Measurements of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix at Belle and Belle II

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On behalf of the Belle and Belle II collaborations

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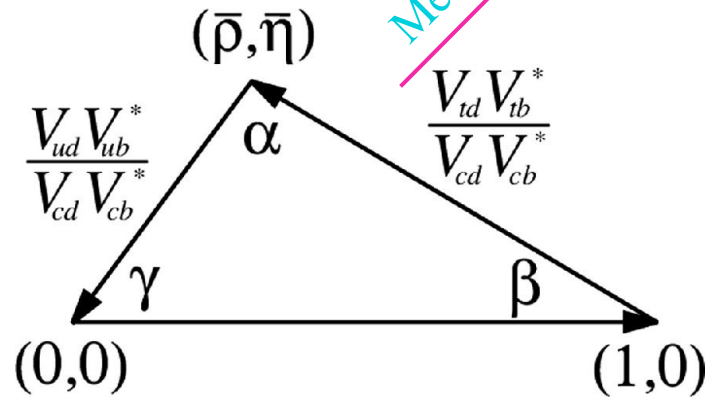
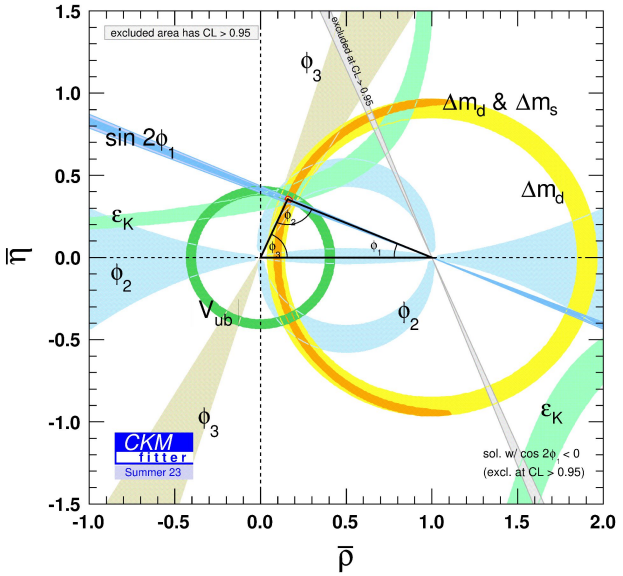
The CKM Matrix

