



# Quark Flavor Physics Experiments: CP Violation

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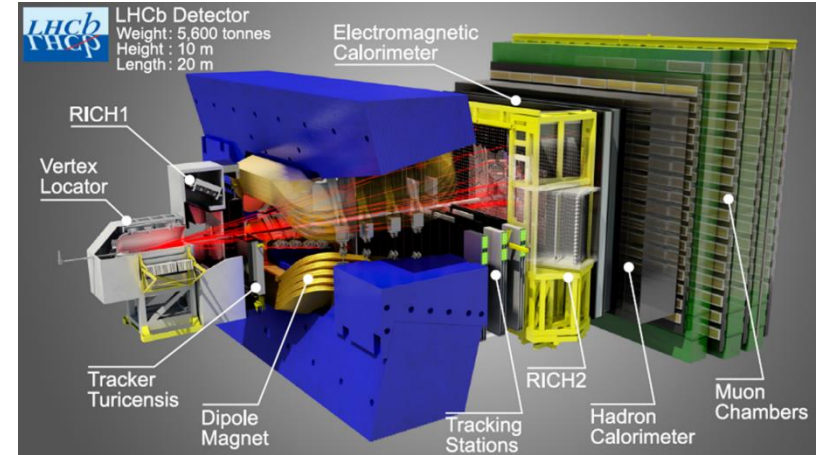
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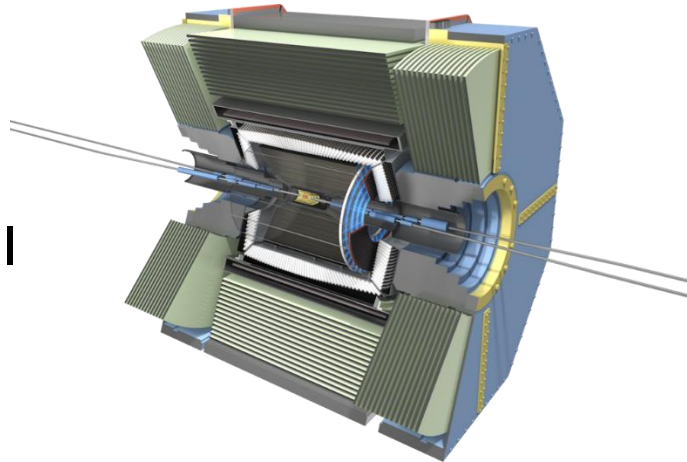
- Introduction
  - ✓ Status of SuperKEKB, Belle II
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  - ✓  $\sin(2\phi_1) / \sin(2\beta)$
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## Flavor Physics Experiments:

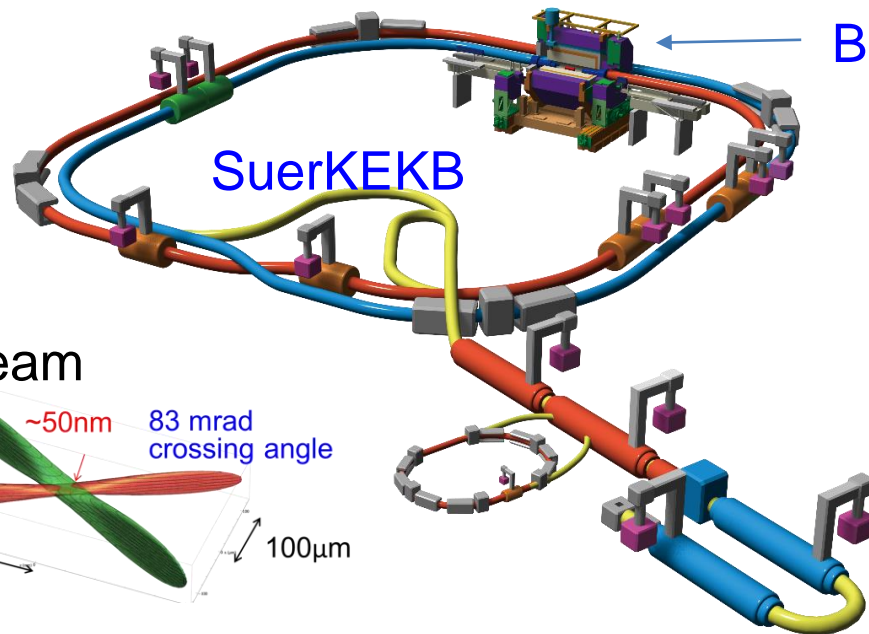
### LHCb



Belle II



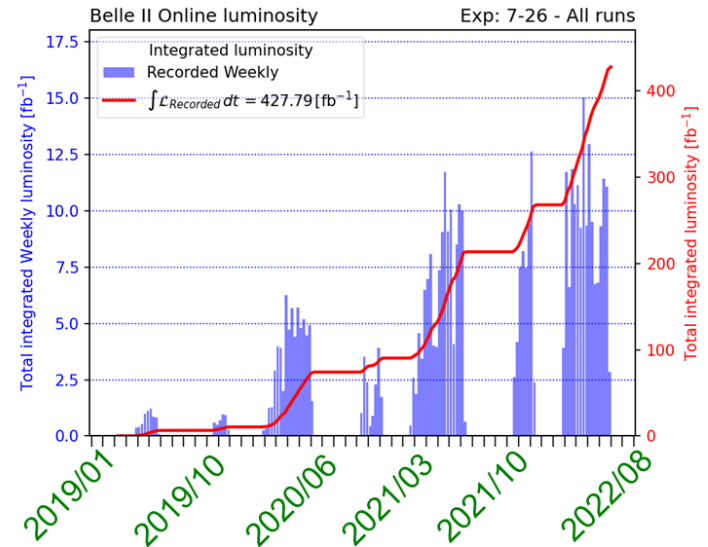
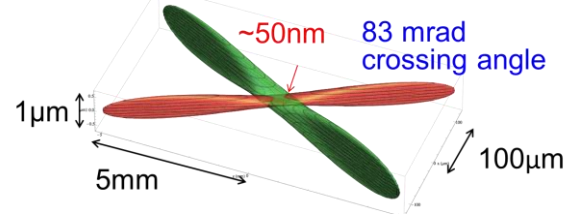
# SuperKEKB and Belle II



Belle II

SuerKEKB

nano beam



- $e^+e^-$  collider (4 GeV  $e^+$  + 7 GeV  $e^-$ ) at KEK.
  - ✓  $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
- Run1 Operation 2019-2022.
- Long shutdown (LS) 1 from summer 2022 to fully install the pixel detector (PXD).
  - ✓ Only 1/6 was installed in the 2nd layer
- Run2 Operation starts from Jan. 2024.

- Luminosity  $4.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  achieved (Jun. 2022):
  - ✓ World record ( $\sim \times 2$  of KEKB)
  - ✓ Aiming one order higher.
- $424 \text{ fb}^{-1}$  of data accumulated so far.
  - ✓ Belle:  $1 \text{ ab}^{-1}$  in 11 years' operation.
  - ✓ Belle II target: O(10) of Belle.

