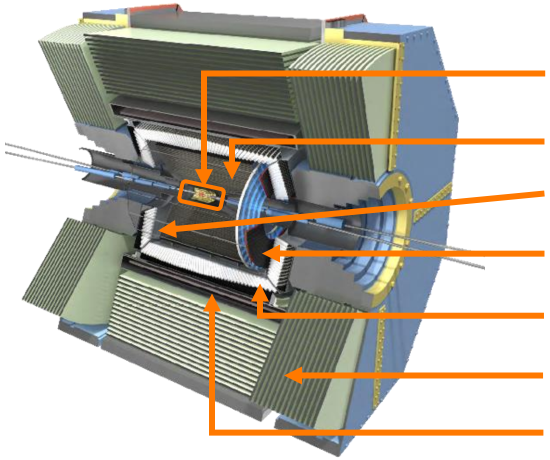
CP violation

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

Belle II experiment



Belle II experiment

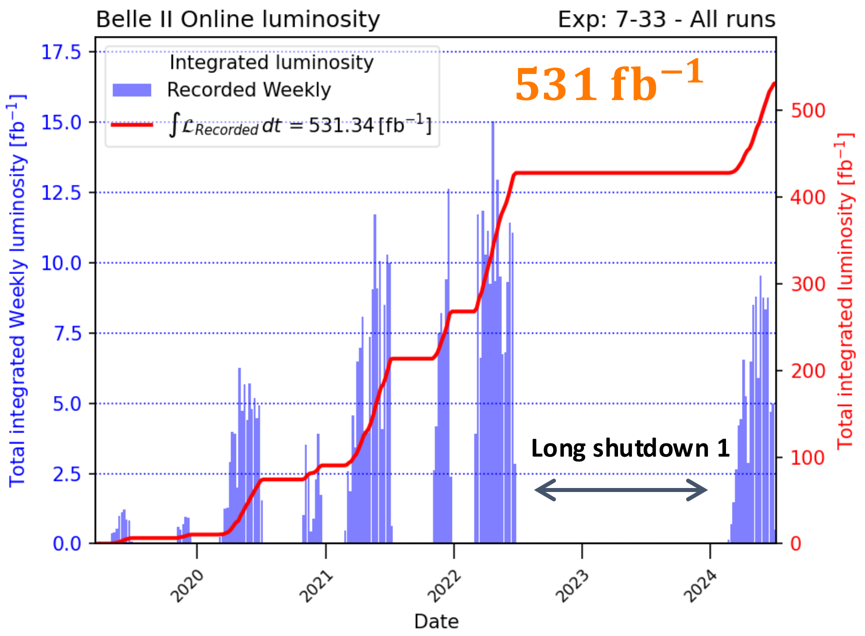
- High luminosity e^-e^+ collider experiment at a center of mass energy of 10.58 GeV.
- Target integral Luminosity : $\mathbf{50\ ab^{-1}}$
- Target peak luminosity : $\mathbf{6 \times 10^{35} cm^{-2} s^{-1}}$

Status of Belle II

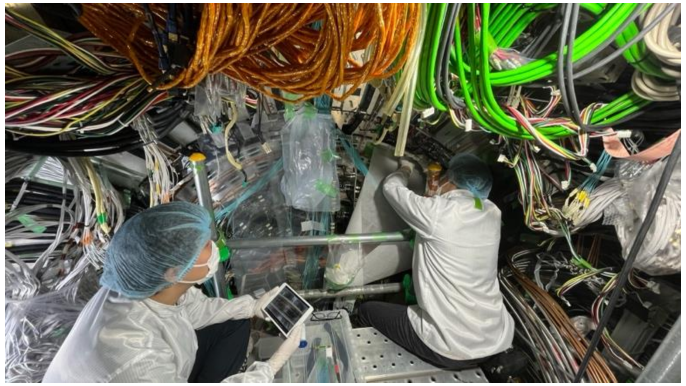
- Integrated $\mathbf{531\ fb^{-1}}$
- Achieved Peak luminosity $\mathbf{4.7 \times 10^{34} cm^{-2} s^{-1}}$ World-best, **2x higher** than Belle.

Long shutdown 1
2022-2023

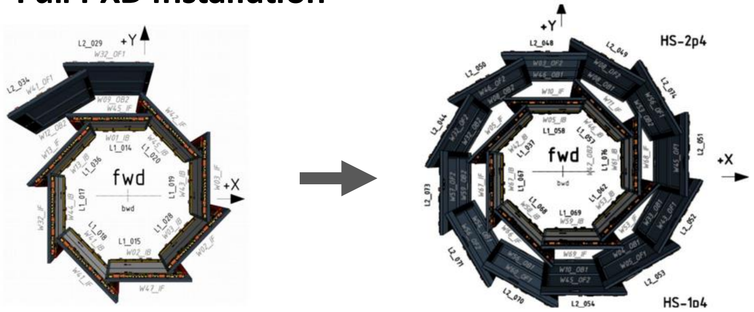
- Acceralator upgrade
- Full Pixcel detector (Innermost vertex detector) installation
- TOP photodetector replacement
- And so on…



TOP PMT replacement during long shutdown1



Full PXD installation



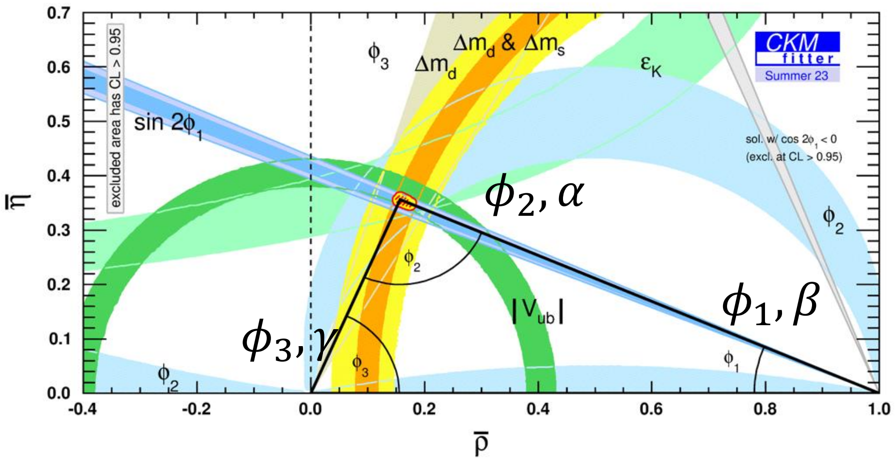
Unitarity triangle

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

Unitarity

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

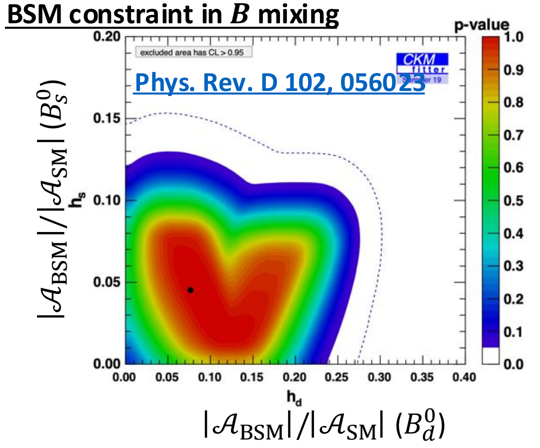
Belle II can measure all ϕ_1, ϕ_2, and ϕ_3



Unitarity triangle measurement at Belle II

- Large statistics + Clean environment
  → Can measure the Unitarity triangle precisely
- Global Fit to Observables
  → Give a Constraint to BSM!
  $|\mathcal{A}_{BSM}|/|\mathcal{A}_{SM}|\ (B_d^0)$<30%

BSM constraint in B mixing



Unitarity triangle angles

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

World average
(CKMFitter, 2023 summer)

ϕ_1	$(22.84^{+0.33}_{-0.30})^\circ$
ϕ_2	$(86.2^{+3.9}_{-3.5})^\circ$
ϕ_3	$(65.9^{+3.3}_{-3.5})^\circ$

