

Search for lepton flavor violation at ATLAS and CMS

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This contribution describes a selection of recent Charged Lepton Flavor Violation searches performed by the ATLAS and CMS collaborations at the Large Hadron Collider (LHC), covering a wide range of sectors including rare tau decays, top-quark interactions, Higgs boson decays, and heavy resonance searches. All the results in this document exploit the full proton-proton collision dataset collected during the LHC Run2 corresponding to an integrated luminosity of approximately 138 fb^{-1} .

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1. Introduction

The Standard Model (SM) categorizes leptons into three distinct flavors: electron, muon and tau. In the SM framework with massless left-handed neutrinos, lepton flavor (LF) quantum numbers are strictly conserved, implying that interaction vertices between different flavors, known as Lepton Flavor Violation (LFV), are forbidden at tree level. Consequently, LF conservation emerges as an accidental symmetry, not supported by any fundamental conservation law.

However, experimental evidence of neutrino oscillations demonstrates that neutrinos are massive and their flavor eigenstates can mix. Thus indicating that LF is not a fundamental symmetry and leading to searches for flavor violating interactions between charged leptons, as well.

Charged Lepton Flavor Violation (cLFV) processes are permitted within the extended SM framework via neutrino oscillations, but with highly suppressed expected branching ratios of the order of 10^{-55} , far below current experimental sensitivities. Such strong suppression makes the cLFV process very promising probes for physics beyond the Standard Model (BSM), potentially signaling phenomena occurring at energy scales substantially higher than the TeV scale currently probed at colliders.

Motivated by these considerations, experiments such as ATLAS [1] and CMS [2] at the Large Hadron Collider (LHC) actively search for direct evidence of cLFV through various decay channels and interactions.

2. LFV in $\tau \rightarrow 3\mu$ decay

The LFV process $\tau \rightarrow 3\mu$ is allowed in the frame of the SM via neutrino oscillation with a predicted branching ratio of the order of 10^{-55} [3]. Many BSM theories, such as the Minimal Supersymmetric SM with the See-Saw mechanism and including R-parity violating operators, predict an enhanced branching ratio up to 10^{-9} - 10^{-8} [4–6]. Hence, within the current experiments' sensitivity. The search for $\tau \rightarrow 3\mu$ decay is part of many experiment scientific program. Up to now no evidence for its existence has been observed. Currently the most stringent upper limit on $\tau \rightarrow 3\mu$ branching ratio is set by the BelleII experiment which measured $\mathcal{B}(\tau \rightarrow 3\mu) < 2.1 \times 10^{-8}$ at 90% Confidence Level (CL) [7].

The CMS experiment performed the search for LFV decay $\tau \rightarrow 3\mu$ using the full Run2 dataset, corresponding to a total integrated luminosity of 131 fb^{-1} [8]. In LHC proton-proton collisions, τ leptons are predominantly produced from heavy-flavor (HF) hadron decays ($D_s^+ \rightarrow \tau\nu X$, $B \rightarrow \tau\nu X$...) and from $W \rightarrow \tau\nu$ processes. HF decays are the most abundant in statistics, although muons in the final state are forward in the detector and have low transverse momentum, hence, they are in a phase space region highly contaminated by combinatorial background. W decays are 10^4 lower in statistics but benefit from a higher reconstruction efficiency. The final state muon isolated topology and the presence of large missing transverse energy, i.e. the invisible neutrino, make the search of $\tau \rightarrow 3\mu$ in the W channel almost background free.

The experimental signature consists of three muons originating from a common secondary vertex, distinct from background processes. The combinatorial background is modeled using data-driven techniques from the sidebands in the 3μ mass distribution. Boosted decision trees (BDTs) are employed to optimize signal selection and enhance sensitivity.

