THE UNIVERSITY OF SYDNEY

Belle II

Measuring $|V_{ub}|$ at Belle II with Semileptonic $B \to \pi e^+ \nu_e$ Decays

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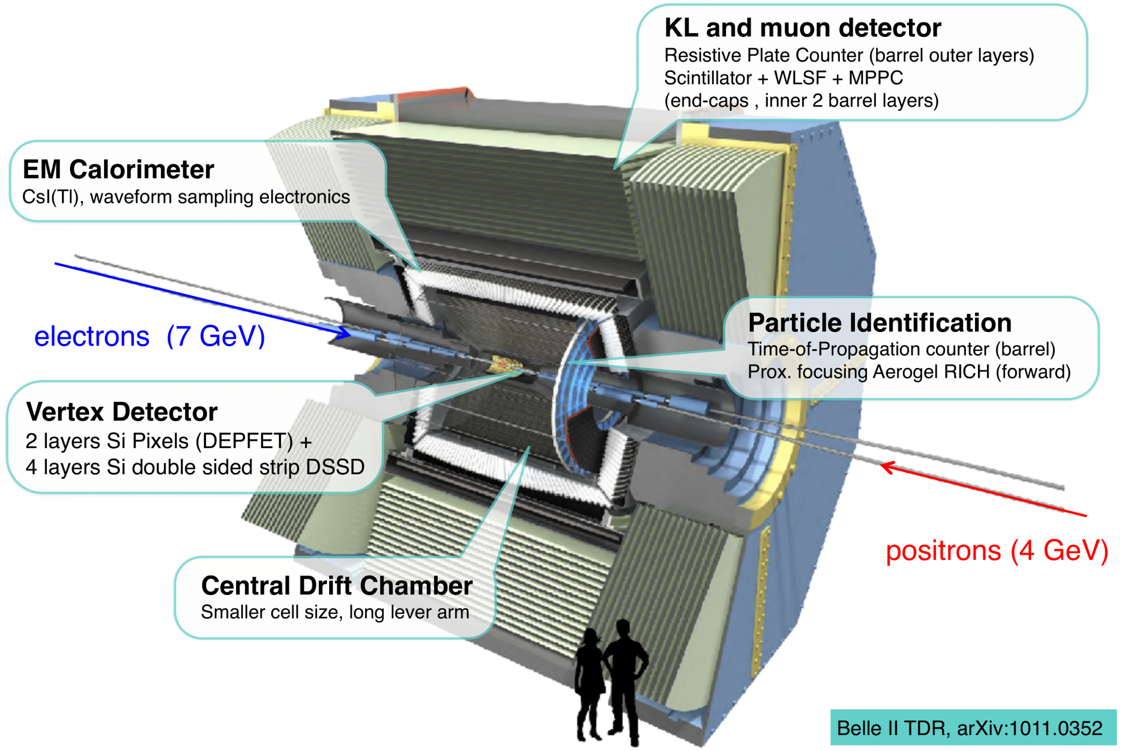
Outline

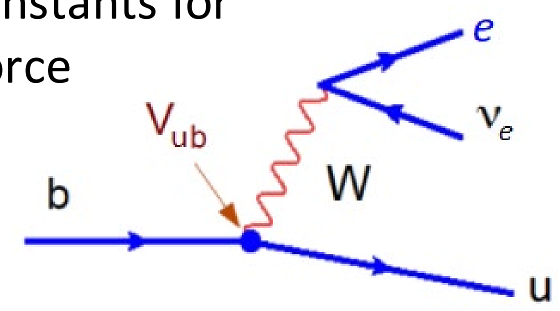
- Motivation
- Reconstruction methods for semileptonic *B*-decays
- Recent results on $B \to \pi e^+ \nu_e$
- $|V_{ub}|$ extraction
- Summary and prospects



The $b \rightarrow u$ Quark Transition and V_{ub}

- The CKM-matrix describes the coupling constants for quark transitions mediated by the weak force

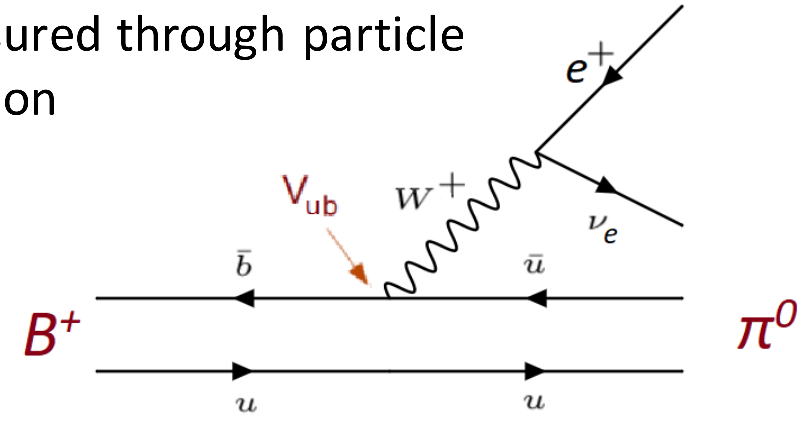
e.g. $b \rightarrow u$ with coupling constant V_{ub}



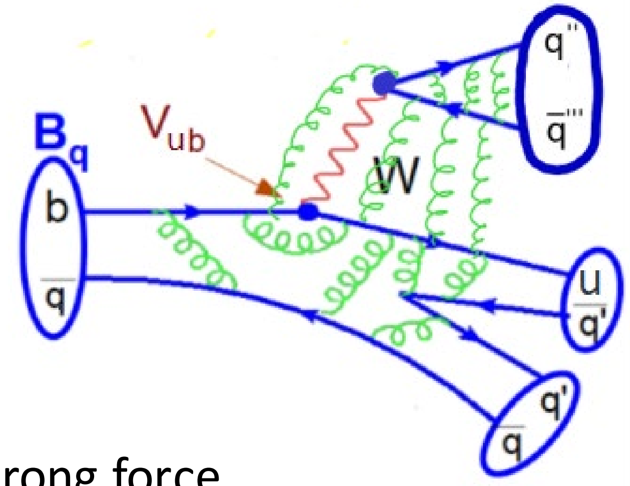
$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}$$

- The magnitude of V_{ub} can be measured through particle decays involving the $b \rightarrow u$ transition

e.g. $B^0 \rightarrow \pi^- e^+ \nu_e$ and $B^+ \rightarrow \pi^0 e^+ \nu_e$



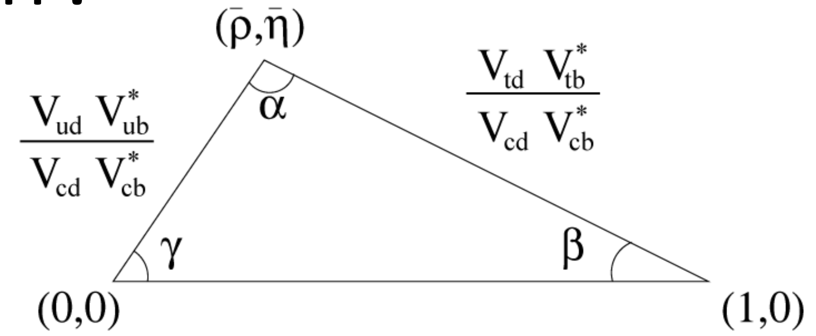
$B^+ \rightarrow \pi^0 e^+ \nu_e$



- In reality, particle decay is complicated by interactions between quarks via the strong force

Why Measure $|V_{ub}|$ at Belle II?

