TDCPV in B_0 and B_S systems

17th International Conference on Heavy Quarks and Leptons

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Stefano Lacaprara

for the Belle II collaboration

INFN Padova

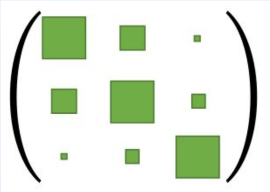
CPV in Standard Model: CKM matrix

- a key for matter-antimatter asymmetry in the universe
  - In SM, only source is complex phase in CKM matrix
  - (and possible similar phase in PMNS matrix)

Dirac Medal 2010

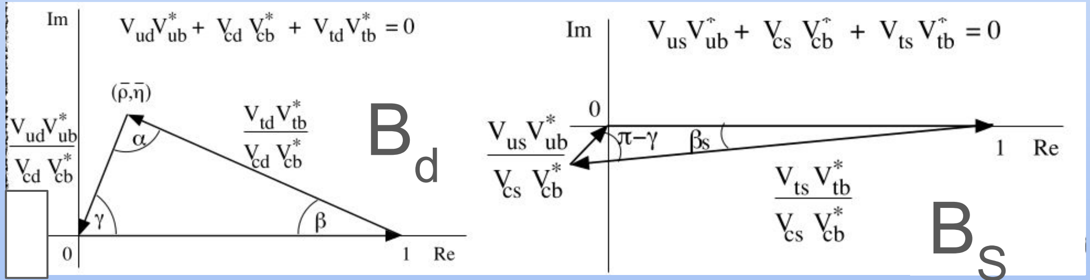
Nobel Prize 2008

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

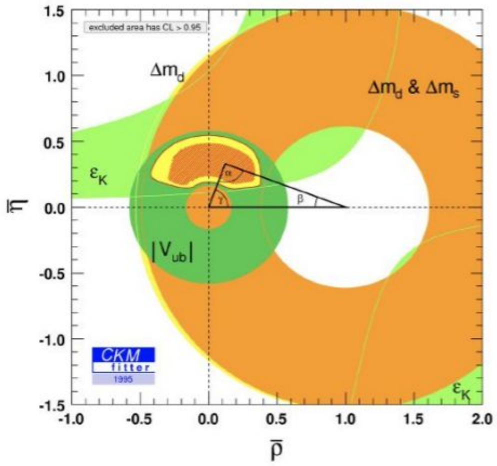


- From CKM unitarity: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \Rightarrow$ Triangles in complex plane

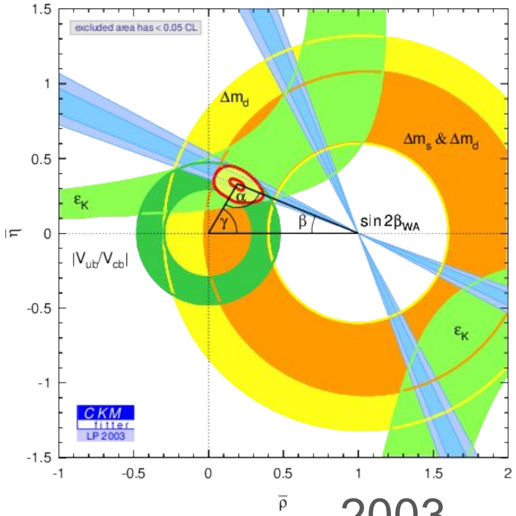
$\phi_1 = \beta$
$\phi_2 = \alpha$
$\phi_3 = \gamma$



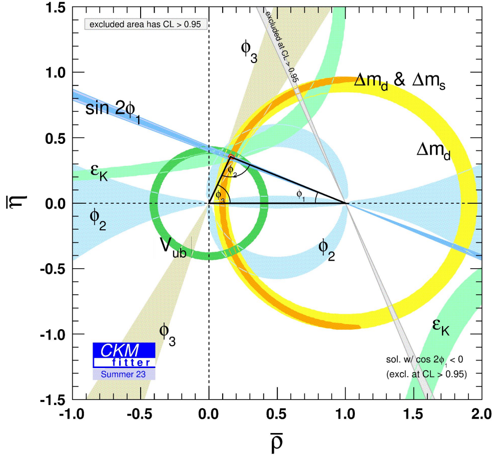
CPV and Unitarity Triangle



1995



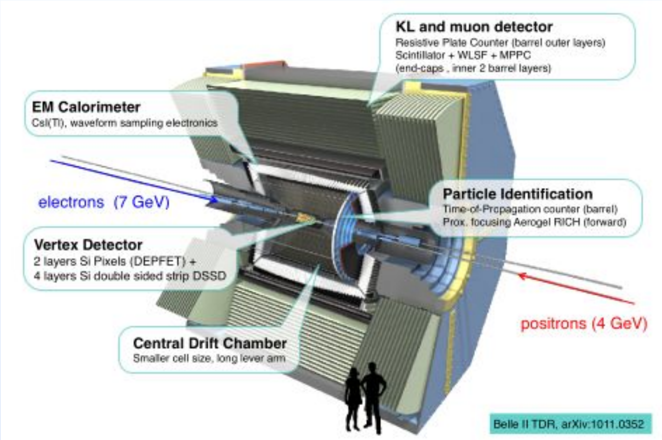
2003

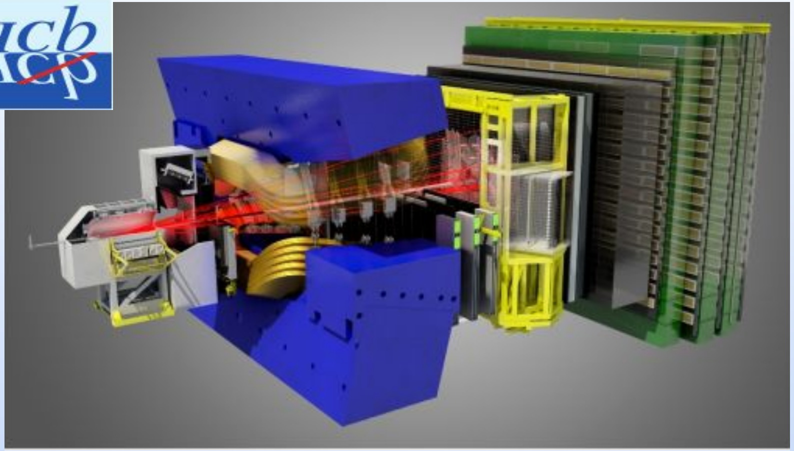


2023

- Precise test of SM by over constraining Unitarity Triangle
- Search for New Physics effects, especially in loop mediated diagrams
- Time Dependent CPV analysis is a powerful tool for precise angles measurements

Belle II and LHCb

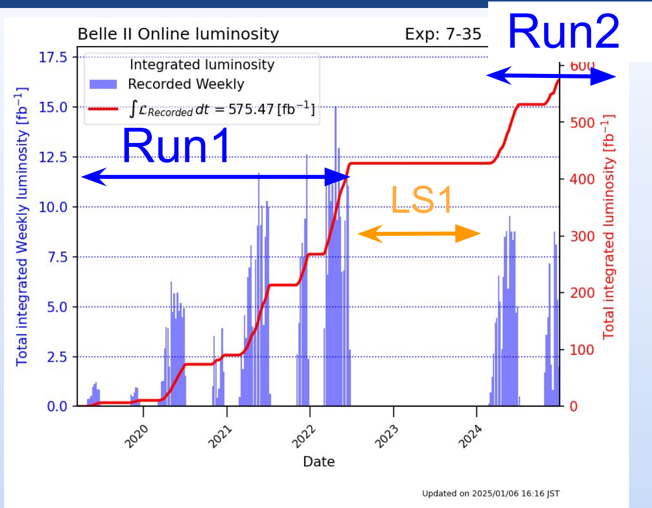


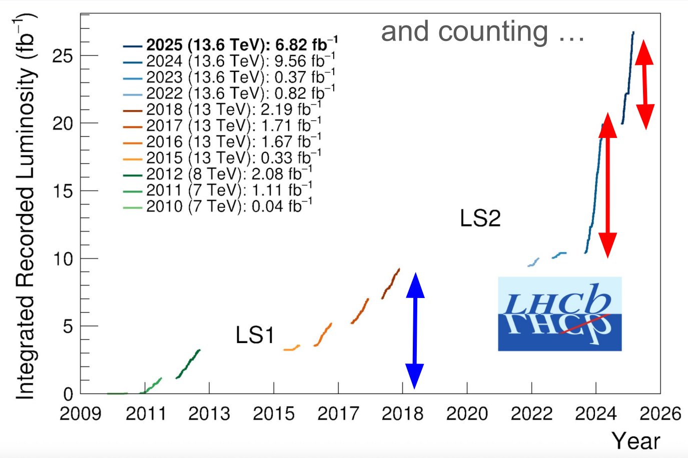


- e^+/e^- (4/7 GeV) at SuperKEK-B
  - Around Υ(4S) resonance
  - B-Bbar produced in coherent QM state
- Largely renovated wrt Belle
- Excellent neutral, electron reconstruction and hermeticity

- pp at LHC 13(.6) TeV
- Covering forward region
- Excellent performance (tracking, vertexing, PID), for B and D physics
- High pile-up, O(100) tracks per event
- Complex trigger (now fully software)

Belle II and LHCb





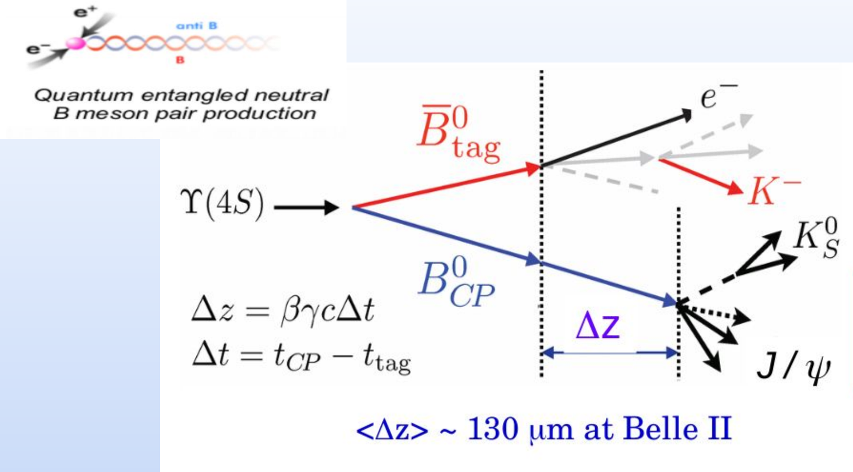
- Luminosity record 5.1x10^{34} cm^{-2}s^{-1}
  - **577 fb^{-1} collected: ~500 fb^{-1} at ϒ(4S)**
    - **Still less than foreseen**
  - **Hard work to improve luminosity and reduce beam backgrounds**
- Run2 data taking to resume from Nov ‘25
  - Long data taking until summer ‘26

