Belle II results related to $b \to c$ anomalies

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We report two novel measurements for tests of lepton flavor universality between electrons and muons using semileptonic B decays with a data sets of 189 fb^{-1} collected at the Belle II experiment between 2019 and 2021. Firstly, we find a ratio of inclusive branching ratios at $R(X_{e/\mu}) \equiv \mathcal{B}(\overline{B} \to Xe^-\overline{\nu}_e)/\mathcal{B}(\overline{B} \to X\mu^-\overline{\nu}_\mu) = 1.007 \pm 0.009(\text{stat.}) \pm 0.019(\text{syst.})$. This inclusive measurement leads to the most precise universality test based on branching ratios. The measured $R(X_{e/\mu})$ is consistent with the Standard-Model prediction. Secondly, we measure a comprehensive set of five angular asymmetries of $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$ decays and obtain agreements with the Standard Model for the asymmetries at a p-value more than 13%. From both tests, no evidence of the universality violation is found.

1 Introduction

The Standard Model (SM) postulates the lepton flavor universality that a gauge boson couples equally to all three generations of leptons. Semileptonic $\bar{b} \to c\ell^-\bar{\nu}_\ell$ transition mediated by a W boson. The branching ratios are described commonly between lepton flavors and only depend on charged lepton masses in SM. The universality agrees with results of experiments that measured decays of gauge bosons, light mesons, and leptons. However, we have recently observed a deviation by more than three sigmas from the SM expectation in tests using semileptonic B decays of $\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell$ [5]. It offers a suspicion that the lepton flavor universality (LFU) could be violated through New Physics processes, such as leptoquarks. In addition, it motivates to test LFU between electron and muons since some of New Physics effects could contribute to interactions with light leptons.

We test the LFU between electrons and muons at the Belle II experiment. Low multiplicity and known initial kinematics of e^+e^- collisions at the B-factory can deliver good conditions to study semileptonic B decays that contain missing neutrinos in the final states. We perform two novel measurements with a ratio of inclusive branching fractions and differences of angular asymmetries, which provide theoretically and experimentally clean probes thanks to major cancellation of uncertainties.

We use an electron-positron collision data of 189 fb^{-1} collected between 2019 and 2021 at a center-of-mass energy of 10.58 GeV, corresponding to the $\Upsilon(4S)$ resonance. The data contains $(198.0 \pm 3.0) \times 10^6$ $B\overline{B}$ pairs. We also analyze an off-resonance data of 18 fb^{-1} at an energy 60 MeV below the $\Upsilon(4S)$ resonance to evaluate background contributions from $e^+e^- \to q\overline{q}$ ($q = u, d, s, c$) processes. The Belle II detector consists of vertex and tracking detectors, particle identification detectors, an electromagnetic calorimeter, 1.5 T solenoid magnets, and a K_L^0 and muon detector from the innermost layer to the outer layer [2]. Monte Carlo (MC) simulation that reflects responses of the Belle II detector is generated to make selection optimization and estimate signal and background distributions. The events from both the data and the simulation are reconstructed with the Belle II Software Framework, `basf2` [3].

2 Measurement of $R(X_{e/\mu})$

We measure a ratio of inclusive branching ratios of semileptonic B decays defined by $R(X_{e/\mu}) = \mathcal{B}(\overline{B} \to X e^- \overline{\nu}_e)/\mathcal{B}(\overline{B} \to X \mu^- \overline{\nu}_\mu)$, where X represents B-daughter hadrons reconstructed inclusively. One of the B mesons, denoting $B_{\rm tag}$, from $\Upsilon(4S)$ decays are fully reconstructed through hadronic B decay channels using the Full Event Interpretation (FEI) algorithm [6] to identify $B\overline{B}$ events. The FEI returns a confidence score between 0 and 1 for each $B_{\rm tag}$ candidate and we allow only one B meson with the highest score in an event. Out of the remaining tracks, we find a lepton candidate that has momentum in the signal B rest frame, p_ℓ^B, above 1.3 GeV/c. The lepton flavor is classified by a multiclass boosted decision tree (BDT) for electrons and a likelihood ratio for muons. Other tracks and clusters not used for the $B_{\rm tag}$ and the lepton are attributed to the inclusive hadron system of signal B daughters. Two B mesons with opposite and same flavors are combined for signal B and background-enriched control channels, respectively. The events with same B flavors allow more contamination of $B\overline{B}$ backgrounds produced by events with a misidentified lepton candidate or with a correct lepton from a secondary decay of a charmed meson in addition to correct signal candidates with B^0-$\overline{B}^0$ mixing. This control channel helps to constrain background yields in the signal channels through a simultaneous fit.

