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Recent Belle II results on the CKM parameters $|V_{cb}|$ and $|V_{ub}|$

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We present the latest semileptonic B decay measurements from the Belle II experiment, which aims to determine the magnitudes of the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$. The data sample used for the results presented was collected at the $\Upsilon(4S)$ resonance and corresponds to an integrated luminosity of 189 fb^{-1}.

$|V_{cb}|$ is determined from analyzing $B \to D^* \ell \nu$ and $B \to D\ell\nu$ decays. $|V_{ub}|$ is measured via $B \to \pi\ell\nu$ decays.

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1. Introduction

The magnitudes of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $|V_{cb}|$ and $|V_{ub}|$ determine the transition rates of b into c and u quarks [1, 2]. Precise knowledge of these fundamental parameters is crucial for precision B physics measurements. Measuring semileptonic $B \to X\ell\nu$ decays, where ℓ is either an electron or muon and X is a hadronic system containing a u/c quark, allows determination of $|V_{cb}|/|V_{ub}|$. These determinations can be *inclusive*, *i.e.*, based on all $X_{c/u}\ell\nu$ final states within a given region of phase space, or *exclusive*, *i.e.*, based only on a single $b \to c/u$ semileptonic decay mode such as $B \to D^{(*)}\ell\nu$ or $B \to \pi\ell\nu$. The two methods of determination are independent due to different theoretical descriptions. Inclusive and exclusive measurements of $|V_{cb}|$ have persistently shown an approximate 3σ discrepancy [3], often referred to as the *exclusive vs inclusive puzzle*. This inconsistency is a limiting factor in precision flavor physics and understanding the discrepancy is crucial for improving predictions.
Belle II is a high-energy physics experiment located at the SuperKEKB collider in Tsukuba, Japan. Electrons and positrons are collided at the energy of the $\Upsilon(4S)$ resonance, producing B mesons in high quantities. The B meson decay products are subsequently reconstructed and analyzed in the Belle II detector. Since data-taking began in March 2019, Belle II collected a data sample corresponding to an integrated luminosity of 362 fb^{-1} up to the current day.
Here we present recent results from the Belle II experiment related to exclusive measurements of these CKM elements, based on a partial data sample corresponding to 189 fb^{-1} collected between 2019 and 2021.

2. $|V_{cb}|$ determinations

2.1 Analysis of untagged $B \to D^*\ell\nu$ decays (preliminary)

We reconstruct $B^0 \to D^{*-}\ell^+\nu_\ell$ ($\ell = e, \mu$) decays, with the subsequent $D^{*-} \to \overline{D}^0\pi^-$ and $\overline{D}^0 \to K^+\pi^-$ decays. No specific decay mode is reconstructed for the other B meson decay in the event; this is referred to as an *untagged* analysis. Electron and muon candidates are identified by combining information from multiple subdetectors. The low mass difference between D^* and D mesons restricts the π originating from the D^* decay to low momenta, allowing cleaner reconstruction due to the unique decay signature.
The $B \to D^*\ell\nu$ decay rate is proportional to $|V_{cb}|^2$ and to a form factor with functional dependence on the four kinematic variables w, θ_ℓ, θ_V and χ. By using theory input from Lattice QCD predicting the form factor normalization at particular points in phase space, we can determine V_{cb} by measuring differential decay rates as a function of the kinematic variables.
The angle between the B meson and the combined $Y = D^*\ell$ system θ_{BY} can be inferred from the reconstructed particle kinematics in combination with the beam energy. The specific direction of the B meson on the cone with opening angle θ_{BY} around p_Y is required to calculate the kinematic variables. A weighted average over possible directions on the cone is determined by assigning weights based on the expected angular direction of the B meson due to the $\Upsilon(4S)$ polarization, as well as additional rest-of-event information of tracks and clusters not explicitly reconstructed.
To measure the differential decay rates we extract signal yields in 10 (8) equidistant bins of w, θ_V and χ (θ_ℓ) by performing a binned maximum-likelihood fit [4]. Background and signal templates

