Measurements of lepton flavour universality in semileptonic B decays at Belle and Belle II

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Abstract. The Belle and Belle II experiments have collected a 1.1 ab^{-1} sample of $e^+e^- \to B\bar{B}$ collisions at the $\Upsilon(4S)$ resonance. These data, with low particle multiplicity, constrained initial state kinematics and excellent lepton identification, are an ideal environment to study lepton flavour universality in semileptonic decays of the B meson. We present measurements of branching-fraction ratios that test the universality of τ and light leptons, using both exclusive and inclusive B semileptonic decays. We also report measurements of angular observables that probe universality between electrons and muons.

1 Introduction

Belle II [1] is a particle detector designed to study 7-on-4 GeV e^-e^+ collisions at the energy of the $\Upsilon(4S)$ resonance, produced at high luminosity by the SuperKEKB collider located at the KEK laboratory in Japan [2]. The $\Upsilon(4S)$ decays almost exclusively into $B\bar{B}$ pairs, resulting in low backgrounds. Belle [3] was the predecessor of the Belle II experiment and it ran from 1999 to 2010. Belle (II) detectors are ideally suited to study decays with missing energy; they are arranged hermetically in a cylindrical geometry around the interaction point allowing to know the energy at $B\bar{B}$ threshold with high precision. The Belle II analyses presented in this document use a sample of 189 fb^{-1} of data containing about 198 milion $B\bar{B}$ pairs collected at the resonance $\Upsilon(4S)$ during the 2019-2021 run period; those at Belle feature a sample of 711 fb^{-1} with 772 milion $B\bar{B}$ pairs.

In the Standard Model (SM) of particle physics, the W boson couples equally to the three lepton generations, an incidental symmetry known as lepton flavour universality (LFU). Semileptonic B decays offer possibilities for stringent tests of LFU and are thus sensitive to physics beyond the SM. For instance, the branching-fraction ratio

$$R(H_\tau/\ell) = \frac{\mathcal{B}(B \to H\tau\nu_\tau)}{\mathcal{B}(B \to H\ell\nu_\ell)}, \tag{1}$$

where ℓ is either an electron or a muon and H is an hadron, is a sensitive probe for the universality of the third generation. Here, the final state hadron H can be $D^{(*)}$, π, or other hadrons from exclusive modes, or it can be an inclusive hadronic system X. This ratio is advantageous because it partially cancels out theoretical uncertainties (e.g. form factors) and

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experimental uncertainties (e.g. efficiencies), providing a more precise test of LFU. In addition, semileptonic B-meson decays involving the quark transition $b \to c\ell\nu_\ell$ provide excellent sensitivity to potential new interactions that would violate the LFU. In particular, the semileptonic $B \to D^*\ell\nu_\ell$ decay offers a rich phenomenology encoded in angular distributions of the final-state particles sensitive to LFU. This can be fully characterized in terms of a recoil energy w and three decay angles θ_ℓ, θ_D and χ. The recoil energy is $w = E_{D^*}/m_{D^*}$, where m_{D^*} is the known D^* meson mass and E_{D^*} is the energy of D^* meson in the B rest frame. The three helicity angles are: θ_ℓ is the angle between the direction of the charged lepton in the virtual W frame and the W in the B frame, θ_D is the angle between the D direction in the D^* frame and the D^* in the B frame, and χ is the angle between the decay planes formed by the virtual W and the D^* in the B frame.

In this document, we present the last $R(D^*)$ and $R(X)$ measurements at Belle II and the measurements of angular distributions of $B \to D^*\ell\nu_\ell$ decays at Belle and Belle II.

2 Measurement of $R(D^*)$ using hadronic B tagging at Belle II

The goal of this analysis is to test the LFU symmetry by measuring

$$R(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\ell\nu_\ell)}, \tag{2}$$

where the denominator is referred to as the normalization mode with $\ell = e, \mu$.
This ratio has been measured by the BaBar [4, 5], Belle [6–8], and LHCb [9–13] Collaborations. The world averages of these measurements, $R(D^*) = 0.287 \pm 0.012$ exceed the SM expectation [14] by 2.5σ.

