Latest semileptonic results from Belle II

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(She/Her/They/Them)

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on behalf of the Belle II Collaboration

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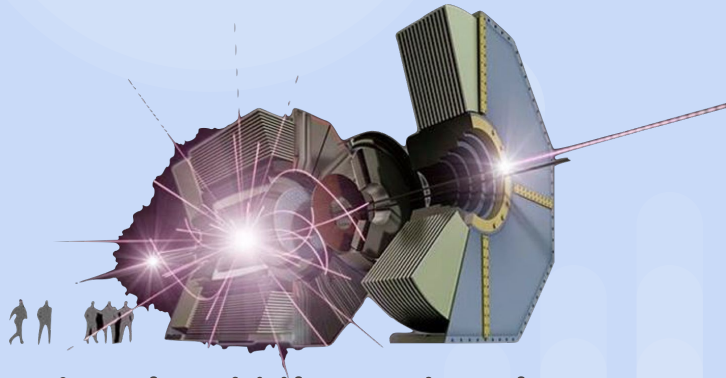
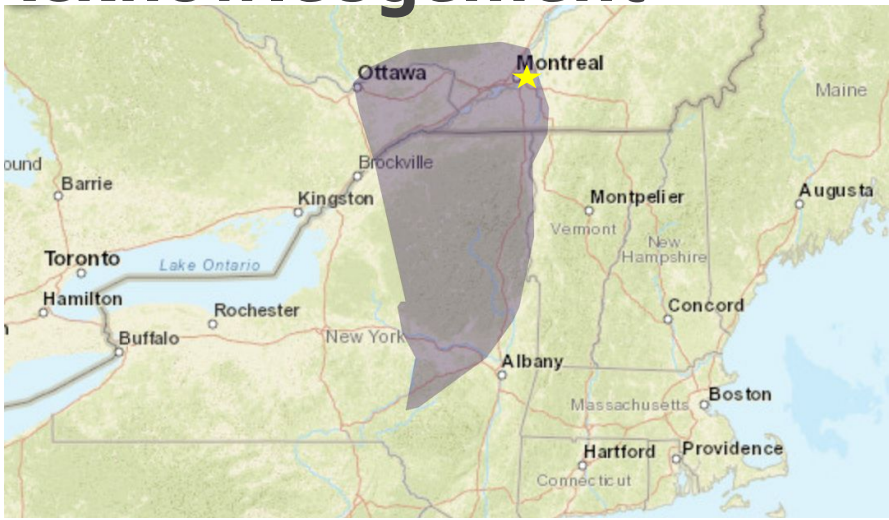


Lake Louise Winter Institute
25th February 2022

Traditional Territory Acknowledgement

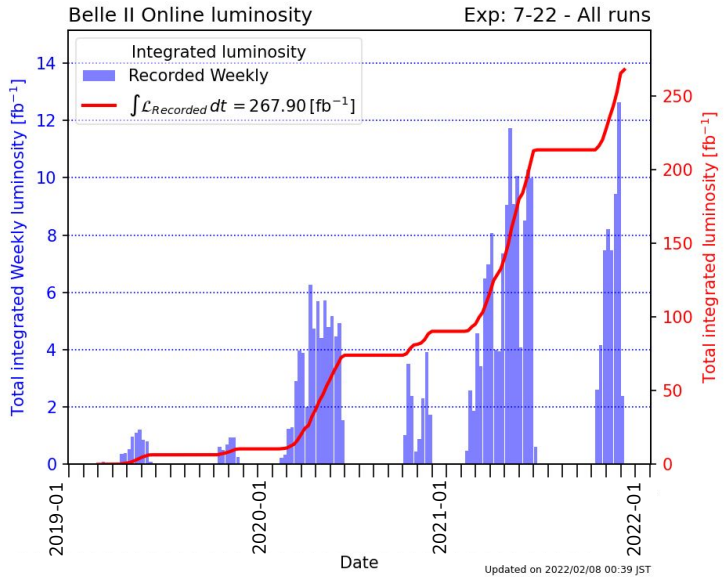
McGill is situated on unceded, Kanien'kehá:ka traditional territory. This means that this land was taken, not paid for or given by the Kanien'kehá:ka people.

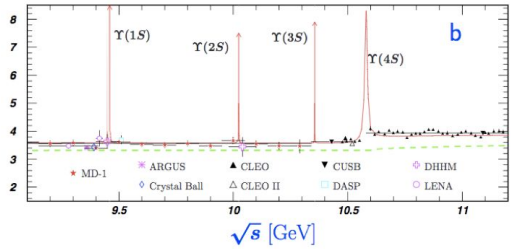


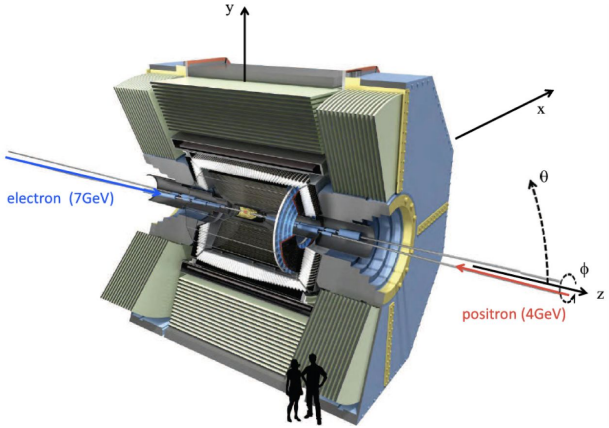
This site has long served as a site of meeting and exchange amongst Indigenous peoples, including the Haudenosaunee and Anishinabeg nations. Through this acknowledgement I hope to respect the diverse Indigenous peoples connected to this territory on which I work and live in today.