# CP Violation and KM theory



- CP violation: a key for the matter-antimatter asymmetry.
- Kobayashi-Maskawa theory (1973)
  - ✓ CP violation in the Standard Model (SM)
  - ✓ **Complex phase in the quark mixing matrix**

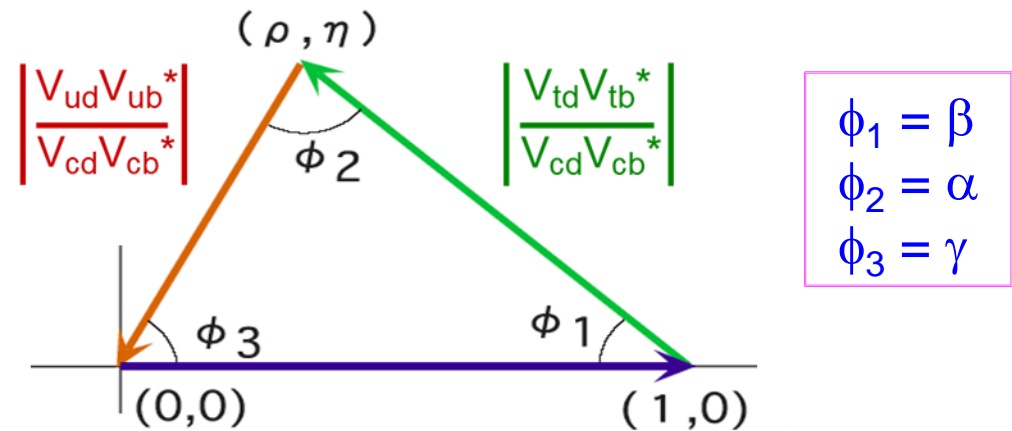


$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

From the unitarity of the matrix:

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

- Triangles in the complex plane.
- Other triangles exist.



# CP Violation in B Meson



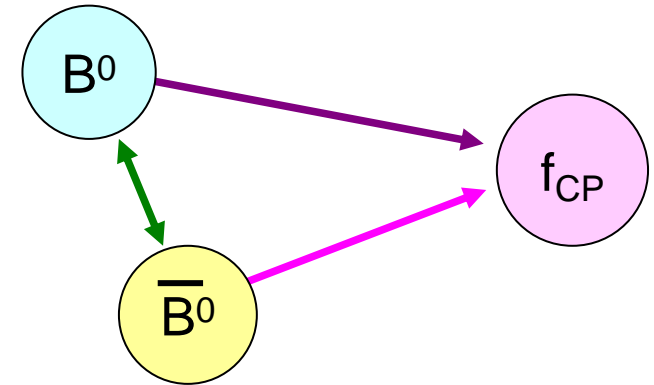
## Mixing-induced CP asymmetry of B mesons

- $B^0$  and  $\bar{B}^0$  decay to a common CP eigenstate  $f_{CP}$ .
- CP violation appears as a decay time difference.

$$A_{CP}(\Delta t) = \frac{\Gamma(\bar{B}^0(\Delta t) \rightarrow f_{CP}) - \Gamma(B^0(\Delta t) \rightarrow f_{CP})}{\Gamma(\bar{B}^0(\Delta t) \rightarrow f_{CP}) + \Gamma(B^0(\Delta t) \rightarrow f_{CP})}$$

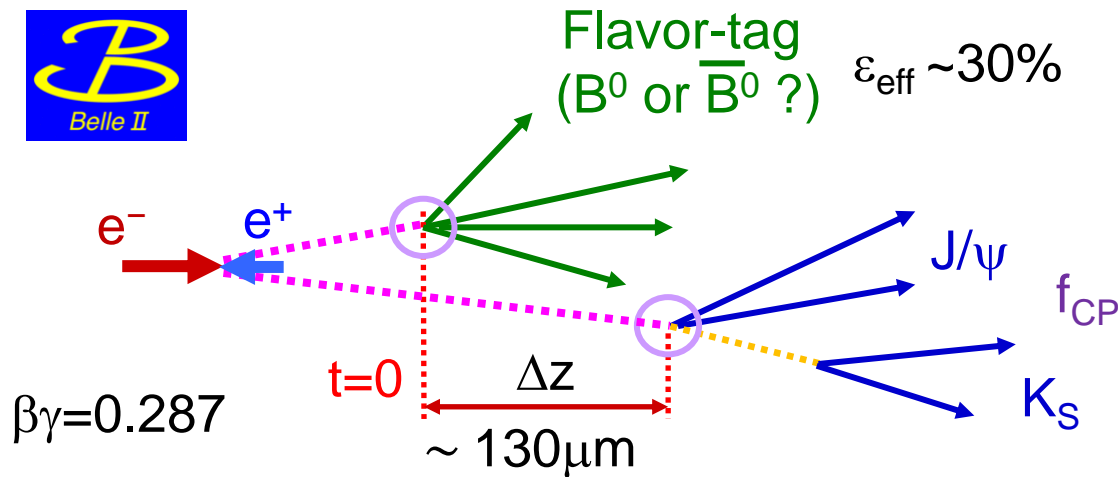
$$= S \sin(\Delta m \Delta t) - C \cos(\Delta m \Delta t)$$

$$S = -\xi \sin(2\phi_1) \text{ for } B \rightarrow J/\psi K_S \quad (\phi_1 = \beta)$$

