Recent CMS results on flavor anomalies and lepton flavor violation

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Recent CMS results on flavor anomalies and lepton flavor violation

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In the last 10 years, several discrepancies, at the level of several standard deviations, between flavor observables and the standard model predictions have been found by the Belle, BaBaR, and LHCb collaborations. In this talk, the results from the CMS experiment on these flavor anomalies are presented. The results are based on 13 TeV pp collision data collected during 2016-2018.

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1. Overview

In the Standard Model (SM), the couplings of the electroweak gauge bosons are the same for all three lepton flavors. This consistency, defined as lepton flavor universality (LFU), isn't derived from any symmetry group, therefore it is accidental. Any deviations could be hints of new physics beyond the SM (BSM). While no such lepton flavor universality violations (LFUV) have been definitively observed, certain inconsistencies with the SM predictions suggest that investigations in this direction might reveal new phenomena [1, 2].

Lepton flavor (LF) conservation in the SM is also attributed to an accidental symmetry. Neutral lepton flavor violations (LFV) have been observed through neutrino oscillations [3]. However, potential violations in the charged LF have not been measured yet. Charged LFV (CLFV) decays, with expected branching ratios (BR) of $\sim 10^{-55}$, could manifest in loop diagrams due to neutrino mixing. Yet, certain BSM models predict that these BR might increase up to values between 10^{-10} and 10^{-8} [4].

Both LF and LFU measurements are crucial in the ongoing search for new physics. Numerous recent results have been published by CMS [5] on these topics. In this proceeding some of them are presented, with a particular emphasis on a new indirect search for LFUV, which has been shown for the first time at this conference.

2. Direct LF(U)V searches

Two of the most recently published searches for LFV in CMS are the search for LFV in the top quark sector [6] and for $\tau \to 3\mu$ decay [7].

The former focuses on LFV processes associated with top quark production and decay [6]. Final states with exactly three charged leptons are selected: one lepton comes from the leptonic decay of the SM top quark, while the remaining two are attributed to CLFV interactions. Background processes are classified into 'prompt' and 'nonprompt' categories, with the latter modeled via data-driven methods. The signal region (SR) is categorised based on the $m(e\mu)$ observable, thus discerning regions predominantly influenced by either top quark production or decay. Boosted decision trees (BDTs) are employed to separate potential LFV signals from SM background. No significant excess is observed over the SM predictions.

The latter is a direct search of the LFV $\tau \to 3\mu$ decay [7]. The most stringent limit for this decay was set by the Belle experiment, with a $\mathcal{B}(\tau \to 3\mu) < 2.1 \times 10^{-8}$ at a 90% confidence level (CL) [8]. The CMS Collaboration has already published a first result using data collected in 2016, with a total integrated luminosity of 33.2 fb^{-1} [9]. The analysis presented in this proceeding is an extension of this aforementioned search, using the complete dataset collected during Run 2. This study makes use of two independent τ production channels: production of the τ in heavy-flavor (HF) and in W boson decays. The HF one targets τ leptons coming from $D_s^+ \to \tau^+\nu$, $B^+ \to \tau X$ and $B^0 \to \tau + X$ inclusive decays. While this presents an abundance of events, the measurement is more challenging due to the low p_T muons in the final state produced at very high pseudorapidity. The other channel includes τ leptons coming from the $W \to \tau\nu$ decay, which includes less events, but a clearer signature. For both channels, a BDT is trained to improve discrimination between signal and background. Additionally, a veto on pairs of oppositely charged muons, with one muon from the τ candidate and one muon not associated with it, is applied to suppress background from dimuon decays of hadronic resonances. No evidence for LFV is found, and upper limits for the two channels are computed, including the combination with the previous search using 2016 data [9], with a result of observed (expected) upper limit at 90% CL of $\mathcal{B}(\tau \to 3\mu) < 2.9(2.4) \times 10^{-8}$, a result competitive with the world's best.

Eventually, the search for the Z' particle with b quark jets [10] in CMS is presented. Theoretical models explaining LFUV predict the existence of a neutral vector boson, Z', which decays into lepton pairs and has a mass around the TeV scale. While previous inclusive searches for this Z' boson at the LHC [11, 12] have been constrained by the significant Drell-Yan (DY) backgrounds, the CMS analysis here presented focuses on a $Z' \to \mu\mu$ resonance with also the presence of b-quark jets. The events are required to have $m_{Z'} > 350$ GeV and they are categorized based on b-quark jet multiplicity. These requirements help reduce the DY and $t\bar{t}$ backgrounds, which are the principal sources of background of the analysis. Other background contributions are further decreased by excluding events with any extra lepton or an isolated high p_{T} charged hadron. Model-independent limits are derived and no significant excess over the SM prediction is observed. Moreover, the results are interpreted in terms of Z' boson couplings to b quarks and muons, and exclusion regions are defined.

