PROCEEDINGS OF SCIENCE

Measurements of lepton-flavour universality in semileptonic B decay at Belle II

Michele Mantovano[a,*]

[a] *Deutsches Elektronen-Synchrotron (DESY), Notkestraße 85, 22607 Hamburg, Germany*

E-mail: michele.mantovano@desy.de

The first run of the Belle II experiment collected a 365 fb^{-1} sample of collisions at a centre-of-mass energy corresponding to the $\Upsilon(4S)$ resonance. These data, characterised by low particle multiplicity, well-constrained initial-state kinematics, and excellent lepton identification, provide an ideal environment to study lepton-flavour universality in semileptonic B decays. We present results on the ratios of semitauonic decay rates compared to those to light leptons in both exclusive and inclusive B decay. These include new measurements of the ratios for exclusive $B \to D^{(*)}\ell\nu_\ell$ decays $R(D^{(*)})_{\tau/\ell}$ in events tagged by a semileptonic B decay.

European Physical Society Conference on High Energy Physics (EPS-HEP)
7-11 July 2025
Marseille, France

*Speaker

 ISSN 1824-8039 . Published by SISSA Medialab.

PoS(EPS-HEP2025)317

1. Introduction

Belle II [1] is a particle detector operating at the SuperKEKB accelerator [2], located at the KEK laboratory in Japan. SuperKEKB collides 7 GeV electrons with 4 GeV positrons at high luminosity, producing the $\Upsilon(4S)$ resonance. This state decays almost exclusively into $B\bar{B}$ pairs, providing a clean experimental environment with relatively low background. Thanks to its hermetic design and nearly cylindrical geometry around the interaction point, the Belle II detector is particularly well suited for studying decays with missing energy, as it enables precise reconstruction of the event kinematics at the $B\bar{B}$ threshold.

In the Standard Model (SM) of particle physics, the W boson couples equally to all three generations of leptons, a symmetry known as lepton-flavour universality (LFU). Semileptonic B decays provide stringent tests of LFU and are therefore sensitive to potential effects of physics beyond the SM. A particularly useful observable is the ratio of branching fractions

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

where ℓ denotes either an electron or a muon, and H represents a hadron. The hadronic state H can correspond to an exclusive final state such as $D^{(*)}$ or to a more inclusive hadronic system X. This ratio is particularly sensitive to deviations from universality in the third lepton generation. Moreover, it benefits from a partial cancellation of both theoretical and experimental uncertainties, thereby providing a cleaner test of LFU.

The measurements presented in this document are based on 189 fb^{-1} and 365 fb^{-1} of data collected at the $\Upsilon(4S)$ resonance during the 2019–2022 run period, corresponding to approximately 198 and 382 million $B\bar{B}$ pairs, respectively. Two different reconstruction techniques, known as *hadronic* and *semileptonic tagging* [3], are employed to reconstruct the companion B meson (B_{tag}) on the non-signal side, in hadronic or semileptonic decay modes, respectively. After fully reconstructing the B_{tag} and assigning the remaining particles to the signal B meson (B_{sig}) that decays via a semitauonic mode, the latter can be distinguished from other semileptonic and background events using several key observables: the missing mass squared, defined as $M^2_{\text{miss}} = (p_{e^+e^-} - p_{\text{visible}})^2$, the residual calorimeter energy not associated with the reconstructed particles, E_{ECL}, and a kinematic constraint from the B_{sig}, defined as $\cos\theta_{BY} = \frac{2E^*_{\text{beam}}E^*_Y - m^2_B - m^2_Y}{2|\vec{p}^*_B||\vec{p}^*_Y|}$, where Y denotes the $D\ell$ system. A graphical representation of these variables is shown in Fig. 1.

