

CP violation

Ryogo Okubo (Nagoya University, Japan)
on behalf of Belle II collaboration

Unitarity triangle

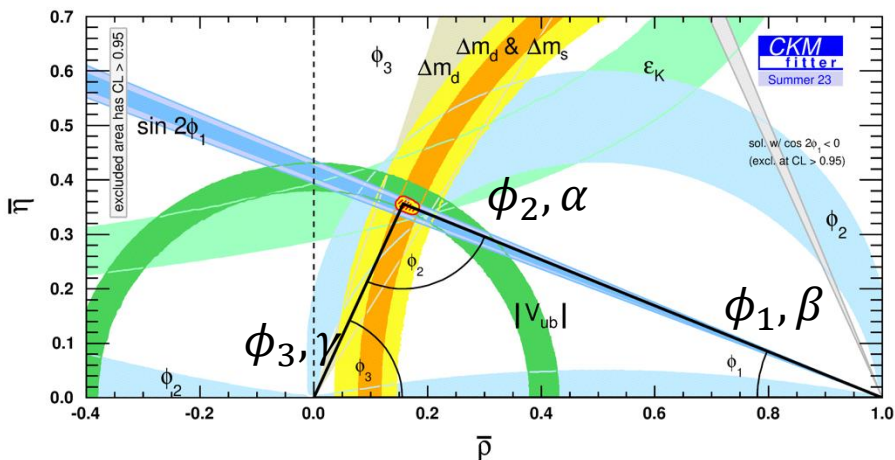
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



Unitarity

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

Belle II can measure all ϕ_1, ϕ_2 , and ϕ_3



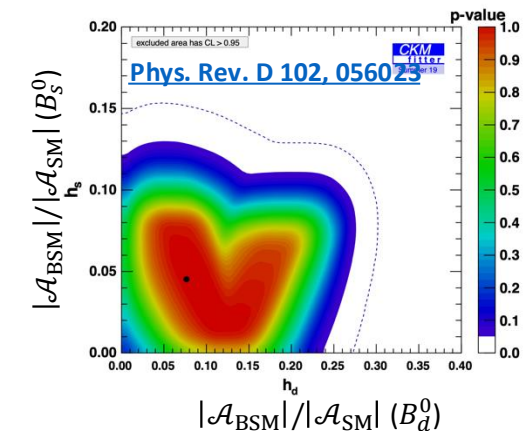
Unitarity triangle parameters measurement at Belle II

Global Fit to Observables

→ Give a Constraint to the physics
Beyond the Standard Model (BSM)!

In B_d^0 mixing BSM / SM < 30%

BSM constraint in B mixing



Unitarity triangle angles

- $\phi_1 = \beta = \arg[-(V_{cd}V_{cb}^*)/(V_{td}V_{tb})]$
 $B^0 \rightarrow J/\Psi K_S^0, B^0 \rightarrow J/\Psi \pi^0 (\phi_{1\text{eff}}) B^0 \rightarrow \eta' K_S^0 (\phi_{1\text{eff}})$
- $\phi_2 = \alpha = \arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*]$
 $B \rightarrow \pi\pi, B^0 \rightarrow \rho^+\rho^-$ **NEW**
- $\phi_3 = \gamma = \arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$
 $B^+ \rightarrow D^0 K^+$ with various D^0 decays

World average

(CKMfitter, 2023 summer)

$$\phi_1 \quad (22.84^{+0.33}_{-0.30})^\circ$$

$$\phi_2 \quad (86.2^{+3.9}_{-3.5})^\circ$$

$$\phi_3 \quad (65.9^{+3.3}_{-3.5})^\circ$$

ϕ_2 has the largest uncertainty

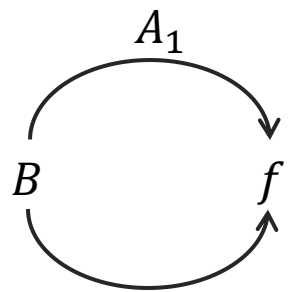
CP violation

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{bmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ \lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(\rho - i\eta) & -A\lambda^2 & 1 \end{bmatrix} \begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} \sim 1 & 0.2 & 0.003 \\ 0.2 & \sim 1 & 0.04 \\ 0.008 & 0.04 & \sim 1 \end{bmatrix}$$

CPV

Direct CPV

- Appears in both B^\pm and B^0 decays
- Interference of two amplitudes
(for example, tree and penguin)
→ CP violation in the magnitude of the amplitudes



$$|\mathcal{A}(B \rightarrow f)| = |A_1 + A_2 \exp(i\phi + \delta)|$$

$$|\mathcal{A}(\bar{B} \rightarrow \bar{f})| = |A_1 + A_2 \exp(-i\phi + \delta)|$$

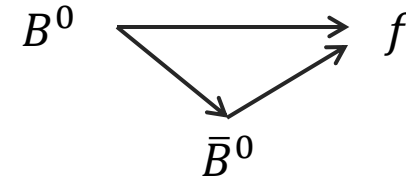
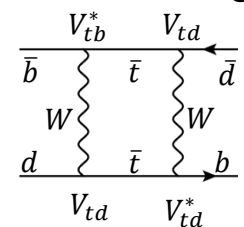
ϕ : Weak phase difference

δ : Strong phase difference

Mixing-induced CPV

- Appears in B^0 decays
- CPV appears in the decay-time

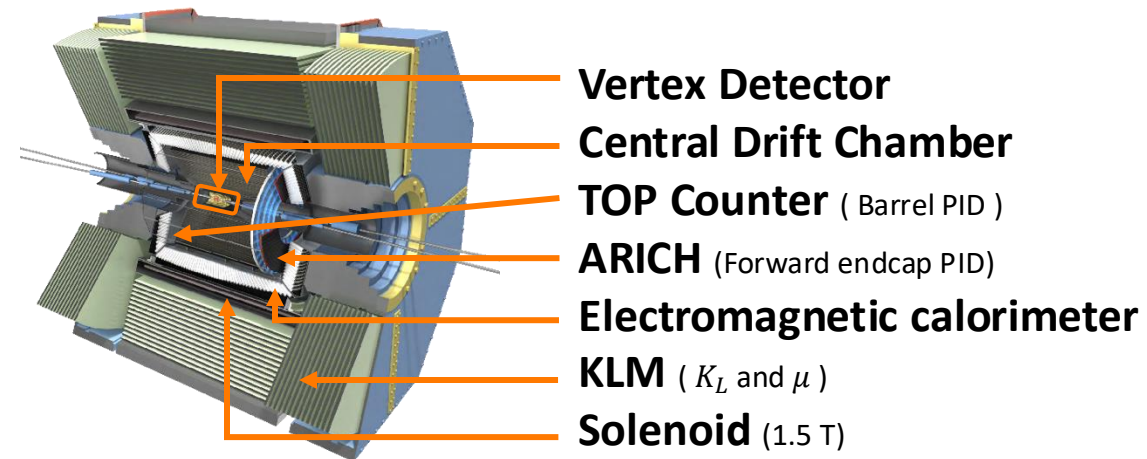
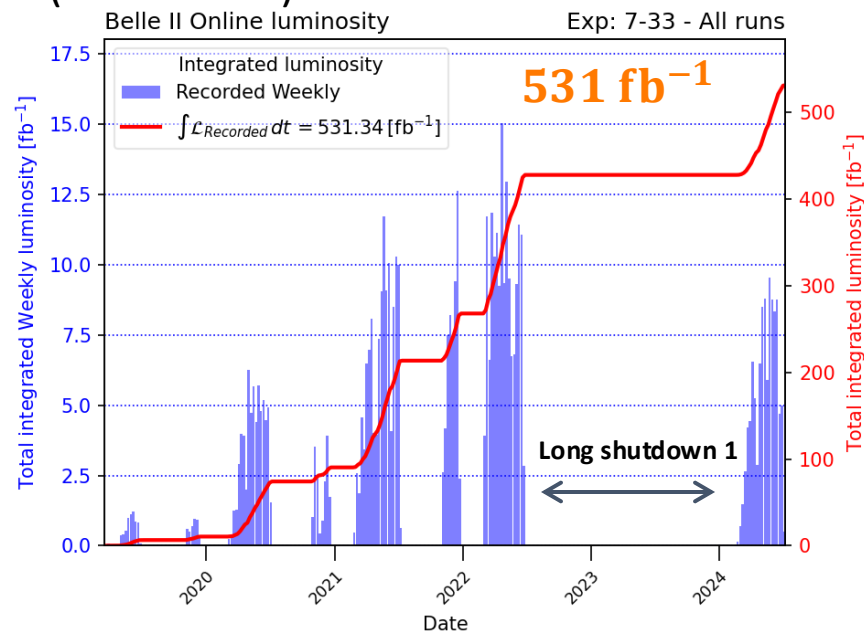
$B^0 - \bar{B}^0$ mixing



$$\frac{\Gamma(\bar{B}^0 \rightarrow f) - \Gamma(B^0 \rightarrow f)}{\Gamma(\bar{B}^0 \rightarrow f) + \Gamma(B^0 \rightarrow f)} = -C \cos \Delta m_d \Delta t + S \sin \Delta m_d \Delta t$$

Belle II experiment at SuperKEKB

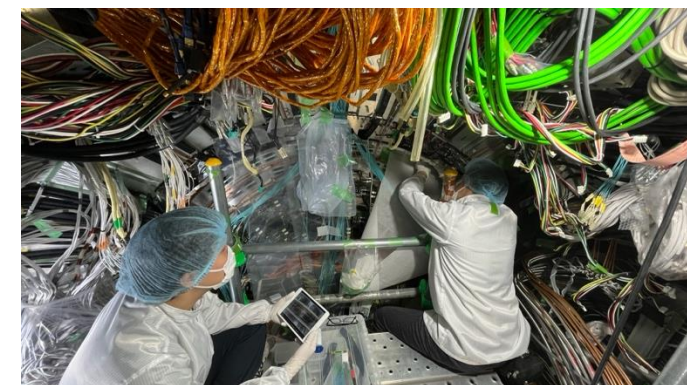
- High luminosity e^-e^+ collider experiment at a center of mass energy of 10.58 GeV.
- Target integrated Luminosity: 50 ab^{-1}
- Target peak luminosity: $6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
- Integrated **531 fb^{-1}**
- Achieved Peak luminosity **$4.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$** (World-best)



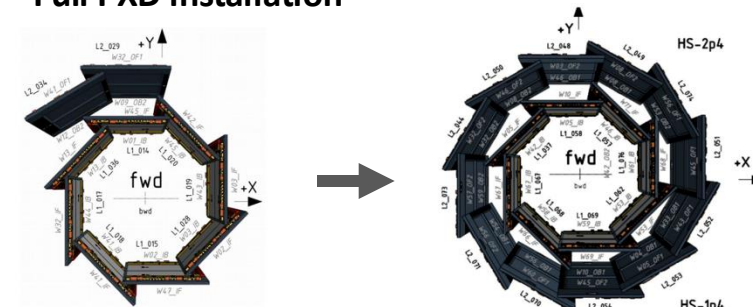
Long shutdown 1 2022-2023

- Accelerator upgrade
- Full Pixel detector (Innermost vertex detector) installation
- TOP photodetector replacement
- Other subdetectors upgrade

TOP PMT replacement during long shutdown1



Full PXD installation



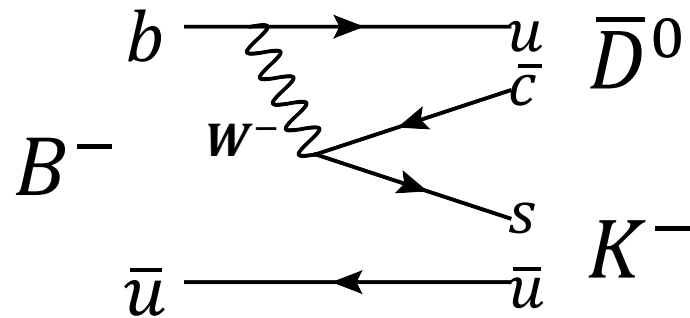
ϕ_3

ϕ_3 measurement

$$\phi_3 = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$$

appears in CPV parameter of $b \rightarrow u\bar{c}s$ and $b \rightarrow c\bar{u}s$ tree decay interference.

