Measurements of CP violation in B decays at Belle II

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Belle II @ SuperKEKB

Asymmetric e^+-e^- collider ($\sqrt{s}$ = 10.58 GeV)

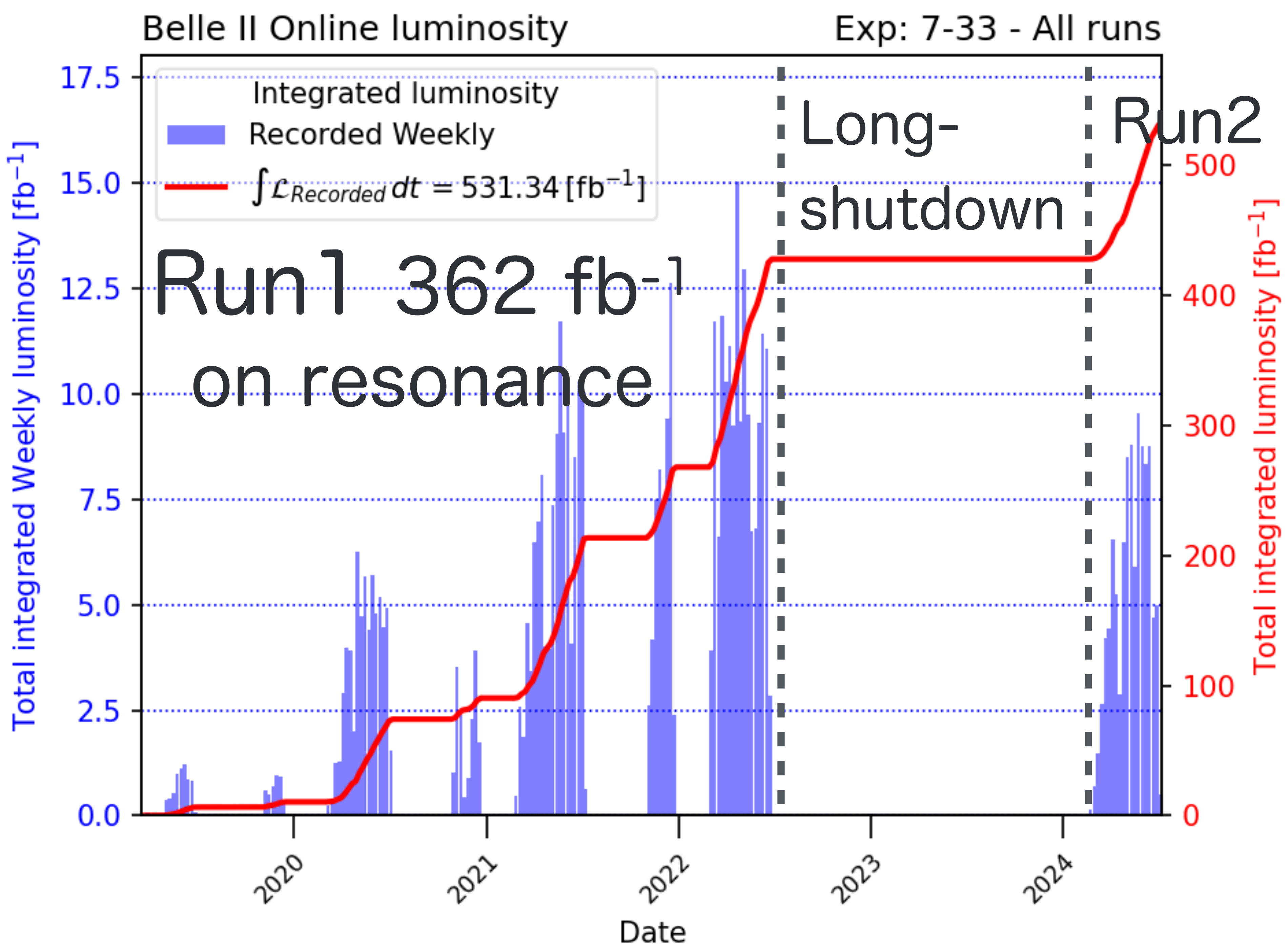
- $e^+e^- \to \Upsilon(4S) \to B\bar{B}$

Four-momenta of B are well known.

Determination of the decay position allows time-dependent analysis.

Luminosity	Design	Accomplished
Integrated	50 ab^{-1} (Belle x50)	531 fb^{-1}
Peak	6.5×10^{35} /cm²/s	4.7×10^{34} /cm²/s

World Record!!



K_L and μ Detection

K_L^0 p resolution: 15 MeV

μ identification eff.: ~90%

Vertex Detector

vertex resolution: 15 μm

Central Drift Chamber

spatial resolution: 100 μm

dE/dx resolution: 5%

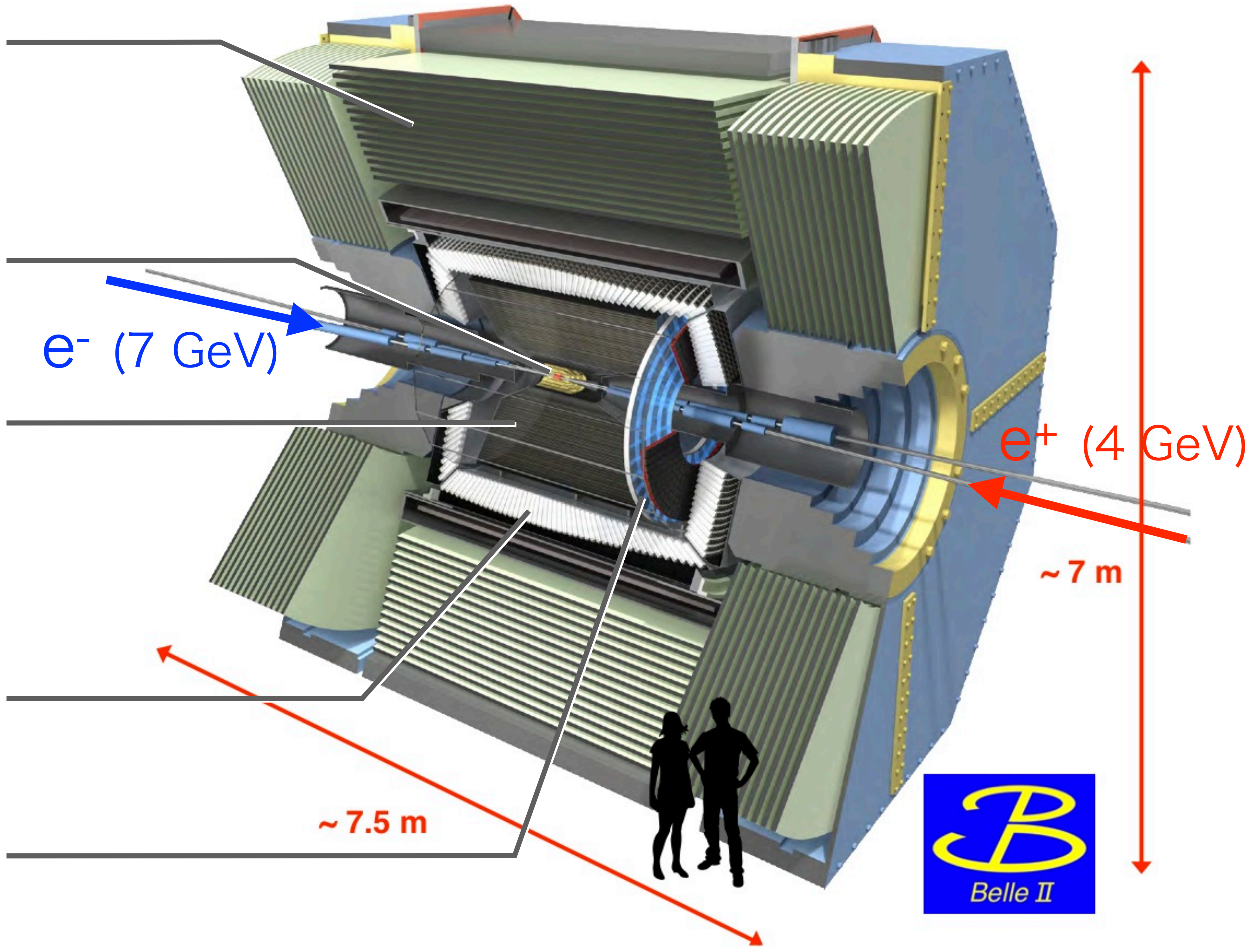
P_T resolution: 0.4%

EM Calorimeter, CsI(Tl)

