

THE UNIVERSITY OF  
SYDNEY



# Measuring $|V_{ub}|$ at Belle II with semileptonic $B$ -meson decays

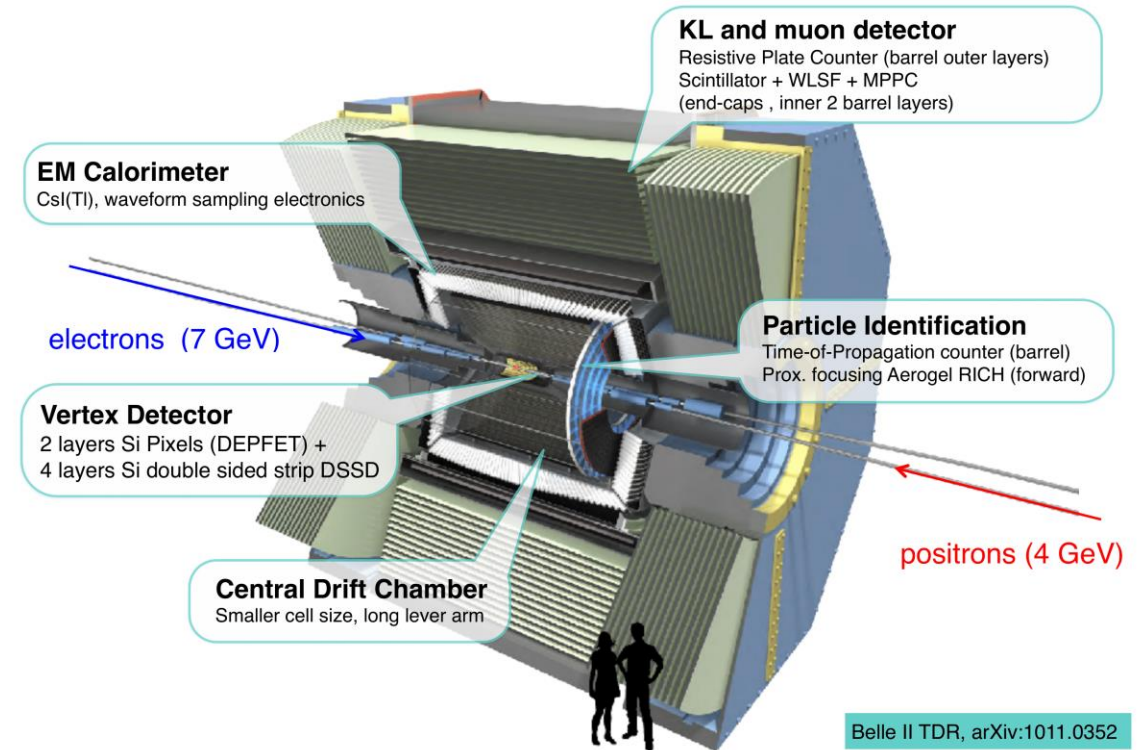
Nadia Toutounji

Fourth Sydney Meeting

27.06.22

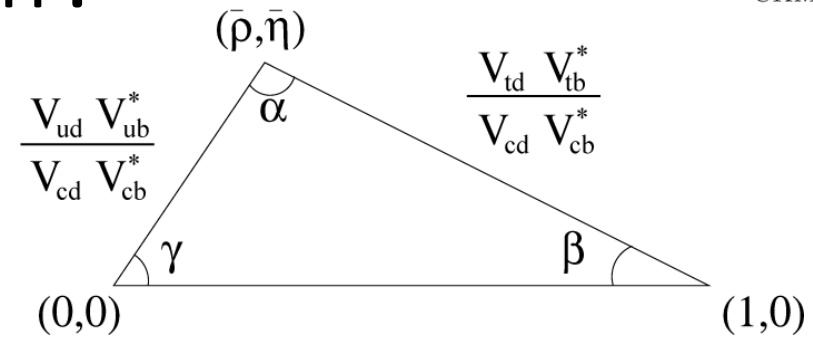
# Outline

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



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

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

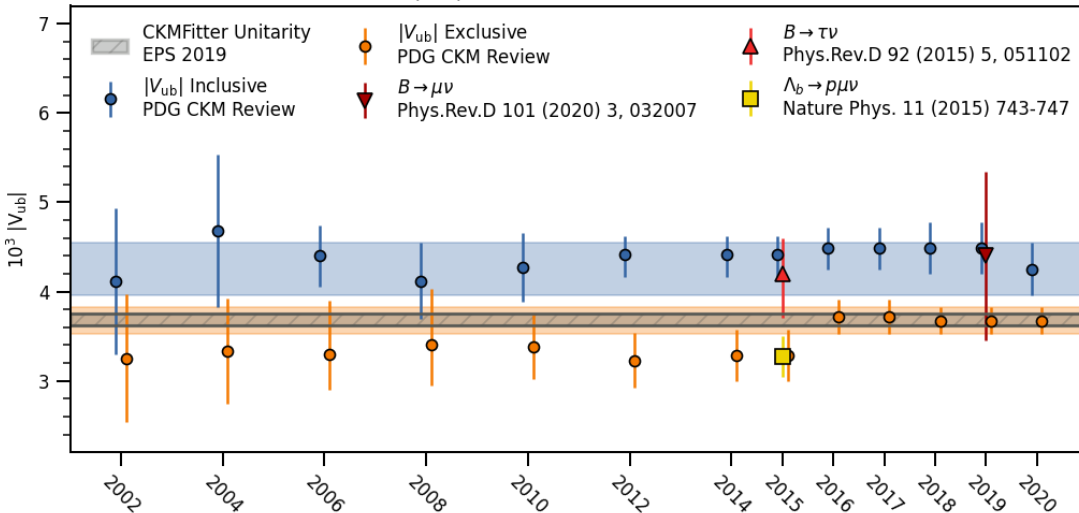


$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

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

$|V_{ub}|$

$|V_{ub}|$  Measurements over Time



- Existing tension between  $|V_{ub}|$  from **exclusive** vs. **inclusive** approaches of order  $\sim 3\sigma$

