectors, using proton-proton collisions at a centre-of-mass energy of 13 TeV.

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Contents

1 Introduction

The Large Hadron Collider (LHC) physics programme has among its main activities the search for new physics processes beyond the Standard Model (SM). Lepton-flavour-violation (LFV) is one of the possible ways that new physics could manifest itself.

LFV is forbidden by construction in the SM and it has never been observed for charged leptons, but neutrino oscillations prove that LFV is possible in Nature. Many extensions of the SM allow LFV processes involving charged leptons. For instance, LFV decays of the Z boson are predicted by models with heavy neutrinos [1], extended gauge models [2] and supersymmetry (SUSY) [3], which also allows for LFV decays of the Higgs boson [4,5]. SUSY models also allow the possibility of LFV decays of the τ-lepton into charged leptons, such as $\tau \to 3\mu$ [6]. Additionally, while the universality of lepton couplings has been confirmed with very high precision by many low-energy experiments, recent results from LHCb [7,8], Belle [9] and BaBar [12] collaborations show some tension with the SM, motivating the need for further measurements in this sector. In this proceeding, the latest tests of lepton flavour conservation and universality by ATLAS [10] and CMS [11] experiments with Run 2 data of the LHC are presented.

2 Searches and projections for $\tau \to 3\mu$ decay

The CMS collaboration has performed a search for $\tau \to 3\mu$ decay using 33.2 fb^{-1} of Run 2 data at a centre of mass energy of 13 TeV [13]. The main sources of τ-leptons at LHC are decays of D mesons (>70%), B mesons (∼25%) and W bosons (∼ 0.01%). Dedicated channels are employed for τ decays from heavy flavour (HF) mesons decays and from W decays.

In the HF channel, the high rate of hadronic particles produced in proton-proton collisions is one of the main challenges. Muons produced from an eventual signal in this channel are expected to be boosted in the forward pseudorapidity (η) region, where the resolution of the invariant mass of the 3μ system is typically worse than in the central region. Dedicated online triggers are used for the event selection. A multivariate analysis based on a Boosted Decision Tree (BDT) is used to separate the signal from the background. Events are separated in six categories based on their expected mass resolution and BDT score.

In the W channel, the expected background is significantly lower than for the HF channel. The final state of this channel is characterised by isolated and high transverse momentum (p_T) muons and large missing transverse momentum ($E_\mathrm{T}^\mathrm{miss}$). A different BDT is used to separate the signal from the background and events are divided into two categories.

Figure 1 shows the invariant mass distributions of the categories with the best invariant mass resolution. The branching fraction $\mathcal{B}(\tau \to 3\mu)$ is extracted from a simultaneous unbinned maximum likelihood fit to the trimuon invariant mass distribution in the 1.6–2.0 GeV mass range of each category of the two channels.

The observed (expected) upper limit at 90% confidence level (CL) on $\mathcal{B}(\tau \to 3\mu)$ using all events categories is 8.0×10^{-8} (6.9×10^{-8}). Fitting the W boson and HF channels separately returns observed (expected) 90% CL upper limits of 20×10^{-8} (13×10^{-8}) and 9.2×10^{-8} (10.0×10^{-8}), respectively. The present best limit of $< 2.1 \times 10^{-8}$ at 90% CL was obtained by the Belle experiment [14].

ATLAS performed a simulation-based analysis of the expected sensitivity which the experiment can achieve with the HL-LHC data-taking campaign corresponding to an integrated luminosity of 3000 fb^{-1} [15]. Both the W boson and HF channels are considered. For the W channel, three scenarios are considered: 1) Non-improved scenario, where only integrated luminosity and higher production cross section at $\sqrt{s} = 14$ TeV are considered with respect