energy resolution: 1.6%-4%

Particle Identification

K eff.: 90%, fake π rate: 5%



Determination of CKM parameters at Belle II

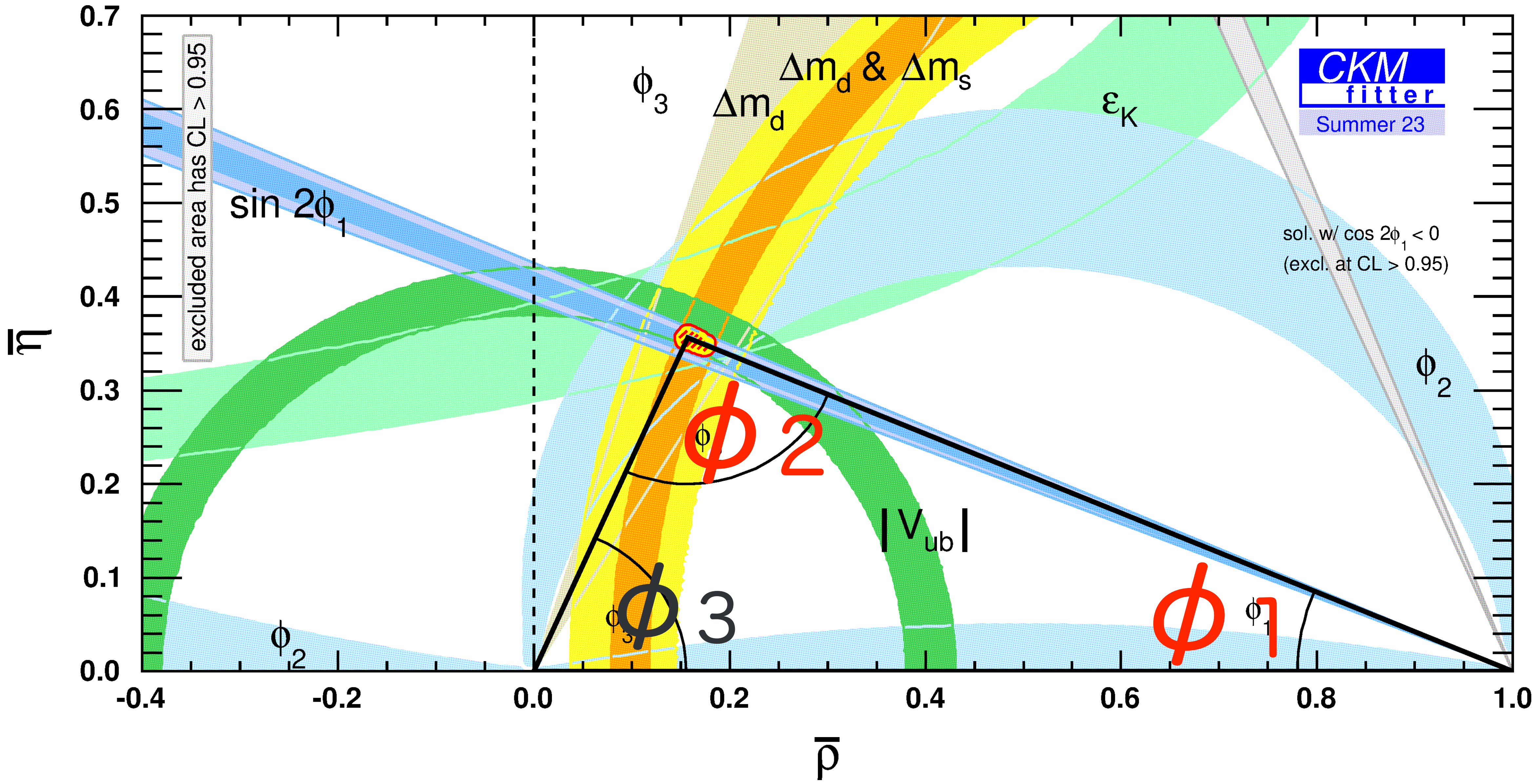
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) = (22.2 \pm 0.7)^\circ$$

$$\phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) = \left(85.2^{+4.8}_{-4.3}\right)^\circ$$

$$\phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) = \left(65.9^{+3.3}_{-3.5}\right)^\circ$$

PDG2024



Precise test of SM over constraint the unitarity triangle (UT).

- Loop amplitudes provide sensitive probe to new physics (NP).
  e.g.) B^0-$\bar{B}^0$ mixing ← Time-dependent CP asymmetry measurement
- goal: accurate measurement of all UT angles and sides

Belle II at e^+-e^- collider:

- clean environment, quantum entangled $B\bar{B}$ pairs,
  high tagging efficiency, neutral particles in the final states

Today's contents

Decay mode		Target
$B^0 \to J/\psi\pi^0$	$(b \to c\bar{c}d)$	ϕ_1
$B^0 \to \eta' K_S$	$(b \to s\bar{s}s)$	$\phi_1^{\rm eff}$, NP
$B^0 \to K_S\pi^0\gamma$	$(b \to s\gamma)$	NP
$B^0 \to \pi^0\pi^0$	$(b \to u\bar{u}d)$	ϕ_2

ϕ_3: Talk by VISMAYA V S

Time-Dependent CPV analysis

PRD.110.012001

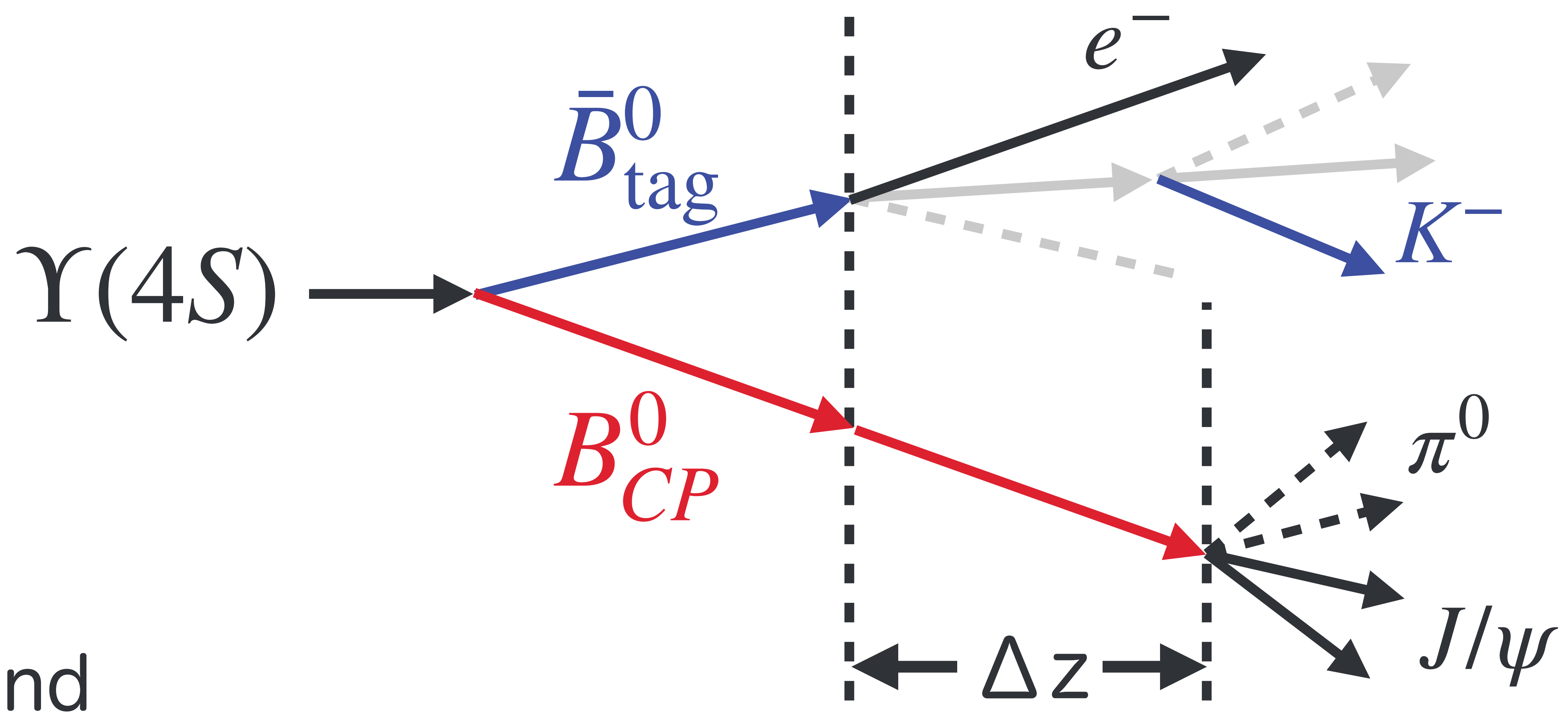
arXiv:2402.17260

$$A_{CP}^{B\to f}(\Delta t) \equiv \frac{\Gamma(B^0(\Delta t)\to f) - \Gamma(\bar{B}^0(\Delta t)\to f)}{\Gamma(B^0(\Delta t)\to f) + \Gamma(\bar{B}^0(\Delta t)\to f)}$$

$$= S \cdot \sin(\Delta m_d \Delta t) - C \cdot \cos(\Delta m_d \Delta t)$$

mixing-induced CPV: $S_{CP} = |\sin(2\phi_i^{\mathrm{eff}})|$

Direct CPV: $A_{CP} = -C_{CP}$



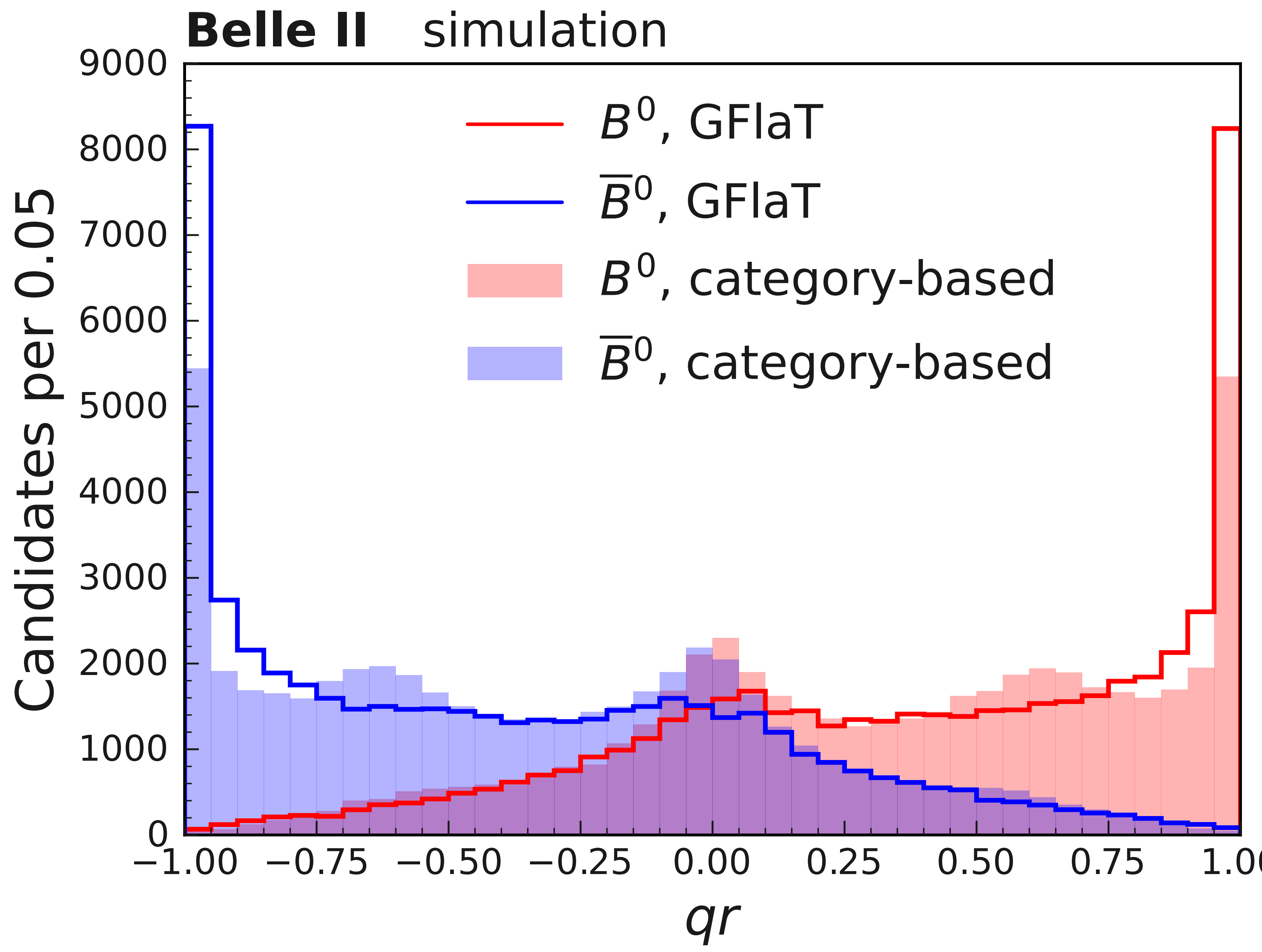
~130 μm at Belle II

- Signal extraction using beam-constraint variables, and BDT to discriminate $q\bar{q}$ backgrounds