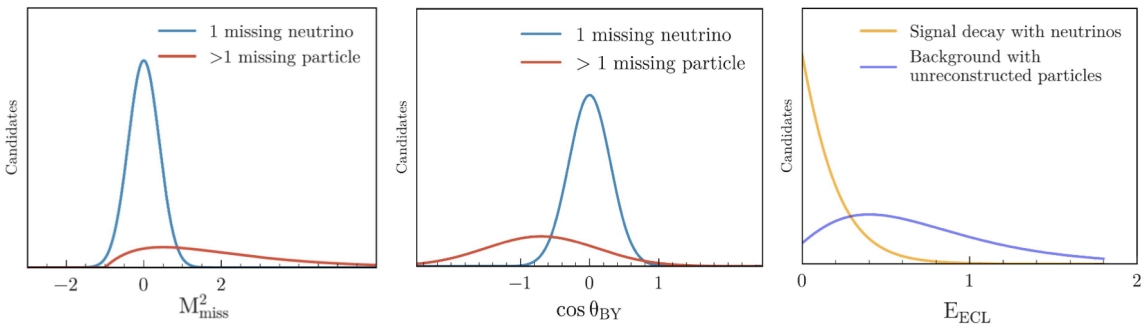


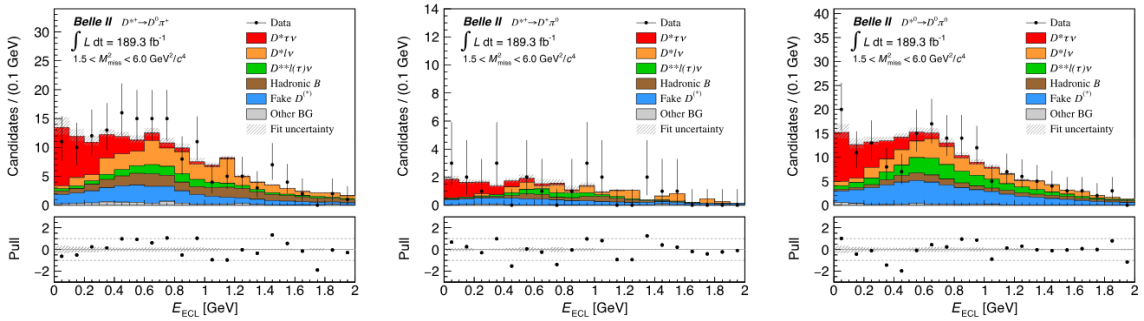
Figure 1: Graphical representation of the M^2_{miss}, $\cos\theta_{BY}$ and E_{ECL} variables described in the text.

For each analysis presented in this document, the variables used are explicitly specified.

2. Measurement of the $R(D^*)_{\tau/\ell}$ with hadronic B-tagging method

The purpose of this analysis is to test LFU by measuring the ratio $R(D^*)_{\tau/\ell}$. This observable has been extensively studied by the BaBar [4], Belle [5], and LHCb [6] collaborations. The analysis is based on 189 fb^{-1} of data, using the hadronic B-tagging method. The remaining particles in the event are used to reconstruct the signal decay $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$ and the normalisation channel $\bar{B} \to D^* \ell^- \bar{\nu}_\ell$. The D mesons are reconstructed in three channels: $D^{*+} \to D^0 \pi^+$, $D^{*+} \to D^+ \pi^0$, and $D^{*0} \to D^0 \pi^0$. For the τ lepton, only the leptonic decay modes $\tau^- \to e^- \bar{\nu}_e \nu_\tau$ and $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ are considered.

The extraction of $R(D^*)_{\tau/\ell}$ is performed through a two-dimensional fit to the M^2_{miss} and E_{ECL}. Fit projections in the signal-enhanced region are shown in Fig. 2.



(a) (b) (c)

Figure 2: Distributions of E_{ECL} in the signal-enhanced region $1.5 < M^2_{\text{miss}} < 6.0\,\text{GeV}^2/c^4$ for the $D^{*+} \to D^0 \pi^+$ (a), $D^{*+} \to D^+ \pi^0$ (b), and $D^{*0} \to D^0 \pi^0$ (c) 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.

We obtain [7]

$$R(D^*)_{\tau/\ell} = 0.262^{+0.041}_{-0.039}(\text{stat})^{+0.035}_{-0.032}(\text{syst}), \tag{2}$$

corresponding to a signal $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$ yield of 108 ± 16. The measured $R(D^*)_{\tau/\ell}$ value is consistent with SM prediction [8].

