CPV and mixing in B decays at LHCb

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on behalf of the LHCb Collaboration

Implications of LHCb measurements and future prospects
25–27 Oct 2023

Co-financed by the Connecting Europe Facility of the European Union

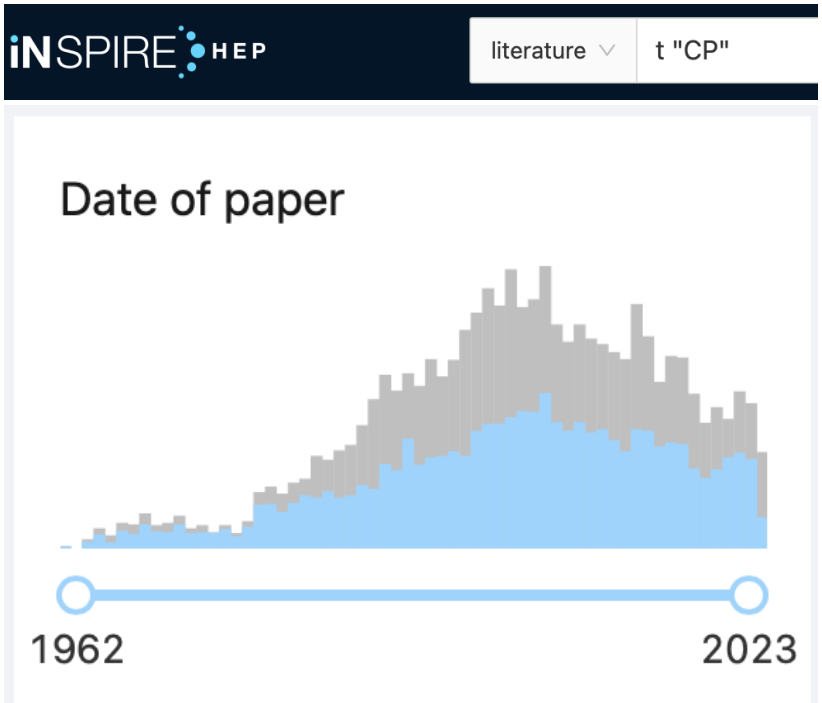
Introduction

The SM mechanism of CP Violation (still) gives an accurate picture of nature: no clear indication of NP

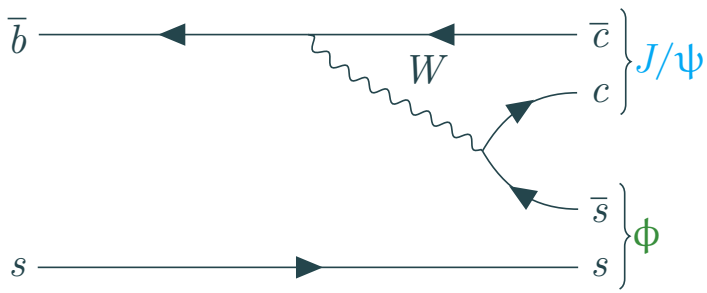
CP violation generally represents a major constraint on models beyond the SM.

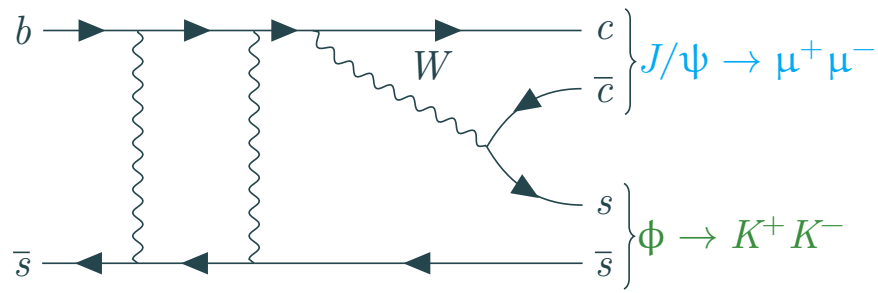
What this talk covers:

- The angles $\phi_{s,d}$, $\phi_s^{s\bar{s}s}$
- Mixing parameter $\Delta\Gamma_s$
- γ from various $B \to Dh$ decays



