CP violation in heavy flavour decays

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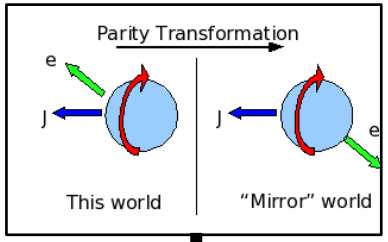
(on behalf of LHCb & Belle II Collaborations)

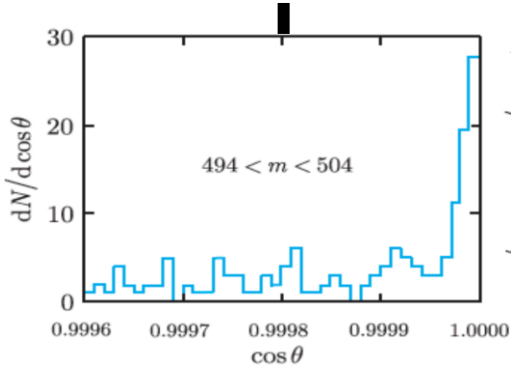
31st International Symposium on Lepton Photon Interactions at High Energies

Melbourne, Australia, 17-21 July 2023

Sixty years of CP violation

P violation
1956, Wu et al.





CP violation in K^0 mixing
1964, Cronin, Fitch et al.

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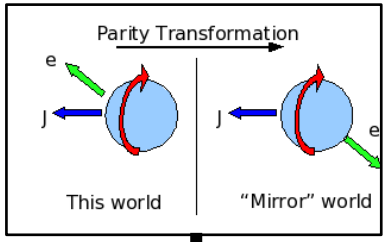
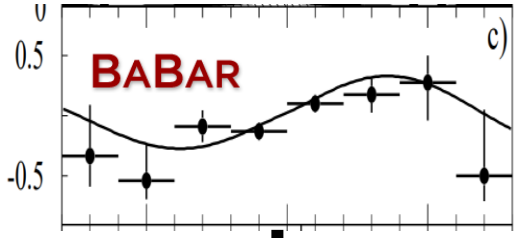
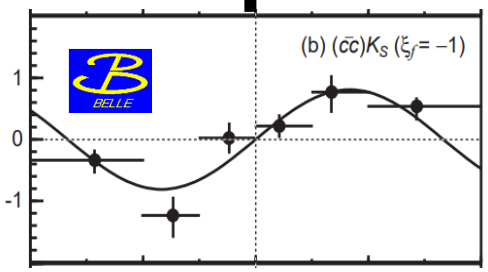
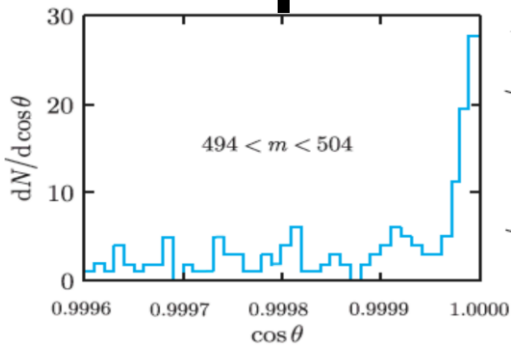


Time-dependent CP violation in B^0 decays
2001, BaBar & Belle







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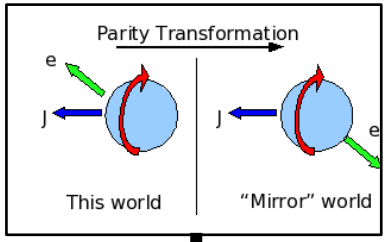

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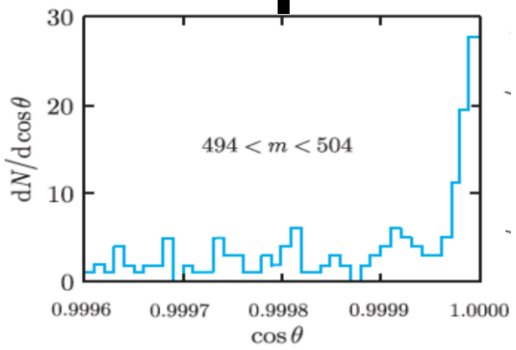

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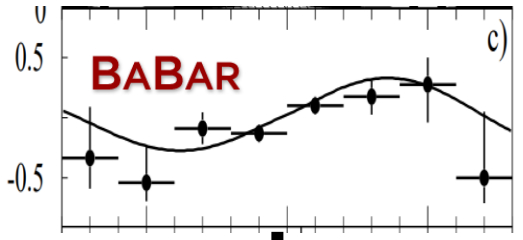
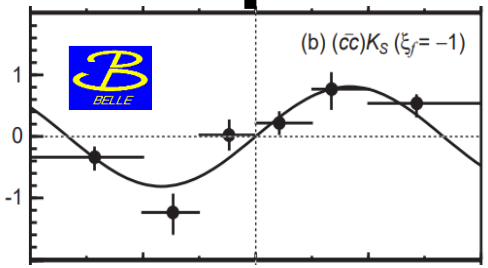
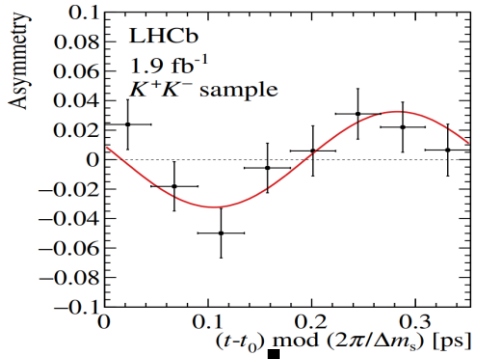




Time-dependent CP violation in B_s^0 decays
2020, LHCb



CP violation in D^0 decay
2019, LHCb

CKM mechanism: the current theory

- **EWSB & diagonalisation of Yukawa mass matrix ⇒ quark mixing matrix**

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\mathcal{L}_{W\pm} = \frac{g}{\sqrt{2}} \left(\bar{U}_L \gamma^\mu W_\mu^+ V_{CKM} D_L + \bar{D}_L \gamma^\mu W_\mu^- V_{CKM}^+ U_L \right)$$

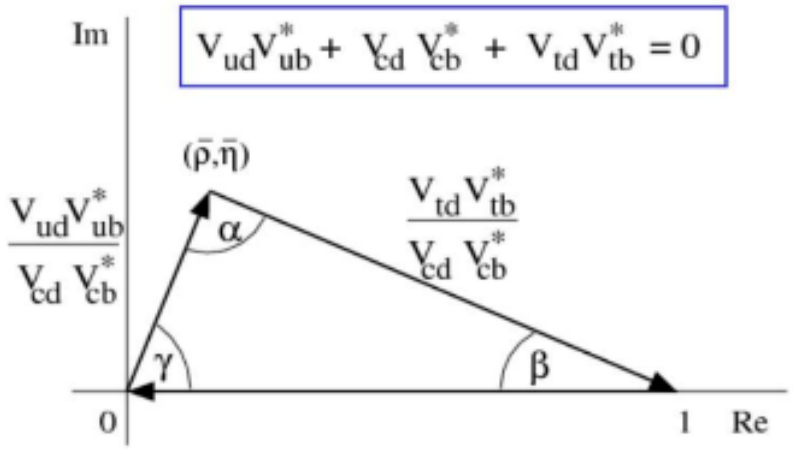
$$V_{CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

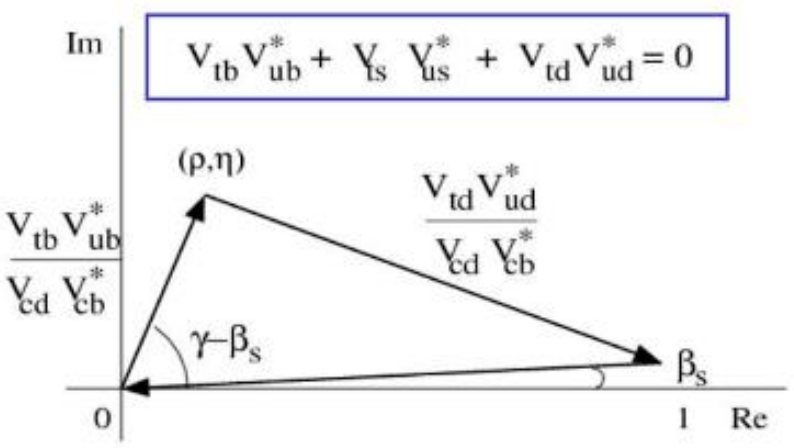
L.Wolfenstein PRL 51 (1983) 1945

(A, λ, ρ, η) to be measured in data

$\eta \neq 0 \Rightarrow$ CP violation

- **Unitarity of the CKM matrix: $V^\dagger V = I$**

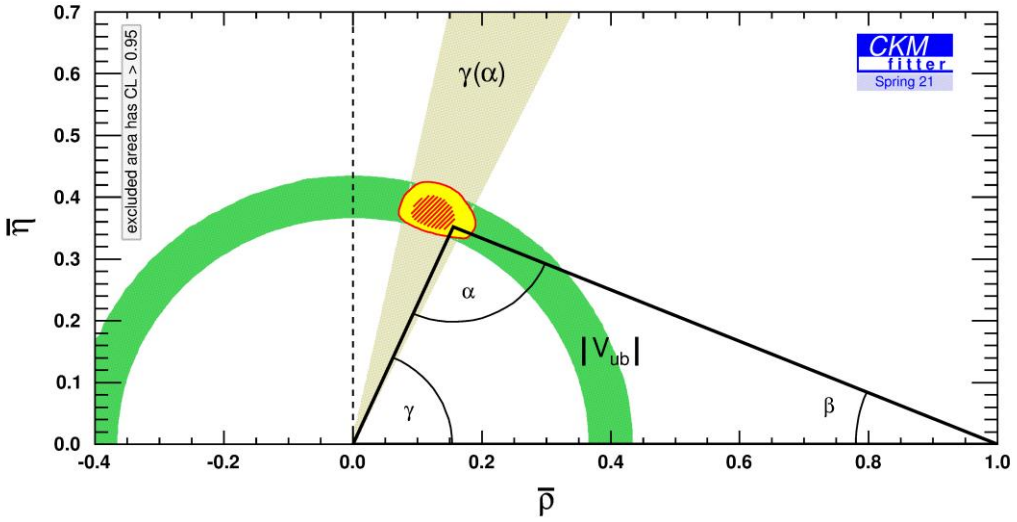


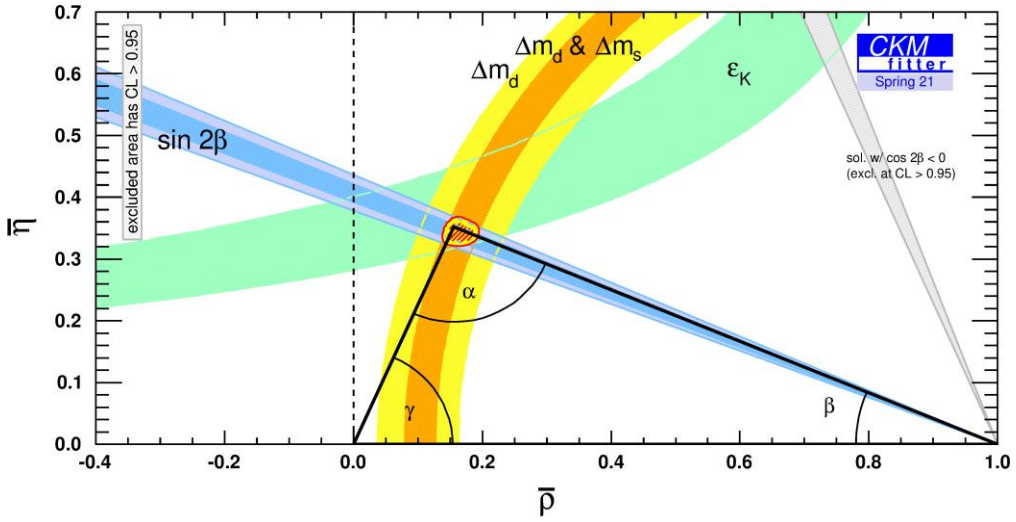


Test of CKM unitarity

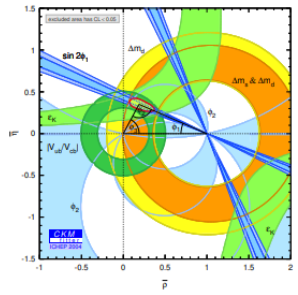
Test the CKM mechanism via over-constraining the four parameters

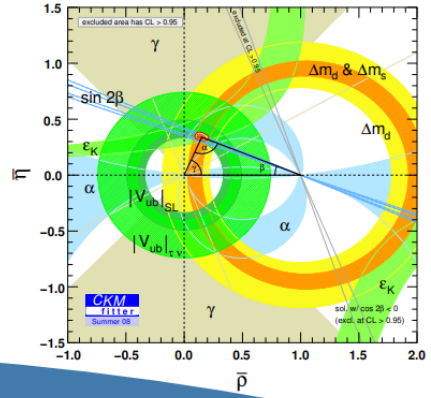
- **Tree quantities**
  - γ from $B \to Dh$
  - V_{ub} from $B \to \rho/\pi l^{-}\bar{\nu}$
  - …
- **Loop quantities**
  - B^0 mixing phase 2β
  - B mixing frequencies Δm_d & Δm_s
  - CPV in kaon mixing ϵ_K
  - …

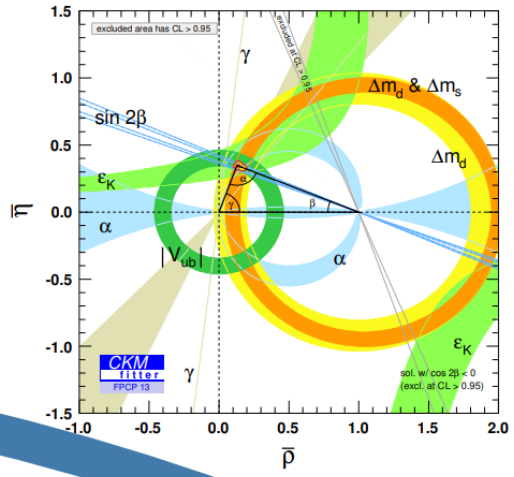


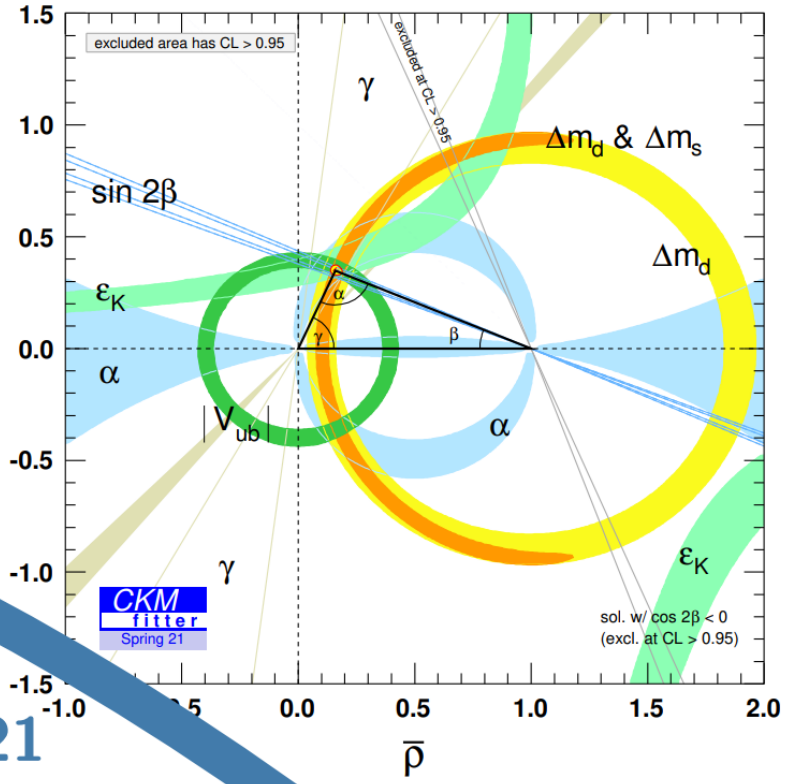


Great successes but …









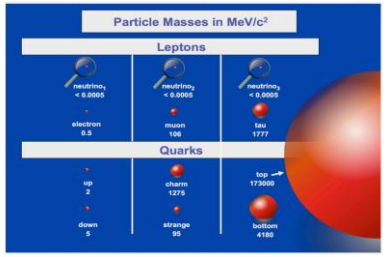
2004

2008

2013

2021

2023



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

Origin?

Selected highlights for today

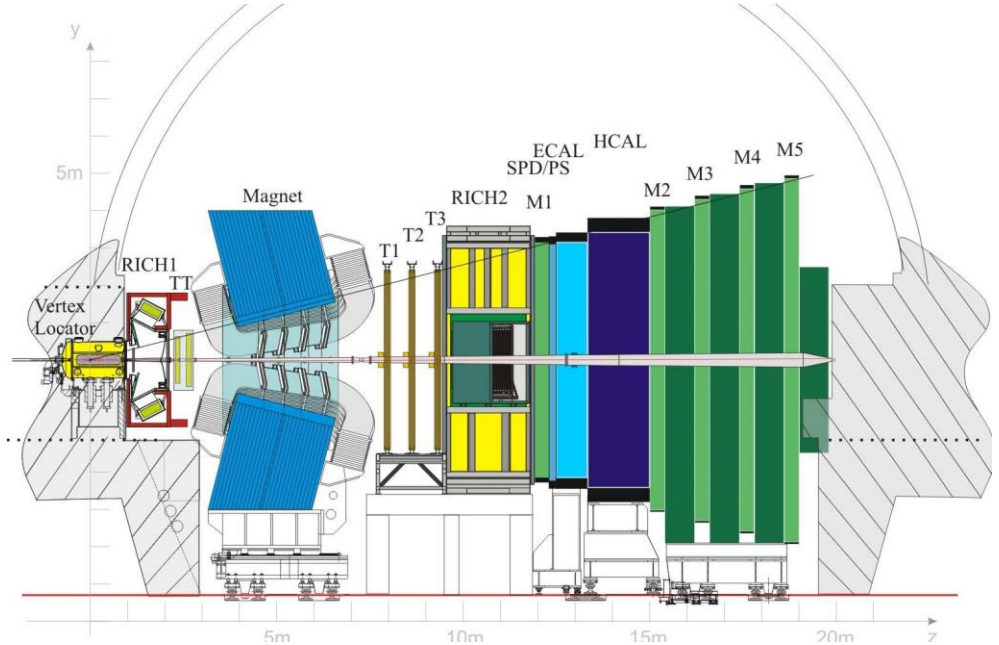
- Significant improvements of β, β_s, γ by LHCb
- Belle II early measurements of β, γ, α
- Intriguing results in direct CP violation ($B \to 3h, B \to K\pi, D \to hh$)

Apologize for the biased selection of topics due to limited time.