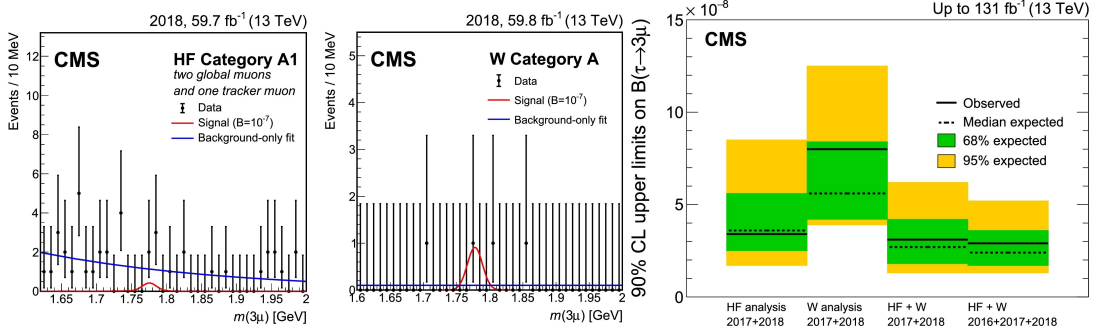


Figure 1: Three muon invariant mass distribution in the highest sensitivity category of HF (left) and W (middle) channel. The red solid line represents expected signal from simulation, assuming $\mathcal{B}(\tau \rightarrow 3\mu) = 10^{-7}$, and the blue solid line represents the background model obtained for the fit to the mass sidebands. On the right the expected and observed upper limit on $\mathcal{B}(\tau \rightarrow 3\mu)$ for the full Run2 [8].

Events are divided in orthogonal categories based on the 3μ candidate relative mass resolution and $\mathcal{B}(\tau \rightarrow 3\mu)$ is obtained via a simultaneous maximum likelihood fit on the 3μ invariant mass distribution in all the categories of the two channels.

No significant excess is seen and an observed (expected) upper limit of 2.9×10^{-8} (2.4×10^{-8}) is set at 90% CL, assessing the competitiveness of the CMS sensitivity compared to the dedicated B-factory experiments. Results are reported in Figure 1 [8].

3. LFV in top quark sector

SM extensions, such as leptoquark models predict LFV interactions in top quark production and decay, manifesting in rare signatures that can be explored at the LHC [9]. Both ATLAS and CMS apply a model-independent approach to such searches interpreting the results in the framework of SMEFT (Standard Model Effective Field Theory) with dimension-6 operators.

3.1 LFV searches targeting $t\mu\tau q$ interactions vertices

The target cLFV processes are the single top production (ST) in $gq \rightarrow t\mu\tau$ and the top decay $t \rightarrow \mu\tau q$ in $t\bar{t}$ events (TT) where one of the top undergoes $t \rightarrow \mu\tau q$. In both the production and decay modes the experimental signature comprises one μ and one hadronic τ of opposite sign plus at least one b-jet. The CMS analysis uses the full Run 2 data set and employs a multi-class DNN (Deep Neural Network) with three classes for ST, TT and background, mainly populated by SM $t\bar{t}$ events [10]. Similarly, the ATLAS analysis exploits multivariate techniques for background reduction and the signal strength in the EFT frame is extracted from a simultaneous profile likelihood fit to the scalar sum $H_T = p_T^\mu + p_T^\tau + p_T^q$ [11]. Both ATLAS and CMS measure the signal strength separately for different EFT operator Lorentz structure and set limits on Wilson coefficients $c_{t\mu\tau u}$ and $c_{t\mu\tau c}$, distinguishing the coupling to light-quarks initiated jets and c-tagged jets. The results in Figure 2 show that limits are the strongest for tensor operators couplings, stronger for u -quark than for c -quark coefficients and the total sensitivity is dominated by the ST $gu \rightarrow t\mu\tau$ process.

