Latest results on semileptonic and electroweak penguin decays at Belle II

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The Belle II Collaboration presents four new analyses: The measurement of $|V_{ub}|$ from $B \to \pi e \nu_e$ decays with a fit to the differential q^2 spectrum, the determination of $|V_{cb}|$ using a fit to the differential w distribution from $B^0 \to D^{*-}\ell^+\nu_\ell$ decays, and the measurement of q^2 moments in inclusive $B \to X_c \ell \nu_\ell$ decays. In all these analyses tag-side B meson is reconstructed in a fully hadronic decay chain. The last result are branching fraction measurement of $B \to K^* \ell^+ \ell^-$ decays using an untagged approach.

1 Introduction

The Belle II Collaboration collected a data set corresponding to an integrated $189\,\mathrm{fb}^{-1}$ at the $\Upsilon(4S)$ resonance. The data is recorded with the Belle II detector and the SuperKEKB e^+e^--collider located at KEK in Tsukuba, Japan. This manuscript presents four new recent results from the Belle II Collaboration.

2 Branching Fraction Measurements of $B \to \pi e^+ \nu_e$ Decays and Determination of $|V_{ub}|$

In this analysis reconstructs the decays $B^0 \to \pi^- e^+ \nu_e$ and $B^+ \to \pi^0 e^+ \nu_e$ using hadronic tagging provided by tagging algorithm implemented in the Full-Event-Interpretation [1]. These decays are considered the golden modes to measure the magnitude of the Cabibbo-Kobayashi-Maskawa (CKM) [2,3] matrix element $|V_{ub}|$ in an exclusive approach.

$B \to \pi e^+ \nu_e$ decays are reconstructed in channels with charged and neutral π candidates. The number of signal and background events are determined with a maximum likelihood fit of the missing mass squared $m^2_{\mathrm{Miss}} = (p^*_{B_{\mathrm{sig}}} - p^*_e - p^*_\pi)^2$ in three bins of the four-momentum transfer $q^2 = (p^*_{B_{\mathrm{sig}}} - p^*_\pi)^2$. Here, p^* denotes the four momentum in the center-of-mass of the e^+e^--collision. The four-momentum of the signal B is calculated from the momentum of fully reconstructed tag-side B meson $p^*_{B_{\mathrm{sig}}} = (\frac{m_{\Upsilon(4S)}}{2}, -\boldsymbol{p}^*_{B_{\mathrm{tag}}})$.

In a next step, the unfolded yields are translated into partial branching fractions in bins of q^2. A χ^2-fit of $\mathrm{d}\mathcal{B}/\mathrm{d}q^2$ to the measured partial branching fractions and to the Fermilab/MILC lattice QCD constraints [4] is performed for each reconstruction channel individually and and the combination of charged and neutral B modes. In the fit, the form factors are parameterized using the BCL parameterization [5]. The fit result for the combined fit is shown in Fig. 1. Table 1 lists the extracted $|V_{ub}|$ values. In addition, we report the total branching fractions $\mathcal{B}(B^0 \to \pi^- e^+ \nu_e) = (1.43\pm0.27_{\mathrm{stat}}\pm0.07_{\mathrm{sys}})\times10^{-4}$ and $\mathcal{B}(B^+ \to \pi^0 e^+ \nu_e) = (8.43\pm1.42_{\mathrm{stat}}\pm0.54_{\mathrm{sys}})\times10^{-5}$ obtained by the sum of the partial branching fractions in the three q^2 bins.

Table 1: Extracted $|V_{ub}|$ values by χ^2-fits to $\mathrm{d}\mathcal{B}/\mathrm{d}q^2$ of $B^0 \to \pi^- e^+ \nu_e$ and $B^+ \to \pi^0 e^+ \nu_e$ decays.

Decay mode	$|V_{ub}| \times 10^3$	χ^2/DOF
$B^0 \to \pi^- e^+ \nu_e$	(3.71 ± 0.55)	0.16
$B^+ \to \pi^0 e^+ \nu_e$	(4.21 ± 0.63)	0.02
Combined fit	(3.88 ± 0.45)	0.32

3 Branching Fraction Measurements of $B^0 \to D^{*-}\ell^+\nu_\ell$ Decays and Determination of $|V_{cb}|$

In this analysis, the decay $B^0 \to D^{*-}\ell^+\nu_\ell$ is reconstructed using a hadronic tagging approach. A good understanding of the decay $B \to D^*\ell\nu_\ell$ is important for future measurements of $R(D^{(*)})$ and the precise exclusive determination of the CKM matrix element $|V_{cb}|$.

