

# CP violation

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



# Unitarity triangle

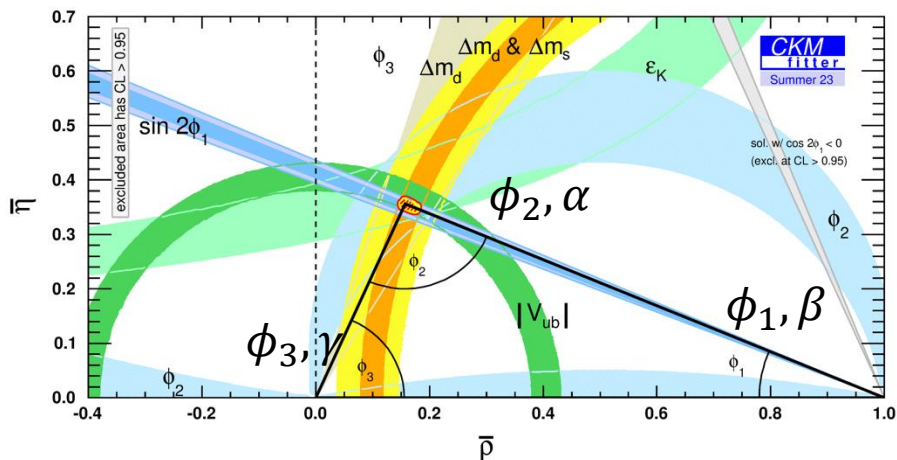
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



**Unitarity**

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

Belle II can measure all  $\phi_1, \phi_2$ , and  $\phi_3$



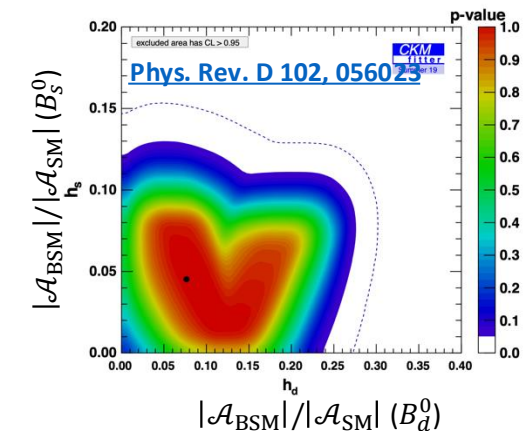
Unitarity triangle parameters measurement at Belle II

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)

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

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

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

$\phi_2$  has the largest uncertainty

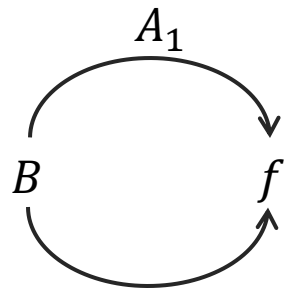
# CP violation

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

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



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

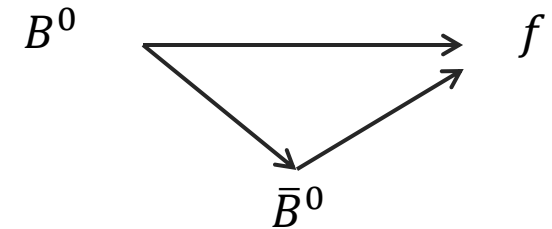
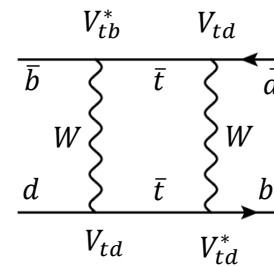
$$|\mathcal{A}(\bar{B} \rightarrow \bar{f})| = |A_1 + A_2 \exp(i(-\phi + \delta))|$$

$\phi$ : Weak phase difference  
 $\delta$ : Strong phase difference

## Mixing-induced CPV

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

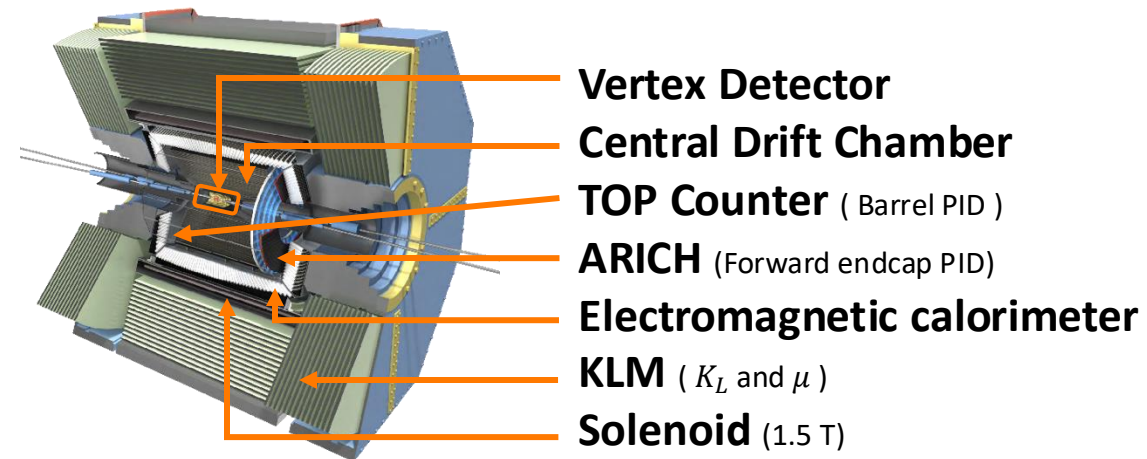
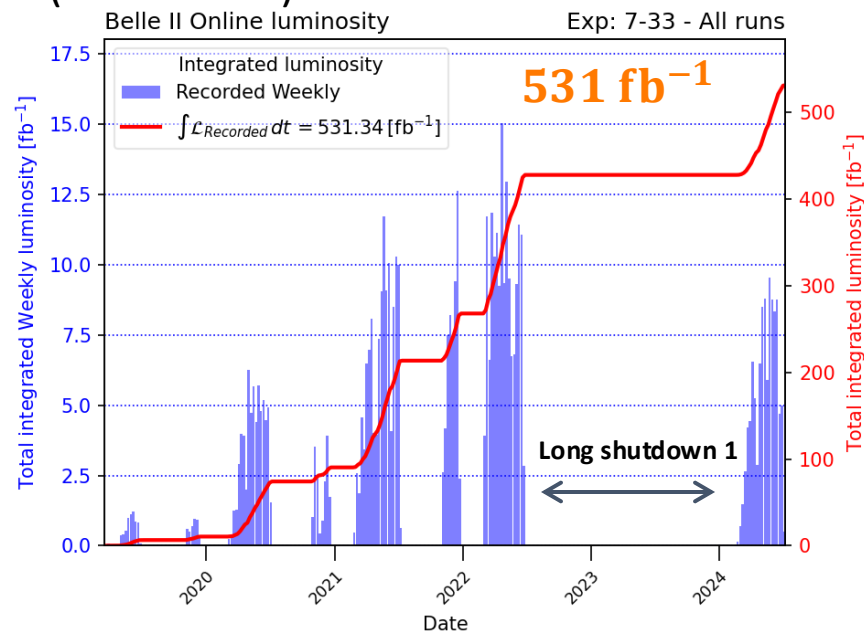
$B^0 - \bar{B}^0$  mixing



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

# Belle II experiment at SuperKEKB

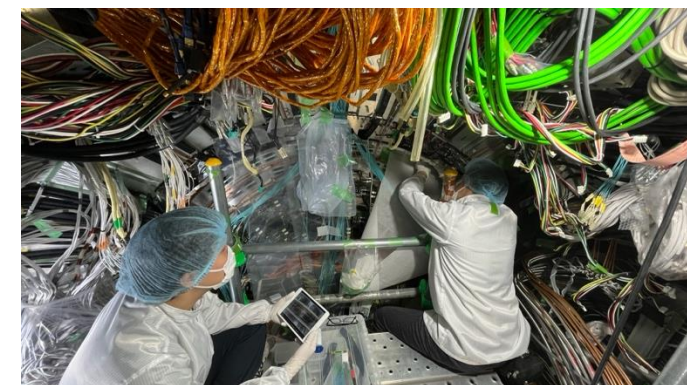
- High luminosity  $e^-e^+$  collider experiment at a center of mass energy of 10.58 GeV.
- Target integrated Luminosity:  $50 \text{ ab}^{-1}$
- Target peak luminosity:  $6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
- Integrated  **$531 \text{ fb}^{-1}$**
- Achieved Peak luminosity  **$4.7 \times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



