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Status and perspectives of Lepton Flavor Violation at ATLAS and CMS

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These proceedings collect a selection of recent experimental results on Lepton Flavor Violation (LFV) searches carried out at the ATLAS and CMS experiments at the LHC. These results are obtained by using the proton-proton collision dataset at $\sqrt{s}$ = 13 TeV, collected during the Run 2 of the LHC, and corresponding to an integrated luminosity of about 140 fb^{-1}.
In the first part of these proceedings, few searches for LFV with multi-lepton final states are presented, followed by the searches for this kind of violation in the Higgs boson decays. Finally, the results from the LFV searches in the top quark sector are discussed.

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PoS(WIFAI2023)018

1. Introduction

In the Standard Model (SM) of particle physics, three lepton families (flavors) exist. The number of leptons of each family seems to be conserved in their interactions, even if there is not a fundamental principle of the theory enforcing this conservation (accidental symmetry). The observation of neutrino oscillations has been the first evidence of Lepton Flavor Violation (LFV), and it indicates that processes violating this conservation do occur in nature. In the SM with neutrino oscillations, LFV involving charged leptons, referred to also as charged lepton flavor violation (CLFV), can occur via neutrino mixing, but it is too rare to be detected by present day experiments. On the other hand, several theories beyond the SM (BSM) predict an enhancement in the branching ratio (BR) of this kind of decays. Therefore, any observation of CLFV would be an unambiguous sign of physics beyond the SM.

Several searches in this direction have been performed at different experiments; in these proceedings I report a selection of results of the searches for LFV carried out in the last years by the ATLAS [1] and CMS [2] experiments at the LHC.

2. Search for LFV in multi-lepton final states

2.1 The $\tau \to 3\mu$ search

In the SM with neutrino oscillations, the $\tau \to 3\mu$ decay has a vanishingly small branching ratio (BR) ($\mathcal{O}(10^{-54})$) [3], which is enhanced up to 10^{-10}–10^{-8} in some BSM theories, such as the Minimal Supersymmetric SM with the See-Saw mechanism [4] or in the R-parity violation [5] framework. Several searches for this decay have been carried out by different experiments, but no evidence for its existence has been observed up to now. The Belle collaboration has set the current best experimental upper limit on $\mathcal{B}(\tau \to 3\mu) < 2.1 \times 10^{-8}$ at 90% confidence level (CL) [6], followed by the upper limits set by the LHC experiments: LHCb (2011–2012 data, 3 fb^{-1}), CMS (2016 data, 33.2 fb^{-1}), and ATLAS (2012 data, 20.3 fb^{-1}), which have set, respectively, upper limits of 4.6×10^{-8} [7], 8.0×10^{-8} [8], and 38×10^{-8} [9], at 90% CL.

The CMS experiment has repeated this search by using the data collected during 2017 and 2018 (corresponding to an integrated luminosity of 97.7 fb^{-1}). Differently from LHCb, which targeted only the tau production from heavy-flavor (HF) hadron decays, and ATLAS, which exploited only tau leptons coming from W bosons, CMS used both channels in its search, reaching a higher analysis sensitivity. Events selected by some customized trigger algorithms in each channel are split into exclusive categories based on the trimuon invariant mass resolution and on the reconstruction algorithm used for the softest muon of the triplet. A multivariate analysis exploiting boosted decision trees (BDTs) is then performed to suppress the background, and events in each category are further split into 4 bins based on the per-event BDT score. The bin with the lowest BDT score is then discarded, leading to a total of 36 categories. The bin boundaries are optimized to give the largest expected signal significance (before unblinding the signal region, i.e. the trimuon invariant mass region compatible with the tau lepton mass).

