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# New measurements of $|V_{cb}|$ and $|V_{ub}|$ at Belle and Belle II

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We present the latest results for the magnitudes of the Cabibbo–Kobayashi–Maskawa (CKM) matrix elements $|V_{cb}|$ and $|V_{ub}|$ from (semi)leptonic $B$ meson decays from Belle and Belle II experiments. The data samples used for the presented measurements are collected at the $\Upsilon(4S)$ resonance and correspond to an integrated luminosity of 711 fb$^{-1}$ for Belle and 365 fb$^{-1}$ for Belle II.

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## 1. Introduction

The Cabibbo–Kobayashi–Maskawa (CKM) [1] matrix quantifies the transition probabilities between different quark flavours in weak interactions within the Standard Model (SM). Precise determinations of $|V_{cb}|$ and $|V_{ub}|$ are crucial to test the CKM unitarity triangle [2] and serve as key inputs for precise SM predictions.

To determine $|V_{ub}|$ and $|V_{cb}|$ we use three types of $B$ meson decays:

- **Inclusive semileptonic decays**, which are sensitive to all semileptonic final states and at the theory side we rely on the heavy quark expansion and in a case of $|V_{ub}|$ also non-perturbative shape functions are needed.
- **Exclusive semileptonic decays**, where a specific final state meson is reconstructed and the theoretical input comes from precise determination of the relevant form factors.
- **Leptonic decays**, which involve just a pair of leptons in the final state and allow direct determination of $|V_{ub}|$, where the only input from the theory is $B$ decay constant.

Although these measurements are expected to be complementary, there is some tension between inclusive and exclusive determinations of both $|V_{cb}|$ and $|V_{ub}|$. The averaged values are listed in Tab. 1. The existing disagreements at the level of about $3\sigma$ require further theoretical and experimental investigation of this puzzle.

| | $\lvert V_{ub}\rvert$ | $\lvert V_{cb}\rvert$ |
|---|---|---|
| Inclusive | $(4.06 \pm 0.16) \times 10^{-3}$ | $(41.97 \pm 0.48) \times 10^{-3}$ |
| Exclusive $B$, $B_s$ and $\Lambda_b$ decays | $(3.43 \pm 0.12) \times 10^{-3}$ | $(39.77 \pm 0.46) \times 10^{-3}$ |

**Table 1:** The current averages of $|V_{ub}|$ and $|V_{cb}|$ from inclusive and exclusive determinations [3].

(Semi)leptonic $B$ meson decay modes are experimentally accessible at Belle experiments located at KEK Institute in Tsukuba, Japan. The experiment consists of asymmetric $e^+e^-$ collider, operating mostly at the $\Upsilon(4S)$ resonance, producing pairs of $B$ mesons and a detector that is designed for precise vertexing of charged particle tracking, neutral particle detection and particle identification. The Belle experiment ran until 2010, collecting 711 fb$^{-1}$ of data at the $\Upsilon(4S)$ resonance. Belle II started recording data in 2019 at the SuperKEKB collider [4] with the upgraded Belle II detector [5], where several components were replaced or newly added compared with the previous Belle detector. All Belle II analyses we show in this proceedings use the Run 1 dataset that corresponds to 365 fb$^{-1}$ at the $\Upsilon(4S)$ resonance, collected between 2019 and 2022.

To precisely measure (semi)leptonic decays, where the challenge comes from the undetected neutrino in the final state, we employ a tagging method, where we take advantage of precisely known initial state with a pair of $B$ mesons and we reconstruct one $B$ in the event - $B_{\text{tag}}$ in hadronic or semileptonic decay modes and then the information about the other $B$ - $B_{\text{sig}}$ can be recovered. The tagging algorithm developed by the Belle II collaboration is called the Full Event Interpretation (FEI) [6], where $B_{\text{tag}}$ is reconstructed hierarchically using multivariate classifiers. There is also an option of inclusive tagging (untagged approach), where we reconstruct only the signal $B$ in the event.