are derived from simulation, and fitted to the experimental data via a two-dimensional fit to $\cos\theta_{BY}$ as well as the reconstructed mass difference of the D^* and D mesons. Systematic uncertainties on template shapes are accounted for in the fit by including Gaussian constraints for the relevant shape parameters. Detector acceptance effects are corrected with SVD unfolding [5].
The form factors are fitted to the differential decay rates by minimizing a χ^2 containing predicted and measured decay rates, as well as the full covariance matrix accounting for both systematic and statistical correlations. We use the Boyd-Grinstein-Lebed (BGL) parametrization [6] of the form factor, with truncation order $(n_a, n_b, n_c) = (1, 2, 2)$ decided using the Nested Hypothesis Test [7]. Decay rates from Lattice QCD at zero hadronic recoil $w = 1$ are used to constrain the normalization, allowing determination of $|V_{cb}|$. We measure

$$|V_{cb}|_{\text{BGL}} = (40.9 \pm 0.3_{\text{stat}} \pm 1.0_{\text{sys}} \pm 0.6_{\text{theo}}) \times 10^{-3} \tag{1}$$

Additionally, summing up decay rates over all bins of kinematic variables results in a measurement of the branching ratio

$$\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell) = (4.94 \pm 0.02_{\text{stat}} \pm 0.22_{\text{sys}})\%. \tag{2}$$

Finally, we measure the lepton universality parameters $R_{e/\mu}$, the ratio between electron and muon branching ratios, and $\Delta\mathcal{A}_{fb}$, the difference in forward-backward asymmetries of electron and muon, as

$$\mathcal{R}_{e/\mu} = 1.001 \pm 0.009_{\text{stat}} \pm 0.021_{\text{sys}} \tag{3}$$

$$\Delta\mathcal{A}_{fb} = (-4 \pm 16_{\text{stat}} \pm 18_{\text{sys}}) \times 10^{-3} \tag{4}$$

in agreement with Standard Model expectations.

2.2 Analysis of untagged $B \to D\ell\nu$ decays (preliminary) [8]

We reconstruct both $B^0 \to D^-\ell^+\nu_\ell$ ($\ell = e, \mu$) and $B^+ \to \overline{D}^0\ell^+\nu_\ell$ decay modes with ($\ell = e, \mu$). The D mesons subsequently decay to $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$. The absence of the slow pion in the decay complicates the reconstruction leading to higher backgrounds, particularly from semileptonic $X_c\ell\nu$ events and specifically $D^*\ell\nu$ down-feed. To reduce backgrounds from $B \to D^*\ell\nu$, active vetoes are employed.
The decay rate of B mesons to pseudo-scalar D mesons is determined by a single kinematic variable w, without the angular dependencies of decays to vector D^* mesons.
To extract signal yields, we perform a one-dimensional maximum-likelihood fit to $\cos\theta_{BY}$ in 10 bins of w. To estimate systematic uncertainties and their correlations, we use a toy MC approach.
The method of determining V_{cb} is analogous to the $D^*\ell\nu$ analysis: we fit the BGL parametrized form factor, truncated at $N = 3$, to the measured differential decay rates in bins of w, by minimizing a χ^2 containing the full covariance matrix. Lattice QCD inputs from FNAL/MILC [9] and HPQCD [11] are included via additional Gaussian constraints. The fit yields

$$|V_{cb}| = (38.3 \pm 1.2) \times 10^{-3}. \tag{5}$$

The largest systematic uncertainties arise from the modelling of $B\overline{B}$ backgrounds, especially the $B \to D^*\ell\nu$ downfeed.

