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# Towards first results on $|V_{ub}|$ and $|V_{cb}|$ with the Belle II experiment

**Racha Cheaib**[1,*]

*University of British Columbia,*
*Department of Physics & Astronomy*
*325 - 6224 Agricultural Road*
*Vancouver, BC V6T 1Z1*

*E-mail:* rachac@mail.ubc.ca

Precision measurements of $|V_{ub}|$ and $|V_{cb}|$ play a central role in tests of the CKM sector of the Standard Model and complement direct measurements of CP violation in $B$ meson decays. In this talk, first studies for measuring $|V_{ub}|$ and $|V_{cb}|$ with semi-leptonic decays are presented using collision events recorded at the $\Upsilon(4S)$ resonance by the Belle II experiment. Belle II is located at the SuperKEKB accelerator complex near Tokyo in Japan, and started recording collision data in Spring 2019. We report the status of measuring branching fractions and kinematic properties of inclusive and exclusive decays using untagged and tagged approaches with 36.7 fb$^{-1}$ of Belle II data.

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[1] now at DESY, racha.cheaib@desy.de

[*] Speaker on behalf of the Belle II collaboration.

## 1. The Belle II experiment

The Belle II experiment is a $B$ meson factory in Tsukuba, Japan based at the SuperKEKB accelerator complex, which collides electrons and positrons at the center-of-mass energy of the $\Upsilon(4S)$ resonance. The aim of Belle II is to collect 50 $\text{ab}^{-1}$ of data, 50 times more than its predecessor Belle. This will allow for a panorama of precision measurements in the $B$ meson, charm, and $\tau$ sector, along with an unprecedented accuracy in the determination of the CKM (Cabibo-Kobayashi-Maskawa) matrix elements, specifically $|V_{ub}|$ and $|V_{cb}|$ [1]. Collisions started at Belle II in Spring 2019 and the total integrated luminosity collected to date is 64 $\text{fb}^{-1}$ at the $\Upsilon(4S)$ resonance. The results presented here include 34.6 $\text{fb}^{-1}$ of Belle II reprocessed data.

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

The CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$ can be determined primarily using measurements of semi-leptonic $B$ meson decays, with $b \to u\ell\nu$ or $b \to c\ell\nu$ transitions. Both exclusive and inclusive approaches have been employed by current experiments to determine $|V_{ub}|$ and $|V_{cb}|$ and an overall discrepancy of $3\sigma$ between both techniques remains a puzzling anomaly. In the exclusive approach, the decay products of the $B$ meson, such as $B \to D^{(*)}\ell\nu_\ell$, are explicitly reconstructed. Using the inclusive approach, only the lepton is identified and the charm or charmless resonance is not explicitly reconstructed. The presence of the neutrino in semi-leptonic decays is in both cases inferred by looking at the momentum and energy distributions of the other particles in a given collision event, i.e. neutrinos do not leave a signature in the Belle II detector and thus are accounted for as missing energy. One analysis technique for decays with neutrinos is exclusive hadronic tagging. With this approach, the first $B$ in the event, the $B_{\text{tag}}$, is exclusively reconstructed using hadronic decays. The search for a semi-leptonic decay is then performed on the remaining charged tracks and clusters in the event. At Belle II, a multivariate algorithm based on a hierarchal approach, called the Full Event Interpretation (FEI), is used for hadronic tagging [2].

## 3. $B \to D^*\ell\nu_\ell$

$|V_{cb}|$ can be measured using the exclusive decay rate of $\bar{B^0} \to D^{+*}\ell^-\bar{\nu}_\ell$ determined in the spectrum of the hadronic recoil parameter $w$. 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 leptons. In the limit of the maximum momentum transfer to the leptons, the normalization of the decay rate is predicted by Heavy Quark Symmetry (HQS) and $V_{cb}$ can be extracted at $w = 1$. In an effort to measure $|V_{cb}|$ at Belle II, the branching fraction of $B \to D^*\ell\nu_\ell$ is measured using both tagged and untagged approaches. In the untagged approach, event reconstruction is based only on the signal $B^0$, where $B^0 \to D^*\ell^+\nu_\ell$, $D^{*-} \to D^0\pi^-, D^0 \to K^-\pi^+$. Lepton candidates are required to satisfy 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 $D^*$. Continuum events, where $e^+e^- \to q\bar{q}$ and q=u,d,s or c quark, are further suppressed using a cut on the ratio of the second and zeroth Fox-Wolfram moment $R_2$, $R_2 < 0.25$ [4]. The signal yield is then extracted from a fit to $\cos\theta_{BY}$, which is given by