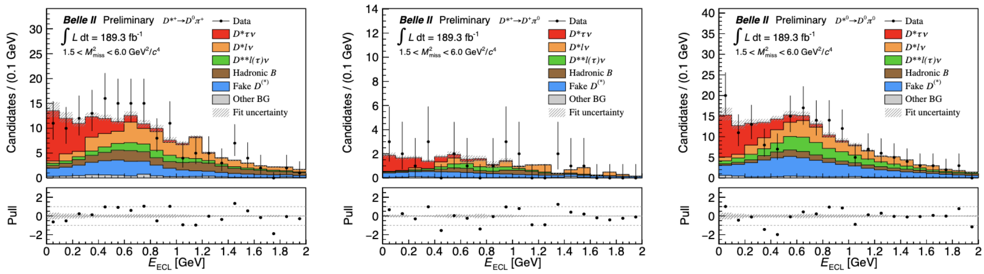
In this analysis, the partner B meson (B_{tag}) is fully reconstructed via hadronic decay modes [15] and the remaining particles in the event are used to reconstruct the pair-produced signal, $B \to D^*\tau\nu_\tau$, and normalization mode decays, $B \to D^*\ell\nu_\ell$. The D^* mesons are reconstructed in three modes $D^{*+} \to D^0\pi^+$, $D^{*+} \to D^+\pi^0$, and $D^{*0} \to D^0\pi^0$ while only $\tau^- \to e^-\bar{\nu}_e\nu_\tau$ and $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ decays are considered. The $R(D^*)$ value is extracted by using a two-dimensional fit to two variables: the missing mass squared, M^2_{miss}, and the energy detected in the calorimeter not associated with the reconstructed $B\bar{B}$ pair, E_{ECL}. The M^2_{miss} is given by

$$M^2_{miss} = (E^*_{beam} - E^*_{D^*} - E^*_\ell)^2 - (-\vec{p^*}_{B_{tag}} - \vec{p^*}_{D^*} - \vec{p^*}_\ell)^2, \tag{3}$$

where $E^*_{beam} = \sqrt{s}/2$ represents the beam energy, whereas $E^*_{D^*}$ ($\vec{p^*}_{D^*}$), E^*_ℓ ($\vec{p^*}_\ell$) and ($\vec{p^*}_{B_{tag}}$) are the energies (momentum vectors) of the D^*, ℓ, and B_{tag}. All quantities are calculated in the centre-of-mass frame. The fit projections in a signal-enhanced region are shown in Fig. 1. The preliminary $R(D^*)$ measurement [16] obtained is:

$$R(D^*) = 0.262^{+0.041}_{-0.039}(\text{stat})^{+0.035}_{-0.032}(\text{syst}), \tag{4}$$

corresponding to a signal $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ yield of 108 ± 16. The $R(D^*)$ value is consistent with SM and it has been included in the global fit performed by the Heavy Flavor Averaging Group (HFLAV) [14] shown in Fig. 2.



(a) (b) (c)

Figure 1. Distributions of E_{ECL} in the signal-enhanced region $1.5 < M^2_{miss} < 6.0GeV^2/c^4$ for the $D^{*+} \to D^0\pi^+$ (left), $D^{*+} \to D^+\pi^0$ (middle), and $D^{*0} \to D^0\pi^0$ (right) modes, with fit projections overlaid. The bottom panel presents pull values from fit results. The rectangular-shaded regions on the histograms and in the pull plot correspond to statistical uncertainties in the fit.

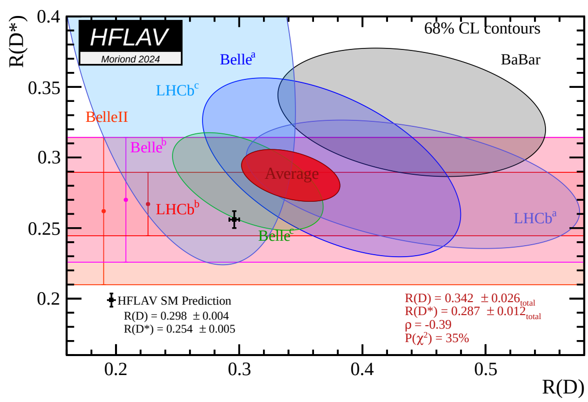


Figure 2. The latest world average results of $R(D)$-$R(D^*)$ from HFLAV (updated on the 20^{th} of May 2024).