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

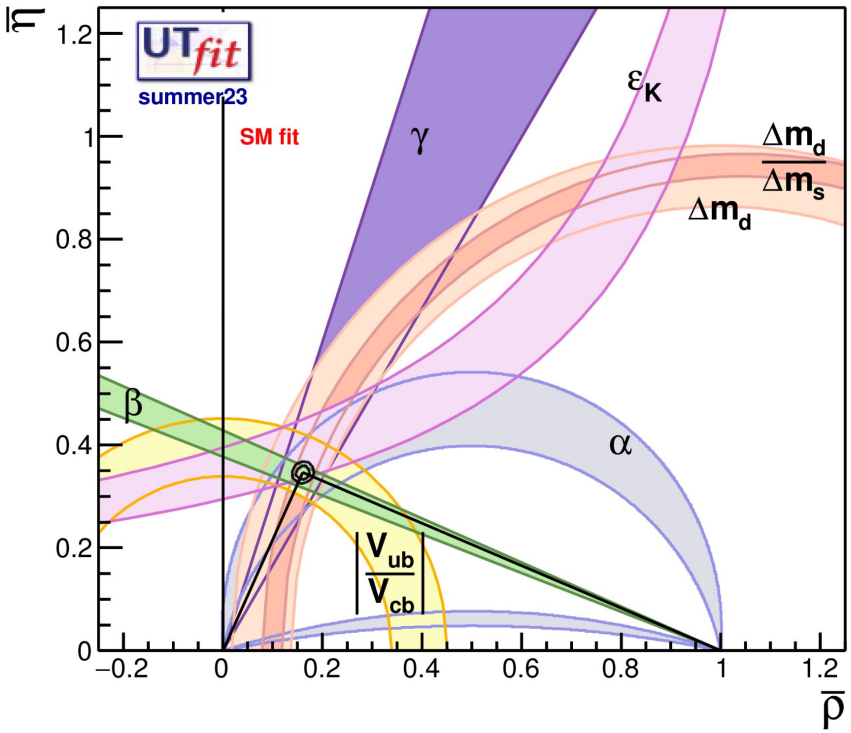
Unitarity

Measurements





The CKM Matrix

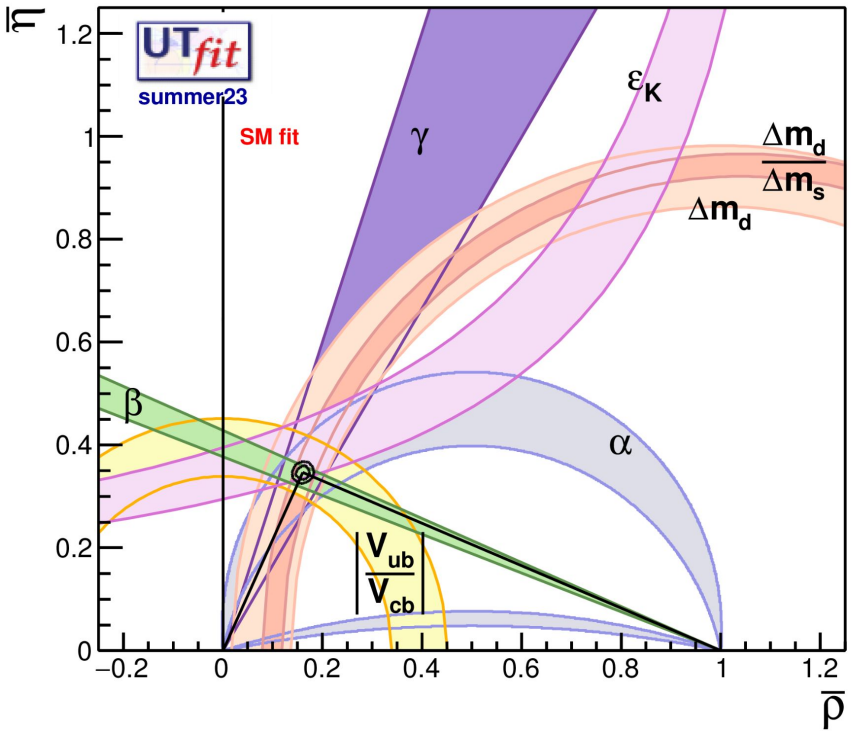


Angles
- α (ϕ_2)
- β (ϕ_1)
- γ (ϕ_3)

Sides
- $|V_{ub}|$
- $|V_{cb}|$

Mixing
- Δm_d
- Δm_s
- ε_K

The CKM Matrix



This talk!

Angles
- α (ϕ_2) → $B^0 \to \pi^0\pi^0$, $B^0 \to \rho^+\rho^-$
- β (ϕ_1)
- γ (ϕ_3)

Sides
- $|V_{ub}|$ → $B \to X_u l\nu$, $B^+ \to \tau^+\nu$
- $|V_{cb}|$ → $B \to Dl\nu$

Mixing
- Δm_d
- Δm_s
- ε_K

SuperKEKB and Belle II

SuperKEKB: upgrade of asymmetric e^+e^- collider KEKB with electron (positron) beam energy at 7.0 (4.0) GeV.

