

Recent Belle II results on tests of lepton flavor universality in semileptonic B meson decays

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In this article, we review three recently published experimental results of lepton flavor universality tests in semileptonic B meson decays based on the Run 1 data sample of the Belle II experiment. We present measurements of the branching fraction ratios $\mathcal{R}(D^*)$ using hadronic B-tagging, alongside both $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ using semileptonic B-tagging. Additionally, we include the first inclusive probe of the $b \rightarrow c\tau\nu$ transition via $\mathcal{R}(X_{\tau/\ell})$ using hadronic B-tagging. Finally, we summarize the current global experimental status and provide an outlook on the sensitivity prospects for the Run 2 target: 10 ab^{-1} integrated luminosity.

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1. Introduction

Lepton Flavor Universality (LFU) is an accidental symmetry of the Standard Model (SM) arising from the identical gauge couplings of leptons. Semileptonic B decays serve as an ideal laboratory[1] to test this symmetry, as they are theoretically clean and sensitive to tree-level New Physics contributions (i.a. extended Higgs sector, leptoquarks, W' , . . .), that may couple preferentially to fermions from the third generation. We test LFU via the branching fraction ratio:

$$\mathcal{R}(D^{(*)})_{\tau/\ell} = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \rightarrow D^{(*)}\ell\nu_\ell)} \quad (\ell = e, \mu), \quad (1)$$

which benefits from significant uncertainty cancellations: the $|V_{cb}|$ dependency drops out entirely, while form factor uncertainties and experimental systematics, including luminosity, $\sigma_{b\bar{b}}$, reconstruction efficiencies, and particle identifications are partially canceled.

Persistent tensions between Standard Model predictions and experimental measurements of $\mathcal{R}(D^{(*)})$ provide a strong motivation for the diverse physics program at Belle II. Current efforts are focused on providing updated measurements of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with the full Run 1 dataset, alongside complementary ratios in both inclusive, $\mathcal{R}(X)_{\tau/\ell}$, and exclusive modes, such as $\mathcal{R}(\pi)$. Beyond branching fraction ratios, the experiment is moving toward higher-dimensional analyses by utilizing observables sensitive to specific interaction structures. This includes the measurement of integrated angular observables, such as D^* and τ polarizations, as well as the study of differential kinematic spectra like the squared four-momentum transfer q^2 . These additional probes will be essential for discriminating between various New Physics scenarios if the current anomalies persist.

2. Experimental techniques

The analyses presented here utilize data collected by the Belle II experiment at the SuperKEKB asymmetric-energy e^+e^- collider located at the KEK laboratory in Japan. As an intensity-frontier machine, SuperKEKB provides high-luminosity collisions of 7 GeV electrons with 4 GeV positrons at a center-of-mass energy corresponding to the $\Upsilon(4S)$ resonance mass. The Belle II detector is a hermetic, multipurpose, large-solid-angle magnetic spectrometer designed to achieve high reconstruction efficiency for both charged and neutral particles. The results presented in this article are based on 189 fb^{-1} and 365 fb^{-1} of data collected at the $\Upsilon(4S)$ resonance during the 2019–2022 period, collectively referred to as Run 1. These datasets correspond to approximately 198×10^6 and 382×10^6 $B\bar{B}$ pairs, respectively.

The reconstruction of semileptonic B decays is experimentally challenging due to the large missing energy from multiple neutrinos in the final state; this limits the full reconstruction of the signal side, resulting in the absence of a distinct signal peak in invariant mass distributions. To handle this, we employ "B-tagging" techniques, where one B meson (B_{tag}) is reconstructed to constrain the kinematics of the signal B meson (B_{sig}). All analyses described herein utilize the Full Event Interpretation (FEI), a BDT-based hierarchical algorithm that reconstructs $O(10^4)$ unique decay chains. The algorithm begins from detector level objects – such as tracks and calorimeter cluster – and builds up to final-state leptons, mesons and baryons to eventually reconstruct the B_{tag} candidates. The optimal B-tagging technique depends on the specific signal-side signature,

and the overall efficiency and purity are ultimately determined by the final selection requirements. Namely, hadronic B-tagging exclusively reconstructs $B_{\text{tag}} \rightarrow D^{(*)} n\pi$ modes, providing high purity and full kinematic constraints at a lower efficiency ($\epsilon_{\text{had}} \approx 0.5\%$), while semileptonic B-tagging via $B_{\text{tag}} \rightarrow D^{(*)} \ell \nu$ offers higher statistics ($\epsilon_{\text{SL}} \approx 2\%$) at the cost of additional missing neutrino on the tag side.

