PROCEEDINGS OF SCIENCE

PoS(ICHEP2022)695

Test of lepton flavor (universality) violation at CMS through heavy mesons and leptons decays

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

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

E-mail: federica.riti@cern.ch

Results are presented on lepton flavor (universality) violation tests through precise measurements of decays involving heavy mesons and leptons. These measurements are compared to the standard model predictions. The studies use 13 TeV proton-proton collision data collected by the CMS experiment at the LHC.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

*Speaker

1. Overview

In the Standard Model (SM) the electroweak gauge bosons have equal couplings to the three lepton flavors. This symmetry is called lepton flavor universality (LFU) and it is accidental, since it is not guaranteed by any symmetry group. 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.

Also lepton flavor (LF) is conserved in the SM through an accidental symmetry. There is already evidence of neutral lepton flavor violation (LFV) due to neutrino oscillations [1], that have already been proved. On the other hand a violation in the charged LF sector has not been seen yet. Charged LFV 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 BR could be predicted to increase up to 10^{-10} - 10^{-8} [2].

LF and LFU measurements are strategic sectors to look for new physics. Some experiments are built to make these measurements, like LHCb at LHC and the b-factories Belle and BaBar. CMS 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 like LHCb in the LF(U)V measurements. In this proceeding the test of LF(U)V measurements at CMS will be described.

2. LFV search for the $\tau \to 3\mu$ decay

One of the processes that can be investigated to test LF conservation is the $\tau \to 3\mu$ decay. The best available limit to date for this decay was set by the Belle experiment [3], with a $\mathcal{B}(\tau \to 3\mu) < 2.1 \cdot 10^{-8}$ at 90% confidence level (CL).
The CMS Collaboration performed this measurement with proton-proton collision data at $\sqrt{s} = 13$ TeV for a total of 33.2 fb^{-1} of integrated luminosity at the LHC in 2016 [4]. This analysis makes use of two independent τ production channels: production of the τ in heavy-flavor (HF) and in W boson decays. The HF channel targets τ leptons coming from $D_s^+ \to \tau^+\nu$, $B^+ \to \tau X$ and $B^0 \to \tau + X$ inclusive decays. These processes are abundant, but their measurement is challenging because of the very low p_T muons in the final state produced at very high pseudorapidity. Other complications are due to uncertainties in the production of HF hadrons, but these can be reduced using the decay $D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ to normalise the signal yield. A Boosted Decision Tree (BDT) is trained to improve the signal to background ratio, using ten variables, including final μ kinematics and isolation and 3μ vertex properties. Six categories are defined to improve the sensitivity of the analysis, using the signal purity (BDT score), and the resolution of the invariant mass of the 3μ system. In Fig. 1 the invariant mass of the 3μ system in the six categories is shown. The other channel targets τ coming from a W boson decay: $W \to \tau\nu$. This process is less abundant than the HF decays, but the signature is more clear. Also in this case a BDT is trained to better distinguish signal from background, using 18 variables, e.g. τ properties and the final state muon quality. The BDT score is used to apply a selection and two categories in τ pseudorapidity are defined to improve the sensitivity of the analysis. In Fig. 2 the invariant mass distributions of the 3μ system for the two

