PROCEEDINGS OF SCIENCE

# Exclusive Semi-leptonic Decays at Belle II

**Nadia Toutounji, on behalf of the Belle II Collaboration**

*School of Physics, The University of Sydney,*
*Sydney, Australia*

*E-mail:* ntou5237@uni.sydney.edu.au

We present the study of exclusive semi-leptonic $B$-meson decays at Belle II, with the aim of producing precision measurements of the CKM-matrix elements $|V_{\mathrm{cb}}|$ and $|V_{\mathrm{ub}}|$. We provide a brief overview of the different experimental methods of reconstructing such decays and quote a number of recent results from the experiment together with future prospects.

*11th International Workshop on the CKM Unitarity Triangle (CKM2021)*
*22-26 November 2021*
*The University of Melbourne, Australia*

## 1. Introduction

The Standard Model of particle physics has, over the last few decades, seen a number of successful experimental confirmations of several key predicted phenomena. Not least of these was the mechanism put forward by Kobayashi and Maskawa [1] to explain the existence of CP-violation, attributing this to the inclusion of a complex phase in the 3x3 quark-mixing (CKM-)matrix. $B$-factories, namely BaBar [2] and Belle [3], were instrumental in demonstrating the first evidence for CP-violation in the neutral $B$-meson system. Today, the Belle II experiment, which has a broad physics program with a high focus on searches for new physics, aims to improve the precision on measurements of the CKM-matrix elements, particularly that of $|V_{\mathrm{ub}}|$, which currently forms the dominant uncertainty in standard model fits of the Unitarity Triangle [4].

Exclusive semi-leptonic $B$-meson decays, in which the parent $B$-meson decays to a specified hadronic system, lepton and corresponding neutrino, are key processes for the measurements of the CKM-matrix elements $|V_{\mathrm{cb}}|$ and $|V_{\mathrm{ub}}|$. Furthermore, tensions of the order of $3\sigma$ exist between recent measurements of $|V_{\mathrm{cb}}|$ and $|V_{\mathrm{ub}}|$ from exclusive approaches versus inclusive ones [5], in which no explicit hadronic system is specified. In conjunction with improvements to theoretical predictions, Belle II aims to improve the statistical precision on these measurements using both approaches, and thus help to resolve this tension. We present the status of current Belle II analyses investigating the exclusive semi-leptonic decays $B \to D^{(*)}\ell\nu$, $B \to \pi\ell\nu$ and $B \to \rho\ell\nu$, in preparation for first extractions of the respective CKM-matrix elements.

## 2. The Belle II Detector and SuperKEKB Collider

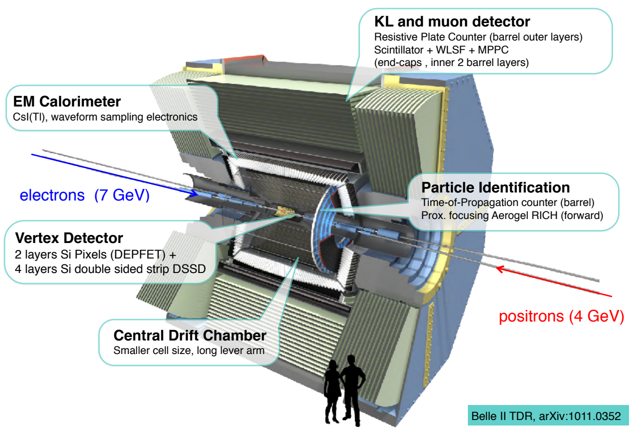


**Figure 1:** The Belle II detector [6].

The SuperKEKB collider is the driving force of the Belle II Experiment located in Tsukuba, Japan, colliding electrons and positrons at a centre-of-mass energy of 10.58 GeV, corresponding to the mass of the $\Upsilon(4S)$ resonance. In June of 2021, a world-record peak luminosity of 3.1 $\times 10^{34}/\mathrm{cm}^2/\mathrm{sec}$ was delivered by the collider. This success is most notably attributed to the employment of the novel nano-beam scheme, involving the squeezing of the individual beams in order to minimise their region of overlap.