- LHC performances are simply great
  - Max Luminosity levelled at 2.1x10^{33} cm^{-2}s^{-1}
  - Integrated luminosity 2x in 2024
  - 2025 going great too

Belle II vs LHCb: summary

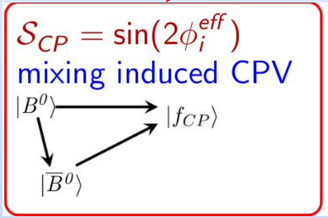
Feature	Belle II	LHCb
σ_{bb}[nb]	~1.1	~150 000
Int Lumi (goal)	multi 10 ab^{-1}	50 fb^{-1} (phase I)
Background level	Low	High
Neutral efficiency	High	Low
Initial state	Well known	Mostly unknown
Decay-time resolution	Good	Excellent
Collision spot size	Tiny	Large
B-flavour tagging efficiency	~37%	4-8%

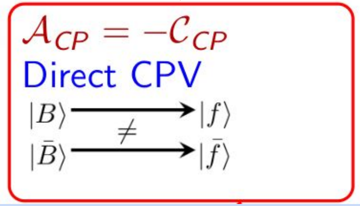
Time-Dependent CPV analysis @Belle II



$$\mathcal{A}_{CP}(\boldsymbol{\Delta t}) = \frac{\Gamma\left(B_{\text{tag}=B^0}(\boldsymbol{\Delta t}) \to \boldsymbol{f_{CP}}\right) - \Gamma\left(B_{\text{tag}=\bar{B}^0}(\boldsymbol{\Delta t}) \to \boldsymbol{f_{CP}}\right)}{\Gamma\left(B_{\text{tag}=B^0}(\boldsymbol{\Delta t}) \to \boldsymbol{f_{CP}}\right) + \Gamma\left(B_{\text{tag}=\bar{B}^0}(\boldsymbol{\Delta t}) \to \boldsymbol{f_{CP}}\right)} =$$

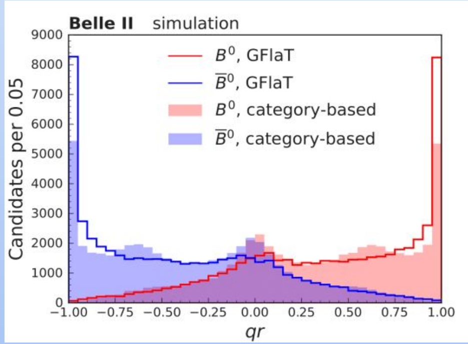
$$= \boldsymbol{S} \cdot \sin(\Delta m_d \Delta t) - \boldsymbol{C} \cdot \cos(\Delta m_d \Delta t)$$





- **B$_{CP}$** fully reconstructed CP eigenstate
- **B$_{tag}$** vertex and flavour information
  - New **GFLaT** algorithm based on GNN
  - Improvement over previous (**C**ategory **B**ased) +18%

ε^{eff}_{tag}(CB) = (31.7 ± 0.5 ± 0.4) %
ε^{eff}_{tag}(GFlaT) = (**37.4 ± 0.4 ± 0.3**) %



Time-Dependent CPV analysis @LHCb

$$|B_{L,H}\rangle = |B_q^0\rangle q \pm |\bar{B}_q^0\rangle p$$

$$A_f = \langle f | H_W | B^0_{(s)}\rangle$$

$$\bar{A}_f = \langle f | H_W | \bar{B}^0_{(s)}\rangle$$

$$(q\bar{A}_f)/(pA_f) \equiv \lambda_f = |\lambda_f| e^{i\phi^f_{d(s)}}$$

No CPV in mixing $|q/p| = 1$

$$A_{CP,f}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{S_f \sin(\Delta m_{d(s)} t) - C_f \cos(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)}$$

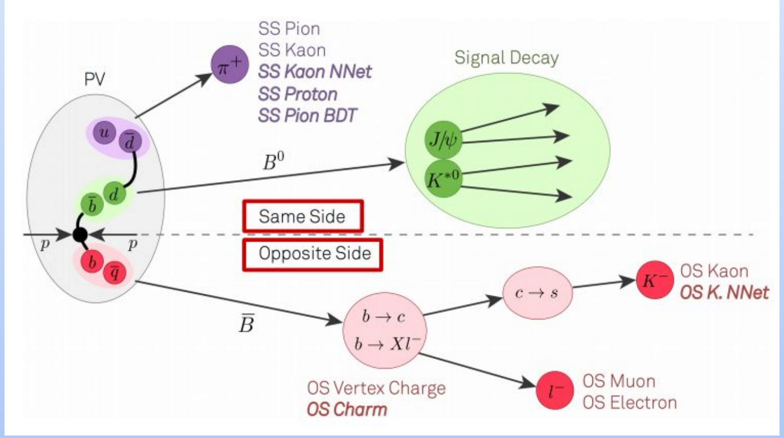
$$(S_f)^2 + (C_f)^2 + (A_f^{\Delta\Gamma})^2 = 1$$

$$C_{f_{CP}} = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2} \qquad S_{f_{CP}} = \frac{2\mathrm{Im}[\lambda_{f_{CP}}]}{1 + |\lambda_{f_{CP}}|^2}$$

CPV in the decay

CPV in interference of mixing and decay

- Production of **B** and **B$_s$**
  - $\Delta\Gamma_s/\Gamma_s = 0.124 \pm 0.007$
- **Tagging** from Same and Opposite side:
  - Effective tagging efficiency: 4-8%
- Large boost + excellent vertex resolution
  - ⇒ 60 fs time resolution



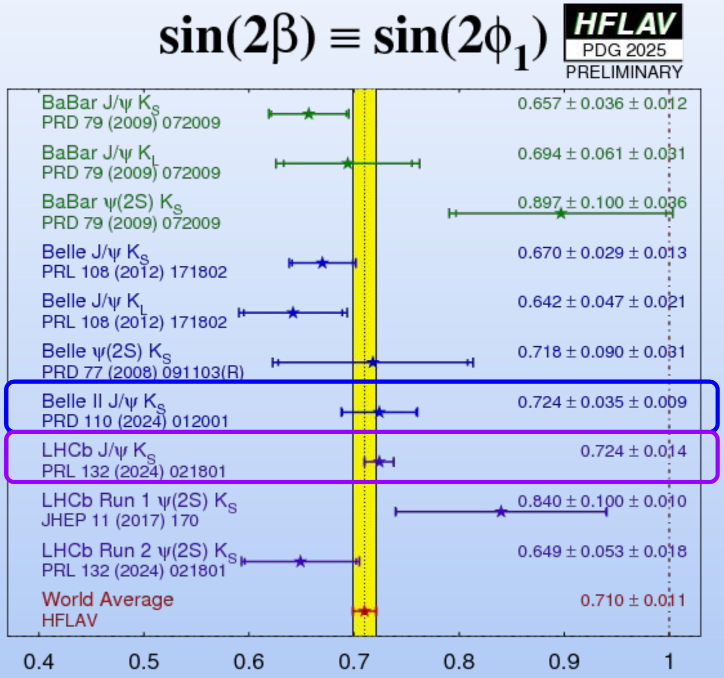
ϕ_1/β

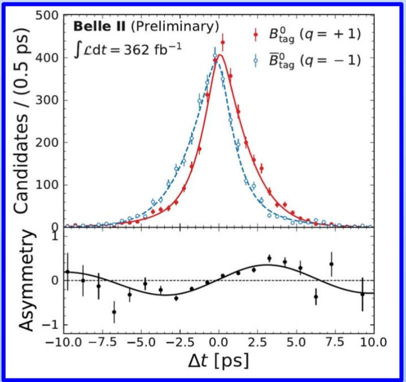
$\sin(2\phi_1/\beta)$ from $B \to J/\psi K_S$

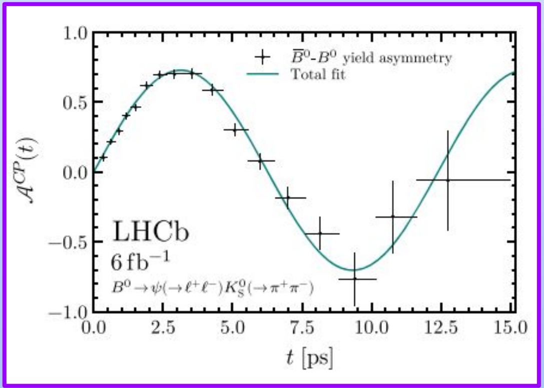
PRD 110 (2024), 12001
PRD 132 (2024), 0210801

- Golden channel, tree-dominated, little penguin pollution

	Belle II	LHCb
B-tagging eff.	~37%	4-6%
# candidates	~6.3k	~370k
Δt resolution	~1 ps	~60 fs
$\int \mathcal{L}\, dt$	362 fb^{-1}	6 fb^{-1}



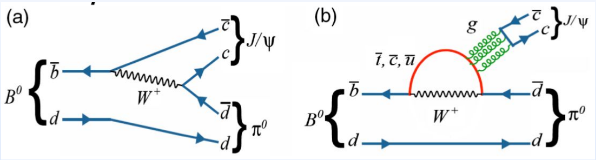


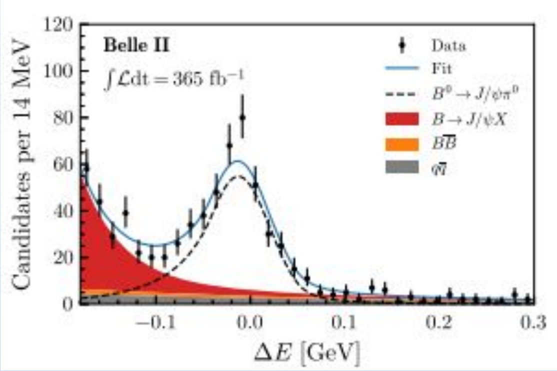


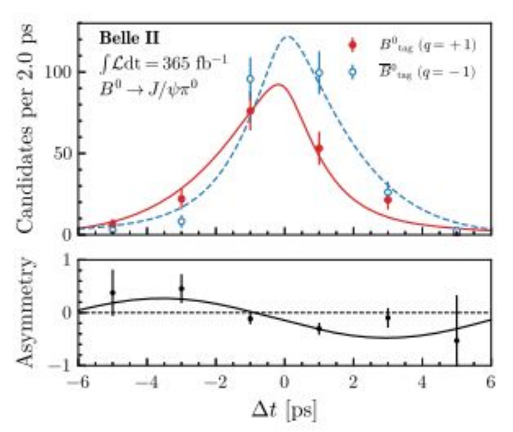
CPV in B → $J/\psi\pi^0$

PRD 111 (2024), 12011
Belle II 365 fb^{-1}

- Color-suppressed $b \to c\bar{c}d$ B → $J/\psi\pi^0$ constraint small penguin pollution in B → $J/\psi K_S$
  - Relevant with increasing precision
- $\phi_d^{eff} = 2\phi_1 + \Delta\phi_d$, with $\Delta\phi_d \approx 0.5^\circ$
- Using both $\mu\mu$ and ee
- Challenges:
  - π^0 reconstruction
  - $J/\psi X$ background