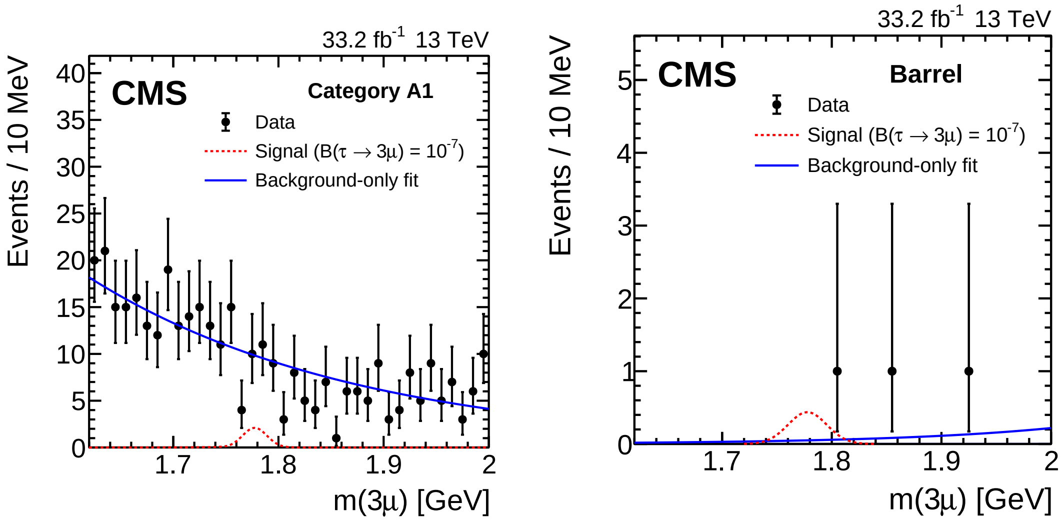

Figure 1: Trimuon invariant mass distributions in the event category with best invariant mass resolution used in (a) the heavy-flavor channel and (b) the W boson channel. The data are shown with filled circles and vertical bars representing the statistical uncertainty. The background-only fit and the expected signal for $\mathcal{B}(\tau \to 3\mu) = 10^{-7}$ are shown with solid and dashed lines, respectively [13].

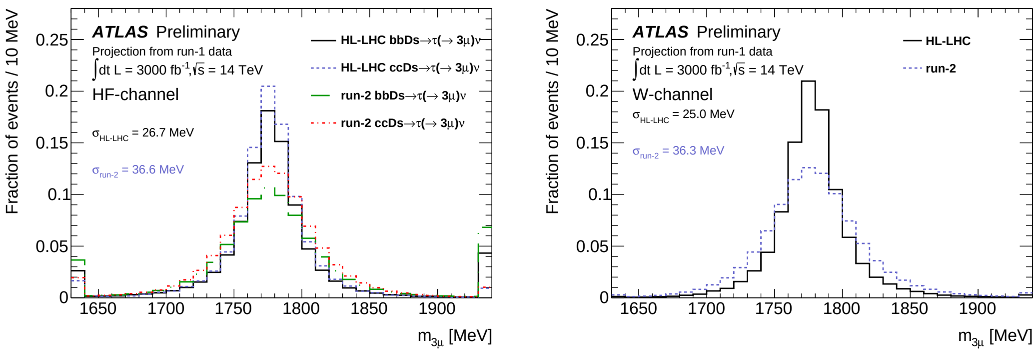

Figure 2: Comparison of tau mass resolutions in the (a)HF channels and (b) W boson in Run 2 and under HL-LHC detector conditions. The quoted widths are obtained from a double Gaussian fit [15].

to the Run 1 analysis; 2) Intermediate scenario, where the improvements in triggering and reconstruction of low p_{T} muons estimated from Run 2 Monte Carlo (MC) are also included in the projection; 3) Improved scenario, where the signal search window is tightened, taking into account expected improvements at the HL-LHC in mass resolution. For the HF channel, the three scenarios taken into account are the High, Medium and Low background scenarios, where the background levels are rescaled from the Run 1 W channel analysis based on the integrated luminosity and higher cross section of the HL-LHC and an additional penalty factor of ten, three and one is applied, respectively. Figure 2 shows the expected improvements of the 3μ invariant mass for the W and HF channels. The projections to HL-LHC conditions of the expected exclusion limits at 90% CL on $\mathcal{B}(\tau \to 3\mu)$ are 5.4×10^{-9} for the Improved scenario of the W boson channel and 1.0×10^{-9} for the Low background scenario of the HF channel.

3 Search for LFV decays of the Z boson

The ATLAS searches for LFV decays of the Z boson is performed with 139 fb^{-1} of LHC Run 2 data and include all flavour combination $Z \to e\tau$, $Z \to \mu\tau$ [16, 17] and $Z \to e\mu$ [18].