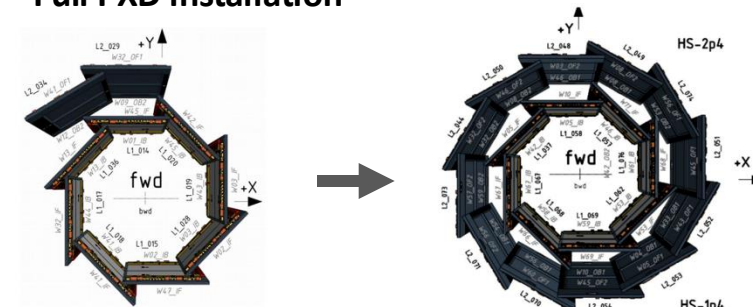
## Long shutdown 1 2022-2023

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

## TOP PMT replacement during long shutdown1



## Full PXD installation



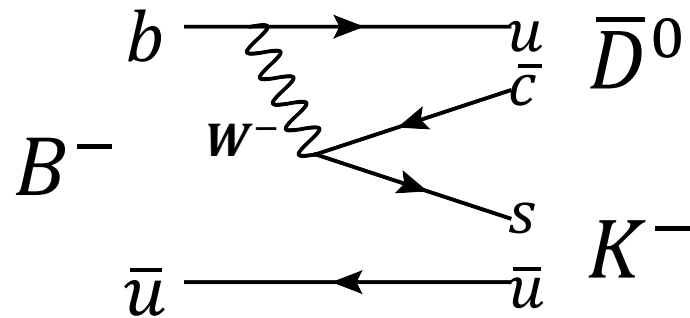
$\phi_3$

# $\phi_3$ 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.

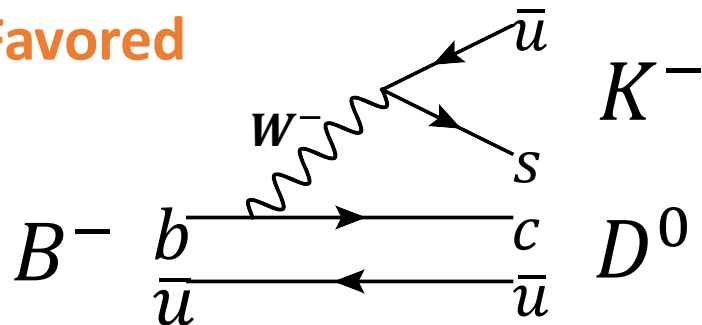
## Suppressed



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

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

## Favored



## Methods to measure $\phi_3$ 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  $\mathcal{B}$  ratio

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

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

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

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

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



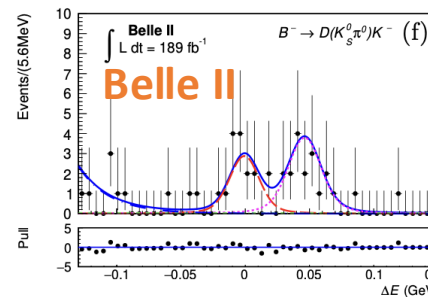
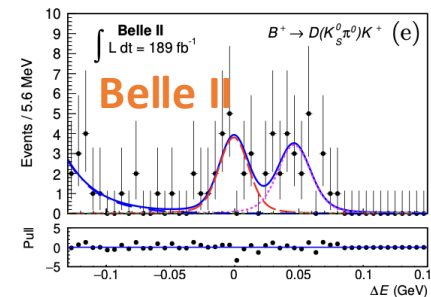
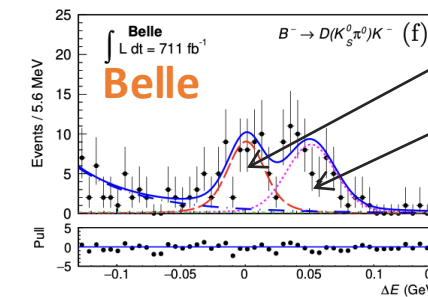
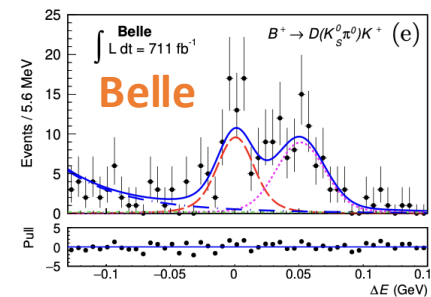
$$\mathcal{R}_{CP\pm} = 1 + r_B^2 \pm 2r_B \cos \delta_B \cos \phi_3,$$

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

(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



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

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

$$\mathcal{A}_{CP+} = (+12.5 \pm 5.8 \pm 1.4)\%,$$

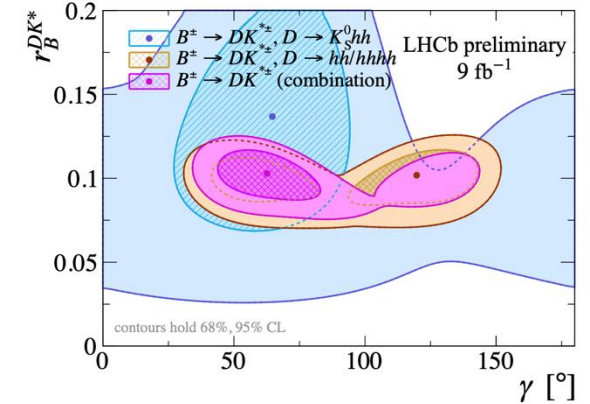
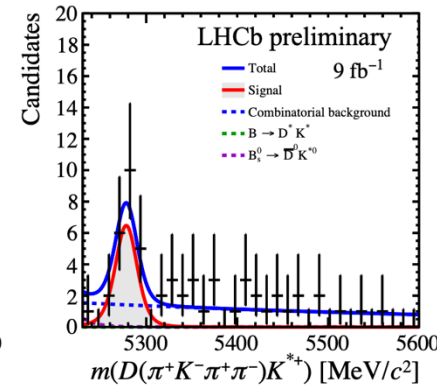
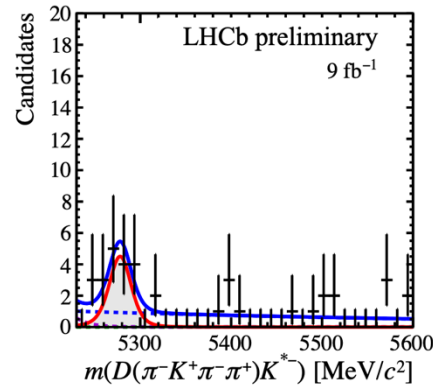
$$\mathcal{A}_{CP-} = (-16.7 \pm 5.7 \pm 0.6)\%, \quad 3.5 \sigma \text{ evidence for } \mathcal{A}_{CP+} \neq \mathcal{A}_{CP-}$$

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

# Recent $\phi_3$ measurements by LHCb

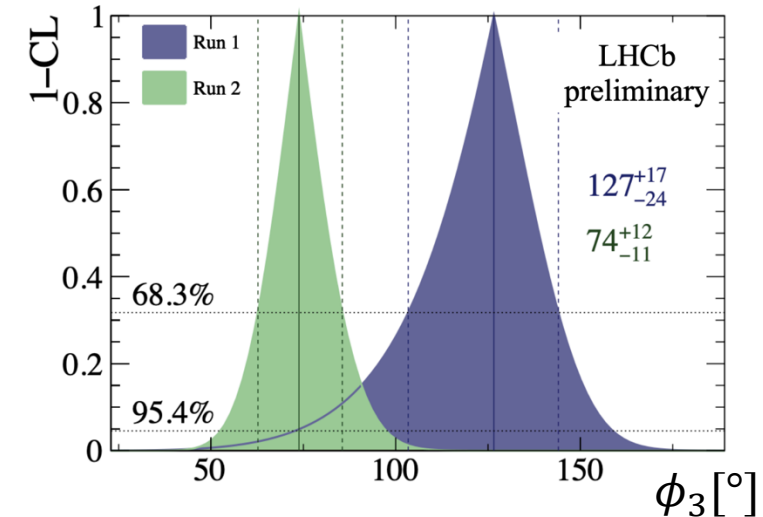
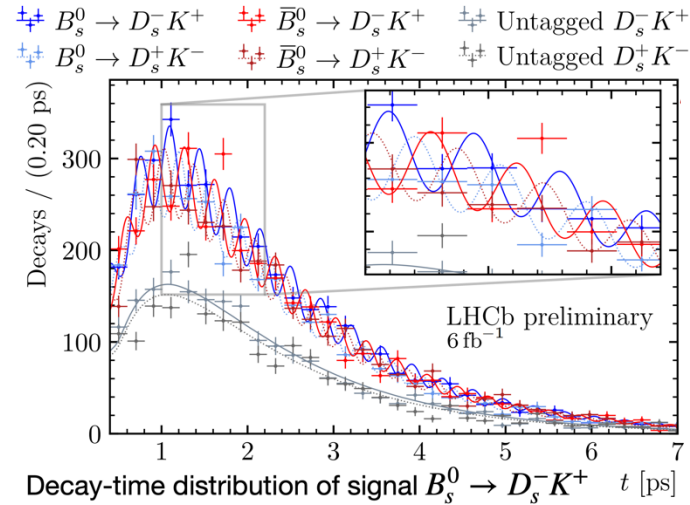
## $B^\pm \rightarrow DK^{*\pm}$ (LHCb-PAPER-2024-023)

- $D \rightarrow K\pi(\pi\pi), D \rightarrow \pi\pi(\pi\pi), D \rightarrow KK,$   
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-2024-020)

- $CPV$  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!





# $\phi_3$ combination

## First Belle + Belle II combined $\phi_3$ 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]

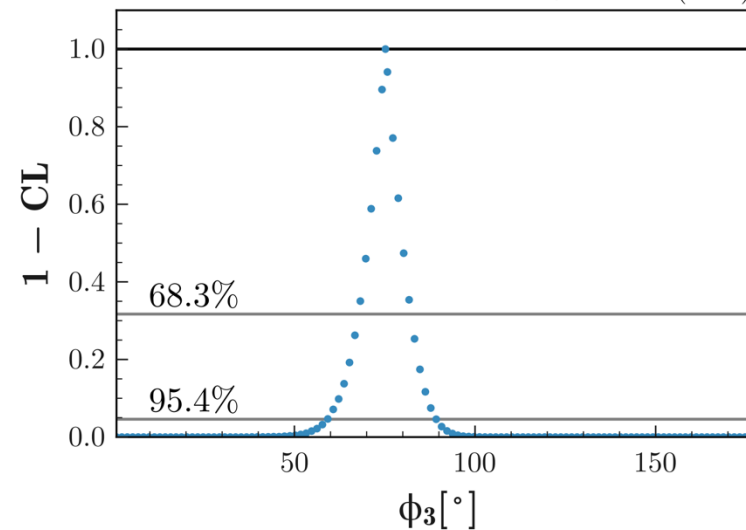
### Inputs for $\phi_3$ measurement

B decay	D decay	Method	Data set (Belle + Belle II)[fb <sup>-1</sup> ]
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0\pi^0, K^-K^+$	GLW	711 + 189 <b>Belle II</b>
$B^+ \rightarrow Dh^+$	$D \rightarrow K^+\pi^-, K^+\pi^-\pi^0$	ADS	711 + 0
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0K^-\pi^+$	GLS	711 + 362 <b>Belle II</b>
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0h^-h^+$	BPGGSZ (m.i.)	711 + 128 <b>Belle II</b>
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0\pi^-\pi^+\pi^0$	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 :**

