SEMILEPTONIC AND RARE DECAYS AT BELLE II*

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Received 30 September 2022, accepted 2 January 2023, published online 15 February 2023

The Belle II Collaboration presents their first measurements of the magnitude of the Cabibbo–Kobayashi–Maskawa matrix elements $|V_{cb}|$ and $|V_{ub}|$, as well as their first branching fraction measurement of $B \to K^* \ell^+ \ell^-$ based on up to 189.3 fb^{-1} of data collected at the $\Upsilon(4S)$ resonance. The magnitude $|V_{cb}|$ was measured using $B^0 \to D^{*-} \ell^+ \nu_\ell$ by performing a fit to its w distribution. In particular, $|V_{ub}|$ was obtained using a fit to the q^2 distribution of $B^+ \to \pi^0 e^+ \nu_e$ and $B^0 \to \pi^- e^+ \nu_e$. Finally, the results of an inclusive $|V_{cb}|$ fit based on measurements of q^2 moments are presented.

DOI:10.5506/APhysPolBSupp.16.3-A4

1. Introduction

The unitarity of the 3×3 Cabibbo–Kobayashi–Maskawa (CKM) matrix [1] can be probed experimentally, *e.g.* by measuring the matrix element magnitudes $|V_{cb}|$ and $|V_{ub}|$. Semileptonic decays $B \to X_q \ell \nu$ $(\ell = e, \mu)$, where X_q denotes a hadron with a specific quark flavor q, can be used for precision measurements of these magnitudes. In addition, semileptonic and rare decays can be used to search for new physics such as lepton flavor universality (LFU) violation by measuring branching fraction ratios between final states involving different lepton families such as $R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)} \tau \nu_\tau)}{\mathcal{B}(B \to D^{(*)} \ell \nu_\ell)}$, for which the average of existing measurements exhibits a 3σ tension with the prediction from the Standard Model of Particle Physics (SM) [2].

The magnitudes $|V_{cb}|$ and $|V_{ub}|$ can be measured using two different approaches: in exclusive reconstructions, a specific final state is reconstructed, *e.g.* $B \to D^{(*)} \ell \nu$ or $B \to \pi \ell \nu$; in the inclusive method, the sum of all possible final states is reconstructed, *e.g.* $B \to X_c \ell \nu$ or $B \to X_u \ell \nu$.

* Presented at the XIV International Conference on *Beauty, Charm and Hyperon Hadrons*, Kraków, Poland, 5–10 June, 2022.

The quark currents of semileptonic decays are described using hadronic matrix elements. In exclusive measurements, the hadronic matrix elements are parameterized using form factors [3–5]. Input from non-perturbative techniques such as lattice QCD is required to determine the form-factor normalization. In inclusive measurements, one uses the heavy-quark expansion (HQE) [6]. While it is expected for both methods to agree with one another, there is a long-standing 3σ discrepancy between exclusive and inclusive measurements of $|V_{cb}|$ and $|V_{ub}|$ [2].

2. SuperKEKB and Belle II

The data used for Belle II measurements are produced at the asymmetric e^-e^+ collider SuperKEKB located in Tsukuba, Japan. Colliding e^- and e^+ with energies of 7 GeV and 4 GeV results in collisions at the $\Upsilon(4S)$ resonance with a center-of-mass energy of 10.58 GeV. The $\Upsilon(4S)$ mesons decay almost exclusively to neutral or charged $B\bar{B}$ pairs. Clean events with well-known initial states are produced due to the collided particles being fundamental. SuperKEKB has a design luminosity of 6.5×10^{35} cm^{-2} s^{-1} [7] and holds the current luminosity world record of $\sim 4 \times 10^{34}$ cm^{-2} s^{-1}. So far, SuperKEKB delivered 424 fb^{-1} of data and the presented results use a data set of up to 189.3 fb^{-1}.

The measuring of the momenta, tracks, and energies of the final-state particles resulting from the collisions and their identification is done by the Belle II detector. Belle II is a hermetic detector resulting in a high solid angle coverage [7]. Belle II features a muon identification efficiency of 88% and an electron identification efficiency of 86% [8]. In addition, the detector has a high photon detection efficiency [9]. This is needed for the reconstruction of neutral particles, *e.g.* $\pi^0 \to \gamma\gamma$.