Major background processes to the $Z \to \ell\tau$ search ($\ell = e, \mu$) include the irreducible component $Z \to \tau\tau \to \ell + \text{hadrons} + 3\nu$ and reducible backgrounds from W+jets, top-quark pair-production and $Z \to \ell\ell$, where either a jet or a light lepton is misidentified as the decay of a τ-lepton to hadrons. Neural network (NN) classifiers are used to identify the three major background components ($Z \to \tau\tau$, W+jets and $Z \to \ell\ell$). For each type the NN classifier is trained and validated with MC simulations. The NN classifiers are combined to maximize the sensitivity. Figure 3(a) show the combined NN distribution of the of the $Z \to \mu\tau$ candidates events with 1-prong τ decay candidates. The 95% upper limits for LFV Z decays to a τ and a lighter lepton are obtained with different assumptions about the polarization state and combined with previous results obtained with Run 1 data. In the scenario where the τ-leptons are unpolarized, the observed upper limits at 95% CL on $\mathcal{B}(Z \to e\tau)$ and $\mathcal{B}(Z \to e\tau)$ are 5.0×10^{-6} and 6.5×10^{-6}, respectively. They are about 2 times more stringent than previous best constraints on LFV Z-boson decays involving τ-leptons, set by LEP.

The search for the LFV $Z \to e\mu$ decay is performed by fitting the $m_{e\mu}$ distribution. Events with high-p_{T} jets and large $E_{\mathrm{T}}^{\mathrm{miss}}$ are vetoed to reduce the $t\bar{t}$ and $Z \to \tau\tau$ backgrounds. A BDT classifier is used to further improve the background rejection. Normalization of the Z cross section is determined from data using a sample of $Z \to ee$ and $Z \to \mu\mu$ events. Figure 3(b) show the $m_{e\mu}$ distribution of the of the $Z \to e\mu$ candidates events. An upper bound $\mathcal{B}(Z \to e\mu) < 3.04 \times 10^{-7}$ is obtained [18].

4 Search for LFV decays of the H boson

The CMS searches for LFV decays $H \to e\tau$ and $H \to \mu\tau$ are performed with 137 fb^{-1} of LHC pp collisions [19]. ATLAS performed a search for $H \to e\mu$ decay with 139 fb^{-1} of data [20].

The major background processes in the $H \to \ell\tau$ searches are $Z \to \tau\tau$, $H \to \tau\tau$, top-quark production processes, diboson production, $H \to WW$ as well as W+jets, $Z \to \ell\ell$ and multi-jet production where at least a jet or a light lepton is misidentified as τ hadronic decay or a light lepton of different nature. To model the $Z \to \tau\tau$ background, an embedding data-driven technique is used. The signatures of the muons of data events enriched in $Z \to \mu\mu$ process, are removed and substituted with simulated τ leptons with the same 4-momentum of the original muon. The events are then re-reconstructed. The events passing the event selection are divided into four categories, based on jet multiplicity and topology. The analysis exploits a BDT as the final discriminant to enhance the signal separation from backgrounds in each category of the two searches. Figure 4(a) and (b) show the obtained 95% CL upper limits for $\mathcal{B}(H \to \mu\tau)$ and $\mathcal{B}(H \to e\tau)$, respectively.

The main backgrounds of the ATLAS search for the $H \to e\mu$ decay mainly $Z \to \tau\tau$, top-quark production, diboson production and W+jets and multi-jet processes, where at least one jet is misidentified as a light lepton. The signal is separated from the background primarily by identifying a narrow peak in the invariant mass distribution of the two leptons, $m_{e\mu}$, corresponding to a decay of the Higgs boson with $m_H = 125\,\text{GeV}$. The event selection divides the events into eight categories. The signal is extracted from an unbinned fit of the $m_{e\mu}$ distribution, as shown in Fig 4(c), where the background is modeled by a Bernstein polynomial of degree two with category-dependent parameters and the signal is modeled by the sum of a Crystal Ball and a Gaussian function. No excess is observed and a 95% CL limit is set, $\mathcal{B}(H \to e\mu) < 6.1 \times 10^{-5}$ (5.8×10^{-5} expected).