ϕ_2 has the largest uncertainty

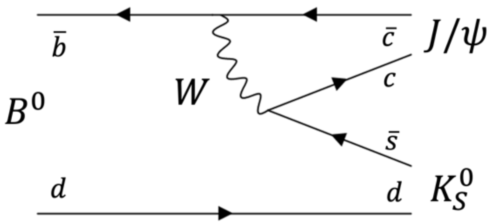
ϕ_1

ϕ_1, β Measurement

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

Time-dependent CPV

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



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

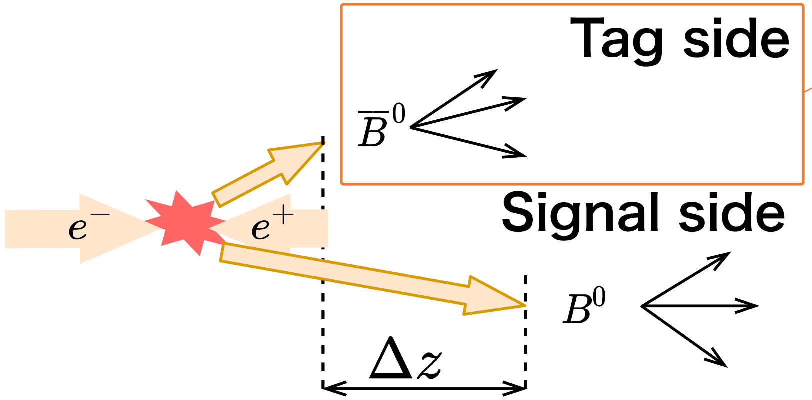
$C = 0$ (Direct CPV)

$S = \sin 2\phi_1$ (Mixing induced CPV)

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

Decay vertex distance Δz

→**Decay time difference Δt**



Flavor tagging

PhysRevD.110.012001

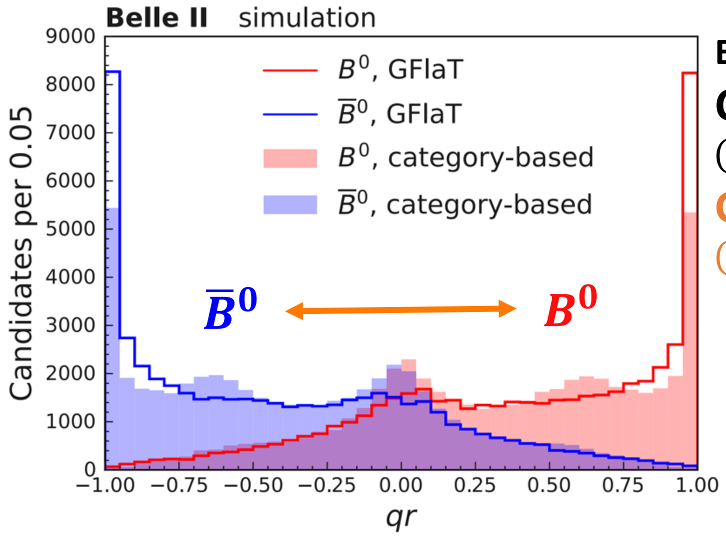
Kinematics, charge, PID of charged particles

→ Identify tag-side B^0 flavor

Updated Category based FastBDT flavor tagger to

Graph neural network flavor tagging(GFlaT).

Improved performance by learning correlations between final-state particles



Effective tagging efficiency

Category-based:

$(31.68 \pm 0.45)\%$

GFlaT:

$(37.40 \pm 0.43 \pm 0.36)\%$

$B^0 \to J/\Psi K_s^0$ using GflaT Flavor tagger

PhysRevD.110.012001

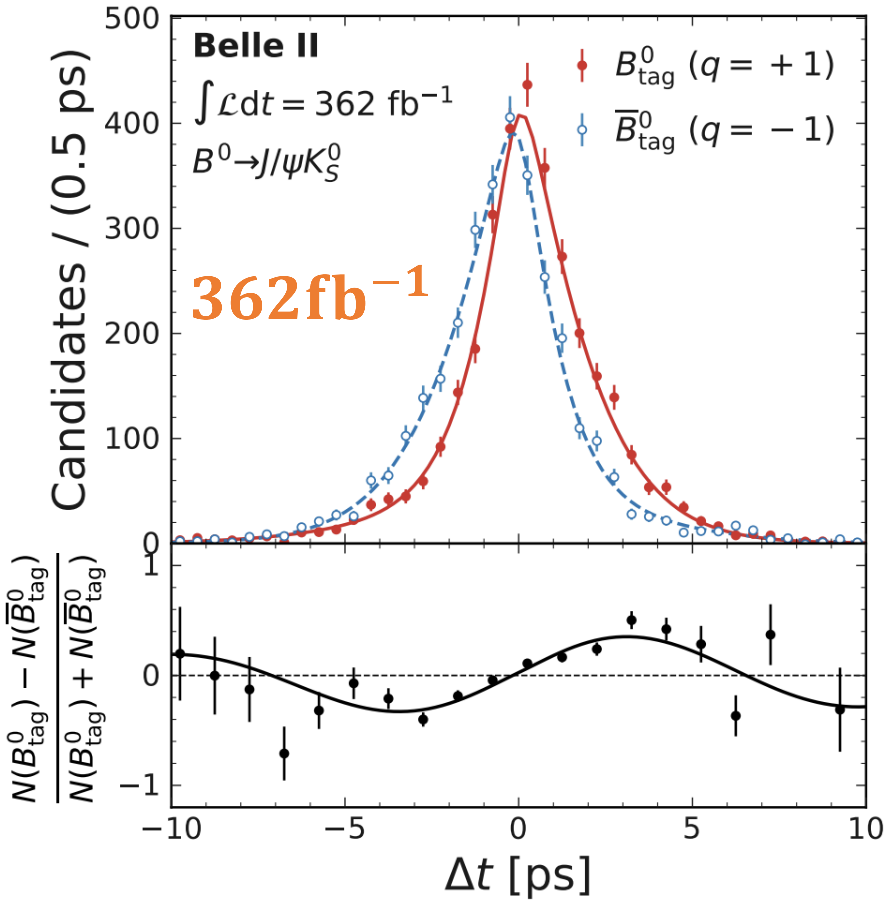
Improved statistical uncertainty 8% (S) and 7% (C) compared to category-based FBDT flavor tagger!

$$S = 0.724 \pm 0.035 \pm 0.009$$
$$\to \phi_1 = (23.2 \pm 1.5 \pm 0.6)^\circ$$
$$C = -0.035 \pm 0.026 \pm 0.029$$

	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
$B^0 \to J/\Psi K_S^0(CP-\text{odd})$ and $B^0 \to J/\Psi K_L^0(CP-even)$.

