Studies of CP violation at Belle and Belle II

Radek Žlebčík
on behalf of the Belle II collaboration

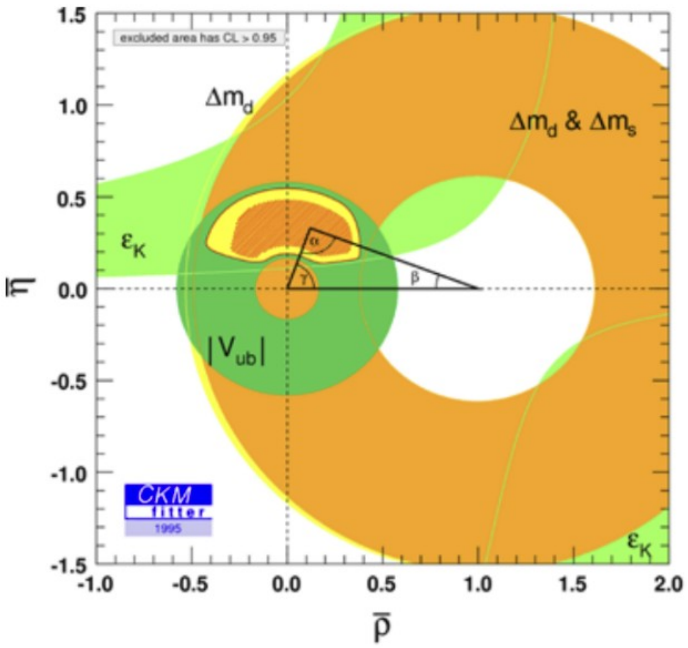
December 3, 2024
DISCRETE 2024
Ljubljana, Slovenia

Unitarity triangle : 30 years of development

- Unitarity Triangle constructed from CKM matrix has angles and sides which are well-defined (physics) quantities

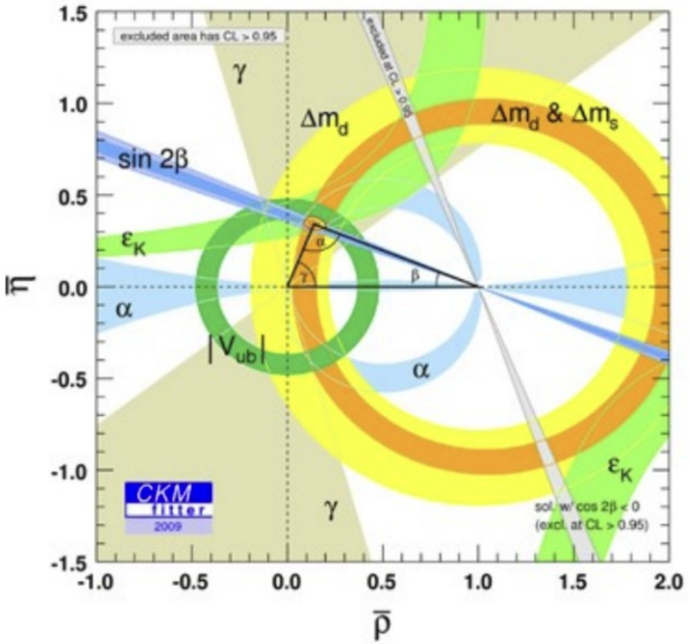
$$V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}=0$$

1995



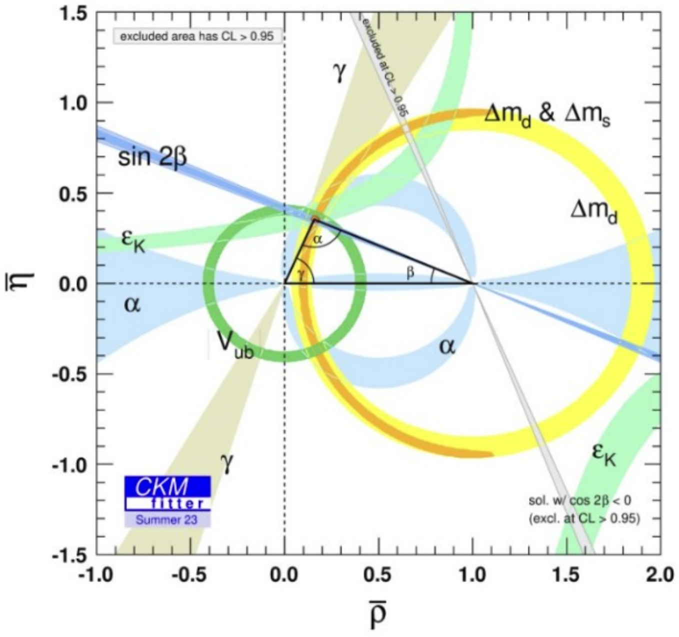
Pre 1st generation *B* factories

2009



Post 1st generation *B* factories
+ CDF B_s mixing

2023

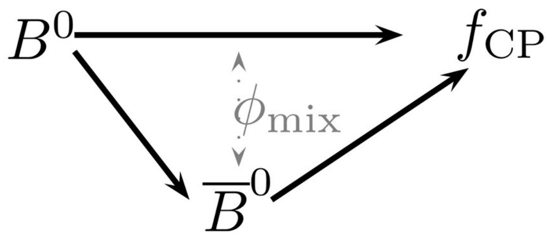


Today
+ LHCb and improved theory

6 ways of (over)constraining the Apex of the Unitarity Triangle

CP violation in interference of mixing and decay

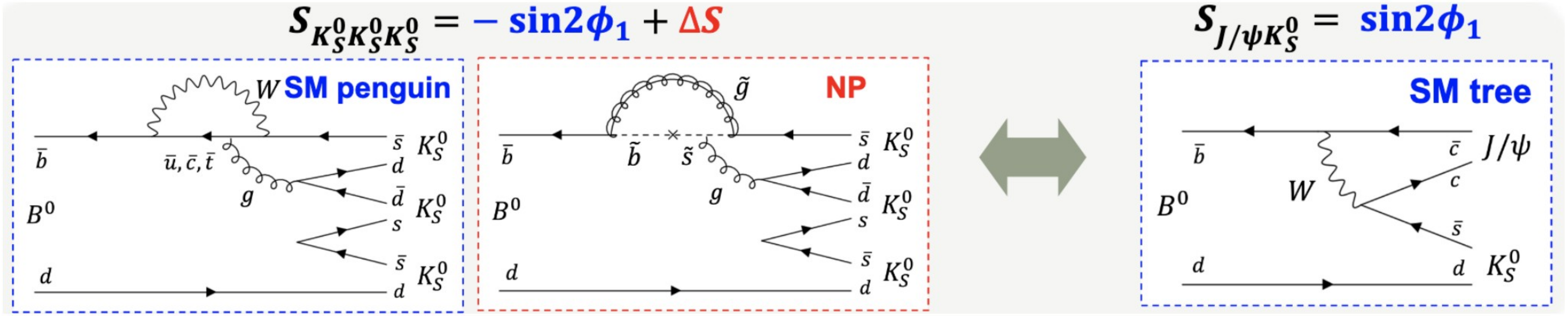
- The S measurable from the time-dependent asymmetry between $B^0 \rightarrow f_{CP}$ and $\overline{B}^0 \rightarrow f_{CP}$



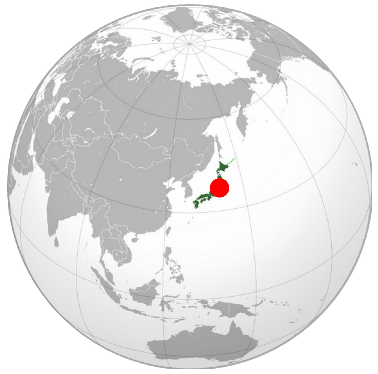
$$\mathcal{A}_{\rm CP}(\Delta t) = \frac{\mathcal{B}(\bar{B}^0 \to f_{\rm CP})(\Delta t) - \mathcal{B}(B^0 \to f_{\rm CP})(\Delta t)}{\mathcal{B}(\bar{B}^0 \to f_{\rm CP})(\Delta t) + \mathcal{B}(B^0 \to f_{\rm CP})(\Delta t)} = S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)$$

