CP violation measurements at Belle II

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on behalf of Belle/Belle II

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Electroweak Interactions & Unified Theories
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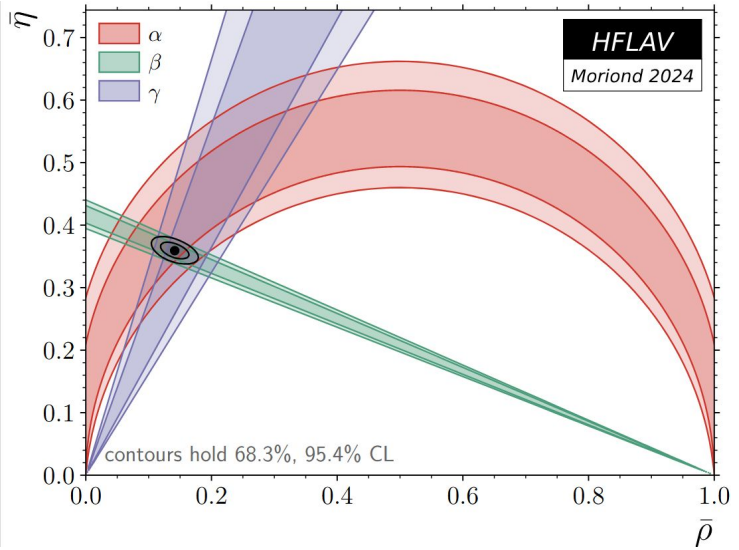
Unitarity triangle

New results by Belle II

Measurement of $\phi_1(\beta)$:

- $B^0 \to J/\psi\pi^0$ [Phys. Rev. D 111, 012011 (2025)]

  First time CPV observed in this mode.



Constraints on angle $\phi_2(\alpha)$:

- $B^0 \to \pi^0\pi^0$ [To appear in PRDL]
- $B^0 \to \rho^+\rho^-$ [Submitted to PRD]

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

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

Belle II experiment

At SuperKEKB, running since 2019.

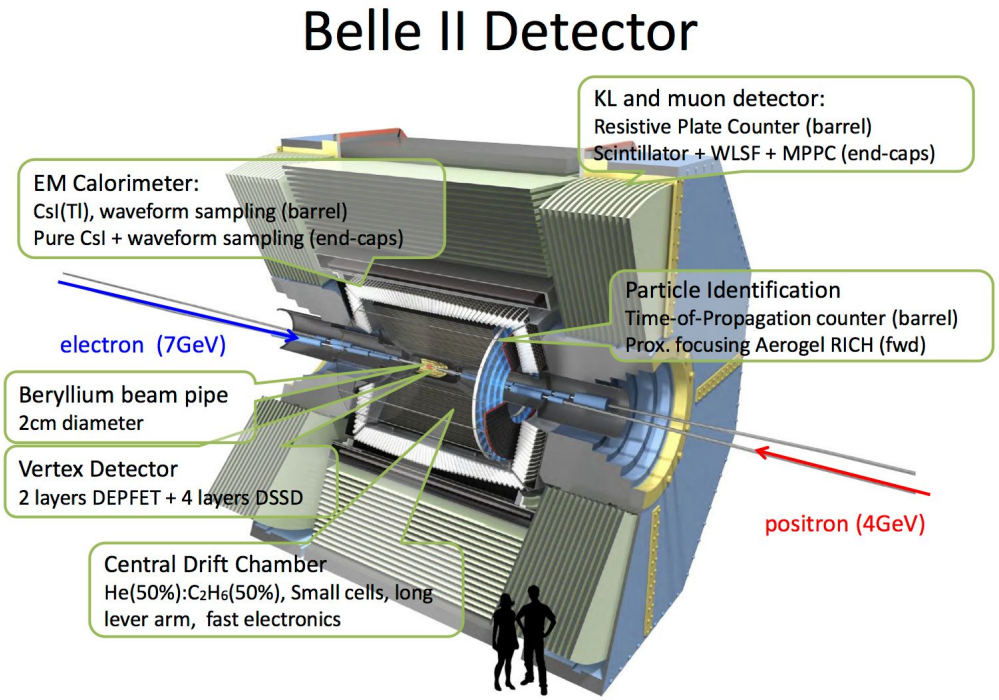
- Asymmetric e^+- e^- collider at Y(4S) energy.
- B-factory, but also huge τ and charm production.