**Exclusive:**

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

**Inclusive:**

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

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

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

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

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

Experiment:

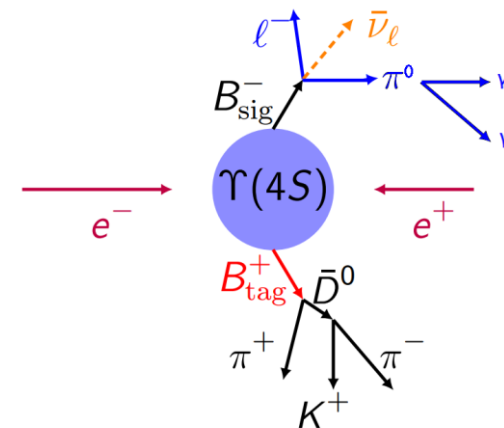
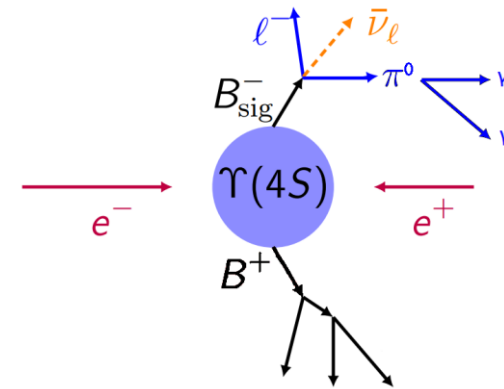
Measure differential decay rate as a function of the square of the 4-momentum transfer to the leptonic system,  $q^2$

Theory:

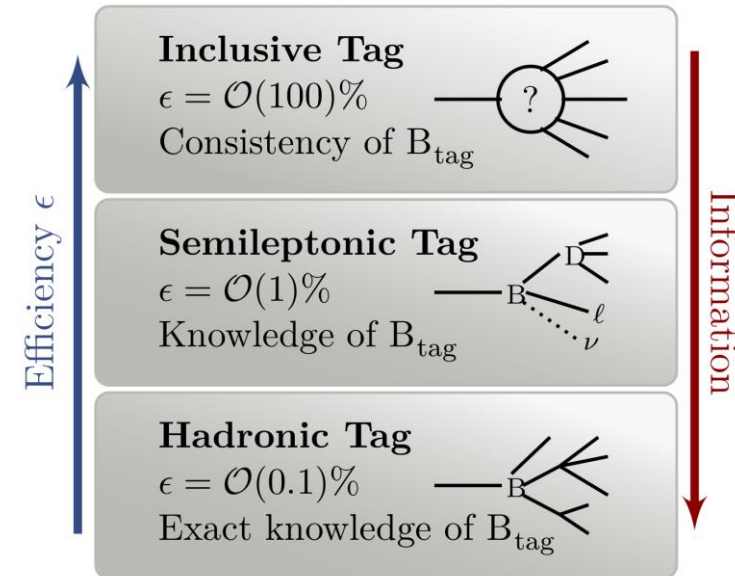
Description of the form factors including suitable parameterisation

