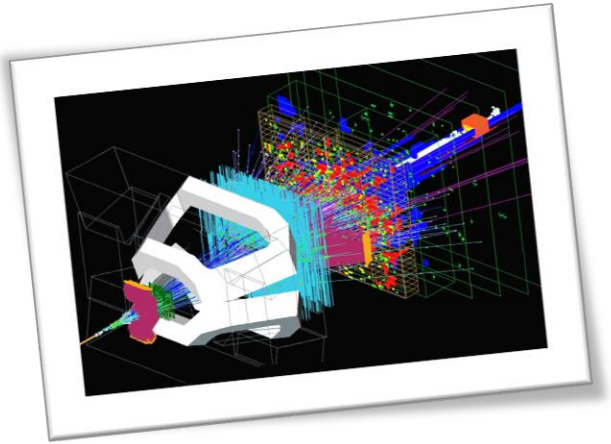
Recent Measurements of CKM Angles at LHCb

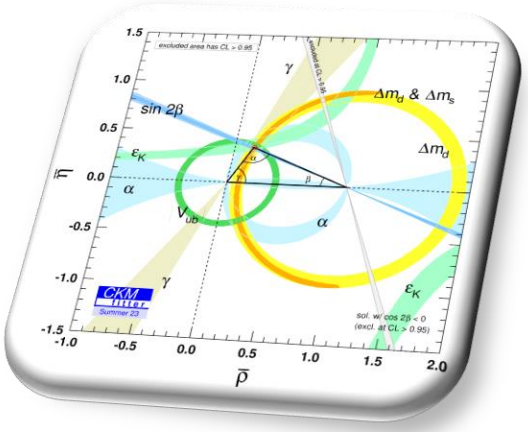


Ji Peng (IHEP)

(*On behalf of the LHCb Collaboration*)

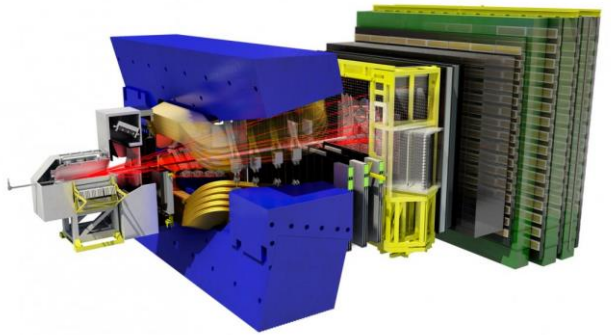
5th LHCb China Workshop

April 26, 2025

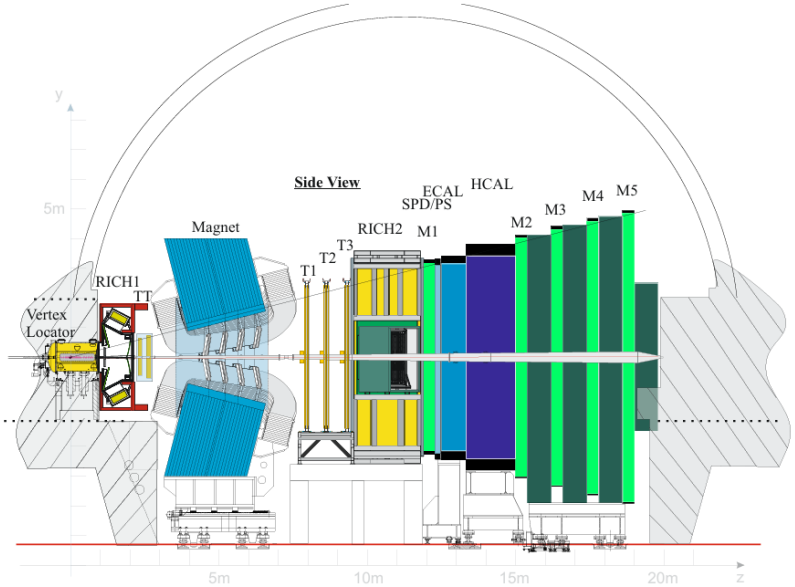


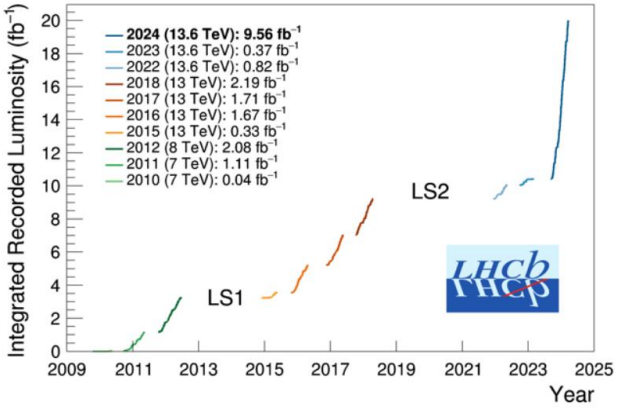
Outline

- **Introduction**
- **γ :**
  - **Methods → How to measure γ**
  - **Recent measurements of γ**
- **$\sin(2\beta)$: $B^0 \to \psi(\to l^+l^-)K_S^0(\to \pi^+\pi^-)$**
- **ϕ_s: $B_s^0 \to J/\psi K^+K^-$**
- **$\phi_s^{s\bar{s}s}$: $B_s^0 \to \phi\phi$**
- **Summary**



LHCb experiment





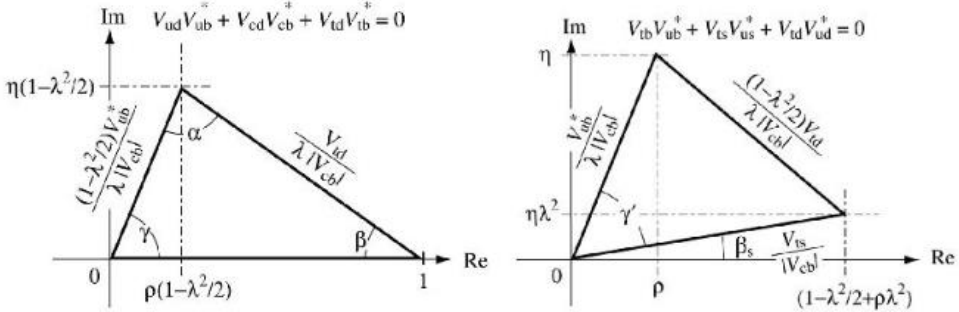
- Excellent vertex resolution (10 – 40 μm in xy-plane and 50 – 300 μm in z-axis)
- Particle identification efficiencies ~ 97% for μ, e and ~ 3% π misidentification, good separation between π, K, p
- Run 1 + 2: 9 fb^{-1} of pp collisions

