Semileptonic and Leptonic B Physics at Belle II

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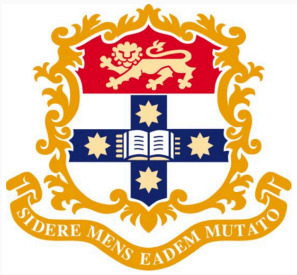
On behalf of the Belle II collaboration

EDSU Conference - November 8, 2022



Reconstruction Strategies

Energies of e^+, e^- beams are tuned to produce $\Upsilon(4S) \to B\overline{B}$

Tagged vs Untagged

Tagged

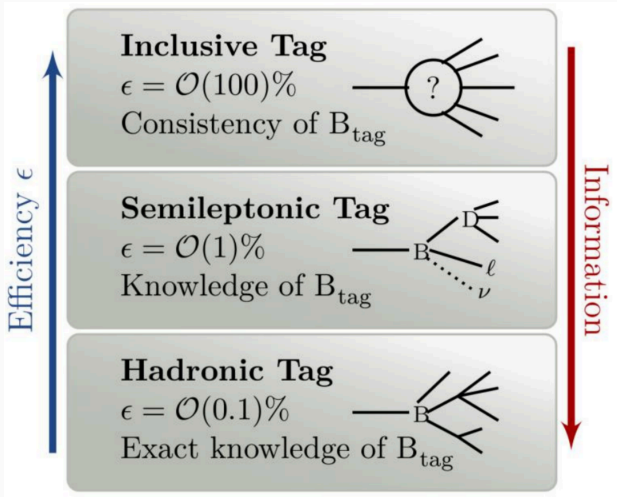
Both B_{sig} and B_{tag} are reconstructed

+ high purity
- low efficiency

Untagged
(Inclusive tagged)

Only the B_{sig} is reconstructed

+ high efficiency
- high backgrounds



Exclusive vs Inclusive: depends on reconstruction of B_{sig}

- Exclusive - B_{sig} is reconstructed in a specific decay mode
- Inclusive - B_{sig} reconstructed as many modes e.g. $B_{\text{sig}} \to X\ell\nu$

$\to$ different approaches are complementary and ideally should agree

FEI: tag is reconstructed using Full Event Interpretation algorithm
[Comput. Softw. Big Sci. 3, 6 (2019)] + more detail in backup slides

Motivation - The CKM Matrix

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

- Matrix must be unitary → imposes constraint to test SM
- Tension between exclusive (orange band) and inclusive (blue band)

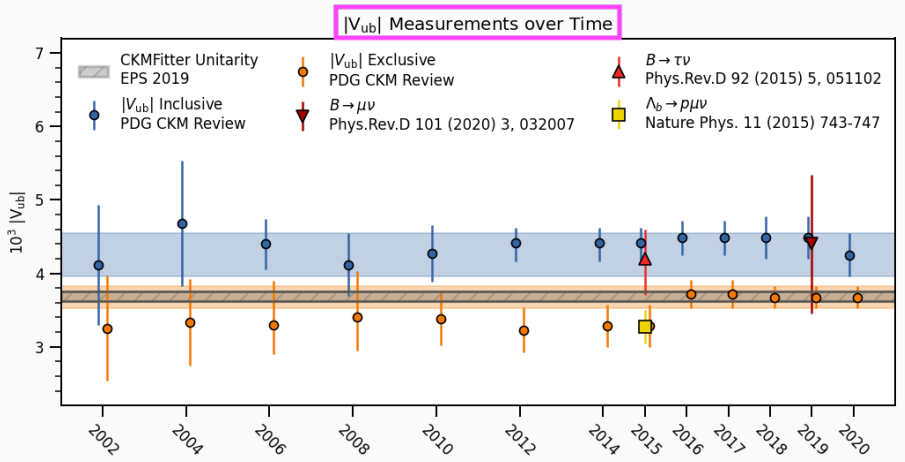
Precision from semileptonic decays. Typical modes studied:

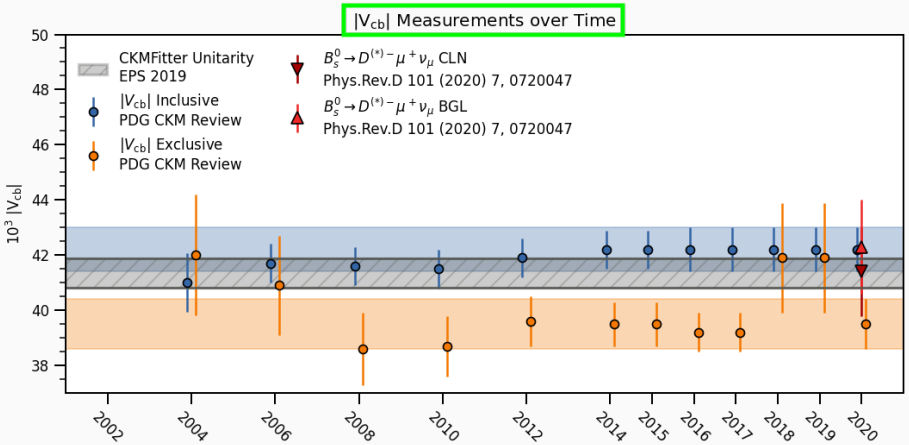
- V_{ub} - $b \to u$ transitions

  e.g. $B \to X_u \ell\nu$, $B \to \rho\ell\nu$, $\mathbf{B \to \pi\ell\nu}$ **tagged/untagged**

- V_{cb} - $b \to c$ transitions

  e.g. $B \to X_c \ell\nu$, $B \to D^*\ell\nu$, $\mathbf{B \to D\ell\nu}$ **untagged** (tagged in backup)





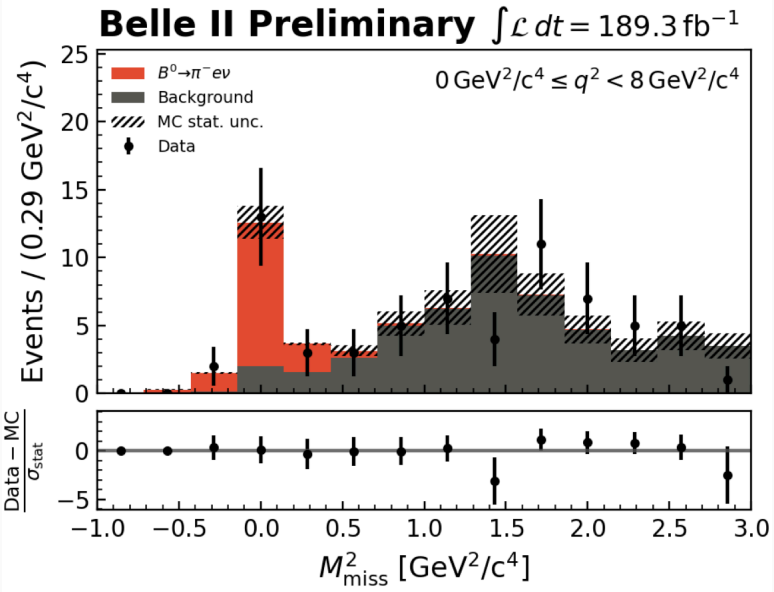
Tagged $B \to \pi \ell \nu$ (arXiv:2206.08102)

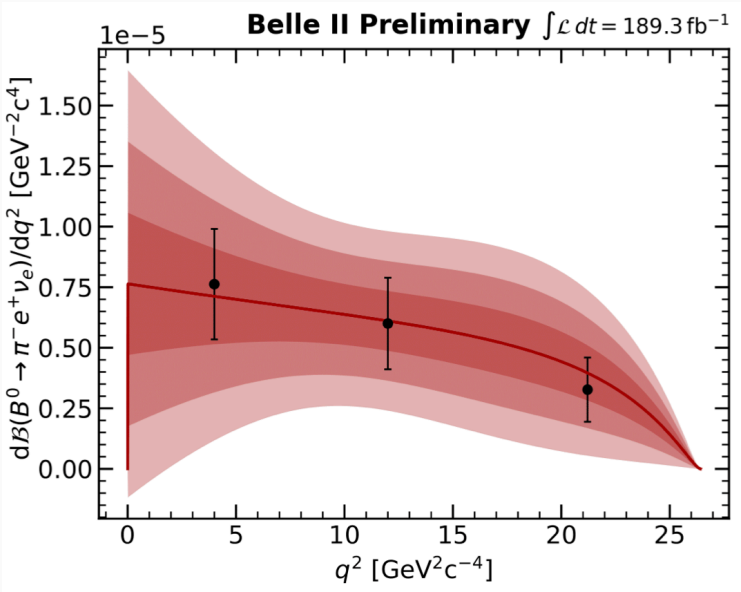
B_{sig} - $B^0 \to \pi^- e^+ \nu_e$ and $B^+ \to \pi^0 e^+ \nu_e$ / B_{tag} - hadronic tag using FEI