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

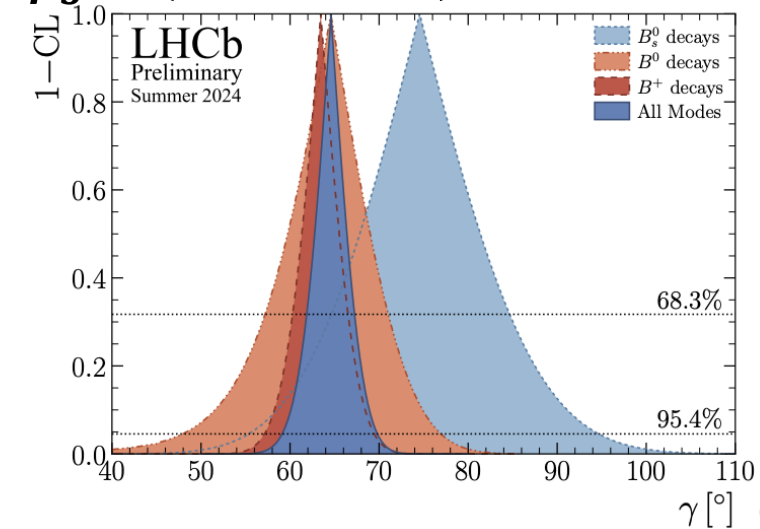


[arXiv:2404.12817](https://arxiv.org/abs/2404.12817)  
( accepted by JHEP )

**LHCb:**

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

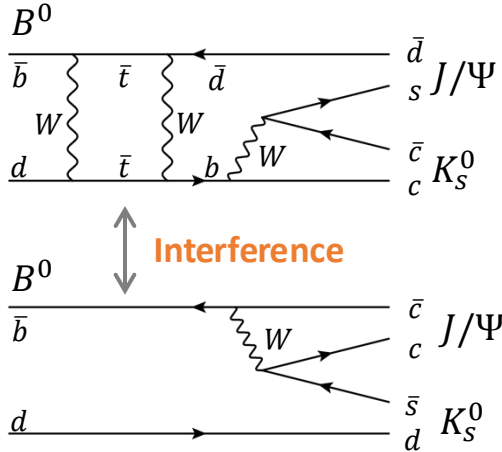
[LHCb-CONF-2024-004](https://arxiv.org/abs/2404.12817)



$\phi_1$

# $\phi_1$ Measurement

## Time-dependent CPV



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

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

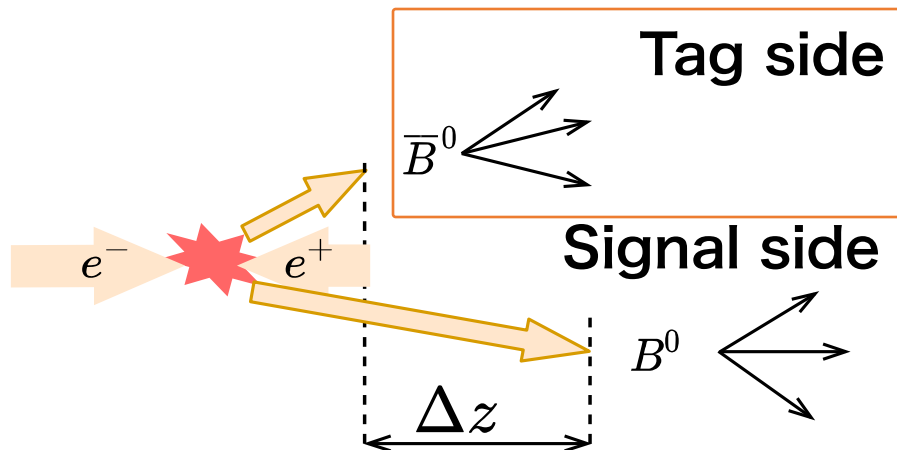
$$\mathcal{C} = 0 \text{ (Direct CPV)}$$

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

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

Decay vertex distance  $\Delta z$

$\rightarrow$  Decay time difference  $\Delta t$



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

## Flavor tagging

[PhysRevD.110.012001](https://arxiv.org/abs/1107.1332)

### Category-based FBBDT flavor tagger

- Kinematics, charge, PID of charged particles

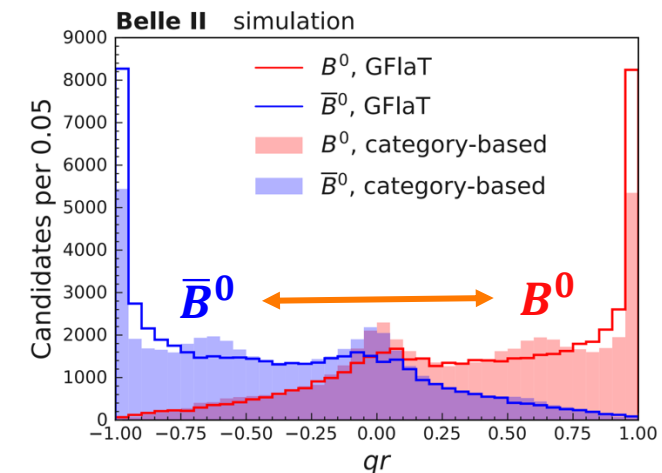
$$\epsilon_{\text{eff}} = (31.68 \pm 0.45)\%$$

### 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 FBBDT 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 <a href="https://arxiv.org/abs/PhysRevLett.108.171802">PhysRevLett.108.171802</a>	LHCb <a href="https://arxiv.org/abs/PhysRevLett.132.021801">PhysRevLett.132.021801</a>
$S$	$0.670 \pm 0.029 \pm 0.013$	$0.722 \pm 0.014 \pm 0.007$
$C$	$-0.015 \pm 0.021^{+0.045}_{-0.023}$	$0.015 \pm 0.013 \pm 0.003$

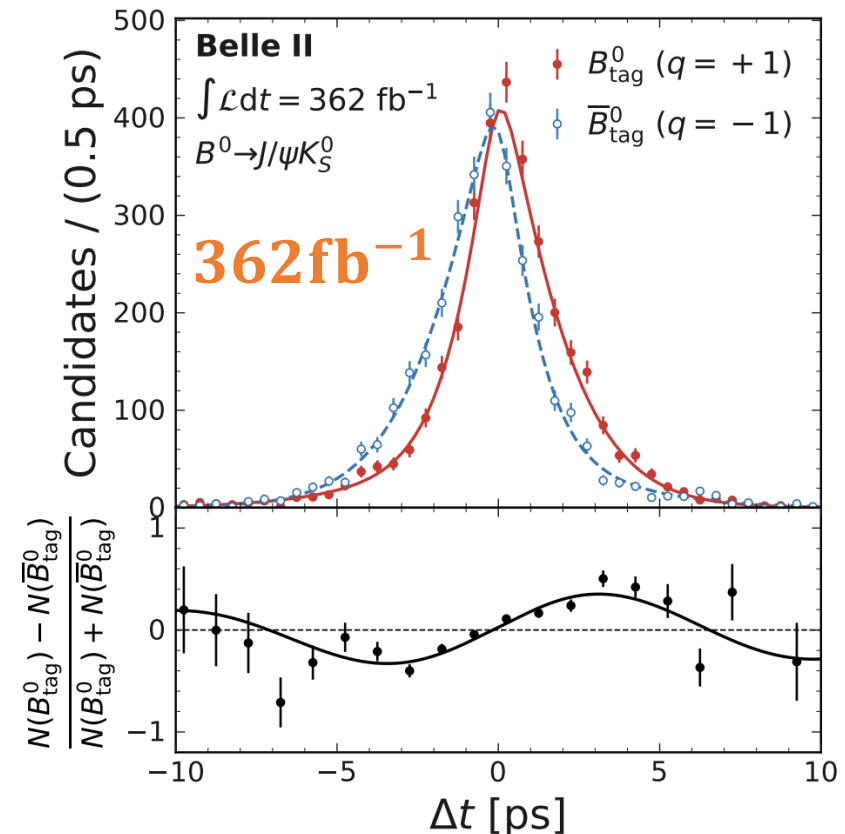
Dominant systematic uncertainty on  $C$ :

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



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

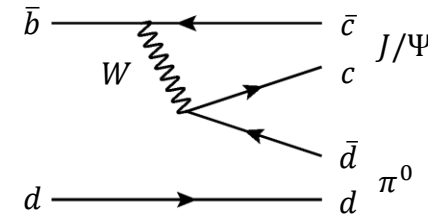
$S = -\sin 2\phi_1$ ,  $C = 0$  if there is only tree amplitude

Tree is color and CKM suppressed

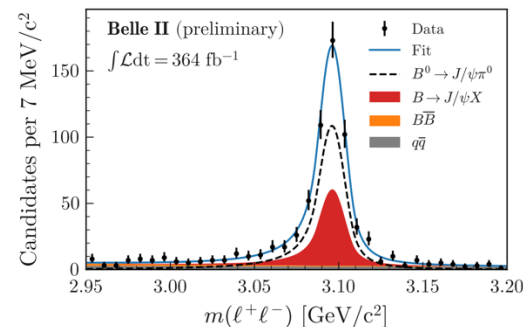
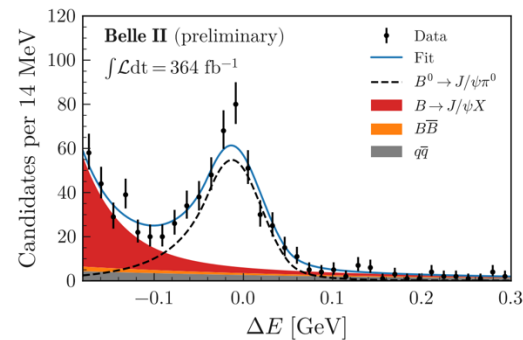
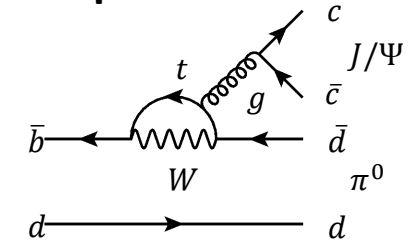
→ can be used to understand the loop contribution in  $B^0 \rightarrow J/\Psi K_S^0$