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

$$M_{\mathrm{bc}} = \sqrt{s/4 - p_B^{*2}}$$

- Excellent vertex resolution: σ_z ~ 26/50 μm (CP/tag side)
- Graph-neural-network flavor tagging (GFlaT)
  - Updated from a category-based algorithm
  - Looks at additional correlations of particles information (charge of lepton/hadron, high-p tracks)
  - Perfomance: $\varepsilon_{\mathrm{tag}}^{\mathrm{eff}}$ (CB) = (31.7 ± 0.5 ± 0.4)%
    $\varepsilon_{\mathrm{tag}}^{\mathrm{eff}}$ (GFlaT) = (37.4 ± 0.4 ± 0.3)%



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

New for ICHEP2024

Paper in preparation

- Mediated by b→$c\bar{c}d$ transition, probe for loop contributions to b→$c\bar{c}s$ for determination of ϕ_1
- Apply GFlaT and 3 BDTs for fake photon, beam background, and $q\bar{q}$ suppression
- Fit ΔE and $m(\ell\ell)$ for background subtraction (separately for ee and μμ);
  Fit Δt for CPV-parameter extraction

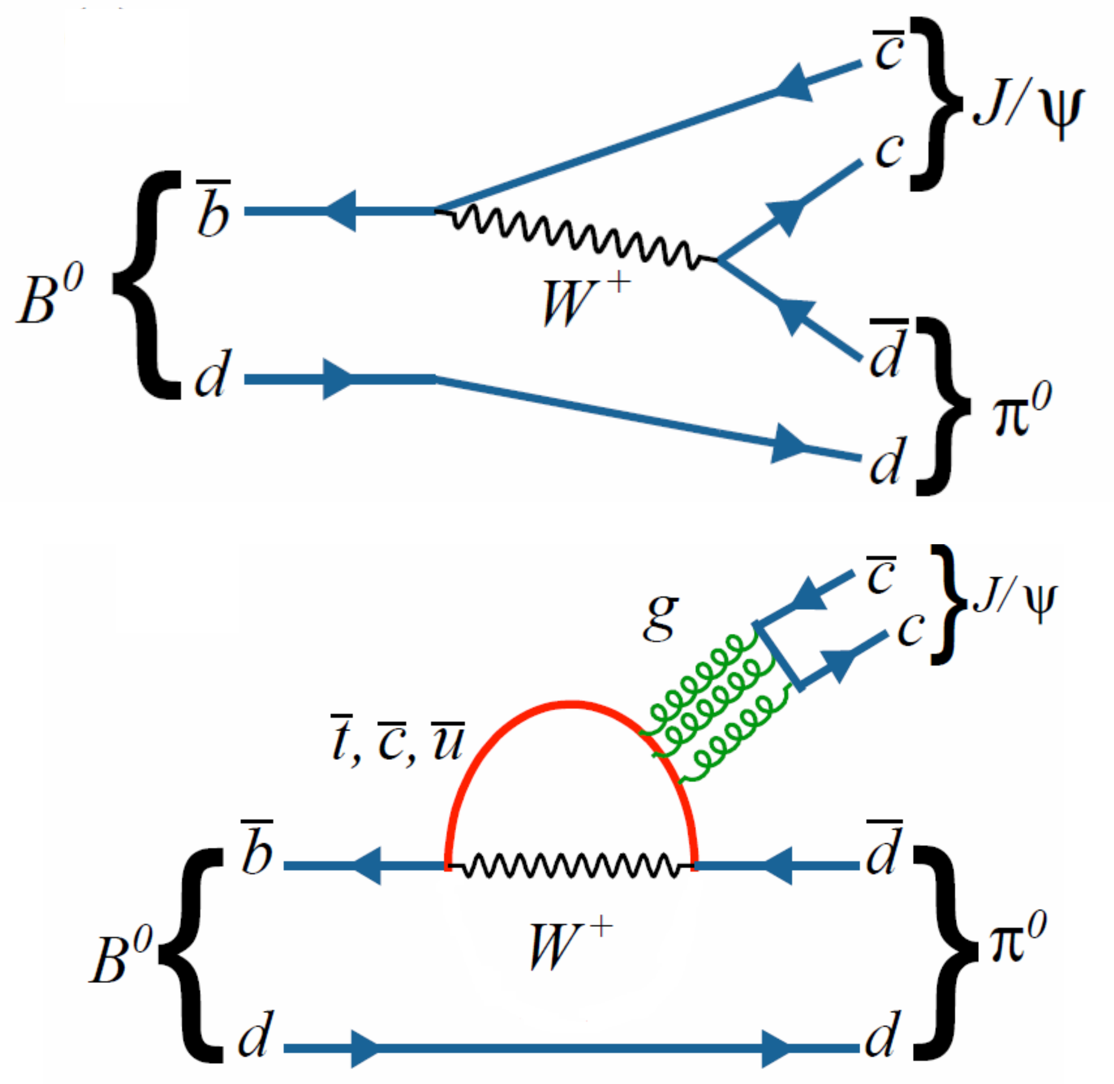
BF = $(2.00 \pm 0.12 \pm 0.10) \times 10^{-5}$