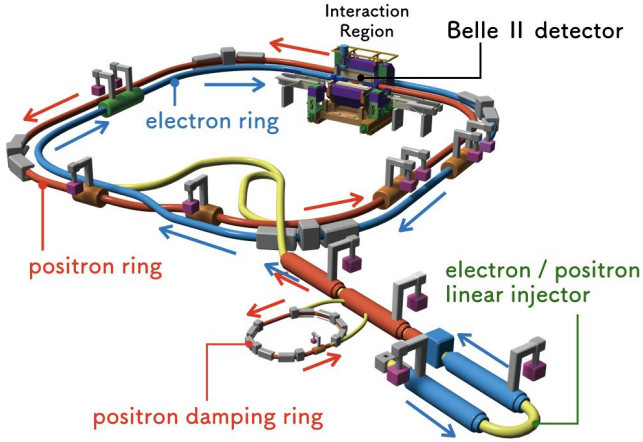
➔ World's record for the highest instantaneous luminosity (5.1×10^{34} $cm^{-2}s^{-1}$)!

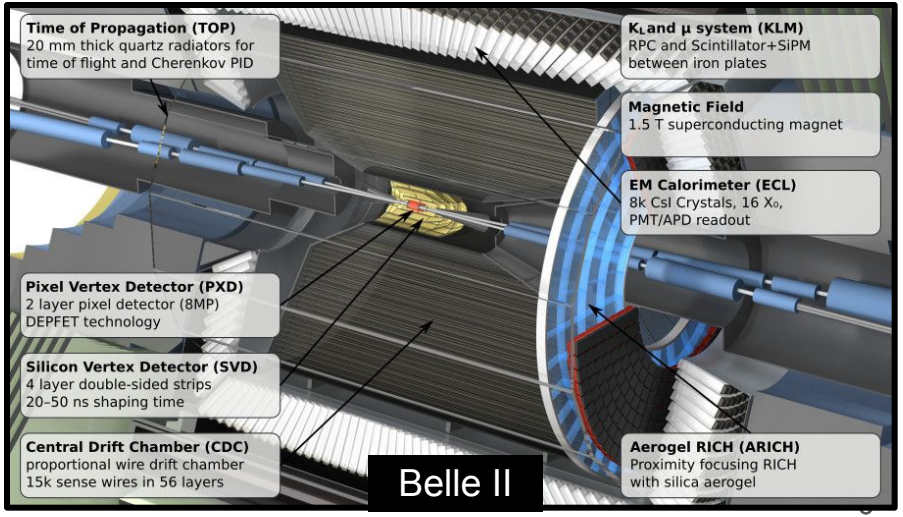
➔ Total $\Upsilon(4S)$ data: ~485 fb^{-1}

Belle II: upgrade of Belle detector at the IP of SuperKEKB.

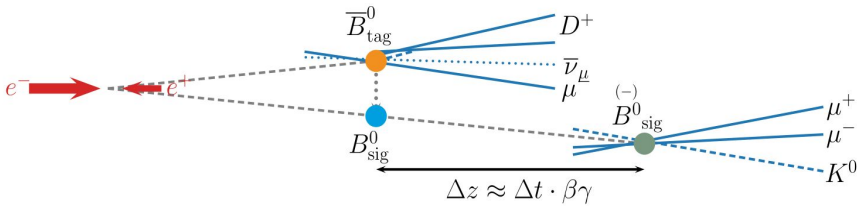
➔ New (since Belle): vertexing detectors (PXD, SVD), tracking and PID systems (CDC, TOP, ARICH)

➔ Upgraded (since Belle): Calorimeter (ECL electronics), K_L and μ system (KLM).





Physics at Belle (II)



Inclusive / missing energy analyses:

- ➔ Full Event Interpretation (*FEI*[1]): Reconstruct B_{tag} in hadronic, semi-leptonic modes or inclusively.
- ➔ Reconstruct B_{sig} into decay of interest using kinematic constraints imposed by the initial conditions.