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

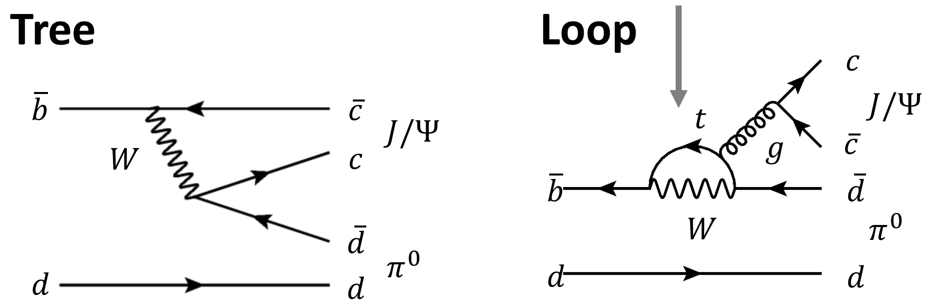


arXiv:2410.08622
Submitted to PRD

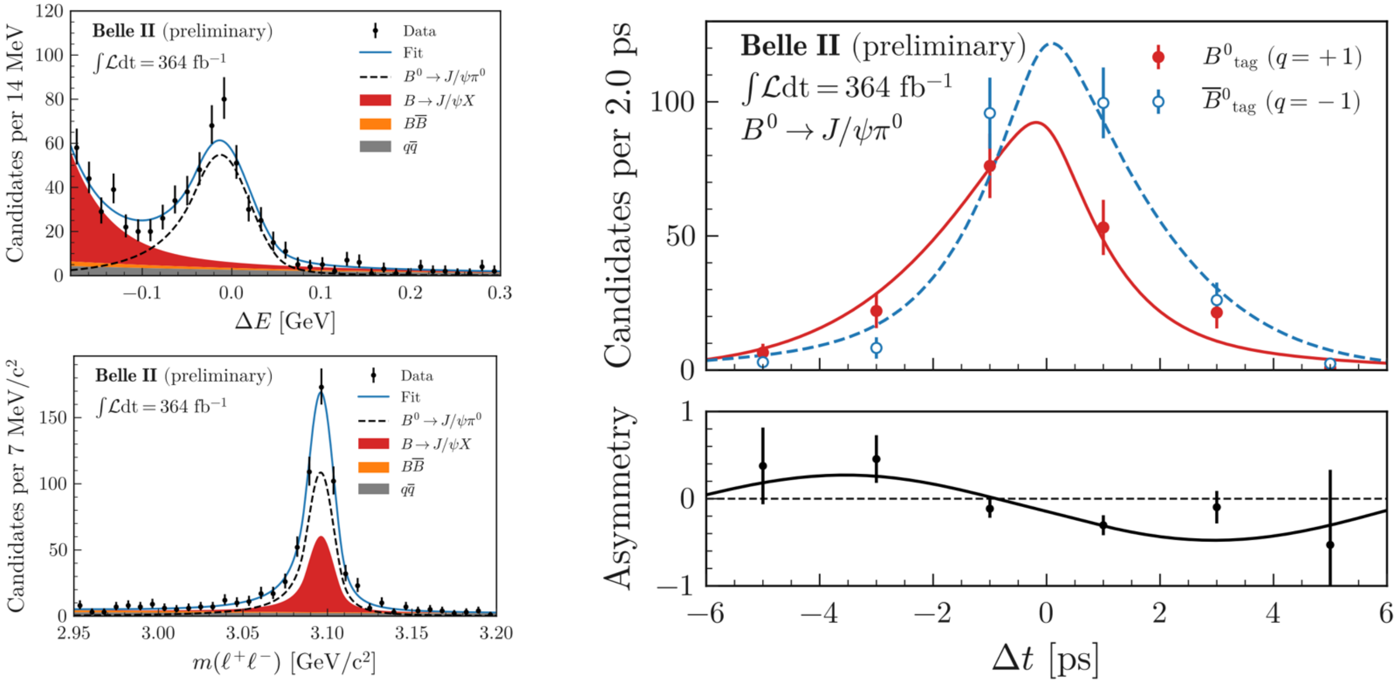
$B^0 \to J/\Psi\pi^0$

$S = -\sin 2\phi_1$, $C = 0$ if there are only tree amplitude.
Loop process and **BSM process** can shift S and C.
Tree is color and CKM suppressed
→ can be used to understand the loop contribution in $B^0 \to J/\Psi K_s^0$

BSM contribution?



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



$S = -0.88 \pm 0.17 \pm 0.03$
$C = 0.13 \pm 0.12 \pm 0.03$
$\mathcal{B} = (2.02 \pm 0.12 \pm 0.10) \times 10^{-5}$

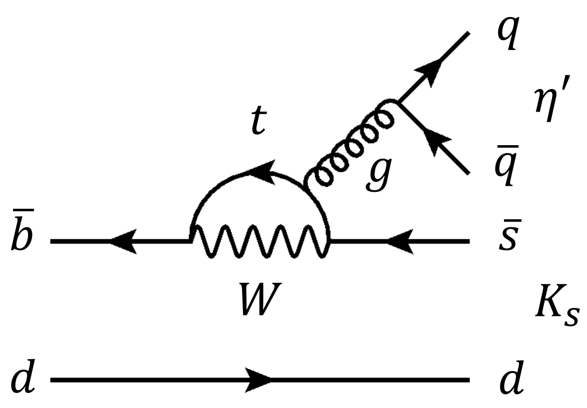
Most precise, and comparable with previous measurement

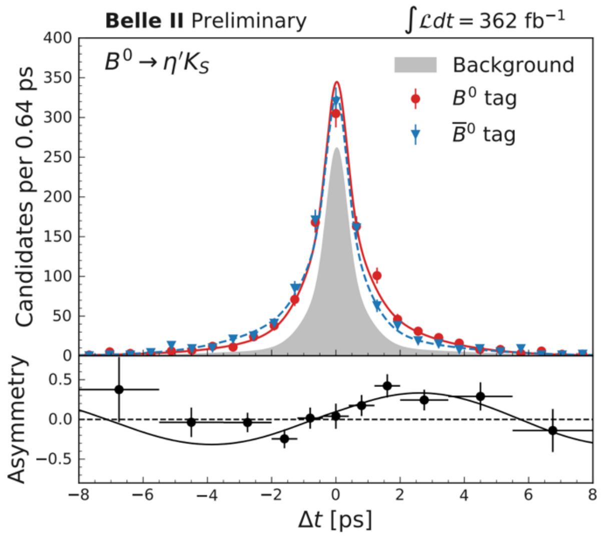
	Belle PhysRevD.98.112008	BaBar PhysRevLett.101.021801
S	$-0.59 \pm 0.19 \pm 0.03$	$-1.23 \pm 0.21 \pm 0.04$
C	$0.15 \pm 0.14^{+0.03}_{-0.04}$	$-0.2 \pm 0.19 \pm 0.03$
$\mathcal{B}(\times 10^{-5})$	$(1.62 \pm 0.11 \pm 0.06)$	$(1.69 \pm 0.14 \pm 0.07)$

