Cabibbo-Kobayashi-Maskawa matrix related measurements at Belle II

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on behalf of Belle II

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Research supported by

Cabibbo-Kobayashi-Maskawa matrix

- Mass eigenstates $\neq$ eigenstates of weak interaction
- Superposition described via complex CKM matrix
- Quark transition proportional to matrix elements
- Irreducible phase of CKM matrix = source of CP violation

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \boldsymbol{V}_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

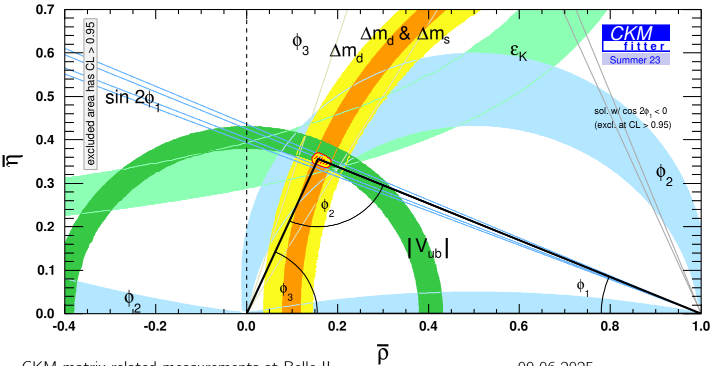
- Unitarity of CKM matrix:

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

$$\phi_1 = \beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

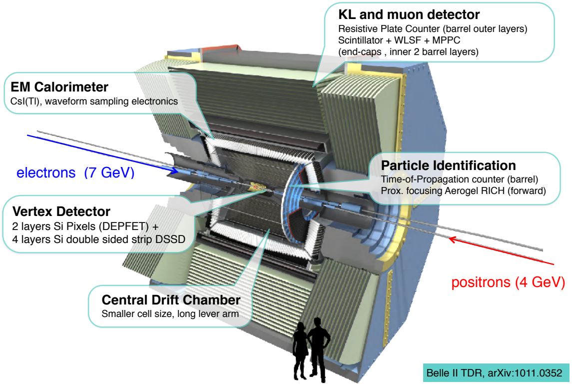
$$\phi_2 = \alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\phi_3 = \gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

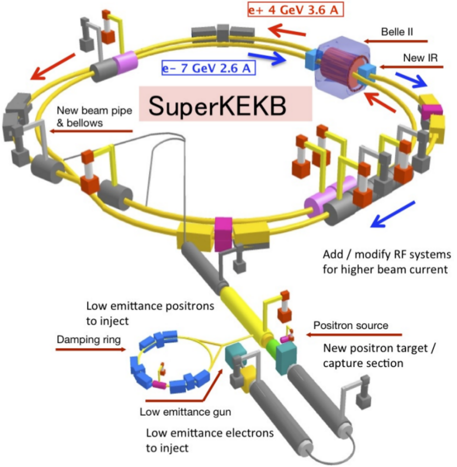


The Belle II experiment

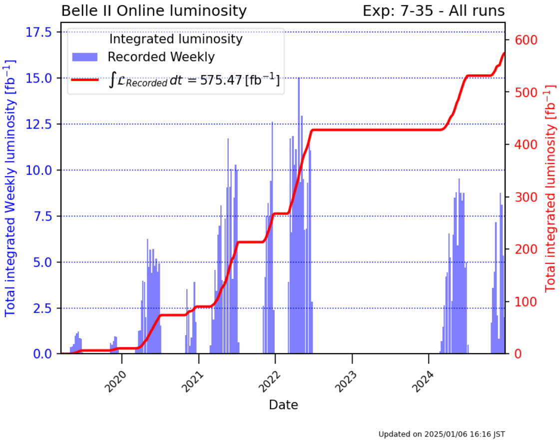
- Asymmetric collision of e^+e^-
- Center-of-mass energy mostly at $\Upsilon(4S)$ resonance
- $\Upsilon(4S) \to B^+B^-$ ($\sim$51.5 %), $\Upsilon(4S) \to B^0\overline{B}^0$ ($\sim$48.5 %)



Belle II TDR, arXiv:1011.0352



Luminosity



- From 2019 to 2022 collected $428\ \mathrm{fb}^{-1}$ of data
  - $365\ \mathrm{fb}^{-1}$ at the $\Upsilon(4S)$ resonance
    $\Rightarrow 387\,\mathrm{M}\ \Upsilon(4S)$ decays
  - $61\ \mathrm{fb}^{-1}$ below and above the $\Upsilon(4S)$ resonance
- Several analyses combine the Belle and Belle II data
  $\Rightarrow$ adding $711\ \mathrm{fb}^{-1}$ on resonance data
- Data taken in run 2 since 2024 is currently analyzed: first publications expected later this summer

Determination of $|V_{cb}|$ using $B \to \bar{D}\ell^+\nu_\ell$ Decays at Belle II

to be submitted to PRD

Concept

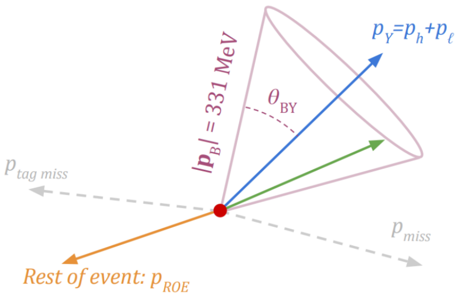
- Differential measurement of $B \to \overline{D}\ell^+\nu_\ell$ decay width as a function of recoil variable $w = \frac{m_B^2+m_D^2-q^2}{2m_B m_D}$
- w boundaries
  - $w_{\text{min}} = 1$ for D at rest in B rest frame
  - $w_{\text{max}} = \frac{m_B^2+m_D^2}{2m_B m_D} \approx 1.59$ for lepton at rest in B rest frame

$$\frac{d\Gamma(B \to \overline{D}\ell^+\nu_\ell)}{dw} \propto (w-1)^{3/2}\,\eta_{\text{EW}}^2\,(1+\delta_C^{+,0})\,\mathcal{G}^2(w)\,|V_{cb}|^2$$ Phys. Rept. 245, 259 (1994)

- η_{EW}: short-distance QED correction
- $\delta_C^{+,0}$: long-distance QED correction
- $\mathcal{G}(w)$: form factor
  - BCL (Bourrely, Caprini and Lellouch) parametrization [PRD 79, 013008 (2009)]
  - CLN (Caprini, Lellouch, and Neubert) parametrization [Nucl. Phys. B 530, 153 (1998)]

Reconstruction of w

- Due to undetected neutrino direction of B unknown
- Cone around $Y = D\ell$ system: $\cos\theta_{\mathrm{BY}} = \frac{2E_{\mathrm{beam}}E_Y - m_B^2 - m_Y^2}{2|\vec{p}_B||\vec{p}_Y|}$
- Assume several configurations of B momentum on cone $\rightarrow$ calculate w
- Weighted average over all configurations using weight $\frac{1}{2}(1 - \hat{p}_B^* \cdot \hat{p}_{\mathrm{ROE}}^*)\sin^2\theta_B^*$
  - $\hat{p}_{\mathrm{ROE}}^*$: unit vector in CM frame of sum of all particles in event not used in Y reconstruction
  - θ_B^*: angle in CM frame of B meson wrt beam axis