Due to the previously described features of the experimental setup and event topology, decays can be reconstructed either untagged or tagged using Belle II's full event interpretation [10]. In the untagged approach, only the signal-side B meson (B_{sig}) is reconstructed, while in the tagged approach, the B_{sig} meson as well as the tag-side B meson (B_{tag}) are reconstructed.

3. Semileptonic decays

3.1. Determination of $|V_{ub}|$ from $B \to \pi e\nu$

The magnitude $|V_{ub}|$ was measured by reconstructing $B^+ \to \pi^0 e^+ \nu_e$ and $B^0 \to \pi^- e^+ \nu_e$ decays using the hadronic tagging method. The main challenge of this analysis is its small sample size due to the low tagging efficiency of $\mathcal{O}(0.1)$% and CKM-suppressed branching fraction.

The signal yield was obtained using a binned likelihood-fit to the missing mass squared $M^2_{\mathrm{miss}} = (p^*_{e^+e^-} - p^*_{B_{\mathrm{tag}}} - p^*_e - p^*_\pi)^2$ in three bins of the momentum transfer squared $q^2 = (p^*_{e^+e^-} - p^*_{B_{\mathrm{tag}}} - p^*_\pi)^2$, where p^* are four vectors in the center-of-mass frame.

These yields are unfolded and used to determine $|V_{ub}|$ using its relation to the differential branching fraction $\frac{\mathrm{d}\mathcal{B}(B\to\pi e\nu)}{\mathrm{d}q^2} \propto |V_{ub}|^2 f_+^2(q^2)$. The value of $|V_{ub}|$ was obtained by performing a combined χ^2-fit to $\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}$ using the BCL parameterization [5] and LQCD constraints [11]. The resulting fit, shown in Fig. 1, yielded $|V_{ub}| = (3.88 \pm 0.45) \times 10^{-3}$. The uncertainty includes both statistical and systematic contributions. Simultaneously, the branching fractions over all bins of q^2 of the individual channels were measured to be $\mathcal{B}(B^0 \to \pi^- e^+ \nu_e) = (1.43 \pm 0.27_{\mathrm{stat}} \pm 0.07_{\mathrm{sys}}) \times 10^{-4}$ and $\mathcal{B}(B^+ \to \pi^0 e^+ \nu_e) = (8.33 \pm 1.67_{\mathrm{stat}} \pm 0.55_{\mathrm{sys}}) \times 10^{-5}$ [12].

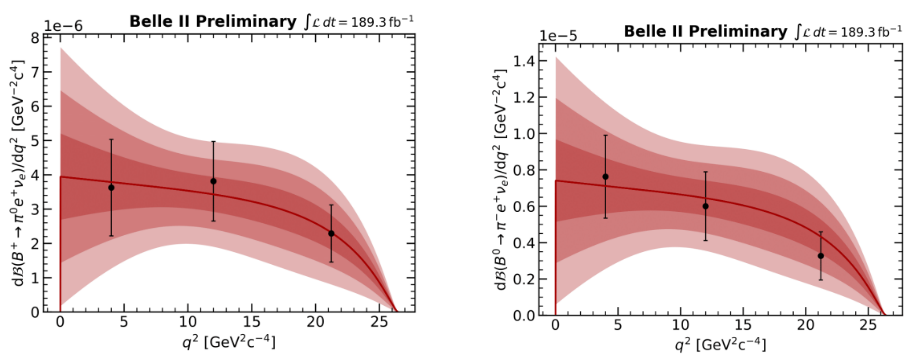

Fig. 1. The combined χ^2-fit projection of $\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}$ for $B^+ \to \pi^0 e^+ \nu_e$ (left) and $B^0 \to \pi^- e^+ \nu_e$ (right) shown as a red line with its 1, 2, and 3σ error band. The black data points denote the measured $\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}$ values [12].