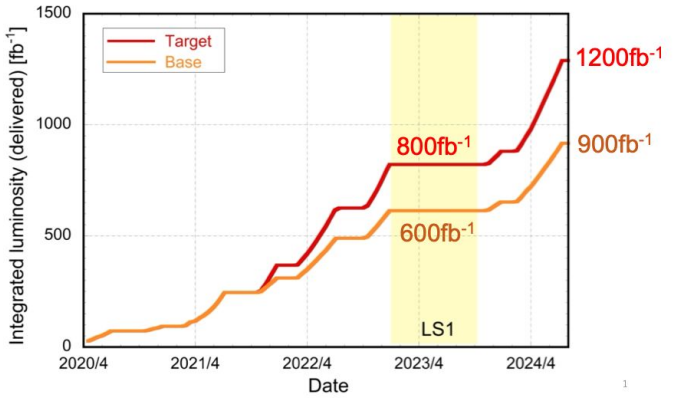
The Belle II Experiment & SuperKEKB

- Asymmetric e^-e^+ collider at 7 GeV and 4 GeV in Tsukuba, Japan
- B meson factory (~1.1x10^9 $B\bar{B}$ pairs per ab^{-1})
- Target luminosity of 50 ab^{-1} (Belle ~710 fb^{-1}, BaBar ~424 fb^{-1})
- Studying B, D and τ physics, hadron spectroscopy and dark-sector searches



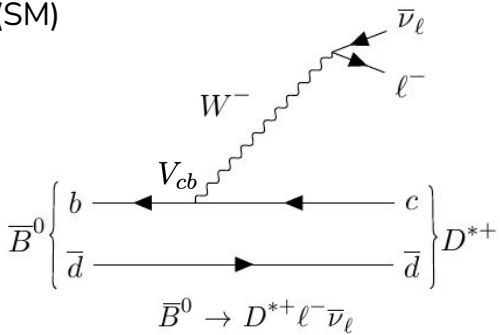






Semileptonic decays

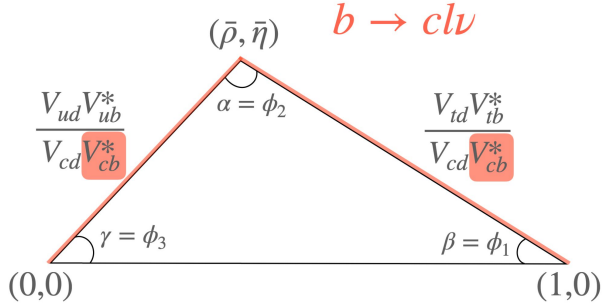
- Decays with 1 or more hadrons, 1 charged lepton l and corresponding neutrinos ν; mediated by the W boson in the Standard Model (SM)



- The ν are inferred as missing energy in our detector
- $b \to c l \nu^{\dagger}$ and $b \to u l \nu$ transitions are crucial for the determination Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix elements
- Measured inclusively $B \to X \ell \nu$ or exclusively $B \to D^* \ell \nu$

$$V_{\mathrm{CKM}} = \begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix}$$

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



A unitary CKM triangle highlighting $|V_{cb}|$ in $b \to c l \nu$

The Belle II Physics Book arXiv:1808.10567

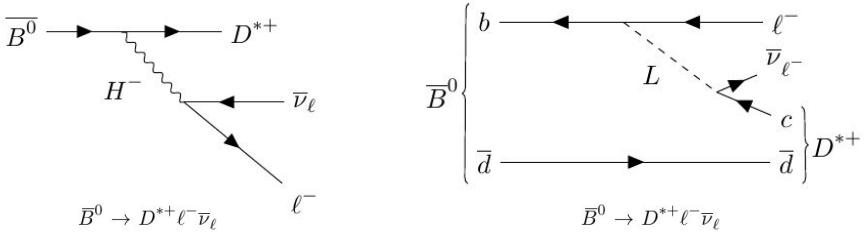
† l represents either an e or μ.

