CP violation in B decays at BelleII

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Aug 18, 2025

Vietnam Flavour Physics Conference 2025
18–22 Aug 2025

CKM Unitarity triangle

- New results by Belle II Constraints on angle : $\phi_2(\alpha)$

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

PRD 111, 092001 (2025)

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

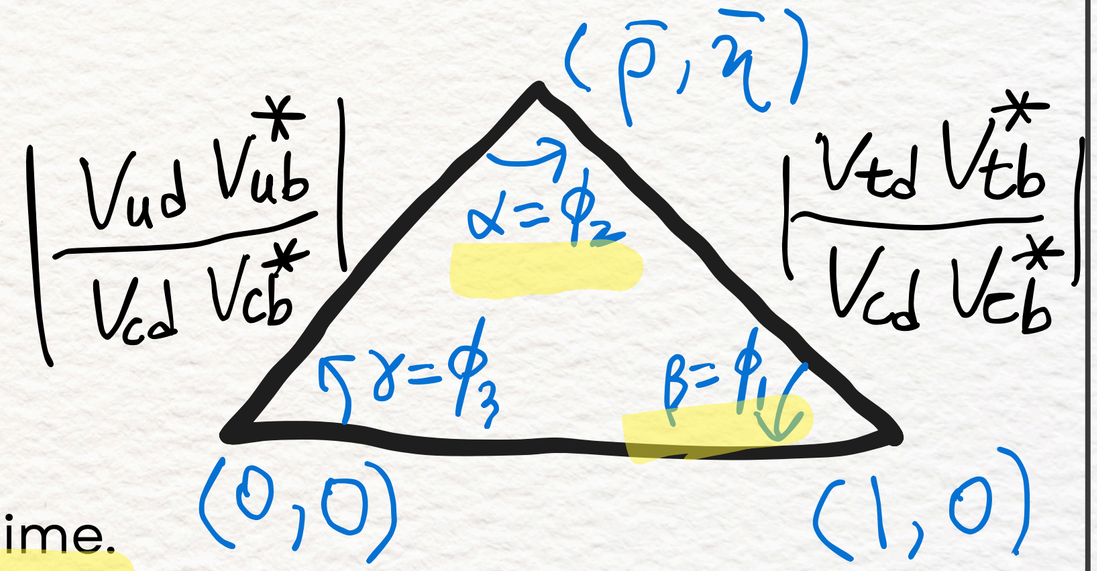
PRD 111, L071102(2025)

- Measurement of : $\phi_1(\beta)$

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

PRD 111, 012011 (2025)

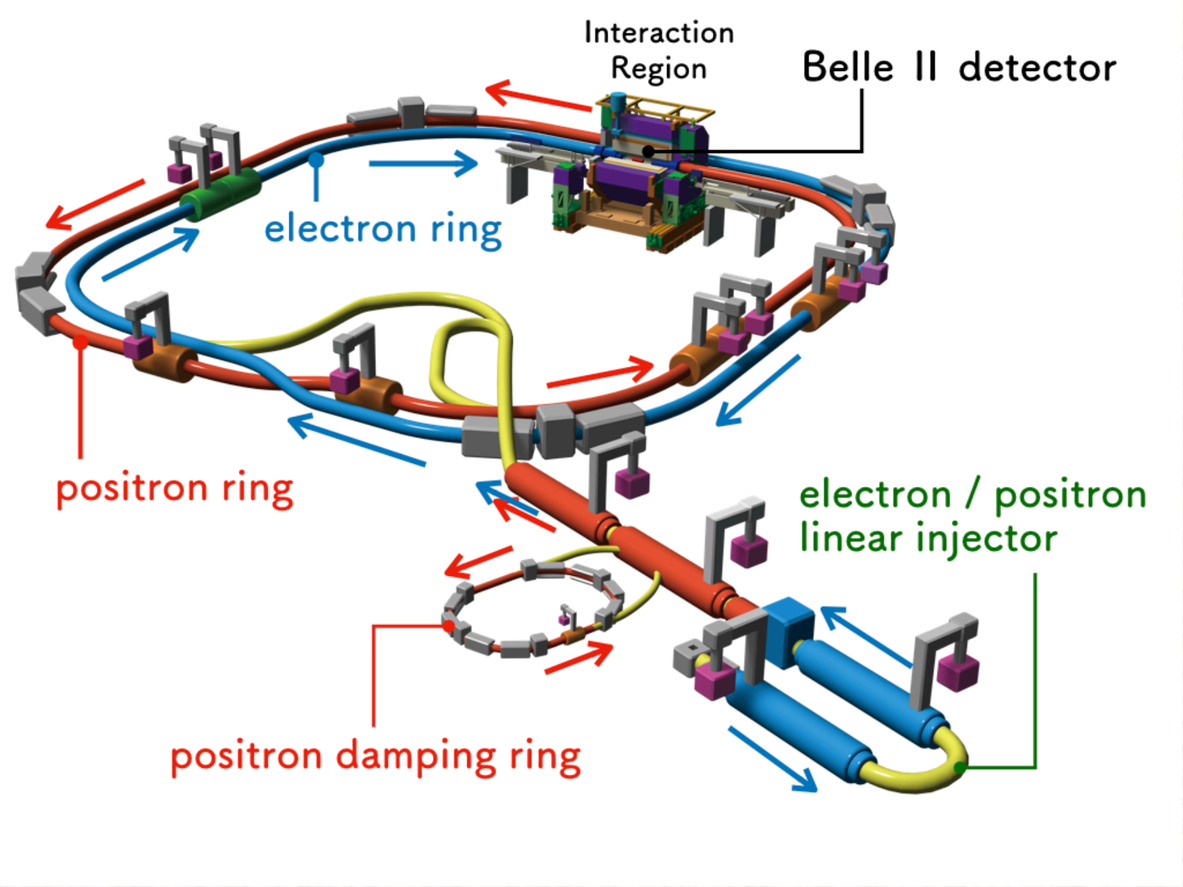
CPV observed in this mode for the first time.