3. Measurement of the $R(D^{(*)})_{\tau/\ell}$ with semileptonic B-tagging method

We present the first combined measurement of $R(D)_{\tau/\ell}$ and $R(D^*)_{\tau/\ell}$, based on the Run I data set corresponding to 365 fb^{-1}, using semileptonic B-tagging method at Belle II.

The analysis uses $B^0 \bar{B}^0$ pairs produced in $\Upsilon(4S)$ decays. The B_{tag} is reconstructed in a semileptonic decay and combined with an oppositely flavored semitauonic or semileptonic decay candidate, which is defined as B_{sig}. Signal candidates are reconstructed in the $D^+ \ell^-$ and $D^{*+} \ell^-$ final states ($\ell = e, \mu$). These can originate either from semitauonic decays, $\bar{B}^0 \to D^{(*)+} \tau^- \bar{\nu}_\tau$ with $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$, or from direct semileptonic decays, $\bar{B}^0 \to D^{(*)+} \ell^- \bar{\nu}_\ell$. The D mesons are reconstructed in multiple decay channels: 26 modes on the tag side and 13 modes on the signal side [9].

To distinguish B_{sig} candidates originating from semitauonic, semileptonic, and background sources, we employ multivariate classifiers trained on five variables that use the kinematic properties

of both the B_{sig} and B_{tag} candidates. The most powerful discriminating variable is $\cos\theta_{BY}$ of the B_{sig} candidate, followed by the E_{ECL}. The third most important observable is $\cos^2\Phi_B$ [9], which combines the $\cos\theta_{BY}$ information from both the B_{sig} and B_{tag} candidates with the angle between their Y momenta. The fourth and fifth most important input variables are the centre-of-mass momenta of the D (p^*_D) and lepton (p^*_ℓ) candidates, respectively. Good separation between semitauonic and semileptonic signals is achieved in $\cos\theta_{BY}$, $\cos^2\Phi_B$, p^*_ℓ, and p^*_D while E_{ECL} provides strong discrimination between signal processes and generic backgrounds. The three resulting classification scores are denoted as z_τ, z_ℓ, and z_{bkg} for semitauonic, semileptonic, and background events, respectively. We extract the signal using a binned two-dimensional log-likelihood fit to the variables z_τ and $z_{\text{diff}} = z_\ell - z_{\text{bkg}}$. Four categories of events are considered: D^+e^-, $D^{*+}e^-$, $D^+\mu^-$, and $D^{*+}\mu^-$ candidates. The fitted classifier distributions for all categories are shown in Fig. 3.