Fit to M^2_{miss} in 3 bins of q^2: [0, 8] [8, 16] [16, 26.4] GeV^2

$$M^2_{\text{miss}} = (p_{e^+e^-} - p_{B_{\text{tag}}} - p_e - p_\pi)^2 \ , \ q^2 = (p_{e^+e^-} - p_{B_{\text{tag}}} - p_\pi)^2$$

Results for B^0 mode





χ^2 fit of diff. decay width using BCL parametrisation [Phys. Rev. D 79, 013008] of form factors and FNAL/MILC lattice QCD constraints [Phys. Rev. D 92, 014024]

$$|V_{ub}| = (3.88 \pm 0.45) \times 10^{-3} \quad \text{c.f. PDG: } (3.67 \pm 0.15) \times 10^{-3}$$

$\to$ precision will improve with larger data set

Untagged $B \to \pi \ell \nu$ (arXiv:2210.04224)

Reconstruct $B^0 \to \pi^- \ell^+ \nu$ ($\ell = e, \mu$) with no $B_{\rm tag}$ reconstructed (untagged)

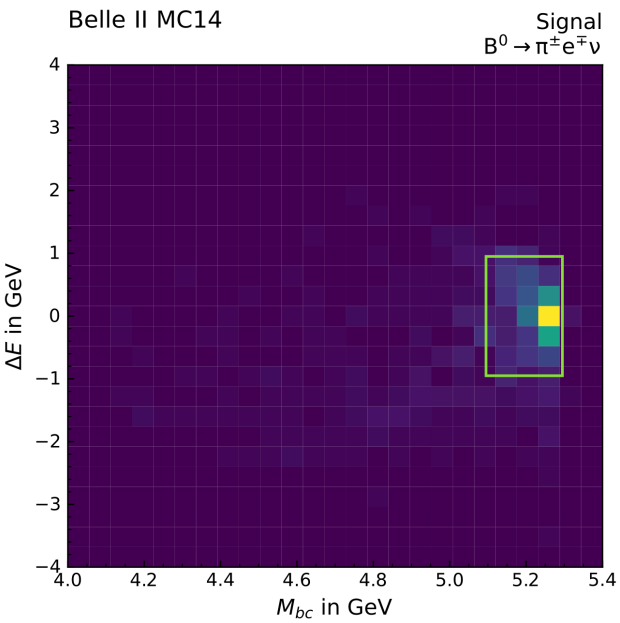
Signal extracted by 2D fit to $M_{\rm bc}$ and ΔE

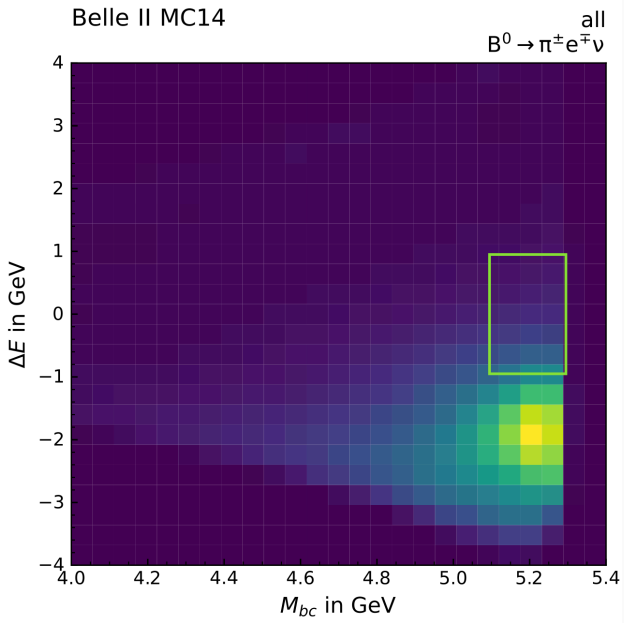
$$M_{\rm bc} = \sqrt{E^{*2}_{\rm beam} - p^{*2}_B} \qquad \Delta E = E^*_B - E^*_{\rm beam}$$