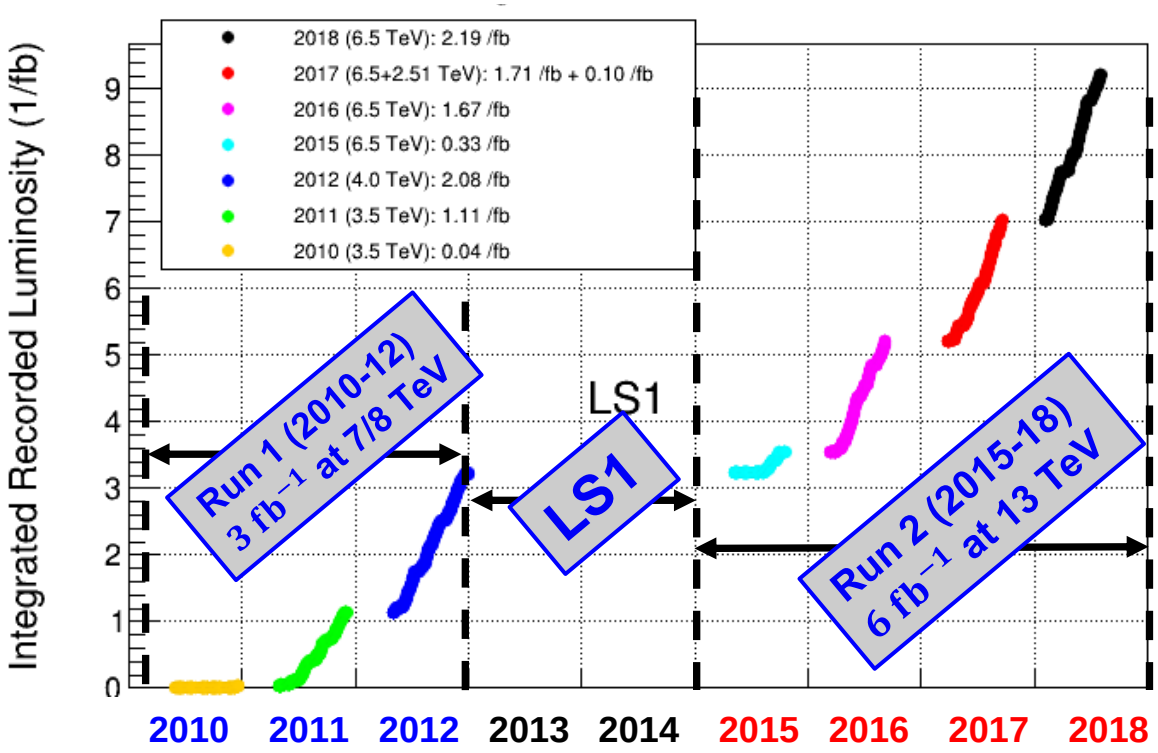
For a complete picture, see LHCb and Belle II talks in parallel sessions

- Charmless b-hadron decays at LHCb, Rongrong Song, 07/17
- Measurements of the CKM angle gamma at LHCb, Fidan Suljik, 07/18
- Mixing and CPV in charm decays at LHCb, Tom Hadavizadeh, 07/18
- Recent Belle II results on time-dependent CP violation and charm physics, Michele Verones, 07/18
- Recent Belle II results on hadronic B decays, Xiaodong Shi, 07/18

LHCb experiment



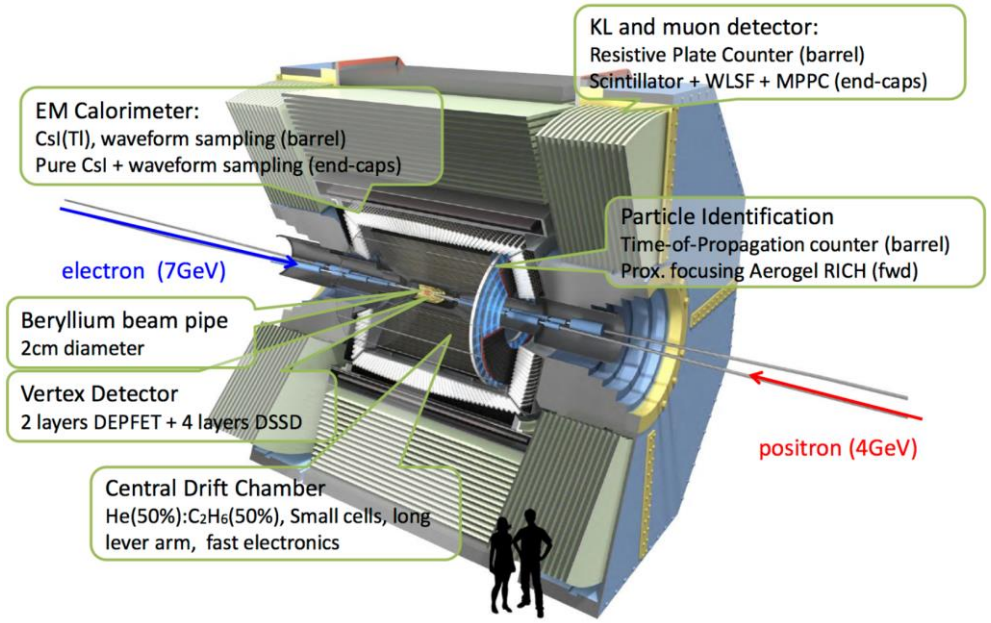
- Flavour physics experiment at LHC
- Unique strength to study all b and c hadron species, particularly B_s^0
- 9 fb^{-1} @ 7, 8, 13 TeV

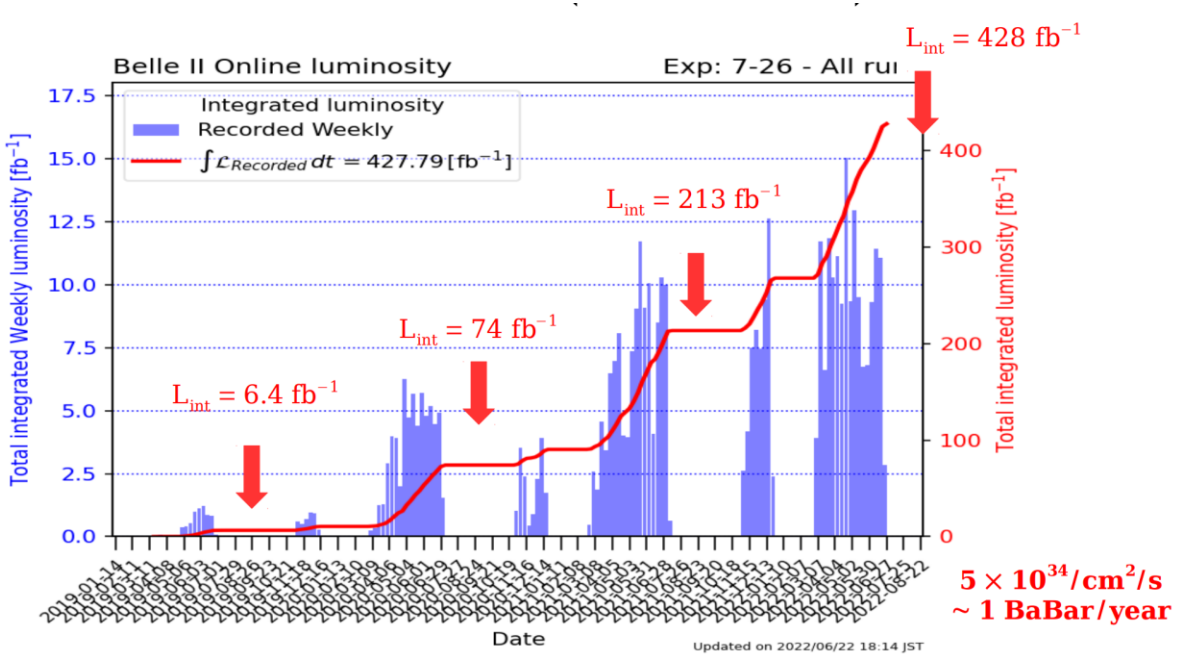


Results shown today based on full Run1 and Run2 data samples

JINST 3 (2008) S08005

Belle II experiment



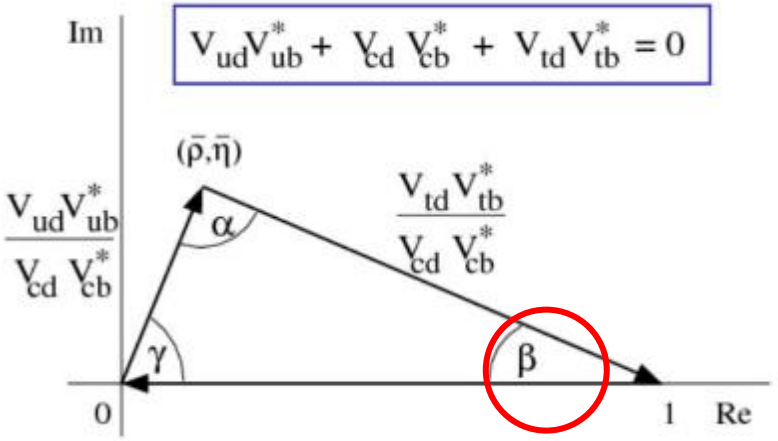


- SuperB factory at SuperKEKB
- Unique strength to study final states with neutrinos and neutral particles
- 362 fb^{-1} @ $\Upsilon(4S)$ for study of $B^0, B^{\pm}$

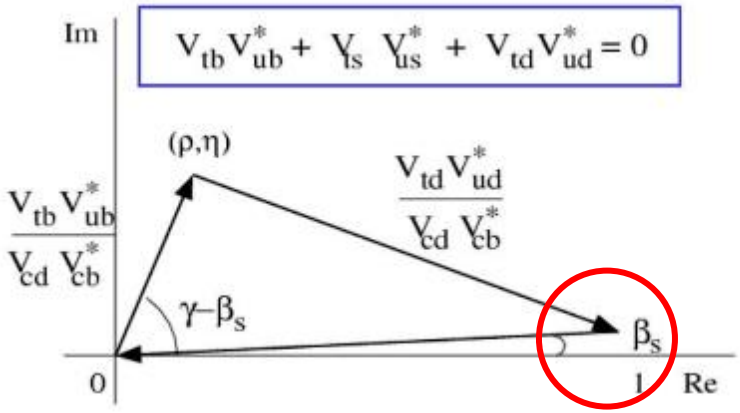
Results shown today mainly based on data taken before 2022

arXiv:1011.0352

Time-dependent CP violation in beauty



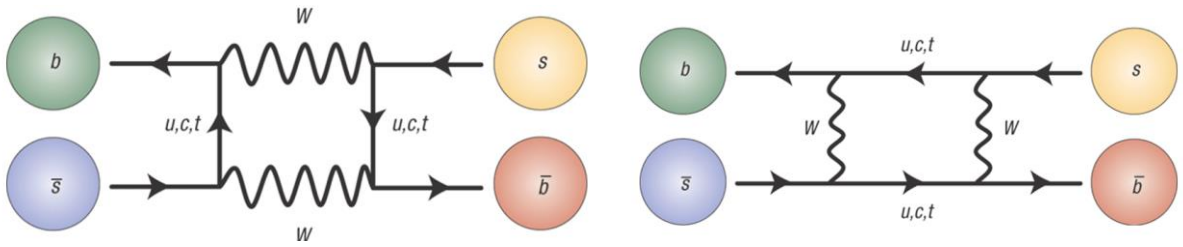
$$\phi_d = 2\beta^{\mathrm{eff}}$$



$$\phi_s = -2\beta_s^{\mathrm{eff}}$$

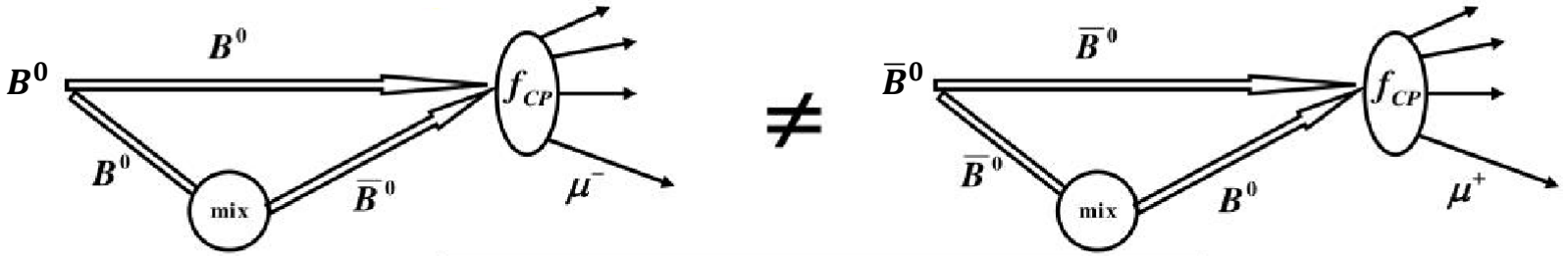
Neutral B mixing and CPV

- Neutral B mesons: $B^0 = (\bar{b}d)$ $\bar{B}^0 = (b\bar{d})$ $B_s^0 = (\bar{b}s)$ $\bar{B}_s^0 = (b\bar{s})$
- $B_q^0 - \bar{B}_q^0$ $(q = d, s)$ oscillation



$$B_L = p|B_q\rangle + q|\bar{B}_q\rangle$$
$$B_H = p|B_q\rangle - q|\bar{B}_q\rangle$$
$$\Delta m_q = m_H - m_L,\ \Delta\Gamma_q = \Gamma_L - \Gamma_H$$

- CPV in interference of B_q^0 decay to CP eigenstate with and w/o mixing



$$\Gamma(B^0 \to f_{CP}) \neq \Gamma(\bar{B}^0 \to f_{CP})$$

Measuring time-dependent (TD) CPV

$$A_{CP}(t) = \frac{\Gamma\left(\bar{B}_q^0(t) \to f_{CP}\right) - \Gamma\left(B_q^0(t) \to f_{CP}\right)}{\Gamma\left(\bar{B}_q^0(t) \to f_{CP}\right) + \Gamma\left(B_q^0(t) \to f_{CP}\right)} = \frac{-C_f \cos\left(\Delta m_q t\right) + S_f \sin\left(\Delta m_q t\right)}{\cosh\frac{\Delta\Gamma_q t}{2} - D_f \sinh\frac{\Delta\Gamma t}{2}}$$

$$\lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f} = \eta_f \frac{q}{p}\frac{\overline{A}_{\bar{f}}}{A_f}, \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \quad S_f = \frac{2\Im\lambda_f}{1+|\lambda_f|^2}, \quad D_f = \frac{2\Re\lambda_f}{1+|\lambda_f|^2}$$

$S_f \neq 0$: mixing induced CPV

η_f: CP eigen-value, affecting sign of S_f

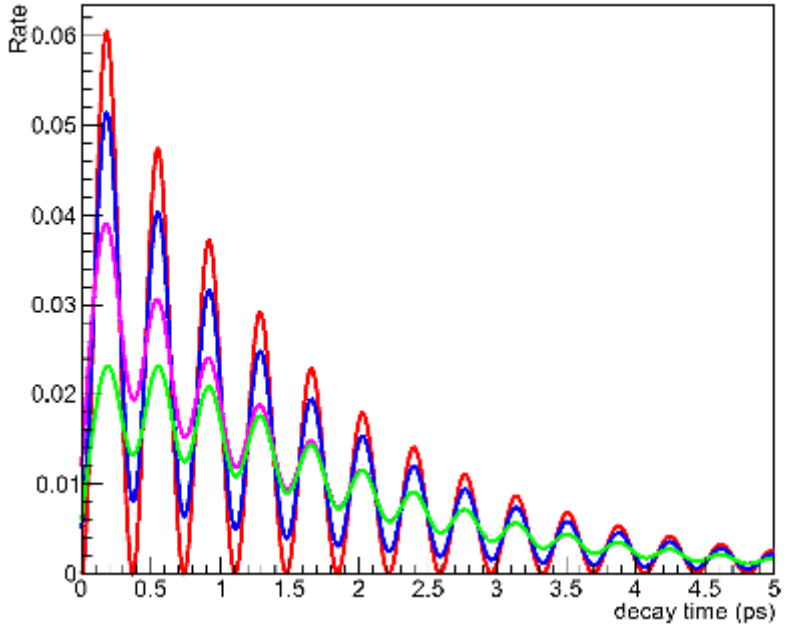
$C_f \neq 0$: direct CPV in decay

Requirements on experiments

- Identify the initial flavour B or $\bar{B}$
- Reconstruct the proper decay time t
- Understand experimental dilutions on S_f and C_f

Experimental effects

$\Delta m_s = 17.7\ \mathrm{ps}^{-1}$
$\sigma_t = 50\ \mathrm{fs}$
$\omega = 0.2$
$\epsilon(t) = 1/(1+\exp(-2t))$