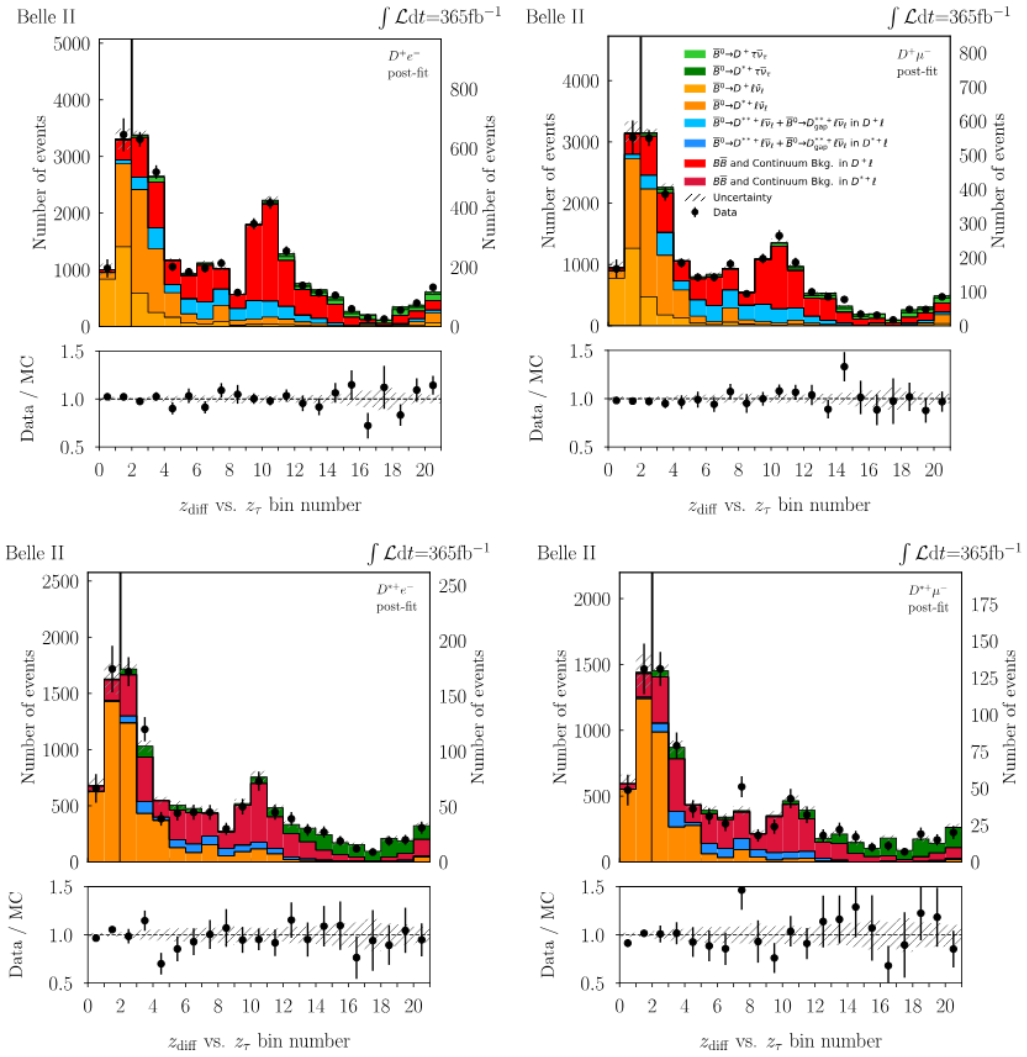


Figure 3: The fitted classifier distributions for the D^+e^-, $D^{*+}e^-$, $D^+\mu^-$, and $D^{*+}\mu^-$ categories are shown. The hatched regions of the histograms correspond to the systematic uncertainties. The black lines demarcate the first two bins from the remaining bins, which contain significantly fewer events, and are thus displayed with two different y-axis scales on the left and right sides.

We measure [9]

$$R(D^+)_{\tau/\ell} = 0.418^{+0.075}_{-0.073}\,(\text{stat})^{+0.049}_{-0.056}\,(\text{syst}) \tag{3}$$

$$R(D^{*+})_{\tau/\ell} = 0.306^{+0.035}_{-0.033}\,(\text{stat})^{+0.016}_{-0.018}\,(\text{syst}) \tag{4}$$

with a correlation of $\rho = -0.24$. These values are consistent with the SM expectations [8] within 1.7 standard deviations. The tension between the LFU-sensitive quantities and SM predictions increases to 3.8 standard deviation as shown in Fig. 4.