$M_{\rm bc}$ is the beam-energy constrained mass ($E^*_{\rm beam}$ substituted for $E_{\rm B}$)
ΔE is the difference of true and reconstructed energy of the B

Difficulties: suppressing continuum and peaking backgrounds from other semileptonic B decays

Multiple BDTs used to suppress background components



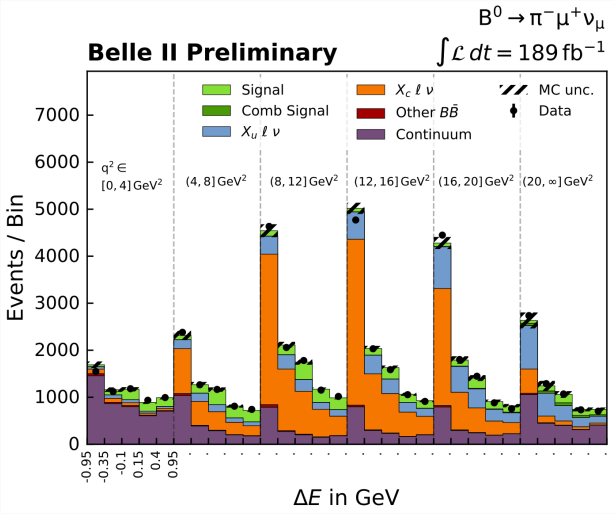


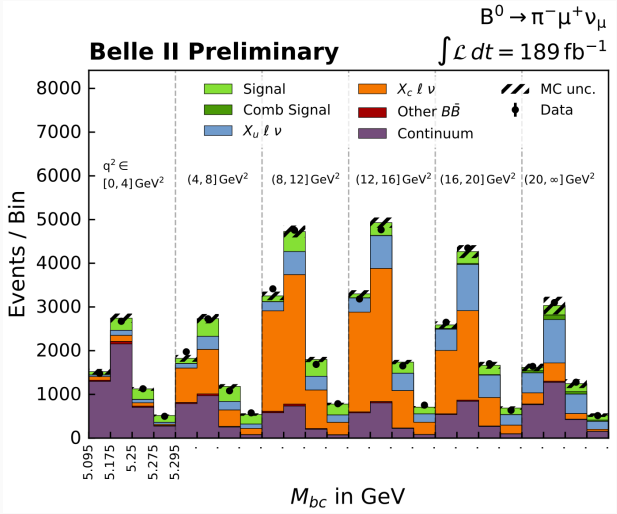
Untagged $B \to \pi \ell \nu$ (arXiv:2210.04224)

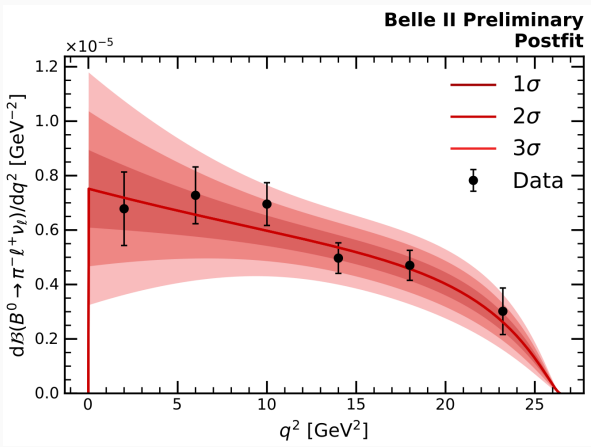
Perform fit in 6 q^2 bins: [0, 4] [4, 8] [8, 12] [12, 16] [16, 20] [20, 26.4] GeV^2

$$q^2 = (q_B - q_\pi)^2$$

- Main components: signal, $X_u \ell \nu$, $X_c \ell \nu$, continuum







Differential decay width dependent on $|V_{ub}|$ and form factors:

$$\frac{d\Gamma}{dq^2} \propto |V_{ub}|^2 |f_+(q^2)|^2$$

BCL parametrisation [Phys. Rev. D 79, 013008] of form factors and FNAL/MILC lattice QCD constraints [Phys. Rev. D 92, 014024] used to extract $|V_{ub}|$