$B^0 \to \eta' K_s$

https://arxiv.org/abs/2402.03713

- 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!**

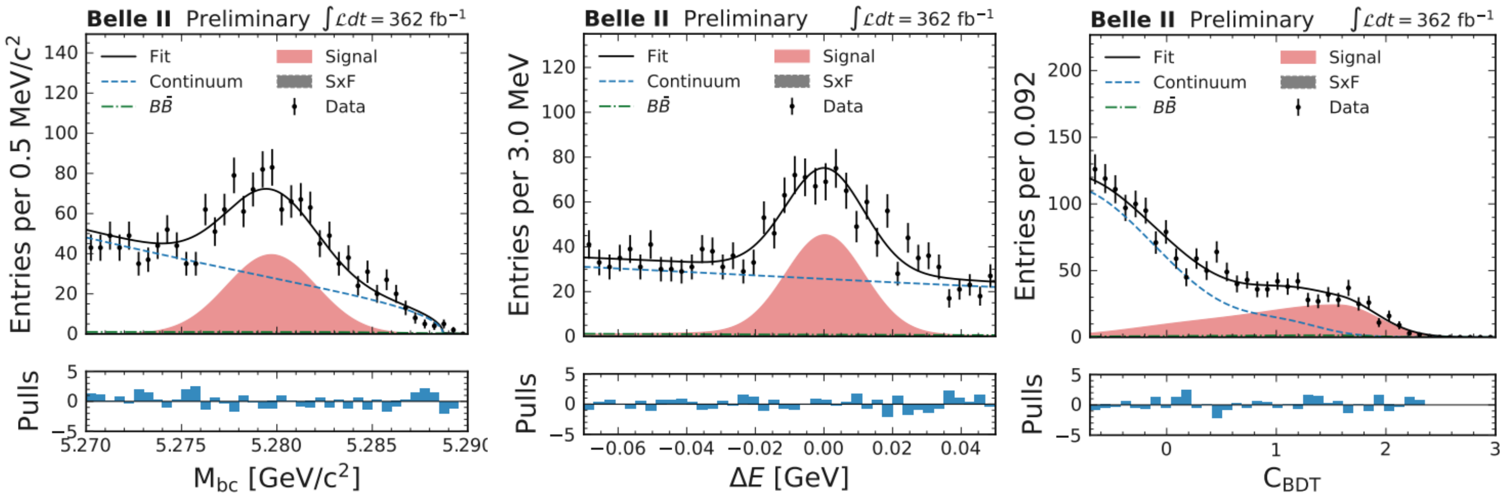




$S = \quad 0.67 \pm 0.10 \pm 0.04$
$C = -0.19 \pm 0.08 \pm 0.03$

	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



C_{BDT} : qq suppression output

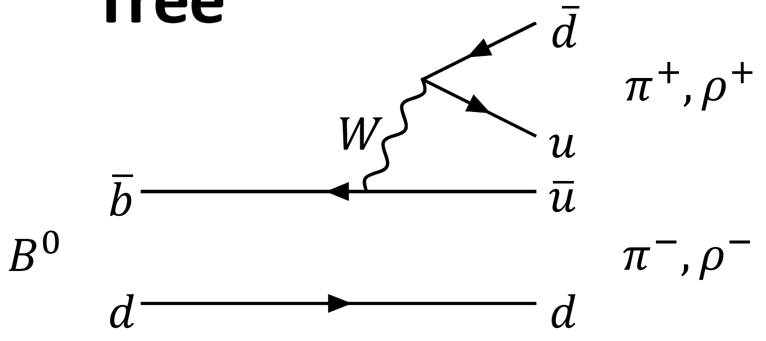
Consistent, and compatible precision with previous experiments!

ϕ_2

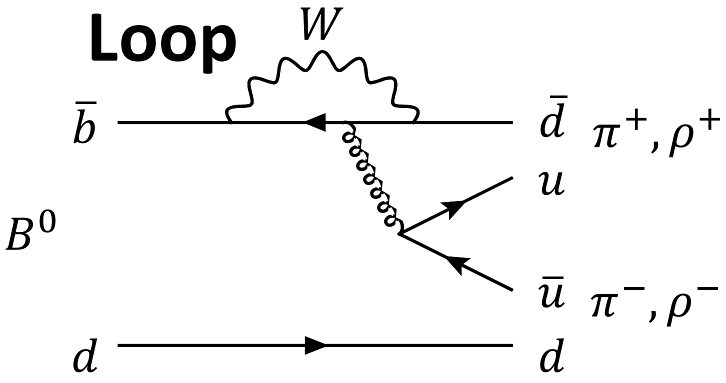
ϕ_2 Measurement

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

Tree



Loop



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

Using $\boldsymbol{b \to u}$ tree decays (ex. $\boldsymbol{B^0 \to \pi^+\pi^-, \rho^+\rho^-}$),

$S = \sin(2\phi_2)\ , C = 0$

Due to the interference between and tree and loop ($\boldsymbol{b \to d}$),

$\boldsymbol{S = \sin(2\phi_2 + \Delta\phi_2)\ , C \neq 0}$

Need to extract the effect from the loop amplitude

Isospin analysis

Isospin relations

	Tree	Loop
$\pi^+\pi^-$	◯	◯
$\pi^+\pi^0$	◯	×
$\pi^0\pi^0$	△ (color suppressed)	◯

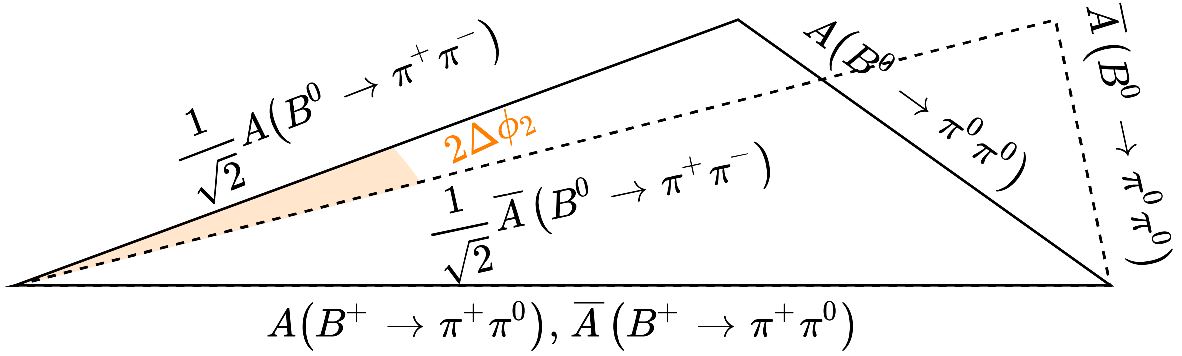
Observables to measure ϕ_2

$\pi^+\pi^-, \rho^+\rho^-$	BF, S,C
$\pi^+\pi^0, \rho^+\rho^0$	BF, C
$\pi^0\pi^0, \rho^0\rho^0$	BF, C, S(only $\rho^0\rho^0$)

Granou-London isospin relations

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

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



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

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

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

PhysRevD.109.012001

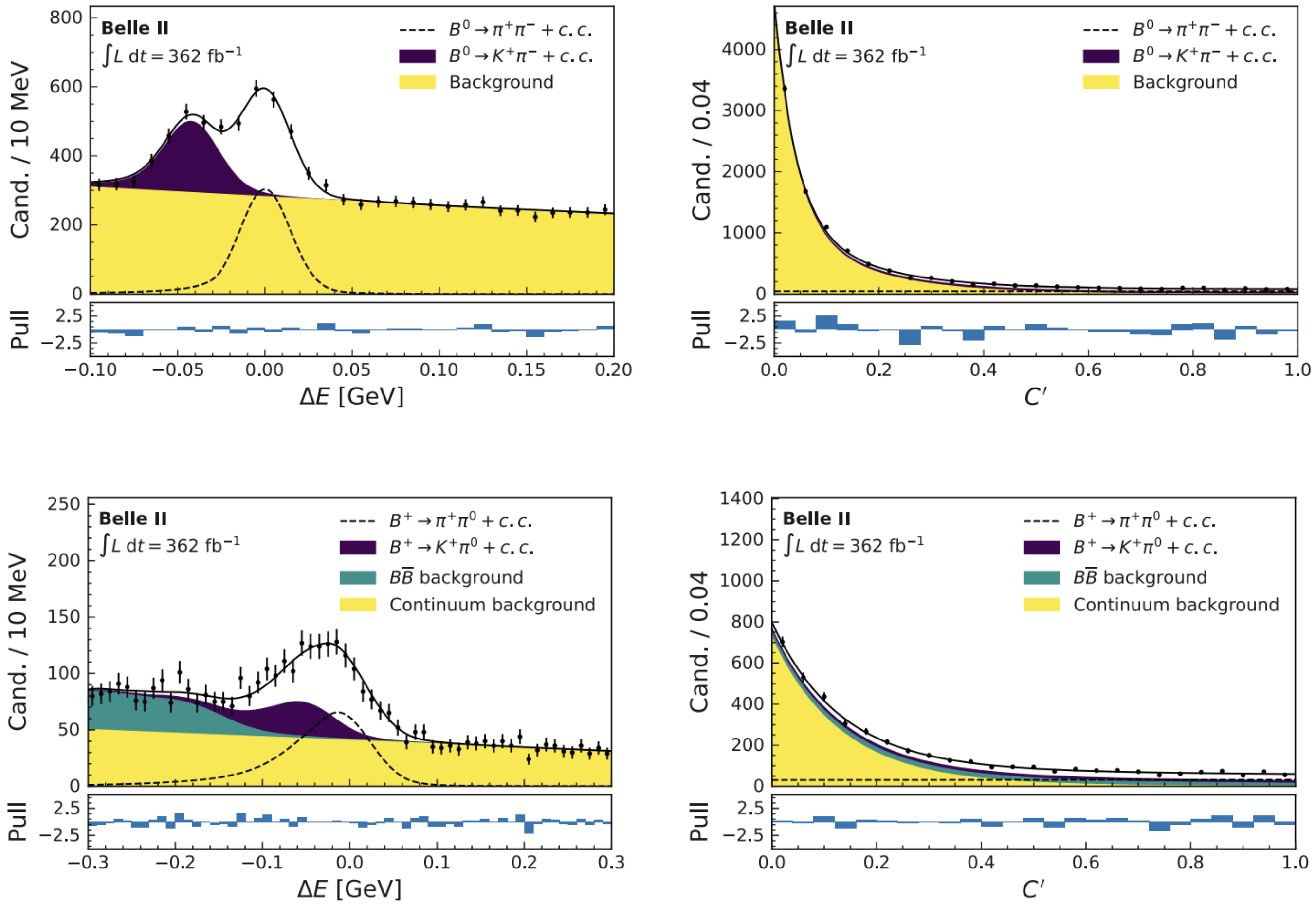
Good agreement with previous measurements
Sensitivity is comparable with Belle using only a half size of the data!