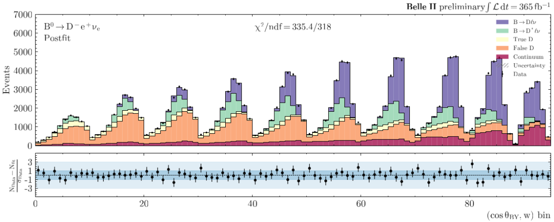


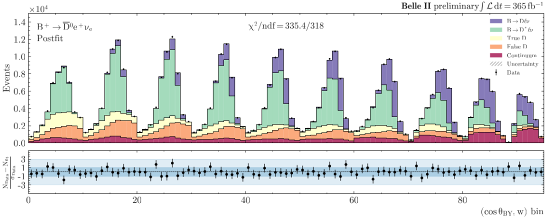
Signal extraction

- Impose tight PID cuts for electron and muon
- Reconstruct $D^- \to K^+\pi^-\pi^-$ and $D^0 \to K^-\pi^+$
- Require minimum vertex fit quality
- Apply vetoes against Feed-down background from $B \to \overline{D}^*\ell^+\nu_\ell$
- No exclusive reconstruction of second B meson
- Reduce contamination from continuum and $B\overline{B}$ backgrounds
- Find $87\,000$ $B^0 \to D^-\ell^+\nu_\ell$ and $136\,000$ $B^+ \to \overline{D}^0\ell^+\nu_\ell$

Signal extraction

- Maximum likelihood fit to 10 bins of $\cos\theta_{\mathrm{BY}}$ in range $[-4,\,2]$
- Simultaneously extract signal yield in 10 equidistant w bins for neutral and charged modes
- Fit templates from MC for five components:
  - $B \to \overline{D}\ell^+\nu_\ell$ signal
  - Feed-down background from $B \to \overline{D}^*\ell^+\nu_\ell$
  - Combinatorial background with correctly reconstructed D meson
  - Combinatorial background with fake D meson
  - Continuum background



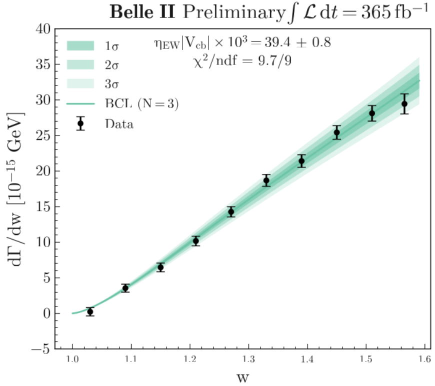


- Signal yield converted to differential decay width via $\dfrac{\Delta\Gamma_i}{\Delta w} = \dfrac{N_i}{N_B \mathcal{B}(D)\varepsilon_i \tau_B \left(1+\delta_C^{+,0}\right)\Delta w}$

Determination of $|V_{cb}|$

- Truncate BCL expansion of vector and scalar form factors at $N = 3 \rightarrow$ five free parameters
- Minimize $\chi^2 = \sum_{i,j}^{10} \left(\frac{\Delta\Gamma_i}{\Delta w} - \frac{\Delta\Gamma_{i,\mathrm{BCL}}}{\Delta w} \right) C_{ij}^{-1} \left(\frac{\Delta\Gamma_j}{\Delta w} - \frac{\Delta\Gamma_{j,\mathrm{BCL}}}{\Delta w} \right) + \sum_{k,l}^{5} (c_k - c_{k,\mathrm{FLAG}}) D_{kl}^{-1} (c_l - c_{l,\mathrm{FLAG}})$
- Coefficients of BCL expansion constrained to FLAG average [arXiv:2411.04268] of FNAL/MILC [PRD 92, 034506 (2015)] and HPQCD [PRD 92, 054510 (2015)] calculations of $B \rightarrow \overline{D}\ell^+\nu_\ell$ form factor

	Values	Correlation Coefficients				
a_0	0.8959 ± 0.0092	1	0.26	-0.38	0.95	0.51
a_1	-8.03 ± 0.15		1	0.17	0.33	0.86
a_2	49.3 ± 3.1			1	-0.31	0.16
b_0	-0.7813 ± 0.0073				1	0.47
b_1	-3.38 ± 0.15					1



Summary of uncertainties on $|V_{cb}|$

- Statistical uncertainty: 0.9%
- Theoretical uncertainties: 1.3%
  - Lattice QCD inputs: 1.2%
  - Long-distance QED: 0.5%
- Dominant systematic uncertainties
  - Number of $\Upsilon(4S)$ candidates in data sample: 0.7%
  - Kaon identification: 0.6%
  - Branching fraction of $\mathcal{B}(D \to K\pi(\pi))$: 0.5%
  - Tracking efficiency uncertainty of 0.24% per track: 0.5%
  - Allowing templates to vary within their simulation sample size in each bin: 0.5%
- Total uncertainty: 2.1%

Results

$$|V_{cb}| = (39.2 \pm 0.4\,(\text{stat}) \pm 0.6\,(\text{syst}) \pm 0.5(\text{th})) \times 10^{-3}$$

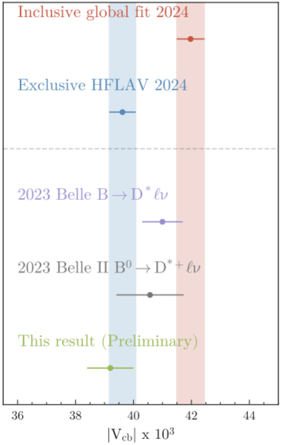
- Signal branching fractions from sum over w bins:

$$\mathcal{B}(B^0 \to D^-\ell^+\nu_\ell) = (2.06 \pm 0.05\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$
$$\mathcal{B}(B^+ \to \overline{D}^0\ell^+\nu_\ell) = (2.31 \pm 0.04\,(\text{stat}) \pm 0.09\,(\text{syst}))\%$$

WA: $2.12 \pm 0.06\%$ $(B^0 \to D^-\ell^+\nu_\ell)$ / $2.21 \pm 0.06\%$ $(B^+ \to \overline{D}^0\ell^+\nu_\ell)$

- Test of lepton flavor universality:

$$\frac{\mathcal{B}(B \to \overline{D}e^+\nu_e)}{\mathcal{B}(B \to \overline{D}\mu^+\nu_\mu)} = 1.020 \pm 0.020\,(\text{stat}) \pm 0.022\,(\text{syst})$$



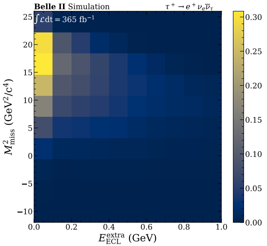
Measurement of $B^+ \to \tau^+ \nu_\tau$ branching ratio with a hadronic tagging method at Belle II

arXiv:2502.04885 (submitted to PRD)

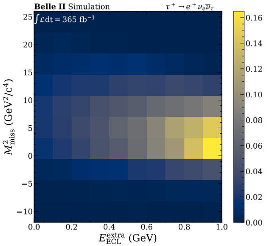
Duke University

Introduction

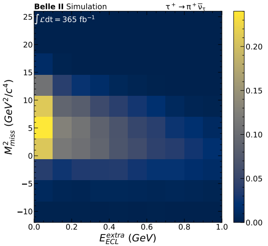
- In the standard model $\mathcal{B}(B^+ \to \tau^+\nu_\tau) = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$
- Allows direct measurement of $|V_{ub}|$ independent of exclusive and inclusive semileptonic $B \to X_u \ell \nu_\ell$ decays
- Branching fraction enhanced (or suppressed) in beyond-the-standard-model physics like models with charged Higgs or Higgs Doublet Model
- Reconstruct $\tau^+ \to e^+\nu_e\overline{\nu}_\tau$, $\tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau$, $\tau^+ \to \pi^+\overline{\nu}_\tau$, and $\tau^+ \to \rho^+\overline{\nu}_\tau$ (72% of τ decay modes covered)
- Reconstruct other B meson in hadronic decays using Full Event Interpretation Comput. Softw. Big Sci. 3 (2019)
- Extract branching fraction from 2D fit to residual energy in calorimeter and missing mass squared



