Exclusive semileptonic decays at Belle II

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on behalf of the Belle II collaboration

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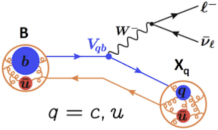
Semileptonic decays

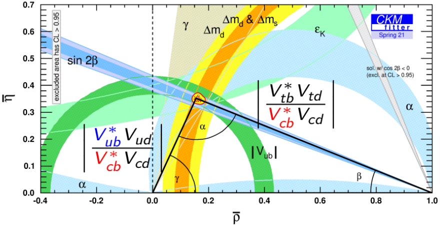
- SM precision measurements
  - Semileptonic decays used to measure the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$
- Potential probes of new physics
  - $\sim 3\sigma$ discrepancy from SM in measurements of ratios

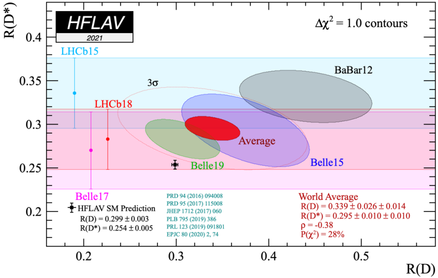
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)} \quad (\ell = \mu, e)$$



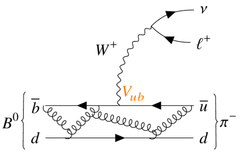
$q = c, u$

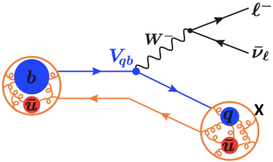
$$q^2 = (p_\ell + p_\nu)^2$$





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



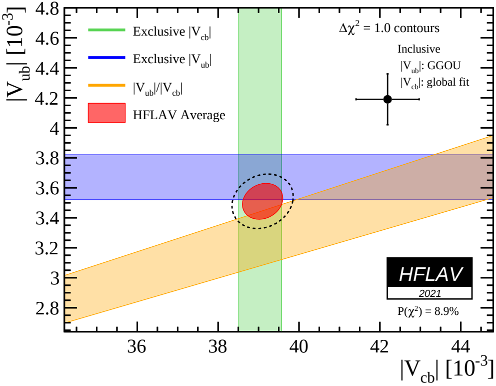


- **Exclusive**: Reconstruct specific final states
  - Measure all visible final state particles
- *i.e.:*
  - $|V_{cb}|$: $B \to D^{(*)}\ell\nu$
  - $|V_{ub}|$: $B \to \pi\ell\nu$
- Theory: Lattice QCD
- $\to$ covered today

- **Inclusive**: Measure general $X\ell\nu$ decay
  - Measure some particles in decay
  - Assign remaining unmeasured parts to X
- *i.e.:*
  - $|V_{cb}|$: $B \to X_c\ell\nu$
  - $|V_{ub}|$: $B \to X_u\ell\nu$
- Theory: HQET
- $\to$ talk by Frank Meier on Tuesday

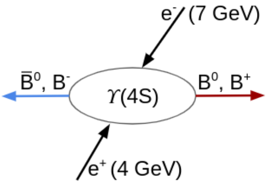
Status of $|V_{cb}|$ and $|V_{ub}|$

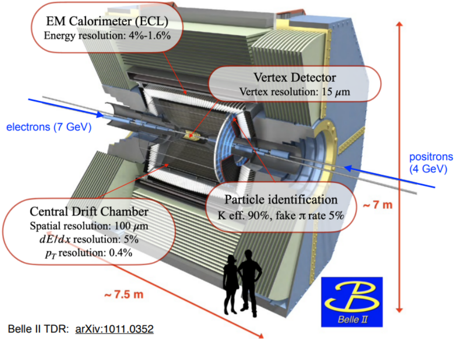
- $\sim 3.3\sigma$ discrepancy between inclusive and exclusive $|V_{cb}|$ and $|V_{ub}|$ measurements