3.2. Determination of $|V_{cb}|$ from $B \to D^* \ell \nu$

The decay $B^0 \to D^{*-} \ell^+ \nu_\ell$ was reconstructed with the subsequent decays $D^{*-} \to \bar{D}^0 \pi^-_{\mathrm{S}}$ and $\bar{D}^0 \to K^+ \pi^-$ after having reconstructed a hadronic tag-side. Here, π_{S} denotes the slow pion with a momentum below 300 MeV. The magnitude $|V_{cb}|$ can be extracted from $B^0 \to D^{*-} \ell^+ \nu_\ell$ by using the relation $\frac{\mathrm{d}\Gamma(\mathcal{B}(B\to D^* \ell \nu_\ell))}{\mathrm{d}w} \propto \eta^2_{\mathrm{EW}} F^2(w) |V_{cb}|^2$, where w is the hadronic recoil $w = \frac{P_B P_{D^*}}{m_B m_D} = \frac{m_B^2 + m_{D^*} - q^2}{2 m_B m_{D^*}}$ and η_{EW} an electroweak correction factor. The product $\eta_{\mathrm{EW}} F(1) |V_{cb}|$ was measured using the CLN parameterization [3], where the form factor $F(w)$ is parameterized using ρ^2, $R_1(1)$ and $R_2(1)$. The parameter ρ^2 was determined by the fit, while external inputs [2] were used for $R_1(1)$ and $R_2(1)$.

The result of a χ^2-fit to the differential decay rate $\frac{d\Gamma}{dw}$ in ten bins of the unfolded w distribution and the result of the χ^2 function in the plane of $\eta_{\rm EW}F(1)|V_{cb}|$ and ρ^2 are shown in Fig. 2. This analysis measured $\eta_{\rm EW}F(1)$ $|V_{cb}| = (34.6 \pm 2.5) \times 10^{-3}$ and $\rho^2 = 0.94 \pm 0.21$ yielding $|V_{cb}| = (37.9 \pm 2.7) \times 10^{-3}$ by using the external inputs $\eta_{\rm EW} = 1.0066$ [13] and $F(1) = 0.906 \pm 0.004_{\rm stat} \pm 0.0012_{\rm sys}$ [13]. At the same time, the analysis obtained the branching fraction $\mathcal{B}(B \to D^*\ell\nu) = (5.27 \pm 0.22_{\rm stat} \pm 0.38_{\rm sys})\%$ over the entire w spectrum, with the uncertainty being systematically dominated by the $\pi_{\rm S}$ reconstruction efficiency.

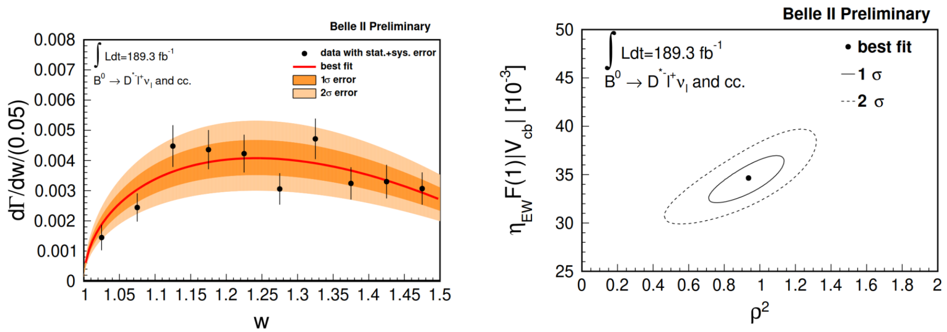

Fig. 2. The χ^2-fit projection to $\frac{d\Gamma}{dw}$ (left) and the resulting χ^2 function in the plane of $\eta_{\rm EW}F(1)|V_{cb}|$ and ρ^2 (right).

3.3. Determination of $|V_{cb}|$ from $B \to X_c\ell\nu$

By describing the decay width using the operator product expansion (OPE), $|V_{cb}|$ can be determined from an inclusive analysis. In the established approach [14], the moments of the lepton energy and the hadronic mass are used to determine the parameters of the expansion up to the order of $n = 3$. However, the number of parameters rises quickly at higher orders, which complicates their determination and leads to a precision loss.

