Lepton Flavor Violation in Heavy Flavor decays at the CMS experiment

F. Nenna on behalf of the CMS Collaboration

Diparitmento di Fisica e Astronomia, Università di Padova - Via F. Marzolo 8, 35121 Padova, Italy
Dipartimento di Fisica, Università di Bari - Via E. Orabona 4, 70125 Bari, Italy
INFN, Sezione di Bari - Via E. Orabona 4, 70125 Bari, Italy

Summary. — The study of lepton flavor conservation and its universality is essential for uncovering signs of New Physics beyond the Standard Model (SM). While the SM allows for lepton flavor violation (LFV), its predicted rates are negligible. In contrast, several beyond the SM (BSM) scenarios foresee enhanced LFV or lepton flavor universality violations (LFUV) that could be detectable with current experiments. New gauge interactions in these models may cause deviations in lepton interactions across generations. The CMS experiment is sensitive to many such effects. This contribution summarizes CMS results on LFV and LFUV in 13 TeV proton-proton collisions, focusing on heavy hadron decays, including $\tau \to 3\mu$, $B^{\pm} \to K^{\pm}\ell^{+}\ell^{-}$, and $B_c^{\pm} \to J/\psi \ell^{\pm}\nu_{\ell}$. In the context of the European Particle Physics Strategy (EPPS), this contribution will present the estimated projections in the search for LFV in the high luminosity scenario of the High Luminosity LHC.

1. – Introduction

Lepton flavor is an accidental symmetry in the Standard Model (SM). It is currently violated only via neutrino oscillations resulting in extremely low branching fractions, making its observation impossible at existing experiments. However, many New Physics (NP) models predict Lepton Flavor Violation (LFV) with rates compatible with current experimental sensitivities, for example, $\tau \to 3\mu$ decay branching fraction increases from $\sim 10^{-55}$ via neutrino oscillation [1], to $\sim 10^{-8}$ in NP scenarios [2]. The negligible SM contributions make LFV a clear signal of NP.
Besides, the SM gauge sector is lepton-universal, *i.e.* with equal couplings of the three lepton families (e, μ, τ) to the gauge bosons W, Z, and γ. Tests of Lepton Flavor Universality (LFU) in W and Z boson decays have shown excellent agreement with SM predictions [3]. Rare b hadron decays offer a complementary environment to test LFU, as BSM processes could modify branching fractions differently for different lepton species.

2. – B-Physics at CMS

During LHC Run-2 (2015–2018), the CMS detector efficiently collected about 150 fb^{-1} of high-quality proton-proton collision data. Even if CMS was not specifically designed for flavor physics analyses, its large integrated luminosity allows for results in Heavy Flavour (HF) measurements that are competitive with specialized experiments, like LHCb and the B-factories. Nevertheless, the large Run 2 luminosity also introduced challenges: higher event rates required more advanced trigger algorithms, and greater pileup led to more complex backgrounds. In response, CMS adopted sophisticated analysis techniques and innovative "parking" triggers, to enhance signal selection and analysis performance [4]. Accordingly, this report summarizes the main LFV and LFU tests conducted by the CMS experiment using Run 2 data, highlighting the techniques used to face the aforementioned challenges.

3. – Test of LFV in $\tau \to 3\mu$ decay

Among lepton flavor violating decay channels, $\tau \to 3\mu$ is considered the golden channel at the LHC due to its clean, muon-only final state and the high τ production rate at the LHC. Nowadays, the best result for the observed upper limit has been reached by Belle II, *i.e.* 1.9×10^{-8} (90% C.L.) [5].
In fig. 1, the main τ production modes at the LHC are shown; they can be grouped into two categories:

1. Heavy Flavor (HF) decays: about 99% of τ leptons originate from B and D meson decays, typically characterized by low transverse momentum (p_T) and large pseudorapidity $|\eta|$.

2. W boson decays, accounting for $\sim$0.01% of produced τ's, with a higher p_T, smaller $|\eta|$, and missing energy in the final state due to undetected neutrino.

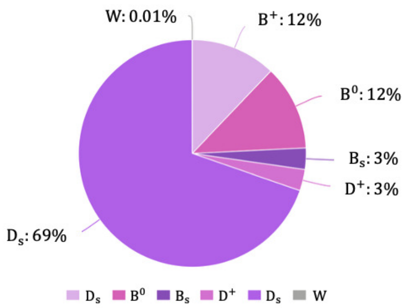

Fig. 1. – τ production modes at the LHC.