Semileptonic decays

$$|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3} \text{ (inclusive)}$$
$$|V_{cb}| = (39.5 \pm 0.9) \times 10^{-3} \text{ (exclusive)}$$

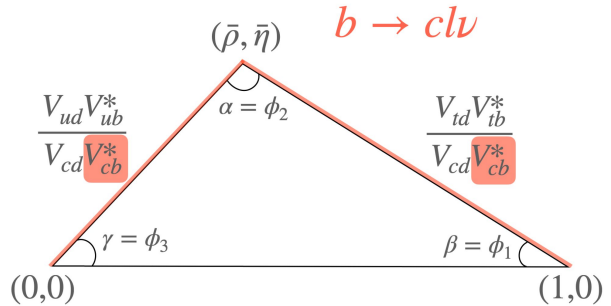
(PDG values. Tension of order 3σ)

- Existing tension between inclusive and exclusive approaches in measurements of $|V_{ub}|$ and $|V_{cb}|$
- Full projected Belle II dataset will be key in understanding this tension through examination at higher precision and through accessing other variables
- Could be sensitive to New Physics



Example models: Two-Higgs Doublet Model and leptoquark model

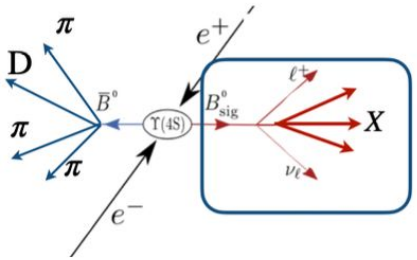
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



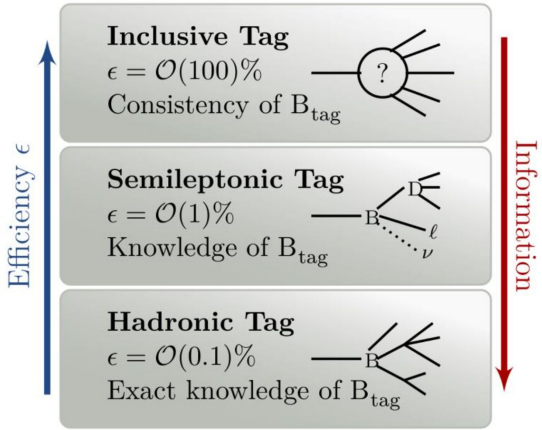
A unitary CKM triangle highlighting $|V_{cb}|$ in $b \to c l\nu$

The Belle II Physics Book arXiv:1808.10567
P.A. Zyla *et al.* (Particle Data Group),Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

Reconstruction methods



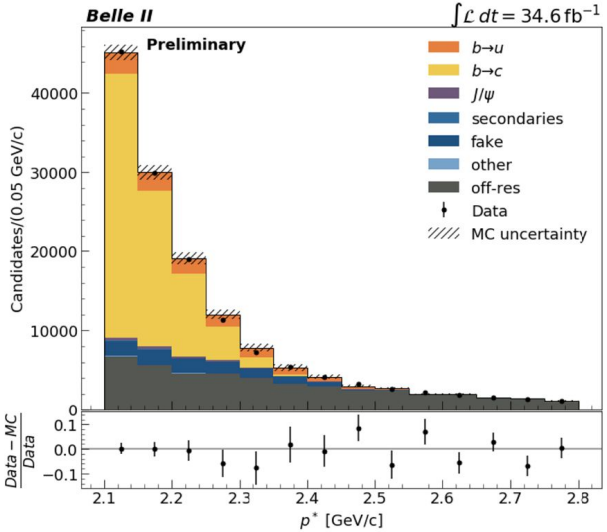
- Untagged approach (“inclusive tag”)
  - Signal decay B_{sig} is reconstructed
  - Particles in the rest of event assigned to the “inclusive tag”
  - Very efficient but low purity
- Tagged approach (semileptonic and hadronic tags)
  - Both B mesons in event are reconstructed, Signal B_{sig} and other B_{tag}
  - $B_{tag}$is exclusively reconstructed using
    - semileptonic decay modes (only partial B_{tag} knowledge)
    - hadronic decay modes (exact knowledge of the B_{tag})
  - Hadronic tagging essential in missing energy measurements