The background candidates from $e^+e^- \to q\overline{q}$ ($q = u, d, s, c$) events are suppressed with a dedicated BDT employing 21 event-topology variables. The BDT rejects 55% of $q\overline{q}$ backgrounds and discriminates $B\overline{B}$ candidates at a 97% retention rate. The $q\overline{q}$ background distributions are described by the off-resonance data which is scaled by the luminosity and $q\overline{q}$ cross section.

The signal yields of both electron and muon modes are extracted with a binned maximum-likelihood simultaneous fit to p_ℓ^B for the signal and control channels. The signal and $B\overline{B}$ background templates are prepared based on the MC simulation. From the fit, we obtain

$$R(X_{e/\mu}) = 1.007 \pm 0.009(\text{stat.}) \pm 0.019(\text{syst.}). \tag{1}$$

Figure 1 illustrates the fit distributions on p_ℓ^B. The most significant systematic uncertainty is induced by the lepton identification at 1.9%, which is followed by the simulation sample size at 0.9%. The other uncertainties from $\overline{B} \to X\ell^-\overline{\nu}_\ell$ branching ratios and $\overline{B} \to X\ell^-\overline{\nu}_\ell$ form factors are smaller at 0.2% due to cancellation between electron and muon modes in the $R(X_{e/\mu})$ ratio. The measured $R(X_{e/\mu})$ value agrees with a previous test result performed by the Belle experiment using exclusive $\overline{B} \to D^*\ell^-\overline{\nu}_\ell$ decays [7]. This result is also consistent with the SM prediction under the LFU [8]. Our $R(X_{e/\mu})$ measurement has provided the most precise result for a test of light-lepton flavor universality based on branching ratios of semileptonic B decays by utilizing inclusive modes in the test for the first time. More details of our $R(X_{e/\mu})$ measurement are described in Ref. [9].

3 Measurement of angular asymmetry $\Delta\mathcal{A}_x(w)$

We perform a measurement of angular asymmetries and their differences for $B^0 \to D^*\ell^-\overline{\nu}_\ell$ decays with a set of five variables, $A_{\rm FB}$, S_3, S_5, S_7, and S_9. The $B^0 \to D^*\ell^-\overline{\nu}_\ell$ decays are characterized by a recoil parameter, $w \equiv (m_{B^0}^2 + m_{D^{+*}}^2 - (p_{B^0} - p_{D^{+*}})^2)/2m_{B^0}m_{D^{*+}}$, and three helicity angles: the angle between the charged lepton in the virtual W frame and the W in the B^0 frame, θ_ℓ, the angle between the D^0 in the D^{*+} rest frame and the D^{*+} in the B^0 frame, $\cos\theta_V$, and the angle between the decay planes formed by the virtual W and the D^{*+} in the B^0 frame, χ. The angular asymmetries are described by differential rates of the recoil parameter and helicity angles,

$$\mathcal{A}_x(w) \equiv \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}w}\right)^{-1} \left[\int_0^1 - \int_{-1}^0\right] \mathrm{d}x \frac{\mathrm{d}^2\Gamma}{\mathrm{d}w\mathrm{d}x}, \tag{2}$$

