Studies of CP violation at Belle and Belle II

Radek Žlebčík
on behalf of the Belle II collaboration

December 3, 2024
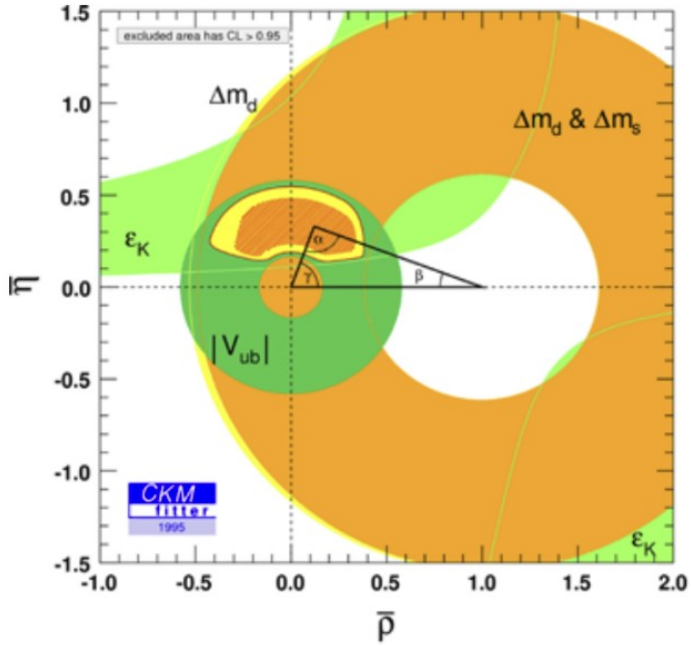DISCRETE 2024
Ljubljana, Slovenia

Unitarity triangle : 30 years of development

- Unitarity Triangle constructed from CKM matrix has angles and sides which are well-defined (physics) quantities
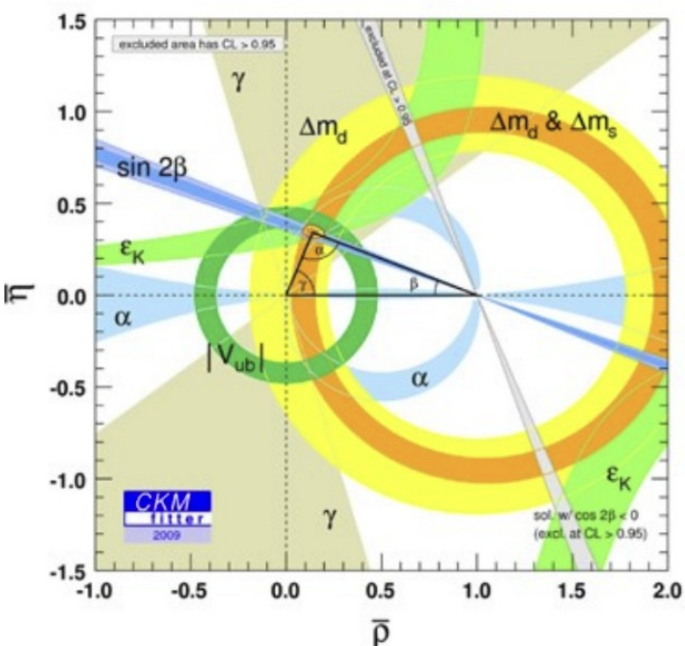
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$
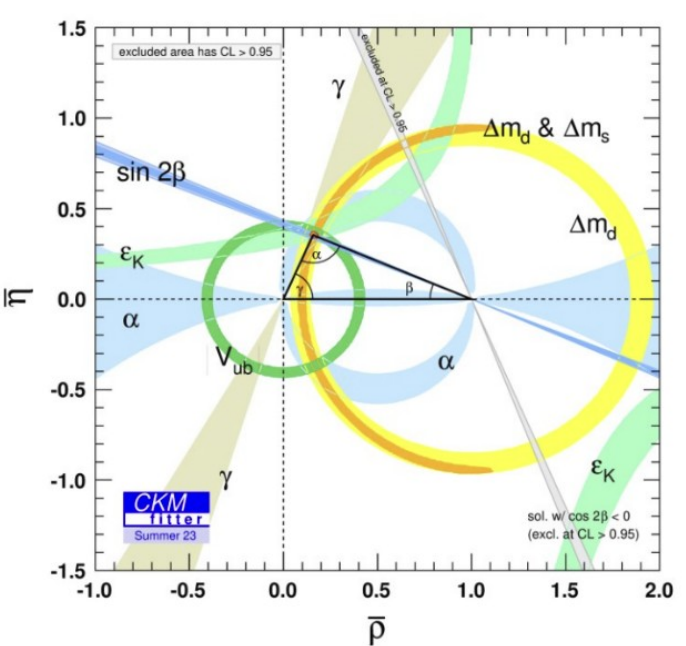
1995

Pre 1st generation *B* factories

2009

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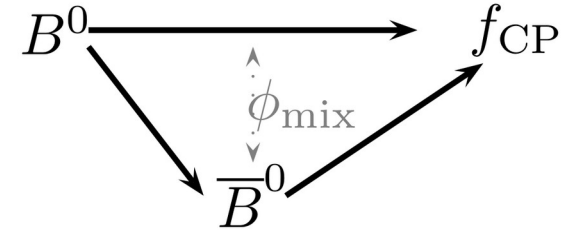+ CDF B_s mixing

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 $B^0 \to f_{\mathrm{CP}}$ and $\bar{B}^0 \to f_{\mathrm{CP}}$
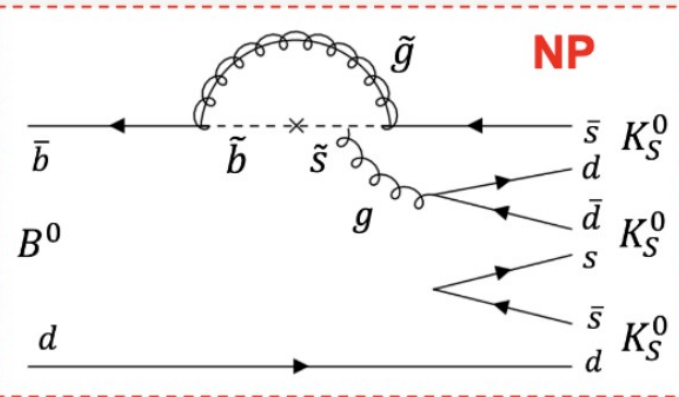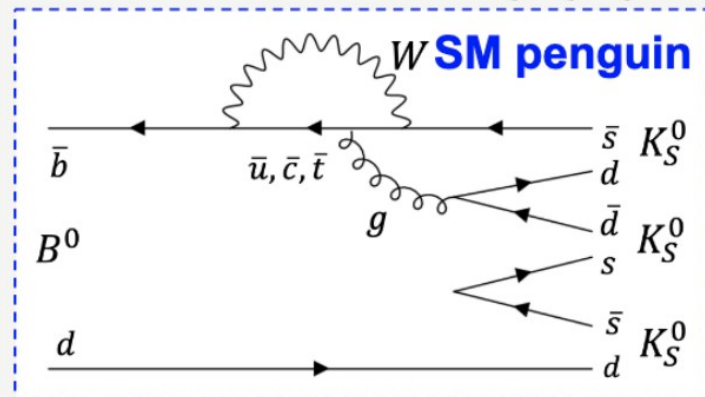

$$\mathcal{A}_{\mathrm{CP}}(\Delta t) = \frac{\mathcal{B}(\bar{B}^0 \to f_{\mathrm{CP}})(\Delta t) - \mathcal{B}(B^0 \to f_{\mathrm{CP}})(\Delta t)}{\mathcal{B}(\bar{B}^0 \to f_{\mathrm{CP}})(\Delta t) + \mathcal{B}(B^0 \to f_{\mathrm{CP}})(\Delta t)} = S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta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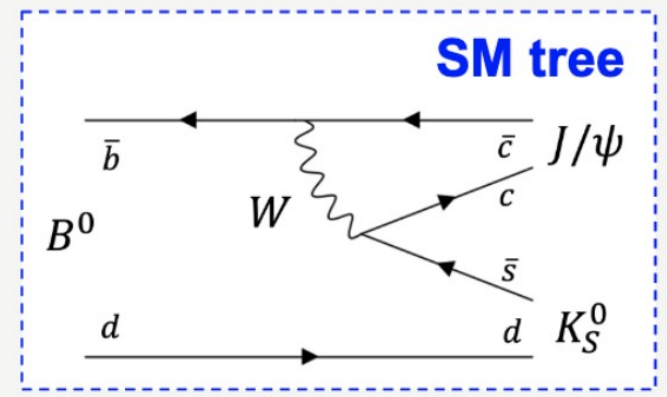
Mixing-induced CPV

