Semileptonic and rare decays at Belle II

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on behalf of the Belle II collaboration

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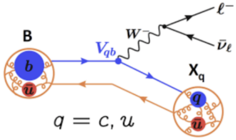
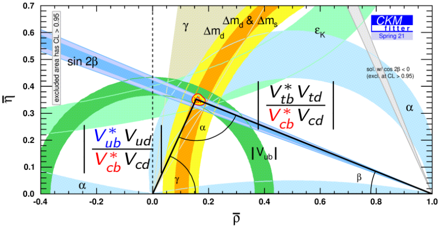
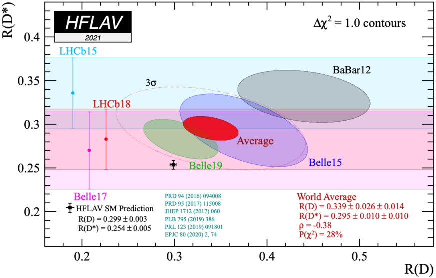
- Precision measurements to probe Standard Model (SM):
  - Used to extract CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$
- Probing potential new physics:
  - $\sim 3\sigma$ discrepancy from SM in measurements of ratios

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)} \ (\ell = \mu, e)$$



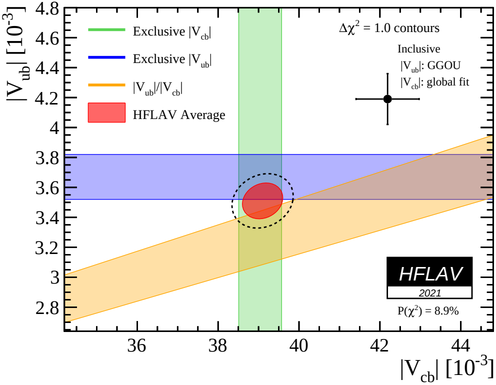




Status of $|V_{cb}|$ and $|V_{ub}|$

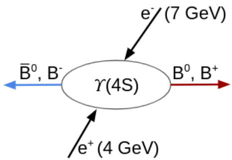
- **Exclusive**: reconstruct specific final states
  - $B \to D^{(*)}\ell\nu$
  - $B \to \pi\ell\nu$
- **Inclusive**: reconstruct all $X\ell\nu$ final states
  - $B \to X_c\ell\nu$
  - $B \to X_u\ell\nu$

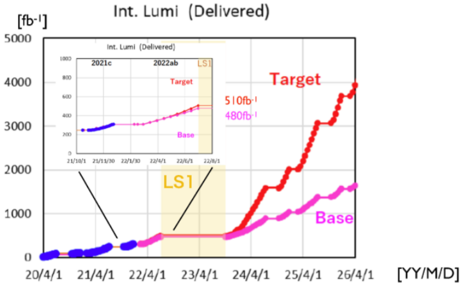
- $\sim 3\sigma$ discrepancy between inclusive and exclusive $|V_{cb}|$ and $|V_{ub}|$ measurements



SuperKEKB

- Asymmetric e^-e^+ collider with CM energy of 10.58 GeV ($\Upsilon(4S)$ resonance)
- Point like particles: clean events, initial state well known
- Design luminosity: 6.5×10^{35} cm^{-2} s^{-1} ($\sim 30\times$KEKB)
- Luminosity world record: $\sim 4 \times 10^{34}$ cm^{-2}s^{-1}
- Nanobeam scheme (20$\times$smaller beam spot) and higher beam current
- Currently recorded luminosity ~ 400fb^{-1}
- Results presented will be up to 189.3fb^{-1}