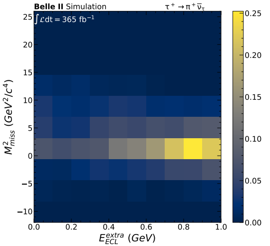
- signal e channel



- bkg e channel



- signal π channel



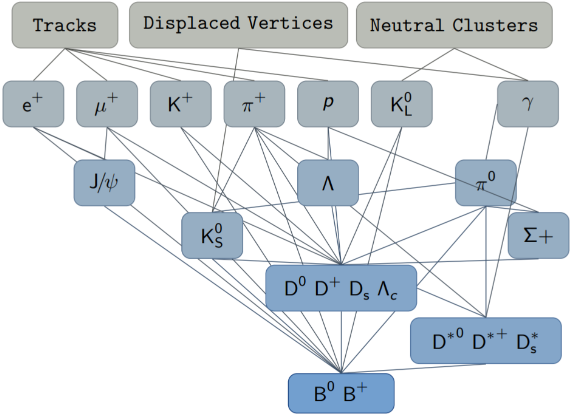
- bkg π channel

Full Event Interpretation Comput. Softw. Big Sci. 3 (2019)

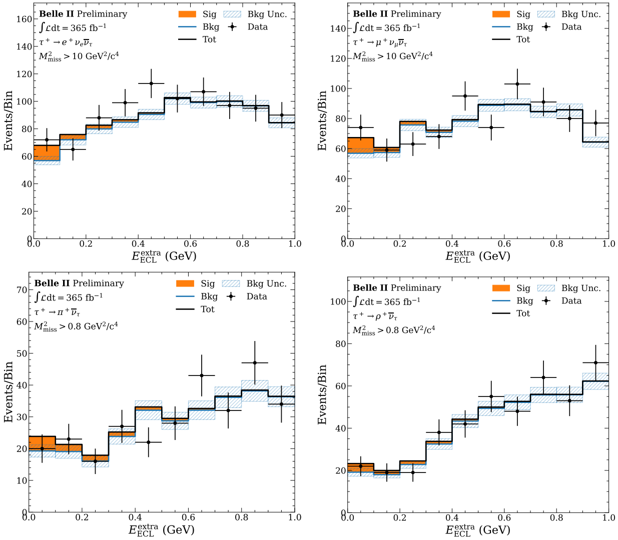
- Fully reconstruct one of the B mesons (tag-side) in many exclusive modes

- Train BDT for each stage
  $\Rightarrow$ signal probability
- Fraction of $\Upsilon(4S)$ events with correctly reconstructed charged B_{tag} candidate $\approx 0.30\%$ with purity of 29%
- Reduce misreconstructed events with requirements on beam-constrained mass M_{bc} and energy difference ΔE

$$M_{\text{bc}} = \sqrt{(E^*_{\text{beam}})^2 - |\vec{p}^{\,*}_{\text{tag}}|^2}$$
$$\Delta E = E^*_{\text{tag}} - E^*_{\text{beam}}$$



Fit



- Simultaneous binned maximum likelihood fit to all the four τ categories
- Floating parameters in fit: $\mathcal{B}(B^+ \to \tau^+ \nu_\tau)$ and background yields of each category
- Signal yields related via efficiencies

Source	Syst. (%)
Simulation statistics	**13.3**
Fit variables PDF corrections	**5.5**
Decays branching fractions in MC	**4.1**
Tag B^- reconstruction efficiency	2.2
Continuum reweighting	1.9
π^0 reconstruction efficiency	0.9
Continuum normalization	0.7
Particle identification	0.6
Number of produced $\Upsilon(4S)$	1.5
Fraction of B^+B^- pairs	2.1
Tracking efficiency	0.2
Total	15.5

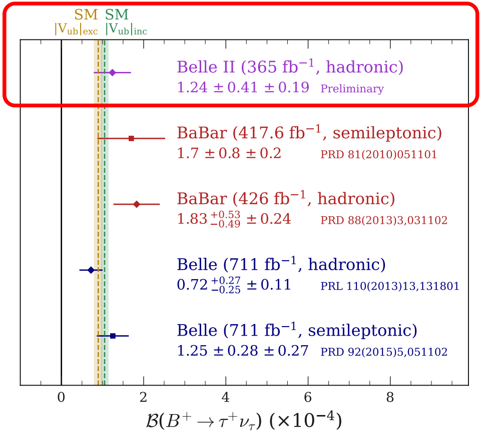
Results

Decay mode	n_s	$\mathcal{B}\ (10^{-4})$
Simultaneous	94 ± 31	1.24 ± 0.41
$e^+\nu_e\overline{\nu}_\tau$	13 ± 16	0.51 ± 0.63
$\mu^+\nu_\mu\overline{\nu}_\tau$	40 ± 20	1.67 ± 0.83
$\pi^+\overline{\nu}_\tau$	31 ± 13	2.28 ± 0.93
$\rho^+\overline{\nu}_\tau$	6 ± 25	0.42 ± 1.82

- Assuming SM and $f_B = (190.0 \pm 1.3)$ MeV

$$\boxed{|V_{ub}|_{B^+\to\tau^+\nu_\tau} = (4.41^{+0.74}_{-0.89}) \times 10^{-3}}$$

- $|V_{ub}|_{\text{SM}}$ (exclusive): $(3.75 \pm 0.06 \pm 0.19) \times 10^{-3}$
- $|V_{ub}|_{\text{SM}}$ (inclusive): $(4.06 \pm 0.12 \pm 0.11) \times 10^{-3}$

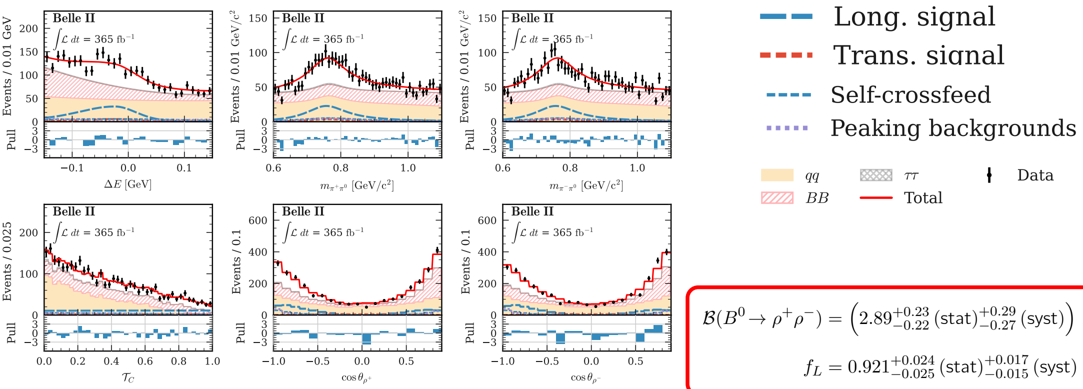


Measurement of the branching fraction, polarization, and time-dependent CP asymmetry in $B^0 \to \rho^+\rho^-$ decays and constraint on the CKM angle ϕ_2