3 Measurement of $R(X)$ as an inclusive test of the $b \to c\tau\nu_\tau$ anomaly at Belle II

We present a complementary probe of LFU through the first measurement of the tau-to-light-lepton ratio of inclusive semileptonic B-meson branching fractions:

$$R(X_{\tau/\ell}) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}\,. \tag{5}$$

This approach incorporates D and D^* mesons regardless of their decay mode and includes a 14% - 20% expected contribution from unexplored semitauonic B-meson decays. Since the predictions for $R(X_{\tau/\ell})$ [17] and those for the ratios of exclusive decays $R(D^*)$ [14] are based on different theoretical input, this measurement provides a LFU test that is statistically and theoretically distinct from $R(D^*)$, sensitive to different systematic uncertainties, and is potentially more precise.

The partner B meson (B_{tag}), is fully reconstructed via hadronic decay modes and associated remaining particle candidates, which must include a lepton identified as an electron or muon, with the accompanying signal B meson (B_{sig}). The event is called signal if the lepton is the decay product of a primary τ lepton in a $B \to X\tau\nu_\tau$ decay and normalization if the lepton is the primary lepton in a $B \to X\ell\nu_\ell$ decay.

The signal and normalization yields are simultaneously extracted by using a two-dimensional fit to the distribution of p_ℓ^B, the lepton momentum in the rest frame of the B_{sig} meson, and the missing mass squared M^2_{miss}, defined as Eq. (3) with the D^* meson replaced by the hadronic system X. The fit projections in slices of M^2_{miss} regions are shown in Fig. 3.

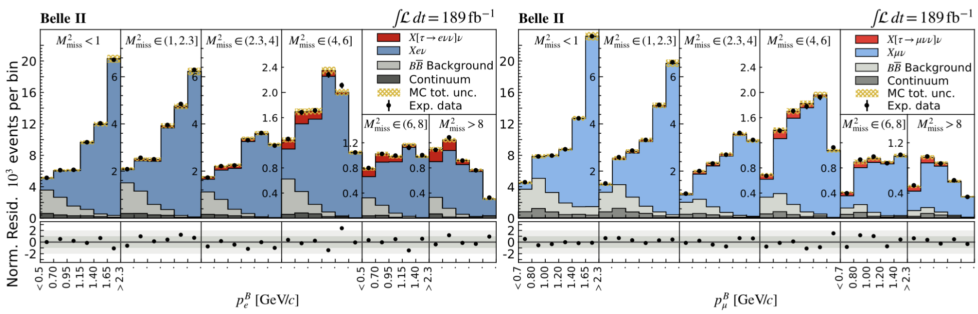


Figure 3. Two-dimensional distributions of electron (left) and muon (right) momentum p_l^B in the B_{sig} rest frame and the missing mass squared M^2_{miss}, flattened to one dimension in intervals as used in the signal extraction fit, with the fit results overlaid. The hatched area shows the total statistical and systematic uncertainty, added in quadrature for each interval. The residuals are normalized to the statistical uncertainty of the data points and the M^2_{miss} intervals are given in units of GeV^2/c^4.

we obtain [18]

$$R(X_{\tau/\ell}) = 0.228 \pm 0.016(\text{stat}) \pm 0.036(\text{syst}), \tag{6}$$

corresponding to a signal yields of $N_{\tau\to e} = 2590 \pm 450$ and $N_{\tau\to\mu} = 1810 \pm 460$. The $R(X_{\tau/\ell})$ value is in agreement with an average of SM predictions [17] of $R(X_{\tau/\ell})^{SM} = 0.223 \pm 0.005$ and it is also consistent with a hypothetically enhanced semitauonic branching fraction as indicated by the $R(D^{(*)})$ world average [14] (Fig. 4).