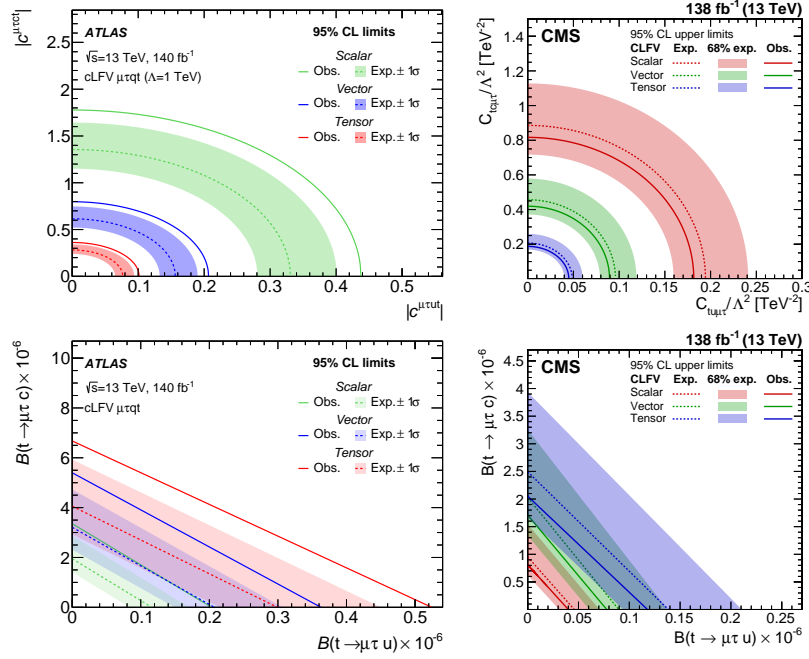


Figure 2: ATLAS (left) and CMS (right) interpolated 95% CL upper limits on the Wilson coefficients (top) and the branching ratio (bottom) for the LFV $t\mu\tau q$ interaction vertices. The upper limits are shown in different colors for tensor-, vector-, and scalarlike cLFV interactions [10, 11].

3.2 LFV searches in trilepton final states

Searches for cLFV in top quark sector can also exploit trilepton final states targeting $t\mu e q$ vertices where two opposite sign leptons $\mu^\pm e^\mp$ come from the LFV vertex and the third from the W boson decay. The CMS experiment performed a search targeting both the production and the decay mode in two orthogonal signal regions defined by $M(e\mu)$ lower and greater than 150 GeV, respectively [12].

The background is modeled in lepton flavor conserving (LFC) categories with three electrons or three muons in the final state while the potential LFV events are categorized upon the third lepton flavor. Two multivariate analyses, exploiting BDTs, target top production and decay signature separately to discriminate between cLFV signals and dominant SM backgrounds (mainly $WZ, t\bar{t} + X$, and non-prompt leptons). The backgrounds are modeled using Monte Carlo simulations for prompt contributions and data-driven approaches for non-prompt sources. A binned maximum likelihood fit to the BDT output distributions across signal regions is performed, separately testing various Lorentz structures of the underlying effective operators. The expected upper limits on $\mathcal{B}(t \rightarrow e\mu\mu)$ ($\mathcal{B}(t \rightarrow e\mu c)$) are set to $0.032(0.498)\times 10^{-6}$, $0.022(0.369)\times 10^{-6}$, and $0.012(0.216)\times 10^{-6}$ for tensor-, vector-, and scalar-like interactions, respectively (Figure 3). These bounds are ten times more stringent compared to those set on $\mathcal{B}(t \rightarrow \tau\mu q)$.

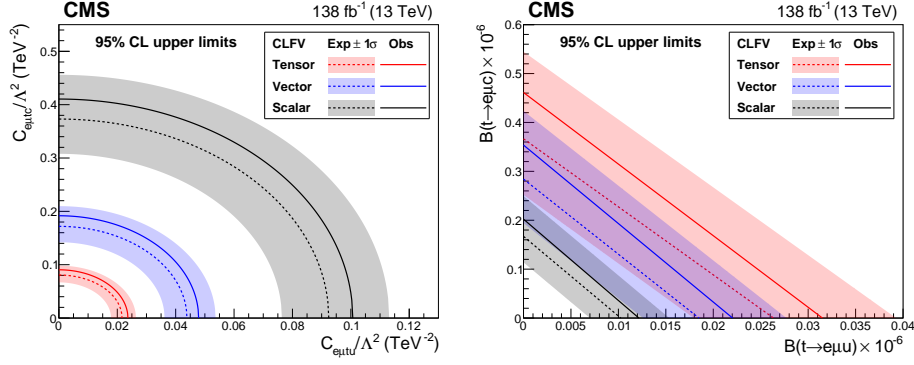


Figure 3: Two-dimensional 95% CL upper limits on the Wilson coefficients (left) and the branching fractions (right) for the LFV $t\mu eq$ vertices. The observed (expected) upper limits for tensor-, vector-, and scalar-like cLFV interactions are shown in red, blue, and black solid (dotted) lines, respectively. The shaded bands contain 68% of the distribution of the expected upper limits [12].

4. LFV in Higgs boson sector

Charged Lepton Flavor Violation in Higgs boson decays provides a powerful window into potential new physics. Many theoretical SM extensions, including supersymmetric (SUSY) scenarios, composite Higgs models, and models with multiple Higgs doublets, predict measurable LFV effects through off-diagonal Yukawa couplings $|Y_{\mu e}|$, $|Y_{\mu\tau}|$ and $|Y_{e\tau}|$ [13–15].