Time-dependent CPV in B decays



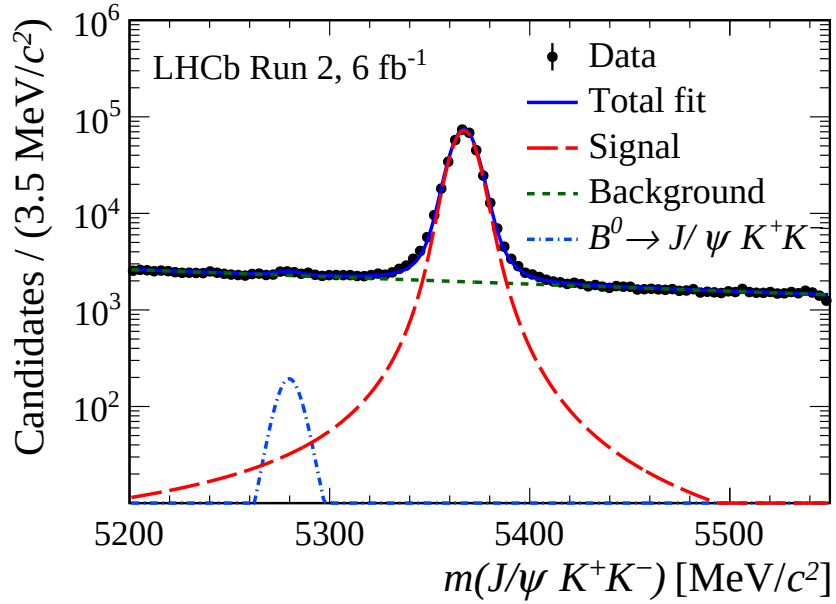


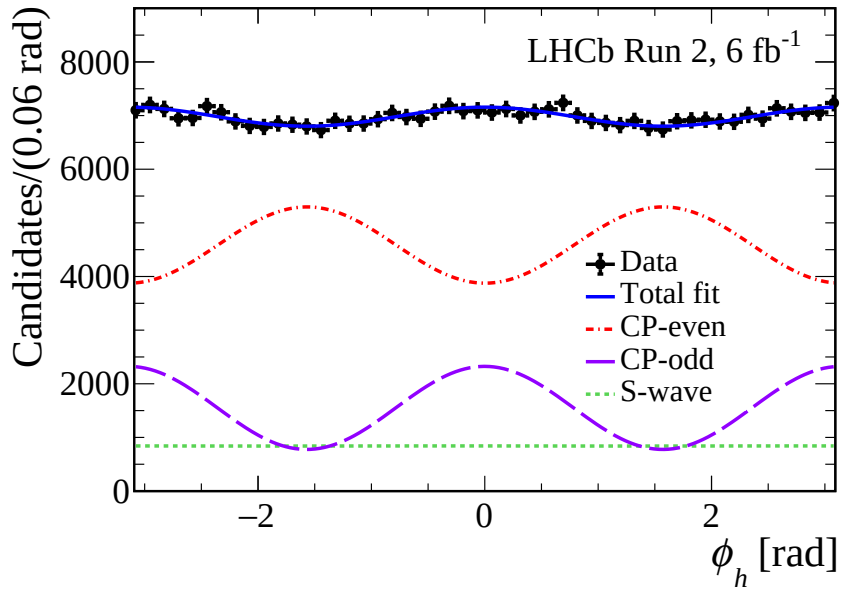
$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0_{(s)} \to f) - \Gamma(B^0_{(s)} \to f)}{\Gamma(\overline{B}^0_{(s)} \to f) + \Gamma(B^0_{(s)} \to f)} = \frac{S_f^{d(s)} \sin(\Delta m_{d(s)} t) - C_f^{d(s)} \cos(\Delta m_{d(s)} t)}{\cosh(\Delta\Gamma_{d(s)} t/2) + D_f^{d(s)} \sinh(\Delta\Gamma_{d(s)} t/2)}$$

ϕ_s FROM $B_s^0 \to J/\psi K^+K^-$ [PAPER-2023-016]

- $S_f \approx sin(\phi_s)$ and $\phi_s \approx -2\beta_s$
- Time dependent-flavor tagged-angular analysis
- Using full run 2 data
- Polarization dependent results (statistical only):

Parameters	Values
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]	$0.022^{+0.027}_{-0.026}$
$\lvert\lambda^0\rvert$	$0.969^{+0.025}_{-0.024}$
$\lvert\lambda^{\parallel}/\lambda^0\rvert$	$0.982^{+0.055}_{-0.052}$
$\lvert\lambda^{\perp}/\lambda^0\rvert$	$1.107^{+0.082}_{-0.076}$
$\lvert\lambda^{S}/\lambda^0\rvert$	$1.121^{+0.084}_{-0.078}$





ϕ_s FROM $B_s^0 \to J/\psi K^+K^-$ [PAPER-2023-016]

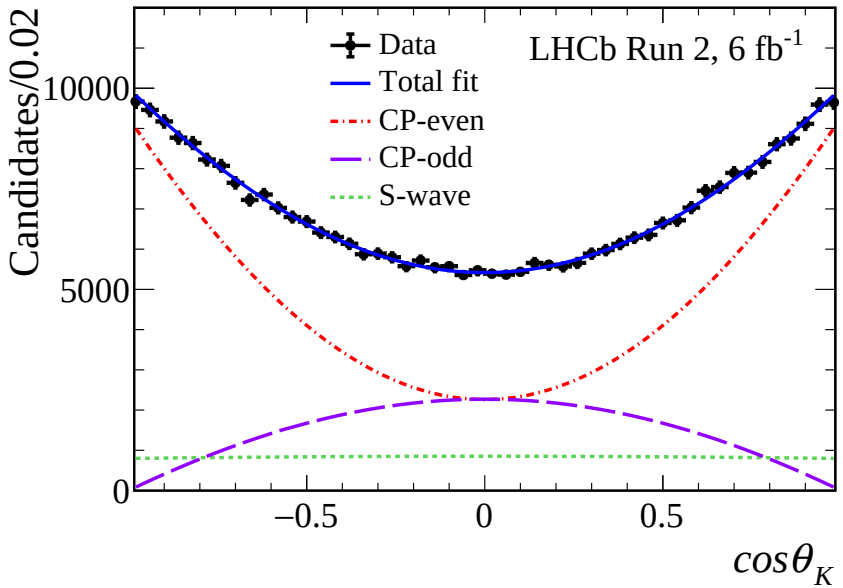
- Polarization independent results:

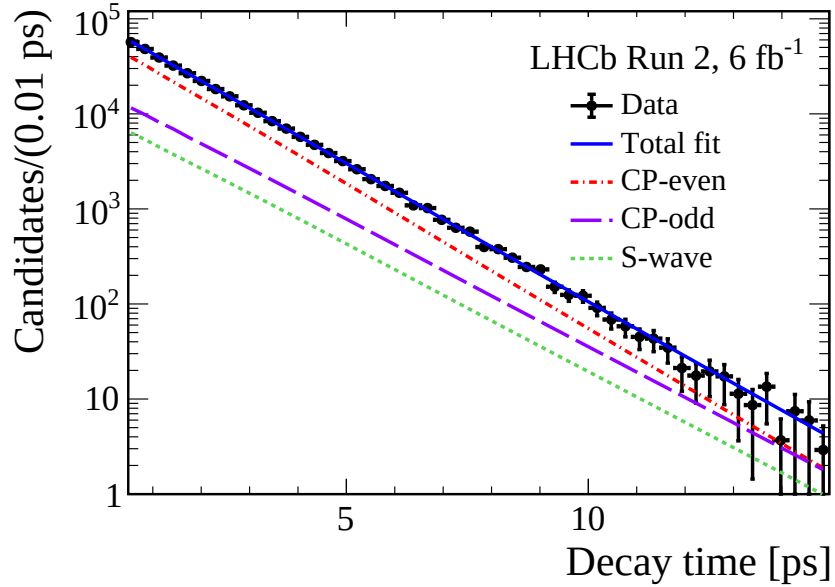
Parameter	Values		
ϕ_s [rad]	-0.039	± 0.022	± 0.006
$\lvert\lambda\rvert$	1.001	± 0.011	± 0.005
$\Gamma_s - \Gamma_d$ [ps^{-1}]	-0.0056	$^{+0.0013}_{-0.0015}$	± 0.0014
$\Delta\Gamma_s$ [ps^{-1}]	0.0845	± 0.0044	± 0.0024
Δm_s [ps^{-1}]	17.743	± 0.033	± 0.009
$\lvert A_\perp\rvert^2$	0.2463	± 0.0023	± 0.0024
$\lvert A_0\rvert^2$	0.5179	± 0.0017	± 0.0032
$\delta_\perp - \delta_0$ [rad]	2.903	$^{+0.075}_{-0.074}$	± 0.048
$\delta_\parallel - \delta_0$ [rad]	3.146	± 0.061	± 0.052

- Combined with run 1:

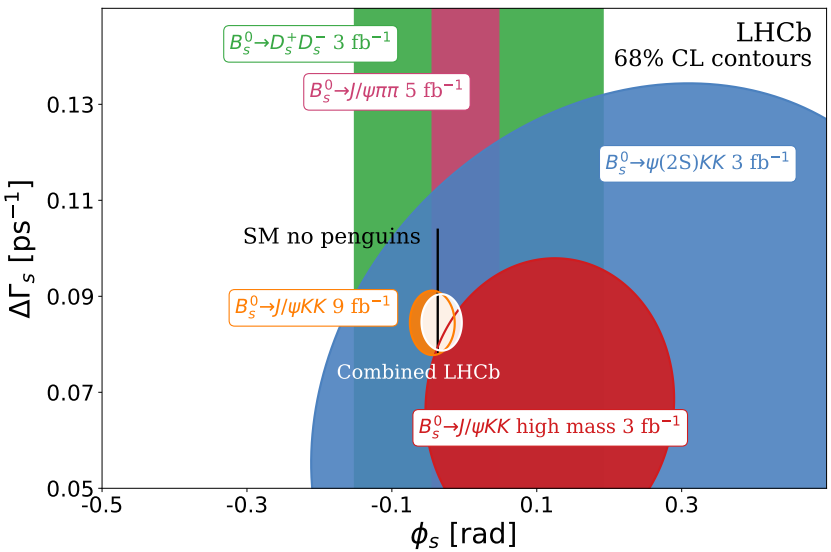
$\phi_s = -0.044 \pm 0.020$ rad

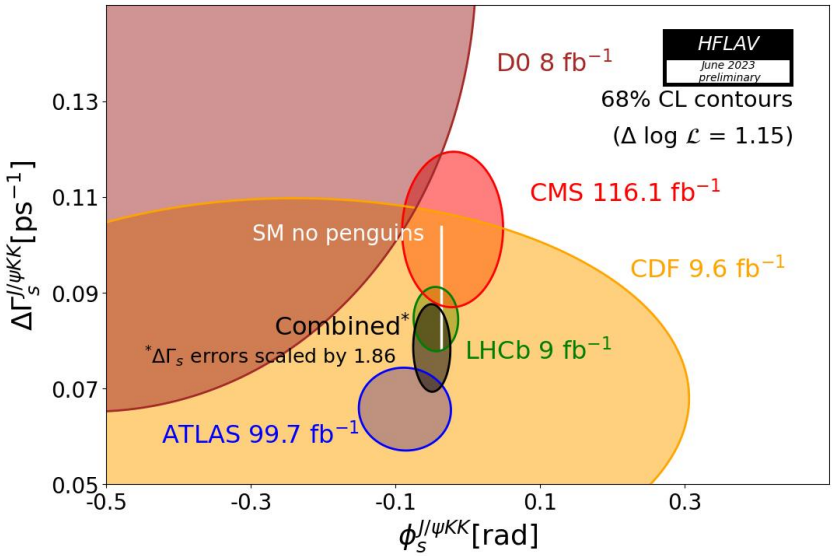
$\lambda = 0.990 \pm 0.010$





Every ϕ_s from LHCb [PAPER-2023-016]