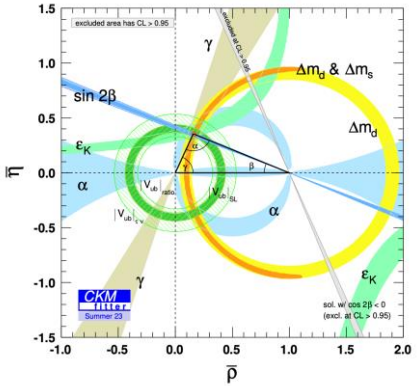
CKM matrix & unitarity triangle

- **The CKM matrix describes quark mixing in the Standard Model**
  - Its complex phase is the only known source of CP violation in the SM

$$V_{\mathrm{CKM}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} = \left(\quad \right)$$

- **Unitarity leads to unitarity triangles (UTs)**
  - Provides indirect probes for physics beyond the SM (BSM)

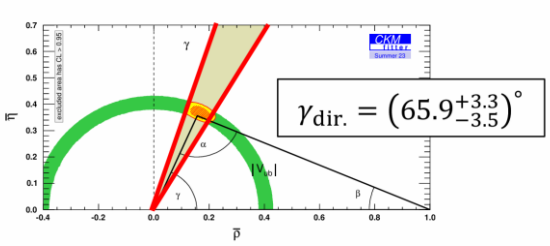


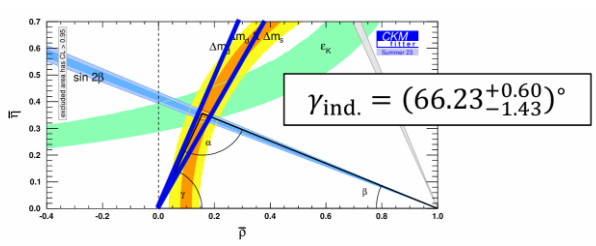


Angle γ

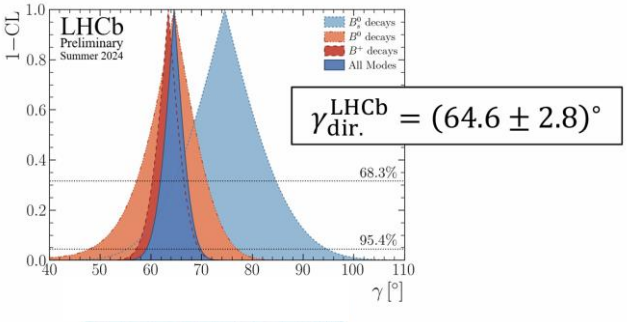
- Tree-level accessible, free of top quark by definition
- Negligible theoretical uncertainty, SM benchmark [arXiv:1308.5663]
- New physics probe:
  - Direct: Tree-level decay
  - Indirect: assume UT is closed

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$





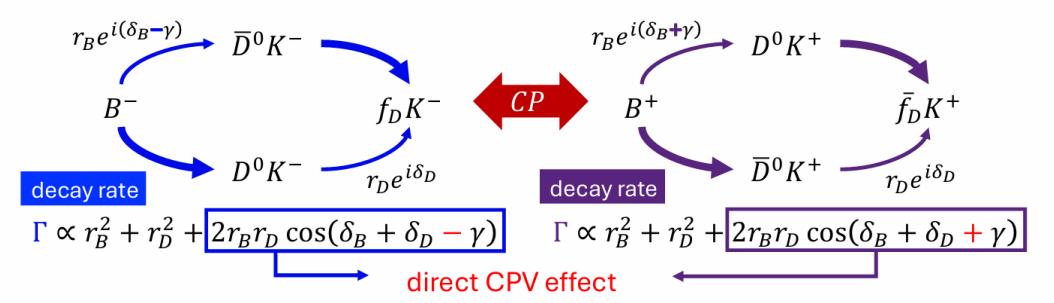
[CKMfitter-2023]



[LHCb-CONF-2024-004]

γ - Methods

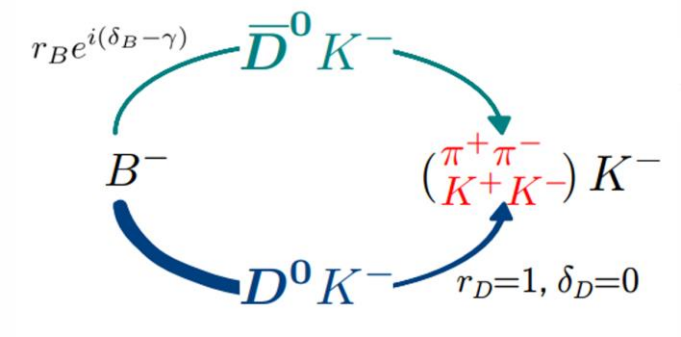
- Probe γ via interference between $b \to u\bar{c}s$ and $b \to c\bar{u}s$ transitions
  - The "textbook" case is $B^{\pm} \to DK^{\pm}$, $D \to f$



  - Different methods according to D decay modes
    - GLW method: CP eigenstates e.g. $D \to KK$, $D \to \pi\pi$
    - ADS method: CF or DCS decays e.g. $D \to K\pi$
    - BPGGSZ method: 3-body final states e.g. $D \to K^0_S \pi\pi$

γ - GLW Method

- GLW method: CP eigenstates e.g. $D \to KK,\ D \to \pi\pi$ [Phys. Lett. B 253 (1991) 483]
- Gronau, London, Wyler [Phys. Lett. B 265 (1991) 172]



$$A_{CP} = \frac{\Gamma(B^- \to D^0_{CP}K^-) - \Gamma(B^+ \to D^0_{CP}K^+)}{\Gamma(B^- \to D^0_{CP}K^-) + \Gamma(B^+ \to D^0_{CP}K^+)} = \frac{\pm 2 r_B \sin(\delta_B)\sin(\gamma)}{1 + r_B^2 \pm 2 r_B \cos(\delta_B)\cos(\gamma)}$$

$$R_{CP} = \frac{\Gamma(B^- \to D^0_{CP}K^-) + \Gamma(B^+ \to D^0_{CP}K^+)}{\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to D^0 K^+)} = 1 + r_B^2 \pm 2 r_B \cos(\delta_B)\cos(\gamma)$$