# 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  $\rightarrow$  missing neutrino momentum can be determined



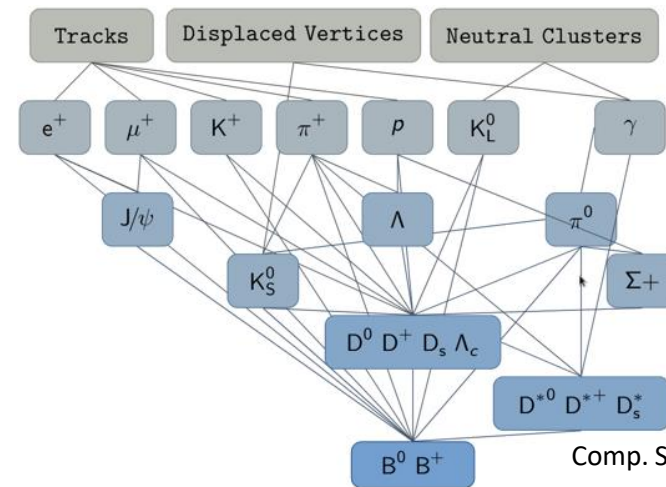
$\ell = e, \mu$



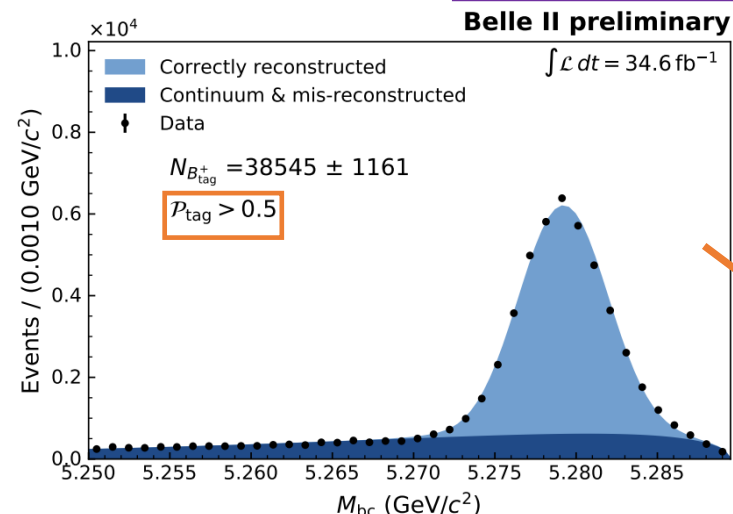
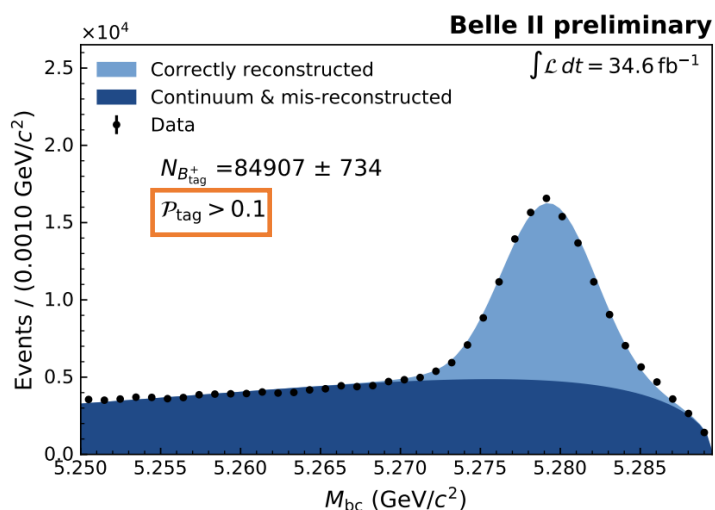
.....  
missing momentum

