THE UNIVERSITY OF SYDNEY

Exclusive Semi-leptonic Decays at Belle II

Nadia Toutounji

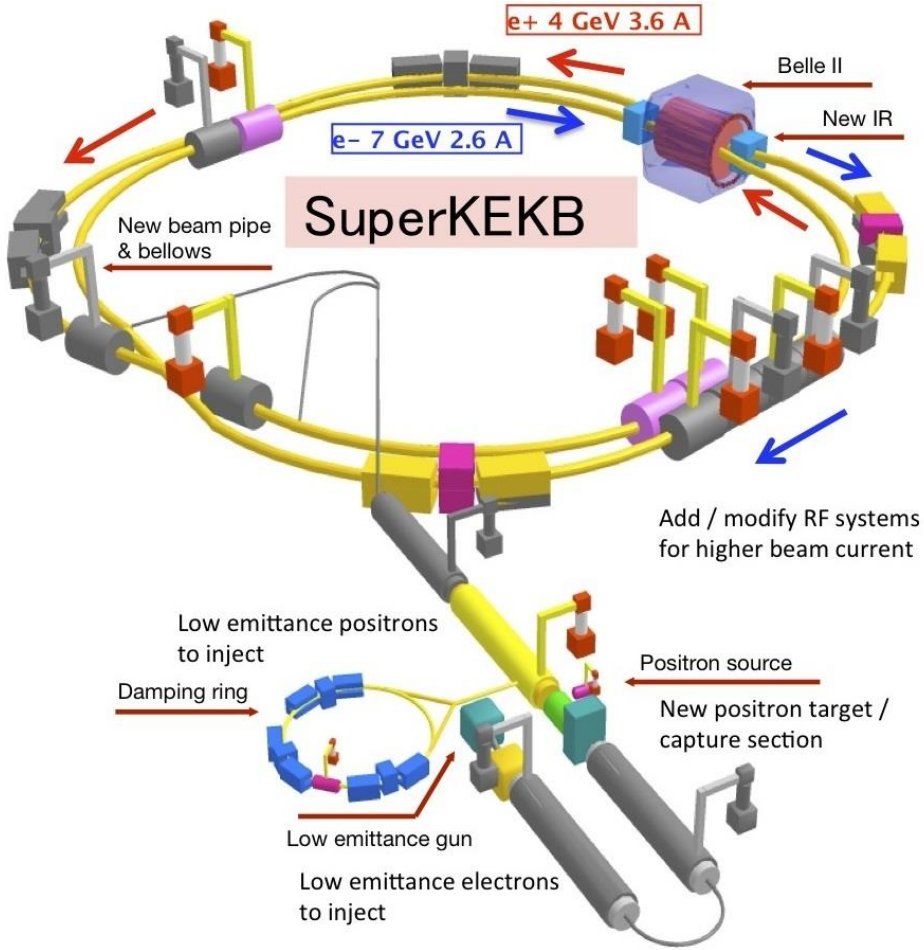
(on behalf of the Belle II Collaboration)