(Time-Dependent) CP Violation analyses:

- ➔ Determine the B_{tag} flavor (*GFlaT*[2])
- ➔ Reconstruct B_{tag} and B_{sig} vertices to infer the decay time difference (Δt) between these two mesons.
- ➔ CP violation parameters encoded in Δt asymmetry between two tag flavors (B^0 vs $\overline{B^0}$):

$$\begin{aligned}\mathcal{A}_{CP} &= \frac{\Gamma(\bar{B}^0 \to f_{CP})(\Delta t) - \Gamma(B^0 \to f_{CP})(\Delta t)}{\Gamma(\bar{B}^0 \to f_{CP}(\Delta t)) + \Gamma(B^0 \to f_{CP})(\Delta t)} \\ &= (S_{CP}\sin(\Delta m_d \Delta t) - C_{CP}\cos(\Delta m_d \Delta t))\end{aligned}$$

mixing-induced CPV — direct CPV

[1] Comput Softw Big Sci 3, 6 (2019)

[2] Phys. Rev. D 110, 012001 (18% improvement)

α (ϕ_2) measurement: $B^0 \to \pi^0\pi^0$

PRD 111, L071102 (2025)

α least well known CKM angle $(84.1^{+3.7}_{-3.0})^\circ$

Measurement from $B \to \pi\pi$ isospin analysis (unc. dominated by $B^0 \to \pi^0\pi^0$ $\mathcal{B}$ and A_{CP})

TDCPV very difficult due to lack of π^0 vertices. (New technique: PRD 112, 032011 (2025))

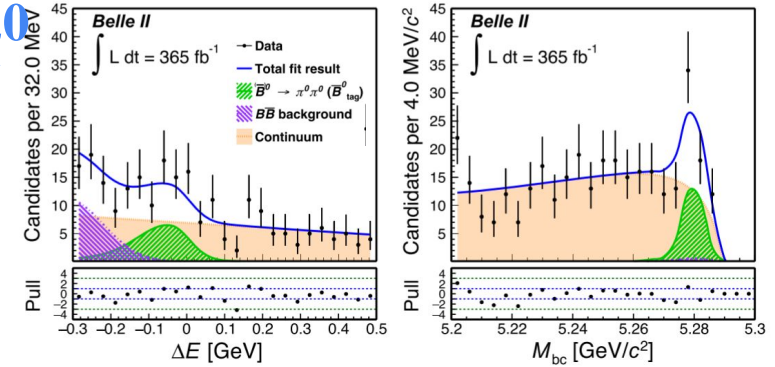
Analysis Methodology

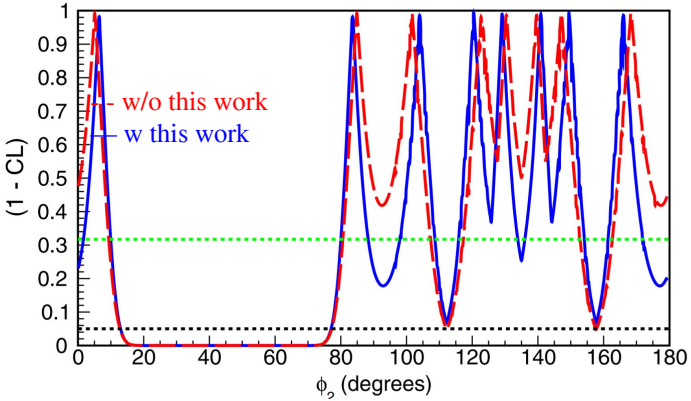
Reconstruct π^0 from diphoton final state.

MVAs to suppress photon and qq bkgs.

Tag side flavor determined using *GFlaT*.

Fits to M_{bc}, ΔE, C', w on both B_{tag} flavors to measure $\mathcal{B}$ and A_{CP}.





$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.26 \pm 0.20 \pm 0.11) \times 10^{-6}$$
$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = 0.03 \pm 0.30 \pm 0.05$$

α (ϕ_2) measurement: $B^0 \to \rho^+\rho^-$

PRD 111, 092001 (2025)

Measurement from $B \to \rho\rho$ isospin analysis.