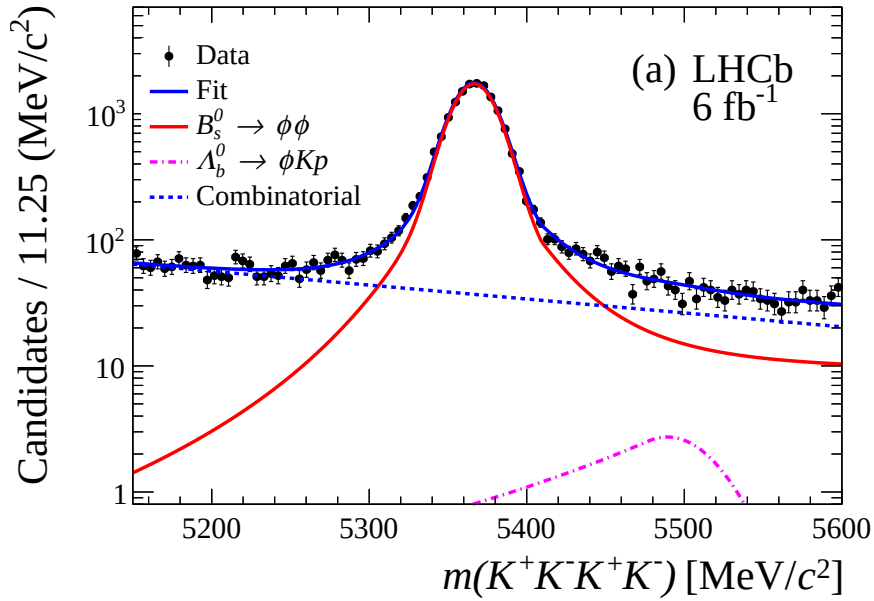
HFLAV 2021 $\Rightarrow$ HFLAV 2023

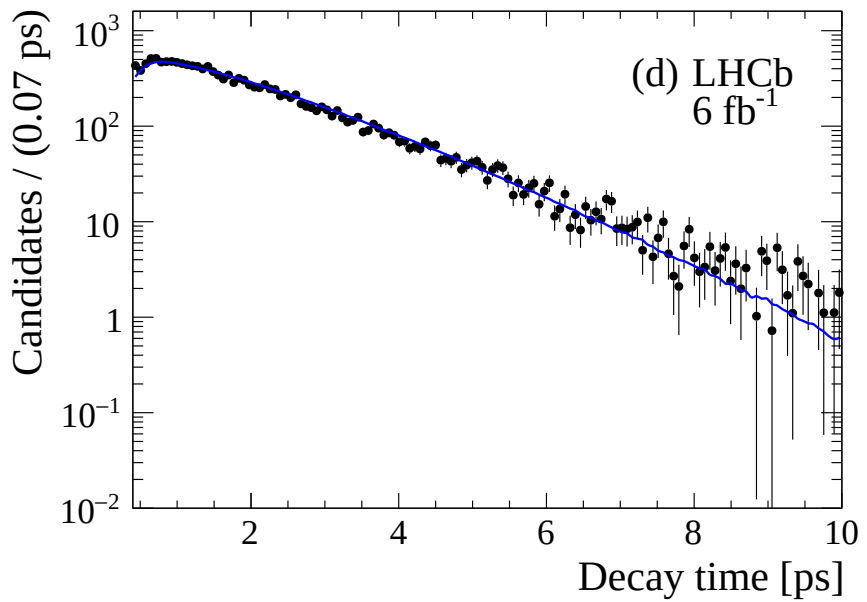
$$\phi_s^{c\bar{c}s} = -0.049 \pm 0.019 \Rightarrow -0.039 \pm 0.016 [\text{rad}]$$
$$\Delta\Gamma_s = 0.074 \pm 0.006\ \text{ps}^{-1} \Rightarrow 0.080 \pm 0.006\ [\text{ps}^{-1}]$$
$$\Gamma_s = 0.6627 \pm 0.0036\ \text{ps}^{-1} \Rightarrow 0.6620 \pm 0.0033\ [\text{ps}^{-1}]$$

$\phi_s^{s\bar{s}s}$ FROM $B_s \to \phi\phi$ [PAPER-2023-001]

- $S_f \approx sin(\phi_s^{s\bar{s}s}$ and $\phi_s^{s\bar{s}s} \approx 0$ in SM
- Time dependent-flavor tagged-angular analysis
- Using full run 2 data
- Results:

Parameter	Result
$\phi_s^{s\bar{s}s}$ [rad]	$-0.042 \pm 0.075 \pm 0.009$
$\lvert\lambda\rvert$	$1.004 \pm 0.030 \pm 0.009$
$\lvert A_0\rvert^2$	$0.384 \pm 0.007 \pm 0.003$
$\lvert A_\perp\rvert^2$	$0.310 \pm 0.006 \pm 0.003$
$\delta_\parallel - \delta_0$ [rad]	$2.463 \pm 0.029 \pm 0.009$
$\delta_\perp - \delta_0$ [rad]	$2.769 \pm 0.105 \pm 0.011$