Mixing-induced CPV

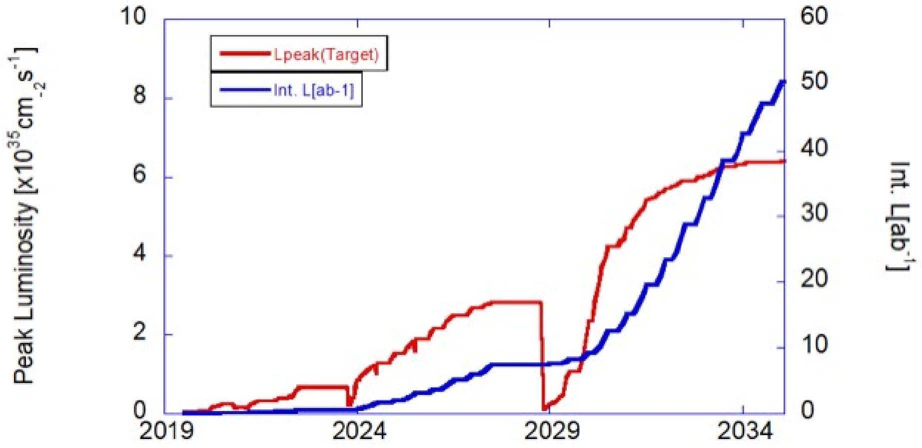
Direct CPV



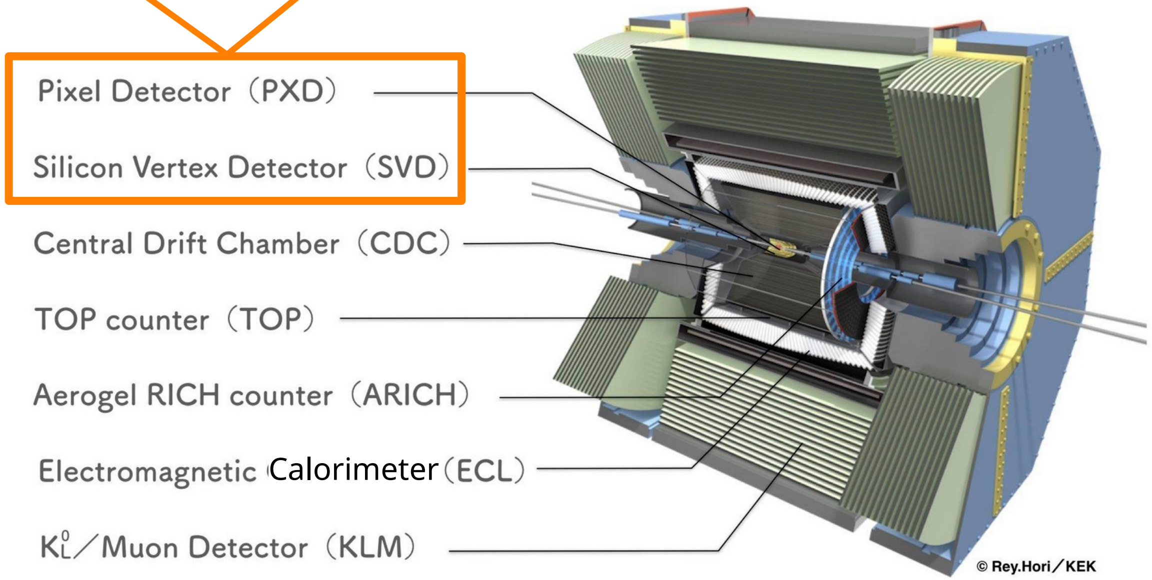
Belle2 & SuperKEKB status



- 550 fb^{-1} of integrated luminosity collected so far (most analyses based on 365 fb^{-1} of Run 1 4S data)
- World record instantaneous luminosity 0.47×10^{35} cm^{-2} s^{-1} → target 6×10^{35} cm^{-2} s^{-1}

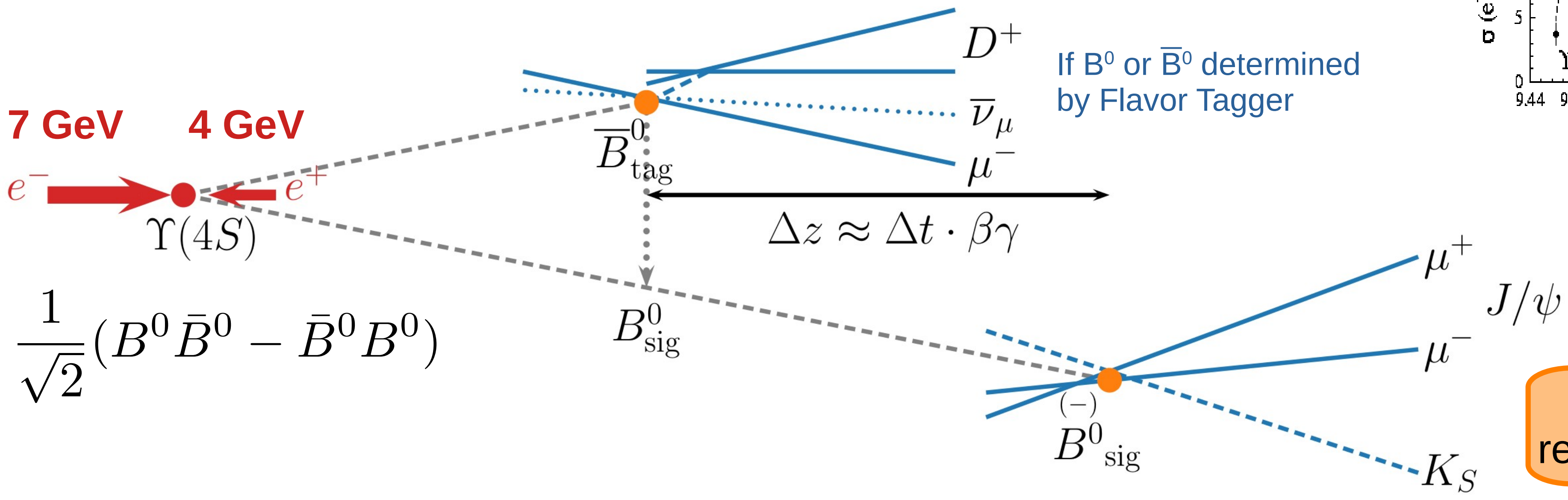


Frequent beam instabilities has resulted in smaller integrated luminosity, and even to preventive turn-off of PXD in 2024
→ Most of the 2024 runtime dedicated to accelerator studies

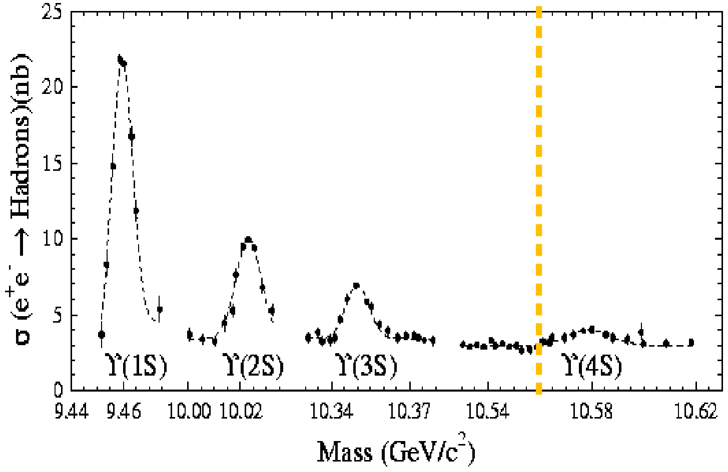


Measuring time-dep. CPV at Belle II

- Collisions energy just above $B^0\bar{B}^0$ production threshold
- Due to the asymmetric beam energies B-mesons fly in the direction of the e^- beam



$B^0\bar{B}^0$ mass



Time-measurement ⟺ distance-measurement

Belle II : $\Delta z \approx 130\,\mu m$

Belle : $\Delta z \approx 200\,\mu m$

$$\beta\gamma = 0.288$$

Fully reconstructed

From rest of event

$$\Delta t = \frac{(\vec{v}_{\rm sig} - \vec{v}_{\rm tag}) \cdot \vec{n}_{\rm boost}}{\gamma\beta c}$$

In this talk

Global average dominated by...

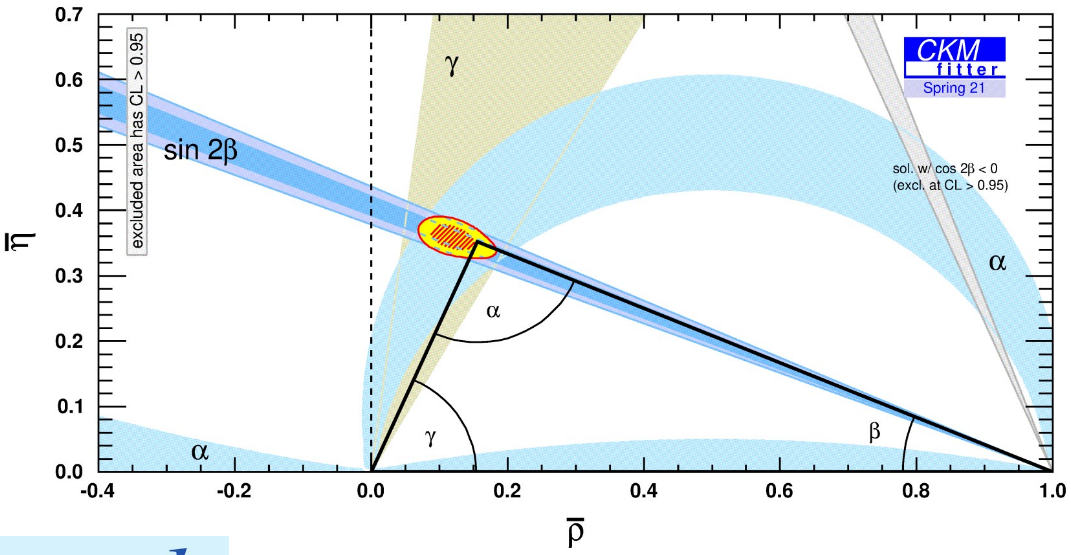
$\alpha/\phi_2=(84\pm4)°$:

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

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

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

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



$\beta/\phi_1=(22.6\pm0.5)°$ $b\rightarrow c$:

$B^0 \rightarrow J/\psi K^0_s$

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

$\gamma/\phi_3=(66\pm3)°$

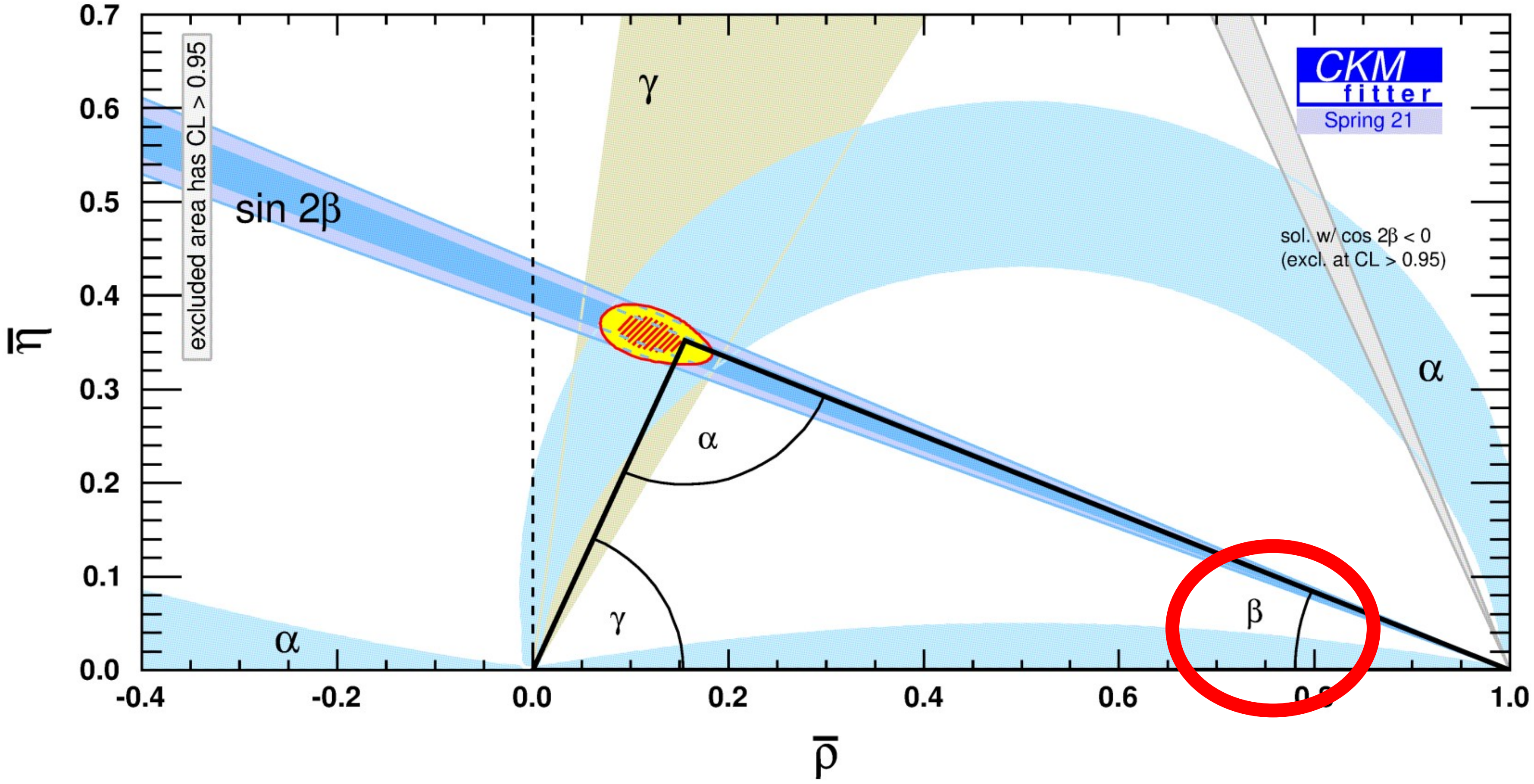
$\beta/\phi_1=(20.4\pm1.4)°$ $b\rightarrow s$:

$B^0 \rightarrow \eta' K^0_s$

$B^0 \rightarrow \varphi K^0_s$

$B^0 \rightarrow K^0_s K^0_s K^0_s$

$\phi_1 = \beta$


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.4
-0.2
0.0
0.2
0.4
0.6
1.0
$\bar{\eta}$
$\bar{\rho}$
excluded area has CL > 0.95
sin 2β
γ
α
β
CKM fitter
Spring 21
sol. w/ cos 2β < 0
(excl. at CL > 0.95)

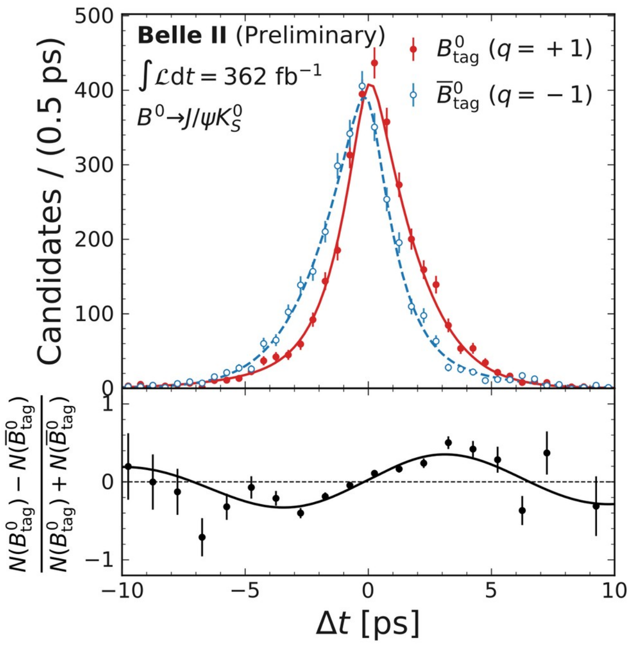
GNN-based Flavor tagger and $B^0 \to J/\psi K^0_s$

- The Graph Neural Network based Flavor tagger leads to ~20% gain in the effective statistics compared to category-based FT
- FT tested in $B^0 \to J/\psi K^0_s$, the golden channel for the $S \sim \sin 2\phi_1$ measurement

Phys.Rev.D 110 (2024)

$\varepsilon^{\text{eff}}_{\text{tag}}$ (CB) = (31.7 ± 0.5 ± 0.4)%

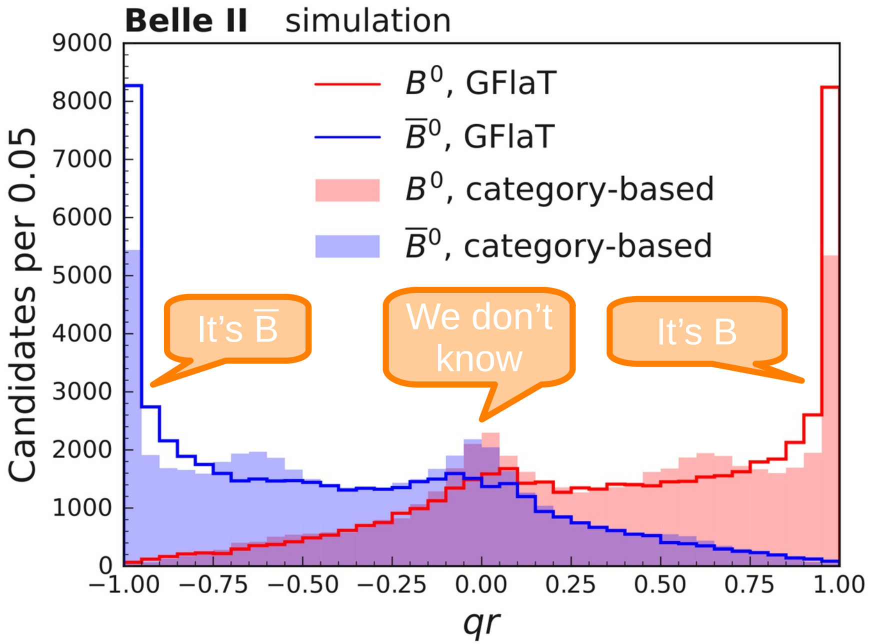
$\varepsilon^{\text{eff}}_{\text{tag}}$ (GFlaT) = (37.4 ± 0.4 ± 0.3)%



$$S = +0.724 \pm 0.035 \pm 0.009$$
$$C = -0.035 \pm 0.026 \pm 0.029$$

Latest LHCb result
Phys.Rev.Lett. 132 (2024) 2
$$S = +0.726 \pm 0.014$$

Important validation of time-dep. CPV machinery, already more precise than BaBar.