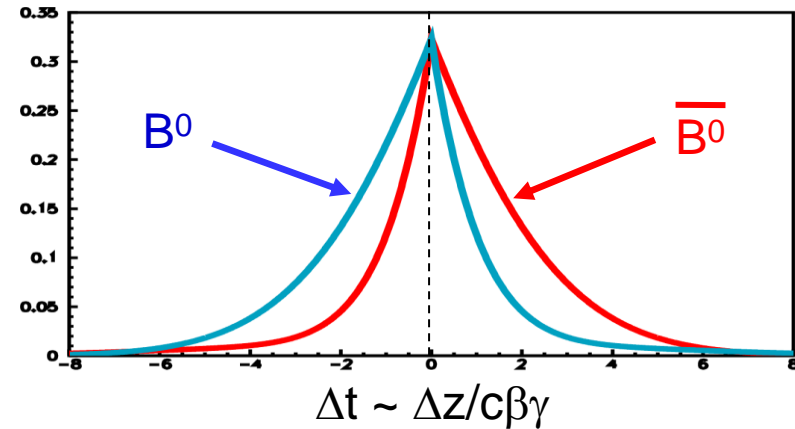


**S** : mixing induced CPV

**C** : direct CPV (= -A)



measure position instead of time



# Unitarity Triangle



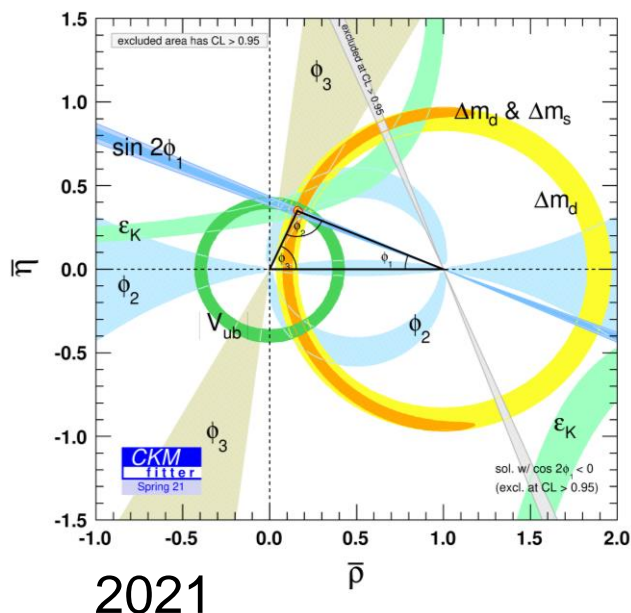
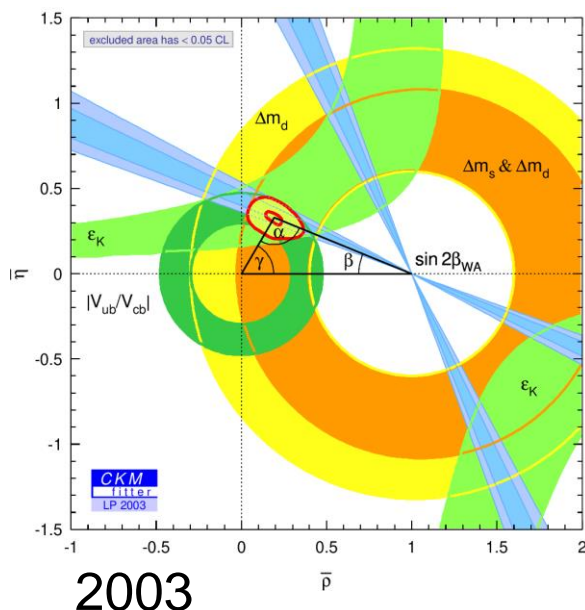
Observation CP violation in B mesons (2001): BaBar and Belle

$$\sin(2\beta) = 0.687 \pm 0.028 \pm 0.012 \quad (\text{BaBar [PRD79, 072009 (2009)])}$$

$$\sin(2\phi_1) = 0.667 \pm 0.023 \pm 0.012 \quad (\text{Belle [PRL 108, 171802 (2012)])}$$



2008 Nobel Prize



?

$$\begin{aligned} \phi_1 &= \beta \\ \phi_2 &= \alpha \\ \phi_3 &= \gamma \end{aligned}$$

- Precise measurement of the Unitarity Triangle → Test of the SM
  - ✓ “Over-constrain” the triangle.
  - ✓ Still room of New Physics effect.



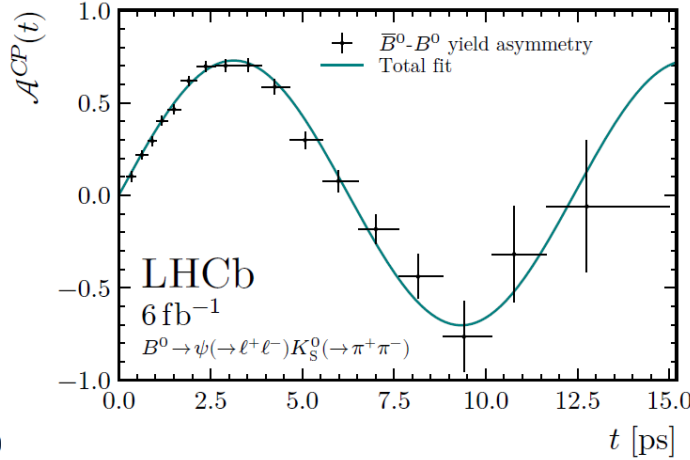
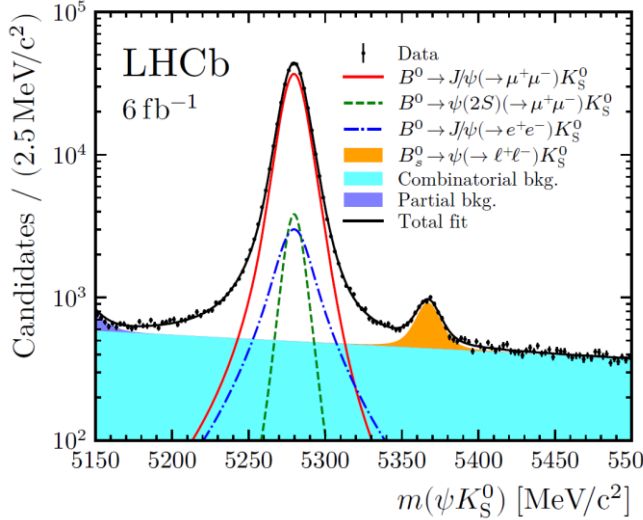


# sin(2β) at LHCb

[arXiv:2309.09728]



- New result from LHCb using Run2 data (6 fb<sup>-1</sup>).
- B → J/ψ (→ μ<sup>+</sup>μ<sup>-</sup>, e<sup>+</sup>e<sup>-</sup>) K<sub>S</sub>, ψ(2S) (→ μ<sup>+</sup>μ<sup>-</sup>) K<sub>S</sub>.



$\sin(2\beta) \equiv \sin(2\phi_1)$  **HFLAV**  
Summer 2023  
PRELIMINARY

$$S(\psi K_S) = 0.717 \pm 0.013 \pm 0.008$$

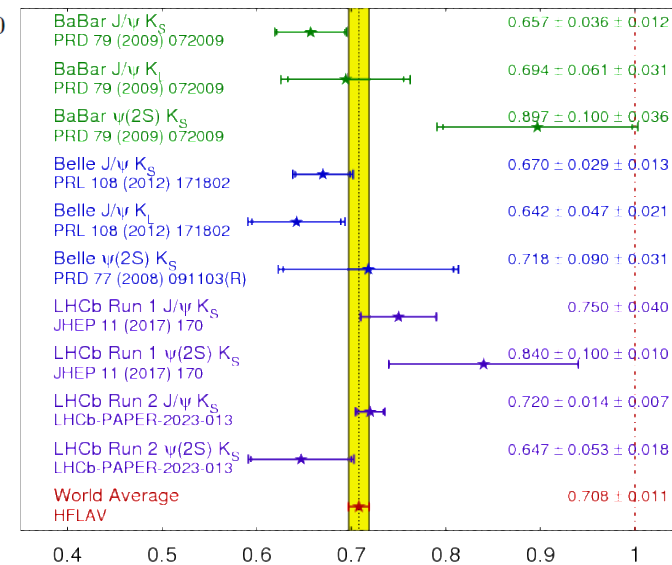
$$C(\psi K_S) = 0.008 \pm 0.012 \pm 0.003$$

statistics dominant

Combined with Run2:  $S(\psi K_S) = 0.724 \pm 0.014$

$$C(\psi K_S) = 0.004 \pm 0.012$$

Most precise results.