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

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

- First 5σ observation of mixing-induced CP in this mode

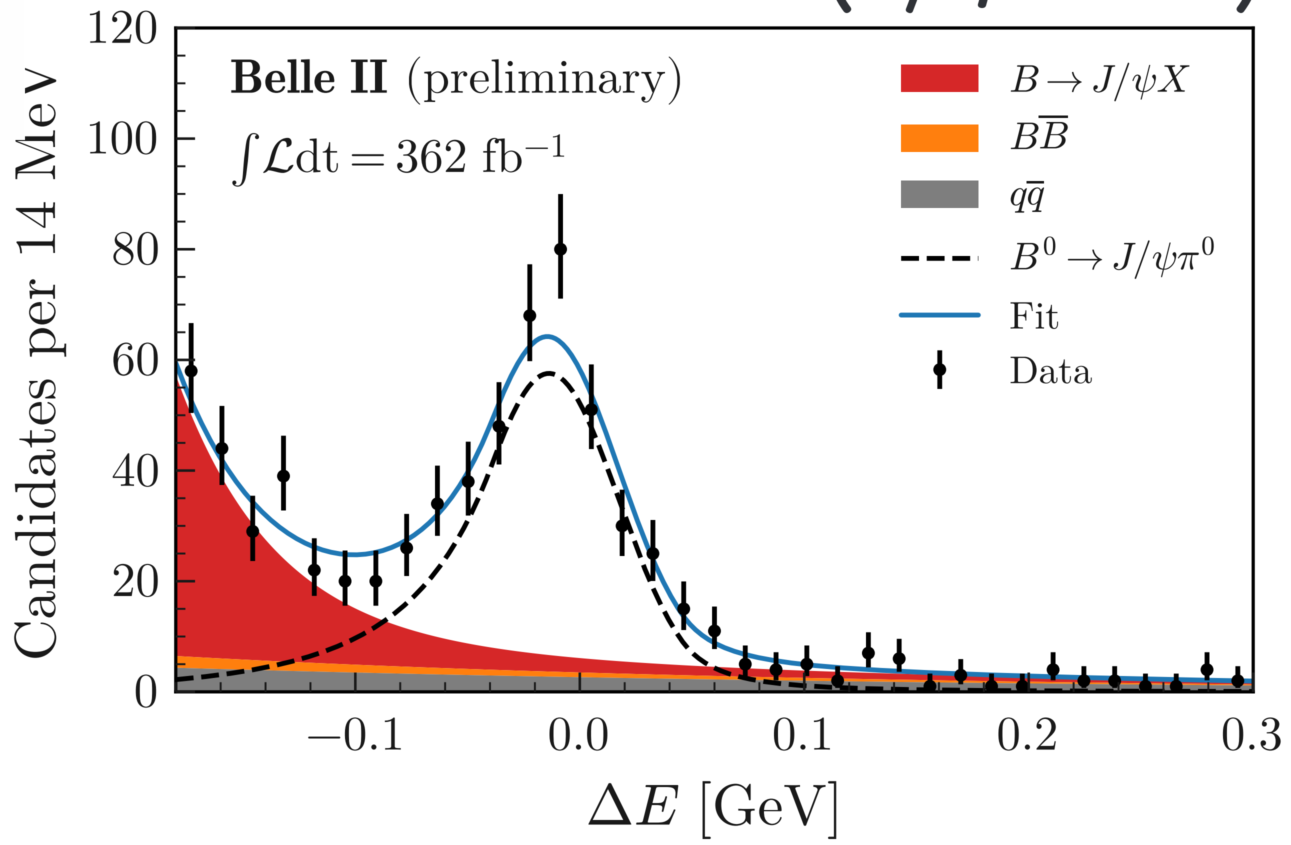
Color/CKM suppressed

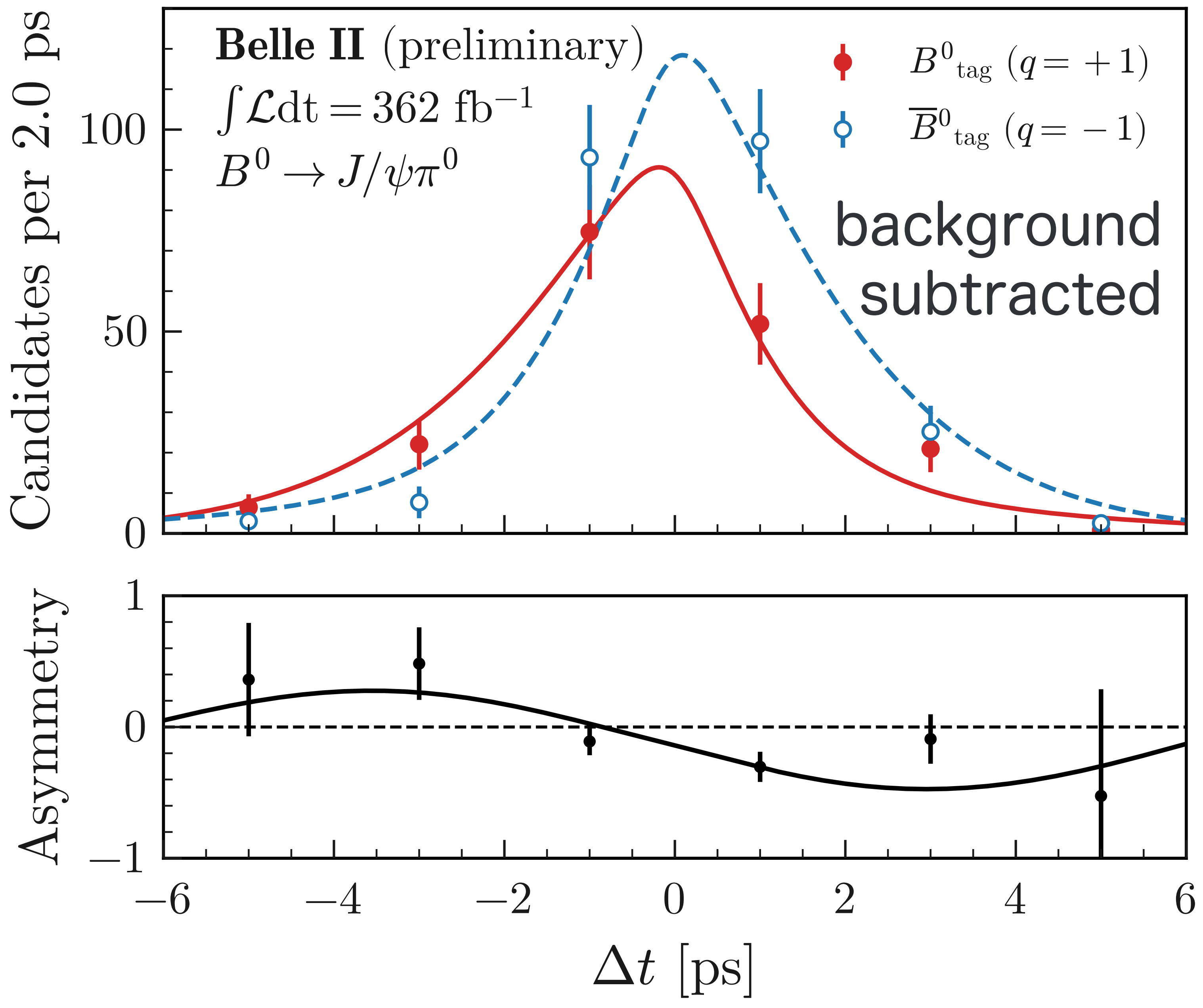


PRD.98.112008

203±17 (J/ψ→μμ)

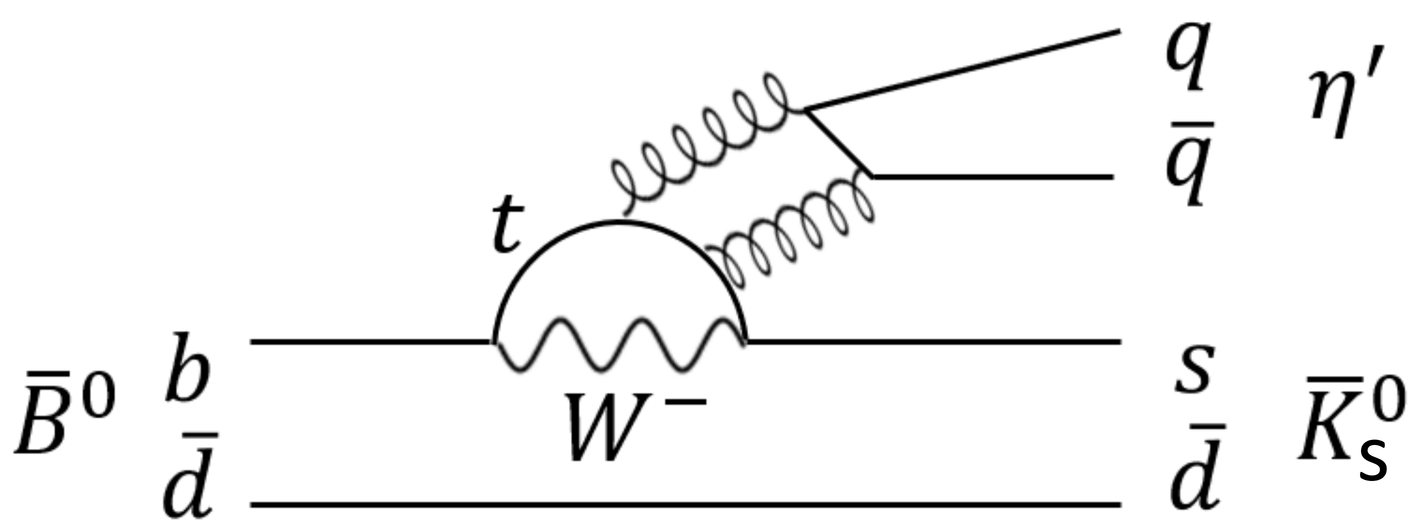
186±16 (J/ψ→ee)