## 2. Exclusive determinations of $|V_{cb}|$ and $|V_{ub}|$

### 2.1 Analysis of untagged $B \to D\ell\nu_\ell$ decays to determine $|V_{cb}|$ at Belle II

To determine $|V_{cb}|$ we measure the differential decay rate in terms of recoil variable $w$ [7]. We reconstruct the signal $B$ meson candidates from neutral or charged $D$ combined with light charged leptons $\ell = e, \mu$. The considered decays of $D$ mesons are $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$. A useful variable to discriminate signal from background is the cosine of the angle between the $B$ meson and $Y = D\ell$ system, $\cos\theta_{BY}$. To calculate kinematic variable $w$, the specific direction of the $B$ meson on the cone with opening angle $\theta_{BY}$ around $p_Y$ is required. Weights for a weighted average over possible directions on the cone are computed as $\alpha = \frac{1}{2}(1 - \vec{p}^*_B \cdot \vec{p}^*_{\mathrm{ROE}}) \sin^2\theta^*_B$, where we take into account the expected angular direction of the $B$ meson due to $\Upsilon(4S)$ polarization and additional information from the rest-of-event (ROE), that consists of tracks and clusters not explicitly reconstructed [8]. For correctly reconstructed events with a single missing neutrino the $\cos\theta_{BY}$ takes values between $-1$ and 1, while for background events the reconstructed value often falls outside this physical region. The main background comes from feed-down of the more abundant $B \to D^*\ell\nu_\ell$ events and is still significant despite an active $D^*$ veto. Another background contribution coming from continuum events is suppressed with a set of selections on variables describing the event topology [9].

We extract signal yields in 10 bins of $w$ using a maximum-likelihood fit to $\cos\theta_{BY}$ simultaneously in the electron and muon channels and for the charged and neutral modes. $|V_{cb}|$ is extracted by fitting the measured differential decay rate using BCL form factor parametrisation [10]. Lattice QCD inputs from the The Flavor Lattice Averaging Group (FLAG) [11] are included as nuisance parameters. The obtained value is

$$|V_{cb}| = (39.2 \pm 0.4(\mathrm{stat.}) \pm 0.6(\mathrm{syst.}) \pm 0.5(\mathrm{th.})) \times 10^{-3}, \tag{1}$$

where the largest systematic uncertainties arise from the estimation of the number of $\Upsilon(4S)$ decays from the measurement and lattice QCD inputs from theory. This result is the most precise determination of $|V_{cb}|$ using $B \to D\ell\nu_\ell$ decay and is consistent with HFLAV exclusive average.

### 2.2 Analysis of tagged $B^+ \to \tau^+\nu_\tau$ decays to determine $|V_{ub}|$ at Belle II

We extract $|V_{ub}|$ from the measurement of the branching fraction of purely leptonic decay with the $\tau$ lepton in the final state [12]. Theoretically, $|V_{ub}|$ precision is limited by the uncertainty of the calculations of the $B$ meson decay constant and experimentally this decay is very challenging due to small number of expected events and the presence of multiple undetectable neutrinos. To infer this missing information we reconstruct $B_{\mathrm{tag}}$ using FEI with hadronic tag. On the signal side the $\tau$ lepton is reconstructed using four 1 prong decay modes: $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$, $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$, $\tau^+ \to \pi^+\bar{\nu}_\tau$ and $\rho^+\bar{\nu}_\tau$, taking into account approximately 72% of all $\tau$ decays [13]. Once both $B_{\mathrm{sig}}$ and $B_{\mathrm{tag}}$ are reconstructed, we can define the ROE, that consists of unassigned neutral clusters and charged tracks. Two powerful variables to identify the signal are used:

- The sum of energy in the calorimeter, $E^{\mathrm{extra}}_{\mathrm{ECL}}$, from the energy deposits that cannot be directly associated with the reconstructed daughters of the $B_{\mathrm{sig}}$ or $B_{\mathrm{tag}}$, which should peak at zero for correctly reconstructed signal events.

- The missing mass squared defined as $M^2_{\text{miss}} = (p_{e^+e^-} - p_{B_{\text{tag}}} - p_{\text{track}} - p_{\text{ROE}})^2$, which peaks at zero for decays with one neutrino in the final state and takes larger values due to the presence of multiple neutrinos.

To suppress background from continuum events, two BDTs are used, trained separately for leptonic and hadronic $\tau$ decay modes. We optimise cuts on the three key variables to enhance the signal: the output of the FEI algorithm ($O_{\text{FEI}}$), the output of the continuum suppression BDT ($O_{\text{CS}}$) and the momentum of the reconstructed daughter of the $\tau$ ($p_{\text{cand.}}$). We extract signal yield from a simultaneous 2D fit on $E^{\text{extra}}_{\text{ECL}}$ and $M^2_{\text{miss}}$ to all four tau decay channels. The obtained value for the branching fraction is $\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (1.24 \pm 0.41(\text{stat.}) \pm 0.19(\text{syst.})) \times 10^{-4}$, which is consistent with the current world average and the SM prediction. The corresponding value of $|V_{ub}|$ assuming the SM and using the $B$ decay constant from the Lattice QCD [11] is

$$|V_{ub}| = (4.41^{+0.74}_{-0.89}) \times 10^{-3}. \tag{2}$$

While this result is statistically limited its uncertainty is still comparable to previous hadronically tagged measurements from BaBar [14] and Belle [15] despite smaller data set used.

