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Measurements of lepton flavour universality in B_c^+ meson decays

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Abstract

The CMS experiment results on R(J/ψ) = $\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$ lepton flavor universality observable are reported using two channels of reconstruction of the τ lepton: $\tau^+ \to \mu^+\nu_\mu\bar{\nu_\tau}$ (leptonic) and $\tau^+ \to \pi^+\pi^-\pi^+(+\pi^0)\bar{\nu_\tau}$ (hadronic). These measurements use 13 TeV proton-proton collision data from the LHC Run 2. The results are consistent with the predictions of the Standard Model.

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Measurements of lepton flavour universality in B_c^+ meson decays

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The CMS experiment results on $\mathrm{R}(J/\psi) = \mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$ lepton flavor universality observable are reported using two channels of reconstruction of the τ lepton: $\tau^+ \to \mu^+\nu_\mu\bar{\nu_\tau}$ (leptonic) and $\tau^+ \to \pi^+\pi^-\pi^+(+\pi^0)\bar{\nu_\tau}$ (hadronic). These measurements use 13 TeV proton-proton collision data from the LHC Run 2. The results are consistent with the predictions of the Standard Model.

I. INTRODUCTION

In the Standard Model (SM), the three families of leptons exhibit identical behavior in terms of their interactions mediated by electroweak forces, a phenomenon known as lepton flavor universality (LFU). Consequently, the discrepancies in the rates of decay between processes involving different leptons are solely attributable to the differences in their respective masses. Any deviations from this fundamental principle may be attributed to the existence of particles or interactions beyond the Standard Model (BSM).

The lepton-flavour universality (LFU) has been thoroughly investigated and confirmed in leptonic W and Z decays, as reported in the studies published by different collaborations [1–3]. Furthermore, LFU has been subject to extensive study in the context of b-hadron decays, where there is evidence of potential lepton flavour violation in $b \to c\tau\nu$ transitions. Collaborations such as BaBar [4], Belle [5], and LHCb [6] have explored the branching ratios

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$\mathrm{R}(D) = \frac{\mathcal{B}(B^0 \to D^- \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \to D^- \mu^+ \nu_\mu)}$ and $\mathrm{R}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \to D^{*-} \mu^+ \nu_\mu)}$. When combining $\mathrm{R}(D)$ and $\mathrm{R}(D^*)$ measurements, the resulting value exceeds the prediction of the Standard Model [7] by 3.2 standard deviations. The LHCb collaboration has conducted a measurement of the ratio $\mathrm{R}(J/\psi)$, which is defined as the ratio of the branching fractions

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

The result obtained is $\mathrm{R}(J/\psi) = 0.71 \pm 0.17$ (stat) ± 0.18(syst), as reported in reference [8], where the τ lepton was reconstructed in its muonic decay mode. This measurement deviates from the Standard Model [9] prediction by two standard deviations.

It is important to highlight that the B_c^+ mesons, and consequently the measurement of the $\mathrm{R}(J/\psi)$ parameter, are currently accessible exclusively through experiments at the LHC, including the CMS detector [10]. Multiple indications of a possible discrepancy in the $b \to c\tau\nu$ transition strongly motivate conducting measurements in the CMS experiment. This paper presents two measurements of the $\mathrm{R}(\mathrm{J}/\psi)$, performed by the CMS collaboration using leptonic [11] and hadronic [12] decay channels of the τ lepton.

II. LEPTONIC τ DECAY CHANNEL

The first measurement of the $\mathrm{R}(J/\psi)$, performed by the CMS experiment, uses the leptonic decay mode of the τ lepton, $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$. The analysis uses a sample of data corresponding to an integrated luminosity of 59.7 fb^{-1} collected in 13 TeV proton-proton collisions.