- BR uncertainty at level of Belle with half dataset
- First >5σ observation of mixing-induced CPV

$N_{sig}(\mu\mu) = 204 \pm 17$
$N_{sig}(ee) = 188 \pm 17$
$BR = (2.00 \pm 0.12 \pm 0.09)\ 10^{-5}$

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

$B \to K_S \pi^0 \gamma$

PRL 134, 011802 (2025)

Belle II 362 fb^{-1}

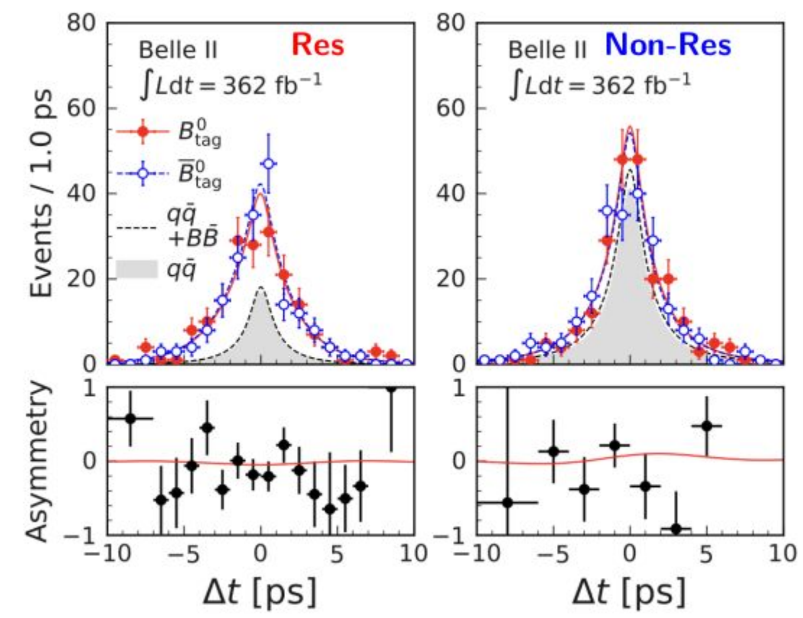
- $B^0 \to K_S \pi^0 \gamma$ is expected to have small/none mixing induced CPV in SM
  - $b \to s\gamma_R$ is helicity suppressed (m_s/m_b) wrt $b \to s\gamma_L$
  - $B^0 \to s\gamma_L$ vs $B^0 \to \bar{B}^0 \to s\gamma_R$
- Vertex from $K_S \to \pi^+\pi^-$ and IP constraint
- Measured separately for resonant $K^{*0}(\to K_S\pi^0)\gamma$

$$S = 0.00 \,^{+0.27}_{-0.26}\,^{+0.03}_{-0.04}$$
$$C = 0.10 \pm 0.13 \pm 0.03$$

- and inclusive (non resonant) decay $K_S\pi^0\gamma$

$$S = 0.04 \,^{+0.45}_{-0.44} \pm 0.10$$
$$C = -0.06 \pm 0.25 \pm 0.07$$

Most precise result so far

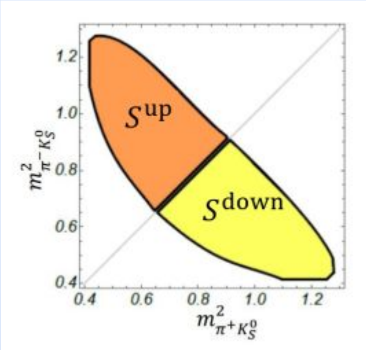


$B \to K_S \pi^+ \pi^- \gamma$

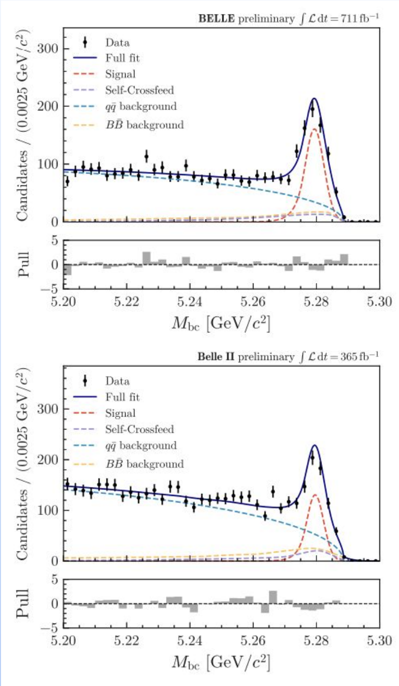
new

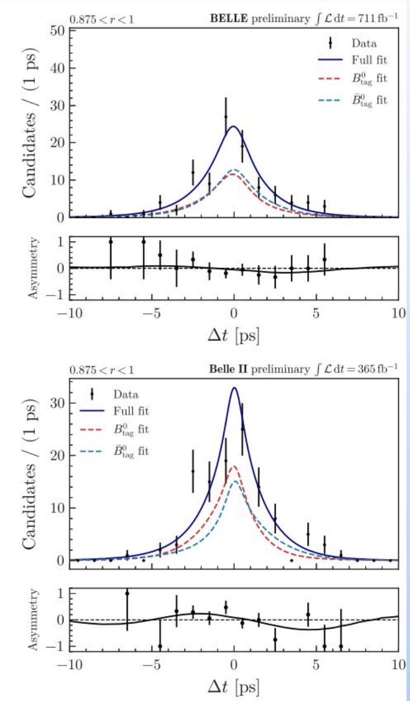
Belle + Belle II 711+365 fb^{-1}

- Also helicity suppressed m_s/m_b
- Sensitive to NP
  - Only ($K_S \rho$)γ are true CP eigenstate
  - Other intermediate resonance (eg $K^*\pi$) requires full amplitude analysis (not done)
- $S^{\pm} = S^{up} \pm S^{down}$
  - Help in constraining C_7/C'_7
  - [JHEP09(2019)034]



$$
\begin{aligned}
\mathcal{C} &= -0.17 \pm 0.09 \pm 0.04 \\
S &= -0.29 \pm 0.11 \pm 0.05 \\
S^+ &= -0.57 \pm 0.23 \pm 0.10 \\
S^- &= 0.31 \pm 0.24 \pm 0.05
\end{aligned}
$$





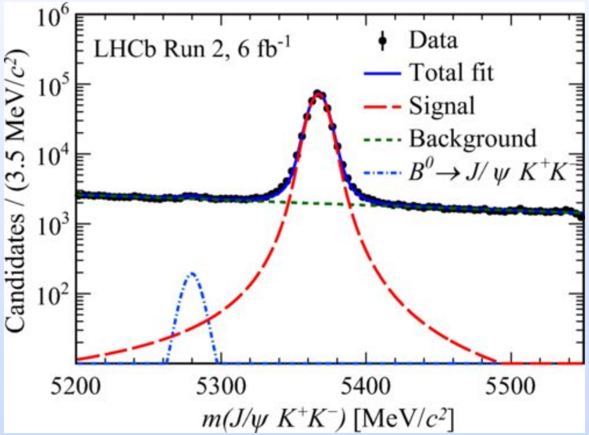
x2 smaller uncertainty than Belle or BaBar

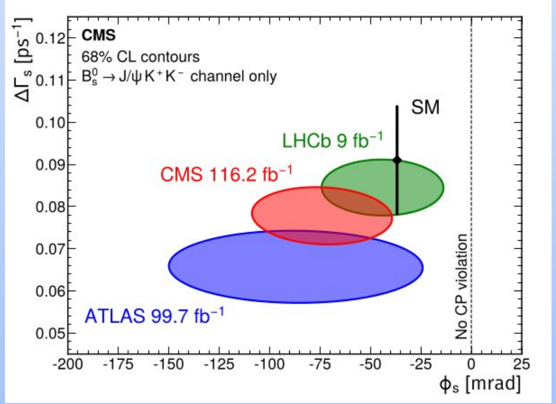
CPV in $B_s \to J/\psi\, \phi$

PRL 132 (2024) 051802
LHCb Run2 6 fb^{-1}

- $\phi_s \simeq -2\beta_s = -2arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$
- Precise determination from indirect from SM fit
  - $\phi_s = -0.0368^{+0.0008}_{-0.0006}$
  - NP can significantly change ϕ_s [RevModPhys.88.045002]
  - Excellent NP probe
- Combine angular and t fit to cope with P→VV decay
  - Disentangle CP-odd/CP-even polarization
- LHCb
  - Most precise measurement to date
  - Combination with other LHCb measurement:
  - $\phi_s = -0.031 \pm 0.018\ \text{rad}$
- Nice results also from CMS/ATLAS
  - Xin Chen's talk after this

349000 candidates





CPV in $B_s \to D_S^+ D_S^-$

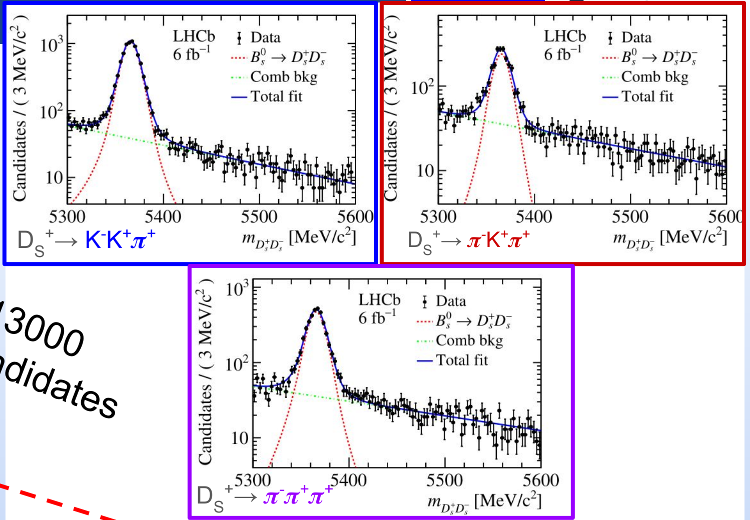
[JHEP 01 (2025) 61] LHCb Run2 6 fb^{-1}

- Together $B_0 \to D^+D^-$
  - One $D_S^{\pm} \to KK\pi$ and other $D_S^+ \to K^-K^+\pi^+ / \pi^-K^+\pi^+ / \pi^-\pi^+\pi^+$
  - $D^+ \to K^-\pi^+\pi^+$: Critical K-π separation, using MVA
  - Fit to $m(D_S^+D_S^-)$ to extract signal
    - S-weighted time distribution fit
- B_s results consistent with no CP asymmetry