Events are reconstructed in a single decay chain, where the D^* decays into a neutral $\overline{D}$ meson and a charged pion π^-. The $\overline{D}$ meson is reconstructed in the decay channel $\overline{D} \to K^+\pi^-$.

We measure a branching fraction of $\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell) = (5.27 \pm 0.22_{\mathrm{stat}} \pm 0.38_{\mathrm{sys}})\%$. $|V_{cb}|$ is determined with a fit of the differential decay rate to the unfolded w spectrum. Here, w denotes the product of B and D^* four-velocities $w = v_B v_{D^*} = (m_B^2 + m_{D^*}^2 - q^2)/(2m_B m_{D^*})$. The differential decay rate is given by

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}w} = \frac{\eta_{\mathrm{EW}}^2 G_F^3}{48\pi^2} m_{D^*}^3 (m_B - m_{D^*})^2 g(w) F^2(w) |V_{cb}|^2. \tag{1}$$

The product $g(w)F^2(w)$ is parameterized with $R_1(1)$, $R_2(1)$ and ρ^2 in the CLN form factor parameterization [6]. The result of a χ^2 fit of $\mathrm{d}\Gamma/\mathrm{d}w$ is shown in Fig. 2. $R_1(1)$ and $R_2(1)$ are constrained to external measurements [7] in the fit. A 2D scan of the χ^2 function in the ρ^2 and $\eta_{\mathrm{EW}} F(1)|V_{cb}|$ plane is also shown in Fig. 2. With $\eta_{\mathrm{EW}} = 1.0066$ [8] and $F(1) = 0.906 \pm 0.004_{\mathrm{stat}} \pm 0.0012_{\mathrm{sys}}$ [8] we obtain $|V_{cb}| = (37.9 \pm 2.7) \times 10^{-3}$.

4 Measurement of q^2 Moments in $B \to X_c \ell \nu_\ell$ Decays

We present measurements of the first to fourth raw and central q^2 moments of $B \to X_c \ell \nu_\ell$ decays as functions of lower q^2 threshold from $1.5\,\mathrm{GeV}^2/\mathrm{c}^4$ up to $8.5\,\mathrm{GeV}^2/\mathrm{c}^4$. Lepton energy and hadronic mass moments have been used to determine $|V_{cb}|$ and parameters of the Heavy-Quark-Expansion (HQE) up to $\mathcal{O}(1/m_b^3)$ in a model independent way using a global fit. At higher order,
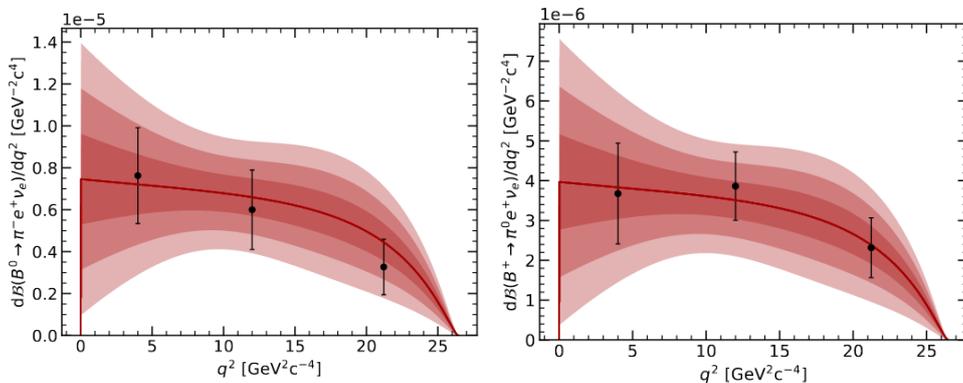