3. Indirect LFUV search

LFU can be probed within the B sector by evaluating the ratios defined as $R_{H_\mathrm{s}} = \frac{\mathcal{B}(H_\mathrm{b} \to H_\mathrm{s}\mu^+\mu^-)}{\mathcal{B}(H_\mathrm{b} \to H_\mathrm{s}e^+e^-)}$ for the $b \to sl^+l^-$ transitions, and $R_{H_\mathrm{c}} = \frac{\mathcal{B}(H_\mathrm{b} \to H_\mathrm{c}\tau^-\bar{\nu_\tau})}{\mathcal{B}(H_\mathrm{b} \to H_\mathrm{c}\mu^-\bar{\nu_\mu})}$ for the $b \to cl^-\bar{\nu}_\mathrm{l}$ transitions. The former involves a loop-level decay, resulting in a smaller branching ratio (BR), but there are no neutrinos in the final state. The latter transition, being at tree-level, has a larger BR, but the neutrinos in the final state make these decays more susceptible to systematic uncertainties. LFUV investigations are conducted in both scenarios.

In this proceeding, the first $b \to cl^-\bar{\nu}_\mathrm{l}$ test of LFUV in CMS is presented [13], based on data collected by the CMS experiment in 2018, with a total integrated luminosity of $59.7 fb^{-1}$. The analysis aims at measuring the value $R(J/\psi) = \frac{\mathcal{B}(B_\mathrm{c}^+ \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B_\mathrm{c}^+ \to J/\psi\mu^+\nu_\mu)}$, leveraging only on the muonic decay of the $\tau^+ \to \mu^+\nu_\mu\bar{\nu_\tau}$ and of the $J/\psi \to \mu^+\mu^-$. The SM prediction for this value is 0.2582(38) [14], and the only previous measurement is from the LHCb collaboration [15], with a result of $R(J/\psi) = 0.71 \pm 0.17(\mathrm{stat}) \pm 0.18(\mathrm{syst})$, two standard deviations larger than the SM prediction.

Due to the presence of neutrinos in the final state, the B_c^+ direction of flight and four-momentum are inferred from an approximation. The original B_c^+ meson direction of flight is assumed to be aligned to that of its visible decay products, and its four momentum is defined as $p^{B_\mathrm{c}^+} = \frac{m_{B_\mathrm{c}^+}}{m_\mathrm{reco}} p_\mathrm{reco}^{B_\mathrm{c}^+}$. The two processes of interest have the same final state of $3\mu + \nu$s, where the muon not coming from the J/ψ decay is reffered to as the third muon, hence the same reconstruction is applied and they are simultaneously fit.

Alongside the two signal channels, several background sources are accounted for. The dominant background contribution includes processes where a particle is mistakenly recognized as the third muon, referred to as the *muon fakes* background, which mostly includes decay in flight of $K \to \mu\nu$. This background is estimated from data control regions. Other subdominant backgrounds include processes where the third muon doesn't originate from a B_c^+ vertex, known as the H_b *background*, and alternative $B_c^+ \to J/\psi X$ decays, including also decays from excited $c\bar{c}$ states into J/ψ, called the *B_c^+ background*. These processes are estimated from simulations, complemented with inputs from data. The last background source is estimated from data control regions and it includes the combination of random muons generating an invariant mass $m_{\mu\mu}$ close to the J/ψ resonance, identified as the *combinatorial dimuon +μ^+ background*.

The muon fakes background is derived from data control regions, with four categories defined based on the identification and isolation criteria for the third muon, where the SR corresponds to both identification and isolation selections satisfied. The fake rate probability fr_{iso} for the third muon satisfying the isolation criteria is measured in regions defined by a false identification condition. Given the dependence of fr_{iso} on various kinematic and topological parameters, it is modeled using a neural network binary classifier. The classifier outputs are interpreted as event weights, corresponding to the fr_{iso} probability. These probabilities are then used as event weights for both data and MC events in the regions meeting the identification criteria, producing two distinct templates. The final estimation of the muon fakes background in the signal region is obtained by subtracting the MC template from the data one. This subtraction is operated in-situ, allowing the fit to vary the MC templates and propagate the effect to the fakes background, accordingly. The method has been validated with several studies, with the most relevant validation performed on data control regions. Employing the same approach of the muon fakes estimation in four control regions enriched in muon fakes, there is good agreement between the estimated muon fakes background and the data. Based on this and other complementary studies, several uncertainties have been considered for this background.

A binned maximum likelihood fit is performed to directly extract the $R(J/\psi)$ value. During the development of the analysis methods, the fit result has been masked scaling the prefit signal yield of the $B_c^+ \to J/\psi\tau^+\nu_\tau$ with a random factor. To avoid making assumptions on the B_c^+ and H_b background normalisations, these are left completely free in the fit. The muon fakes estimate is performed as an in-situ part of the simultaneous fit.

Four observables are selected for the fit model. Their selection is based on their capability to distinguish between different contributions or enhance the overall sensitivity of the analysis, as shown in Figure 1. The variable that can discriminate the most between the two signals is $q^2 = (p_{B_c^+} - p_{J/\psi})^2$. The invariant mass of the three final state muons $m(3\mu)$ is used to constrain the H_b background, and the $L_{xy}/\sigma_{L_{xy}}$ observable, where L_{xy} is the distance in the transverse plane between the J/ψ decay vertex and the beam spot and $\sigma_{L_{xy}}$ is its uncertainty, is useful to separate various processes. Eventually, the analysis sensitivity is improved thanks to the employment of the IP3D/σ_{IP3D} variable, where the 3D impact parameter (IP3D) is the shortest distance from the third muon track to the J/ψ vertex with a sign depending on whether the trajectory of the third muon reaches the minimum distance before or after the J/ψ vertex along the J/ψ flight direction and σ_{IP3D} is its uncertainty.