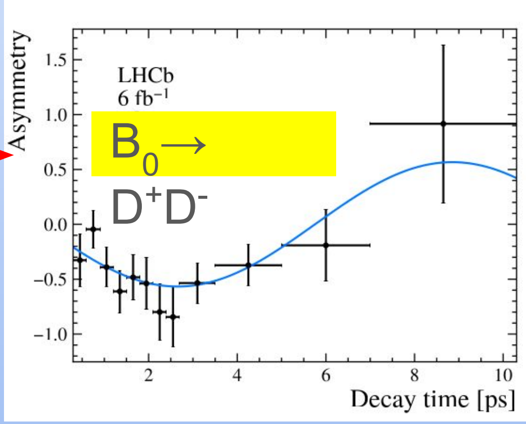
$$\phi_s = -0.055 \pm 0.090\,(\text{stat}) \pm 0.021\,(\text{syst})\,\text{rad},$$
$$|\lambda_{D_s^+ D_s^-}| = 1.054 \pm 0.099\,(\text{stat}) \pm 0.020\,(\text{syst}),$$

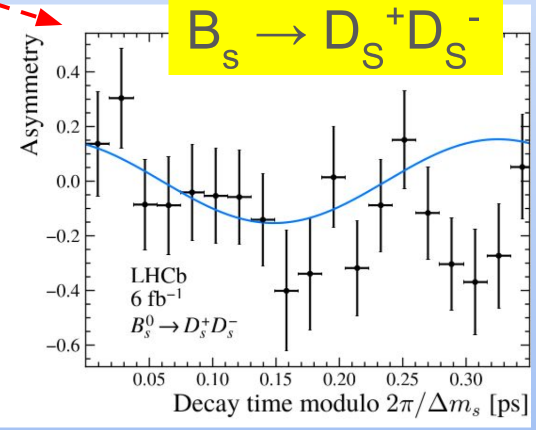
- B_0 results show CPV at 6σ

$$S_{D^+D^-} = -0.552 \pm 0.100\,(\text{stat}) \pm 0.010\,(\text{syst}),$$
$$C_{D^+D^-} = 0.128 \pm 0.103\,(\text{stat}) \pm 0.010\,(\text{syst}).$$



~13000 candidates





ϕ_2/α

ϕ_2/α: B$\rightarrow \rho^+\rho^-$

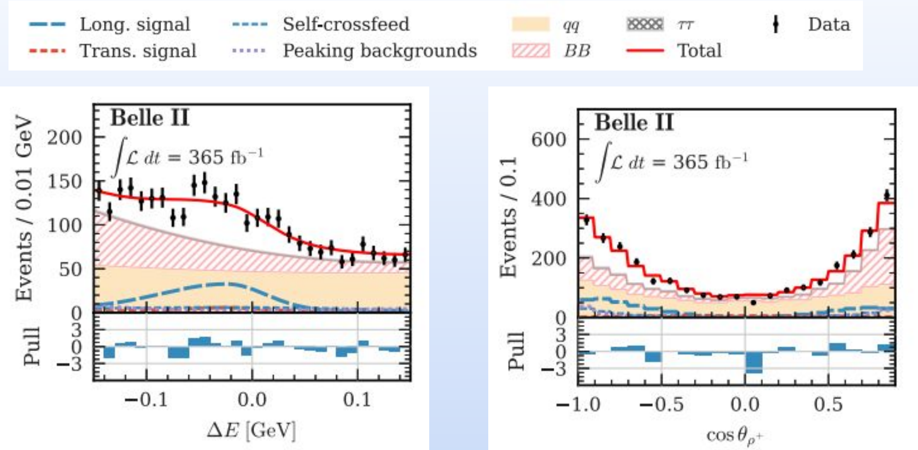
[PRD 111, (2025) 092001](PRD 111, (2025) 092001)

Belle II 365 fb^{-1}

- Tree level b$\rightarrow$ u$\bar{\text{u}}$d for B$\rightarrow\pi\pi/\pi\rho/\rho\rho$
  - Weak phase ϕ_2
  - Small b$\rightarrow$d loop amplitudes contributes with additional $\Delta\phi_2$
  - $S = \sqrt{(1 - C^2)}\sin(2\phi_2 + \Delta\phi_2)$
- Challenges:
  - reconstruct $2\pi^0$
  - Angular analysis to measure polarization in P$\rightarrow$VV decay

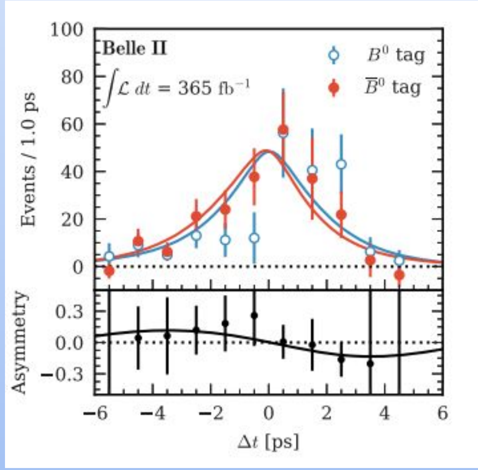
$$\mathcal{B}(B^0 \rightarrow \rho^+\rho^-) = (2.89^{+0.23}_{-0.22}) \times 10^{-5},$$
$$f_L = 0.921^{+0.024}_{-0.025},$$

$$S = -0.26 \pm 0.19$$
$$C = -0.02 \pm 0.12,$$



- Results in ~8% improvement on ϕ_2 from B$\rightarrow \rho\rho$ using isospin analysis

$$\phi_2 = (92.6^{+4.5}_{-4.7})^\circ$$
$$\Delta\phi_2 = (2.4^{+3.8}_{-3.7})^\circ$$

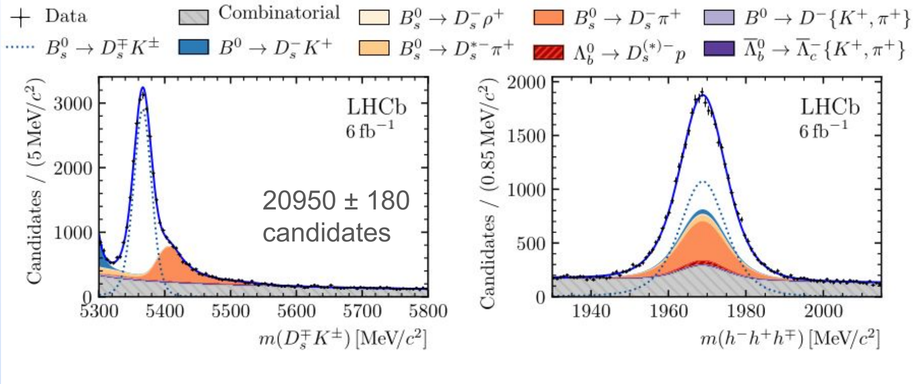


B$^0\rightarrow \pi^0\pi^0$ results in Nakao-san's talk

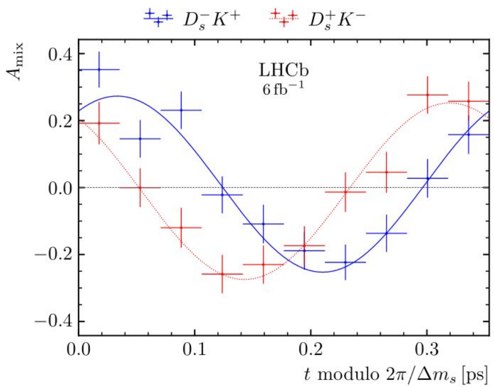
ϕ_3/γ

LHCb: γ/φ_3 with $B_s \to D_s^{\mp}K^{\pm}$ decays

JHEP 03 (2025) 139
LHCb 6 fb^{-1}



- Tree-level decay
  - Sensitive to $(\gamma - 2\beta_s)$ phase
  - $r_{DsK} \simeq 0.4$ ($r_{DK} \simeq 0.02$)
    - $A(b \to c\bar{s}u) \sim A(b \to u\bar{c}s) \sim O(\lambda^3)$
- $D_s \to KK\pi/K\pi\pi/\pi\pi\pi$
- 2D mass fit to get signal ($_s$*Plot*)
- Flavor-tag 6.1% OS/SS
- External input (ϕ_S, production and detection asymmetries)
- Combined with Run1



$$\gamma = (81^{+12}_{-11})^\circ\,,$$
$$\delta = (347.6 \pm 6.3)^\circ$$
$$r_{D_sK} = 0.318^{+0.034}_{-0.033}\,.$$

Used for LHCb γ combination (not competitive)
γ/ϕ_3=(64.6 ± 2.8)° LHCb-CONF-2024-004

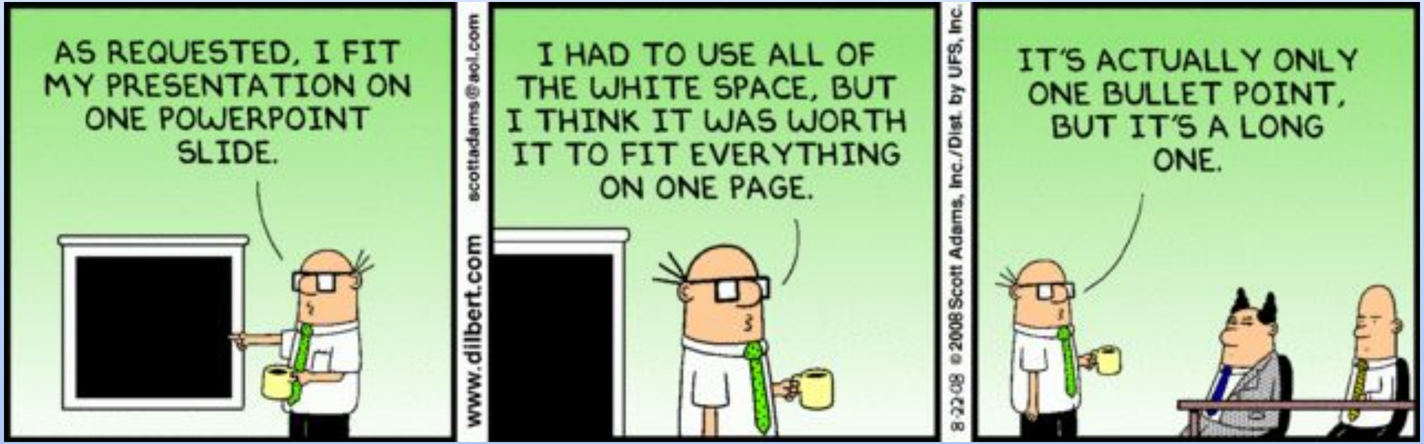
Combination Belle/BelleII **ϕ_3=(78.6±7.3)°**
Few ab^{-1} needed to compete with LHCb results
JHEP 10 2024, 143 (2024)