Smaller $b \to d$ loop contribution, smaller $\Delta\phi_2$.

ρ:3 helicity states, need f_L for ϕ_2 extraction.

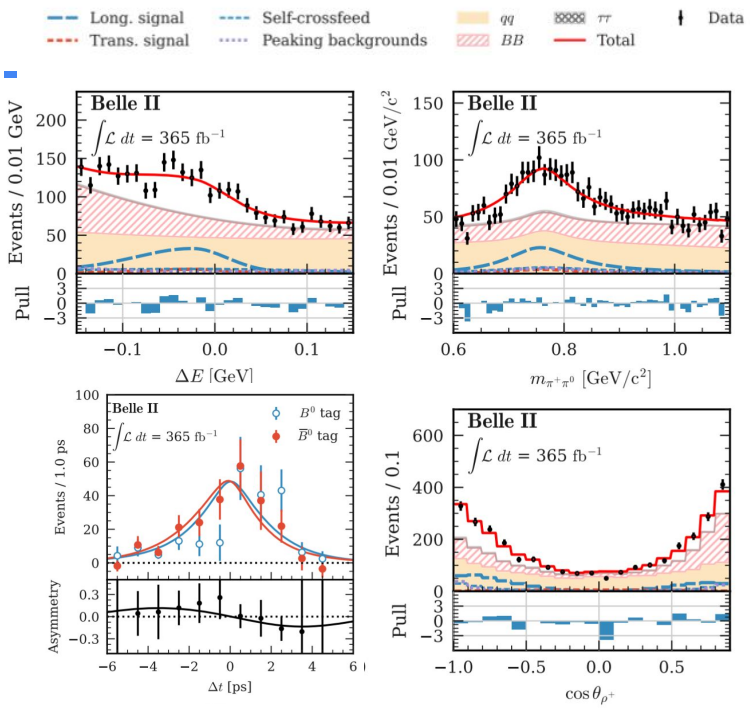
Analysis Methodology

Reconstruct $\rho^{+/-}$ from $\pi^{+/-}\pi^0$ final states.

BDT for photon bkg supp., NN for qq supp.

Angular analysis for f_L, $\mathcal{B}$; fit to ΔE, $m_{\pi\pi}$, $\cos\theta_\rho$ and $\mathcal{T}_c$ (transformed NN output).

TDCPV analysis for C_{CP}, S_{CP}; fit to Δt in both B_{tag} flavors with component fractions from previous fit.



$$\mathcal{B} = (2.89^{+0.23\,+0.29}_{-0.22\,-0.27}) \times 10^{-6}$$

$$f_L = 0.921^{+0.024\,+0.017}_{-0.025\,-0.015}$$

$$S_{CP} = -0.26 \pm 0.19 \pm 0.08$$

$$C_{CP} = -0.02 \pm 0.12^{+0.06}_{-0.05}$$

$$\phi_2 = (92.6^{+4.5}_{-4.7})^\circ \text{ (8\% rel. improv.)}$$

α (ϕ_2) measurement: $B^0 \rightarrow \rho^+\rho^-$

PRD 111, 092001 (2025)

Measurement from B→ρρ isospin analysis.