The J/ψ meson is reconstructed by its decay into a pair of muons. Therefore, both the $B_c^+ \to J/\psi \tau^+ \nu_\tau$ decay, which is in the numerator, and the $B_c^+ \to J/\psi \mu^+ \nu_\mu$ decay, which is in the denominator, have the same visible products — three muons. The difference lies only in the number of neutrinos, enabling a differentiation between these two modes of B_c^+ decay. To better distinguish between the signals, the analysis uses the $q^2 = (p^{B_c^+} - p^{J/\psi})^2$ variable, which is sensitive to the different numbers of neutrinos in the final state. Here $p^{J/\psi}$ is the 4-momentum of J/ψ meson candidate. To obtain B_c^+ momentum ($p^{B_c^+}$) the collinear approximation is used (assumption that B_c^+ has the same direction as the visible final states, and its value is $p^{B_c^+} = \frac{m_B}{m_{3\mu}^{vis}} \cdot p_{3\mu}^{vis}$). Three additional observables also provide a reasonable separation ability: $m(3\mu)$, IP3D/$\sigma_{\rm IP3D}$ and $L_{xy}/\sigma_{L_{xy}}$. $m(3\mu)$ is the invariant mass of three muons. IP3D/$\sigma_{\rm IP3D}$ is the ratio of the 3D impact parameter (IP3D), which is the shortest distance between the third muon track to the J/ψ vertex, to its uncertainty $\sigma_{\rm IP3D}$. The sign of IP3D indicates whether the third muon's trajectory reaches the minimum distance before or after the J/ψ vertex along the J/ψ momentum direction. $L_{xy}/\sigma_{L_{xy}}$ is the ratio of the distance between the J/ψ meson decay vertex and the beam line in the transverse plane L_{xy} to its uncertainty $\sigma_{L_{xy}}$.

Events are classified into seven pairs of non-overlapping categories before the fitting procedure. The R(J/ψ) value is extracted from simultaneous, binned maximum likelihood fit of q^2 observable for events with $q^2 > 5.5$ GeV and $L_{xy}/\sigma_{L_{xy}}$ observable for events with $q^2 < 5.5$ GeV. The fit model includes different components. In addition to the signal component, there are four types of background. 1.Muon fakes - these are events in which the reconstructed muon is actually different particle (kaon or pion). 2. Dimuon background - events with randomly matched muons that do not originate from the same J/ψ candidate. 3. Component with events involving a J/ψ meson, where the additional muon does not originate from a B_c^+ decay. 4. Background from the feed-down processes of B_c^+ decays and other charmed B_c^+ decays. The distributions with the fit results are shown in Figure 1 for the most signal-sensitive (left) and for one of background-enriched (right) category.

Systematic uncertainties are included in the fit as nuisance parameters and the $R(J/\psi)$ value is measured to be 0.17 ± 0.33 [11]. This result is consistent with the Standard Model prediction of $R(J/\psi) = 0.2582 \pm 0.0038$ [9], within 0.3 standard deviations, and it is also compatible with the previous LHCb measurement [8], which is within 1.3 standard deviations.

III. HADRONIC τ DECAY CHANNEL

Another measurement of $R(J/\psi)$ is performed with hadronic τ decay channel, which is $\tau^+ \to \pi^+\pi^-\pi^+(+\pi^0)\bar{\nu_\tau}$. Analysis is based on 2016 - 2018 years CMS experiment data collected in pp collisions and corresponding to an integrated luminosity of 138 fb^{-1}.

The final products of the reconstructed τ lepton decay are two muons and three charged tracks with a common vertex. Since τ decays into three prong pions have a good chance to produce an intermediate $\rho(770)$ resonances the unrolled $\rho_1 - \rho_2$ distribution is used as signal discriminating variable, where ρ_1 and ρ_2 are opposite sign charged track pairs combinations.

A large number of events pass the selection. Therefore, a boosted decision tree (BDT) classifier is trained using kinematic variables from the reconstructed final particles, as well as global variables from the entire event. The BDT score variable (Figure 2) is used to separate the signal region (SR) and control region (SB).