The primary variable used to identify missing energy in these decays is the squared missing mass (M_{miss}^2), defined as:

$$M_{\text{miss}}^2 = (p_{e^+e^-} - p_{B_{\text{tag}}} - p_Y)^2, \quad (2)$$

where $p_{e^+e^-}$ is the initial e^+e^- four-momentum and Y represents the system of visible decay products on the signal side (e.g., $Y = D^{(*)}\ell$). For decays with a single missing neutrino, M_{miss}^2 peaks near zero, while semitauonic signals and backgrounds with multiple missing particles exhibit higher values ($M_{\text{miss}}^2 > 0$). Beyond the tag-side reconstruction, two key variables can be used to validate the signal candidate is correctly identified. The first is $\cos \theta_{BY}$, the cosine of the angle between the B meson momentum and the momentum of the visible signal-side products Y ($D^{(*)}\ell$) in the $\Upsilon(4S)$ rest frame:

$$\cos \theta_{BY} = \frac{2E_{\text{beam}}E_Y^* - m_B^2 - m_Y^2}{2|\vec{p}_B^*||\vec{p}_Y^*|} \quad (3)$$

For correctly reconstructed decays with a single missing massless neutrino, $\cos \theta_{BY}$ is physically constrained within $[-1, 1]$. In contrast, decays with multiple missing particles, such as semitauonic modes, typically yield values $\ll -1$. Unlike the missing mass squared (M_{miss}^2), $\cos \theta_{BY}$ is independent of the B_{tag} reconstruction, providing a robust kinematic constraint. The second variable, $E_{\text{ECL}}^{\text{extra}}$, is the sum of energies of neutral clusters in the Electromagnetic Calorimeter (ECL) not associated with the $\Upsilon(4S)$ decay products. While correctly reconstructed signal events concentrate at $E_{\text{ECL}}^{\text{extra}} \approx 0$, background events or incorrectly reconstructed signal typically exhibit higher values due to additional energy depositions. To optimize this discriminant, specific photon selection criteria are applied to suppress beam backgrounds and hadronic split-offs.

3. $\mathcal{R}(D^*)$ with exclusive hadronic B-tagging

The presented analysis employs hadronic B-tagging on the 189 fb^{-1} dataset collected during the 2019–2021 period. The tag-side B meson is reconstructed using the hadronic FEI algorithm, requiring a probability greater than 0.01, $M_{\text{bc}} > 5.27 \text{ GeV}/c^2$, and $-0.15 < \Delta E < 0.1 \text{ GeV}$. On the signal side, both $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$ and $B^+ \rightarrow \bar{D}^{*0}\tau^+\nu_\tau$ chains are targeted, with τ leptons identified via leptonic decays. Charmed mesons are reconstructed in three modes ($D^{*+} \rightarrow D^0\pi^+$, $D^{*+} \rightarrow D^+\pi^0$, and $D^{*0} \rightarrow D^0\pi^0$), with D^+ reconstructed through $K^-\pi^+\pi^+$, $K_S^0\pi^+$, and $K^-K^+\pi^+$, and D^0 identified via $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, $K_S^0\pi^+\pi^-\pi^0$, $K^-\pi^+$, $K_S^0\pi^+\pi^-$, $K_S^0\pi^0$, K^-K^+ , and $\pi^-\pi^+$. Remaining events are vetoed if they contain additional charged tracks or π^0 candidates.

A 2D likelihood fit to M_{miss}^2 and $E_{\text{ECL}}^{\text{extra}}$ is performed in the signal region ($q^2 > 4.0 \text{ GeV}^2$) to extract signal and normalization yields. The fit is simultaneous across six channels defined by the D^* decay modes and the light lepton flavor (e, μ). The primary components include signal, normalization, and backgrounds with either true or fake D^* mesons. To address the challenge of background modeling, particularly for $\bar{B} \rightarrow D^{**}\ell\bar{\nu}$, we employ a data-driven validation using control regions.