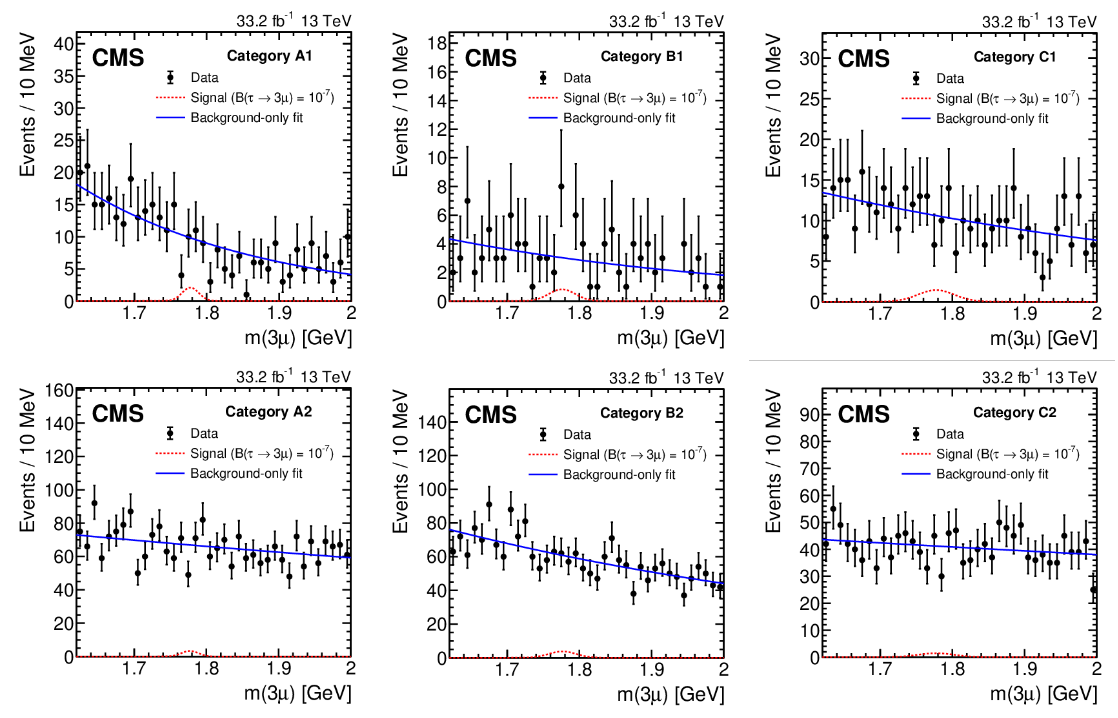

Figure 1: Fit to the invariant mass of the 3μ system distributions in the six categories. There are three mass resolution bins: $\sigma_m/m < 0.7\%$, $0.7\% < \sigma_m/m < 1.0\%$, and $\sigma_m/m > 1.0\%$, labeled A, B, and C. Each of these categories is further split into two BDT bins, "1" for the highest in signal-to-background ratio, and "2" for the other bin.

independent categories are shown. For both channels, a veto on pairs of oppositely charged muons,

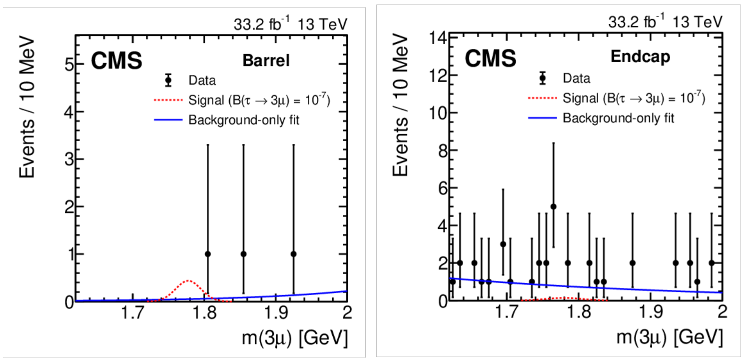

Figure 2: Fit of the invariant mass distribution of the 3μ system for the two categories in τ pseudorapidity.

with one muon from the τ candidate and one muon not associated with it, is applied. The veto consists in rejecting events where the muon pairs come from the same vertex and have an invariant mass within the width of a know resonance with a dimuon decay. The veto therefore suppresses background from dimuon decays of hadronic resonances. No evidence of LFV is found, with the observed (expected) upper limits for the two channels being $9.2 \cdot 10^{-8}(10.0 \cdot 10^{-8})$ with 90% CL for the HF channel and $20 \cdot 10^{-8}(13 \cdot 10^{-8})$ with 90% CL for the W channel, with a combined limit of $8.0 \cdot 10^{-8}(6.9 \cdot 10^{-8})$ with 90% CL. This analysis includes only 2016 data, corresponding to a luminosity of $35.9 fb^{-1}$, but an updated measurement using the complete dataset at $\sqrt{s} = 13$ TeV and an improved analysis strategy is ongoing.

3. Lepton Flavor Universality Violation

The LFU can be tested in the B sector measuring the ratios defined as $R_{H_s} = \frac{\mathcal{B}(H_b \to H_s \mu^+ \mu^-)}{\mathcal{B}(H_b \to H_s e^+ e^-)}$ when $b \to s l^+ l^-$ and $R_{H_c} = \frac{\mathcal{B}(H_b \to H_c \tau^- \bar{\nu_\tau})}{\mathcal{B}(H_b \to H_c \mu^- \bar{\nu_\mu})}$ when $b \to c l^- \bar{\nu}_l$. In the former case the decay is at loop level, then the BR is small, but the kinematics is closed thanks to the absence of neutrinos in the final state. In the latter, the decay is at tree level, with a larger BR. There are neutrinos in the final state, which lead to the use of template fits, therefore these decays are more subject to systematic uncertainties. Studies on LFUV are performed in both cases.