$B^0 \to \eta' K_S$

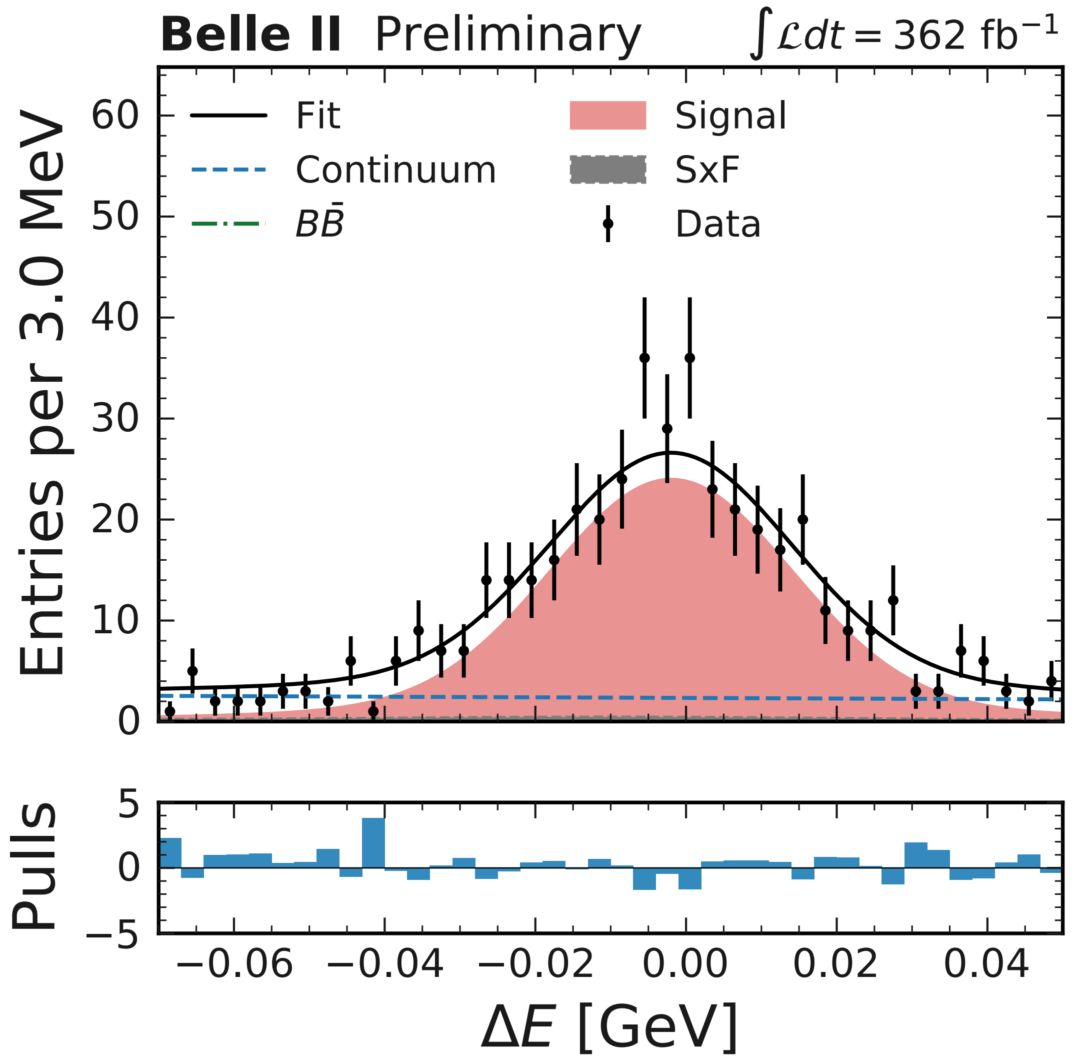
arXiv:2402.03713

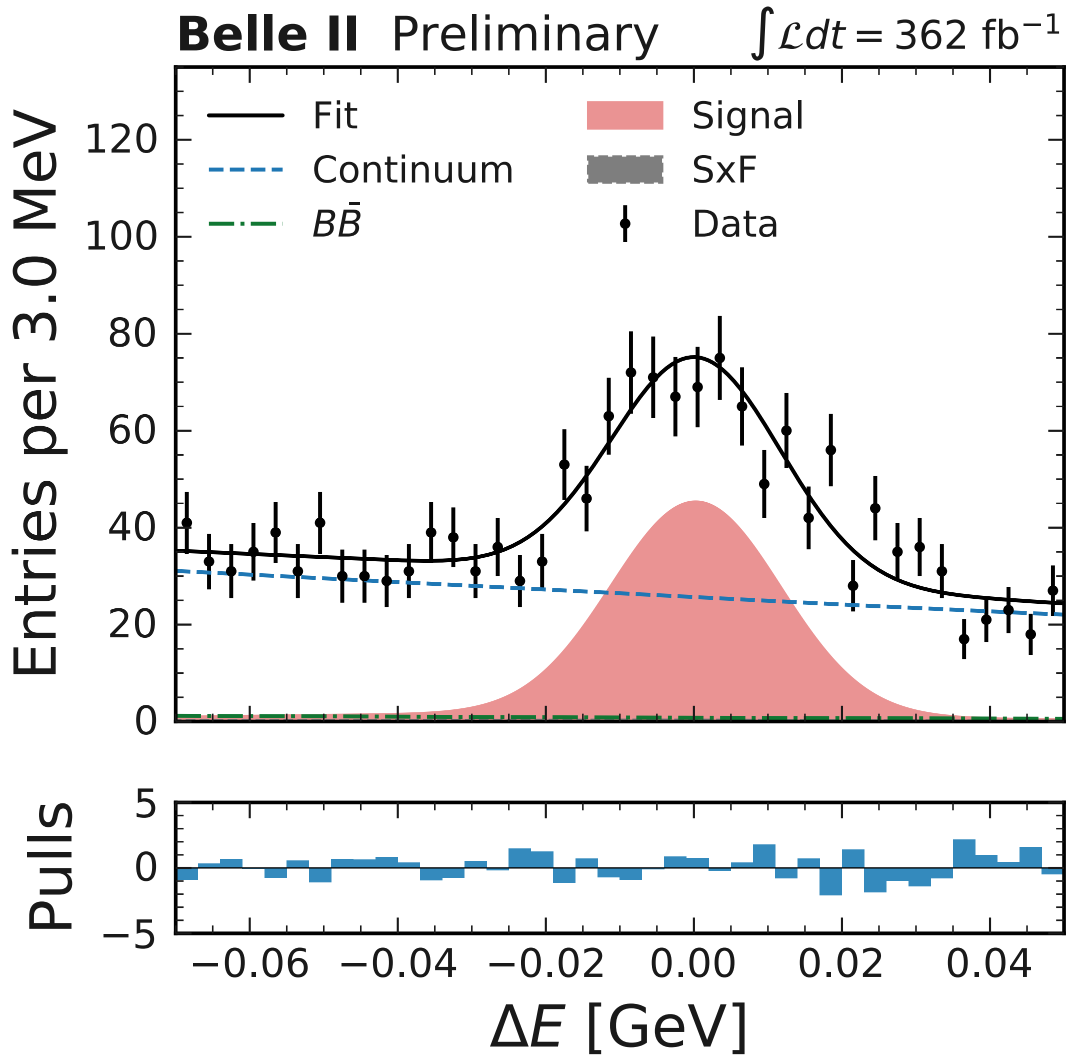


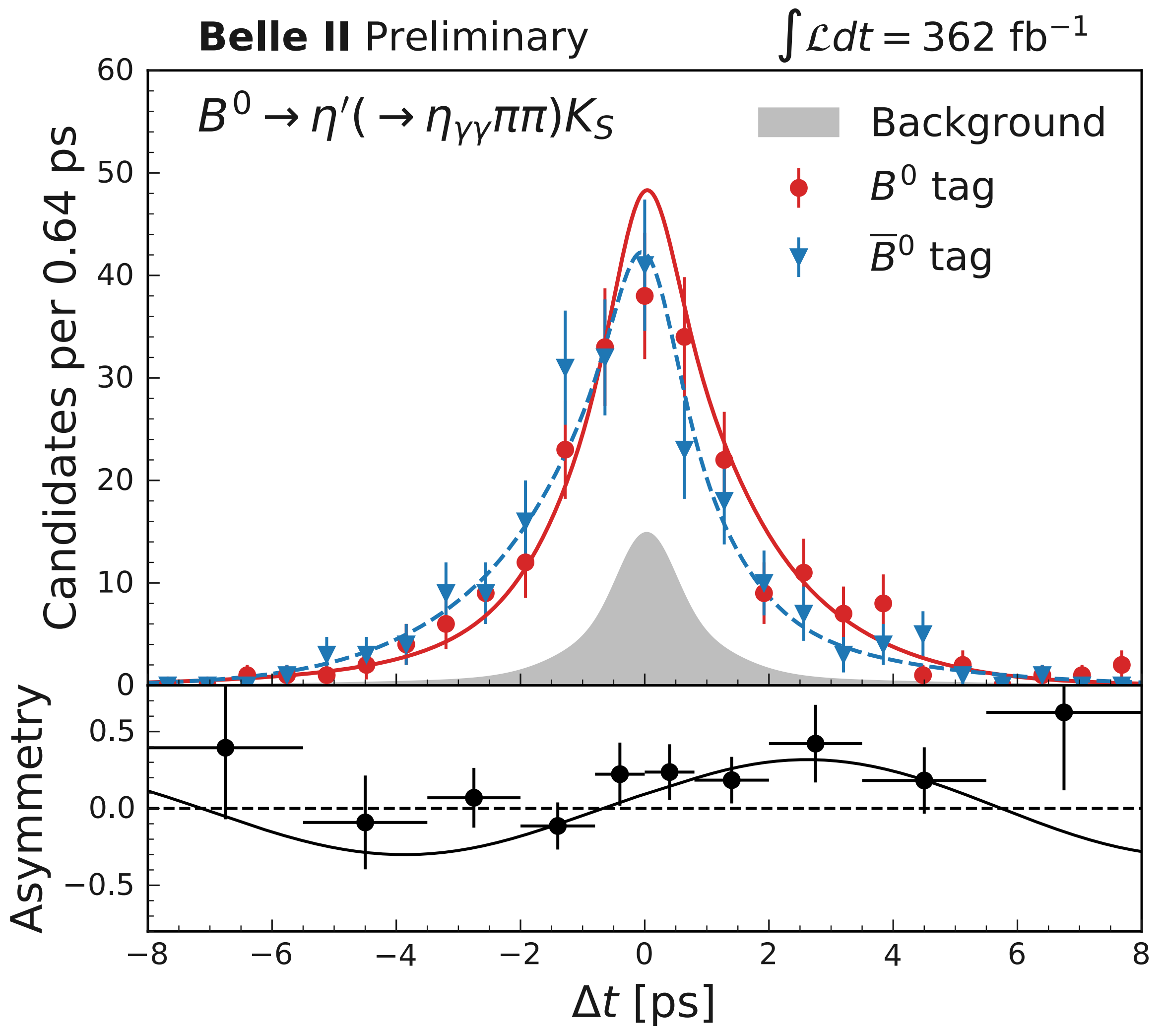
- Gluonic penguin with $b \to s q\bar{q}$
- Sensitive to the new physics in the decay
- Golden mode: Relatively large BF and limited contribution from tree amplitudes.
- In SM, $\Delta S = S(\eta' K_S) - \sin(2\phi_1) \sim 0.01 \pm 0.01$
- Reconstruct $\eta' \to \eta_{(\gamma\gamma)}\pi\pi$ and $\eta' \to \rho_{(\pi\pi)}\gamma$ (Belle II specialities)
- Fit to ΔE, M_{bc}, and $q\bar{q}$ suppression classifier
- Results: $\boxed{\begin{array}{l} S = 0.67 \pm 0.10 \pm 0.04 \\ C = -0.19 \pm 0.08 \pm 0.03 \end{array}}$

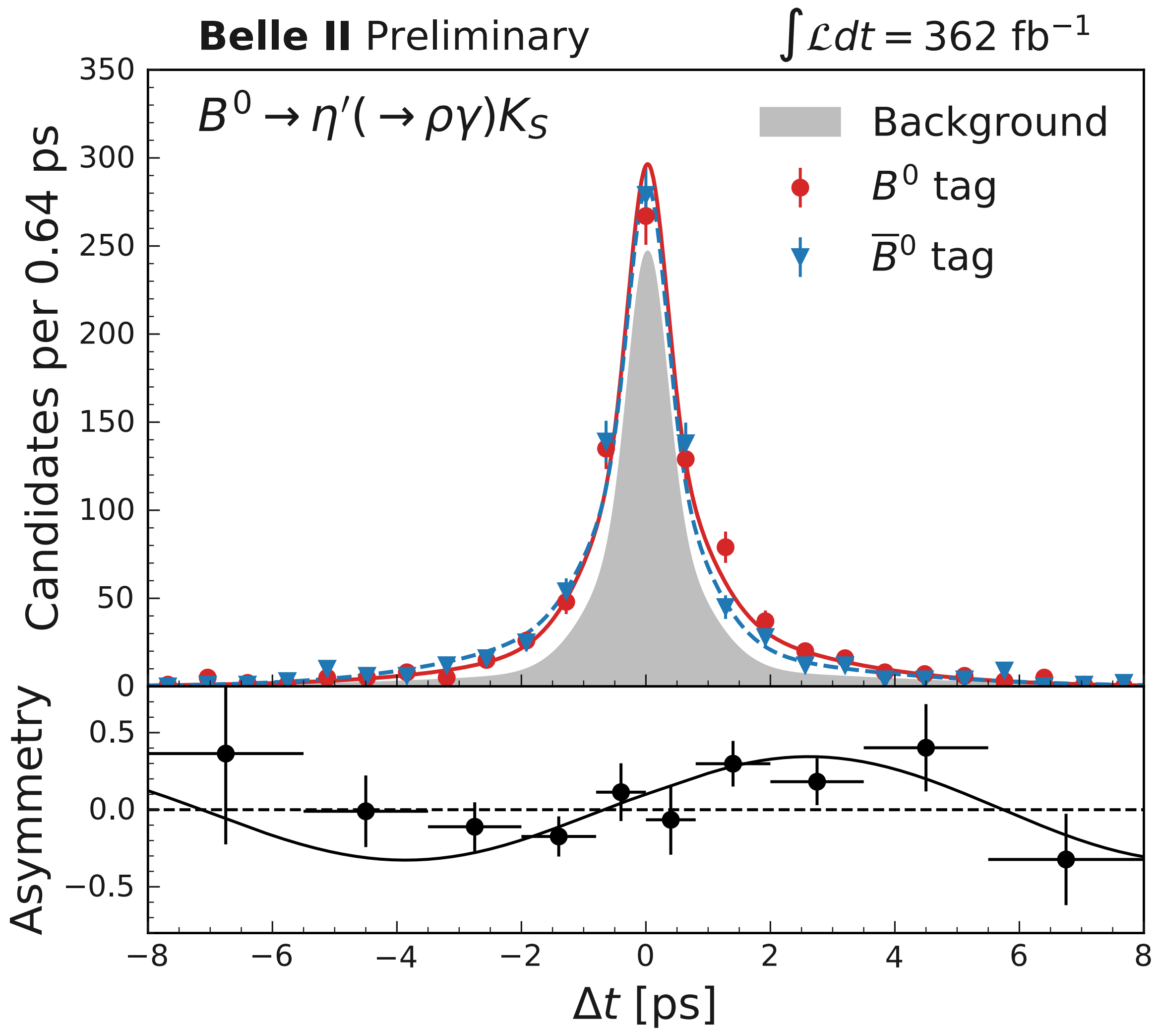
HFLAV: S = 0.63 ± 0.06, C = -0.05 ± 0.04