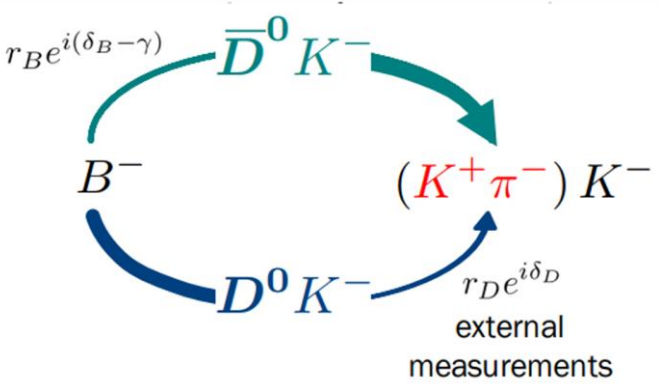
- r_B and δ_B need input
- Can extend to quasi-CP-eigenstates ($D \to KK\pi^0$)

γ - ADS Method

- CF or DCS decays e.g. $D \to K\pi$
- Atwood, Dunietz, Soni

[Phys. Rev. Lett. 78 (1997) 3257]

[Phys. Rev. D 63 (2001) 036005]



$$A_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) - \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)} = \frac{2 r_B r_D \sin(\delta_B+\delta_D)\sin(\gamma)}{r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B+\delta_D)\cos(\gamma)}$$

$$R_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)} = r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B+\delta_D)\cos(\gamma)$$

- r_B and δ_B can be obtained directly, but external input r_D and δ_D
- Can extend to multibody-DSC-decays ($D \to K\pi\pi^0$)

γ - BPGGSZ Method

- 3-body final states e.g. $D \rightarrow K^0_S \pi\pi$ [Phys. Rev. D 68 (2003) 054018]
- Bondar, Poluektov, Giri, Grossman, Soffer, Zupan [Phys. Rev. D 70 (2004) 072003]

$$d\Gamma_{B^\pm}(\mathbf{x}) = A^2_{(\pm,\mp)} + r_B^2 A^2_{(\mp,\pm)} + 2A_{(\pm,\mp)}A_{(\mp,\pm)}\left[\underbrace{r_B\cos(\delta_B \pm \gamma)}_{x_\pm}\cos(\delta_{D(\pm,\mp)}) + \underbrace{r_B\sin(\delta_B \pm \gamma)}_{y_\pm}\sin(\delta_{D(\pm,\mp)})\right]$$

$$r_B \exp[i(\delta_B \pm \gamma)] = x_\pm + iy_\pm$$

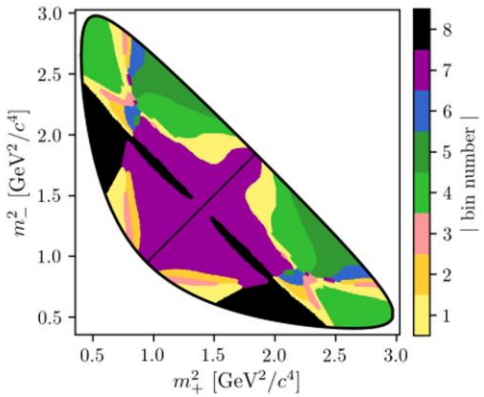
$$N^-_{\pm i} \propto F_{\pm i} + (x_-^2 + y_-^2)F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_\pm c_{\pm i} \mp y_\pm s_{\pm i})$$

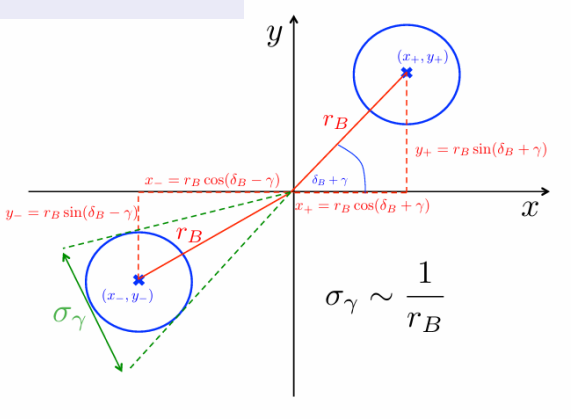
F_i : Fractional yield of flavour tagged D^0 into bin i

Measured in control channel: $\bar{B}^0 \rightarrow D^{*+}\mu^-\nu_\mu X$

c_i/s_i : Strong phase difference of $D^0 - \bar{D}^0$ decays

External input from BESIII and CLEO-c





γ - $B^0 \to DK^{*0}, D \to K^0_S h^+ h^-$

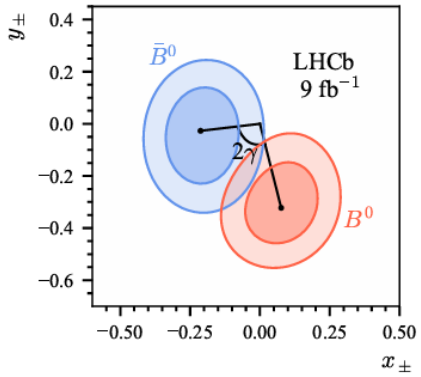
- BPGGSZ method: model-independent
- "Self-tagging" mode, flavor of the B^0 is determined by the charges of the K^{*0} daughters

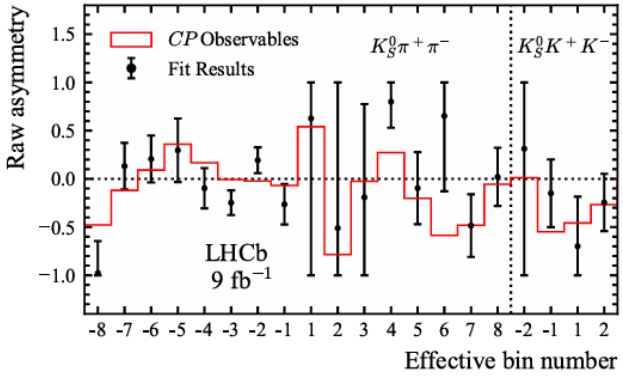
[LHCb-PAPER-2023-009, arXiv:2309.05514]

- Simultaneous fit to extract

$$x_\pm \equiv r_{B^0}^{DK^{(*)0}} \cos\left(\delta_{B^0}^{DK^{(*)0}} \pm \gamma\right)$$

$$y_\pm \equiv r_{B^0}^{DK^{(*)0}} \sin\left(\delta_{B^0}^{DK^{(*)0}} \pm \gamma\right)$$