$\pi^+\pi^-$

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

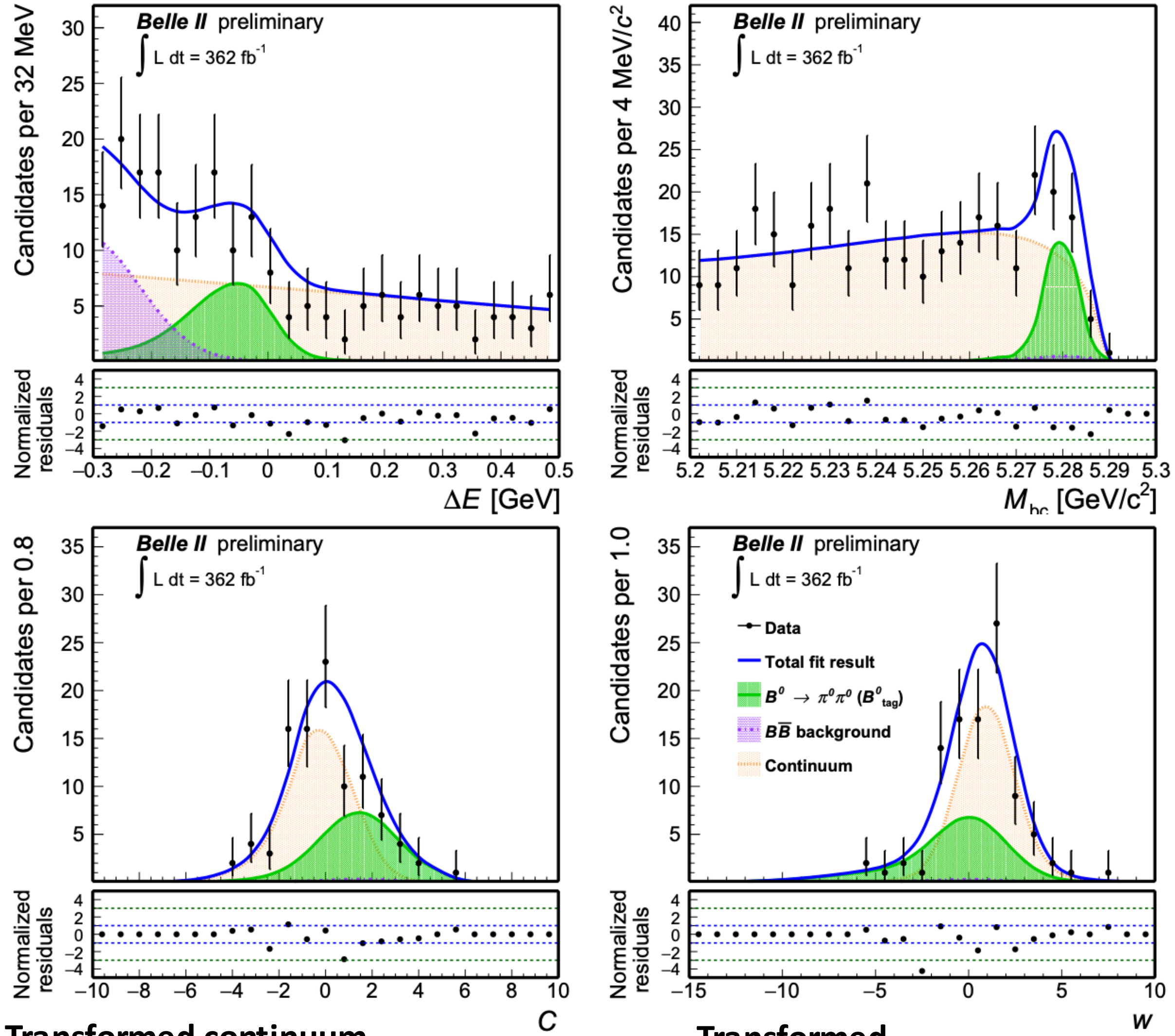
$B^0 \to \pi^0\pi^0$

Require 4γ reconstruction (Belle II Unique) from a large background due to hadronic clusters, beam BG, and so on
→ Developed an MVA for γ selection

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

ϕ_2 extraction using $B \to \pi\pi$ using Belle II results is ongoing
Paper is in progress