3.1 LFUV Anomalies

Results from several experiments [5][6][7] already suggest deviations from the SM predictions for these values. In Fig.3 (left) the summary plot of the $R(K)$ results, with the LHCb measurement at 3.1σ from the SM prediction is shown. In Fig.3 (right) the $R(D)$ and $R(D^*)$ results, with a combined sensitivity of over 3σ are shown.

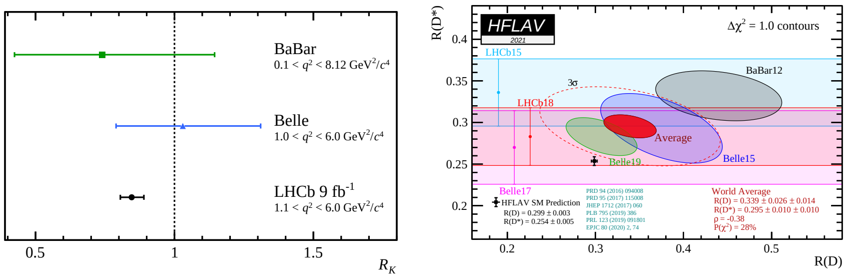

Figure 3: Summary plots for $R(K)$ [8] and $R(D^{(*)})$ [9] results.

These deviations could be explained with theories that include extensions of the SM, with enhanced weak coupling to third-generation leptons and quarks, such as interactions involving a charged Higgs boson, leptoquarks or new vector bosons (W', Z').

3.2 CMS parked data

A huge effort has been done in CMS in the past years to make LFUV measurements in B physics sector possible, with the main challenge being the triggering on leptons with low p_T other than muons.

For 2018 data taking period a new trigger strategy was adopted by the CMS detector targeting low p_T muons from B meson decays [10], called BParking trigger. Events were recorded with a trigger logic that requires the presence of a single displaced muon: the μ candidate responsible for the trigger comes from the "tag-side" b hadron that undergoes a $b \to \mu + X$ decay, while the "signal-side" b hadron decays without any bias from trigger requirements. The trigger threshold of this new BParking trigger depends on the instantaneous luminosity. As luminosity decreases, the rate of physics triggers decreases as well: this allows to loosen the BParking trigger thresholds while keeping a constant total trigger rate. In Fig. 4 (left) the L1 trigger rate that stays constant over time is shown, and in Fig. 4 (right) the HLT rate, where the distinction between BParking and other physics triggers is visible, is shown. In total, 12 billion events were recorded in 2018, with a $b\bar{b}$ purity of 75 %.

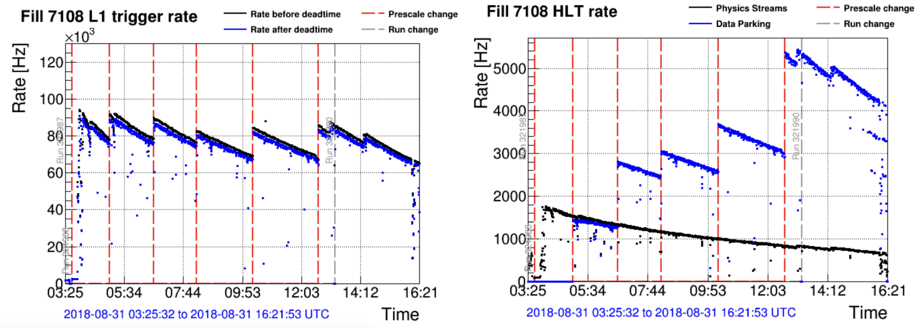

Figure 4: L1 (left) and HLT (right) rates over time for one example Fill [10].