- The best fit value is

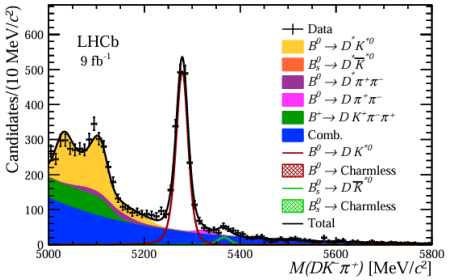
$$\gamma = (49^{+22}_{-19})^\circ$$

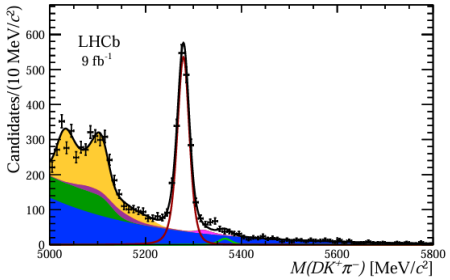
γ - $B^0 \to DK^*(892)^0, D \to hh'(\pi\pi)$

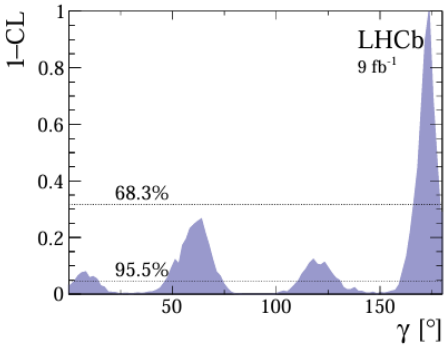
- GLW & ADS method
- Simultaneous measurement
  - $D \to K\pi(\pi\pi)$
  - $D \to \pi\pi(\pi\pi)$
  - $D \to KK$
- Multiple solutions
  - Solution most compatible with existing measurements is $\gamma = (61.7 \pm 8.0)^\circ$
- Combination with $K^0_S h^+ h^-$:

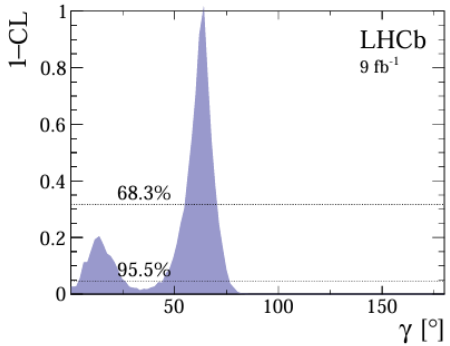
$$\gamma = (63.2^{+6.9}_{-8.1})^\circ$$

[LHCb-PAPER-2023-040, arXiv:2401.17934]









γ - $B^{\pm} \to DK^{*}(892)^{\pm}$

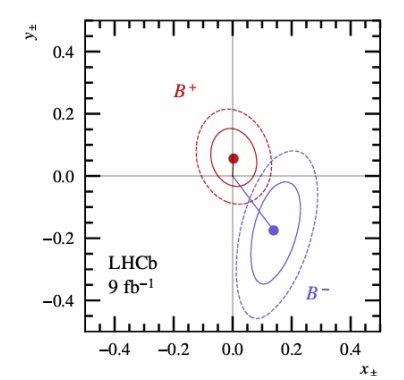
- Simultaneous measurement
  - $D \to K\pi(\pi\pi)$
  - $D \to \pi\pi(\pi\pi)$
  - $D \to KK$
  - $D \to K^0_S h^+ h^-$
- First observation of the the suppressed decays

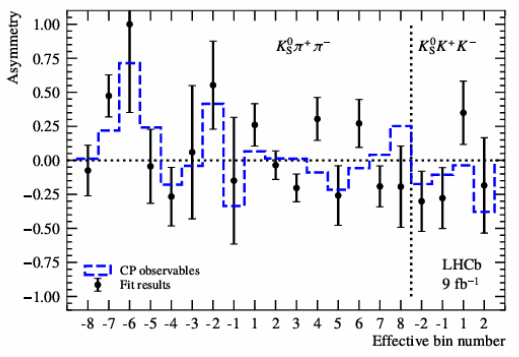
$$B^{\pm} \to DK^{*}(892)^{\pm},\ D \to K\pi(\pi\pi)$$

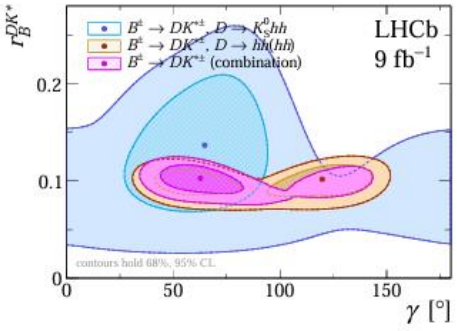
- The fit result is:

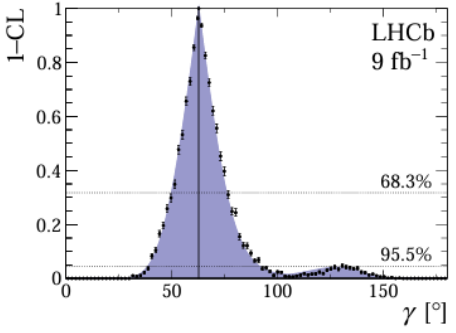
$$\gamma = (63 \pm 13)^{\circ}$$

[LHCb-PAPER-2024-023, arXiv:2410.21115]







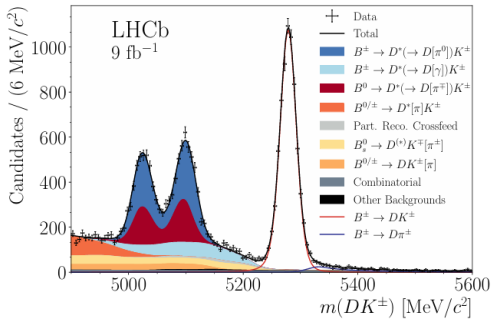


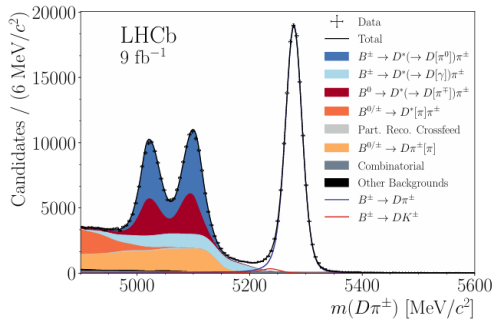
γ - $B^{\pm} \to D^{*}h^{\pm}, D \to K^{0}_{S}h^{+}h^{-}$