CPV in $B^0 \to J/\psi\, \pi^0$

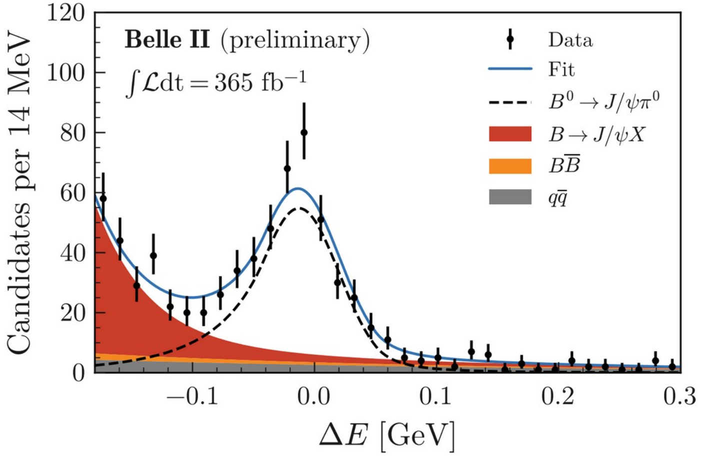
arXiv:2410.08622

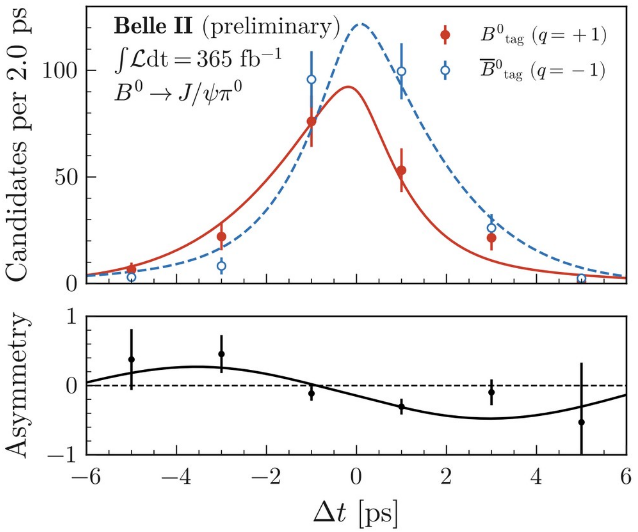
- Color suppressed $b \to c\bar{c}d$ tree-level decay
  → loop contribution plays a role
- Important input to correct for the penguin contamination in the $B^0 \to J/\psi\, K^0_s$
  (tree only: $S = -\sin 2\phi_1 \sim -0.71$)

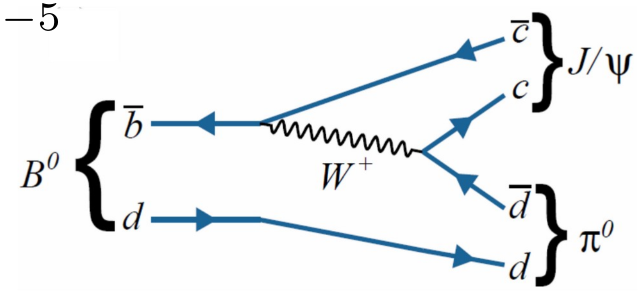
203±17 ($J/\psi \to \mu\mu$)
186±16 ($J/\psi \to ee$)

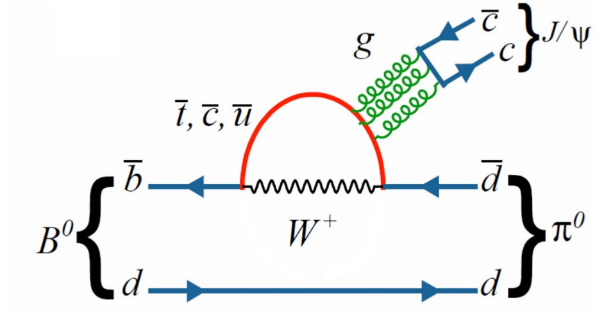
$$S = -0.88 \pm 0.17 \pm 0.03$$
$$C = +0.13 \pm 0.12 \pm 0.03$$

$$\mathrm{BR} = (2.00 \pm 0.12 \pm 0.10) \pm 10^{-5}$$









PhysRevD.98.112008

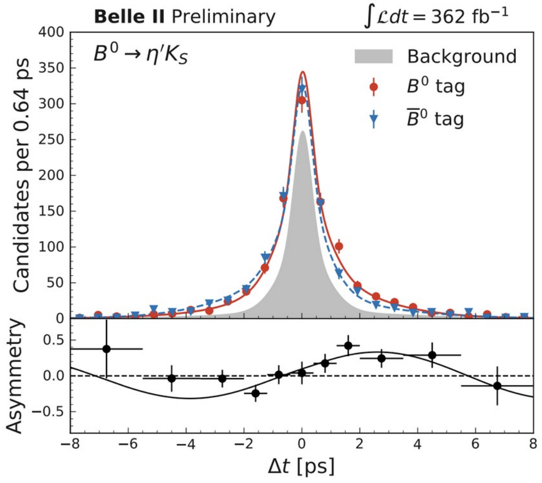
The world's most precise measurement of this mode
(higher precision than Belle)

$\phi_1 = \beta$ from Penguin $b \to s$ transitions

arXiv:2402.03713

$B^0 \to \eta' K^0_s$

- $\eta' \to \eta(\to \gamma\gamma)\pi^+\pi^-$
  $\eta' \to \rho\gamma$
- ~800 signal events

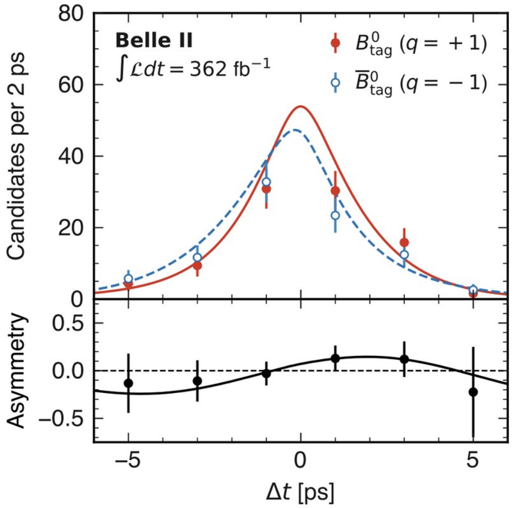


$$S = +0.67 \pm 0.10 \pm 0.04$$
$$C = -0.19 \pm 0.08 \pm 0.03$$

Phys.Rev.D 108 (2023) 7

$B^0 \to \varphi K^0_s$

- Major challenge is from non-resonant $B^0 \to K^+ K^- K^0_S$ background with opposite CP
- ~160 signal events

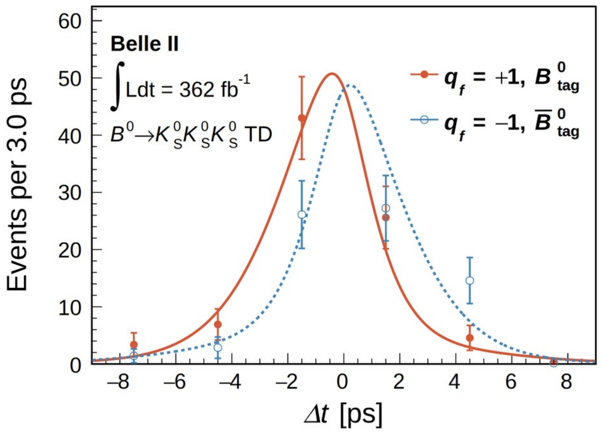


$$S = +0.54 \pm 0.26^{+0.06}_{-0.08}$$
$$C = -0.31 \pm 0.20 \pm 0.05$$

Phys.Rev.D 109 (2024) 11

$B^0 \to K^0_s K^0_s K^0_s$

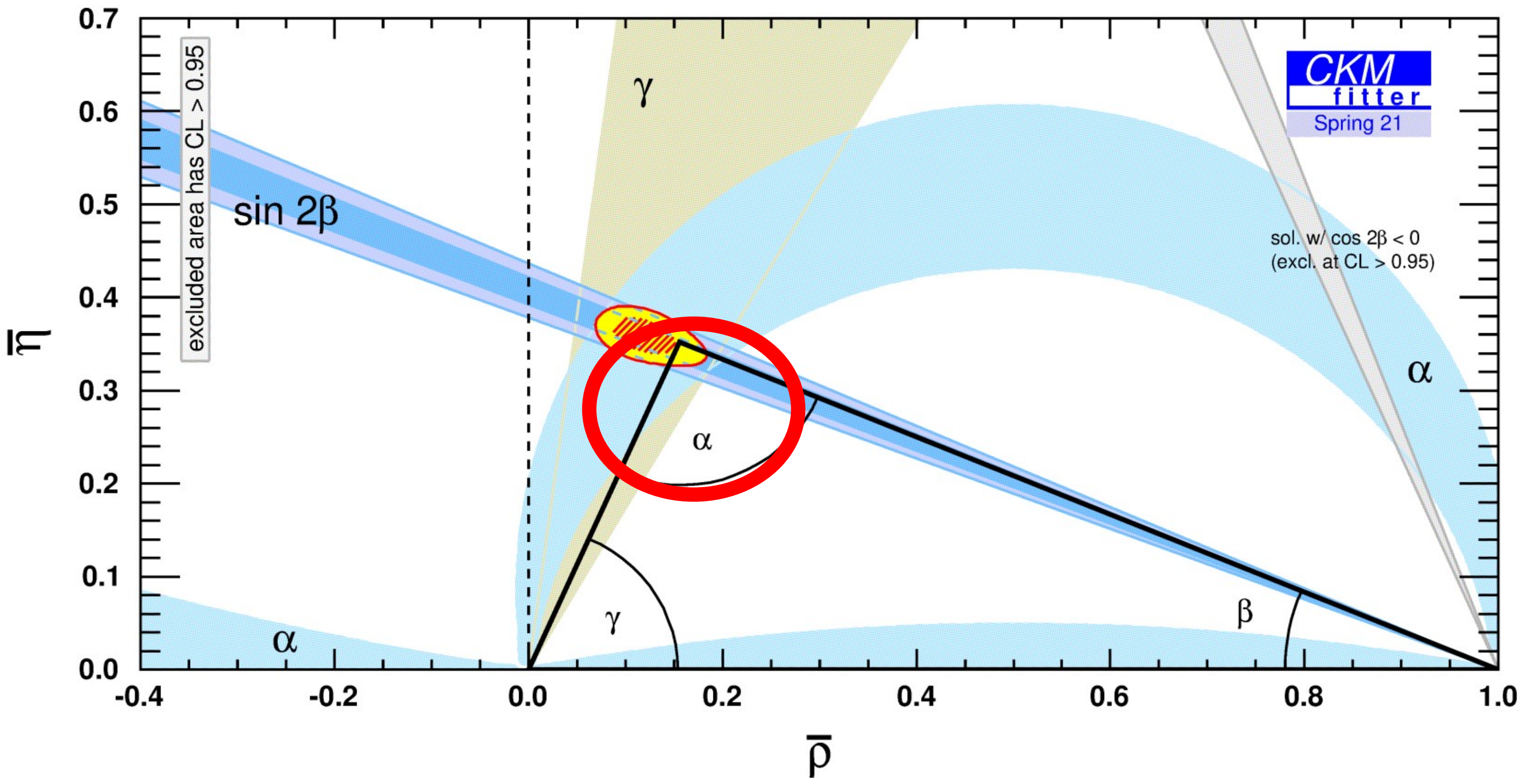
- Major challenge is to reconstruct B^0 vertex from three K^0_s "tracks"
- ~160 signal events