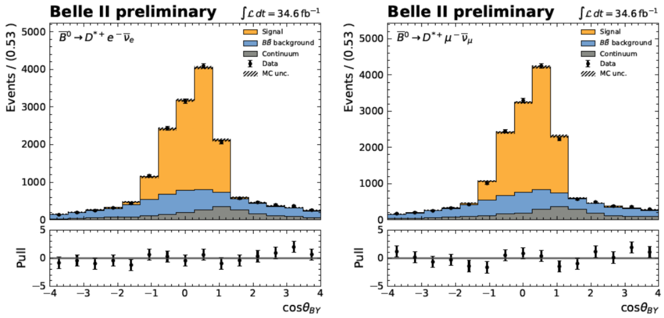

**Figure 1:** The $\cos\theta_{BY}$ for $B^0 \longrightarrow D^{*-}\ell^+\bar{\nu}_\ell$, where properly reconstructed candidates show a peaking distribution around zero.

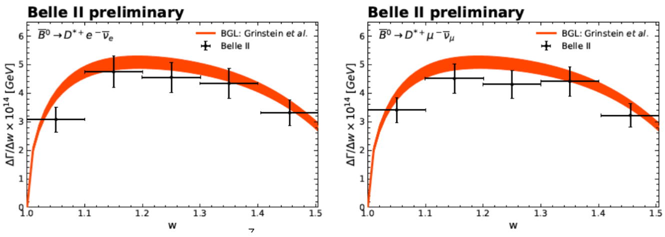

**Figure 2:** The partial branching fractions for $B^0 \longrightarrow D^{*-}e^+\bar{\nu}_e$ (left) and $B^0 \longrightarrow D^{*-}\mu^+\bar{\nu}_\mu$ (right) as compared to the theoretical calculations by Ref. [3] .

$\cos\theta_{BY} = \frac{2E^*_B E^*_Y - m^2_B - m^2_Y}{2|\vec{p}^*_B||\vec{p}^*_Y|}$, 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 resulting yield is shown in Fig. 1 and the branching fraction is determined to be $\mathcal{B}(\bar{B}^0 \longrightarrow D^{*+}\ell\bar{\nu}) = (4.60 \pm 0.05_{(\mathrm{stat})} \pm 0.18_{(\mathrm{sys})} \pm 0.45_{(\pi_s)})\%$ in agreement with the world average [5]. In addition, the $w$ spectrum for $B^0 \longrightarrow D^{*+}\ell\nu_\ell$ is also reconstructed in four bins of equal widths between 1 and 1.4. To do so, the momentum direction of the $B$ meson is constrained to lie on a cone around the $D^{*+}\ell$ system, and then re-weighted using constraints from all the tracks and clusters that are excluded from the $D^{*+}\ell$ reconstruction. The measured $w$ distribution is unfolded to revert resolution effects and efficiencies, and the corresponding partial branching fractions in bins of $w$ are determined as shown in Fig. 2. The current results are in agreement with the partial branching fractions predicted by BGL [3].

