Exclusive semileptonic decays at Belle II

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on behalf of the Belle II collaboration

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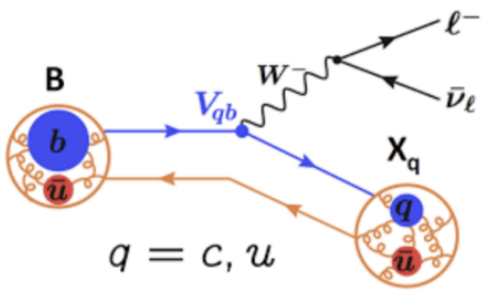
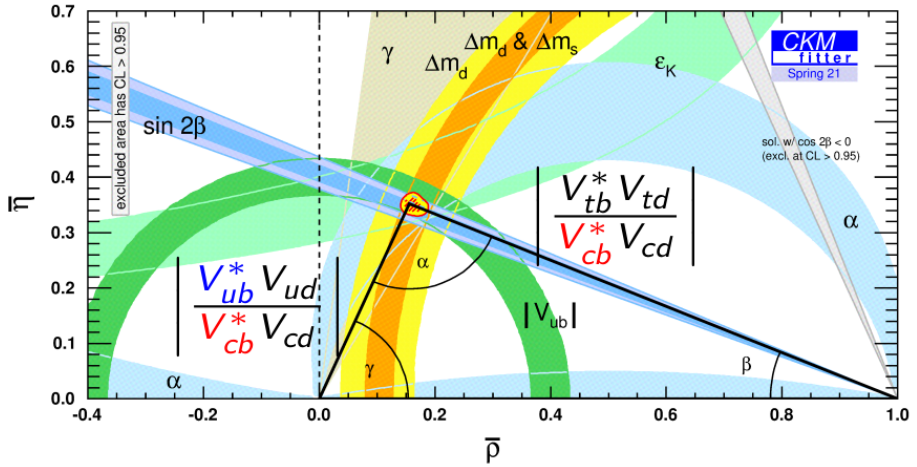
SCIENCES

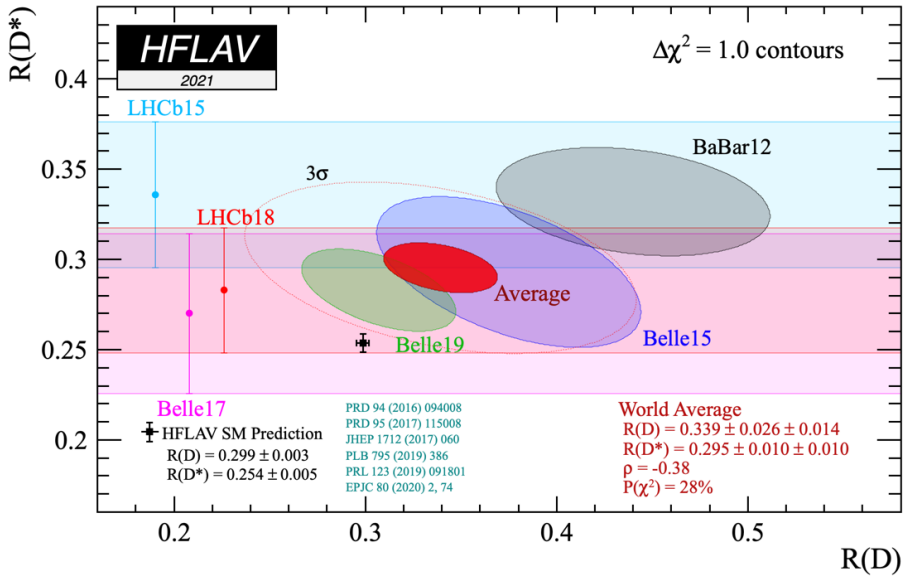
Semileptonic decays

- 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

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





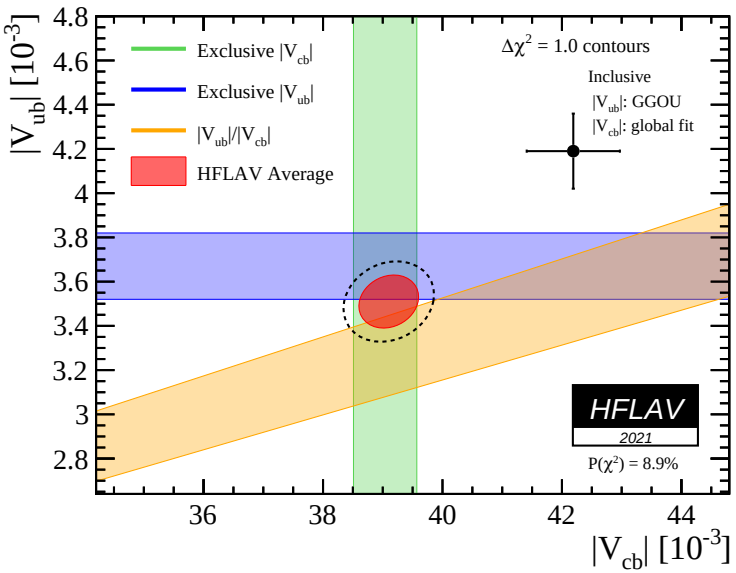


Status of $|V_{cb}|$ and $|V_{ub}|$

- **Exclusive**: Reconstruct specific final states
  - $B \to D^{(*)}\ell\nu$
  - $B \to \pi\ell\nu$
- Theory background: Lattice QCD
- $\to$ covered today