World record instantaneous luminosity: **5.1×10^{34} cm^{-2}s^{-1}**

Belle II recorded:

365 fb^{-1} (run 1), 200 fb^{-1} (run 2)

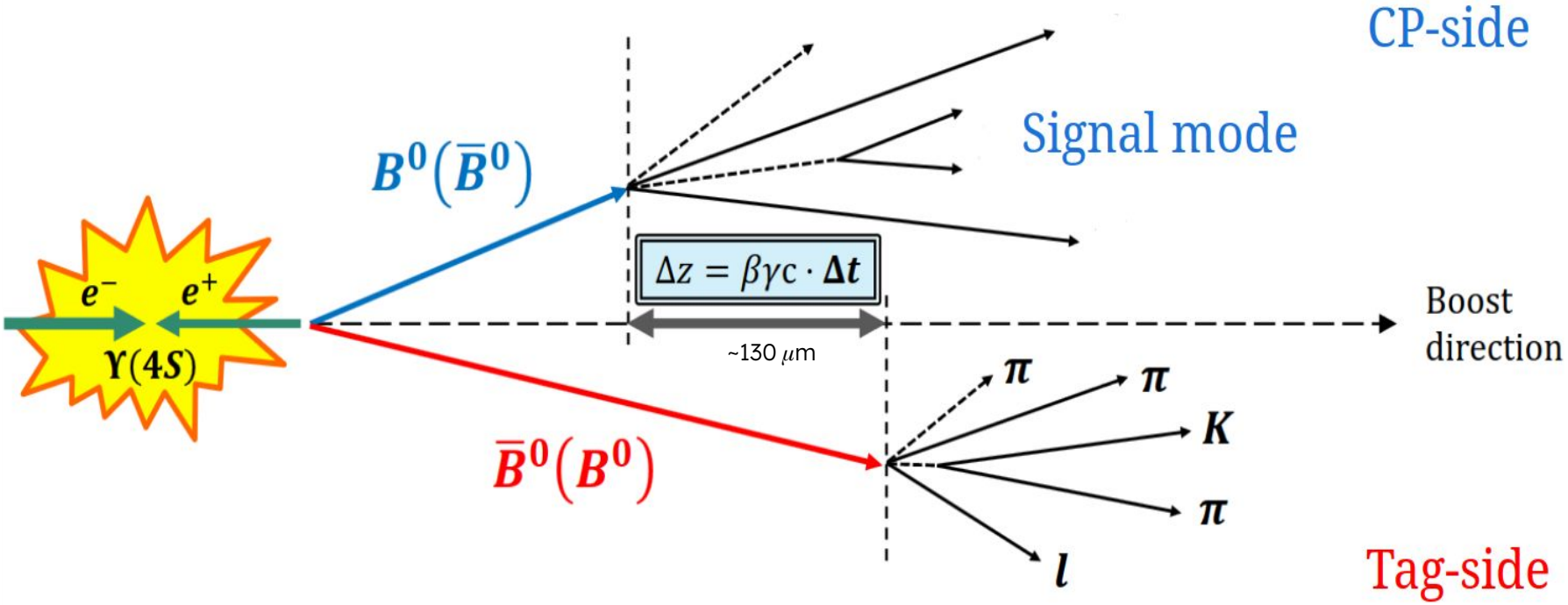
Hermetic detector (4π) with good neutral reconstruction.



Strategy for CP measurements

$B\bar{B}$-pair entanglement → B-meson flavour is opposite to its pair at time of decay, then oscillates in time.

$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\overline{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})}$$

