PROCEEDINGS OF SCIENCE

Lepton flavor (universality) violation studies at CMS

Federica Riti[a,*] **and on behalf of the CMS Collaboration.**

[a] *ETH Zürich,*
Rämistrasse 101, Zürich, Switzerland

E-mail: federica.riti@cern.ch

Recent results on lepton flavor universality violation are presented, based on 13 TeV pp collision data recorded by the CMS experiment.

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*Speaker

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1. Overview

In the Standard Model (SM) the electroweak gauge bosons have the same couplings to the three lepton flavors. This symmetry is accidental, since it is not guaranteed by any symmetry group, and it is called lepton flavor universality (LFU). Observations of an anomalous coupling that violates this symmetry could indicate a contribution of new physics. No lepton flavor universality violations (LFUV) have been found yet, but some discrepancies from the SM predictions suggest that measurements in this sector could be key to new discoveries [1, 2].

Lepton flavor (LF) is also conserved in the SM through an accidental symmetry. There is already evidence of neutral lepton flavor violation (LFV) due to neutrino oscillations [3]. On the other hand, a violation in the charged LF sector has not been seen yet. Charged LFV (CLFV) decays are supposed to happen in loop diagrams through neutrino mixing with a strongly suppressed rate of around 10^{-55}, but within some SM extensions, this branching ratio (BR) is predicted to increase up to $10^{-10} - 10^{-8}$ [4].

LF and LFU measurements are strategic sectors to look for new physics. Some experiments are built specifically to perform them, like LHCb and the b-factories Belle and BaBar. CMS [5] instead is a general purpose detector at LHC, but with its high instantaneous luminosity and central acceptance, thought for high-p_T physics programs, it can be complementary to other experiments in the LF(U)V measurements.

Many analyses have been published in CMS on the topic, and in this proceeding an overview of the most recent results is presented.

2. LFV in the Higgs sector

In the context of LFV studies within the Higgs sector, one of the most recent published results in CMS is the search for LFV decay of a H boson or other exotic resonances with a mass between 110 and 160 GeV to an $e^{\pm}\mu^{\mp}$ pair, using Run II data [6]. The final state of interest consists of a prompt, oppositely-charged electron-muon pair. The dominant sources of backgrounds are leptonic decays of $t\bar{t}$ and WW diboson events, together with Drell-Yan (DY) events with a misidentified lepton.

This analysis targets the two dominant production modes of the Higgs boson at the LHC, gluon fusion (ggH) and vector boson fusion (VBF), and events are firstly divided for each production mechanism. Events with at least two jets with invariant mass higher than 400 GeV and high pseudorapidity separation are classified as VBF category, while the rest are considered to be part of the ggH production mode.

The two broad categories are further split according to the signal purity using the output of two boosted decision trees (BDTs), one for each production category. For both BDTs, a mixture of simulated signal events is used in the training including events of $H \to e\mu$ and $X \to e\mu$ at several mass values, between 110 and 160 GeV from both the ggH and the VBF production modes. Kinematics variables from the dominant sources of backgrounds of di-leptonic decays of $t\bar{t}$ and WW diboson events are used in the training. To avoid the distortion of the background events with $m(e\mu)$ close to the signal resonance to form spurious signal resonances along $m(e\mu)$, the BDT input variables are chosen such that the BDTs do not make use of the $m(e\mu)$ variable.

The $m(e\mu)$ distributions of simulated signal events are fit with a sum of Gaussian distributions for each production mode, category, and mass of the Higgs boson, while the background in each category is modeled with a Bernstein polynomial.

No significant excess of data above the background prediction has been observed for the LFV decay of $H \to e\mu$. The observed (expected) upper limit on $\mathcal{B}(H \to e\mu)$ is 4.4 (4.7) $\times 10^{-5}$ at 95% CL, which is the most stringent limit set from direct searches.

The observed (expected) upper limit at 95% CL on $\sigma(pp \to X \to e\mu)$ is plotted as a function of m_X in the range 110 ˘ 160 GeV on the left in Fig. 1. An excess of events over the background-only hypothesis is observed at $m_X \sim 146$ GeV, where a peak local (global) combined significance of 3.8 (2.8) standard deviations is observed.