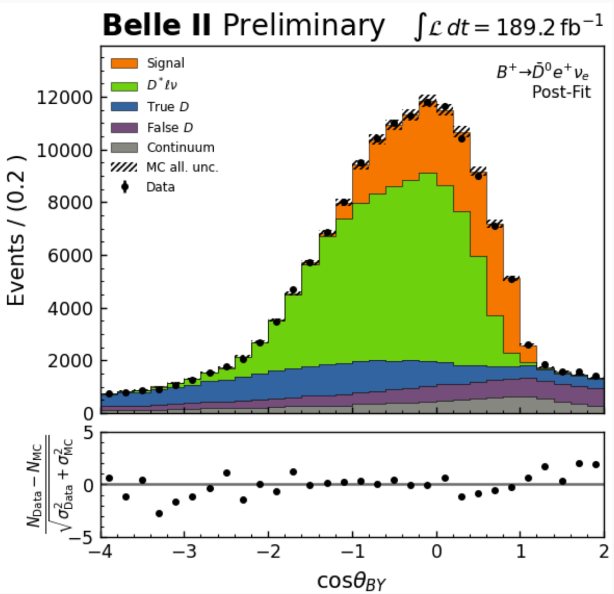
$|V_{ub}| = (3.54 \pm 0.12_{\text{stat}} \pm 0.15_{\text{sys}} \pm 0.16_{\text{th}}) \times 10^{-3}$ c.f. **PDG:** $(3.67 \pm 0.15) \times 10^{-3}$

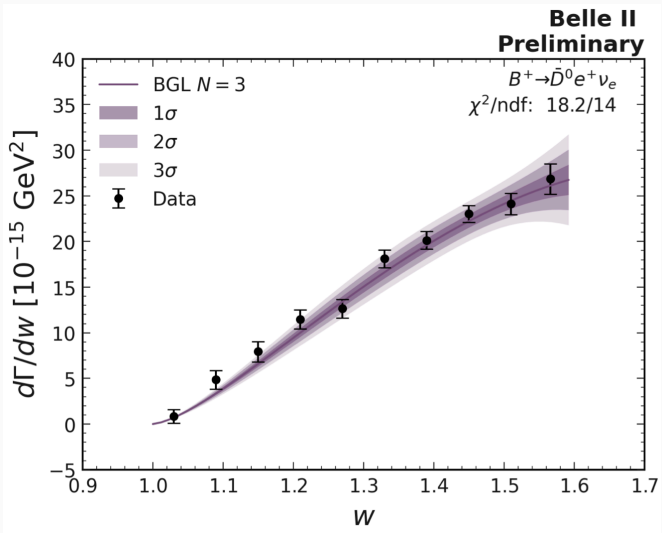
Untagged $B \to D\ell\nu$ (arXiv:2210.13143)

Reconstruct $B^+ \to \bar{D}^0 \ell^+ \nu$ and $B^0 \to D^- \ell^+ \nu$ with $D \to K\pi(\pi)$

Signal extracted from 1D fit to $\cos\theta_{\mathrm{BY}}$ (between -1 and 1 for signal):

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





Diff. decay width depends on $|V_{cb}|$ and form factor:

$$\frac{d\Gamma}{dw^2} \propto |V_{cb}|^2 \mathcal{G}(w^2)$$

$$w = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$$

BGL parametrisation (N=3) [Phys. Rev. D 56, 6895] of form factor and FNAL/MILC, HPQCD [Phys. Rev. D 93, 119906] lattice QCD constraints used to extract $|V_{cb}|$ from 10 bins of w

$$|V_{cb}| = (38.53 \pm 1.15) \times 10^{-3} \quad \text{c.f. PDG: } (39.14 \pm 0.92_{\mathrm{exp}} \pm 0.36_{\mathrm{th}}) \times 10^{-3}$$

$R(X_{e/\mu})$ (To be submitted to PRL)