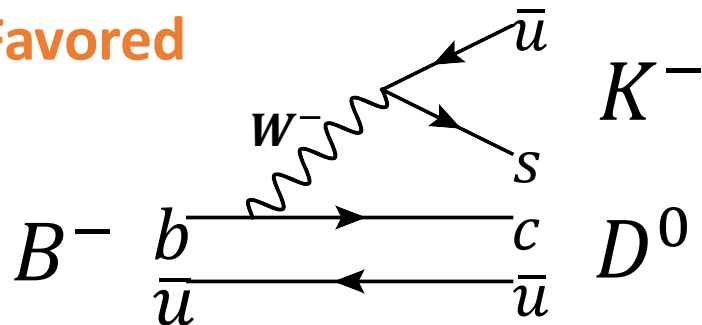
Suppressed



$$\frac{\mathcal{A}(\bar{D}^0 K^-)}{\mathcal{A}(D^0 K^-)} = r_B \exp(i(\delta_B - \phi_3))$$

$r_B = |\mathcal{A}(\bar{D}^0 K^-)|/|\mathcal{A}(D^0 K^-)| \simeq c_f |V_{cs}V_{ub}^*/V_{us}V_{cb}^*| \simeq 0.1$ (c_f : Color suppression factor)
 δ_B : Strong phase difference between 2 modes

Favored



Methods to measure ϕ_3 using different D^0 decays

- GLW method: $D^0 \rightarrow K^+K^-, K_S^0\pi^0$ (CP eigenstates)
- BPGGSZ method: self conjugate multibody decay, ex.) $D^0 \rightarrow K_S^0 h^+ h^-$
- GLS method: $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ (singly Cabibbo-suppressed decays)
- ADS method: $D^0 \rightarrow K^\pm \pi^\mp$

$B^\pm \rightarrow D_{CP\pm} K^\pm$ using Belle + Belle II data

Observables: Direct CPV in B ratio

$$A_{CP\pm} \equiv \frac{\mathcal{B}(B^- \rightarrow D_{CP\pm} K^-) - \mathcal{B}(B^+ \rightarrow D_{CP\pm} K^+)}{\mathcal{B}(B^- \rightarrow D_{CP\pm} K^-) + \mathcal{B}(B^+ \rightarrow D_{CP\pm} K^+)},$$

$$\mathcal{R}_{CP\pm} \equiv \frac{\mathcal{B}(B^- \rightarrow D_{CP\pm} K^-) + \mathcal{B}(B^+ \rightarrow D_{CP\pm} K^+)}{(\mathcal{B}(B^- \rightarrow D_{\text{flav}} K^-) + \mathcal{B}(B^+ \rightarrow \bar{D}_{\text{flav}} K^+))/2}.$$

D_{CP+} : CP-Even decay ($D \rightarrow K^+ K^-$)

D_{CP-} : CP-odd decay ($D \rightarrow K_S^0 \pi^0$)

D_{flav} : Flavor specific decay ($D \rightarrow K^\pm \pi^\mp$)



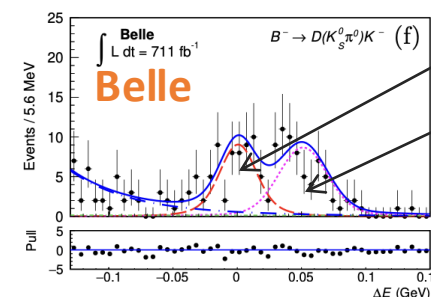
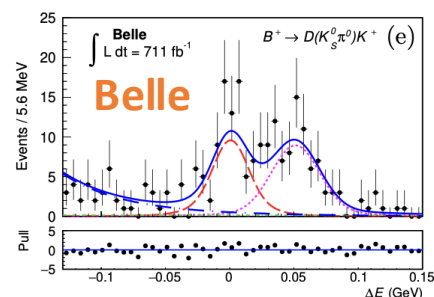
$$\mathcal{R}_{CP\pm} = 1 + r_B^2 \pm 2r_B \cos \delta_B \cos \phi_3,$$

$$A_{CP\pm} = \pm 2r_B \sin \delta_B \sin \phi_3 / \mathcal{R}_{CP\pm}.$$

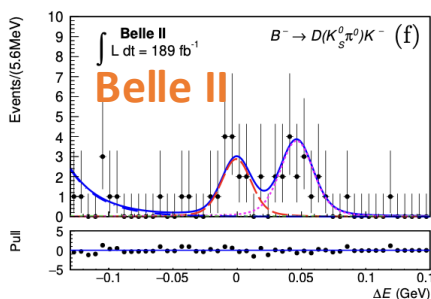
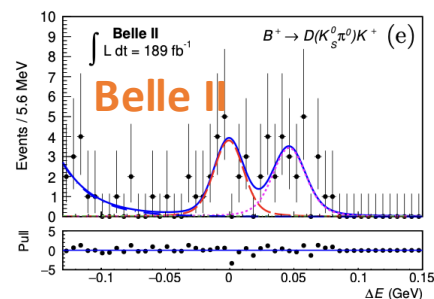
(GLW Method)

Simultaneous fit to $B \rightarrow D\pi, DK$, with different D decays

$B^+ \rightarrow DK, D \rightarrow K^+ K^-$ (CP even), $D \rightarrow K_S^0 \pi^0$ Unique to Belle II



$B \rightarrow DK$
 $B \rightarrow D\pi$



$$\mathcal{R}_{CP+} = 1.164 \pm 0.081 \pm 0.036,$$

$$\mathcal{R}_{CP-} = 1.151 \pm 0.074 \pm 0.019,$$

$$A_{CP+} = (+12.5 \pm 5.8 \pm 1.4)\%,$$

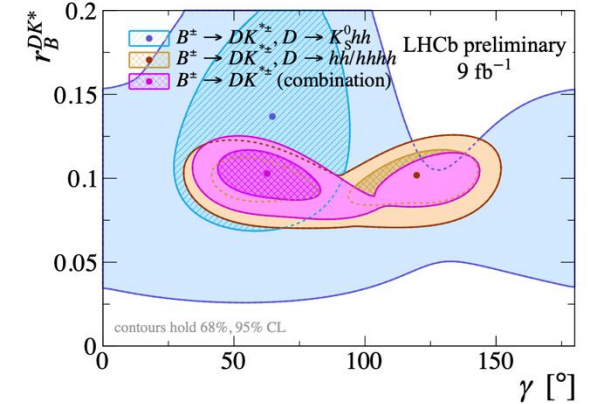
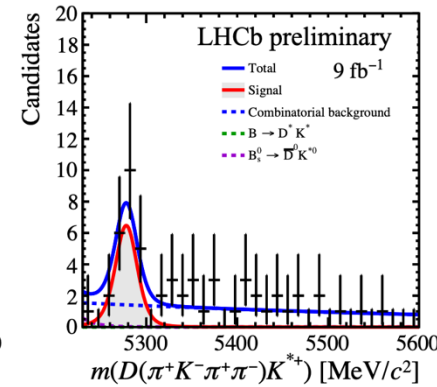
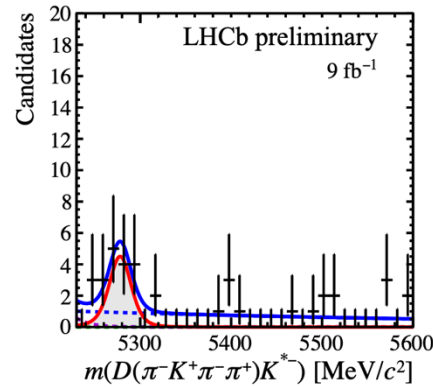
$$A_{CP-} = (-16.7 \pm 5.7 \pm 0.6)\%, \quad 3.5 \sigma \text{ evidence for } A_{CP+} \neq A_{CP-}$$

[JHEP05\(2024\)212](#)

Recent ϕ_3 measurements by LHCb

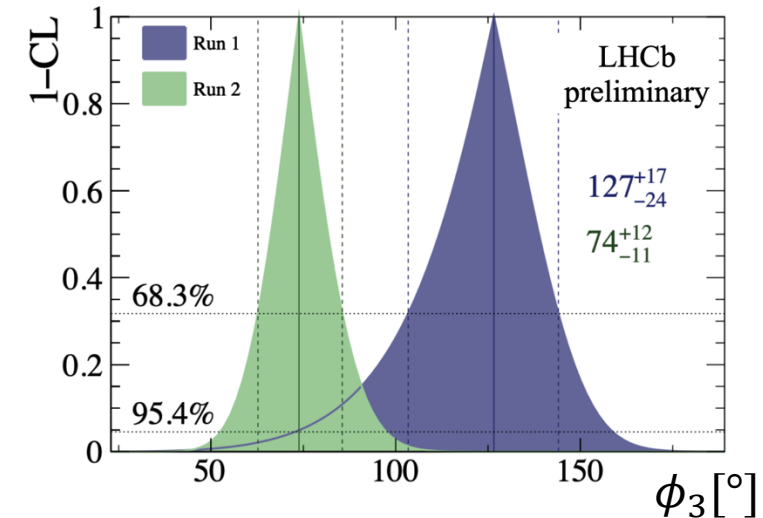
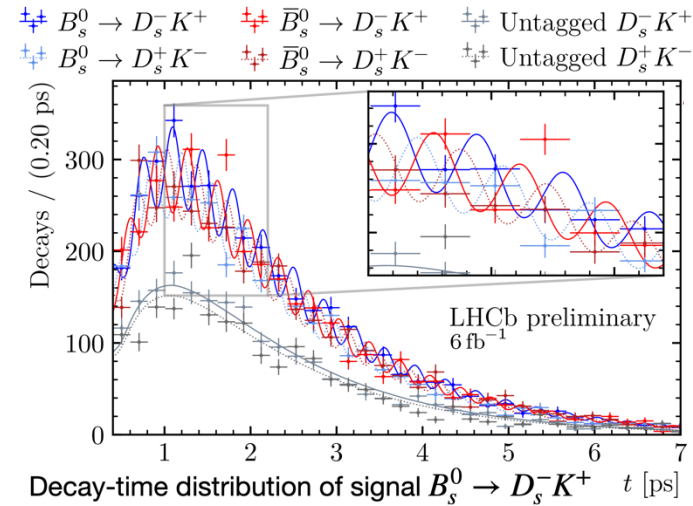
$B^\pm \rightarrow DK^{*\pm}$ (LHCb-PAPER-2024-023)

- $D \rightarrow K\pi(\pi\pi), D \rightarrow \pi\pi(\pi\pi), D \rightarrow KK,$
and $D \rightarrow K_S^0 hh$
- First observation of the
 $B^\pm \rightarrow D(\rightarrow \pi^\pm K^\mp(\pi\pi))K^{*\pm}$
- $\phi_3 = (63 \pm 13)^\circ$



$B_S^0 \rightarrow D_S^- K^+$ (LHCb-PAPER-2024-023)

- CPV parameters depend on $\phi_3 - 2\phi_1(B_S)$
- Simultaneous fit to B_S^0 and D_S^-
- First CPV measurement using decay time distribution
- $\phi_3 = (81_{-11}^{+12})^\circ$ (Run1 + Run2)
- Most precise measurement in B_S^0 decay!



ϕ_3 combination

First Belle + Belle II combined ϕ_3 analysis

Combined analysis using 4 methods

Fit results

Parameters	$\phi_3(^{\circ})$	r_B^{DK}	$\delta_B^{DK}(^{\circ})$	$r_B^{D\pi}$	$\delta_B^{D\pi}(^{\circ})$	$r_B^{D^*K}$	$\delta_B^{D^*K}(^{\circ})$
Best-fit value	75.2	0.115	137.8	0.0165	347.0	0.229	342
68.3% interval	[67.7, 82.3]	[0.102, 0.127]	[128.0, 146.3]	[0.0113, 0.0220]	[337.4, 355.7]	[0.162, 0.297]	[326, 356]
95.4% interval	[59, 89]	[0.089, 0.138]	[116, 154]	[0.006, 0.027]	[322, 366]	[0.10, 0.37]	[306, 371]

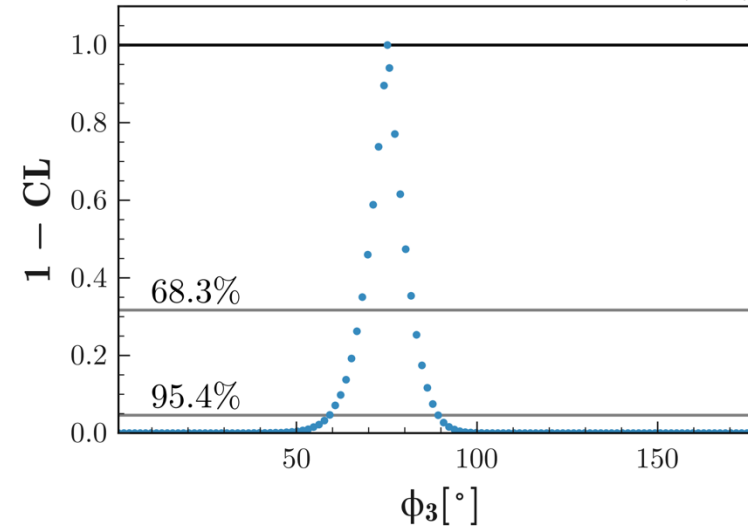
Inputs for ϕ_3 measurement

B decay	D decay	Method	Data set (Belle + Belle II)[fb ⁻¹]
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0\pi^0, K^-K^+$	GLW	711 + 189 Belle II
$B^+ \rightarrow Dh^+$	$D \rightarrow K^+\pi^-, K^+\pi^-\pi^0$	ADS	711 + 0
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0K^-\pi^+$	GLS	711 + 362 Belle II
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0h^-h^+$	BPGGSZ (m.i.)	711 + 128 Belle II
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0\pi^-\pi^+\pi^0$	BPGGSZ (m.i.)	711 + 0
$B^+ \rightarrow D^*K^+$	$D^* \rightarrow D\pi^0, D \rightarrow K_S^0\pi^0, K_S^0\phi, K_S^0\omega,$ $K^-K^+, \pi^-\pi^+$	GLW	210+0
$B^+ \rightarrow D^*K^+$	$D^* \rightarrow D\pi^0, D\gamma, D \rightarrow K_S^0\pi^-\pi^+$	BPGGSZ (m.d.)	605 + 0

Dominated by LHCb, but Belle + Belle II is also improving the precision!