The BR $\mathcal{B}(\tau \to 3\mu)$ is obtained from a maximum likelihood fit performed simultaneously on the trimuon invariant mass distributions in all the categories of the two channels, as shown in Fig.1 (left, middle) for the highest sensitivity category of both channels. No significant excess is seen,

PoS(WIFAI2023)018

and an observed (expected) upper limit of 3.1×10^{-8} (2.7×10^{-8}) has been set at 90% CL [10], by using a frequentist method [11] based on modified profile likelihood test statistics and the CLs criterion [12, 13]. This result has been combined with the previous CMS result obtained with 2016 data [8], leading to an observed (expected) upper limit at 90% CL on $\mathcal{B}(\tau \to 3\mu)$ of 2.9×10^{-8} (2.4×10^{-8}), as shown in Fig.1 (right).

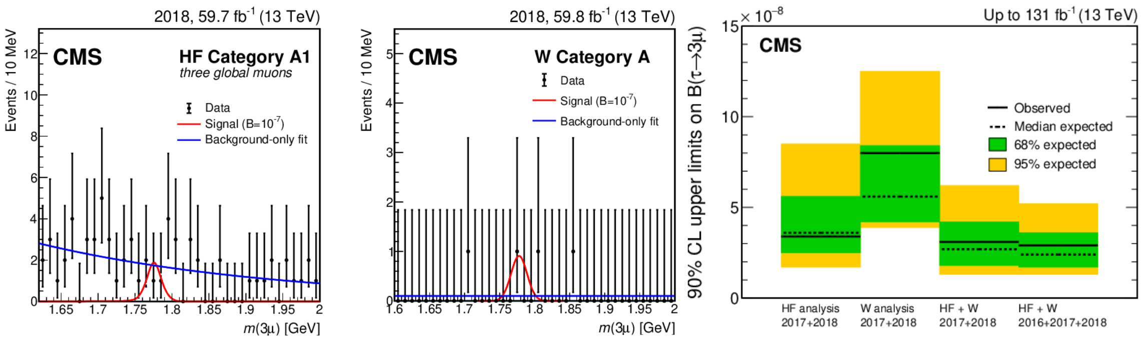

Figure 1: On the left-middle: Three-muon invariant mass distributions in the highest sensitivity category of both channels (HF on the left, W in the middle). Data are shown with filled circles and the vertical bars represent the statistical uncertainty. The solid and dashed lines represent respectively the background-only fit and the expected signal assuming $\mathcal{B}(\tau \to 3\mu) = 10^{-7}$. On the right: Observed and expected upper limits on $\mathcal{B}(\tau \to 3\mu)$ at 90% CL, from the HF analysis, the W boson analysis, the combination of the two analyses, as well as their combination with the previously published result using 2016 data. Figure from [10] .

2.2 Search for LFV in high-mass dilepton final states

The ATLAS Collaboration has performed a search for a heavy particle (TeV range) decaying into different-flavor, dilepton final states ($e\mu$, $e\tau$ or $\mu\tau$). The search utilizes the whole Run 2 dataset, corresponding to 139 fb^{-1}, and extends a previous ATLAS search performed on the subset of the Run 2 dataset collected during 2016, corresponding to 36.1 fb^{-1} [14]. Also the CMS Collaboration has published a result of a similar search, done by using the full Run 2 dataset [15].

The most recent search by ATLAS looks for a localized excess in the dilepton invariant mass distribution above 600 GeV. Three signal regions are defined, one for each decay mode, together with corresponding control regions for the normalization of the most abundant SM backgrounds. Four benchmark models are chosen to interpret the results:

- the Sequential Standard Model (SSM) [16] predicting the existence of a Z′ boson with the same quark couplings and chiral structure as the SM Z one, but allowing for LFV couplings,
- the RPV SUSY model [17, 18] allowing for the creation of a τ-sneutrino ($\tilde{\nu}_\tau$) in the proton–proton collisions, which then decays into $e\mu$, $e\tau$ or $\mu\tau$,
- models with extra spatial dimensions, predicting the possibility for LHC to produce states exceeding the threshold mass to form black holes:
  - the Arkani-Hamed–Dimopoulos–Dvali (ADD) model [19] with 6 extra-dimensions,
  - the Randall–Sundrum (RS) model [19] with 1 extra-dimension.