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

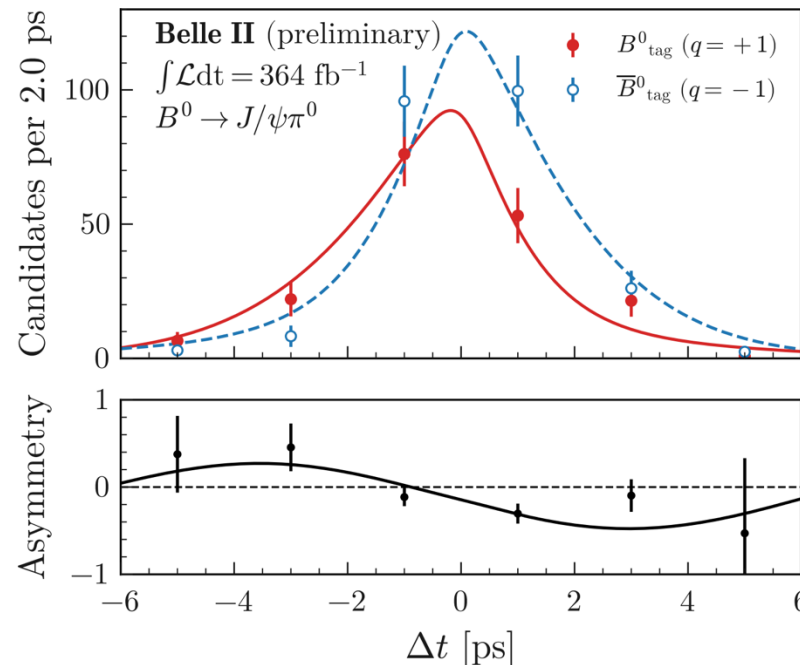
Tree



Loop



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



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

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

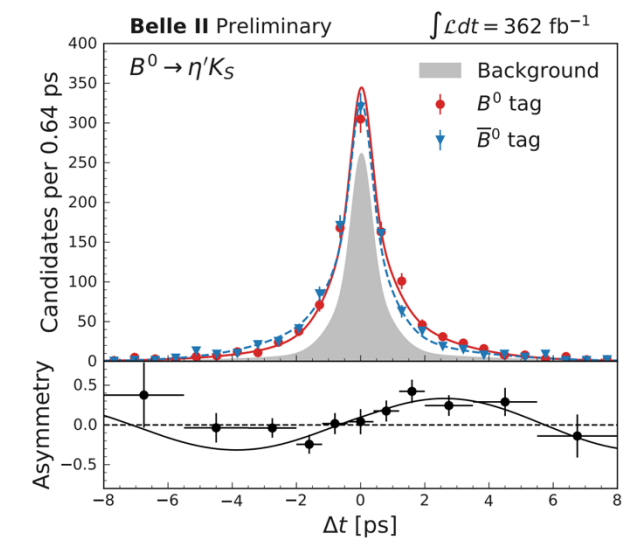
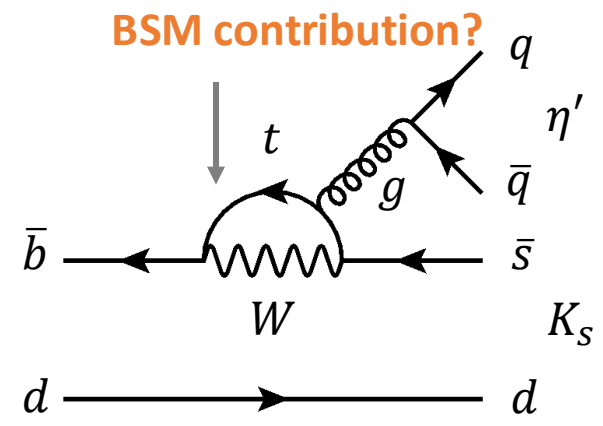
$$B = (2.02 \pm 0.12 \pm 0.10) \times 10^{-5}$$

Most precise,  
and comparable with previous measurement

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

# $B^0 \rightarrow \eta' K_S$

- 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  $\eta' \rightarrow \rho^0(\rightarrow \pi\pi)\gamma$

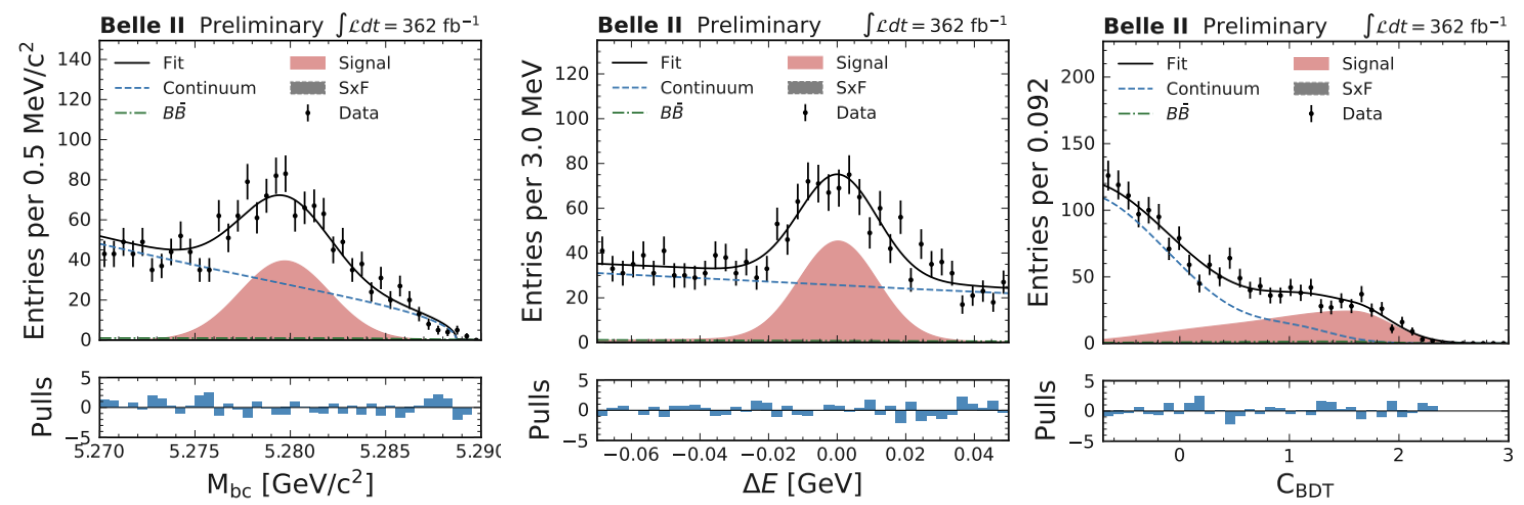


$S = 0.67 \pm 0.10 \pm 0.04$   
 $C = -0.19 \pm 0.08 \pm 0.03$

	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  $S (J/\Psi K_S^0)$ :  $0.709 \pm 0.011$

Consistent, and compatible precision with previous experiments!

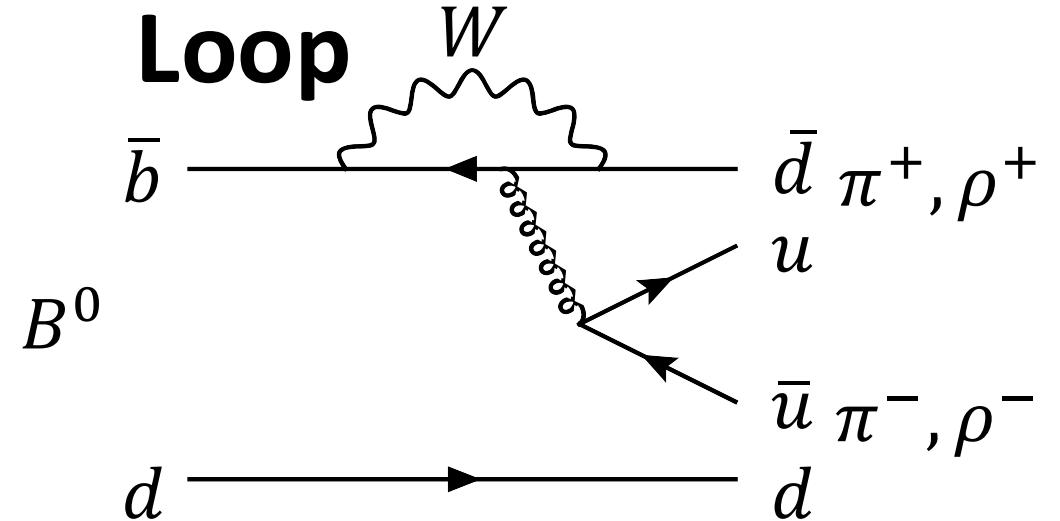
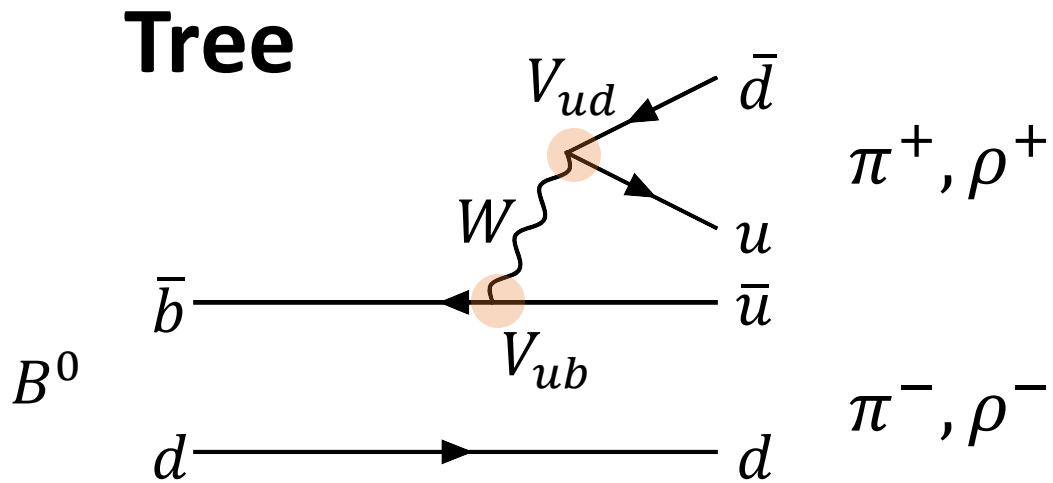