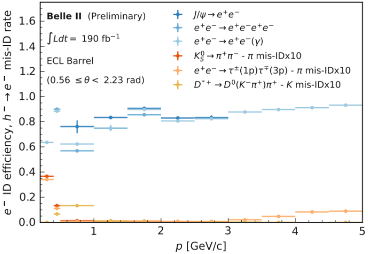
conservative estimation

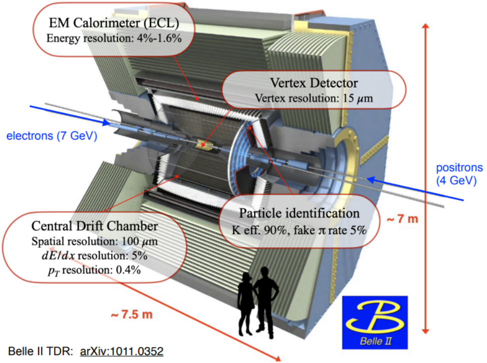
including expected improvements

Belle II

- Hermetic detector: Important to study events with missing energy
- Particle identification: μ-ID superior to Belle, e-ID and K-ID not there yet but improving
- High γ detection efficiency

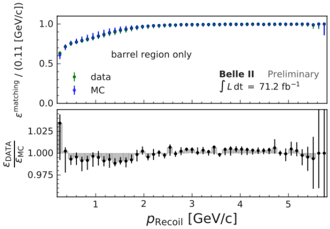
[BELLE2-NOTE-PL-2022-003]



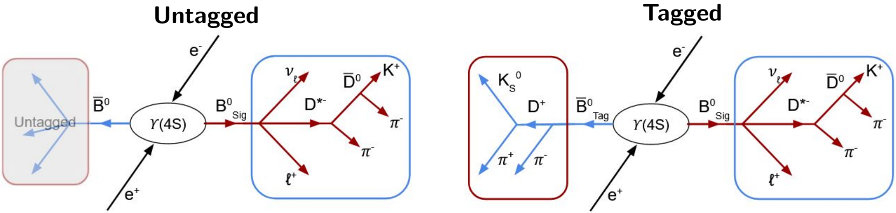


Belle II TDR: arXiv:1011.0352

[BELLE2-NOTE-PL-2021-008]



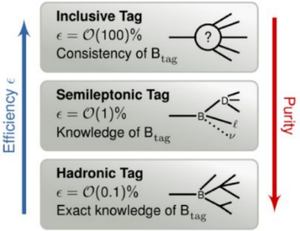
Tag side reconstruction



- Infer signal B flavour and fully resolve event kinematics by fully reconstructing second B meson in the $\Upsilon(4S)$ event e.g.

  $\bar{B}^0_{tag} \rightarrow B^0_{sig}$
  $p_\nu = p_{e^+e^-} - p_\ell - p_{B_{tag}} - p_{X_c}$

- Reconstruction of $\mathcal{O}(10,000)$ decay chains (hadronic tag)
- Up to 30-50% increased efficiency for same purity compared to Belle

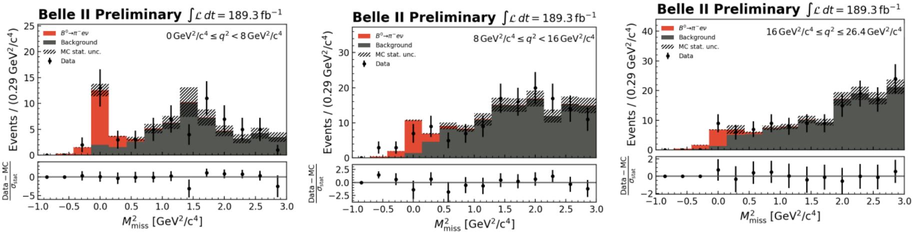


Semileptonic decays

$|V_{ub}|$ from tagged $B \to \pi e \nu$

- Reconstruct $B^0 \to \pi^- e^+ \nu_e$ and $B^+ \to \pi^0 e^+ \nu_e$
- Main challenges: sample size, π^0 reconstruction
- Differential branching fraction: $\frac{d\mathcal{B}(B \to \pi e \nu)}{dq^2} \propto |V_{ub}|^2 f_+^2(q^2)$
- Momentum transfer squared q^2: $q^2 = (p_{e^+e^-} - p_{B_{tag}} - p_\pi)^2$
- Fit M^2_{miss} in 3 bins of q^2: $M^2_{miss} = (p_{e^+e^-} - p_{B_{tag}} - p_e - p_\pi)^2$
- BCL parameters and LQCD constraints [arXiv:1503.07839]