A model containing 4 components is used to describe the unrolled $\rho_1 - \rho_2$ distribution: signal component; B_c^+ decays background ($B_c^+ \to J/\psi D_s^{(*)}(\to$ 3 prong tracks)); other B_c^+ decays such as $B_c^+ \to J/\psi D^{(*)+}$; $B_c^+ \to J/\psi D^+ K^{(*)0}$, $B_c^+ \to J/\psi D^{(*)0} K^+$; background from non-$B_c^+$ hadrons.

A simultaneous fit is performed to the leptonic and hadronic analyses to extract the denominator of the R(J/ψ) from the former and the numerator from the latter. All systematic uncertainties are added as nuisance parameters in the likelihood function. Distributions of data and results of the fit are shown in Figure 3. Since the leptonic analysis uses 2018 data only the R(J/ψ) value is firstly calculated only for 2018 year data: R(J/ψ) $= 0.74^{+0.57}_{-0.53}$ [12]. Adding the contribution from 2016 - 2017 a value R(J/ψ) $= 1.04^{+0.50}_{-0.44}$ is obtained [12]. The final outcome is derived from the fit, which incorporates the numerator from the leptonic and hadronic analyses and the denominator from the leptonic analysis: R(J/ψ) $= 0.49 \pm 0.25$(stat) $\pm\, 0.09$(sist) [12], consistent with the SM [9] within 1σ.

IV. CONCLUSION

To conclude, the paper discusses two recent measurements of the R(J/ψ) ratio performed by the CMS experiment. These are the first such measurements conducted using a general-purpose detector like the CMS. The values obtained in the hadronic and leptonic analysis are consistent with the prediction of the Standard Model. Moreover, the combination of these two results is also consistent with the SM predictions and has an accuracy comparable to the previous LHCb result.

V. ACKNOWLEDGEMENTS

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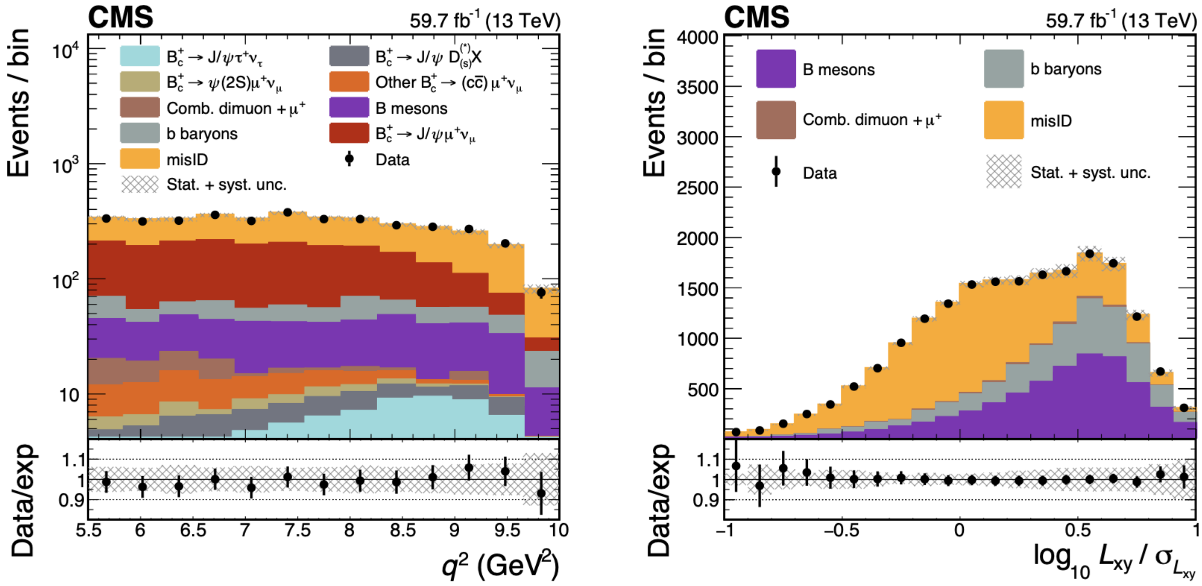

Figure 1: The distributions of the q^2 observable in the most signal-sensitive category (left) and distribution of $L_{xy}/\sigma_{L_{xy}}$ in one of background enriched category (right) [11].