# Tagged Analysis at Belle II: Full Event Interpretation

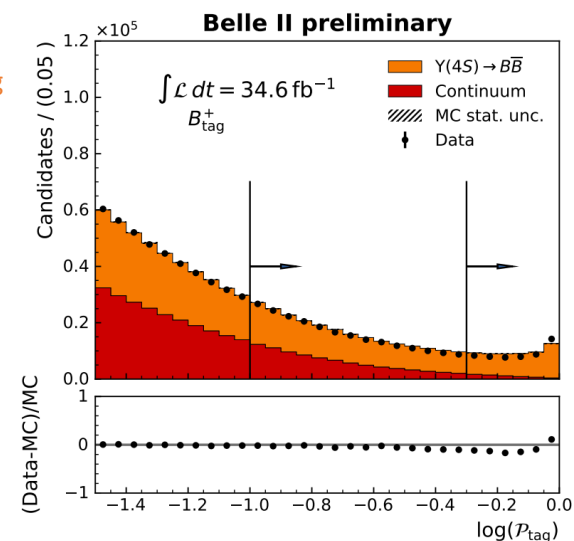
- Multi-variate analysis technique for reconstructing  $B$ -tags via over 4000 unique decay chains
- Includes both hadronic and semi-leptonic tagging functionality



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



Hadronic  $B^+_{\text{tag}}$



- Selection on final classifier output  $P_{\text{tag}}$  provides good signal-background discrimination

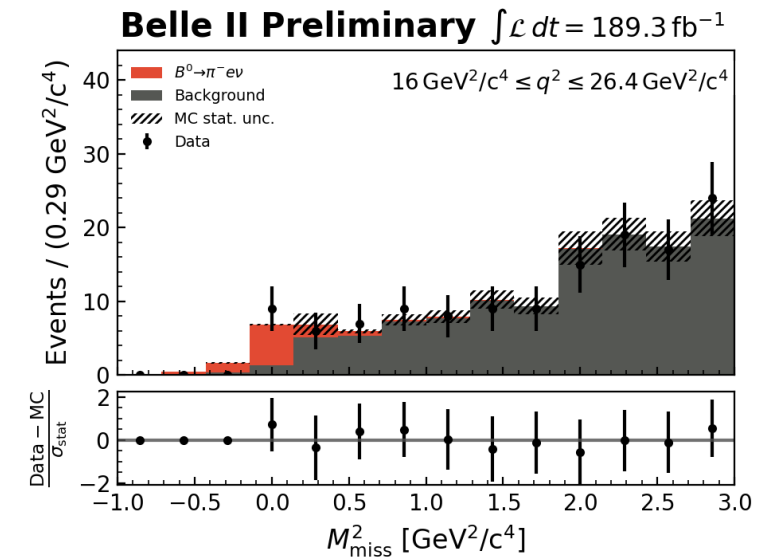
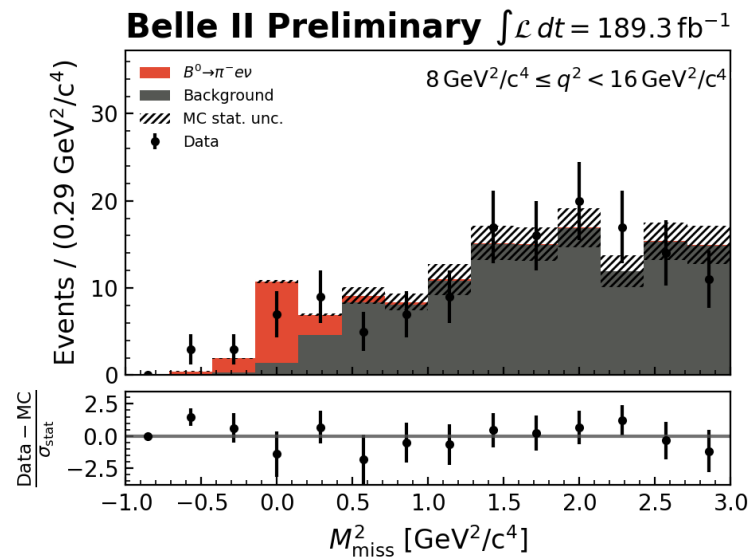
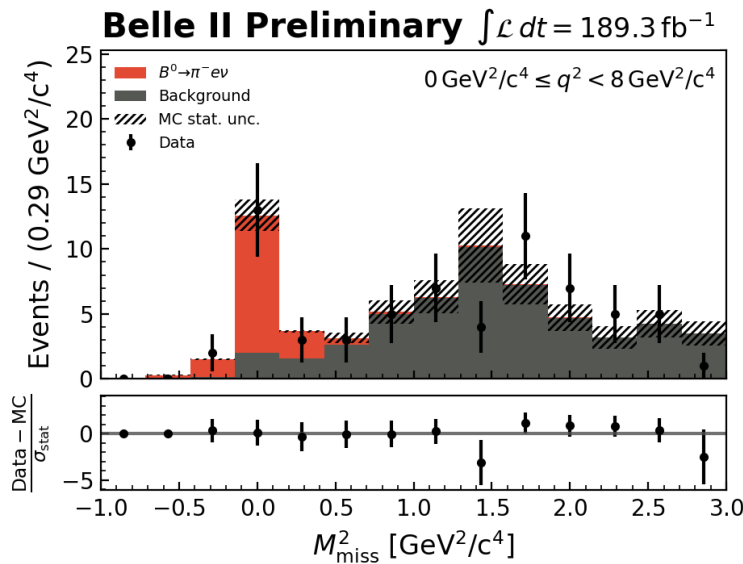
$$M_{bc} = \sqrt{E_{CM}^2 - |\vec{p}_{B_{\text{tag}}}|^2}$$

