Semileptonic B decays

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Abstract

A review of recent measurements from Belle, Belle II and LHCb B-factories with semileptonic B decays is presented. The focus is on lepton flavour universality tests performed comparing semileptonic decays with a τ in the final state and decays with electron and muon, and on measurements of $|V_{cb}|$ and $|V_{ub}|$ CKM matrix elements, including the measurement from purely leptonic $B \to \tau\nu$.

1 Introduction

Semileptonic and leptonic B meson decays provide very important information, both for Standard Model (SM) precision determination and for search of physics beyond the SM. Indeed, the $b \to u$ and $b \to c$ decays at quark level provide access to the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{ub}|$ and $|V_{cb}|$, whose precise determination is essential to set SM predictions. Since the b quark is confined inside hadrons, such measurements can be performed analyzing exclusive decays like $B \to D^{(*)}\ell\nu$ for $|V_{cb}|$ or $B \to \pi\ell\nu$ for $|V_{ub}|$, requiring theory input for the form factor parameterization. Also the purely leptonic decays $B \to \tau\nu$, despite the lower statistics because of the helicity suppression it suffers, allows the extraction of $|V_{ub}|$, with the advantage of a negligible theoretical dependence, confined in the B meson decay constant f_B calculated with Lattice QCD with an uncertainty better than 1% [1]. On the other hand, $|V_{ub}|$ and $|V_{cb}|$ can be extracted with inclusive measurements $B \to X_c/X_u\ \ell\nu$, where the final state is not reconstructed in a specific mode, but all the possible results of the hadronization of the c or u quark are collected and taken into account. It is a long-standing puzzle the tension between the inclusive and exclusive determinations of the CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$ [2]. Finally, the comparison of the decay rates of the various lepton species $\ell = e, \mu, \tau$ can be used to test the lepton flavour universality (LFU) predicted by the SM. In particular, since several years, the ratios of branching ratios $R(D^{(*)}) = \mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}\ell\nu)$, where ℓ is an electron or a muon have been measured to be in tension with the SM expectation [2].

2 Lepton flavour universality ratios

Belle II collaboration measured the $R(D^{*+})$ ratio with a sample of 189 fb^{-1}, using the hadronic reconstruction of a tag B meson ($B_{\rm tag}$), that provides powerful constraints on the accompaining signal B [3]. From the physics objects not used to reconstruct the $B_{\rm tag}$ a D^* is reconstructed in its decays $D^{*+} \to D^0\pi^+$ or $D^+\pi^0$, and $D^{*0} \to D^0\pi^0$. The τ lepton is detected identifying its decay in electron or muon. The signal ($D^*\tau\nu$) and normalization ($D^*\ell\nu$) samples are separated using $M^2_{\rm miss} = (p_B - p_{D^*} - p_\ell)^2$. The total energy measured in the electromagnetic calorimeter $E^{\rm extra}_{\rm ECL}$ is the main discriminant variable between signal and background. Figure 1 shows the distributions for the $D^{*+} \to D^0\pi^+$ decay mode of $M^2_{\rm miss}$ in the entire analysis region and $E^{\rm extra}_{\rm ECL}$ in the signal-enhanced region. In order to extract the signal and the normalization yields, a two dimensional fit to $M^2_{\rm miss}$ and $E^{\rm extra}_{\rm ECL}$ is performed. Background and signal models, taken from MC simulations, are validated by means of control regions in experimental data. The largest systematics uncertainty comes from this source and it is estimated to be 9%. Other systematic uncertainties come from the available MC statistics (7%) and current knowledge of D^{**} modes (5%). The lepton flavor universality ratio is measured to be $R(D^*) = 0.262 \pm 0.04({\rm stat}) \pm 0.03({\rm syst})$, consistent with both the SM expectation $R_{SM}(D^*) = 0.254 \pm 0.005$ and the world average from HFLAV working group $R_{WA}(D^*) = 0.288 \pm 0.012$ [2].

Reconstruction of the tag B with semileptonic decays has been exploited, as well, by the Belle II collaboration to measure the LFU ratios for both D^{*+} and D^+ modes, using