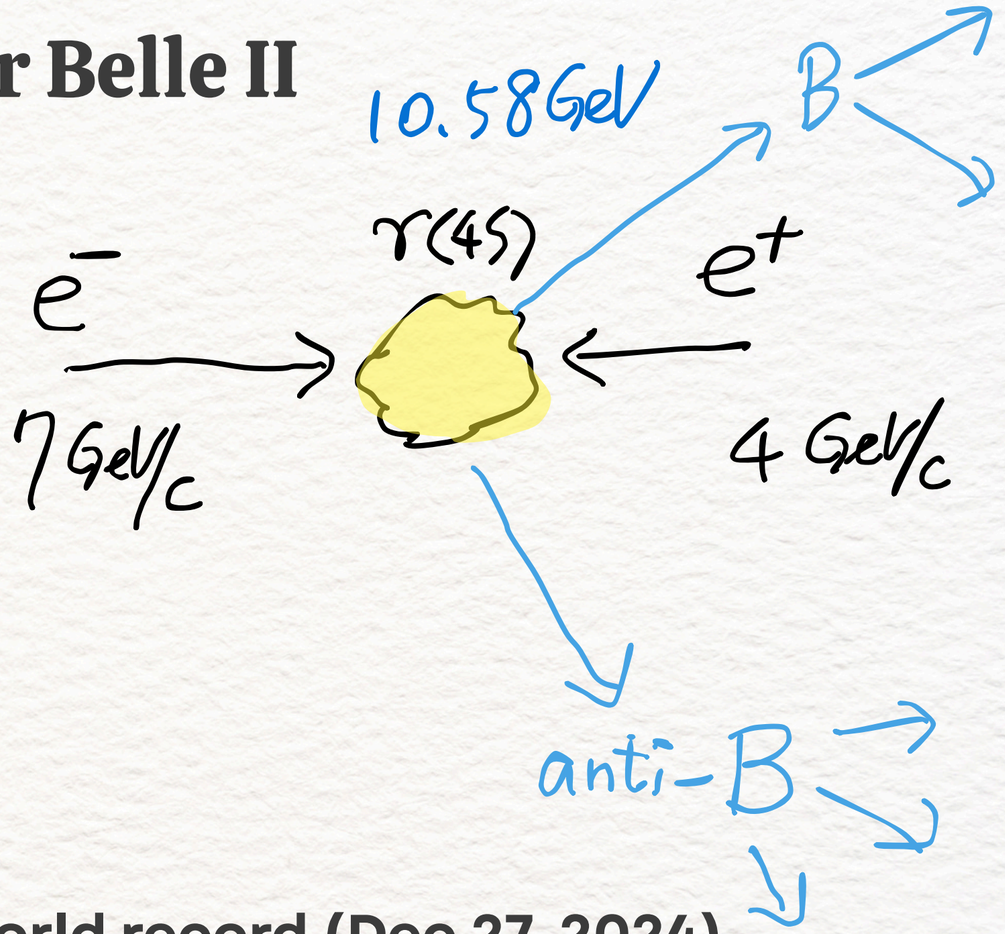


Belle II Collaboration Map

~1,200 members from 124 institutions across 27 countries.

SuperKEKB, accelerator for Belle II





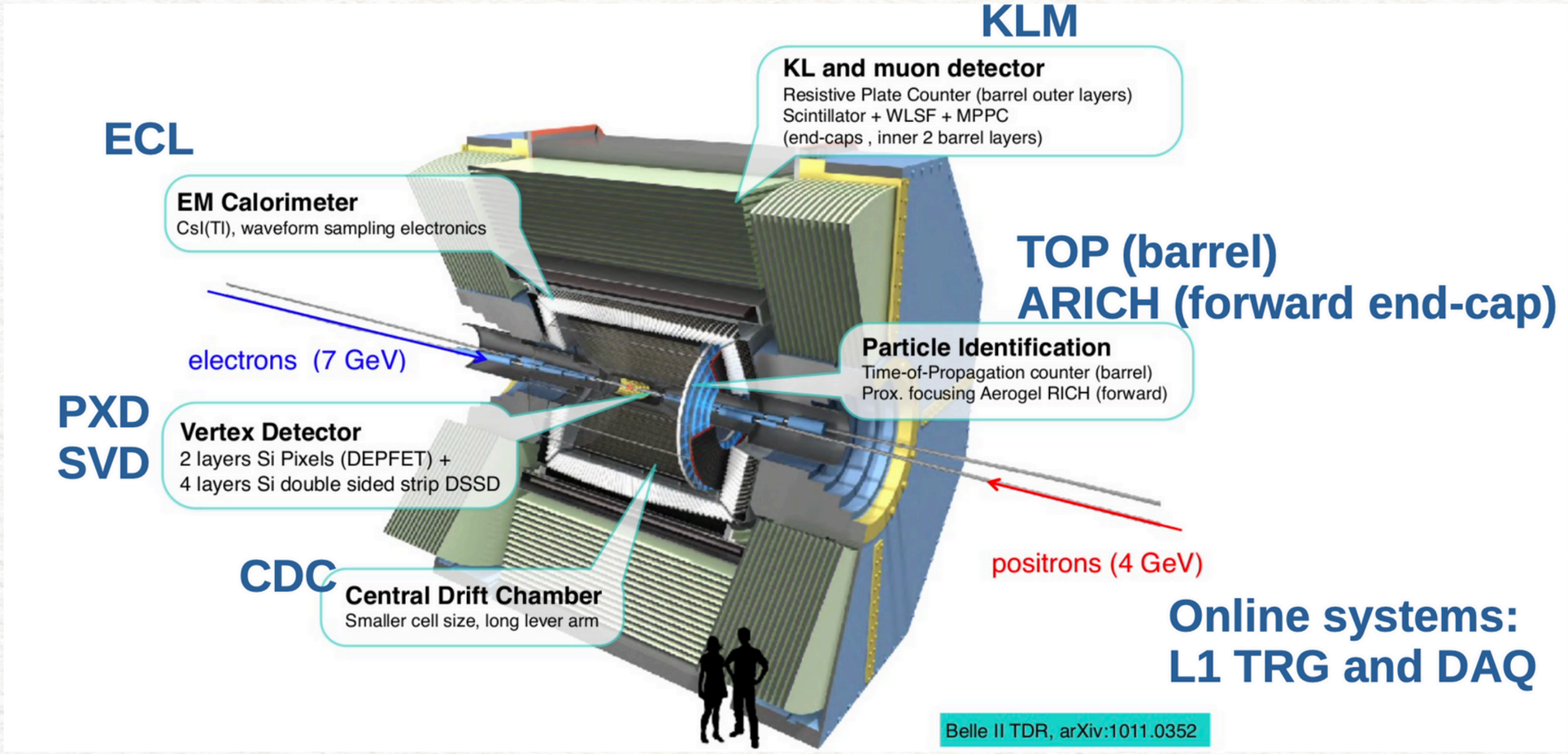
world record (Dec.27, 2024)