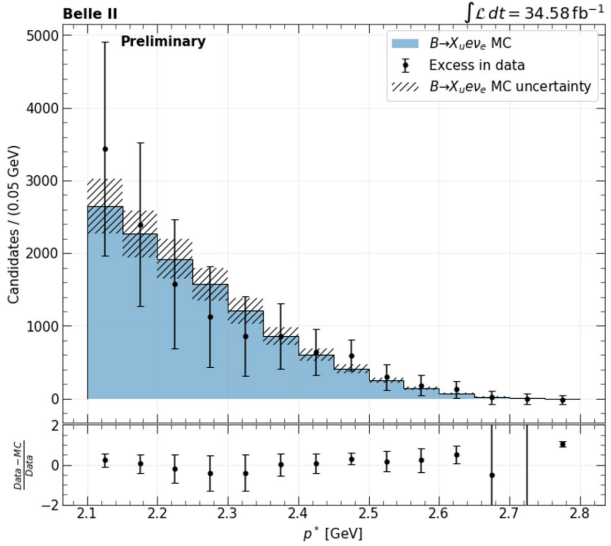


The Belle II Physics Book arXiv:1808.10567

Inclusive $B \to X_u e \nu_e$

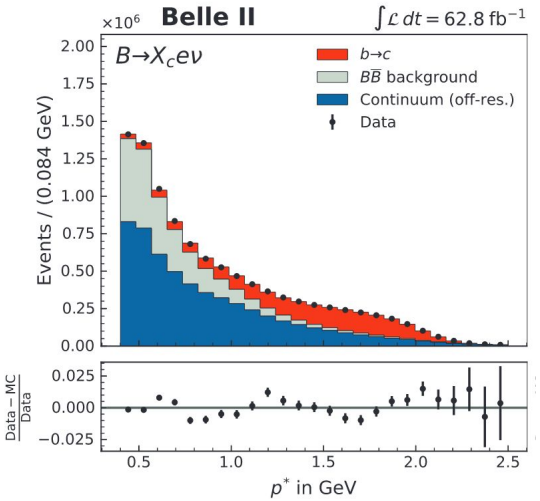
- Untagged method
- Using the lepton endpoint momentum spectrum towards a measurement of $|V_{ub}|$
- Continuum suppressed using multivariate Boosted Decision Tree (MVA BDT) trained with event shape variables
- Evidence for $B \to X_u e \nu_e$ with signal significance in excess of 3σ

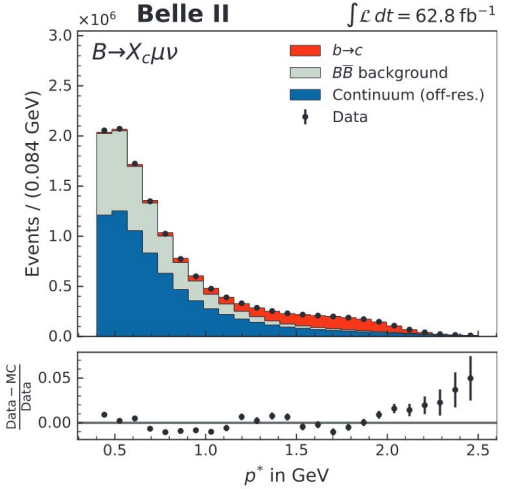




Inclusive $B \to X_c l^- \nu_l$

- Untagged method
- $\mathcal{B}(B \to X_c \ell \nu_\ell) = (9.75 \pm 0.03(\text{ stat }) \pm 0.47(\text{ sys }))\%$
  $\mathcal{B}_{\text{PDG}} = (10.99 \pm 0.28)\%$
- Dominant systematics: $B \to X_c l^- \nu_l$ branching fractions
- Towards to determining $|V_{cb}|$ and m_b
- Next: result will be extended to measure moments of q^2 (see back-up)
  $q^2 = (p_l + p_\nu)^2 = (p_B - p_X)^2$





Inclusive Xc l nu arXiv:2111.09405
An Alternative Method arXiv:1812.07472

Exclusive $B^- \to D^0 l^- \bar{\nu}_l$

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

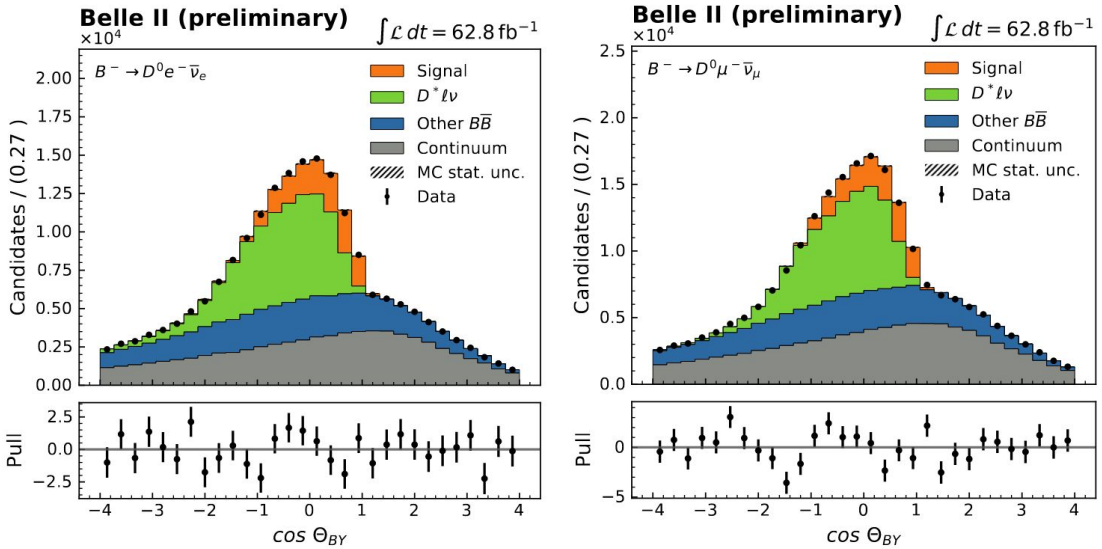
- Untagged method
- Competitive branching fraction measurement consistent with PDG:

$$\mathcal{B}\left(B^- \to D^0 \ell^- \bar{\nu}_\ell\right) = (2.29 \pm 0.05_{\text{stat}} \pm 0.08_{\text{syst}})\,\%$$
$$\mathcal{B}_{\text{PDG}} = (2.31 \pm 0.10)\%$$