- **Time resolution σ_t**

$$S \rightarrow e^{-\frac{(\Delta m \sigma_t)^2}{2}} S = D_{\mathrm{time}} S$$

D_{time} ~0.7 for $\Delta m_s = 17.7\ \mathrm{ps}^{-1}$ with $\sigma_t = 50$ fs
~0.7 for $\Delta m_d = 0.5\ \mathrm{ps}^{-1}$ with $\sigma_t = 1.5$ ps

- **Wrong tag probability ω**

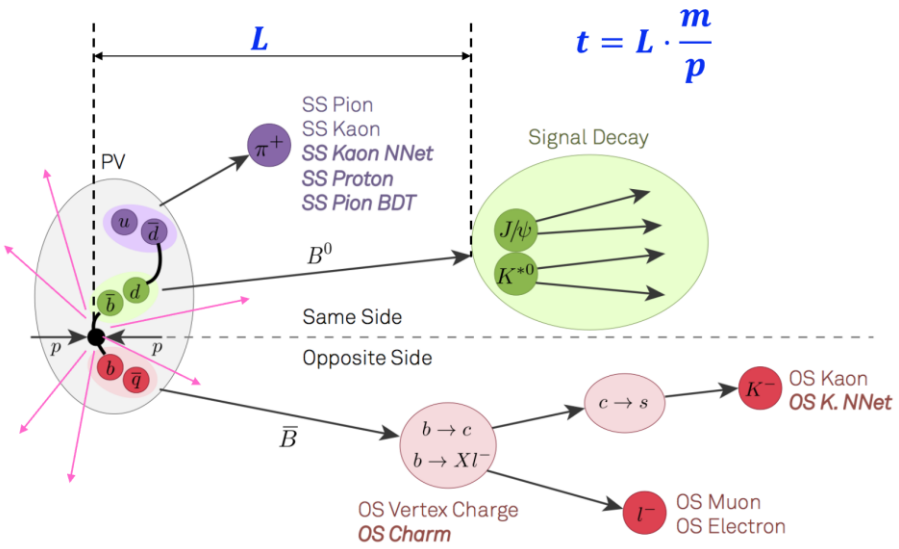
$$S \rightarrow (1-2\omega) S$$

- **Decay-time dependent efficiency $\epsilon(t)$**

$$P(t) \rightarrow \epsilon(t)\, P(t)$$

Obtain info on σ_t, ω and $\epsilon(t)$ from data using control channels

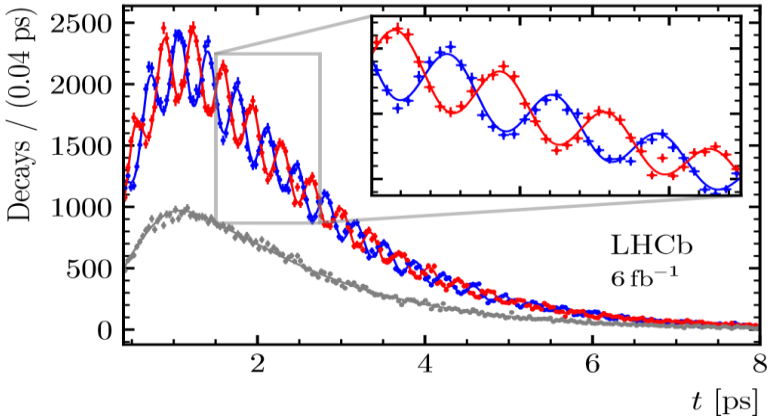
LHCb method for TD study



- Flavour tagging: info from other B & fragmentation particles
  $\epsilon_{\text{tag}}(1-2\omega)^2 \sim 5\%$
- Large boost from pp collision
  $\beta\gamma \sim 10,\ L \sim 1\ \text{cm}$
- Silicon vertex system
  $\sigma_t \sim 45\ \text{fs}$

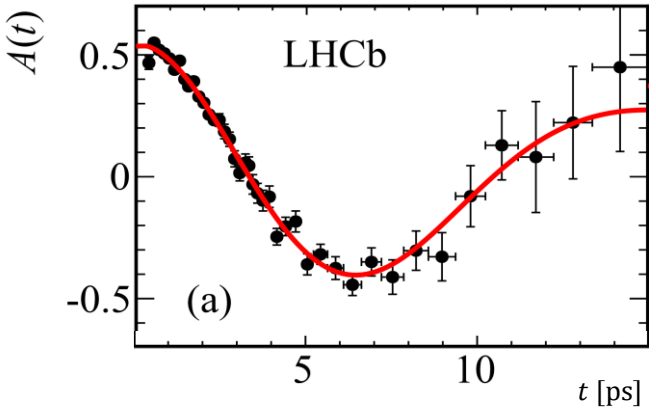
Int. J. Mod. Phys. A30 (2015) 1530022

$B_s^0 \to D_s^- \pi^+$ Nature Physics 18 (2022) 1-5



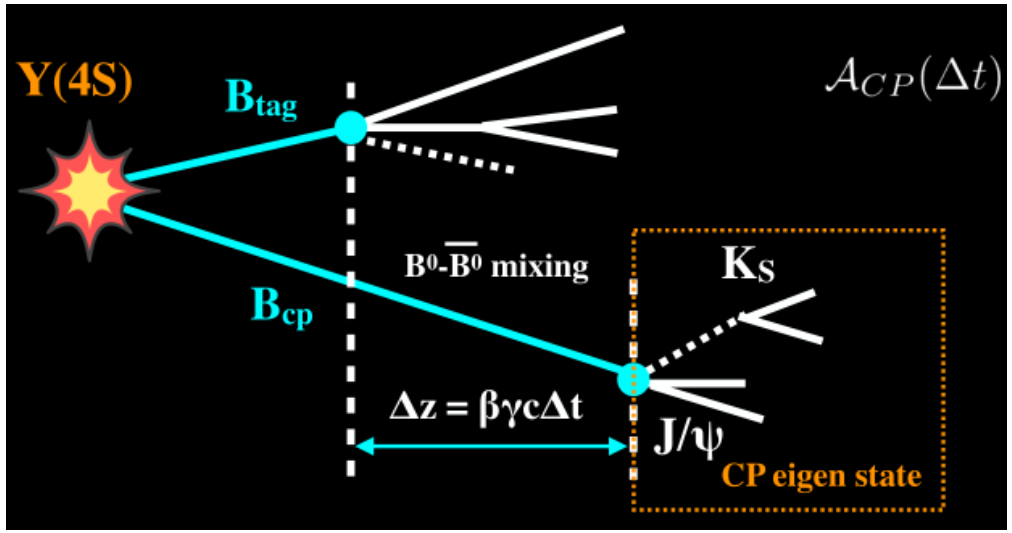
$\Delta m_s = 17.7656 \pm 0.0057(\text{comb})\ \text{ps}^{-1}$

$B_d^0 \to D^{(*)-} \mu^+ \nu$ EPJC 76 (2016) 412



$\Delta m_d = 0.5050 \pm 0.0021(\text{stat}) \pm 0.0010(\text{syst})\ \text{ps}^{-1}$

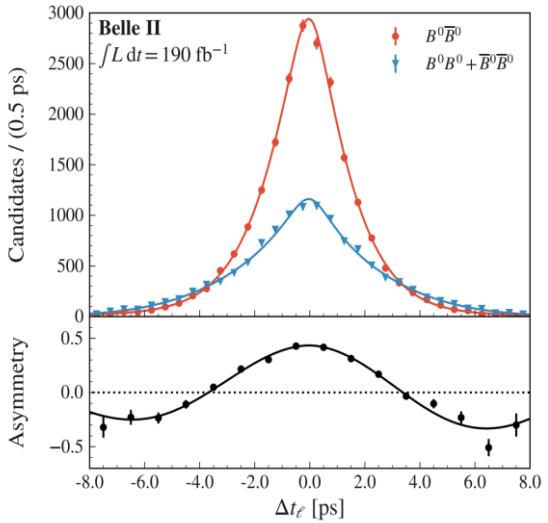
Belle II method for TD study



- Flavour tagging: info from other B
  $\epsilon_{\text{tag}}(1-2\omega)^2 \sim 30\%$
- Asymmetric e^+e^- collision
  $\beta\gamma = 0.28,\ \Delta z \sim 200\ \mu\text{m}$
- Silicon vertex detector
  $\sigma_t \sim 1.5$ ps

arXiv: 1808.10567

$B^0_d \to D^{(*)-}\pi^+$



PRD 107 (2023) L091102

$\Delta m_d = 0.516 \pm 0.008 \pm 0.005\ \text{ps}^{-1}$
$\tau_{B^0} = 1.499 \pm 0.013 \pm 0.005$ ps

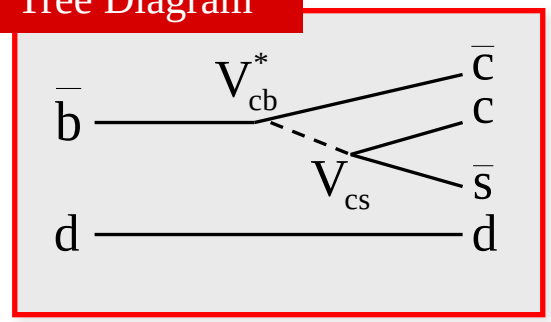
Belle: $\Delta m_d = 0.509 \pm 0.004 \pm 0.005\ \text{ps}^{-1}$

B^0 mixing phase $\phi_d = 2\beta^{\mathrm{eff}}$

B factory flagship!

Tree-dominated $b \to c\bar{c}s$ processse (e.g. $B^0 \to J/\psi K_S^0$)

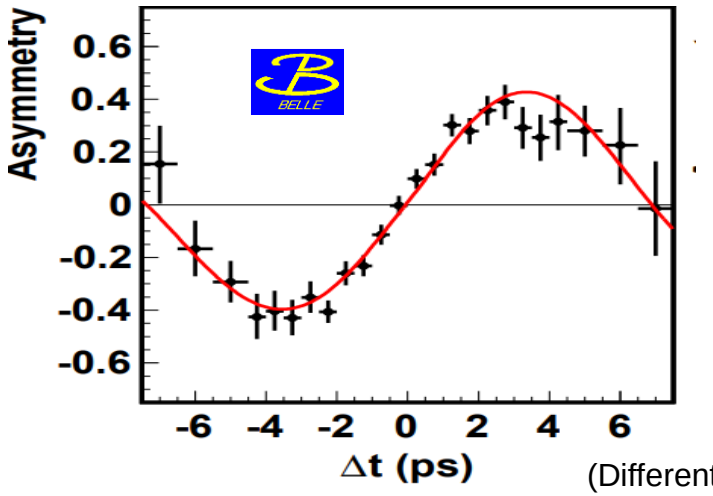
Tree Diagram

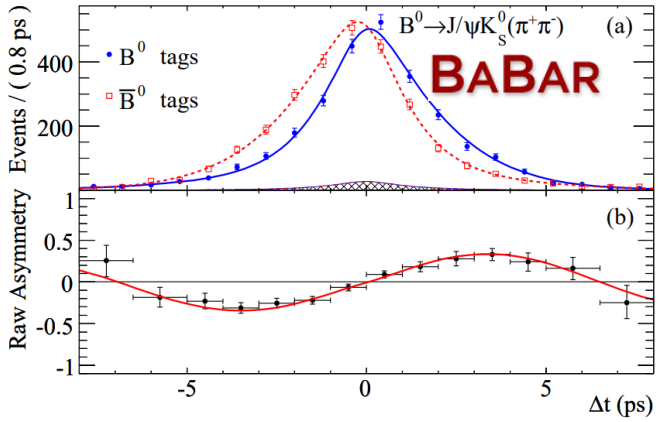


$$\lambda_f = \frac{q}{p}\frac{\bar{A}}{A} = \eta_f e^{-2i\beta}$$
$$S_f = -\eta_f \sin 2\beta$$
$$C_f = 0$$

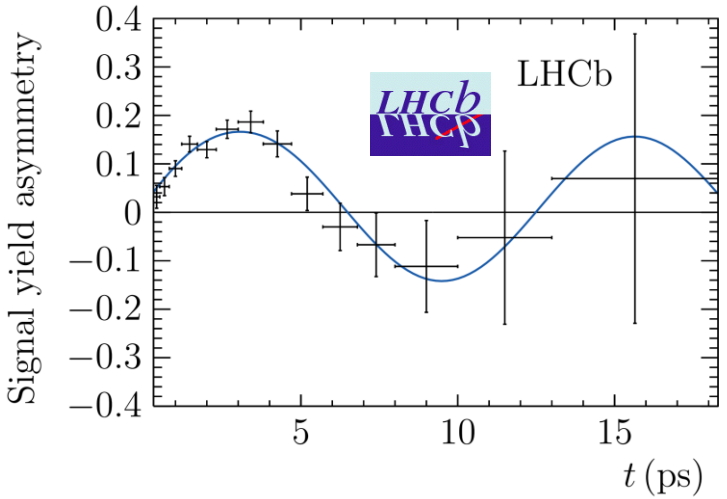
$$A_{CP}(t) = -\eta_f \sin 2\beta \sin(\Delta m_d t)$$

- Belle: $\sin 2\phi_1 = 0.667 \pm 0.023 \pm 0.012$
  PRL 108 (2012) 171802
- BaBar: $\sin 2\beta = 0.687 \pm 0.028 \pm 0.012$
  PRD 79 (2009) 072009
- LHCb Run 1: $\sin 2\beta = 0.760 \pm 0.034$
  PRL 115 (2015) 031601, JHEP 11 (2017) 170





(Different sign convention than LHCb)



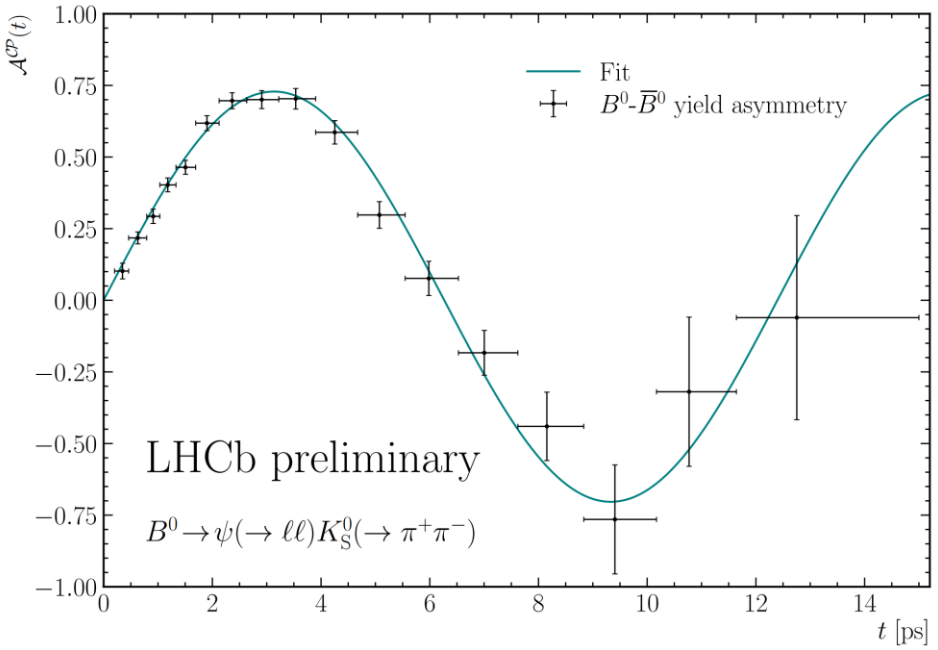
LHCb Run2 update of $\sin 2\beta$

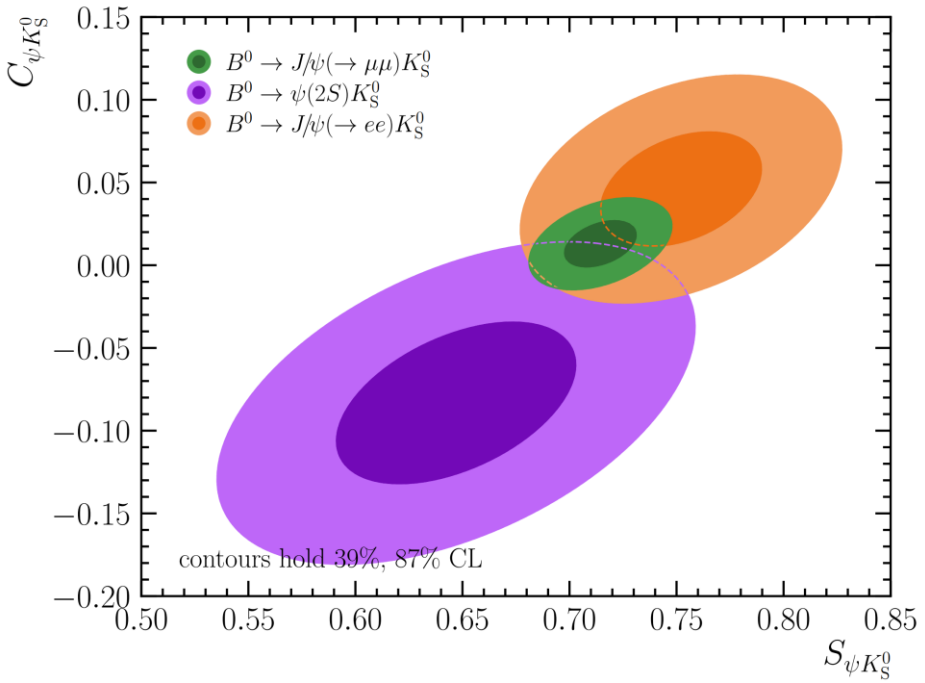
LHCb-paper-2023-013
in preparation

- Three CP-odd $b \to c\bar{c}s$ modes
  - $B^0 \to J/\psi(\to \mu\mu)K_S^0$ (~306k signals)
  - $B^0 \to J/\psi(\to ee)K_S^0$ (~24k signals)
  - $B^0 \to \psi(2S)K_S^0$ (~43k signals)