Despite the much higher production rate of τ leptons in HF decays, their low p_T and large $|\eta|$ lead to significant losses due to limited detector acceptance (*i.e.* for CMS $p_T > 2\,\mathrm{GeV/c}$ and $|\eta| < 2.4$). Uniquely, CMS leverages both HF and W channels, allowing it to set a competitive upper limit on the branching fraction of this forbidden decay [6]. Below, the main steps of such measurement are outlined.
The analyses for the two channels are performed independently and later combined. Both follow a similar strategy: searching for a peak in the tri-muon invariant mass spectrum within the τ mass window, *i.e.* $1.6 < m_{3\mu} < 2.0$ GeV/c^2. Since the signal strength is significantly affected by invariant mass resolution, differences throughout the detector are taken into account, so events are divided into three categories, with a decreasing mass resolution. These three categories correspond to the three regions of the CMS tracker detector: the barrel, the overlap region and the endcaps, respectively.
For improving signal-background discrimination, two Boosted Decision Trees (BDTs) are used. The first, based on muon reconstruction quality distinguishes genuine muons from

misidentified muons. The second, applied to the genuine muons passing the first selection, is trained to separate simulated $\tau \to 3\mu$ signal events from data sidebands events. Throughout the analysis, the $D_s^+ \to \phi(\to \mu^+\mu^-)\pi^+$ is used as a control channel for validating BDT inputs, evaluating systematic uncertainties, and correcting data/MC discrepancies. As such decay has a phase space similar to HF $\tau \to 3\mu$, it is also used for normalization in the HF analysis to reduce systematics. Combining results from both channels using Full Run 2 ($131\,\mathrm{fb}^{-1}$) data yields an observed (expected) upper limit of $2.9(2.4) \times 10^{-8}$ (90% C.L.) [6]. The results obtained from the analyses separately are summarized in fig. 2. As the measurement is dominated by statistical uncertainties, the increase in the collected luminosity will play a central role in setting a more stringent upper limit.

As part of the European Strategy for Particle Physics Update (ESPPU), projections for the High-Luminosity LHC (HL-LHC) were computed and published in collaboration with the other LHC experiments in [7]. CMS estimation on $\tau \to 3\mu$ (described in greater detail in [8]) assume increased luminosity, up to $2-3\,\mathrm{ab}^{-1}$, but do not account for the scheduled detector upgrades (*e.g.*, improved tracker system or extended muon trigger coverage) and PU degradation is assumed to be compensated by analysis and detector improvements. Consequently, the expected combined upper limit improves by $80-85\%$, from 7.2×10^{-9} down to 2.7×10^{-9} (90% C.L.), with the W channel scaling more favorably than the HF channel due to lower background levels.

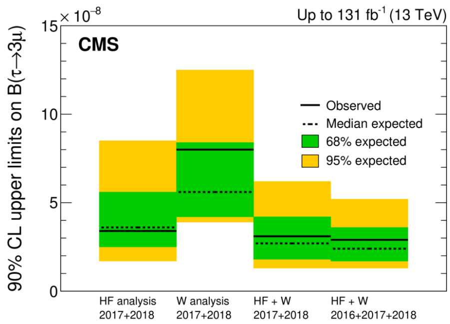

Fig. 2. – Observed and expected upper limits on $\mathcal{B}(\tau \to 3\mu)$ at 90% CL, from the HF analysis, the W boson analysis, the combination of the two analyses, as well as their combination. (from [6])

4. – Test of LFU in $B^\pm \to K^\pm\mu^+\mu^-$ and $B^\pm \to K^\pm e^+e^-$ decay via measurement of the R(K) ratio

Processes of the type $b \to s\ell\ell$ are key probes of LFU. Although they occur only at loop level, their neutrino-less final states make them experimentally clean. In particular, this paper focuses on the measurement of the $R(K)$ ratio [9]:

$$R(K) = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}\,, \tag{1}$$

which is theoretically predicted to be 1.00 ± 0.01 under LFU. To reduce systematic uncertainties, both decay channels are normalized to their corresponding $B \to KJ/\psi(\to \ell\ell)$ decays. Data were collected using the B-parking trigger strategy [4]: once a muon from a B decay is triggered (*tag side*), the rest of the event (*probe side*) is also recorded. This technique yields $\mathcal{O}(10^{10})$ unbiased B decays. In this analysis, the muon mode is reconstructed on the tag side, and the electron mode on the probe side. Nevertheless, the electron channel is still limited by poorer resolution at low p_T. To mitigate this and improve efficiency, the Particle Flow (PF) algorithm is combined with a dedicated low-p_T (LP) electron reconstruction BDT-based algorithm optimized for electrons with $p_T > 1$ GeV/c. The strategy involves inferring the signal yields fitting the invariant mass of the $K^{\pm}\ell^{+}\ell^{-}$ system in three q^2 regions. The signal region is defined as $1.1 < q^2 < 6$ GeV^2, with two control regions at higher q^2. The dominant background arises from semileptonic decays of heavy mesons and is suppressed using a BDT trained on simulated signal and data sidebands for background. The resulting fitted invariant mass distribution are shown in fig. 3 for the muon and electron channels. The final result is [9]:

$$R(K) = 0.78^{+0.46}_{-0.23}\,(\text{stat})^{+0.09}_{-0.05}\,(\text{syst}) \tag{2}$$

which is dominated by the limited statistics of the electron channel and it is compatible within 1σ with the SM prediction as well as with the most precise measurement to date provided by LHCb, *i.e.* $0.846^{+0.060}_{-0.054}{}^{+0.016}_{-0.014}$ [10].

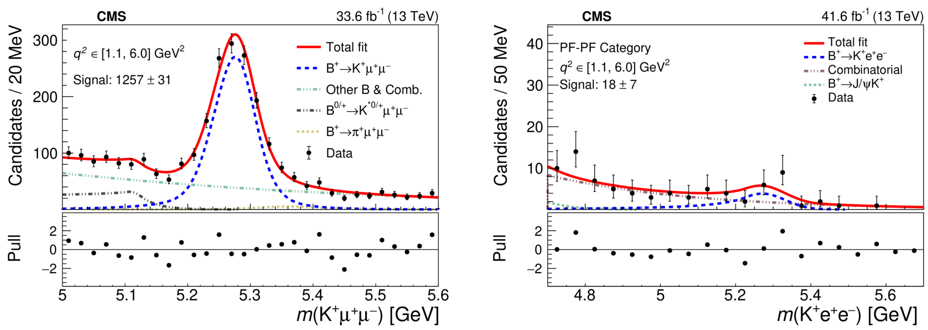

Fig. 3. – Results of an unbinned likelihood fit to the $K^{+}\mu^{+}\mu^{-}$ (left) and $K^{+}e^{+}e^{-}$ (right) invariant mass distributions in the signal q^2 bin. The error bars show the statistical uncertainty in data. (from [9])

5. – Test of LFU in semileptonic B_c^+ meson decay via the R(J/ψ) ratio

Another important test of lepton flavor universality involves $b \to c\ell\nu$ processes, which occur at tree level and are thus characterized by higher branching fractions. However, the presence of neutrinos in the final state makes signal distrimination more challenging. This paper focuses on the measurement of:

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}\,, \tag{3}$$

which is theoretically predicted to be 0.2582 ± 0.0038. This ratio cannot be measured at B-factories due to the absence of B_c^+ meson production, making the LHC the ideal environment for such studies. The first measurement of this ratio was performed by LHCb, which observed a value of $0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$ [11], consistent with the SM prediction within 2σ.
Depending on whether τ decays leptonically or hadronically, CMS measures the aforementioned ratio considering two possible final states of the numerator signal.

If the τ decays leptonically $\tau^+ \to \mu^+\nu_\mu\bar{\nu_\tau}$, it leads to a three-muon final state and the analysis is performed using data collected in 2018 (59.7 fb^{-1}). The main complication in semileptonic channel is the disentanglement of numerator and denominator, which share the same visible final state. Three variables are found to be the most sensitive to the large mass difference between tau leptons and muons and to the presence to the different number of neutrinos in the final state: $q^2 = (p_{B_c} - p_{J/\psi})^2$, the minimal distance between the third muon and J/ψ, and the transverse distance between J/ψ and the beam spot (L_{xy}). The analysis strategy consists of using, first, a Neural Network (NN) to subtract background muons produced by decay-in-flight of light hadrons. Then, a simultaneous fit of L_{xy} and q^2 is performed and the result is shown in fig. 3. The former proved good contraint on the background and on the denominator channel, while the latter is used to extract the signal thanks to its better μ/τ discrimination power.