$$L_{peak} = 5.1 \times 10^{34} cm^{-2} s^{-1}$$

$$L_{int-BelleII} = 573 fb^{-1}$$

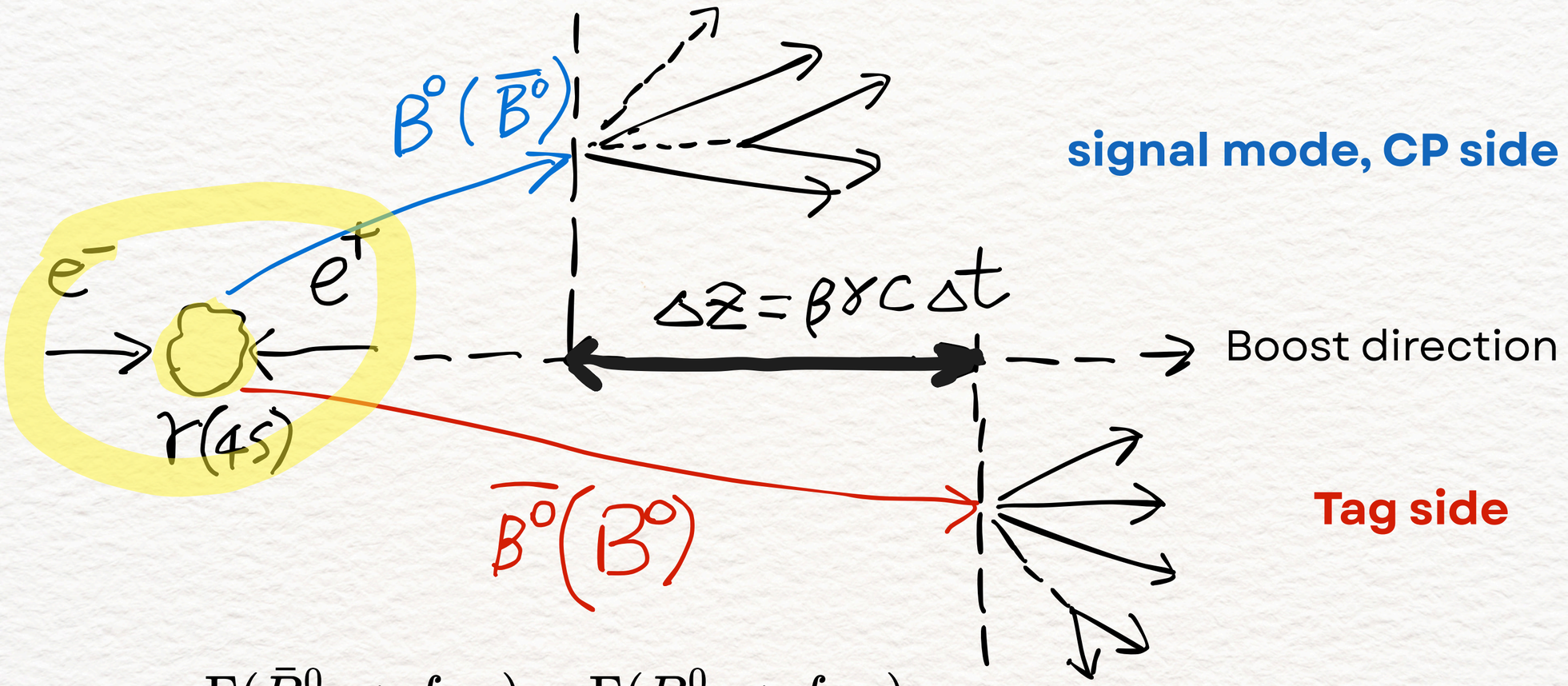
Belle II Detector

Newly designed sub-detectors set to improve detection performance.



Physics target of Belle II: Rare B, tau, charm physics, Dark matter search, and CP Violation.

Strategy for CP measurements



signal mode, CP side

Tag side

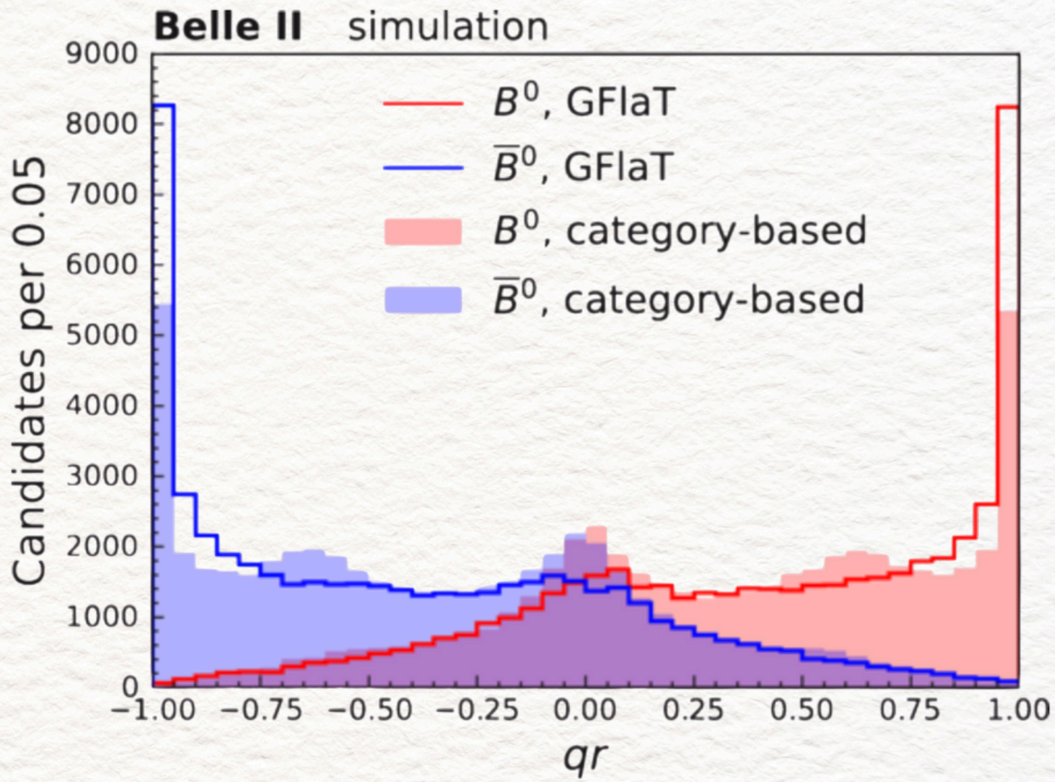
$$A_{CP} = \frac{\Gamma(\bar{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\bar{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})}$$

$$\Delta z \sim 140 \mu m$$

Flavour Tagger

- New tool for Flavour Tagger
  - GFlaT (Graph Flavour Tagger) is a **graph neural network (GNN)**-based algorithm
  - enhance flavour tagging of neutral B mesons produced in $\Upsilon(4S)$ decays.
- **37%** effective tagging efficiency.
- $q = +1, B^0 \text{ tag} - \text{side}$

  $q = -1, \bar{B}^0 \text{ tag} - \text{side}$
- $r \in [0, 1]$ quality of flavor assignments



PRD 110, 012001 (2024)

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

- Constraints of ϕ_2 need isospin analysis due to small contribution from the loop amplitude $(b \to d)$
- Two step measurement:
- 1. Fit to extract branching fraction (BF) and measure longitudinal polarization.