- New LHCb results

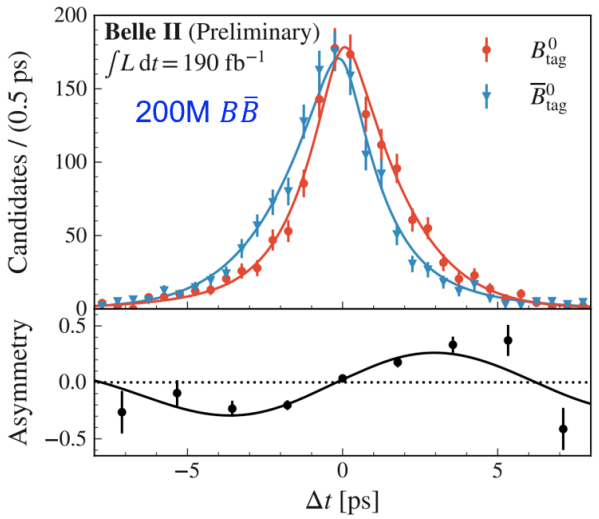
Run2	$\sin 2\beta = 0.716 \pm 0.013 \pm 0.008$ $C = 0.012 \pm 0.012 \pm 0.003$
Run 1	$\sin 2\beta = 0.760 \pm 0.034$
Run1+2	$\sin 2\beta = 0.724 \pm 0.014$



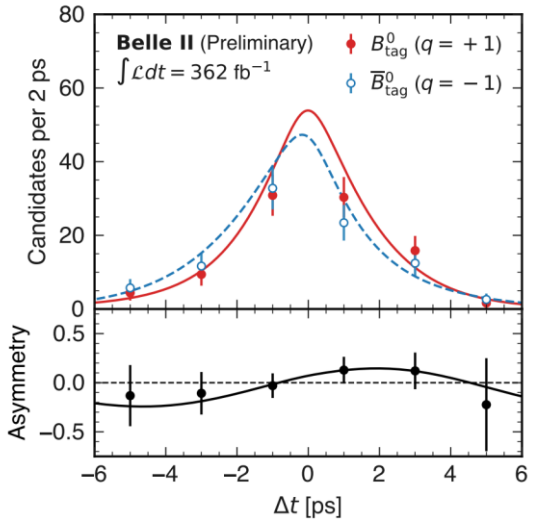


Belle II results of $\sin 2\beta$

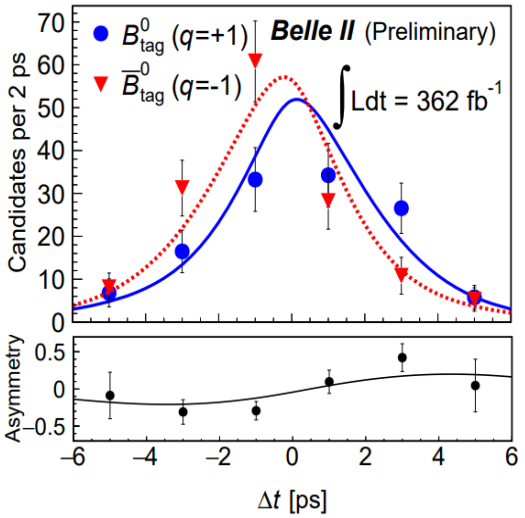
$B^0 \to J/\psi K_S^0$



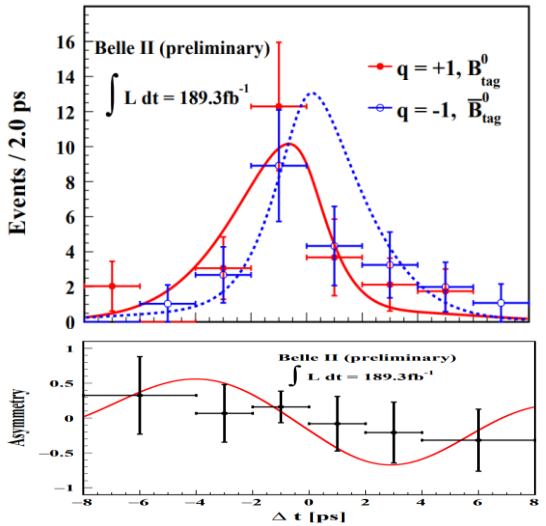
$B^0 \to \phi K_S^0$



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



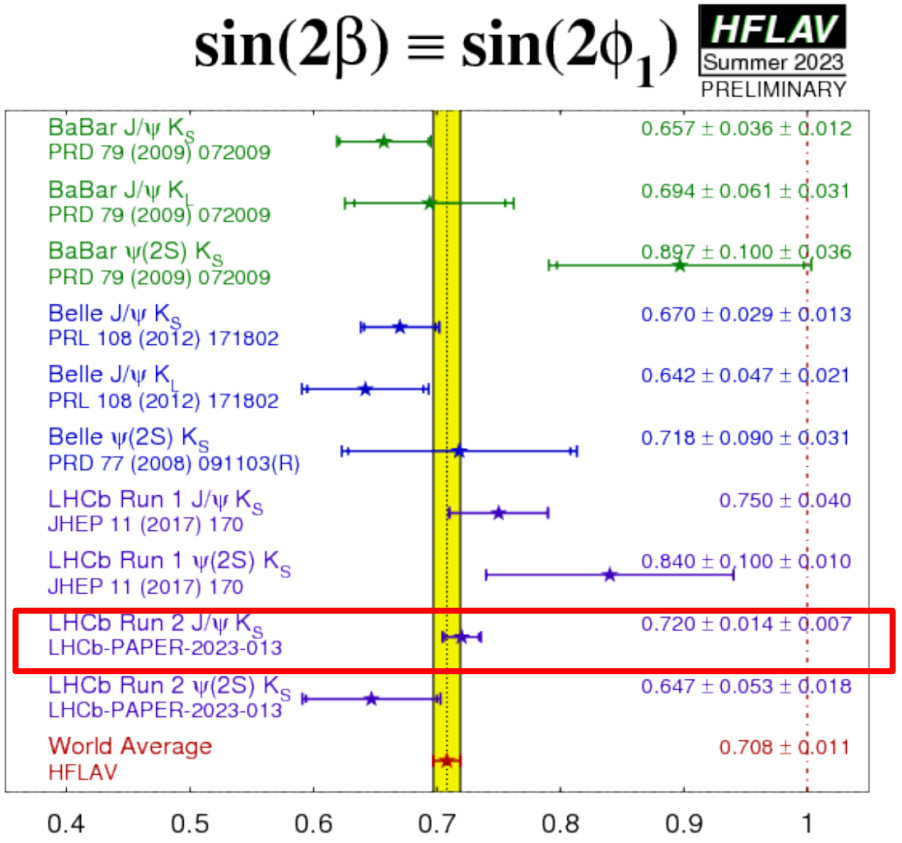
$B^0 \to K_S^0 K_S^0 K_S^0$

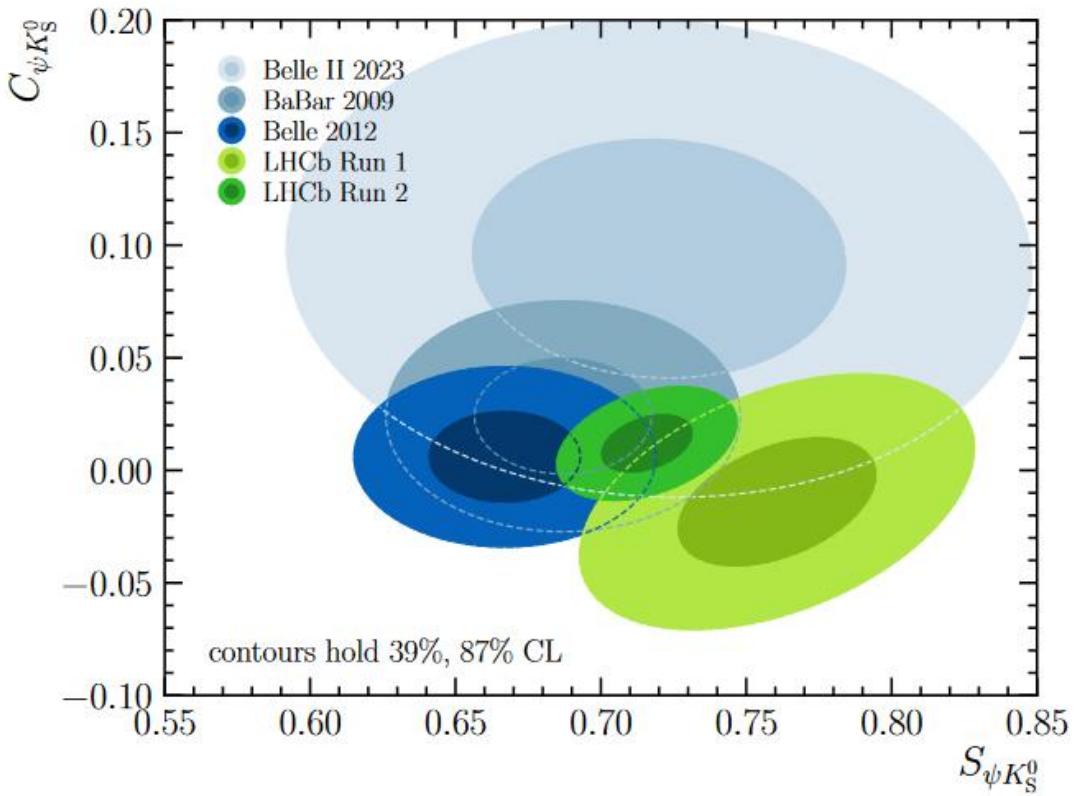


Type	Mode	$\sin 2\phi^{\text{eff}} = -\eta_f S$	$A = -C$	Ref.
$b \to c\bar{c}s$	$B^0 \to J/\psi K_S^0$	$0.720 \pm 0.062 \pm 0.016$	$0.094 \pm 0.044\ ^{+0.042}_{-0.017}$	arXiv:2302.12898
$b \to s\bar{s}s$	$B^0 \to \phi K_S^0$	$0.54 \pm 0.25^{+0.06}_{-0.08}$	$0.31 \pm 0.20 \pm 0.05$	arXiv:2307.02802
$b \to s\bar{d}d$	$B^0 \to K_S^0 \pi^0$	$0.74^{+0.20}_{-0.23} \pm 0.04$	$0.04^{+0.15}_{-0.14} \pm 0.05$	arXiv:2305.07555
$b \to s\bar{d}d$	$B^0 \to K_S^0 K_S^0 K_S^0$	$1.86^{+0.91}_{-0.46} \pm 0.09$	$-0.22^{+0.30}_{-0.27} \pm 0.04$	arXiv:2209.09547

Belle: $\sin 2\phi_1 = 0.667 \pm 0.023 \pm 0.012$ (772M $B\bar{B}$)

World average of $\sin 2\beta$





- With Run2 data, LHCb overtakes B factories in the $\sin 2\beta$ measurement
- New W.A. improved by 35% in precision: $\sin 2\beta = 0.708 \pm 0.011$ (W.A.)
- Consistent with SM prediction: $\sin 2\beta = 0.731^{+0.029}_{-0.016}$ (CKMFitter)

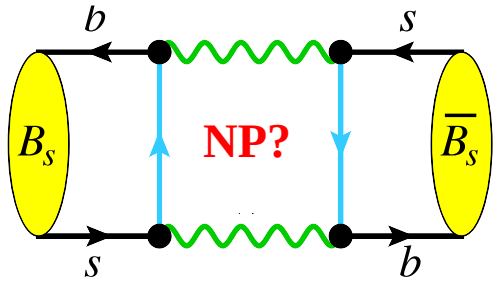
B_s^0 mixing phase $\phi_s = -2\beta_s^{\text{eff}}$

LHC flagship!

- ϕ_s: precisely predicted in SM

  $\phi_s^{\text{SM}} \approx -2\beta_s = -0.0368^{+0.006}_{-0.009}$ rad (CKMFitter)

- Sensitive to NP in mixing



- Golden mode: $B_s^0 \to J/\psi\phi$

$$A_{CP}(t) \approx -\eta_f \sin\phi_s \sin(\Delta m_s t)$$

Angular analysis to separate CP even ($\eta_f = 1$) and odd ($\eta_f = -1$) states

- Major players: LHCb, ATLAS, CMS

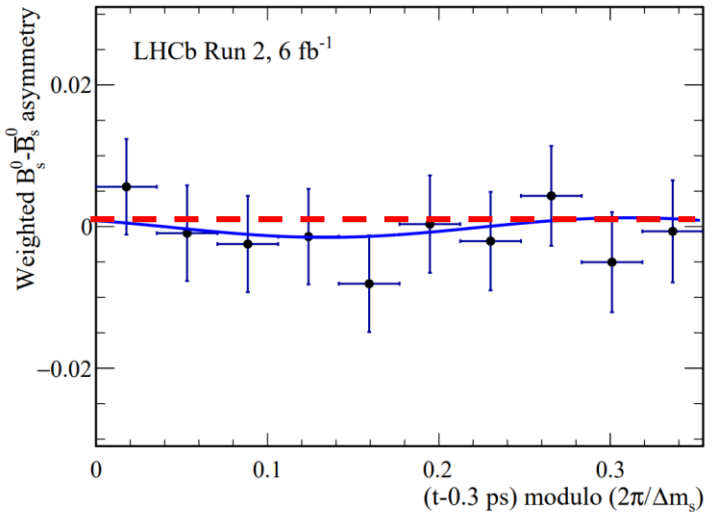
Collab.	ϕ_s (rad)
LHCb early Run2 (all $b \to c\bar{c}s$)	-0.042 ± 0.025
LHCb early Run 2 ($B_s^0 \to J/\psi\phi$)	-0.081 ± 0.032
ATLAS ($B_s^0 \to J/\psi\phi$)	-0.087 ± 0.041
CMS ($B_s^0 \to J/\psi\phi$)	-0.021 ± 0.045
HFLAV	-0.049 ± 0.019

LHCb, EPJC 79 (2019) 706
ATLAS, EPJC 81 (2021) 342
CMS, PLB 816 (2021) 136188

Update of ϕ_s with full Run2

LHCb-paper-2023-016
in preparation

No sign of CP violation



No sign of polarization dependence

ϕ_s^0 [rad]	-0.034 ± 0.023
$\phi_s^{\parallel} - \phi_s^0$ [rad]	-0.002 ± 0.021
$\phi_s^{\perp} - \phi_s^0$ [rad]	$-0.001\,^{+0.020}_{-0.021}$
$\phi_s^{S} - \phi_s^0$ [rad]	$0.022\,^{+0.027}_{-0.026}$
$\lvert\lambda^0\rvert$	$0.969\,^{+0.025}_{-0.024}$
$\lvert\lambda^{\parallel}/\lambda^0\rvert$	$0.982\,^{+0.055}_{-0.052}$
$\lvert\lambda^{\perp}/\lambda^0\rvert$	$1.107\,^{+0.082}_{-0.076}$
$\lvert\lambda^{S}/\lambda^0\rvert$	$1.121\,^{+0.084}_{-0.078}$

New LHCb results

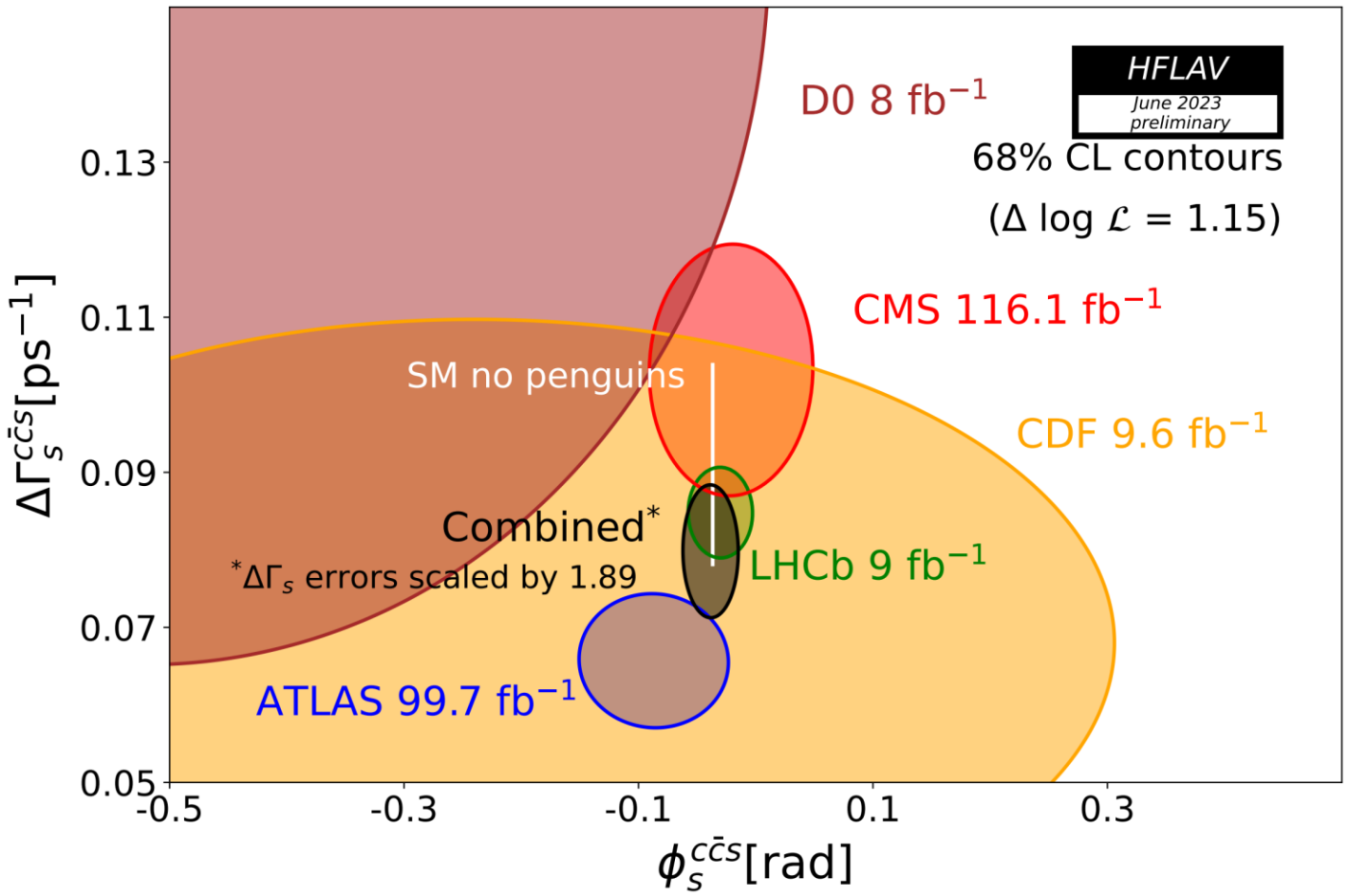
Parameter	Values
ϕ_s [rad]	$-0.039 \pm 0.022 \pm 0.006$
$\lvert\lambda\rvert$	$1.001 \pm 0.011 \pm 0.005$
$\Gamma_s - \Gamma_d$ [ps^{-1}]	$-0.0056\,^{+0.0013}_{-0.0015} \pm 0.0014$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0845 \pm 0.0044 \pm 0.0024$
Δm_s [ps^{-1}]	$17.743 \pm 0.033 \pm 0.009$
$\lvert A_{\perp}\rvert^2$	$0.2463 \pm 0.0023 \pm 0.0024$
$\lvert A_0\rvert^2$	$0.5179 \pm 0.0017 \pm 0.0032$
$\delta_{\perp} - \delta_0$ [rad]	$2.903\,^{+0.075}_{-0.074} \pm 0.048$
$\delta_{\parallel} - \delta_0$ [rad]	$3.146 \pm 0.060 \pm 0.052$