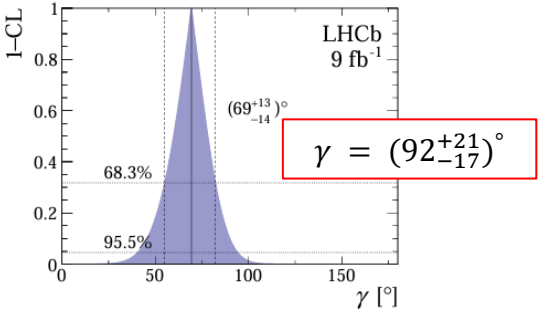
- BPGGSZ method

Partial reconstructed

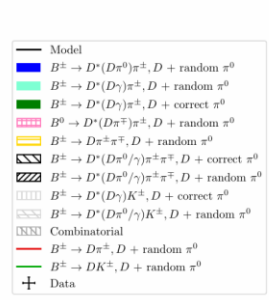
[LHCb-PAPER-2023-029, arXiv:2311.10434]

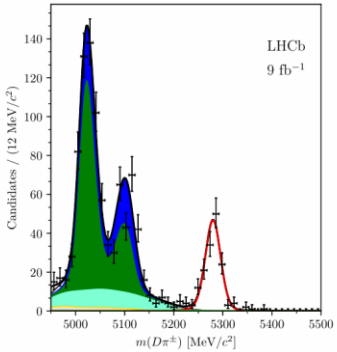


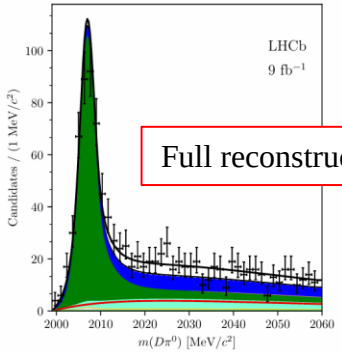




$\gamma = (92^{+21}_{-17})^{\circ}$

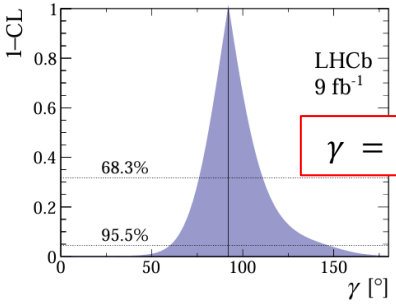






Full reconstructed

[LHCb-PAPER-2023-012, arXiv:2310.04277]

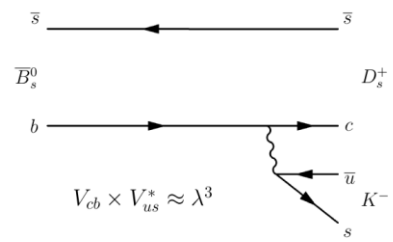


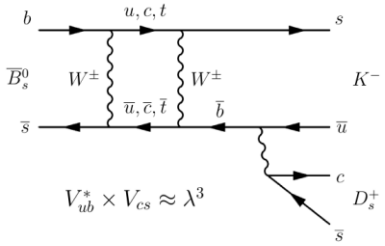
$\gamma = (69^{+13}_{-14})^{\circ}$

γ - $B_s^0 \rightarrow D_s^{\mp} K^{\pm}$

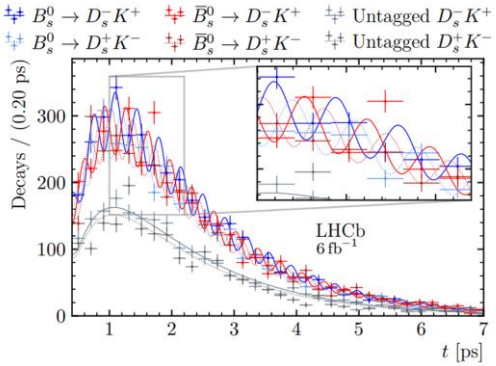
- Another golden decays: $B_s^0 \rightarrow D_s^{\mp} K^{\pm}$
  - Time-dependent measurement
  - CPV in mixing and decay
  - Larger interference: $r_B^{D_s K} \sim 0.4$ ($r_B^{DK^+} \sim 0.1$)
  - Sensitivity to $\gamma - 2\beta_s$

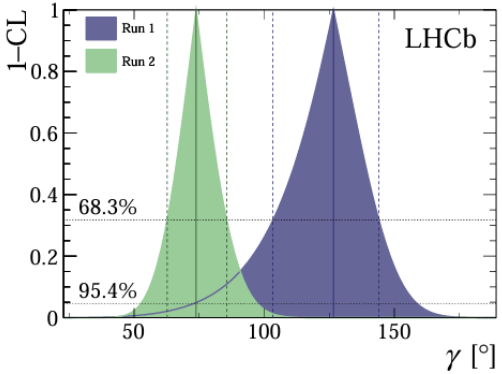
[LHCb-PAPER-2024-020, arXiv:2412.14074]





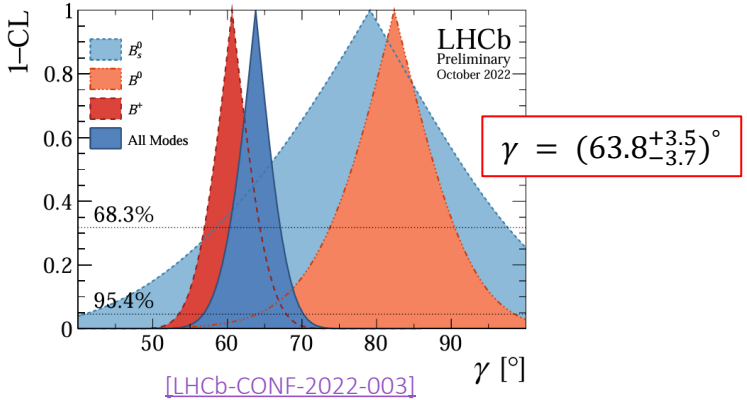
- Results:
  - Run1: $\gamma = (127^{+18}_{-26})^{\circ}$
  - Run2: $\gamma = (74 \pm 12)^{\circ}$
  - Combined: $\gamma = (81^{+12}_{-11})^{\circ}$