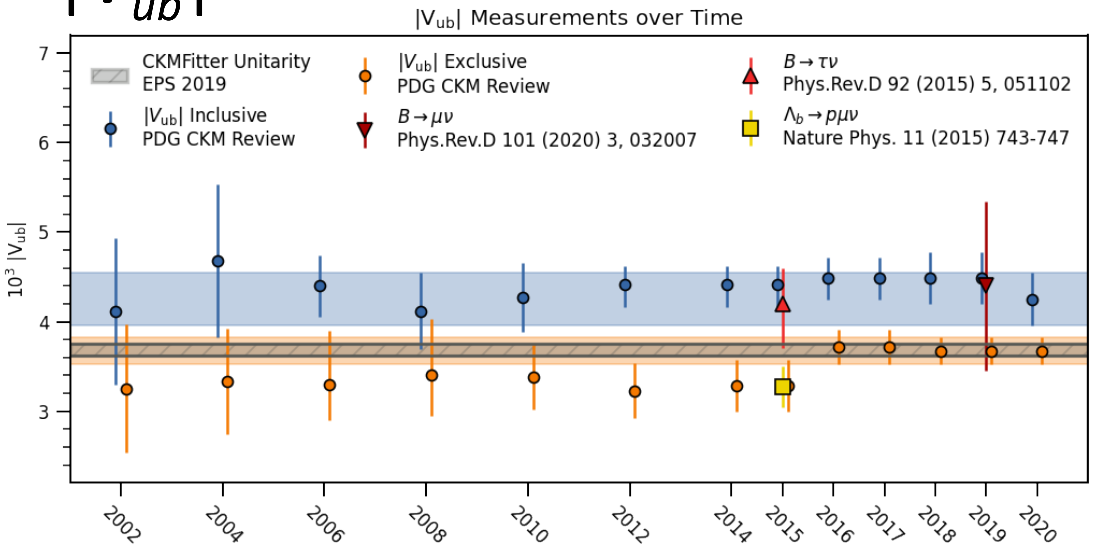
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



- Precision measurements of the magnitudes of CKM matrix elements are key for testing unitarity condition, particularly for $|V_{ub}|$, which forms a dominant uncertainty

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

$|V_{ub}|$



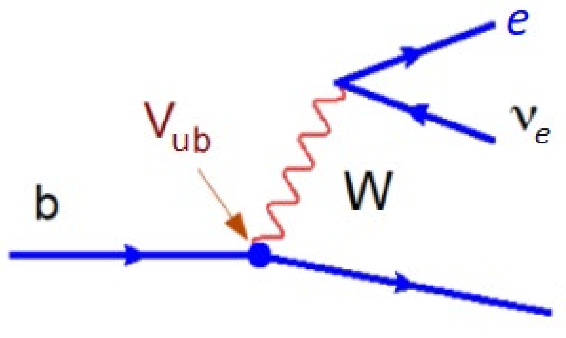
- Existing tension between $|V_{ub}|$ from exclusive vs. inclusive approaches of order ~3σ

Exclusive:
A single final state
e.g. $B^0 \to \pi^- e^+ \nu_e$

Inclusive:
All final states considered
e.g. $B^0 \to X_u^- e^+ \nu_e$

- Projected Belle II dataset will be significant in resolving this tension and improving precision

Exclusive $|V_{ub}|$ at Belle II: $B \to \pi e^+ \nu_e$



$p_W^2 = q^2$

- Exclusive semileptonic decays including $B \to \pi e^+ \nu_e$ are golden modes for measurements of $|V_{ub}|$:

$$\frac{d\Gamma(B^0 \to \pi^- \ell^+ \nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 |p_\pi|^3 |f_+(q^2)|^2$$

Experiment:
Measure differential decay rate as a function of the square of the 4-momentum transfer to the leptonic system, q^2

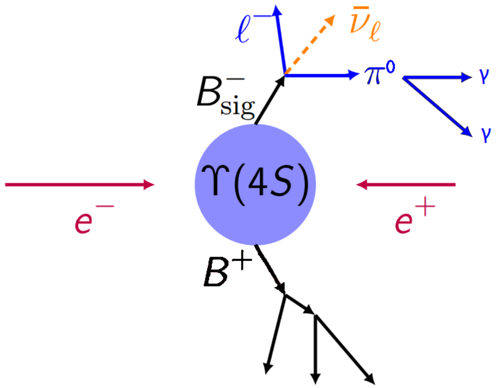
Theory:
Description of the form factors including suitable parameterisation

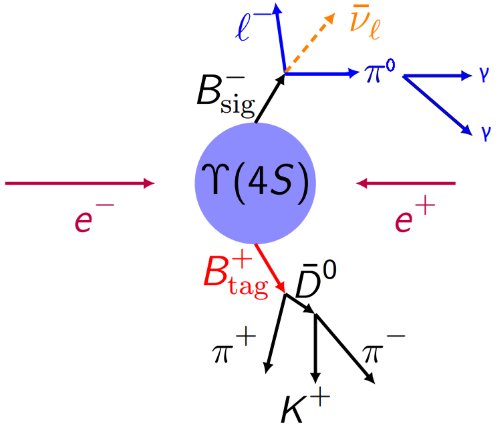
Reconstruction Methods for Exclusive Semi-leptonic Decays at Belle II

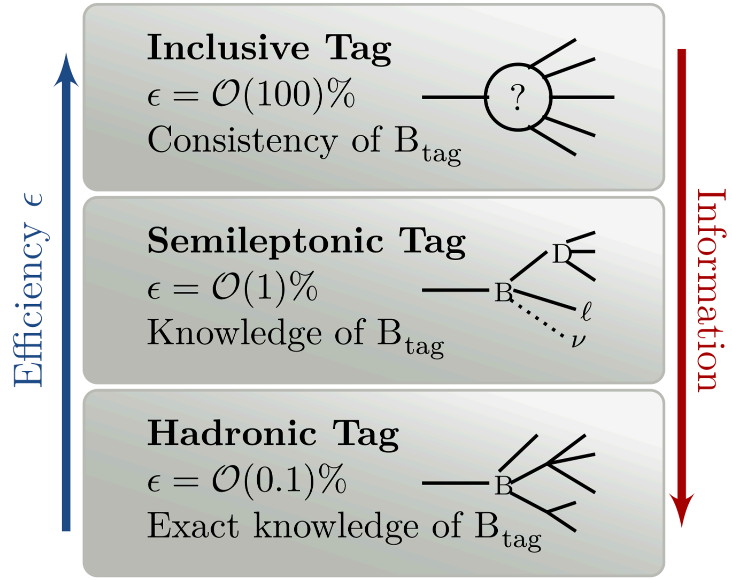
- Untagged(inclusive tagged) approaches:
  - Reconstruct signal decay of interest
  - All remaining particles in event assigned to inclusive tag
  - Highly efficient but low purity, selection optimisation key