## 3. Inclusive determinations $|V_{cb}|$ and $|V_{ub}|$

### 3.1 Analysis of tagged $B \to X_u \ell \nu_\ell$ decays to determine $|V_{ub}|$ at Belle II

In this decay we extract $|V_{ub}|$ from inclusive partial branching fraction in a part of the phase-space to mitigate the overwhelming background coming from Cabibbo-favoured $B \to X_c \ell \nu_\ell$ decays [16]. We reconstruct tag side using FEI with hadronic tag and on the signal side we reconstruct a charged lepton. All detected tracks and clusters not associated with $B_{\text{tag}}$ or the lepton are grouped in the ROE that inclusively describes the hadronic system $X$. We then analyse distributions of lepton energy in the $B_{\text{sig}}$ meson rest frame ($E^{(B)}_\ell$), mass of hadronic system $X$ ($M_X$) and squared momentum transfer ($q^2 = (p_\ell + p_{\nu_\ell})^2$). To suppress backgrounds we train dedicated MVA classifiers, separately for continuum events and for the dominant $B \to X_c \ell \nu_\ell$ contribution. After reconstruction, preselection and continuum suppression we divide the data sample into six regions based on the kaon multiplicity and the $B \to X_c \ell \nu_\ell$ suppression classifier score. For the regions used for signal extraction events with kaons are rejected and the $B \to X_c \ell \nu_\ell$ suppression classifier score is required to be higher than 0.87 for the signal region and lower than 0.60 for the control region. The partial branching fractions are extracted in three different regions of phase-space covering different fraction of signal and background events. In the broadest phase-space region, where only a selection of $E^B_\ell > 1$ GeV is applied, we fit $E^{(B)}_\ell$ and $q^2$ simultaneously in the signal and control regions. The measured partial branching fraction is $\Delta\mathcal{B}(B \to X_u \ell \nu_\ell) = (1.54 \pm 0.08(\text{stat.}) \pm 0.12(\text{syst.})) \times 10^{-3}$. To extract $|V_{ub}|$ we use the averaged $B^+$ and $B^0$ lifetimes, $\tau_B = 1.578 \pm 0.003$ ps [3] and the Gambino, Giordano, Ossola and Uraltsev (GGOU) model [17] for the partial decay rate prediction $\Delta\Gamma(B \to X_u \ell \nu_\ell)$. The value of $|V_{ub}|$ reads

$$|V_{ub}| = (4.01 \pm 0.11(\text{stat.}) \pm 0.16(\text{syst.})^{+0.09}_{-0.07}(\text{th.})) \times 10^{-3}. \tag{3}$$

This measurement is systematically limited primarily due to the modelling of both semileptonic $B \to X_u$ and $B \to X_c$ decays and the obtained value is in agreement with the inclusive HFLAV average, but once again we see that the inclusive value exceeds the exclusive HFLAV average.