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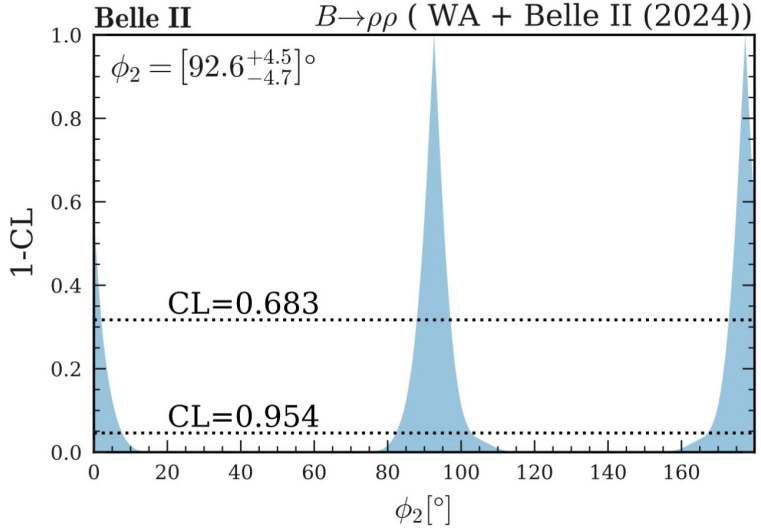

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$|V_{ub}|$ measurement: $B \rightarrow X_u l\nu$

Paper in preparation

Tension between inclusive vs exclusive measurements.

Inclusive measurements theoretically clean, experimentally challenging.

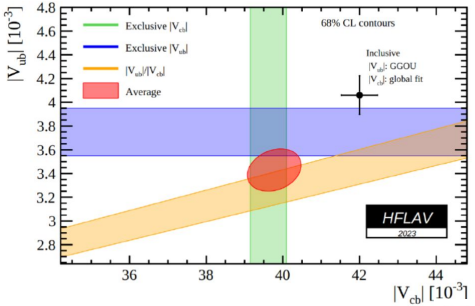
Analysis Methodology

FEI approach: B_{tag} decay into hadronic modes; B_{sig} reconstructed using a lepton and rest is the X_u system.

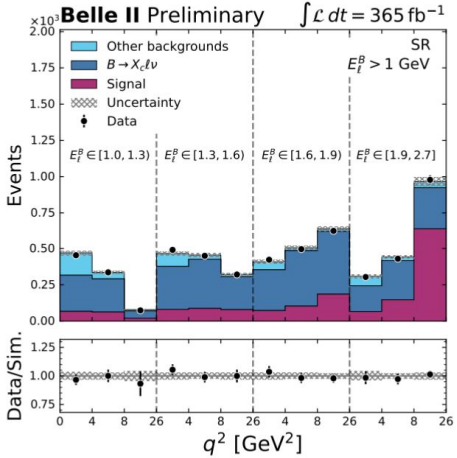
NNs to suppress qq and $B \rightarrow X_c l\nu$ bkgs.

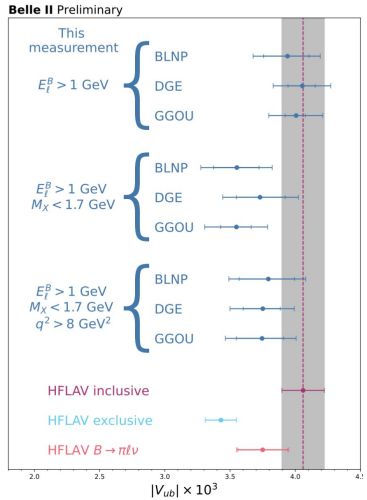
Template fits to q^2/E_l in three overlapping phase space regions to measure $\Delta\mathcal{B}$.

$|V_{ub}|$ extracted from $\Delta\mathcal{B}$ using GGOU model.



See also: Michele's talk





$$\Delta\mathcal{B} = (1.54 \pm 0.07 \pm 0.12) \times 10^{-3}$$

$$|V_{ub}| = (4.01 \pm 0.11 \pm 0.16^{+0.07}_{-0.08}) \times 10^{-3}$$

$|V_{ub}|$ measurement: $B \to \tau\nu$

PRD 112, 072002 (2025)

Theoretically clean (no hadronic FFs), but smaller $\mathcal{B}$; sensitive to BSM.