$$S = -1.37^{+0.35}_{-0.45} \pm 0.03$$
$$C = -0.07 \pm 0.20 \pm 0.05$$

Results compatible with World Average, not at the Belle precision yet.

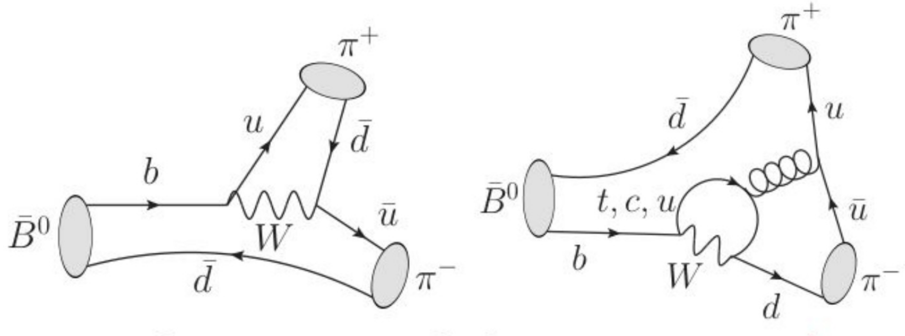
$\phi_2 = \alpha$



CKM fitter
Spring 21
excluded area has CL > 0.95
sin 2β
γ
α
β
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
η̄
ρ̄
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0

Experimental framework

- For $B^0 \to \pi^+\pi^-$ and $B^0 \to \pi^0\pi^0$ the tree-level and loop contribution have similar size, but different phase



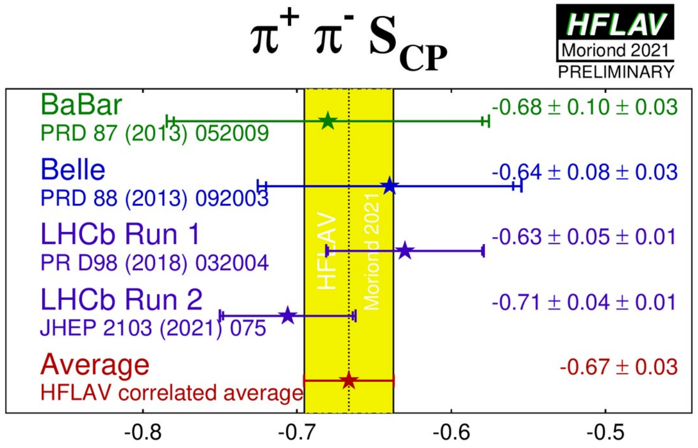
- Usage of Gronau-London isospin relations for $B \to \pi\pi$ to disentangle the effects (CKMfitter, UTfit)

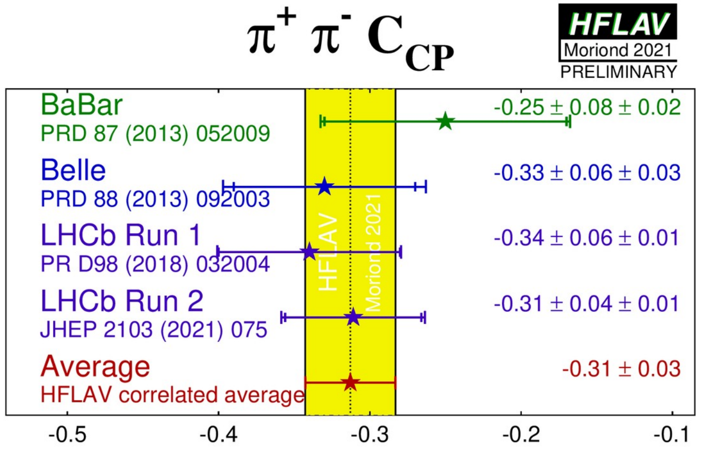
$$A^{+0} = A^{+-}/\sqrt{2} + A^{00}$$
$$\bar{A}^{+0} = \bar{A}^{+-}/\sqrt{2} + \bar{A}^{00}$$
$$|A^{+0}| = |\bar{A}^{+0}|$$

Need for

- All branching fractions
- Direct CP asymmetries C^{00} C^{+-}
- TD CP asymmetries S^{00} S^{+-}

Projected Belle II sensitivity for α is 1% (currently 5%)





Can be also done with $B \to \rho\rho$

Time integrated $B^0 \rightarrow \pi^0 \pi^0$

FPCP2024

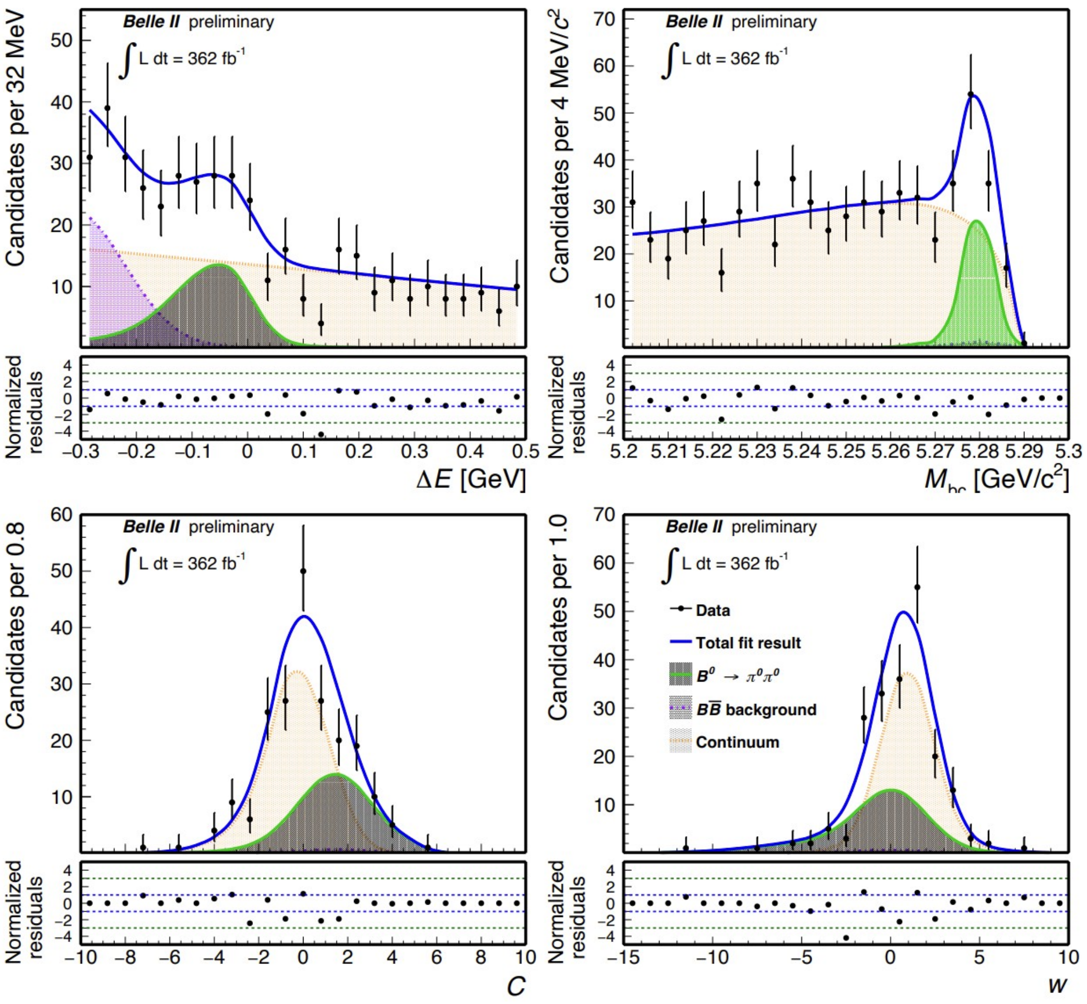
- Very difficult for LHCb, important constraint of penguin component
- Time-integrated analysis
  → getting π^0 vertices is difficult
- BG e.g. from $B^+ \rightarrow \rho^+(\rightarrow \pi^+\pi^0)\, \pi^0$
- 4D unbinned fit in M_{bc}, ΔE, continuum suppression (C) and wrong tag probability (w)

$$B \; = \; (1.26 \pm 0.20 \pm 0.11) \times 10^{-6}$$
$$A_{CP} = +0.06 \pm 0.30 \pm 0.06$$