$C_{BDT}$  :  $q\bar{q}$  suppression output

$\phi_2$

# $\phi_2$ 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

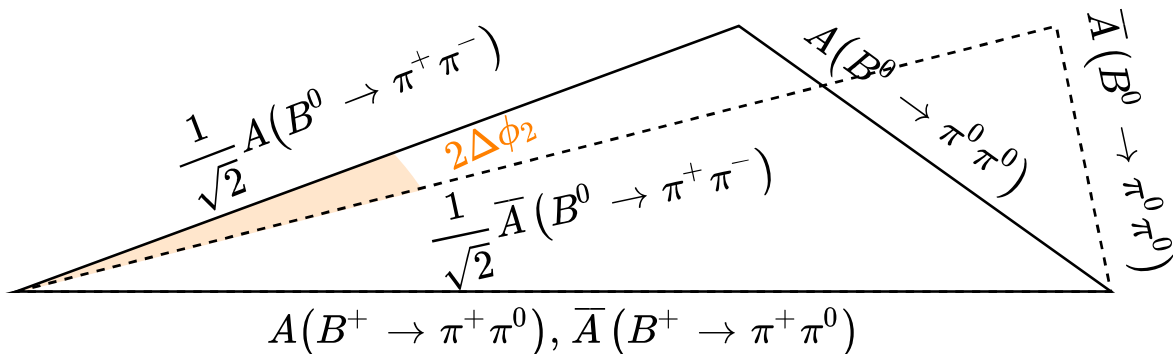
	Tree	Loop	
$\pi^+\pi^-$	○	○	
$\pi^+\pi^0$	○	×	○: Large contribution ×: No contribution
$\pi^0\pi^0$	△	○	△: Smaller contribution

(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 $\phi_2$

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

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

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

- $\pi^0\pi^0, \rho^+\rho^0$ , and  $\rho^+\rho^-$  analyses **need  $\pi^0$  reconstruction**  
→ Belle II has an advantage
- $\rho\rho$  has **much smaller loop** contribution  
→ Dominates  $\phi_2$  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 $B^+ \rightarrow \pi^+ \pi^0$

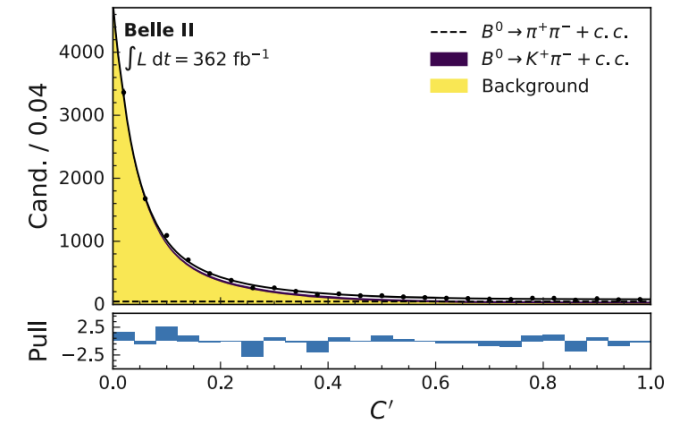
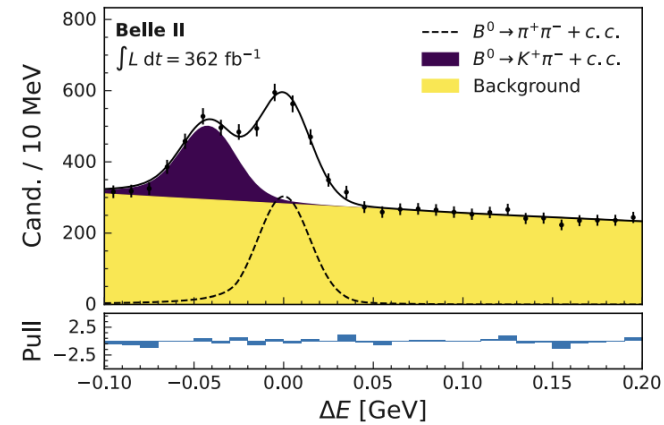
[PhysRevD.109.012001](https://arxiv.org/abs/PhysRevD.109.012001)

Good agreement with previous measurements

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

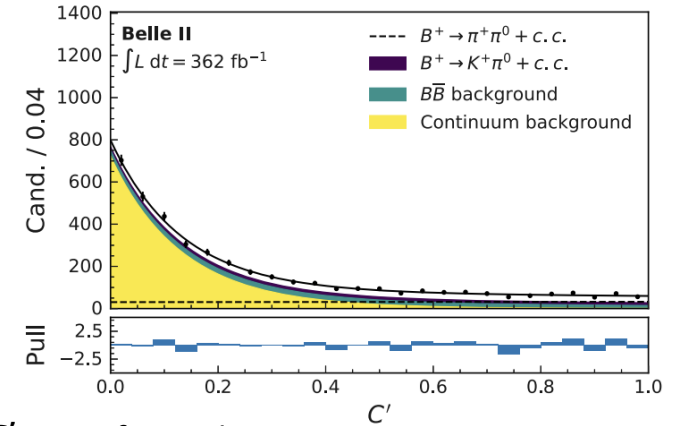
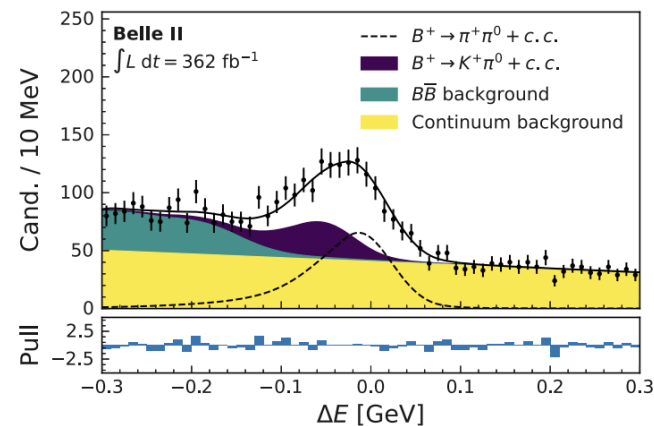
$\pi^+ \pi^-$

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



$\pi^+ \pi^0$

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



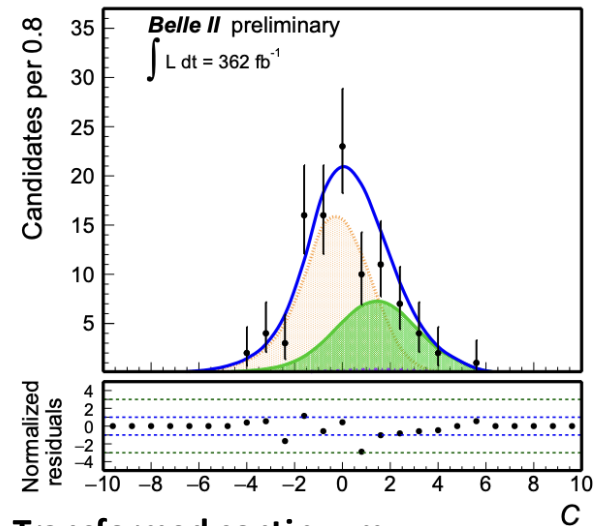
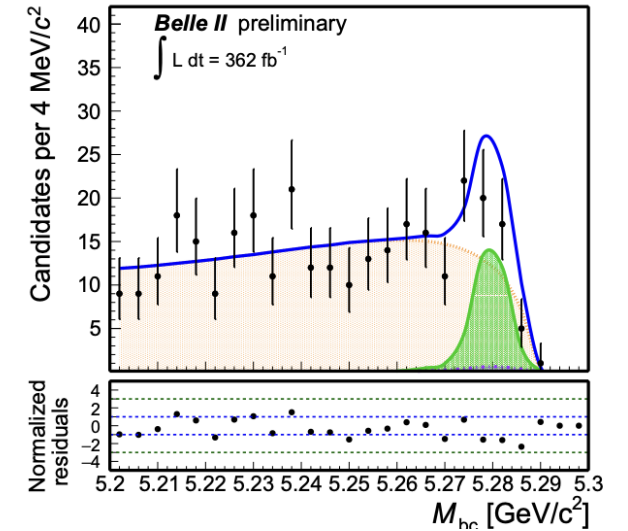
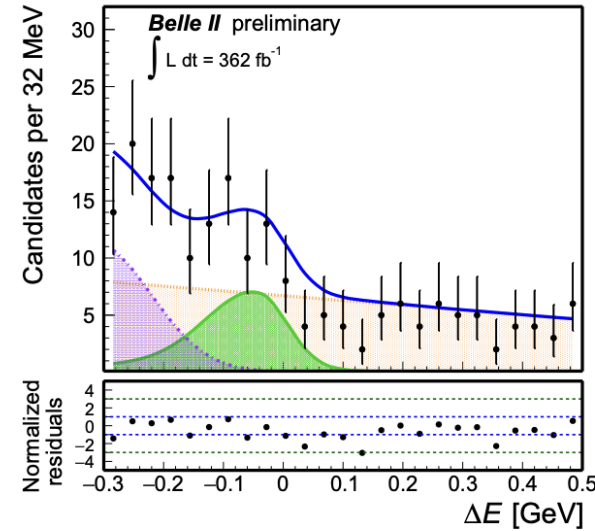
$C'$ : Transformed continuum suppression output  
CP violation, 2024/10/23, 35th Rencontres de Blois, Ryogo Okubo

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

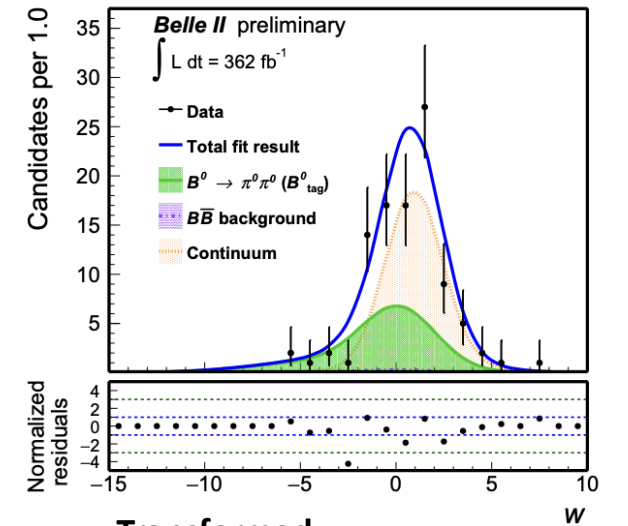
- Require  $4\gamma$  reconstruction ( **Unique to Belle II** ) from a large background due to hadronic clusters, beam background  
→ Developed an MVA for  $\gamma$  selection
- Improved sensitivity by GFlaT.