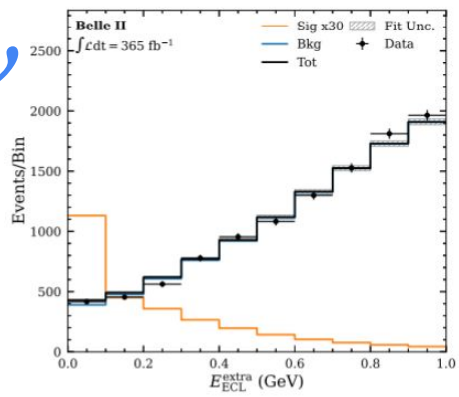
$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left[1 - \frac{m_\tau^2}{m_B^2}\right]^2 f_B^2 |V_{ub}|^2 \tau_B.$$

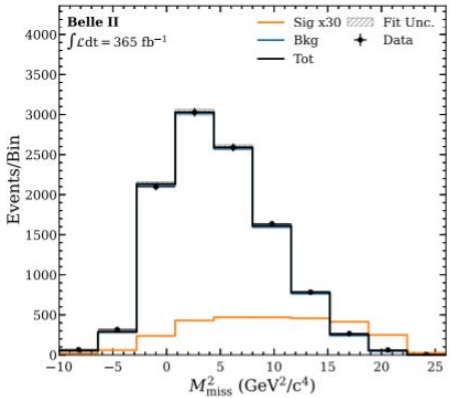
Analysis Methodology

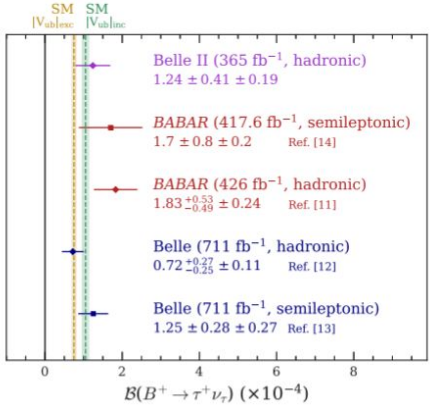
FEI approach: B_{tag} decay into hadronic modes; B_{sig} τ reconstructed into (e/μ/π/ρ) candidate and rest is missing energy.

BDTs to suppress qq bkgs, bkg photons.

Fits to M^2_{miss} and E^{extra}_{ECL} to extract $\mathcal{B}$.







$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = [1.24 \pm 0.41 \pm 0.19] \times 10^{-4}$$
$$|V_{ub}|_{B^+ \to \tau^+\nu_\tau} = \left[4.41^{+0.74}_{-0.89}\right] \times 10^{-3}$$

$|V_{cb}|$ measurement: B → Dlν

arXiv:2506.15256 (Accepted by PRD)

Differential decay rate $d\Gamma/dw$ ($w = v_B.v_D$) can be used to extract $|V_{cb}|$ using the following form:

$$\frac{d\Gamma(B \to D\ell\nu_\ell)}{dw} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B + m_D)^2(w^2-1)^{3/2} \eta_{EW}^2(1+\delta_C^{+,0})\,\mathcal{G}^2(w)\,|V_{cb}|^2$$