PRD 111, 092001 (2025)

Measurement of $\mathcal{B}$ and polarization

- $B^0 \to \rho^+\rho^-$ is pseudo-scalar decaying to two vector mesons $\to$ three helicity states
  - Longitudinal fraction $f_L = |H_0|^2/(|H_0|^2 + |H_+|^2 + |H_-|^2)$ measurable from $\rho^\pm$ helicity angle distributions

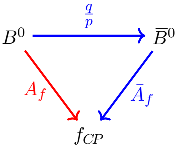


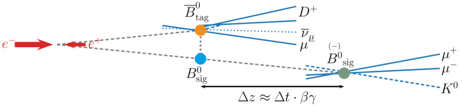
$$\mathcal{B}(B^0 \to \rho^+\rho^-) = \left(2.89^{+0.23}_{-0.22}\,(\text{stat})^{+0.29}_{-0.27}\,(\text{syst})\right) \times 10^{-5}$$

$$f_L = 0.921^{+0.024}_{-0.025}\,(\text{stat})^{+0.017}_{-0.015}\,(\text{syst})$$

Time-dependent CP violation measurement

- CP violation in the interference between
  - direct decay
  - decay after mixing

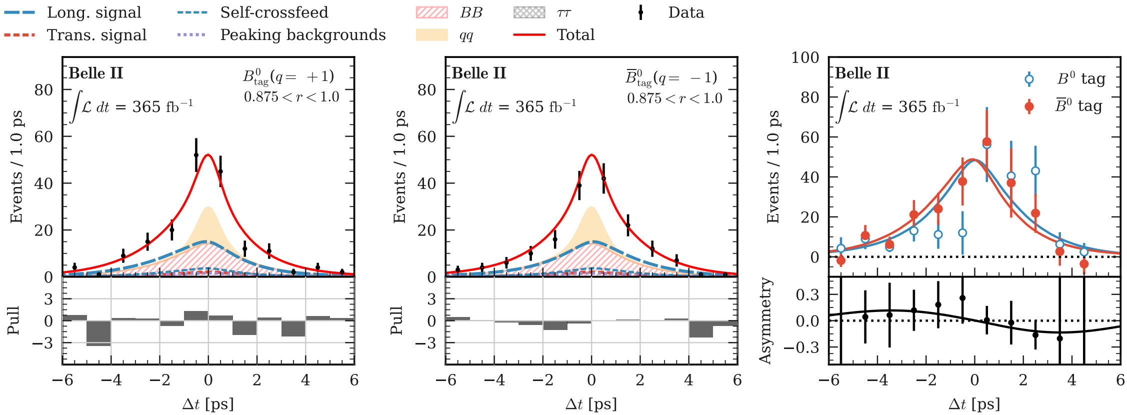




$$\mathcal{A}(\Delta t) \equiv \frac{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}) - \Gamma(B^0(\Delta t) \to f_{CP})}{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}) + \Gamma(B^0(\Delta t) \to f_{CP})} = S_f \sin(\Delta m\, \Delta t) - C_f \cos(\Delta m\, \Delta t)$$

- Initial flavor $\rightarrow$ flavor tagging
  - Introduces diluting mistag fraction
- Proper-time difference $\rightarrow$ reconstruction of distance between B_{sig} and B_{tag} vertices
  - Requires description of proper-time resolution, often via per-event uncertainties $\sigma_{\Delta t}$
- CP observables $\rightarrow$ parameters of interest
  - $S_{b\to u\overline{u}d} = \sqrt{1 - C^2}\,\sin(2\,\phi_2 + \Delta\phi_2)$: loop amplitude obstructs clean extraction of ϕ_2
- Mixing parameters $\rightarrow$ from external measurements

Time-dependent CP-asymmetry fit



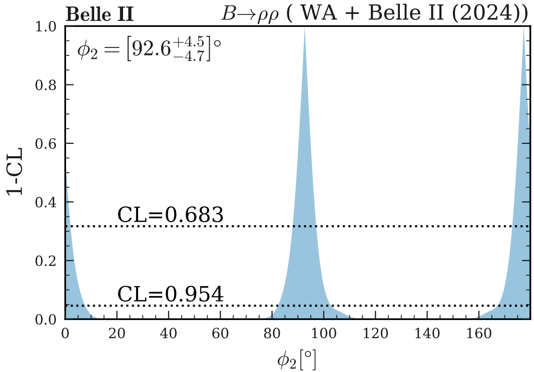
$$S = -0.26 \pm 0.19 \pm 0.08 \qquad C = -0.02 \pm 0.12^{+0.06}_{-0.05}$$

Constraining CKM angle ϕ_2

- Isospin analysis based on Gronau-London isospin relations [PRL 65, 3381 (1990)]:

$$\frac{1}{\sqrt{2}}A_{+-} + A_{00} = A_{+0}$$
$$\frac{1}{\sqrt{2}}\bar{A}_{+-} + \bar{A}_{00} = \bar{A}_{-0}$$

- Combining results from Belle, BaBar, and LHCb for $\mathcal{B}$, f_L, and CP violation parameters for $B^0 \to \rho^+\rho^-$, $B^0 \to \rho^0\rho^0$, and $B^+ \to \rho^+\rho^0$
- Uncertainty on ϕ_2 dominated by S parameters of $B^0 \to \rho\rho$



- two solutions, though second excluded by ϕ_1, ϕ_3, and unitarity
  - $\phi_2 = (\ 92.6^{+4.5}_{-4.7})^\circ \quad \Delta\phi_2 = (\ \ 2.4^{+3.8}_{-3.7})^\circ$
  - $\cancel{\phi_2 = (177.4^{+4.7}_{-4.5})^\circ \quad \Delta\phi_2 = (-2.4^{+3.7}_{-3.8})^\circ}$

Conclusion

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- Measurement of $|V_{cb}|$ using inclusive tagging:

$$\boxed{|V_{cb}| = (39.2 \pm 0.4\,(\text{stat}) \pm 0.6\,(\text{syst}) \pm 0.5(\text{th})) \times 10^{-3}}$$

NEW

- Measurement of $\mathcal{B}(B^+ \to \tau^+ \nu_\tau)$ using hadronic tagging:

$$\boxed{\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = (1.24 \pm 0.41\,(\text{stat}) \pm 0.19\,(\text{syst})) \times 10^{-4}}$$

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- Measurement of ϕ_2 using $B^0 \to \rho^+ \rho^-$:

$$\boxed{\phi_2 = (92.6^{+4.5}_{-4.7})^\circ}$$

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- More data already collected and ready to be analyzed

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Thanks for your attention!