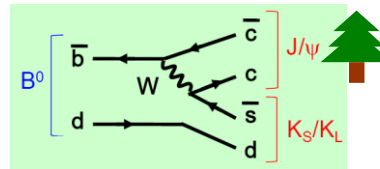
# CPV in $B^0 \rightarrow \eta' K_S$ at Belle II



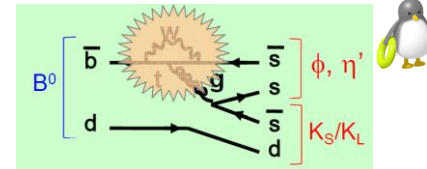
[EPS2023]

- $b \rightarrow s$  penguin process: sensitive to NP
- $S = -\xi \sin(2\phi_1)$  in the SM, but NP contribution can vary S.
- The theoretical uncertainty depends on the final states.  $\eta' K^0$  is one of the cleanest modes.
- $B \rightarrow \eta' K_S$  from Belle II with  $362 \text{ fb}^{-1}$

$b \rightarrow c$  ( $B \rightarrow J/\psi K^0$ )



$b \rightarrow s$  ( $B \rightarrow \eta' K^0$ )

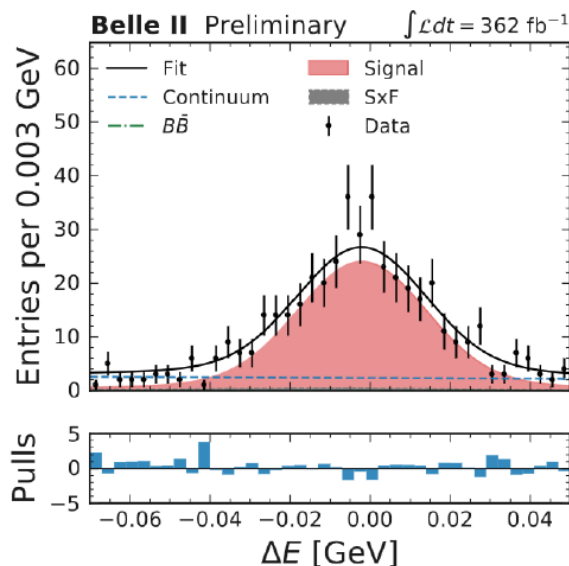


387 M  $B\bar{B}$

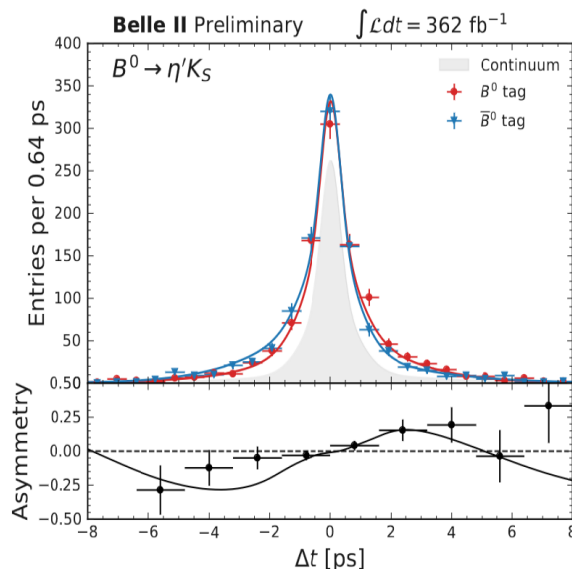
$$S = 0.67 \pm 0.10 \pm 0.04$$

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

( $B \rightarrow \eta' K_L$  or  $\eta \rightarrow \pi^+ \pi^- \pi^0$  modes are not included yet)

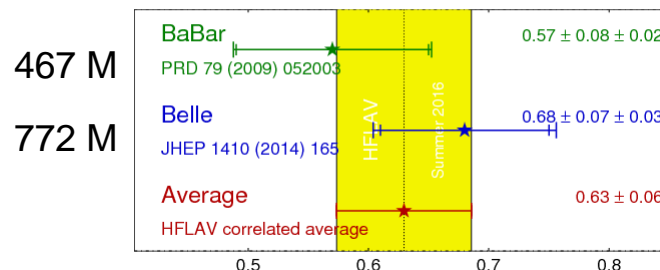


829 ± 35 signal events



$\eta' K^0 S_{CP}$

HFLAV Summer 2016

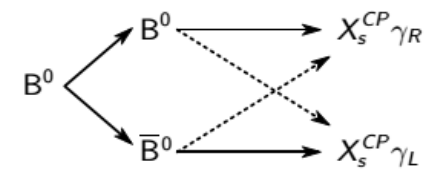
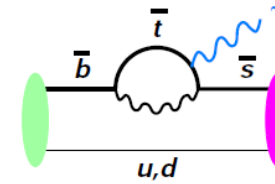




# CPV in $B^0 \rightarrow K_S \pi^0 \gamma$ at Belle II



- SM electroweak is purely left-handed.
  - ✓ Photon from  $b \rightarrow s \gamma$  is almost left-handed.
  - ✓ Right-handed current is a signature of NP.
- No mixed-induced CP violation in the SM in  $b \rightarrow s \gamma$ .
  - ✓  $B^0$  and  $\bar{B}^0$  do not decay to the common final state.
  - ✓ (More correctly)  $S \sim -2(m_s/m_b)\sin(2\phi_1)$

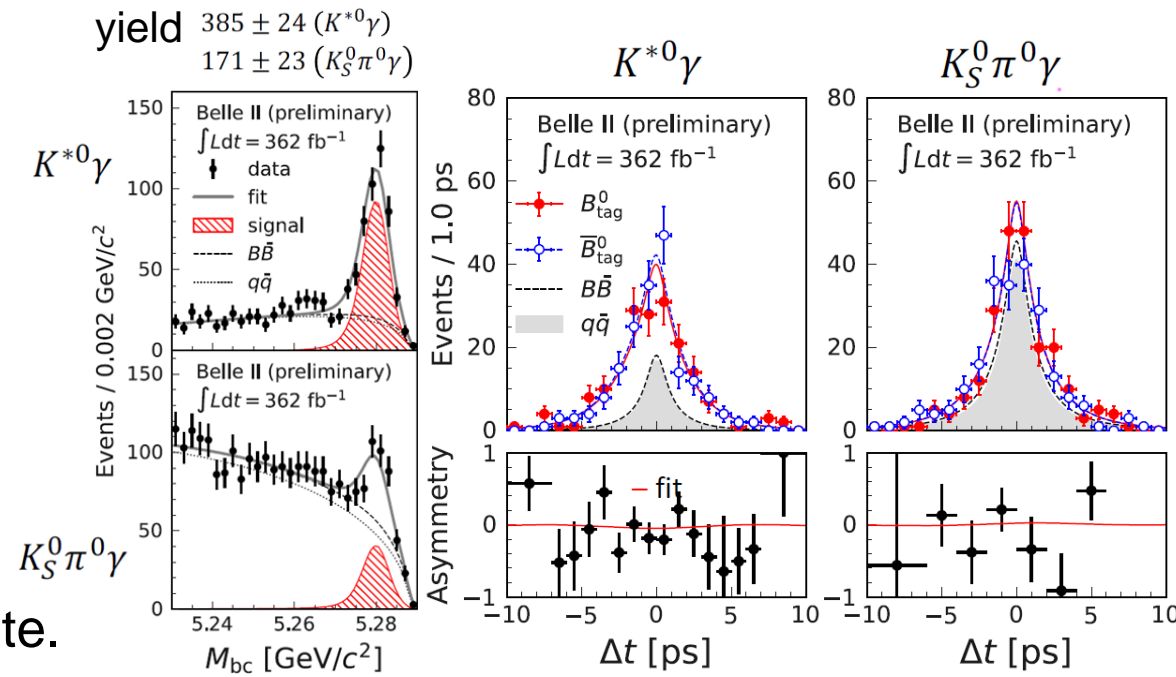


[EPS2023]

- New Belle II result with  $362 \text{ fb}^{-1}$ .
- B vertex from  $K_S$  only.
- Two  $M(K\pi)$  regions:  $K^*$  [0.8,1.0] GeV and the rest of [0.6,1.8] GeV.