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

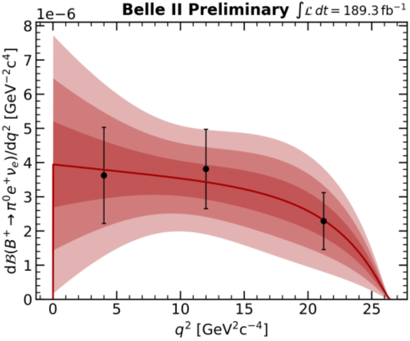


$|V_{ub}|$ from tagged $B \to \pi e \nu$

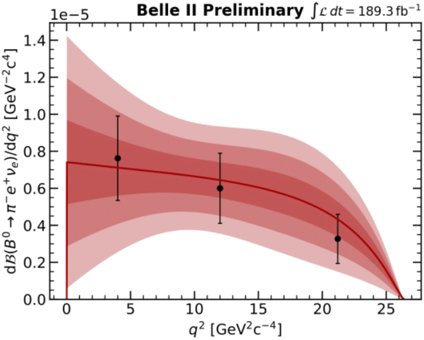
$$\mathcal{B}(B^0 \to \pi^- e^+ \nu_e) = (1.43 \pm 0.27_{(stat)} \pm 0.07_{(sys)}) \times 10^{-4} \text{(PDG:}(1.50 \pm 0.06) \times 10^{-4})$$

$$\mathcal{B}(B^+ \to \pi^0 e^+ \nu_e) = (8.33 \pm 1.67_{(stat)} \pm 0.55_{(sys)}) \times 10^{-5} \text{(PDG:}(7.80 \pm 0.27) \times 10^{-5})$$

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



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



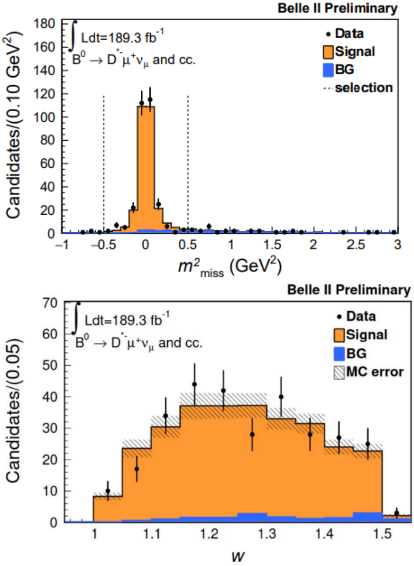
$$|V_{ub}| = (3.88 \pm 0.45) \times 10^{-3} \quad \text{(PDG:}(3.67 \pm 0.15) \times 10^{-3})$$

- Reconstruct decay chain

  $B^0 \to D^{*-}(\to \bar{D}^0(\to K^+\pi^-)\pi_S^-)\ell^+\nu_\ell$
- Main challenge: π_S efficiency
- Differential branching fraction:

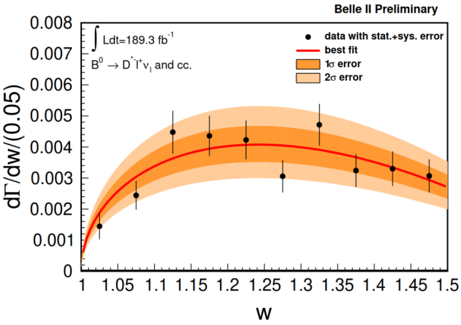
  $\frac{d\Gamma(\mathcal{B}(B\to D^*\ell\nu_\ell))}{dw} \propto \eta_{EW}^2 F^2(w)|V_{cb}|^2$
- Hadronic recoil:

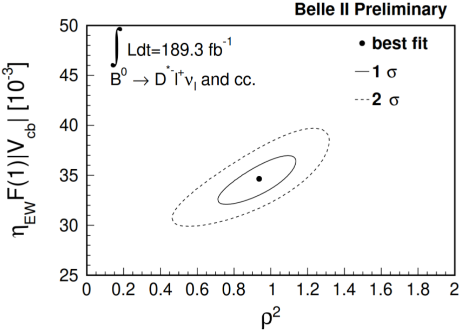
  $w = \frac{P_B \cdot P_{D^*}}{m_B m_D} = \frac{m_B^2 + m_{D*} - q^2}{2 m_B m_{D^*}}$
- CLN paramterization [arXiv:hep-ph/9712417]
- Measure $\eta_{EW} F(1)|V_{cb}|$ and ρ^2