Belle + Belle II :

$$\phi_3 = (75.2 \pm 7.6)^{\circ} \quad \text{Belle + Belle II (2024)}$$

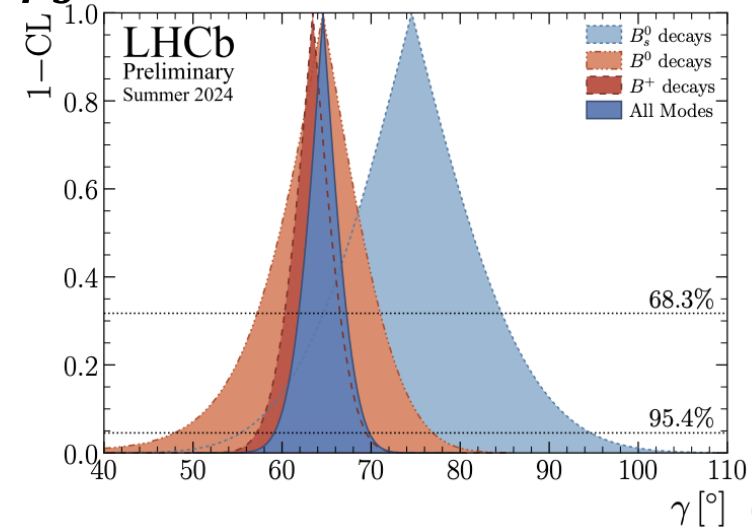


[arXiv:2404.12817](https://arxiv.org/abs/2404.12817)
(accepted by JHEP)

LHCb:

$$\phi_3 = (64.6 \pm 2.8)^{\circ}$$

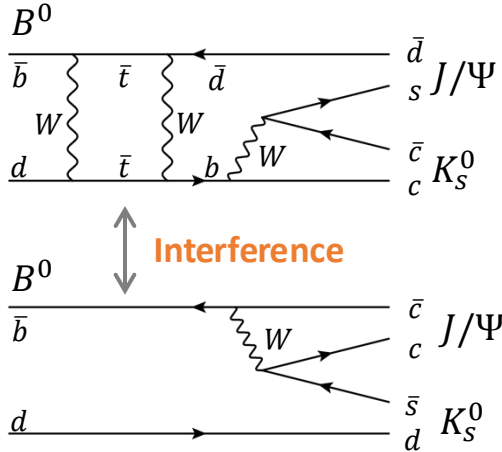
[LHCb-CONF-2024-004](https://arxiv.org/abs/2404.12817)



ϕ_1

ϕ_1 Measurement

Time-dependent CPV



$$\frac{\Gamma(\bar{B}^0 \rightarrow f) - \Gamma(B^0 \rightarrow f)}{\Gamma(\bar{B}^0 \rightarrow f) + \Gamma(B^0 \rightarrow f)} =$$

$$-\mathcal{C} \cos \Delta m_d \Delta t + \mathcal{S} \sin \Delta m_d \Delta t$$

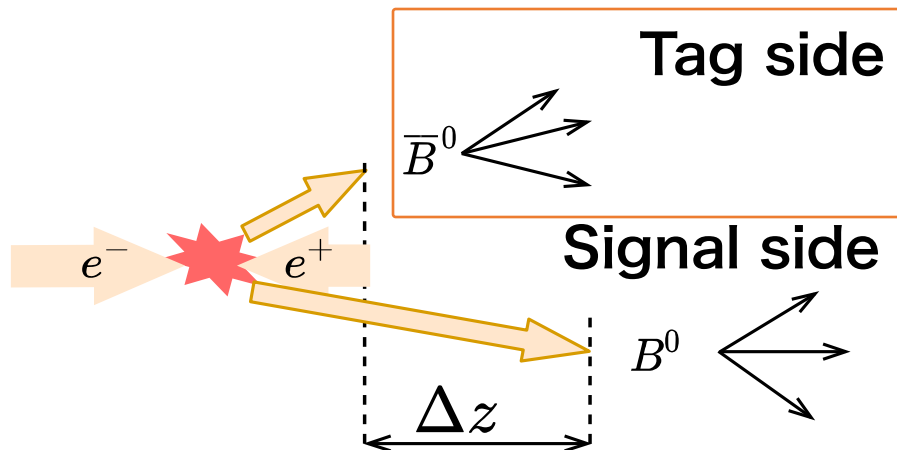
$$\mathcal{C} = 0 \text{ (Direct CPV)}$$

$$\mathcal{S} = \sin 2\phi_1 \text{ (Mixing induced CPV)}$$

$B\bar{B}$ is boosted ($\beta\gamma = 0.28$)

Decay vertex distance Δz

\rightarrow Decay time difference Δt



$$\phi_1 = \arg[-(V_{cd}V_{cb}^*)/(V_{td}V_{tb})]$$

Flavor tagging

[PhysRevD.110.012001](https://arxiv.org/abs/1101.2001)

Category-based FBBDT flavor tagger

- Kinematics, charge, PID of charged particles

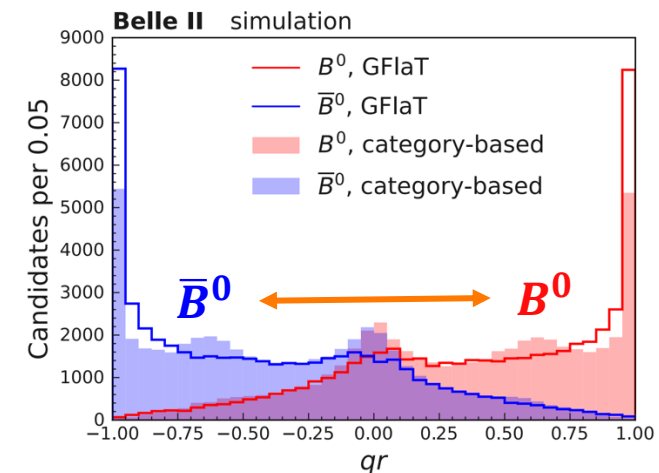
$$\epsilon_{\text{eff}} = (31.68 \pm 0.45)\%$$

Graph neural network flavor tagging (GFlaT)

- Improved performance by learning correlations between final-state particles

$$\epsilon_{\text{eff}} = (37.40 \pm 0.43 \pm 0.36)\%$$

18% improvement!



$B^0 \rightarrow J/\Psi K_S^0$ using GflaT Flavor tagger

[PhysRevD.110.012001](https://arxiv.org/abs/PhysRevD.110.012001)

Improved statistical uncertainty 8% (S) and 7% (C) compared to category-based FBDT flavor tagger!

$$S = 0.724 \pm 0.035 \pm 0.009$$

$$\rightarrow \phi_1 = (23.2 \pm 1.5 \pm 0.6)^\circ$$

$$C = -0.035 \pm 0.026 \pm 0.029$$

	Belle PhysRevLett.108.171802	LHCb PhysRevLett.132.021801
S	$0.670 \pm 0.029 \pm 0.013$	$0.722 \pm 0.014 \pm 0.007$
C	$-0.015 \pm 0.021^{+0.045}_{-0.023}$	$0.015 \pm 0.013 \pm 0.003$

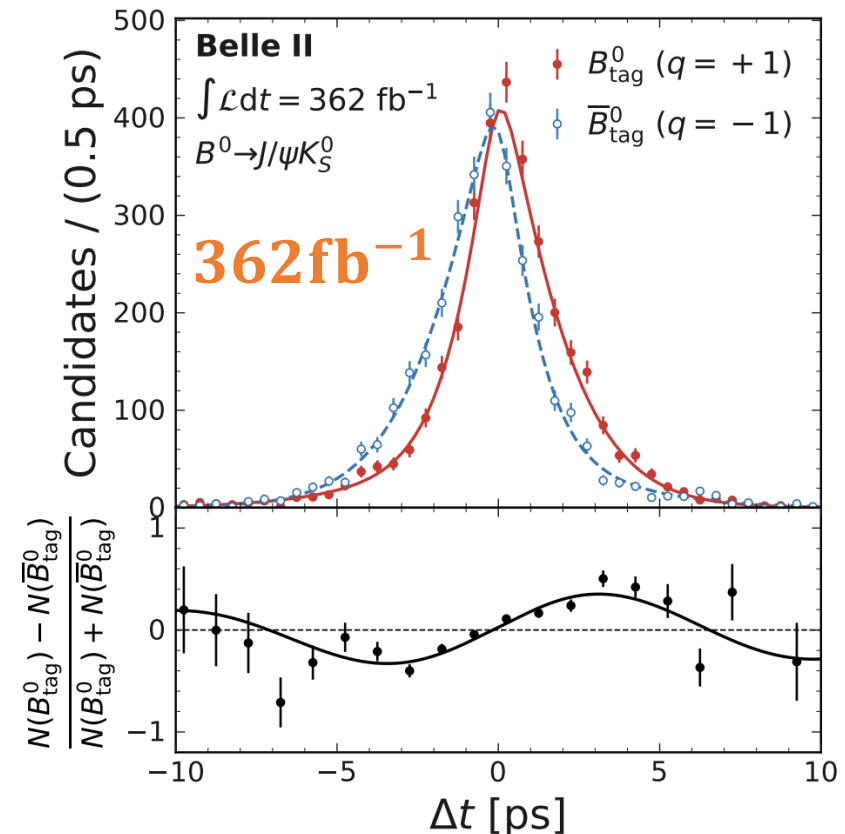
Dominant systematic uncertainty on C :

CP violation in tag side B decays.

This can be reduced by combined measurement of

$B^0 \rightarrow J/\Psi K_S^0$ (CP – odd) and $B^0 \rightarrow J/\Psi K_L^0$ (CP – even).

Time-dependent CPV fit to $B^0 \rightarrow J/\Psi K_S$



$B^0 \rightarrow J/\Psi \pi^0$

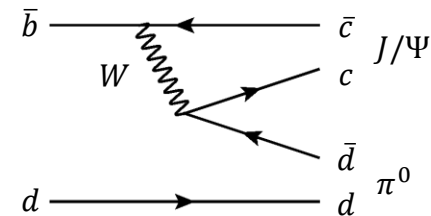
$S = -\sin 2\phi_1$, $C = 0$ if there is only tree amplitude

Tree is color and CKM suppressed

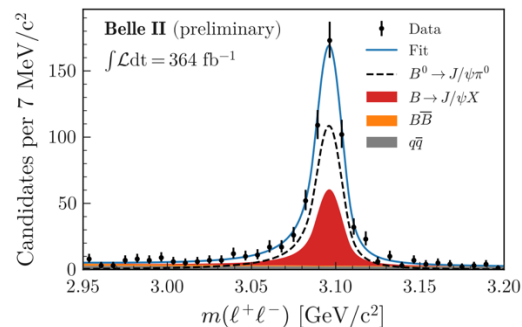
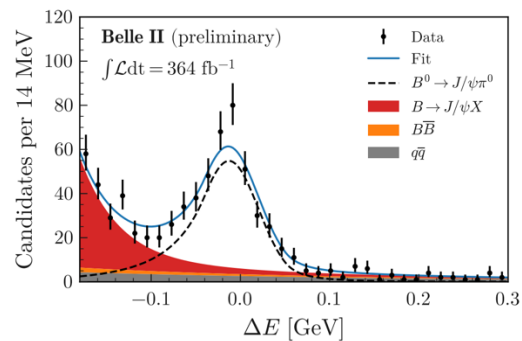
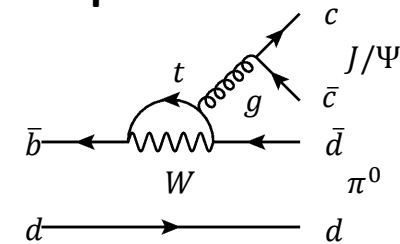
→ can be used to understand the loop contribution in $B^0 \rightarrow J/\Psi K_S^0$