γ – LHCb Combination

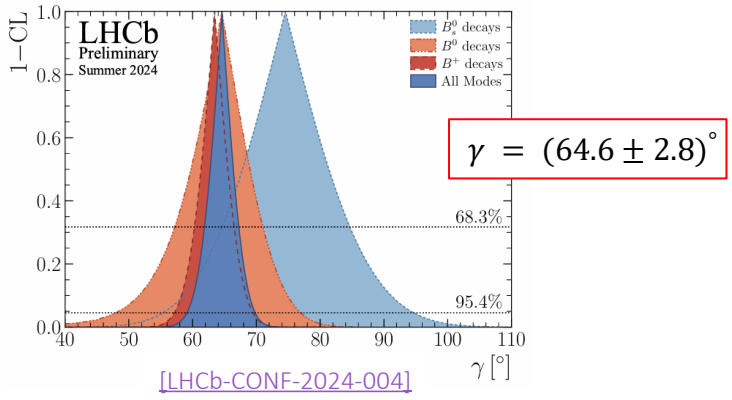
- Combination of all LHCb public results: $\sigma(\gamma) < 3^{\circ}$, much more precise than the 4° goal in Run1&2 [arXiv:1808.08865]
- Previous tension between charged and neutral B resolved
- Large uncertainty for B_s^0 mode



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

[LHCb-CONF-2022-003]

Species	Value [°]	68.3% CL Uncertainty [°]	95.4% CL Uncertainty [°]
B^+	60.6	$^{+4.0}_{-3.8}$	$^{+7.8}_{-7.5}$
B^0	82.0	$^{+8.1}_{-8.8}$	$^{+17}_{-18}$
B_s^0	79	$^{+21}_{-24}$	$^{+51}_{-47}$
All	63.8	$^{+3.5}_{-3.7}$	$^{+6.9}_{-7.5}$



$\gamma = (64.6 \pm 2.8)^{\circ}$

[LHCb-CONF-2024-004]

Species	Value [°]	68.3% CL Uncertainty [°]	95.4% CL Uncertainty [°]
B^+	63.4	$^{+3.2}_{-3.3}$	$^{+6.4}_{-6.5}$
B^0	64.6	$^{+6.5}_{-7.5}$	$^{+12}_{-17}$
B_s^0	75	$^{+10}_{-11}$	± 20
All	64.6	± 2.8	$^{+5.5}_{-5.7}$

$\sin(2\beta)$ - Methods

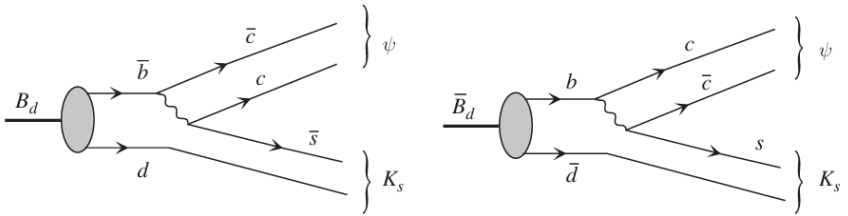
- Golden measurement channel: $B^0 \to \psi K_S^0$
  - Clean experimental signature: $\psi(\to l^+l^-)$, $K_S^0(\to \pi^+\pi^-)$
- Tree dominated $b \to c\bar{c}s$ transition
- Time-dependent *CP* asymmetry:

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to J/\psi K_S) - \Gamma(B^0(t) \to J/\psi K_S)}{\Gamma(\bar{B}^0(t) \to J/\psi K_S) + \Gamma(B^0(t) \to J/\psi K_S)} = \sin(2\beta)\sin(\Delta m_d t)$$

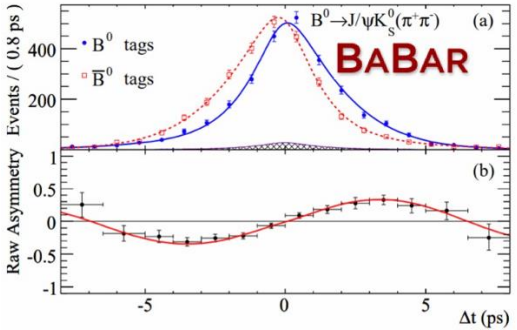
- Historical impact:
  - First observed CP violation outside the kaon system
  - Landmark result for B-factories (BaBar & Belle)

[PRL 108 (2012) 171802]

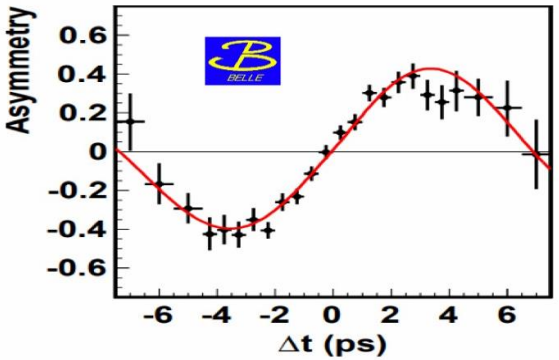
[PRD 79 (2009) 072009]



$\sin 2\beta = 0.687 \pm 0.028 \pm 0.012$



$\sin 2\phi_1 = 0.667 \pm 0.023 \pm 0.012$

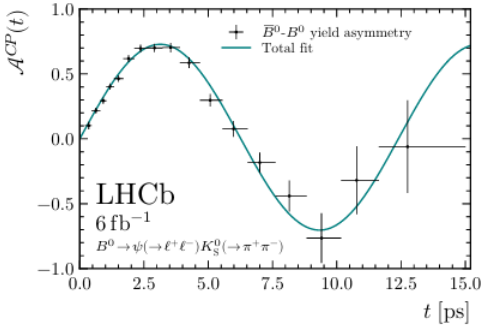


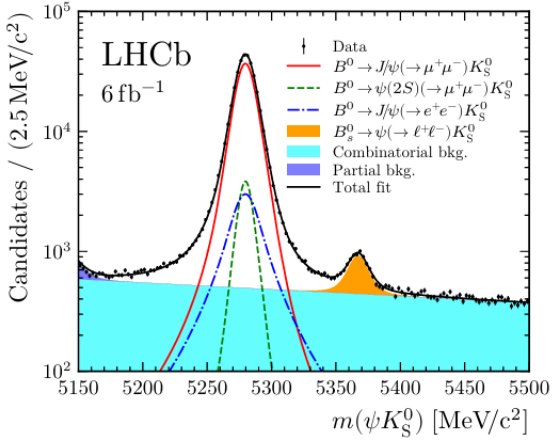
$\sin(2\beta)$ - $B^0 \to \psi(\to l^+l^-)K^0_S(\to \pi^+\pi^-)$