# Hadronic Tagged $B \rightarrow \pi e^+ \nu_e$

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  $\Upsilon(4S)$  reconstruction excluded
- Signal extraction via fitting distribution of  $m^2_{\text{miss}}$  to templates generated from simulation (Monte Carlo) for 3 separate  $q^2$  regions

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



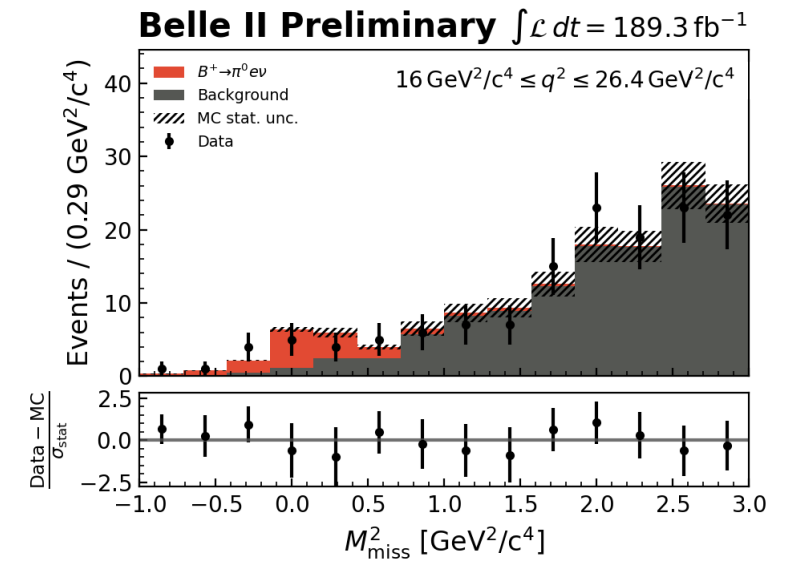
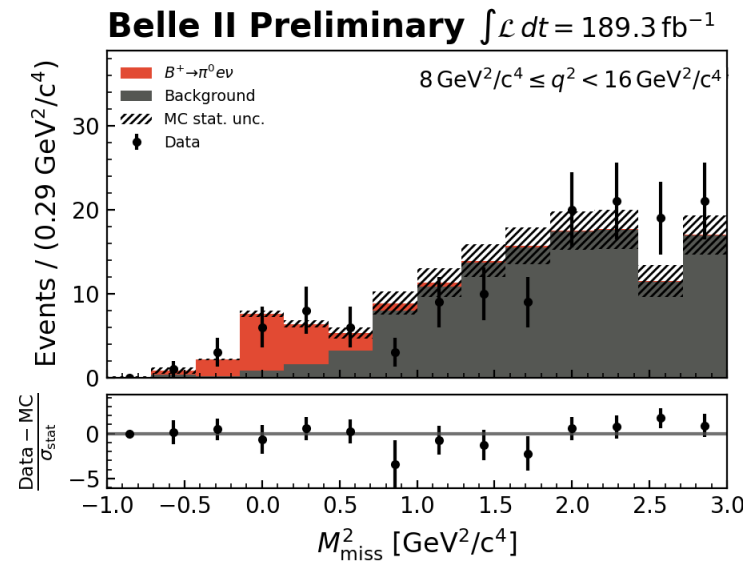
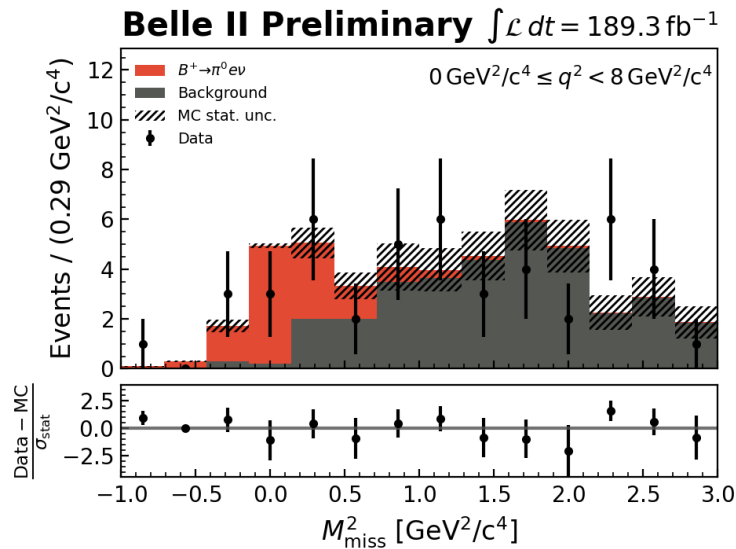
$$B^0 \rightarrow \pi^- e^+ \nu_e$$