Transformed continuum suppression output

Transformed wrong flavor tag probability

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

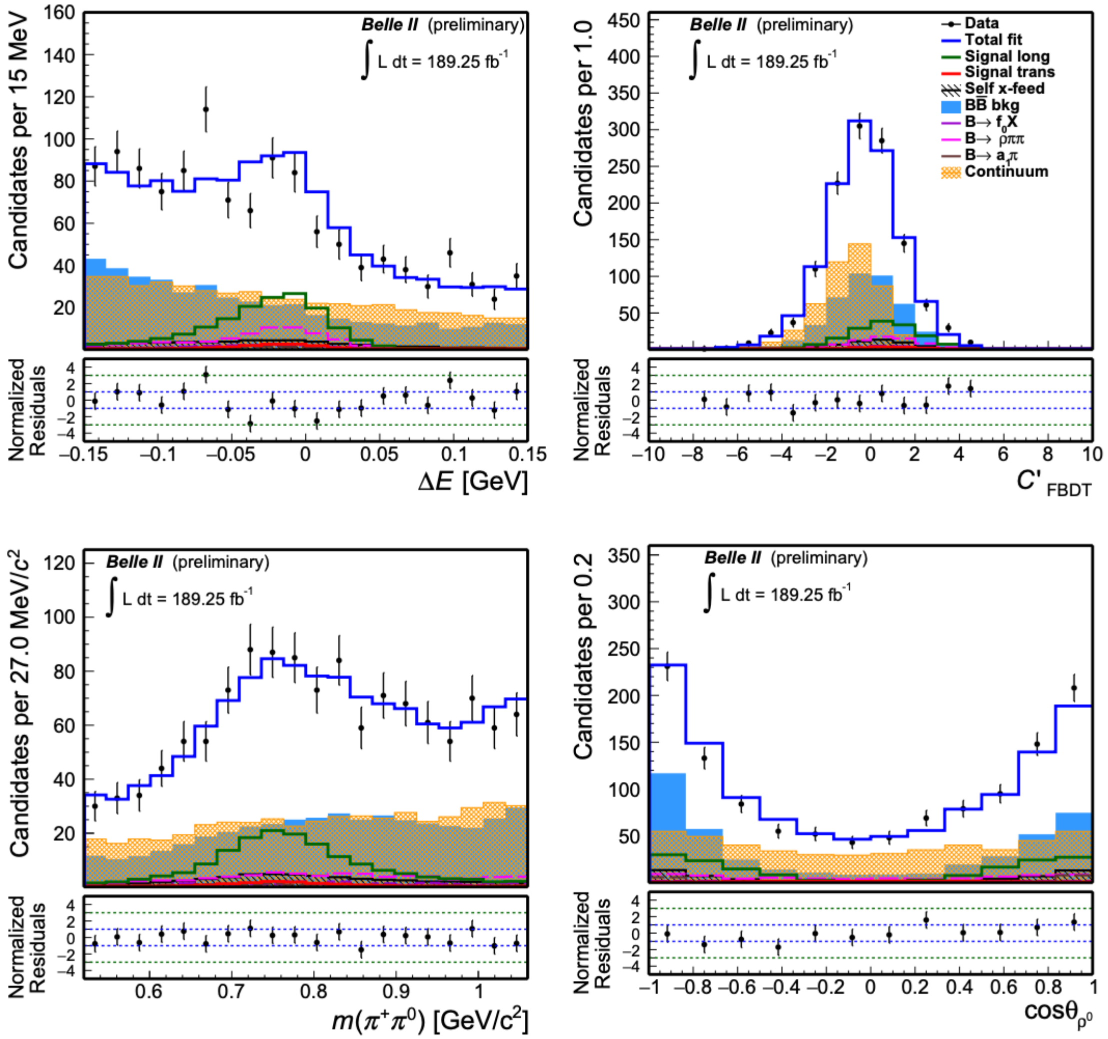
arXiv:2206.12362

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

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

→ $\rho\rho$ 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

→ Needs to be improved by Belle II

Large systematic uncertainty due to **data-MC mismodeling in $\cos\theta_\rho$**

→ Further investigation and analysis with a larger dataset are ongoing!

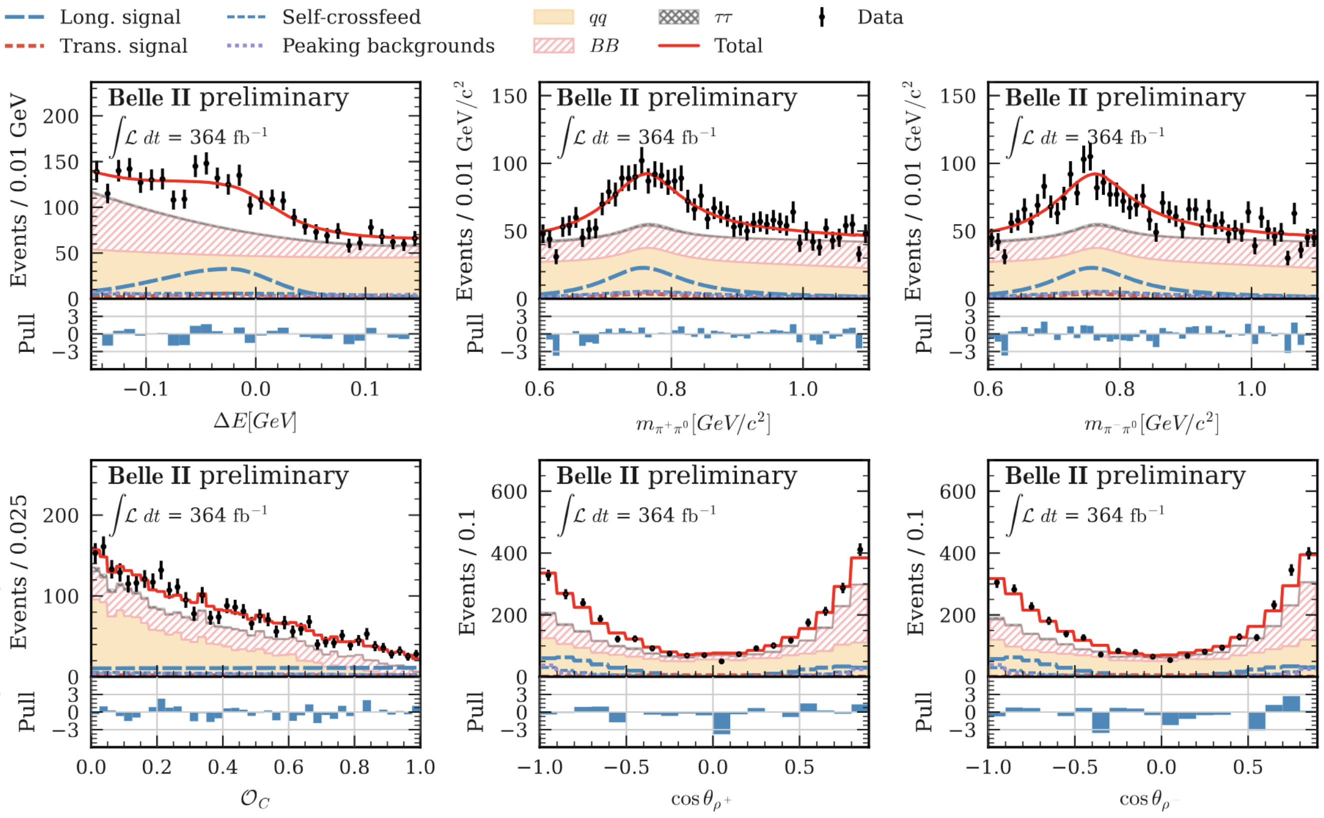
$B^0 \to \rho^+\rho^-$ $\mathcal{B}$ and f_L

NEW

6D Fit for signal Extraction

Analysis challenge

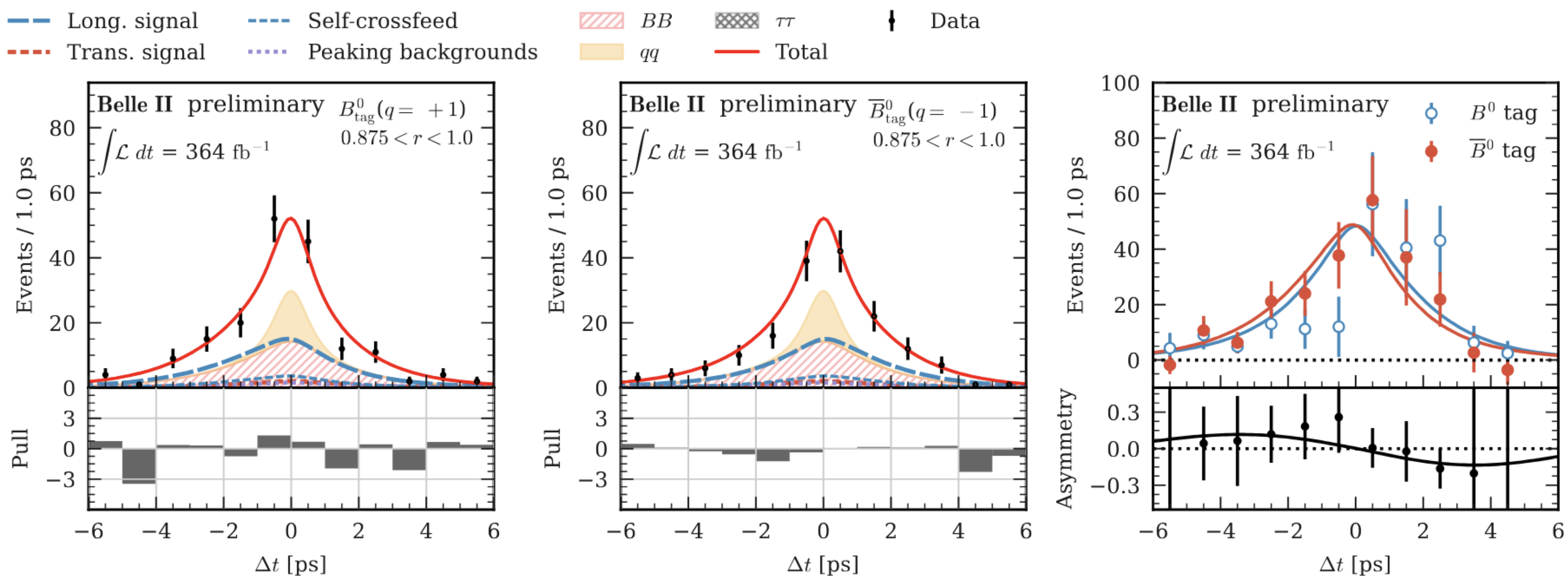
- $B \to \rho\rho$ is $P \to VV$ decay
  → Angular analysis is needed for polarization extraction.
- **π^0 selection**
  Needs two soft π^0 reconstruction from ρ
  → Suppressed backgrounds using machine learning
- **Continuum suppression**
  Large qq background was suppressed by TabNet
  (a kind of neural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