Summary and future

- Time Dependent CPV measurements presented for B and B_S
  - LHCb dominating the scene, CMS/ATLAS contributing for β_s
  - BelleII leading in final states with neutral and in α/ϕ_2
- Future projection as input to EPPSU: arXiv:2503.24346v2
  - ATLAS/CMS/LHCb/BelleII
  - Measurement mostly statistically limited
- Complementarity and cross check in different environments is essential

Experiment Assumed data sample	**LHCb** $50\,\text{fb}^{-1}$	**Belle II** $10\,\text{ab}^{-1}$
CKM angles		
β	$0.20°$	$0.4°$
α	—	$2.5°$
γ	$0.8°$	$2.2°$
ϕ_s [mrad]	8	—
***CP* violation in loop-dominated decays**		
$S(B^0 \to \eta' K^0_S)$	—	0.023
$\phi_s(B^0_s \to \phi\phi)$ [mrad]	22	—
$\phi_s(B^0_s \to K^{*0}\overline{K}^{*0})$ [mrad]	20	—

Backup


AS REQUESTED, I FIT MY PRESENTATION ON ONE POWERPOINT SLIDE.
I HAD TO USE ALL OF THE WHITE SPACE, BUT I THINK IT WAS WORTH IT TO FIT EVERYTHING ON ONE PAGE.
IT'S ACTUALLY ONLY ONE BULLET POINT, BUT IT'S A LONG ONE.
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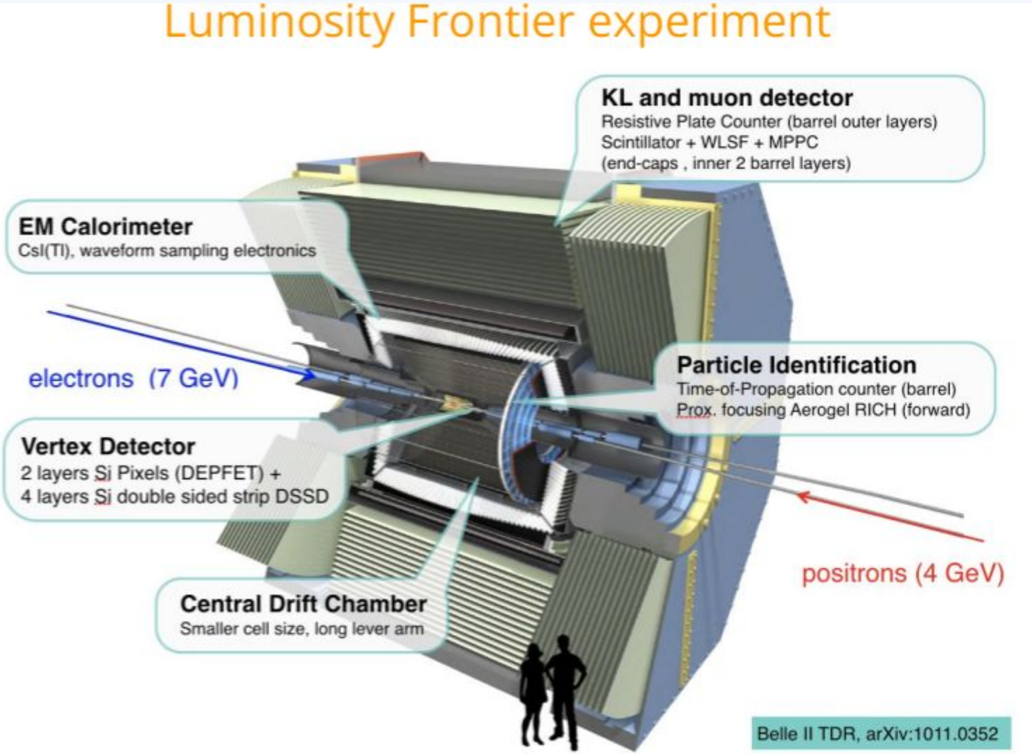
Belle and Belle II

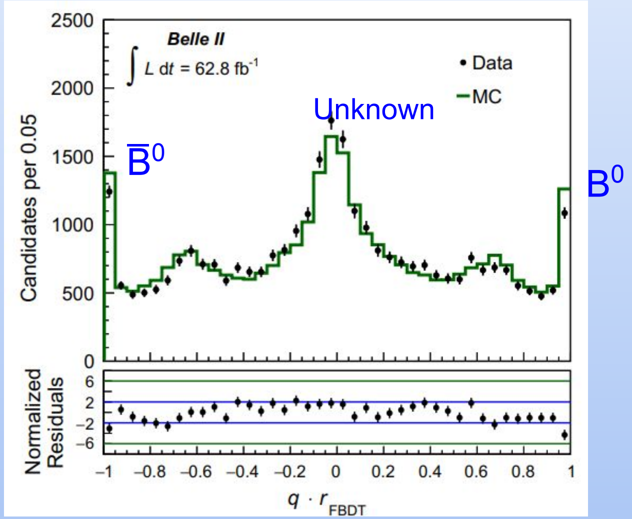
- Asymmetric e^+-e^- colliders- B factories, also charm and τ factories
- Belle Belle II: e^+ (3.5 GeV) e^- (8 GeV) e$^+$ (4 GeV) e$^-$(7 GeV)
- Improved vertex resolution allows lower boost
- 424 fb^{-1} (362 fb^{-1} at Υ(4S)) collected at Belle II so far; Goal: 50 ab^{-1}



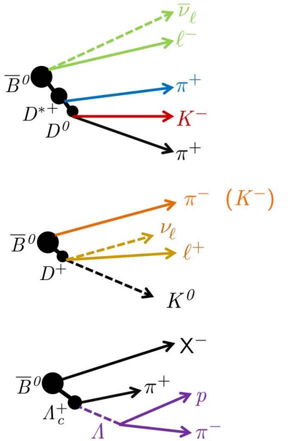
Flavour Tagger

[Eur. Phys. J. C 82, 283(2022)]

- Used to determine the quark-flavour of B_{tag}
- Many different final states considered, combined with two layers of MVA discriminators.
  - Developed also a **D**eep **N**eural **N**etwork with similar performance



Categories	Targets
Electron	e^-
Intermediate Electron	e^+
Muon	μ^-
Intermediate Muon	μ^+
KinLepton	e^-
Intermediate KinLepton	ℓ^+
Kaon	K^-
KaonPion	K^-, π^+
SlowPion	π^+
FastHadron	π^-, K^-
MaximumP	ℓ^-, π^-
FSC	ℓ^-, π^+
Lambda	Λ
Total= 13	



Performance measured on data using $B^0 \to D^{(*)-}h^+$ decays

- Effective efficiency:

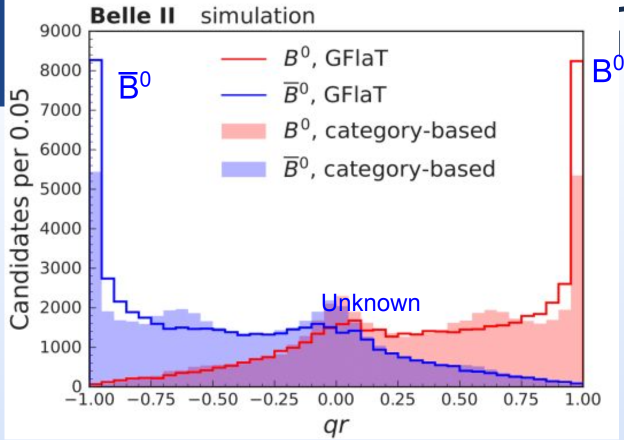
$$\varepsilon_{eff} = \Sigma_i \varepsilon_i (1 - 2w_i)^2$$
$$= (30.0 \pm 1.2 \pm 0.4)\%$$

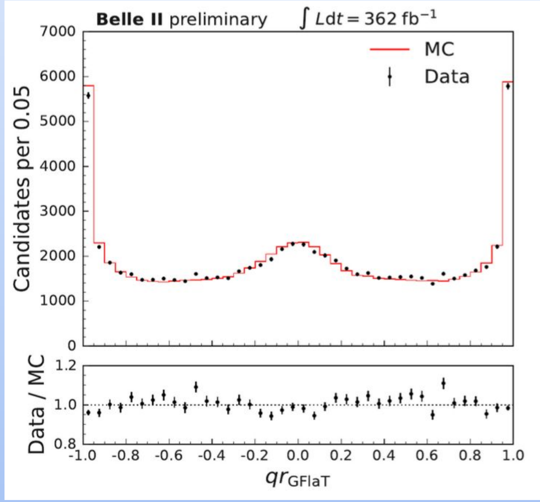
B flavour tagging: GFlaT

arXiv:2402.17260
PRD 110 (2024), 12001

- CPV analysis in Belle II used a category-based (CB) algorithm [Eur. Phys. J 82, 283 (2022)]
- A more advanced algorithm GFlaT, based on graph convolutional neural network (GNN), was developed
  - Using 25 variables for each track from the B_{tag} decay
- Performance evaluated on data using self-tagging $B^0 \to D^{(*)-}\pi^+$ decays
- Significant improvement in performance
  - **+18%** (relative)

ε_{tag}(CB) = (31.7 ± 0.5 ± 0.4) %
ε_{tag}(GFlaT) = (**37.4 ± 0.4 ± 0.3**) %





Measurement of ϕ_2/α

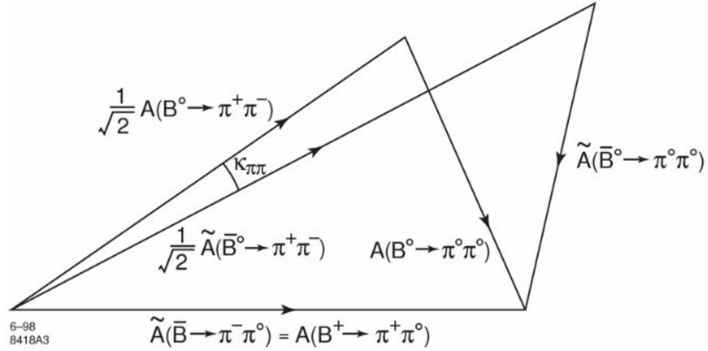
- The measurement of ϕ_2 from B → ππ (or B → ρρ) final states comes from an isospin analysis:

The following equalities hold:

$$\frac{1}{\sqrt{2}}A^{+-} + A^{00} = A^{+0}$$

$$\frac{1}{\sqrt{2}}\tilde{A}^{+-} + \tilde{A}^{00} = \tilde{A}^{+0}$$

$$A^{+0} = \tilde{A}^{+0}$$



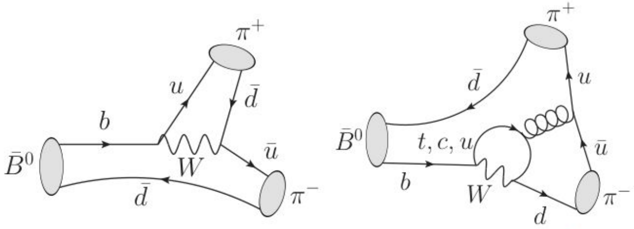
- Observables (for e.g. B → ππ):
  - branching fractions of: $B^0 \to \pi^+\pi^0, \pi^+\pi^-, \pi^0\pi^0$;
  - direct (time-independent) CP asymmetries: C^{+-}, C^{00};
  - time-dependent CP asymmetries: S^{+-}, S^{00}.