This analysis measured the q^2 moments used in a novel approach [15], where the proliferation of parameters is avoided by exploiting the reparameterization invariance. This invariance does not apply to all observables, but holds for q^2 moments. By determining the q^2 moments, one can go up to the order of $n = 4$. The moments are determined using the relation $\langle q^{2n} \rangle = \frac{\sum_i w_i(q^2) q^{2n}_{i,\rm calib}}{\sum_i w_i(q^2)} \mathcal{C}_{\rm calib}\,\mathcal{C}_{\rm gen}$. An event-wise signal probability $w(q^2)$ can be calculated using a background normalization determined by a fit to M_X. The reconstructed $(q^{2n})_{\rm reco}$ needs to be calibrated to account for resolution and detector effects leading to $(q^{2n})_{\rm calib}$ and in addition, a correction to $\mathcal{C}_{\rm calib}$ is applied to take calibration biases into consideration. To correct for selection effects, $\mathcal{C}_{\rm gen}$ is applied.

The moments $\langle q^{2n} \rangle$ are important input constraints for global fits for inclusive $|V_{cb}|$. Such a fit was performed independently by Bernlochner *et al.* [16], which combined measurements using Belle II data [17] and Belle data [18]. Together with the input of the semileptonic branching fraction $\mathcal{B}(B \to X_c \ell \nu_\ell) = (10.63 \pm 0.19)\%$, this method resulted in $|V_{cb}| = (41.69 \pm 0.63) \times 10^{-3}$. The fit-projection to the third and fourth measured q^2 moments for the combined fit is shown in Fig. 3.

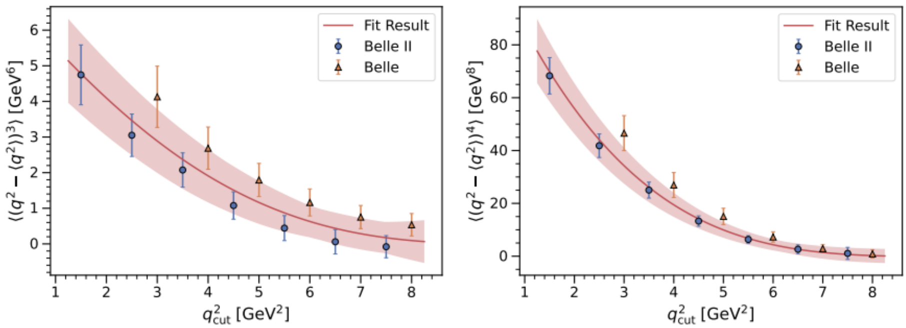

Fig. 3. Fit-projection to the spectra of the third and fourth q^2 moments of the Belle (orange) and Belle II (blue) measurements, shown as a red line with its respective error band [16].

4. Rare decays

4.1. Determination of the $B \to K^* \ell\ell$ branching fraction

Quark flavor transitions $b \to s$ are forbidden at the tree level in the SM, therefore $B \to K^{(*)} \ell\ell$ decays can be used to probe for new physics effects, which affect the branching ratios. Recent measurements of the ratio $R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \to K^{(*)} e^+ e^-)}$ show tensions with the SM prediction [19–21].

At Belle II, the branching fraction of $B \to K^* \ell\ell$ was measured by reconstructing the subsequent decays $K^* \to K^+\pi^-, K^+\pi^0, K_s^0\pi^+$ using an untagged approach and excluding the J/ψ and $\psi(2S)$ resonances [22].

A 2-dimensional likelihood-fit to the beam-constrained mass $M_{bc} = \sqrt{s/4 - p_B^{*2}}$ and the energy deviation of the reconstructed B meson from half the beam energy in the center of mass frame $\Delta E = E_B^* - \sqrt{s}/2$ is used to extract the signal yield (Fig. 4).

The following branching fractions were measured: $\mathcal{B}(B \to K^* \mu\mu) = (1.19 \pm 0.31^{+0.08}_{-0.07}) \times 10^{-6}$, $\mathcal{B}(B \to K^* ee) = (1.42 \pm 0.48^{+0.09}_{-0.09}) \times 10^{-6}$, and $\mathcal{B}(B \to K^* \ell\ell) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6}$. The first uncertainty being statistical and the second systematic [22].