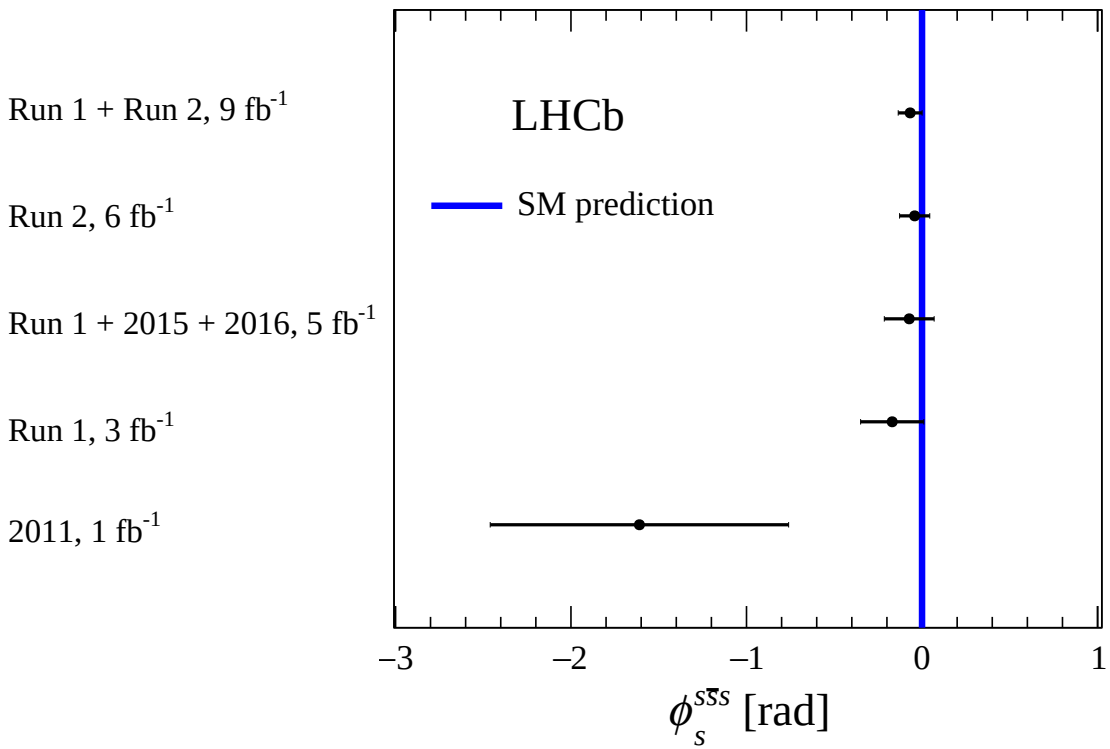


$\phi_s^{s\bar{s}s}$ FROM $B_s \to \phi\phi$ [PAPER-2023-001]

- Polarization dependent results (statistical only):

$$\begin{aligned} \phi_{s,0} &= -0.18 \pm 0.09 \text{ rad}, & |\lambda_0| &= 1.02 \pm 0.17, \\ \phi_{s,\parallel} - \phi_{s,0} &= 0.12 \pm 0.09 \text{ rad}, & |\lambda_\perp/\lambda_0| &= 0.97 \pm 0.22, \\ \phi_{s,\perp} - \phi_{s,0} &= 0.17 \pm 0.09 \text{ rad}, & |\lambda_\parallel/\lambda_0| &= 0.78 \pm 0.21, \end{aligned}$$

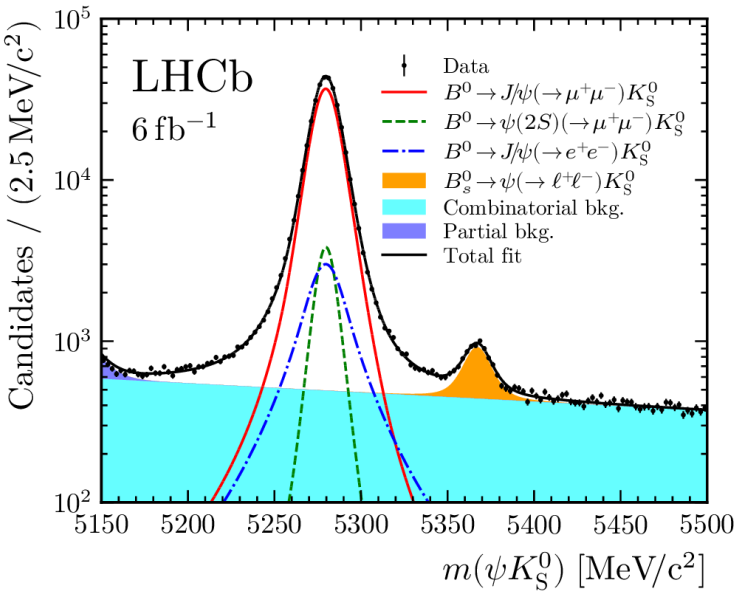
- Combined with run 1:

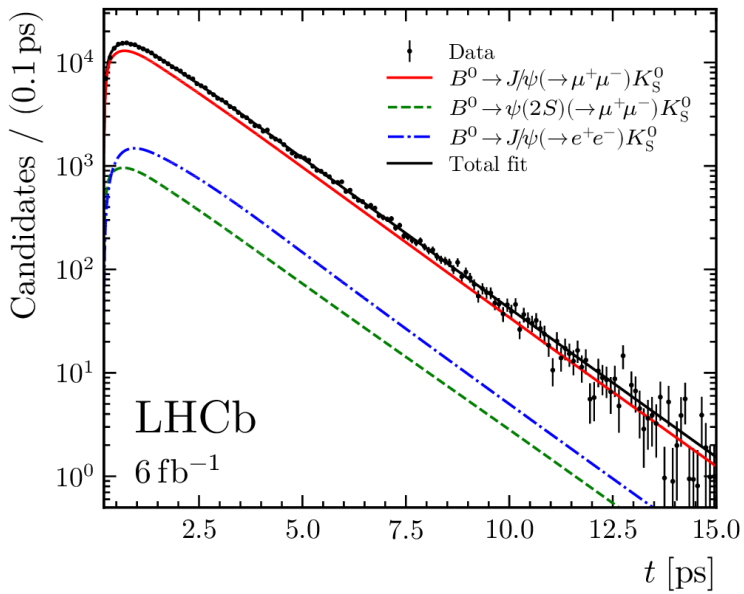


$\sin 2\beta$ FROM $B^0 \to \psi(\to l^+l^-)K_S(\to \pi^+\pi^-)$ [PAPER-2023-013]

- $S_f \approx sin(2\beta)$
- Time dependent-flavor tagged analysis
- Using full run 2 data
- Results:
  $S_{\psi K^0_S} = 0.7158 \pm 0.0133 \pm 0.0078$
  $C_{\psi K^0_S} = 0.0120 \pm 0.0123 \pm 0.0029$

- Use three decay modes
  - $B^0 \to J/\psi(\to \mu^+\mu^-)\, K^0_S$ ~306k signal decays
  - $B^0 \to \psi(2S)(\to \mu^+\mu^-)\, K^0_S$ ~23k signal decays
  - $B^0 \to J/\psi(\to e^+e^-)\, K^0_S$ ~43k signal decays