	$\mathcal{B}(10^{-6})$	f_L	N_{BB}
Belle II	$29.0^{+2.3}_{-2.2}\ ^{+3.1}_{-3.0}$ Total uncertainty: 13.3%	$0.921^{+0.024}_{-0.025}\ ^{+0.017}_{-0.015}$	388×10^6
Belle	$28.3 \pm 1.5 \pm 1.5$ Total uncertainty: 7.5%	$0.988 \pm 0.012 \pm 0.006$	772×10^6
BABAR	$25.5 \pm 2.1\ ^{+3.6}_{-3.9}$ Total uncertainty: 16.3%	$0.992 \pm 0.024\ ^{+0.026}_{-0.013}$	383.6×10^6

Consistent with previous experiments → **Extract CPV parameters**

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



	S	C	N_{BB}
Belle II	$-0.26 \pm 0.19 \pm 0.08$	$-0.02 \pm 0.12^{+0.06}_{-0.05}$	388×10^6
Belle	$-0.13 \pm 0.15 \pm 0.05$	$0.00 \pm 0.10 \pm 0.06$	772×10^6
BABAR	$-0.17 \pm 0.20^{+0.05}_{-0.06}$	$0.01 \pm 0.15 \pm 0.06$	383.6×10^6

- **Consistent with previous experiments**
- Improved precision by GFlaT flavor tagger and better selection.

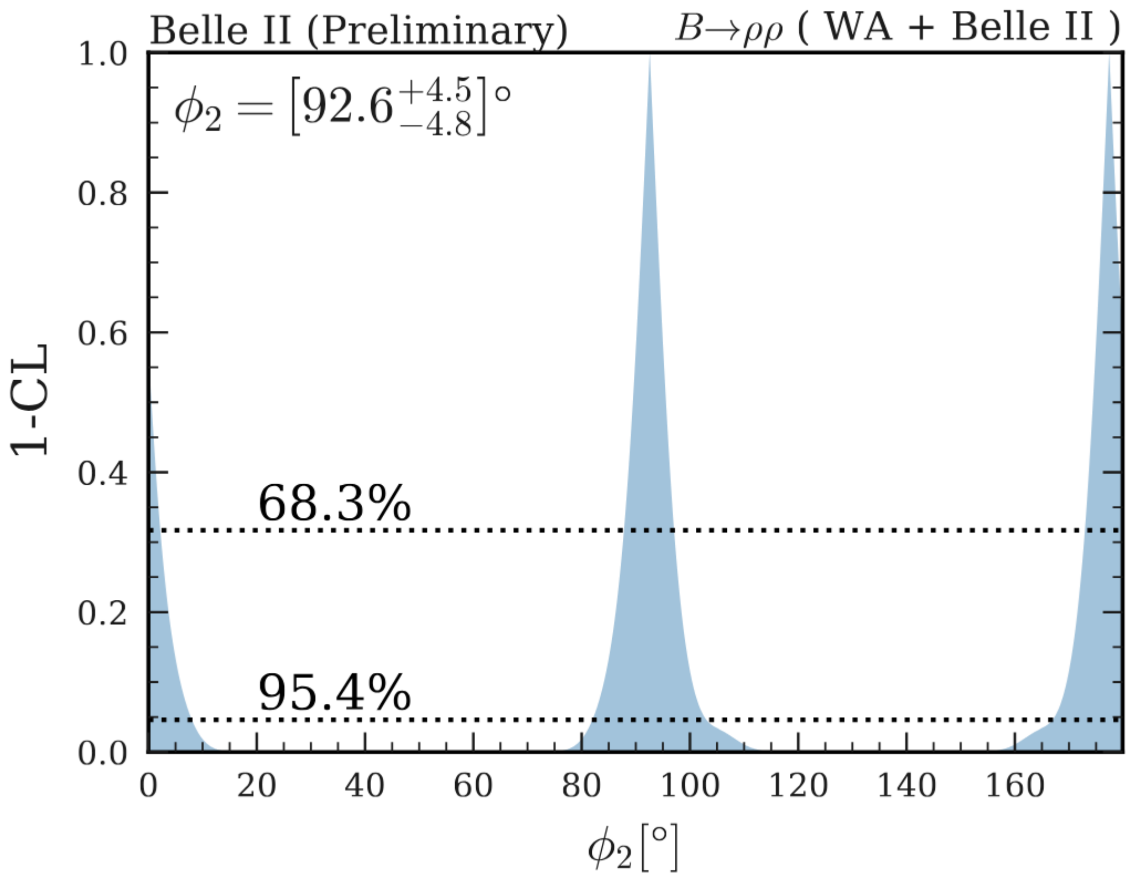
→ Extract ϕ_2 using the new result.

ϕ_2 extraction

NEW

ϕ_2 extraction using $B \to \rho\rho$ world average
$\phi_2 = \left(91.5^{+4.5}_{-5.4}\right)^\circ$
+ Belle II $\rho^+\rho^-$ results
→ $\phi_2 = \left(92.6^{+4.5}_{-4.8}\right)^\circ$

6% improvement by Belle II results!
Dominated by S of $\rho^+\rho^-$ and $\rho^0\rho^0$.
Other $\rho\rho$ analysis is also ongoing in Belle II.



Paper is in progress

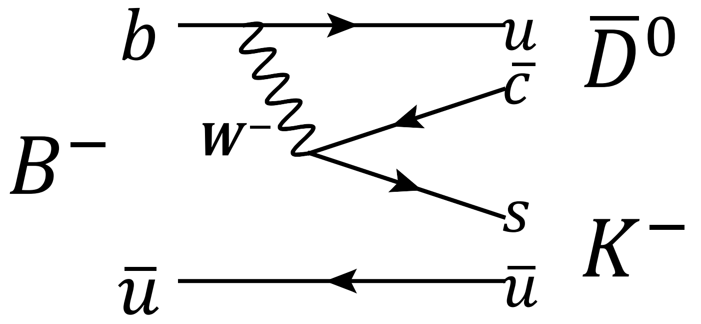
ϕ_3

ϕ_3, γ measurement

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

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

Suppressed

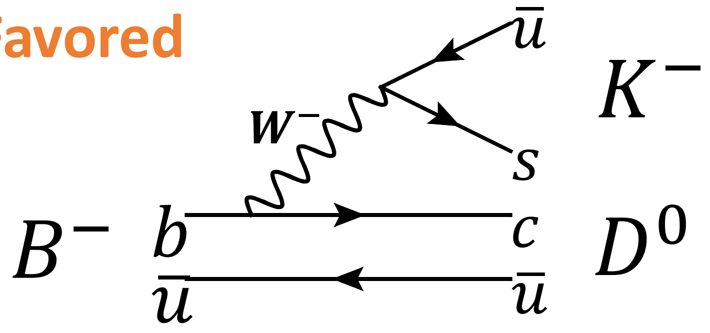


$$\frac{\mathcal{A}(\bar{D}^0K^-)}{\mathcal{A}(D^0K^-)} = r_B \exp(i(\delta_B - \phi_3))$$