- $B \to D^* l \nu_l$ backgrounds reduced using a dedicated veto

- Next: extraction of $|V_{cb}|$ from fits to $\cos(\theta_{BY})$ in bins of hadronic recoil parameter w

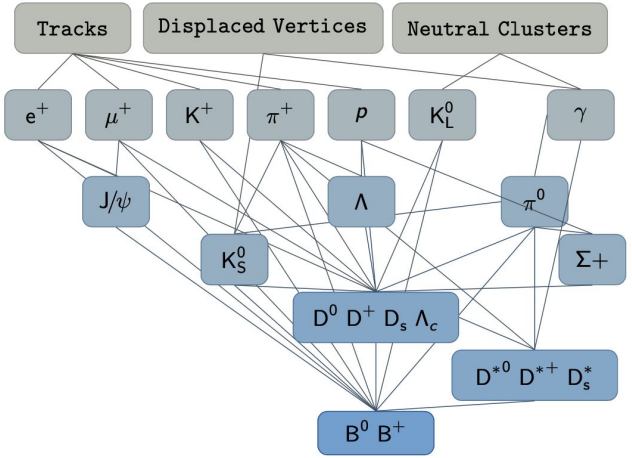
$$w = \frac{m_B^2 + m_{D^{*+}}^2 - q^2}{2 m_B m_{D^{*+}}} = v_B \cdot v_{D^{*+}}$$

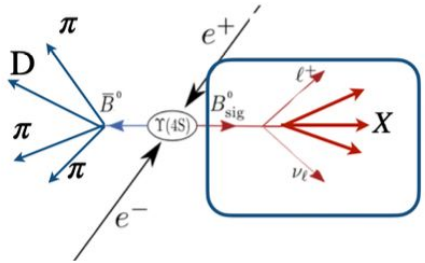


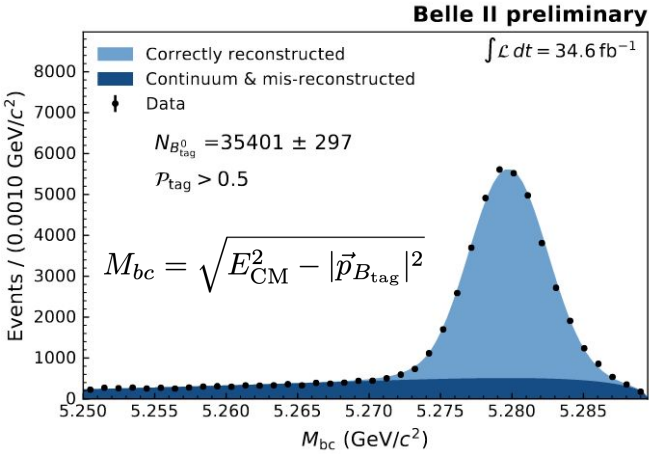
Untagged B → D0 l nu Decays arXiv:2110.02648

Full Event Interpretation

- A MVA tagging algorithm with a hierarchical approach
- 200+ BDTs and 10000+ B decays
- 30-50% improvement in efficiency compared to Full Reconstruction at Belle
- FEI calibrated against data to obtain reconstruction efficiencies
- Hadronic FEI calibration strategy is established using $B \to X l \nu$ with subset of data
- Semileptonic FEI calibration and performance studies projected for summer 2022





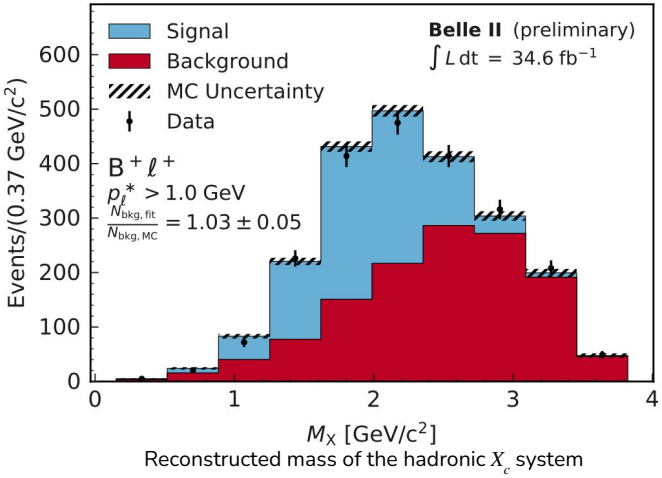


[The Full Event Interpretation arXiv:1807.08680]
[A Hadronic FEI Calibration arXiv:2008.06096]