- Agreement with the world average
- Comparable precision with Belle/BaBar









$B^0 \to K_S \pi^0 \gamma$

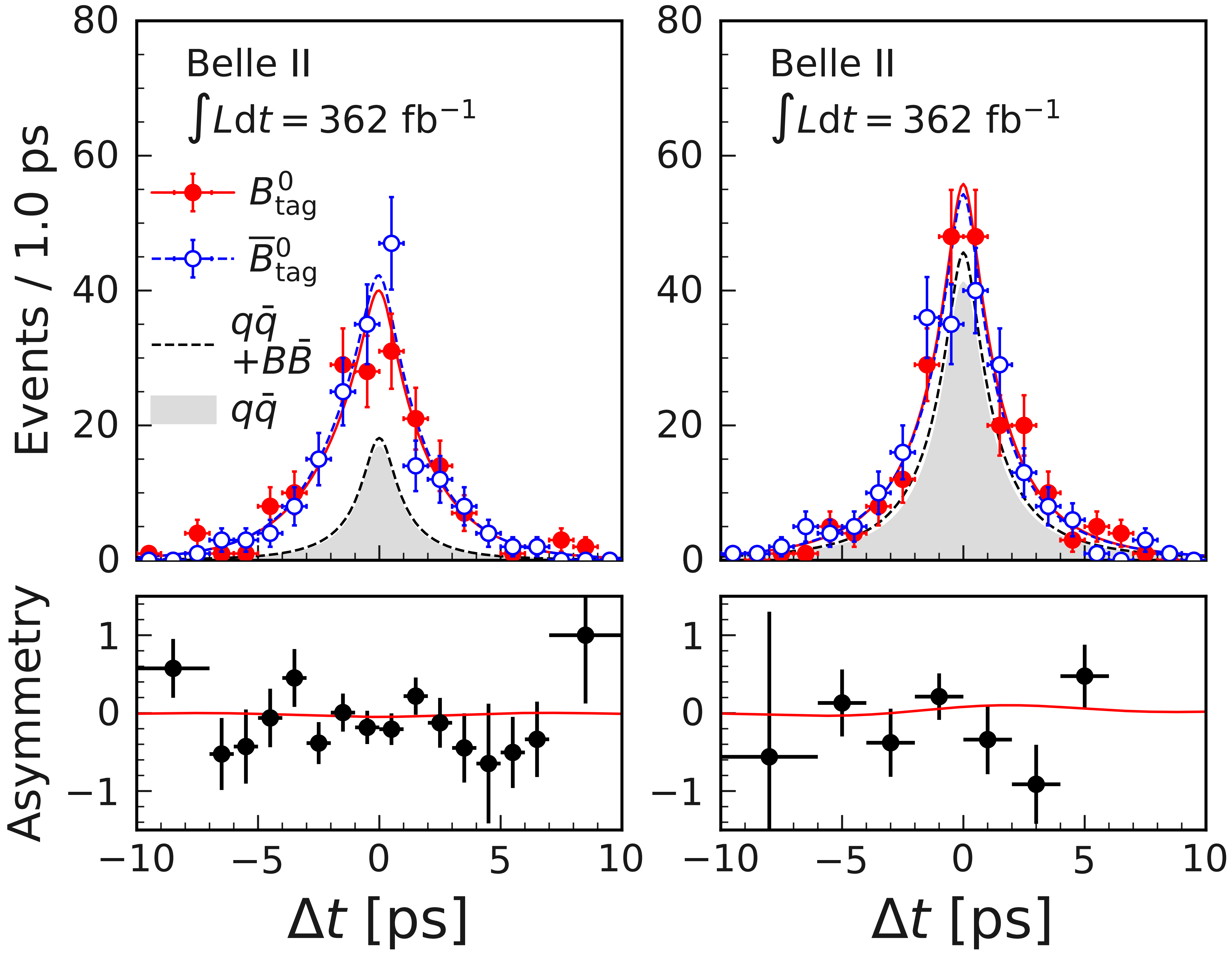
arXiv:2407.09139

- Search for interference with b→sγ_R transition, expected to be small/none in SM because it requires a right-handed interaction.
  - b→sγ_R is helicity suppressed (m_s/m_b) w.r.t. b→sγ_L
- Vertex from $K_S \to \pi\pi$ and IP constraint
- Fit to M_{bc} and ΔE for signal extraction
- Measured separately for

resonant, $K^{*0}(K_S\pi^0)\gamma$	non-resonant, $K_S\pi^0\gamma$
$M_{K_S^0\pi^0} \in (0.8,\ 1.0)$ GeV/c^2	$\in (0.6,\ 0.8) \cup (1.0,\ 1.8)$ GeV/c^2
$S = 0.00^{+0.27}_{-0.26} \pm 0.03$	$S = 0.04^{+0.45}_{-0.44} \pm 0.10$
$C = 0.10 \pm 0.13 \pm 0.04$	$C = -0.06 \pm 0.25 \pm 0.09$

  - Agreement with the world average and SM
  - Most precise measurement with better K_S ID

resonant non-resonant



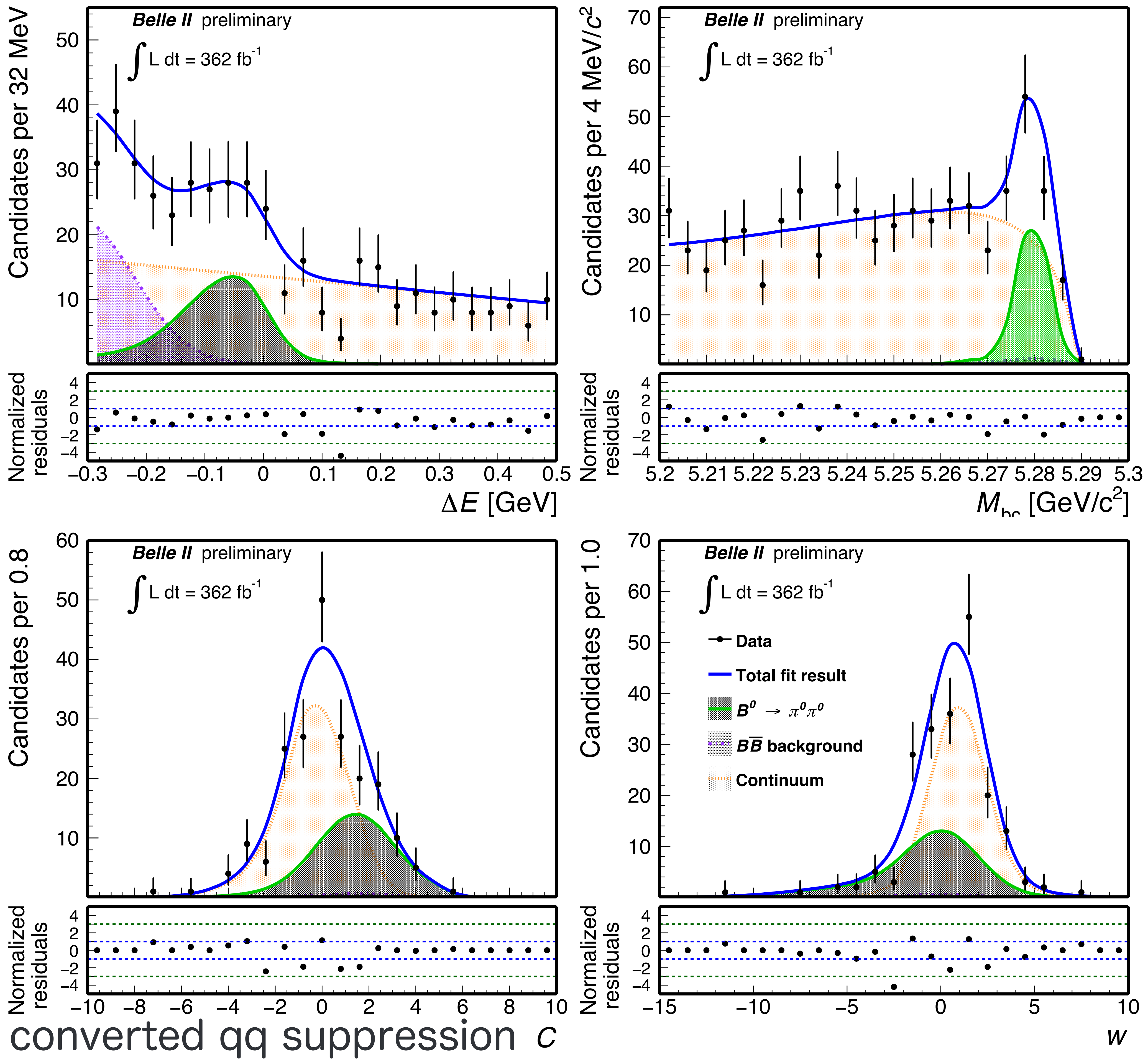
Towards ϕ_2/α: $B^0 \to \pi^0\pi^0$

Paper in preparation

Prev. PRD.107.112009 (2023)

- Tree-level $b \to u\bar{u}d$ processes allow extraction of ϕ_2
  - Interference with penguin amplitudes
  - Statistical limitation due to color suppression in tree diagram
- Experimentally challenging: 4 photons with no tracks
- Update on BF and A_{CP} using full Run-1 statistics with
  - new GNN-based flavor tagger
  - BDT dedicated for photon selection and $q\bar{q}$ suppression
  - reduction of systematic uncertainties
- Signal extraction by simultaneous fit
  - ΔE, M_{bc}, BDT_{qq} output (C), transformed wrong tag probability
- Results: $BF = (1.26 \pm 0.20 \pm 0.11) \times 10^{-6}$, $A_{CP} = 0.06 \pm 0.30 \pm 0.06$
  - BF: world best, A_{CP}: comparable with the world average

126±20 events



converted qq suppression classifier (BDT_{qq}) output

World average: $BF = (1.59 \pm 0.26) \times 10^{-6}$

$A_{CP} = 0.30 \pm 0.20$

Summary

- Belle II is now providing new and updated results on time-dependent CP violation in B decays.