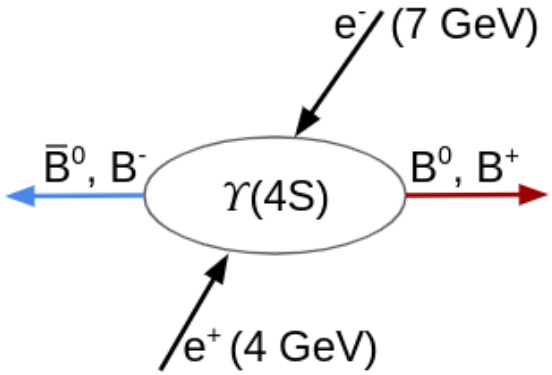
- **Inclusive**: Measure general $X\ell\nu$ decay
  - $B \to X_c\ell\nu$
  - $B \to X_u\ell\nu$
- Theory background: HQET
- $\to$ talk by Frank Meier on Saturday

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

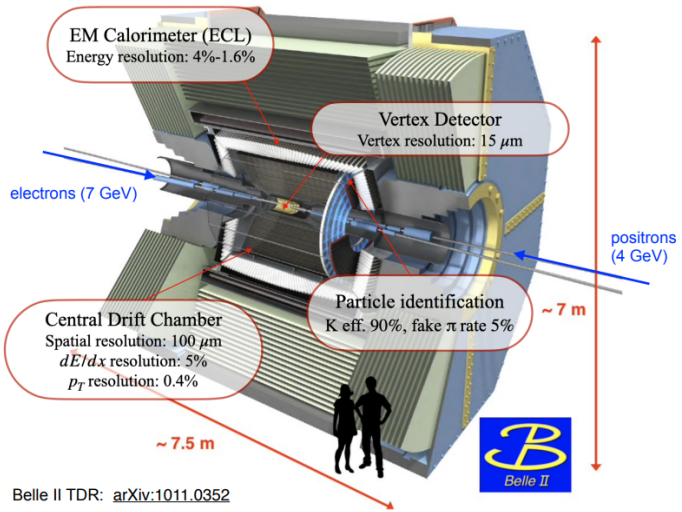


SuperKEKB and Belle II

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

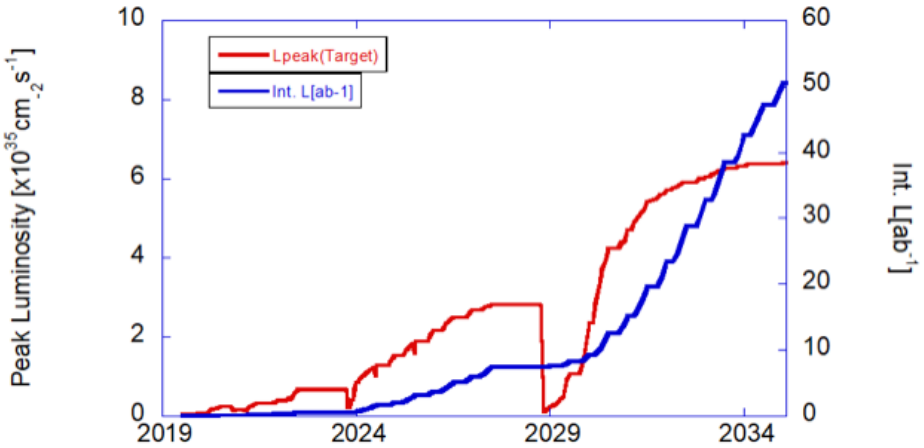


- Belle II:
  - Hermetic detector: important for studying events with missing energy
  - Particle identification
    - μ ID superior to Belle
    - e and K ID not at Belle level yet but improving
  - high γ detection efficiency



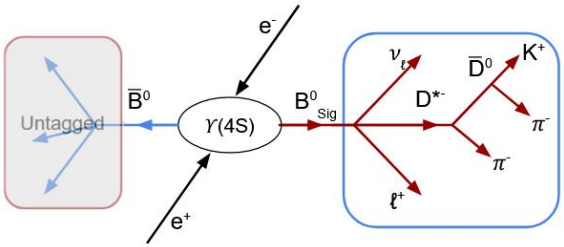
Luminosity

- Data-taking since 2019
- With June 2022 went into Long Shutdown 1 until Fall 2023
- Recorded data up until LS1: **424 fb^{-1}** (BaBar: 425 fb^{-1}, Belle: 711 fb^{-1})
- Long term goal 50 ab^{-1} by $>$ 2030