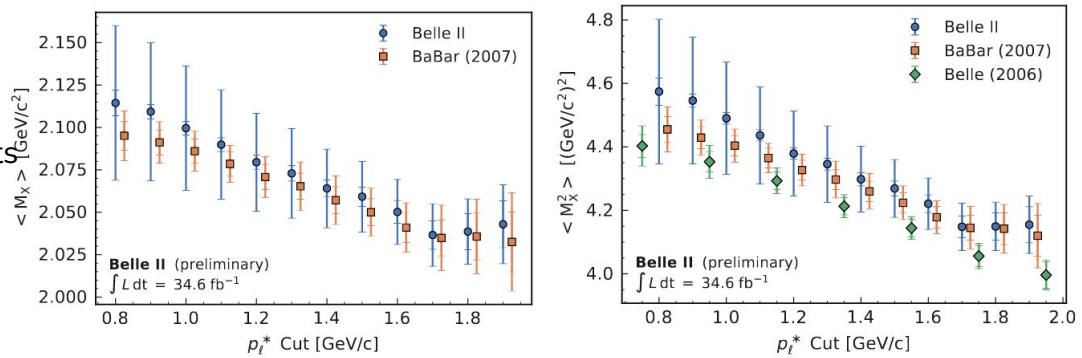
Hadronic mass moments

- Using hadronic FEI tagged $B \rightarrow X_c l \nu_l$
- Moments calibrated and shown in comparison with Belle (2006) and BaBar (2007) results
- Precision not yet competitive
- Towards determination of $|V_{cb}|$ and m_b
- Result will be extended to measure moments of q^2 (see back-up)

$$q^2 = (p_l + p_\nu)^2 = (p_B - p_X)^2$$



Reconstructed mass of the hadronic X_c system



Measured $\langle M_X^n \rangle$ moments as a function of different p_l^* cuts

Hadronic Mass Moments arXiv:2009.04493

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

Exclusive $B \to \pi l \nu_l$

- $B^+ \to \pi^0\, l^+ \nu_l$

  $\mathcal{B}_{\text{PDG}} = (7.80 \pm 0.27) \times 10^{-5}$

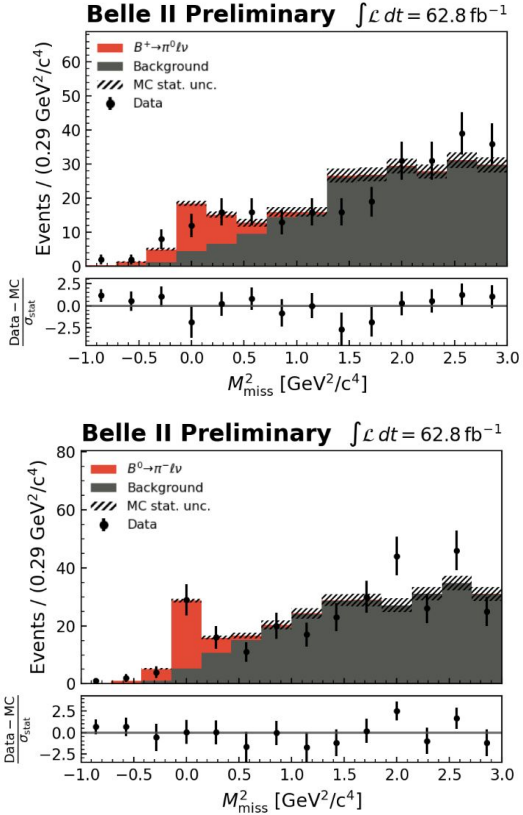
  - Using hadronic tagged FEI
  - Measurement consistent with PDG:
    $\mathcal{B}\left(B^+ \to \pi^0 \ell^+ \nu_\ell\right) = (8.29 \pm 1.99(\text{ stat }) \pm 0.46(\text{ syst })) \times 10^{-5}$
  - Dominant systematics: calibration of FEI algorithm and π^0 reconstruction efficiency

- $B^0 \to \pi^-\, l^+ \nu_l$

  $\mathcal{B}_{\text{PDG}} = (1.50 \pm 0.06) \times 10^{-4}$

  - Using hadronic tagged FEI
  - Measurement consistent with PDG:
    $\mathcal{B}\left(B^0 \to \pi^- \ell^+ \nu_\ell\right) = (1.47 \pm 0.29(\text{ stat }) \pm 0.05(\text{ syst })) \times 10^{-4}$

    from sum of partial branching fractions in 3 q^2 bins
  - Dominant systematic: calibration of FEI algorithm
  - Exclusive $|V_{ub}|$ extraction, semileptonic (un)tagged studies in progress



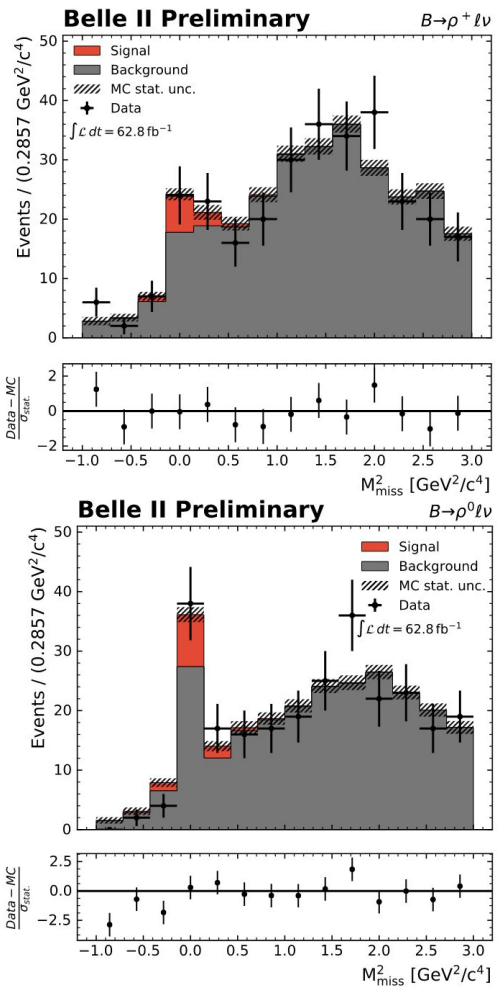
Exclusive B → Xu l nu Decays arXiv:2111.00710