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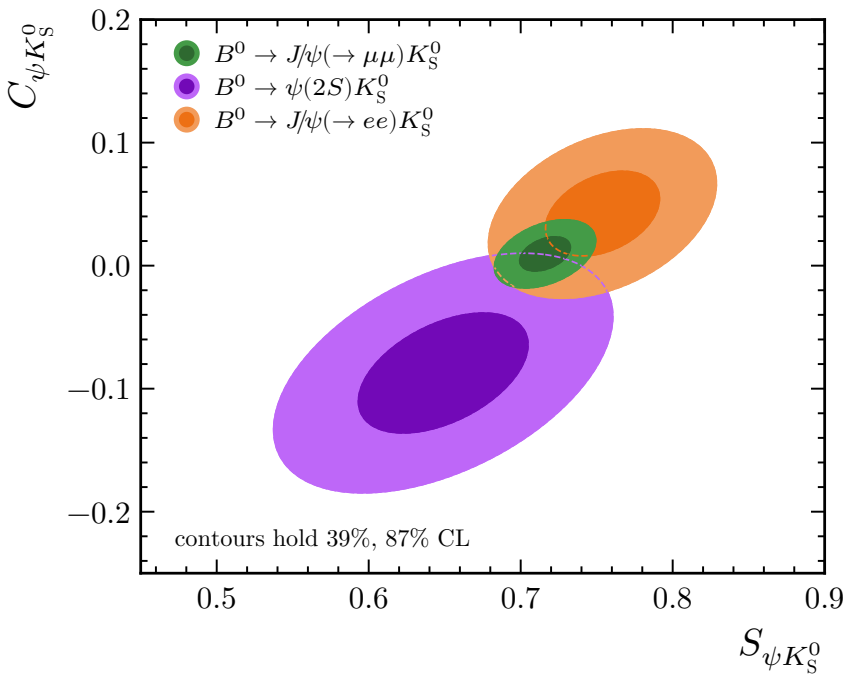
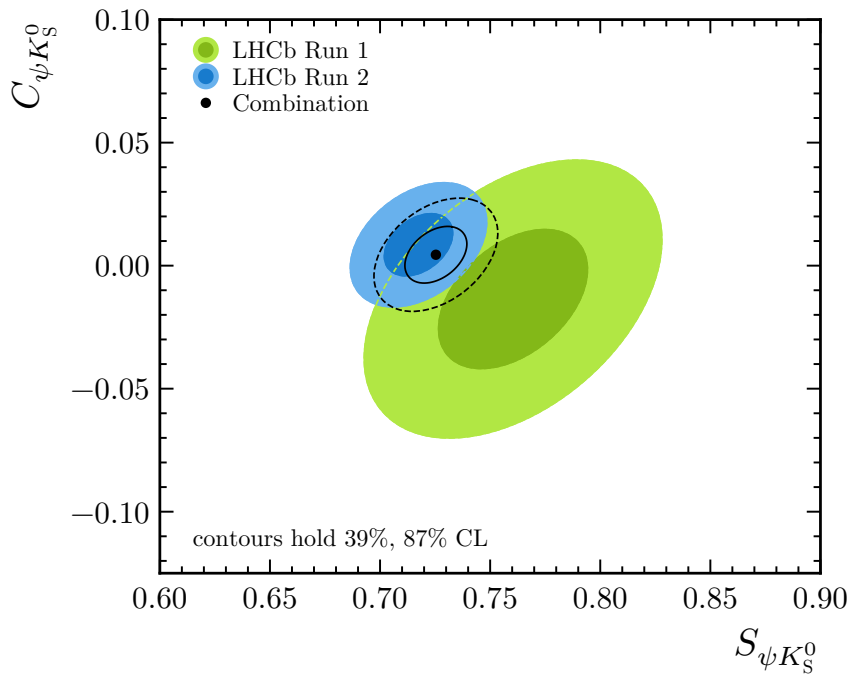