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

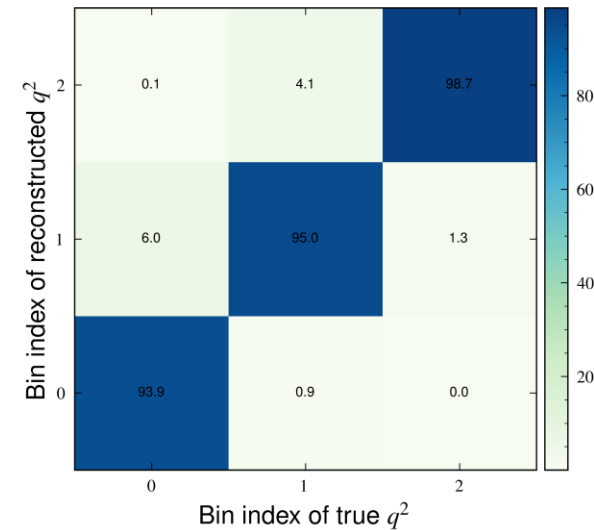
# $q^2$ Unfolding

- 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

- 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

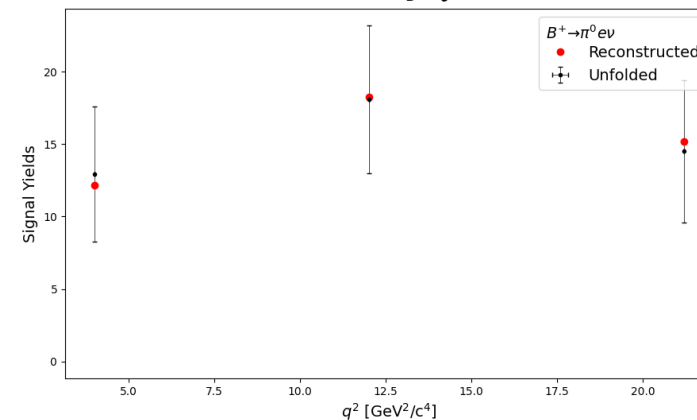
$$B^+ \rightarrow \pi^0 e^+ \nu_e$$

[arXiv:2206.08102](https://arxiv.org/abs/2206.08102)



Monte Carlo

**Belle II Preliminary**  $\int \mathcal{L} dt = 189.3 \text{ fb}^{-1}$



Data

# Measuring the branching fractions of

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

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

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

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

$N_{\text{sig},i}^{\text{data}}$ : Unfolded fitted signal yields from data  
 $f_{+0}$ : Ratio of BF's for  $\Upsilon(4S) \rightarrow B^+ B^- / B^0 \bar{B}^0$   
 $\text{CF}_{\text{FEI}}$ : FEI calibration factor  
 $\text{SF}_{\pi^0}$ : Scaling factor for  $\pi^0$  efficiency  
 $N_{B\bar{B}}$ : Number of  $B\bar{B}$  pairs  
 $\epsilon_i$ : Signal reconstruction efficiencies