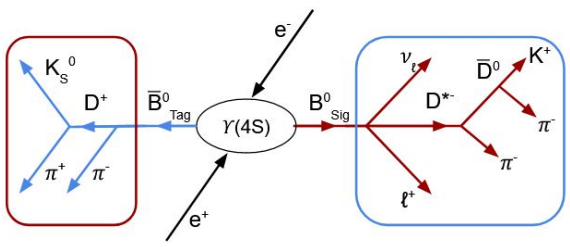
Untagged vs Tagged

Untagged

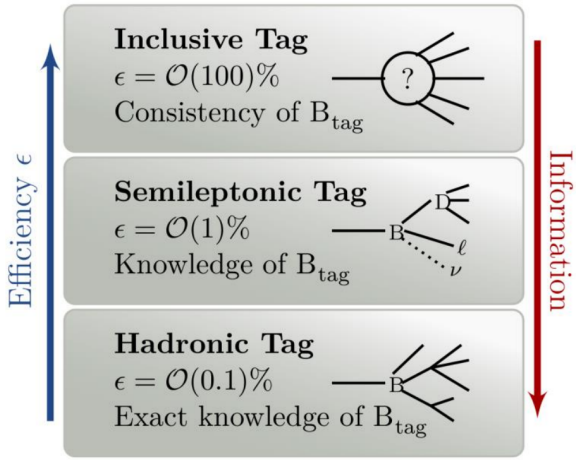


- Reconstruct only B_{sig}
- High efficiency, high backgrounds

Tagged



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



Analyses

Featured analyses with 189 fb^{-1}

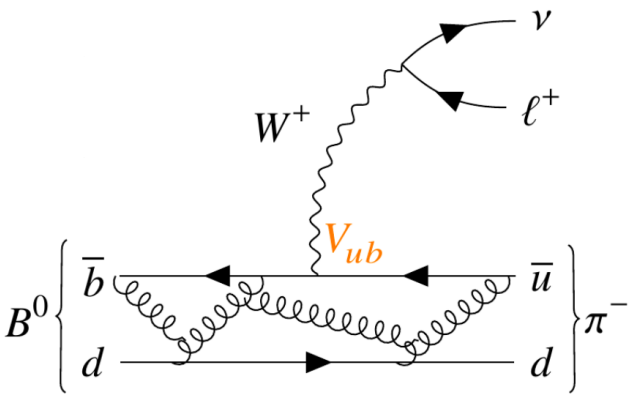
- Exclusive CKM measurements

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

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

Untagged $|V_{ub}|$

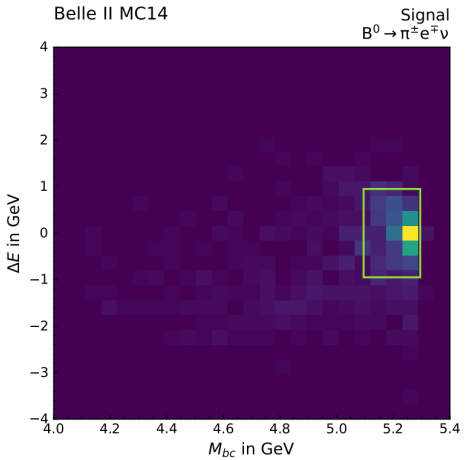
ICHEP 2022



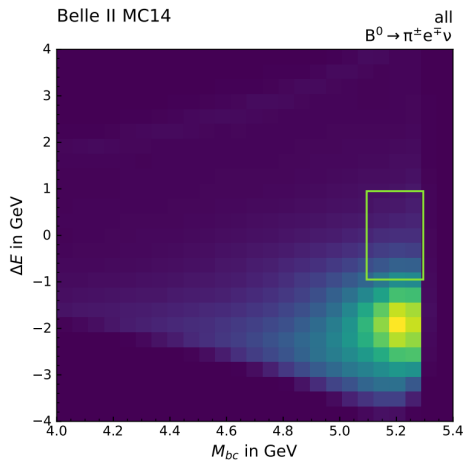
$q^2 = (p_B - p_\pi)^2$

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

Signal



Background



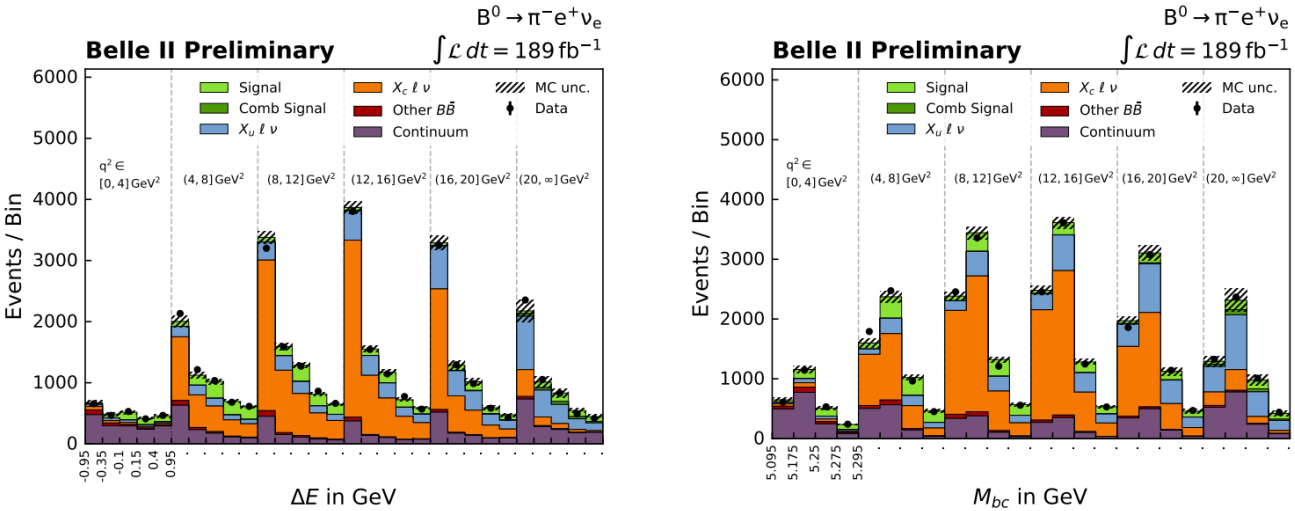