- 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

$\ell = e, \mu$



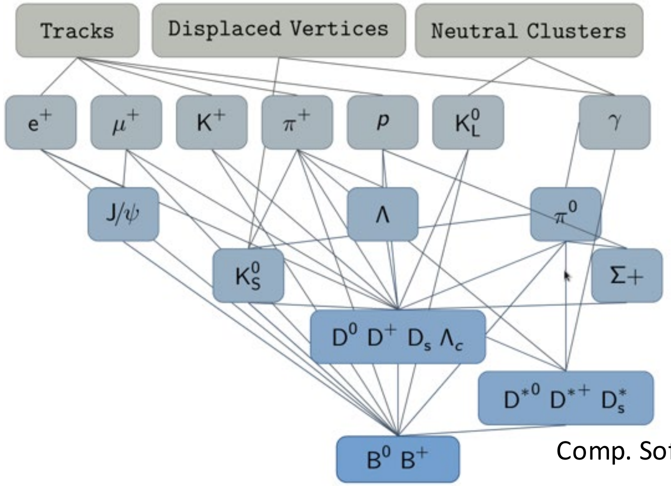




missing momentum

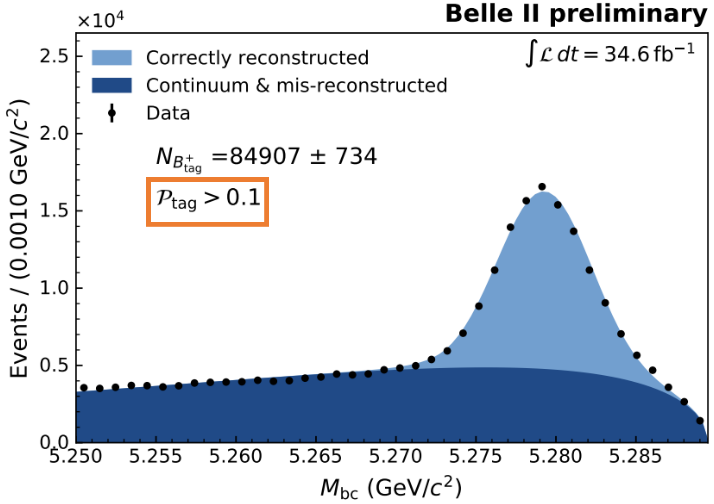
Tagged Analysis at Belle II: Full Event Interpretation

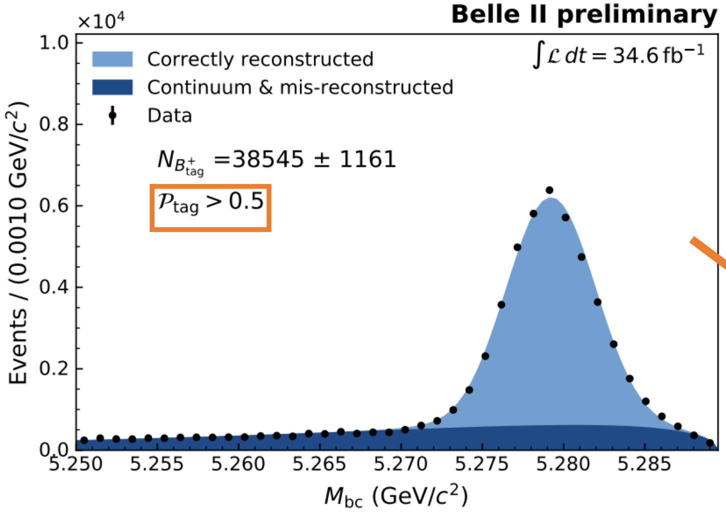
- Multi-variate analysis technique for reconstructing *B*-tags via over 4000 unique decay chains
- Includes both hadronic and semi-leptonic tagging functionality



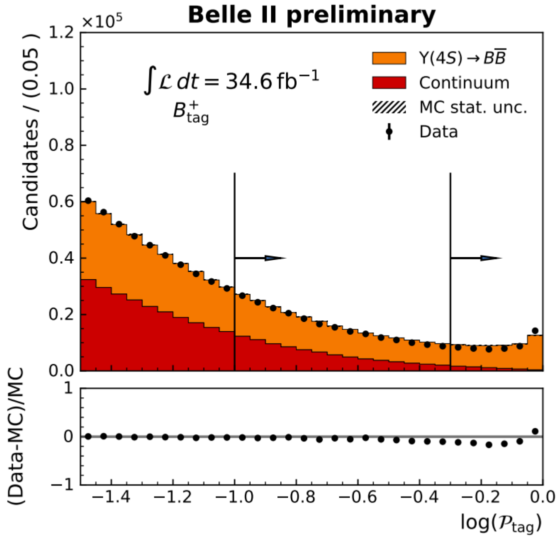
Comp. Soft. Big Sci. (2019) 3: 6

arXiv:2008.06096





Hadronic B^+_{tag}



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

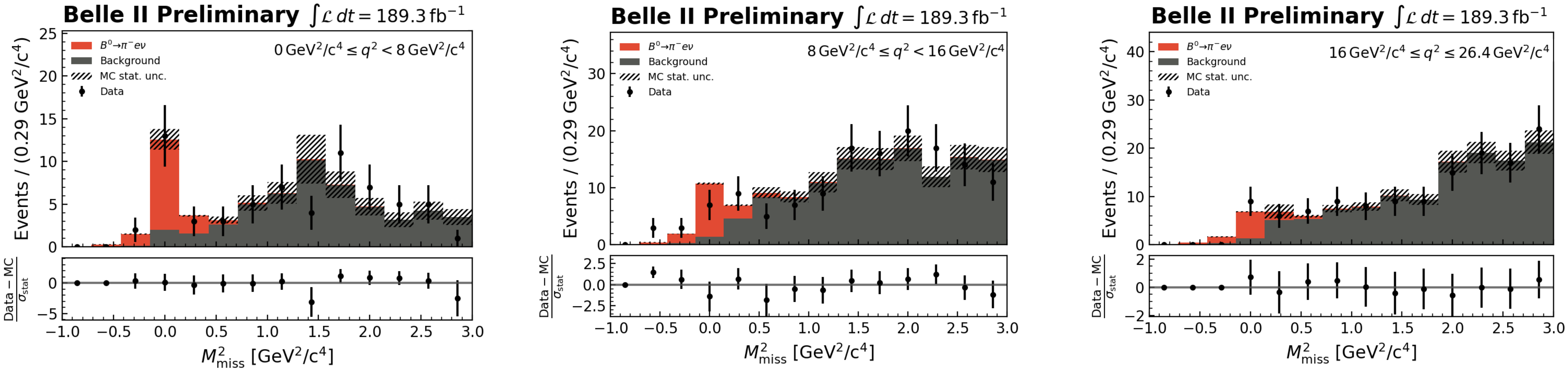
$$M_{bc} = \sqrt{E^2_{CM} - |\vec{p}_{B_{tag}}|^2}$$