Run2 $\quad \phi_s^{J/\psi\phi} = -0.039 \pm 0.022 \pm 0.006$ rad

Run1+2 $\quad \phi_s^{J/\psi\phi} = -0.044 \pm 0.020$ rad

Run1+2 $\quad \phi_s^{c\bar{c}s} = -0.038 \pm 0.018$ rad

World average of ϕ_s vs $\Delta\Gamma_s$



Tention in $\Delta\Gamma_s$ remains

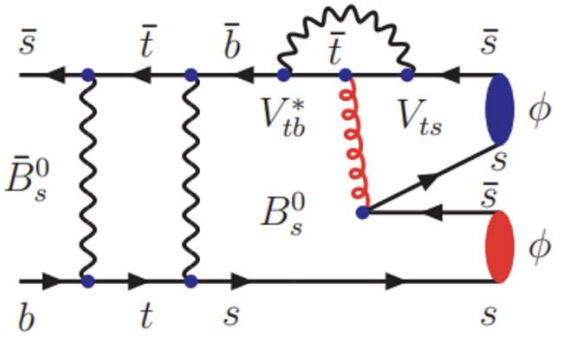
LHCb
$\Delta\Gamma_s = 0.0845 \pm 0.0044 \pm 0.0024$ ps^{-1}
ATLAS
$\Delta\Gamma_s = 0.0657 \pm 0.0043 \pm 0.0037$ ps^{-1}
CMS
$\Delta\Gamma_s = 0.1032 \pm 0.0095 \pm 0.0048$ ps^{-1}

W.A. of ϕ_s improved by 15%: $\phi_s^{c\bar{c}s} = -0.039 \pm 0.016$ rad (W.A.)

Consistent with SM: $\phi_s^{\mathrm{SM}} = -0.0368^{+0.006}_{-0.009}$ rad (CKMFitter)

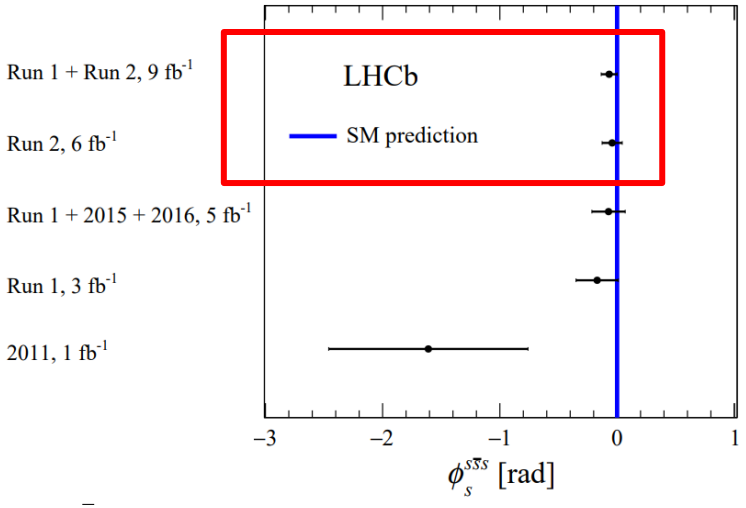
CPV in penguin-dominated $B_s^0 \to \phi\phi$

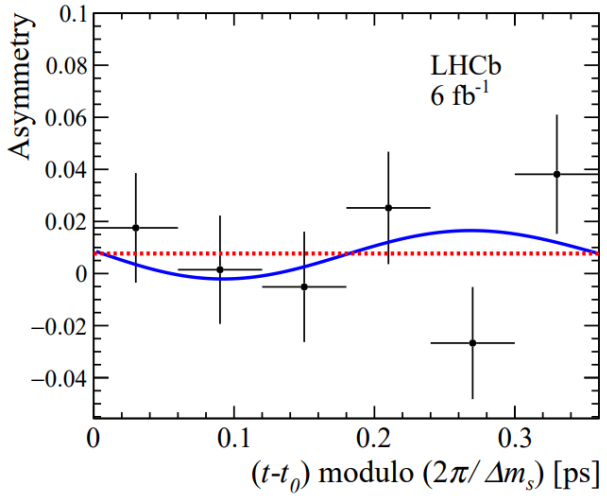
- Tiny CPV expected in SM: $\phi_s^{s\bar{s}s} = 0.00 \pm 0.02$ rad
- Sensitive to NP in mixing and penguin diagrams
- New LHCb results



Run2	$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009$ rad
Run1+2	$\phi_s^{s\bar{s}s} = -0.074 \pm 0.069$ rad

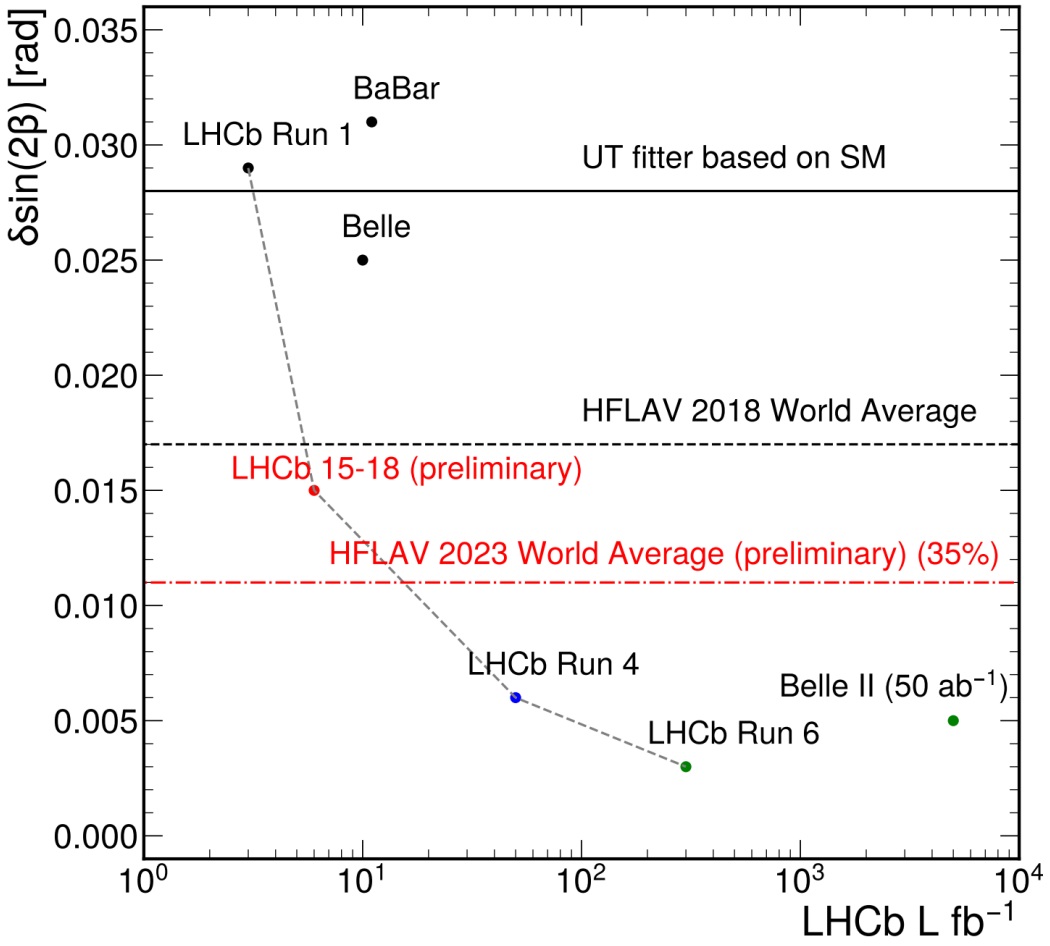
arXiv:2304.06198

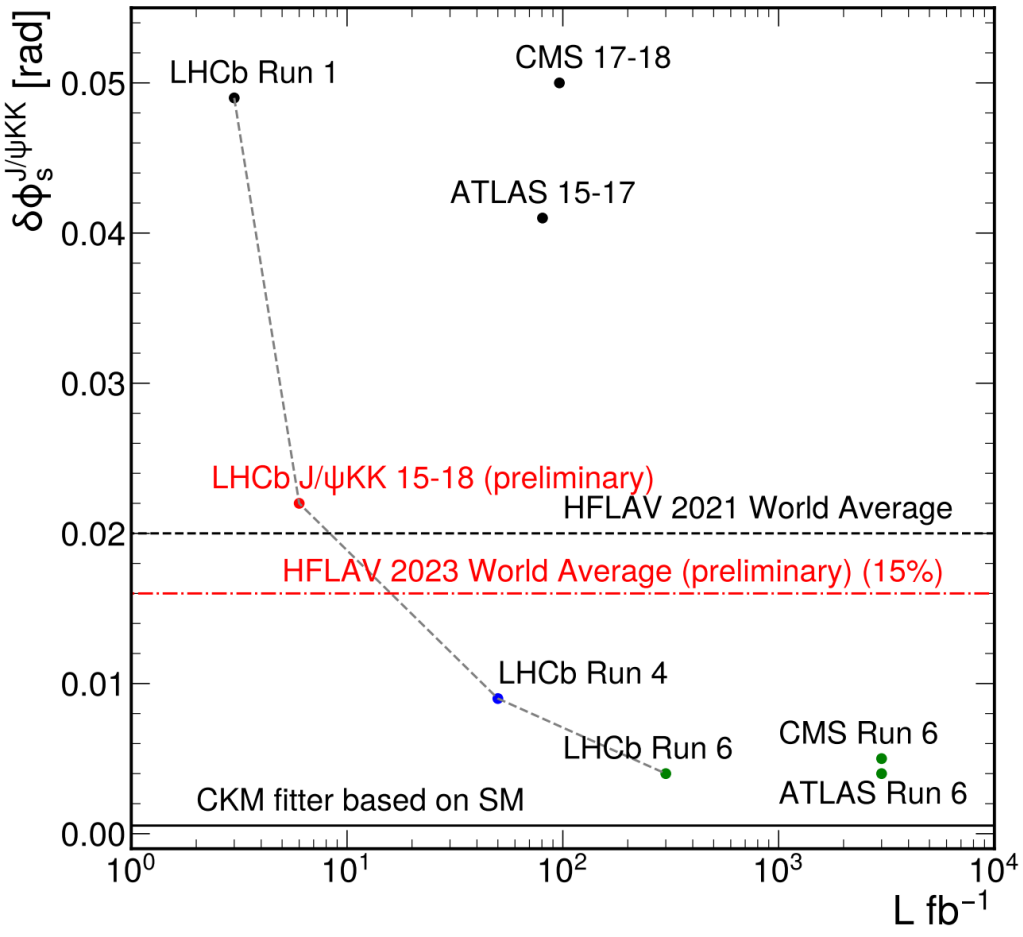




No sign of CP violation & result consistent with SM

Projections for $\sin 2\beta$ and ϕ_s

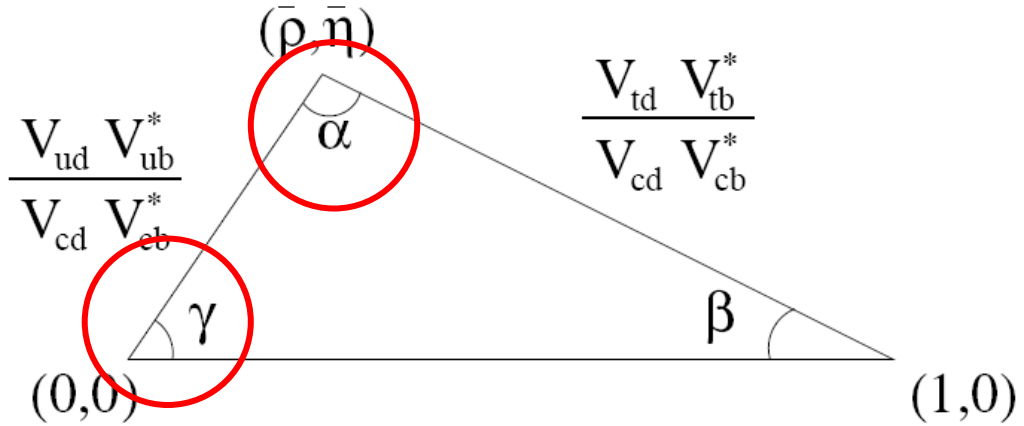




$\sin 2\beta$: σ^{exp} already better than σ^{SM}

ϕ_s: $\sigma^{\mathrm{exp}} >> \sigma^{\mathrm{SM}}$, with large room for improvement

CKM angles γ and α



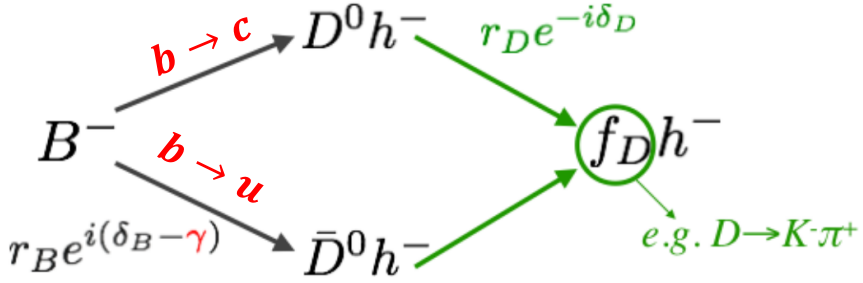
CKM angle γ

LHCb dominating!

- **Access γ from interference of $b \to u$ & $b \to c$ transitions in $B^{\pm} \to Dh^{\pm}$ decays**

$$\Gamma(B^{\pm} \to Dh^{\pm}) \propto |r_D e^{-i\delta_D} + r_B e^{i(\delta_B \pm \gamma)}|^2$$

γ, δ_B, r_B: to be measured δ_D, r_D: external inputs



- **Each B factory: $\sigma_\gamma \approx 15°$**

BaBar: $\gamma = (70 \pm 18)°$ PRD 87 (2015) 052 015

BELLE: $\gamma = \left(73^{+13}_{-15}\right)°$ arXiv: 1301.2033

- **Previous LHCb combination : $\sigma_\gamma \approx 4°$**

LHCb: $\gamma = \left(65.4^{+3.8}_{-4.2}\right)°$ JHEP 12 (2021) 141

Recent updated to include several new γ measurements

- **B decay modes**
  - $B^+ \to Dh^+, B^+ \to D^*h^+, B^+ \to DK^{*+}, B^+ \to Dh^+\pi^+\pi^-$
  - $B^0 \to DK^{*0}, B^0 \to D^{\mp}\pi^{\pm}$
  - $B_s^+ \to D_s^{\mp}K^{\pm}, B_s^+ \to D_s^{\mp}K^{\pm}\pi^+\pi^-$
- **D^0 decay modes**
  - 2-body: $D^0 \to K^+\pi^-$, $D^0 \to h^+h^-$
  - 3-body: $D^0 \to K_S^0 h^+h'^-$, $D^0 \to h^+h'^-\pi^0$
  - 4-body: $D^0 \to K^-\pi^+\pi^-\pi^+$, $D^0 \to K^-K^+\pi^-\pi^+$, $D^0 \to K_S^0\pi^+\pi^-\pi^0$, $D^0 \to \pi^-\pi^+\pi^-\pi^+$

New γ results with $B \to Dh$ decays

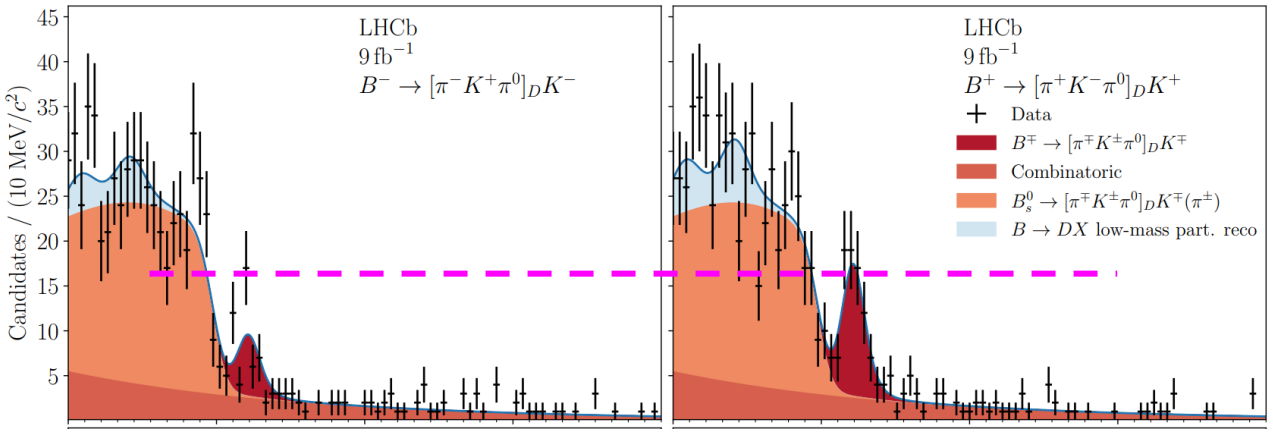
- γ in $B^{\pm} \to D\left[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}\right]h^{\pm}$ arXiv:2209.03692
  - Decay rates measured in bins of $K3\pi$ phase space
  - Per bin strong-phase differences and coherences factor from CLEO and BESIII

$$\gamma = \left(54.8^{+3.8\,+0.6\,+6.7}_{-5.8\,-0.6\,-4.3}\right)^{\circ}$$

Uncertainty of external inputs dominates!