$S = 0.00^{+0.27}_{-0.26} \pm 0.03$	$K^{*0} \gamma$
$C = 0.10 \pm 0.13 \pm 0.03$	
• HFLAV: $S = -0.16 \pm 0.22$ $C = -0.04 \pm 0.14$	
$S = 0.04^{+0.45}_{-0.44} \pm 0.10$	$K_S^0 \pi^0 \gamma$
$C = -0.06 \pm 0.25 \pm 0.08$	
• Belle (2006): $S = 0.50 \pm 0.68$ $C = 0.20 \pm 0.39$	

Most precise measurements to date.



# $B_s \rightarrow J/\psi \phi$

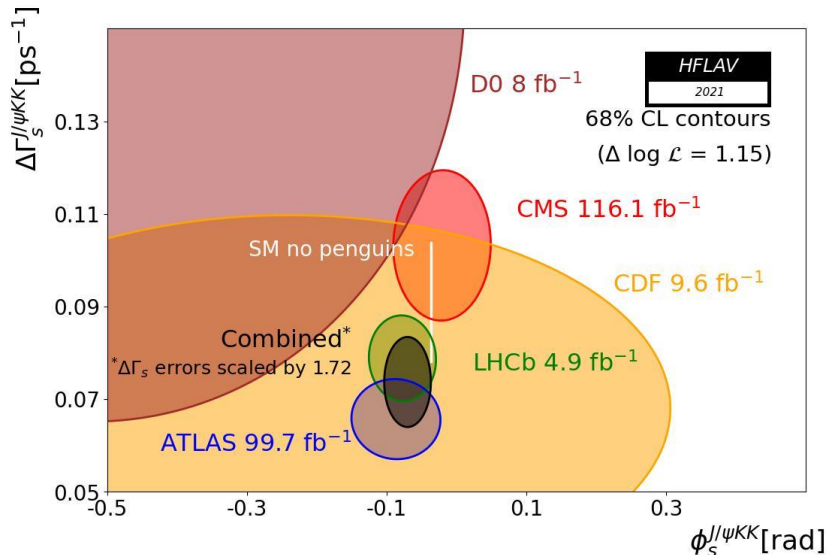
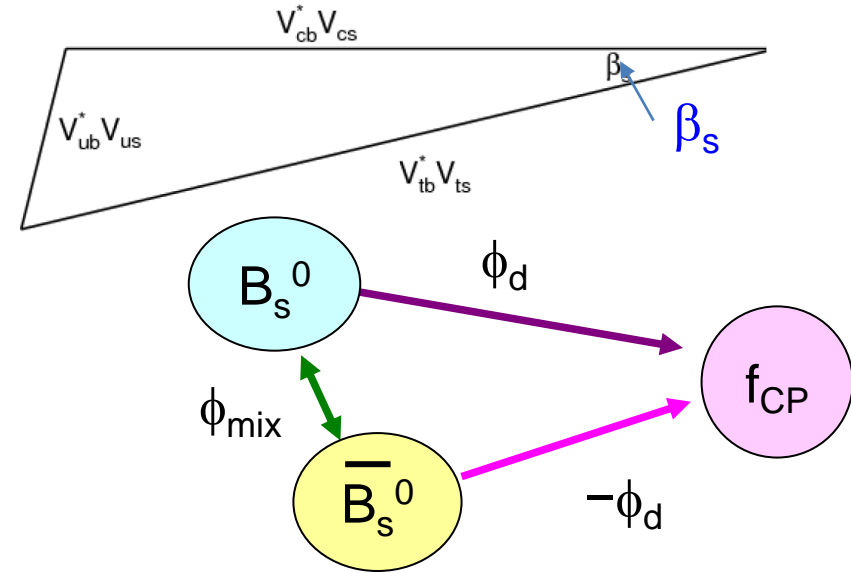
Another combination of the unitarity of the CKM matrix makes a squashed triangle.

$$V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* = 0$$

- $\beta_s$  can be measured in mixing-induced CP violation in  $B_s$  decays like  $B_s \rightarrow J/\psi \phi$ .

$$\phi_s = \phi_{\text{mix}} - 2\phi_d = -2\beta_s \quad (\text{in SM})$$

$$\phi_s = -36.8^{+0.9}_{-0.6} \text{ mrad} \quad (\text{SM})$$



- Excellent time resolution (<100fs) necessary because of fast  $B_s$  oscillation
- Flavor tagging
- Angular distribution to extract CP eigenstate.

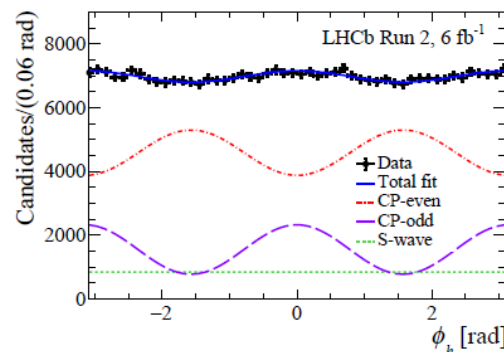
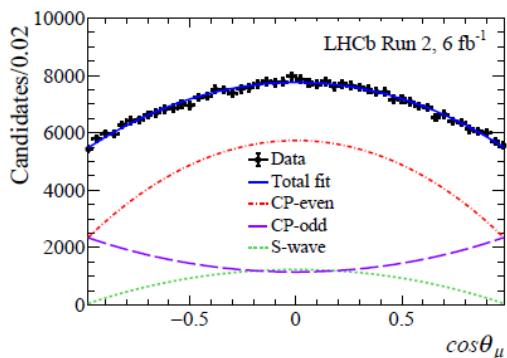
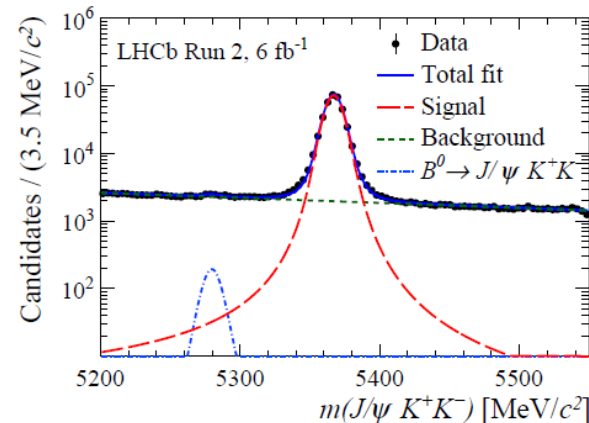
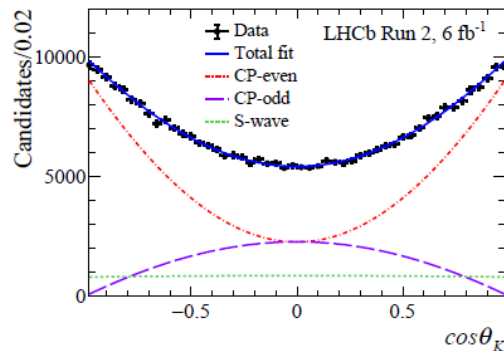
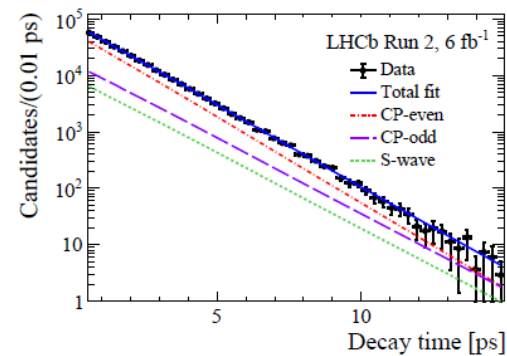
HFLAV  
2021