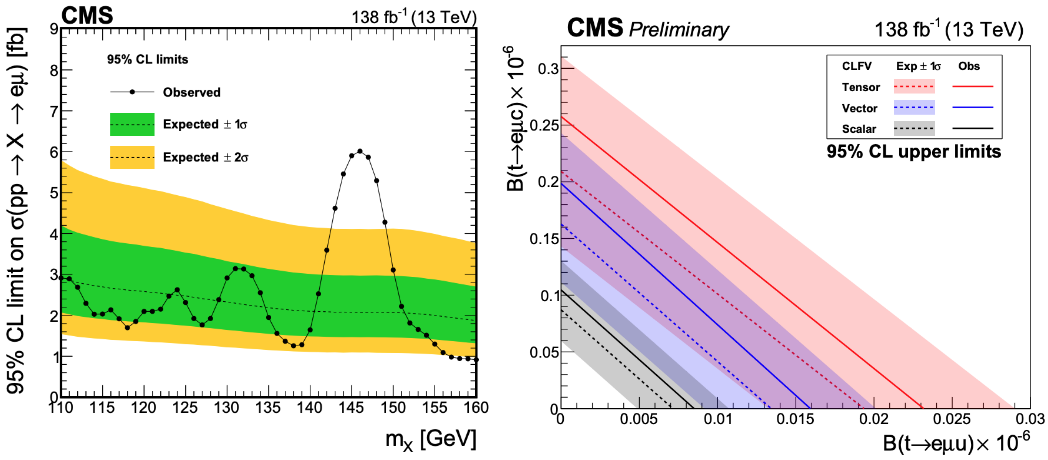

Figure 1: Left: Observed (expected) 95% CL upper limits on $\sigma(pp \to X \to e\mu)$ as a function of m_X assuming the relative SM-like production cross sections of the ggH and VBF production modes [6]. Right: Two-dimensional 95 % CL upper limits on the branching ratios for $t \to e\mu u$ and $t \to e\mu c$. The observed (expected) upper limits for tensor-, vector-, and scalar-like CLFV interactions are shown in red, blue, and black solid (dotted) line, respectively [8].

3. LFV in the top quark sector

Given the LHC's sensitivity to LFV involving top quarks in some BSM models [7], CMS has recently published a search focusing on LFV processes associated with top quark production and decay [8]. CLFV in final states of two opposite-charge leptons have been previously searched for by the CMS collaboration [9], while the ATLAS collaboration already searched for CLFV in three-lepton final states [10, 11].

In this analysis [8], final states with exactly three charged leptons, either electrons or muons, are considered. One of the three leptons originates from the leptonic decay of the SM top quark while the other two leptons originate from CLFV interaction. In addition, the selected events are required to contain at least one jet and at most one jet associated with a bottom quark.

The SM background processes that enter the final selection are divided into two groups: prompt and nonprompt backgrounds. Prompt backgrounds include SM processes that produce at least three leptons via decays of electroweak bosons, and they are modeled with MC simulation. Other processes that fail this criterion, like DY production, are categorized as nonprompt backgrounds and modeled with data-driven techniques.

The SR is further categorized in $m(e\mu)$ to create regions enriched in either top quark production ($m(e\mu) > 150$ GeV) or decay ($m(e\mu) < 150$ GeV) signal events. BDTs are implemented to separate a possible LFV signal from the SM background contributions.

No significant excess is observed over the prediction from the SM. Upper limits are set on the branching ratios $t \to e\mu u$ ($t \to e\mu c$) of 0.023 $\times 10^{-6}$ (0.258 $\times 10^{-6}$), 0.016 $\times 10^{-6}$ (0.199 $\times 10^{-6}$), and 0.009 $\times 10^{-6}$ (0.105 $\times 10^{-6}$) for tensor, vector, and scalar interactions, respectively, as shown on the right of Fig. 1.

4. LFV in the exotic sector

This proceeding highlights two amongts several interesting recent results in the exotic sector: a search for heavy resonances and quantum black holes in $e\mu$, $e\tau$ and $\mu\tau$ final states [12], along with an investigation into a high-mass dimuon resonance paired with b-quark jets [13].

4.1 Heavy resonances in $e\mu$, $e\tau$ and $\mu\tau$ final states

A search for heavy resonances and quantum black holes decaying into $e\mu$, $e\tau$ and $\mu\tau$ final states is performed in CMS, and designed to be as model independent as possible. Additionally, the results are also interpreted in terms of the characteristics of the following possible states: a τ sneutrino ($\tilde{\nu_\tau}$), which can be the lightest supersymmetric (SUSY) particle in R parity violating models, a heavy Z' gauge boson in LFV models, and quantum black holes (QBHs).