Hadronic Tagged $B \to \pi e^+ \nu_e$

arXiv:2206.08102

- Reconstruct signal B-meson recoiling against hadronic tag from the FEI
- Selected tag must satisfy minimum threshold on FEI classifier output
- Events with tracks remaining after ϒ(4S) reconstruction excluded
- Signal extraction via fitting distribution of m^2_{miss} to templates generated from simulation (Monte Carlo) for 3 separate q^2 regions

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



$B^0 \to \pi^- e^+ \nu_e$

Hadronic Tagged $B \to \pi e^+ \nu_e$

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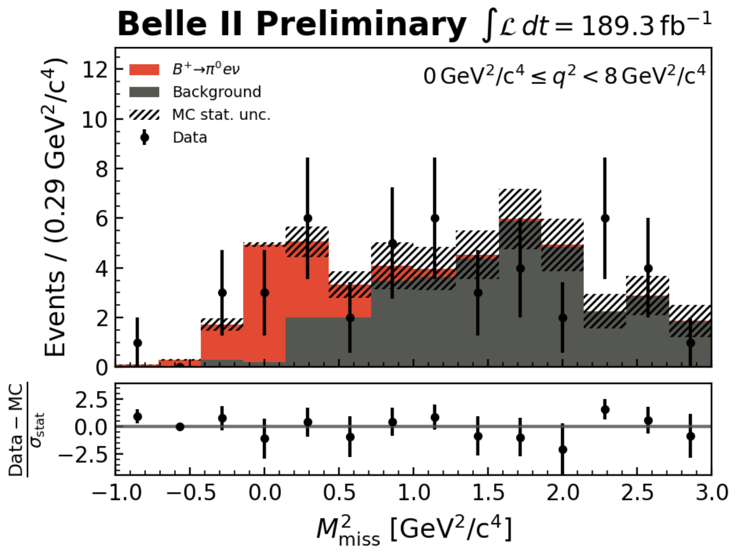

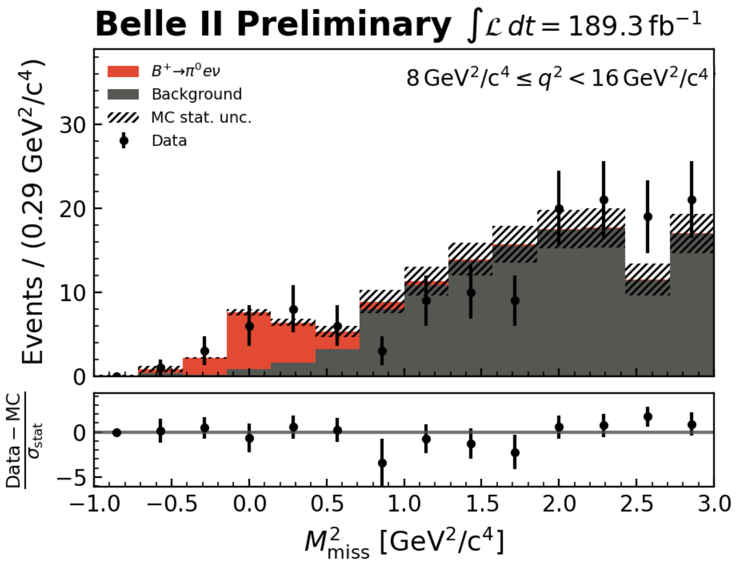

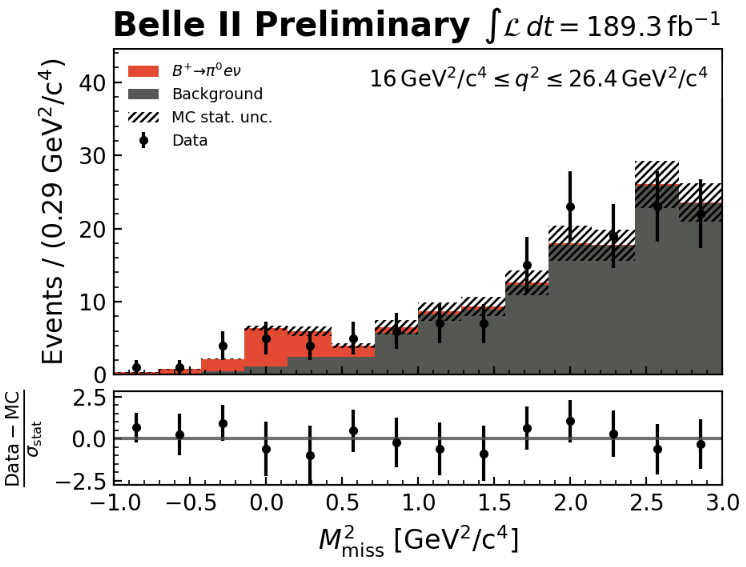

$B^+ \to \pi^0 e^+ \nu_e$

Measuring the branching fractions of $B \to \pi e^+ \nu_e$

arXiv:2206.08102

$N^{\mathrm{data}}_{\mathrm{sig,i}}$: Fitted signal yields from data
f_{+0}: Ratio of BFs for $\Upsilon(4S) \to B^+B^- / B^0\bar{B}^0$
$\mathrm{CF}_{\mathrm{FEI}}$: FEI calibration factor
SF_{π^0}: Scaling factor for π^0 efficiency
$N_{B\bar{B}}$: Number of $B\bar{B}$ pairs
ϵ_i: Signal reconstruction efficiencies

- Using unfolded signal yields in data, we calculate the partial branching fractions in each q^2 bin:

$$\Delta\mathcal{B}_i(B^0 \to \pi^- e^+ \nu_e) = \frac{N^{\mathrm{data}}_{\mathrm{sig,i}}(1 + f_{+0})}{2 \times \mathrm{CF}_{\mathrm{FEI}} \times N_{B\bar{B}} \times \epsilon_i}, \quad \Delta\mathcal{B}_i(B^+ \to \pi^0 e^+ \nu_e) = \frac{N^{\mathrm{data}}_{\mathrm{sig,i}}(1 + f_{+0})}{2 \times \mathrm{CF}_{\mathrm{FEI}} \times N_{B\bar{B}} \times \mathrm{SF}_{\pi^0} \times f_{+0} \times \epsilon_i}$$

- We sum these to obtain the total branching fractions:

$$\mathcal{B}_i(B^0 \to \pi^- e^+ \nu_e) = (1.43 \pm 0.27(\mathrm{stat}) \pm 0.07(\mathrm{syst})) \times 10^{-4}$$
$$\mathcal{B}_i(B^+ \to \pi^0 e^+ \nu_e) = (8.33 \pm 1.67(\mathrm{stat}) \pm 0.55(\mathrm{syst})) \times 10^{-5}$$