- γ in $B^{\pm} \to D\left[h^{\pm}h'^{\mp}\pi^{0}\right]h^{\pm}$ JHEP 07 (2022) 099
  - Evidence for CPV in $B^{\pm} \to \left[\pi^{\pm}K^{\mp}\pi^{0}\right]_{D}K^{\pm}$

$$\gamma = \left(56^{+24}_{-19}\right)^{\circ}$$



- γ in $B^{\pm} \to D[K^{+}K^{-}\pi^{+}\pi^{-}]h^{\pm}$
  - Currently using D^0 amplitude model, expecting measurement of D parameters from BESIII

$$\gamma = \left(116^{+12}_{-14}\right)^{\circ}$$

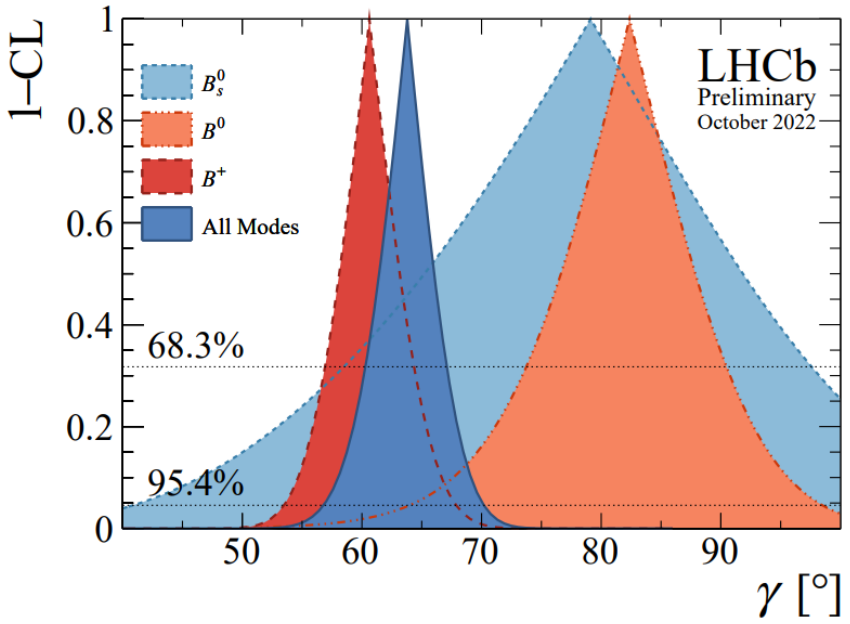
EPJC 83 (2023) 547

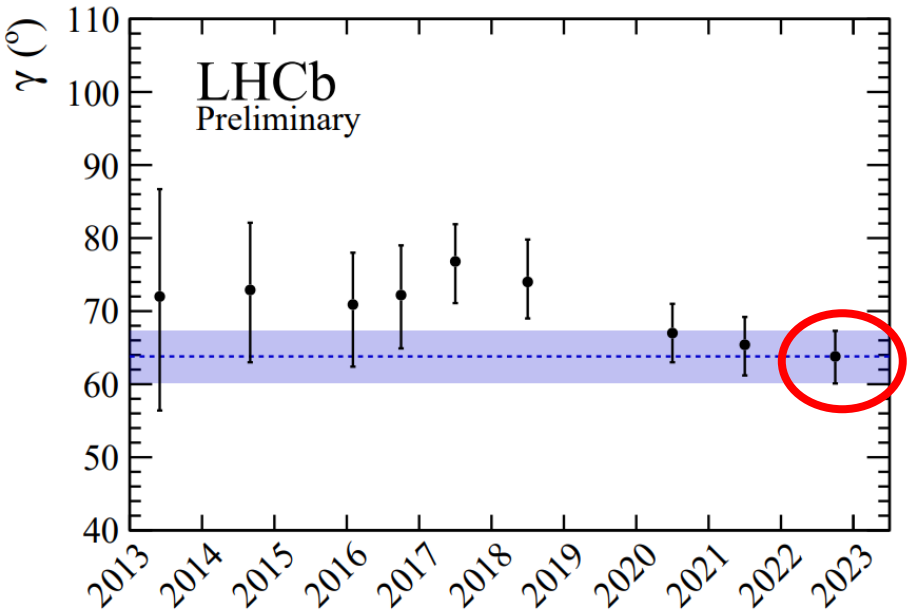
Updated LHCb γ combination

LHCb-CONF-2022-002

- New LHCb combination of many B and D decay modes

$B^{\pm} \to DK^{(*)\pm}$
$B^0 \to DK^{*0}$
$B^0 \to D^{\mp}\pi^{\pm}$
$B_s^0 \to D_s^{\mp}K^{\pm}(\pi\pi)$
$D \to K^+\pi^-$
$D \to K^+\pi^-$
$D \to h^+h^-\pi^0$
$D \to \pi^+\pi^-\pi^+\pi^-$
$D \to K^+\pi^-\pi^0$
$D \to K^{\pm}\pi^{\mp}\pi^+\pi^-$
$D \to K_S^0K^{\pm}\pi^{\mp}$
$D \to K_S^0K^{\pm}\pi^{\mp}$





LHCb: $\gamma = \left(63.8^{+3.5}_{-3.7}\right)°$

10% improvement

Consistent with SM prediction: $\gamma = \left(65.5^{+1.1}_{-2.7}\right)°$ (CKMFitter)

γ/ϕ_3 measurements at Belle II

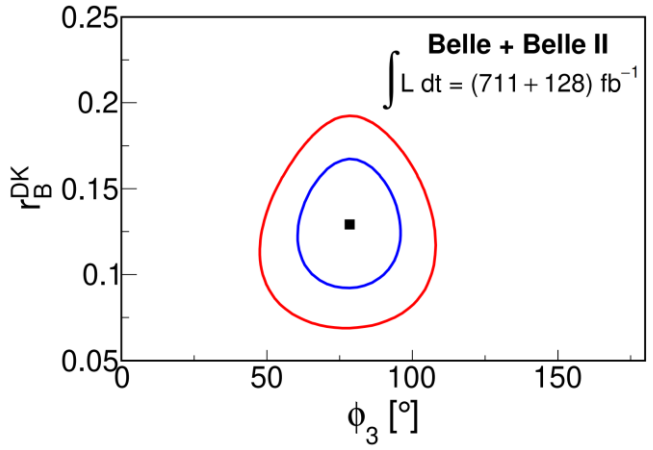
Several efforts to improve γ by adding Belle II early data to Belle data

- **Model-independent binned analysis of $B^{\pm} \to D\left[K^0_S h^+ h^-\right] h^{\pm}$**

  Per bin D^0 strong-phase parameter from CLEO and BESIII using

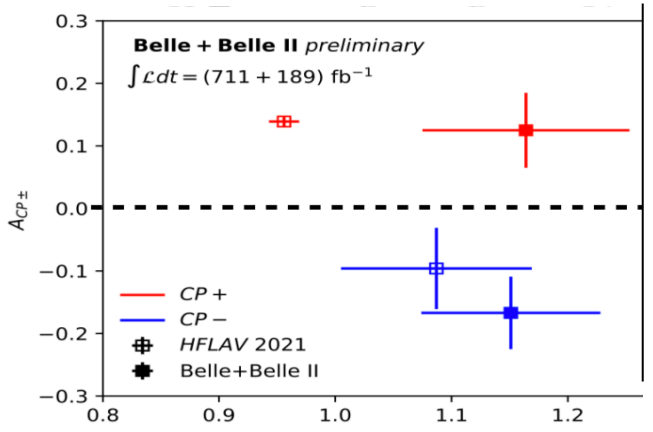
  $$\gamma = \phi_3 = (78.4 \pm 11.4(\text{stat}) \pm 0.5(\text{syst}) \pm 1.0\ (\text{ext}))^\circ$$

  JHEP 02 (2022) 063



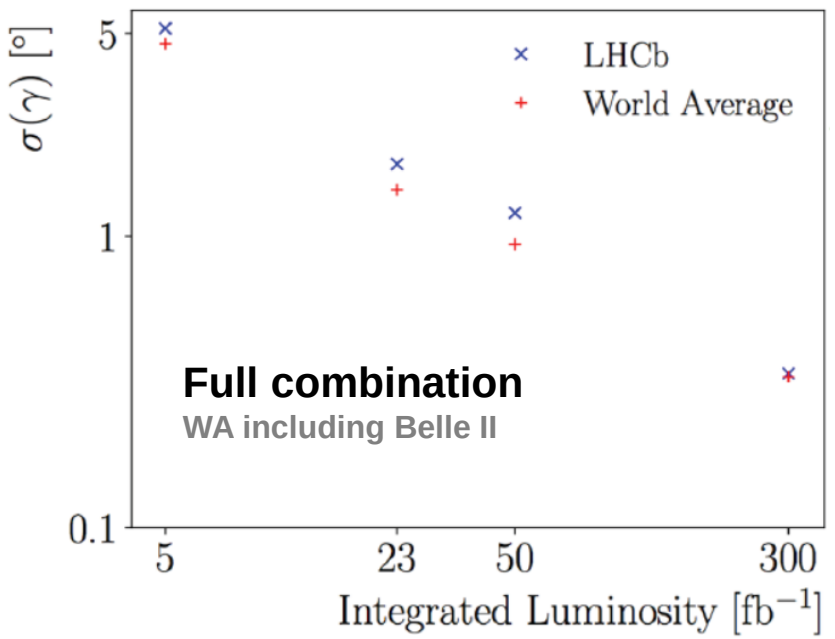
- **CPV and BFs in $B \to DK$ with $D^0 \to K^+K^-$ and $D^0 \to K^0_S\pi^0$**
  - CP-odd accessible only to B-factories
  - Evidence of opposite A_{CP} for even and odd states

  Talk by Xiaodong Shi



- **CPV and BFs in $B \to Dh$ with $D^0 \to K^0_S K\pi$** arXiv:2306.02940

Future prospect for γ



- **Status now**
  - LHCb Run 2: $\sigma_\gamma \approx 4°$
  - BESIII 3 fb^{-1} $D\bar{D}$: error from strong phase $\sim 1°$
- **~2030**
  - LHCb upgrade I: $\sigma_\gamma < 1°$
  - BESIII 20 fb^{-1} $D\bar{D}$: error from strong phase $< 0.5°$
- **~2040**
  - LHCb upgrade II: $\sigma_\gamma < 0.4°$
  - Need future charm factory

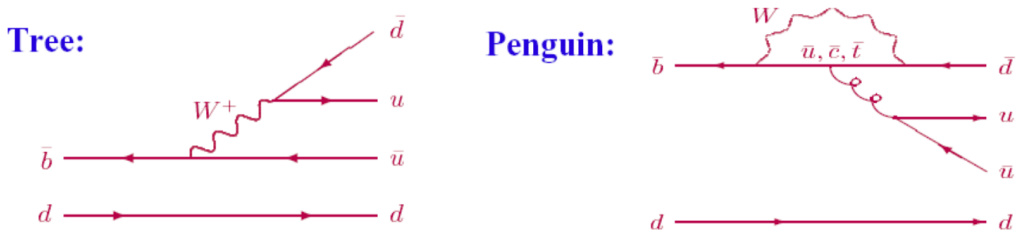
Data source	Integrated Lumi	year	γ sensitivity
LHCb Run1 (7, 8TeV)	3 fb^{-1}	2012	8°
LHCb Run2 (13TeV)	6 fb^{-1}	2018	4°
Belle II Run	50 ab^{-1}	2025	1-2°
LHCb upgrade I	50 fb^{-1}	2030	<1°
LHCb upgrade II	200 fb^{-1}	2040	<0.4°

Belle II potential for α/ϕ_2

- **Access α from TD-CPV in $B^0 \to \pi\pi, \rho\rho$ decays**

$\alpha = (85.2^{+4.8}_{-4.3})°$ (HFLAV)

$$A_{CP}(t) = C\cos(\Delta m_d t) - S\sin(\Delta m_d t)$$
$$S = \sin 2\alpha + 2\,r\cos\delta\,\sin(\alpha+\beta)\cos 2\alpha$$



$A(B^0 \to \pi^+\pi^-) = T\,e^{i\gamma} + P\,e^{i\delta}$, $r = |P|/|T|$

- **Control hadronic parameter r and δ using BFs and CPV of all isospin-related $B \to \pi\pi$ ($B \to \rho\rho$) channels, which are all accessible at Belle II**

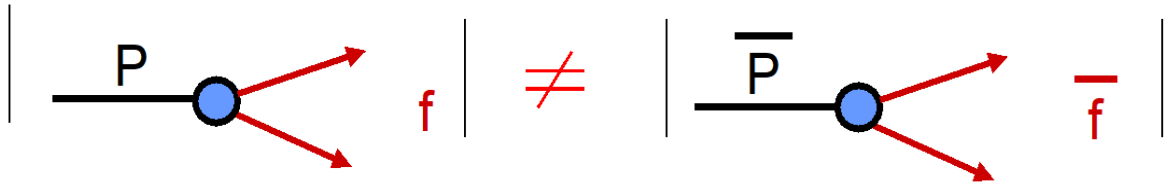
$\mathcal{B}(\rho^+\rho^-) = (2.67 \pm 0.28 \pm 0.28) \times 10^{-5}$, $f_L = 0.956 \pm 0.035 \pm 0.033$ — arXiv:2206.12362

$\mathcal{B}(\rho^+\rho^0) = (2.32 \pm 0.22 \pm 0.27) \times 10^{-5}$, $f_L = 0.943 \pm 0.035 \pm 0.060$
$A_{CP} = -0.069 \pm 0.068 \pm 0.060$ — arXiv:2208.03554

$\mathcal{B}(\pi^+\pi^-) = (5.83 \pm 0.22 \pm 0.17) \times 10^{-6}$,
$\mathcal{B}(\pi^+\pi^0) = (5.10 \pm 0.29 \pm 0.32) \times 10^{-6}$, $A_{CP} = -0.081 \pm 0.054 \pm 0.008$ — Talk by Xiaodong Shi

$\mathcal{B}(\pi^0\pi^0) = (1.38 \pm 0.27 \pm 0.22) \times 10^{-6}$, $A_{CP} = 0.14 \pm 0.46 \pm 0.07$ — PRD 107(2023)112009

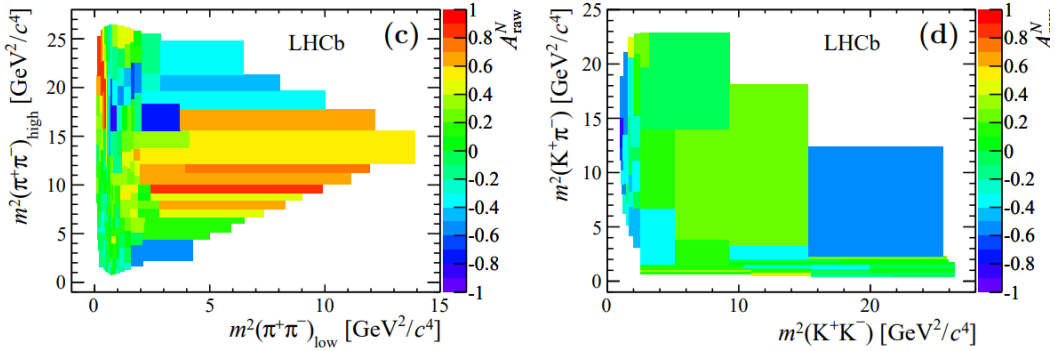
Some results in direct CP violation



$$A_{CP} = \frac{\Gamma(P \to f) - \Gamma(\bar{P} \to \bar{f})}{\Gamma(P \to f) + \Gamma(\bar{P} \to \bar{f})} \propto \sin(\delta_2 - \delta_1)\sin(\varphi_2 - \varphi_1)$$

CPV in charmless 3-body B decay

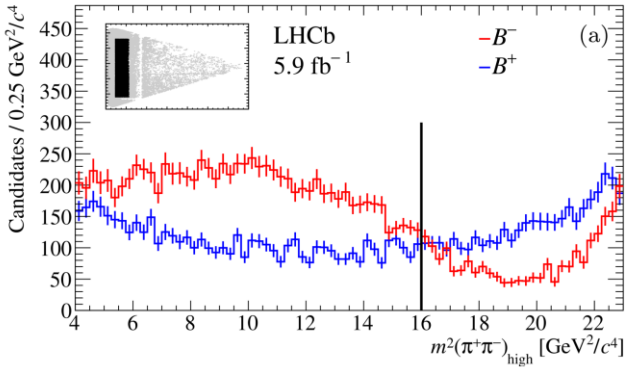
- **Large local CPV observed in $B^{\pm} \to h^+h^-\pi^{\pm}$ decays using Run 1 data** PRD 90 (2014) 112004
- **Analysis of Run 2 data reveals new findings**