Untagged $|V_{ub}|$

- $q^2 = (p_B - p_\pi)^2$ is reconstructed using angle between B and $\pi\ell$ and Rest of Event information
- Differential branching ratios dependent on $|V_{ub}|$ and q^2

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

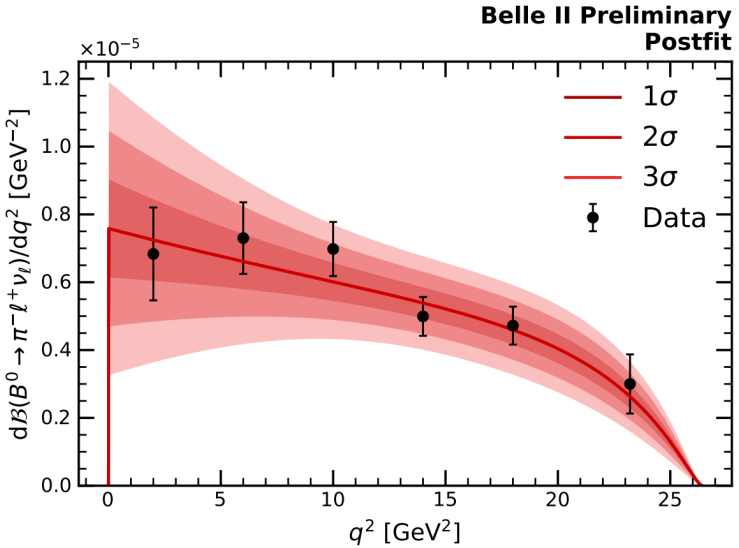
- To extract $|V_{ub}|$ partial branching fractions measured with independent fits in 6 q^2 bins

Post-Fit



Untagged $|V_{ub}|$

- Combine e and μ spectra in weighted average
- Fit partial branching ratios in 6 bins of q^2 to the BCL expansion to determine $|V_{ub}|$ and the FF parameters b_k
- Lattice QCD constraints (Fermilab/MILC) 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: $(3.51 \pm 0.12) \times 10^{-3}$