$|V_{cb}|$ from tagged $B \to D^* \ell \nu$

$$\mathcal{B}(B \to D^* \ell \nu) = (5.27 \pm 0.22_{stat} \pm 0.38_{sys})\% \quad \text{(PDG:}(5.66 \pm 0.22)\%)$$





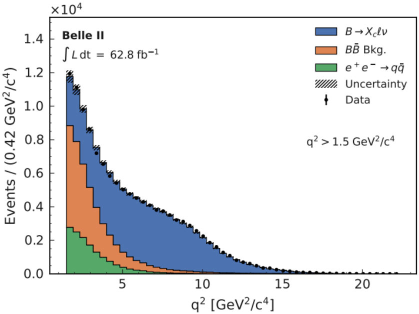
$$\eta_{EW} F(1)|V_{cb}| = (34.6 \pm 2.5_{(stat+sys)}) \times 10^{-3} \qquad \rho^2 = 0.94 \pm 0.21_{(stat+sys)}$$

$$|V_{cb}| = (37.9 \pm 2.7_{(stat+sys)}) \times 10^{-3} \quad \text{(PDG:}(39.5 \pm 0.9) \times 10^{-3})$$

$|V_{cb}|$ from tagged $B \to X_c \ell \nu$

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2\left(1 + \frac{c_5(\mu)O_5(\mu)}{m_b^2} + \mathcal{O}\left(\frac{1}{m_b^3}\right) + \mathcal{O}\left(\frac{1}{m_b^4}\right) + \ldots\right)$$

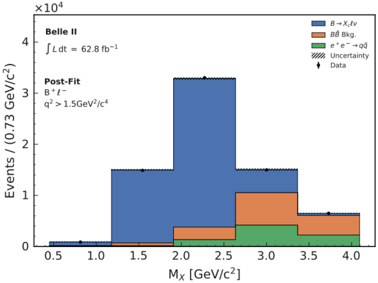
- Established: $|V_{cb}|$ and HQE parameters up to $\mathcal{O}(\frac{1}{m_b^3}) \to$ precision loss [arXiv:1411.6560]
- Problem: Increase expansion $\to$ increase in matrix elements
- Solution: Avoid proliferation by exploiting reparameterization invariance [arXiv:1812.07472]
- Not true for all observables, but holds for $\langle q^2 \rangle$
- Measurement of $\langle q^{2n} \rangle$ up to $n = 4$
- Main challenges: background modelling at low q^2, impact of $B \to X_c \ell \nu_\ell$ modelling on calibration

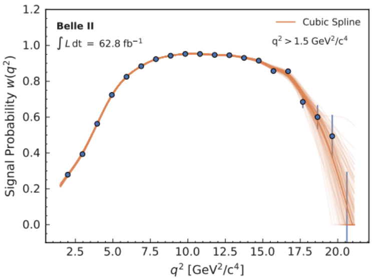


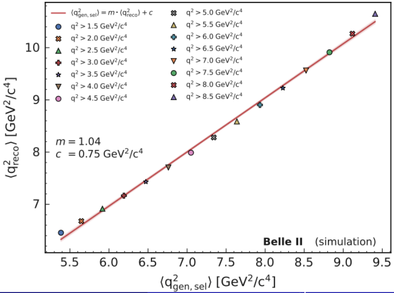
$|V_{cb}|$ from tagged $B \to X_c \ell \nu$

$$\langle q^{2n} \rangle = \frac{\sum_i w_i(q^2) q^{2n}_{i,calib}}{\sum_i w_i(q^2)} \cdot \mathcal{C}_{calib} \cdot \mathcal{C}_{gen}$$