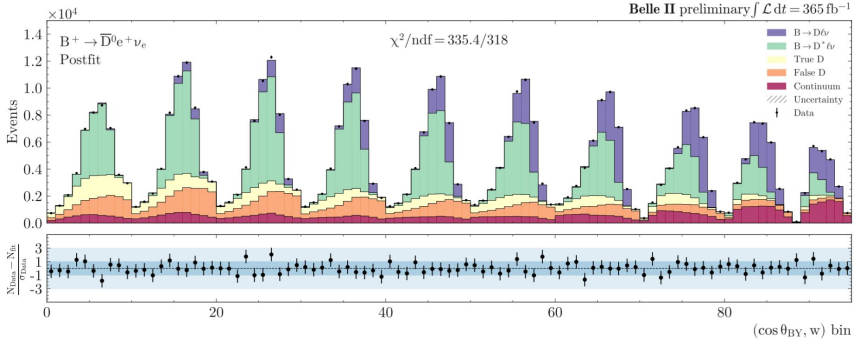
Analysis Methodology

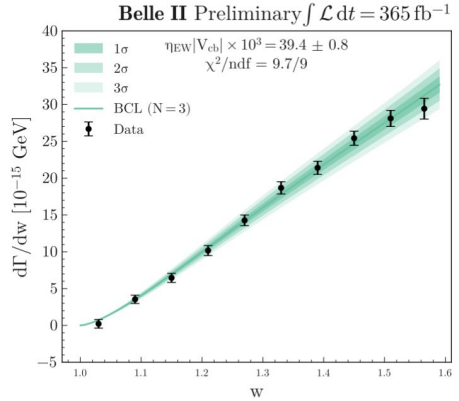
$D^{0/+}$ reconstructed into $K^-\pi^+$/ $K^-\pi^+\pi^+$ systems.

w calculated as weighted average over potential p_B directions inside a cone around Y = Dl system:

$$\cos\theta_{BY} = \frac{2E_{beam}E_Y - m_B^2 - m_Y^2}{2|\vec{p}_B||\vec{p}_Y|}$$

Fits to $\cos\theta_{BY}$ in bins of w to extract $\Delta\Gamma/\Delta w$.

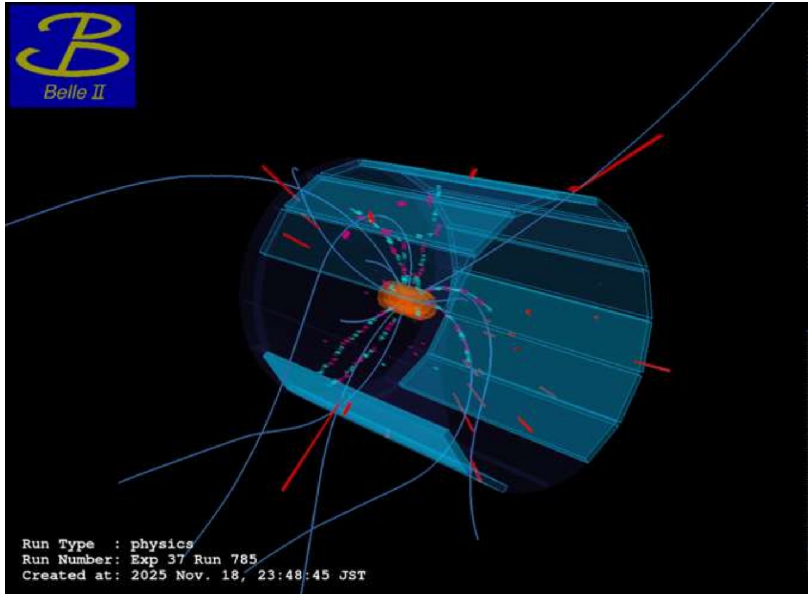




$$\mathcal{B}(B^0 \to D^-\ell^+\nu_\ell) = (2.06 \pm 0.05\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$
$$\mathcal{B}(B^+ \to \bar{D}^0\ell^+\nu_\ell) = (2.31 \pm 0.04\,(\text{stat}) \pm 0.09\,(\text{syst}))\%$$
$$|V_{cb}| = (39.2 \pm 0.4(\text{stat.}) \pm 0.6(\text{sys.}) \pm 0.5(\text{th.})) \times 10^{-3}$$

Conclusions

- ★ CKM measurements are an important input to SM framework and tests for BSM physics.
- ★ Belle and Belle II datasets have unique potential for high precision measurements of these quantities.
- ★ We present five recent results from Belle II which have significant contribution towards improving precisions for ϕ_2, $|V_{ub}|$ and $|V_{cb}|$
- ★ Several other analyses in progress, we restart data taking for 2025.



https://evdisp.belle2.org/

Thank You