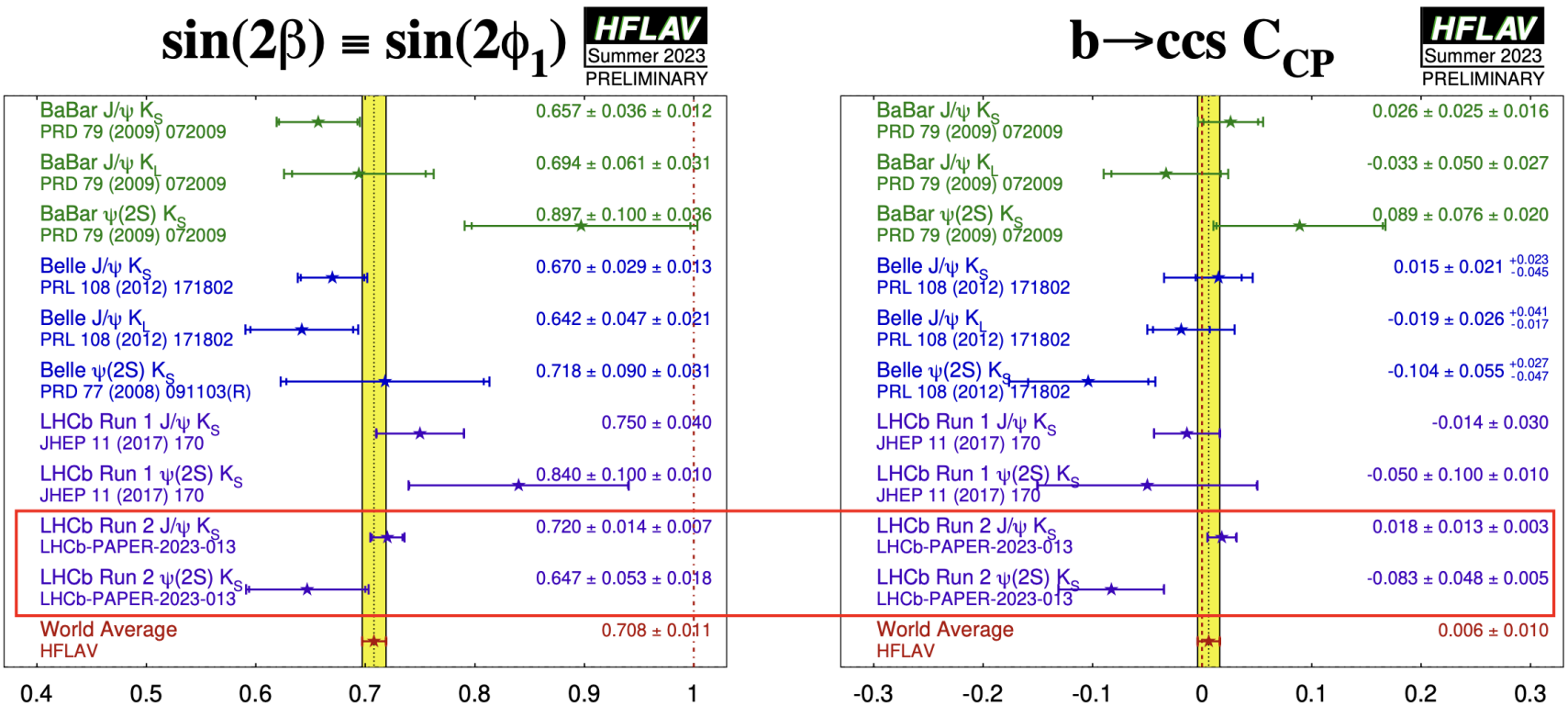


$\sin 2\beta$ FROM $B^0 \to \psi(\to l^+l^-)K_S(\to \pi^+\pi^-)$ [PAPER-2023-013]

HFLAV 2021 $\Rightarrow$ HFLAV 2023

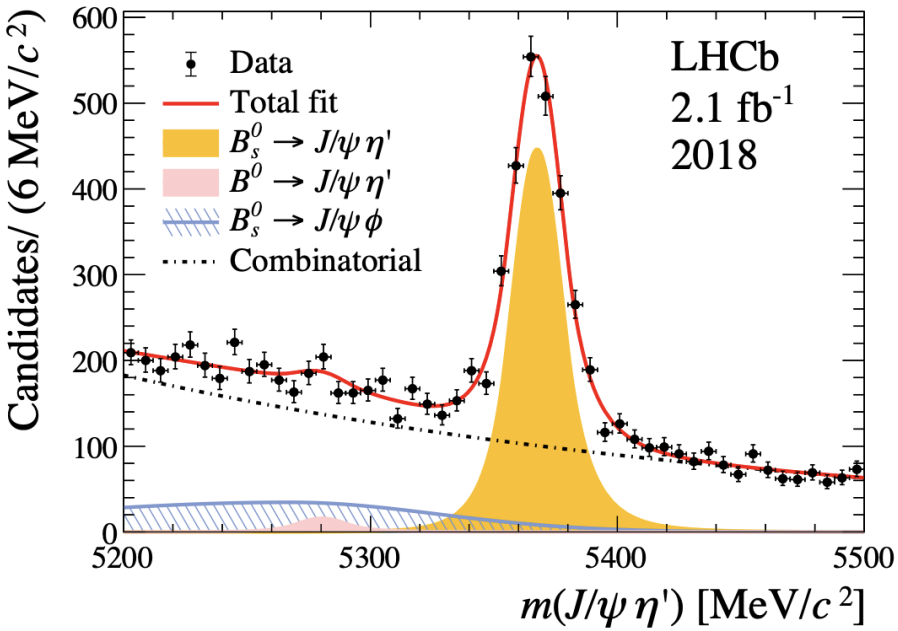
$sin(2\beta) = 0.699 \pm 0.017 \Rightarrow 0.708 \pm 0.011$

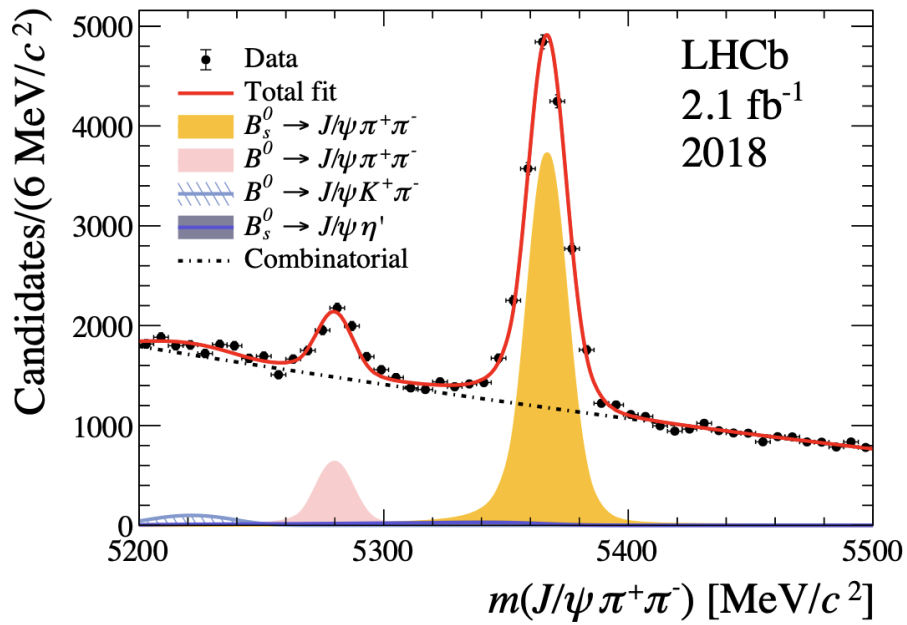
$C_{CP} = 0.005 \pm 0.015 \Rightarrow 0.006 \pm 0.010$