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

Consistent with previous experiments and  
Comparable sensitivity with small statistics.



Transformed continuum  
suppression output



Transformed  
wrong flavor tag probability

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

### Analysis challenge

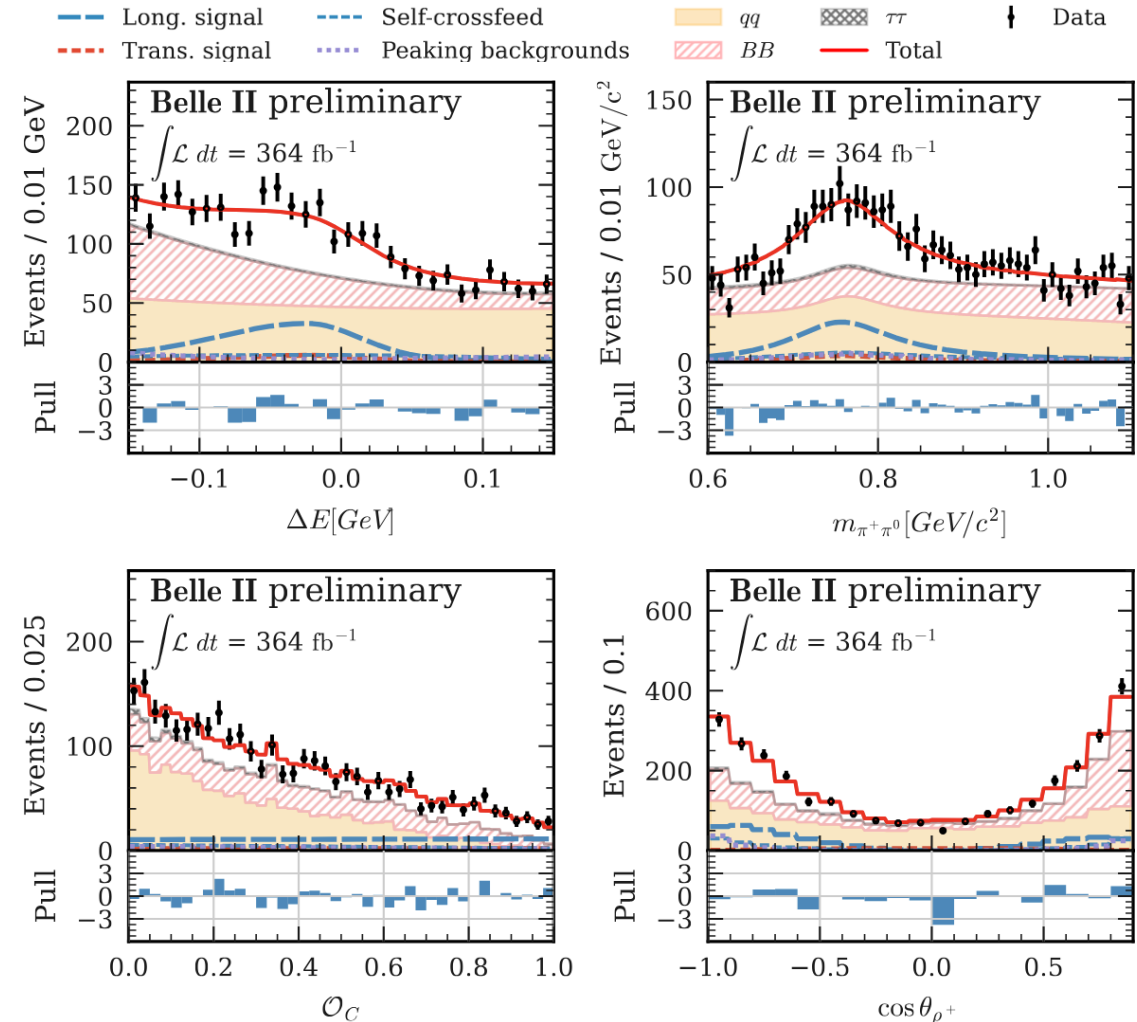
- $B \rightarrow \rho\rho$  is  $P \rightarrow VV$  decay  
→ Angular analysis is needed for polarization extraction.
- $\pi^0$  selection  
Needs two soft  $\pi^0$  reconstruction from  $\rho$   
→ Suppressed backgrounds using machine learning technique
- **Continuum suppression**  
Large  $qq$  background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

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

<b>Belle II</b>	$29.0^{+2.3}_{-2.2} \quad ^{+3.1}_{-3.0}$	$0.921^{+0.024}_{-0.025} \quad ^{+0.017}_{-0.015}$
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**

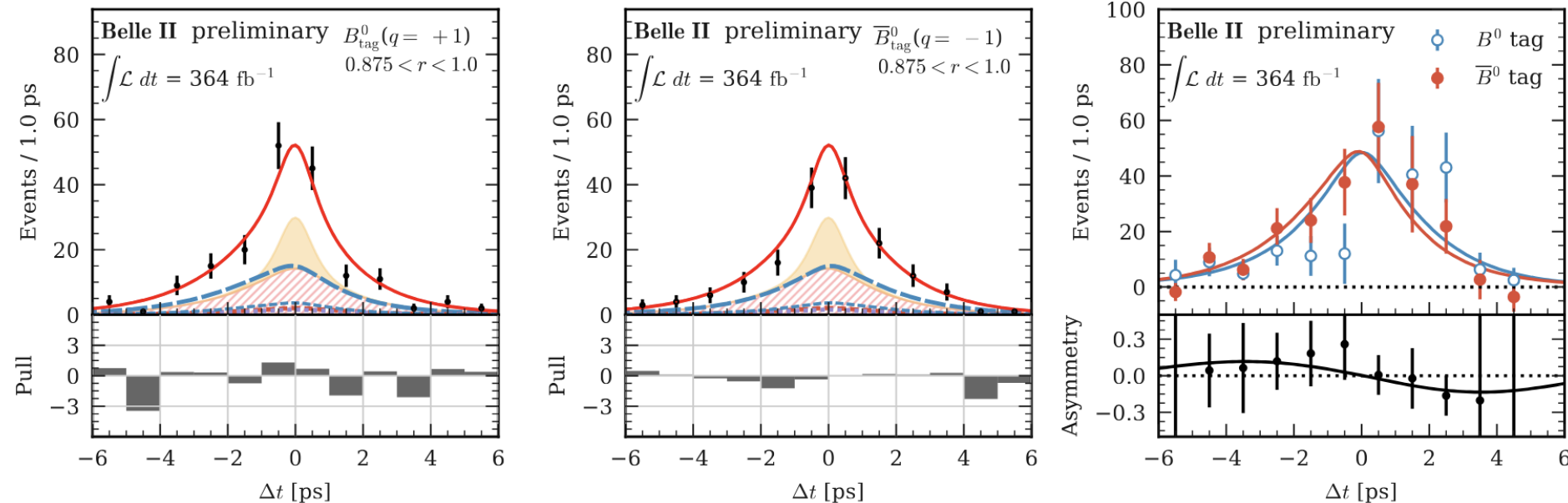
### 6D Fit for signal Extraction



# $B^0 \rightarrow \rho^+ \rho^-$ CPV

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  $\phi_2$  using the new result.