- Observation of inclusive A_{CP} in two modes

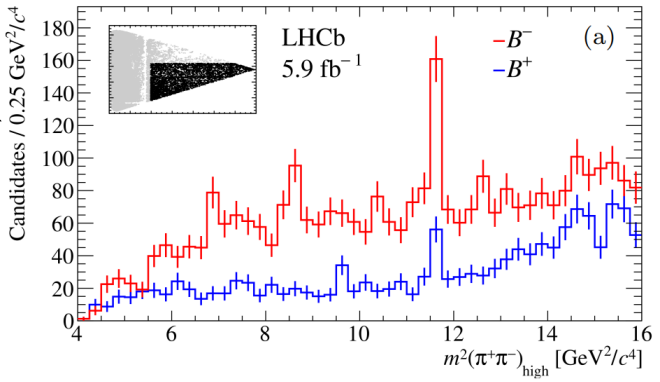
$$A_{CP}(K^{\pm}K^+K^-) = -0.037 \pm 0.002 \pm 0.002 \pm 0.003$$
$$A_{CP}(\pi^{\pm}\pi^+\pi^-) = +0.080 \pm 0.004 \pm 0.003 \pm 0.003$$

arXiv:2206.07622



- Significant A_{CP} in $KK \leftrightarrow \pi\pi$ rescattering region, with a sign change across phase space
- Indication of $\chi_{c0}(1P)$ contribution, with a large A_{CP}
- Observation of A_{CP} in $B \to PV$ modes through angular analysis

arXiv:2202.02038



$$A_{CP}(B^{\pm} \to \rho(770)^0 K^{\pm}) = 0.150 \pm 0.019$$

$K\pi$ isospin sum rule

- **SM predicts $I_{K\pi} = 0$ with $O(1)\%$ theoretical uncertainty**

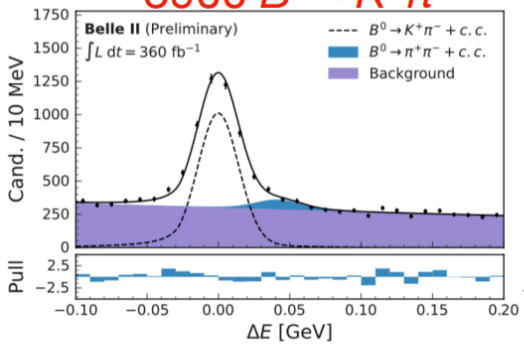
$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

WA: $I_{K\pi} = (-13 \pm 11)\%$, precision limited by $K_S^0\pi^0$

- **Belle II able to access all final states for testing $K\pi$ isospin sum rule**

Talk by Xiaodong Shi

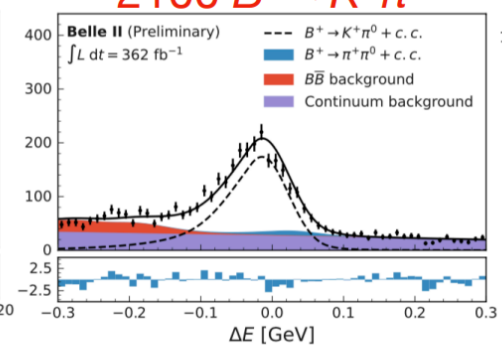
~3900 $B^0 \to K^+\pi^-$



$\mathcal{B} = (20.67 \pm 0.37 \pm 0.62) \times 10^{-6}$

$A_{CP} = (-7.2 \pm 1.9 \pm 0.7)\,\%$

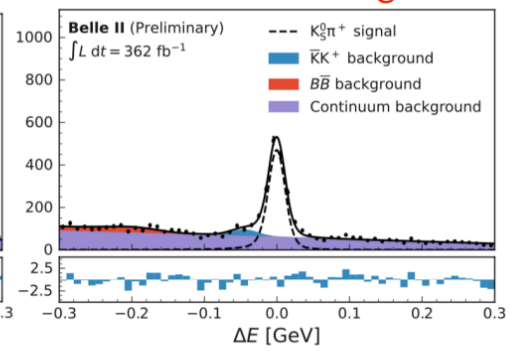
~2100 $B^+ \to K^+\pi^0$



$\mathcal{B} = (14.21 \pm 0.38 \pm 0.85) \times 10^{-6}$

$A_{CP} = (1.3 \pm 2.7 \pm 0.5)\,\%$

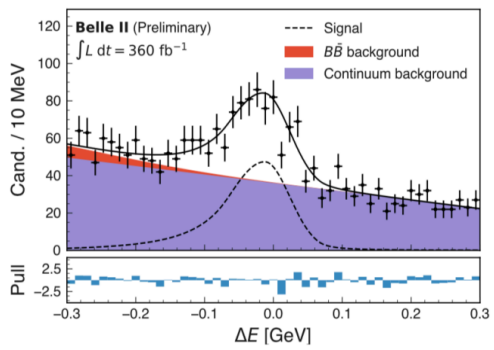
~1500 $B^+ \to K_S\pi^+$



$\mathcal{B} = (24.40 \pm 0.71 \pm 0.86) \times 10^{-6}$

$A_{CP} = (4.6 \pm 2.9 \pm 0.7)\,\%$

~500 $B^0 \to K_S\pi^0$



$\mathcal{B} = (10.50 \pm 0.62 \pm 0.67) \times 10^{-6}$

$A_{CP} = (-1 \pm 12 \pm 5)\,\%$

$I_{K\pi} = (-3 \pm 13 \pm 5)\%$

Consistent with SM and competitive with W.A.

Direct CPV in charm

Evidence of direct CPV in $D^0 \to \pi^-\pi^+$

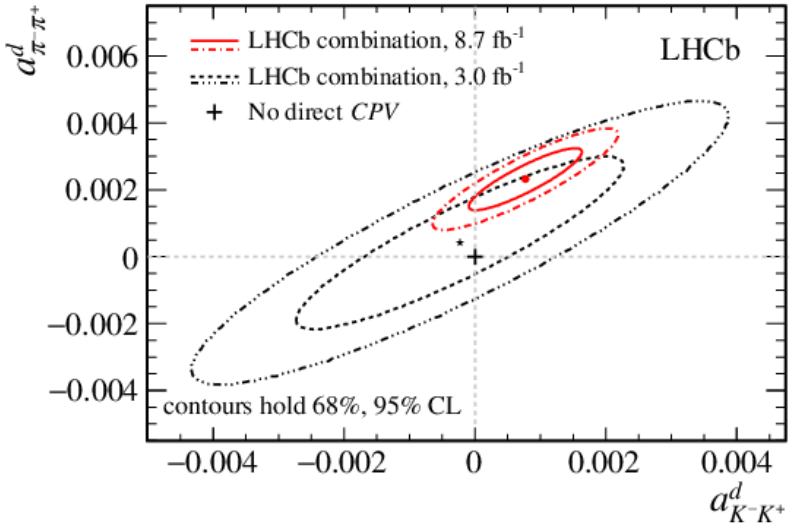
arXiv:2209.03179

PRL 122 (2019) 211803

- CPV observed in $A_{CP}(K^-K^+) - A(\pi^-\pi^+)$
- New measurement of $A_{CP}(K^-K^+)$ using Run2 data
- Subtracting mixing-related CPV: $a_f^d = A_{CP}(f) - \frac{<t>_f}{\tau_D}\Delta Y_f$

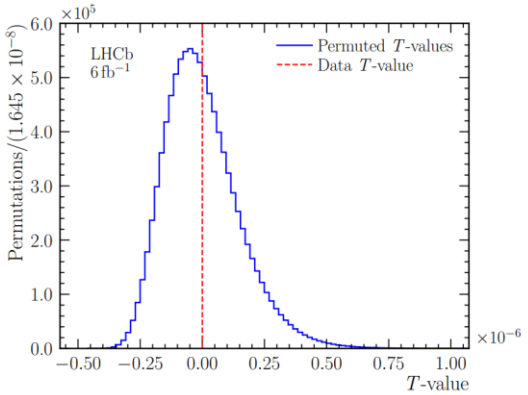
$$a^d_{K^-K^+} = (7.7 \pm 5.7) \times 10^{-4}$$ 1.4σ from zero

$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}$$ 3.8σ from zero

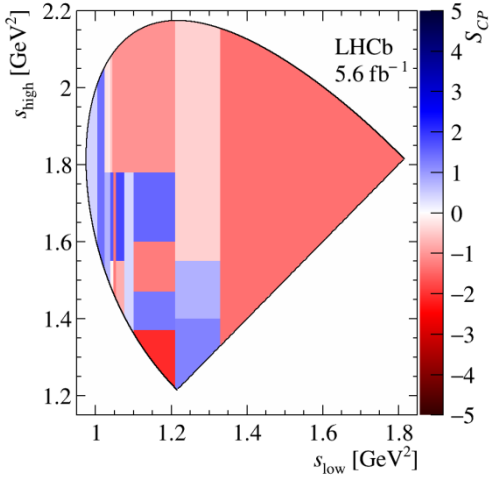


Search for CPV in multi-body decays

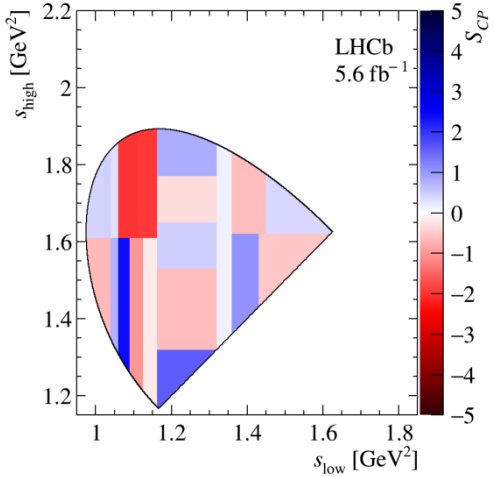
- $D^0 \to \pi^-\pi^+\pi^0$: energy test
  arXiv:2303.04062
- $D^+_{(s)} \to K^-K^+K^+$: per-bin fit
  arXiv:2306.12746
- $D^0 \to h^-h^+\mu^+\mu^-$: angular fit
  PRL 128 (2022) 221801
- No evidence for CPV



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



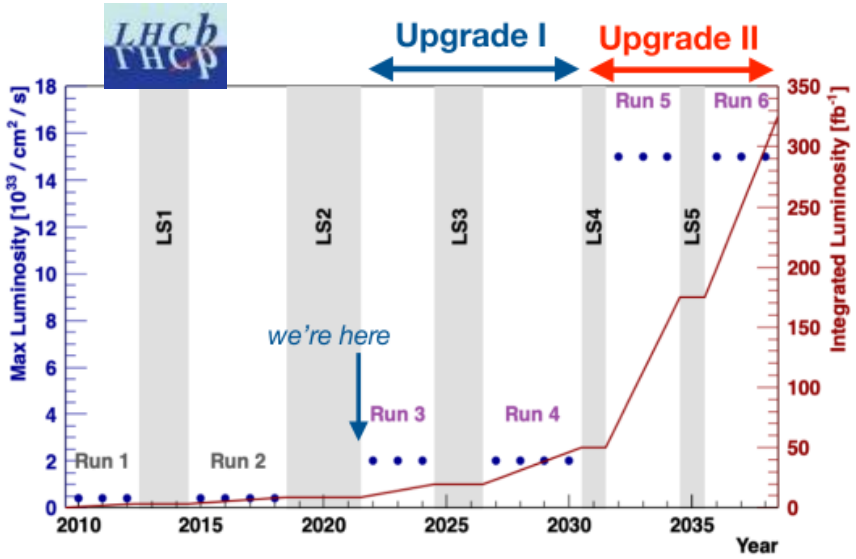
$D_s^+ \to K^-K^+K^+$

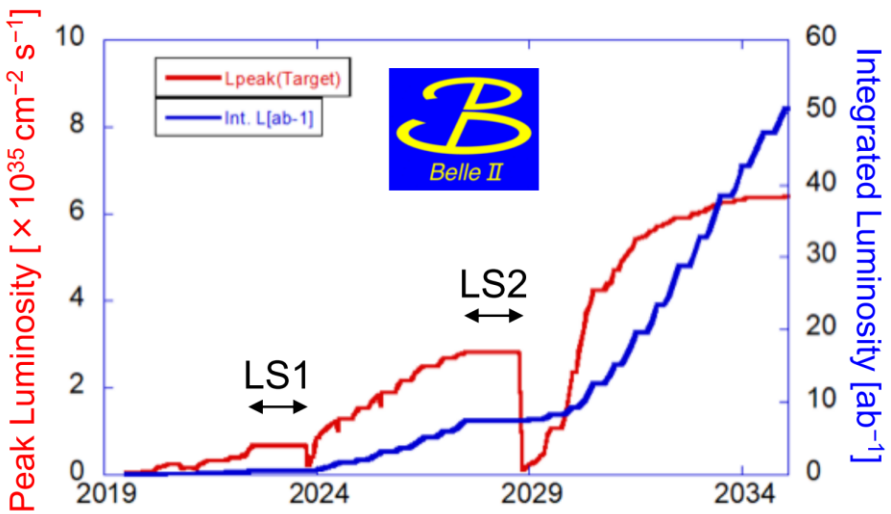


$D^+ \to K^-K^+K^+$

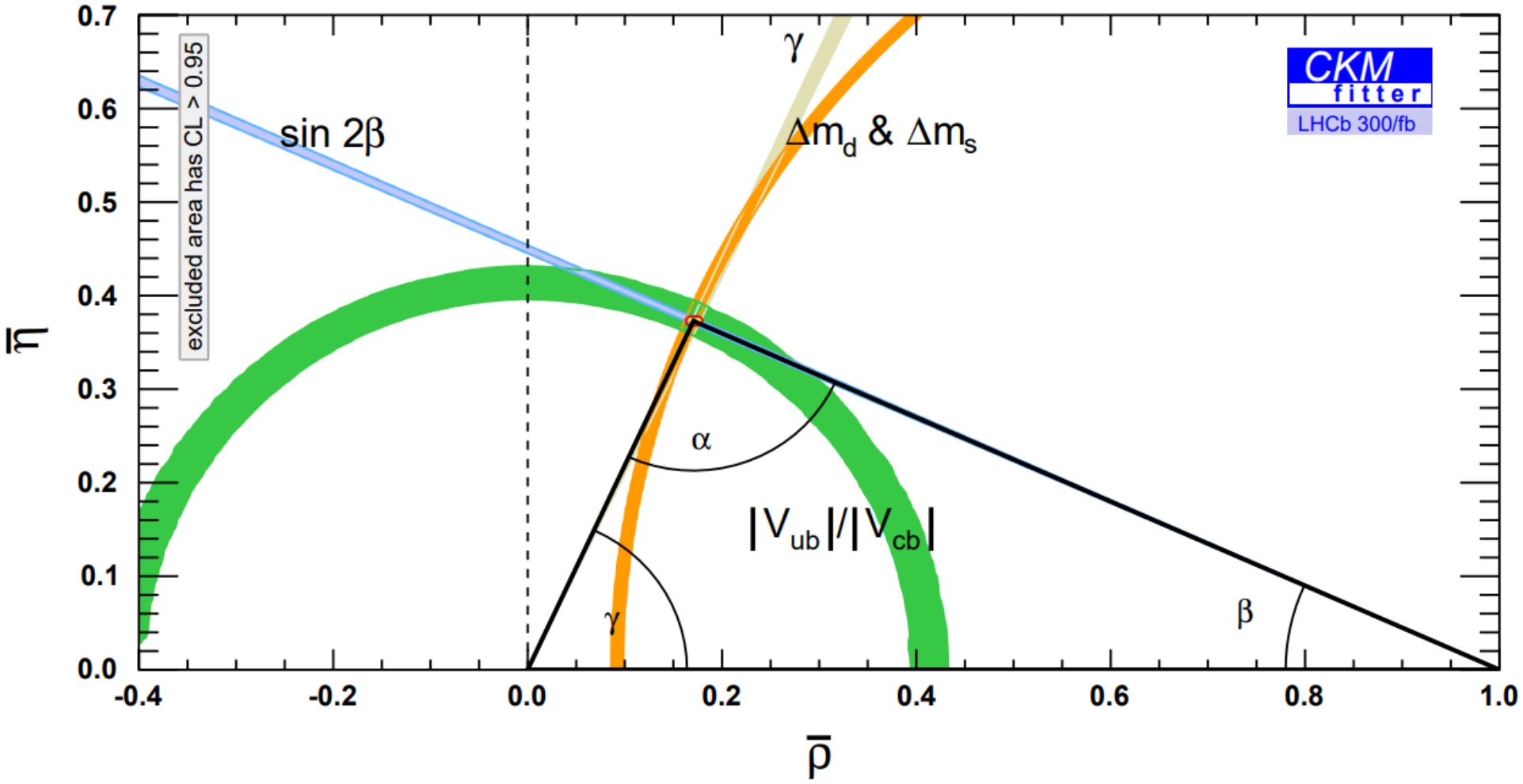
Summary

- The LHCb experiment has achieved the most precise measurements of the CKM angle β, β_s and γ, which all agree with the SM predictions.
- Belle II is ramping up and producing interesting results.
- A deeper understanding of CP violation is a long term goal that requires synergies of LHCb upgrades, Belle II and future charm experiments.





There will be no place for new physics to hide, if it has a non-SM flavour structure!