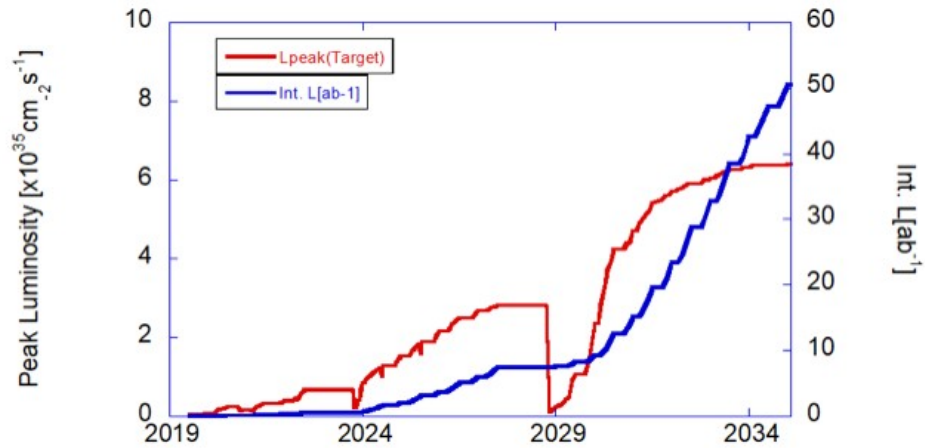Direct CPV

$$S_{K_S^0 K_S^0 K_S^0} = -\sin 2\phi_1 + \Delta S \qquad\qquad S_{J/\psi K_S^0} = \sin 2\phi_1$$

Belle2 & SuperKEKB status

- 550 fb^{-1} of integrated luminosity collected so far
  (most analyses based on 364 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

Crucial for Δt measurement
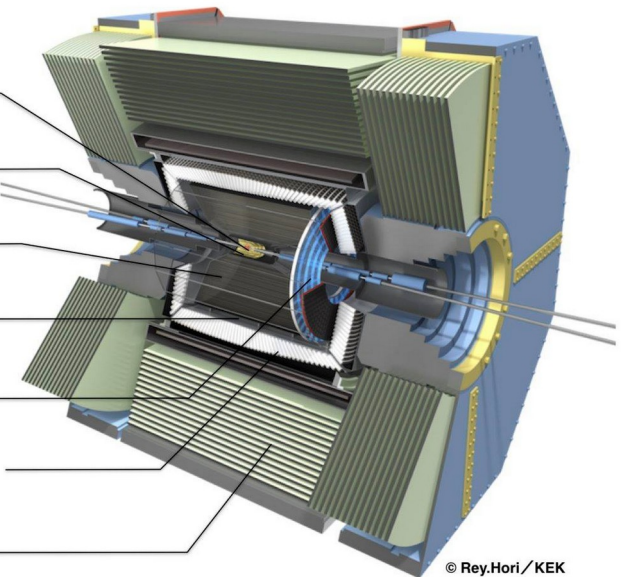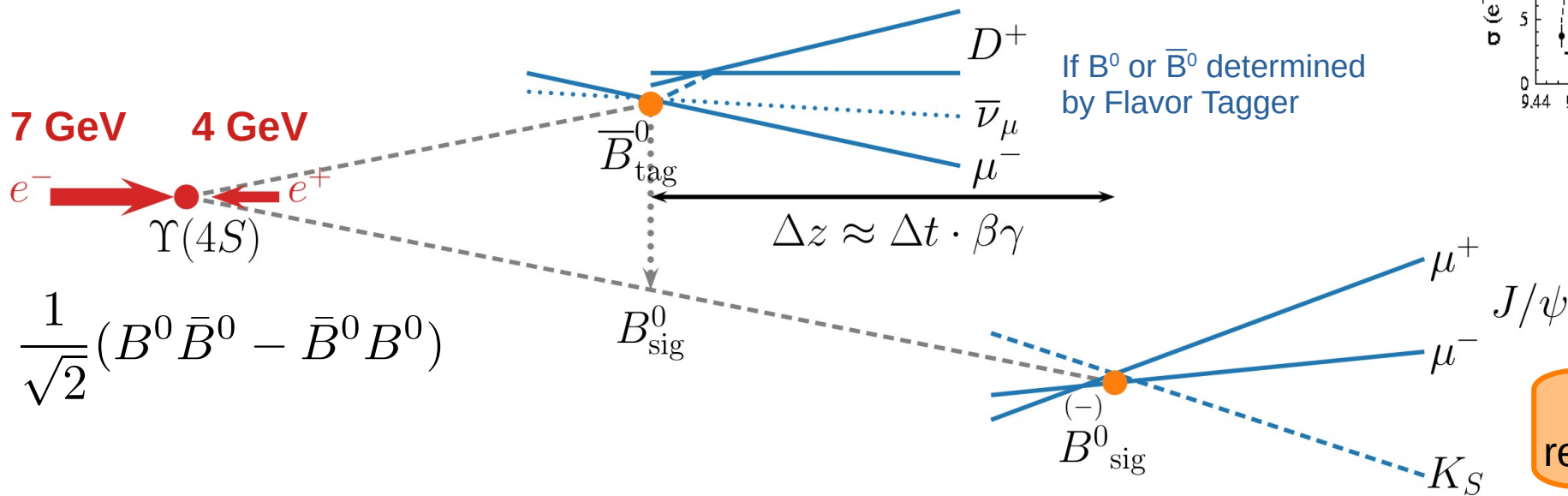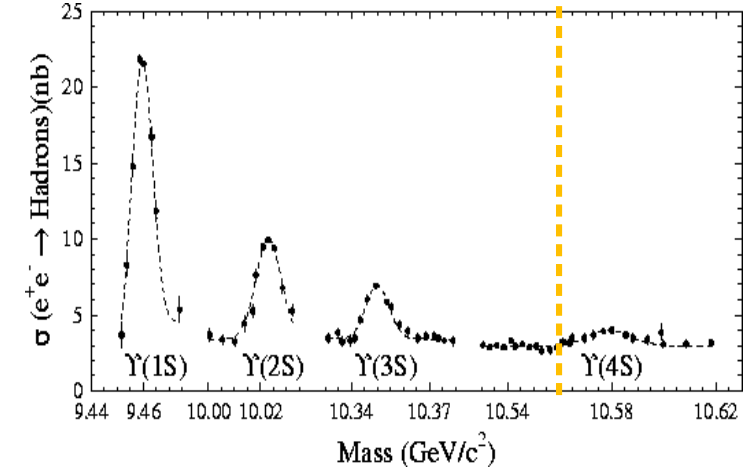
Pixel Detector（PXD）

Silicon Vertex Detector（SVD）

Central Drift Chamber（CDC）

TOP counter（TOP）

Aerogel RICH counter（ARICH）

Electromagnetic Calorimeter（ECL）

K$_L^0$／Muon Detector（KLM）

© Rey.Hori／KEK

Measuring time-dep. CPV at Belle II

- Collisions energy just above B⁰B̄⁰ production threshold
- Due to the asymmetric beam energies B-mesons fly in the direction of the e⁻ beam

7 GeV **4 GeV**

e^- e^+

$\Upsilon(4S)$

$\overline{B}^0_{\text{tag}}$

D^+

If B⁰ or B̄⁰ determined by Flavor Tagger

$\overline{\nu}_\mu$

μ^-

$\Delta z \approx \Delta t \cdot \beta\gamma$

B^0_{sig}

$\frac{1}{\sqrt{2}}(B^0 \bar{B}^0 - \bar{B}^0 B^0)$

μ^+

J/ψ

μ^-

$\overset{(-)}{B}{}^0_{\text{sig}}$

K_S

Fully reconstructed

From rest of event

Time-measurement ⟷ distance-measurement

Belle II : $\Delta z \approx 130\,\mu\text{m}$
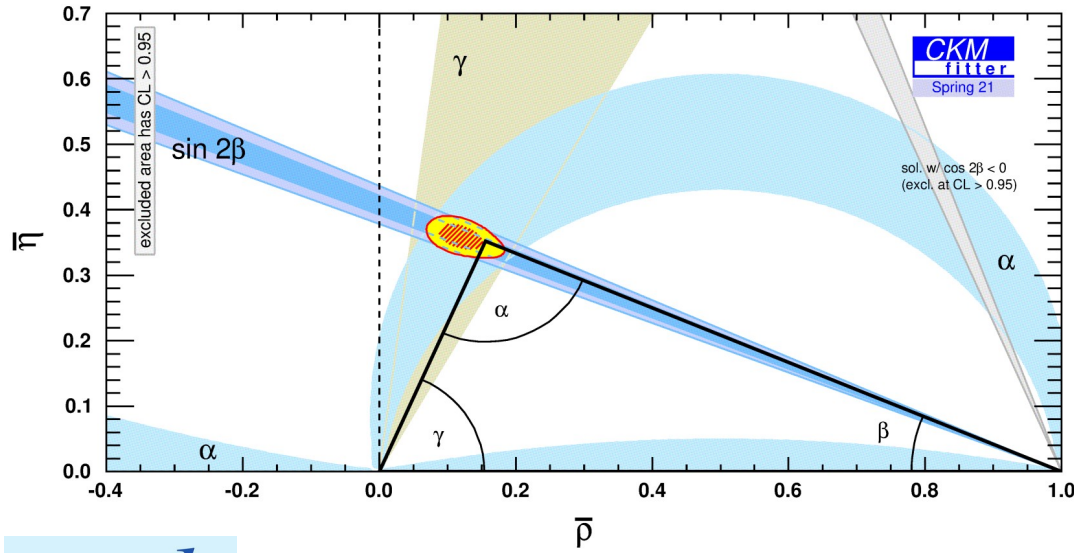Belle   : $\Delta z \approx 200\,\mu\text{m}$