PoS(WIFAI2023)018

Binned maximum-likelihood fits are performed on dilepton invariant mass spectra for each signal scenario. The data are found to be consistent with the SM expectation, and lower limits on the mass of the searched-for heavy resonances have been set for the different models considered, as listed in the Tab. 2.

Model	Observed (expected) 95% CL lower limit [TeV]		
	$e\mu$ channel	$e\tau$ channel	$\mu\tau$ channel
LFV Z'	5.0 (4.8)	4.0 (4.3)	3.9 (4.2)
RPV SUSY $\tilde{\nu}_\tau$	3.9 (3.7)	2.8 (3.0)	2.7 (2.9)
QBH ADD $n = 6$	5.9 (5.7)	5.2 (5.5)	5.1 (5.2)
QBH RS $n = 1$	3.8 (3.6)	3.0 (3.3)	3.0 (3.1)

Figure 2: Expected and observed 95% CL lower limits on the mass of a Z′ boson with lepton-flavour-violating couplings, a supersymmetric τ-sneutrino ($\tilde{\nu}_\tau$) with R-parity-violating couplings, and the threshold mass for quantum black-hole production for the ADD n=6 and RS n=1 models. Table from [20].

3. Search for LFV in Higgs boson decays

The LFV decays of the Higgs boson $H \to e\mu$, $H \to e\tau$, $H \to \mu\tau$ are forbidden in the SM, but can occur according to BSM theories through the off-diagonal LFV Yukawa couplings $|Y_{e\mu}|$, $|Y_{e\tau}|$, $|Y_{\mu\tau}|$, which couple the Higgs boson with leptons of different flavor. Examples of these theories are the models with more than one Higgs doublet [21, 22], the Randall-Sundrum model [23, 24], or composite Higgs models [25, 26]. While the most stringent bound on the LFV decays $H \to e\tau$, $H \to \mu\tau$ are derived from direct searches, in the $H \to e\mu$ case it is obtained indirectly, from the limit on $\mathcal{B}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ [27], that translates into $\mathcal{B}(H \to e\mu) < 10^{-8}$ [28]. However, this limit assumes the SM values for the not yet tightly constrained Yukawa couplings $|Y_{\mu\mu}|$ [29, 30] and the unmeasured $|Y_{ee}|$, thus a direct search also for $H \to e\mu$ remains necessary. Searches for all these decays have been performed both at the ATLAS and CMS experiments with the whole Run 2 dataset; in the following the most recent results are shown, i.e. the $H \to e\mu$ search by CMS [31] and the $H \to e\tau$, $H \to \mu\tau$ search by ATLAS [32].

The search for $H \to e\mu$ decays had been performed by ATLAS (by using the Run 2 dataset, corresponding to 139 fb^{-1}), setting an observed (expected) limit of $\mathcal{B}(H \to e\mu) < 6.2\,(5.9) \times 10^{-5}$ at 95% CL [33]. Similarly, the CMS experiment has carried out the search for a SM Higgs boson decaying into $e\mu$ with the whole Run 2 dataset, corresponding to 138 fb^{-1}. This analysis considers the two dominant production modes of the Higgs boson at the LHC, i.e. the gluon fusion (ggH) and vector boson fusion (VBF), and the events selected are divided into different categories to enhance the signal from these two production mechanisms. Separate BDTs are trained in the two cases, and the categories are further split according to the signal purity, based on the output of the multivariate classifiers. A maximum likelihood fit is performed simultaneously on the $e\mu$ invariant mass distributions in all the categories, and since no excess of data above the SM prediction has been seen, an observed (expected) upper limit of $\mathcal{B}(H \to e\mu) < 4.4\,(4.7) \times 10^{-5}$ is set at 95% CL [31], which is the most stringent limit set thus far from direct searches. This translates into an upper limit on the Yukawa coupling of $\sqrt{|Y_{e\mu}|^2 + |Y_{\mu e}|^2} < 1.9\,(2.0) \times 10^{-4}$, as shown in Fig. 3 (left).
In addition, the CMS experiment performed a search for this decay in case of a potential additional

PoS(WIFAI2023)018

Higgs boson with a mass in the range 110–160 GeV. The largest excess of events over the expected background in the full mass range of the search is observed for an $e^{\pm}\mu^{\mp}$ invariant mass of $\approx$ 146 GeV, with a local (global) significance of 3.8 (2.8) standard deviations, as shown in Fig. 3 (right).