# $B_s \rightarrow J/\psi \phi$ at LHCb

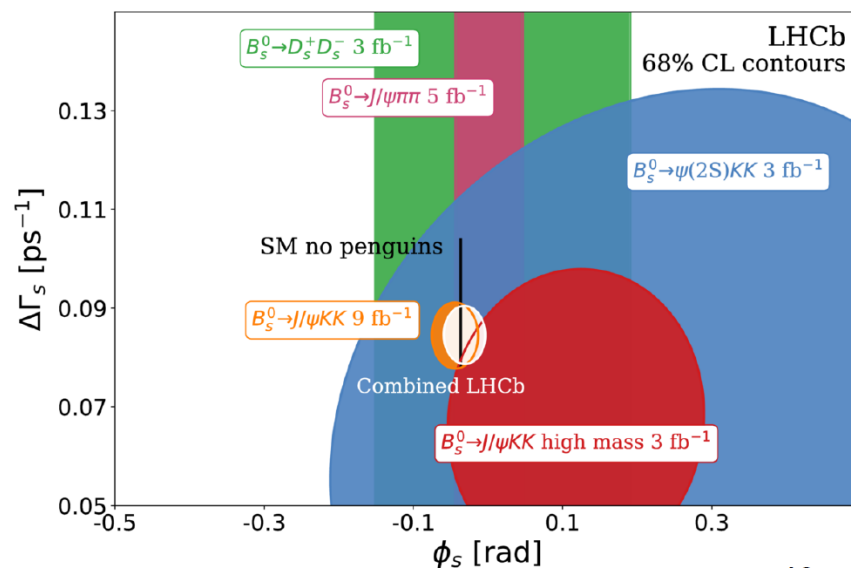


New result from LHCb using Run2 data ( $6 \text{ fb}^{-1}$ ).

[arXiv:2309.09728]

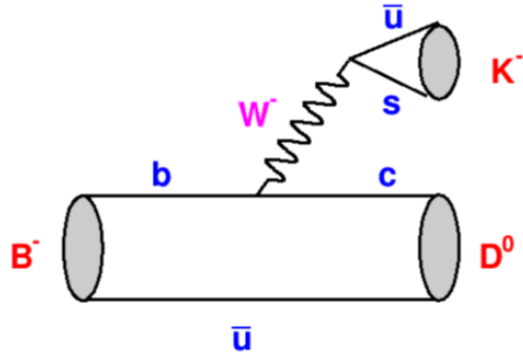


$$\begin{aligned} \phi_s &= -0.039 \pm 0.022 \pm 0.006 \text{ rad} \\ |\lambda| &= 1.001 \pm 0.011 \pm 0.005 \\ \Gamma_s - \Gamma_d &= -0.0056^{+0.0013}_{-0.0015} \pm 0.0014 \\ \Delta\Gamma_s &= 0.0845 \pm 0.0044 \pm 0.0024 \end{aligned}$$



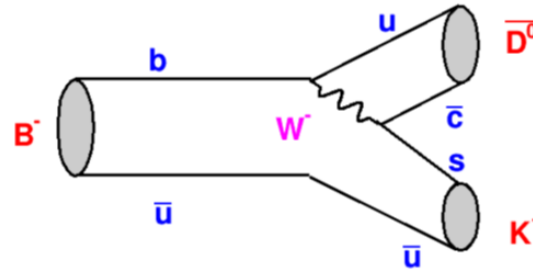
# $\gamma / \phi_3$

- $\gamma / \phi_3$  can be measured using the interference  $B \rightarrow D K$  and  $B \rightarrow \bar{D} K$ .
- ✓ Other modes like  $B \rightarrow D K^*$ ,  $B \rightarrow D \pi$  etc. are



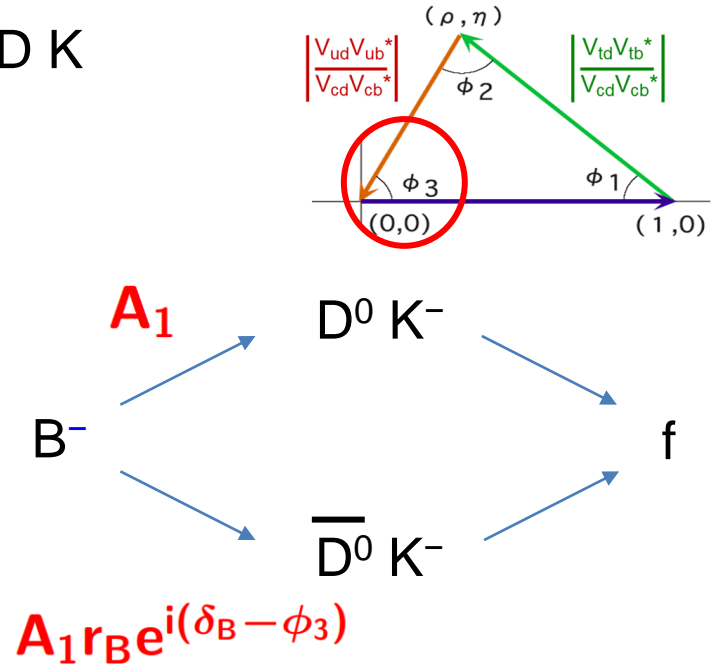
color favored

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



color suppressed

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



- Only tree contributions: theoretically clean.
- Several decay modes (final states) possible to extract  $\gamma / \phi_3$ .
- Amplitude ratio  $r_B$  and strong phase  $\delta_B$  are mode-dependent.
- ✓ sensitivity depends on modes.



- **GLW (Gronau-London-Wyler)** [PLB 253 (1991) 483, PLB 265 (1991) 172]
  - ✓  $B^\pm \rightarrow D_{CP}^0 K^\pm$
  - ✓ Use CP eigenstate of D meson.
- **ADS (Atwood-Dunietz-Soni)** [PRL 78, 3357 (1997), PRD 63. 036005 (2001)]
  - ✓ Enhancement of CP violation by using doubly Cabibbo suppressed decays.
- **BPGGSZ (Bonder-Poluektov-Giri-Grossmann-Soffer-Zupan)** [PRD 68. 054018 (2003)]
  - ✓ 3 (or multi-) body final state.
  - ✓ Different amplitude and strong phase in different region of Dalitz plot.
- **GLS (Grossmann-Ligeti-Soffer)** [PRD 67. 071301 (R) (2003)]
  - ✓ Singly Cabibbo suppressed D decay ( $K_S K \pi$ )

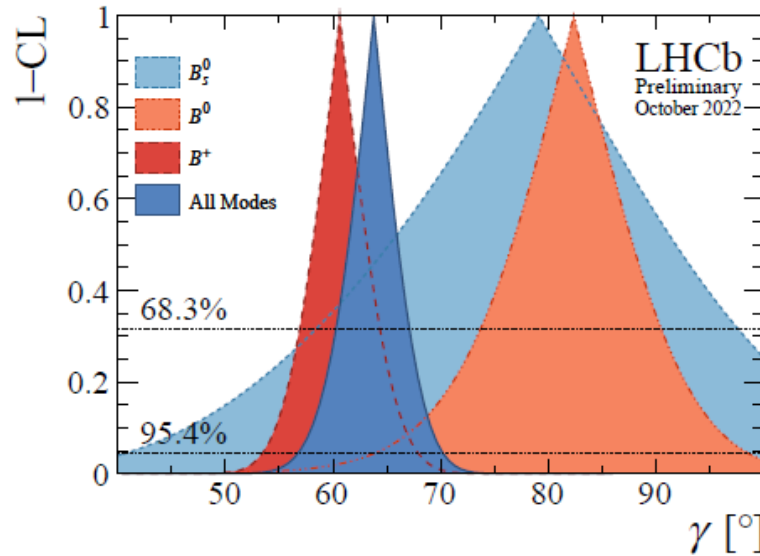
Note) D decay parameters (information on the strong phase) are necessary inputs from CLEO-c, BESIII.