- Improved sensitivity by the better π^0 selection and GflaT
- $\Delta E - m(\ell\ell)$ fit to extract signal

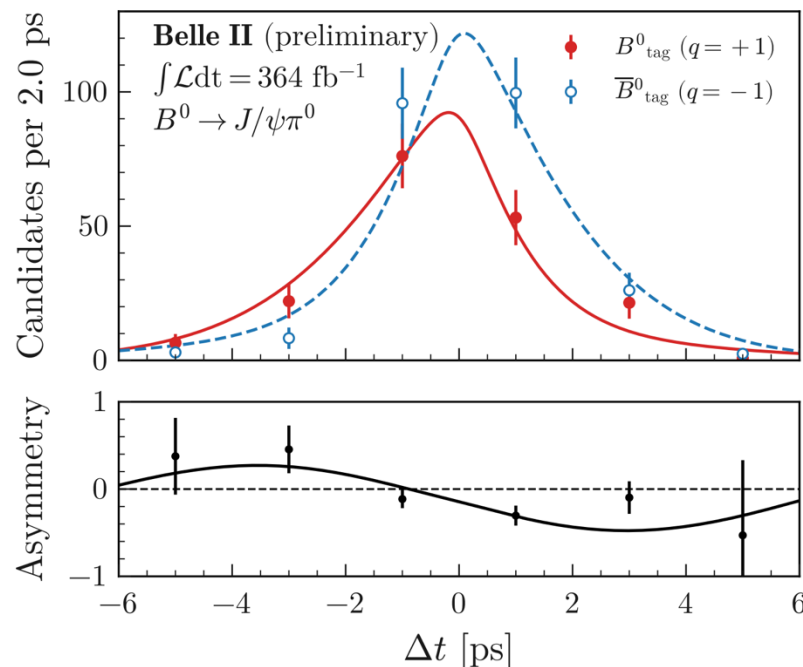
Tree



Loop



$$(\Delta E = E_B - E_{\text{beam}})$$



$$S = -0.88 \pm 0.17 \pm 0.03$$

$$C = 0.13 \pm 0.12 \pm 0.03$$

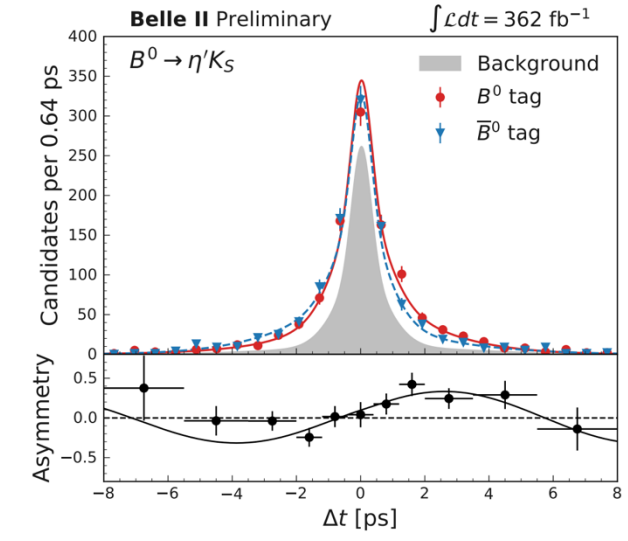
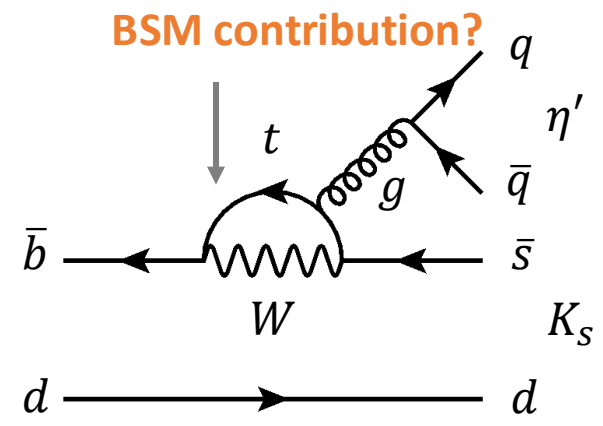
$$B = (2.02 \pm 0.12 \pm 0.10) \times 10^{-5}$$

Most precise,
and comparable with previous measurement

	Belle PhysRevD.98.112008	BaBar PhysRevLett.101.021801
S	$-0.59 \pm 0.19 \pm 0.03$	$-1.23 \pm 0.21 \pm 0.04$
C	$0.15 \pm 0.14^{+0.03}_{-0.04}$	$-0.2 \pm 0.19 \pm 0.03$
$B(\times 10^{-5})$	$(1.62 \pm 0.11 \pm 0.06)$	$(1.69 \pm 0.14 \pm 0.07)$

$B^0 \rightarrow \eta' K_S$

- Dominated by the Loop process
- In SM, $|\sin 2\phi_1 - S(\eta' K_S)| = 0.01 \pm 0.01$
- **BSM could shift S and C !**
- Used $\eta' \rightarrow \eta(\rightarrow \gamma\gamma)\pi\pi$ and $\eta' \rightarrow \rho^0(\rightarrow \pi\pi)\gamma$

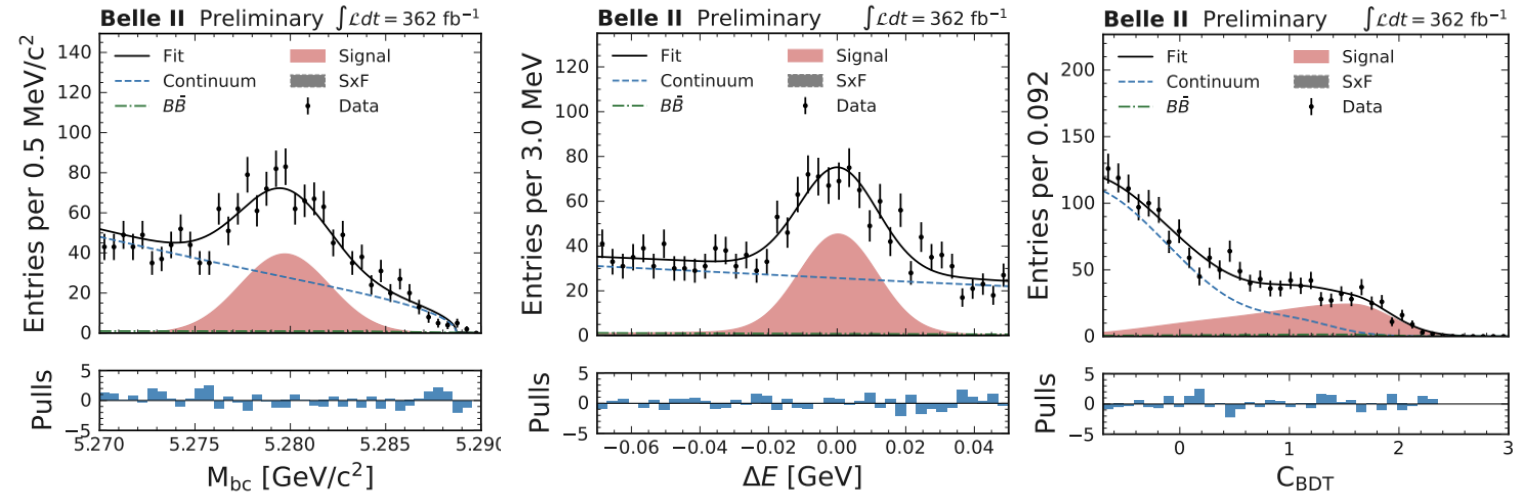


$S = 0.67 \pm 0.10 \pm 0.04$
 $C = -0.19 \pm 0.08 \pm 0.03$

	Belle	BaBar
S	$0.68 \pm 0.07 \pm 0.03$	$0.57 \pm 0.08 \pm 0.02$
C	$-0.03 \pm 0.05 \pm 0.04$	$-0.08 \pm 0.06 \pm 0.02$

World average of $S (J/\Psi K_S^0)$: 0.709 ± 0.011

Consistent, and compatible precision with previous experiments!

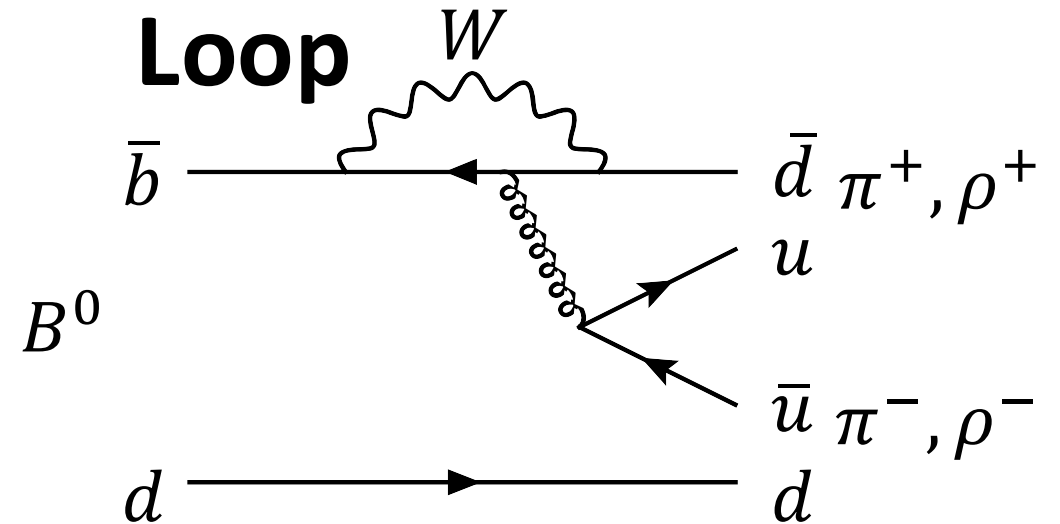
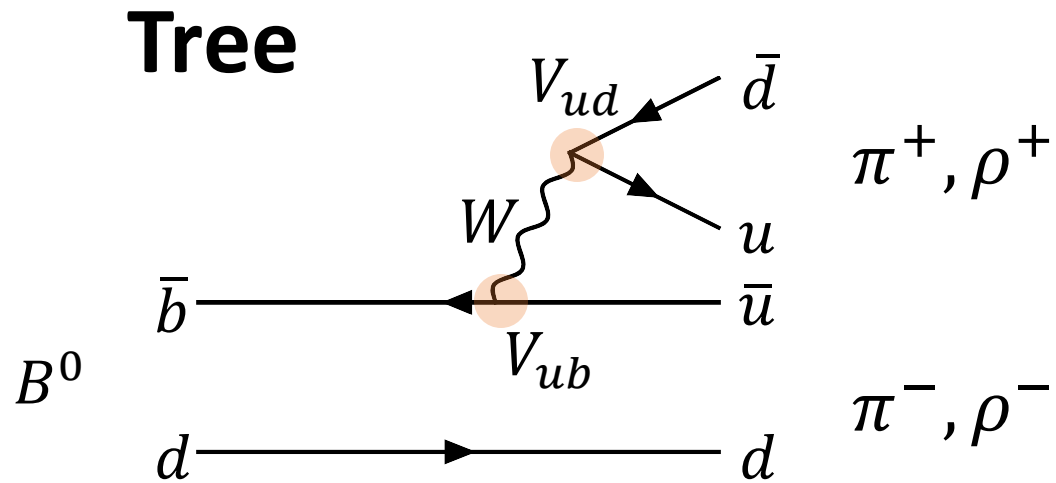


C_{BDT} : $q\bar{q}$ suppression output

ϕ_2

ϕ_2 Measurement

$$\phi_2 = \arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*]$$



$$\frac{\Gamma(\bar{B}^0 \rightarrow f) - \Gamma(B^0 \rightarrow f)}{\Gamma(\bar{B}^0 \rightarrow f) + \Gamma(B^0 \rightarrow f)} = -C \cos \Delta m_d \Delta t + S \sin \Delta m_d \Delta t$$

Using $b \rightarrow u$ tree decays (ex. $B^0 \rightarrow \pi^+ \pi^-, \rho^+ \rho^-$), $S = \sin(2\phi_2)$, $C = 0$

Due to the interference between and tree and loop ($b \rightarrow d$), $S = \sin(2\phi_2 + 2\Delta\phi_2)$, $C \neq 0$