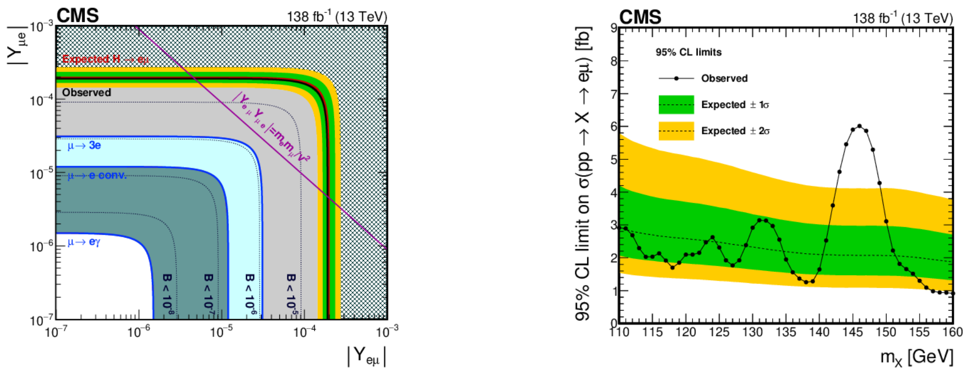

Figure 3: On the left: Constraints on the LFV Yukawa couplings, $|Y_{e\mu}|$ and $|Y_{\mu e}|$. The observed (expected) limit in black (red) line is derived from the limit on $\mathcal{B}(H \to e\mu)$ in this analysis. The hashed region is excluded by this direct search, while other shaded regions represent indirect constraints (with flavor-diagonal Yukawa couplings assumed to be at their SM values) derived from the null searches for $\mu \to 3e$ (gray) [34], $\mu \to e$ conversion (light blue) [35], and $\mu \to e\gamma$ (dark green) [36]. On the right: observed (expected) 95% CL upper limits on $\sigma(pp \to X \to e\mu)$ as a function of the hypothesized m_X assuming the relative SM-like production cross sections of the ggH and VBF production modes. Figure from [31].

The search for $H \to e\tau$, $H \to \mu\tau$ had been performed by the CMS experiment, with the whole Run 2 statistics (137 fb^{-1}), setting an upper limit of $\mathcal{B}(H \to e\tau)$ <0.22% (0.16%) and $\mathcal{B}(H \to \mu\tau)$ <0.15% (0.15%) at 95% CL [37]. Recently, also the ATLAS Collaboration has released the results of its search for these decays, done by using a total integrated luminosity of 138 fb^{-1}, setting the following observed (expected) upper limits have been set at 95% CL: $\mathcal{B}(H \to e\tau)$ <0.20% (0.12%) and $\mathcal{B}(H \to \mu\tau)$ <0.18% (0.09%) [32]. They translate into the following limits on the coupling matrix elements: $\sqrt{|Y_{\tau e}|^2 + |Y_{e\tau}|^2} < 0.0014$ and $\sqrt{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} < 0.0012$, as shown in Fig. 4 (left and middle). In this search, both leptonic and hadronic decays of the τ-lepton are considered, and two different background estimation techniques are employed: the MC-template method (based on data-corrected simulation samples), and the symmetry method, exploiting the symmetry between electrons and muons in the SM backgrounds. The final upper limits are obtained with the MC-template method from a simultaneous measurement of potential $H \to e\tau$ and $H \to \mu\tau$ signals. The best-fit BR difference, $\mathcal{B}(H \to \mu\tau) - \mathcal{B}(H \to e\tau)$, measured with the symmetry method in the channel where the τ-lepton decays to leptons, is (0.25 ± 0.10)%, compatible with a value of zero within 2.5 σ, as displayed in Fig. 4 (right).