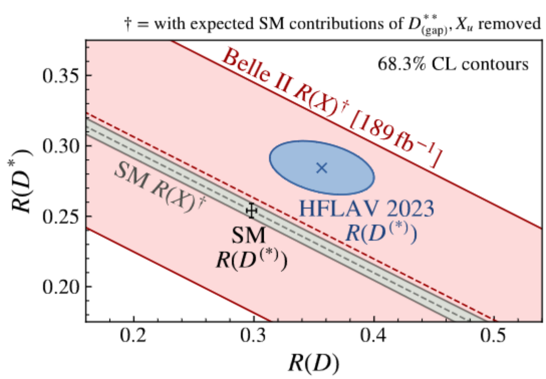


Figure 4. Constraints on $R(D^{(*)})$ from the measured $R(X_{\tau/\ell})$ value (red), compared to the world average of $R(D^{(*)})$ (blue [14]) and the Standard Model expectation (gray/black [14]).

4 Test of Light-Lepton Universality in angular asymmetries of $B^0 \to D^{*-}\ell\nu_\ell$ decays at Belle II

Recently, a possible evidence of LFU violation between the light leptons has been reported based on differences in their angular distributions in semileptonic B decays to D^* mesons [19]. However, that analysis relied on a reinterpretation of Belle results [20] that contained only one-dimensional projections of the multidimensional angular distributions that are needed to fully characterize such decays. We present the first light-lepton test at Belle II using a complete set of angular-asymmetry observables chosen to suppress most theoretical and experimental uncertainties, thus optimizing sensitivity to LFU violation. It is possible to construct one-dimensional integrals of the four-dimensional standard-model differential rates as a function of w and the three decay angles θ_ℓ,θ_D, χ to isolate angular asymmetries that are sensitive to possible LFU violation, called A_{FB}, S_3, S_5, S_7, and S_9 [21]. The forward-backward asymmetry A_{FB} measures the tendency for the charged lepton to travel in the same direction as the virtual W. The S_3 and S_9 asymmetries are sensitive to the alignment of the lepton and D^* momenta, while S_5 and S_7 measure coupled alignments in the orientation of the D with respect to the D^*. The differences between the angular asymmetries of electrons and muons are sensitive to interactions that violate LFU,

$$\Delta\mathcal{A}_x(w) = \mathcal{A}_x^{\mu}(w) - \mathcal{A}_x^{e}(w), \qquad \mathcal{A}_x(w) = \frac{N_x^+(w) - N_x^-(w)}{N_x^+(w) + N_x^-(w)}, \tag{7}$$

with $x = \cos\theta_\ell$ for A_{FB}, $cos2\chi$ for S_3, $\cos\chi\cos\theta_D$ for S_5, $\sin\chi\cos\theta_D$ for S_7, $\sin 2\chi$ for S_9 and N_x^- are the number of signal events with $x \in [-1, 0)$ and N_x^+ those with $x \in [0, 1]$. The analysis is tagged hadronically and in the events with an identified partner B meson (B_{tag}), the signal B meson, $B^0_{sig} \to D^{*-}\ell\nu_\ell$, is reconstructed with $\bar{D}^0$ decaying to different hadronic final states [22].

The numbers of signal events $N_x^{\pm}$ are determined by fitting the M^2_{miss} distributions. We find 1617 (1639) signal events in the electron (muon) mode overall, with a variation of less than one event between variables. The results of the differences between the angular asymmetries of muons and electrons are shown in Fig. 5.

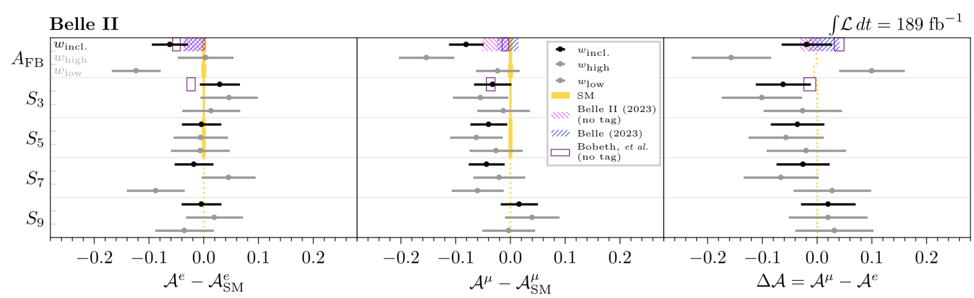


Figure 5. Observed asymmetries and their differences (points with error bar). 1 standard-deviation bands from the Belle [23] and Belle II [24] measurements (hatched boxes), calculations from [19] based on a previous measurement from Belle [20] (empty boxes), and Standard Model expectations (solid boxes). The Standard Model expectation is drawn with a dashed line when its uncertainty is too small to display.