Tagged $|V_{ub}|$

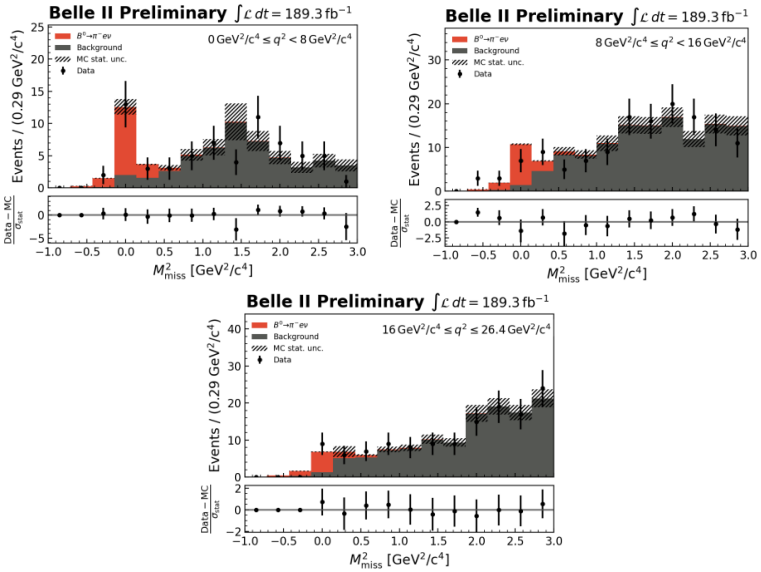
Moriond 2022

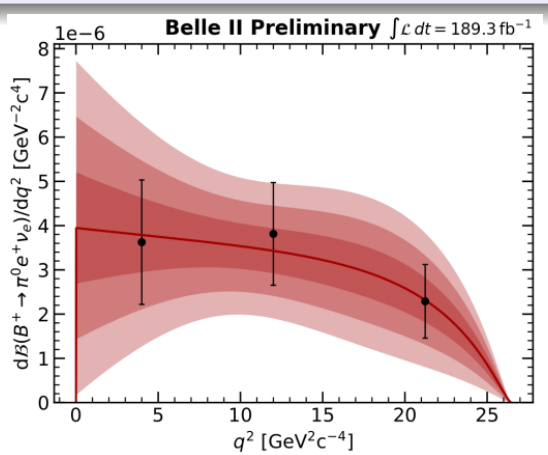
- Reconstruct $B^0 \to \pi^{\pm} e \nu_e$ and $B^{\pm} \to \pi^0 e \nu_e$
- Clean q^2 reconstruction thanks to tag: $q^2 = (p_{e^+e^-} - p_{B_{tag}} - p_{\pi})^2$
- Fit $M^2_{miss} = (p_{e^+e^-} - p_{B_{tag}} - p_e - p_{\pi})^2$ in 3 q^2 bins
- $|V_{ub}|$/FF fit equivalent to untagged analysis

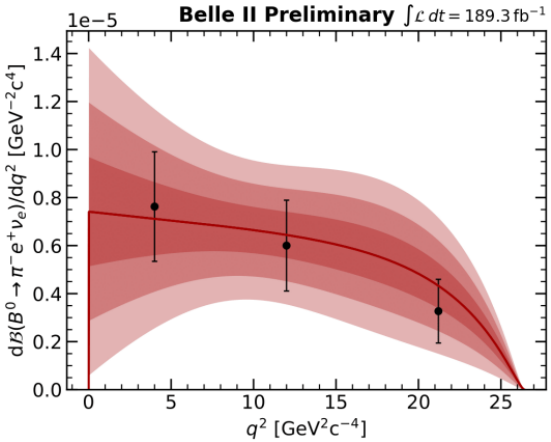
$$|V_{ub}| = (3.88 \pm 0.45) \times 10^{-3}$$

World-average exclusive: $(3.51 \pm 0.12) \times 10^{-3}$

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







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

ICHEP 2022

- 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
- Independent measurement of $B \to \pi\pi\ell\nu$ to subtract background
- BDT to suppress continuum background
- 2-dimensional fit in $M_{\pi\pi}$ and M^2_{miss} to measure branching fractions

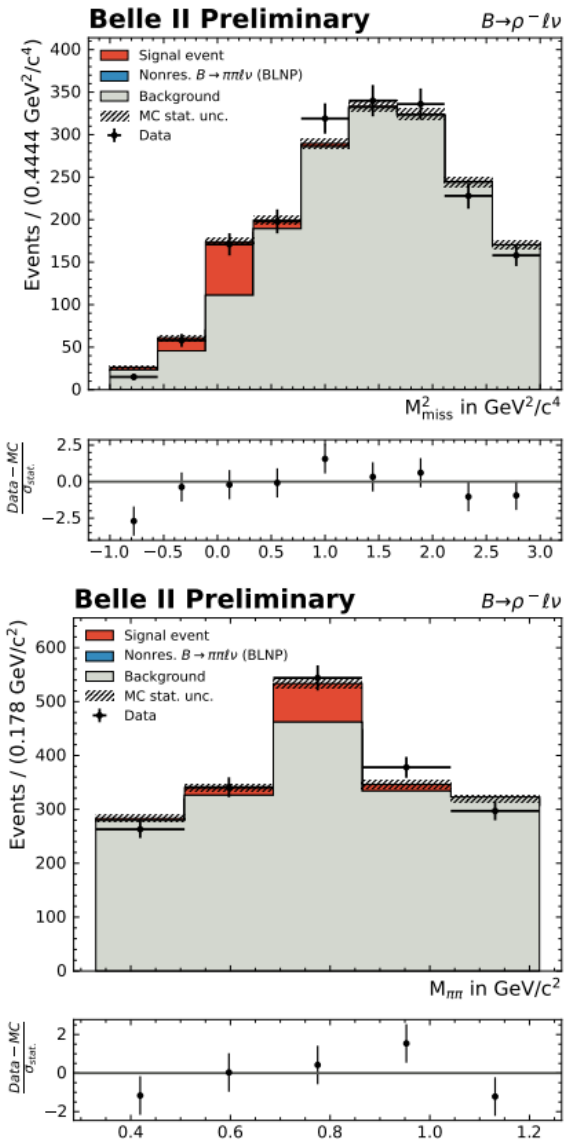
$$\mathcal{B}(B^0 \to \rho^- \ell^+ \nu_\ell) = (4.12 \pm 0.64_{\text{stat}} \pm 1.16_{\text{sys}}) \times 10^{-4},$$