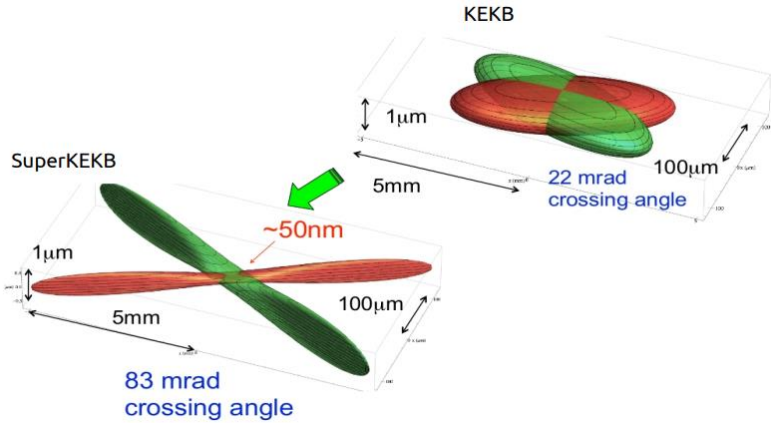
CKM2021

25.11.21

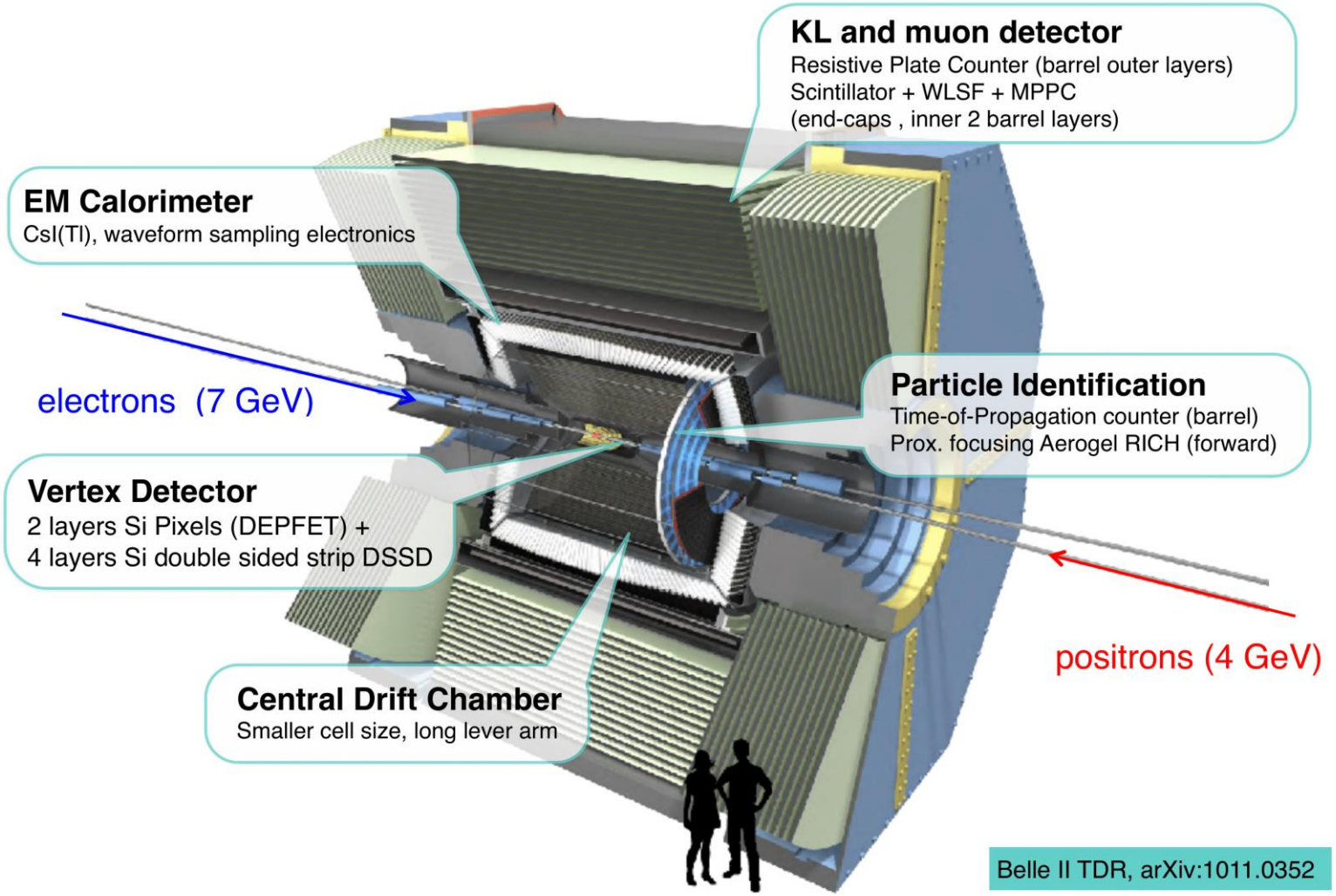
SuperKEKB

- e^+e^- collider with $\sqrt{s}$ = 10.58 GeV, the Υ(4S) resonance
- Peak luminosity of 3.1 x 10^{34}/cm²/sec reached in June of this year – new world record!
  - ~50% increase from KEKB record luminosity
- Record luminosity largely due to new nano-beam scheme and doubling of beam currents



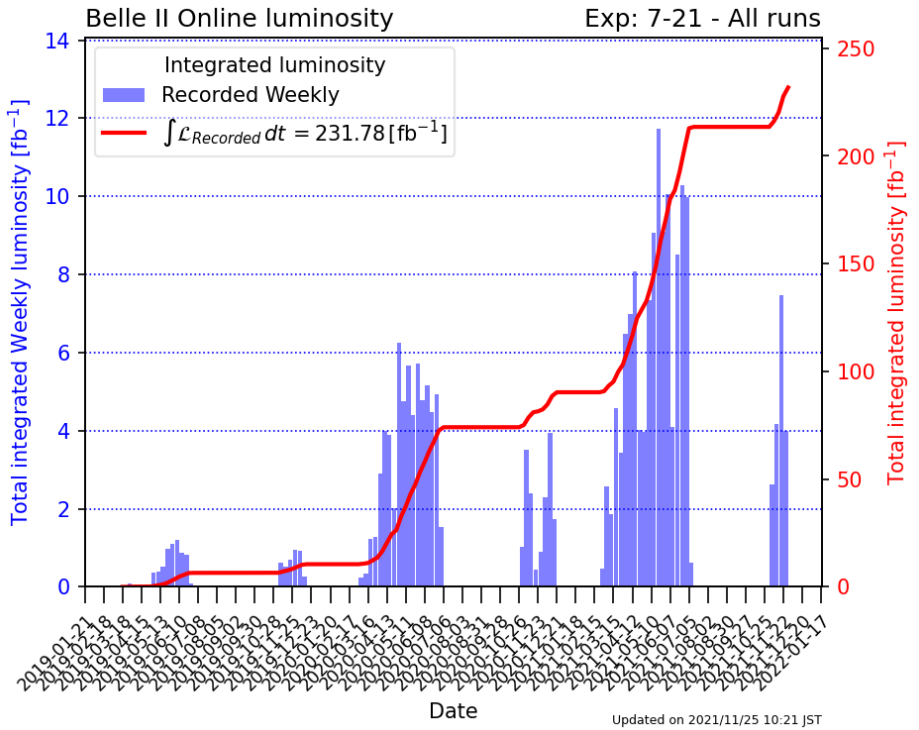


The Belle II Detector



Belle II Data-taking: Status and Outlook

- Collected over 231 fb^{-1} of data thus far
- Dataset size comparable to Belle targeted for end of 2022, of order 800 fb^{-1}
- Long-term: 50 ab^{-1} (50 x Belle dataset) by end of experiment



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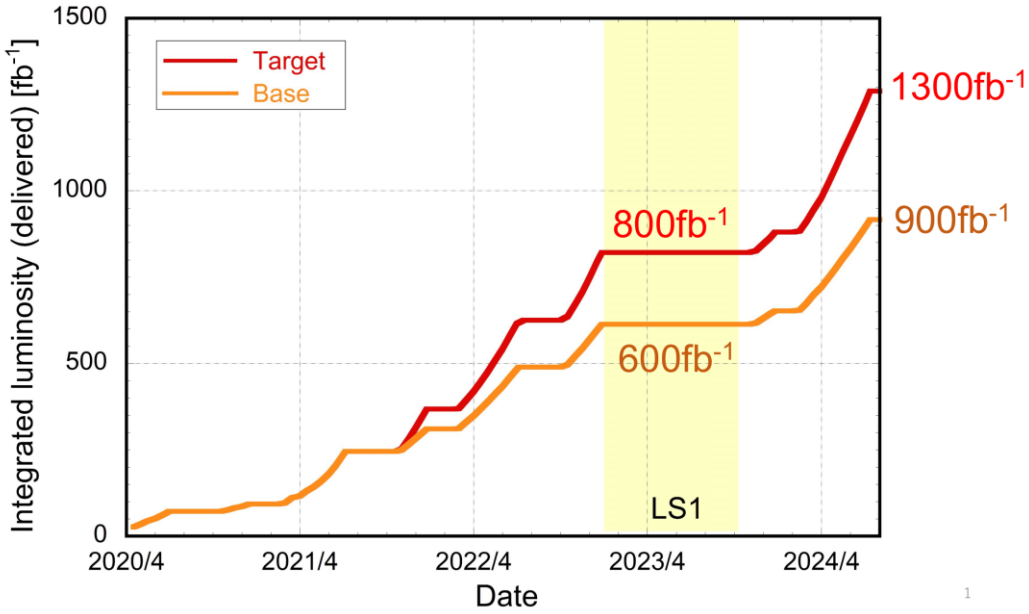
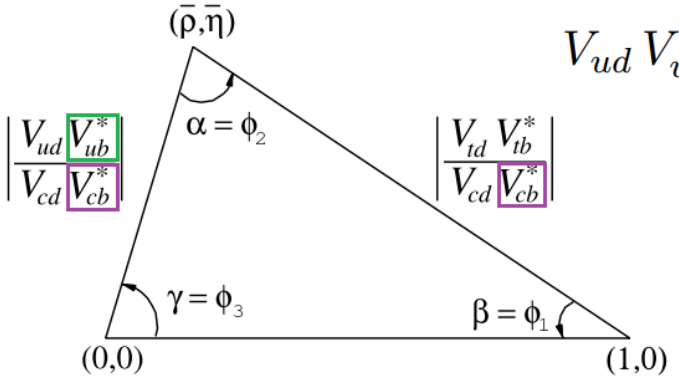