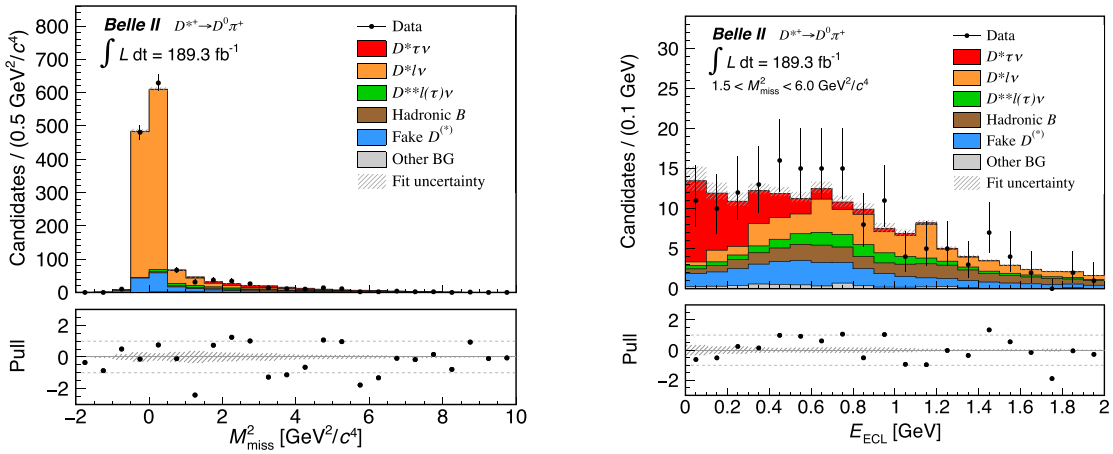

FIG. 1: Distributions for the $D^{*+} \to D^0\pi^+$ decay mode of $M^2_{\rm miss}$ in the entire region (left) and $E^{\rm extra}_{\rm ECL}$ in the signal-enhanced region (right).

a sample of 365 fb^{-1} [4]. The tag B is reconstructed in $B_{\rm tag} \to D^*\ell\nu$ and $B_{\rm tag} \to D\ell\nu$ in 26 different decay chains. The reconstructed objects in the event not used to make the $B_{\rm tag}$ are examined for signal, and, subsequently, $D^+\ell^-$ and $D^{*+}\ell^-$ pairs are reconstructed in 13 different modes. The most discriminating variables are the $E^{\rm extra}_{\rm ECL}$ and $\cos\theta_{BY} = \frac{2E_{beam}E_Y - m_B^2 - m_Y^2}{2p_Bp_Y}$, where Y is a $D\ell$ pair. $E^{\rm extra}_{\rm ECL}$ is the total energy reconstructed in the electromagnetic calorimeter from neutral objects not associated to the B or the $D\ell$ pair. The second variable, $\cos\theta_{BY}$, is the cosine of the angle between the B meson and Y system in the case of an actual semileptonic decay (one missing particle), while it shows a broader distribution in other kind of decays. These variables are combined with other discriminating variables in a boosted decision tree that selects three classes of events: signal (z_τ), normalization (z_ℓ) and background (z_{bkg}).

Signal, normalization and background yields are extracted by a two-dimensional likelihood fit to z_τ and $z_{diff} = z_\ell - z_{bkg}$ in four decay modes ($D^{*+}e^-$, D^+e^-, $D^{*+}\mu^-$, $D^+\mu^-$). Figure 2 shows fitter classifier distributions in the four decay modes. The result is still limited by statistics (11% for R(D^*) and 18% for R(D)). The largest systematics uncertainties are due to limited MC simulation statistics and knowledge D^{**} branching fractions and distributions in experimental data. The obtained results are $R(D^{*+}) = 0.306 \pm 0.034({\rm stat}) \pm 0.018({\rm syst})$ and $R(D^+) = 0.418 \pm 0.074({\rm stat}) \pm 0.051({\rm syst})$, consistent with the SM expectations and with the world average.

LHCb collaboration recently measured the ratios $R(D^{*+})$ and $R(D^+)$ with a muon in the final state and reconstructing $D^+ \to K^-\pi^+\pi^+$ and $D^{*+} \to D^+\pi^0$, with a sample of 2 fb^{-1} of the Run 2 dataset [5]. This analysis extends an analysis with a similar strategy previously published with 3 fb^{-1} Run 1 dataset, which determine R(D^0) and $R(D^+)$ using $D^0 \to K^+\pi^+$ and $D^{*+} \to D^0\pi^+$ and a muon in the final state [6]. The signal and the normalization yields are extracted by a three-dimensional likelihood fit to the distributions of the momentum transfer of the lepton pair q^2 , the missing mass squared $M^2_{\rm miss}$ and the muon energy E^*_μ. The likelihood uses as probability distribution functions the templates of these observables taken from MC simulation, that are validated on control samples