# $\phi_2$ extraction

NEW

$B \rightarrow \rho\rho$  world average

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

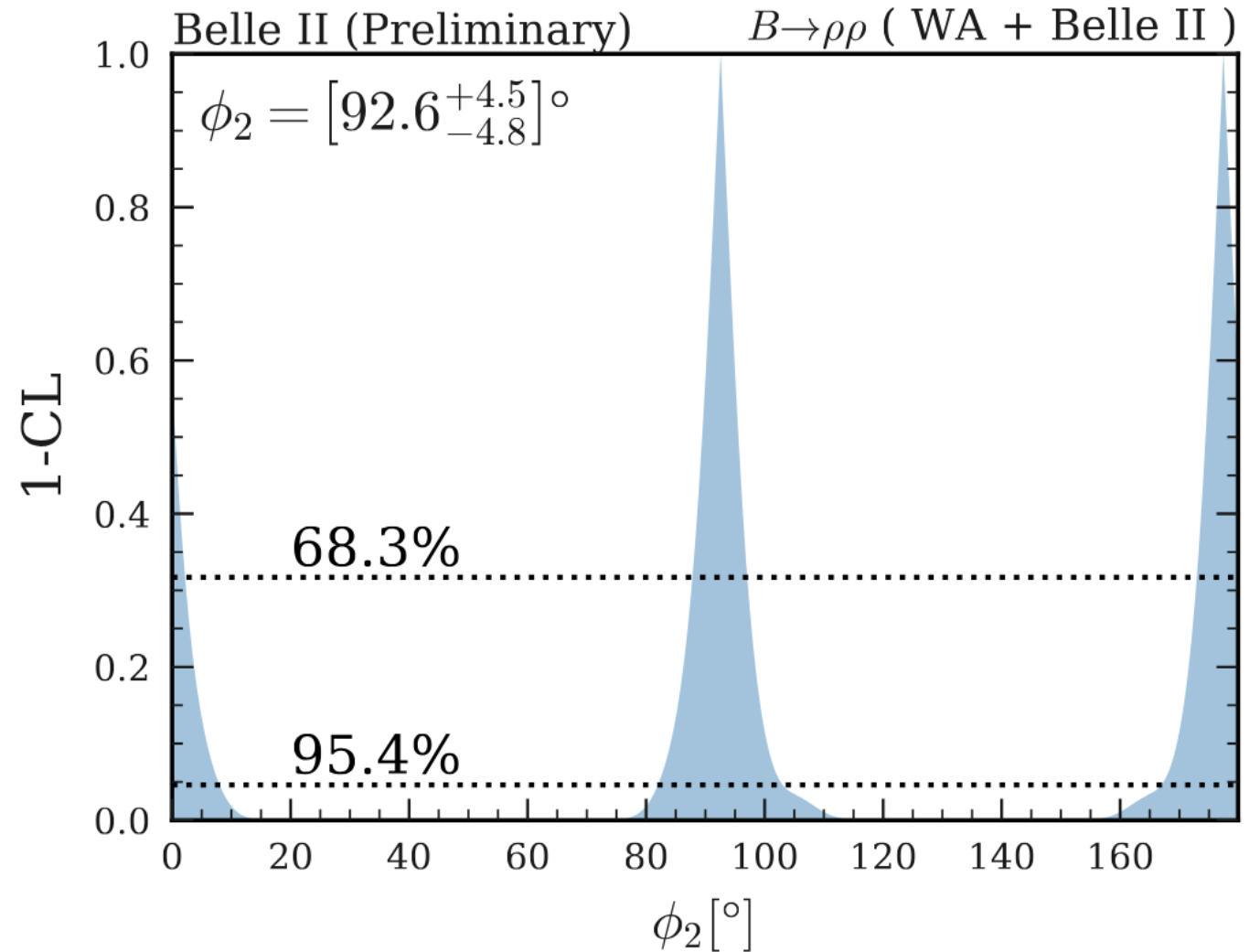
$B \rightarrow \rho\rho$  world average

+ 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**

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

- CPV measurement based on triple and quadruple products of momenta

In  $C_{TP}$ ,

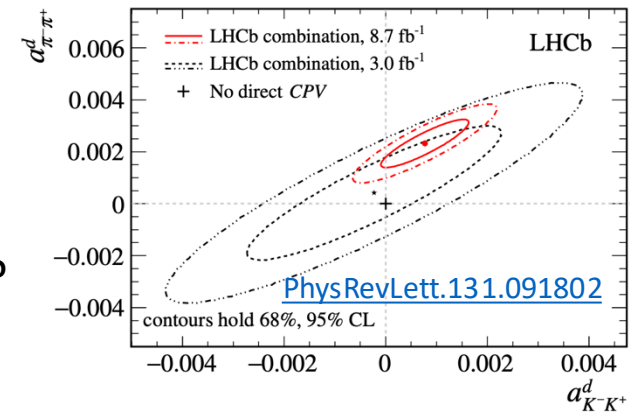
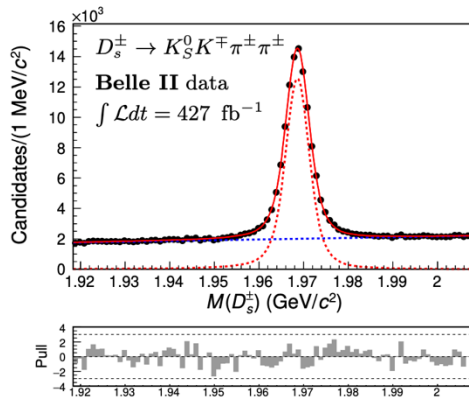
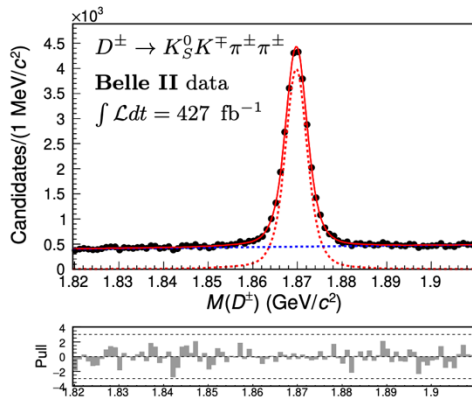
- $A_{CP}(D^+) = (-2.3 \pm 4.5 \pm 1.5) \times 10^{-3}$
- $A_{CP}(D_{(s)}^+) = (+0.2 \pm 2.4 \pm 0.8) \times 10^{-3}$

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

[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

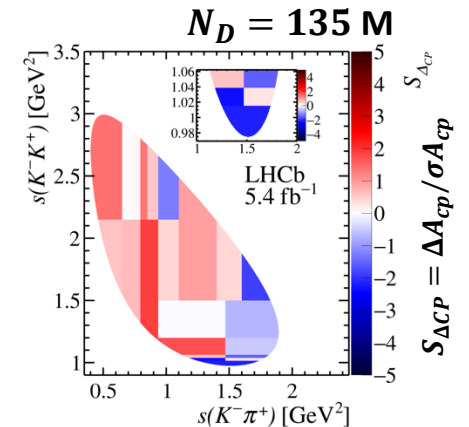


## $D^+ \rightarrow K^- K^+ \pi^+$ (LHCb) [arXiv:2409.01414](https://arxiv.org/abs/2409.01414)

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

$$A_{CP|S}^{\phi\pi^+} = (0.95 \pm 0.43 \pm 0.26) \times 10^{-3}$$

$$A_{CP|S}^{\bar{K}^{*0}K^+} = (-0.26 \pm 0.56 \pm 0.18) \times 10^{-3}$$



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

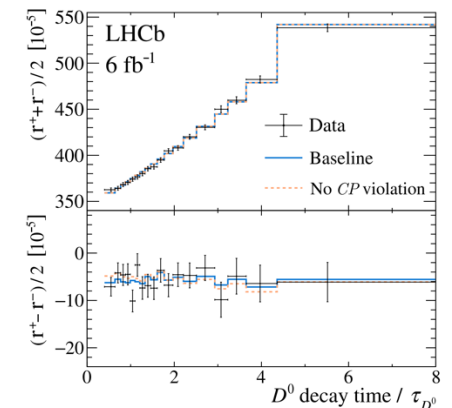
- Direct CPV search + mixing measurement

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

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
- $c'$ : 3.4σ evidence



# Summary

- Belle II is a high-luminosity  $e^+e^-$  collider experiments that have already collected **531 fb<sup>-1</sup>** 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%**.
- $\phi_1$ :  $B^0 \rightarrow J/\Psi K_S^0, B^0 \rightarrow \eta' K_S^0, B^0 \rightarrow J/\Psi \pi^0$ .  
 $B^0 \rightarrow J/\Psi \pi^0$ : Significant improvement, and obtained most precise result!
- $\phi_2$ :  $B \rightarrow \pi^+ \pi^-, \pi^+ \pi^0, \pi^0 \pi^0, B^0 \rightarrow \rho^+ \rho^-$   
 $\rho^+ \rho^-$ : New result, improved precision, first  $\phi_2$  extraction with improved precision!
- $\phi_3$ : 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. D 108, 072012 \(2023\)](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  $\epsilon_{\text{tag}}$  for  $B^0 \rightarrow D^{(*)-}\pi^+$  and,  $S$  and  $C$  for  $B^0 \rightarrow J/\psi K_S^0$ .

Source	$\epsilon_{\text{tag}}$ [%]	$S$	$C$
Detector alignment	0.08	0.005	0.003
Interaction region	0.16	0.002	0.002
Beam energy	0.03	<0.001	0.001
$\Delta E$ -fit background model	0.11	0.001	0.001
$\Delta E$ -fit signal model	0.08	0.003	0.006
$sWeight$ background subtraction	0.24	0.001	0.001
Fixed resolution-function parameters	0.07	0.004	0.004
$\tau$ and $\Delta m_d$	0.06	0.001	<0.001
$\sigma_{\Delta t}$ binning	0.04	<0.001	<0.001
$\Delta t$ -fit bias	0.09	0.002	0.005
$CP$ violation in $B_{\text{tag}}$ 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 $\Delta t$ 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
$\tau_{B^0}$ and $\Delta m_d$	< 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
$C_{\text{BDT}}$ mismodeling	0.004	0.010
Signal and background modeling	0.020	0.014
Observable correlations	0.008	0.001
$\Delta t$ resolution fixed parameters	0.005	0.009
$\Delta t$ resolution model	0.004	0.019
Flavor tagging	0.007	0.004
$\tau_{B^0}$ and $\Delta m_d$	< 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
$\pi^0$ efficiency		3.8
$K_S^0$ efficiency		
CS efficiency	0.2	0.7
PID correction	0.1	0.2
$\Delta E$ 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	$B^+ \rightarrow \pi^+ \pi^0$
$\Delta E$ 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	$\mathcal{B}$	$\mathcal{A}_{CP}$
$\pi^0$ 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
$\pi^0$ 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	$\pm 0.54$	—
$\pi^0$ eff.	$\pm 7.67$	—
PID	$\pm 0.08$	—
$\mathcal{T}_C$	$\pm 2.87$	—
MC stat.	$\pm 0.24$	$\pm 0.2$
$f_{+-}/f_{00}$	$\pm 2.60$	—
$N_{BB}$	$\pm 1.45$	—
Best candidate selection	$\pm 0.55$	$\pm 0.3$
SxF ratio	$+2.97$ $-2.45$	$+0.2$ $-0.3$
$\mathcal{B}$ 's of peaking backgrounds	$+0.94$ $-0.98$	$\pm 0.1$
$\tau^+ \tau^-$ background yield	$+0.65$ $-0.69$	$\pm 0.0$
Signal model	$+1.14$ $-2.02$	$\pm 0.2$
$q\bar{q}$ 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	$\pm 1.20$	$\pm 0.5$
Data-MC mis-modeling	$+3.51$ $-1.70$	$+0.8$ $-0.3$
Fit bias	$\pm 1.03$	$\pm 1.2$
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	$+0.6$ $-0.5$	$\pm 0.1$
$\tau\tau$ background yield	$\pm 0.9$	$+0.0$ $-0.1$
Data-MC mis-modeling	$+0.6$ $-1.1$	$+1.5$ $-0.6$
Best candidate selection	$\pm 1.3$	$\pm 1.9$
SxF ratio	$+0.5$ $-0.4$	$+0.7$ $-0.0$
Signal model	$+1.1$ $-1.4$	$+0.3$ $-0.4$
$q\bar{q}$ model	$+2.2$ $-1.0$	$\pm 0.2$
$B\bar{B}$ model	$\pm 0.9$	$+0.7$ $-0.5$
$\tau\tau$ model	$\pm 0.1$	$\pm 0.0$
Peaking model	$+0.8$ $-0.4$	$+0.2$ $-0.4$
Fit bias	$\pm 2.0$	$\pm 0.6$
Interference	$\pm 2.8$	$\pm 1.7$
Resolution	$+3.4$ $-4.4$	$+1.9$ $-1.4$
Event fraction	$+0.9$ $-1.0$	$\pm 0.6$
$\Delta t$ PDF for $q\bar{q}$ and $B\bar{B}$	$+3.8$ $-1.8$	$+0.7$ $-0.1$
Physics Parameters	$+1.4$ $-1.6$	$\pm 0.3$
Tag side interference	$\pm 0.5$	$\pm 2.1$
Wrong tag fraction	$+0.2$ $-0.3$	$\pm 0.5$
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	$\pm 1.4$	$\pm 0.5$
Total systematic uncertainty	$+8.3$ $-7.8$	$+6.1$ $-5.4$
Statistical uncertainty	$\pm 18.8$	$\pm 12.1$