4.1 Search for $H \rightarrow e\tau$ and $H \rightarrow \mu\tau$ decays

The ATLAS and CMS collaborations have conducted comprehensive searches for LFV Higgs boson decays, specifically focusing on the channels $H \rightarrow \mu\tau$ and $H \rightarrow e\tau$. These analyses target final states with hadronic τ decays ($e\tau_h$ and $\mu\tau_h$) as well as leptonic τ decays ($e\tau_\mu$ and $\mu\tau_e$), ensuring that the two leptons in the final state are of different flavors. This strategy significantly suppresses the $Z \rightarrow \ell\ell$ background.

Both analyses categorize events aiming to separate the contributing Higgs boson production mechanisms, i.e. the gluon-gluon fusion (ggF) and the vector boson fusion (VBF). In the ATLAS search $\ell\tau$ events are split into VBF and non-VBF categories and the signal is extracted via subsequent BDTs targeting different background sources, to improve signal sensitivity. A separate maximum likelihood fit is performed on the one dimensional variable obtained from the various BDTs scores combination [16]. Analogously, in the CMS search, the $\ell\tau$ events are split into 8 categories, based on the τ decay mode and on the number of jets in the event in order to isolate VBF and ggF production mode. BDTs are trained separately on $\ell\tau_h$ and $\ell\tau_\ell$ to reject background, mainly from SM Higgs boson production [17]. Limits are set on $H \rightarrow \ell\tau$ decays independently with respect to other LFV couplings, i.e. assuming zero $\mathcal{B}(H \rightarrow \ell'\tau)$. ATLAS and CMS have compatible sensitivity and they observe $\mathcal{B}(H \rightarrow \mu\tau)$ ($\mathcal{B}(H \rightarrow e\tau)$) $< 0.18\%$ (0.20%) at 95% CL and $\mathcal{B}(H \rightarrow \mu\tau)$ ($\mathcal{B}(H \rightarrow e\tau)$) $< 0.15\%$ (0.22%) at 95% CL, respectively. The limits obtained on the off-diagonal Yukawa couplings obtained from direct $H \rightarrow \ell\tau$ searches are much more stringent with respect to indirect bounds that can be derived from $\tau \rightarrow 3\ell$ and $\tau \rightarrow \ell\gamma$ searches (Figure 4).

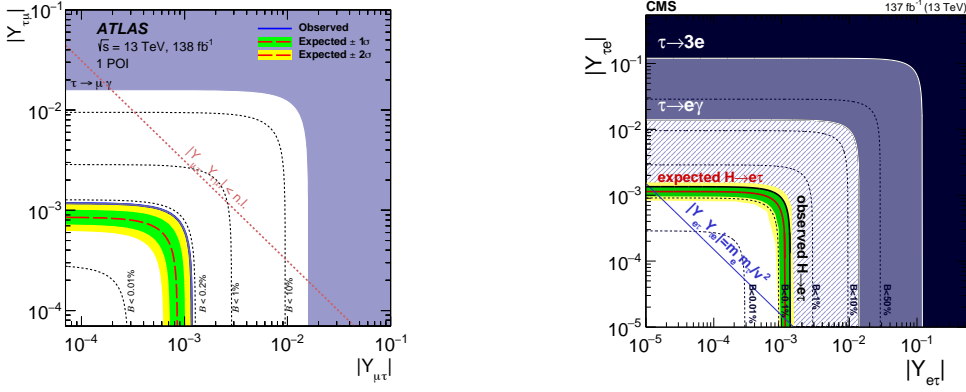


Figure 4: Expected and observed 95% CL upper limits on the LFV Yukawa couplings, $|Y_{\mu\tau}|$ vs $|Y_{\tau\mu}|$ in the ATLAS analysis (left) [16] and $|Y_{e\tau}|$ vs $|Y_{\tau e}|$ in the CMS one [17]. The $|Y_{\mu\tau}|$ and $|Y_{e\tau}|$ couplings correspond to left chiral muon or electron and right chiral τ lepton, the opposite is for $|Y_{\tau\mu}|$ and $|Y_{\tau e}|$ couplings.