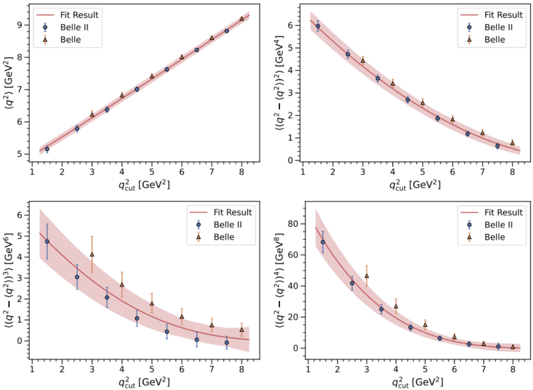
- Determine background normalisation using M_X fit
- Calculate event-wise signal probability $w(q^2)$
- Calibration to correct resolution and detector effects $(q^{2n})_{reco} \to (q^{2n})_{calib}$, $\mathcal{C}_{calib}$
- Correct for selection effects $\mathcal{C}_{gen}$

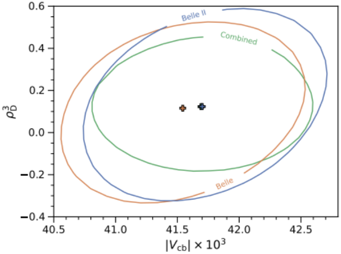






$|V_{cb}|$ from $B \to X_c \ell \nu$





Belle, Belle II, Combined

Combined measurement: Belle data and 62.8fb^{-1} of Belle II data
Fit by F. Bernlochner et al. [arXiv:2205.10274] to the Belle and Belle II q^2 moments using

$$\mathcal{B}(B \to X_c \ell \nu_\ell) = (10.63 \pm 0.19)\%$$

$$|V_{cb}| = (41.69 \pm 0.63) \times 10^{-3}$$ (PDG: $(42.19 \pm 0.78) \times 10^{-3}$)

Rare decays

- $b \to s$ quark level transition forbidden at tree level in the SM e.g. $B \to K^*\ell\ell$
- 3.1σ evidence for LFU violation in $R(K)$ at LHCb
- Belle II has nearly symmetric e/μ reconstruction performance:
  - Provide independent check for $R(K^{(*)})$ anomalies with > 1 ab^{-1}
  - Measure $R(X_S)$

SM

$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} = 1 \pm \mathcal{O}(10^{-2})$$

$q^2 \in [1(1.1), 6]$ for $R(K^{(*)})$

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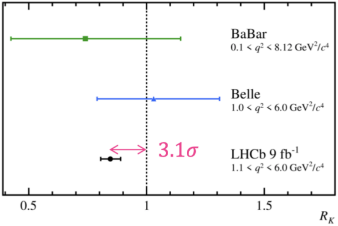
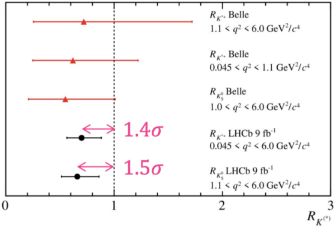


arXiv:2103.11769, arXiv:2110.09501



$B \to K^*\ell\ell$ branching fraction

- Reconstruct $B \to K^*(\to K^+\pi^-, K^+\pi^0, K_s^0\pi^+)\ell^+\ell^-$
- 2D likelihood fit to $M_{bc} = \sqrt{s/4 - p_B^{*2}}$, $\Delta E = E_B^* - \sqrt{s}/2$
- Branching fraction measured over whole q^2 range
- J/ψ and $\psi(2S)$ resonances excluded
- Signal significance $3.6\sigma - 5.9\sigma$

$$\mathcal{B}(B \to K^*\mu\mu) = (1.28 \pm 0.29^{+0.08}_{-0.07}) \times 10^{-6}$$

(PDG:$(1.06 \pm 0.09) \times 10^{-6}$)

$$\mathcal{B}(B \to K^*ee) = (1.04 \pm 0.48^{+0.09}_{-0.09}) \times 10^{-6}$$

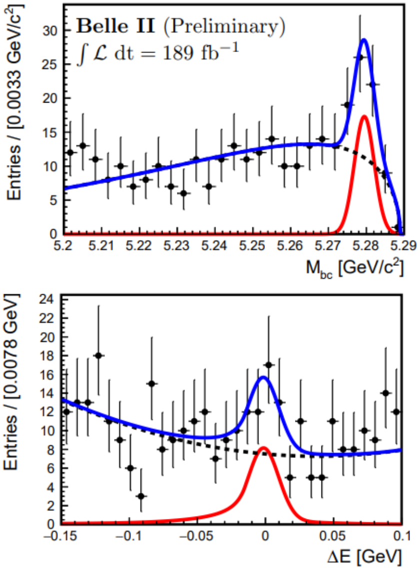
(PDG:$(1.19 \pm 0.20) \times 10^{-6}$)

$$\mathcal{B}(B \to K^*\ell\ell) = (1.22 \pm 0.28^{+0.08}_{-0.07}) \times 10^{-6}$$