SuperKEKB and Belle II

- **SuperKEKB:**
  - e^+e^- collider at 10.58 GeV, the $\Upsilon(4S)$ resonance
  - Peak luminosity reached: $4.71 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, June 22, 2022
    - World record!
    - $>$ 100% increase over KEKB (Belle)

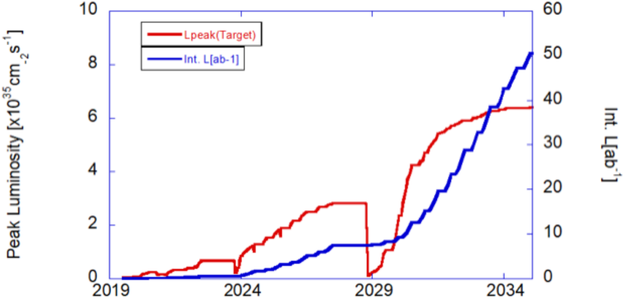




Belle II TDR: arXiv:1011.0352

- **Belle II:**
  - Hermetic detector
    - 3-dimensional missing momentum measurements
    - Important for studying events with missing energy
  - Particle identification
    - μ ID superior to Belle
    - e and K ID not at Belle level yet but improving
  - high γ detection efficiency

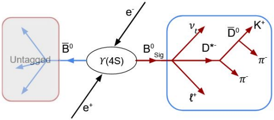
Luminosity



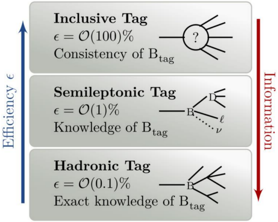
- Data-taking since 2019
- With June 2022 went into Long Shutdown 1
- Recorded data up until LS1: **424 fb^{-1}** (BaBar: 425 fb^{-1}, Belle: 711 fb^{-1})
- Current results: 189 fb^{-1}
- Long term goal 50 ab^{-1} by > 2030

Untagged vs Tagged

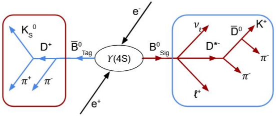
Untagged



- Reconstruct only B_{sig}
- High efficiency, high backgrounds



Tagged



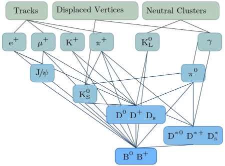
- B_{sig} and B_{tag} are reconstructed
- Tag can be hadronic or semileptonic
- Precisely determine missing neutrino momentum

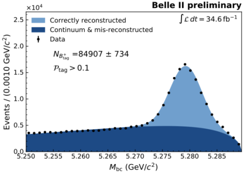
Terminology

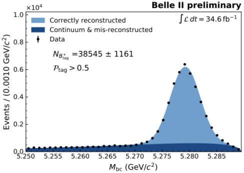
- **Untagged - Tagged**
  - Only one or both B mesons reconstructed per event
- **Exclusive - Inclusive**
  - Reconstruction of $B_{sig} \to$ specific decay or $B_{sig} \to X\ell\nu$

Full Event Interpretation

- Full Event Interpretation algorithm [Comput Softw Big Sci 3, 6 (2019)] to reconstruct B_{tag}
  - Reconstruct B candidate with all combination of daughters
  - Calculate signal probability with multivariate classifiers







$$M_{bc} = \sqrt{E_{beam}^2/4 - (p_{B_{\mathrm{tag}}}^{\mathrm{cm}})^2} > 5.27\ \mathrm{GeV}/c^2$$

- Hadronic FEI
  - Over 200 BDTs to reconstruct $\mathcal{O}(10000)$ distinct decay chains
  - $\epsilon_{B^+} \approx 0.5\%$, $\epsilon_{B^0} \approx 0.3\%$ at $\sim 15\%$ purity
    - $\sim 50\%$ increase over Belle tag