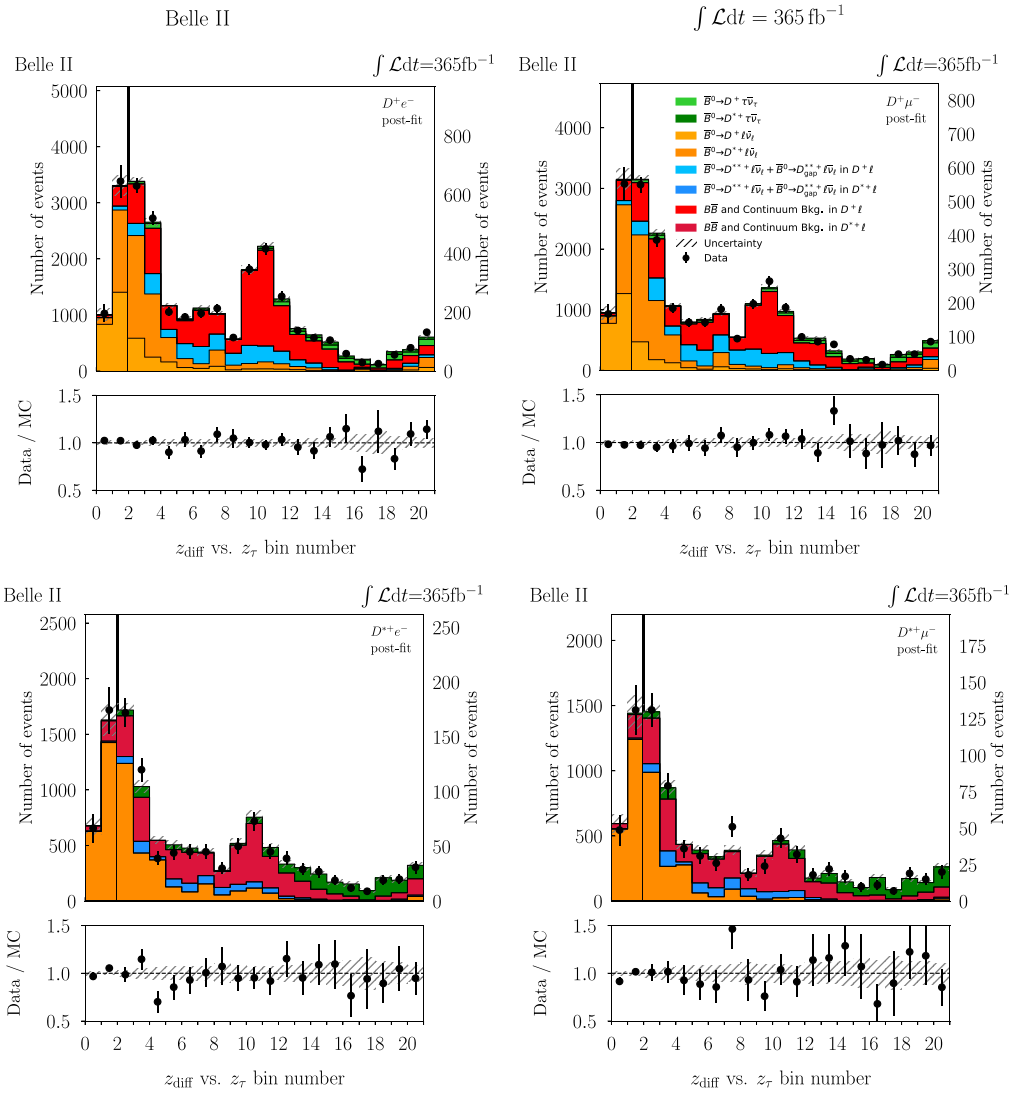

FIG. 2: The fitter classifier distributions in the $D^{*+}e^-$, D^+e^-, $D^{*+}\mu^-$, $D^+\mu^-$ modes. The hatched regions of the histograms cover the systematic uncertainties. The black line separates the first two bins from the remaining bins, that are displayed with a different y-axis scale on the right side.

in experimental data. Figure 3 shows the fitted distributions. The obtained results are $R(D^{*+}) = 0.402 \pm 0.081(\text{stat}) \pm 0.085(\text{syst})$ and $R(D^{+}) = 0.249 \pm 0.043(\text{stat}) \pm 0.047(\text{syst})$, consistent with the SM expectations and with the world average.