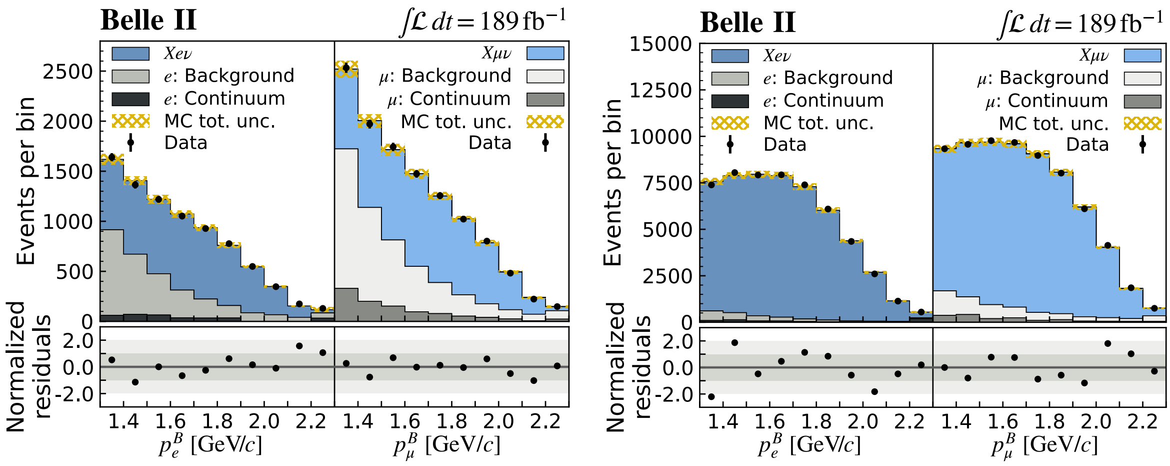

Figure 1 – Fit results of lepton momentum spectra in the $B_{\rm sig}$ rest frame, p_ℓ^B ($\ell = e, \mu$), for same-charge control channel (left) and in opposite-charge signal channel (right). Total statistical and systematic uncertainties of the MC samples are shown by yellow hatched areas. Electron and muon modes are illustrated on left and right side of each plot. The last bins of p_ℓ^B include overflow entries.

where $x = \cos\theta_\ell$ for $A_{\rm FB}$, $\cos 2\chi$ for S_3, $\cos\chi\cos\theta_V$ for S_5, $\sin\chi\cos\theta_V$ for S_7, and $\sin 2\chi$ for S_9. We compare electron and muon modes by $\Delta\mathcal{A}_x(w) = \mathcal{A}_x^\mu(w) - \mathcal{A}_x^e(w)$ to test the LFU. $A_{\rm FB}$, S_3, and S_5 is highly sensitive to the LFU violation induced by SM extensions. On the other hand, S_7 and S_9 have reduced senditivity or no sensitivity to the LFU, respectively. Thus, they are taken advantage of as control variables of the analysis method.

One B meson is fully reconstructed with the FEI algorithm and only one B meson is selected with the highest confidence score in the event. The remaining tracks and clusters are assigned for the signal B reconstruction. The $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$ decays are reconstructed by combining a D^{*+} candidate with an electron (muon) candidate that is required to have a momentum above 0.4 GeV. The lepton flavors are identified by the BDT for electrons and the likelihood ratio for muons. D^{*+} candidates are reconstructed through $D^{*+} \to D^0\pi^+$. D^0 candidates are reconstructed via eight decay modes of $K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+\pi^0$, $K_S^0\pi^+\pi^-$, $K_S^0\pi^+\pi^-\pi^0$, $K_S^0\pi^0$, and K^+K^-. The $D^{(*)}$ candidates must satisfy $M_{D^0} \in [1.85, 1.88]$ GeV ($\Delta M_{D^{*+}} \in [0.143, 0.148]$ GeV), where $\Delta M_{D^{*+}} \equiv M_{D^{*+}} - M_{D^0}$. We require that no tracks remain in addition to those used for the reconstruction in the event. Only one candidate is selected by taking a candidate with $\Delta M_{D^{*+}}$ closest to the PDG value [?].