4. Search for LFV in the top quark sector

The LHC is expected to potentially have the best sensitivity to LFV processes involving a heavy particle, such as the Higgs boson (as seen in the previous section), but even more favored would be the heaviest of all elementary particles, the top quark [38]. For this reason, several searches for LFV in the top quark sector have been performed at the ATLAS and CMS experiments. The CMS

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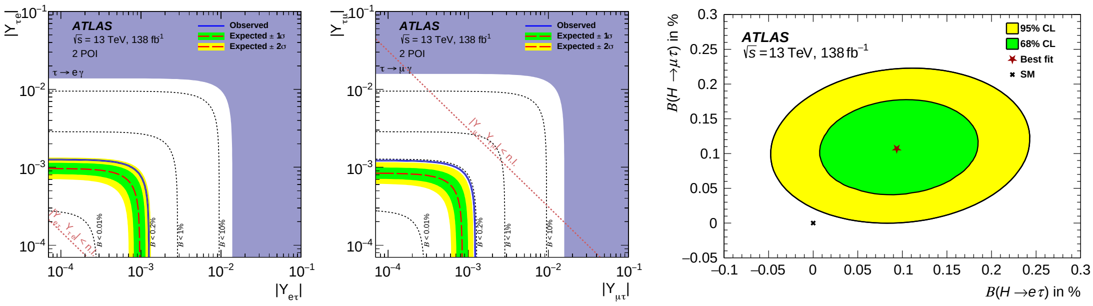

Figure 4: On the left and in the middle: expected (red long-dashed line) and observed (solid blue line) 95% CL upper limits from the simultaneous fit of the two searches on the absolute value of the couplings $Y_{\tau\ell}$ and $Y_{\ell\tau}$ together with the most stringent indirect limits from $\tau \to \ell\gamma$ searches (dark purple region) for $\ell = e$ (left) or $\ell = \mu$ (middle). On the right: best-fit value (red star) of B($H \to e\tau$) and B($H \to \mu\tau$), and likelihood contours at 68% and 95% CL obtained from the simultaneous fit of $H \to e\tau$ and $H \to \mu\tau$ signals based on the MC-template method, compared with the SM expectation (black cross). Figure from [32].

Collaboration has previously performed a search for CLFV involving the top quark with final states having two oppositely charged leptons [39]. The latest released search, instead, targets final states containing one opposite-sign electron-muon pair, a third charged lepton (which can be an electron or a muon), and at least one jet, at most one of which is identified as a bottom quark [40]. For this search the whole Run 2 dataset, corresponding to an integrated luminosity of 138 fb^{-1}, has been used. A multivariate analysis exploiting BDTs is carried out, to better discriminate the signal from background. No excess has been observed, and the results have been interpreted in the context of effective field theory [41], translating into upper limits set at 95% CL on the Wilson coefficients, displayed in Fig. 5 (left). The limits can be converted to upper limits on BRs involving up (charm) quarks, $t \to e\mu u$ ($t \to e\mu c$), of 0.032 (0.498) $\times 10^{-6}$, 0.022 (0.369) $\times 10^{-6}$, and 0.012 (0.216) $\times 10^{-6}$ for tensor-like, vector-like, and scalar-like interactions, respectively, as shown in Fig. 5 (right).

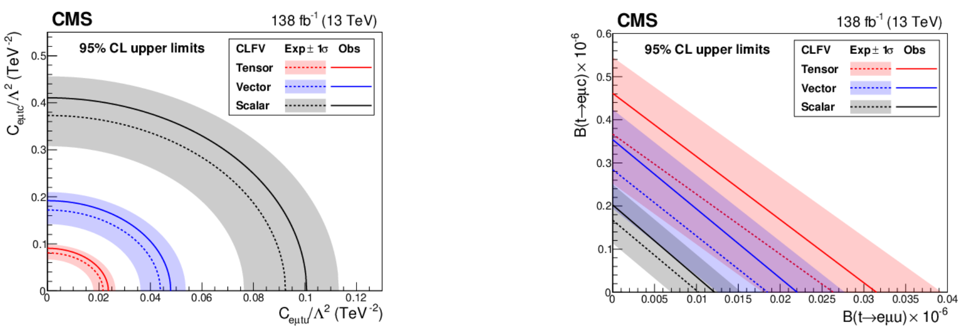

Figure 5: Two-dimensional 95% CL upper limits on the Wilson coefficients (left) and the BR (right). The observed (expected) upper limits for tensor-, vector-, and scalar-like CLFV interactions are shown in red, blue, and black solid (dotted) lines, respectively. The shaded bands contain 68% of the distribution of the expected upper limits. Figure from [40].