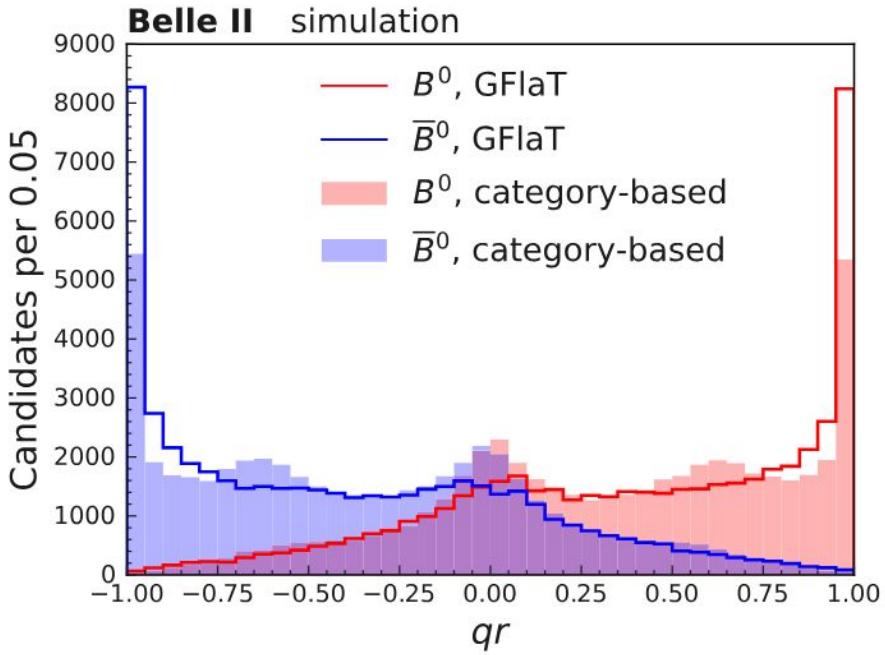


Flavour Tagger

[Phys. Rev. D 110, 012001]

New tool for Flavour Tagging (GFlaT)

- Graph NN, using information of all charged particles and their relations.
- **37% effective tagging efficiency**.
  - ~20% relative improvement.



$q = +1(B^0), -1(\overline{B}^0) \quad r = 1 - 2w$

w miss-tag prob.

In time-dependent measurements:

$$\mathcal{T}(\Delta t, q = \pm 1) \approx \frac{e^{|\Delta t|/\tau_B}}{4\tau_B}\left(1 - [q(1-2w)]\,[S\sin(\Delta m \Delta t) - C\cos(\Delta m \Delta t)]\right)$$

$\phi_1 : B^0 \to J/\psi\pi^0$

[Phys. Rev. D 111, 012011 (2025)]

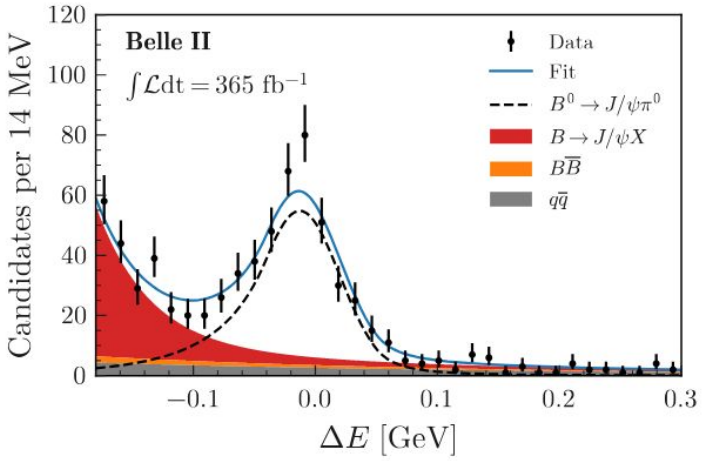
Cabibbo suppressed transition (ϕ_1).

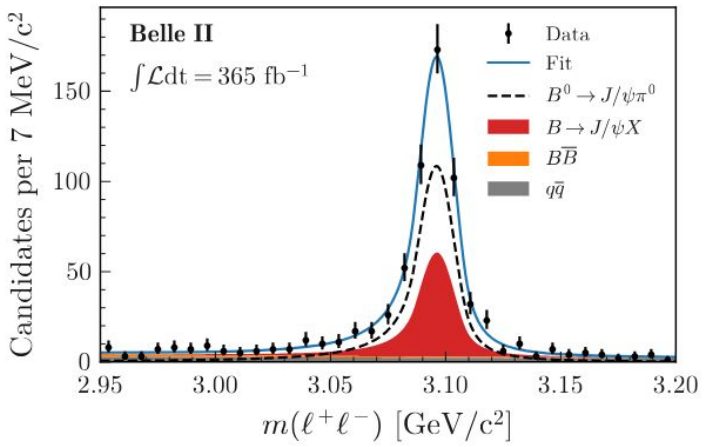
Branching fraction and CP asymmetries can constrain penguin pollution in $B^0 \to J/\psi K^0$.

- Current uncertainty on $2\phi_1$ ~ 1°.
- Penguin contributions can shift it up to 0.5°.

Measurement combines both electrons and muons final states, $J/\psi \to l^+l^-$.