Need to extract the effect from the loop amplitude

Isospin analysis

Isospin relations

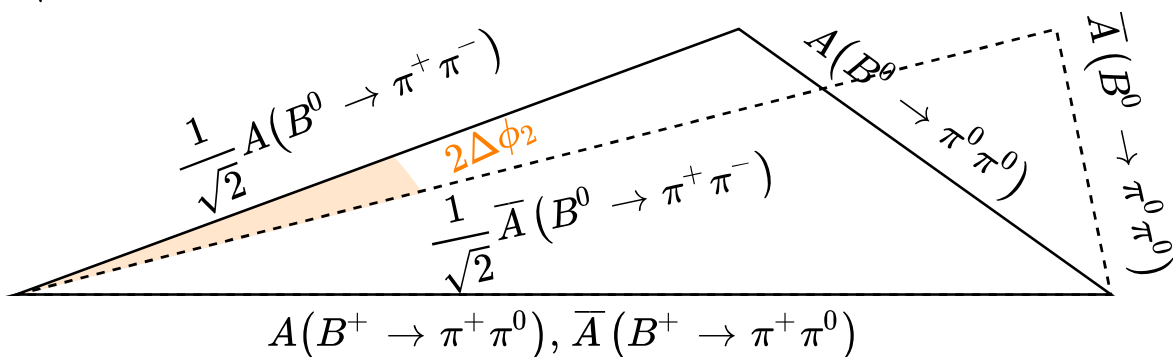
	Tree	Loop	
$\pi^+\pi^-$	○	○	
$\pi^+\pi^0$	○	×	○: Large contribution ×: No contribution
$\pi^0\pi^0$	△	○	△: Smaller contribution

(color suppressed)

Granou-London isospin relations

$$\frac{1}{\sqrt{2}} A(B^0 \rightarrow \pi^+\pi^-) - A(B^0 \rightarrow \pi^0\pi^0) = A(B^+ \rightarrow \pi^+\pi^0)$$

$$\frac{1}{\sqrt{2}} \bar{A}(B^0 \rightarrow \pi^+\pi^-) - \bar{A}(B^0 \rightarrow \pi^0\pi^0) = \bar{A}(B^+ \rightarrow \pi^+\pi^0)$$



$\Delta\phi_2$ can be extracted using this relationship

Observables to measure ϕ_2

$$\pi^+\pi^-, \rho^+\rho^- \quad \text{BF, S, C}$$

$$\pi^+\pi^0, \rho^+\rho^0 \quad \text{BF, } A_{\text{cp}}$$

$$\pi^0\pi^0, \rho^0\rho^0 \quad \text{BF, } A_{\text{cp}} \text{ or C, } S(\text{only } \rho^0\rho^0)$$

- $\pi^0\pi^0, \rho^+\rho^0$, and $\rho^+\rho^-$ analyses **need π^0 reconstruction**
→ Belle II has an advantage
- $\rho\rho$ has **much smaller loop** contribution
→ Dominates ϕ_2 precision.
- $B \rightarrow \rho\rho$ is $P \rightarrow VV$ decay
Longitudinal has CP-even, and transverse is a mixture of CP-even and CP-odd.
Angular analysis is needed to extract polarization.

$B^0 \rightarrow \pi^+ \pi^-$ and $B^+ \rightarrow \pi^+ \pi^0$

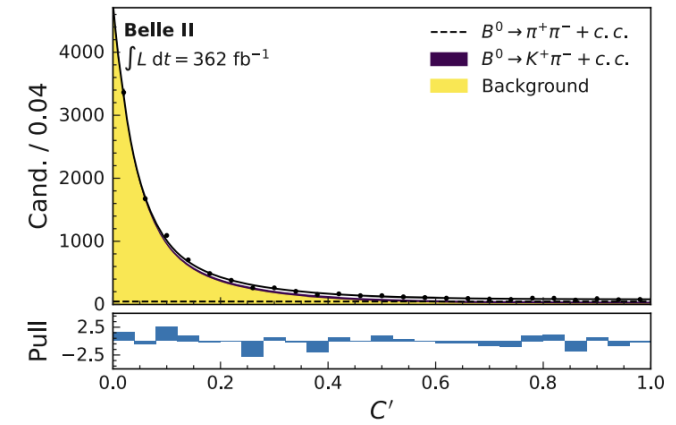
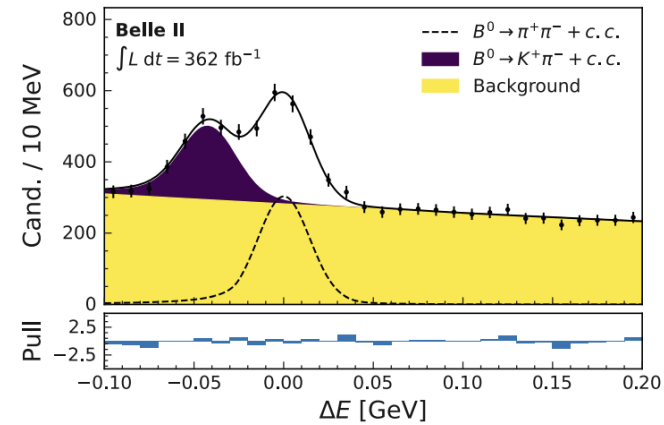
[PhysRevD.109.012001](https://arxiv.org/abs/PhysRevD.109.012001)

Good agreement with previous measurements

Sensitivity is comparable with Belle using only half of Belle's data!

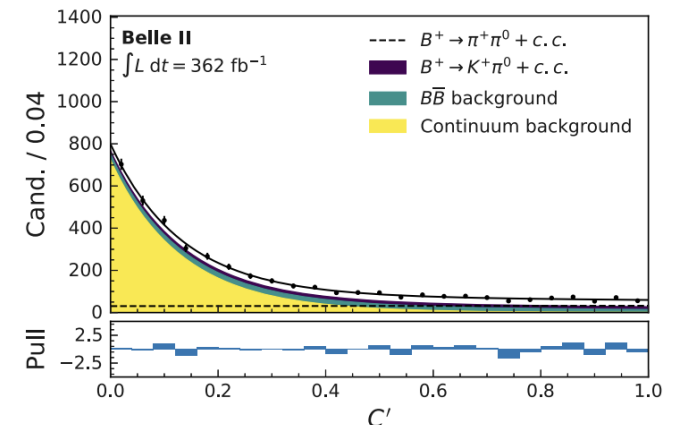
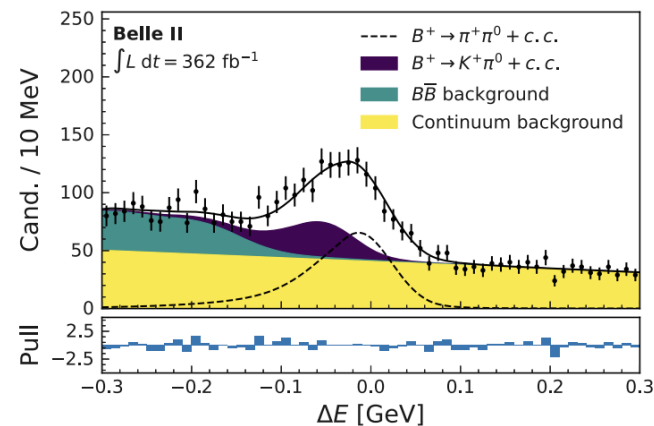
$\pi^+ \pi^-$

	$\mathcal{B}(\times 10^{-6})$	N_{BB}
Belle II	$5.83 \pm 0.22 \pm 0.17$	388×10^6
Belle	$5.04 \pm 0.21 \pm 0.18$	772×10^6
BABAR	$5.5 \pm 0.4 \pm 0.3$	383.6×10^6



$\pi^+ \pi^0$

	$\mathcal{B}(\times 10^{-6})$	A_{cp}	N_{BB}
Belle II	$5.10 \pm 0.29 \pm 0.27$	$-0.081 \pm 0.054 \pm 0.008$	388×10^6
Belle	$5.86 \pm 0.26 \pm 0.38$	$0.025 \pm 0.043 \pm 0.007$	772×10^6
BABAR	$5.02 \pm 0.46 \pm 0.29$	$0.03 \pm 0.08 \pm 0.01$	383.6×10^6



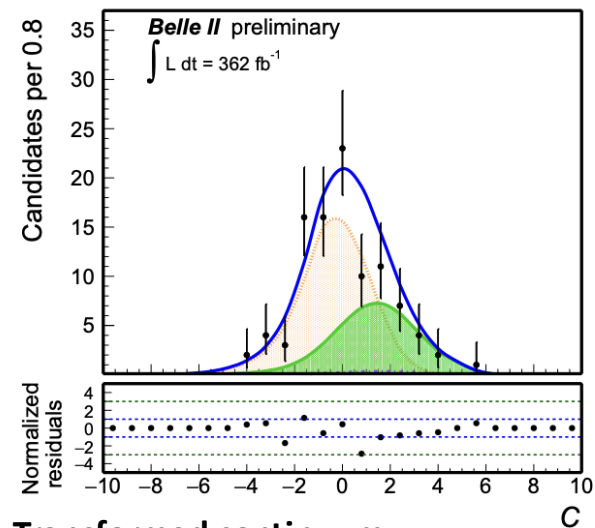
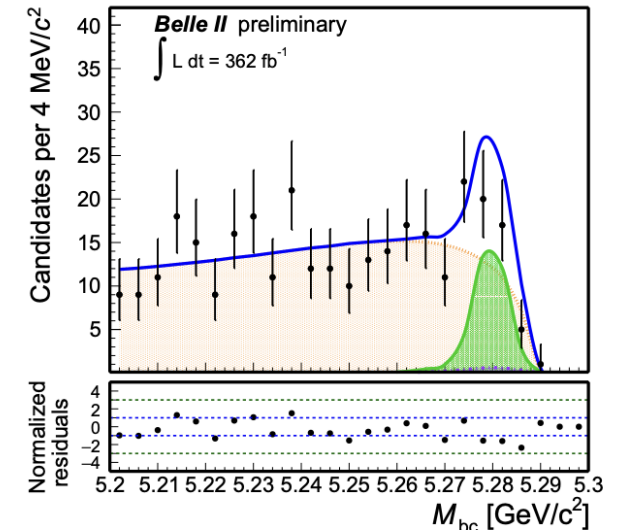
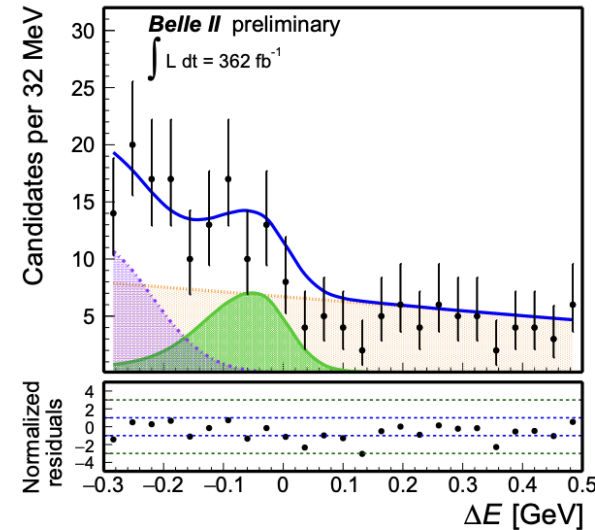
C' : Transformed continuum suppression output
CP violation, 2024/10/22, 35th Rencontres de Blois, Ryogo Okubo

$B^0 \rightarrow \pi^0 \pi^0$

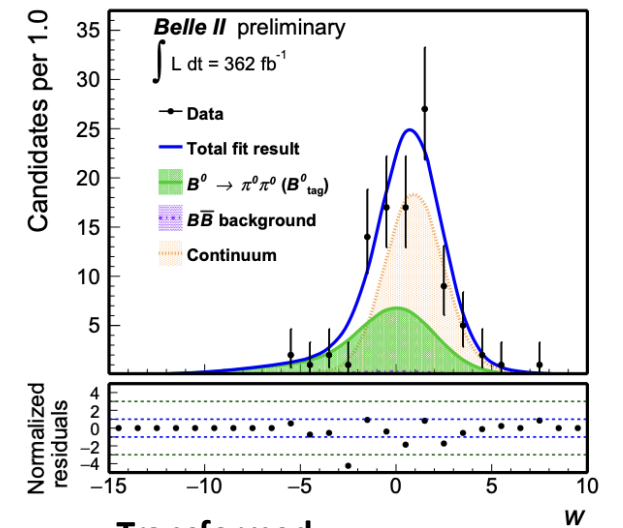
- Require 4γ reconstruction (**Unique to Belle II**) from a large background due to hadronic clusters, beam background
→ Developed an MVA for γ selection
- Improved sensitivity by GFlaT.

	$B(\times 10^{-6})$	C	N_{BB}
Belle II	$1.26 \pm 0.20 \pm 0.12$	$-0.06 \pm 0.30 \pm 0.05$	388×10^6
Belle	$1.31 \pm 0.19 \pm 0.19$	$-0.14 \pm 0.36 \pm 0.10$	772×10^6
BABAR	$1.83 \pm 0.21 \pm 0.13$	$-0.43 \pm 0.26 \pm 0.05$	383.6×10^6

Consistent with previous experiments and
Comparable sensitivity with small statistics.