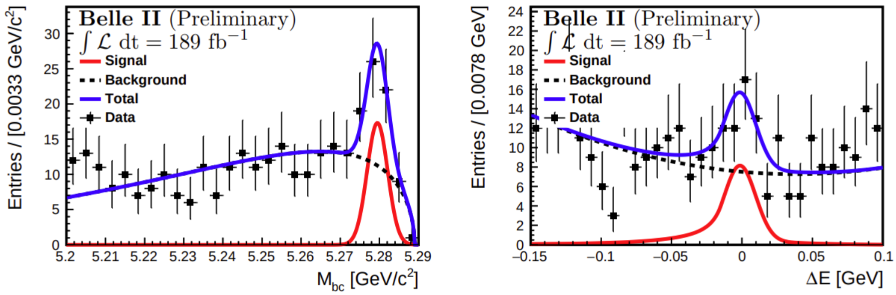

Fig. 4. Post-fit projection of M_{bc} (left) and ΔE (right) for $B \to K^*\ell\ell$ [22].

5. Conclusion

A value of $|V_{cb}| = (37.9 \pm 2.7) \times 10^{-3}$ was obtained from $B^0 \to D^{*-}\ell^+\nu_\ell$ decays in tagged Belle II events. By combining $B^+ \to \pi^0 e^+\nu_e$ and $B^0 \to \pi^- e^+\nu_e$ decays, $|V_{ub}|$ was measured to be $(3.88 \pm 0.45) \times 10^{-3}$. The $|V_{cb}|$ and $|V_{ub}|$ measurements include both the statistical and systematic uncertainties. An inclusive $|V_{cb}|$ fit by Bernlochner *et al.* [16] to combined q^2 moments measurements of $B \to X_c\ell\nu$ from Belle and Belle II yielded $|V_{cb}| = (41.69 \pm 0.63) \times 10^{-3}$. In addition, the branching fraction of the rare decay $B \to K^*\ell\ell$ was measured for the first time at Belle II. This analysis yielded a branching fraction of $\mathcal{B}(B \to K^*\ell\ell) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6}$, where the first and second uncertainties are statistical and systematic, respectively.

REFERENCES

[1] M. Kobayashi, T. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973).

[2] Heavy Flavor Averaging Group (Y. Amhis *et al.*), *Eur. Phys. J. C* **81**, 226 (2021).

[3] I. Caprini, L. Lellouch, M. Neubert, *Nucl. Phys. B* **530**, 153 (1998).

[4] C.G. Boyd, B. Grinstein, R.F. Lebed, *Phys. Rev. Lett.* **74**, 4603 (1995).

[5] C. Bourrely, L. Lellouch, I. Caprini, *Phys. Rev. D* **79**, 013008 (2009).

[6] A.J. Bevan *et al.*, *Eur. Phys. J. C* **74**, 3026 (2014).

[7] T. Abe *et al.*, `arXiv:1011.0352 [physics.ins-det]`.

[8] Belle II Collaboration, `https://docs.belle2.org/record/2895`

[9] H. Svidras *et al.*, `https://docs.belle2.org/record/2604/`

[10] T. Keck *et al.*, *Comput. Softw. Big Sci.* **3**, 6 (2019).

[11] Fermilab Lattice and MILC collaborations (J.A. Bailey *et al.*), *Phys. Rev. D* **92**, 014024 (2015).

[12] Belle II Collaboration, `arXiv:2206.08102 [hep-ex]`.

[13] Fermilab Lattice and MILC collaborations (J.A. Bailey *et al.*), *Phys. Rev. D* **89**, 114504 (2014).

[14] A. Alberti, P. Gambino, K.J. Healey, S. Nandi, *Phys. Rev. Lett.* **114**, 061802 (2015).

[15] M. Fael, T. Mannel, K.K. Vos, *J. High Energy Phys.* **2019**, 177 (2019).

[16] F. Bernlochner *et al.*, `arXiv:2205.10274 [hep-ph]`.

[17] Belle II Collaboration, `arXiv:2205.06372 [hep-ex]`.

[18] Belle Collaboration (R. van Tonder *et al.*), *Phys. Rev. D* **104**, 112011 (2021).

[19] B. Capdevila *et al.*, *J. High Energy Phys.* **2018**, 093 (2018).

[20] LHCb Collaboration (R. Aaij *et al.*), `arXiv:2103.11769 [hep-ex]`.

[21] LHCb Collaboration (R. Aaij *et al.*), *Phys. Rev. Lett.* **128**, 191802 (2022).

[22] Belle II Collaboration, `arXiv:2206.05946 [hep-ex]`.