- Thanks to the GNN-based classifier, the flavor-tagging efficiency is improved by 18%. ($B^0 \to J/\psi\pi^0$, $B^0 \to \pi^0\pi^0$)

- Four recent results, with one newly presented at ICHEP.

$B \to J/\psi\,\pi^0$ BF = $(2.00 \pm 0.12 \pm 0.10) \times 10^{-5}$

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

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

Today's contents

	Decay mode		**Target**
new	$B^0 \to J/\psi\pi^0$	$(b \to c\bar{c}d)$	ϕ_1
	$B^0 \to \eta' K_S$	$(b \to s\bar{s}s)$	$\phi_1^{\rm eff}$, NP
	$B^0 \to K_S\pi^0\gamma$	$(b \to s\gamma)$	NP
updated	$B^0 \to \pi^0\pi^0$	$(b \to u\bar{u}d)$	ϕ_2

Backup

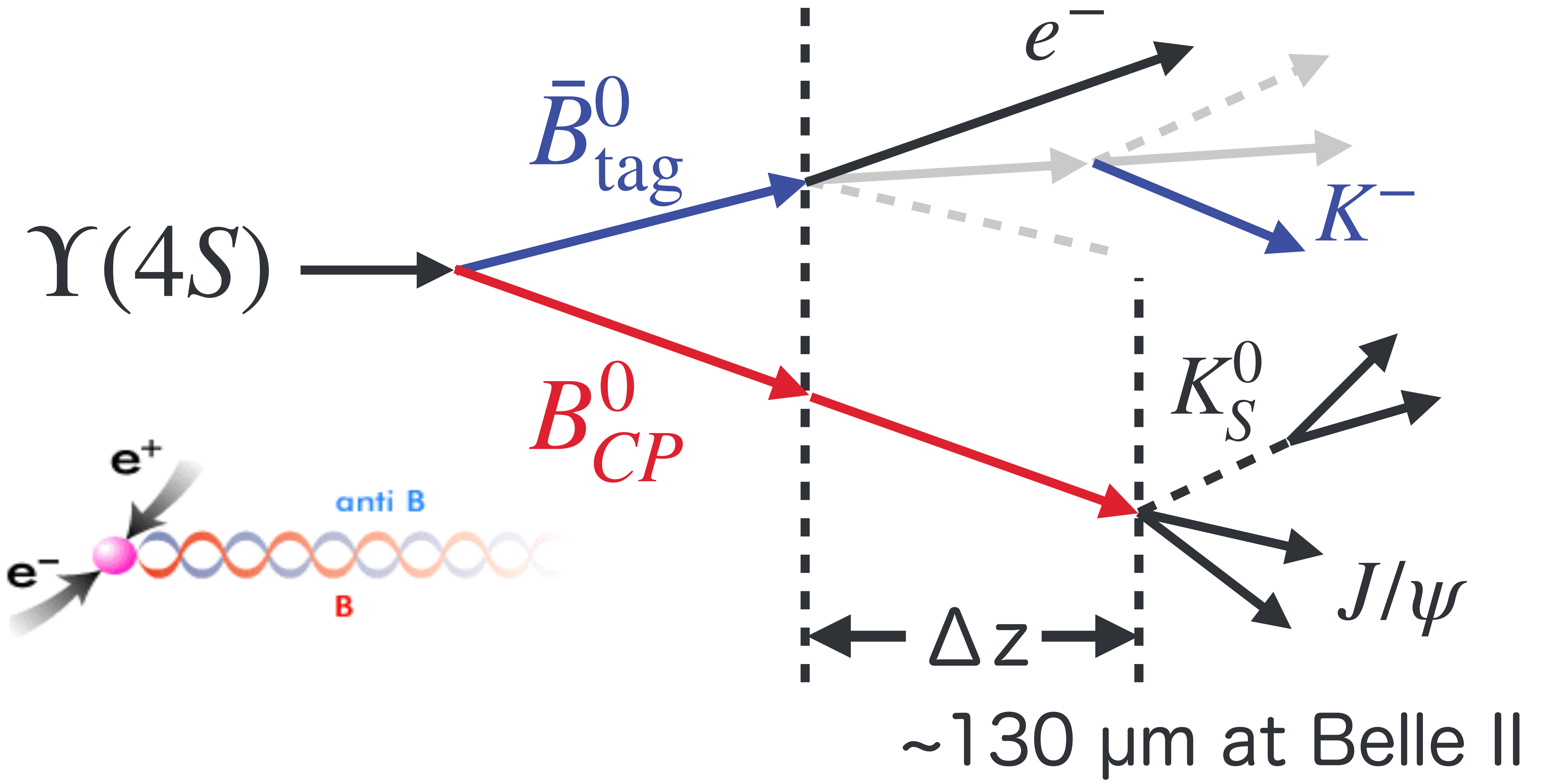
Time-Dependent CPV analysis at Belle II

$$A_{CP}^{B\to f}(\Delta t) \equiv \frac{\Gamma(B^0(\Delta t)\to f) - \Gamma(\bar{B}^0(\Delta t)\to f)}{\Gamma(B^0(\Delta t)\to f) + \Gamma(\bar{B}^0(\Delta t)\to f)}$$

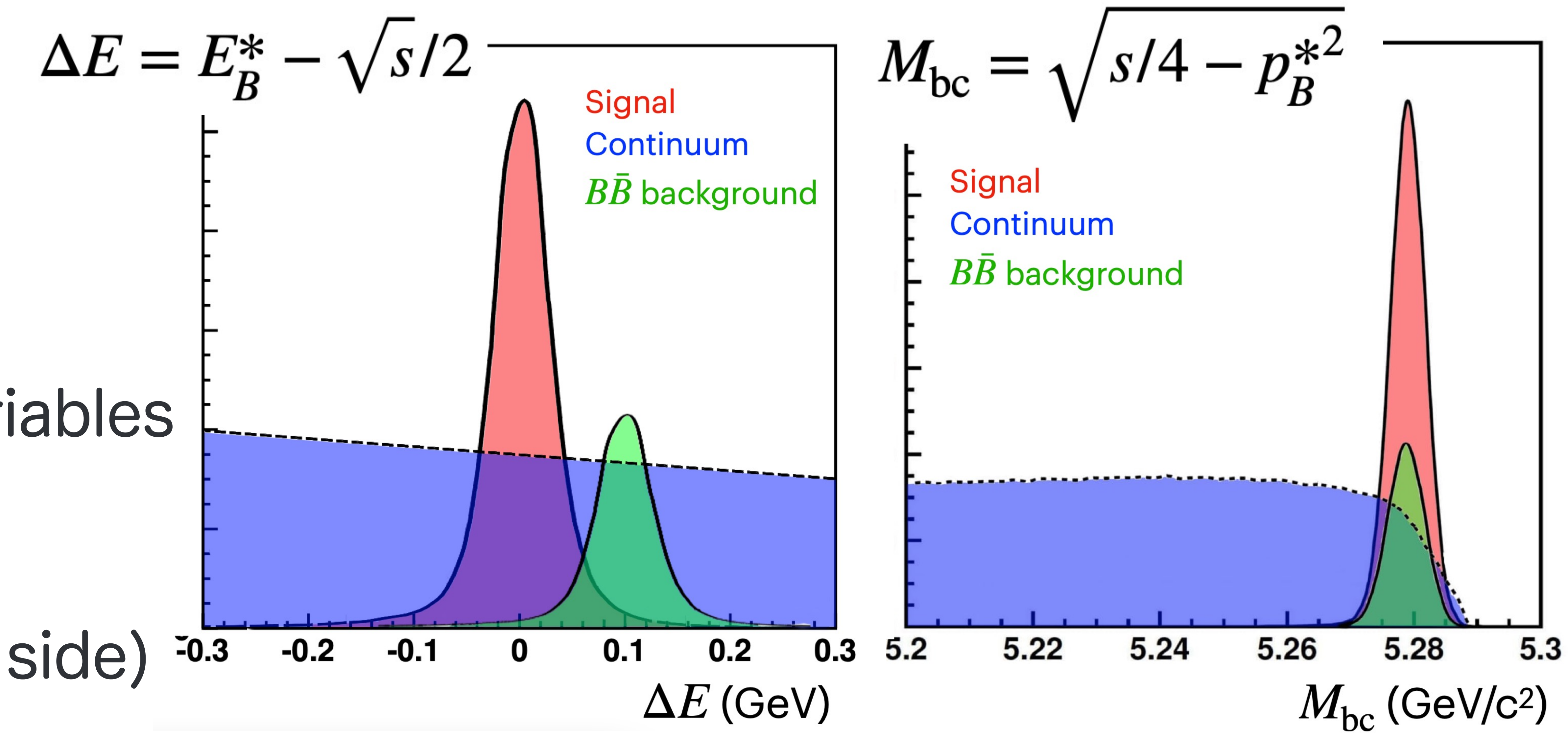
$$= \boxed{S}\cdot \sin(\Delta m_d \Delta t) - \boxed{C}\cdot \cos(\Delta m_d \Delta t)$$