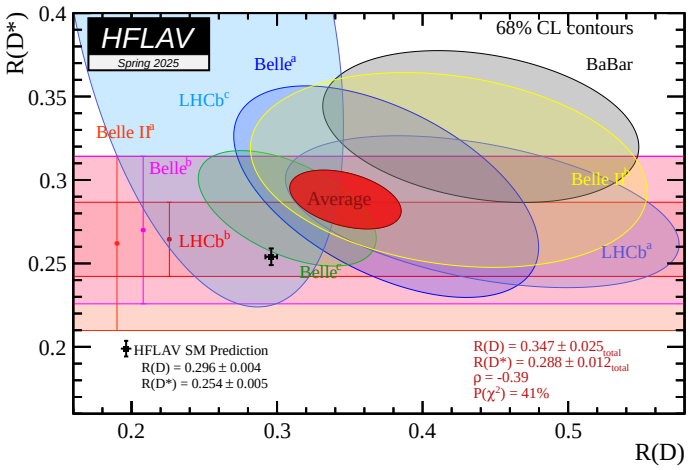


Figure 4: Average of $R(D^{(*)})_{\tau/\ell}$ according to HFLAV (Spring 2025) [10]. The $R(D^{(*)})_{\tau/\ell}$ measurement using semileptonic B tagging, discussed in the text, is represented by the yellow blob (Belle II$^{\text{b}}$), while the red point (Belle II$^{\text{a}}$) corresponds to the measurement of $R(D^*)_{\tau/\ell}$ with hadronic B tagging presented in the previous paragraph. Note that, at the time of writing, an additional Belle II measurement of $R(D^{(*)})_{\tau/\ell}$ using hadronic B tagging had been approved by the Belle II Collaboration but is not shown here, as it was not ready in time for the EPS-HEP Conference.

In addition, for the ratio of the semileptonic signal branching fractions of electrons to muons we find [9],

$$R(D^+)_{e/\mu} = 1.068^{+0.050}_{-0.048}\,(\text{stat})^{+0.024}_{-0.023}\,(\text{syst}) \tag{5}$$

$$R(D^{*+})_{e/\mu} = 1.079^{+0.037}_{-0.036}\,(\text{stat})^{+0.020}_{-0.019}\,(\text{syst}) \tag{6}$$

with a correlation coefficient of $\rho = -0.398$, both consistent with the expectation of LFU within 1.2 and 1.6 standard deviations, respectively.

4. Measurement of the $R(X)_{\tau/\ell}$ with hadronic B-tagging method

We present a complementary test of LFU through the first measurement of the ratio of inclusive semileptonic B-meson branching fractions $R(X)_{\tau/\ell}$. In this inclusive approach, both D and D^* mesons are included irrespective of their decay modes, together with an expected 14%–20% contribution from semitauonic B decays that have not yet been explored. Predictions for $R(X)_{\tau/\ell}$ [11]

rely on theoretical inputs different from those used for the exclusive ratios such as $R(D^{(*)})_{\tau/\ell}$ [8]. As a result, this observable provides an independent probe of LFU, with distinct statistical and systematic sensitivities, and the potential to reach higher precision.

The analysis is based on 189 fb^{-1} of data, using the hadronic B-tagging method. The remaining particles in the event are assigned to the B_{sig} candidate. Events are classified as signal when the final-state lepton originates from a primary τ in $B \to X\tau\nu_\tau$ decays, and as normalisation when the lepton is produced in $B \to X\ell\nu_\ell$ decays.

The signal and normalisation yields are simultaneously determined through a two-dimensional fit to two observables: the lepton momentum in the B_{sig} rest frame, p_ℓ^B, and the M^2_{miss}. Fit projections in different M^2_{miss} regions are shown in Fig. 5.

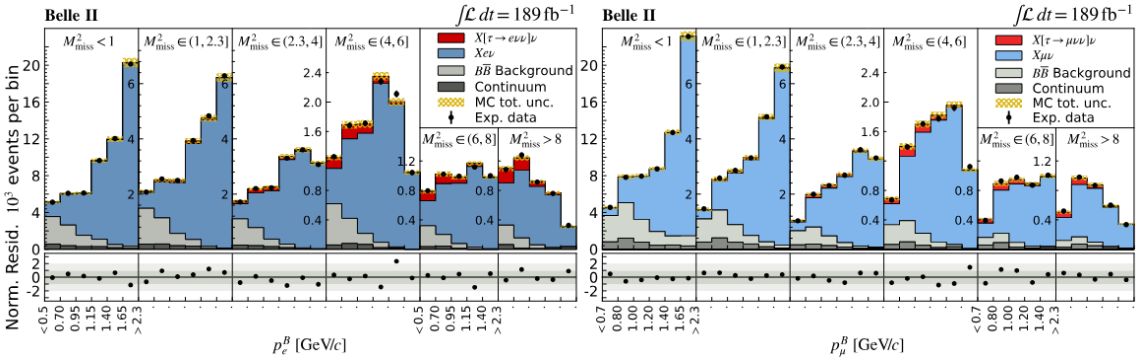


Figure 5: Two-dimensional distributions of electron (left) and muon (right) momentum p_ℓ^B in the B_{sig} rest frame and the missing mass squared M^2_{miss}, flattened to one dimension in intervals as used in the signal extraction fit, with the fit results overlaid. The hatched area shows the total statistical and systematic uncertainty, added in quadrature for each interval. The residuals are normalised 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 [12]