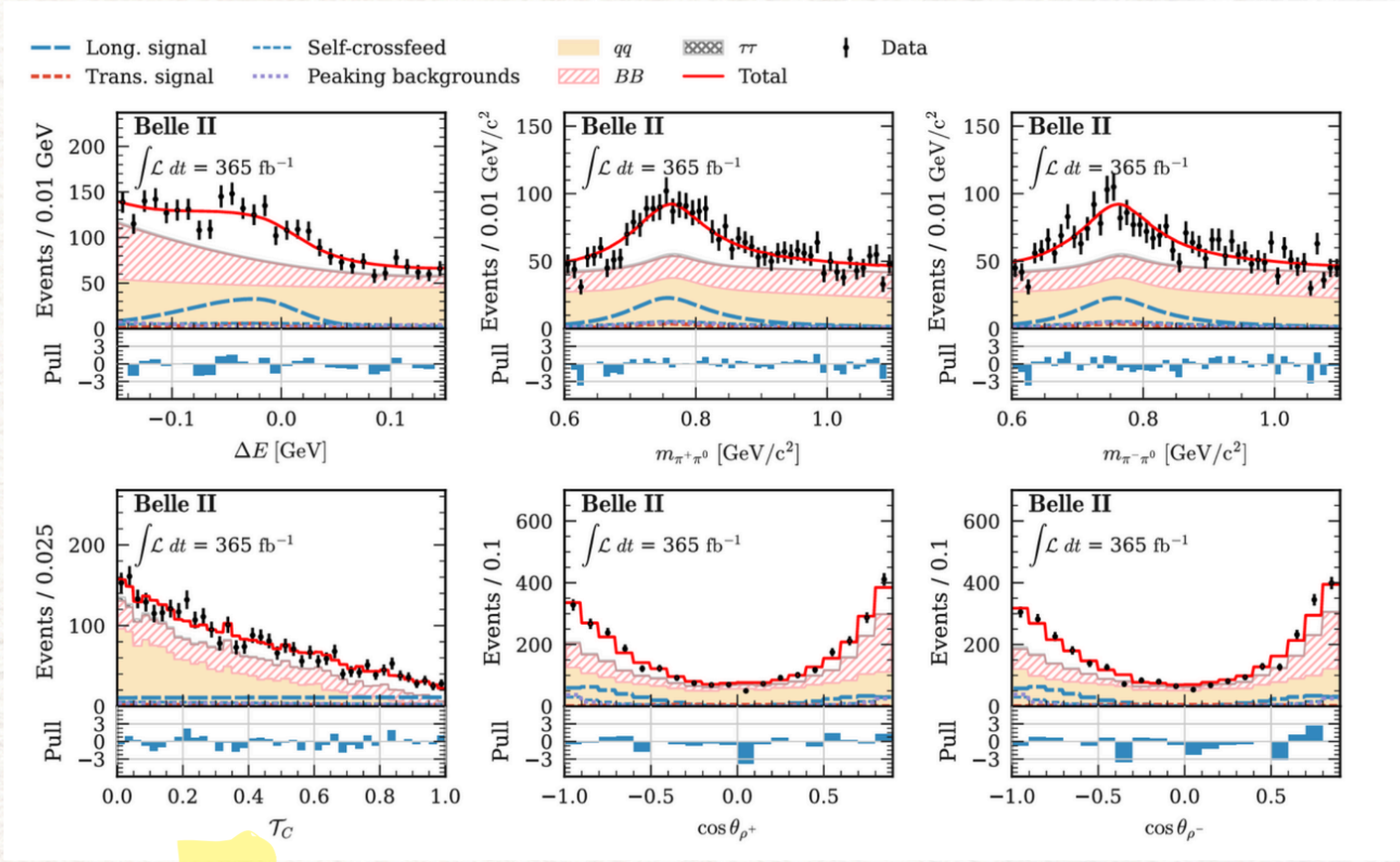
$$Br(B^0 \to \rho^+\rho^-) = (2.89 \pm^{0.23}_{0.22} \pm^{0.29}_{0.27}) \times 10^{-5}$$

$$f_L = 0.921 \pm^{0.024}_{0.025} \pm^{0.017}_{0.015}$$

$$LP_{sig} = 436.3 \pm^{34.2}_{33.5} \text{ candidates}$$

$$TP_{sig} = 65.4 \pm^{24.3}_{22.6} \text{ candidates}$$

PRD 111, 092001 (2025)



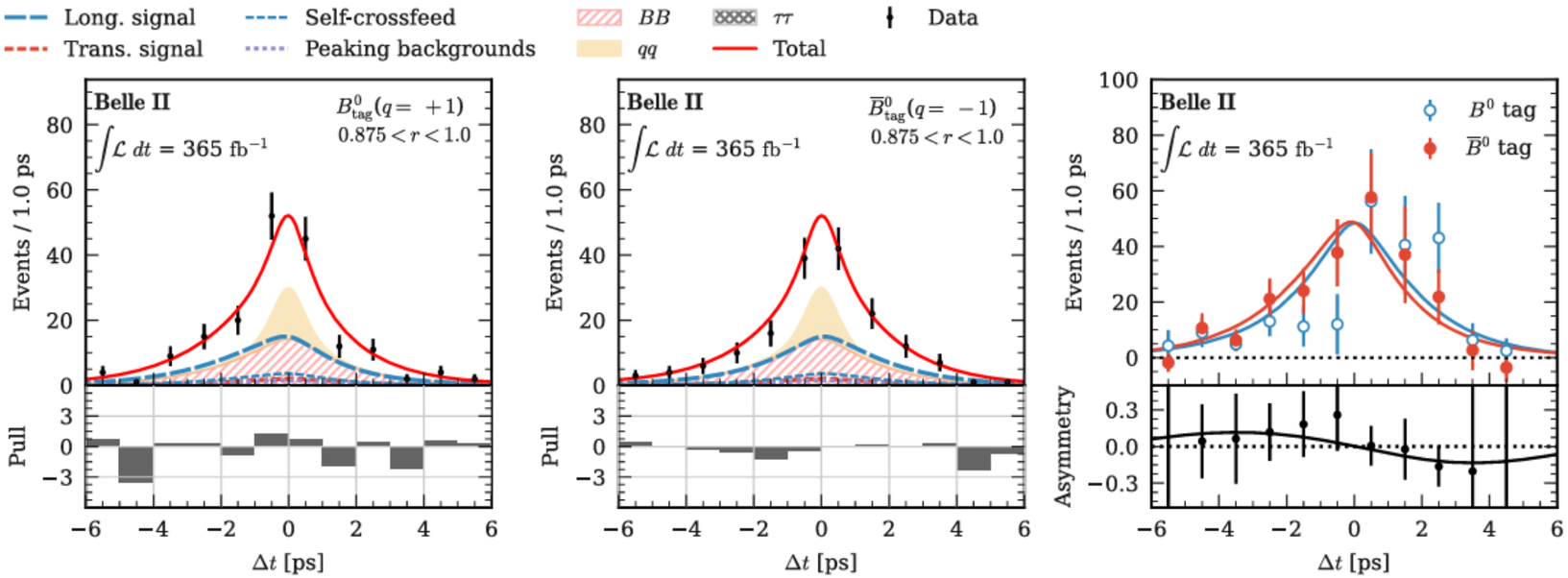
a transformed output of the TabNet classifier (deep learning architecture)