The Belle II detector, depicted in Figure 1 and described in detail here [6], has likewise been considerably upgraded from Belle, including the addition of a double layer of pixels to the vertex detector and improved particle identification systems. By the end of the experiment, Belle II aims to record a target integrated luminosity of 50 ab$^{-1}$, roughly 50 times the size of the full Belle dataset. Since its first data taking in 2019, Belle II has to date collected over 231 fb$^{-1}$ of data.

## 3. Status of $|V_{\rm cb}|$-type Analyses from Exclusive Semi-leptonic Decays

At Belle II, multiple analyses are currently underway targeting exclusive extractions of the CKM-matrix element $|V_{\rm cb}|$ via two different approaches, and using the semi-leptonic decays $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ and $B^- \to D^0\ell^-\bar{\nu}_\ell$. In untagged approaches, after the reconstruction of the signal $B$-meson in an $\Upsilon(4S) \to B\bar{B}$ event, the remaining particles in the event are not explicitly reconstructed in any known $B$-meson decay mode. Contrarily, with tagged reconstruction methods, both $B$-mesons in the event, the signal and the tag, must be explicitly reconstructed, resulting in a lower efficiency for reconstruction with a much higher purity.

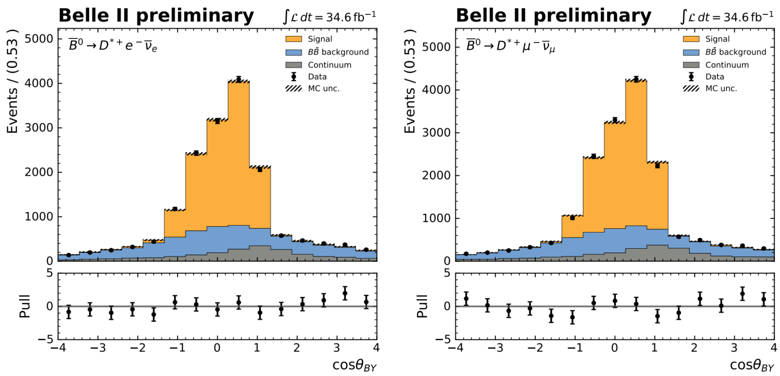


**Figure 2:** Fitted $\cos\theta_{\rm BY}$ distributions for untagged $\bar{B}^0 \to D^{*+}e^-\bar{\nu}_e$ (L) and $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ (R) [7].

In the untagged reconstruction of $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ ($D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$) at Belle II [7], four charged particle tracks are reconstructed per event. A selection on the mass difference between the $D^*$ and $D$-mesons, $\Delta m_{(D^*,D)} \in [0.144, 0.148]$ GeV/c$^2$, favours real $D^*$ candidates and is effective at mitigating backgrounds. The number of signal events in a data sample corresponding to an integrated luminosity of 34.6 fb$^{-1}$ was estimated via a binned maximum-likelihood fit to the $\cos\theta_{\rm BY}$ distribution (Figure 2), defined as the cosine of the angle between the flight directions of the parent $B$-meson and combined $D^* - \ell$ system ($Y$). The branching fraction subsequently extracted from the fitted signal yields, $\mathcal{B}(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell) = (4.60 \pm 0.05_{\rm stat} \pm 0.17_{\rm sys} \pm 0.45_{\pi_s})\%$, is consistent with the world average [5], with a dominant systematic uncertainty due to the tracking of the slow pion $\pi_s$ from the $D^*$ decay. This uncertainty is determined via an independent data-driven study of $B \to D^*\pi$ and $B \to D^*\rho$ decays, and is expected to decrease with further statistics. The analysis aims next to perform the signal extraction in multiple bins of the hadronic recoil parameter $w$, which will allow for an extraction of $|V_{\rm cb}|$ from the partial branching fractions evaluated in each bin.