### 3.2 Analysis of tagged $\bar{B} \to X\ell\bar{\nu}_\ell$ decays to determine $\frac{|V_{ub}|}{|V_{cb}|}$ at Belle

We determine the ratio of $|V_{ub}|$ and $|V_{cb}|$ from tagged inclusive $\bar{B} \to X\ell\bar{\nu}_\ell$ decays [18]. In this analysis we use the full Belle dataset, but for the tag-side reconstruction we employ the Belle II FEI algorithm with hadronic tagging. Since now we are interested in both inclusive semileptonic $B \to X_u$ and $B \to X_c$ decays, we separate the dataset into $\bar{B} \to X_u\ell\bar{\nu}_\ell$ enhanced and depleted subsamples based on the kaon multiplicity. In the $\bar{B} \to X_u\ell\bar{\nu}_\ell$ enhanced sample we further suppress $\bar{B} \to X_c\ell\bar{\nu}_\ell$ contributions using a simple cut-based selection on $|M^2_{\text{miss}}| < 0.43\,\text{GeV}^2$ and we veto $D^*$ to suppress $B \to D^*\ell\nu_\ell$ decays. To extract the ratio off $|V_{ub}|$ and $|V_{cb}|$, we need the signal yields from both inclusive semileptonic decays of $B$ meson. The $\bar{B} \to X_u\ell\bar{\nu}_\ell$ signal yield is extracted from the $\bar{B} \to X_u\ell\bar{\nu}_\ell$ enhanced sample. We perform a 2D fit to the $q^2$, and $E^B_\ell$, where the latter must be larger than 1 GeV is performed using four templates: the signal component and we divide background into 3 contributions. First is the continuum ($q\bar{q}$), then the contribution with the secondary and fake lepton (S + F) and the dominant $\bar{B} \to X_c\ell\bar{\nu}_\ell$ component. For the latter, we derive a data-driven template from the $\bar{B} \to X_u\ell\bar{\nu}_\ell$ depleted sample as $T_i = \tau_i(N^{\text{Data}}_{i,D} - \eta^{\bar{B}\to X_u\ell\bar{\nu}_\ell}_{i,D} - \eta^{q\bar{q}}_{i,D} - \eta^{\text{S+F}}_{i,D})$, where $\tau_i$ is a transfer factor from $\bar{B} \to X_c\ell\bar{\nu}_\ell$ depleted to enhanced subsample derived from the simulation, subscript $D$ denotes $\bar{B} \to X_c\ell\bar{\nu}_\ell$ depleted sample, $N^{\text{Data}}_i$ is the data yield in the $i$-th bin and $\eta$s are yields for each component determined from the simulation. To extract $\bar{B} \to X_c\ell\bar{\nu}_\ell$ yield we perform a simple background subtraction in total $\bar{B} \to X\ell\bar{\nu}_\ell$ sample as $N^{X_c\to\ell\bar{\nu}_\ell} = N^{\text{Data}} - \eta^{q\bar{q}} - a\eta^{X_u\ell\bar{\nu}_e ll} - \eta^{\text{S+F}}$, where $a$ is obtained from the previous fit and $N^{\text{Data}}$ is the data yield in the broadened selection, while $\eta$s are yields for each component from determined from the simulation. The measured ratio of partial branching fractions for the part of the phase-space with lepton energy being greater than 1 GeV is $\Delta\mathcal{B}(\bar{B} \to X_u\ell\bar{\nu}_\ell)/\Delta\mathcal{B}(\bar{B} \to X_c\ell\bar{\nu}_\ell) = (1.99 \pm 0.17(\text{stat.}) \pm 0.16(\text{syst.})) \times 10^{-2}$. Combining this result with the predictions for $\Delta\Gamma^{\text{GGOU}}(\bar{B} \to X_u\ell\bar{\nu}_\ell) = 58.5^{+2.7}_{-2.3}\ \text{ps}^{-1}$ and $\Delta\Gamma(\bar{B} \to X_c\ell\bar{\nu}_\ell) = 29.7 \pm 1.2\ \text{ps}^{-1}$, we measure

$$\begin{aligned}\frac{|V_{ub}|}{|V_{cb}|} =& \big(10.06 \pm 0.43(\text{stat.}) \pm 0.39(\text{syst.}) \\ & \pm 0.23(\Delta\Gamma(\bar{B} \to X_u\ell\bar{\nu}_\ell)) \pm 0.20(\Delta\Gamma(\bar{B} \to X_c\ell\bar{\nu}_\ell))\big) \times 10^{-2}.\end{aligned}$$

Most important sources of systematic uncertainties come from modelling of the $\bar{B} \to X_u\ell\bar{\nu}_\ell$ component and the composition of the secondary and fake lepton component. The obtained value is in agreement with the world averages of both the inclusive and exclusive determinations of the ratio of $|V_{ub}|$ and $|V_{cb}|$.

## 4. Conclusion

We presented recent measurements of the CKM matrix element magnitudes $|V_{ub}|$ and $|V_{cb}|$ including both untagged and tagged analyses with exclusive or inclusive final states using Belle or Belle II datasets. We demonstrate strong experimental performance of Belle II, because even with the currently limited dataset corresponding to an integrated luminosity of 365 $\text{fb}^{-1}$, we are already producing competitive results. As we collect more data in the future, we plan to play a central role in the precision measurements and contribute to the fundamental tests of the Standard Model or beyond.

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