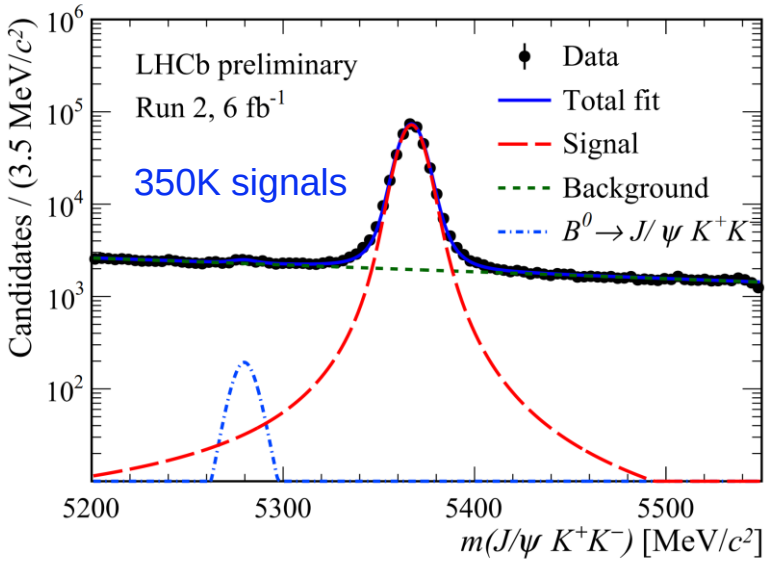


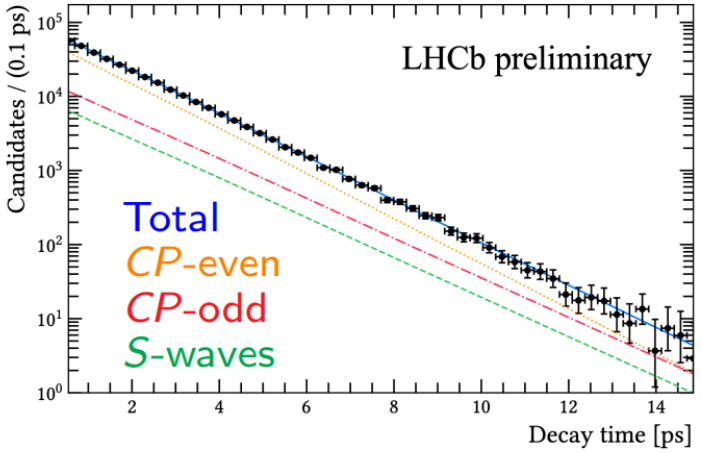
Spare slides

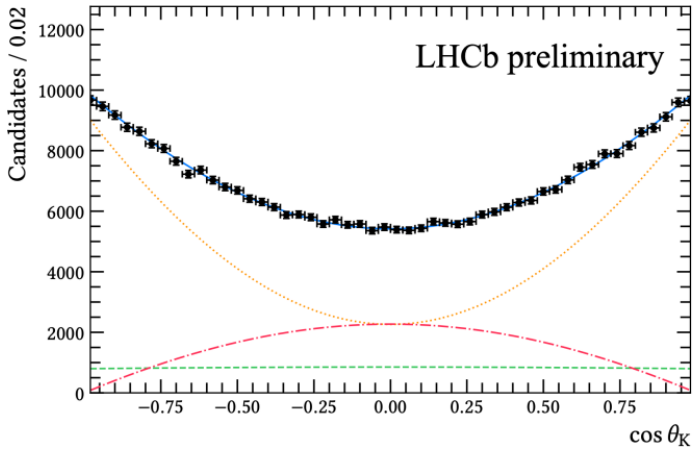
LHCb Run2 $B_s^0 \to J/\psi\phi$ analysis

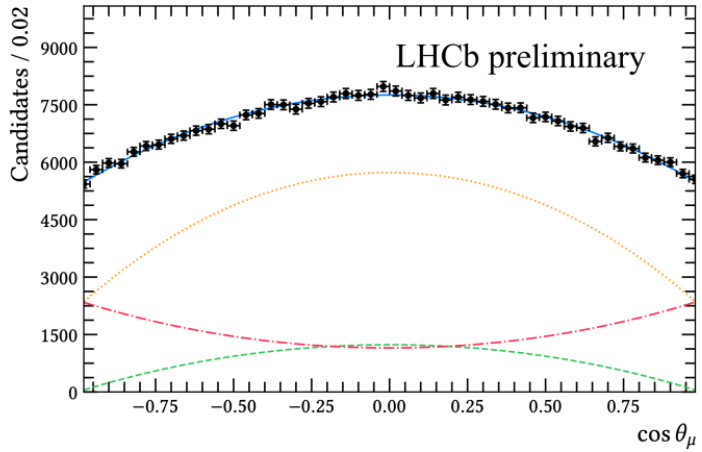
LHCb-paper-2023-016
in preparation

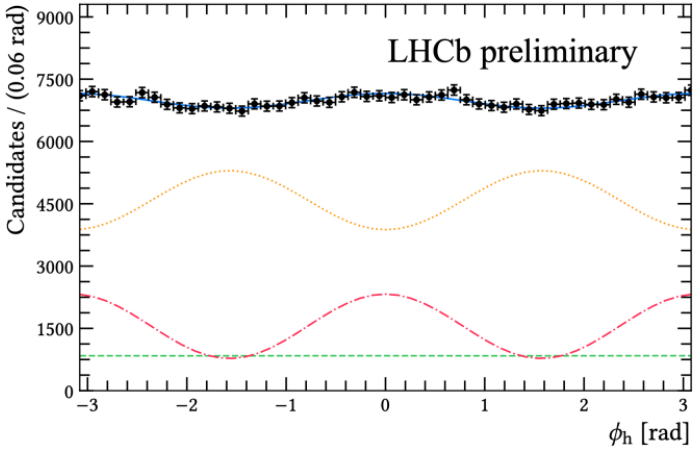
- **Maximum-likelihood fit to TD angular distributions of tagged B_s^0 and $\bar{B}_s^0$ decays**





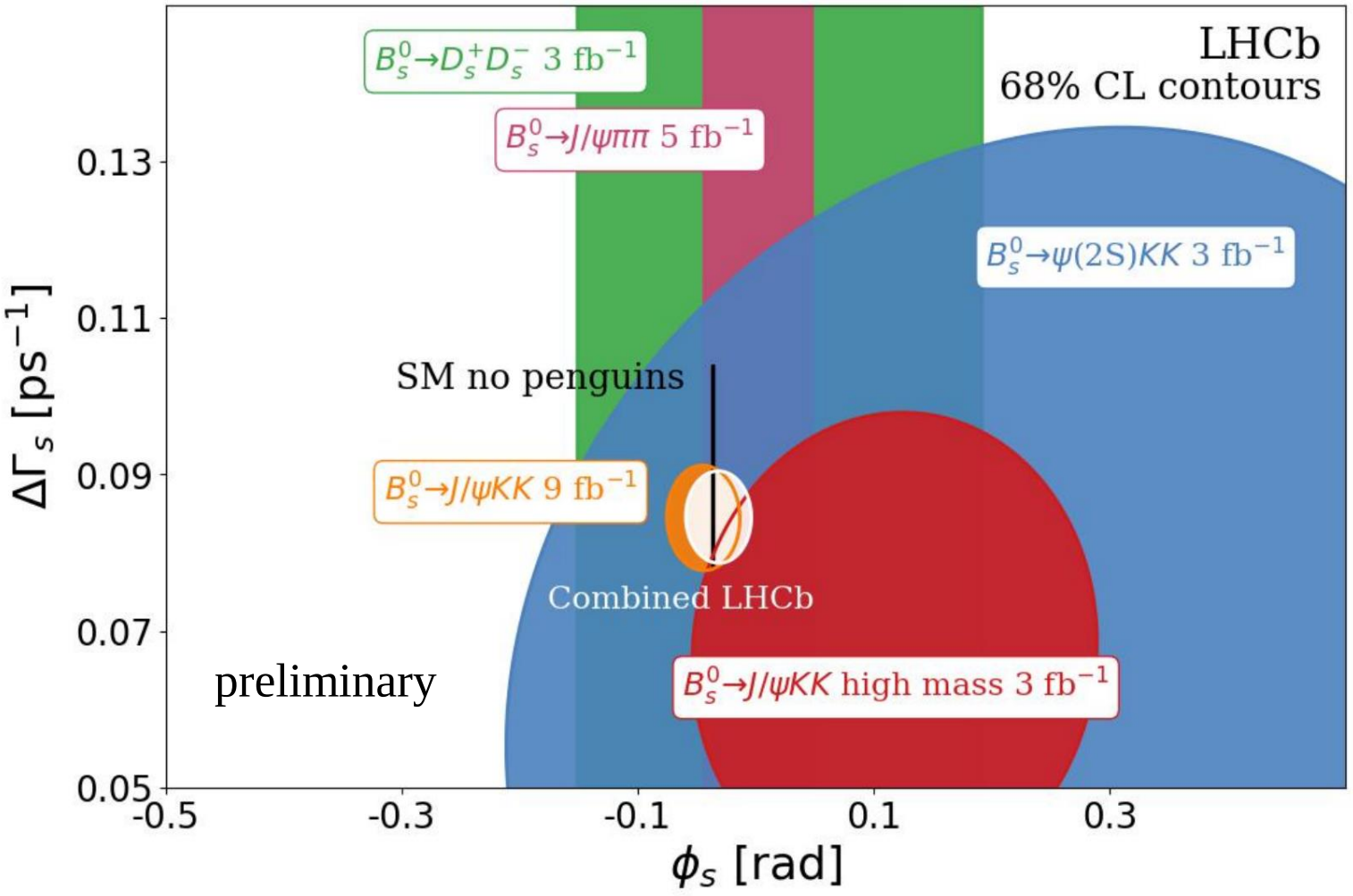






LHCb ϕ_s combination

LHCb-paper-2023-016
in preparation



LHCb Run2 $B_s^0 \to J/\psi\phi$ systematics

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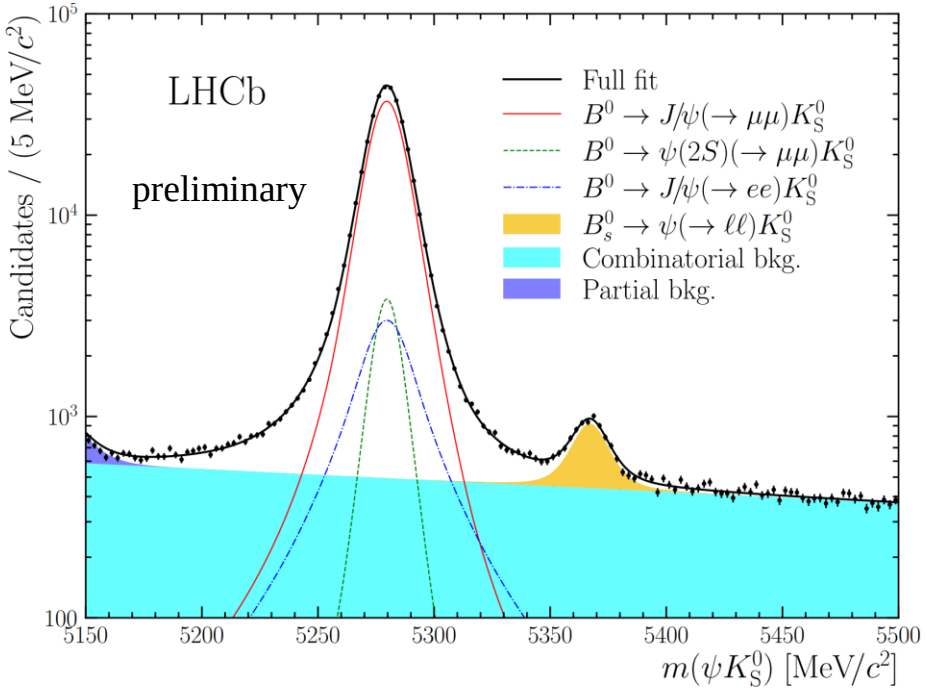
Table 3: Summary of the systematic uncertainties ($\times 0.01$) for the main physics parameters.

Source	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	ϕ_s [rad]	$\lvert\lambda\rvert$	$\delta_\perp - \delta_0$ [rad]	$\delta_\parallel - \delta_0$ [rad]	$\Gamma_s - \Gamma_d$ [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [ps^{-1}]
Mass parametrization	0.04	0.03	0.03	0.02	0.15	0.12	0.02	0.04	0.03
Mass: shape statistical	0.04	0.04	0.05	0.09	0.62	0.33	0.02	0.01	0.11
Mass factorization	0.11	0.10	0.42	0.19	0.54	0.60	0.12	0.16	0.18
B_c^+ contamination[2]	0.04	0.05	–	0.02	–	0.17	(0.07)	(0.03)	–
D–wave component	0.04	0.04	0.02	–	0.07	0.13	0.01	0.03	0.02
Ghost tracks	0.07	0.04	0.02	0.10	0.18	0.18	0.02	–	0.01
Multiple candidates	0.01	–	0.27	0.22	0.90	0.41	0.01	0.01	0.24
Particle identification	0.06	0.09	0.27	0.27	1.31	0.51	0.05	0.15	0.46
$C_{\rm SP}$ factors	–	0.01	0.01	0.03	0.73	0.41	–	0.01	0.04
DTR[3] calibration	–	–	0.03	0.02	0.11	0.07	–	–	0.05
DTR model applicability	–	–	0.08	0.03	0.26	0.09	–	–	0.09
Time bias correction	0.04	0.05	0.06	0.05	0.77	0.11	0.03	0.05	0.44
Angular efficiency	0.05	0.14	0.25	0.32	0.42	0.44	0.01	0.02	0.13
Angular resolution	0.01	0.01	0.02	0.01	0.02	0.08	–	0.01	0.02
Kinematic weighting	0.24	0.09	0.01	0.01	0.98	0.86	0.02	0.03	0.31
Momentum uncertainty	0.08	0.04	0.04	–	0.07	0.11	0.01	–	0.13
Longitudinal scale	0.07	0.04	0.04	–	0.10	0.09	0.02	–	0.31
Neglected correlations	–	–	–	–	4.20	4.96	–	–	–
Total systematic uncertainty	0.32	0.24	0.6	0.5	4.8	5.2	0.14	0.24	0.9
Statistical uncertainty	0.17	0.23	2.2	1.1	7.5	6.0	0.14	0.44	3.3

LHCb Run2 $B^0 \to J/\psi K^0_S$

LHCb-paper-2023-016
in preparation



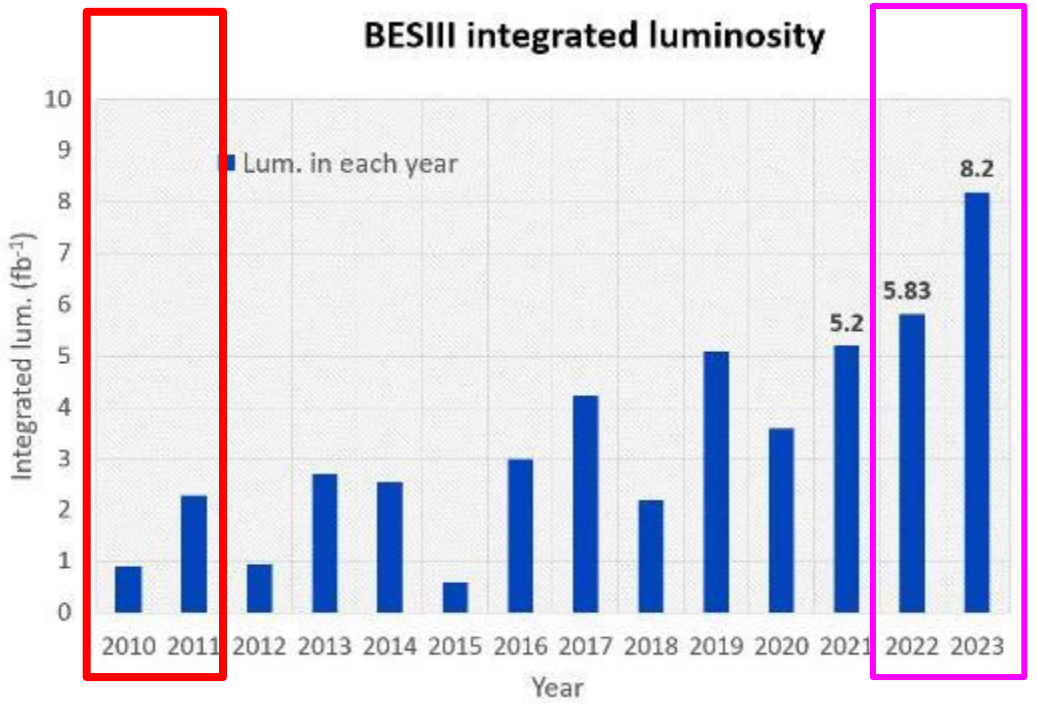
Source	$\sigma(S)$	$\sigma(C)$
Fitter validation	0.0004	0.0006
Decay-time bias model	0.0007	0.0013
FT $\Delta\epsilon_{\text{tag}}$ portability	0.0014	0.0017
FT calibration portability	0.0053	0.0001
$\Delta\Gamma_d$ uncertainty	0.0055	0.0017

D^0 parameters from BESIII

mode	Para.	Ref.
$D^0 \to K^0_{S,L}\pi^+\pi^-$	Strong phase	PRD 101 (2020) 112002
$D^0 \to K^0_S K^+ K^-$	Strong phase	PRD 102 (2020) 052008
$D^0 \to K^+\pi^-$	Strong phase	EPJC 82 (2022) 1009
$D^0 \to K^-\pi^+\pi^+\pi^-$	Strong phase	arXiv:2103.05988
$D^0 \to K^+K^-\pi^+\pi^-$	CP-even fraction	arXiv:2212.06489
$D^0 \to K^0_S\pi^+\pi^-\pi^0$	CP-even fraction	arXiv:2305.03975
$D^0 \to \pi^+\pi^-\pi^+\pi^-$	CP-even fraction	arXiv:2208.10098

Used for D parameters

To be used



- Current BESIII measurements of D^0 strong-phase parameters used 3 fb^{-1} of $\psi(3770) \to D\bar{D}$ data
- BESIII will accumulate 20 fb^{-1} of $\psi(3770) \to D\bar{D}$ data this year

LHCb upgrade II sensitivity

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a^s_{sl}	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B^0_s, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B^0_s \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K^0_S\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–