(PDG:$(1.06 \pm 0.10) \times 10^{-6}$)

$K^*\ell\ell$ fit projections

signal PDF, total PDF, background PDF, ● data



Summary and outlook

- First results of tagged exclusive $|V_{cb}|$ and $|V_{ub}|$ measurements
- First tagged inclusive $|V_{cb}|$ result using $\langle q^2 \rangle$
- First Belle II measurements of $B \to K^* \ell\ell$ branching fractions
- All measurements in agreement with current world average within 1σ
- Have already doubled the amount of data from the shown results
- Expect more competitive measurements using a bigger data sample soon

Backup

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

Input variables

Variables	Values
N^{rec}	545 (data)
N^{bg}	29.4 ± 11.2
ϵ	$(9.55 \pm 0.67) \times 10^{-4}$
$N_{B\bar{B}}$	$(197.17 \pm 5.72) \times 10^{6}$
f_{+0}	1.058 ± 0.024
$\mathcal{B}\left(D^{*-} \to \pi^- \overline{D}^0\right)$	$(67.7 \pm 0.5)\%$
$\mathcal{B}\left(\overline{D}^0 \to K^+ \pi^-\right)$	$(3.950 \pm 0.031)\%$

Systematics

Systematic sources	Relative uncertainty (%)
FEI efficiency	3.9
Low momentum π efficiency	4.1
Tracking efficiency	0.9
Lepton particle identification	2.0
Background	1.2
$N_{B\bar{B}}$	2.9
f_{+0}	1.2
$\mathcal{B}\left(D^{*-} \to \pi^- \overline{D}^0\right)$	0.7
$\mathcal{B}\left(\overline{D}^0 \to K^+ \pi^-\right)$	0.8
ECL energy	1.0
Form factor	0.1
MC statistics	1.8
Total	7.3

$$\mathcal{B}\left(B^0 \to D^{*-} \ell^+ \nu_\ell\right) = \frac{\left(N^{\text{rec}} - N^{\text{bg}}\right) \times \epsilon^{-1}}{4 \times N_{B\bar{B}} \times (1 + f_{+0})^{-1} \times \mathcal{B}\left(D^{*-} \to \pi^- \overline{D}^0\right) \times \mathcal{B}\left(\overline{D}^0 \to K^+ \pi^-\right)}$$

Tagged $B \to \pi e \nu$ branching fractions

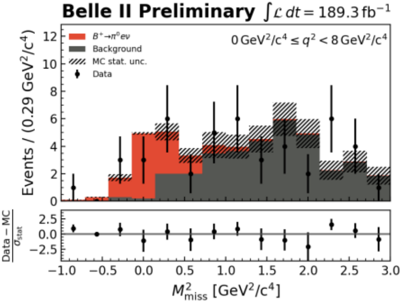
q^2 bin	Signal efficiency	Unfolded signal yield	$\Delta\mathcal{B}$
		$B^+ \to \pi^0 e^+ \nu_e$	
$0\ \text{GeV}^2 \leq q^2 < 8\ \text{GeV}^2$	$(0.329 \pm 0.004)\%$	12.9 ± 4.7	$(2.90 \pm 1.12(\text{stat}) \pm 0.19(\text{syst}))\ \times 10^{-5}$
$8\ \text{GeV}^2 \leq q^2 < 16\ \text{GeV}^2$	$(0.439 \pm 0.005)\%$	18.1 ± 5.1	$(3.05 \pm 0.91(\text{stat}) \pm 0.20(\text{syst}))\ \times 10^{-5}$
$16\ \text{GeV}^2 \leq q^2 \leq 26.4\ \text{GeV}^2$	$(0.451 \pm 0.006)\%$	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 [10]	–	–	$(7.80 \pm 0.27)\ \times 10^{-5}$

