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

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In this talk, the latest measurements of $|V_{ub}|$ and $|V_{cb}|$ by the Belle II collaboration are presented. These results are based on 189 fb^{-1} of Belle II data recorded at the $\Upsilon(4S)$ resonance. We report measurements with inclusive and exclusive B decays. Two main strategies are employed for these results, one where the other B in the event is exclusively reconstructed (tagged) and another where the other B is not (untagged). We also report on a novel approach to measuring inclusive $|V_{cb}|$ by determining the $< q^2 >$ moments of $B \to X_c \ell \nu$.

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1. The Belle II experiment

The Belle II experiment is a B meson factory in Tsukuba, Japan based at the SuperKEKB accelerator complex. The latter collides electrons and positrons at the center-of-mass energy of the $\Upsilon(4S)$ resonance, which almost instantly decays to a pair of B mesons. The target at Belle II is to reach a world-record luminosity and collect a dataset that is at least 30 times the size of its predecessor Belle. This will facilitate the rich physics program in the B meson, charm, and τ sectors, along with unprecedented accuracy in the determination of the CKM (Cabibo-Kobayashi-Maskawa) matrix elements, specifically $|V_{ub}|$ and $|V_{cb}|$ [**?**]. Data collection took place between Spring 2019 and July 2021 and will resume at Belle II in December 2024. The total integrated luminosity collected to date is 363 fb^{-1} at the $\Upsilon(4S)$ resonance. The results presented here are based mainly on 189 fb^{-1} of Belle II reprocessed data.

2. $|V_{ub}|$ and $|V_{cb}|$

Semi-leptonic B meson decays, where $b \to u/c\ell\nu$, are golden channels for the determination of the CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$. Previous experiments have used both exclusive and inclusive approaches to determine $|V_{ub}|$ and $|V_{cb}|$ and an overall discrepancy of 3σ between both techniques has been observed. In the exclusive approach, the decay products of the B meson, such as $B \to D^{(*)}\ell\nu_\ell$, are explicitly reconstructed. However, with the inclusive approach, only the lepton is identified and the charm or charmless resonance is not explicitly reconstructed. The discrepancy between the inclusive and exclusive approaches remains a puzzling anomaly. At Belle II, both the inclusive and exclusive approaches have been employed and the results will be shown here.

3. Exclusive $|V_{cb}|$

The decay $\bar{B^0} \to D^{+*}\ell^-\bar{\nu}_\ell$ is the golden channel for measuring exclusive $|V_{cb}|$. It is a clean mode with low background, where the differential rate can be measured as a function of the hadronic recoil parameter, w, and three angles: $\cos\theta_\ell$,$\cos\theta_\nu$, and χ. Here, $w = \frac{m_B^2 - m_{D^*}^2 - q^2}{2m_B m_{D^*}}$, where m_B and m_{D*} are the mass of the B and D^* meson respectively and q^2 is the momentum transfer squared imparted to the lepton-neutrino pair. Also, $\cos\theta_\ell$ ($\cos\theta_\nu$) is the angle between the lepton (D)and the direction opposite to the B meson in the W (D^*) rest frame and χ is the azimuthal angle between the two decay planes spanned by the $W - \ell$ and $D^* - D$ systems in the B meson rest frame. In the limit of maximum momentum transfer to the leptons, at $w = 1$, $|V_{cb}|$ can be extracted as the average of the measured differential rate with input from Lattice Quantum Chromodynamics (LQCD).

The first Belle II measurement of exclusive $|V_{cb}|$ is untagged, i.e. only the signal B^0, denoted as B_{sig}, is reconstructed via $B^0 \to D^*\ell^+\nu_\ell$, $D^{*-} \to D^0\pi^-$, $D^0 \to K^-\pi^+$. For B_{sig} reconstruction, lepton candidates are identified using particle identification (PID) criteria obtained using information from the different sub-detectors. D^0 candidates are formed using oppositely charged tracks and then combined with a low momentum pion to form a D^* candidate. The direction of the signal B is determined by combining angular information from the $Y = D^*\ell$ system with rest-of-event information from all tracks and clusters not associated with $D^*\ell$. With the B_{sig} direction, the distributions of $\cos\theta_\ell$,$\cos\theta_\nu$, χ, and w can be determined. The signal yield in each bin of the