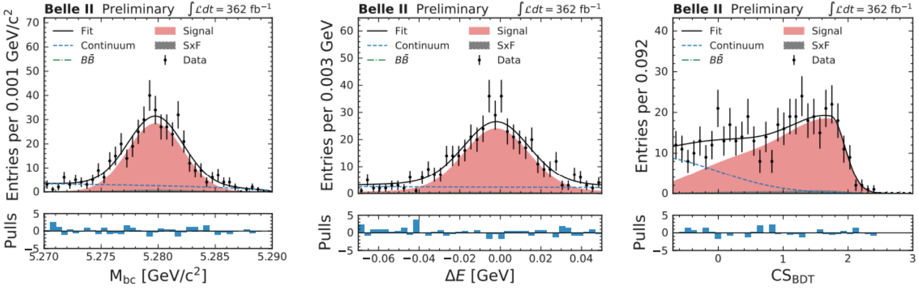
Backup

Measurements of the CKM angle ϕ_1

Measurement of CP asymmetries in $B^0 \to \eta' K^0_S$ decays PRD 110, 112002 (2024)

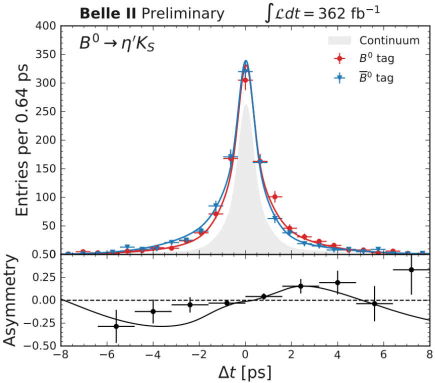
Duke UNIVERSITY

- $B^0 \to \eta' K^0_S$ is $b \to s q\bar{q}$ transition that proceeds via loop amplitudes
- comparison of CP observables with $\sin 2\phi_1$ probes beyond standard model contributions
- reconstruct $\eta' \to \eta(\to \gamma\gamma)\pi^+\pi^-$ and $\eta' \to \rho^0(\to \pi^+\pi^-)\gamma$
- perform B vertex fit and remove multiple candidates via best fit probability
- continuum suppression with BDT (validated on off-resonance data)
- four components in maximum-likelihood fit: signal, self-cross-feed, $q\bar{q}$ background, and $B\bar{B}$ background
- perform maximum likelihood fit to beam-constrained mass M_{bc}, energy difference ΔE, BDT output CS_{BDT}



Measurement of CP asymmetries in $B^0 \to \eta' K_S^0$ decays PRD 110, 112002 (2024)

- add proper-time difference as fourth fit observable
- flavor tag and proper-time uncertainty conditional observables
- resolution function determined with $B^0 \to D^{(*)-}\pi^+$ decays
- 358 ± 20 signal in $\eta' \to \eta(\to \gamma\gamma)\pi^+\pi^-$ channel at 79% purity
- 346 ± 21 signal in $\eta' \to \rho^0(\to \pi^+\pi^-)\gamma$ channel at 24% purity
- largest systematic uncertainties from
  - fixing shape parameters
  - Δt resolution model
  - motion of B-meson in $\Upsilon(4S)$ frame
- results of CP observables in agreement with current world averages
- sensitivity approaching that of Belle and BaBar



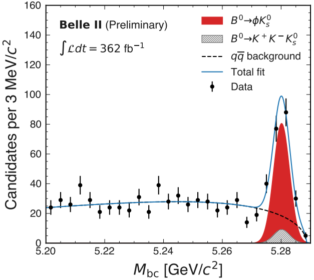
$$S_{\eta' K_S^0} = 0.67 \pm 0.10 \pm 0.04$$
$$C_{\eta' K_S^0} = 0.19 \pm 0.08 \pm 0.03$$

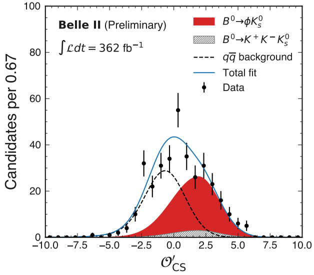
- correlation$(S,\, C)$: 3.4%

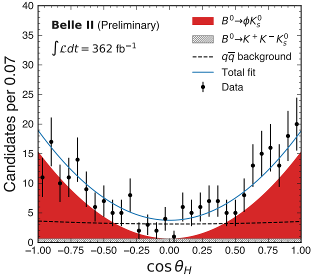
Measurement of CP asymmetries in $B^0 \to \phi K^0_S$ decays with Belle II

PRD 108, 072012 (2023)

- $B^0 \to \phi K^0_S$ proceeds via penguin diagram $\Rightarrow$ sensitive to physics beyond the SM
- reconstruct $\phi \to K^+K^-$ and $K^0_S \to \pi^+\pi^-$
- restrict sample to narrow region around ϕ mass $\Rightarrow$ quasi-two-body analysis
- continuum suppression via BDT
- unbinned extended maximum-likelihood fit to four dimensions:
  - beam-constrained mass M_{bc} and transformed BDT output $\mathcal{O}'_{CS}$ to separate signal from continuum
  - helicity angle $\cos\theta_H$ to distinguish non-resonant $B^0 \to K^+K^-K^0_S$
  - proper-time difference Δt to extract CP observables







Measurement of CP asymmetries in $B^0 \to \phi K^0_S$ decays with Belle II

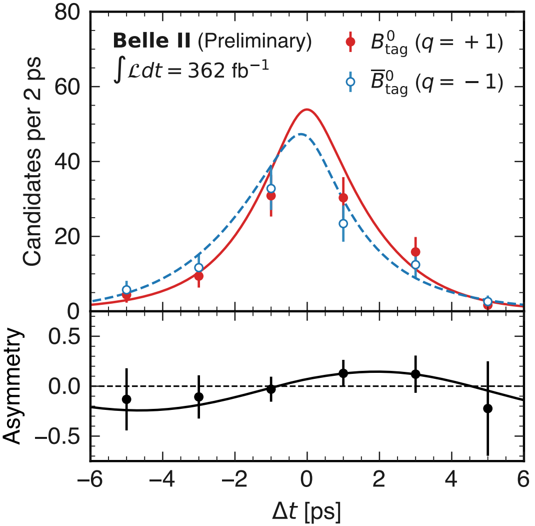
PRD 108, 072012 (2023)

- found 162 ± 17 signal candidates

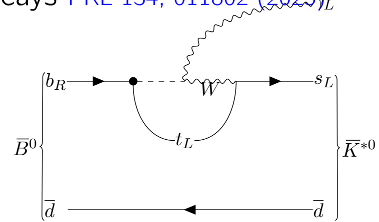
$$\boxed{\begin{aligned} S_{\phi K^0_S} &= 0.54 \pm 0.26^{+0.06}_{-0.08} \\ C_{\phi K^0_S} &= -0.31 \pm 0.20 \pm 0.05 \end{aligned}}$$

- largest systematic uncertainties arise from
  - fit bias
  - neglecting $B\overline{B}$ backgrounds

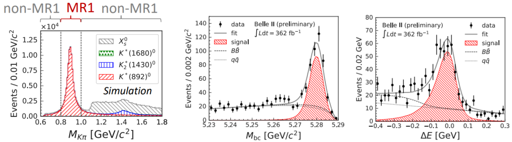
  and for C also
  - treatment of multiple candidates
  - non-resonant background
- results compatible with previous measurements
- no significant shift wrt $\sin 2\phi_1$ observed



Measurement of CP asymmetries in $B^0 \to K_S^0 \pi^0 \gamma$ decays PRL 134, 011802 (2025)