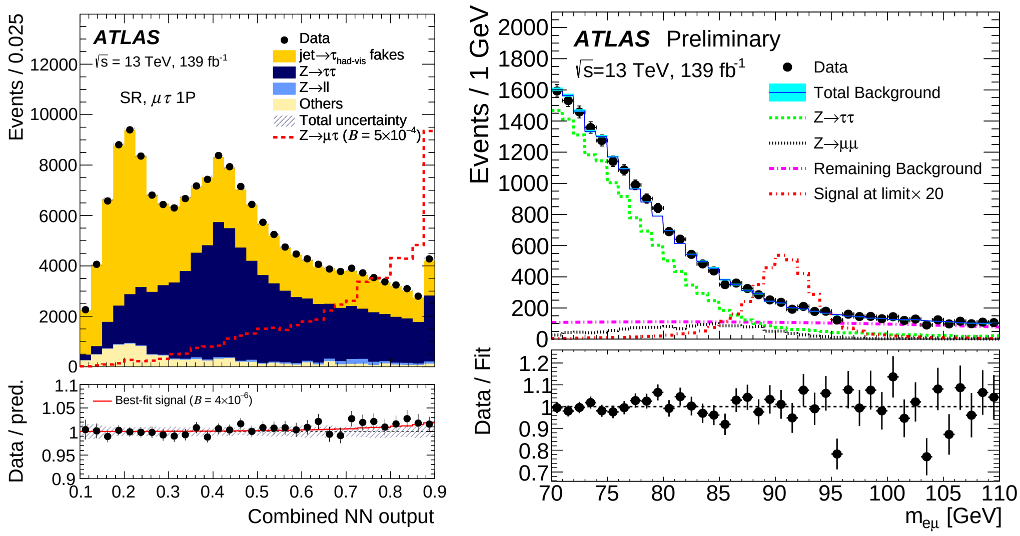

Figure 3: (a) Distribution of the combined NN output in the signal region for $\mu\tau$ events with 1-prong τ decay candidates. The expected contributions are determined in the fit to data. The expected signal, normalized to $\mathcal{B}(Z \to \mu\tau) = 5 \times 10^{-4}$, is shown as a dashed red histogram. The panel below the plot shows the ratios of the observed yields (dots) and the best-fit background-plus-signal yields (solid red line) to the best-fit background yields [16]. (b) Distribution of the invariant mass $m_{e\mu}$ of the $Z \to e\mu$ candidates, for data (points) and expected backgrounds (solid lines) after the likelihood fit. A hypothetical $Z \to e\mu$ signal, whose branching fraction is scaled to 20 times the observed upper limit, is shown in red for illustration purposes. The lower panel shows the ratio of observed data to expected background yields [18].

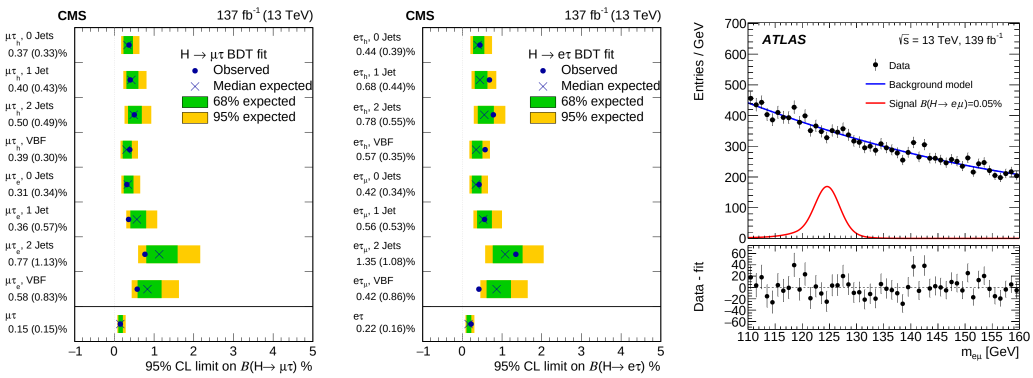

Figure 4: Observed (expected) 95% CL upper limits obtained by CMS on the (a) $\mathcal{B}(H \to \mu\tau)$ and (b) $\mathcal{B}(H \to e\tau)$ for each individual category and combined [19]. (c) Distribution of the invariant mass $m_{e\mu}$ of the $H \to e\mu$ candidates for all categories summed together of the ATLAS search. Data (points) and expected background-only model (blue line) are shown after the likelihood fit. The signal parameterisation with branching fractions set to $\mathcal{B}(H \to e\mu) = 0.05\%$ is also shown (red line). The bottom panels show the difference between data and the background-only fit [20].