Need improvements by BESIII for more precise measurement of  $\gamma / \phi_3$ .

# LHCb Combined $\gamma$ ( $=\phi_3$ )



B decay	D decay	Ref.	Dataset
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow h^+h^-$	29	Run 1&2
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow h^+\pi^-\pi^+\pi^-$	30	Run 1
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow K^\pm\pi^\mp\pi^+\pi^-$	18	Run 1&2
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow h^+h^-\pi^0$	19	Run 1&2
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow K_S^0 h^+h^-$	31	Run 1&2
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow K_S^0 K^\pm\pi^\mp$	32	Run 1&2
$B^\pm \rightarrow D^*h^\pm$	$D \rightarrow h^+h^-$	29	Run 1&2
$B^\pm \rightarrow DK^{*\pm}$	$D \rightarrow h^+h^-$	33	Run 1&2(*)
$B^\pm \rightarrow DK^{*\pm}$	$D \rightarrow h^+\pi^-\pi^+\pi^-$	33	Run 1&2(*)
$B^\pm \rightarrow Dh^\pm\pi^+\pi^-$	$D \rightarrow h^+h^-$	34	Run 1
$B^0 \rightarrow DK^{*0}$	$D \rightarrow h^+h^-$	35	Run 1&2(*)
$B^0 \rightarrow DK^{*0}$	$D \rightarrow h^+\pi^-\pi^+\pi^-$	35	Run 1&2(*)
$B^0 \rightarrow DK^{*0}$	$D \rightarrow K_S^0\pi^+\pi^-$	36	Run 1
$B^0 \rightarrow D^{\mp}\pi^\pm$	$D^+ \rightarrow K^-\pi^+\pi^+$	37	Run 1
$B_s^0 \rightarrow D_s^\mp K^\pm$	$D_s^+ \rightarrow h^+h^-\pi^+$	38	Run 1
$B_s^0 \rightarrow D_s^\mp K^\pm\pi^\mp$	$D_s^+ \rightarrow h^+h^-\pi^+$	39	Run 1&2
D decay	Observable(s)	Ref.	Dataset
$D^0 \rightarrow h^+h^-$	$\Delta A_{CP}$	24 40 41	Run 1&2
$D^0 \rightarrow K^+K^-$	$A_{CP}(K^+K^-)$	16 24 25	Run 2
$D^0 \rightarrow h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	42	Run 1
$D^0 \rightarrow h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	15	Run 2
$D^0 \rightarrow h^+h^-$	$\Delta Y$	43 46	Run 1&2
$D^0 \rightarrow K^+\pi^-$ (Single Tag)	$R^\pm, (x^\pm)^2, y^\pm$	47	Run 1
$D^0 \rightarrow K^+\pi^-$ (Double Tag)	$R^\pm, (x^\pm)^2, y^\pm$	48	Run 1&2(*)
$D^0 \rightarrow K^\pm\pi^\mp\pi^+\pi^-$	$(x^2 + y^2)/4$	49	Run 1
$D^0 \rightarrow K_S^0\pi^+\pi^-$	$x, y$	50	Run 1
$D^0 \rightarrow K_S^0\pi^+\pi^-$	$x_{CP}, y_{CP}, \Delta x, \Delta y$	51	Run 1
$D^0 \rightarrow K_S^0\pi^+\pi^-$	$x_{CP}, y_{CP}, \Delta x, \Delta y$	52	Run 2
$D^0 \rightarrow K_S^0\pi^+\pi^-$ ( $\mu^-$ tag)	$x_{CP}, y_{CP}, \Delta x, \Delta y$	17	Run 2



[LHCb-CONF-2022-003]

$$\gamma = (63.8^{+3.5}_{-3.7})^\circ$$

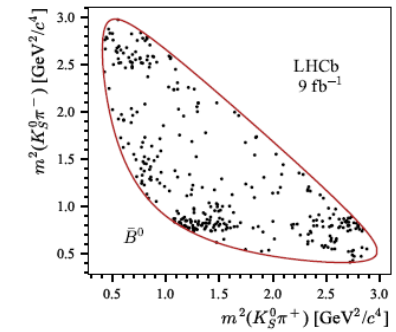
Global fit by CKM fitter

$$\gamma = (65.5^{+1.1}_{-2.7})^\circ$$

- Leading the  $\gamma$  measurement.
- Initial goal of  $4^\circ$  measurement achieved.

- A few more new results came this year (not included above)
  - ✓ e.g.,  $B^0 \rightarrow D K^*$  with  $D \rightarrow K_S h^+h^-$  [arXiv:2309.05514].

$$\gamma = (49^{+22}_{-19})^\circ$$





# Belle + Belle II Combined $\phi_3$ ( $=\gamma$ )

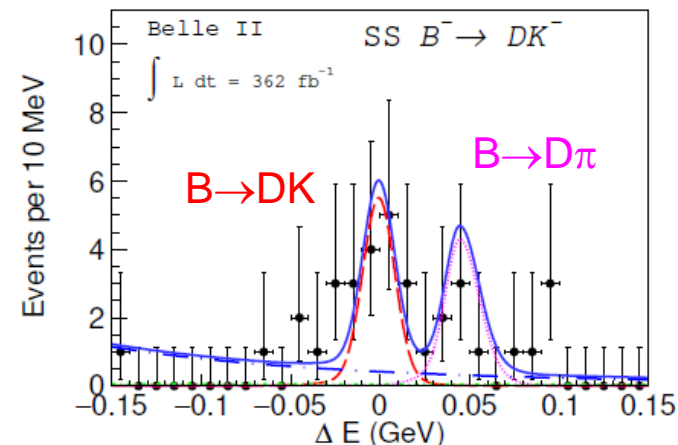


Belle II starts getting new results with Belle + Belle II combined analysis.

- Example:  $B^\pm \rightarrow DK^\pm$ ,  $D\pi^\pm$  with  $D \rightarrow K_S K^\pm \pi^\mp$  (GLS method)
- Belle  $711 \text{ fb}^{-1}$  + Belle II  $362 \text{ fb}^{-1}$
- The results alone do not determine  $\phi_3$ , Combined with other results.