- We sum these to obtain the total branching fractions:

$$\begin{aligned}
 \mathcal{B}_i(B^0 \rightarrow \pi^- e^+ \nu_e) &= (1.43 \pm 0.27(\text{stat}) \pm 0.07(\text{syst})) \times 10^{-4} \\
 \mathcal{B}_i(B^+ \rightarrow \pi^0 e^+ \nu_e) &= (8.33 \pm 1.67(\text{stat}) \pm 0.55(\text{syst})) \times 10^{-5}
 \end{aligned}$$

World averages:

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

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

# Extracting $|V_{ub}|$

- 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:

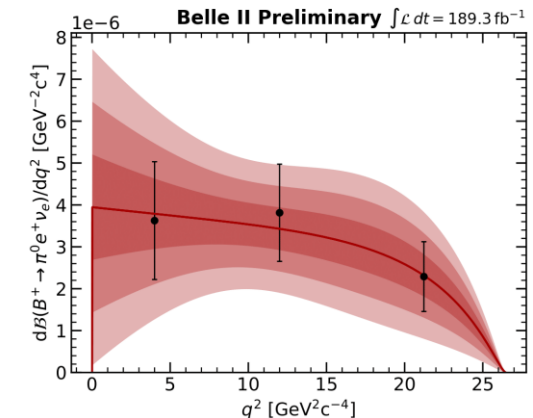
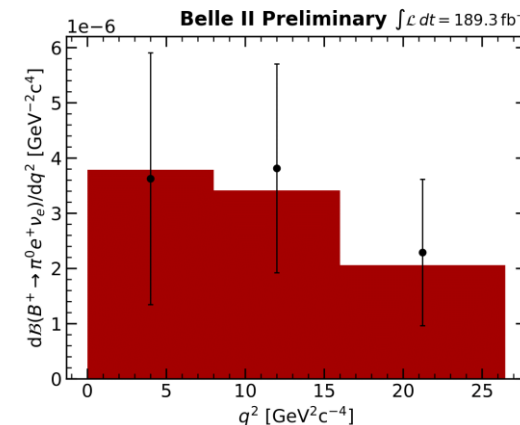
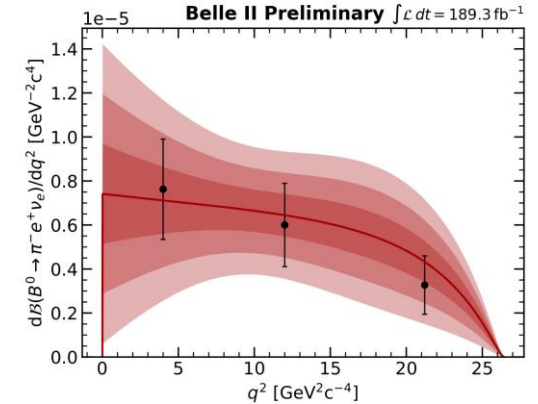
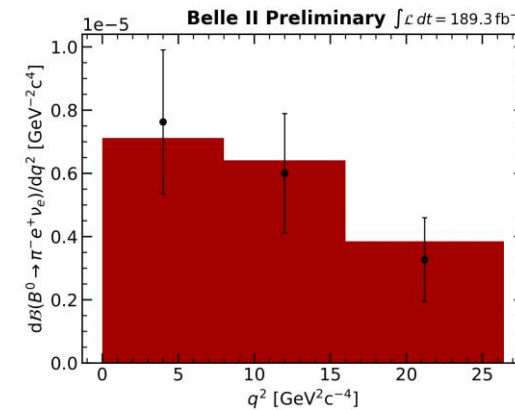
Phys. Rev. D **79**, 013008