$\beta\gamma = 0.288$

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

In this talk

Global average dominated by...

α/φ₂=(84±4)°:

$\alpha/\phi_2 = (84\pm4)°$:

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

β/φ₁=(22.6±0.5)° b→c:

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

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

γ/φ₃=(66±3)°

$\gamma/\phi_3 = (66\pm3)°$

β/φ₁=(20.4±1.4)° b→s:

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

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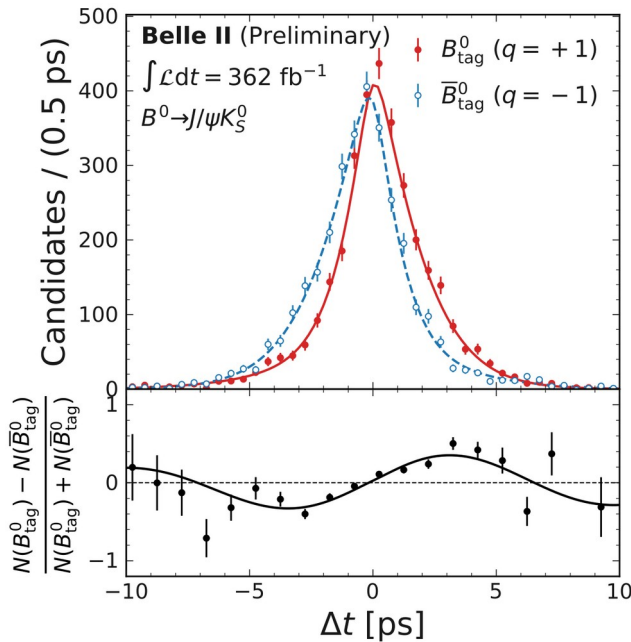$B^0 \to \varphi K^0_s$
$B^0 \to K^0_s K^0_s K^0_s$

φ₁ = β
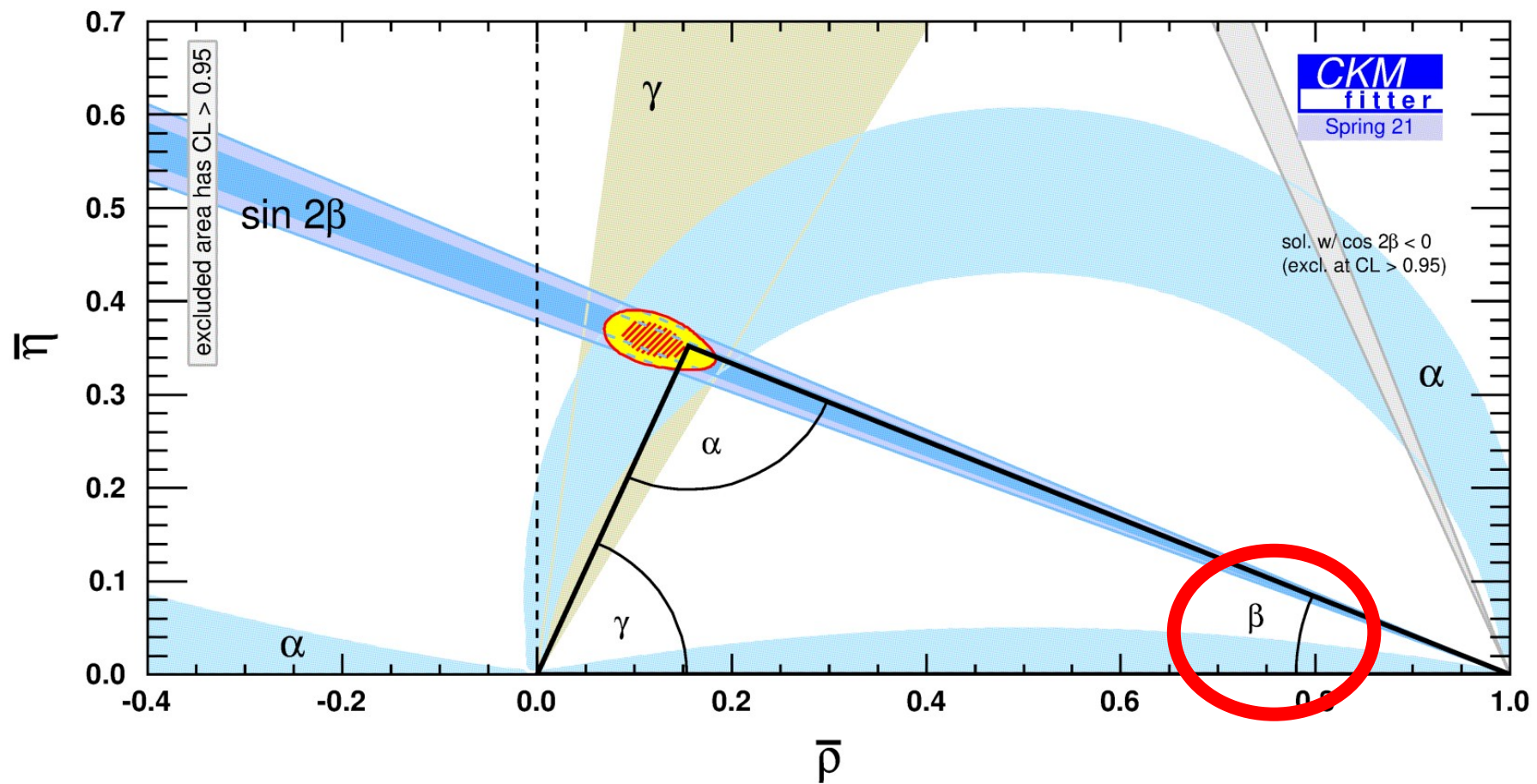
GNN-based Flavor tagger and $B^0 \to J/\psi \, K^0_s$

- 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~sin $2\phi_1$ measurement

Phys.Rev.D 110 (2024)

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

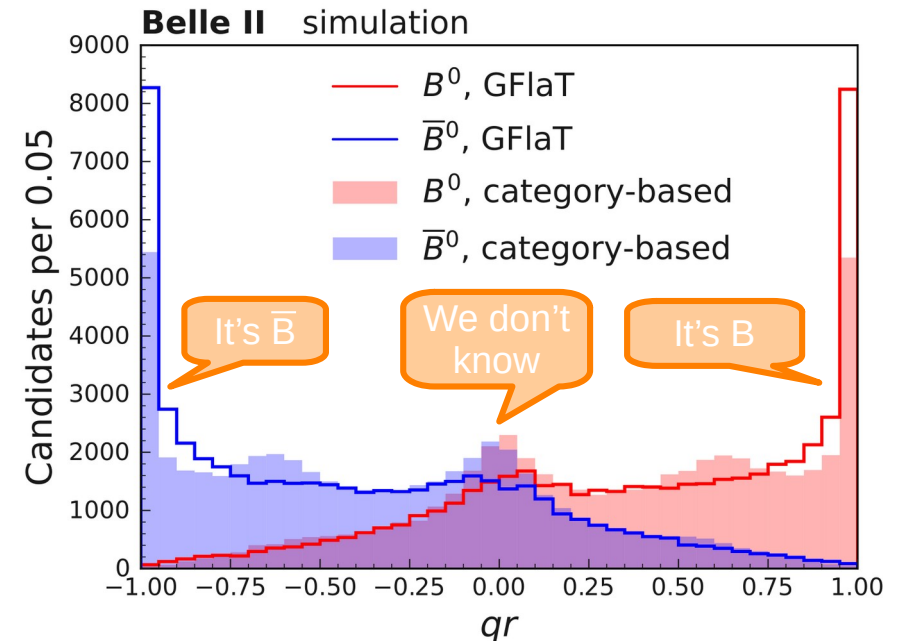$\varepsilon^{\text{eff}}_{\text{tag}}$ (GFlaT) $= (37.4 \pm 0.4 \pm 0.3)\%$