$r_B = |\mathcal{A}(\bar{D}^0K^-)|/|\mathcal{A}(D^0K^-)| \simeq c_f|V_{cs}V_{ub}^*/V_{us}V_{cb}^*| \simeq 0.1$ (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: $D^0 \to K^+K^-, K_S^0\pi^0$ (CP eigenstates)
- BPGGSZ method: self conjugate multibody decay, ex.) $D^0 \to K_S^0h^+h^-$
- GLS method: $D^0 \to K_S^0K^{\pm}\pi^{\mp}$ (singly Cabibbo-suppressed decays)
- ADS method: $D^0 \to K^{\pm}\pi^{\mp}$

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

Observables: Direct CPV in $\mathcal{B}$ ratio

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

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

D_{CP+} : CP-Even decay ($D \to K^+K^-$)
D_{CP-} : CP-odd decay ($D \to K_S^0\pi^0$)
$D_{\rm flav}$: Flavor specific decay ($D \to K^{\pm}\pi^{\mp}$)

↓

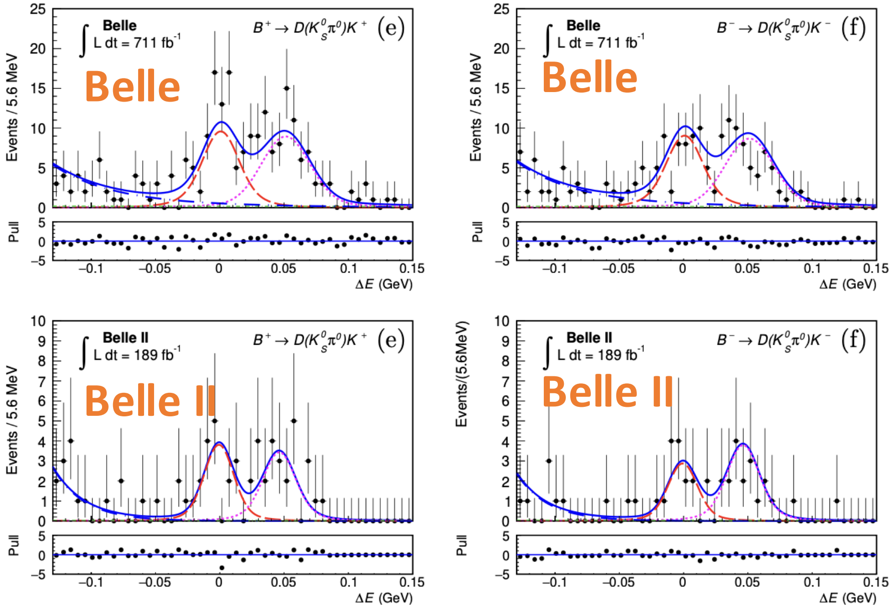
$$\mathcal{R}_{CP\pm} = 1 + r_B^2 \pm 2r_B \cos\delta_B \cos\phi_3,$$

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

(GLW Method)

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

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



$$\mathcal{R}_{CP+} = 1.164 \pm 0.081 \pm 0.036,$$
$$\mathcal{R}_{CP-} = 1.151 \pm 0.074 \pm 0.019,$$
$$\mathcal{A}_{CP+} = (+12.5 \pm 5.8 \pm 1.4)\%,$$
$$\mathcal{A}_{CP-} = (-16.7 \pm 5.7 \pm 0.6)\%,$$

JHEP05(2024)212

3.5 σ evidence for $A_{CP+} \neq A_{CP-}$

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]

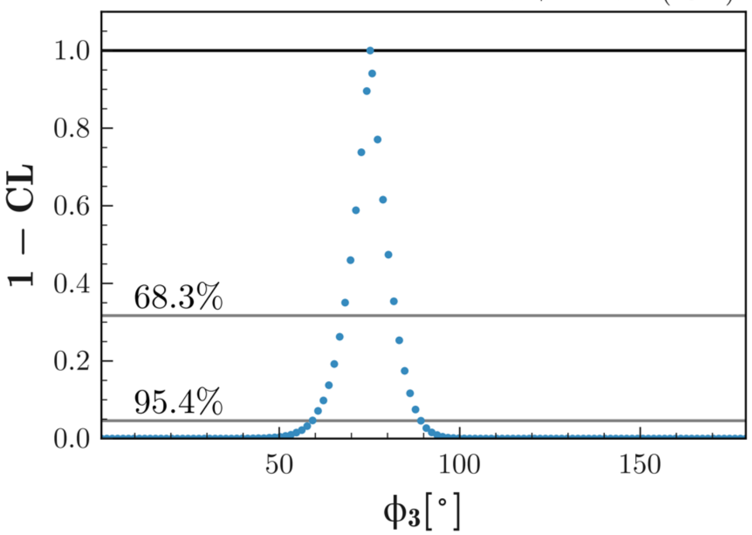
Inputs for ϕ_3 measurement

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

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

Belle + Belle II :

$\phi_3 = (75.2 \pm 7.6)^\circ$

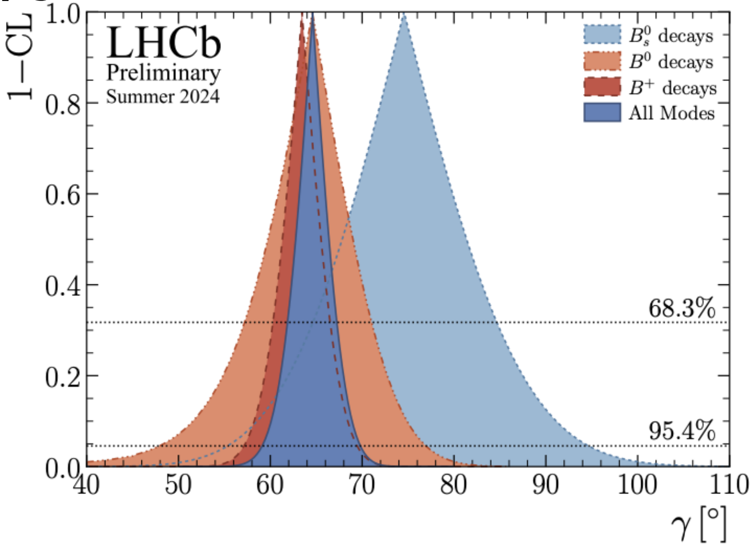


arXiv:2404.12817
(accepted by JHEP)

LHCb:

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

LHCb-CONF-2024-004



Summary

- Belle II is a high-luminosity $\boldsymbol{e^+e^-}$ collider experiments, collected $\mathbf{531\ fb^{-1}}$ of data (equivalent of BaBar, half of Belle)
- Belle II is improving the CP violation measurement using collected data, improved detectors, and improved analysis technique.
- The new GNN-based flavor tagger improved the precision by about 10%!
- ϕ_1: $B^0 \to J/\Psi K_s^0, B^0 \to \eta' K_s^0, B^0 \to J/\Psi \pi^0$.
  $\boldsymbol{B^0 \to J/\Psi\pi^0}$: Significant improvement, and obtained most precise result!
- ϕ_2: $B \to \pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0, B^+ \to \rho^+\rho^0, B^0 \to \rho^+\rho^-$
  $\boldsymbol{\rho^+\rho^-}$: New result, improved precision, first $\boldsymbol{\phi_2}$ extraction with improved precision!
- $\boldsymbol{\phi_3}$:
  The first Belle + Belle II combined analysis, improved sensitivity!

Systematic uncertainty

$B^0 \to J/\Psi K_s^0$

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

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
sWeight 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
$B^0 \to D^{(*)-}\pi^+$ sample size		0.004	0.007
Total systematic uncertainty	0.36	0.009	0.029
Statistical uncertainty	0.43	0.035	0.026

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

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

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
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 $B\overline{B}$ 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
$B\overline{B}$ background asymmetry	0.008	0.006
Candidate selection	0.007	0.009
Total	0.027	0.037

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

Branching fraction

Source	$B^0 \to \pi^+\pi^-$	$B^+ \to \pi^+\pi^0$
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	$B^+ \to \pi^+\pi^0$
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 ($B^0 \to \pi^0\pi^0$)

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

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

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
$B\overline{B}$ 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 ($B^0 \to \rho^+\rho^-$)

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