Transformed continuum
suppression output



Transformed
wrong flavor tag probability

$$B^0 \rightarrow \rho^+ \rho^- \mathcal{B} \text{ and } f_L = \frac{\mathcal{B}(\text{Long.})}{\mathcal{B}(\text{Long.}) + \mathcal{B}(\text{Trans.})} \quad \text{NEW}$$

Analysis challenge

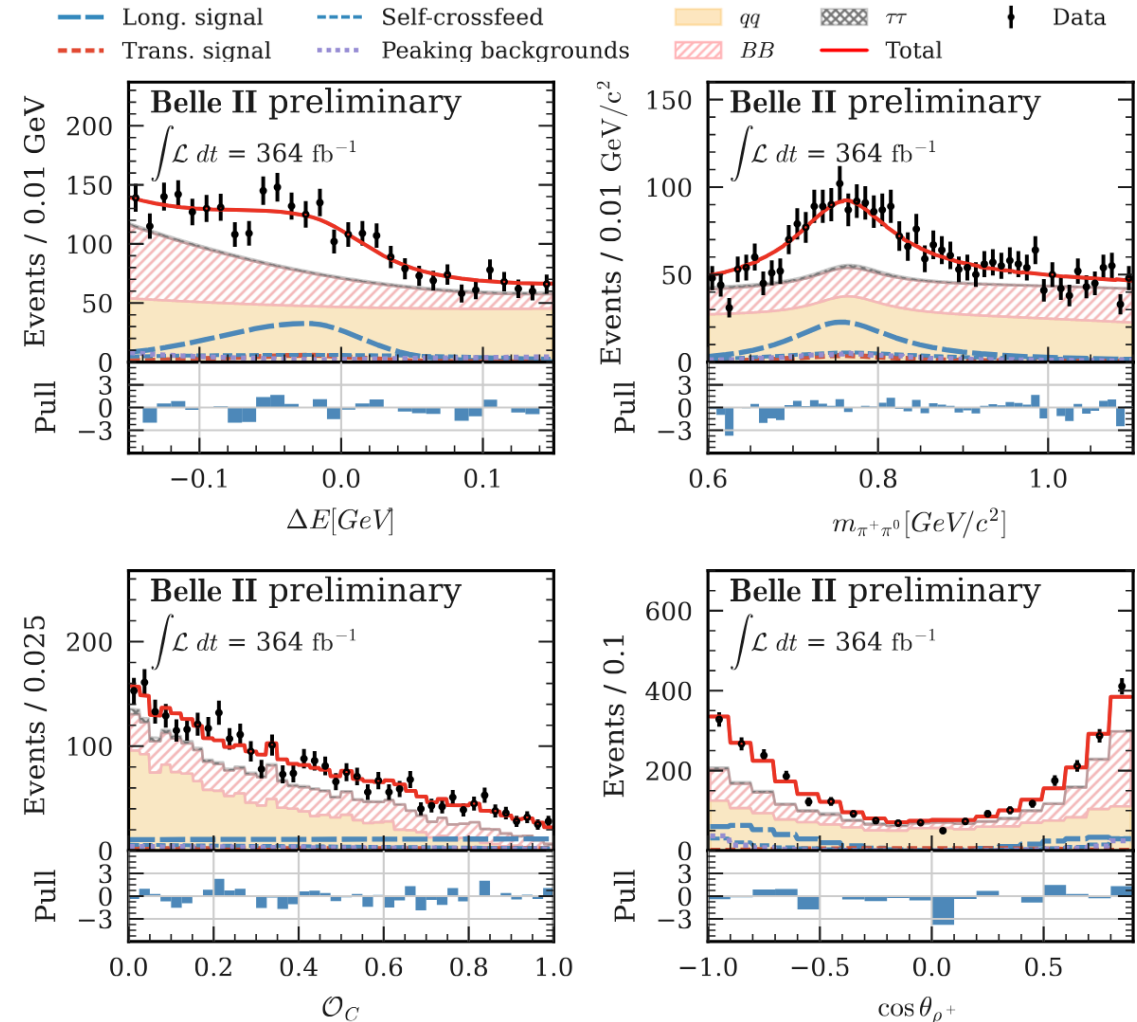
- $B \rightarrow \rho\rho$ is $P \rightarrow VV$ decay
→ Angular analysis is needed for polarization extraction.
- π^0 selection
Needs two soft π^0 reconstruction from ρ
→ Suppressed backgrounds using machine learning technique
- **Continuum suppression**
Large qq background was suppressed by TabNet
(a kind of neural network, [arXiv:1908.07442](https://arxiv.org/abs/1908.07442))

 $\mathcal{B}(10^{-6})$
 f_L

Belle II	$29.0^{+2.3}_{-2.2} \quad ^{+3.1}_{-3.0}$	$0.921^{+0.024}_{-0.025} \quad ^{+0.017}_{-0.015}$
Belle	$28.3 \pm 1.5 \pm 1.5$	$0.988 \pm 0.012 \pm 0.006$
BABAR	$25.5 \pm 2.1 \quad ^{+3.6}_{-3.9}$	$0.992 \pm 0.024 \quad ^{+0.026}_{-0.013}$

Consistent with previous experiments → Extract CPV parameters

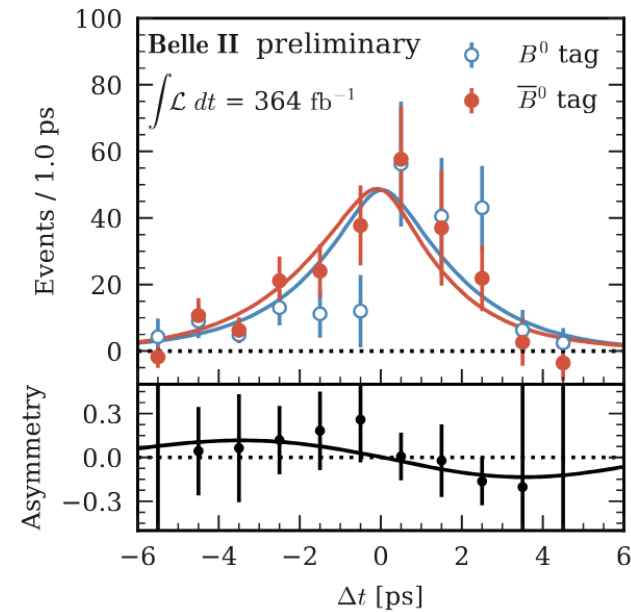
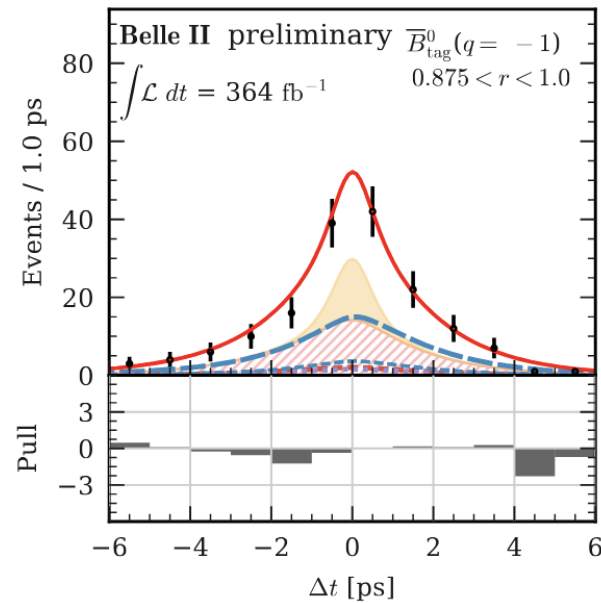
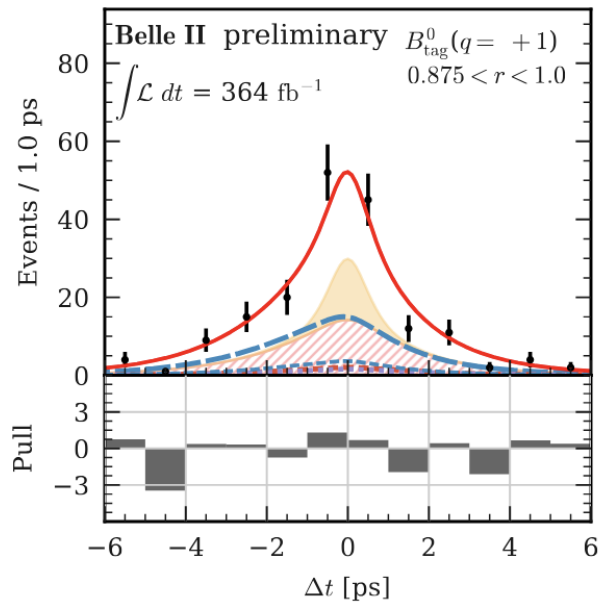
6D Fit for signal Extraction



$B^0 \rightarrow \rho^+ \rho^-$ CPV + Constraint on ϕ_2

NEW

— Long. signal - - - Self-crossfeed BB $\tau\tau$ \downarrow Data
 Trans. signal Peaking backgrounds qq Total

 S C

Belle II	$-0.26 \pm 0.19 \pm 0.08$	$-0.02 \pm 0.12^{+0.06}_{-0.05}$
Belle	$-0.13 \pm 0.15 \pm 0.05$	$0.00 \pm 0.10 \pm 0.06$
BABAR	$-0.17 \pm 0.20^{+0.05}_{-0.06}$	$0.01 \pm 0.15 \pm 0.06$

- Consistent with previous experiments
 - Improved precision by GFlaT flavor tagger and better selection criteria
- Extract ϕ_2 using the new result.

ϕ_2 extraction

NEW

$B \rightarrow \rho\rho$ world average

$$\phi_2 = (91.5^{+4.5}_{-5.4})^\circ$$

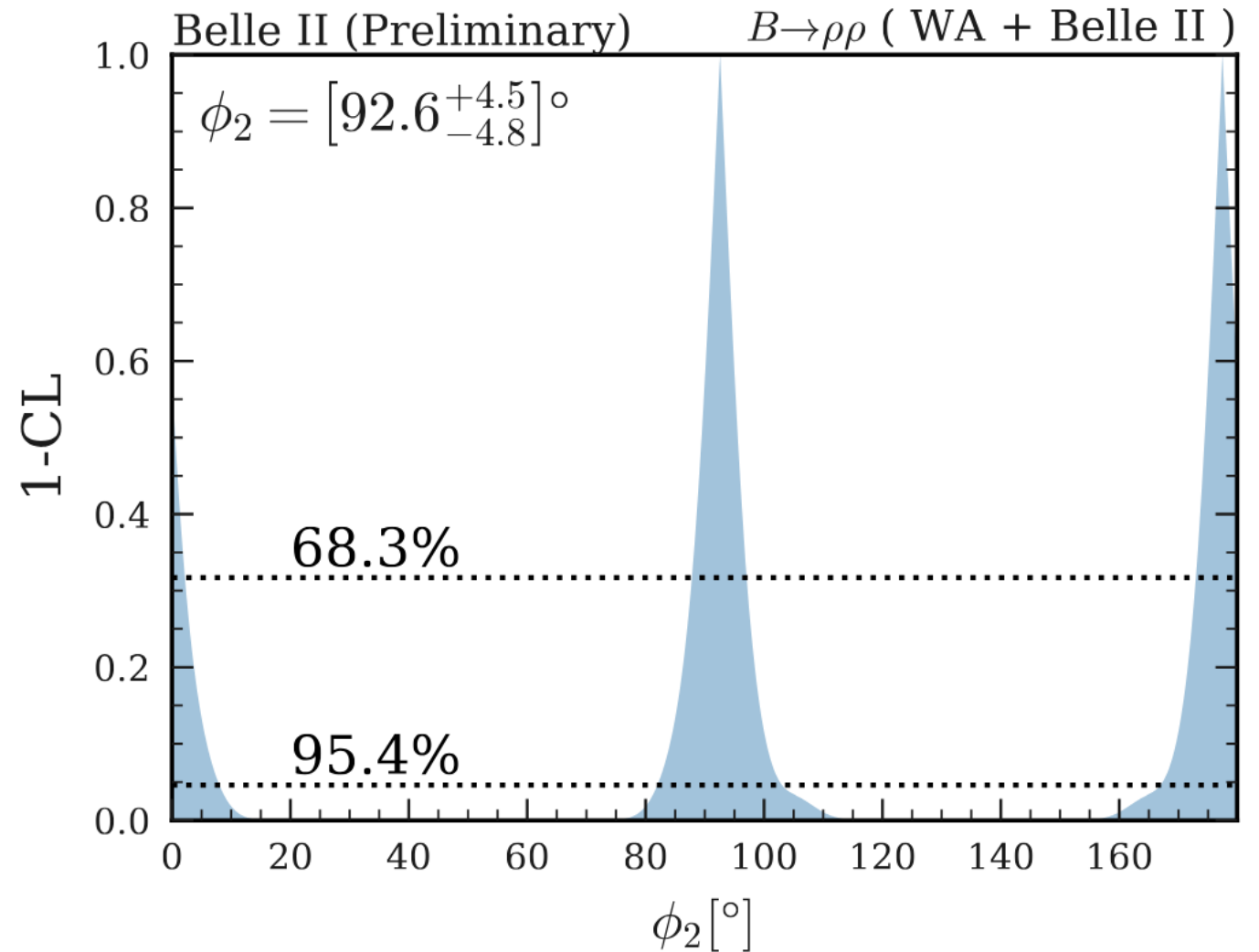
$B \rightarrow \rho\rho$ world average

+ Belle II $\rho^+\rho^-$ results

$$\rightarrow \phi_2 = (92.6^{+4.5}_{-4.8})^\circ$$

6% improvement by Belle II results!