Validated with $B^+ \to J/\psi K^{*+}$ and $B^0 \to J/\psi K^0_S$





$\phi_1 : B^0 \to J/\psi\pi^0$

[Phys. Rev. D 111, 012011 (2025)]

Two step measurement:

1. Extract yields from fit to ΔE and m(l^+l^-)

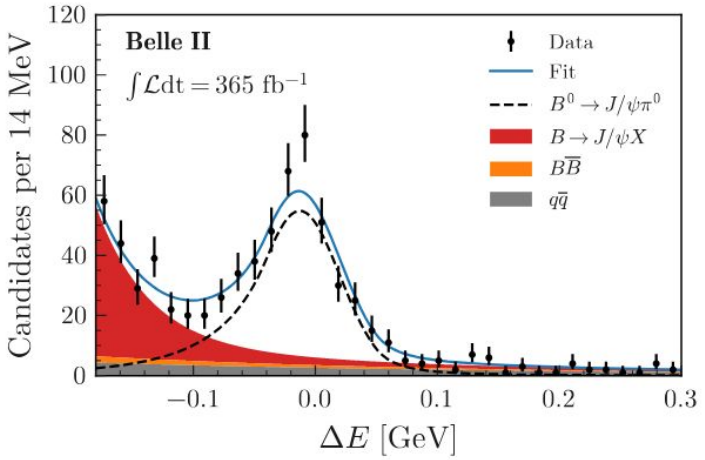
   392±24 candidates

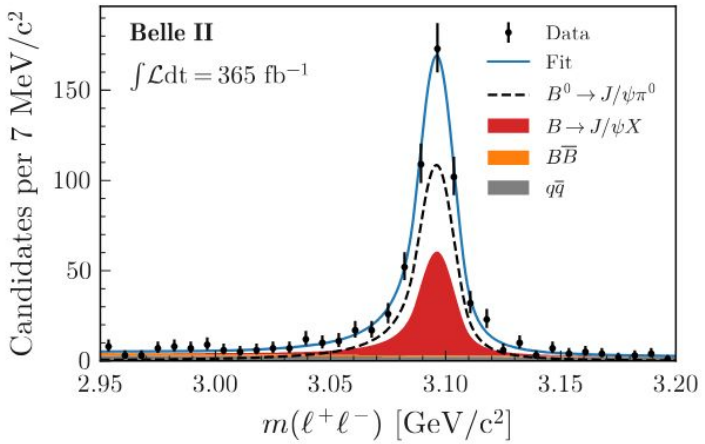
$$\mathcal{B}(B^0 \to J/\psi\pi^0) = (2.00 \pm 0.12 \pm 0.09) \times 10^{-5}$$

2. Fit Δt in signal enhanced region.

   With q=±1 and 7 bins of tag-quality (r)

$$C_{CP} = 0.13 \pm 0.12 \pm 0.03,$$
$$S_{CP} = -0.88 \pm 0.17 \pm 0.03,$$





$\phi_1 : B^0 \to J/\psi\pi^0$

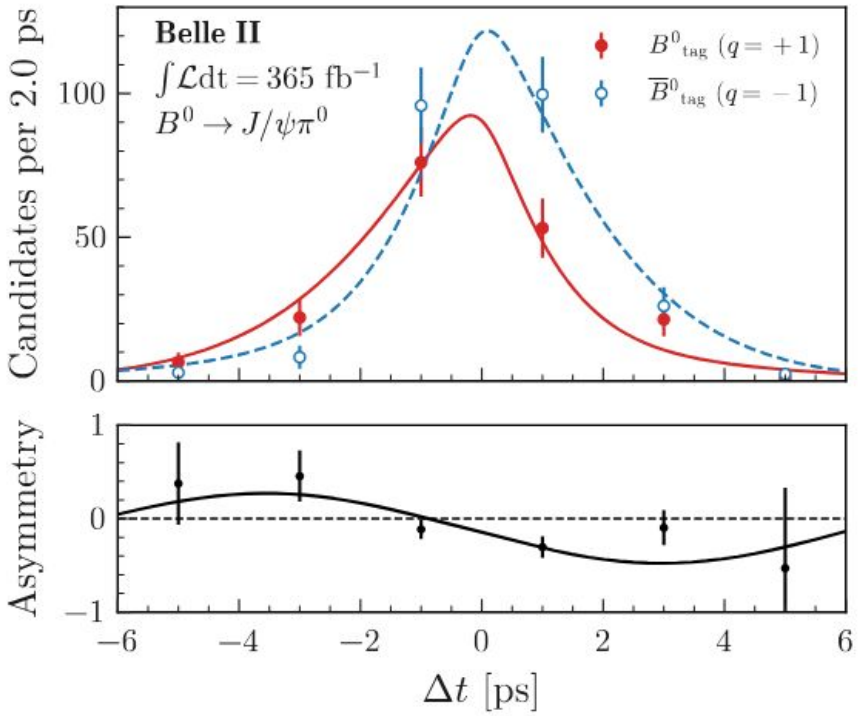
[Phys. Rev. D 111, 012011 (2025)]

Most precise, and first observation of mixing-induced CP asymmetry in this mode.

$$C_{CP} = 0.13 \pm 0.12 \pm 0.03,$$
$$S_{CP} = -0.88 \pm 0.17 \pm 0.03,$$

Expected improvement when accounting the penguin pollution in the uncertainty of $2\phi_1$ up to 10% .