The ATLAS experiment has also performed a search for CLFV in the top quark sector. In particular, this search targets events containing two muons, a hadronically decaying tau lepton and

PoS(WIFAI2023)018

at least one jet (with exactly one jet associated with a b quark), produced by a $\mu\tau qt$ interaction in the top-quark production or decay. As the previous searches, also in this case the full dataset collected during Run 2 has been used, corresponding to an integrated luminosity of 139 fb^{-1}. Two different signal regions (SRs) are defined to target the signal CLFV processes in the decay and production, and different simulated samples have been produced for different EFT couplings contributing to the signal process, separately for these two SRs. The signal contribution in these regions is estimated with a binned profile-likelihood fit. The contribution from non prompt muon background is estimated with a template fit in a dedicated control region. No excess above the SM background is observed, and the different EFT samples are used to determine limits on each coupling individually, while two additional samples, generated with all couplings activated simultaneously, are fitted together to determine an inclusive BR limit. Limits are set on $\mathcal{B}(t \to \mu\tau q) < 11 \times 10^{-7}$, as reported in Tab. 6, and on the Wilson coefficient limits, based on the flavor of the associated light quark and the Lorentz structure of the coupling, as listed in Tab. 7.

	95% CL upper limits on BR($t \to \mu\tau q$)	
	Stat. only	**All systematics**
Expected	8×10^{-7}	10×10^{-7}
Observed	9×10^{-7}	11×10^{-7}

Figure 6: Expected and observed 95% CL upper limits on the inclusive BR corresponding to the decay of a top quark to a muon and a τ lepton through a CLFV process. Table from [42].

	95% CL upper limits on BR($t \to \mu\tau q$) ($\times 10^{-7}$)							
	$c_{lq}^{-(ijk3)}$	$c_{eq}^{(ijk3)}$	$c_{lu}^{(ijk3)}$	$c_{eu}^{(ijk3)}$	$c_{lequ}^{1(ijk3)}$	$c_{lequ}^{1(ij3k)}$	$c_{lequ}^{3(ijk3)}$	$c_{lequ}^{3(ij3k)}$
Expected (u)	4.6	4.2	4.0	4.5	2.5	2.5	5.8	5.8
Observed (u)	5.1	4.6	4.4	5.0	2.8	2.8	6.4	6.4
Expected (c)	54	51	51	52	35	35	61	61
Observed (c)	60	56	56	57	38	38	68	68

Figure 7: Expected and observed 95% CL upper limits on the BR corresponding to the decay of a top quark to a muon and a τ lepton through a CLFV process using specific Wilson coefficients corresponding to 2Q2L EFT operators. The lepton generations are denoted by i,j=2,3 for μ and τ (where i $\neq$ j) and the quark generations are denoted by k=1,2 for u and c, respectively. Table from [42].

5. Summary and prospects

An overview of a selection of CLFV searches performed recently by the ATLAS and CMS experiments has been presented. All these analyses exploited the whole proton proton collisions dataset collected during the Run 2 of the LHC, corresponding to $\sim$ 138 fb^{-1}. All results are compatible with the SM predicitions, and in almost all the cases, the most stringent upper limits to date have been set. All of the analysis presented are statistically limited; improvements in these results are expected from the increased data set sizes being collected during the Run 3 of LHC (started in 2022), not only coming from the higher luminosity delivered by the accelerator, but also exploiting new trigger and data acquisition techniques, which will allow us to maximize the experiments' acceptance to these rare decays.

PoS(WIFAI2023)018

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