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

PRD 111, 092001 (2025)

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

Fit in Δt with $q = \pm 1$ 7 bins of tag-quality(r)



$$S = -0.26 \pm 0.19 \pm 0.08$$

$$C = -0.02 \pm 0.12 \pm^{0.06}_{0.05}$$

$$\mathcal{P}(\Delta t, \bar{t}, q) = \frac{1}{4\tau_{B^0}} \exp\left(\frac{-2\bar{t}}{\tau_{B^0}}\right) \{1 - q\Delta w_r + q a^{\rm tag}_{\varepsilon,r}(1 - 2w_r) + [q(1 - 2w_r) + a^{\rm tag}_{\varepsilon,r}(1 - q\Delta w_r)] \times [S \sin(\Delta m_d \Delta t) - C \cos(\Delta m_d \Delta t)]\},$$

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

Isospin analysis to extract ϕ_2 constraints.

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

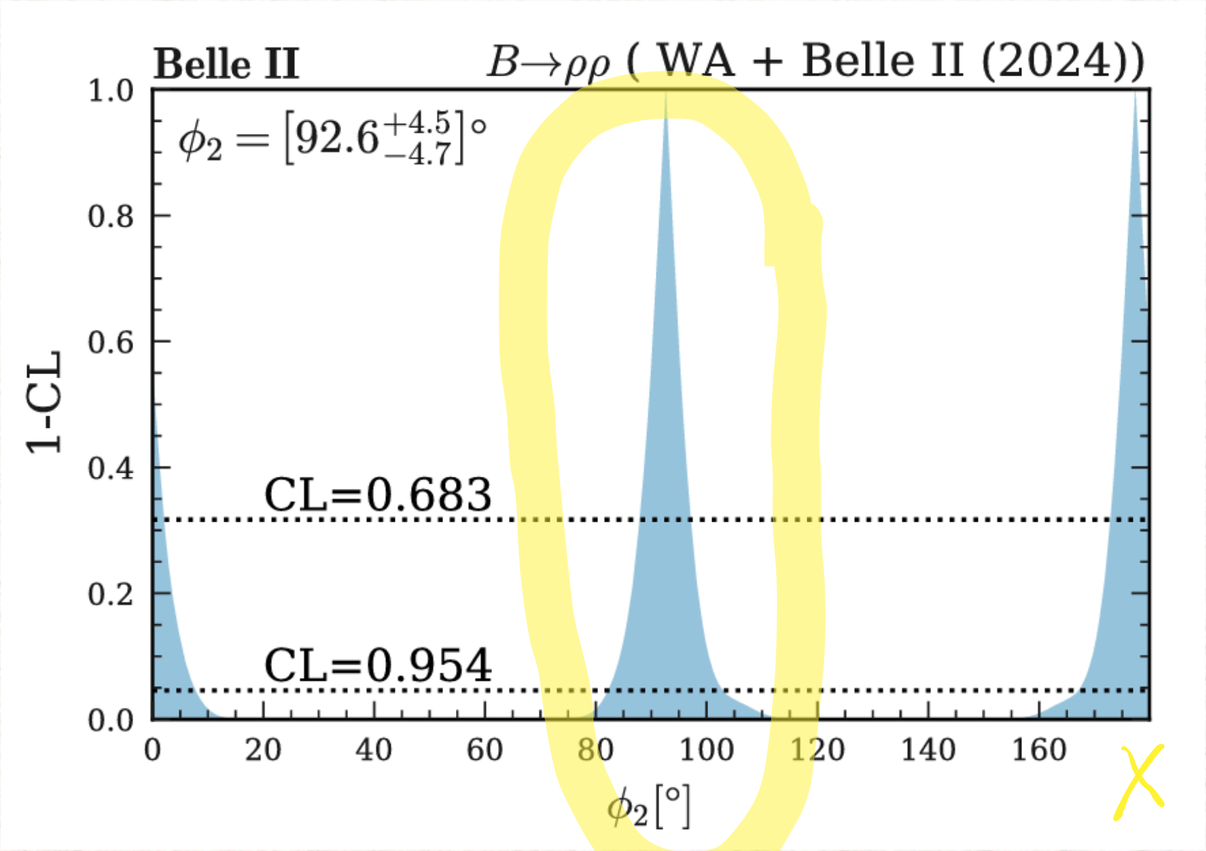
  $B^+ \to \rho^+\rho^0$ and $\mathrm{B}^0 \to \rho^+\rho^-$

- Solution compatible with SM:

$$\phi_2 = (92.6 \pm^{4.5}_{4.7})^\circ$$

$$\Delta\phi_2 = (2.4 \pm^{3.8}_{3.7})^\circ$$

PRD 111, 092001 (2025)