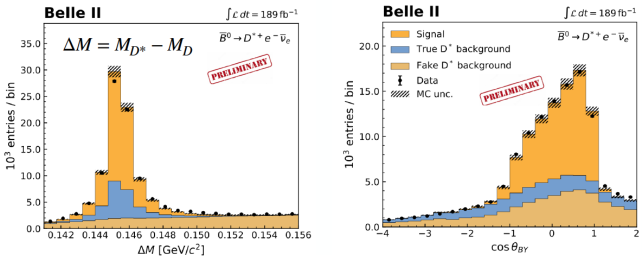

Figure 1: The distribution of ΔM and $\cos\theta_{BY}$ for $B^0 \to D^* e^+ \nu_e$ after full reconstruction.

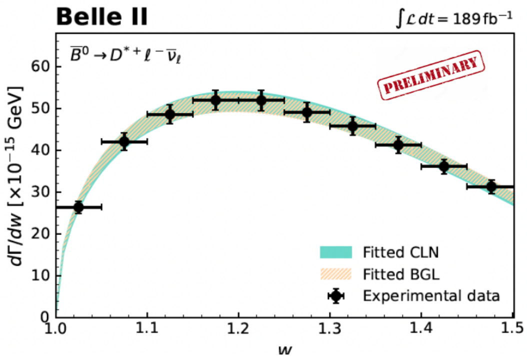

Figure 2: The partial decay rates for $B^0 \to D^{*+} \ell^- \bar{\nu}_\ell$ with input from CLN and BGL parametrizations.

kinematic variables is extracted with a two-dimensional likelihood fit to $\Delta M = M_{D^*} - M_D$ and $\cos\theta_{BY} = \frac{2E_B^* E_Y^* - m_B^2 - m_Y^2}{2|\vec{p}_B^*||\vec{p}_Y^*|}$, shown in Fig. 1, where E_B, E_Y and $\vec{p}_B$, $\vec{p}_Y$ are the center-of-mass (CM) energy and momentum of the B and $D^*\ell$ system respectively. The partial decay rates in terms of the kinematic variables are then combined and averaged to determine the total rate: $\mathcal{B}(B^0 \to D^* \ell^+ \nu_\ell) = 4.922 \pm 0.023 \pm 0.220)\%$, with $\ell = e$ or μ. The ratio of the electron and muon branching fractions is also determined to be $0.998 \pm 0.009 \pm 0.020$, in agreement with the Standard Model (SM).

The partial decay rates can be expressed in terms of $|V_{cb}|$ and the form factors which are matrix elements that describe the non-perturbative physics of the $B \to D^*$ transition.

The form factors are parameterized using either the Boyd-Grinstein-Lebed (BGL)[3] or Caprini-Lellouch-Neubert (CLN)[2] approaches. Using the averaged decay rate, a final fit to $|V_{cb}|$ and the form factors is performed. The result is shown in Fig.2 as a function of w. Agreement between both the BGL and CLN fits, and with the world average of the inclusive and exclusive $|V_{cb}|$ measurements is observed. The measured values of $|V_{cb}|$ are: $|V_{cb}| = (40.13 \pm 0.47 \pm 0.93 \pm 0.58 \times 10^{-3})$ and $|V_{cb}|_{BGL} = (40.57 \pm 0.31 \pm 0.95 \pm 0.58 \times 10^{-3})$, where the final systematic is due to input from LQCD at zero recoil. Furthermore, the final fit for $V_|cb|$ is repeated with the recent LQCD results beyond zero recoil incorporated as additional constraints. These additional constraints shift the value of $V_|cb|$ and lead to tension with predictions from FNAL/MILC[4].

Another approach to measuring exclusive $|V_{cb}|$ is to *fully* reconstruct the other B meson in the

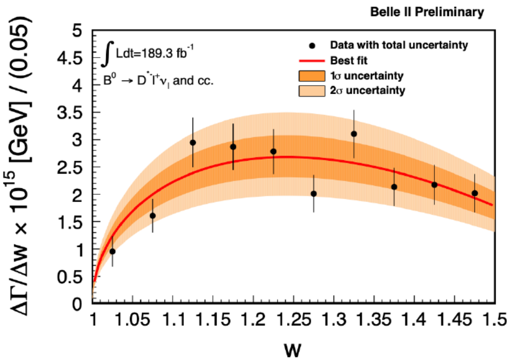

Figure 3: The partial decay rate as a function of w for tagged $B^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ events.