[arxiv2501.09414]



$\phi_2 : B^0 \to \pi^0\pi^0$

[arxiv:2412.14260]

Uncertainty on ϕ_2 from $B \to \pi\pi$ is limited by precision of $B^0 \to \pi^0\pi^0$ BF and CP asymmetry.

Reconstruction challenge: 2 $\pi^0 \to \gamma\gamma$ decays.

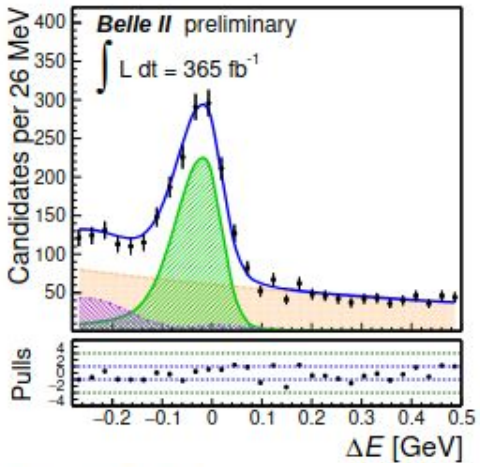
- 4-photon final state.
- Currently only possible in Belle II.

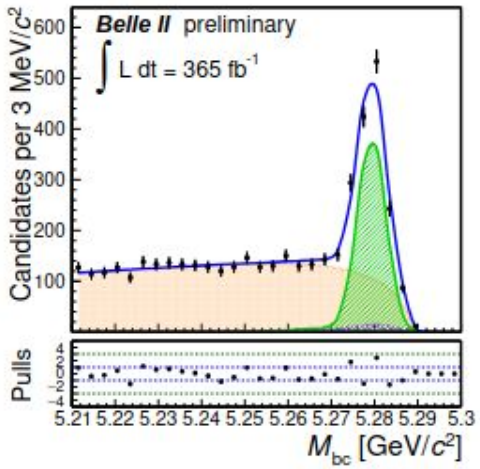
Measurement of the BF and time-integrated CP-asymmetry, A_{CP}.

Validated through control modes:

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

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





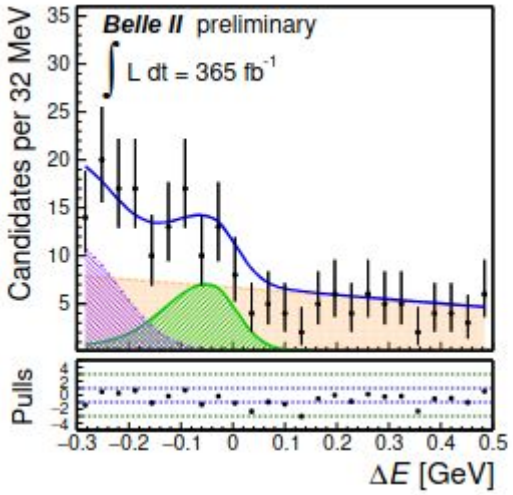
$\phi_2 : B^0 \to \pi^0\pi^0$

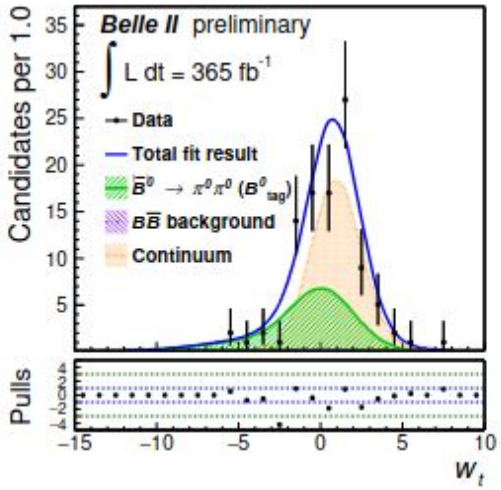
[arxiv:2412.14260]

Selection to suppress high combinatorial background present.

Split in q=±1, simultaneous fit in: ΔE, M_{bc}, C_t, w_t.