The extracted yields are $N_{D^*\tau\nu} + N_{D^*\tau\nu,\ell\text{-misID}} = 108 \pm 16$ and $N_{D^*\ell\nu} = 2164 \pm 80$. The ratio is calculated as:

$$\mathcal{R}(D^*) = \frac{N_{\bar{B} \rightarrow D^* \tau^- \bar{\nu}_\tau}}{N_{\bar{B} \rightarrow D^* \ell^- \bar{\nu}_\ell} / 2} \cdot \frac{\varepsilon_{\bar{B} \rightarrow D^* \ell^- \bar{\nu}_\ell}}{\varepsilon_{\bar{B} \rightarrow D^* \tau^- \bar{\nu}_\tau}}, \quad (4)$$

where ε denotes the reconstruction efficiency. We find[5]:

$$\mathcal{R}(D^*) = 0.262^{+0.041}_{-0.039} \text{ (stat)}^{+0.035}_{-0.032} \text{ (syst)}, \quad (5)$$

consistent with the SM and the HFLAV world average (0.288 ± 0.012)[8]. The measurement is statistically limited ($^{+15.7\%}_{-14.7\%}$), though it achieves improved precision per fb^{-1} compared to previous efforts[7] due to an optimized FEI and selection. Leading systematic uncertainties arise from PDF shapes ($^{+9.1\%}_{-8.3\%}$), simulation sample size ($\pm 7.5\%$), and modeling of $\mathcal{B}(\bar{B} \rightarrow D^{**} \ell \bar{\nu})$ ($^{+4.8\%}_{-3.5\%}$) decays, with a total systematic uncertainty of $^{+13.5\%}_{-12.3\%}$. An update is underway using the full Run 1 dataset to measure both $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$. The new analysis will include more D decay modes and better background rejection, further increasing the precision of the results.

4. $\mathcal{R}(D^{(*)+})$ with exclusive semileptonic B-tagging

The measurement is performed by reconstructing the tag-side B mesons through semileptonic exclusive modes ($B^0 \rightarrow D^{(*)} \ell \nu$) using the FEI algorithm. On the signal side, we target $B^0 \rightarrow D^{(*)-} \tau^+ \nu$ signal decays and $B^0 \rightarrow D^{(*)-} \ell^+ \nu$ normalization decays, where both the τ (via leptonic channels) and the prompt light lepton ℓ share the same experimental signature. To reconstruct the D mesons, the analysis utilizes six D^\pm and seven D^0 decay modes. Specifically, D^+ candidates are reconstructed in the $K^- \pi^+ \pi^+$, $K_s^0 \pi^+ \pi^0$, $K_s^0 \pi^+ \pi^+ \pi^-$, $K_s^0 \pi^+$, $K^- K^+ \pi^+$, and $K_s^0 K^+$ channels. The D^0 candidates are identified via $K^- \pi^+ \pi^0$, $K^- \pi^+ \pi^+ \pi^-$, $K_s^0 K^+ K^-$, $K^+ K^-$, $K^- \pi^+$, $K_s^0 \pi^+ \pi^-$, and $\pi^- \pi^+$ modes. In the preselection stage, candidates must satisfy specific kinematic constraints. All tag-side B candidates are required to have $\cos \theta_{\text{BY}}^{\text{tag}} \in [-1.75, 1.1]$, which reduces the fraction of semitauonic decays in the tag-side sample. For the signal side, we require $\cos \theta_{\text{BY}}^{\text{sig}} \in [-15, 1.1]$. Additionally, the extra energy in the electromagnetic calorimeter, $E_{\text{ECL}}^{\text{extra}}$, serves as a powerful discriminant; we retain only events with $E_{\text{ECL}}^{\text{extra}} < 1.2$ GeV, as correctly reconstructed events concentrate near zero while backgrounds exhibit higher values.