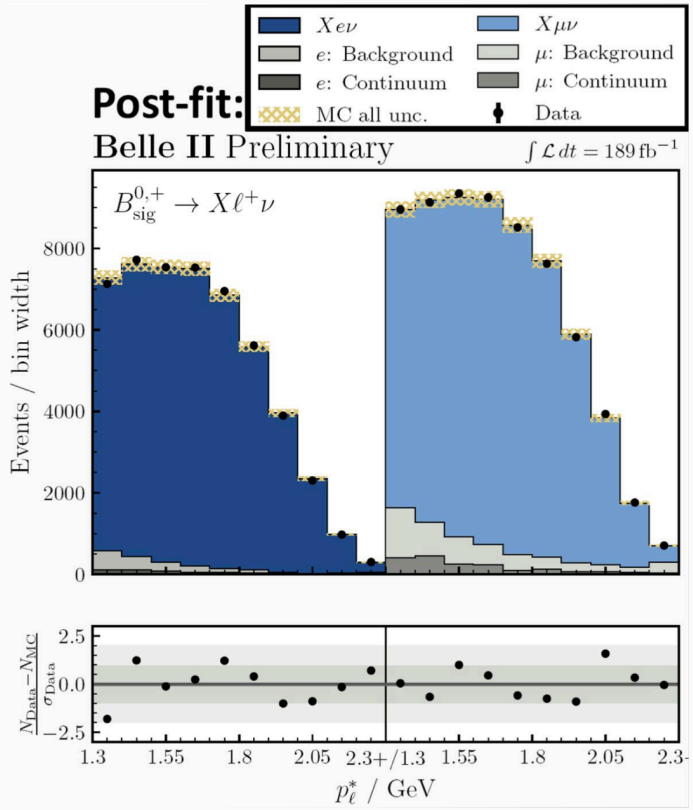
New lepton flavour universality test for light leptons

$$R(X_{e/\mu}) = \frac{\mathcal{B}(B \to Xe\nu)}{\mathcal{B}(B \to X\mu\nu)}$$

Inclusive reconstruction: $B^+/B^0 \to X\ell\nu$ with hadronic tag using FEI

Fit templates for signal, continuum and background (incorrect charge sideband)

Simultaneous binned likelihood fits for e, μ modes in 10 bins of p^*_ℓ



See dedicated ICHEP 2022 talk

$$R(X_{e/\mu})^{p^*_\ell > 1.3\ \mathrm{GeV}} = 1.033 \pm 0.010_{\mathrm{stat}} \pm 0.020_{\mathrm{sys}}$$

Most precise BF based LFU test

$\to$ compatible with Belle result for $R(D^*_{e/\mu})$ [Phys. Rev. D100, 052007 (2019)]

$\to$ paves the way for $R(X_{\tau/\ell})$

Summary

First measurements of $|V_{ub}|$ and $|V_{cb}|$ from Belle II

- Key to understanding exclusive-inclusive tension
- Important in testing CKM parameters in the context of SM predictions

World-leading BF based LFU test with $R(X_{e/\mu})$ result

- Important test for SM and probe beyond the SM physics

Other Semileptonic Results

Measurement of $\mathcal{B}(B \to X_c \ell \nu)$

[arXiv: 2111.09405]

Measuring q^2 moments from $B \to X_c \ell \nu$

[arXiv: 2205.06372]

Main Ongoing Leptonic Analyses

$B \to \mu\nu$ w/ semileptonic tag

$B \to \mu\nu$ untagged

$B \to \tau\nu$ w/ hadronic tag

$B \to \tau\ell$ w/ hadronic tag (mine)

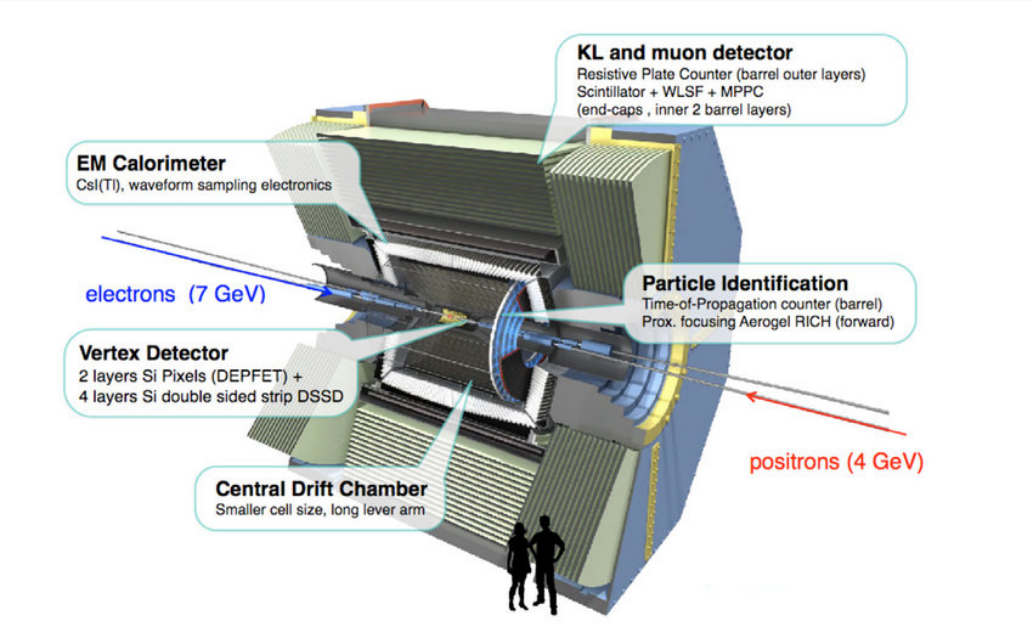
Soon: $R(D^*)$, A_{fb} from $B \to D^* \ell \nu$ and more on $|V_{ub}|$ and $|V_{cb}|$