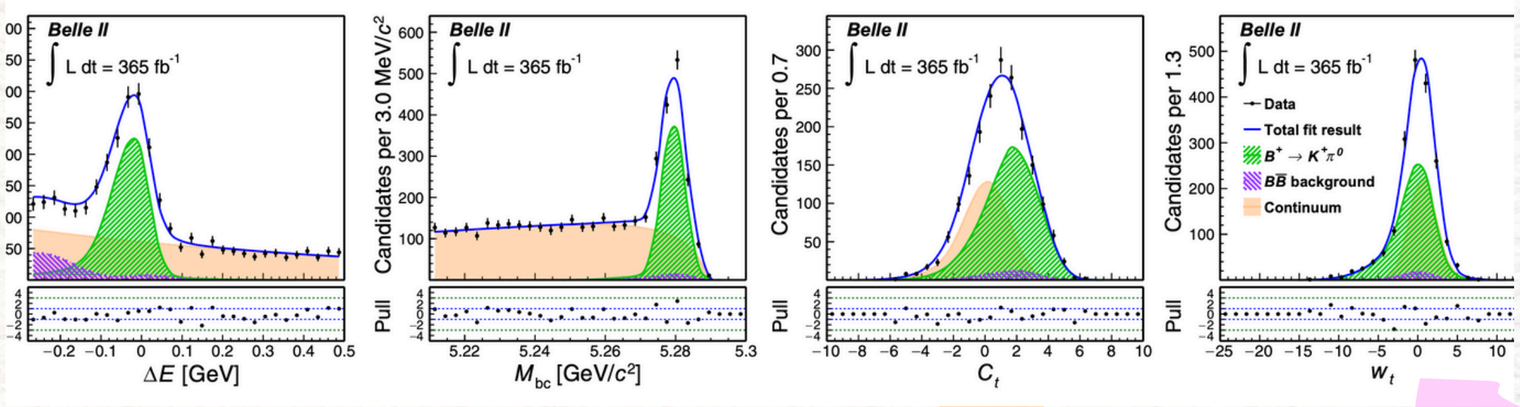


$B^0 \to \pi^0\pi^0$

PRD 111, L071102(2025)

probability for wrongly flavour tagging

boosted-decision-tree classifier

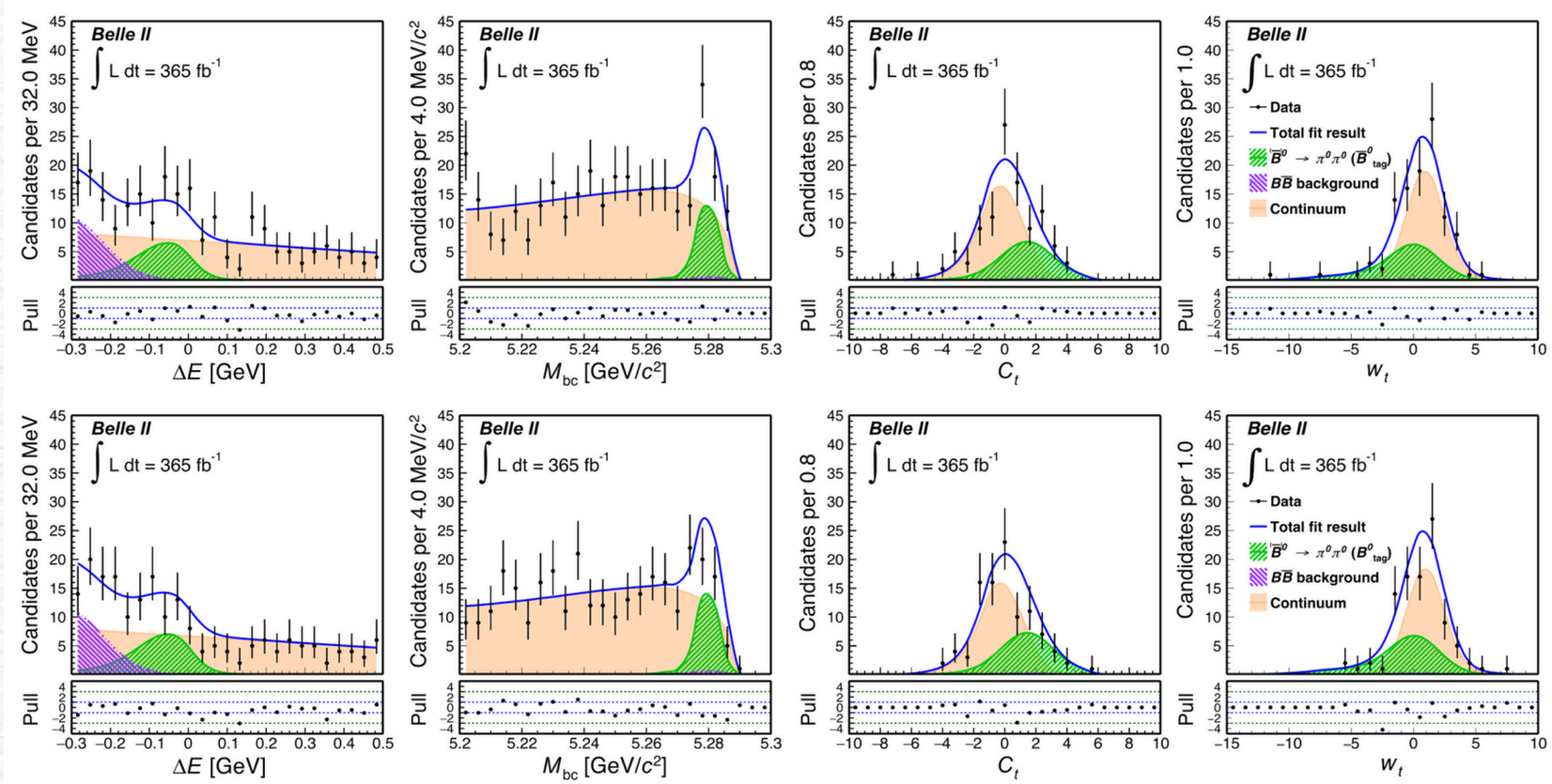


- Uncertainty on ϕ_2 from $B \to \pi\pi$ is dominated by $B \to \pi^0\pi^0$ BF and CP asymmetry.
- Reconstruction challenge: 2 $\pi^0 \to \gamma\gamma$ decays, 4-photon final state.
- **Currently only possible in Belle II.**
- Measurement of the BF and time-integrated CP-asymmetry, A_{CP}
- Validated through $B^+ \to K^+\pi^0$ and $\mathrm{B}^0 \to (\bar{\mathrm{D}}^0 \to \mathrm{K}^+\pi^-\pi^0)\pi^0$

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

PRD 111, L071102(2025)

- Selection to suppress high combinatorial background present.
- Split in q=±1, simultaneous fit in four observables, time integrated



B^0

$\bar{B}^0$

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

$$A_{CP}(B^0 \to \pi^0\pi^0) = (0.03 \pm 0.30 \pm 0.04)$$

125 ± 20 candidates

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

- Reduced fractional statistic and systematic uncertainties for BF and CP asymmetry with respect to the previous measurement.
- Isospin analysis with new results:
  - Fractional precision of ϕ_2 increased up to **30%** with the addition of this result.