Exclusive $B \to \varrho l \nu_l$

- Using hadronic tagged FEI
- Low signal significance at this sample size

  ∴ 95% CL upper limits on these branching fractions
- $\mathcal{B}\left(B^0 \to \rho^- \ell^+ \nu_\ell\right) < 3.37 \times 10^{-4} \qquad \mathcal{B}_{\mathrm{PDG}} = (2.94 \pm 0.21) \times 10^{-4}$
- $\mathcal{B}\left(B^+ \to \rho^0 \ell^+ \nu_\ell\right) < 1.97 \times 10^{-4} \qquad \mathcal{B}_{\mathrm{PDG}} = (1.58 \pm 0.11) \times 10^{-4}$
  - Measured branching fraction consistent with PDG
- Uncertainties dominated by sample size

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



Exclusive B to Xu l ν arXiv:2111.00710

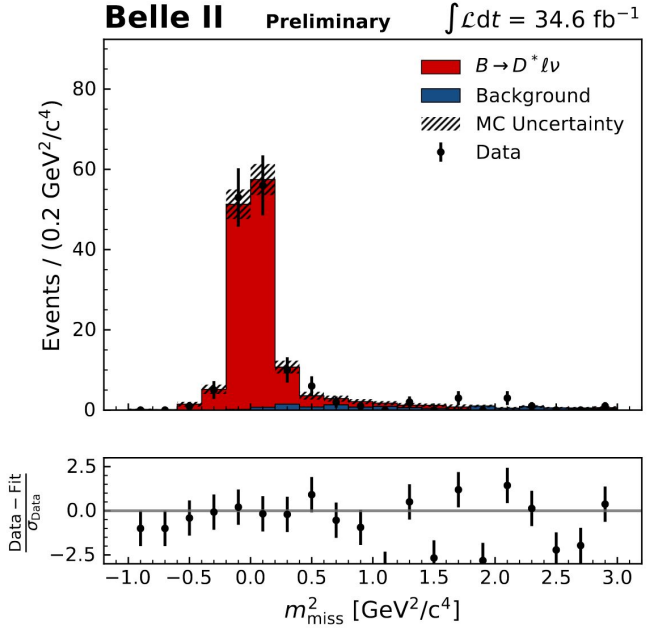
$$\mathcal{B}_{\mathrm{PDG}} = (5.06 \pm 0.12)\,\%$$

Exclusive $\bar{B}^0 \to D^{*+} l^- \bar{\nu}_l$

- Using hadronic tagged FEI
- With $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$ (golden mode)
- Signal extraction via $m^2_{\mathrm{miss}} = \left(p_{e^+e^-} - p_{B_{tag}} - p_{D_*} - p_\ell\right)^2$

  $\mathcal{B}\left(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_l\right) = (4.51 \pm 0.41_{\mathrm{stat}} \pm 0.27_{\mathrm{syst}} \pm 0.45_{\pi_s})\,\%$
- Dominant systematic: slow pion efficiency $(D^{*+} \to D^0 \pi_s^+)$

- Study expanded to include more than golden mode
- MVA in development for D^{**} background and continuum suppression
- Optimization of this mode as the denominator in $R(D^{(*)})$
  - Test of LFU
- Aim of first result summer 2022



$$R(D^*) \equiv \frac{\mathcal{B}\left(B \to D^{(*)}\tau^-\bar{\nu}_\tau\right)}{\mathcal{B}\left(B \to D^{(*)}\ell^-\bar{\nu}_\ell\right)}$$

Exclusive B → D* l nu Decay arXiv:2008.10299

Summary

Belle II is an ideal environment in which to study semileptonic decays

Full Event Interpretation developed and calibrated

- Untagged analyses
  - Inclusive $B \to X_u e \nu_e$ arXiv:2103.02629
  - Inclusive $B \to X_c l^- \nu_l$ arXiv:2111.09405
  - Exclusive $B^- \to D^0 l^- \nu_l$ arXiv:2110.02648
- Hadronic tagged analyses
  - FEI Calibration arXiv:2008.06096
  - Hadronic mass moments arXiv:2009.04493
  - Exclusive $B \to \pi l \nu_l$ arXiv:2111.00710
  - Exclusive $B \to \varrho l \nu_l$ arXiv:2111.00710
  - Exclusive $B^0 \to D^{*+} l^- \nu_l$ arXiv:2008.10299

More exciting results to come with more data!