4.2 Search for $H \rightarrow e\mu$ decay

LFV in Higgs sector could also arise in decays of additional Higgs bosons in the Type-III two Higgs doublet model (2HDM) [18]. The 2HDM parameter space is expected to be strongly constrained from searches for additional Higgs bosons, in the LFV decay channel, with a mass below twice the W boson mass. A recent CMS search for LFV in $H \rightarrow e\mu$ decay targets an experimental signature consisting in an opposite sign $e\mu$ pair with invariant mass between 100 GeV and 160 GeV [19]. The event categorization aims to separate the ggF and VBF production modes; a BDT is trained to maximize the signal sensitivity, rejecting the largest part of background mainly constituted by $t\bar{t}$ and diboson processes.

A simultaneous maximum likelihood fit is performed over the $m_{e\mu}$ invariant mass distribution, simultaneously in all the categories. Constraints are extracted separately for SM and for possible BSM Higgs boson and no significant excess is found (Figure 5 left). In the hypothesis of a SM Higgs the observed (expected) upper limit on the branching ratio is determined to be $\mathcal{B}(H \rightarrow e\mu) < 4.4(4.7) \times 10^{-5}$ at 95% CL. This result improves by almost 30% the previous limit set by ATLAS [20]. Nevertheless, the most stringent constraint, $\mathcal{B}(H \rightarrow e\mu) < 10^{-8}$, comes from the $\mu \rightarrow e\gamma$ search [21]. However the indirect bound on $H \rightarrow e\mu$ assumes the SM values for the not yet tightly constrained Yukawa couplings $Y_{\mu\mu}$ and the unmeasured Y_{ee} , which justifies to directly test LFV in $H \rightarrow e\mu$ decays.

In the search for an additional Higgs boson, the CMS experiment observes the largest excess of events of local (global) 3.8σ (2.8σ) around 146 GeV, which is still too low to claim for any observation (Figure 5 right).

5. Conclusions and prospects

Searches for cLFV at ATLAS and CMS provide an excellent opportunity to probe physics beyond the Standard Model. Given the extremely suppressed SM predictions for cLFV processes, these decays represent ideal channels for detecting possible new interactions at energy scales significantly above those currently accessible at the LHC.

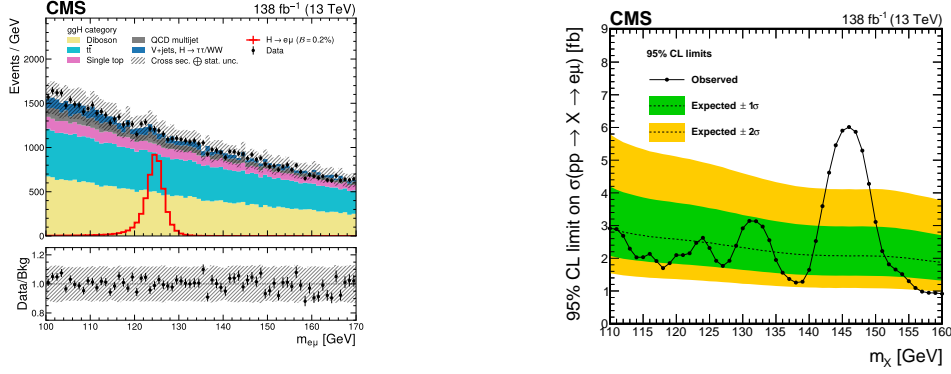


Figure 5: Left: $m_{e\mu}$ distribution for data, simulated backgrounds and $H \rightarrow e\mu$ signal in the ggF category. $\mathcal{B}(H \rightarrow e\mu)$ 0.2% is assumed to draw the signal. Right: the observed and expected 95% CL upper limits on $\sigma(pp \rightarrow X \rightarrow e\mu)$ as a function of the hypothesized m_X assuming the relative SM-like production cross sections of the ggF and VBF production modes [19].

In this contribution, a selection of recent cLFV searches conducted by the ATLAS and CMS experiments using the full Run2 proton-proton collision dataset (138 fb^{-1}) has been presented. These analyses explore multiple physics sectors, including low- p_T heavy-flavor processes such as $\tau \rightarrow 3\mu$, and cLFV signatures involving the top quark and the Higgs boson, but have not yet observed significant deviations from SM expectations.

Currently, the sensitivity of these searches remains statistically limited. Therefore, the ongoing data taking in LHC Run3 will be crucial to enhance the precision of existing measurements and impose tighter constraints on theoretical models. Improved experimental methods, such as enhanced trigger strategies and advanced reconstruction algorithms, are expected to further increase sensitivity, particularly for low- p_T leptonic final states.

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