World averages:
$(1.50 \pm 0.06) \times 10^{-4}$
$(7.80 \pm 0.27) \times 10^{-5}$

arXiv:2206.08102

Extracting $|V_{ub}|$

$$\frac{d\Gamma(B^0 \to \pi^- \ell^+ \nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 |p_\pi|^3 |f_+(q^2)|^2$$

- Use a set of predictions for the partial branching fractions based on lattice quantum chromodynamics (LQCD) – *(Fermilab, MILC collaborations)*
- Use Bourrely, Caprini, and Lellouch (BCL) parameterisation for the form factors:

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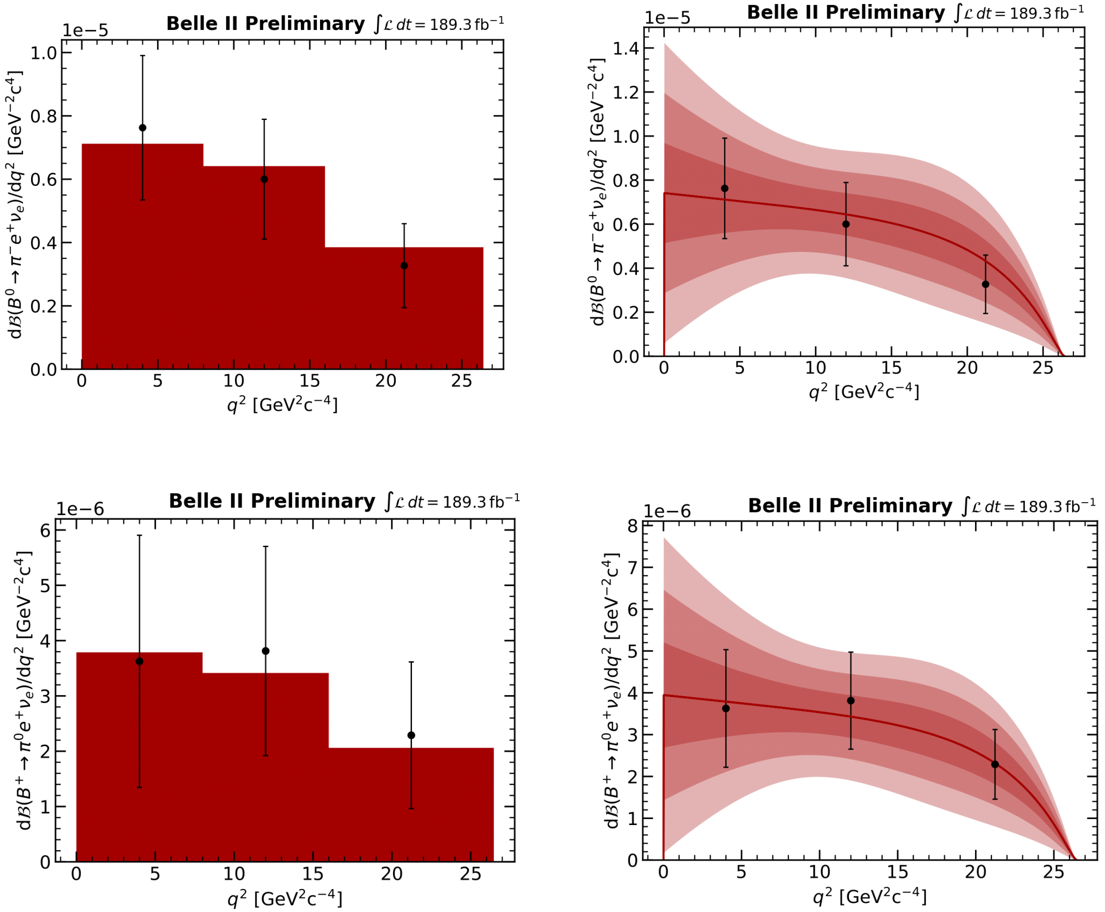
$$f_+(q^2) = \frac{1}{1 - q^2/m_{B^*}^2} \sum_{k=0}^{K-1} b_k \left[z^k - (-1)^{k-K} \frac{k}{K} z^K \right]$$

- Perform simultaneous χ^2 fit to the LQCD predictions (red histograms), and both sets of measured partial branching fractions (data points)

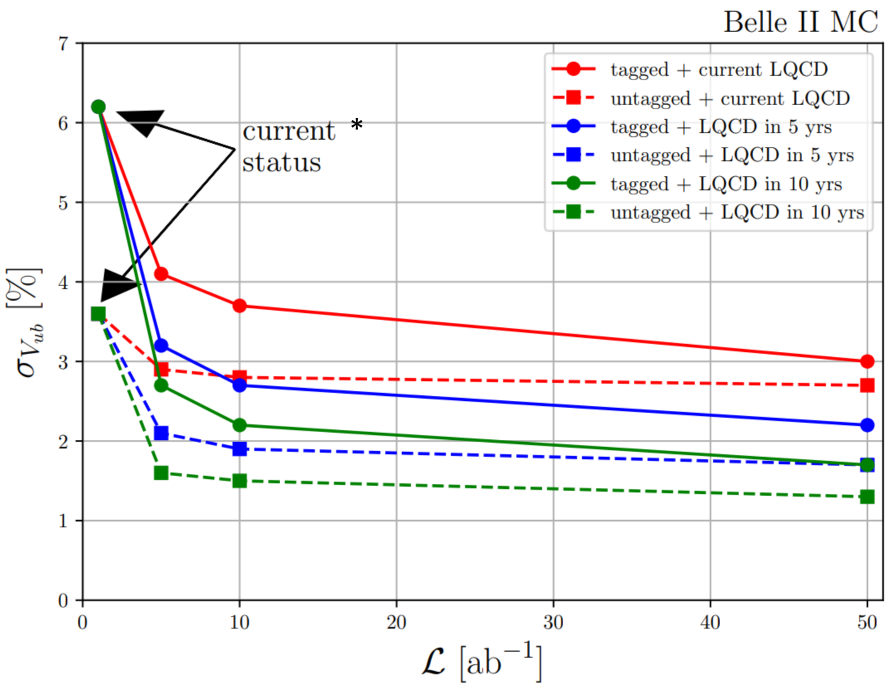
$$|V_{ub}| = (3.88 \pm 0.45) \times 10^{-3}$$



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

arXiv:1808.10567

- This analysis: ≈12% precision on $|V_{ub}|$ using hadronic tagged approach
- Current world average at ≈6% precision
- Belle II simulation: Potential to reduce this to ≈2% with full expected Belle II dataset, alongside projected reductions in lattice QCD errors
- Lowest projected error via untagged approach, at ≈ 1.5%