M. Gronau and D. London, PRL 65 (1990), 3381

- Belle II will be able to measure all these observables;
- We expect to push the sensitivity to α to ~1°.

Measurement of ϕ_2/α

Two amplitudes of comparable size with different weak phase:



Penguin in $B^0 \to \pi^+\pi^-, \pi^0\pi^0$, but not in $B^\pm \to \pi^\pm\pi^0$

$$\phi_2 = (\widehat{\bar{A}^{+0}, A^{+0}}),\ \phi_2^{eff} = (\widehat{\bar{A}^{+-}, A^{+-}})$$

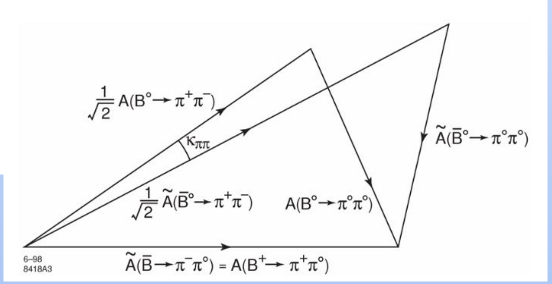
Isospin analysis[Gronau-London PRL, 64 3381 (1990)]: constraints B^0 and $B^\pm$ amplitudes:

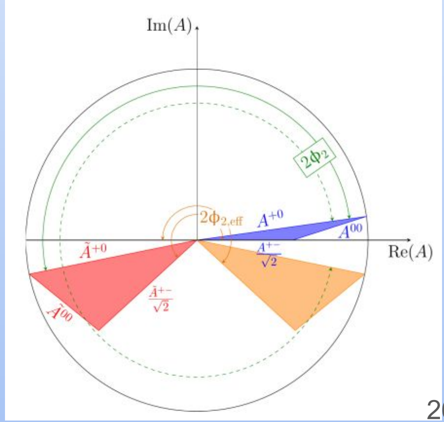
$$A^{+0} = A^{+-}/\sqrt{2} + A^{00}$$

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

$$|A^{+0}| = |\bar{A}^{+0}|$$

- Need all branching fractions;
- Direct CP asymmetries: C^{+-}, C^{00};
- TD CP asymmetries: S^{+-}, S^{00};
  - S^{00} reduces folding ambiguities
- Belle II will be able to measure all these observables
  - Final sensitivity ~1°





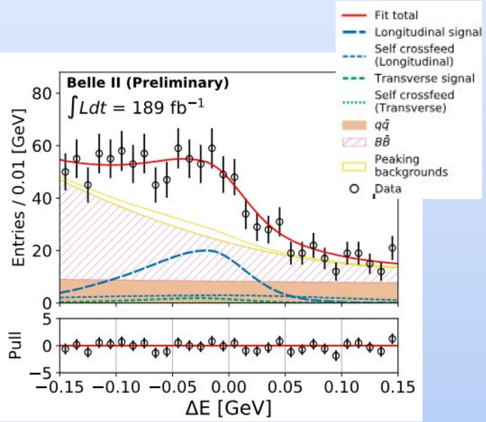
Similar for $B \to \rho\rho$

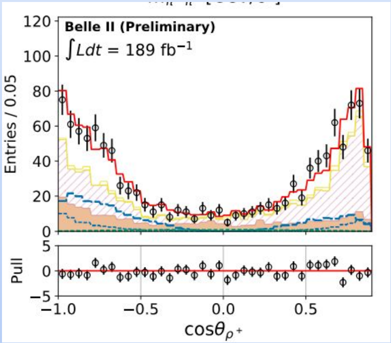
Toward ϕ_2/α: $B \rightarrow \rho\rho$

arxiv:2208.03554
arxiv:2206.12362

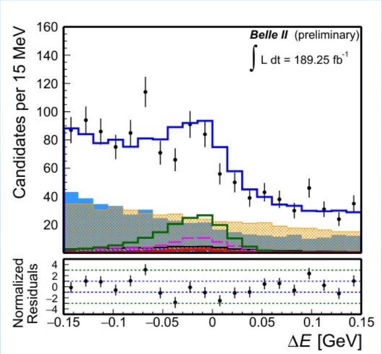
- Broad resonances of vector mesons, π^0 in final state
  - multiple non-negligible peaking background contributions
- CP analysis requires measurement of longitudinal polarization:
  - angular analysis using helicity angles of ρ's

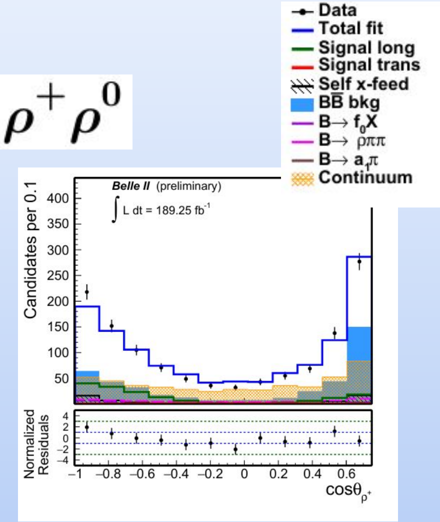
$$B^0 \rightarrow \rho^+\rho^-$$





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





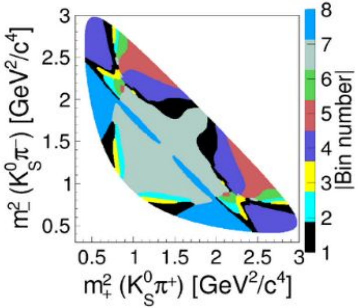
$$\mathcal{B}(B^0 \rightarrow \rho^+\rho^-) = [2.67 \pm 0.28\,(\mathrm{stat}) \pm 0.28\,(\mathrm{syst})] \times 10^{-5},$$
$$f_L = 0.956 \pm 0.035\,(\mathrm{stat}) \pm 0.033\,(\mathrm{syst}),$$

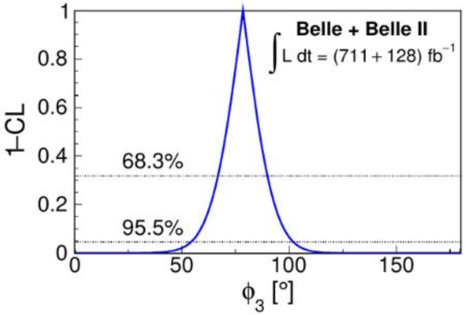
$$\mathcal{B}(B^+ \rightarrow \rho^+\rho^0) = [23.2^{+\,2.2}_{-\,2.1}(\mathrm{stat}) \pm 2.7(\mathrm{syst})] \times 10^{-6},$$
$$f_L = 0.943^{+\,0.035}_{-\,0.033}(\mathrm{stat}) \pm 0.027(\mathrm{syst}),$$
$$\mathcal{A}_{CP} = -0.069 \pm 0.068(\mathrm{stat}) \pm 0.060(\mathrm{syst}).$$

Belle/BelleII combined results on γ/ϕ_3

- Best sensitivity from the BPGGSZ method, exploiting the interference in the $D^0 \rightarrow K_S \pi^+ \pi^-$ Dalitz plot:

J. High Energ. Phys. 2022, 63 (2022)





$$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ\,,$$
$$r_B^{DK} = 0.129 \pm 0.024 \pm 0.001 \pm 0.002,$$
$$\delta_B^{DK} = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ\,,$$
$$r_B^{D\pi} = 0.017 \pm 0.006 \pm 0.001 \pm 0.001,$$
$$\delta_B^{D\pi} = (341.0 \pm 17.0 \pm 1.2 \pm 2.6)^\circ\,.$$

- GLW method [Phys.Lett.B 253 (1991) 483-488, Phys.Lett.B 265 (1991) 172-176]: consider decays of the D^0 to odd (-) and even (+) CP eigenstates and measure the observables:

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

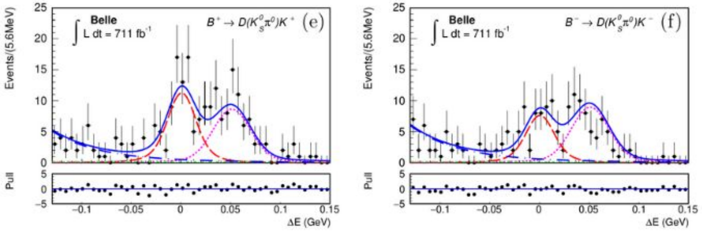
which are related to ϕ_3:

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

Belle/BelleII combined results on γ/φ$_3$

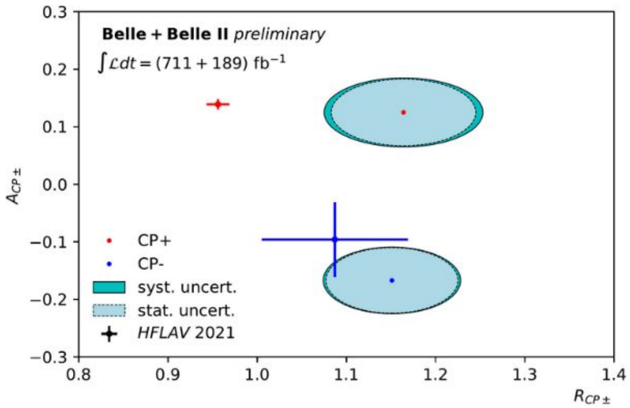
- Considering $D^0 \to K^+K^-$ as CP+, $D^0 \to K_S\pi^0$ as CP-, and $D^0 \to K^-\pi^+$ as flavor specific final state, we measure (on the Belle + Belle II data set):