The analysis identifies four primary components: signal and normalization modes, and backgrounds from $B \rightarrow D^{**} \ell \nu$ transitions and other $B\bar{B}$ or continuum processes. Because no single kinematic variable provides sufficient discrimination to separate the signal from the normalization and these various background sources, we employ a multivariate approach. A Boosted Decision Tree (BDT) is trained to combine multiple features into a powerful classifier, utilizing five variables ordered by importance: $\cos \theta_{\text{BY}}^{\text{sig}}$, $E_{\text{ECL}}^{\text{extra}}$, $\cos^2 \Phi_B$, and the $\Upsilon(4S)$ rest-frame momenta of the D meson (p_D^*) and the lepton (p_ℓ^*). The variable $\cos^2 \Phi_B$ is particularly effective in this combination for identifying events with multiple missing neutrinos. It integrates the $\cos \theta_{\text{BY}}$ information from both the signal and tag candidates with the angle γ between their visible momenta (p_γ):

$$\cos^2 \Phi_B = \frac{\cos^2 \theta_{\text{BY}}^{\text{sig}} + \cos^2 \theta_{\text{BY}}^{\text{tag}} + 2 \cos \theta_{\text{BY}}^{\text{sig}} \cos \theta_{\text{BY}}^{\text{tag}} \cos \gamma}{\sin^2 \gamma}.$$

For correctly reconstructed semileptonic decays with a single missing neutrino, $\cos^2 \Phi_B$ is physically constrained between zero and one, whereas signal decays typically exhibit larger values due to the additional neutrinos in the τ decay chain. The BDT classifies events into three categories (signal, normalization, and background), assigning each event the scores z_τ , z_ℓ , and z_{bkg} . Signal yields are extracted via a simultaneous 2D binned template fit of z_τ and $z_{\text{diff}} = z_\ell - z_{\text{bkg}}$ across four independent channels: $D^0 e^-$, $D^0 \mu^-$, $D^+ e^-$, and $D^+ \mu^-$. The fit employs ten parameters (two signal, two normalization, and six background) and a non-uniform binning scheme. This scheme provides higher granularity in regions sensitive to semitauonic and D^{**} events, while using coarser bins for well-separated $B \rightarrow D^* \ell \nu$ normalization events.

Using the full Belle II Run 1 dataset of 365 fb^{-1} , we measure[6]:

$$\begin{aligned}\mathcal{R}(D^+) &= 0.418_{-0.073}^{+0.075} (\text{stat})_{-0.056}^{+0.049} (\text{syst}), \\ \mathcal{R}(D^{*+}) &= 0.306_{-0.033}^{+0.035} (\text{stat})_{-0.018}^{+0.016} (\text{syst}),\end{aligned}$$

with a correlation of $\rho = -0.24$.

The results for $\mathcal{R}(D^{(*)+})$ are consistent with SM predictions within 1.7σ . The measurement remains statistically limited, with relative uncertainties of 18.0% for $\mathcal{R}(D)$ and 11.0% for $\mathcal{R}(D^*)$, which are expected to improve significantly with the inclusion of B^+ decay modes. Furthermore, LFU tests comparing electrons and muons yield $\mathcal{R}(D_{e/\mu}^+) = 1.068_{-0.048}^{+0.050} (\text{stat})_{-0.023}^{+0.024} (\text{syst})$ and $\mathcal{R}(D_{e/\mu}^{*+}) = 1.079_{-0.036}^{+0.037} (\text{stat})_{-0.019}^{+0.020} (\text{syst})$, with a correlation coefficient of $\rho = -0.398$, consistent with the SM within 1.2σ and 1.6σ , respectively. The systematic uncertainties for $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ are dominated by the finite size of simulated samples, contributing 8.0% and 4.7%, respectively. Uncertainties from the $\mathcal{B}(B \rightarrow D^{**} \ell \nu)$ branching fractions account for 6.4% and 0.1%, while muon identification efficiency contributes 2.9% and 0.9%. Summing these and other sources, the total systematic uncertainty is determined to be 12.0% for $\mathcal{R}(D)$ and 6.2% for $\mathcal{R}(D^*)$.