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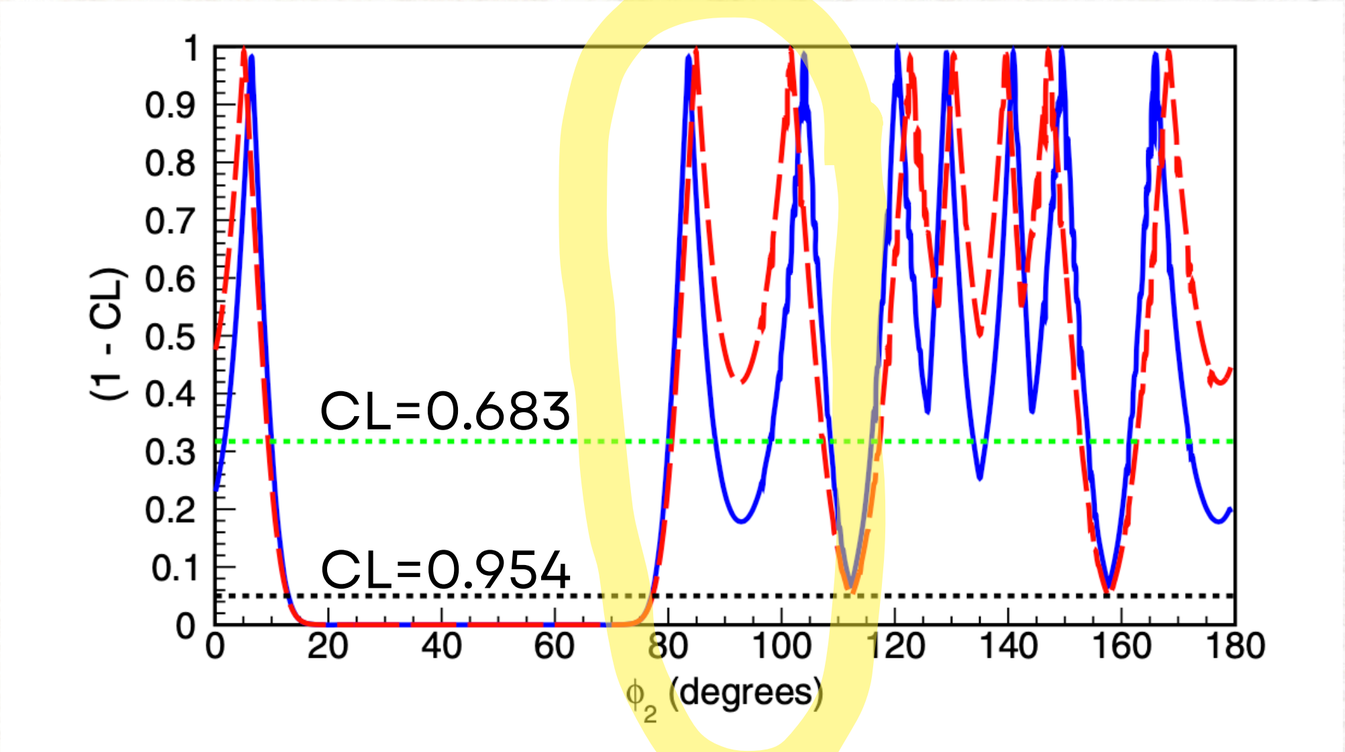

$B \to \rho\rho$

- Blue = new
- Red = old

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

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- Color suppressed

  $b \to c\bar{c}d$ transition(ϕ_1)

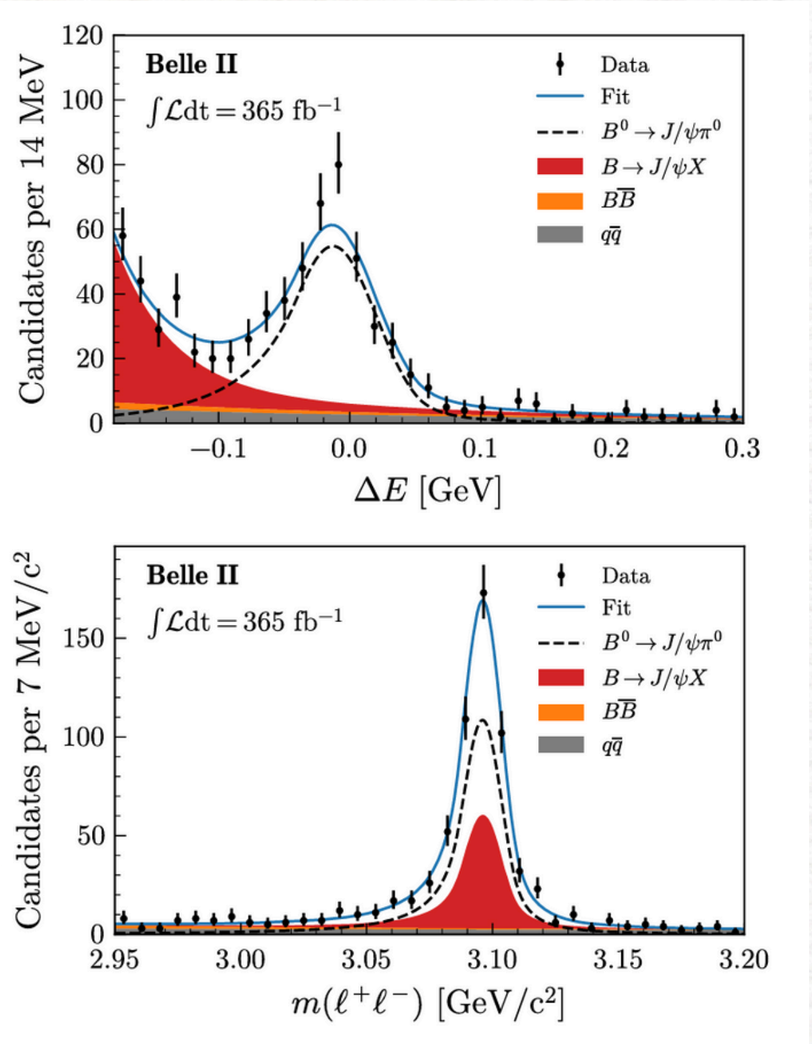
- BF and CP asymmetries can constrain penguin contributions in $B^0 \to J/\psi K^0$