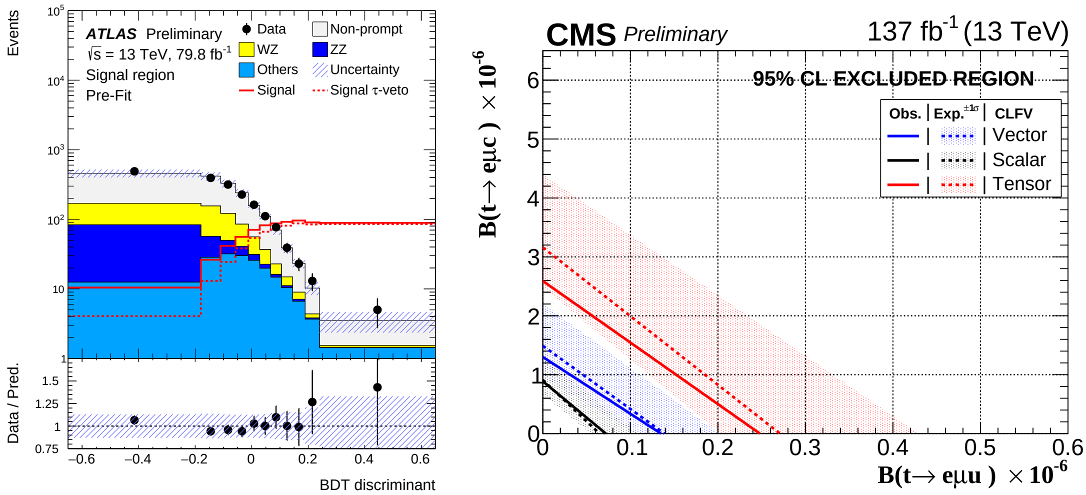

Figure 5: (a) BDT discriminant pre-fit distribution obtained by ATLAS with the signal including and excluding τ leptons in the charged-LFV vertex overlaid. The signals are normalised according to branching ratios $\mathcal{B}(t \to q\ell^{\pm}\ell'^{\mp}) = 3 \times 10^{-4}$ and $\mathcal{B}(t \to qe\mu) = 1 \times 10^{-4}$. All sources of systematic uncertainty are included. Data (black points) are compared to the sum of backgrounds in the upper panel, while the ratio is shown in the lower panel [21]. (b) The 95% exclusion limits obtained by CMS on $B(t \to ce\mu)$ as a function of $B(t \to ue\mu)$ for the scalar, vector and tensor like charged-LFV interactions [22].

5 Search for LFV decays of the top quark

The large rate of $pp \to t\bar{t}$ production at the LHC allows probing for charged-LFV in top-quark decays. ATLAS search [21] uses 79.8 fb^{-1} of data and includes the top decays to a quark and two leptons of different flavour $t \to (u,c)LL'$, where ($L = e, \mu$ or τ), while the CMS search [22] uses 137 fb^{-1} of data and is specific for the $t \to (u,c)e\mu$ final state. The ATLAS event selection requires three isolated leptons and at least 2 jets with $p_{\mathrm{T}} > 25$ GeV. The main backgrounds are lepton flavour conserving decays of the top quarks and Z+jets events, with an additional non-prompt lepton in the final state. A BDT trained on MC simulation is used to improve the background separation. The distribution of the BDT discriminant for events entering in the signal region is shown in Figure 5(a). Observed (expected) 95% CL upper limits are $\mathcal{B}(t \to qLL') < 1.86 \times 10^{-5}$ (1.36×10^{-5}) and $\mathcal{B}(t \to qe\mu) < 6.6 \times 10^{-6}$ (4.8×10^{-6}).

The event selection of the CMS search requires exactly 1 jet tagged as b-jet. Events having more than 1 b-jet enter in a control region used to check the $t\bar{t}$ background. The result is extracted from a simultaneous binned likelihood fit performed on the BDT discriminant distributions in the signal region and $t\bar{t}$ control region. The 95% CL upper limits are shown in Figure 5(b) under different assumptions of scalar, vector and tensor interaction. The results on the branching fractions are also interpreted in terms of limits on vector, scalar and tensor four-fermion interactions originating from dimension-six operators within the EFT framework with a new physics scale chosen to be $\Lambda = 1$ TeV.