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



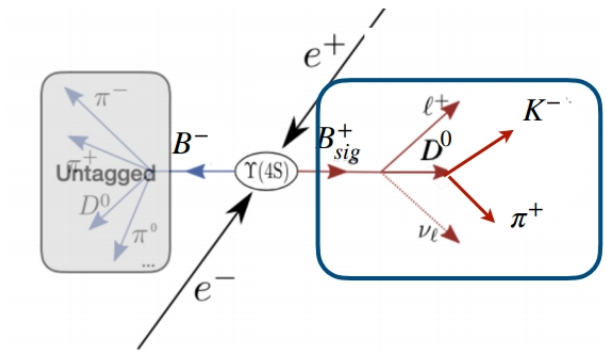
Untagged $|V_{cb}|$

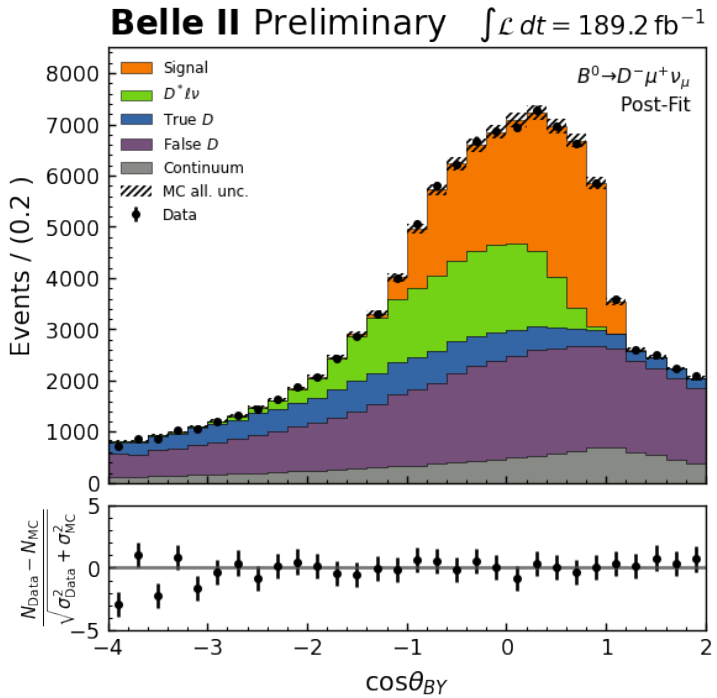
ICHEP 2022

- 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 $Y(D\ell)$

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

- D^* veto to reduce $B \to D^* \ell\nu$ candidates



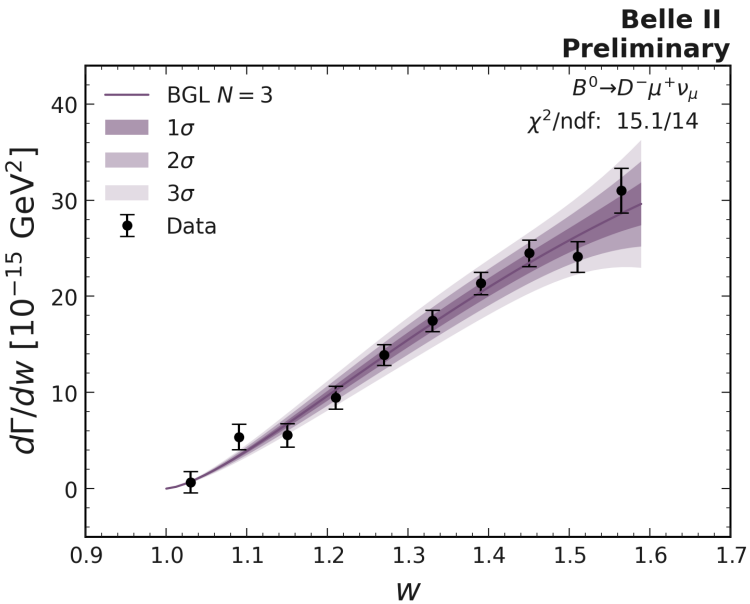


Untagged $|V_{cb}|$

- 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 $w = \frac{P_B \cdot P_{D^*}}{m_B m_D} = \frac{m_B^2 + m_{D^*} - q^2}{2 m_B m_{D^*}}$ and form factor $\mathcal{G}(w)$
- Fit form factor differential decay rates in 10 bins of w
- BGL (N=3) parametrization with FNAL/MILC and HPQCD Lattice QCD results