event, referred to as $B_{\rm tag}$, using hadronic modes and subsequently infer the direction of the signal B. This is done at Belle II with the Full Event Interpretation (FEI) algorithm, where a multivariate approach employs more than 200 Boosted Decision trees to reconstruct B mesons in more than 1000 decay channels. This approach yields a 30-50% improvement in efficiency compared to previous similar algorithms at Belle [5]. With this approach, $B_{\rm tag}$ candidates are reconstructed first and a requirement on the $M_{bc} = \sqrt{E^{*2}_{\rm beam} - \vec{p}^{\,2}_B}$ and $\Delta E = E_{\rm beam}/2 - E_{B_{\rm tag}}$ is applied, $M_{bc} > 5.27$ GeV/c^2 and $-0.15 < \Delta E < 0.10$ GeV, where E_{beam} ($E_{B_{\rm tag}}$) is the energy of the beam ($B_{\rm tag}$) and $p_{beam}(p_{B_{\rm tag}})$ is the 4-momentum of the beam ($B_{\rm tag}$). To reconstruct $D^*\ell$ on the signal side, the lepton candidate must have a momentum greater than 1 GeV/c. The D^{*+} is reconstructed using a similar selection as in the untagged approach. The signal yield is extracted from a template fit to $m^2_{\rm miss} = (p_{e^+e^-} - p_{B_{\rm tag}} - p_{D^*})$, with $p_{e^+e^-}, p_{B_{\rm tag}}$, and p_{D^*} being the four-momentum vectors of the collision, the $B_{\rm tag}$ and the D^* respectively. $|V_{cb}|$ is determined using a fit to the total differential distribution and the total decay rate in the CLN parameterization using input values on the form factors .The determined partial decay rate as a function of w is shown in Fig.3 and the resulting value for $|V_{cb}|$ is determined to be $(37.9 \pm 2.7) \times 10^{-3}$.

4. Inclusive $|V_{cb}|$

$|V_{cb}|$ can also be extracted by measuring the partial width, $\Gamma(B \to X_c\ell\nu_\ell)$, which is theoretically expressed as a Heavy Quark Expansion (HQE) in powers of m_b, the b quark mass. The parameters of the Heavy Quark Expansion can be determined by measuring the hadronic mass moments, $< m_X >$, of the differential rate[6]. To achieve a more precise determination of $|V_{cb}|$ theoretically, higher orders of m_b can be introduced, and reparametrization invariance isi employed to reduce the overall number of parameters. This is a novel technique and is implemented by measuring the q^2 moments of $B \to X_c\ell\nu_\ell$. At Belle II, the q^2 moments are measured using 62.8 fb^{-1} of data. The FEI algorithm is first applied to a collision event and then one lepton is identified on the signal side. The remaining tracks and clusters in an event are then assigned as the X_c system, where a kinematic fit is applied to improve the overall resolution of q^2. The background is subtracted using an event-wise continuous function and applied on the m_X distribution. The measured spectrum is

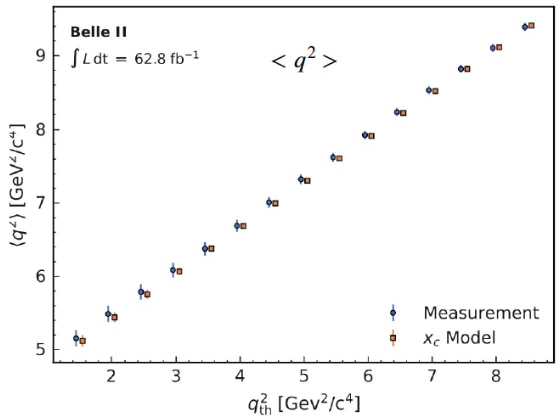

Figure 4: The $n = 1$ $B \to X_c \ell \nu_\ell$ $< q^2 >$ moments measured at Belle II and validated using a dedicated X_c model.

then corrected for detector and resolution effects and the unbiased $< q_2^n >$ moments are determined for $n = 1$ to 4 in the region $q^2 = 1.5 - 8.0$ GeV$^2/c^4$. The results are shown in Fig. 5 for $n = 1$ and are compared to moments extracted using a dedicated X_c model to validate the overall analysis approach. This is the first measurement of $< q^{2n} >$ at Belle II, which provides critical input for a novel determination of inclusive $|V_{cb}|$. These results are combined with a similar measurement at Belle and the resulting value of $|V_{cb}|$ is found to be $|V_{cb}| = (41.69 \pm 0.63) \times 10^{-3}$, consistent with previous inclusive determinations[8].