- Uses $J/\psi \to \ell^+\ell^-(\ell = e, \mu)$

- Two step measurement:
- Yields from fit to ΔE and $\mathrm{m}(\ell^+\ell^-)$

$$392 \pm 24 \text{ candidates}$$

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



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

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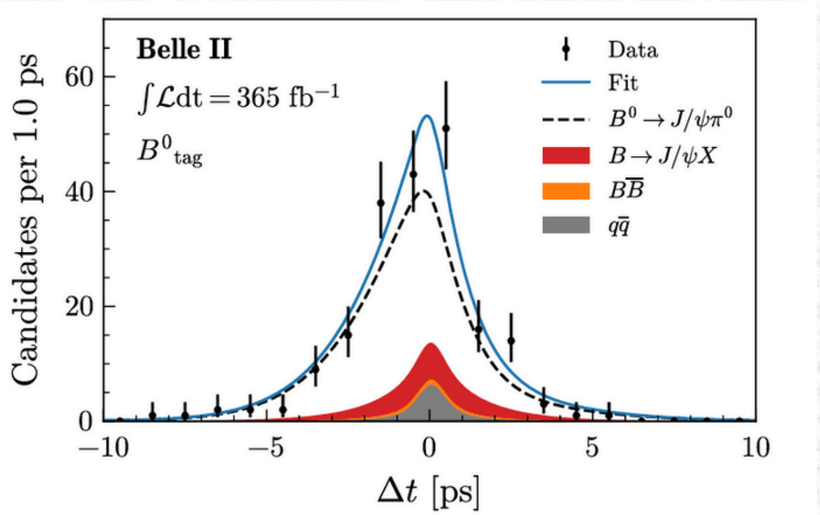
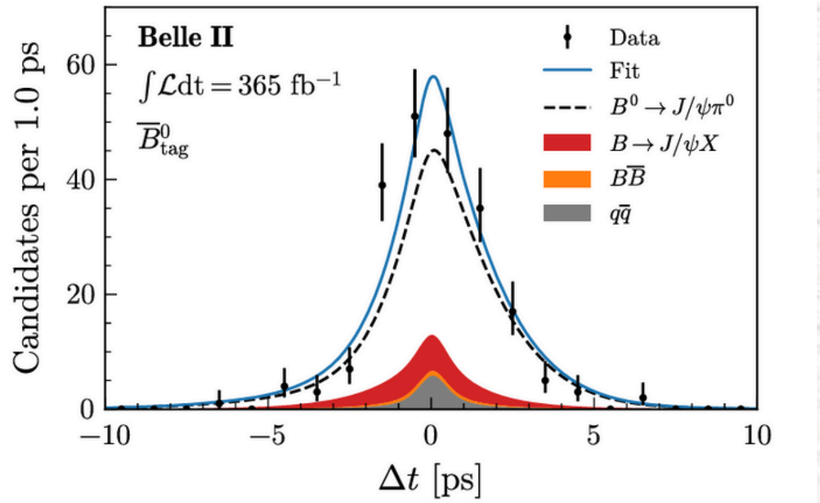
- 2- Fit Δt in signal enhanced region.
  With q=±1 and 7 bins of tag-quality (r)

$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{1 + q[S_{CP}\sin(\Delta m_d \Delta t) - C_{CP}\cos(\Delta m_d \Delta t)]\},$$





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

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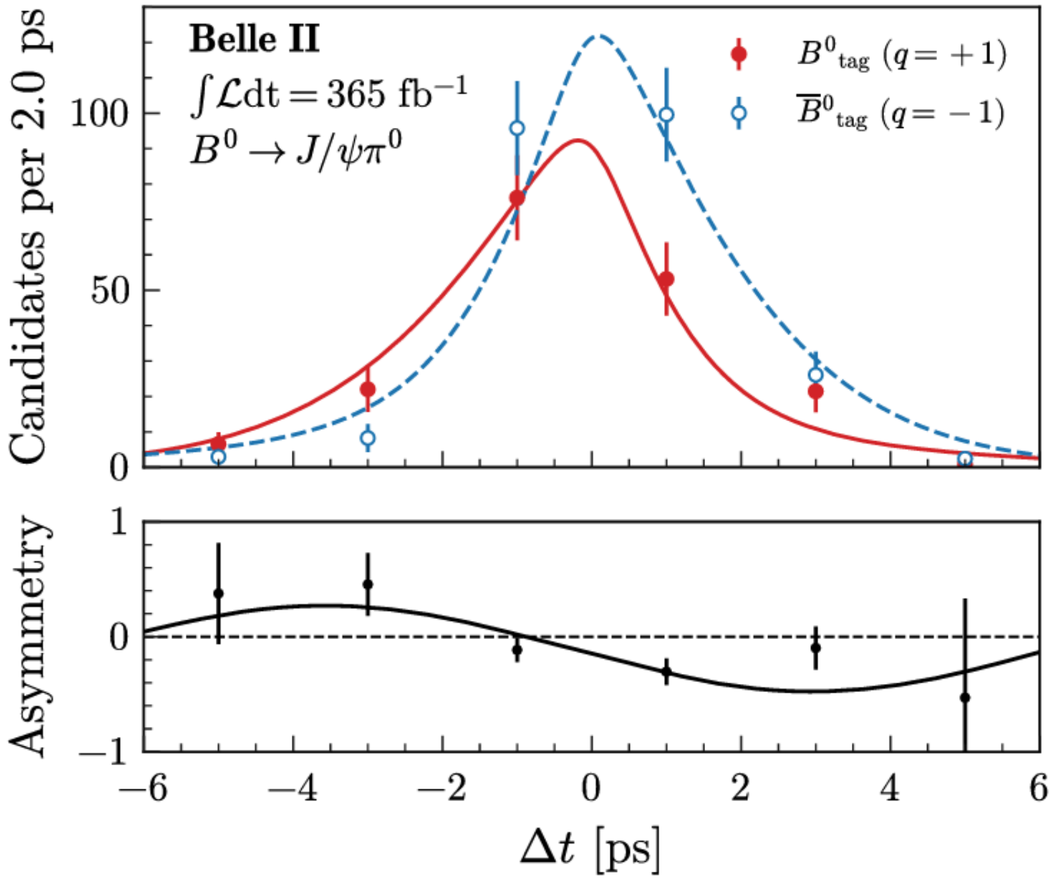
- Most precise, and first observation of mixing-induced CP asymmetry in this mode.

$$C_{CP} = 0.13 \pm 0.12 \pm 0.03$$

$$S_{CP} = -0.88 \pm 0.17 \pm 0.03$$



Distributions and fit projections of Δt for background-subtracted

Summary

$\phi_2(\alpha) : B^0 \to \rho^+\rho^-$,

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

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

New measurements in2025 by the Belle II collaboration in CP violation.

$$Br(B^0 \to \rho^+\rho^-) = (2.89 \pm^{0.23}_{0.22} \pm^{0.29}_{0.27}) \times 10^{-5}$$

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

$$A_{CP}(B^0 \to \pi^0\pi^0) = (0.03 \pm 0.30 \pm 0.04)$$

$$A_{CP} = -C_{CP}$$

$$392 \pm 24 \text{ candidates}$$

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

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References

- CKM Matrix
https://pdg.lbl.gov/2021/reviews/rpp2020-rev-ckm-matrix.pdf

- New graph-neural-network flavor tagger for Belle II
PRD 110, 012001 (2024)

- The CP violation parameter C is also defined as A = −C.