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

[arXiv:2206.12362](https://arxiv.org/abs/2206.12362)

$B \rightarrow \rho\rho$  : Another way for  $\phi_2$  extraction

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

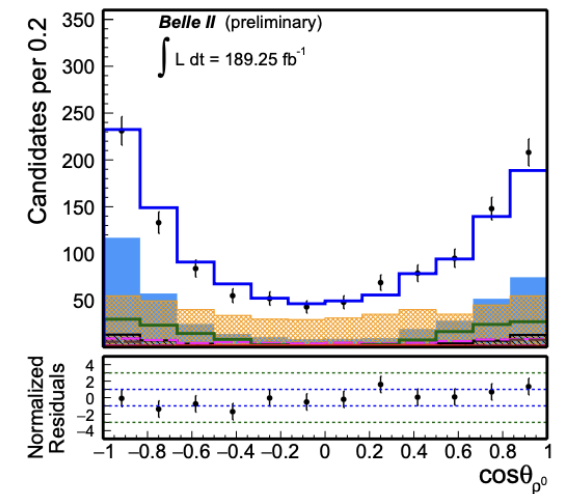
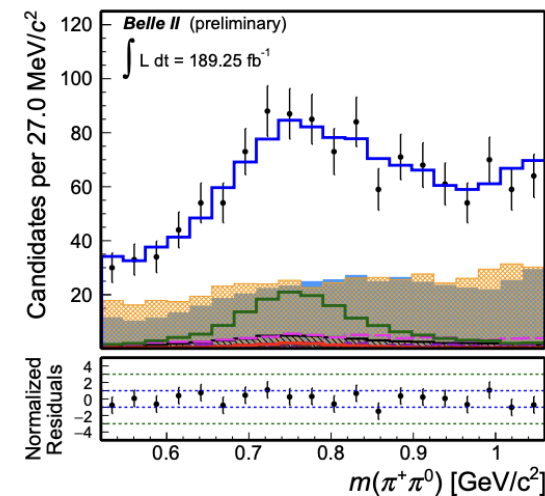
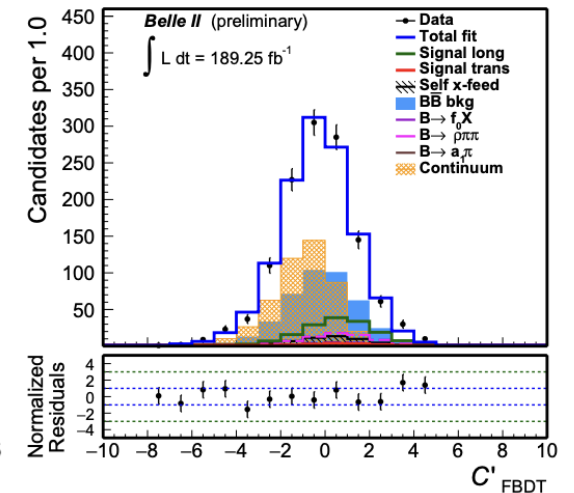
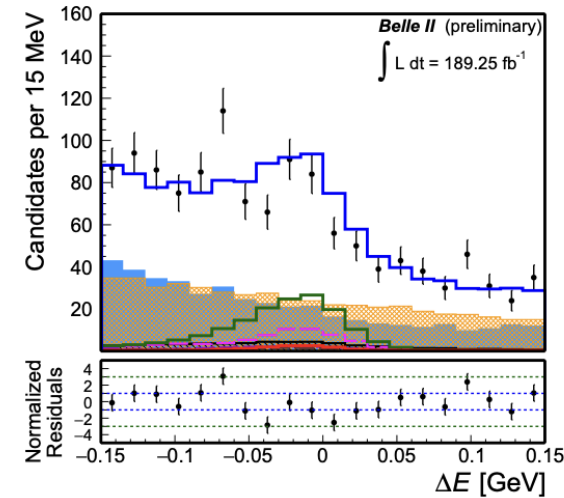
$\rightarrow$   $\rho\rho$  system has a better sensitivity to  $\phi_2$

	$\mathcal{B}(10^{-6})$	$f_L$
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	$23.7 \pm 1.4 \pm 1.4$	$0.950 \pm 0.015 \pm 0.006$

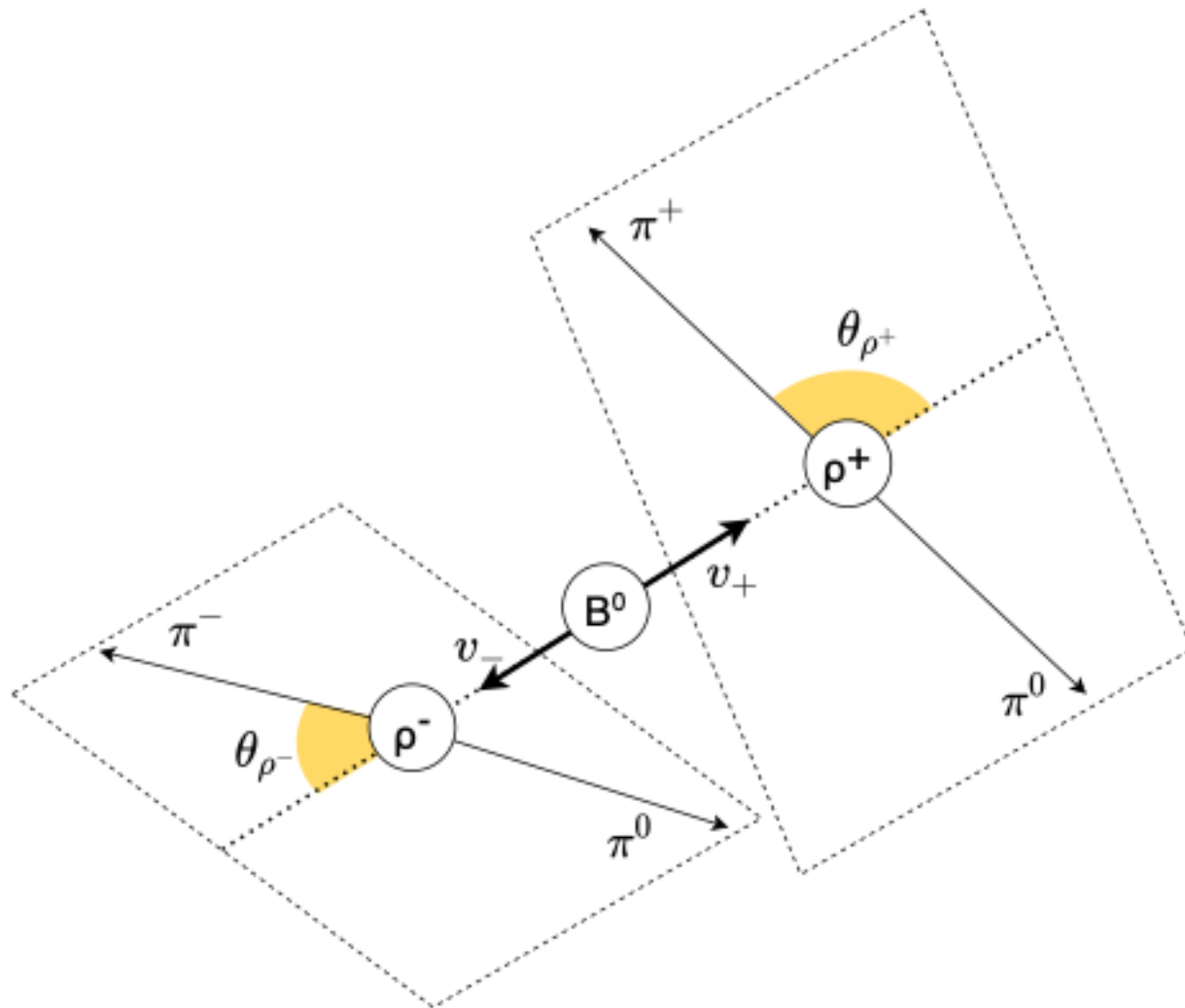
Good agreement with previous experiments.

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

$\rightarrow$  Needs to be improved by Belle II



# Definition of the cosine helicity angle



$\cos\theta_{\rho}$ :

Cosine of the angle between  $\pi^+$  and  $B^0$  boost direction in  $\rho^{\pm}$  CMS frame.