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

World-average exclusive:

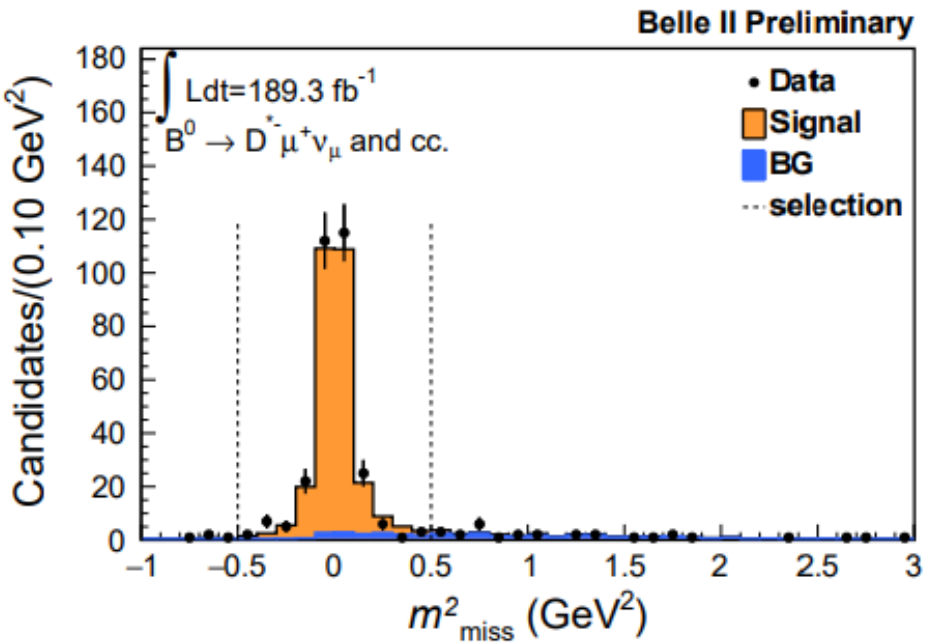
$(39.10 \pm 0.50) \times 10^{-3}$

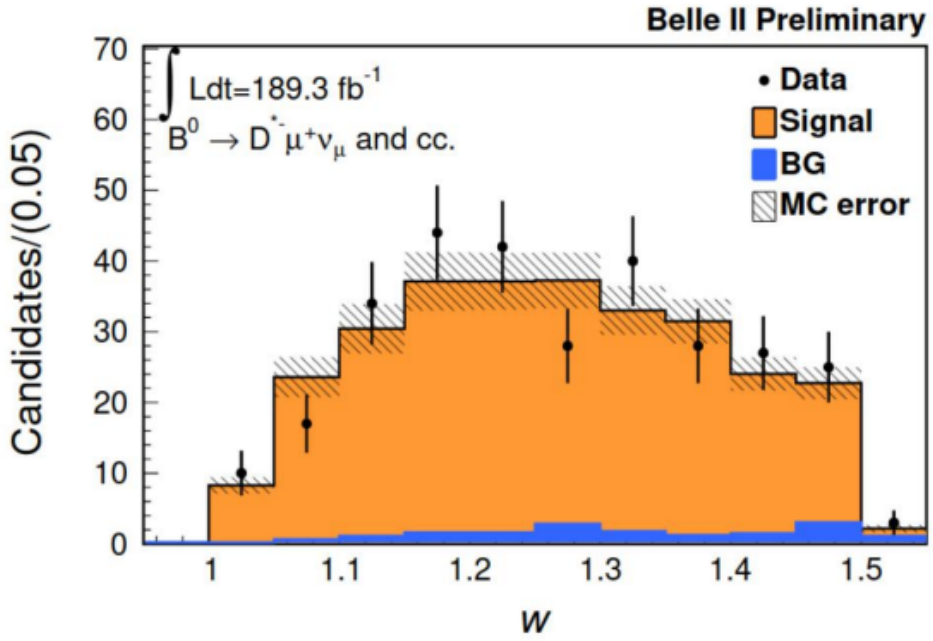
- Consistent with the exclusive world average
- $\sim 3\%$ error, comparable to the past measurements