World average:

$$B \; = (1.59 \pm 0.26) \times 10^{-6}$$
$$A_{CP} = \; 0.30 \pm 0.20$$

126±20 signal events



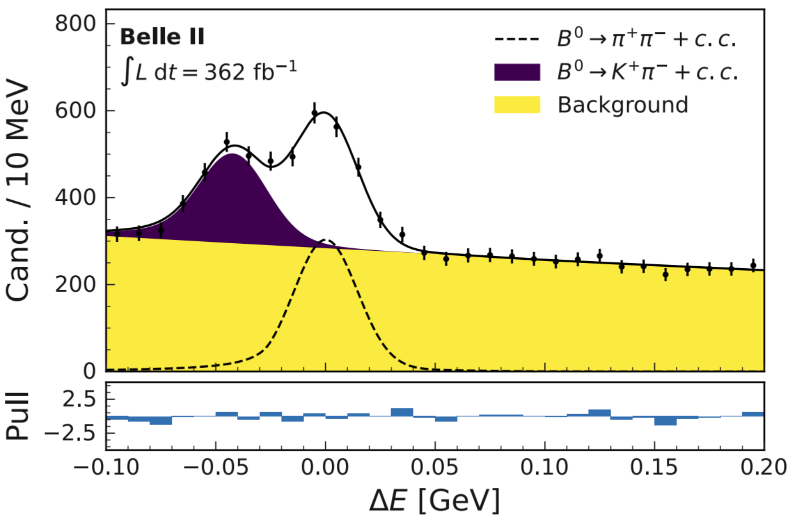
World best measurement of B and C

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

Phys.Rev.D 109 (2024) 1

- All decay modes are still stat-dominated since the π^0 efficiency systematics will improve with more data
- Measurement of the $B^0 \to \pi^+\pi^-$ CP asymmetries in the pipe-line

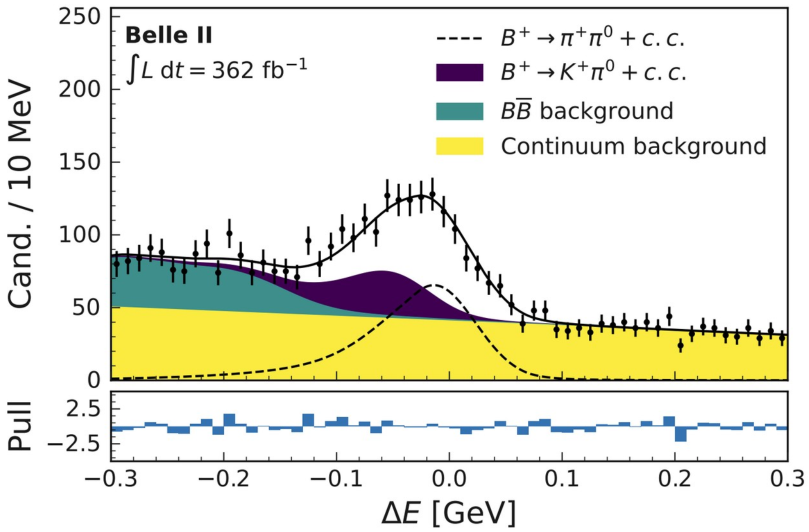
~1500 $B^0 \to \pi^+ \pi^-$ events



$$B = (5.83 \pm 0.22 \pm 0.17) \times 10^{-6}$$

World best

~900 $B^+ \to \pi^+ \pi^0$ events



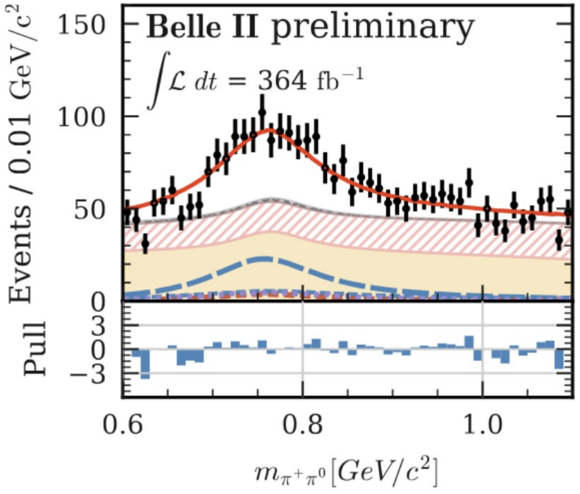
$$B = (5.10 \pm 0.29 \pm 0.32) \times 10^{-6}$$

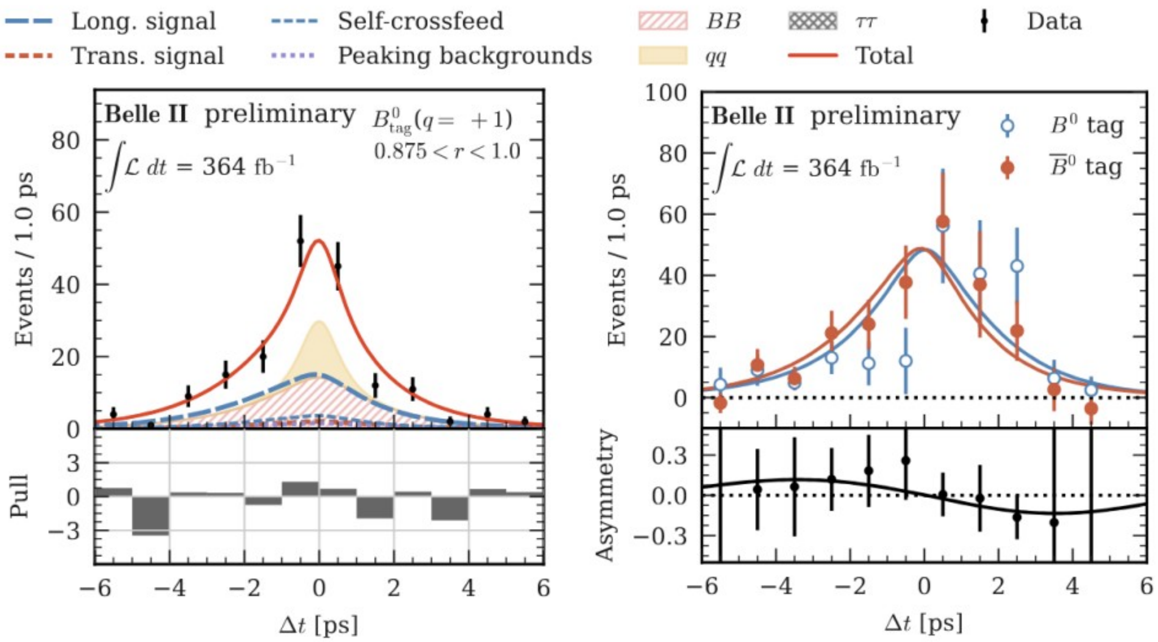
$$A_{CP} = (-0.081 \pm 0.054 \pm 0.008) \times 10^{-6}$$

Time-dependent CPV in $B^0 \to \rho^+ \rho^-$

Blois 2024

- The $P \to VV$ decay, i.e. full angular analysis needed for polarization extraction, notice $\rho^+ \to \pi^+ \pi^0$
- Two soft π^0 in the final state
  → difficult for LHCb
- 6D time-dependent fit for signal extraction





	$\mathcal{B}(10^{-6})$	f_L
Belle II	$29.0^{+2.3}_{-2.2}\ {}^{+3.1}_{-3.0}$	$0.921^{+0.024}_{-0.025}\ {}^{+0.017}_{-0.015}$
Belle	$28.3 \pm 1.5 \pm 1.5$	$0.988 \pm 0.012 \pm 0.006$
BABAR	$25.5 \pm 2.1\ {}^{+3.6}_{-3.9}$	$0.992 \pm 0.024\ {}^{+0.026}_{-0.013}$

	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	$-0.17 \pm 0.20^{+0.05}_{-0.06}$	$0.01 \pm 0.15 \pm 0.06$

All parameters are measured with precision better than BaBar but worse than Belle
→ extract ϕ_2 using new data

Impact on the ϕ_2/α

Blois 2024

- The world average of ϕ_2 is dominated by B factories and $B\to\pi\pi$ & $B\to\rho\rho$ decay modes
- The $B\to\rho\rho$ only world average:

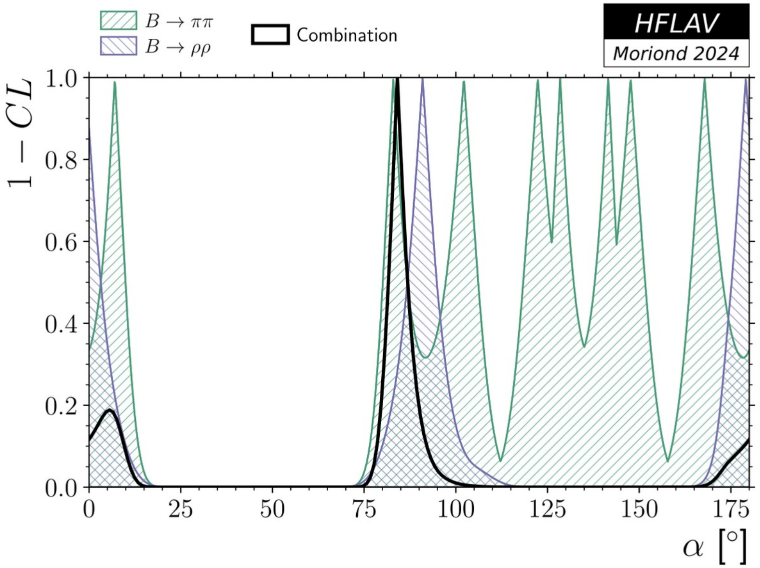
$$\phi_2 = (91.5^{+4.5}_{-5.4})^\circ$$

- The $B\to\rho\rho$ only world average (+ Belle II $B^0\to\rho^+\rho^-$)

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

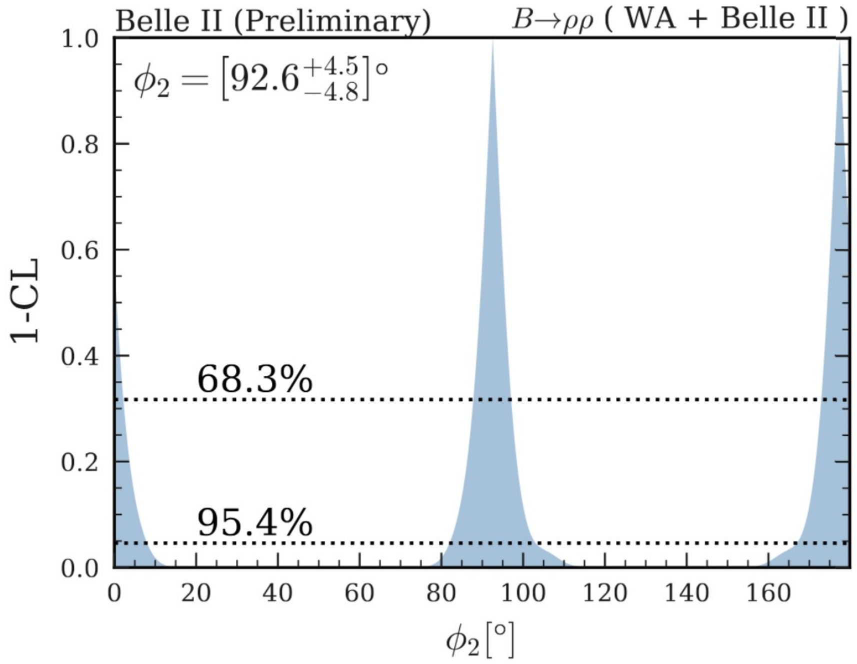
Current world average:

$$\phi_2 = (84.1^{+4.5}_{-3.8})^\circ$$



7% improvement in the ϕ_2 precision.
The fit dominated by $S(\rho^+\rho^-)$ and $S(\rho^0\rho^0)$, both only measured at B factories.

The ρ-based estimate is slightly higher than π-based but still consistent within 2σ.



Conclusion

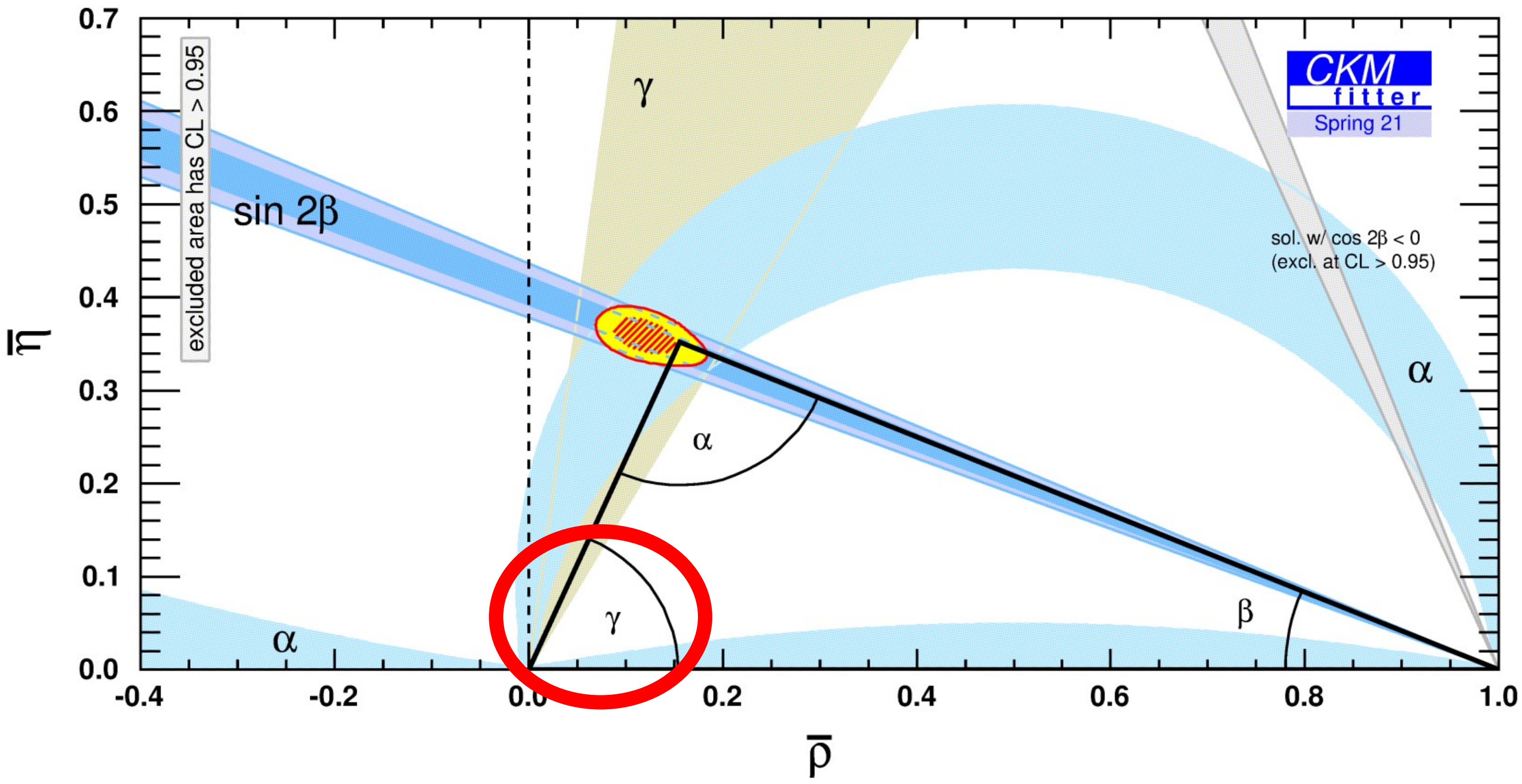
- Broad CPV physics program at Belle II
  → **Precise** measurements of Unitarity Triangle angles
  → CPV in **rare** $b \to s$ decays sensitive to New Physics

- The Run I Belle II dataset similar to BaBar but often the precision is better:
  → Smaller interaction region
  → Better vertex resolution
  → The GNN-based B flavor tagging

- After LS1 (Spring 2024) Belle II continues in data taking
  → Exceeding Belle statistics in one or two years

Backup

$\phi_3 = \gamma$

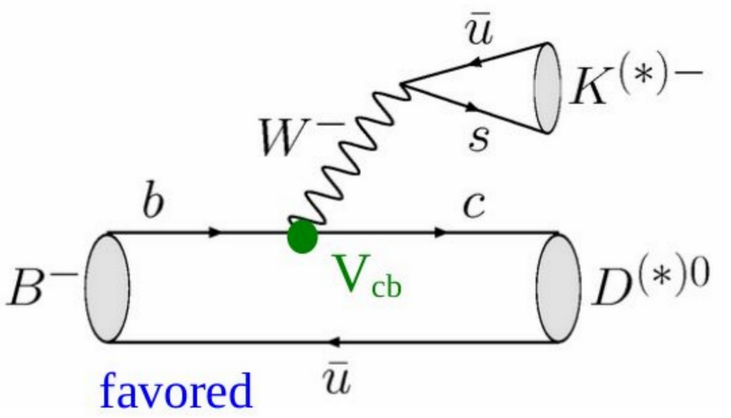


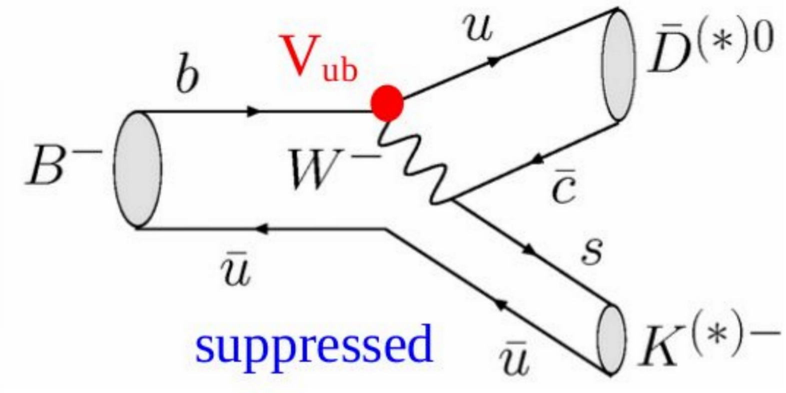
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
η̄
ρ̄
excluded area has CL > 0.95
sin 2β
γ
α
β
CKM fitter
Spring 21
sol. w/ cos 2β < 0
(excl. at CL > 0.95)