Dominated by S of $\rho^+\rho^-$ and $\rho^0\rho^0$.



Charm CPV

- CPV in charm is very small in SM
- LHCb found the CPV in $D \rightarrow \pi\pi, KK \rightarrow$ Is this within the SM prediction?

Charm CPV search is ongoing in both **Belle II** and **LHCb**

$D_{(S)}^0 \rightarrow K_S^0 \pi^- \pi^+$ (Belle + Belle II)

- CPV measurement based on triple and quadruple products of momenta

In C_{TP} ,

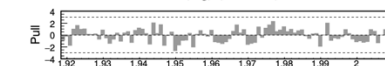
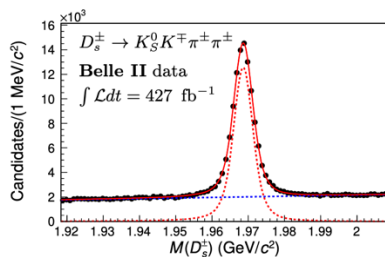
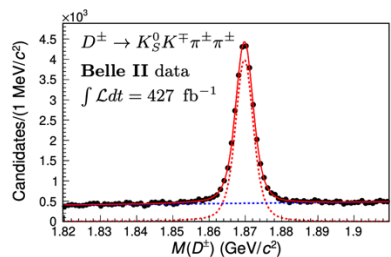
- $A_{CP}(D^+) = (-2.3 \pm 4.5 \pm 1.5) \times 10^{-3}$
- $A_{CP}(D_{(S)}^+) = (+0.2 \pm 2.4 \pm 0.8) \times 10^{-3}$

$$C_{TP} = (\vec{p}_{K^-} \times \vec{p}_{\pi_h^+}) \cdot \vec{p}_{K_S^0},$$

[arXiv:2409.15777](https://arxiv.org/abs/2409.15777)

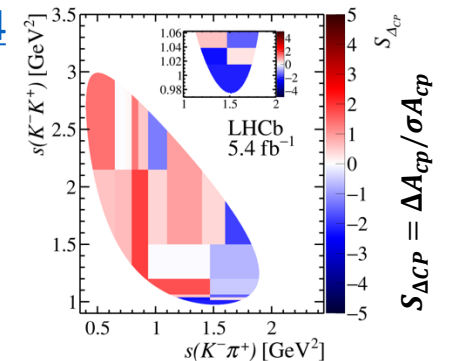
$$C_{QP} = (\vec{p}_{K^-} \times \vec{p}_{\pi_h^+}) \cdot (\vec{p}_{K_S^0} \times \vec{p}_{\pi_l^+}),$$

Submitted to JHEP



$D^+ \rightarrow K^- K^+ \pi^+$ (LHCb) [arXiv:2409.01414](https://arxiv.org/abs/2409.01414)

- CPV search in Dalitz plane
- Model-independent approach
- $\chi^2 / \text{ndf} = 31.8 / 22$
- P-value(CP conservation hypothesis): 8.1%



$D^0 \rightarrow K^+ \pi^-$ (LHCb) [arXiv:2407.18001](https://arxiv.org/abs/2407.18001)

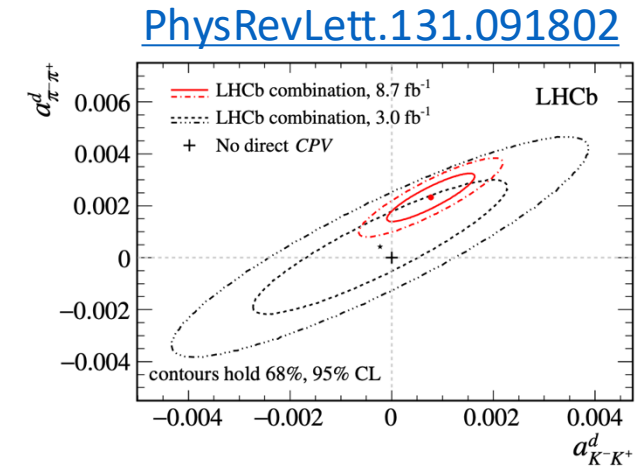
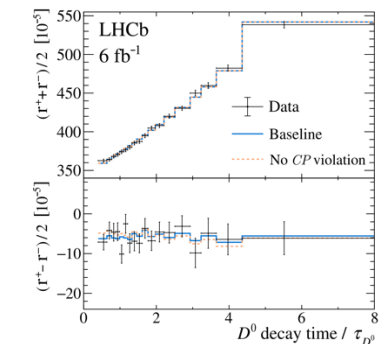
- Direct CPV search + mixing measurement

$$R_{K\pi}^\pm(t) \approx R_{K\pi} (1 \pm A_{K\pi}) + \sqrt{R_{K\pi} (1 \pm A_{K\pi})} (c_{K\pi} \pm \Delta c_{K\pi}) t + (c'_{K\pi} \pm \Delta c'_{K\pi}) t^2$$

Parameters

$R_{K\pi}$	$(342.7 \pm 1.9) \times 10^{-5}$
$c_{K\pi}$	$(52.8 \pm 3.3) \times 10^{-4}$
$c'_{K\pi}$	$(12.0 \pm 3.5) \times 10^{-6}$
$A_{K\pi}$	$(-6.6 \pm 5.7) \times 10^{-3}$
$\Delta c_{K\pi}$	$(2.0 \pm 3.4) \times 10^{-4}$
$\Delta c'_{K\pi}$	$(-0.7 \pm 3.6) \times 10^{-6}$

- No CPV was observed
- c' : 3.4 σ evidence



Summary

- Belle II is a high-luminosity e^+e^- collider experiments that have already collected **531 fb⁻¹** of data (equivalent of BaBar, half of Belle data)
- Belle II is improving the CP violation measurements improved detectors, and improved analysis technique.
- New GNN-based flavor tagger improved effective tagging efficiency by **18%**.
- ϕ_1 : $B^0 \rightarrow J/\Psi K_S^0, B^0 \rightarrow \eta' K_S^0, B^0 \rightarrow J/\Psi \pi^0$.
 $B^0 \rightarrow J/\Psi \pi^0$: Significant improvement, and obtained most precise result!
- ϕ_2 : $B \rightarrow \pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0, B^+ \rightarrow \rho^+\rho^0, B^0 \rightarrow \rho^+\rho^-$
 $\rho^+\rho^-$: New result, improved precision, first ϕ_2 extraction with improved precision!
- ϕ_3 : First Belle + Belle II combined analysis with improved sensitivity!
- Charm: $D_{(s)}^0 \rightarrow K_S^0 \pi^- \pi^+$ (Belle + Belle II), $D^+ \rightarrow K^- K^+ \pi^+$ (LHCb), $D^0 \rightarrow K^+ \pi^-$ (LHCb)

Related papers:

Measurement of CP asymmetries in $B^0 \rightarrow K_S^0 \pi^0 \gamma$ decays at Belle II [arXiv:2407.09139](https://arxiv.org/abs/2407.09139) Submitted to PRL

Measurement of CP asymmetries in $B^0 \rightarrow K_S^0 K_S^0 K_S^0$ decays at Belle II [Phys. Rev. D 109, 112020 \(2024\)](https://arxiv.org/abs/2407.09139)

Measurement of CP asymmetries in $B^0 \rightarrow \phi K_S^0$ with Belle II [Phys. Rev. Lett. 131, 121802 \(2023\)](https://arxiv.org/abs/2407.09139)

Measurement of CP asymmetries and branching-fraction ratios for $B^\pm \rightarrow DK^\pm$ and $D\pi^\pm$ with $D \rightarrow K_S^0 K^\pm \pi^\mp$ using Belle and Belle II data [JHEP 09 \(2023\) 146](https://arxiv.org/abs/2407.09139)

Measurement of CP violation in $B^0 \rightarrow D^+ D^-$ and $B_s^0 \rightarrow D_s^+ D_s^-$ decays (LHCb) [arXiv:2409.03009](https://arxiv.org/abs/2407.09139)

Systematic uncertainty

$$B^0 \rightarrow J/\Psi K_S^0$$

$$B^0 \rightarrow J/\Psi \pi^0$$

TABLE I. Systematic and statistical uncertainties on ϵ_{tag} for $B^0 \rightarrow D^{(*)-}\pi^+$ and, S and C for $B^0 \rightarrow J/\psi K_S^0$.

Source	ϵ_{tag} [%]	S	C
Detector alignment	0.08	0.005	0.003
Interaction region	0.16	0.002	0.002
Beam energy	0.03	<0.001	0.001
ΔE -fit background model	0.11	0.001	0.001
ΔE -fit signal model	0.08	0.003	0.006
s Weight background subtraction	0.24	0.001	0.001
Fixed resolution-function parameters	0.07	0.004	0.004
τ and Δm_d	0.06	0.001	<0.001
$\sigma_{\Delta t}$ binning	0.04	<0.001	<0.001
Δt -fit bias	0.09	0.002	0.005
CP violation in B_{tag} decay		<0.001	0.027
$B^0 \rightarrow D^{(*)-}\pi^+$ sample size		0.004	0.007
Total systematic uncertainty	0.36	0.009	0.029
Statistical uncertainty	0.43	0.035	0.026

Table III: Systematic uncertainties on the CP asymmetries compared with the statistical uncertainties.

Source	C_{CP}	$-\eta_f S_{CP}$
Calibration with $B^0 \rightarrow D^{*-}\pi^+$	0.017	0.023
Signal extraction fit	0.003	0.017
Backgrounds composition	0.005	0.009
Backgrounds Δt shapes	< 0.001	0.001
Fit bias	0.010	0.010
Multiple candidates	< 0.001	0.002
Tracking detector misalignment	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	0.123	0.171

Systematic uncertainty ($B^0 \rightarrow \eta' K_S^0$)

Table II: Summary of systematic uncertainties for $C_{\eta'K_S^0}$ and $S_{\eta'K_S^0}$.

Source	$C_{\eta'K_S^0}$	$S_{\eta'K_S^0}$
Signal and continuum yields	< 0.001	0.002
SxF and $B\bar{B}$ yields	< 0.001	0.006
C_{BDT} mismodeling	0.004	0.010
Signal and background modeling	0.020	0.014
Observable correlations	0.008	0.001
Δt resolution fixed parameters	0.005	0.009
Δt resolution model	0.004	0.019
Flavor tagging	0.007	0.004
τ_{B^0} and Δm_d	< 0.001	0.002
Fit bias	0.003	0.002
Tracker misalignment	0.004	0.006
Momentum scale	0.001	0.001
Beam spot	0.002	0.002
B -meson motion in the $\Upsilon(4S)$ frame	< 0.001	0.017
Tag-side interference	0.005	0.011
$B\bar{B}$ background asymmetry	0.008	0.006
Candidate selection	0.007	0.009
Total	0.027	0.037

Systematic uncertainty ($B \rightarrow \pi^+ \pi^-, \pi^+ \pi^0$)

Branching fraction

Source	$B^0 \rightarrow \pi^+ \pi^-$	$B^+ \rightarrow \pi^+ \pi^0$
Tracking	0.5	0.2
$N_{B\bar{B}}$	1.5	1.5
$f^{+-/00}$	2.5	2.4
π^0 efficiency		3.8
K_S^0 efficiency		
CS efficiency	0.2	0.7
PID correction	0.1	0.2
ΔE shift and scale	0.2	2.0
$K\pi$ signal model	0.2	<0.1
$\pi\pi$ signal model	0.1	<0.1
$K\pi$ feed-across model	0.1	0.1
$\pi\pi$ feed-across model	0.2	0.1
$K_S^0 K^+$ model		
$B\bar{B}$ model		0.5
$q\bar{q}$ flavor model		
Multiple candidates	< 0.1	0.3
Total	3.0	5.2

Direct CPV

Source	$B^+ \rightarrow \pi^+ \pi^0$
ΔE shift and scale	0.002
$K_S^0 K^+$ model	
$B\bar{B}$ background asymmetry	
$q\bar{q}$ background asymmetry	
$q\bar{q}$ flavor model	
Fitting bias	0.007
Instrumental asymmetry	0.004
Total	0.008