Questions?

Future of Belle II - Detector Upgrades

Promising upgrades for Belle II in future - some relevant highlights

Subdetector	Improvements	Key Impacts
VXD	Tracking efficiency at low momentum Vertex and IP resolution	V_{cb} studies which use $q^2 \equiv (p_l + p_\nu)^2$ Vetoes for rare B decays Time-dependent CP violation studies B decays with $b \to s\ell\ell$ processes
TOP/ARICH	Minimisation of QE losses Timing resolution	Cabibbo suppressed hadronic B decays, $\|V_{ub}\|$ from inclusive semileptonic B decays
KLM	Time-of-flight measurements	Time-dependent CP violation studies Background suppression for all analyses
Trigger	Track trigger from CDC and VXD	Higher efficiency for precision measurements, rare B decays, dark sector and τ physics



Snowmass paper for detector upgrade: arXiv:2203.11349

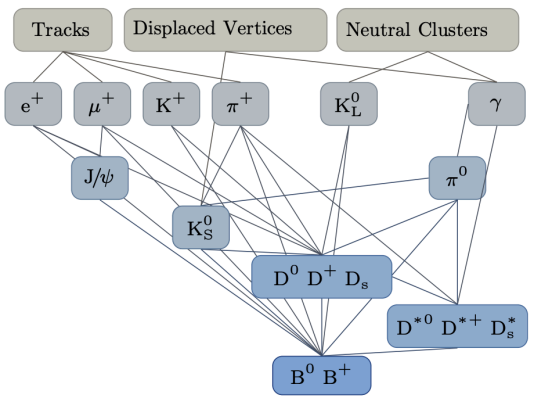
Full Event Interpretation (FEI)

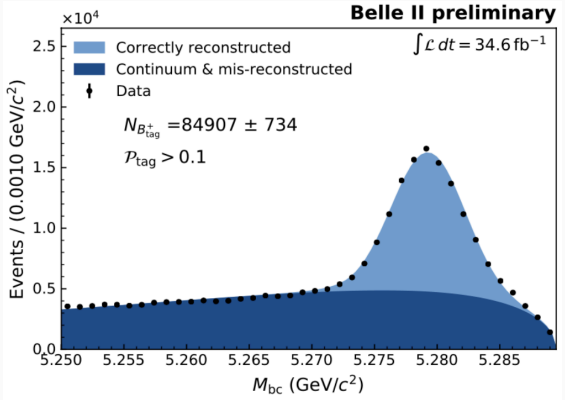
FEI algorithm is used to reconstruct B_{tag}

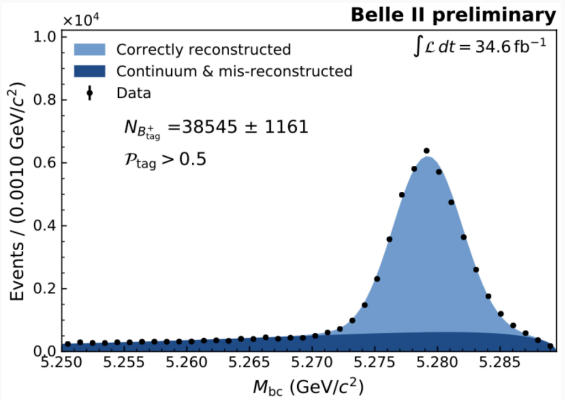
- Uses $\approx$ 200 BDTs to reconstruct $\mathcal{O}(10000)$ different B decay chains using detector information
- Probability of correct B candidate is assigned
- Max tag-side efficiency: hadronic B_{tag} = 0.76% ($B^{\pm}$), 0.46% (B^{0})