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

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 B⁰ → J/ψ π⁰

- Color suppressed b → c̄cd tree-level decay
  → loop contribution plays a role
- Important input to correct for the penguin contamination in the $B^0 \to J/\psi K^0_s$
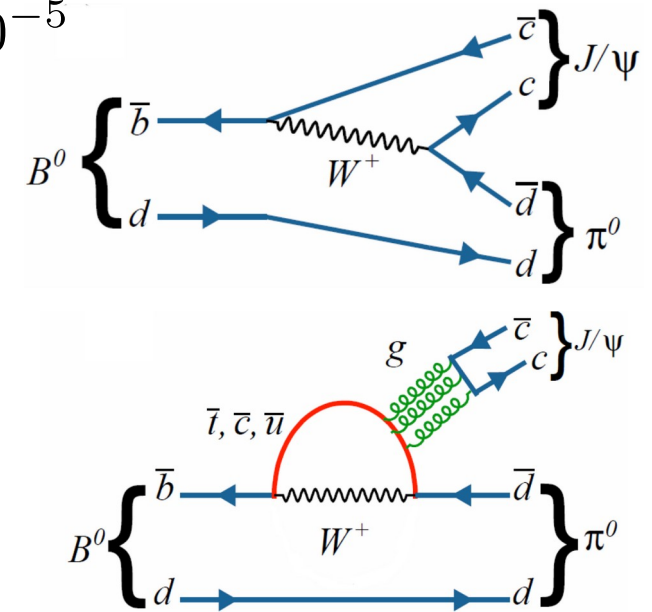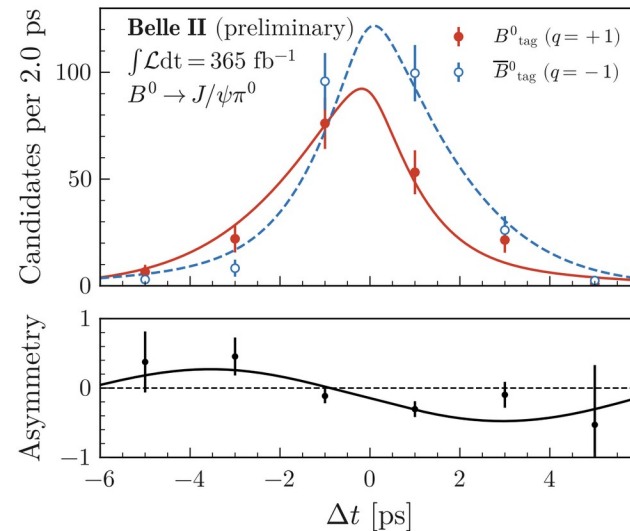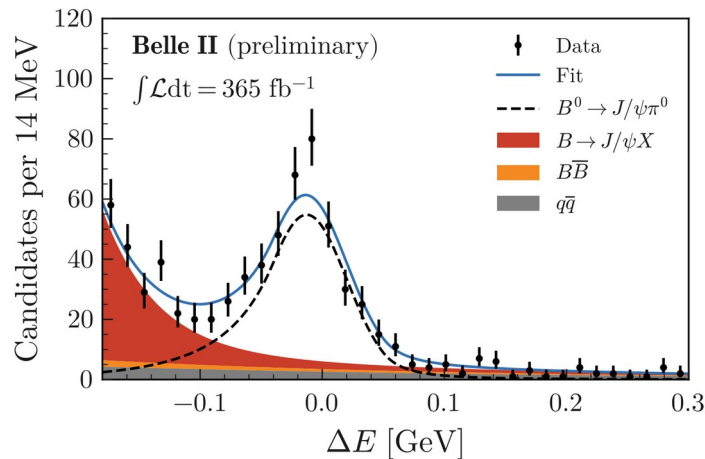 (tree only: S=-sin 2ϕ_1 ~ -0.71)

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

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

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

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

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

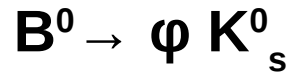# φ₁ = β from Penguin b → s transitions

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

- $\eta' \to \eta(\to \gamma\gamma)\pi^+\pi^-$
  $\eta' \to \rho\gamma$

- ~800 signal events

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

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

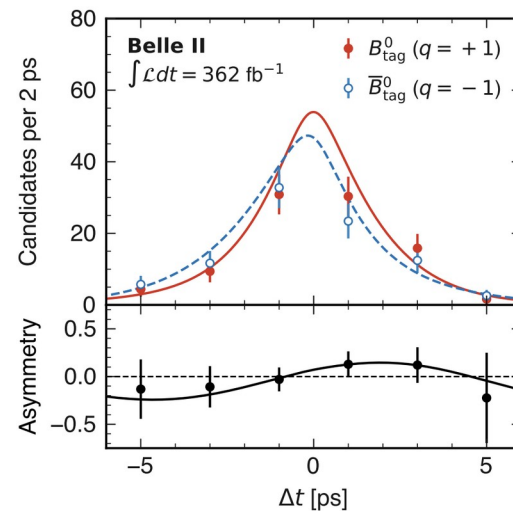- ~160 signal events

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

- Major challenge is to reconstruct B^0 vertex from three K^0_s "tracks"
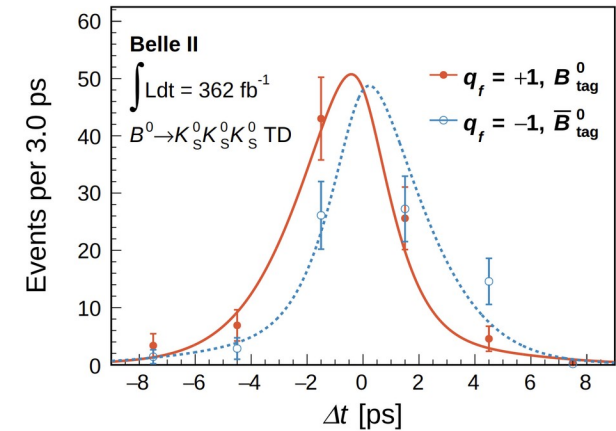
- ~160 signal events
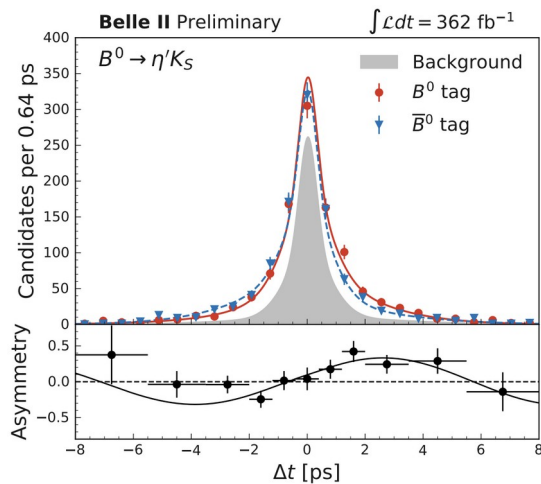
$$S = +0.67 \pm 0.10 \pm 0.04$$