Time-integrated measurement.





126±20 candidates

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.25 \pm 0.20 \pm 0.11) \times 10^{-6}$$

$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = 0.03 \pm 0.30 \pm 0.04,$$

$\phi_2 : B^0 \to \pi^0\pi^0$

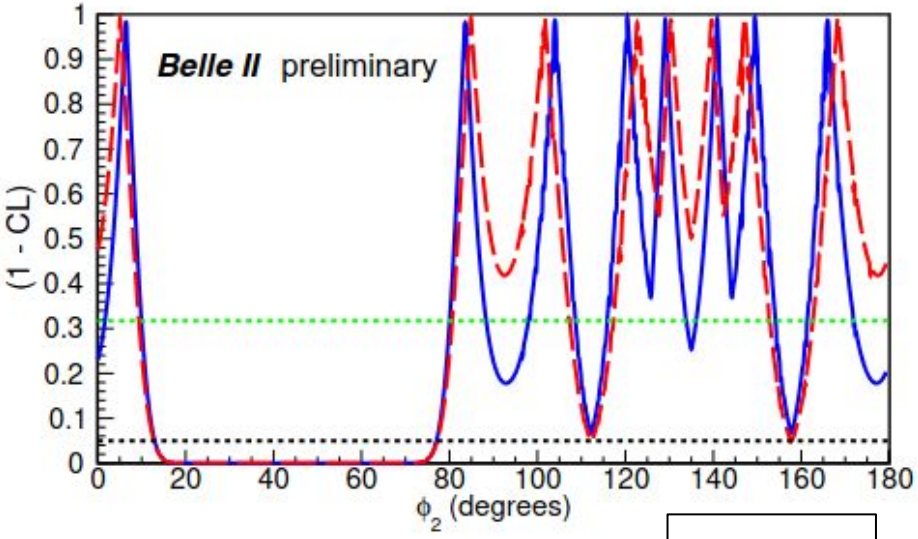
[arxiv:2412.14260]

- Reduced fractional statistic and systematic uncertainties for BF and CP asymmetry with respect to the previous measurement.
  [Phys. Rev. D 107, 112009 (2023)]

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.25 \pm 0.20 \pm 0.11) \times 10^{-6}$$
$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = 0.03 \pm 0.30 \pm 0.04,$$

Isospin analysis with new results:

- Fractional precision of ϕ_2 increased up to 30% with the addition of this result.



$\phi_2 : B^0 \to \rho^+\rho^-$

[arxiv:2412.19624]

The $B^0 \to \rho^+\rho^-$ decay gives stringent constraints of ϕ_2 due to small contribution from loop amplitude (b→d).

Pseudoscalar→VV, 3 possible polarizations.

Decay chain of $\rho^\pm \to \pi^\pm\pi^0$ and $\pi^0 \to \gamma\gamma$.

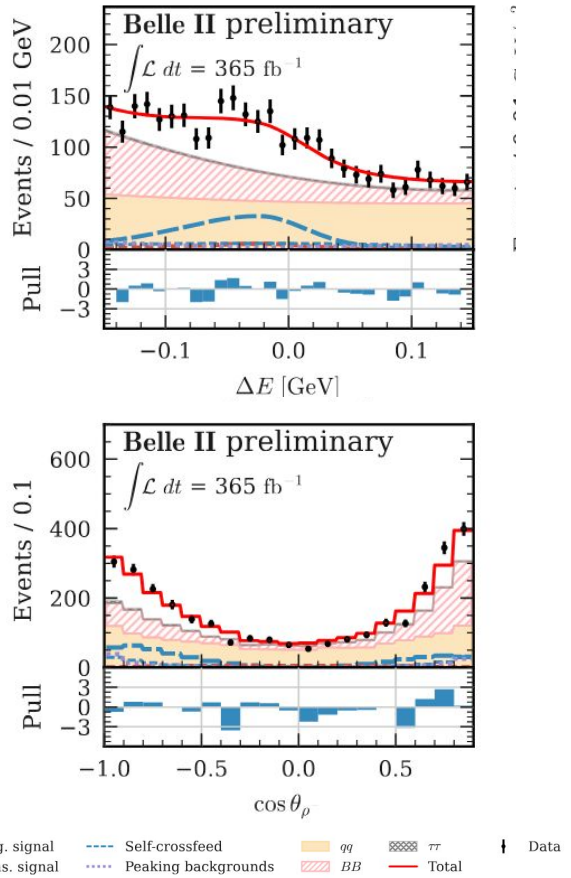
Validation: $B^0 \to D^{*-}\pi^+$, $B^+ \to D^0\rho^+$