* 'current status' on plot refers to 1 ab^{-1}

Summary

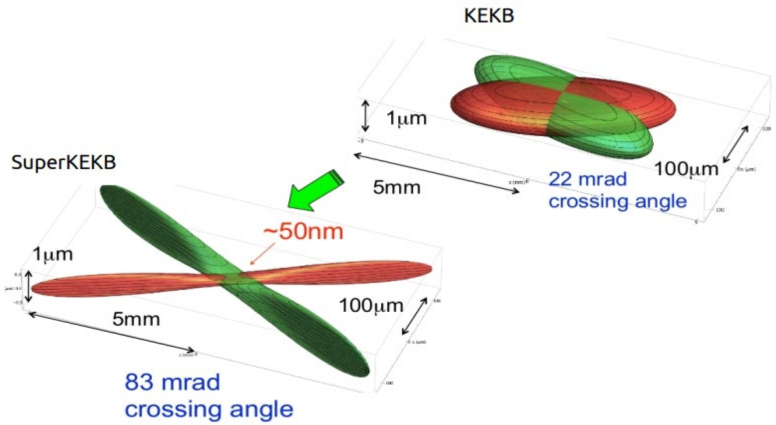
- First Belle II measurement of $|V_{ub}|$ from $B \to \pi e^+ \nu_e$ decays using a hadronic tagged approach
- Signal extracted from m^2_{miss} distribution, with partial branching fractions evaluated in three bins of q^2
- With large projected dataset and improved detector, Belle II aims to increase precision of this measurement and resolve tension between inclusive and exclusive results
- Currently updating results with larger dataset (nearly double the current size), including decays involving muons