In this LFV dilepton search, there are multiple processes within the SM that yield a final state of two distinct-flavor charged leptons. The primary source of background comes from $t\bar{t}$ production. Subdominant background contributions arise from diboson, $Z \to ll$, $W\gamma$, and single top quark production mechanisms. These backgrounds are estimated from MC simulations. Additionally, backgrounds from multijet and W+jets processes occur due to the incorrect identification of jets as leptons and are determined directly from data.

Model-specific limits for the product of the cross section and the branching fraction were obtained for the RPV SUSY, Z', and QBH signals. No excess over the SM expectations are observed, and these are the most stringent limits available from collider experiments for heavy particles that undergo LFV decays.

Model-independent cross section limits are also obtained, shown in the left plot in Fig. 2 for the $e\mu$ final state.

4.2 High-mass dimuon resonance paired with b-quark jets

Numerous theoretical models predict the presence of a new neutral vector boson, Z', that decays into lepton pairs, and has a mass around the TeV scale. Inclusive searches for Z' bosons have taken place at the LHC [14, 15], but they are limited by the large DY background and might not be sensitive to scenarios where the Z' couples to second or third generation quarks. The CMS analysis here presented primarily aims at detecting a $Z' \to \mu\mu$ resonance requiring the presence of b quark jets.

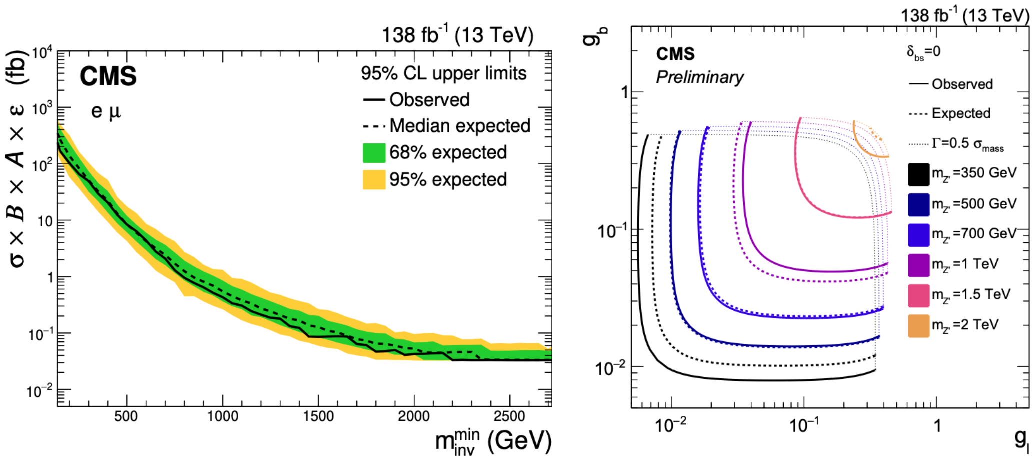

Figure 2: Left: Model-independent upper limits at 95% CL on the product of the cross section, the branching fraction, acceptance, and efficiency are shown for the search for heavy resonances and quantum black holes decaying into $e\mu$, $e\tau$ and $\mu\tau$ [12]. Right: Observed (solid) and median expected (dashed) exclusion limits at 95% CL in the $g_b - g_l$ plane for the LFU model in the search for high-mass dimuon resonance paired with b-quark jets [13]. The enclosed regions are excluded.

The investigation targets a narrow $Z' \to \mu^-\mu^+$ resonance with a mass $m_{Z'} > 350$ GeV, with at least one b quark jet. The resonance's width is considered narrow compared to the dimuon invariant mass ($m_{\mu\mu}$) resolution.

Events are categorized based on the multiplicity of b quark jets: $N_b = 1$ and $N_b \geq 2$. The predominant background sources across the $m_{\mu\mu}$ spectrum emerge from the DY process and $t\bar{t}$ production. The DY background is already reduced by asking the presence of a minimum of one b quark jet. The $t\bar{t}$ one is suppressed by imposing that the minimum invariant mass for any lepton–b quark jet pairing exceed the t quark mass of 175 GeV. Additional background contributors, such as $tZ + X$, $tW + X$, $t\bar{t}V$ (where $V = W, Z, H$) processes, and diboson (W or Z), are further decreased by excluding events with any extra lepton or an isolated high p_T charged hadron.