2.3 Analysis of tagged $B \to D^* \ell \nu$ decays (preliminary) [10]

In the tagged analysis of $B^0 \to D^{*-}\ell^+\nu_\ell$ decays, one B meson is reconstructed in a fully hadronic decay using the Full Event Interpretation (FEI) algorithm [12]. In events where the B_{tag} satisfies a minimum requirement on the FEI output qualifier, $B^0 \to D^{*-}\ell^+\nu_\ell$ decays are reconstructed on the signal side. Requiring a hadronically reconstructed tag side reduces the reconstruction efficiency but allows precise determination of kinematic variables and reduces backgrounds.

In the analysis, we extract signal yields in 10 bins of w with a one-dimensional fit to the missing neutrino mass squared distribution. The Caprini-Lellouch-Neubert (CLN) parametrization [13] is fitted to the measured differential decay rates to yield

$$|V_{cb}| = (37.9 \pm 2.7) \times 10^{-3}. \tag{6}$$

3. $|V_{ub}|$ determinations

3.1 Analysis of untagged $B \to \pi \ell \nu$ decays (preliminary) [14]

We present two measurements of $|V_{ub}|$ via $B \to \pi \ell \nu$ decays, the first one being an untagged measurement where only the signal side B meson is reconstructed. Lepton and pion candidates are identified using particle identification likelihood ratios.

To suppress large backgrounds from incorrectly reconstructed events, including $B \to X_c \ell \nu$, $B \to X_u \ell \nu$, other $B\overline{B}$ and $e^+e^- \to q\overline{q}$ ($q = u, d, c, s$) continuum contributions, several Boosted Decision Trees (BDT) are trained using the FastBDT methodology [15] to distinguish signal from background. Kinematics of the signal pion and lepton, as well as rest-of-event information, are used to distinguish $B\overline{B}$ backgrounds, while event-topology variables are used in the continuum suppression BDT.

The momentum transfer q^2 is calculated via a weighted average over possible B meson directions, described in Sec. 2.1.

The signal is extracted in a two-dimensional fit to $M_{bc} = \sqrt{E^{*2}_{\text{beam}} - |\vec{p}^{\,*}_B|^2}$ and $\Delta E = E^*_B - E^*_{\text{beam}}$ in 6 bins of q^2. Detector acceptance effects are corrected by using bin-by-bin unfolding.

A χ^2 fit is performed on the measured rates, using data from lattice QCD as a constraint on the parameters of the BCL parametrized [16] form factor. The combined result from the e and μ mode is

$$|V_{ub}| = (3.55 \pm 0.12_{\text{stat}} \pm 0.13_{\text{sys}} \pm 0.17_{\text{theo}}) \times 10^{-3} \tag{7}$$

with leading systematic uncertainties coming from the modelling of continuum backgrounds.

3.2 Analysis of tagged $B \to \pi \ell \nu$ decays (preliminary) [17]

In the tagged analysis, the e modes $B^0 \to \pi^\pm e \nu_e$ and $B^\pm \to \pi^0 e \nu_e$ are reconstructed on the signal side, after the hadronic FEI requirements are passed on the tag side.

The improved background rejection and resolution in q^2 comes at the cost of reduced reconstruction efficiencies and signal yields.

We extract signal yields in 3 bins of q^2 with a one-dimensional fit to the missing neutrino mass squared distribution. Using the BCL parametrized form factor, we measure

$$|V_{ub}| = (3.88 \pm 0.45) \times 10^{-3}, \tag{8}$$

with the largest uncertainties stemming from statistics and the FEI calibration.

4. Conclusion

We presented recent exclusive measurements of the CKM matrix element magnitudes $|V_{cb}|$ and $|V_{ub}|$ at the Belle II experiment. With a data sample corresponding to an integrated luminosity of 189 fb^{-1}, we demonstrate precisions of the order of 3 % and 7 % in untagged analyses of $|V_{cb}|$ and $|V_{ub}|$ respectively. While the tagged measurements are currently less precise than the untagged measurements, the improved resolution in kinematic variables becomes increasingly important as the collected Belle II data sample grows.
Efforts are ongoing to provide updated exclusive and inclusive measurements with the full data sample of 362 fb^{-1} recorded so far.

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