Analyses

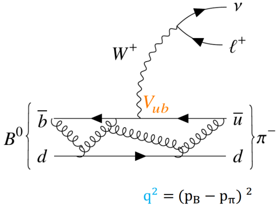
Featured analyses with 189 fb^{-1}

- Exclusive CKM measurements

Analyses covered	$\lvert V_{ub}\rvert$	$\lvert V_{cb}\rvert$
Untagged	$B \to \pi\ell\nu$ (2022)	$B \to D\ell\nu$ (2022)
Tagged	$B \to \pi e\nu$ (2022)	$B \to D^*\ell\nu$ (2022)

- Branching ratio measurements
  - Tagged $\mathcal{B}(B \to \rho\ell\nu)$ (2022)

Untagged $|V_{ub}|$ via $B \to \pi\ell\nu$



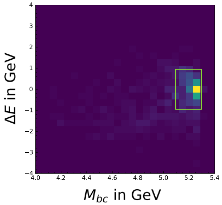
- Reconstruct $B^0 \to \pi^{\pm}\ell\nu$ with $\ell = (e, \mu)$
- Main challenge: large backgrounds from continuum and other semileptonic decays
- Separate boosted decision trees to suppress background
- Signal extraction via binned 2D fit using ΔE and M_{bc}

$$\Delta E = E_B^* - E_{\text{beam}}^*$$

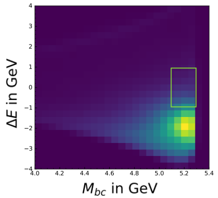
$$M_{bc} = \sqrt{(E_{\text{beam}}^*)^2 - (p_B^*)^2}$$

$B \to \pi e \nu_e$

Signal

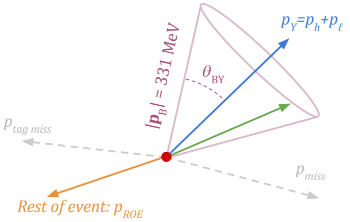


Background



Untagged $|V_{ub}|$ via $B \to \pi \ell \nu$

- Momentum transfer $q^2 = (p_B - p_\pi)^2 = (p_\ell + p_\nu)^2$ important parameter for $|V_{ub}|$ extraction



- Untagged analysis: p_B not known, estimated with new method (extension of BABAR's diamond frame [Phys. Rev. D 74, 092004]):
  - Calculate angle between B meson and combined $\pi\ell = Y$

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

  - Calculate Rest of Event (ROE) momentum p_{ROE}
  - Likely direction on $\cos\theta_{BY}$ cone: close to back-to-back of p_{ROE}
  - Build weighted average over 10 uniformly distributed vectors on cone with weights

$$\frac{1}{2}(1 - \hat{p}_{\mathrm{ROE}} \cdot \hat{p}_{\mathrm{B}}) \sin^2\theta_B$$

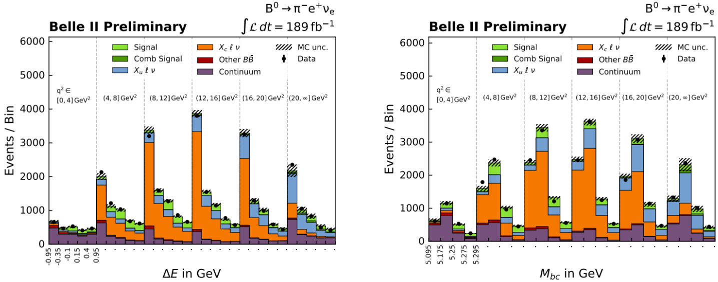
Untagged $|V_{ub}|$ via $B \to \pi \ell \nu$

- Differential branching ratios dependent on $|V_{ub}|$ and q^2

$$\frac{d\mathcal{B}(B \to \pi\ell\nu)}{dq^2} \propto |V_{ub}|^2 \times f_+(q^2)$$

- To extract $|V_{ub}|$ partial branching fractions measured with independent fits in 6 q^2 bins