An untagged analysis of $B^- \to D^0\ell^-\bar{\nu}_\ell$ [8] has also been undertaken at Belle II, for an integrated luminosity of 62.8 fb$^{-1}$. The $\cos\theta_{\mathrm{BY}}$ distribution (with $Y$ now the $D^0 - \ell$ system) is likewise used for signal extraction (Figure 3). Significant backgrounds due to $B \to D^*\ell\nu$ decays introduce some complexity to the signal reconstruction, but are reduced via dedicated $D^*$ vetoes. The branching fraction extracted, $\mathcal{B}(B^- \to D^0\ell^-\bar{\nu}_\ell) = (2.29 \pm 0.05_{\mathrm{stat}} \pm 0.08_{\mathrm{sys}})\%$ is not only consistent with the world average [5], but already at a competitive standard. A first $|V_{\mathrm{cb}}|$ extraction is similarly planned, via fitting the $\cos\theta_{\mathrm{BY}}$ distribution in multiple $w$ bins.

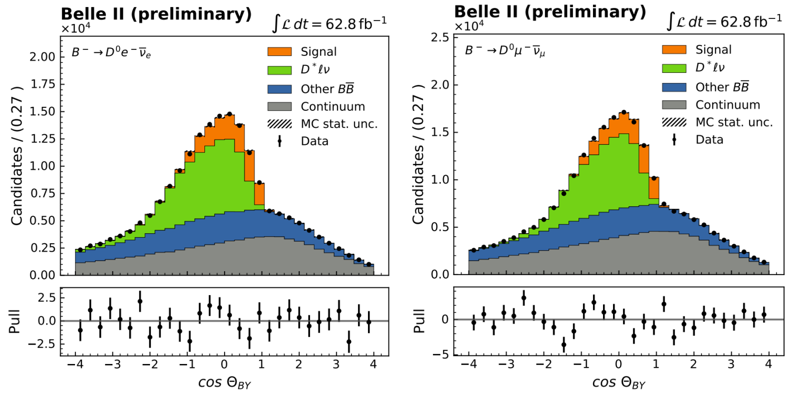


**Figure 3:** Fitted $\cos\theta_{\mathrm{BY}}$ distributions for untagged $B^- \to D^0 e^- \bar{\nu}_e$ (L) and $B^- \to D^0\mu^-\bar{\nu}_\mu$ (R) [8].

Tagged analysis at Belle II is performed using a multi-variate analysis technique known as the Full Event Interpretation (FEI) [9], which reconstructs $B$-mesons in over 4000 unique hadronic or semi-leptonic decay chains. The technique involves hierarchically reconstructing $B$-mesons in stages, training a classifier at each stage until the final output is obtained. The final classifier then provides powerful discrimination between real and fake $B$-meson decays.

We also report results of a $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ analysis with hadronic tagging provided by the FEI [10]. In this case, both the signal $B$-meson and a hadronic tag are reconstructed in the event, with the latter satisfying an optimal selection on the FEI classifier output. For signal extraction, the square of the missing four-momentum in the event is used, $M^2_{\mathrm{miss}} = (p_{e^+e^-} - p_{B_{\mathrm{tag}}} - p_{D^*} - p_\ell)$. As all particles in the hadronically tagged event can be reconstructed except the neutrino, a clear peak at $M^2_{\mathrm{miss}} = 0$ is thus expected only for true signal decays. The resultant fitted $M^2_{\mathrm{miss}}$ distribution (Figure 4, left plot) illustrates a substantially low level of background, with the extracted branching fraction, $\mathcal{B}(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell) = (4.51 \pm 0.41_{\mathrm{stat}} \pm 0.27_{\mathrm{sys}} \pm 0.45_{\pi_s})\%$ consistent with the world average [5], with a relatively large statistical uncertainty at the given data sample size of 34.6 fb$^{-1}$.