mixing-induced CPV — Direct CPV

$S_{CP} = \sin(2\phi_i^{\mathrm{eff}})$ — $A_{CP} = -C_{CP}$



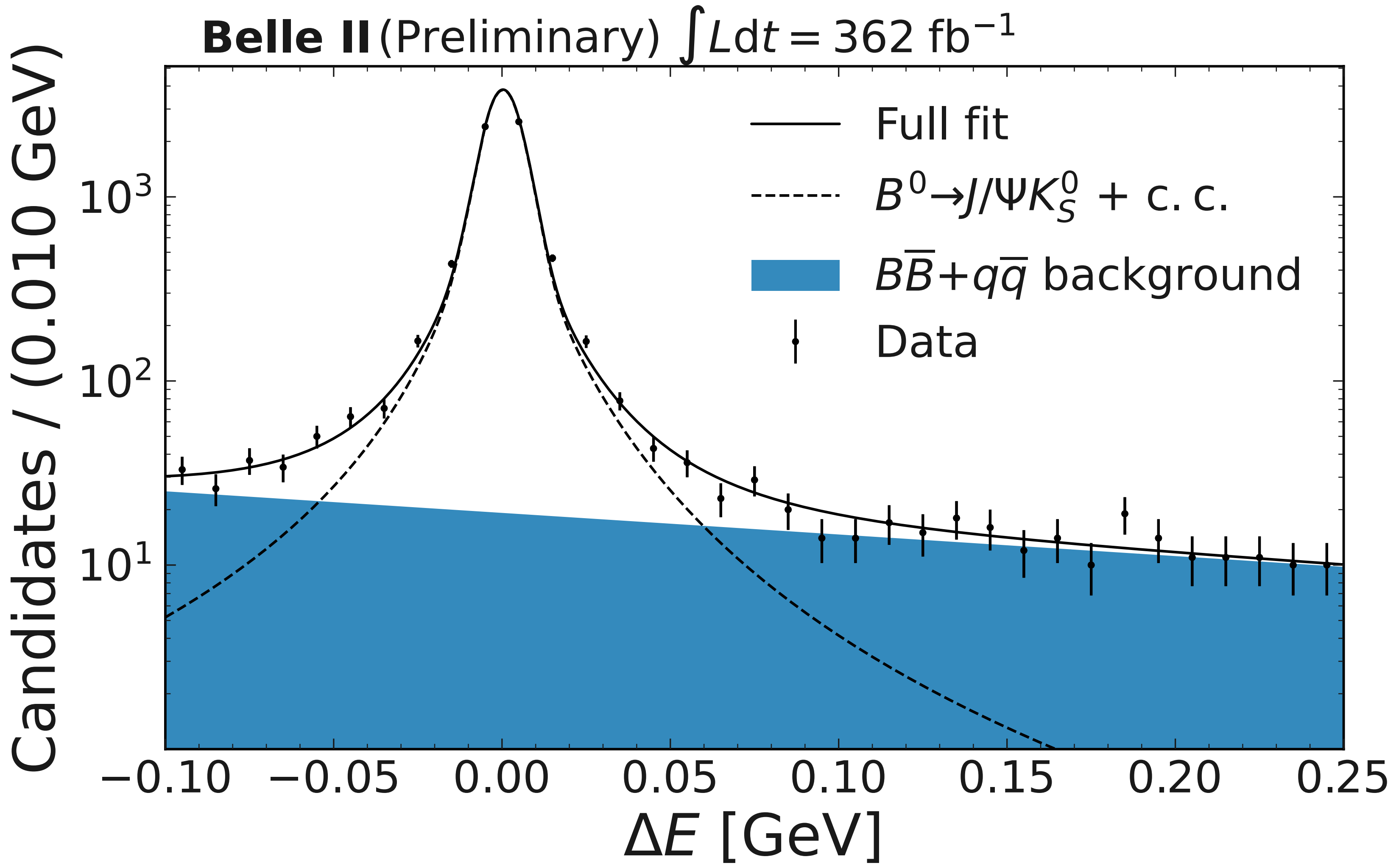
- B_{CP}: fully reconstructed CP eigenstate
  B_{tag}: vertex and flavor information
- Signal extraction
  - Two variables using the collision energy
  - Multivariate (BDT) classifier to discriminate continuum (qq) backgrounds using event-shape variables
- CPV-paramenter extraction:
  - excellent vertex resolution σ_z ~ 26/50 μm (CP/tag side)



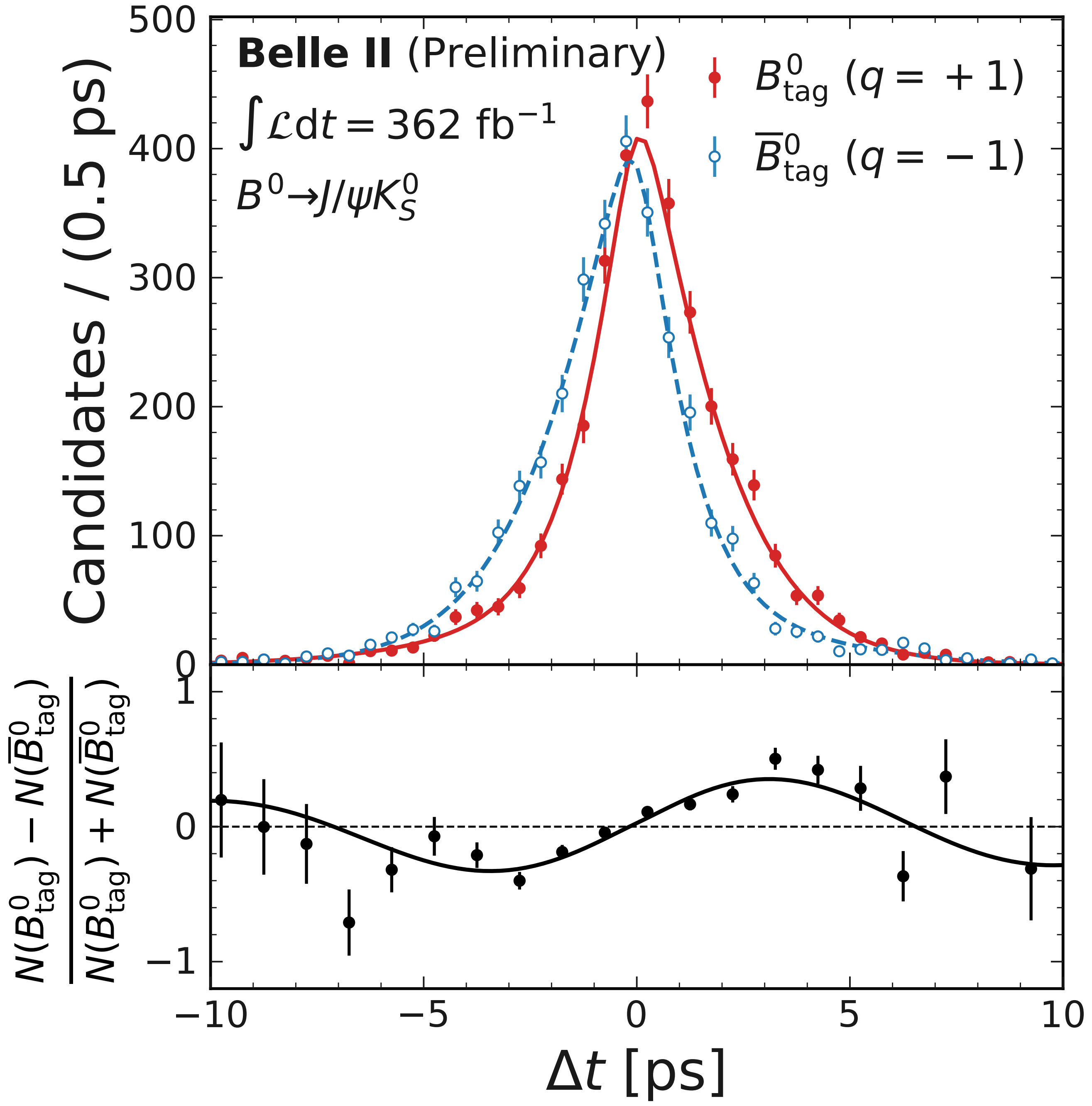
sin(2ϕ_1/β) from B->J/ψKs (b→ccd)

PRD.110.012001
arXiv:2402.17260

- Golden channel, almost background free
- Updated results using GFlaT
- Staging approach
  - Fit ΔE distribution to subtract background
  - Fit background-subtracted Δt distribution to extract CPV parameters.
- Results: S = 0.724 ± 0.035 ± 0.014
  C = -0.035 ± 0.026 ± 0.013
- Statistical uncertainties 8% smaller compared to the category-based flavor tagging.



World average
(Ks mode only)
S = 0.695 ± 0.019
C = 0.000 ± 0.020



Systematics: $J/\psi\,\pi^0$

Table II. Relative systematic uncertainties on the branching fraction.

Source	Relative uncertainty on BF[%]
π^0 efficiency	3.7
Lepton ID	0.4
BDT	0.3
Tracking Efficiencies	0.5
PDG inputs	0.4
$N(B\overline{B})$	1.4
f^{+-}/f^{00}	2.5
Fixed parameters	0.7
Backgrounds composition	0.4
Multiple candidates	0.5
Total systematic uncertainty	4.9
Statistical uncertainty	6.1

Table III. Systematic uncertainties on the CP asymmetries.

Source	C_{CP}	$-\eta_f S_{CP}$
Calibration with $B^0 \to D^{*-}\pi^+$	0.017	0.023
Signal extraction fit	0.003	0.017
Background composition	0.005	0.009
Backgrounds Δt shapes	< 0.001	0.001
Fit bias	0.010	0.010
Multiple candidates	< 0.001	0.002
Detector mis-alignment	0.002	0.002
Tag-side interference	0.027	0.001
τ_{B^0} and Δm_d	< 0.001	< 0.001
Total systematic uncertainty	0.034	0.032
Statistical uncertainty	0.124	0.171

Systematics: $\pi^0\pi^0$

Source	$\mathcal{B}$	$\mathcal{A}_{CP}$
π^0 efficiency	8.6 %	n/a
$\Upsilon(4S)$ branching fractions $(1 + f^{+-}/f^{00})$	2.5 %	n/a
Continuum-suppression efficiency	1.9 %	n/a
$B\overline{B}$-background model	1.7 %	0.034
Sample size $N_{B\bar{B}}$	1.5 %	n/a
Signal model	1.2 %	0.021
Continuum-background model	0.9 %	0.025
Wrong-tag probability calibration	n/a	0.008
Total systematic uncertainty	9.6 %	0.048
Statistical uncertainty	15.9 %	0.303