Two step measurement:

1. 6-dimensional fit to extract BF and measure longitudinal polarization.

$$\mathcal{B}(B^0 \to \rho^+\rho^-) = (2.88\,^{+0.23\,+0.29}_{-0.22\,-0.27}) \times 10^{-5}$$
$$f_L = 0.921\,^{+0.024\,+0.017}_{-0.025\,-0.015}$$

436 ± 35 candidates

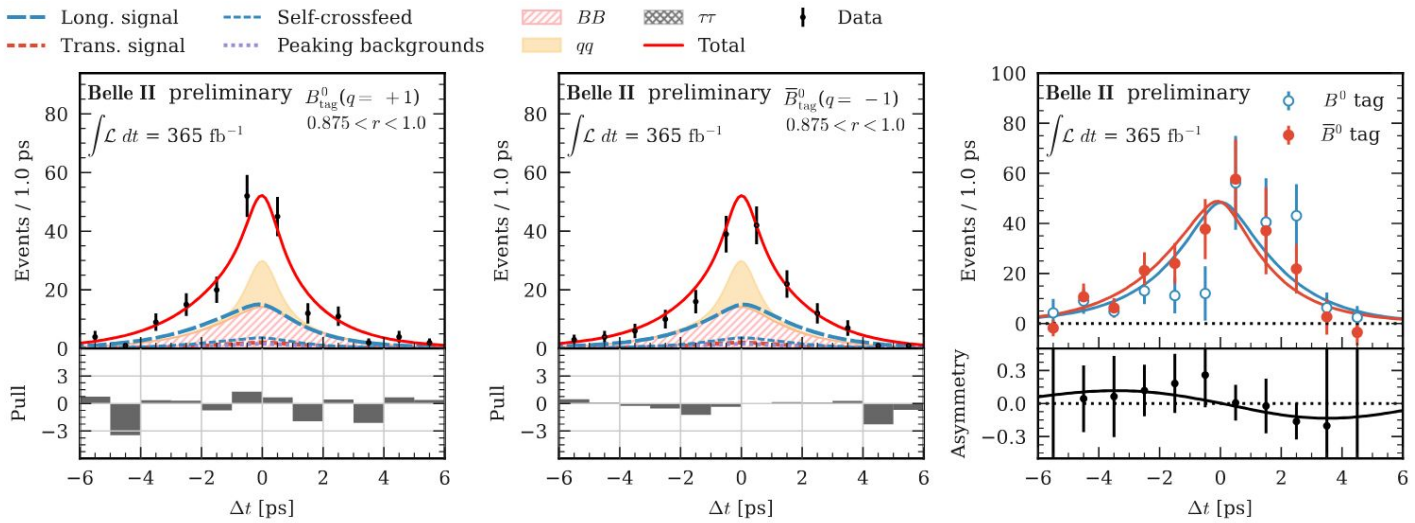


$\phi_2 : B^0 \to \rho^+\rho^-$

[arxiv:2412.19624]

2. Time-dependent CP fit to extract CP parameters.

   Fit in Δt with q=±1, 7 bins of tag-quality (r).



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

$\phi_2 : B^0 \to \rho^+\rho^-$

[arxiv:2412.19624]

Isospin analysis to extract ϕ_2 constraints.

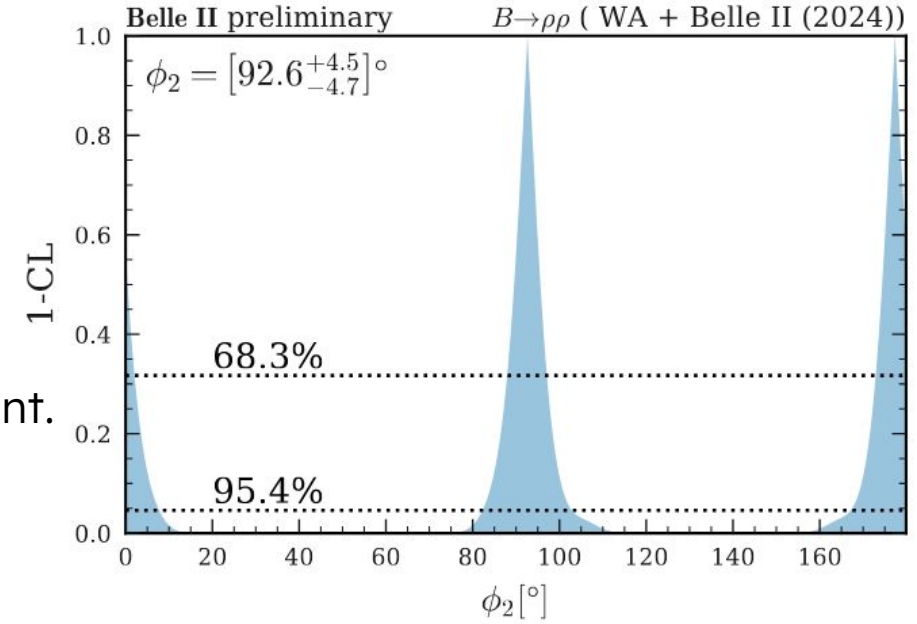
- Plus external parameters from Belle, Babar, and LHCb for $B^0 \to \rho^0\rho^0$ and $B^+ \to \rho^+\rho^0$.