5. Exclusive $|V_{ub}|$

$|V_{ub}|$ is almost 3 orders of magnitude smaller than V_{cb} and its measurement is more challenging due to the dominant $B \to X_c \ell \nu_\ell$ background. The dominant decay channel to determine $|V_{ub}|$ is $B^0 \to \pi^- i \ell^+ \nu_\ell$. In the untagged approach, a lepton is combined with a pion to reconstruct the signal B, and a similar strategy is applied as discussed above to determine the B_{sig} direction. The remaining tracks and clusters in the event are used to reconstruct the other B. The final signal yield is then extracted using a two-dimensional fit to theM_{bc} and ΔE distributions of the other B. The branching fraction is then determined to be $\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.426 \pm 0.056 \pm 0.125) \times 10^{-4}$. Furthermore, the partial branching fractions are determined in 6 bins of q^2 as shown in Fig. **??**. To extract $|V_{ub}|$ the BCL[**?**] parameterization is used, where input from LQCD on the 8 form factors is assigned as nuisance parameters in the final fit. The resulting value of $|V_{ub}|$ is determined to be $(3.55 \pm \text{(stat)} \pm 0.13\text{(syst)} \pm 0.17\text{(theo)}) \times 10^{-3}$.

In addition, $|V_{ub}|$ is also measured at Belle II using a tagged approach and the signal mode $B \to \pi e \nu_e$, where here charged and neutral modes are considered. Once again, the FEI algorithm is employed and combined with a pion and electron candidate on the signal side. The final signal yield is extracted with a fit to M^2_{miss} and the resulting branching fraction is determined to be: $\mathcal{B}(B^0 \to \pi^- e^+ \nu_e) = (1.42 \pm 0.27\text{(stat)} \pm 0.07\text{(syst)}) \times 10^{-4}$ and $\mathcal{B}(B^+ \to \pi^0 e^+ \nu_e) = (8.33 \pm 1.67\text{(stat)} \pm 0.55\text{(syst)}) \times 10^{-5}$. $|V_{ub}|$ is extracted using the partial decay rates, determined

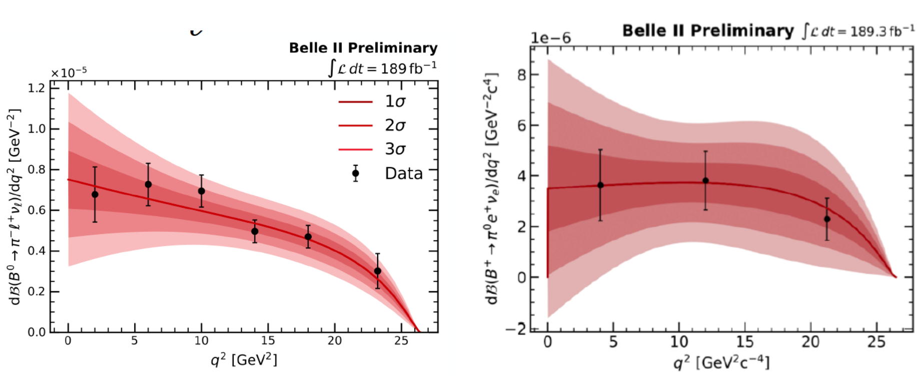

Figure 5: The $B^0 \to \pi^- \ell^+ \nu_\ell$ partial branching fractions measured at Belle II in bins of q^2: (left) untagged (right) tagged.

in 3 bins of q^2, shown in Fig. 5. Both tagged and untagged measurements of $|V_{ub}|$ are consistent with the world average,

6. Conclusion

Belle II is producing new results for $|V_{ub}|$ and $|V_{cb}|$ and will continue to play a leading role in such measurements. A list of inclusive and exclusive measurements have been presented and there is much more in development. More precision is expected as the size of the Belle II dataset increases and as a better understanding of leading systematic uncertainties is achieved.

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