Figure 1 – Resulting projections for the charged (left) and neutral (right) pion channel of the combined fit of the differential branching fraction $\mathrm{d}\mathcal{B}/\mathrm{d}q^2$.
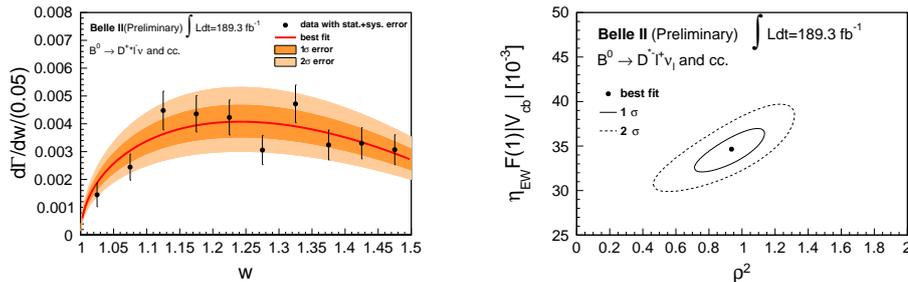
Figure 2 – Result of the fit of the differential decay rate $\mathrm{d}\Gamma/\mathrm{d}w$ (left) and 2D scan of the χ^2 function in the ρ^2 and $\eta_{\mathrm{EW}}F(1)|V_{cb}|$ plane (right).
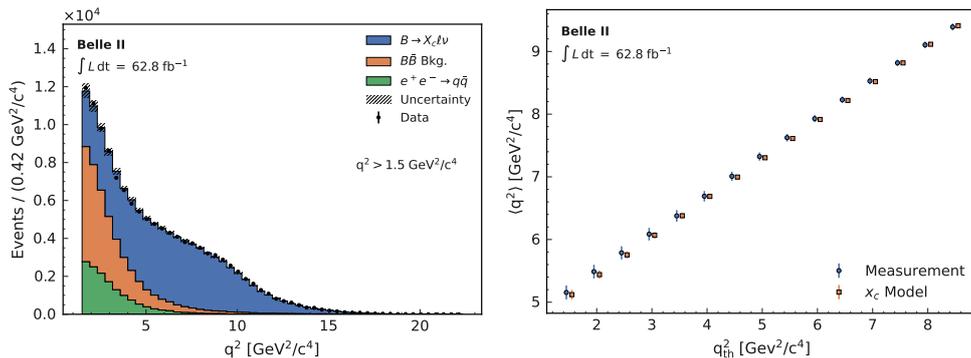

Figure 3 – Reconstructed q^2 spectrum (left) and first raw q^2 moment $\langle q^2 \rangle$ (right).

the determination of the HQE is complicated by a proliferation of non-perturbative matrix elements. Ref.[9] outlines an alternative approach to determine $|V_{cb}|$ from inclusive decays avoiding this proliferation of HQE parameters by exploiting reparameterization invariance. However reparameterization invariance is not retained by the lepton energy and hadronic mass moments. Thus, the measurement of q^2 moments is proposed.

Semileptonic decays are reconstructed in an inclusive approach without assuming exclusive hadronic charmed resonances in the the $B \to X\ell\nu_\ell$ decay. The hadronic X system is identified with the remaining charged particles and photons not used in the tag-side B meson and signal lepton reconstruction. Figure 3 shows the reconstructed q^2 spectrum.

Before calculating the moments, a calibration of the q^2 spectrum $q^2_{\mathrm{reco}} \to q^2_{\mathrm{calib}}$ is applied to correct for detector resolution and reconstruction efficiency effects. The remaining background is subtracted directly in the calculation of the q^2 moments by assigning a signal probability as event weight $w_i(q^2)$. The raw moments are calculated as a weighted mean

$$\langle q^{2n} \rangle = \frac{\sum w_i q^2_{i,\mathrm{calib}}}{\sum w_j} \times \mathcal{C}_{\mathrm{calib}} \times \mathcal{C}_{\mathrm{gen}}. \tag{2}$$

Here, $\mathcal{C}_{\mathrm{calib}}$ and $\mathcal{C}_{\mathrm{gen}}$ are two additional correction factors correcting imperfections of the calibration procedure and for different selection efficiencies of the $B \to X_c\ell\nu_\ell$ components. The measurement of the first raw moment $\langle q^2 \rangle$ are also shown in Fig. 3. The moments for the assumed X_c model are show for comparison. We provide numerical results and covariance matrices on HEPData.