Another approach to measure $\mathcal{B}(B^0 \longrightarrow D^*\ell^+\nu_\ell)$ is using hadronic tagging of one $B$ and reconstructing the $D^*\ell$ system from the remaining information in the event. Using the FEI algorithm, $B_{\mathrm{tag}}$ candidates are reconstructed, where the output of the FEI is a probability ranging between 0 (mis-reconstructed) and 1 (properly reconstructed). Candidates are required to have a FEI probability > 0.001 and a beam-constrained mass, given by $M_{bc} = \sqrt{E^{*2}_{\mathrm{beam}} - \vec{p}^{\,2}_B}$, greater than 5.27 GeV/$c^2$. The beam energy difference, $\Delta E = E_{\mathrm{beam}}/2 - E_{B_{\mathrm{tag}}}$ is required to lie between -0.15 and 0.10 GeV. The same selection is applied on the $B_{\mathrm{tag}}$ candidates for all analyses that employ FEI in this paper. 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

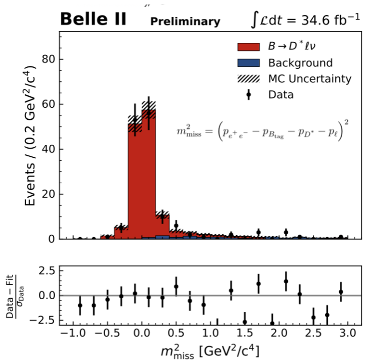

**Figure 3:** The $m^2_{\rm miss}$ distribution is shown for the tagged $B^0 \to D^{*-}\ell^+\nu_\ell$ events.

signal yield is then 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. Fig. 3 shows the $m^2_{\rm miss}$ fit in the range between -1 and 3 GeV$^2/c^4$. The resulting branching fraction is $\mathcal{B}(\bar{B}^0 \to D^{*+}\ell\nu_\ell) = (4.51 \pm 0.41_{\rm stat} \pm 0.27_{\rm syst} \pm 0.45_{\pi_s})\%$ in agreement with both the world average and the untagged approach [6]. The two methods will eventually yield precision measurements of $|V_{cb}|$ as the size of the Belle II dataset increases.

## 4. $B \to X_c\ell\nu_\ell$

The most precise method for extracting $|V_{cb}|$ is by measuring the partial width $\Gamma(B \to X_c\ell\nu_\ell)$. The parameters of the Heavy Quark Effective Theory, to which the Operator Product Expansion is applied relating the partial width to $|V_{cb}|$, are constrained by measuring the moments of the hadronic mass spectrum in $B \to X_c\ell\nu_\ell$ [8] . At Belle II, this is done by first applying the FEI and then identifying one lepton on the signal side, without exclusively reconstructing the $X_c$ system. The lepton is required to have a CM momentum greater than 800 MeV/c and pass PID likelihood criteria. The $X_c$ system is identified using the remaining tracks and clusters in the $\Upsilon(4S)$ rest of event. A multi-variate algorithm based on event shape variables is used to further suppress contributions from continuum events. Six signal channels are considered, $B^0\ell^\pm, B^+\ell^-$ and their conjugates, while two control samples, $B^\pm\ell^\pm$, are used to estimate the combinatorial background. To extract the $m_{X_c}$ moments, the background contributions are subtracted by assigning a signal probability to each event, determined using a fit of the bin-wise difference of the measured $m_{X_c}$ spectrum and the remaining backgrounds simulated using Monte Carlo (MC) and normalized to the measured distribution. Furthermore, the measured $M_{X_c}$ spectrum is then corrected for detector and resolution effects to determine the unbiased moments. The $< M^n_X >$ moments are then determined as a function of lepton momentum cut in the rest frame of the signal $B$, as shown in Fig. 4 [9]. The results are in agreement with previous measurements by BaBar [10] and Belle [11].

## 5. Inclusive untagged $B \to X_u e\nu_e$

The inclusive $B \to X_u e\nu_e$ decay rate similarly leads the most precise determination of $|V_{ub}|$. Here, the decay is only measured in the lepton momentum endpoint spectrum i.e. $p^*_\ell > 2.1$ GeV/c.

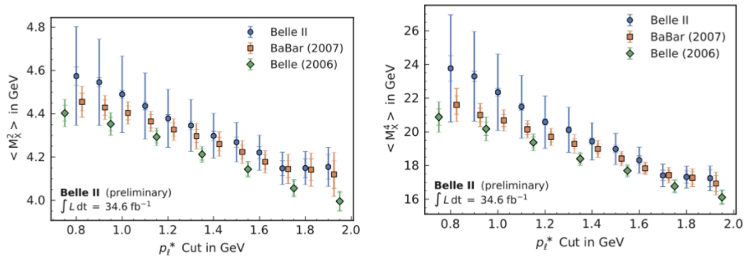

**Figure 4:** The $M_X^n$ moments, for $n = 2$ and $n = 4$, determined using hadronic tagged $B \to X_c \ell \nu_\ell$ decays.