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

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

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

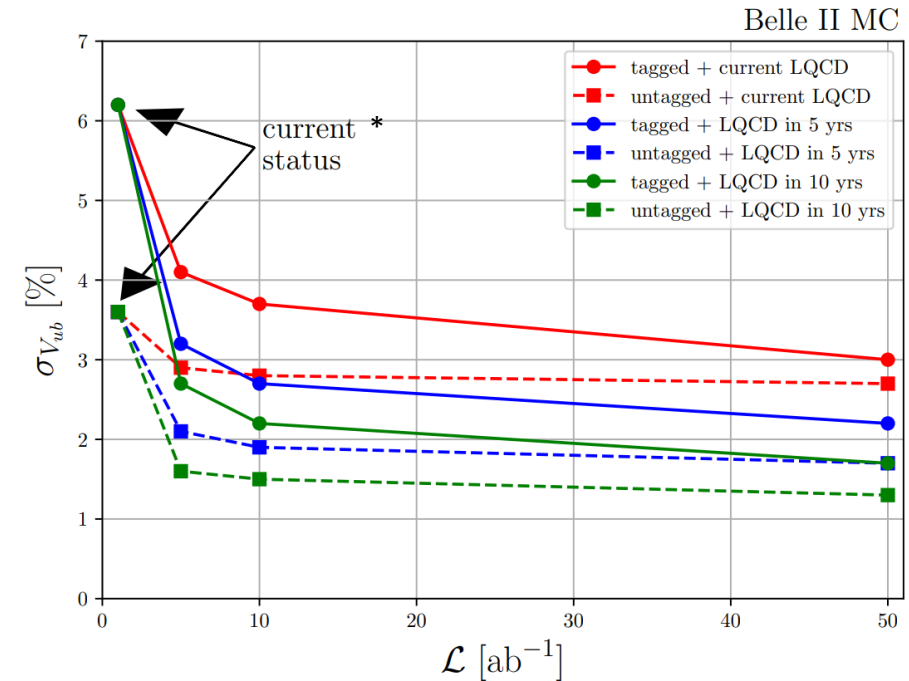
$$\frac{d\Gamma(B^0 \rightarrow \pi^- \ell^+ \nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 |p_\pi|^3 |f_+(q^2)|^2$$



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

arXiv:1808.10567

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



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

# Summary

- First Belle II measurement of  $|V_{ub}|$  from  $B \rightarrow \pi e^+ \nu_e$  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
- Semileptonic and untagged analyses of  $B \rightarrow \pi e^+ \nu_e$  also underway with results expected in the coming months



*The Belle II Collaboration*

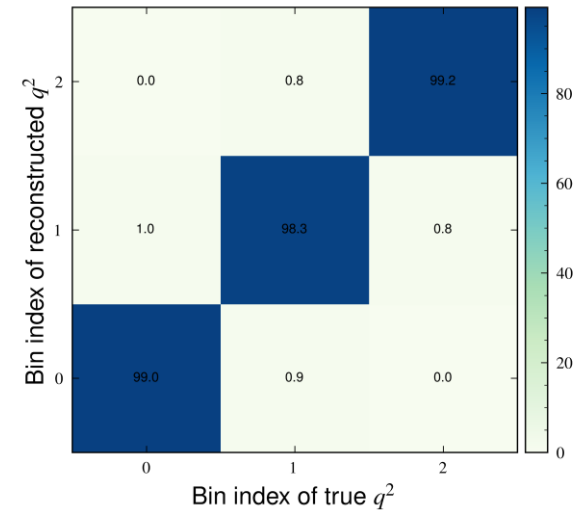
Back-up

# $q^2$ Unfolding

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

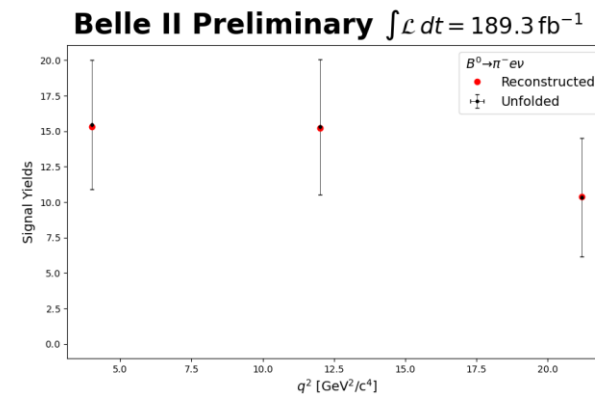
[arXiv:2206.08102](https://arxiv.org/abs/2206.08102)

- Due to detector resolution effects, some events may be reconstructed in a different  $q^2$  bin than they belong
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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
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Data

# Partial Branching Fractions

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

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

# Systematics

Source		% of $\mathcal{B}(B^0 \rightarrow \pi^- e^+ \nu_e)$			% of $\mathcal{B}(B^+ \rightarrow \pi^0 e^+ \nu_e)$		
$q^2$ 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		
$\pi^0$ efficiency		—			4.8		
Signal efficiency $\epsilon$	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	