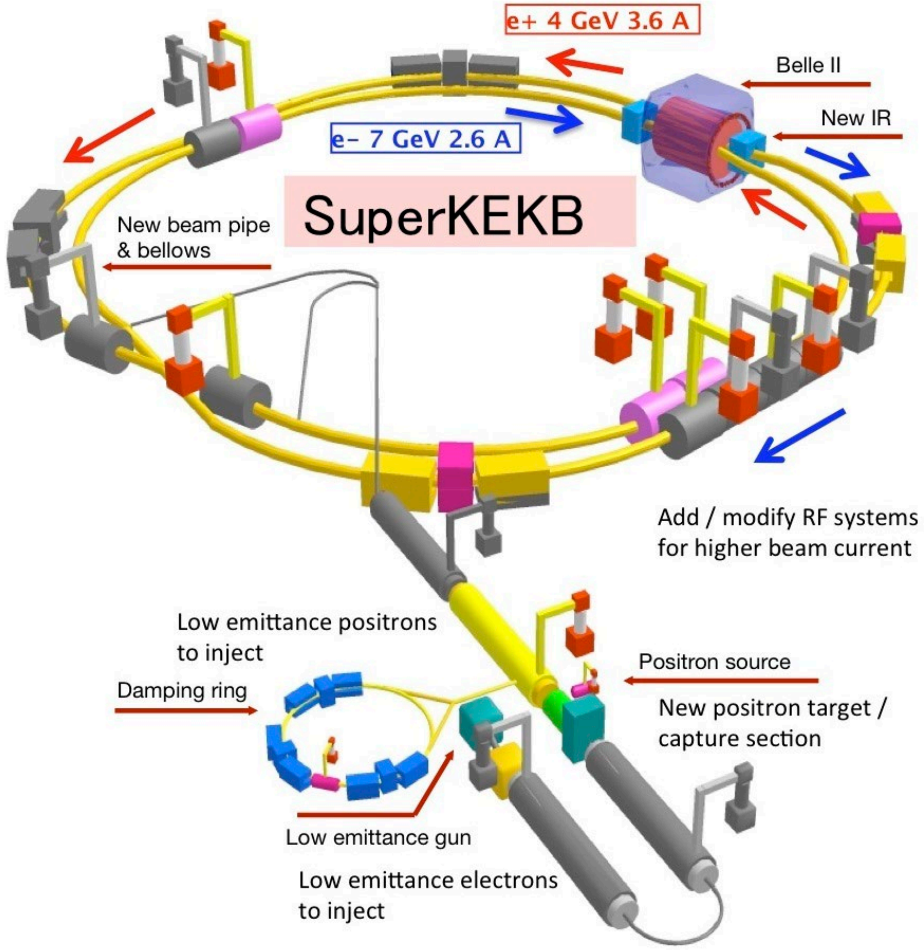
The Belle II Collaboration

Back-up

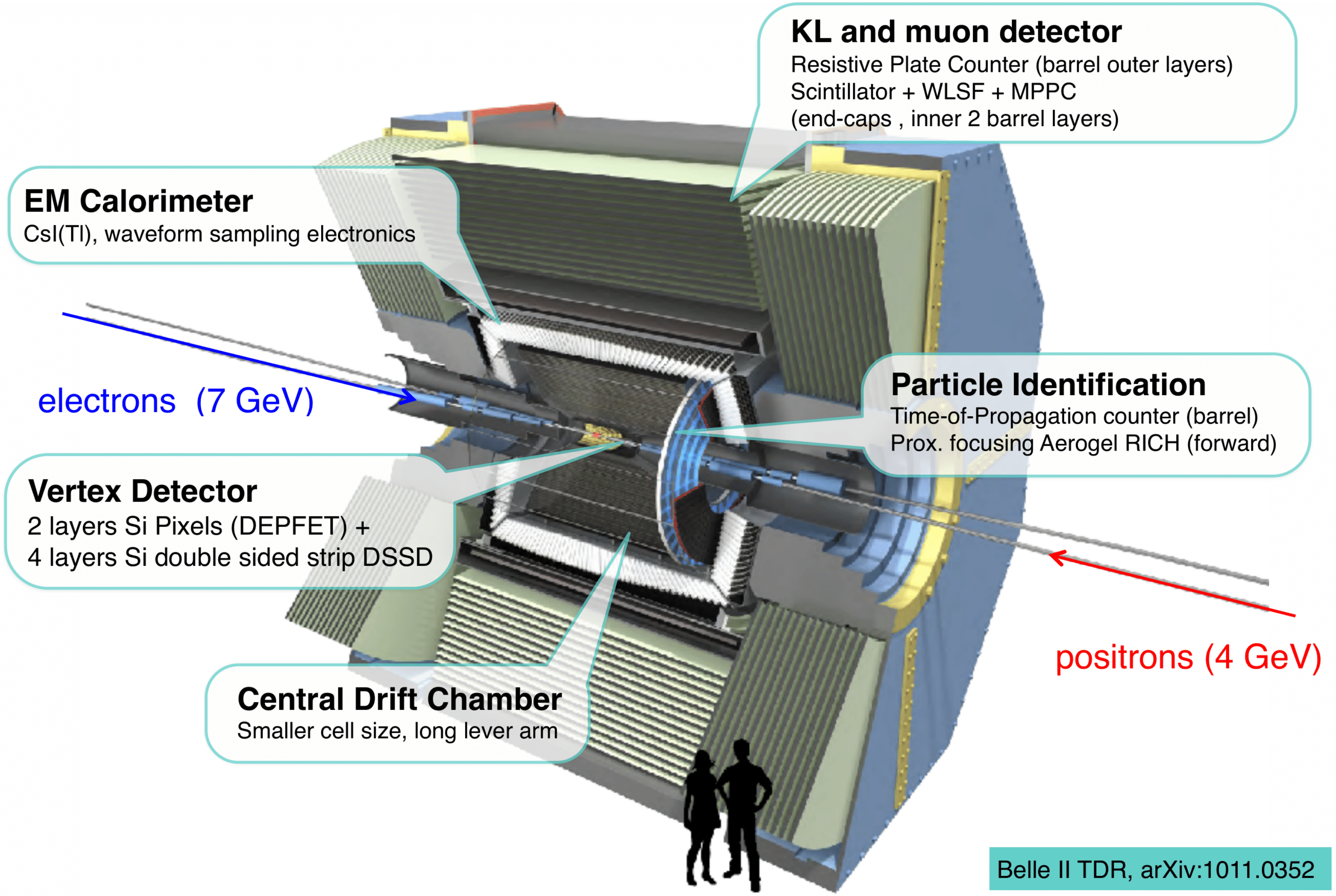
SuperKEKB

- 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



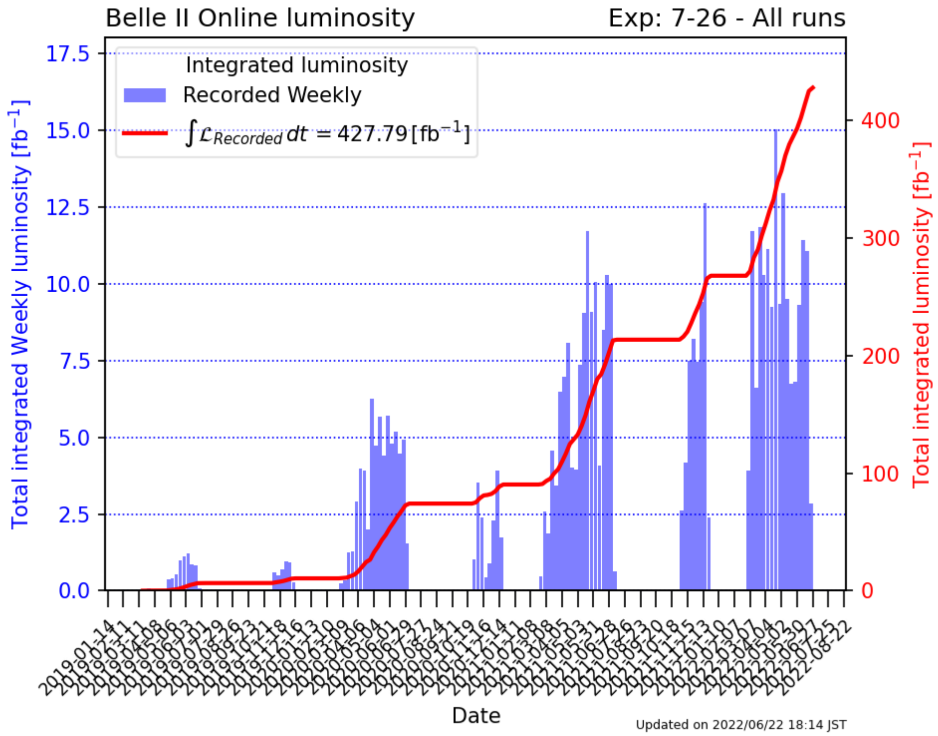


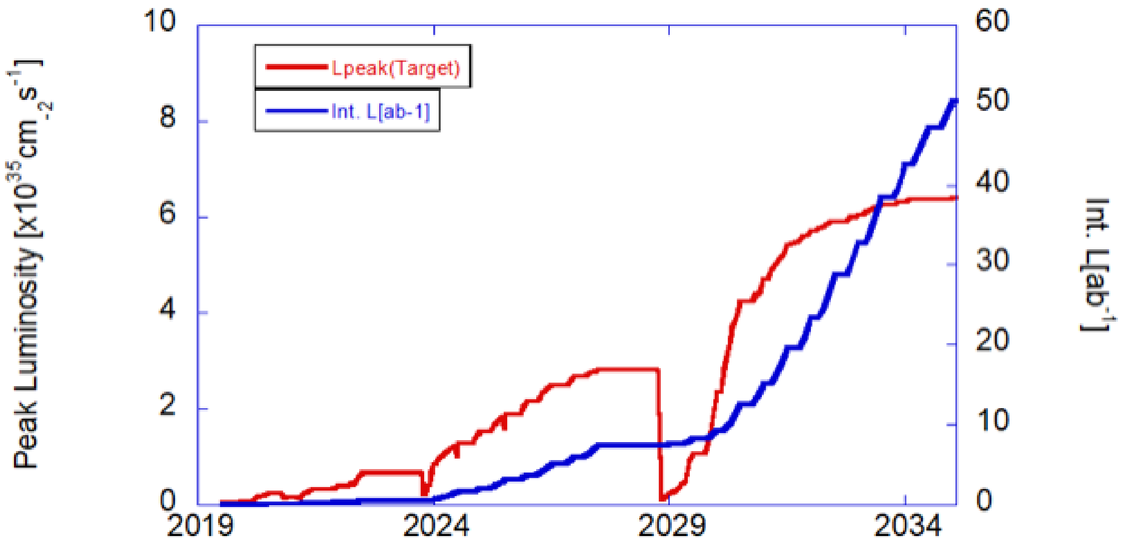
The Belle II Detector



Belle II Data-taking: Status and Outlook

- Collected over 420 fb^{-1} of data before first long shutdown





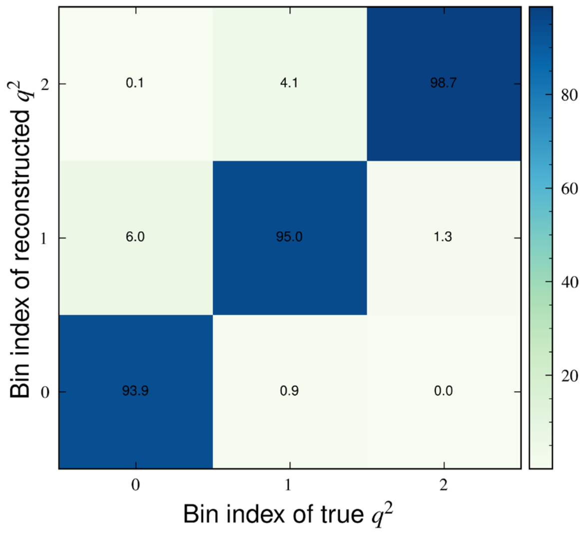
- Long-term: 50 ab^{-1} (50 x Belle dataset) by mid 2030s

q^2 Unfolding

- Due to detector resolution effects, some events may be reconstructed in a different q^2 bin than they belong
- We can use Monte Carlo (MC) to investigate the extent to which this occurs as we have access to the underlying truth of the event