## 4. Status of $|V_{\mathrm{ub}}|$-type Analyses from Exclusive Semi-leptonic Decays

The exclusive semi-leptonic $B \to \pi\ell\nu$ decays are largely regarded as golden modes for the extraction of the CKM-matrix element $|V_{\mathrm{ub}}|$. Current results from Belle II utilise hadronic tagging provided by the FEI [11]. For $B^+ \to \pi^0\ell^+\nu_\ell$ decays in a data sample corresponding to 62.8 fb$^{-1}$, a pair of photons ($\pi^0 \to \gamma\gamma$) and a single lepton are reconstructed recoiling against a hadronic tag satisfying a minimum threshold on the FEI classifier output. The number of signal events is similarly estimated via an unbinned maximum-likelihood fit to the square of the missing

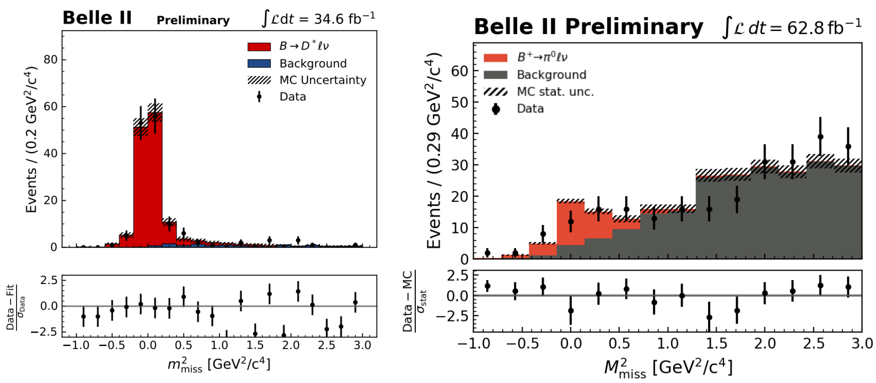


**Figure 4:** Fitted $M^2_{\rm miss}$ distributions for hadronically tagged $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ (L) [10], $B^+ \to \pi^0\ell^+\nu_\ell$ (R) [11].

four-momentum in the event (Figure 4, right plot). The measured branching fraction, $\mathcal{B}(B^+ \to \pi^0\ell^+\nu_\ell) = (8.29 \pm 1.99_{\rm stat} \pm 0.46_{\rm sys}) \times 10^{-5}$, is consistent with the world average [5], with an uncertainty dominated by the statistical component.

For the charged pion mode, $B^0 \to \pi^-\ell^+\nu_\ell$, a similar methodology is implemented, with the signal side reconstruction consisting of a charged pion and lepton track separated by no more than 1 mm in their points of closest approach to the $z$-axis beam direction. The signal extraction is considered in three bins of $q^2$, the squared momentum transfer to the leptonic system (Figure 5). The partial branching fractions measured from each bin are summed to give a total branching fraction of $\mathcal{B}(B^0 \to \pi^-\ell^+\nu_\ell) = (1.47 \pm 0.29_{\rm stat} \pm 0.05_{\rm sys}) \times 10^{-4}$, a value similarly consistent with the current world average [5] within a relatively large statistical uncertainty. A significant update to the analysis is expected soon, with a first extraction of $|V_{\rm ub}|$ based on these partial branching fractions. $B \to \pi\ell\nu$ analyses via both untagged and semi-leptonically tagged approaches are also currently under investigation at Belle II, and will release results at a later date.

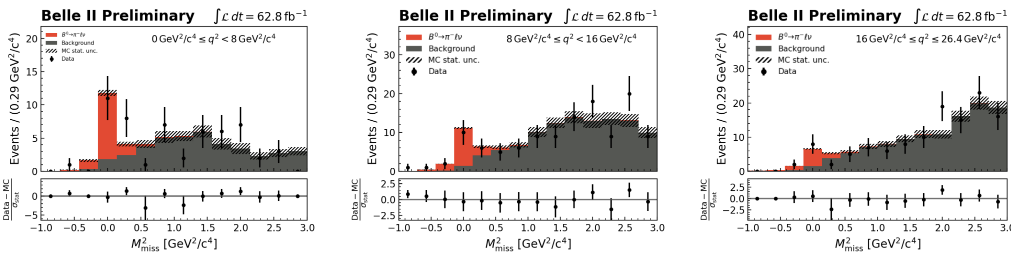


**Figure 5:** Fitted $M^2_{\rm miss}$ distributions for hadronically tagged $B^0 \to \pi^-\ell^+\nu_\ell$ in three bins of $q^2$ [11].