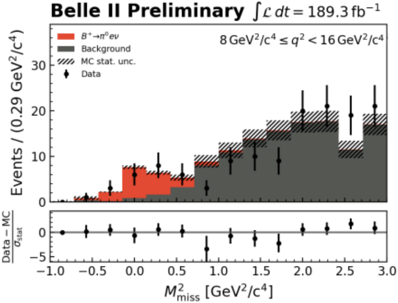
q^2 bin	Signal efficiency	Unfolded signal yield	$\Delta\mathcal{B}$
		$B^0 \to \pi^- e^+ \nu_e$	
$0\ \text{GeV}^2 \leq q^2 < 8\ \text{GeV}^2$	$(0.189 \pm 0.002)\%$	15.5 ± 4.6	$(0.61 \pm 0.18(\text{stat}) \pm 0.03(\text{syst}))\ \times 10^{-4}$
$8\ \text{GeV}^2 \leq q^2 < 16\ \text{GeV}^2$	$(0.239 \pm 0.003)\%$	15.3 ± 4.8	$(0.48 \pm 0.15(\text{stat}) \pm 0.02(\text{syst}))\ \times 10^{-4}$
$16\ \text{GeV}^2 \leq q^2 \leq 26.4\ \text{GeV}^2$	$(0.229 \pm 0.003)\%$	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 [10]	–	–	$(1.50 \pm 0.06)\ \times 10^{-4}$

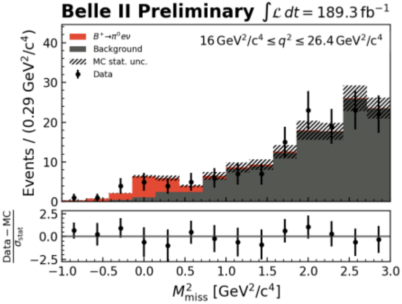
Tagged $B \to \pi e \nu$ systematics

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

Tagged $B^+ \to \pi e \nu$ M^2_{miss} fit and results



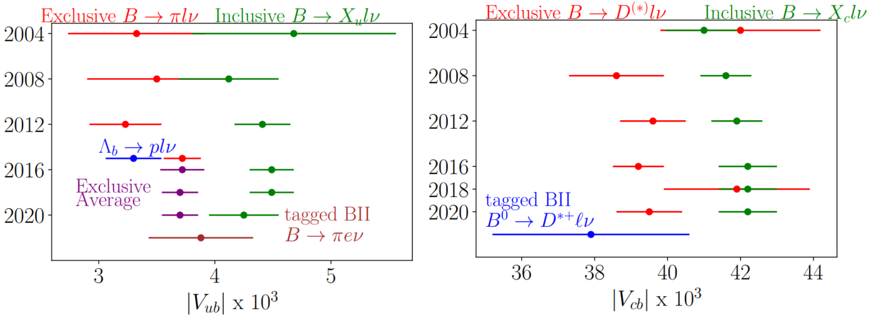




Decay mode	Fitted $\lvert V_{ub}\rvert$
$B^0 \to \pi^- e^+ \nu_e$	$(3.71 \pm 0.55)\ \times 10^{-3}$
$B^+ \to \pi^0 e^+ \nu_e$	$(4.21 \pm 0.63)\ \times 10^{-3}$
Combined fit	$(3.88 \pm 0.45)\ \times 10^{-3}$

First exclusive $|V_{cb}|$ and $|V_{ub}|$ results

- First $|V_{cb}|$ and $|V_{ub}|$ measurements statistically very limited
- Expecting untagged measurements with higher precision soon $\epsilon \sim 20 - 30\%$