$$C = -0.19 \pm 0.08 \pm 0.03$$

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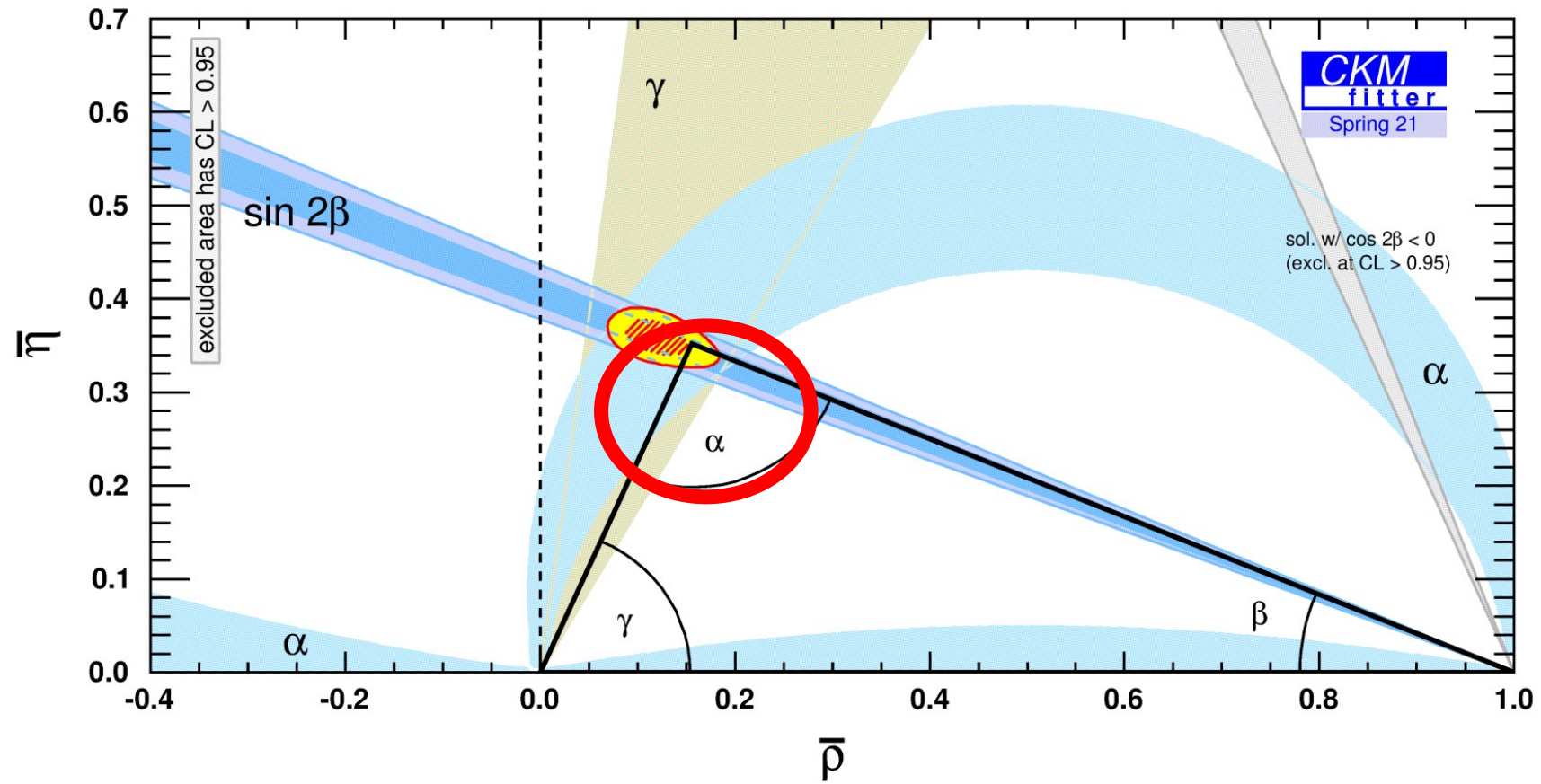
$$C = -0.31 \pm 0.20 \pm 0.05$$

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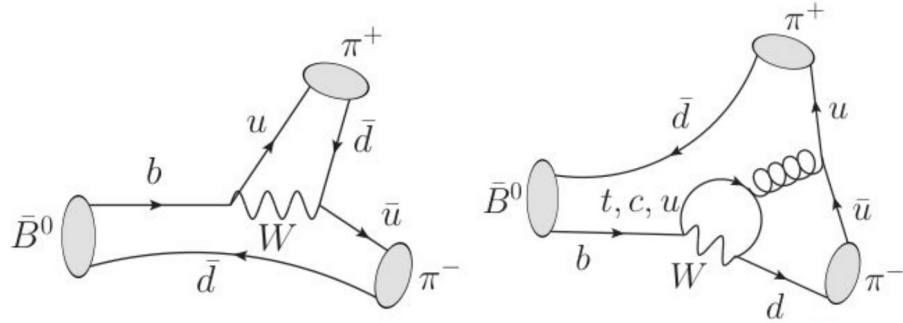
$$C = -0.07 \pm 0.20 \pm 0.05$$

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

φ₂ = α

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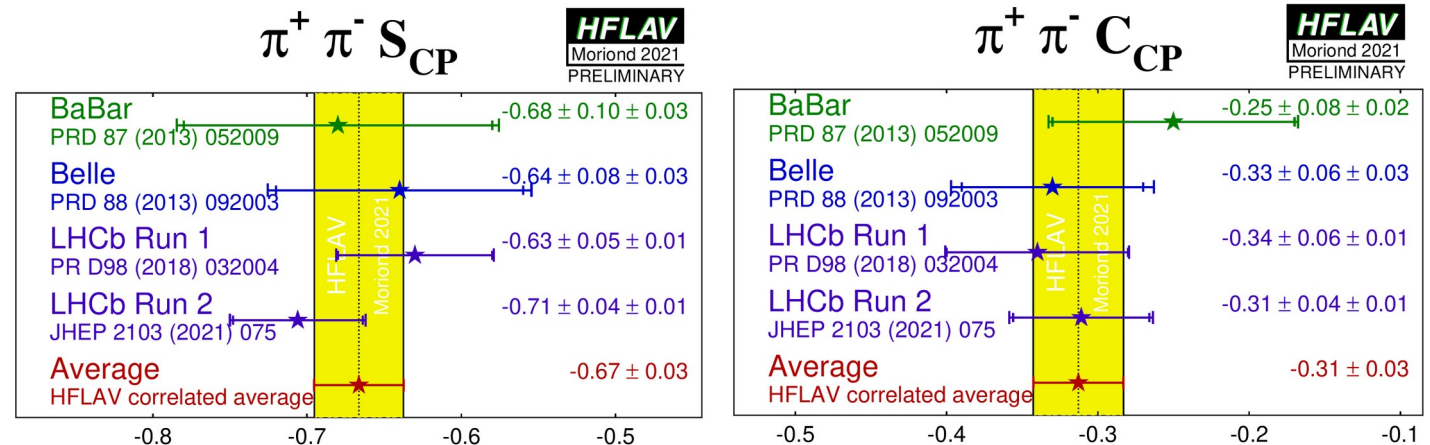
Can be also done with $B \to \rho\rho$

Time integrated B⁰ → π⁰ π⁰

- Very difficult for LHCb, important constraint of penguin component

- Time-integrated analysis
  → getting π^0 vertices is difficult

- BG e.g. from $B^+ \to \rho^+(\to \pi^+\pi^0)\,\pi^0$

- 4D unbinned fit in M_{bc}, ΔE, continuum suppression (C) and wrong tag probability (w)

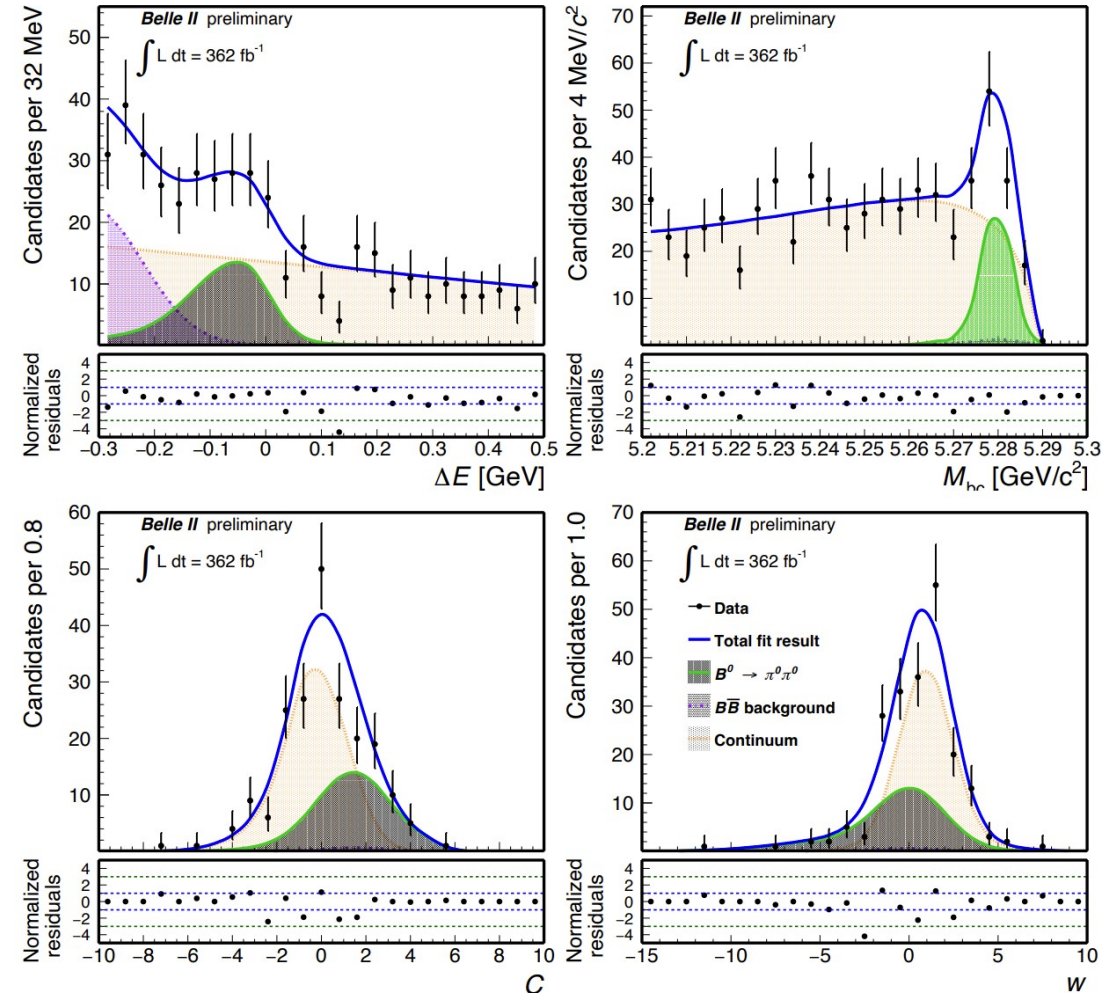$$B = (1.26 \pm 0.20 \pm 0.11) \times 10^{-6}$$
$$A_{CP} = +0.06 \pm 0.30 \pm 0.06$$