- Solution compatible with SM:

$$\phi_2 = (92.6^{+4.5}_{-4.7})^\circ$$
$$\Delta\phi_2 = (2.4^{+3.8}_{-3.7})^\circ$$

8% relative uncertainty improvement.

Uncertainty dominated by S in $B^0 \to \rho^+\rho^-$ and $B^0 \to \rho^0\rho^0$.



Summary and outlook

- New measurements by the Belle II collaboration in CP violation.

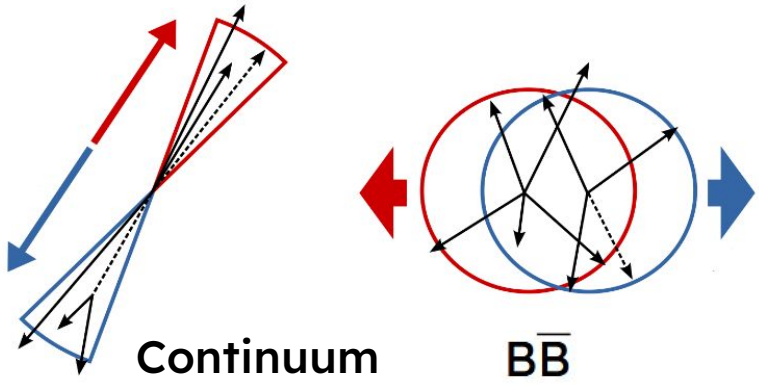
  ➔ $\phi_1(\beta)$: $B^0 \to J/\psi\pi^0$

  ➔ $\phi_2(\alpha)$: $B^0 \to \rho^+\rho^-$ and $B^0 \to \pi^0\pi^0$

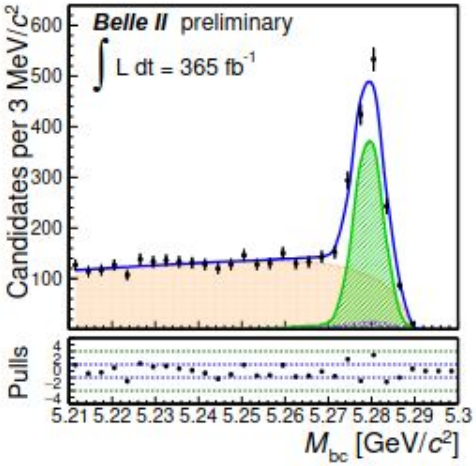
- Competitive or better with respect to Belle/BaBar with smaller samples.
- Belle II has access to unique modes (neutral) to constrain UT.
- **Expect more CP measurements soon!**

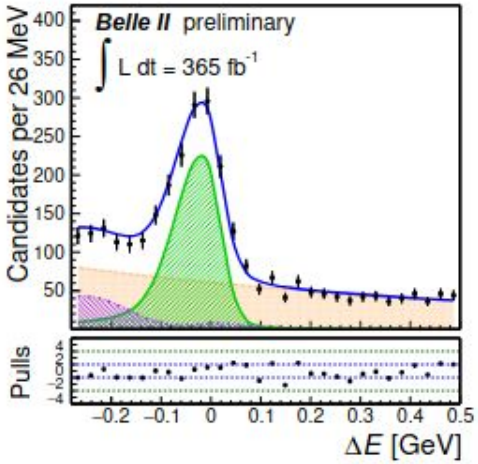
BACKUP

B-factory distributions



Typical distributions for continuum vs BB event shapes





$$M_{\rm bc} \equiv \sqrt{(\sqrt{s}/2)^2 - p_B^{*2}}$$

$$\Delta E \equiv E_B^* - \sqrt{s}/2$$