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



- The A_{CP}'s differ from each other at ~3.5σ;
- This translates into constraints on ϕ_3:

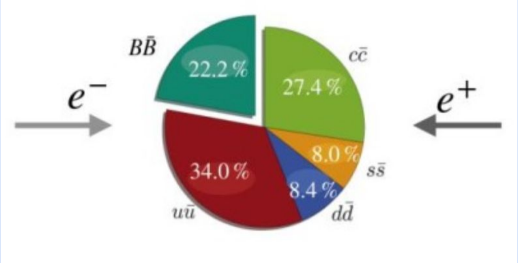
	68.3% CL	95.4% CL
ϕ_3 (°)	[8.7, 20.5] [83.8, 96.1] [163.4, 173.1]	[4.7, 175.8]
r_B	[0.282, 0.489]	[0.069, 0.560]

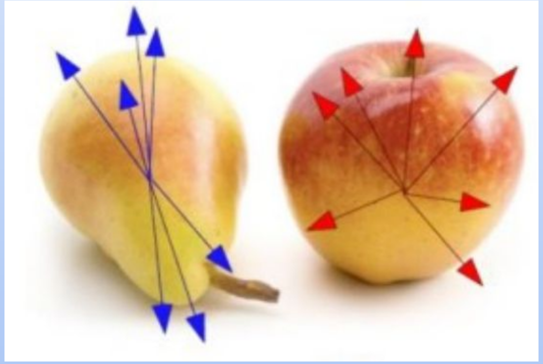


arXiv:2308.05048 [hep-ex]

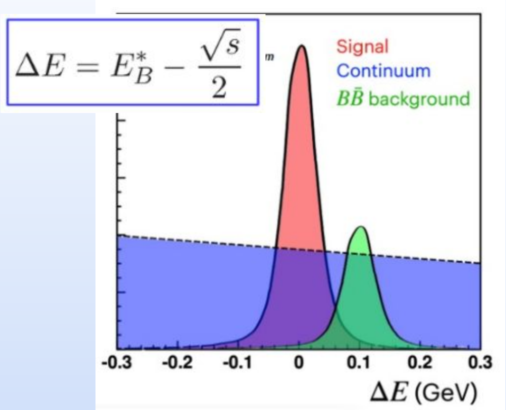
B-Factory variables

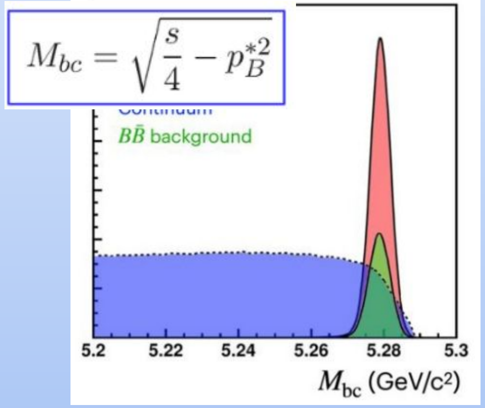
- Two key variables to discriminate fully reconstructed (hadronic) signal from background
  - Background from continuum (qq-bar) and from BB
- Discrimination against continuum (qq-bar) background using event-shape variables via a multivariate classifier





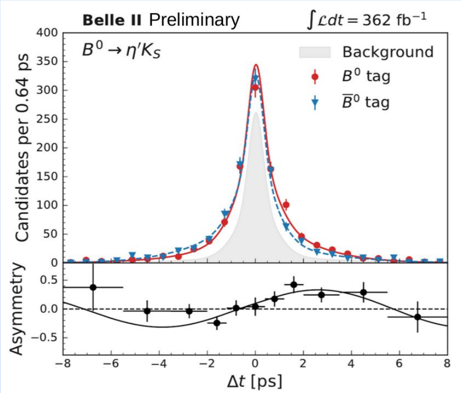
$q\bar{q}$ events $\quad$ $B\bar{B}$ events





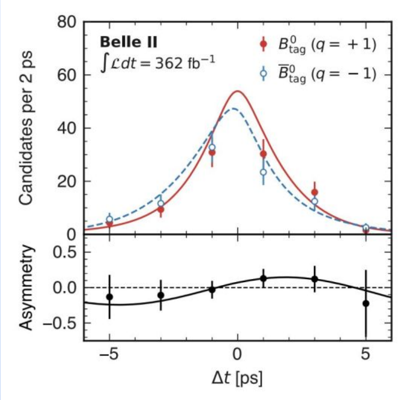
TDCPV in Charmless B decay

- $B \to \eta' K_S$ arXiv:2402.03713
  - $\eta' \to \eta(\to \gamma\gamma)\pi^+\pi^-$
  - $\eta' \to \rho\gamma$
- High $\mathcal{B}$, theoretically clean
  - ~800 signal events



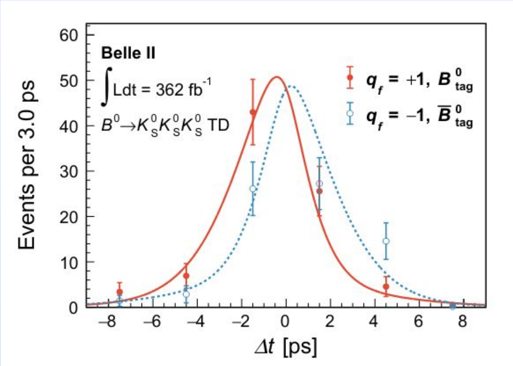
S = 0.67 ± 0.10 ± 0.04
C = - 0.19 ± 0.08 ± 0.03

- $B \to \phi K_S$ PRD 108, 072012 (2023)
- Challenge: non resonant background with opposite-CP
  - ~160 signal events



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

- $B \to K_S K_S K_S$ arXiv:2403.02590 Accepted by PRD
- Challenge: no prompt tracks from B vertex
  - Use $K_S \to \pi^+\pi^-$ extrapolated to IP
  - ~160 signal events

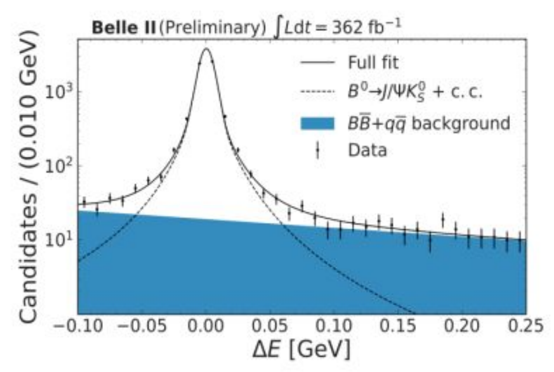


S = -1.37 $^{+0.35}_{-0.45}$ ± 0.03
C = - 0.07 ± 0.20 ± 0.05

$\sin(2\phi_1/\beta)$ from $B \to J/\psi K_S$

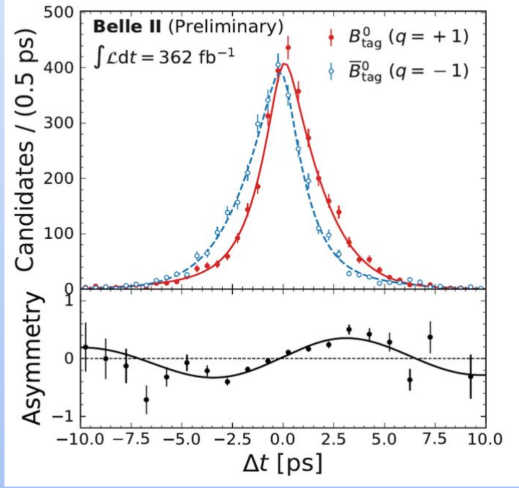
arXiv:2402.17260
PRD 110 (2024), 12001

- Golden channel, almost background free
- Updated results using improved GFlaT flavour tagger
- Fit ΔE distribution to subtract background
- Fit background-subtracted Δt distribution to extract CPV parameters



S = 0.724 ± 0.035 ± 0.014
C = - 0.035 ± 0.026 ± 0.013

World average (K_S mode only):
$S_{CP} = 0.695 \pm 0.019$
$A_{CP} = 0.000 \pm 0.020$

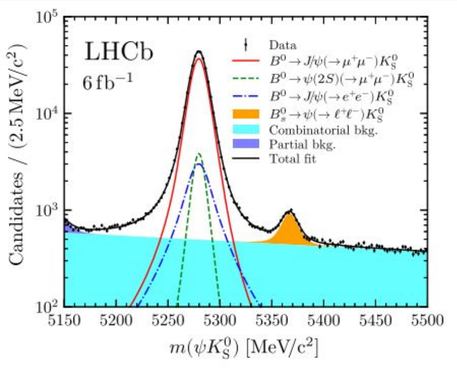


- Statistical uncertainties **8%** smaller than with category-based Flavour Tagger

sin 2β measurement @ LHCb

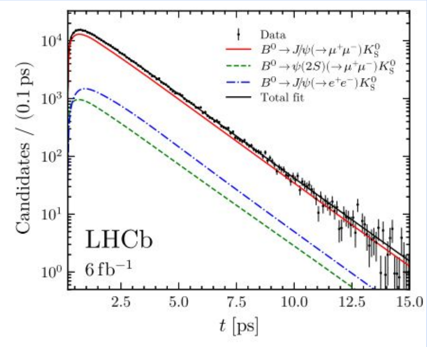
PRD 132 (2024), 0210801

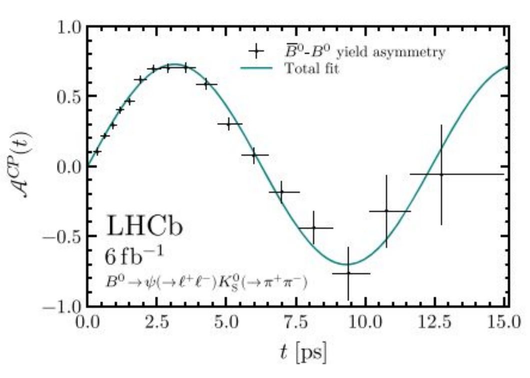
6 fb^{-1} collected in Run2



Channel	$\epsilon_{tag}(\%)$	$\mathcal{D}^2(\%)$
$B^0 \to J/\psi(\to \mu^+\mu^-)K^0_S$	85.34 ± 0.05	4.661 ± 0.013
$B^0 \to J/\psi(\to e^+e^-)K^0_S$	92.20 ± 0.08	6.462 ± 0.032
$B^0 \to \psi(2S)(\to \mu^+\mu^-)K^0_S$	84.81 ± 0.15	4.59 ± 0.04