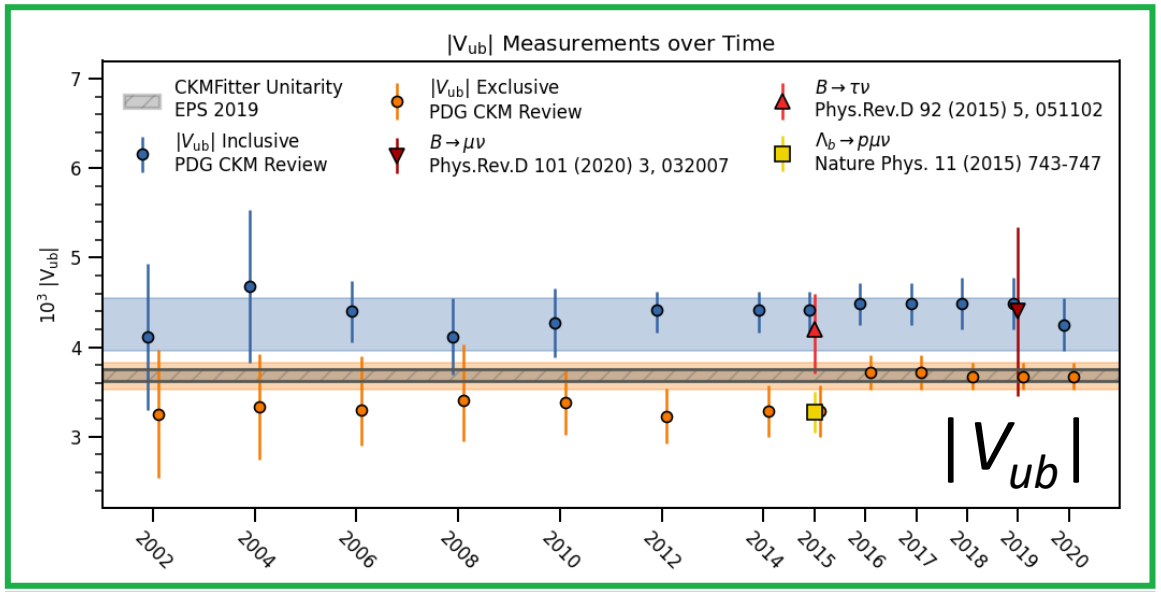
LS1 = Long Shutdown 1

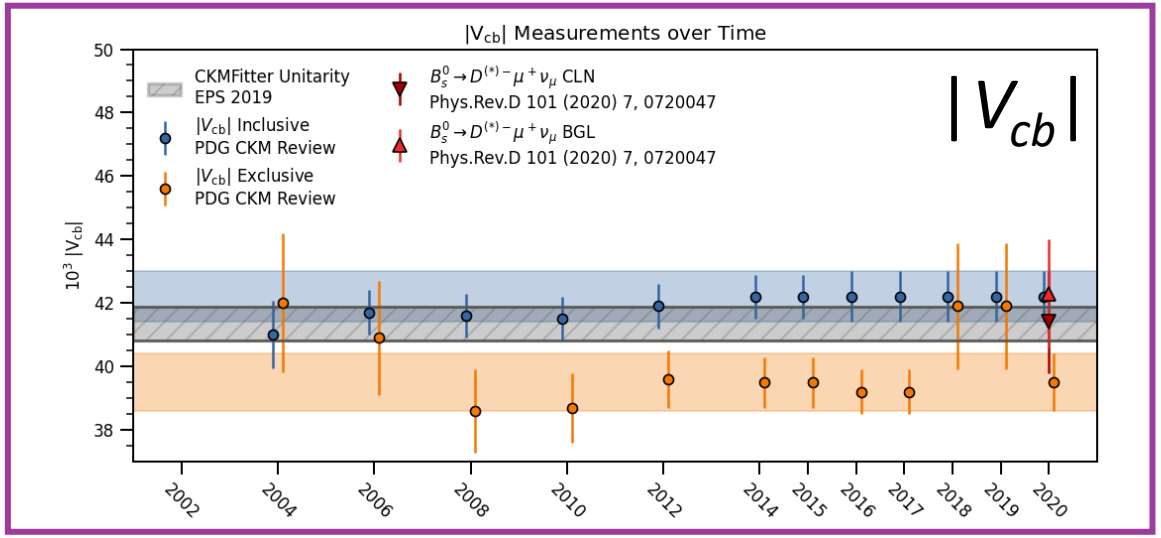
Motivation: Exclusive Semi-leptonic Decays

- Precision measurements of CKM matrix elements key for testing unitarity condition, particularly for $|V_{ub}|$, which forms dominant uncertainty
- Exclusive semi-leptonic decays golden modes for measurements of $|V_{ub}|$and $|V_{cb}|$, e.g. $B\to\pi\ell\nu_{\ell}$, $B\to D^{(*)}\ell\nu_{\ell}$
- Existing tension between $|V_{ub}|$ and $|V_{cb}|$ from inclusive vs. exclusive approaches, each of order ~3σ
- Projected Belle II dataset will be significant in resolving this tension and improving precision