The lepton p_T distributions collected with this sample are very soft, implying challenges related to electron and tau reconstruction efficiencies. For this reason new low-p_T reconstruction algorithms for these two leptons have been developed, with better performances than the standard algorithms. The BParking dataset has been validated while it was being collected: invariant mass distributions, shown in Fig. 5, were computed for some B decays using a small fraction of the whole dataset. This dataset makes B single-μ analyses possible for the first time in CMS, but also other

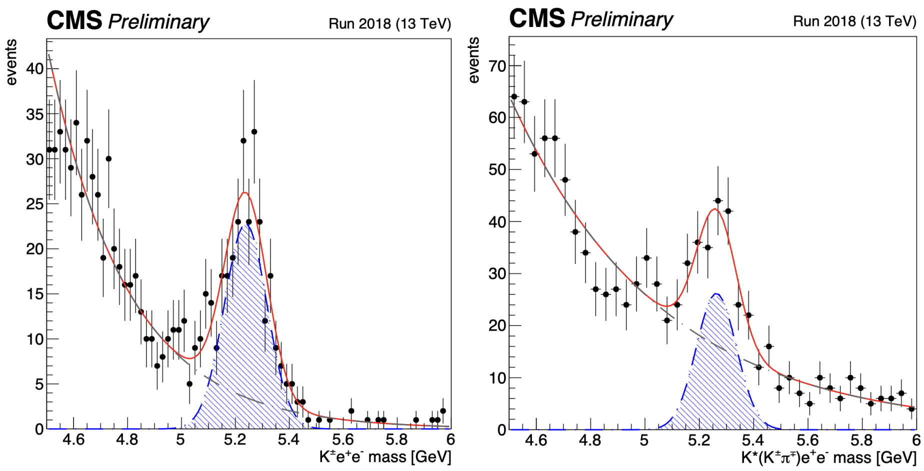

Figure 5: Standard Candles using a small percentage of the BParking dataset during data taking. [10].

new measurements are possibile, using the unbiased part of the sample, such as hadronic decays that were precluded before.

4. Conclusions

LF(U)V is an exciting field to look for new physics, and the CMS collaboration is devoting a great effort in this research sector. The $\tau \to 3\mu$ LFV analysis with data collected by the CMS experiment in 2016, for a total of $33.2 fb^{-1}$, was published and an analysis with the full dataset at $\sqrt{s}$ = 13 TeV is ongoing. Thanks to the BParked dataset collected in 2018, with the B-single muon dataset being the largest ever collected, the CMS collaboration can also enter the test of LFUV measurements.

References

[1] 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]].

[2] 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]].

[3] K. Hayasaka, K. Inami, Y. Miyazaki, K. Arinstein, V. Aulchenko, T. Aushev, A. M. Bakich, A. Bay, K. Belous and V. Bhardwaj, *et al.* "Search for Lepton Flavor Violating Tau Decays into Three Leptons with 719 Million Produced Tau+Tau- Pairs," Phys. Lett. B **687**, 139-143 (2010) doi:10.1016/j.physletb.2010.03.037 [arXiv:1001.3221 [hep-ex]].

[4] CMS Collaboration, "Search for the lepton flavor violating decay $\tau \rightarrow 3\mu$ in proton-proton collisions at $\sqrt{s}$ = 13 TeV," JHEP **01**, 163 (2021) doi:10.1007/JHEP01(2021)163 [arXiv:2007.05658 [hep-ex]].

[5] The BABAR Collaboration, "Measurement of an excess of $\overline{B} \rightarrow D^{(*)}\tau^-\overline{\nu}_\tau$ decays and implications for charged Higgs bosons," Phys. Rev. D, no.88, 7 (2013) doi = 10.1103/PhysRevD.88.072012.

[6] The Belle Collaboration, "Measurement of the τ lepton polarization and $R(D^*)$ in the decay $\overline{B} \rightarrow D^*\tau^-\overline{\nu}_\tau$ with one-prong hadronic τ decays at Belle," Phys. Rev. D, no.97, 1 (2018) doi = 10.1103/PhysRevD.97.012004.

[7] LHCb Collaboration, "Test of lepton flavor universality by the measurement of the $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$ branching fraction using three-prong τ decays," Phys. Rev. D, no.97, 7 (2018) doi = 10.1103/PhysRevD.97.072013.

[8] R. Aaij *et al.* [LHCb], "Test of lepton universality in beauty-quark decays," Nature Phys. **18**, no.3, 277-282 (2022) doi:10.1038/s41567-021-01478-8 [arXiv:2103.11769 [hep-ex]].

[9] Y. Amhis *et al.* [HFLAV], "Averages of b-hadron, c-hadron, and τ-lepton properties as of 2021," [arXiv:2206.07501 [hep-ex]].

[10] CMS Collaboration, "Recording and reconstructing 10 billion unbiased b hadron decays in CMS" http://cds.cern.ch/record/2704495.