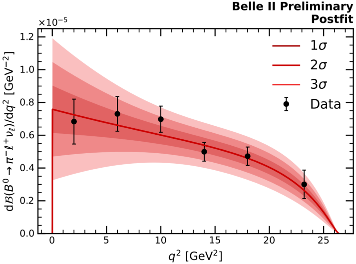
Post-Fit



Bin	$[q^2_{min}, q^2_{max}]$ [GeV^2]
1	[0,4]
2	[4,8]
3	[8,12]
4	[12,16]
5	[16,20]
6	[20,∞]

Untagged $|V_{ub}|$ via $B \to \pi \ell \nu$

- Combine e and μ spectra in weighted average
- Fit partial branching ratios to BCL expansion [Phys. Rev. D 79, 013008] to determine $|V_{ub}|$
- FNAL/MILC [Phys. Rev. D 92, 014024] Lattice QCD constraints included as nuisance parameters



$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.42 \pm 0.06_{\text{stat}} \pm 0.13_{\text{sys}}) \times 10^{-4},$$

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

$$|V_{ub}| = (3.54 \pm 0.12_{\text{stat}} \pm 0.15_{\text{sys}} \pm 0.16_{\text{theo}}) \times 10^{-3}$$

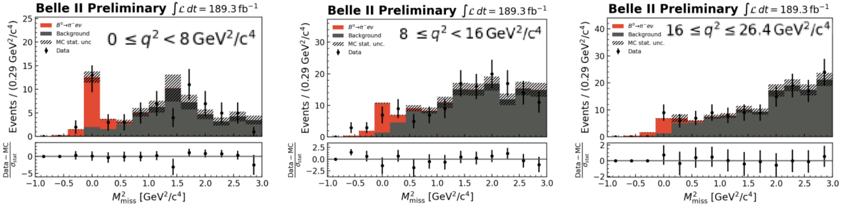
World-average exclusive $\pi \ell \nu$: $(3.67 \pm 0.15) \times 10^{-3}$ [arXiv:2206.07501]

Tagged $|V_{ub}|$ via $B \to \pi e \nu$

arXiv:2206.08102

- Reconstruct $B^0 \to \pi^\pm e \nu_e$ and $B^\pm \to \pi^0 e \nu_e$
- Hadronic FEI
- Clean q^2 reconstruction thanks to tag: $q^2 = (p_{e^+e^-} - p_{B_{tag}} - p_\pi)^2$
- Fit $M^2_{miss} = (p_{e^+e^-} - p_{B_{tag}} - p_e - p_\pi)^2$ in 3 q^2 bins

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



Tagged $|V_{ub}|$ via $B \to \pi e \nu$

- Fit partial branching ratios to BCL expansion [Phys. Rev. D 79, 013008] to determine $|V_{ub}|$
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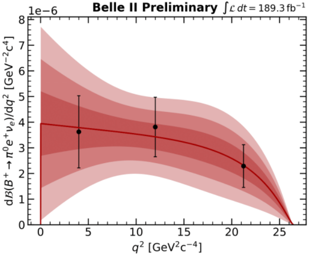
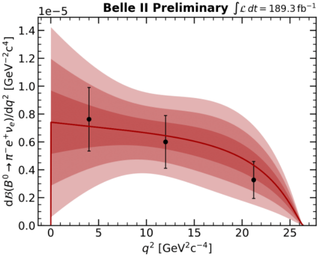




$$|V_{ub}| = (3.88 \pm 0.45) \times 10^{-3}$$

World-average exclusive $\pi \ell \nu$: [arXiv:2206.07501]

$(3.67 \pm 0.15) \times 10^{-3}$

- Leading systematic: Tag calibration factor

Tagged $\mathcal{B}(B \to \rho\ell\nu)$

- Tagged measurement of $B^0 \to \rho^\pm \ell\nu$ and $B^\pm \to \rho^0 \ell\nu$ with $\rho \to \pi\pi$
  - Potential new avenue to measure $|V_{ub}|$ with independent sample
  - Previously observed tensions in both $\rho^\pm$ and ρ^0 modes
- 2-dimensional fit in $M_{\pi\pi}$ and M^2_{miss} to measure branching fractions
- BDT to suppress continuum background