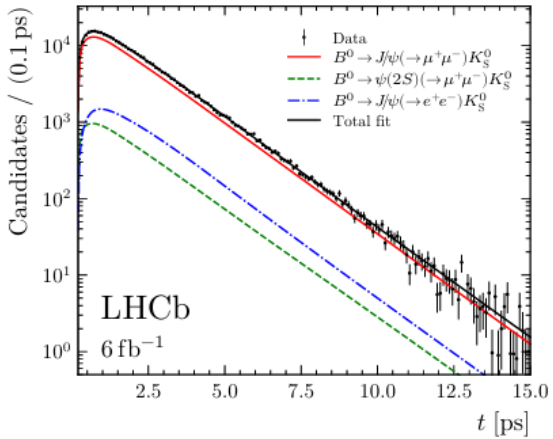
- LHCb Run2 (6 fb^{-1}) results using $B^0 \to J/\psi\, K^0_S$ and $B^0 \to \psi(2S)\, K^0_S$
- Flavor-tagged time-dependent analysis to determine observables related to angle β:

[LHCb-PAPER-2023-013, arXiv:2309.09728]

$$S^{\text{Run 1\&2}}_{\psi K^0_S} = 0.724 \pm 0.014\,(\text{stat+syst})$$
$$C^{\text{Run 1\&2}}_{\psi K^0_S} = 0.004 \pm 0.012\,(\text{stat+syst})$$

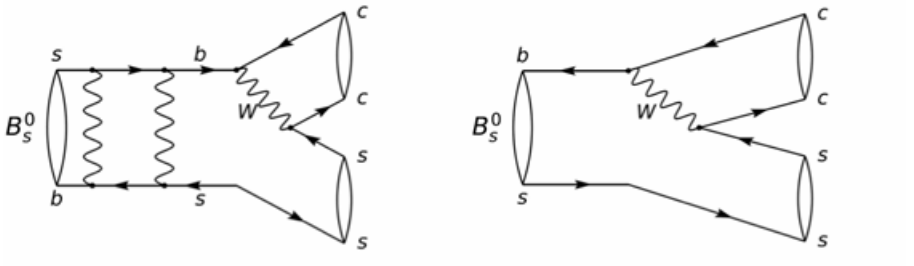




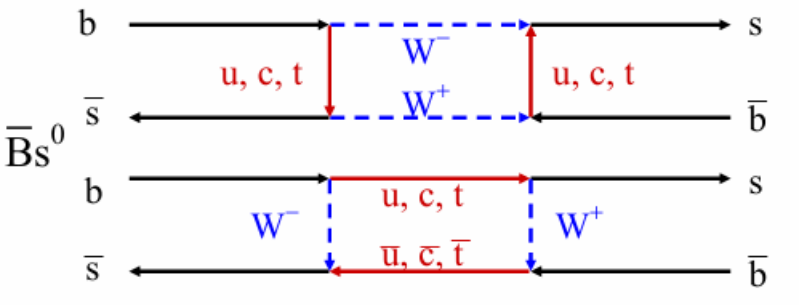


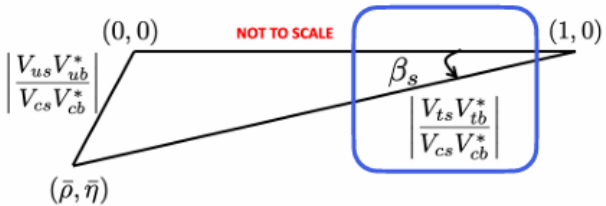
ϕ_s - Methods

- This angle arises in $B_s^0 - \bar{B}_s^0$ mixing,
- Mearing via $B_s^0 \to J/\psi\,\phi$
  - Clean experimental signature
    $J/\psi \to \mu^+\mu^-, \phi \to K^+K^-$
- Larger values possible in models of New Physics



SM predicts: $\phi_s^{CKMFitter} \approx -2\beta_s = (-0.0368^{+0.0006}_{-0.0009})$ rad





$$\phi_s \approx -2\beta_s = 2arg(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*})$$

(ignoring penguin contribution)

ϕ_s - $B_s^0 \to J/\psi K^+K^-$

- Measure ϕ_s using $B_s^0 \to J/\psi K^+K^-$ in the vicinity of $\phi(1020)$ meson
- Full LHCb Run 2 dataset
- Angular analysis
- Simultaneous fit of decay time and angular distributions
- The fit result

$$\phi_s = -0.039 \pm 0.022 \pm 0.006 \text{ rad}$$

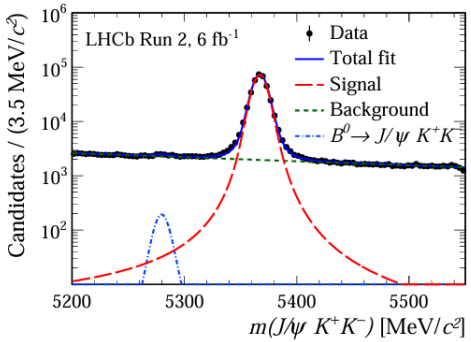
- Combined with Run 1

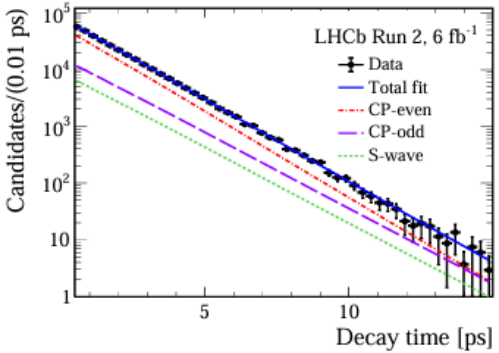
$$\phi_s = -0.044 \pm 0.020 \text{ rad}$$

- Combined over $b \to c\bar{c}s$ transition

$$\phi_s = -0.031 \pm 0.018 \text{ rad}$$

[LHCb-PAPER-2023-016, arXiv:2308.01468]





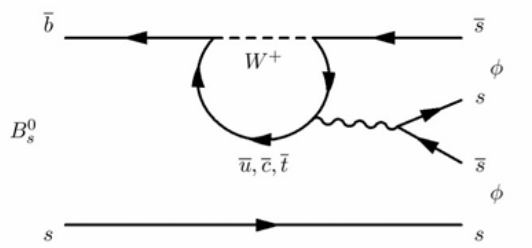
$\phi_s^{s\bar{s}s}$ - $B_s^0 \to \phi\phi$