Systematic uncertainty ($B^0 \rightarrow \pi^0 \pi^0$)

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
$B\bar{B}$ -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

Systematic uncertainty ($B^+ \rightarrow \rho^+ \rho^0$)

Source	\mathcal{B}	f_L	\mathcal{A}_{CP}
Tracking	0.9%	n/a	n/a
π^0 efficiency	5.7%	n/a	n/a
PID and continuum-supp. eff.	1.2%	n/a	n/a
$N_{B^+ B^-}$	3.1%	n/a	n/a
Instrumental asymmetry correction	n/a	n/a	0.005
Single candidate selection	2.2%	1.1%	0.037
Signal model	0.10%	0.02%	0.002
Continuum bkg. model	0.04 %	1.2%	0.003
$B\bar{B}$ bkg. model	0.05%	0.08%	0.002
Fit biases	4.4%	1.1%	0.010
Data-simulation mismodeling	8.0%	2.1%	0.002
Peaking background CP asymmetries	0.3%	0.1%	0.046
Total	11.5%	2.9%	0.060

Systematic uncertainty ($B^0 \rightarrow \rho^+ \rho^-$)

Source	\mathcal{B} [%]	$f_L[10^{-2}]$
Tracking	± 0.54	—
π^0 eff.	± 7.67	—
PID	± 0.08	—
\mathcal{T}_C	± 2.87	—
MC stat.	± 0.24	± 0.2
f_{+-}/f_{00}	± 2.60	—
N_{BB}	± 1.45	—
Best candidate selection	± 0.55	± 0.3
SxF ratio	$+2.97$ -2.45	$+0.2$ -0.3
\mathcal{B} 's of peaking backgrounds	$+0.94$ -0.98	± 0.1
$\tau^+ \tau^-$ background yield	$+0.65$ -0.69	± 0.0
Signal model	$+1.14$ -2.02	± 0.2
$q\bar{q}$ model	$+0.49$ -0.51	$+0.1$ -0.2
$B\bar{B}$ model	$+1.00$ -0.40	$+0.3$ -0.1
$\tau^+ \tau^-$ model	$+0.17$ -0.26	$+0.0$ -0.1
Peaking model	$+1.37$ -1.01	$+0.3$ -0.5
Interference	± 1.20	± 0.5
Data-MC mis-modeling	$+3.51$ -1.70	$+0.8$ -0.3
Fit bias	± 1.03	± 1.2
Total systematic uncertainty	$+10.29$ -9.75	$+1.7$ -1.5
Statistical uncertainty	$+7.93$ -7.58	$+2.4$ -2.5

Source	$S[10^{-2}]$	$C[10^{-2}]$
\mathcal{B} 's of peaking backgrounds	$+0.6$ -0.5	± 0.1
$\tau\tau$ background yield	± 0.9	$+0.0$ -0.1
Data-MC mis-modeling	$+0.6$ -1.1	$+1.5$ -0.6
Best candidate selection	± 1.3	± 1.9
SxF ratio	$+0.5$ -0.4	$+0.7$ -0.0
Signal model	$+1.1$ -1.4	$+0.3$ -0.4
$q\bar{q}$ model	$+2.2$ -1.0	± 0.2
$B\bar{B}$ model	± 0.9	$+0.7$ -0.5
$\tau\tau$ model	± 0.1	± 0.0
Peaking model	$+0.8$ -0.4	$+0.2$ -0.4
Fit bias	± 2.0	± 0.6
Interference	± 2.8	± 1.7
Resolution	$+3.4$ -4.4	$+1.9$ -1.4
Event fraction	$+0.9$ -1.0	± 0.6
Δt PDF for $q\bar{q}$ and $B\bar{B}$	$+3.8$ -1.8	$+0.7$ -0.1
Physics Parameters	$+1.4$ -1.6	± 0.3
Tag side interference	± 0.5	± 2.1
Wrong tag fraction	$+0.2$ -0.3	± 0.5
Background CP Violation	$+3.8$ -3.6	$+4.2$ -3.7
CP Violation in TP signal	$+0.8$ -0.2	$+0.2$ -0.4
Mis-Alignment	± 1.4	± 0.5
Total systematic uncertainty	$+8.3$ -7.8	$+6.1$ -5.4
Statistical uncertainty	± 18.8	± 12.1

$$B^0 \rightarrow \rho^+ \rho^0$$

arXiv:2206.12362

$B \rightarrow \rho\rho$: Another way for ϕ_2 extraction

$B^0 \rightarrow \rho^+ \rho^-$ has much smaller loop contribution compared to $\pi\pi$

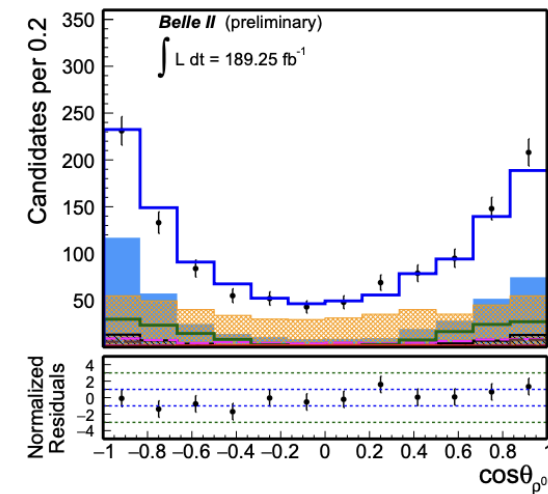
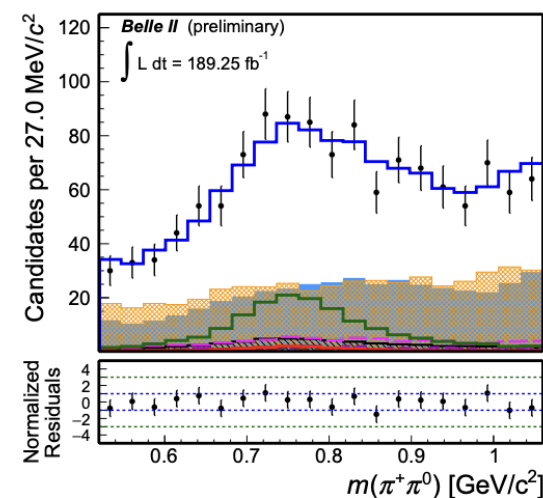
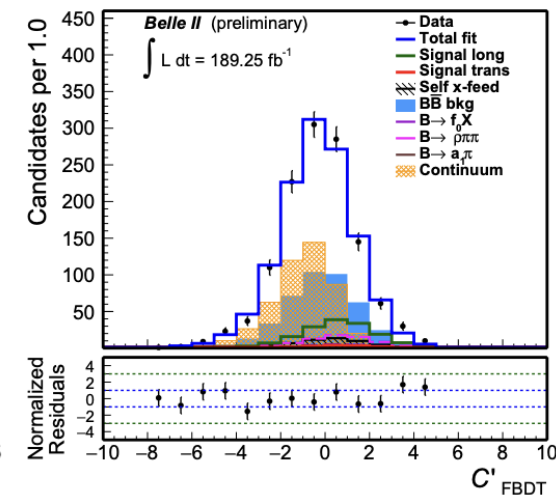
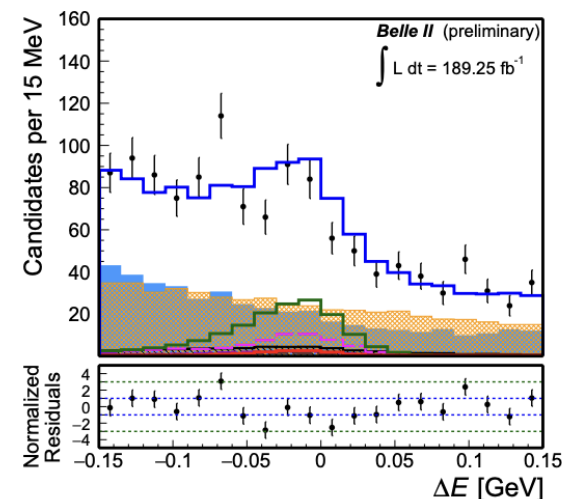
$\rightarrow \rho\rho$ system has a better sensitivity to ϕ_2

	$\mathcal{B}(10^{-6})$	f_L
Belle II	$23.2^{+2.2}_{-2.1} \pm 2.7$	$0.943^{+0.035}_{-0.033} \pm 0.027$
Belle	$31.7 \pm 7.1^{+3.8}_{-6.7}$	$0.948 \pm 0.106 \pm 0.021$
BABAR	$23.7 \pm 1.4 \pm 1.4$	$0.950 \pm 0.015 \pm 0.006$

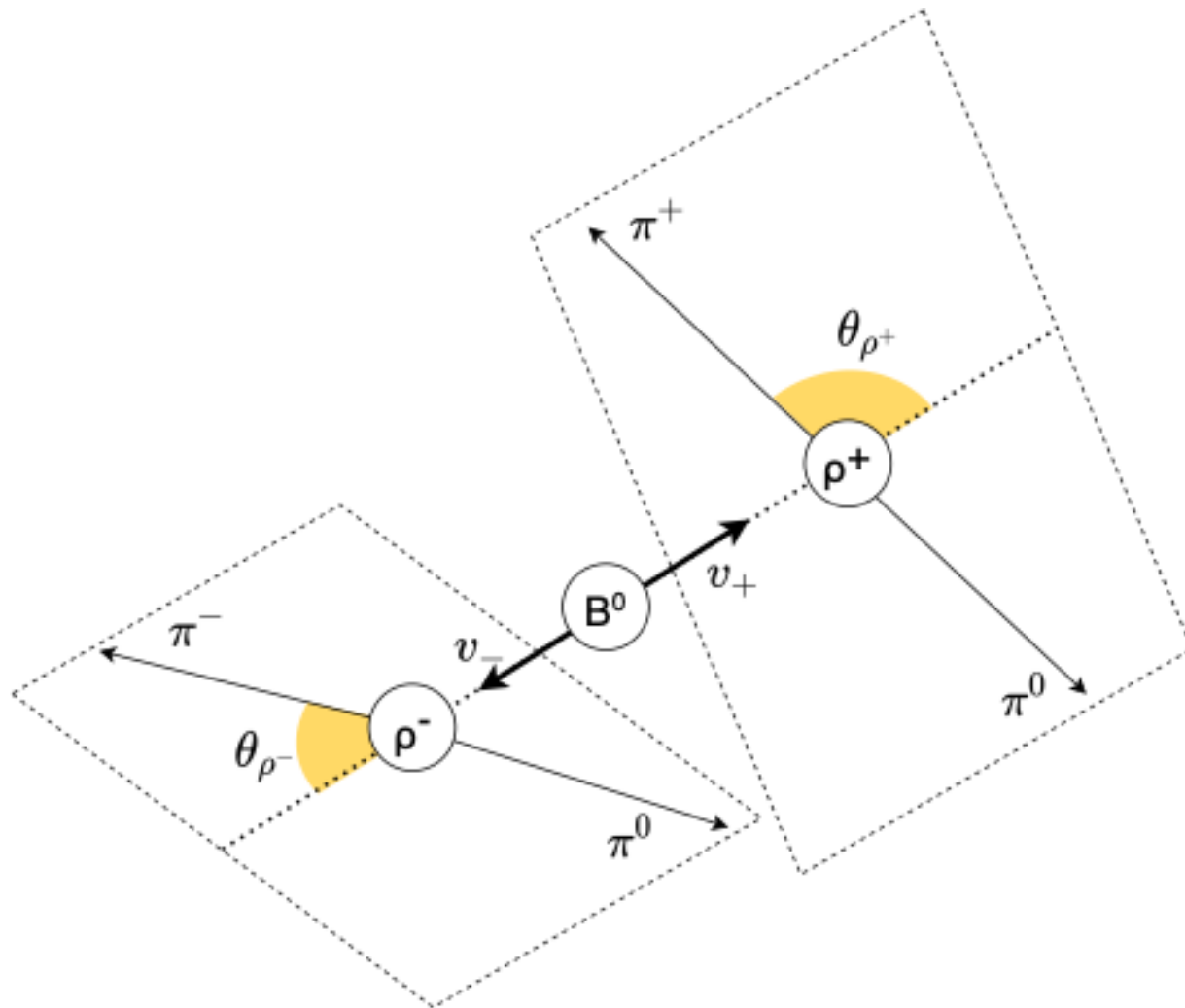
Good agreement with previous experiments.

Belle analysis was done with only 78fb^{-1} Data

\rightarrow Needs to be improved by Belle II



Definition of the cosine helicity angle



$\cos\theta_\rho$:

Cosine of the angle between π^+ and B^0 boost direction in ρ^\pm CMS frame.