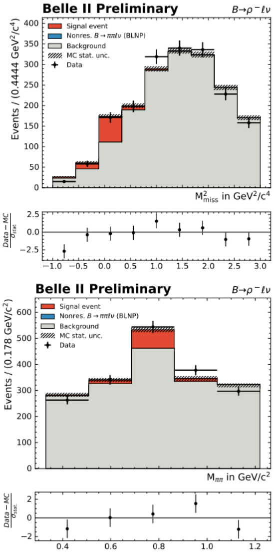
$$\mathcal{B}(B^0 \to \rho^- \ell^+ \nu_\ell) = (4.12 \pm 0.64_{\text{stat}} \pm 1.16_{\text{sys}}) \times 10^{-4},$$

PDG: $(2.94 \pm 0.11 \pm 0.18) \times 10^{-4}$

$$\mathcal{B}(B^+ \to \rho^0 \ell^+ \nu_\ell) = (1.77 \pm 0.23_{\text{stat}} \pm 0.36_{\text{sys}}) \times 10^{-4}$$

PDG: $(1.58 \pm 0.11) \times 10^{-4}$

- Large systematic from $B \to \pi\pi\ell\nu$ background

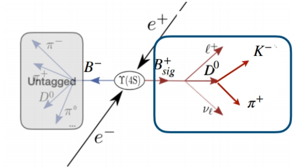


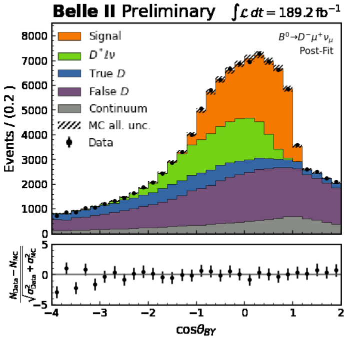
Untagged $|V_{cb}|$ via $B \to D\ell\nu$

- Reconstruct $B^{\pm} \to D^0\ell\nu$ and $B^0 \to D^{\pm}\ell\nu$ with $\ell = (e, \mu)$ and $D \to K\pi(\pi)$
- Main challenge: large backgrounds from $D^*\ell\nu$
- Signal extraction via 1 dimensional fit of angle between B and $Y(D\ell)$
  - Only between -1 and 1 for signal

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

- D^* veto to reduce $B \to D^*\ell\nu$ candidates
  - Reconstruct slow pion π_s with $p < 0.35$ GeV
  - If π_s and D candidate can be combined to D^* with $m_D^* - m_D \in [140, 150]$ MeV $\to$ veto event



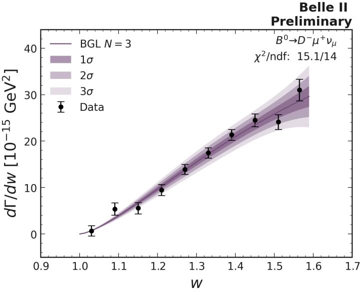


Untagged $|V_{cb}|$ via $B \to D\ell\nu$

- Differential decay width proportional to V_{cb} and hadronic recoil w

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}w}(B \to D\ell\nu_\ell) = \frac{G_F^2}{48\pi^3}(m_B + m_D)^2 m_D^3 \eta_{EW} |V_{cb}|^2 (w^2 - 1)^{3/2} \mathcal{G}(w)^2,$$

- with $w = \frac{P_B \cdot P_D}{m_B m_D} = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$ and form factor $\mathcal{G}(w)$
- Fit form factor to differential decay rates in 10 bins of w
- BGL (N=3) parametrization [Phys. Rev. D 56, 6895 (1997)]
- FNAL/MILC [Phys. Rev. D 92, 034506] and HPQCD Lattice QCD [Phys. Rev. D 92, 054510 (2015)] as nuisance parameters



$$|V_{cb}| = (38.3 \pm 1.2) \times 10^{-3}$$

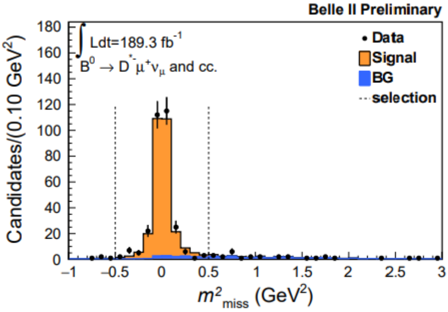
World-average exclusive $D\ell\nu$: [arXiv:2206.07501]