Finally, Belle II currently also reports first results on $B \to \rho\ell\nu$ decays with hadronic tagging [11]. In a method largely similar to the reconstruction of $B \to \pi\ell\nu$ decays, $\rho$-meson candidates ($\rho \to \pi\pi$) are selected within an appropriate invariant mass window, $M_{\pi\pi} \in [0.333, 1.217]$ GeV/c$^2$ and combined with a lepton track to form the signal $B$-meson. Signal extraction is likewise performed via fits to the $M^2_{\rm miss}$ distributions (Figure 6), but due to low signal significance ($< 2\sigma$) at the given data sample size of 62.8 fb$^{-1}$, 95% confidence level upper limits are quoted on the measured branching fractions instead, with $\mathcal{B}(B^0 \to \rho^-\ell^+\nu_\ell) < 3.37 \times 10^{-4}$ and $\mathcal{B}(B^+ \to \rho^0\ell^+\nu_\ell) < 1.97 \times 10^{-4}$.

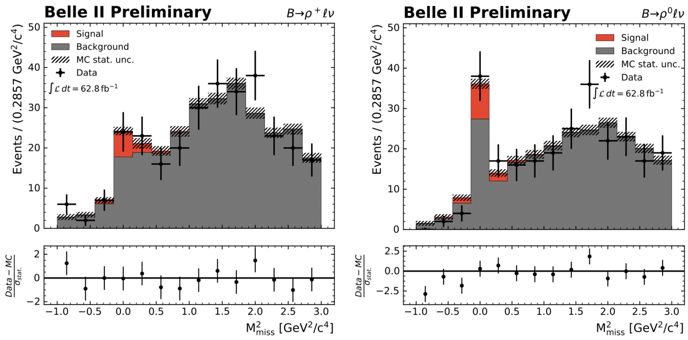


**Figure 6:** Fitted $M^2_{\text{miss}}$ distributions for hadronically tagged $B^0 \to \rho^- \ell^+ \nu_\ell$ (L) and $B^+ \to \rho^0 \ell^+ \nu_\ell$ (R) [11].

## 5. Conclusions

In summary, a number of exclusive semi-leptonic analyses are currently underway at Belle II, with plans to extract measurements of $|V_{\text{cb}}|$ and $|V_{\text{ub}}|$ in the near future. Projections based on Belle II simulation over the course of the full experiment [12] show the potential for the experimental uncertainties on these matrix elements to reach as low as 1.5% and 2%, respectively, due to the low expected statistical uncertainties and projected reduction of relevant systematic uncertainties.

## References

[1] M. Kobayashi, T. Maskawa, CP-Violation in the Renormalizable Theory of Weak Interaction, Progress of Theoretical Physics, Volume 49, Issue 2, 652–657, 1973.

[2] B. Aubert et al., BABAR Collaboration, Observation of CP Violation in the $B^0$ Meson System, Phys. Rev. Lett. 87, 091801, 2001.

[3] K. Abe et al., Belle Collaboration, Observation of Large CP Violation in the Neutral B Meson System, Phys. Rev. Lett. 87, 091802, 2001.

[4] CKMfitter Group, Eur. Phys. J. C41, 1-131 (2005), UTfit Collaboration, JHEP 10, 081 (2006).

[5] P. A. Zyla et al., Particle Data Group, PTEP 2020, no.8, 083C01, 2020.

[6] T. Abe et al., Belle II Tech. Design Report, `arXiv:1011.0352[physics.ins-det]`, 2010.

[7] Belle II Collaboration, `arXiv:2008.07198 [hep-ex]`.

[8] Belle II Collaboration, `arXiv:2110.02648 [hep-ex]`.

[9] T. Keck et al., The Full Event Interpretation - An exclusive tagging algorithm for the Belle II experiment, Computing and Software for Big Science 3(1), 2019.

[10] Belle II Collaboration, `arXiv:2008.10299 [hep-ex]`.

[11] Belle II Collaboration, `arXiv:2111.00710 [hep-ex]`.

[12] E. Kou et al., Belle II Collaboration, The Belle II Physics Book, Progress of Theoretical and Experimental Physics, Volume 12, 2050-3911, 2019.