[JHEP09(2023)146]

$$\begin{aligned}
 A_{SS}^{DK} &= 0.055 \pm 0.119 \pm 0.020, \\
 A_{OS}^{DK} &= 0.231 \pm 0.184 \pm 0.014, \\
 A_{SS}^{D\pi} &= 0.046 \pm 0.029 \pm 0.016, \\
 A_{OS}^{D\pi} &= 0.009 \pm 0.046 \pm 0.009, \\
 R_{SS}^{DK/D\pi} &= 0.093 \pm 0.012 \pm 0.005, \\
 R_{OS}^{DK/D\pi} &= 0.103 \pm 0.020 \pm 0.006, \\
 R_{SS/OS}^{D\pi} &= 2.412 \pm 0.132 \pm 0.019,
 \end{aligned}$$



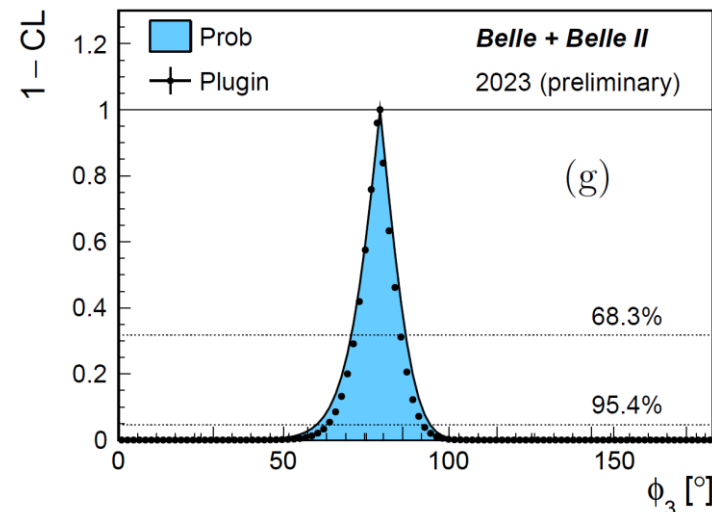
B decay	D decay	Method	Data set (Belle + Belle II)[fb <sup>-1</sup> ]
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0 h^- h^+$	BPGGSZ	711 + 128
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0 \pi^- \pi^+ \pi^0$	BPGGSZ	711 + 0
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0 \pi^0, K^- K^+$	GLW	711 + 189
$B^+ \rightarrow Dh^+$	$D \rightarrow K^+ \pi^-, K^+ \pi^- \pi^0$	ADS	711 + 0
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0 K^- \pi^+$	GLS	711 + 362
$B^+ \rightarrow D^* K^+$	$D \rightarrow K_S^0 \pi^- \pi^+$	BPGGSZ	605 + 0
$B^+ \rightarrow D^* K^+$	$D \rightarrow K_S^0 \pi^0, K_S^0 \phi, K_S^0 \omega,$ $K^- K^+, \pi^- \pi^+$	GLW	210+0

[CKM2023]

Likelihood fit with 60 input observables and 16 auxiliary inputs (external D-decay parameters).

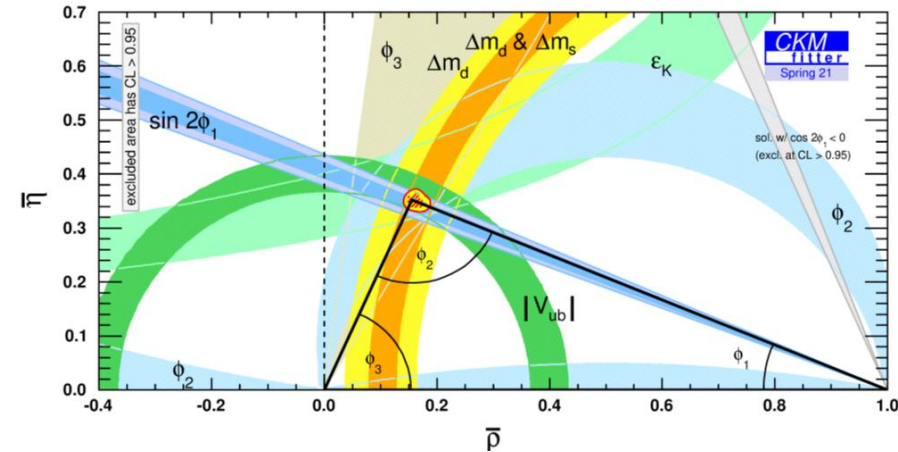
$$\phi_3 = (78.6 \pm 7.3)^\circ \quad \text{Consistent with WA.}$$

Prospect:  $1.5^\circ$  at  $50 \text{ ab}^{-1}$  [arXiv:2203.11349]



## Topics that cannot be covered

- $B_d$  and  $B_s$  mixing
    - ✓ Measurements by LHCb
  - $|V_{ub}|$  and  $|V_{cb}|$  from semi-leptonic B decays
    - ✓ Recent progress in Belle, Belle II
  - Measurement of  $\phi_2 / \alpha$
  - $\phi_s$  from loop diagram
  - .....
- and
- Direct CP violations in charmless B decays
  - .....



# Prospects

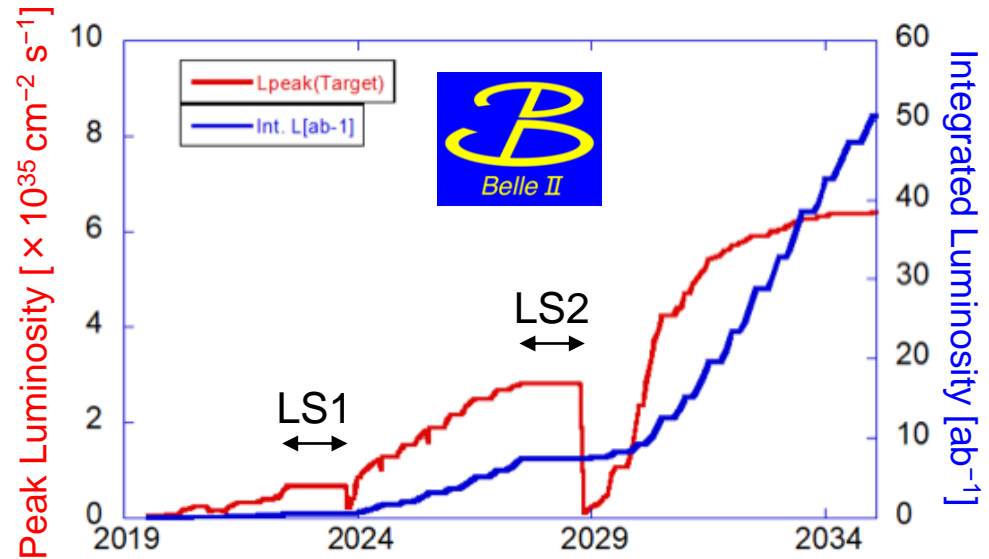


LHCb



Further improvements are expected with one order higher data sample.

- LHCb ( $9 \text{ fb}^{-1} \rightarrow 300 \text{ fb}^{-1}$ )
  - ✓ precision of  $\gamma$  :  $4^\circ \rightarrow 0.35^\circ$
  - ✓ precision of  $\phi_s$  (from  $B_s \rightarrow J/\psi \phi$ ):  $22 \text{ mrad} \rightarrow 4 \text{ mrad}$
- Belle II ( $1 \text{ ab}^{-1} \rightarrow 50 \text{ ab}^{-1}$ )
  - ✓ precision of  $S(\eta'K_S)$  :  $0.08 \rightarrow 0.015$



[LHCb-PUB-2022-012, arXiv:2203.11349]

# Summary and Conclusion



- Precise measurements of Unitarity Triangle provides an interesting test for New Physics.
- LHCb has been improving the measurements.
- Belle II started and has joined the game.
  - ✓ Unique measurements for some modes.

[PTEP (2019) 123C01  
(arXiv:1808.10567)]