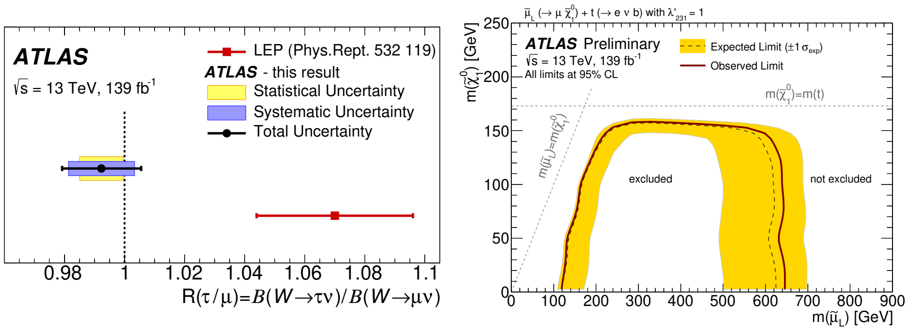

Figure 6: (a) The measurement of $R(\tau/\mu)$ is shown (black circular marker) and compared with the previous LEP result (red square marker). The statistical and systematic errors are shown separately and also the total error of the measurement. The vertical dashed line indicates the Standard Model's prediction lepton-flavour universality, with equal W boson branching ratios to different lepton flavours [23]. (b) Expected and observed exclusion limits are shown for RPV-supersymmetry models which allow for production of a single smuon (decaying to a muon and neutralino) in association with a top quark (decaying leptonically). The smuon is produced through the λ'_{231} coupling, which is fixed at unity. All limits are computed at 95% confidence level and all uncertainties are included. Also shown are dotted lines to indicate the two kinematic limits for the RPV process considered [25].

6 Measurement of $\mathcal{B}(W \to \tau\nu)/\mathcal{B}(W \to \mu\nu)$ and $e^+\mu^-/\mu^+e^-$ asymmetry

ATLAS performed a test of lepton flavour universality by measuring the ratio $R(\tau/\mu)$ defined in Equation 1 with 139 fb^{-1} of Run 2 data [23].

$$R(\tau/\mu) \equiv \mathcal{B}(W \to \tau\nu)/\mathcal{B}(W \to \mu\nu)\,. \tag{1}$$

The ratio $R(\tau/\mu)$ is predicted to be equal to 1 by the SM, neglecting mass effects of $O(10^{-4})$. The previous most precise measurement was performed at LEP [24], $R(\tau/\mu) = 1.070 \pm 0.026$, having a 2.7σ tension with the SM. A pure sample of W decays is obtained from $t\bar{t}$ events. To reduce the systematic uncertainties in the ratio measurement, only $\tau \to \mu\nu\nu$ (τ_μ) decays are used in the measurement. The difference in transverse impact parameter d_0 is exploited to differentiate between prompt μ and τ_μ decays of the W boson. A 2D profile likelihood in p_T–d_0 (3×8 bins) is performed to extract the $R(\tau/\mu)$ measurement. The result, shown in Figure 6(a), is $R(\tau/\mu) = 0.992 \pm 0.013$. It is two times more precise than the previous LEP measurement and it is in agreement with the SM expectations.

Another test of lepton universality performed by ATLAS is the measurement of ρ defined in Equation 2 using 139 fb^{-1} of Run 2 data [25].

$$\rho \equiv \frac{\sigma(pp \to e^+\mu^- + X)}{\sigma(pp \to e^-\mu^+ + X)}\,. \tag{2}$$

The SM predicts $\rho = 1$, but new physics models, such as RPV SUSY and Leptoquarks, predict deviations from unity. The ATLAS search is for deviations $\rho > 1$, because experimental effects tend to bias the ρ ratio measurement to lower values. Experimental source of biases that are corrected for are: differences in mis-identified leptons contribution ($e^-_{\text{fake}}\mu^+_{\text{real}} > e^+_{\text{fake}}\mu^-_{\text{real}}$); the difference in μ^+ and μ^- reconstruction efficiency due to the ATLAS toroid field; a p_T-dependent charge asymmetry, caused by detector misalignments. Events are divided into categories based on $E_{\mathrm{T}}^{\mathrm{miss}}$ and number of jets to target different new physics signatures. No excess compatible with $\rho > 1$ is observed and 95% CL upper limits are set for RPV SUSY (as shown in Figure 6(b)) and scalar LQ models.

7 Conclusions

There is growing evidence for anomalies in lepton interactions, but no direct evidence of LFV processes so far. ATLAS and CMS experiments have an extensive programme to search for new physics related to deviations from lepton flavour conservation and universality. Recent results on $\tau \to 3\mu$, LFV decays of the Z, Higgs bosons and top-quark have been presented as well as tests of lepton flavour universality in W decays and $e^{\pm}\mu^{\mp} + X$ final states.

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