- $b \to s\gamma$ proceeds via one-loop diagrams at lowest order
  $\Rightarrow$ sensitive to physics beyond the SM
- weak interaction couples to left-handed fermions
  $\Rightarrow$ for $\overline{B}^0$ decay photon predominantly left-handed
- interference between B^0 and $\overline{B}^0$ highly suppressed
- select highest energetic photon and reject potential π^0 and η combinations with BDT
- define two mass regions, around K^{*0} and everywhere else
- separate signal from background with fit to $M_{\rm bc}$ and ΔE
- extract CP observables from simultaneous fit to Δt and time-integrated rate
- most precise results to date
- E and p scale as well as $B\overline{B}$ background asymmetries dominant systematics



$$S_{K^{*0}\gamma} = 0.00^{+0.27+0.03}_{-0.26-0.04} \qquad S_{K_S^0\pi^0\gamma} = 0.04^{+0.45}_{-0.44} \pm 0.10$$
$$C_{K^{*0}\gamma} = 0.10 \pm 0.13 \pm 0.03 \qquad C_{K_S^0\pi^0\gamma} = -0.06 \pm 0.25 \pm 0.07$$

Improvements of flavor tagging

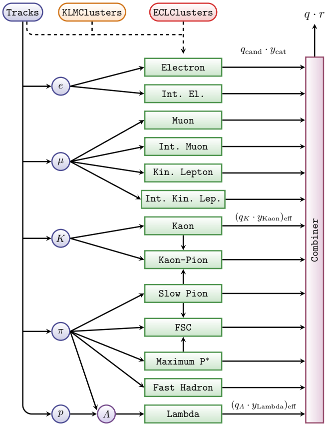
- so far used BDT-based two-stage approach of categories that are then combined

Categories	Targets for $\overline{B}^0$
Electron	e^-
Intermediate Electron	e^+
Muon	μ^-
Intermediate Muon	μ^+
Kinetic Lepton	ℓ^-
Intermediate Kinetic Lepton	ℓ^+
Kaon	K^-
Kaon-Pion	K^-, π^+
Slow Pion	π^+
Maximum p^*	ℓ^-, π^-
Fast-Slow-Correlated (FSC)	ℓ^-, π^+
Fast Hadron	π^-, K^-
Lambda	Λ

$$\overline{B}^0 \to D^{*+}\ \bar{\nu}_\ell\ \ell^-$$
$$\hookrightarrow D^0\ \pi^+$$
$$\hookrightarrow X\ K^-$$

$$\overline{B}^0 \to D^+\ \pi^-\ (K^-)$$
$$\hookrightarrow \overline{K}^0\ \nu_\ell\ \ell^+$$

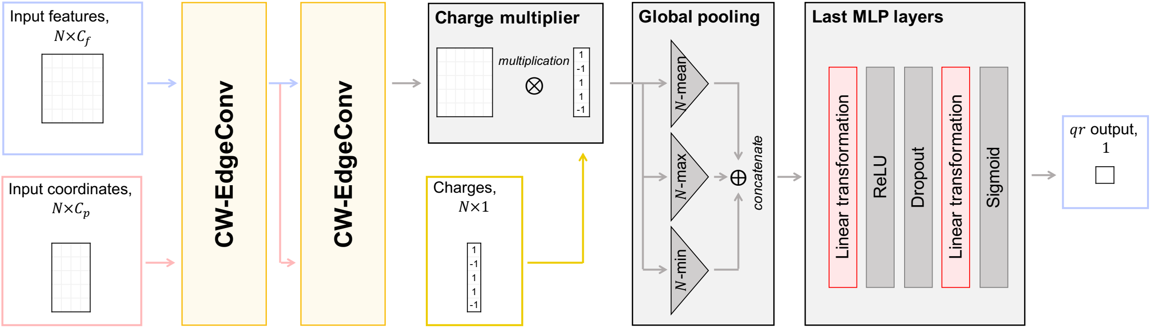
$$\overline{B}^0 \to \Lambda_c^+\ X^-$$
$$\hookrightarrow \Lambda\ \pi^+$$
$$\hookrightarrow p\ \pi^-$$



- effective tagging efficiency:
  $\varepsilon_{\text{eff}} = \varepsilon_{\text{tag}}(1-2\omega)^2 = (31.68 \pm 0.45)\%$
- only kept best candidate per category so lost potential tagging power

Improvements of flavor tagging

- feed up to 16 tracks into graph neural network
- input features of tracks: output of 13 former categories + momentum components + PID variables
- coordinates: initially point-of-closest approach to IP, then position in feature space



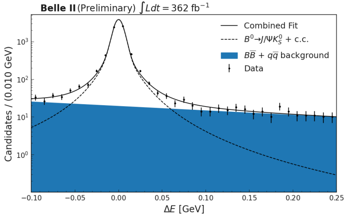
- effective tagging efficiency increases to $\varepsilon_{\text{eff}} = (37.40 \pm 0.43 \pm 0.34)\%$

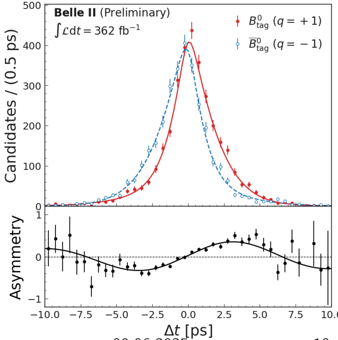
Validation of new flavor tagging algorithm PRD 110, 012001 (2024)

- perform CP violation measurement in golden channel $B^0 \to J/\psi K^0_S$
- reconstruct $J/\psi \to \mu^+\mu^-$ and $J/\psi \to e^+e^-$ and $K^0_S \to \pi^+\pi^-$
- fit energy difference ΔE and calculate signal weights
- fit weighted Δt distribution $\Rightarrow$ only signal parameterization needed

$$\boxed{\begin{aligned} S_{J/\psi K^0_S} &= 0.724 \pm 0.035 \pm 0.014 \\ C_{J/\psi K^0_S} &= -0.035 \pm 0.026 \pm 0.012 \end{aligned}}$$

- results in agreement with previous measurements
- statistical precision 7.9% / 7.1% better than with old flavor tagging algorithm
- largest systematic uncertainty from tag-side interference





Measurements of the CKM angle ϕ_2

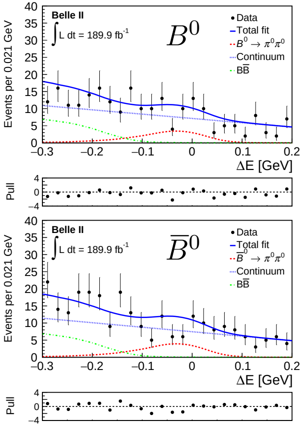
Measurement of the branching fraction and CP asymmetry of $B^0 \to \pi^0\pi^0$

PRD 107, 112009 (2023)

- ϕ_2 least known CKM angle
- if only tree-level $b \to u$ processes $B^0 \to \pi^+\pi^-$ would allow extraction of ϕ_2
- however significant loop contributions present so combine multiple charmless $B^0 \to hh$ modes
- challenging reconstruction since final state are just 4 photons
- signal photon selection via BDT
- another BDT to suppress continuum background
- signal yield extraction with 3D fit to beam-constrained mass $M_{\rm bc}$, energy difference ΔE, and transformed BDT output

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.38 \pm 0.27 \pm 0.22) \times 10^{-6}$$
$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = 0.14 \pm 0.46 \pm 0.07$$

- same precision on branching fraction as Belle with only 1/3 of data



![Duke University]