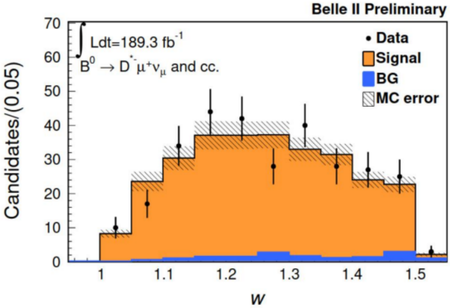
$(39.14 \pm 0.92_{\mathrm{exp}} \pm 0.36_{\mathrm{th}}) \times 10^{-3}$

- Consistent with the exclusive world average
- $\sim 3\%$ error, comparable to the past measurements

Tagged $|V_{cb}|$ via $B \to D^*\ell\nu$

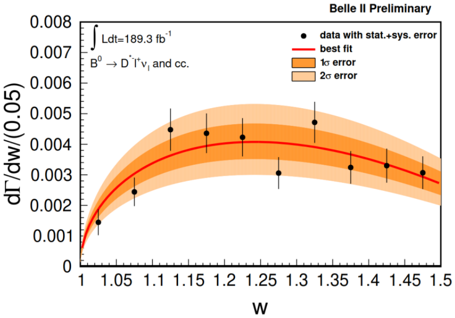
- Tagged measurement of $B^0 \to D^{*\pm}\ell\nu$ with $\ell = (e, \mu)$, $D^{*-} \to D^0\pi_s^-$ and $D^0 \to K^-\pi^+$
- High signal purity thanks to tagging and clean signature of $D^*\ell\nu$ mode
- Fit m^2_{miss} in 10 bins of w





Tagged $|V_{cb}|$ via $B \to D^* \ell \nu$

- Fit CLN parametrized form factor [NPB530, 153 (1998)] to differential decay rates



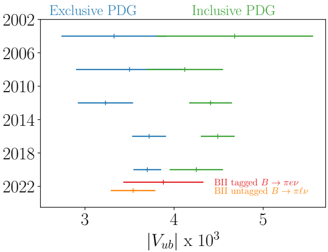
$$|V_{cb}| = (37.9 \pm 2.7) \times 10^{-3}$$

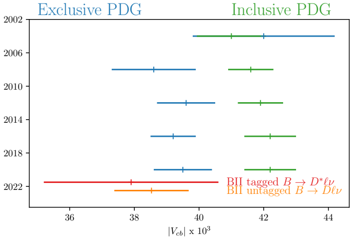
World-average exclusive $D^* \ell \nu$: [arXiv:2206.07501]

$$(38.46 \pm 0.40_{\text{exp}} \pm 0.55_{\text{th}}) \times 10^{-3}$$

- Major systematic errors: slow π efficiency and tag calibration

Summary





- Improved measurements of $|V_{cb}|$ and $|V_{ub}|$ are essential to increase the constraining power of the Unitarity triangle fit
- First exclusive measurements of $|V_{cb}|$ and $|V_{ub}|$ at Belle II with 189 fb^{-1}
- Results are in agreement with previous results and approaching their precision
- *Soon:* $|V_{cb}|$ from untagged $D^*\ell\nu$, A_{fb} in $D^*\ell\nu$, first $R(D^*)$ results and many more!

- Related talks:
  - Frank Meier: Belle II results on inclusive $B \to X\ell\nu$
  - Koji Hara: LFU measurements in semileptonic $b \to c\ell\nu$ decays