A total of 14 categories are defined with the aforementioned observables, where q^2 and $L_{xy}/\sigma_{L_{xy}}$ are also directly fit. A comprehensive set of systematic uncertainties is included, with the most impacting ones being the theoretical uncertainties on the B_c^+ form factors [16] and the uncertainties on the muon fakes background. In Fig. 2, postfit distributions for the most relevant categories are shown.

The final result of the measurement is $R(J/\psi) = 0.17^{+0.18}_{-0.17}\,(\text{stat.})^{+0.21}_{-0.22}\,(\text{syst.})^{+0.19}_{-0.18}\,(\text{theo.}) =$

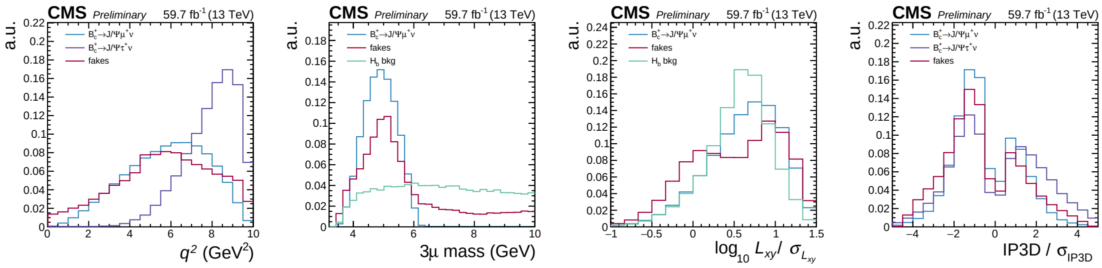

Figure 1: Distributions of the (from left to right) q^2, $m(3\mu)$, $L_{\rm xy}/\sigma_{L_{\rm xy}}$ and IP3D/$\sigma_{\rm IP3D}$ observables for several distributions: $B_c^+ \to J/\psi\tau^+\nu_\tau$ (purple), $B_c^+ \to J/\psi\mu^+\nu_\mu$ (blue), the fakes background (red) and the $H_{\rm b}$ background (green) [13].

0.17 ± 0.33, which is in agreement with the SM prediction within 0.3 standard deviations, and compatible with the LHCb result within 1.3 standard deviations.

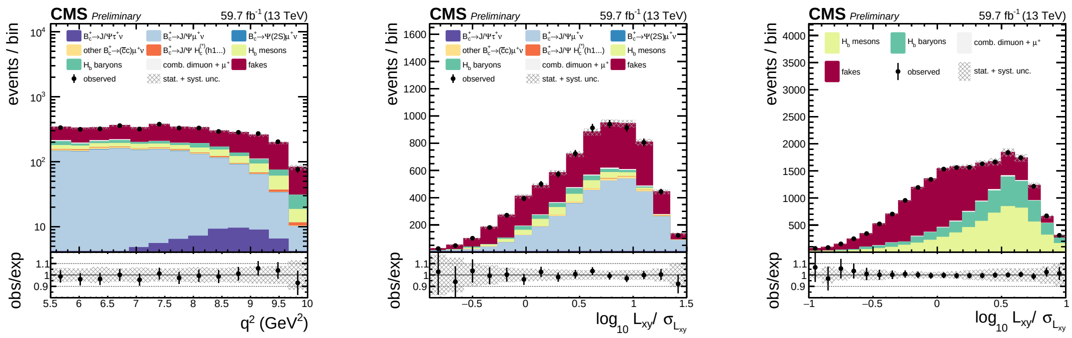

Figure 2: Distributions of the q^2 observable in the signal-enriched data region, defined by $m(3\mu) < m_{B_c^+}$ in the bin of $q^2 > 5.5$ GeV^2 and IP3D/$\sigma_{\rm IP3D} > 2$ (left); of the $L_{\rm xy}/\sigma_{L_{\rm xy}}$ observable in the data region defined by $m(3\mu) < m_{B_c^+}$ in the bin of $q^2 < 4.5$ GeV^2 and IP3D/$\sigma_{\rm IP3D} > 0$ (center) and in the data region defined by $m(3\mu) > m_{B_c^+}$(right). In each figure, data are compared to the expectation, with the normalization, shape parameters for the different contributions as well as $R(J/\psi)$ shown at their best-fit values. The ratio between the data and the expected stack of signal and background contributions is shown in the lower panel. The post-fit total uncertainty of the expectation is represented by the hashed band [13].

This is the first LFUV result in $b \to c l^- \bar{\nu}_l$ in CMS, and performed only on limited part of the statistics. The sensitivity is expected to be significantly improved in the next iterations.

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