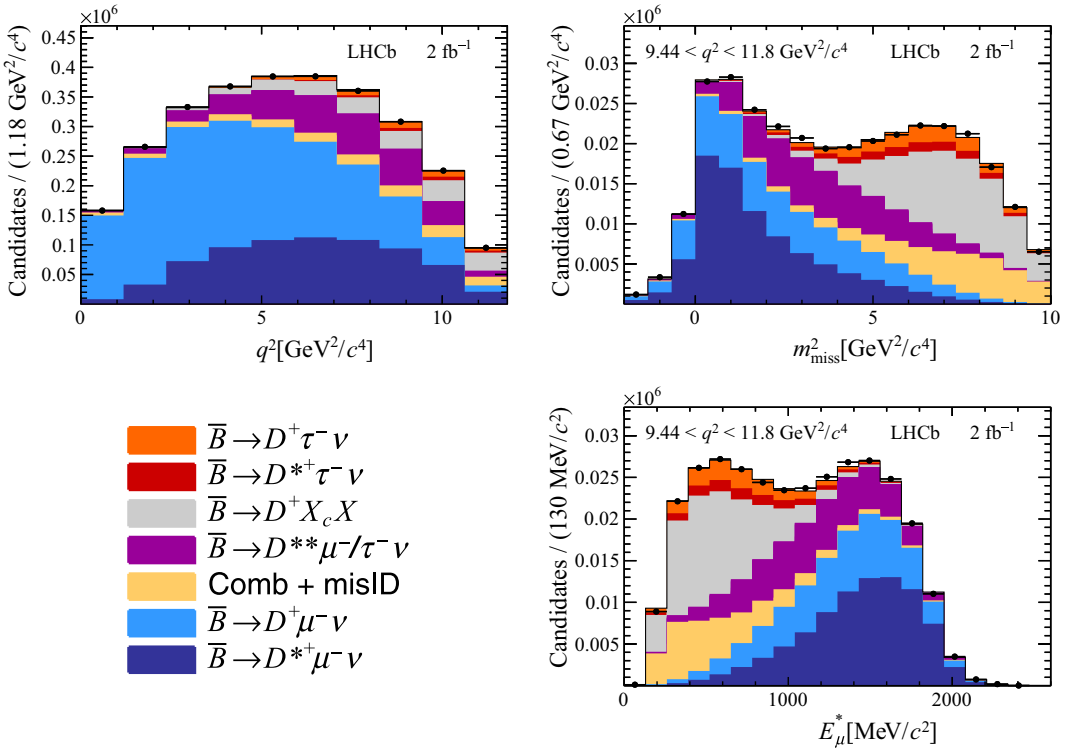

FIG. 3: Distributions of q^2, M^2_{miss} and E^*_μ in the signal region, with the fit result overlaid. The q^2 distribution is shown in the full range, while the other two are shwon for $9.44 < q^2 < 11.8 GeV^2/c^2$.

If evidence of new physics is found in the mainstream decay modes in D and D^* mesons, it has to be consistently found in decays to higher charm resonances, collectively referred to as D^{**}. LHCb collaboration did the first step toward this goal finding evidence of $B \to D^{**0}\tau\nu$ decays with a significance of 3.5σ [7], analyzing 9 fb^{-1} of experimental data at LHC. The τ lepton is identified by its decay $\tau^+ \to \pi^+\pi^-\pi^+\nu$, reconstructing the displaced vertex of the three pions and requiring an hard cut on its distance from the primary vertex, in order to suppress the large $B \to D^*\pi^+\pi^-\pi^+X$ background. The D^{**} mesons considered in this analysis are any of the two narrow D resonances, $D_1(2420)$ and $D_2(2460)$ that are reconstructed in their decay to $D^{*+}\pi^-$. Their yield is extracted by a maximum likelihood fit to the mass distribution as shown in the left plot of Figure 4. As normalization sample, the $B \to D^{**}D_s$ decays, with $D_s \to \pi\pi\pi$ are reconstructed. In order to enhance the signal and suppress the background a multivariate analysis is carried out (right plot of Figure 4). Being the final states the same, many systematic uncertainties cancel out in the ratio of branching fractions $\mathcal{B}(B \to D^{**0}\tau\nu)/\mathcal{B}(B \to D^{**0}D_s^{(*)})$ that is measured. The obtained significance of the signal, including systematic uncertainties, is estimated to be 3.5σ. In order to estimate the corresponding LFU ratio $R(D^{**0})$, external

input from the $\mathcal{B}(B \to D^{**0}\mu\nu)$ and $\mathcal{B}(B \to D^{**0}D_s^{(*)})$ is used, obtaining $R(D^{**0}) = 0.13 \pm 0.03(\text{stat}) \pm 0.01(\text{syst}) \pm 0.02(\text{ext})$.

Belle II collaboration exploited the unique capabilities of the detector and the clean e^+e^- enviroment, using inclusive semileptonic decays to measure the LFU ratio $\mathcal{B}(B \to X\tau\nu)/\mathcal{B}(B \to X\ell\nu)$[8]. The X system, of course, contains all the $b \to c$ and $b \to u$ quark decays. Therefore, an important issue consists in correctly modeling the X system. Experimentally, the signal mode is selected by requiring the identification of an electron or a muon, and a fully reconstructed hadronic B_{tag}. Signal and normalization yields are extracted by a two-dimensional binned likelihood fit to the momentum of the reconstructed lepton in the B rest frame p_ℓ^B and missing mass squared M^2_{miss}, as shown in Figure 5. The largest systematics uncertainties are due to modeling of the X system, with uncertainty in inclusive semileptonic decays form factors accounting for 8%, uncertainties in the branching fractions for 8%. Since the agreement between experimental data and MC simulation in the inclusive spectra is not perfect, a reweighting procedure is implemented. The systematic uncertainty in this procedure is estimated to be 7%. The measurement is already limited by systematics, with the largest contributions estimated from data, so it is expected to scale with sample size in future measurements. The obtained LFU ratio is $R(X) = 0.228 \pm 0.016(\text{stat}) \pm 0.036(\text{syst})$.