372 350 tagged events





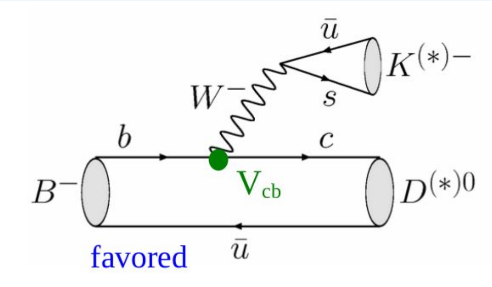
$$S^{\text{Run 1\&2}}_{\psi K^0_S} = 0.724 \pm 0.014(\text{stat} + \text{syst}),$$

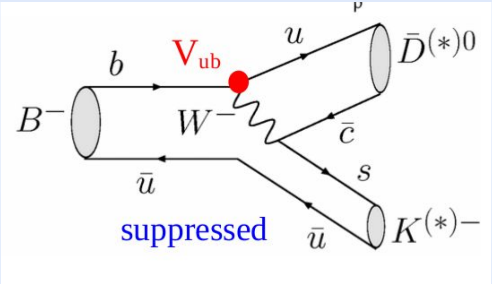
$$C^{\text{Run 1\&2}}_{\psi K^0_S} = 0.004 \pm 0.012(\text{stat} + \text{syst}),$$

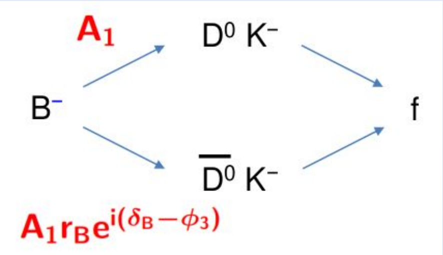
~60 fs time resolution

Results on γ/φ_3

- γ/φ_3 from interference of tree level amplitudes:
  - Fundamental input of CKM UT fit
- φ_3 can be measured using interference $B\to DK$ and $B\to \bar{D}K$ (or D^*K^*, $D\pi$)







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

A_1

$B^- \to \bar{D}^0K^- \approx V_{ub}V^*_{cs}$

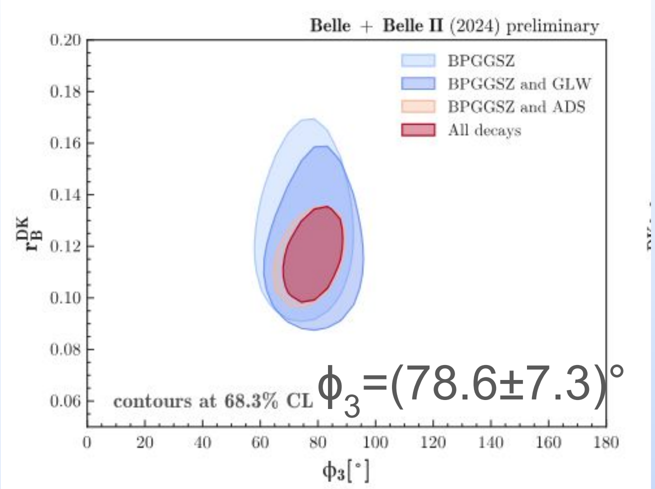
$A_1 r_B e^{i(\delta_B - \phi_3)}$

- Amplitude ratio r_B and strong phase δ_B are mode-dependent

Belle/BelleII combined results on γ/ϕ_3

arXiv [2404.12817]

- Several methods used
  - GLW $B^{\pm} \to D^0_{CP} K^{\pm}$ arXiv:2308.05048 [hep-ex]
    - Use CP eigenstate of D meson
  - ADS PRL 78 (1997) 3257
    - Enhancement of CP violation by using doubly Cabibbo suppressed decays.
  - BPGGSZ $D^0 \to K_S h^+ h^-$ JHEP 2022(2022), 63
    - Different amplitude and strong phase in different region of Dalitz plot.
  - GLS $D^0 \to K_S K \pi$ JHEP 09(2023)146
- D-decay strong phase from CLEO-c & BESIII
  - Need improvement by BESIII



LHCb: $\phi_3=(64.6 \pm 2.8)^\circ$ LHCb-CONF-2024-004
Few ab^{-1} needed for a meaningful comparison

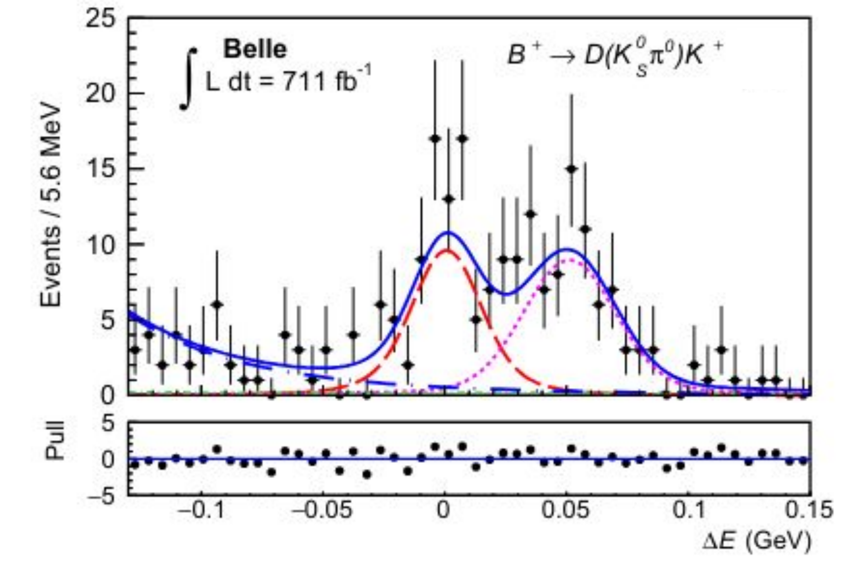
- Likelihood with 60 input observables
  - including 15 auxiliary inputs (D-decay)
  - 16 free parameters
- $r_B(\delta_B)$ with little high-fluctuation
  - Worse precision with WA values

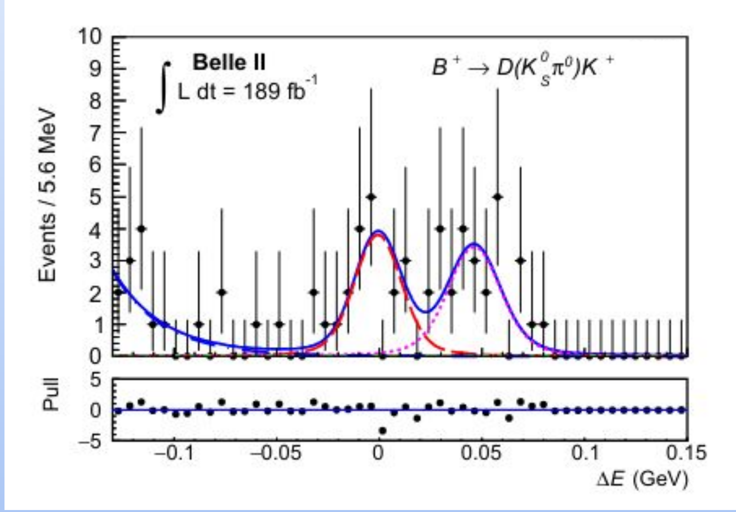
Belle + Belle II Combined γ/ϕ_3

arXiv:2308.05048
Belle II 189 fb^{-1}

- Example:
  - $B^{\pm}\to D_{CP}K^{\pm}$ (GLW)
  - CP-odd $D_{CP}\to K_S\pi^0$: only in Belle(II)
  - Combined Belle and BelleII analysis

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.)	$605+0$



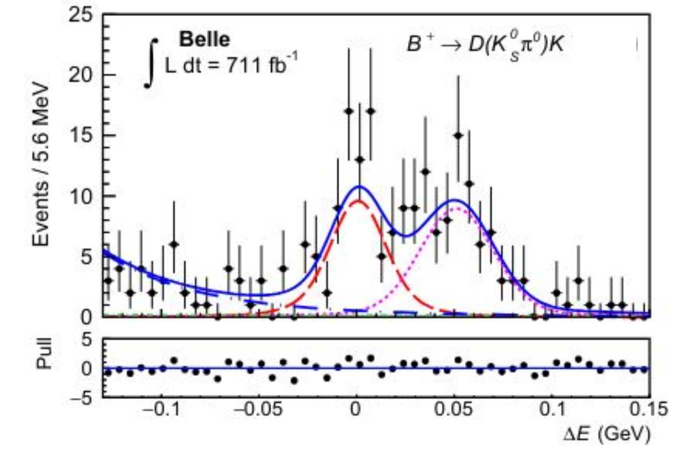


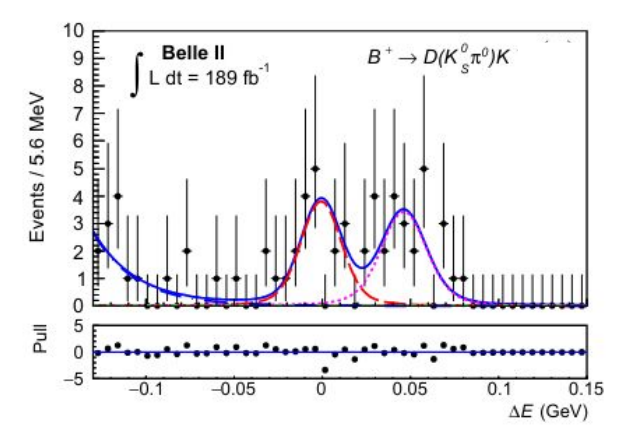
Belle + Belle II Combined γ/φ_3

arXiv:2308.05048
Belle II 189 fb^{-1}

- An example (not TD)
  - $B^\pm \to D_{CP} K^\pm$ (GLW)
  - CP-odd $D_{CP} \to K_S \pi^0$: only in Belle(II)
  - Combined Belle and BelleII analysis

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.)	$605+0$





Combinazione $\phi_3=(78.6\pm7.3)°$ JHEP 10 2024, 143 (2024)
Few ab^{-1} needed for a meaningful comparison with LHCb results

Summary and future

Experiment Assumed data sample	ATLAS 20.3-99.7 fb^{-1}	CMS 116-140 fb^{-1}	LHCb 2-9 fb^{-1}	Belle II 364-1075 fb^{-1}
CKM angles				
β	—	—	0.57° [15]	1.2° [16]
α	—	—	—	6.6° [17]
γ	—	—	2.8° [18]	13° [17]
ϕ_s [mrad]	42 [19]	23 [20]	20 [21]	—
***CP* violation in loop-dominated decays**				
$S(B^0 \to \eta' K^0_S)$	—	—	—	0.087 [17]
$\phi_s(B^0_s \to \phi\phi)$ [mrad]	—	—	69 [22]	—
$\phi_s(B^0_s \to K^{*0}\overline{K}^{*0})$ [mrad]	—	—	130 [23]	—