$$V_{ud}\,V_{ub}^{*} + V_{cd}\,V_{cb}^{*} + V_{td}\,V_{tb}^{*} = 0$$

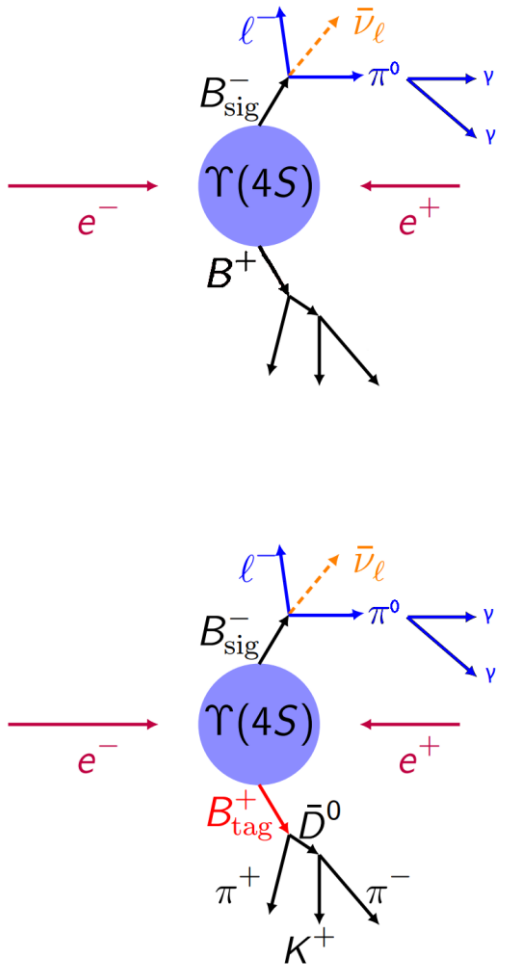




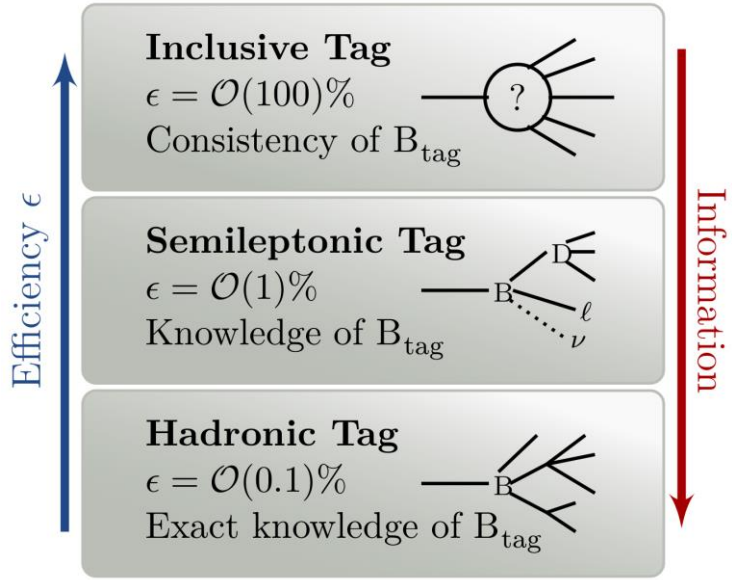
Reconstruction Methods for Exclusive Semi-leptonic Decays at Belle II

- Untagged(inclusive tagged) approaches:
  - Reconstruct signal decay of interest
  - All remaining particles in event assigned to inclusive tag
  - Highly efficient but low purity, selection optimisation key

- Tagged approaches:
  - Reconstruct both signal *B* decay and other *B*-meson in event (tag)
  - Tag can be hadronic or semi-leptonic
  - Unique advantage of hadronic tagging for semi-leptonic signal decays → missing neutrino momentum can be determined



$\ell = e, \mu$

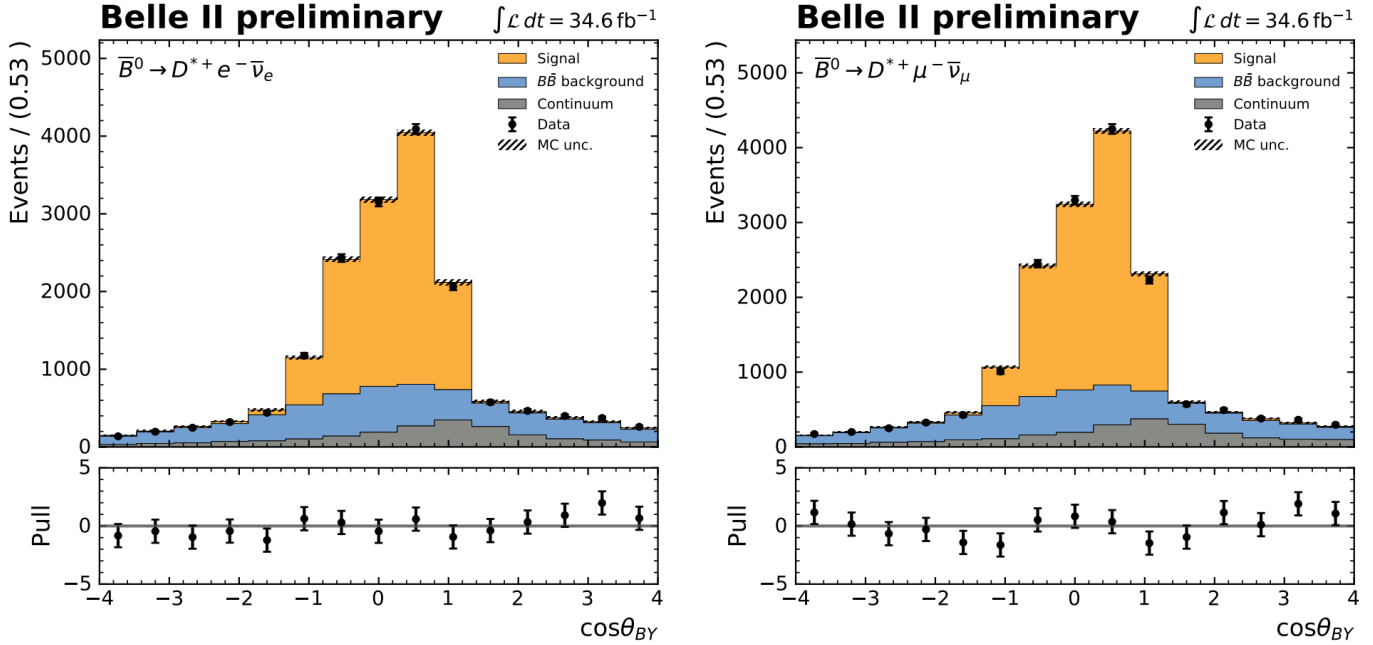


missing momentum

Untagged $\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}_\ell$

arXiv:2008.071

- Here, $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$, with $\Delta m_{(D^*,D)} \in [0.144, 0.148]$ GeV/c^2
- Signal extraction via distribution of $\cos(\theta_{BY})$: cosine of angle between flight directions of B-meson and combined D^*-ℓ system (Y)
- Branching fraction consistent with PDG, but large systematic uncertainty due to slow pion tracking
- Next steps: Extract $|V_{cb}|$ from fits to $\cos(\theta_{BY})$ in bins of hadronic recoil parameter, w



$$\mathcal{B}(\overline{B}^0 \to D^{*+} \ell^- \overline{\nu}_l) = (4.60 \pm 0.05_{\text{stat}} \pm 0.17_{\text{syst}} \pm 0.45_{\pi_s})\,\%$$