$B \to \pi\pi$ results

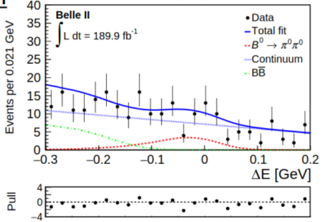
First measurement of $B^0 \to \pi^0\pi^0$ at Belle II

- unique channel to Belle II
- 4 photons in final state
- large background

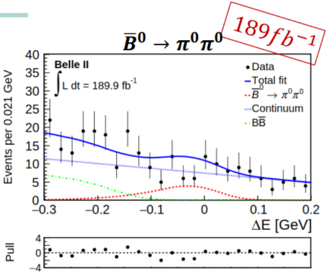
$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.38 \pm 0.27 \pm 0.22) \times 10^{-6}$$
$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = 0.14 \pm 0.46 \pm 0.07$$

- same BR precision as Belle with 1/3 of data

$B^0 \to \pi^0\pi^0$

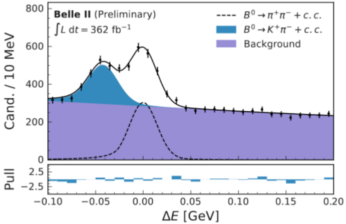


$\bar{B}^0 \to \pi^0\pi^0$

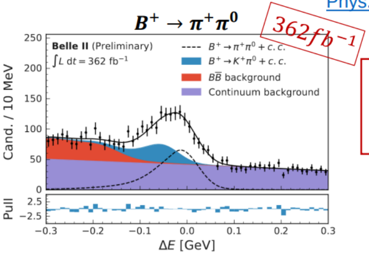


Phys. Rev. D 107, 112009

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



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

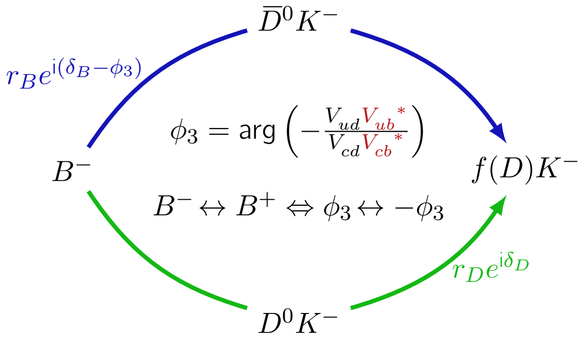


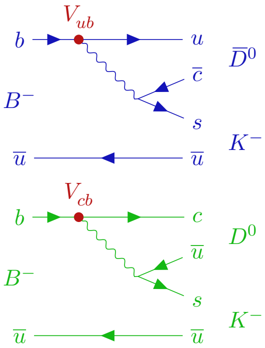
$$\mathcal{B}(B^0 \to \pi^+\pi^-) = (5.83 \pm 0.22 \pm 0.17) \times 10^{-6}$$
$$\mathcal{B}(B^+ \to \pi^+\pi^0) = 5.10 \pm 0.29 \pm 0.27 \times 10^{-6}$$
$$\mathcal{A}_{CP}(B^+ \to \pi^+\pi^0) = -0.081 \pm 0.054 \pm 0.008$$

- compatible with world averages
- worlds best $BR(B^0 \to \pi^+\pi^-)$

Measurements of the CKM angle ϕ_3

Concept of tree-level ϕ_3 measurements





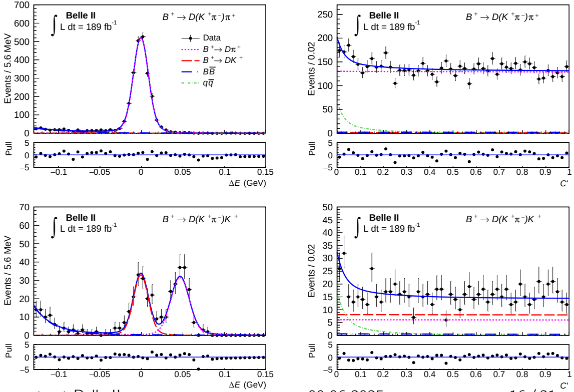
- interference between $b \to u$ and $b \to c$ transitions
- δ_B: strong phase difference, r_B: ratio between favored and suppressed amplitudes $\Rightarrow \sigma_{\phi_3} \propto \frac{1}{r_B}$
- r_D and δ_D may require external charm input
- GLW: D decay to CP eigenstates, like $D \to K^+K^-$ or $D \to \pi^+\pi^-$ PLB 265 (1991) 172, PLB 253 (1991) 483
- GLS: singly Cabibbo-suppressed D decays PRD 67 (2003) 071301

GLW measurement of ϕ_3 using $B^{\pm} \to D_{CP\pm} K^{\pm}$ decays JHEP 05 2024, 212

- using full Belle data ($711\ \text{fb}^{-1}$) and first half of Belle II data ($189\ \text{fb}^{-1}$)
- reconstructed D final states: $K^-\pi^+$ (flavor-specific), $K^0_S\pi^0$ (CP-odd), and K^+K^- (CP-even)
- measured CP asymmetries

$$\mathcal{A}_{CP\pm} \equiv \frac{\mathcal{B}(B^-\to D_{CP\pm}K^-) - \mathcal{B}(B^+\to D_{CP\pm}K^+)}{\mathcal{B}(B^-\to D_{CP\pm}K^-) + \mathcal{B}(B^+\to D_{CP\pm}K^+)} \qquad \mathcal{R}_{CP\pm} \equiv \frac{\mathcal{B}(B^-\to D_{CP\pm}K^-) + \mathcal{B}(B^+\to D_{CP\pm}K^+)}{(\mathcal{B}(B^-\to D_{\text{flav}}K^-) + \mathcal{B}(B^+\to \overline{D}_{\text{flav}}K^+))/2}$$

- K-π separation based on PID likelihood
- continuum suppression via BDT
- extraction of signal yields
  - 2D fit of ΔE and transformed BDT output C'
  - simultaneous fit in 12 subsets split by B charge, D final state, bachelor hadron
- found peaking $B \to K K^+K^-$ background using D mass sideband
  - fix shape from MC and yield from data



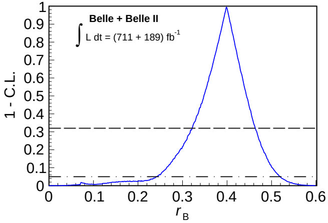
GLW measurement of ϕ_3 using $B^\pm \to D_{CP\pm} K^\pm$ decays JHEP 05 2024, 212

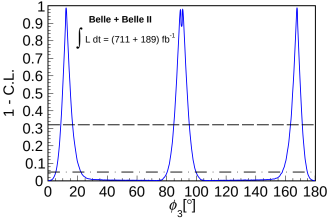
$$\mathcal{R}_{CP+} = 1.164 \pm 0.081 \pm 0.036$$
$$\mathcal{R}_{CP-} = 1.151 \pm 0.074 \pm 0.019$$
$$\mathcal{A}_{CP+} = (+12.5 \pm 5.8 \pm 1.4)\%$$
$$\mathcal{A}_{CP-} = (-16.7 \pm 5.7 \pm 0.6)\%$$

- significance for CP violation: $2.0\,\sigma$ $(2.8\,\sigma)$ in CP-even (CP-odd) mode
- $3.5\,\sigma$ evidence for $\mathcal{A}_{CP+} \neq \mathcal{A}_{CP-}$
- $\mathcal{R}_{CP+}$ $2.2\,\sigma$ larger than world average
- good agreement for $\mathcal{R}_{CP-}$ with world average