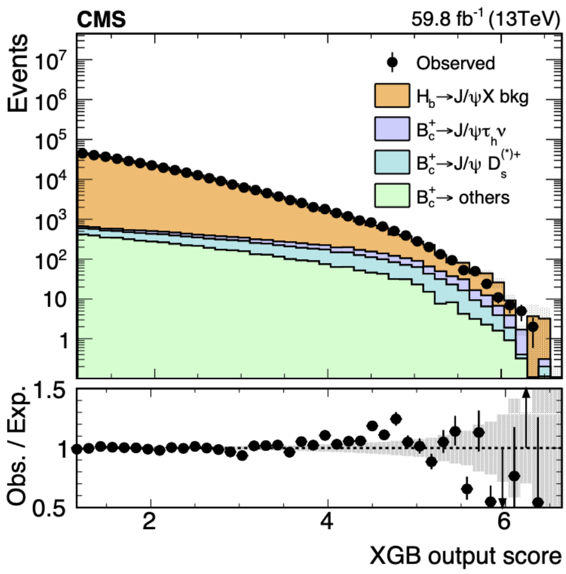

Figure 2: Distributions of the BDT score in the hadronic τ reconstruction channel [12].

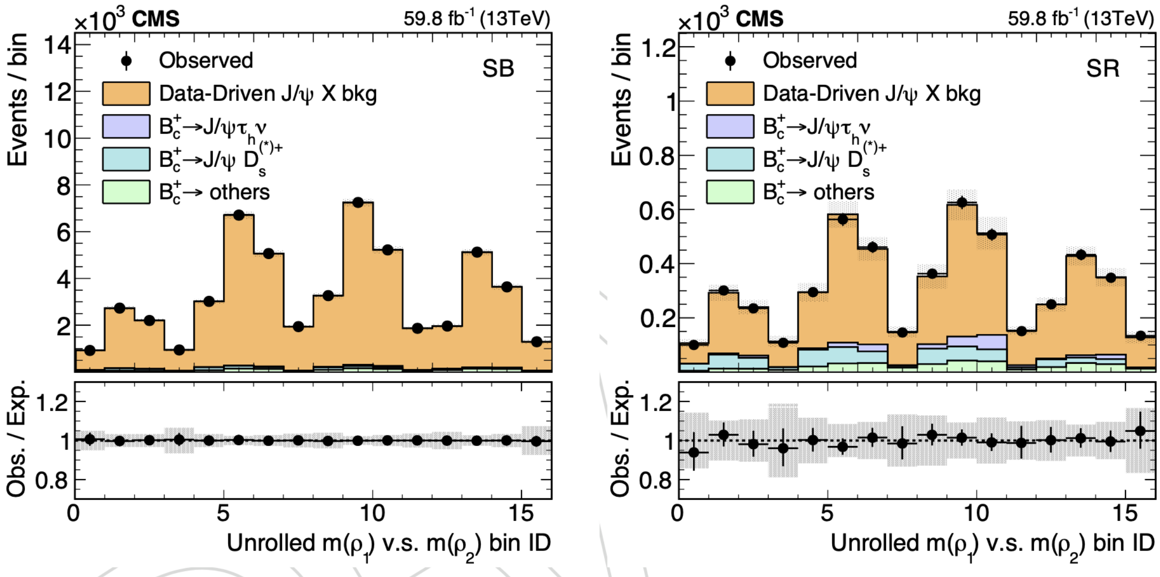

Figure 3: Distributions of the unrolled ρ^0 in the SB (left) and SR (right) categories [12].