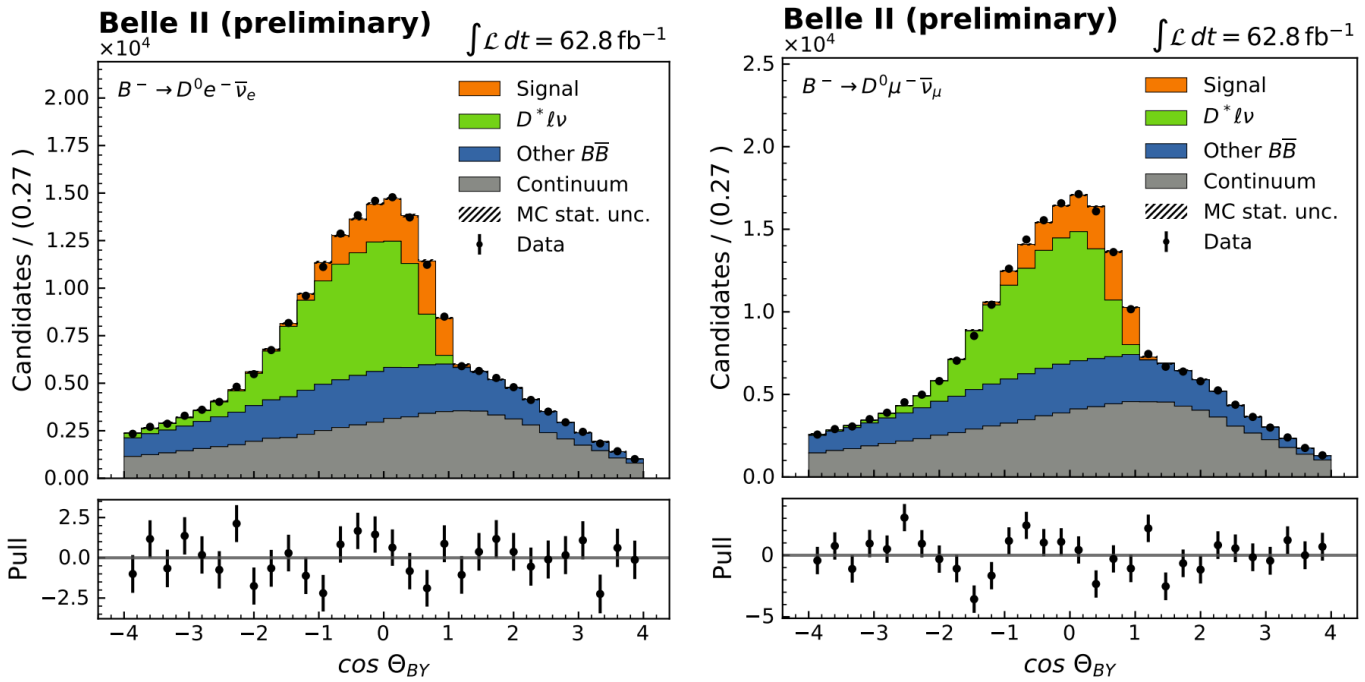
PDG: $(5.05 \pm 0.14)\,\%$

$$\cos\theta_{BY} = \frac{2\,E_B^* E_Y^* - m_B^2 - m_Y^2}{2|p_B^*||p_Y^*|}$$

Untagged $B^- \to D^0 \ell^- \bar{\nu}_\ell$

arXiv:2110.02648

- Signal extraction via distribution of $\cos(\theta_{BY})$: cosine of angle between flight directions of *B*-meson and combined *D*-ℓ system (*Y*)
- Large backgrounds from $B \to D^* \ell \nu_\ell$ decays reduced via dedicated veto
- Competitive branching fraction measurement, consistent with PDG
- Next steps: Extract $|V_{cb}|$ from fits to $\cos(\theta_{BY})$ in bins of hadronic recoil parameter, *w*



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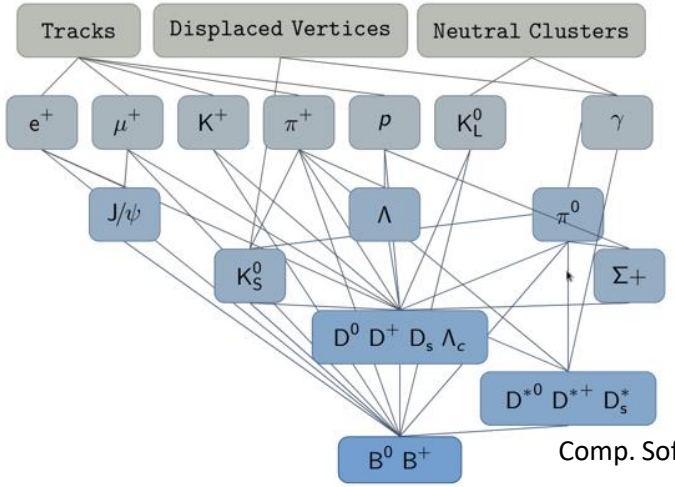
$$\mathcal{B}(B^- \to D^0 \ell^- \bar{\nu}_\ell) = (2.29 \pm 0.05_{\text{stat}} \pm 0.08_{\text{syst}})\%$$

PDG: $(2.35 \pm 0.03_{\text{stat}} \pm 0.09_{\text{syst}})\%$

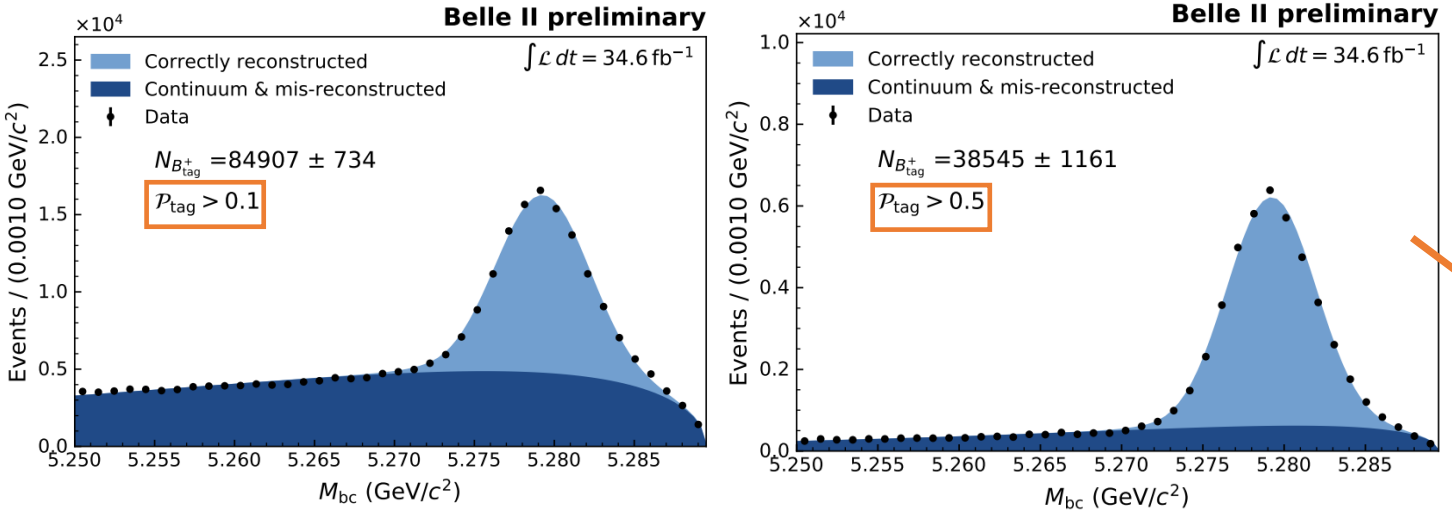
Tagged Analysis at Belle II: Full Event Interpretation