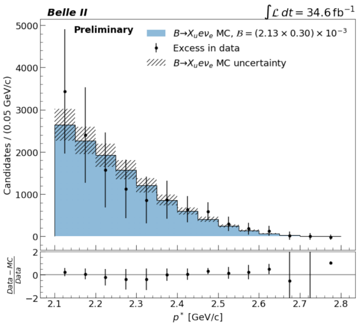

**Figure 5:** The background subtracted lepton momentum end point spectrum where the untagged $B \to X_u e \nu_e$ component is clearly observed.

In this region, contributions from the CKM favoured $B \to X_c \ell \nu_\ell$ are heavily suppressed. However, the theoretical calculations in this region are more challenging, since the introduction of a non-perturbative distribution function is required and its form is still unknown [7]. In this approach, an electron is identified using PID algorithms. A multi-variate algorithm based on event shape variables, such as $R_2$, is then trained to suppress contributions from continuum events. Backgrounds from $B\bar{B}$, especially $B \to X_c e \nu_e$, are determined using MC samples and then subtracted from the lepton end-point spectrum to isolate the $B \to X_u e \nu_e$ component. As can be readily seen in Fig 5 an excess is clearly observed in data with a significance greater than $3\sigma$ [12].

## 6. $B^0 \to \pi^- \ell^+ \nu_\ell$

The exclusive $B^0 \to \pi^- \ell^+ \nu_\ell$ is also measured using the Belle II dataset and can be used to extract $|V_{ub}|$ in the limit of $w = 1$. $B_{\mathrm{tag}}$ candidates are identified with FEI using the same selection criteria as described in the tagged $B^0 \to D^{*+} \ell^- \nu_\ell$ analysis and then used to determine $p_{B_{\mathrm{sig}}}$, the momentum of the signal $B$. On the signal side, oppositely charged pion and lepton are identified, where the latter is selected using PID criteria. $E_{miss}$ is defined as the energy component of the missing momentum vector $p_{\mathrm{miss}} = (E_{\mathrm{miss}}, \vec{p_{\mathrm{miss}}}) = p_{B_{\mathrm{sig}}} - p_Y$, where Y is the reconstructed pion-lepton system, and is required to be greater than 300 MeV. The signal yield is then extracted in the region $M^2_{\mathrm{miss}} \leq 1\ \mathrm{GeV}^2/c^4$. With the current Belle II dataset, the observed signal significance for $B^0 \to \pi^- \ell \nu_\ell$ is 5.69 $\sigma$ and the branching fraction is measured to be $(1.58 \pm 0.43_{\mathrm{stat}} \pm 0.07_{\mathrm{sys}}) \times 10^{-4}$, in agreement with the world average [13].

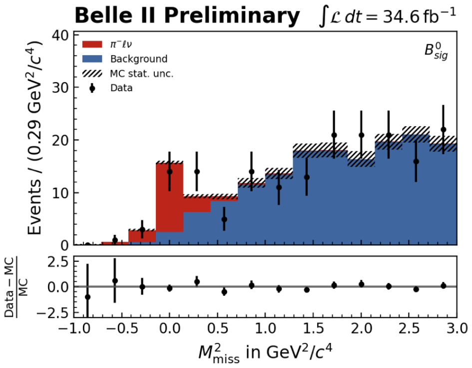

**Figure 6:** The $M^2_{\mathrm{miss}}$ distribution is shown for the tagged $B^0 \to \pi^-\ell^+\nu_\ell$.

## 7. Towards higher luminosities

The increasing size of the Belle II dataset will allow for increased precision in measurements at $|V_{cb}|$ and $|V_{ub}|$. Along with improved analysis techniques, this may unfold the current puzzle tied to the exclusive vs. inclusive determinations and enhance our current understanding of the theory of semi-leptonic $B$ meson decays.

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