  $\approx$ 50% higher efficiency than Belle

[Comput. Softw. Big Sci. 3, 6 (2019)]





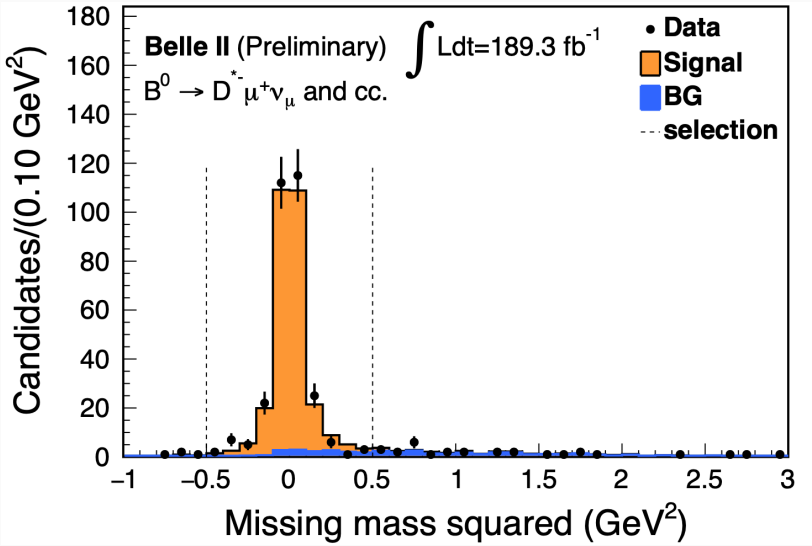


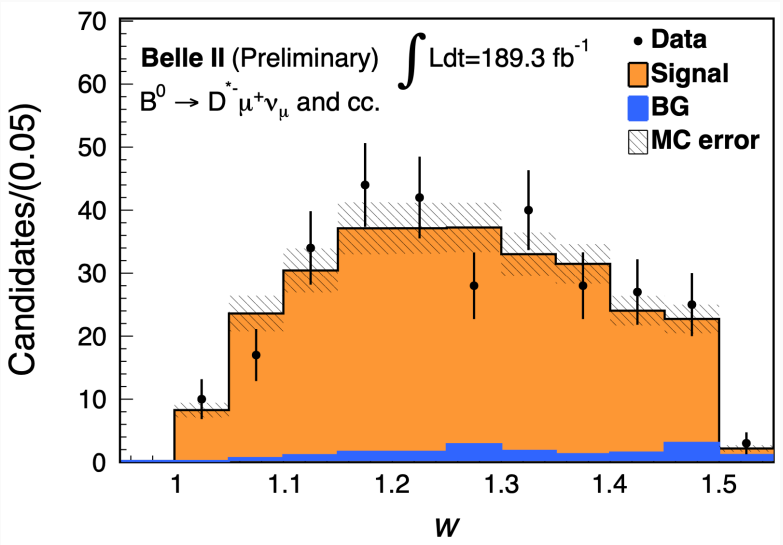
$$M_{\mathrm{bc}} = \sqrt{E^{*2}_{\mathrm{beam}} - p^{*2}_{B}}$$

Tagged $B \to D^* \ell \nu$

Reconstruct $B^0 \to D^{*-} \ell^+ \nu$ with $D^{*-} \to \bar{D}^0 \pi_s^-$, $\bar{D}^0 \to K^+ \pi^-$ and hadronic tag

Fit m^2_{miss} in 10 bins of $w = (m_B^2 + m_{D^*}^2 - q^2)/(2 m_B m_{D^*})$





Fit diff. decay width using CLN parametrised form factor

[Nucl. Phys. B530 (1998) 153-181]

$$|V_{cb}| = (37.9 \pm 2.7) \times 10^{-3}$$

c.f.

World Av: $(38.46 \pm 0.4_{\mathrm{exp}} \pm 0.55_{\mathrm{th}})$