- Multi-variate analysis technique for reconstructing *B*-tags via over 4000 unique decay chains
- Includes both hadronic and semi-leptonic tagging functionality

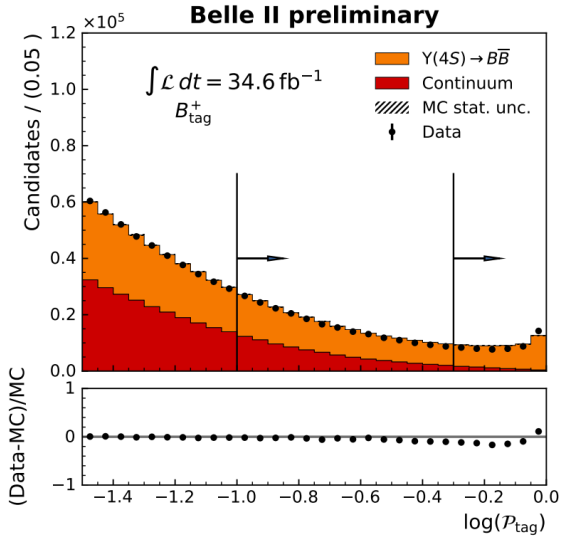


Comp. Soft. Big Sci. (2019) 3: 6

arXiv:2008.06096



Hadronic B^+_{tag}



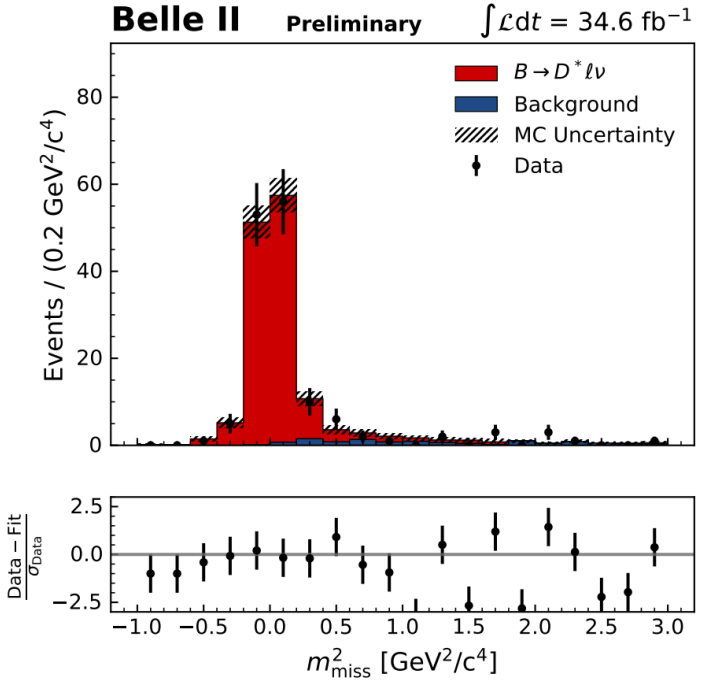
- Selection on final classifier output $\mathcal{P}_{tag}$ provides good signal-background discrimination

$$M_{\mathrm{bc}} = \sqrt{E^2_{CM} - |\vec{p}_{B_{\mathrm{tag}}}|^2}$$

Hadronic Tagged $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$

arXiv:2008.10299

- Here, $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$, with $\Delta m_{(D^*,D)} \in [0.143, 0.148]$ GeV/c^2
- Hadronic tag reconstructed recoiling against signal *B*-meson, whilst satisfying an optimal selection on the FEI classifier output
- Events with tracks remaining after ϒ(4S) reconstruction excluded
- Signal extraction via distribution of m^2_{miss}, the square of the missing four-momentum in the event
- Branching fraction consistent with PDG, with dominant systematic uncertainty due to slow pion tracking



$$\mathcal{B}(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_l) = \left(4.51 \pm 0.41_{\text{stat}} \pm 0.27_{\text{syst}} \pm 0.45_{\pi_s}\right)\%$$

PDG: $(5.05 \pm 0.14)\,\%$

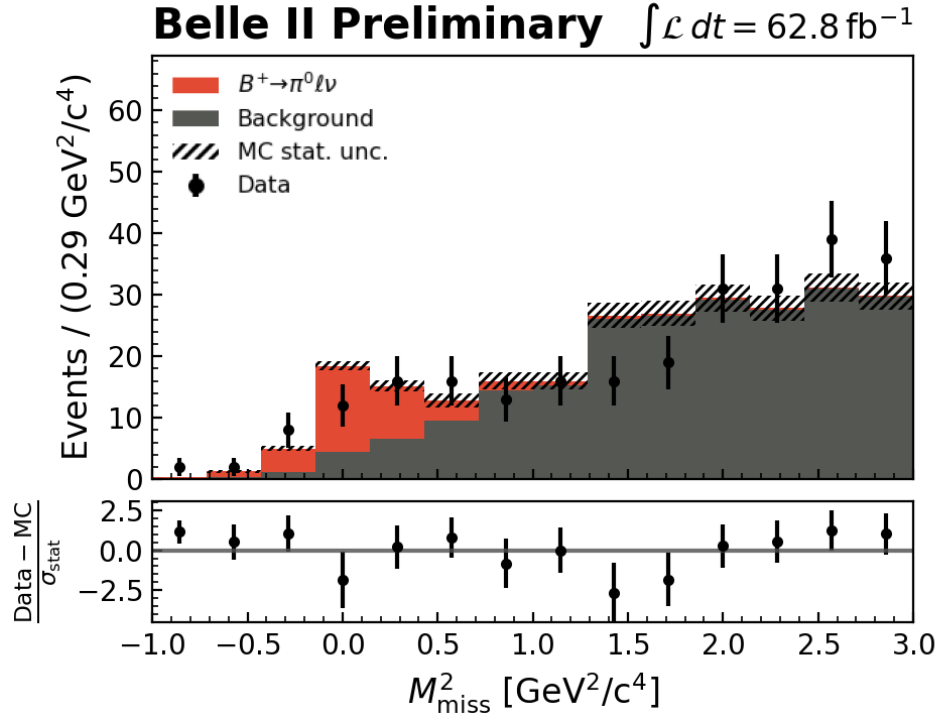
$$m^2_{\text{miss}} = \left(p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^*} - p_\ell\right)^2$$