- convert CP asymmetries to angle ϕ_3 via

$$\mathcal{R}_{CP\pm} = 1 + r_B^2 \pm 2\,r_B \cos\delta_B \cos\phi_3 \qquad \mathcal{A}_{CP\pm} = \pm 2\,r_B \sin\delta_B \sin\phi_3 / \mathcal{R}_{CP\pm}$$





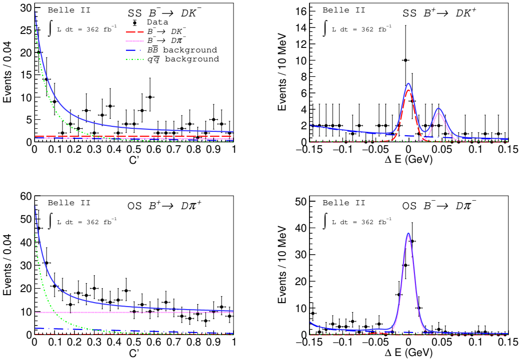
- large $\mathcal{R}_{CP+} \to$ large r_B
  $\Rightarrow$ low uncertainty on ϕ_3
- at 68.3% CL three intervals for ϕ_3
  - $[8.5°, 16.5°] \cup [84.5°, 95.5°] \cup [163.3°, 171.5°]$

GLS measurement of ϕ_3 JHEP 09 2023, 146

- $B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$ with $D \to K^0_S K^\pm \pi^\mp$ using Belle and Belle II data
- split into same-sign (SS), i.e., charge of B same as charge of K in $D \to K^0_S K^\pm \pi^\mp$, and opposite-sign (OS)
- seven observables: four CP asymmetries and three branching-fraction ratios

$$\mathcal{A}_m^{Dh} \equiv \frac{N_m^{Dh^-} - N_m^{Dh^+}}{N_m^{Dh^-} + N_m^{Dh^+}} \qquad \mathcal{R}_m^{DK/D\pi} \equiv \frac{N_m^{DK^-} + N_m^{DK^+}}{N_m^{D\pi^-} + N_m^{D\pi^+}} \qquad \mathcal{R}^{D\pi}_{SS/OS} \equiv \frac{N^{\mathrm{SS}}_{D\pi^-} + N^{\mathrm{SS}}_{D\pi^+}}{N^{\mathrm{OS}}_{D\pi^-} + N^{\mathrm{OS}}_{D\pi^+}}$$

- K-π separation based on PID likelihood
- continuum suppression via BDT
- extraction of signal yields
  - 2D fit of ΔE and transformed BDT output C'
  - simultaneous fit in 16 subsets split by B charge, OS/SS, $DK/D\pi$, Belle/Belle II
- two configurations:
  - full D phase space
  - $D \to K^{*\mp} K^\pm$ with $K^{*\pm} \to K^0_S \pi^\pm$



GLS measurement of ϕ_3 JHEP 09 2023, 146

full D phase space	SS	OS
$\mathcal{A}^{DK}$	-0.089 $\pm$ 0.091 $\pm$ 0.011	0.109 $\pm$ 0.133 $\pm$ 0.013
$\mathcal{A}^{D\pi}$	0.018 $\pm$ 0.026 $\pm$ 0.009	-0.028 $\pm$ 0.031 $\pm$ 0.009
$\mathcal{R}^{DK/D\pi}$	0.122 $\pm$ 0.012 $\pm$ 0.004	0.093 $\pm$ 0.013 $\pm$ 0.003
$\mathcal{R}^{D\pi}_{\text{SS/OS}}$	1.428 $\pm$ 0.057 $\pm$ 0.002	

$K^{*\pm}$ region	SS	OS
$\mathcal{A}^{DK}$	0.055 $\pm$ 0.119 $\pm$ 0.020	0.231 $\pm$ 0.184 $\pm$ 0.014
$\mathcal{A}^{D\pi}$	0.046 $\pm$ 0.029 $\pm$ 0.016	0.009 $\pm$ 0.046 $\pm$ 0.009
$\mathcal{R}^{DK/D\pi}$	0.093 $\pm$ 0.012 $\pm$ 0.005	0.103 $\pm$ 0.020 $\pm$ 0.006
$\mathcal{R}^{D\pi}_{\text{SS/OS}}$	2.412 $\pm$ 0.132 $\pm$ 0.019	

- values consistent with LHCb's results
- measurement statistically limited
- on their own results do not allow unambiguous determination of ϕ_3 but help in global fits
- largest systematic uncertainties
  - fixing shape parameters from MC
  - assumption that efficiencies of $D \to K^0_S K^- \pi^+$ and $D \to K^0_S K^+ \pi^-$ are equal

Event selection of $B \to \overline{D}\ell^+\nu_\ell$ analysis

- Impose tight PID cuts for electron and muon
- Reconstruct $D^- \to K^+\pi^-\pi^-$ and $D^0 \to K^-\pi^+$ with $p(D)_{\text{CMS}} < 2.4$ GeV/c
- Require minimum vertex fit quality
- Apply vetoes against $D^{*+} \to D^0\pi^+$, $D^{*+} \to D^+\pi^0$, and $D^{*0} \to D^0\pi^0$
- No exclusive reconstruction of second B meson
- Reduce contamination from continuum and $B\overline{B}$ backgrounds using seven variables:
  - Modified Fox-Wolfram moment H_{20}^{so}, m_Y, p^*_{miss}, m_{ROE}, p_{ROE}, $\cos\angle(\ell,W)$, $\angle(D,\ell)$
  - Use simulated annealing (simultaneous optimization of multiple variables using Markov chains) to pick rectangular cuts that maximize geometric mean of expected signal significance across all w bins
- Find $87\,000$ $B^0 \to D^-\ell^+\nu_\ell$ and $136\,000$ $B^+ \to \overline{D}^0\ell^+\nu_\ell$

Systematic uncertainties

Source		Uncertainty [%]
Statistical		0.9
Systematic		1.5
	$B^{0/-}$ lifetime	0.1
	Signal form factor	0.1
	$B \to \bar{D}^{*}\ell^{+}\nu_{\ell}$ form factor	0.1
	$\mathcal{B}(B \to X_c \ell \nu_\ell)$	0.3
	$\mathcal{B}(D \to K\pi(\pi))$	0.5
	Tracking efficiency	0.5
	$N_{\Upsilon(4S)}$	0.7
	f_{00}/f_{+-}	0.1
	$f_{\not{\mathcal{B}}}$	0.4
	Background w modelling	0.3
	$E^{*}_{Y} - m_{Y}$ reweighting	0.3
	Lepton identification	0.3
	Kaon identification	0.6
	Vertex fit χ^2 correction	0.3
	Simulation sample size	0.5
Theoretical		1.3
	Lattice QCD inputs	1.2
	Long-distance QED	0.5
Total		2.1

- Irreducible external inputs
- 0.24% uncertainty per track for data-MC efficiency differences
- Background w modeling determined from control samples (wrong-sign combination, sideband, inverted D^* veto)
- Particle efficiencies and misidentification rates determined in momentum and polar angle bins
- Correction from control sample $B \to K^{*}\ell$
- Templates allowed to vary within their MC statistic in each bin
- Assume long-distance Coulomb correction to be $\delta_C^{+,0} = 0$, but add nuisance parameter with width of 0.023 for δ_C^0
- Negligible systematic uncertainties