World average:

$$B = (1.59 \pm 0.26) \times 10^{-6}$$
$$A_{CP} = 0.30 \pm 0.20$$
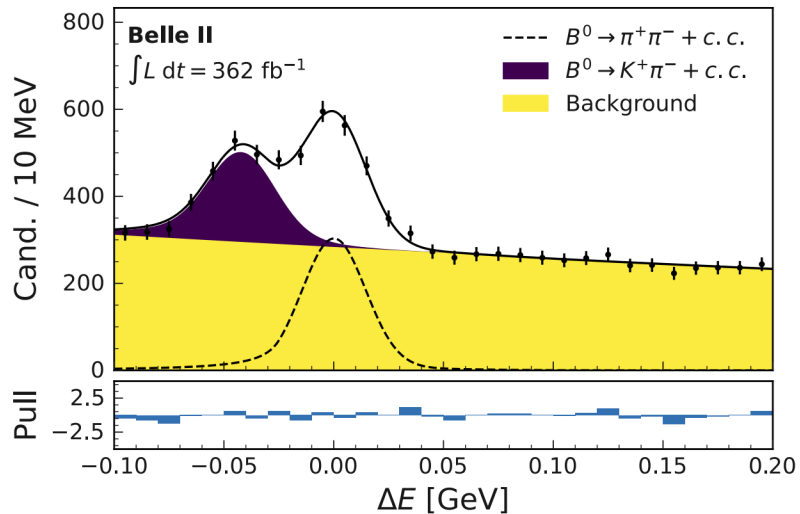
126±20 signal events

World best measurement of B and C

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

- 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

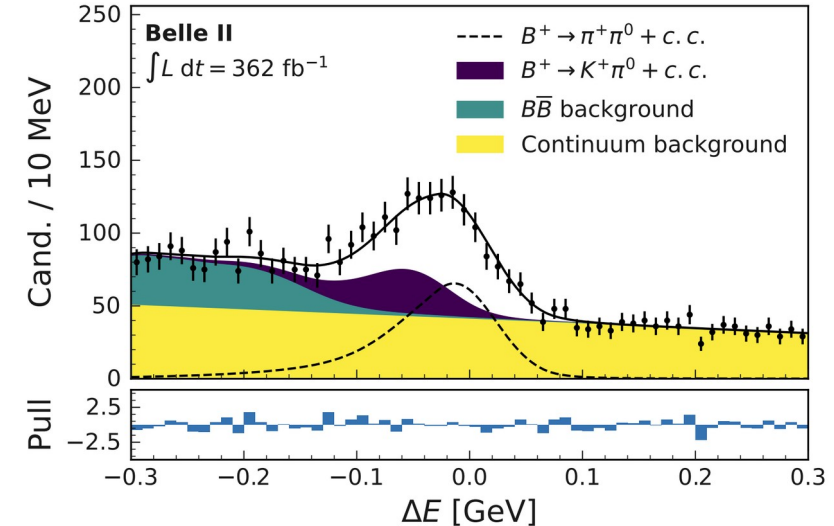**~1500 $B^0 \to \pi^+ \pi^-$ events**

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

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

World best

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

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

Time-dependent CPV in B⁰ → ρ⁺ ρ⁻

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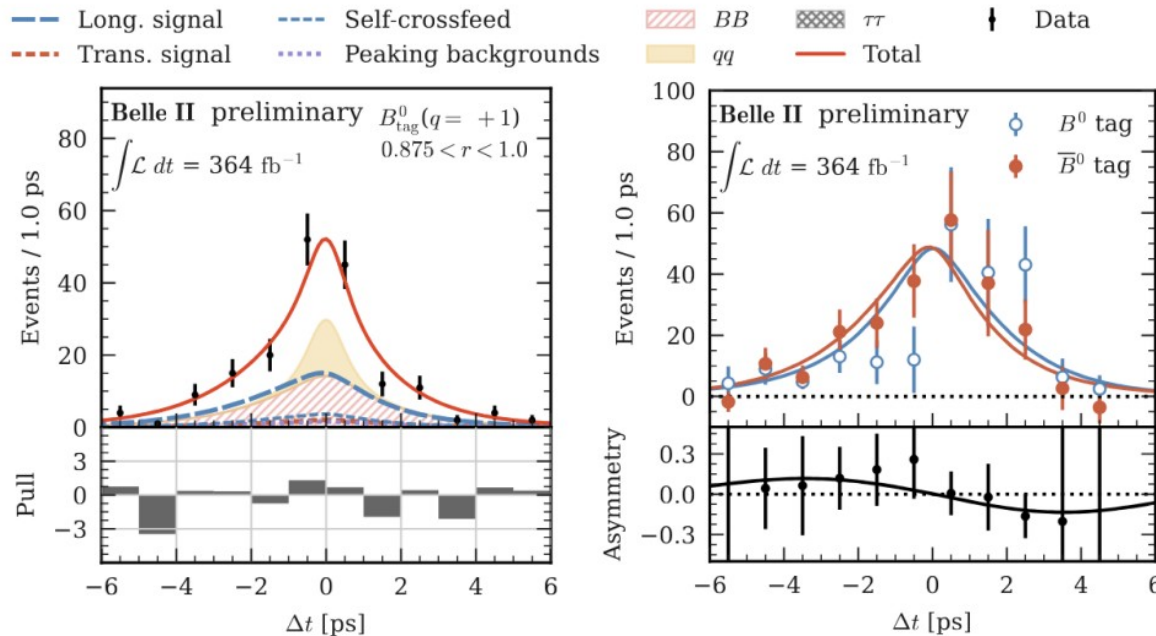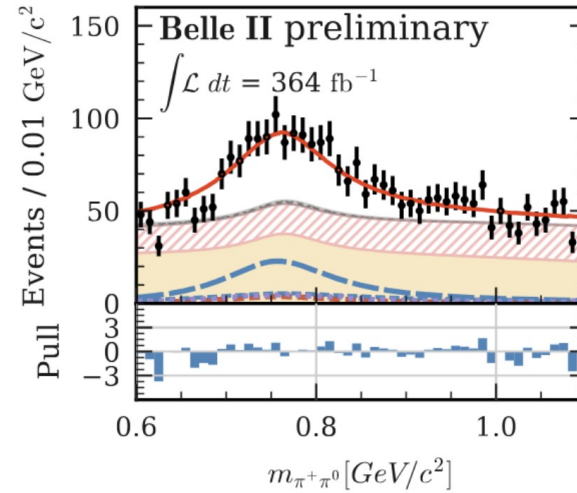
	$\mathcal{B}(10^{-6})$	f_L
Belle II	$29.0^{+2.3}_{-2.2}\,^{+3.1}_{-3.0}$	$0.921^{+0.024}_{-0.025}\,^{+0.017}_{-0.015}$
Belle	$28.3 \pm 1.5 \pm 1.5$	$0.988 \pm 0.012 \pm 0.006$
BABAR	$25.5 \pm 2.1\,^{+3.6}_{-3.9}$	$0.992 \pm 0.024\,^{+0.026}_{-0.013}$

	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

- 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:

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

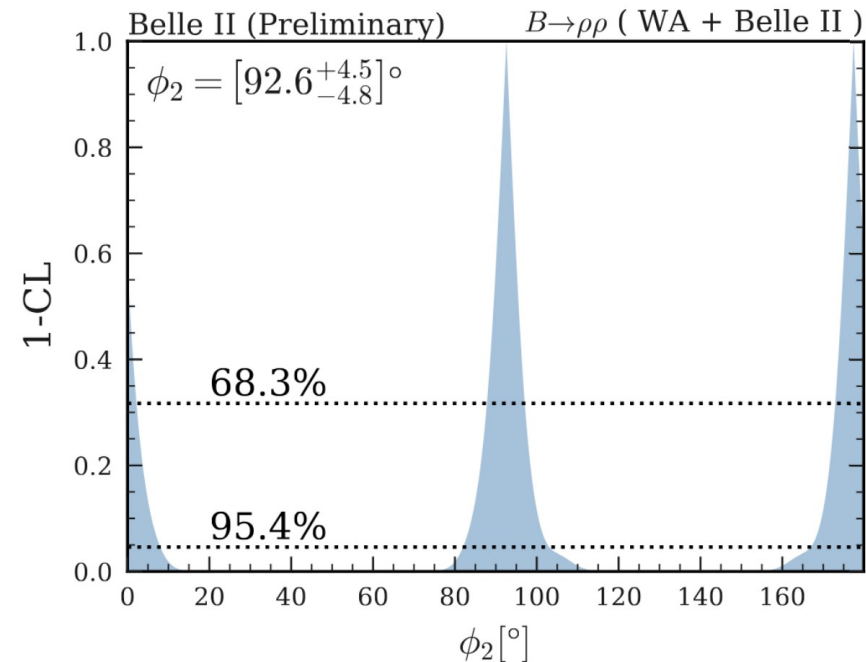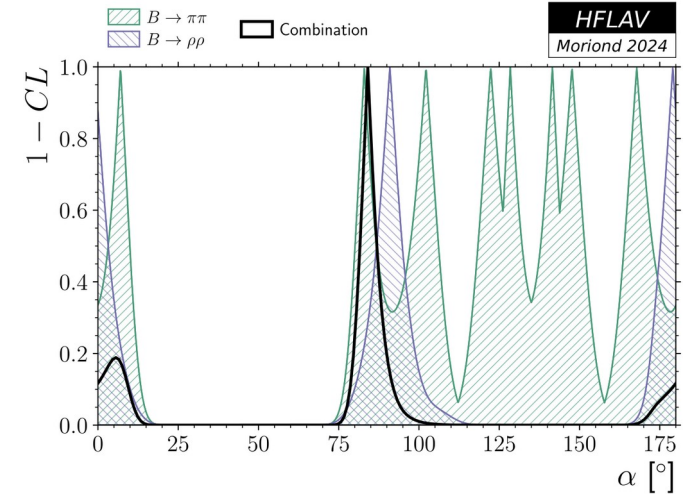- The $B \to \rho\rho$ only world average (+ Belle II $B^0 \to \rho^+\rho^-$)

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

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.

Current world average:

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

Conclusion

- Broad CPV physics program at Belle II
  - → **Precise** measurements of Unitarity Triangle angles
  - → CPV in **rare** b→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
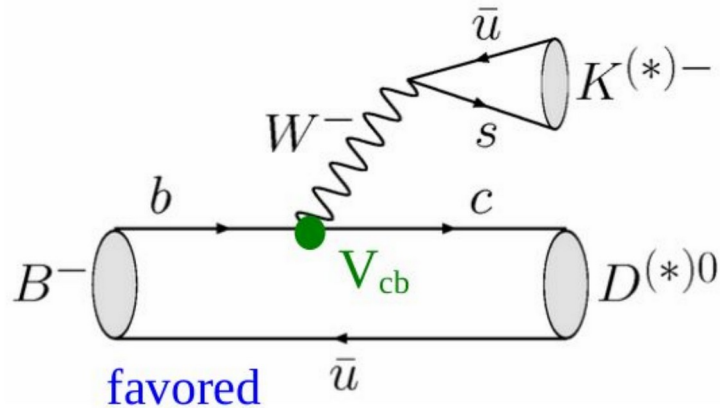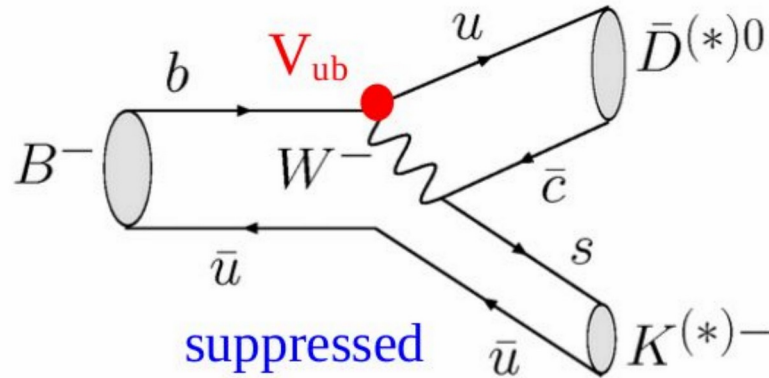 - → Exceeding Belle statistics in one or two years
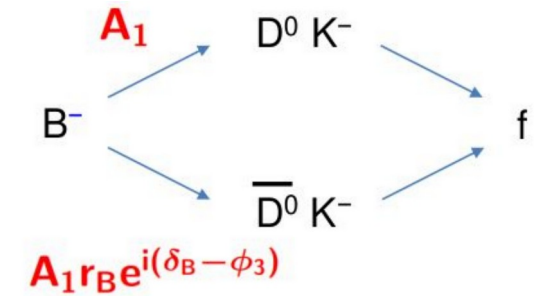
Backup

φ₃ = γ
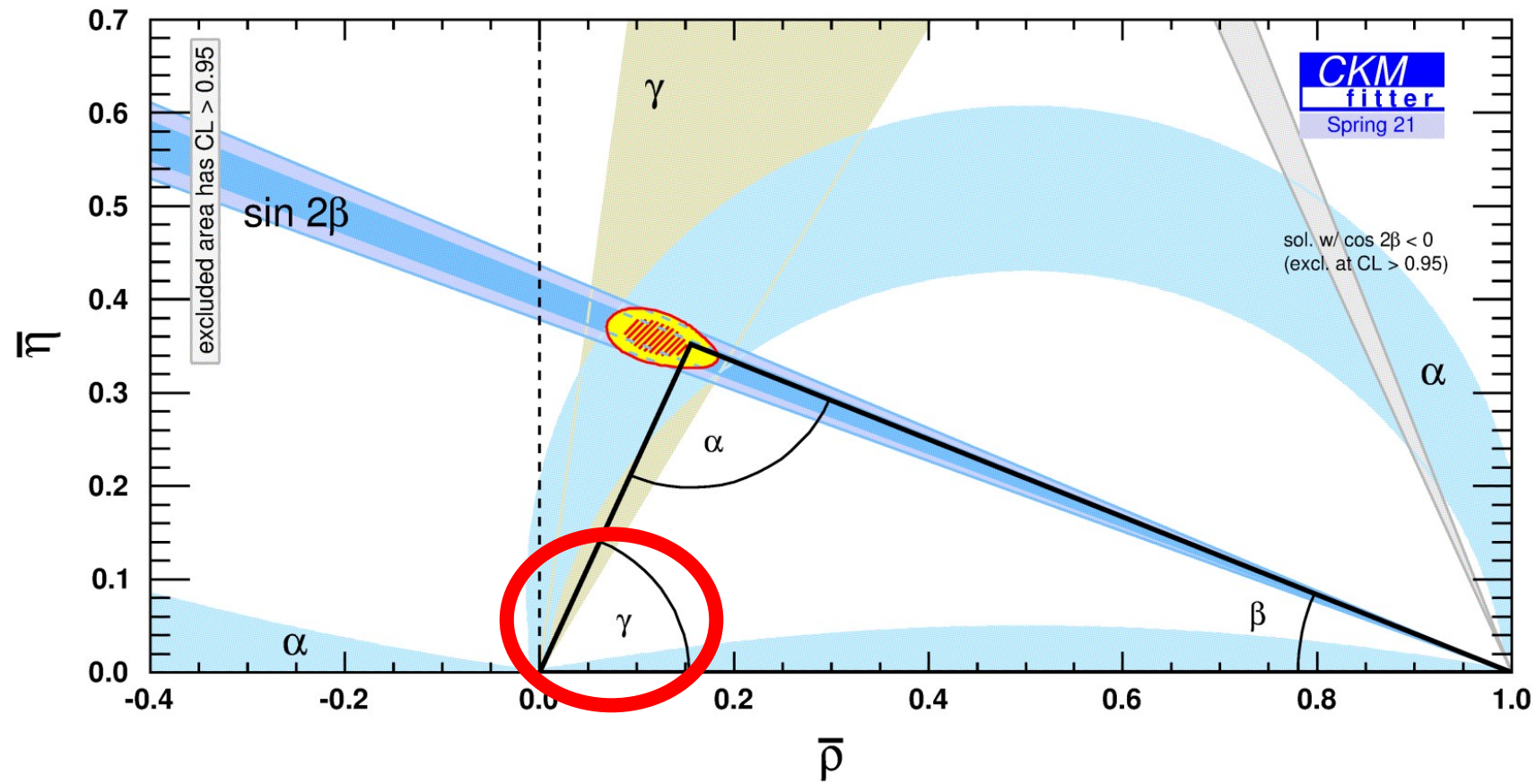
Combined Belle & Belle II fit

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

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

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

- The amplitude ratio r$_B$ and strong phase δ$_B$ are model dependent
  → There are several methods of determining γ