Hadronic Tagged $B \to \pi \ell \nu_\ell$

- Hadronic tag selected satisfying minimum threshold on FEI classifier output
- Events with tracks remaining after Υ(4S) reconstruction excluded
- Signal extraction via distribution of m^2_{miss}
- $B^+ \to \pi^0 \ell \nu_\ell$: Branching fraction consistent with PDG, dominant systematic uncertainties from calibration of FEI algorithm and π^0 reconstruction efficiency

$$m^2_{\text{miss}} = \left(p_{e^+ e^-} - p_{B_{\text{tag}}} - p_{\pi} - p_{\ell} \right)^2$$

arXiv:2111.007



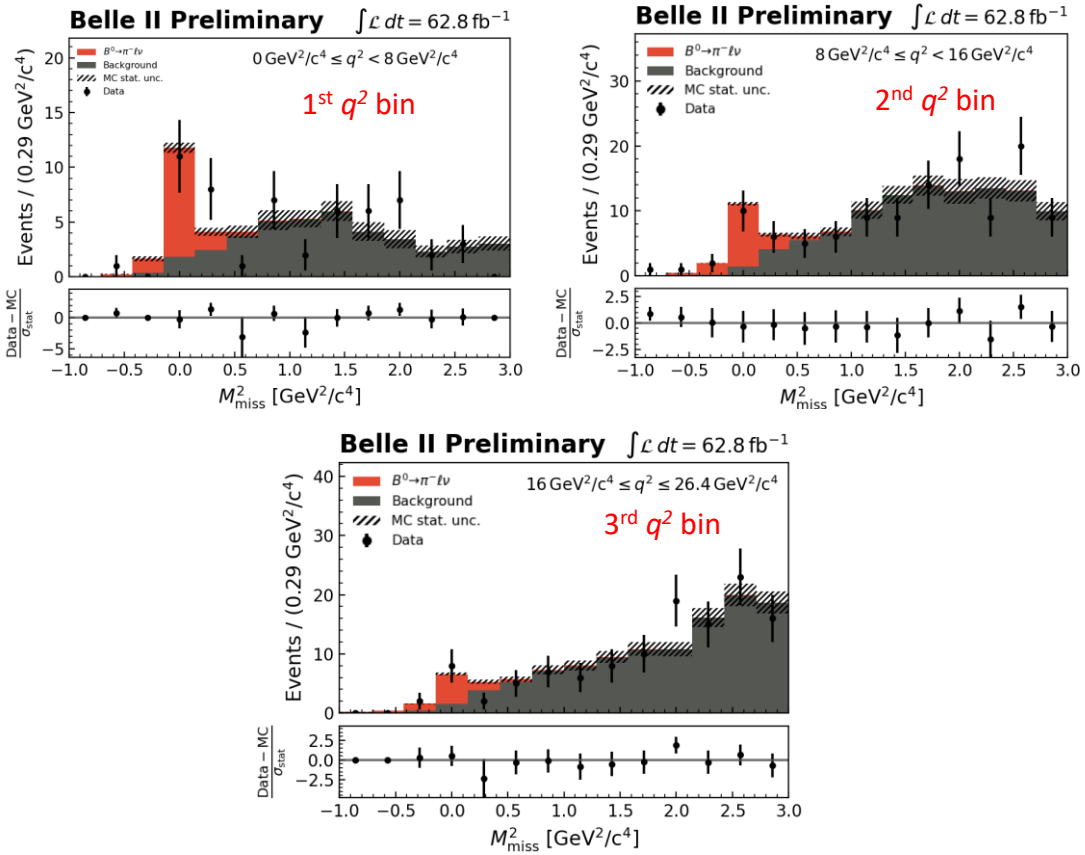
$$\mathcal{B}(B^+ \to \pi^0 \ell^+ \nu_\ell) = (8.29 \pm 1.99(\text{stat}) \pm 0.46(\text{syst})) \times 10^{-5}$$

PDG: $(7.80 \pm 0.27) \times 10^{-5}$

Hadronic Tagged $B \to \pi \ell \nu_\ell$

arXiv:2111.00710

- For $B^0 \to \pi^- \ell \nu_\ell$, signal extraction via 3 bins of the square of the 4-momentum transfer to the leptonic system, q^2
- Branching fraction consistent with PDG, dominant systematic uncertainty due to calibration of FEI algorithm



- Next steps: $|V_{ub}|$ extraction
- Semi-leptonic tagged and untagged $B \to \pi \ell \nu_\ell$ in progress

$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.47 \pm 0.29(\text{stat}) \pm 0.05(\text{syst})) \times 10^{-4}$$

(from sum of partial branching fractions in 3 q^2 bins)