$q2$ moments uncertainties

	q^2_{th} [Gev^2/c^4]	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
	$\langle q^2 \rangle$ [Gev^2/c^4]	5.16	5.49	5.79	6.09	6.38	6.69	7.01	7.32	7.62	7.93	8.23	8.53	8.82	9.10	9.39
Calibration (MC Statistics)	Calib. Curve (Stat. Unc.)	0.63	0.56	0.49	0.43	0.38	0.33	0.29	0.26	0.25	0.26	0.28	0.30	0.33	0.37	0.40
	Bias Corr. (Stat. Unc.)	0.10	0.09	0.09	0.08	0.08	0.08	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.06
Calibration (X_c Model)	$\mathcal{B}(B \to D\ell\nu)$	0.10	0.09	0.08	0.07	0.06	0.05	0.04	0.04	0.03	0.02	0.02	0.01	0.01	0.00	0.00
	$\mathcal{B}(B \to D^*\ell\nu)$	0.33	0.29	0.24	0.21	0.17	0.14	0.11	0.09	0.07	0.05	0.04	0.03	0.02	0.01	0.00
	$\mathcal{B}(B \to D^{**}\ell\nu)$	0.71	0.63	0.55	0.48	0.40	0.34	0.28	0.23	0.18	0.13	0.10	0.07	0.05	0.03	0.02
	Non-Res. X_c Dropped	0.31	0.63	0.75	0.76	0.69	0.60	0.48	0.39	0.32	0.25	0.18	0.14	0.11	0.08	0.06
	Non-Res. X_c Repl. w/ D_1', D_0^*	0.34	0.49	0.51	0.45	0.37	0.29	0.18	0.10	0.04	0.02	0.00	0.03	0.03	0.03	0.01
	$B \to D\ell\nu$ Form Factor	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	$B \to D^*\ell\nu$ Form Factor	0.08	0.07	0.07	0.07	0.06	0.06	0.06	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.03
Calibration (Reconstruction)	PID Uncertainty	0.14	0.12	0.11	0.09	0.08	0.07	0.05	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01
	N_γ Reweighted	0.30	0.27	0.24	0.22	0.20	0.18	0.16	0.14	0.14	0.13	0.13	0.12	0.11	0.10	0.10
	N_{tracks} Reweighted	1.09	1.00	0.92	0.85	0.78	0.72	0.65	0.60	0.55	0.51	0.47	0.44	0.41	0.38	0.35
	$E_{\mathrm{miss}} - p_{\mathrm{miss}}$ Reweighted	0.26	0.22	0.21	0.19	0.18	0.17	0.15	0.15	0.14	0.14	0.13	0.12	0.12	0.11	0.09
	Tracking Efficiency	0.13	0.12	0.11	0.10	0.09	0.09	0.08	0.07	0.06	0.06	0.05	0.05	0.05	0.04	0.04
Background Subtraction	Spline Smooth. Factor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bkg. Yield & Shape	1.39	1.15	0.90	0.77	0.63	0.47	0.33	0.23	0.16	0.10	0.06	0.03	0.02	0.05	0.06
Other	Non-Closure Bias	0.18	0.21	0.16	0.11	0.06	0.05	0.02	0.02	0.01	0.02	0.02	0.02	0.01	0.01	0.02
	Stat. Uncertainty	0.27	0.24	0.21	0.20	0.18	0.16	0.16	0.15	0.14	0.14	0.13	0.13	0.13	0.13	0.13
	Syst. Uncertainty	2.14	1.99	1.80	1.64	1.44	1.23	1.02	0.88	0.77	0.69	0.62	0.59	0.57	0.56	0.57
	Total Uncertainty	2.16	2.00	1.81	1.65	1.45	1.24	1.03	0.89	0.78	0.70	0.64	0.61	0.59	0.58	0.58

Source	Systematic (%)
signal PDF shape	~ 1.0
muon identification	$^{+1.9}_{-0.8}$
electron identification	$^{+0.9}_{-0.5}$
kaon identification	0.4
pion identification	2.5
K_S^0 identification	2.0
π^0 identification	3.4
FastBDT	1.3 – 1.7
limited MC statistics	< 0.5
signal cross feed	$\sim 1\%$
tracking	1.2 – 1.5
$\mathcal{B}(\Upsilon(4S) \to B^+B^-)[(\mathcal{B}(\Upsilon(4S) \to B^0\bar{B}^0))$	1.2
number of $B\bar{B}$ pairs	2.9
Total	$^{+6.7}_{-6.0}$