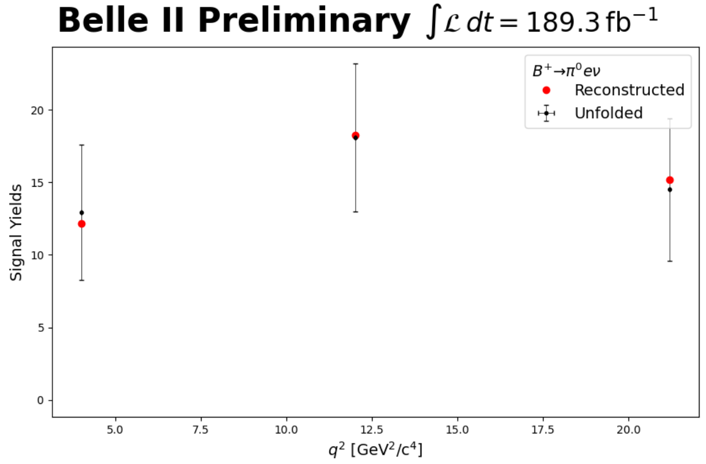
$B^+ \to \pi^0 e^+ \nu_e$

arXiv:2206.08102



Monte Carlo

- Derive a set of corrections using MC to correct the measured signal yields in each q^2 bin – 'unfold' the q^2 distribution
- Effect of unfolding is minimal at low statistics



Data

q^2 Unfolding

$B^0 \rightarrow \pi^- e^+ \nu_e$

arXiv:2206.08102

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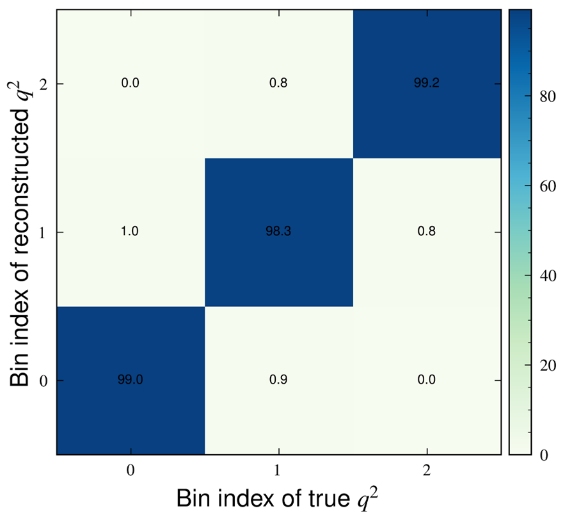

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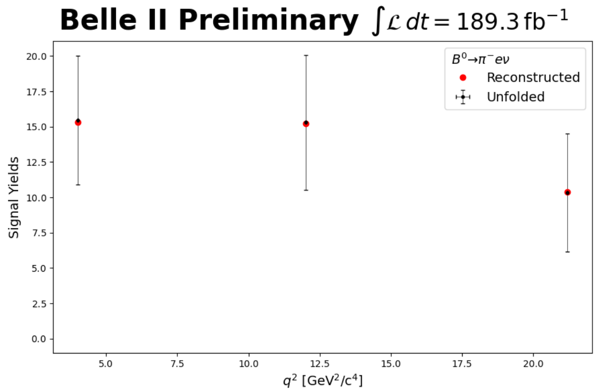

Data

Partial Branching Fractions

q^2 bin	Signal efficiency	Unfolded signal yield	$\Delta\mathcal{B}$
		$B^0 \to \pi^- e^+ \nu_e$	
$0 \leq q^2 < 8$ GeV^2	$(0.189 \pm 0.002)\%$	15.5 ± 4.6	$(0.61 \pm 0.18(\text{stat}) \pm 0.03(\text{syst})) \times 10^{-4}$
$8 \leq q^2 < 16$ GeV^2	$(0.239 \pm 0.003)\%$	15.3 ± 4.8	$(0.48 \pm 0.15(\text{stat}) \pm 0.02(\text{syst})) \times 10^{-4}$
$16 \leq q^2 \leq 26.4$ GeV^2	$(0.229 \pm 0.003)\%$	10.3 ± 4.2	$(0.34 \pm 0.14(\text{stat}) \pm 0.02(\text{syst})) \times 10^{-4}$
Sum	–	41.1 ± 7.8	$(1.43 \pm 0.27(\text{stat}) \pm 0.07(\text{syst})) \times 10^{-4}$
Fit over full q^2 range	$(0.217 \pm 0.002)\%$	42.0 ± 7.9	$(1.45 \pm 0.27(\text{stat}) \pm 0.07(\text{syst})) \times 10^{-4}$
World average [2]	–	–	$(1.50 \pm 0.06) \times 10^{-4}$

q^2 bin	Signal efficiency	Unfolded signal yield	$\Delta\mathcal{B}$
		$B^+ \to \pi^0 e^+ \nu_e$	
$0 \leq q^2 < 8$ GeV^2	$(0.329 \pm 0.004)\%$	12.9 ± 4.7	$(2.90 \pm 1.12(\text{stat}) \pm 0.19(\text{syst})) \times 10^{-5}$
$8 \leq q^2 < 16$ GeV^2	$(0.439 \pm 0.005)\%$	18.1 ± 5.1	$(3.05 \pm 0.91(\text{stat}) \pm 0.20(\text{syst})) \times 10^{-5}$
$16 \leq q^2 \leq 26.4$ GeV^2	$(0.451 \pm 0.006)\%$	14.5 ± 4.9	$(2.38 \pm 0.85(\text{stat}) \pm 0.16(\text{syst})) \times 10^{-5}$
Sum	–	45.5 ± 8.5	$(8.33 \pm 1.67(\text{stat}) \pm 0.55(\text{syst})) \times 10^{-5}$
Fit over full q^2 range	$(0.402 \pm 0.003)\%$	43.9 ± 8.3	$(8.06 \pm 1.62(\text{stat}) \pm 0.53(\text{syst})) \times 10^{-5}$
World average [2]	–	–	$(7.80 \pm 0.27) \times 10^{-5}$

Systematics

Source	% of $\mathcal{B}(B^0 \to \pi^- e^+ \nu_e)$			% of $\mathcal{B}(B^+ \to \pi^0 e^+ \nu_e)$		
q^2 bin index	1	2	3	1	2	3
$N_{B\bar{B}}$	2.9					
f_{+0}	1.2					
FEI calibration	3.2			3.1		
Tracking	0.6			0.3		
π^0 efficiency	–			4.8		
Signal efficiency ϵ	1.3	1.2	1.4	1.3	1.2	1.3
Electron ID	1.0	0.4	0.4	1.0	0.5	0.5
Pion ID	0.4	0.4	0.4	–		
Total	4.8	4.7	4.8	6.7	6.7	6.7
Stat. uncertainty	29.5	31.3	41.2	38.6	29.8	35.7