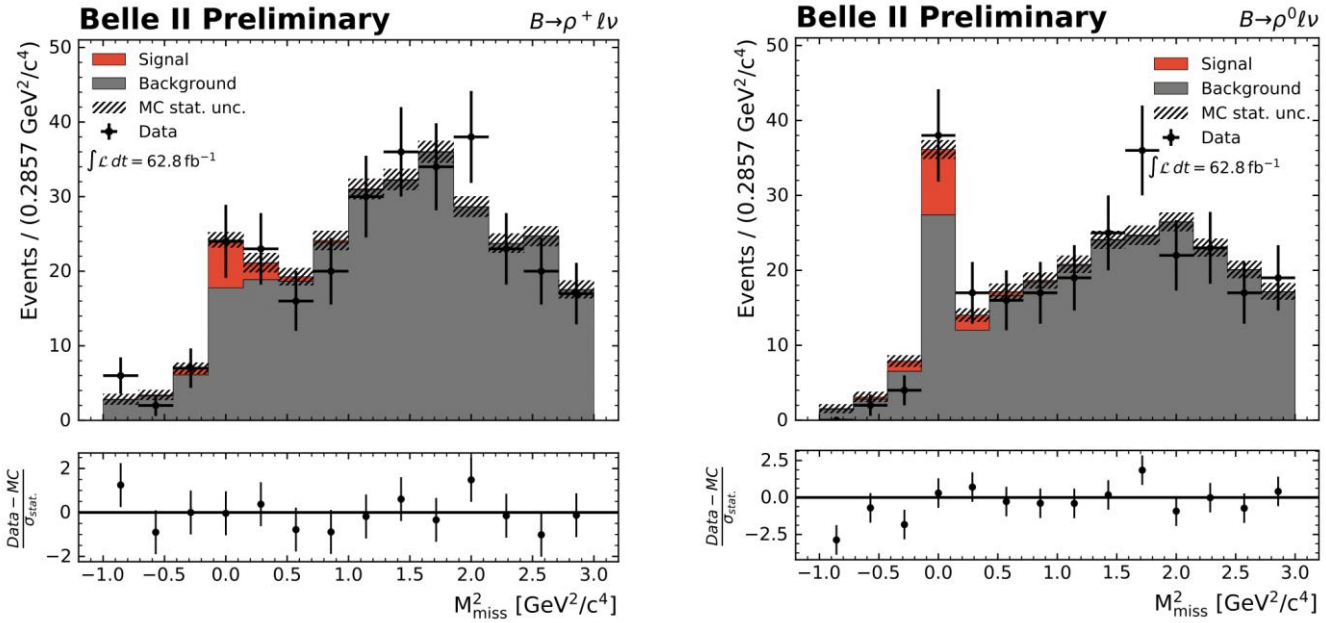
PDG: $(1.50 \pm 0.06) \times 10^{-4}$

$$m^2_{\text{miss}} = \left(p_{e^+e^-} - p_{B_{\text{tag}}} - p_\pi - p_\ell\right)^2$$

First Results: Hadronic Tagged $B \to \rho \ell \nu_\ell$

arXiv:2111.00710

- Hadronic tag selected satisfying minimum threshold on FEI classifier output
- ρ-meson selected within mass window $M_{\pi\pi} \in [0.333, 1.217]$ GeV/c^2
- Events with tracks remaining after $\Upsilon(4S)$ reconstruction excluded
- Signal extraction via distribution of m^2_{miss}
- Next steps: 2-dimensional signal extraction via m^2_{miss} and $M_{\pi\pi}$ to constrain backgrounds



Due to low signal significance at this sample size (< 2σ), 95% CL upper limits on branching fractions quoted at present:

$$\mathcal{B}(B^0 \to \rho^- \ell^+ \nu_\ell) < 3.37 \times 10^{-4} \qquad \mathcal{B}(B^+ \to \rho^0 \ell^+ \nu_\ell) < 1.97 \times 10^{-4}$$

$$m^2_{\text{miss}} = \left(p_{e^+ e^-} - p_{B_{\text{tag}}} - p_\rho \quad - p_\ell \right)^2$$

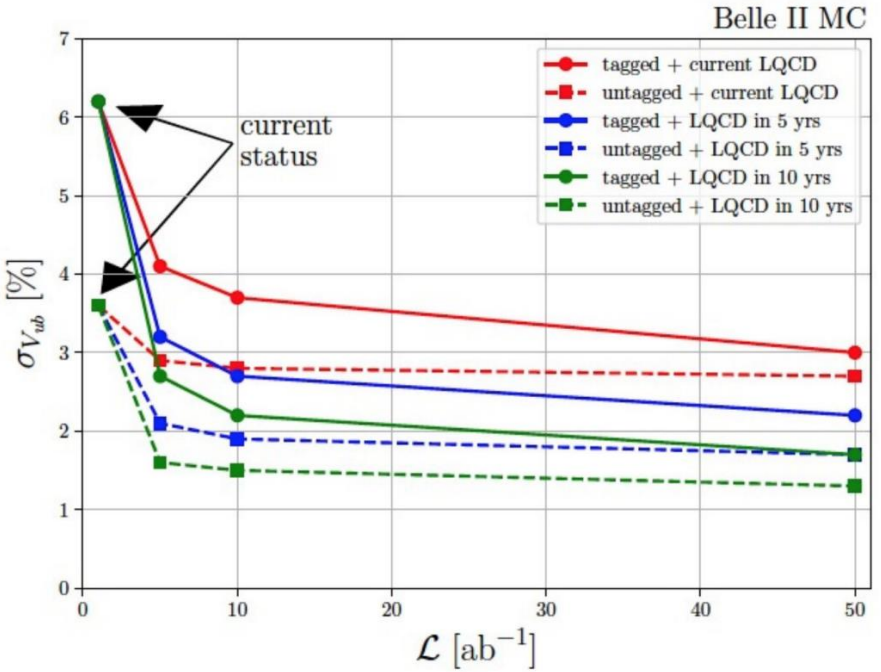
PDG: $(2.94 \pm 0.11 \pm 0.18) \times 10^{-4}$

PDG: $(1.58 \pm 0.11) \times 10^{-4}$

Prospects for $|V_{ub}|$ and $|V_{cb}|$ with Exclusive Semi-leptonic Decays

arXiv:1808.10567

- Dominant uncertainty in unitarity triangle fits due to $|V_{ub}|$
- Belle II simulation: potential to reduce uncertainty on $|V_{ub}|$ by a factor of 2 (untagged) at target integrated luminosity
- Improved precision on exclusive $|V_{cb}|$ also anticipated



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Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb

The Belle II Physics Book

(for target 50 ab^{-1})

Summary

- Exclusive semi-leptonic *B*-meson decays are golden modes for extractions of CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$
- With large projected dataset and improved detector, Belle II aims to increase precision of these measurements and resolve tension between inclusive and exclusive results
- Multiple studies of exclusive semi-leptonic decays underway using various analysis approaches, with first $|V_{ub}|$ and $|V_{cb}|$ measurements planned for 2022
- Related topics: - Inclusive semi-leptonic decays (Raynette van Tonder)

  - Exclusive semi-leptonic decays involving τ leptons (Racha Cheaib)

The Belle II Collaboration

Back-up

First Results: Hadronic Tagged $B \to \rho \ell \nu_\ell$

	$B^0 \to \rho^- \ell^+ \nu_\ell$	$B^+ \to \rho^0 \ell^+ \nu_\ell$
$N_{\rm sig}^{\rm data}$	11.0 ± 8.3	13.7 ± 9.4
$\mathcal{B}$	$(1.51 \pm 1.13(\text{stat}) \pm 0.09(\text{syst})) \times 10^{-4}$	$(9.26 \pm 6.33(\text{stat}) \pm 0.38(\text{syst})) \times 10^{-5}$
95% CL limit	$< 3.37 \times 10^{-4}$	$< 19.7 \times 10^{-5}$
$\mathcal{B}_{\rm PDG}$	$(2.94 \pm 0.11 \pm 0.18) \times 10^{-4}$	$(1.58 \pm 0.11) \times 10^{-4}$