Tagged $|V_{cb}|$

Moriond 2022

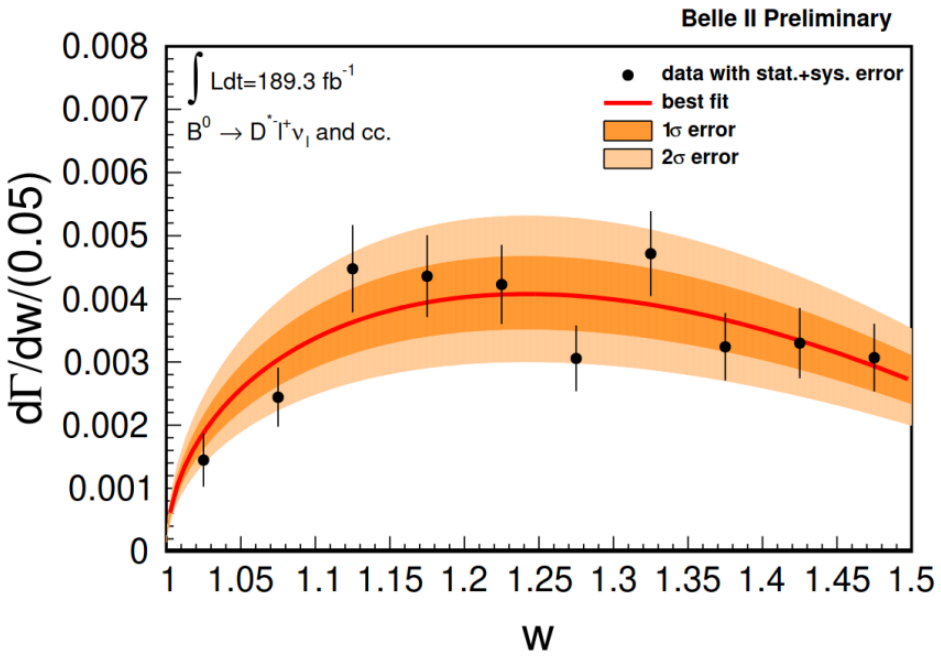
- Tagged measurement of $B \to D^* \ell \nu$ with $\ell = (e, \mu)$, $D^* \to D\pi_s$ and $D \to K\pi$
- High signal purity thanks to tagging and clean signature of $D^* \ell \nu$ mode
- Fit m^2_{miss} in 10 bins of w





Tagged $|V_{cb}|$

- Fit CLN parametrized form factor to differential decay rates

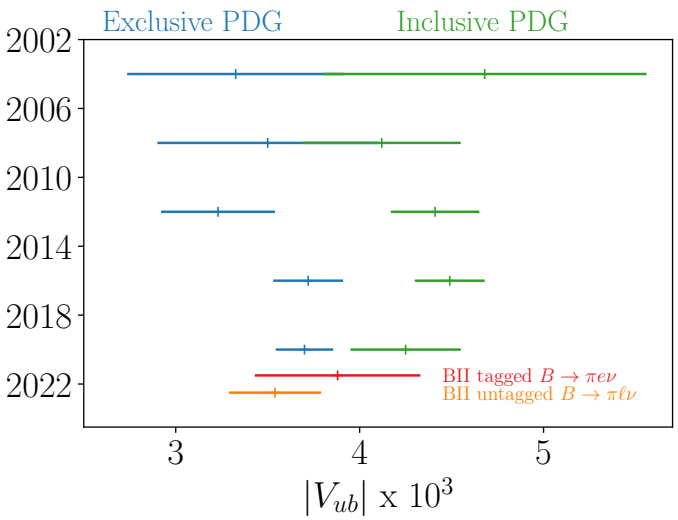


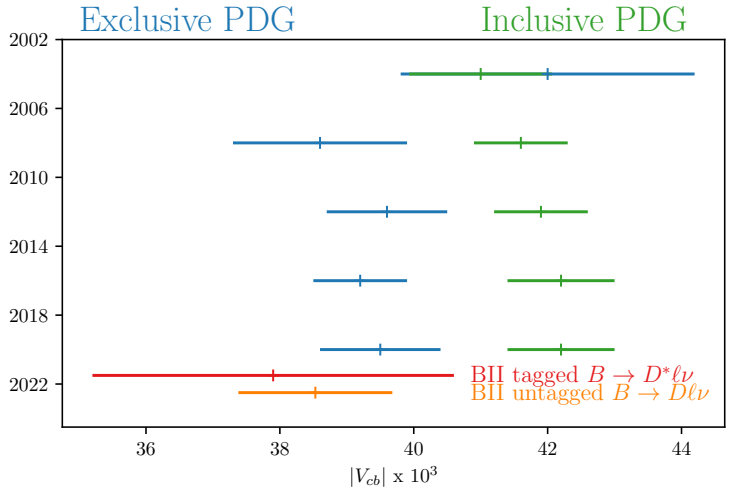
$$|V_{cb}| = (37.9 \pm 2.7) \times 10^{-3}$$

World-average exclusive: $(39.10 \pm 0.50) \times 10^{-3}$

- 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:* Untagged $D^*\ell\nu$, first $R(D^*)$ results and many more!

- Related talks:
  - Frank Meier: Belle II results on inclusive $B \to X\ell\nu$ [HF Saturday 15:30]
  - Koji Hara: LFU measurements in semileptonic $b- > c\ell\nu$ decays [HI Saturday 14:30]

Backup

V_{xb} with B mesons