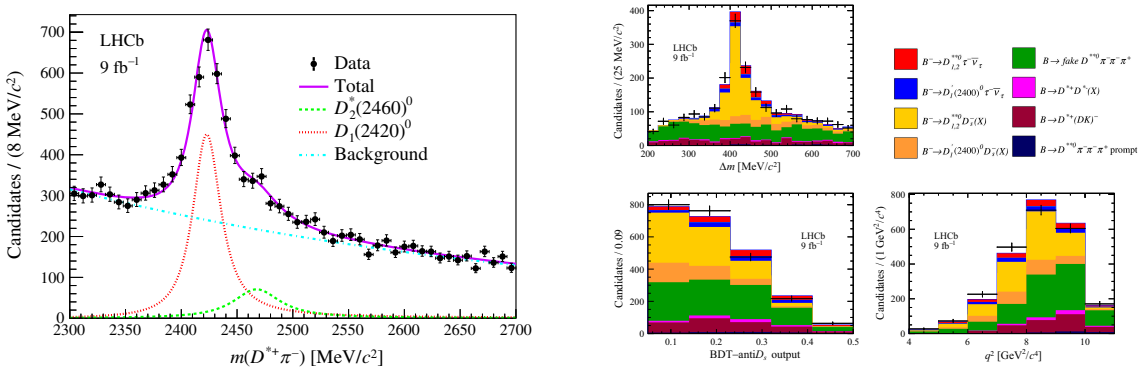

FIG. 4: Left plot: Distribution of the $D^{*+}\pi^-$ mass for all the selected $B \to D^{*+}\pi^-\pi^-\pi^+$ with the fit superimposed. Right plot: main discriminant variables distributions for events passing the D^{**} selection.

3 Recent results on $|V_{cb}|$ and $|V_{ub}|$

Belle II collaboration measured the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cb}|$ from the decay $B \to D\ell\nu$ using a 365 fb^{-1} data sample [9]. The semileptonic decay of one B meson is reconstructed in $B^0 \to D^-\ell^+\nu$, with $D^- \to K^+\pi^-\pi^-$ and $B^+ \to D^0\ell^+\nu$, with $D^0 \to K^+\pi^-$, with ℓ being an electron or a muon. The second B meson in the $\Upsilon(4S)$ is not reconstructed explicitly (untagged analysis). The recoil variable $w = v_B \cdot v_D = \frac{m_B^2+m_D^2-q^2}{2m_Bm_D}$, where v_B and v_D are the four-velocities of the B and the D meson, respectively, q^2 is the squared momentum trasfer to the lepton pair, m_B and m_D are the mass of the B and D mesons, is determined using an inclusive reconstruction of the unobserved neutrino.

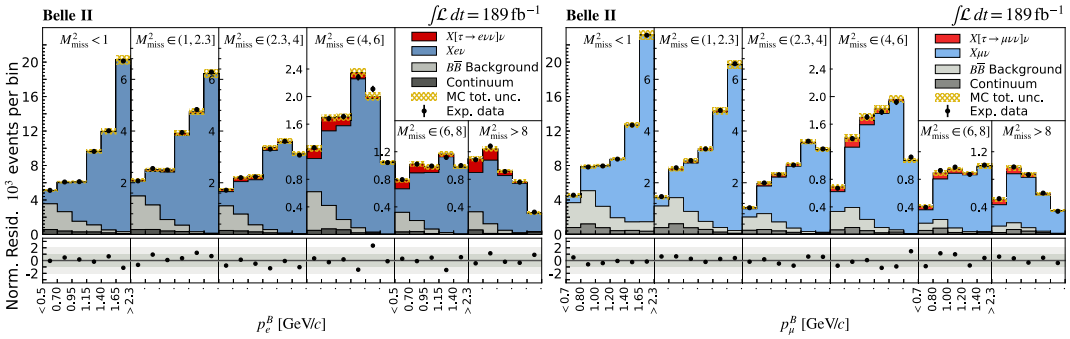

FIG. 5: Two-dimensional distributions of electron (left) and muon (right) momentum in the signal B rest frame p^B_ℓ and the missing mass squared flattened to one dimension in intervals as used in the signal extraction fit, with the fit results overlaid.