- Very similar analysis strategy as $B_s^0 \to J/\psi K^+K^-$
- Time-dependent flavor-tagged angular analysis
- Full Run 2 dataset
- The fit result:

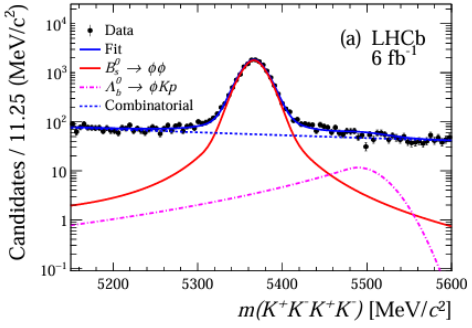
$$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009 \text{ rad}$$

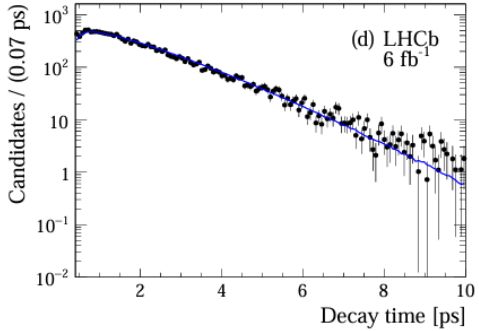
- Combined with Run 1:

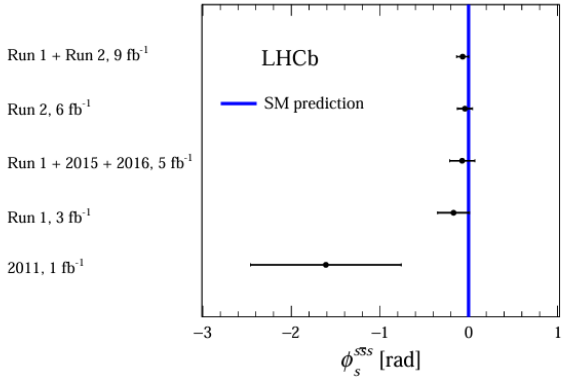
$$\phi_s^{s\bar{s}s} = -0.074 \pm 0.069 \text{ rad}$$



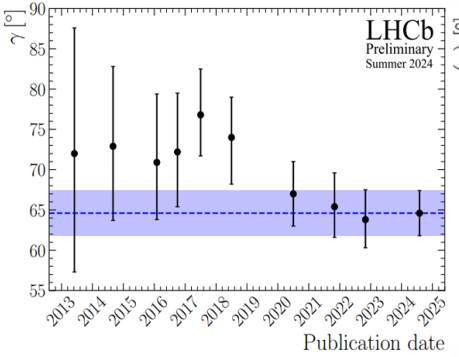
[LHCb-PAPER-2023-001, arXiv:2304.06198]

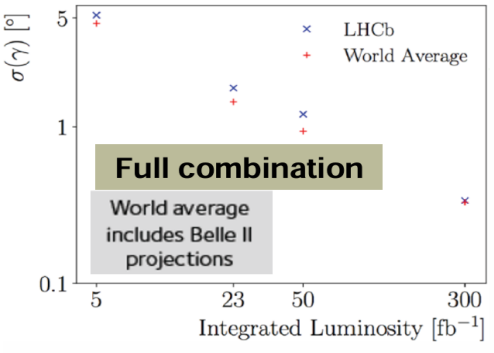


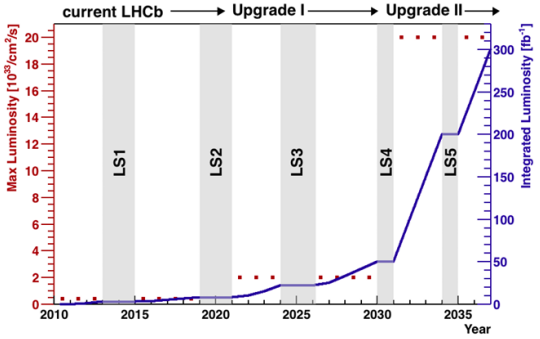




Future prospects







Observable	Upgrade II
γ, with $B_s^0 \to D_s^+ K^-$	1°
γ, all modes	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.003
ϕ_s, with $B_s^0 \to J/\psi\phi$	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	11 mrad

[arXiv:1808.08865]

Summary

Observable	Decay mode	Method	Value	Reference
γ	$B^0 \to DK^{*0}, D \to K^0_S h^+ h^-$	BPGGSZ	$\gamma = (49^{+22}_{-19})^\circ$	[LHCb-PAPER-2023-009]
	$B^0 \to DK^*(892)^0, D \to hh'(\pi\pi)$	GLW & ADS	Multiple solutions	[LHCb-PAPER-2023-040]
	$B^\pm \to DK^*(892)^\pm$	GLW, ADS & BPGGSZ	$\gamma = (63 \pm 13)^\circ$	[LHCb-PAPER-2024-023]
	$B^\pm \to D^* h^\pm, D \to K^0_S h^+ h^-$ Partial reconstructed	BPGGSZ	$\gamma = (92^{+21}_{-17})^\circ$	[LHCb-PAPER-2023-029]
	$B^\pm \to D^* h^\pm, D \to K^0_S h^+ h^-$ Full reconstructed	BPGGSZ	$\gamma = (69^{+13}_{-14})^\circ$	[LHCb-PAPER-2023-012]
	$B^0_s \to D^\mp_s K^\pm$	Time-dependent	$\gamma = (74 \pm 12)^\circ$	[LHCb-PAPER-2024-020]
$sin(2\beta)$	$B^0 \to \psi(\to l^+ l^-) K^0_S(\to \pi^+\pi^-)$	Time-dependent	$S^{\text{Run 1\&2}}_{\psi K^0_S} = 0.724 \pm 0.014\,(\text{stat+syst})$ $C^{\text{Run 1\&2}}_{\psi K^0_S} = 0.004 \pm 0.012\,(\text{stat+syst})$	[LHCb-PAPER-2023-013]
ϕ_s	$B^0_s \to J/\psi K^+ K^-$	Time-dependent	$\phi_s = -0.039 \pm 0.022 \pm 0.006$ rad	[LHCb-PAPER-2023-016]
$\phi_s^{s\bar{s}s}$	$B^0_s \to \phi\phi$	Time-dependent	$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009$ rad	[LHCb-PAPER-2023-001]

Thanks