Model-independent limits are derived on signal events with Nb = 1 and ≥ 2. The limits are presented as a function of the dimuon resonance mass values and no significant excess over the SM prediction is observed. Results are also interpreted in terms of a LFU model that involves Z' boson couplings to b quarks (g_b) and muons (g_l). The exclusions in this model are presented in terms of the coupling strengths g_l and g_b, and $m_{Z'}$, and shown in the right plot in Fig. 2.

References

[1] LHCb Collaboration, "Measurement of the Ratios of Branching Fractions $\mathcal{R}(D^*)$ and $\mathcal{R}(D^0)$," doi:10.1103/PhysRevLett.131.111802

[2] LHCb Collaboration, "Measurement of CP-Averaged Observables in the $B^0 \to K^{*0}\mu^+\mu^-$ Decay," doi:10.1103/PhysRevLett.125.011802

[3] B. J. Rebel [MINOS], "First MINOS results with the NuMI beam," Nucl. Phys. B Proc.

Suppl. **168**, 195-198 (2007) doi:10.1016/j.nuclphysbps.2007.02.014 [arXiv:hep-ex/0701049 [hep-ex]].

[4] M. Raidal, A. van der Schaaf, I. Bigi, M. L. Mangano, Y. K. Semertzidis, S. Abel, S. Albino, S. Antusch, E. Arganda and B. Bajc, *et al.*, "Flavour physics of leptons and dipole moments," Eur. Phys. J. C **57**, 13-182 (2008) doi:10.1140/epjc/s10052-008-0715-2 [arXiv:0801.1826 [hep-ph]].

[5] CMS Collaboration, JINST 3 S08004 (2008)

[6] CMS Collaboration, "Search for the lepton-flavor violating decay of the Higgs boson and additional Higgs bosons in the eμ final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV," doi:10.48550/arXiv.2305.18106 [arXiv:2305.18106 [hep-ph]]

[7] S. Davidson, M. L. Mangano, S. Perries, and V. Sordini, "Lepton flavour violating top decays at the LHC," Eur. Phys. J. C 75 (2015) 450 doi:10.1140/epjc/s10052-015-3649-5, arXiv:1507.07163.

[8] CMS Collaboration, "Search for charged lepton flavor violation in the top quark sector in trilepton final states with the CMS detector at $\sqrt{s}$ = 13 TeV," CMS-PAS-TOP-22-005 https://cds.cern.ch/record/2851002

[9] CMS Collaboration, "Search for charged-lepton flavor violation in top quark production and decay in pp collisions at $\sqrt{s}$ = 13 TeV," JHEP 06 (2022) 082, doi:10.1007/JHEP06(2022)082, arXiv:2201.07859

[10] ATLAS Collaboration, "Search for charged lepton-flavour violation in top-quark decays at the LHC with the ATLAS detector," ATLAS CONF Note ATLAS-CONF-2018-044, 2018.

[11] ATLAS Collaboration, "Search for charged-lepton-flavour violating $\mu\tau qt$ interactions in top-quark production and decay with the ATLAS detector at the LHC,", ATLAS CONF Note ATLAS-CONF-2023-001, 2023.

[12] CMS collaboration, "Search for heavy resonances and quantum black holes in $e\mu$, $e\tau$, and $\mu\tau$ final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV," J. High Energ. Phys. 2023, 227 (2023). https://doi.org/10.1007/JHEP05(2023)227

[13] CMS Collaboration, "Search for a high mass dimuon resonance associated with b quark jets at $\sqrt{s}$ = 13 TeV," CMS-PAS-EXO-22-016 https://cds.cern.ch/record/2859355

[14] CMS Collaboration, "Search for resonant and nonresonant new phenomena in high-mass dilepton final states at $\sqrt{s}$ = 13 TeV," JHEP 07 (2021) 208, doi:10.1007/JHEP07(2021)208, arXiv:2103.02708.

[15] ATLAS Collaboration, "Search for high-mass dilepton resonances using 139 fb-1 of pp collision data collected at $\sqrt{s}$ = 13 TeV with the ATLAS detector," Phys. Lett. B 796 (2019) 68, doi:10.1016/j.physletb.2019.07.016, arXiv:1903.06248.