The discriminating observable $\cos\theta_{BY} = \frac{2E_{beam}E_Y - m_B^2 - m_Y^2}{2p_B p_Y}$, where Y is the $D\ell$ pair is used to separate the $B \to D\ell\nu$ signal (for which the variable approximate the angle between the B meson and the Y pair) and the background, for which the distribution is broader. The signal yield is extracted with a likelihood fit to the $\cos\theta_{BY}$ variable as a function of w (10 bins), as shown in Figure 6 (left plots). The B^0 and B^+ branching fractions resulting from the fit are $\mathcal{B}(B^0 \to D^-\ell^+\nu) = (2.06 \pm 0.05(\text{stat}) \pm 0.10(\text{syst}))\%$ and $\mathcal{B}(B^+ \to \overline{D}^0\ell^+\nu) = (2.31 \pm 0.04(\text{stat}) \pm 0.09(\text{syst}))\%$. Assuming isospin to combine B^0 and B^+ results, $|V_{cb}|$ is determined with a fit to the differential decay rate using the BCL parameterization of the form factor [10] to be $|V_{cb}|_{BCL} = (39.2 \pm 0.4(\text{stat}) \pm 0.6(\text{syst}) \pm 0.5(\text{th})) \times 10^{-3}$, the most precise value using $B \to D\ell\nu$ decays. The result of the fit to the BCL expansion is shown in Figure 6 (right plot).

Belle II collaboration performed a measurement of $|V_{ub}|$ from inclusive $b \to u$ semileptonic decays, exploiting the hadronic B_{tag} reconstruction, with a sample of 365 fb^{-1}. In this analysis, a fully reconstructed B_{tag} in hadronic decays plus an electron or a muon are required, while the rest of reconstructed objects are assigned to the an hadronic X_u system, looking for a $B \to X_u\ell\nu$ decay. The three main observables describing the kinematics are the lepton energy in the B rest frame E^B_ℓ, the invariant mass of the X system M_X, and the squared momentum transfer q^2. The largest background of charmed semileptonic decays $B \to X_c\ell\nu$ is suppressed using a dedicated Neural Network. The yields of signal and background are extracted from a binned likelihood fit simultaneously to a signal sample and a control sample of $B \to X_c\ell\nu$ decays. The P.D.F. are histogram templates of signal $B \to X_u\ell\nu$, main charm backgrounds $B \to X_c\ell\nu$ and other backgrounds (fake leptons, secondary leptons and continuum $e^+e^- \to q\bar{q}$ events). The fit is performed in several fiducial regions (requiring cuts on E^B_ℓ, M_X and q^2) to get partial branching ratio in these regions. For the nominal region ($E^B_\ell > 1\,\text{GeV}$, the most inclusive) the partial branching fraction $\Delta\mathcal{B}(B \to X_u\ell\nu) = (1.54 \pm 0.08(\text{stat}) \pm 0.12(\text{syst})) \times 10^{-3}$ is obtained. The partial branching ratio can be extrapolated to fully phase space to extract $|V_{ub}|$, using different theory models as $|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u\ell\nu)}{\tau_B \Delta\Gamma(B \to X_u\ell\nu)}}$. The used nominal model is the GGOU parameterization [11] for which $|V_{ub}| = (4.01 \pm 0.11(\text{stat}) \pm 0.16(\text{syst})^{+0.09}_{-0.07}) \times 10^{-3}$ is obtained.