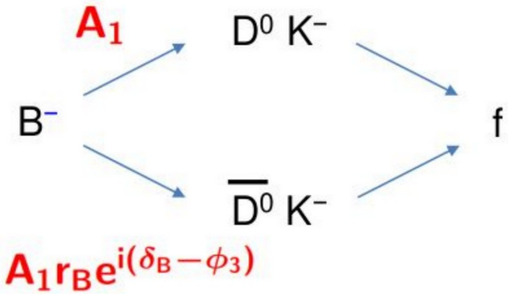
Combined Belle & Belle II fit

JHEP 10 (2024) 143

- Interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$







$B^- \to D^0K^- \approx V_{cb}V^*_{us}$
A_1

$B^- \to \bar{D}^0K^- \approx V_{ub}V^*_{cs}$
$A_1 r_B e^{i(\delta_B - \phi_3)}$

- The amplitude ratio r_B and strong phase δ_B are model dependent
  → There are several methods of determining γ

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

$B^+ \to D^0 (K_S h^+ h^-) h^+$

JHEP 02 (2022) 063

- Model-independent BPGGSZ method using Dalitz-binned D^0 amplitudes:
  → NN-based K_S reconstruction
  → Considering h=π, K

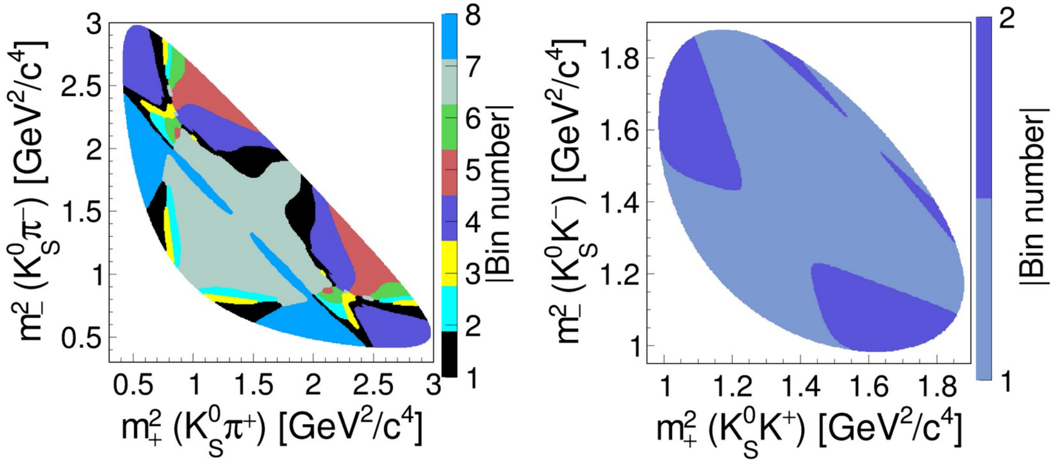
$$A_{B^+}\left(m_-^2, m_+^2\right) \propto A_{\bar{D}}\left(m_-^2, m_+^2\right) + r_B^{DK} e^{i\left(\delta_B^{DK}-\phi_3\right)} A_D\left(m_-^2, m_+^2\right)$$

$$\gamma = 78.4 \pm 11.4(\text{stat}) \pm 0.5(\text{syst}) \pm 1.0(\text{ext})\ \text{deg}$$

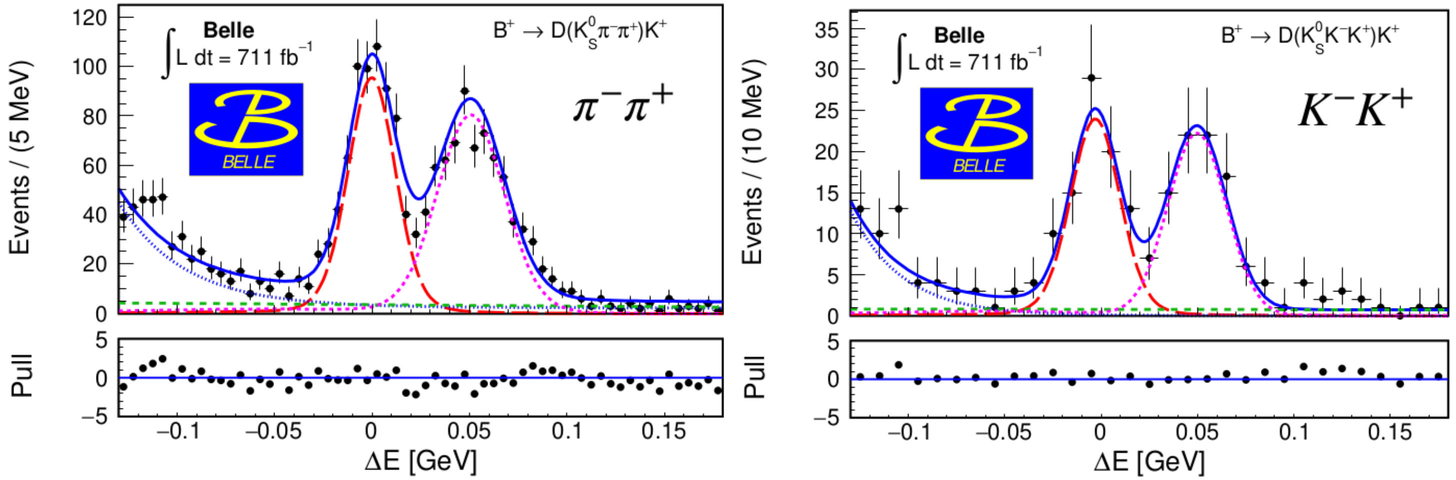
Strong D^0-$\bar{D}^0$ phases from CLEO & BESIII

BaBar: γ = (69 ± 17) deg

$D^0 \to K_S \pi^+ \pi^-$ $D^0 \to K_S K^+ K^-$



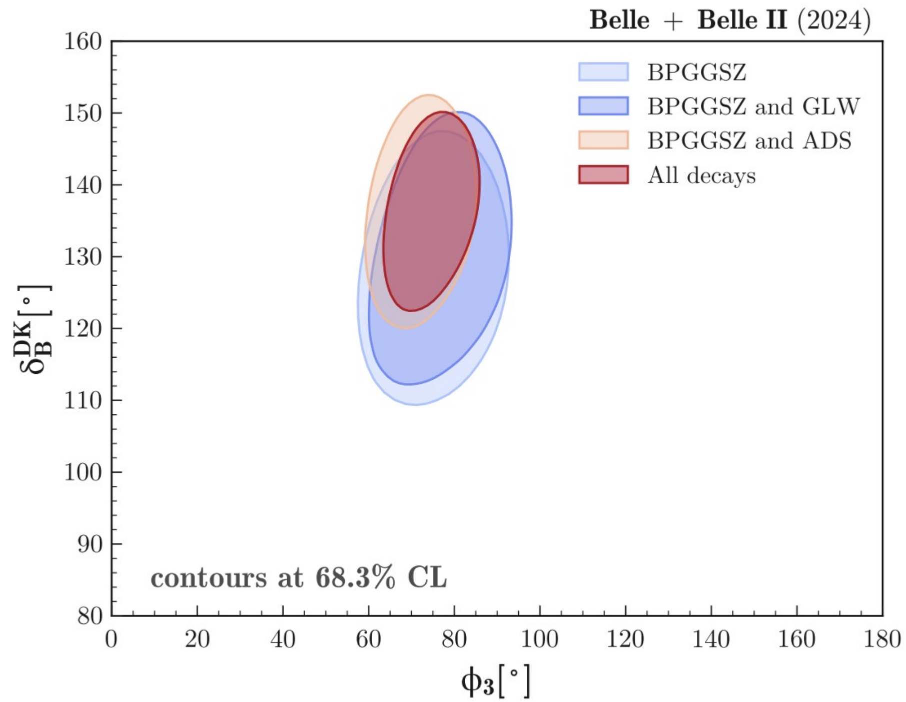
Bins from BESIII & CLEO



Combined Belle & Belle II fit: Results

JHEP 10 (2024) 143

- Fitted combined likelihood with 18 free parameters, inputs:
  → 45 Belle/Belle II data points
  → 14 “external inputs” (D decays)
- Consistent results for various methods and various decay modes, good fit quality (chi2/ndf = 38 / 41)
- Small correlations between Φ_3 and the strong phases δ_B & amplitude ratios r_B



Belle II result:
$\Phi_3 = (75.2 \pm 7.6)^\circ$

LHCb result:
$\Phi_3 = (64.6 \pm 2.8)^\circ$

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	$711 + 189$
$B^+ \to Dh^+$	$D \to K^+\pi^-, K^+\pi^-\pi^0$	ADS	$711 + 0$
$B^+ \to Dh^+$	$D \to K_S^0 K^-\pi^+$	GLS	$711 + 362$
$B^+ \to Dh^+$	$D \to K_S^0 h^- h^+$	BPGGSZ (m.i.)	$711 + 128$
$B^+ \to Dh^+$	$D \to K_S^0\pi^-\pi^+\pi^0$	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.)	$605 + 0$