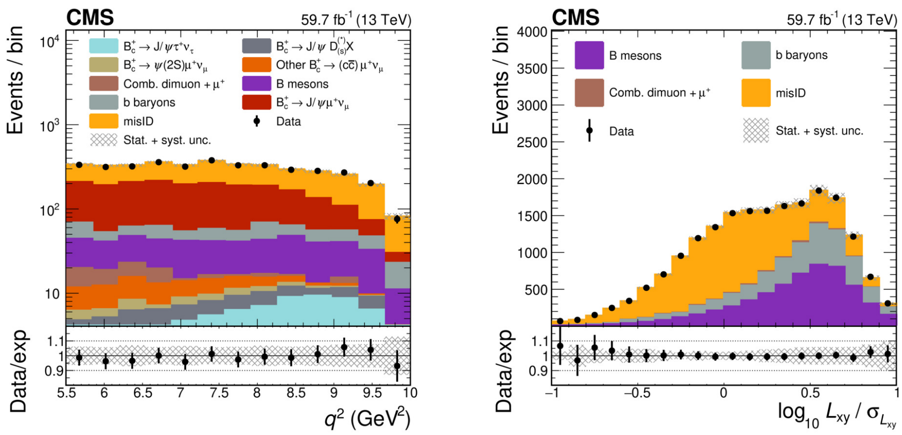

Fig. 4. – Distributions of the q^2 observable in the signal-enriched category, and of the $L_{xy}/\sigma_{L_{xy}}$ observable. In each panel, data is compared to the best-fit results. (from [12])

The final result obtained is [12]:

$$(4) \qquad R(J/\psi) = 0.17^{+0.18}_{-0.17}\,(\text{stat})^{+0.21}_{-0.22}\,(\text{syst})^{+0.19}_{-0.18}\,(\text{theo})\ .$$

Besides, the considered hadronic channel is $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\nu_\tau$. Its analysis is based on Full Run 2 data, collected triggering on a J/ψ and an additional track. It is crucial to discriminate signal from background processes, represented by inclusive J/ψ decays from B^0 and $B^\pm$ hadrons. A BDT is used for this purpose; it is trained to discriminate $B_c^+ \to J/\psi\tau^+\nu_\tau$ signal events from inclusive $J/\psi X$ decays.
Then, pion triplets in the final state are organized in pairs, *i.e.* ρ^0 candidates, and ordered based on their p_T in ρ_1 and ρ_2 respectively. A genuine τ lepton would show a resonance structure in one of the two pairs, because of the possible 3-prong decay $\tau^+ \to \rho^0(\to \pi^+\pi^-)\pi^+\nu_\tau$. Consequently, as shown in fig. 5, a fit of the unrolled $m(\rho_1)$ vs $m(\rho_2)$ is used to compute the ratio, simulatenously with the fits performed in the leptonic analysis. The final result, for the hadronic channel only, is $1.04^{+0.50}_{-0.44}$, that combined with the leptonic channel yields [13]:

$$(5) \qquad R(J/\psi) = 0.49 \pm 0.09\,(\text{stat}) \pm 0.25\,(\text{syst})\ ,$$

which combines the good constraints of the leptonic analysis with the incremented statistics from the hadronic channel.

The measurement is dominated by systematic uncertainties, primarily driven by the modeling of the inclusive J/ψ background.

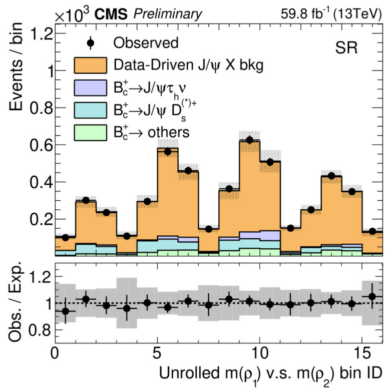

Fig. 5. – Distributions of the unrolled ρ^0 mass variable in the signal-enriched data region. (from [13])

6. – Conclusions

This paper summarizes key CMS analyses on lepton flavor violation (LFV) and lepton flavor universality violation (LFUV). For LFV, the latest upper limit on the $\tau \to 3\mu$ decay is presented, using the full Run 2 dataset and combining the HF and W channels. Projections for the ESPPU highlight CMS strong sensitivity in the High-Luminosity LHC era. For LFUV, measurements of $R(K)$ and $R(J/\psi)$ are reported. The $R(K)$ result agrees with Standard Model predictions within 1σ, though limited by low statistics in the electron channel. The $R(J/\psi)$ measurement, combining leptonic and hadronic τ decay modes, is also consistent with the SM within 1 standard deviation.

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