We extract the signal yields by binned maximum-likelihood template fits to the M_{miss}^2 distributions. The extracted yields are corrected for M_{miss}^2 bin migrations, migration of angular and w ranges, efficiencies, and acceptance effects with a migration matrix. To address the SM extensions with optimized sensitivity, we set three w ranges for integration of angular asymmetries in Eq. (2) and determine all asymmetry variables simultaneously for both electron and muon modes in different w ranges.

We find angular asymmetries for electron and muon modes and their differences as summarized in Figure 2. The systematic uncertainty is dominated by the simulation sample size to estimate the migration matrix around a quarter to a half of statistical uncertainties. Other systematic uncertainties, such as lepton identification, is small up to 0.004.

χ^2 tests are performed to evaluate agreements with the SM predictions for sets of all asymmetries, three asymmetries of $A_{\rm FB}$, S_3, and S_5, and two asymmetries of S_7 and S_9. The tests returns $chi^2/N_{\rm dof} = 14.6/10 (p = 0.14)$, $2.0/3 (p = 0.57)$, and $0.6/2 (p = 0.76)$ in the $w_{\rm incl.}$ range, respectively. The tests in w subranges, $w_{\rm high}$ and $w_{\rm low}$, also have p-values no less than 0.13. Therefore, there is no evidence of violation of the light-lepton flavor universality observed.

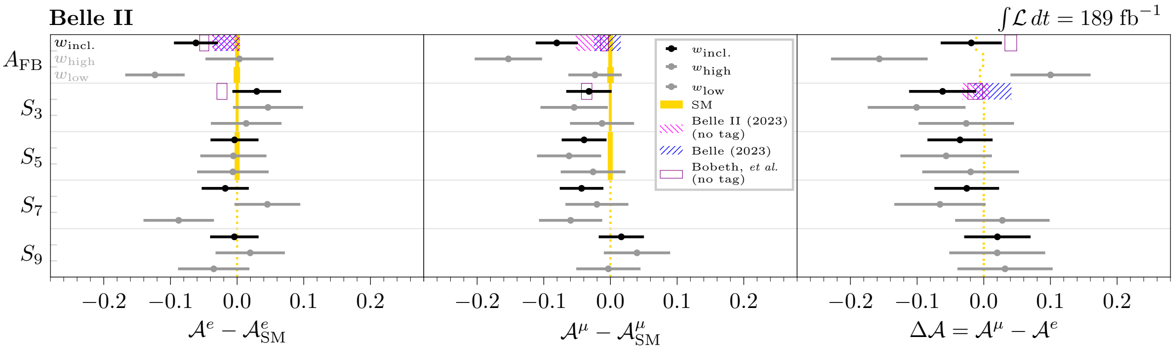

Figure 2 – Measured asymmetries for electron (left) and muon (middle) modes and their differences (right). Black and gray points are determined in range of full w range and high or low w ranges, respectively. Yellow solid box show the SM prediction.

4 Conclusion

In the SM, the coupling of gauge bosons is presupposed to be common between all lepton flavors as LFU. However, it is recently challenged between tau and light leptons by several experimental results using semileptonic B decays. To test the LFU between electrons and muons, we perform two first measurements utilizing a ratio of inclusive branching fractions, $R(X_{e/\mu})$, and differences of angular asymmetries, $\Delta\mathcal{A}_x(w)$, with the 189 fb^{-1} data set collected at the Belle II experiment between 2019 and 2021. We determine $R(X_{e/\mu}) = 1.007 \pm 0.009(\text{stat.}) \pm 0.019(\text{syst.})$. The inclusive measurement results in the world-leading precision and the obtained $R(X_{e/\mu})$ agrees with the SM prediction. In addition, we find lepton flavor universality for a comprehensive asymmetry set of A_{FB}, S_3, S_5, S_7, and S_9 with at least a p-value of 13%. From both tests, no evidence of the LFU violation is found.

Acknowledgments

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