All PDG values quoted from P.A. Zyla *et al.* (Particle Data Group),Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

Back-up

$$\mathcal{B}_{\mathrm{PDG}} = (5.06 \pm 0.12)\%$$

Exclusive $\bar{B}^0 \to D^{*+} l^- \bar{\nu}_l$ (An older result)

- Untagged method
- Branching fraction consistent with PDG:

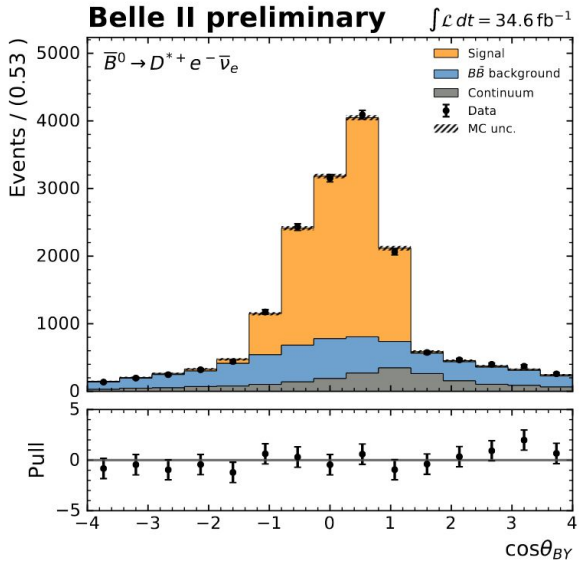
$$\mathcal{B}\left(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_l\right) = (4.60 \pm 0.05_{\mathrm{stat}} \pm 0.17_{\mathrm{syst}} \pm 0.45_{\pi_s})\,\%$$

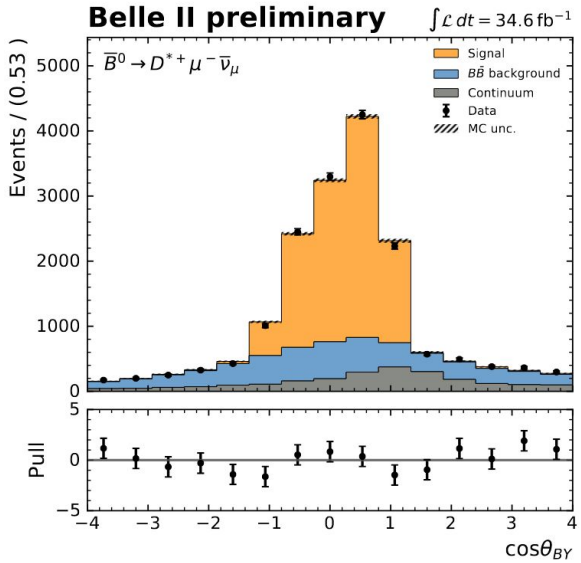
- Dominant systematic:
  - Slow pion tracking $(D^{*+} \to D^0\pi_s^+)$

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

- Next: Extraction of $|V_{cb}|$ from fits $\cos(\theta_{BY})$ in bins of hadronic recoil parameter w

$$w = \frac{m_B^2 + m_{D^{*+}}^2 - q^2}{2m_B m_{D^{*+}}} = v_B \cdot v_{D^{*+}}$$





Untagged B → D l nu Decays arXiv:2008.07198

q^2 moments

- Heavy Quark Expansion (HQE) expansion for Hadronic Mass Moments:

$$\mathrm{Br}\left(\bar{B} \to X_c \ell \bar{\nu}\right) \propto \frac{|V_{cb}|^2}{\tau_B}\left[\Gamma_0 + \Gamma_{\mu_\pi}\frac{\mu_\pi^2}{m_b^2} + \Gamma_{\mu_G}\frac{\mu_G^2}{m_b^2} + \Gamma_{\rho_D}\frac{\rho_D^3}{m_b^3}\right]$$

- ALTERNATIVE (NOVEL) APPROACH to determining $|V_{cb}|$ and m_b
  - With the established method, including higher order HQE terms increases parameters
  - Using q^2 moments and Leptonic invariant mass moments, number of additional HQE parameters can be reduced using "reparametrization invariance" to link different orders of $1/m_b$
  - Tagged and untagged methods in progress

$$\mathrm{Br}(\bar{B} \to X_c \ell \bar{\nu}) \propto \frac{|V_{cb}|^2}{\tau_B}\left[\Gamma_{\mu_3\mu_3} + \Gamma_{\mu_G}\frac{\mu_G^2}{m_b^2} + \Gamma_{\tilde{\rho}_D}\frac{\tilde{\rho}_D^3}{m_b^3} + \Gamma_{r_E}\frac{r_E^4}{m_b^4} + \Gamma_{r_G}\frac{r_G^4}{m_b^4} + \Gamma_{s_B}\frac{s_B^4}{m_b^4} + \Gamma_{s_E}\frac{s_E^4}{m_b^4} + \Gamma_{s_{qB}}\frac{s_{qB}^4}{m_b^4}\right]$$

An Alternative Method arXiv:1812.07472