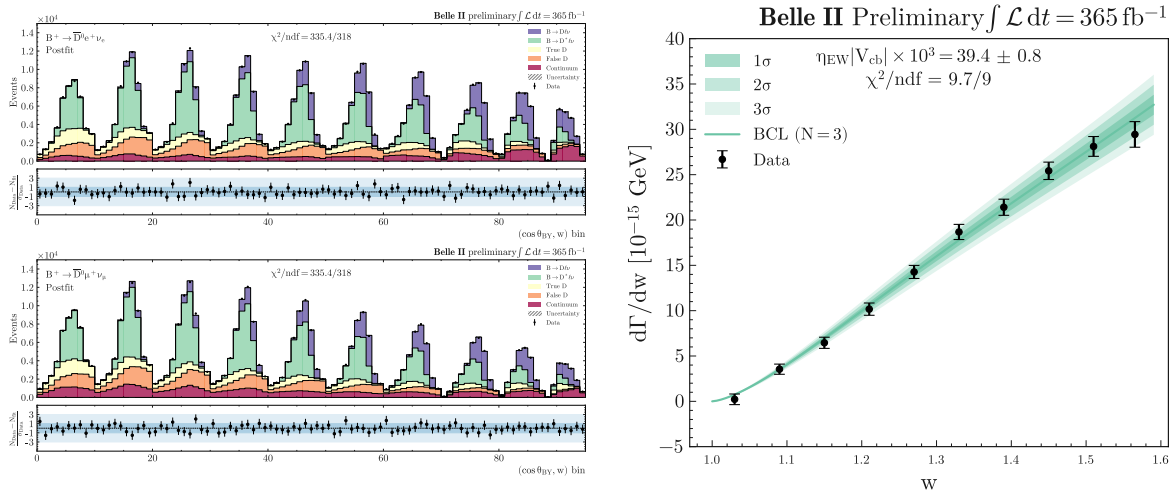

FIG. 6: Left plots: Fitted distributions of $cos\theta_{BY}$ in bins of w in the D^0e (top plot) and $D^0\mu$ (bottom plot) samples. The Belle II data are the points with error bars. The stacked histograms are simulated events normalized according to the fit result. Right: Form factor resulting from the fit to the differential decay rate, using the BCL expansion.

The result is in very good agreement with the current world average from HFLAV. Belle II collaboration searched for the purely leptonic decay $B^+ \to \tau^+\nu$, with the hadronic B_{tag} reconstruction with a sample of 365 fb^{-1} [12]. In addition to the reconstruction of an high quality B_{tag}, the τ from signal $B^+ \to \tau^+\nu$ is identified from its one-prong decay, requiring the reconstruction in the rest of the event of only one additional track. The analysis is performed simultaneously on the four mutually exclusive signal categories $\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$, $\tau \to \pi\nu$ and $\tau \to \pi\pi^0\nu$, based on particle identification criteria applied on the signal track and the reconstruction of a π^0 that paired to the signal π is compatible to a $\rho \to \pi\pi^0$ decay. A Boosted Decision Tree, based on event topology, is used to further suppress backgrounds from $q\bar{q}$ continuum end $B\bar{B}$ events. The most discriminating variables are $E^{\text{extra}}_{\text{ECL}}$, the total energy measured in the calorimeter not associated to B_{tag} or signal τ, and the missing mass squared M^2_{miss}, determined from the known beams four-momenta and the completely reconstructed B_{tag} and τ decay products. The $B \to \tau\nu$ branching fraction is extracted with a simultaneous fit to the four signal categories using a two dimensional binned likelihood on $E^{\text{extra}}_{\text{ECL}}$ and M^2_{miss}. The largest systematic uncertainties are due to limited MC statistics of background templates (13%), the data driven corrections to those templates (5.5%) and the uncertainties on branching fractions of backgrounds (4.1%). A 3.0σ (including systematics) excess of signal events is found, for an estimated Branching fraction $\mathcal{B}(B \to \tau\nu) = (1.24 \pm 0.41(\text{stat}) \pm 0.19(\text{syst})) \times 10^{-4}$. Figure 7 shows the results of the fit superimposed to experimental data and the comparison of the Belle II , BaBar and Belle measurements of $\mathcal{B}(B \to \tau\nu)$. Assuming the value of the B decay constant $f_B = (190.0 \pm 1.3)$MeV from Lattice QCD [1], the measurement of the Branching Fractions results in $|V_{ub}|_{B\to\tau\nu} = (4.41^{+0.74}_{-0.89}) \times 10^{-3}$.