All the angular asymmetries and their differences are compatible with the SM, showing no evidence for LFU violation.

5 Measurement of Angular Coefficients of $\bar{B} \to D^* \ell \nu_\ell$ as Test of Lepton Flavour Universality at Belle

The four-dimensional differential decay rate for $\bar{B} \to D^* \ell \nu_\ell$ can be expressed in terms of 12 functions $J_i = J_i(w)$, which only depend on the recoil parameter, w, as

$$\frac{d\Gamma(\bar{B} \to D^* \ell \bar{\nu}_\ell)}{dw d\cos\theta_\ell d\cos\theta_D d\chi} = \frac{2G_F^2 \eta_{EW}^2 |V_{cb}|^2 m_B^4 m_{D^*}}{2\pi^4} \times \Big(J_{1s} \sin^2\theta_D + J_{1c} \cos^2\theta_D + \\ + (J_{2s} \sin^2\theta_D + J_{2s} \cos^2\theta_D) \cos\theta_\ell + J_3 \sin^2\theta_D \sin^2\theta_\ell \cos 2\chi + \\ + J_4 \sin 2\theta_D \sin 2\theta_\ell \cos\chi + J_5 \sin 2\theta_D \sin\theta_\ell \cos\chi + \\ + (J_{6s} \sin^2\theta_D + J_{6c} \cos^2\theta_D) \cos\theta_\ell + J_7 \sin 2\theta_D \sin\theta_\ell \sin\chi + \\ + J_8 \sin 2\theta_D \sin 2\theta_\ell \sin\chi + J_9 \sin^2\theta_D \sin^2\theta_\ell \sin 2\chi \Big). \quad (8)$$

Two B meson candidates are reconstructed, a partner B meson (B_{tag}), which decays hadronically, and a signal B meson (B_{sig}). Signal B mesons are reconstructed by considering both charged and neutral B mesons with the decay chains $\bar{B}^0 \to D^{*+} \ell \bar{\nu}_\ell$, $D^{*+} \to D^0 \pi^+$, $D^{*+} \to D^+ \pi^0$, and $B^- \to D^{*0} \ell \bar{\nu}_\ell$ with $D^{*0} \to D^0 \pi^0$; D mesons are reconstructed in different hadronic decays [25]. The angular coefficients are extracted in four bins of w by fitting the M^2_{miss} distribution. The preliminary results of the differences of the angular coefficients are shown in Fig. 6.

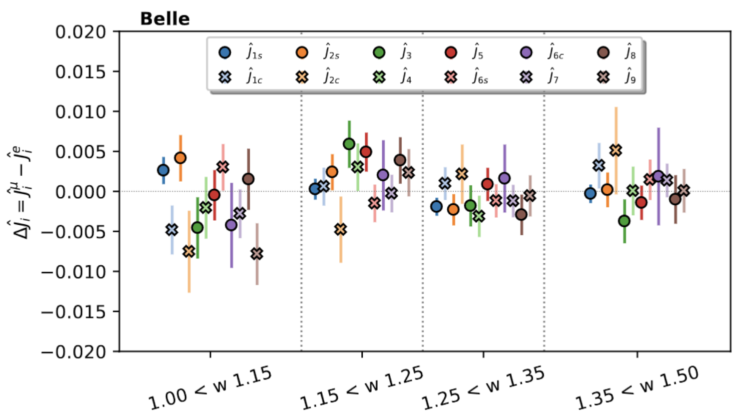


Figure 6. Differences of the angular coefficients J_i in four bins of w. All the differences are consistent with the SM expectation.

All the differences show no deviation from the SM expectation.

6 Summary

The Belle and Belle II experiments have recently provided many new results in semileptonic B decays. The measured values of $R(D^*)$ and $R(X)$, and the measurement of the angular coefficients of $B \to D^*\ell\nu$ for testing LFU are all found to be consistent with SM predictions. Beyond these important results, a continuous effort both on the experimental and theoretical side, e.g. discrepancies in LQCD predictions and measured $B \to D^*\ell\nu$ form factors, are essential to improve the future measurements.

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