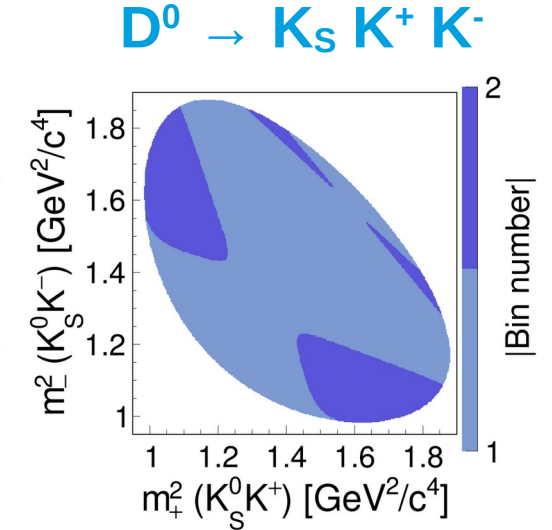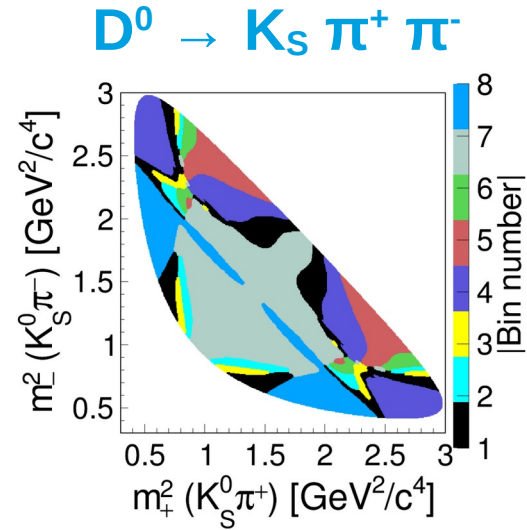| B decay	D decay	Method	Data set (Belle + Belle II)[fb^{-1}]
$B^+ \to Dh^+$	$D \to K_S^0\pi^0, K^-K^+$	GLW	$711 + 189$
$B^+ \to Dh^+$	$D \to K^+\pi^-, K^+\pi^-\pi^0$	ADS	$711 + 0$
$B^+ \to Dh^+$	$D \to K_S^0K^-\pi^+$	GLS	$711 + 362$
$B^+ \to Dh^+$	$D \to K_S^0h^-h^+$	BPGGSZ (m.i.)	$711 + 128$
$B^+ \to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

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

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

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

$$\gamma = 78.4 \pm 11.4(\text{stat})$$

$$\pm 0.5(\text{syst}) \pm 1.0(\text{ext}) \deg$$

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

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

Bins from BESIII & CLEO

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

BaBar: γ = (69 ± 17) deg
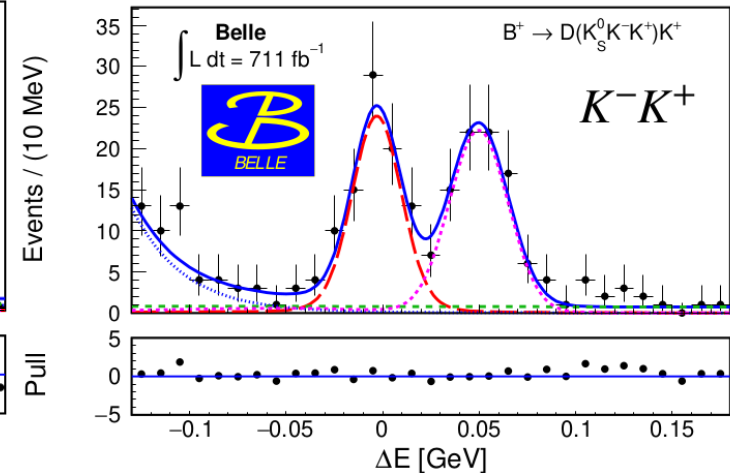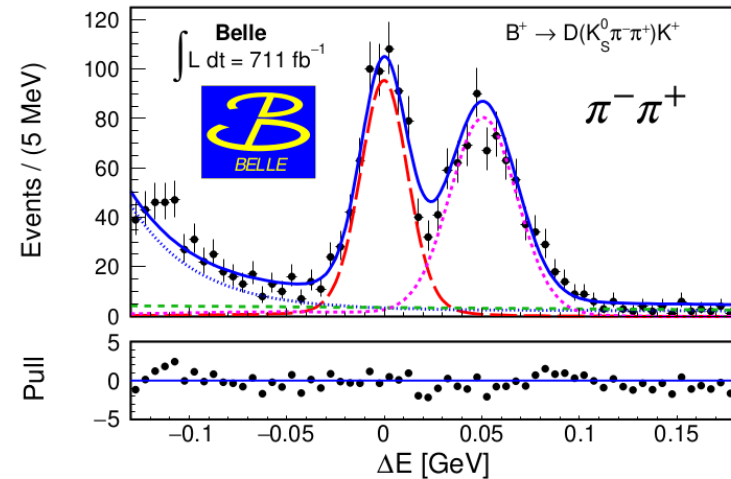
Combined Belle & Belle II fit: Results

- 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 + Belle II (2024)

- BPGGSZ
- BPGGSZ and GLW
- BPGGSZ and ADS
- All decays

contours at 68.3% CL

$\phi_3[°]$ / $\delta_B^{DK}[°]$
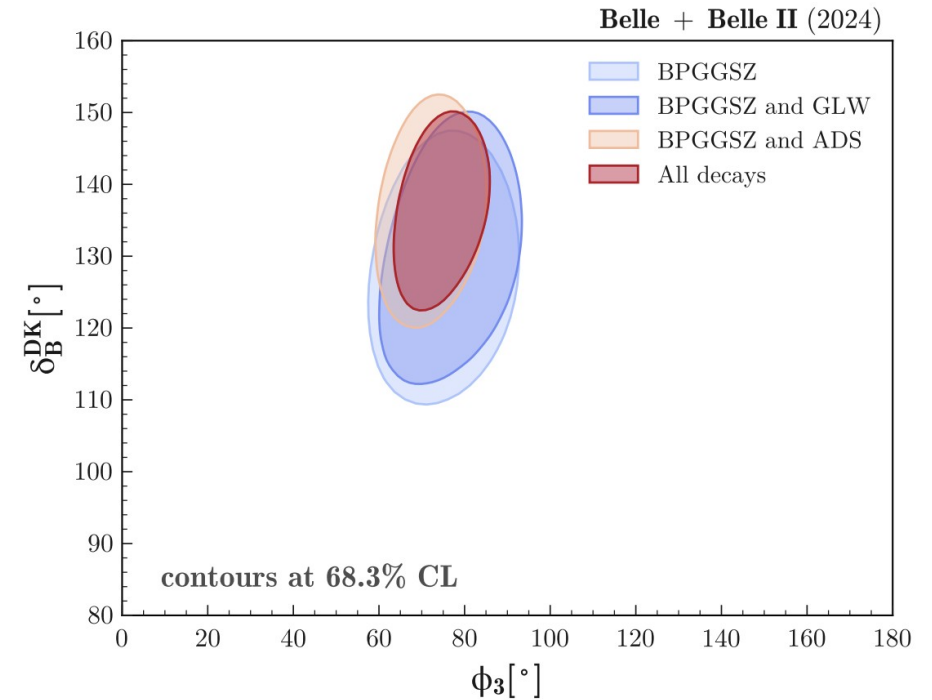
Belle II result:
$\Phi_3 = (75.2 \pm 7.6)°$

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

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	$711 + 0$
$B^+ \to Dh^+$	$D \to K_S^0K^-\pi^+$	GLS	$711 + 362$
$B^+ \to Dh^+$	$D \to K_S^0h^-h^+$	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.)	$605 + 0$