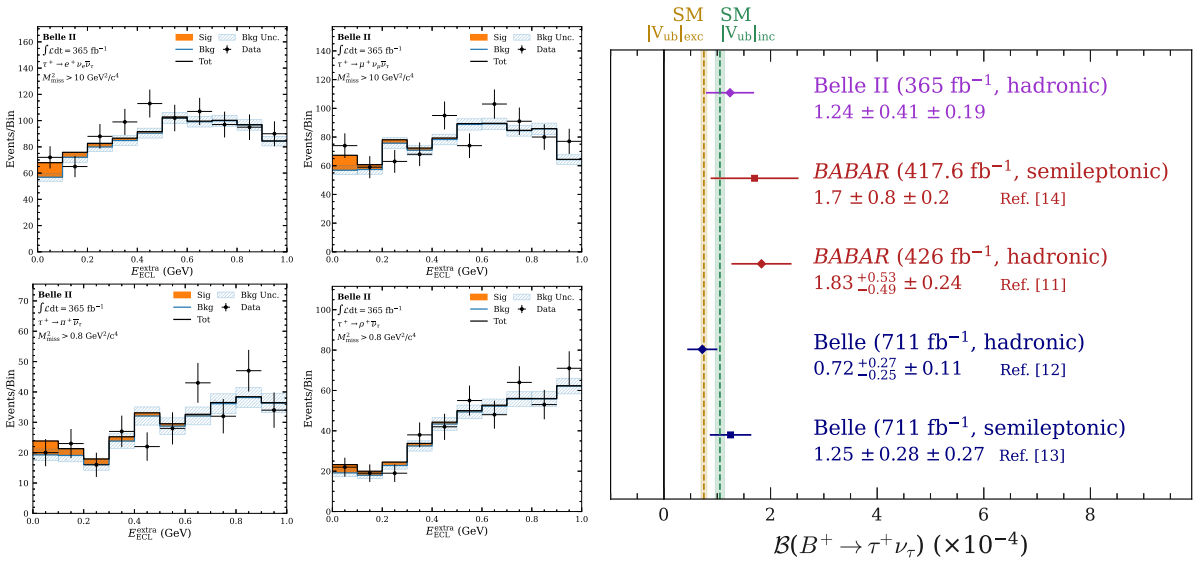

FIG. 7: Left plots, first row: distributions of $E_{\rm ECL}^{\rm extra}$ with the fit results superimposed for the leptonic categories in a signal enriched region of $M_{\rm miss}^2 > 10{\rm GeV}^2$. Left plots, second row: distributions of $E_{\rm ECL}^{\rm extra}$ with the fit results superimposed for the hadronic categories in a signal enriched region of $M_{\rm miss}^2 > 0.8{\rm GeV}^2$. Right plot:Branching fraction $\mathcal{B}(B \to \tau\nu)$ measured by Belle II compared with the past measurements and two SM expectation values, calculated from the exclusive determination $|V_{ub}| = (3.75 \pm 0.06 \pm 0.19) \times 10^{-3}$ and the inclusive determination $|V_{ub}| = (4.06 \pm 0.12 \pm 0.11) \times 10^{-3}$.

4 Conclusions

Precise and robust measurements of the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$ are essential ingredients to set the SM baseline, when looking for new physics effects. Measurements of $R(D)$ and $R(D^*)$ are not yet able to resolve the tension with SM model expectations. Growing Belle II and LHCb datasets will allow to deepen investigations in several ways: additional modes and more detailed differential distributions available, improvents on most systematics uncertainties using data driven estimations, new or better measurements of the still poorly known background shapes and branching fractions.

References

[1] FLAG, Y. Aoki *et al.*, *Flag Review 2024*, `arXiv:2411.04268`.

[2] HFLAV, S. Banerjee *et al.*, *Averages of b-hadron, c-hadron, and τ-lepton properties as of 2023*, `arXiv:2411.18639`.

[3] Belle II Collaboration, I. Adachi *et al.*, *Test of lepton flavor universality with a measurement of $R(D^*)$ using hadronic B tagging at the Belle II experiment*, Phys. Rev. D **110** (2024) 072020, `arXiv:2401.02840`.

[4] Belle II Collaboration, I. Adachi *et al.*, *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** (2025) 032010, arXiv:2504.11220.

[5] LHCb Collaboration, R. Aaij *et al.*, *Measurement of the Branching Fraction Ratios $R(D^+)$ and $R(D^{*+})$ Using Muonic τ Decays*, Phys. Rev. Lett. **134** (2025) 061801, arXiv:2406.03387.

[6] LHCb Collaboration, R. Aaij *et al.*, *Measurement of the Ratios of Branching Fractions $R(D^*)$ and $R(D^0)$*, Phys. Rev. Lett. **131** (2023) 111802, arXiv:2302.02886.

[7] LHCb Collaboration, R. Aaij *et al.*, *Evidence for $B \to D^{**0}\tau^-\nu$ Decays*, Phys. Rev. Lett. **135** (2025) 021802, arXiv:2501.14943.

[8] Belle II Collaboration, I. Adachi *et al.*, *First Measurement of $R(X_{\tau/\ell})$ as an Inclusive Test of the $b \to c\tau\nu$ Anomaly*, Phys. Rev. Lett. **132** (2024) 211804, arXiv:2311.07248.

[9] Belle II Collaboration, I. Adachi *et al.*, *Determination of $|V_{cb}|$ using $B \to D\ell\nu$ Decays at Belle II*, arXiv:2506.15256.

[10] Bourrely, C. Lellouch, L. and Caprini, I. , *Model-independent description of $B \to \pi\ell\nu$ decays and a determination of $|V_{ub}|$*, Phys. Rev. D **79** (2009) 013008, arXiv:0807.2722.

[11] Gambino, P. Giordano, P. Ossola, G. Uralstev, N. , *Inclusive semileptonic B decays and the determination of $|V_{ub}|$*, JHEP **07** (2007) 058, arXiv:0707.2493.

[12] Belle II Collaboration, I. Adachi *et al.*, *Measurement of $B \to \tau^+\nu$ branching fraction with a hadronic tagging method at Belle II*, Phys. Rev. D **112** (2025) 072002, arXiv:2502.04885.