$$R(X)_{\tau/\ell} = 0.228 \pm 0.016(\text{stat}) \pm 0.036(\text{syst}), \tag{7}$$

corresponding to a signal yields of $N_{\tau\to e} = 2590 \pm 450$ and $N_{\tau\to\mu} = 1810 \pm 460$.
The measured $R(X)_{\tau/\ell}$ value is in agreement with the SM prediction [11], $R(X)^{SM}_{\tau/\ell} = 0.223 \pm 0.005$, and it is also consistent with a hypothetically enhanced semitauonic branching fraction as indicated by the $R(D^{(*)})_{\tau/\ell}$ world average [8].

5. Summary

The Belle II experiment has recently reported several new results on semileptonic B decays. In particular, the latest measurements of $R(D^{(*)})_{\tau/\ell}$ and $R(X)_{\tau/\ell}$ presented here are consistent with the SM predictions. However, the tension between the LFU-sensitive quantities $R(D^{(*)})_{\tau/\ell}$ and the SM predictions has increased to 3.8 standard deviations. For this reason, continuous efforts on both the experimental and theoretical sides remain crucial. Experimentally, Belle II will significantly improve the precision of future measurements with larger data samples, while theoretical developments (e.g., D^{**} modelling, form factors) will be essential for reducing systematic uncertainties and fully exploiting the physics potential of Belle II.

References

[1] T. Abe *et al.* (Belle II Collaboration), *Belle II Technical Design Report* (2010), arXiv:1011.0352.

[2] Akai, K., Furukawa, K., Koisoon, H., *SuperKEKB collider*, *Nucl. Instrum. Meth.* A **907**, 188 (2018).

[3] Keck, T., Abudinén, F., Bernlochner, F.U. *et al.*, *The Full Event Interpretation*, *Comput Softw Big Sci* **3**, 6 (2019).

[4] Lees, J. P. *et al.* (BaBar Collaboration), *Measurement of an excess of* $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ *decays and implications for charged Higgs bosons*, *Phys. Rev.* D **88**, 072012 (2013).

[5] Caria, G. *et al.* (Belle Collaboration), *Measurement of* $\mathcal{R}(D)$ *and* $\mathcal{R}(D^*)$ *with a Semileptonic Tagging Method*, *Phys. Rev. Lett.* **124**, 161803 (2020).

[6] Aaij, R. *et al.* (LHCb Collaboration), *Measurement of the Ratios of Branching Fractions* $\mathcal{R}(D^*)$ *and* $\mathcal{R}(D^0)$, *Phys. Rev. Lett.* **131**, 111802 (2023).

[7] Adachi, I. *et al.* (Belle II Collaboration), *A test of lepton flavor universality with a measurement of* $\mathcal{R}(D^*)$ *using hadronic B tagging at the Belle II experiment*, *Phys. Rev.* D **110**, 072020 (2024)

[8] Sw. Banerjee *et al.* (HFLAV Collaboration), *Averages of b-hadron, c-hadron, and* τ*-lepton properties as of 2023*, arXiv:2411.18639.

[9] Adachi, I., *et al.* (Belle II Collaboration), *Test of lepton flavor universality with measurements of* $R(D^+)$ *and* $R(D^{*+})$ *using semileptonic B tagging at the Belle II experiment*, *Phys. Rev.* D **112**, 032010 (2025).

[10] HFLAV Collaboration, *HFLAV official website*, `https://hflav.web.cern.ch/`.

[11] Rahimi, M., Vos, K.K., *Standard Model predictions for lepton flavour universality ratios of inclusive semileptonic B decays*, *J. High Energy Phys.* **11**, 007 (2022).

[12] Adachi, I. *et al.* (Belle II Collaboration), *First Measurement of* $R(X_{\tau/\ell})$ *as an Inclusive Test of the* $b \to c\tau\nu$ *Anomaly*, *Phys. Rev. Lett.* **132**, 211804 (2024).

PoS(EPS-HEP2025)317