5 Branching Fraction Measurements of $B \to K^*\ell^+\ell^-$ Decays

The decay $B \to K^*\ell^+\ell^-$ involves a $b \to s$ transition mediated by a flavour changing neutral current which is forbidden at tree level and thus, highly suppressed. The decay is sensitive

to new physics contributions, which might enhance or suppress the decay amplitude or modify the angular distributions. The here reported branching fractions measurements are a first step towards a measurement of $R(K^*)$ at Belle II. Recent determinations of $R(K^*)$ show tensions with the SM expectation [10,11,12].

The analysis considers three decay modes: $B^0 \to K^{*0}(\to K^+\pi^-)\ell^+\ell^-$ and $B^+ \to K^{*+}(\to K_S^0\pi^+, \to K^+\pi^0)\ell^+\ell^-$. The second B meson in the $\Upsilon(4S)$ decay is not explicitly reconstructed. The number of signal decays is extracted from a 2D maximum likelihood fit to the beam-constrained mass $M_{\mathrm{bc}} = \sqrt{s/4 - p_B^{*2}}$ and the energy difference $\Delta E = (E_B^* - \sqrt{s}/2)$.

We measure $\mathcal{B}(B \to K^*\mu^+\mu^-) = (1.28 \pm 0.29^{+0.08}_{-0.07}) \times 10^{-6}$, $\mathcal{B}(B \to K^*e^+e^-) = (1.04 \pm 0.48^{+0.09}_{-0.09}) \times 10^{-6}$ and $\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.22 \pm 0.28^{+0.08}_{-0.07}) \times 10^{-6}$ with the first and second uncertainty being statistical and systematic, respectively.

References

1. T. Keck et al. The Full Event Interpretation: An Exclusive Tagging Algorithm for the Belle II Experiment. *Comput. Softw. Big Sci.*, 3(1):6, 2019.
2. Nicola Cabibbo. Unitary Symmetry and Leptonic Decays. *Phys. Rev. Lett.*, 10:531–533, Jun 1963.
3. Makoto Kobayashi and Toshihide Maskawa. CP-Violation in the Renormalizable Theory of Weak Interaction. *Progress of Theoretical Physics*, 49(2):652–657, 02 1973.
4. Jon A. Bailey et al. $B \to D\ell\nu$ form factors at nonzero recoil and $|V_{cb}|$ from $2 + 1$-flavor lattice QCD. *Phys. Rev. D*, 92:034506, Aug 2015.
5. Claude Bourrely, Laurent Lellouch, and Irinel Caprini. Model-independent description of $B \to \pi l\nu$ decays and a determination of $|V_{ub}|$. *Phys. Rev. D*, 79:013008, Jan 2009.
6. Irinel Caprini, Laurent Lellouch, and Matthias Neubert. Dispersive bounds on the shape of form factors. *Nuclear Physics B*, 530(1-2):153–181, oct 1998.
7. Y. Amhis et al. Averages of b-hadron, c-hadron, and τ-lepton properties as of 2018. *The European Physical Journal C*, 81(3), mar 2021.
8. Jon A. Bailey et al. Update of $|V_{cb}|$ from the $\overline{B} \to D^*\ell\overline{\nu}$ form factor at zero recoil with three-flavor lattice QCD. *Phys. Rev. D*, 89:114504, Jun 2014.
9. Matteo Fael, Thomas Mannel, and K. Keri Vos. V_{cb} determination from inclusive $b \to c$ decays: an alternative method. *JHEP*, 02:177, 2019.
10. R. Aaij et al. Test of lepton universality with $B^0 \to K^{*0}\ell^+\ell^-$ decays. *Journal of High Energy Physics*, 2017(8), aug 2017.
11. R. Aaij et al. Tests of lepton universality using $B^0 \to K_S^0\ell^+\ell^-$ and $B^+ \to K^{*+}\ell^+\ell^-$ decays. 2021.
12. S. Wehle et al. Test of Lepton-Flavor Universality in $B \to K^*\ell^+\ell^-$ Decays at Belle. *Phys. Rev. Lett.*, 126:161801, Apr 2021.