5. $\mathcal{R}(X_{\tau/\ell})$ with exclusive hadronic B-tagging

Belle II has performed the first test of LFU using inclusive $B \rightarrow X \tau \nu$ decays[3], where X denotes any system of charmed hadrons. This approach incorporates D and D^* mesons regardless of their decay mode and includes a 14%–20% expected contribution from higher-state D^{**} and non-resonant "gap" semitauonic decays. Using a 189 fb^{-1} dataset, the tag-side B meson is reconstructed via the hadronic FEI ($\epsilon_{\text{had}} \approx 0.1\%$). Continuum backgrounds are suppressed using a BDT, and lepton identification requirements are optimized to suppress fake and secondary leptons. The primary challenge in the inclusive measurement is the modeling of the X system. Significant systematic uncertainties arise from the composition of $B \rightarrow X \ell \nu$ backgrounds, particularly the modeling of D , D^* , D^{**} , and the non-resonant hadronic "gap". To address mismodeling in the mass of charmed hadrons system (M_X) distribution – often caused by an incorrect abundance of K_L^0 in simulation – we apply data-driven template reshaping. Simulation samples are reweighted based on the lepton laboratory momentum p_ℓ^{lab} and the hadronic mass M_X . These corrections are validated using two control samples: a "high- p_ℓ^B " sample ($p_\ell^B > 1.4 \text{ GeV}/c$) composed of 95% $B \rightarrow X \ell \nu$, and a "same-charge" sample enriched with fakes and continuum events. The signal is extracted via a 2D binned likelihood fit to the lepton momentum in the signal B rest frame, $p_\ell^{B_{\text{sig}}}$,

and the squared missing mass, M_{miss}^2 . The fit considers four components: signal, normalization, $B\bar{B}$ background, and continuum (with yields constrained by off-resonance data). The fit extracts yields of $N_\tau = 2590 \pm 450$ (1810 ± 460) and $N_\ell = 95690 \pm 770$ (89970 ± 810) for the electron (muon) channels. The measured ratios and combined average are[3]:

$$\mathcal{R}(X_{\tau/e}) = 0.232 \pm 0.020 \text{ (stat)} \pm 0.037 \text{ (syst)}, \quad (6)$$

$$\mathcal{R}(X_{\tau/\mu}) = 0.222 \pm 0.027 \text{ (stat)} \pm 0.050 \text{ (syst)}, \quad (7)$$

$$\mathcal{R}(X_{\tau/\ell}) = 0.228 \pm 0.016 \text{ (stat)} \pm 0.036 \text{ (syst)}, \quad (8)$$

which is consistent with the SM prediction[4] of 0.223 ± 0.005 within 1.7σ . Additionally, a light-lepton LFU test yields $\mathcal{R}(X_{e/\mu}) = 1.07 \pm 0.05 \pm 0.02$. The measurement is currently systematically limited (17.5%), with leading uncertainties attributed to X_c form factors (7.8%), $B \rightarrow X\ell\nu$ branching fractions (7.7%), and M_X reweighting (7.1%).

Crucially, the statistical overlap between this inclusive result and the exclusive $\mathcal{R}(D^*)$ measurement is only $\approx 0.4\%$, with a total correlation below 0.1. This makes the inclusive measurement a largely independent and robust probe of the $b \rightarrow c\tau\nu$ anomaly.

6. Summary and Outlook

As of Spring 2025[8], the global tension in the $\mathcal{R}(D)$ – $\mathcal{R}(D^*)$ plane has reached 3.8σ relative to the SM, an increase from the 3.2σ reported prior to recent Belle II and LHCb updates. This discrepancy is characterized by individual deviations of 2.0σ for $\mathcal{R}(D)$ and 2.7σ for $\mathcal{R}(D^*)$, with a correlation of $\rho = -0.39$. The relative precision stands at 7.2% for $\mathcal{R}(D)$ and 4.2% for $\mathcal{R}(D^*)$.

Belle II aims to resolve this anomaly through a diverse LFU program across $\mathcal{R}(Y)$ observables ($Y = \pi, D, D^*, X_{c,u}$). Sensitivity projections [9][10] indicate that with the 10 ab^{-1} target for Run 2, Belle II will reach relative precisions of 3.0% for $\mathcal{R}(D)$ and 1.8% for $\mathcal{R}(D^*)$. These sensitivities would allow for a definitive exclusion of the SM if current central values persist. A key priority is the precise tagged measurement of $B \rightarrow D^{**}\ell\nu$ decays, which remain the most significant and poorly constrained background. Improved modeling of this D^{**} feed-down is essential to mitigate systematic biases and achieve the precision necessary to confirm or reject New Physics effects in $b \rightarrow c\tau\nu$ transitions.

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