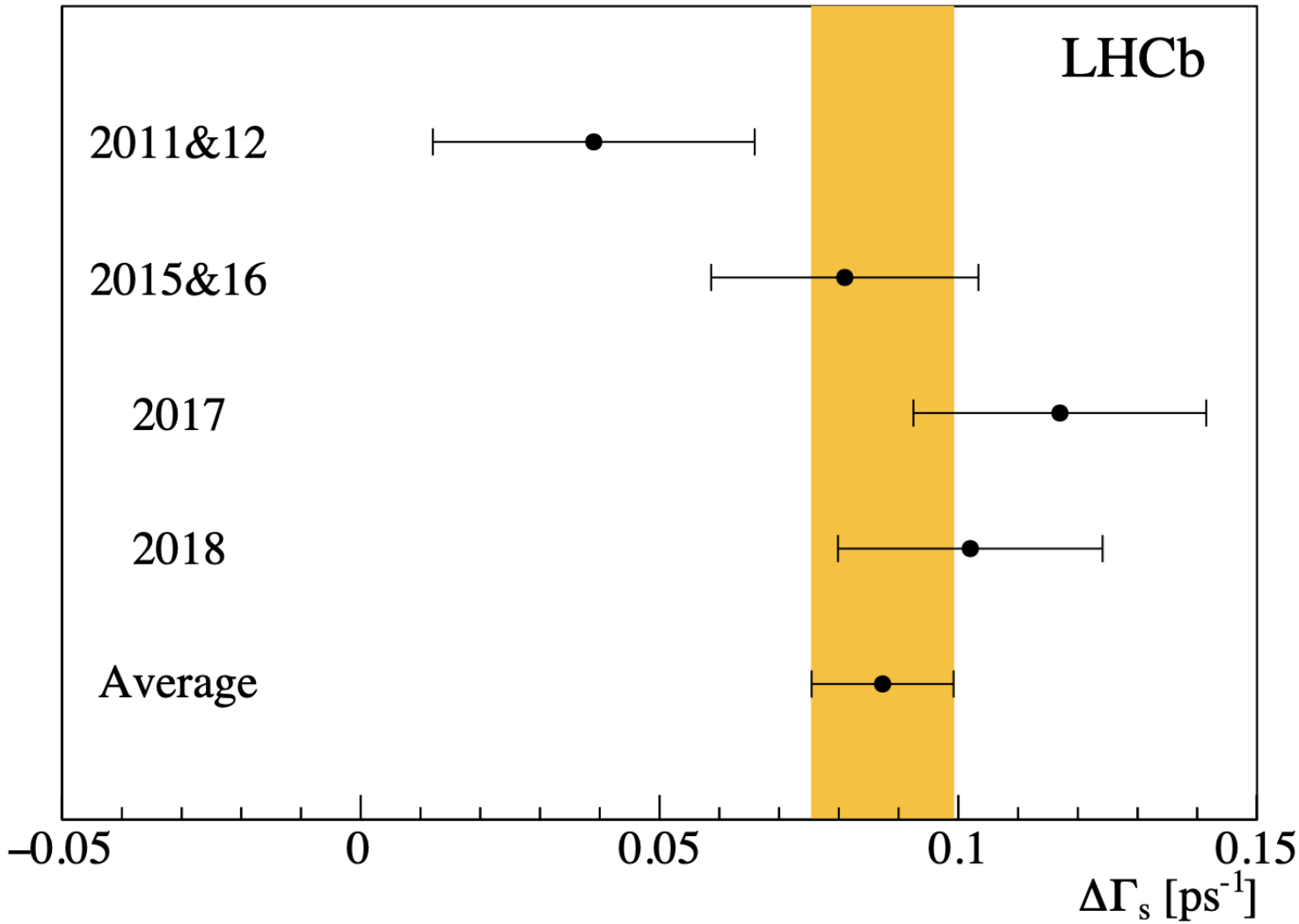
$\Delta\Gamma_s$ MEASUREMENT [PAPER-2023-025]

- CP-even $B_s^0 \to J/\psi\eta'(\to \rho^0\gamma)$ and CP-odd $B_s^0 \to J/\psi f0(980)(\to \pi^+\pi^-)$
- Extended unbinned simultaneous maximum-likelihood fit to the 8 decay-time bins
- Ratio of yields in each bin is corrected by the relative decay-time acceptance





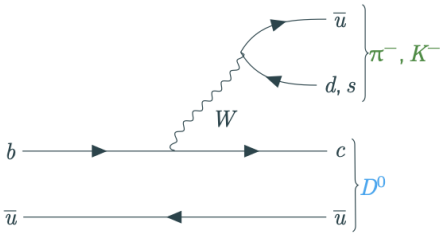
$\Delta\Gamma_s$ MEASUREMENT [PAPER-2023-025]



$$\Delta\Gamma_s = 0.087 \pm 0.012 \pm 0.009 ps^{-1}$$

HFLAV: $\Delta\Gamma_s = 0.080 \pm 0.006 ps^{-1}$

γ measurements at LHCb



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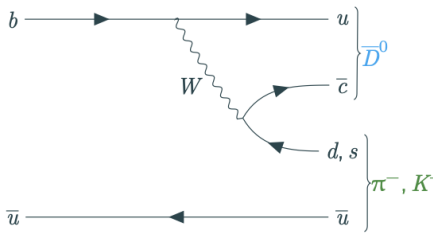
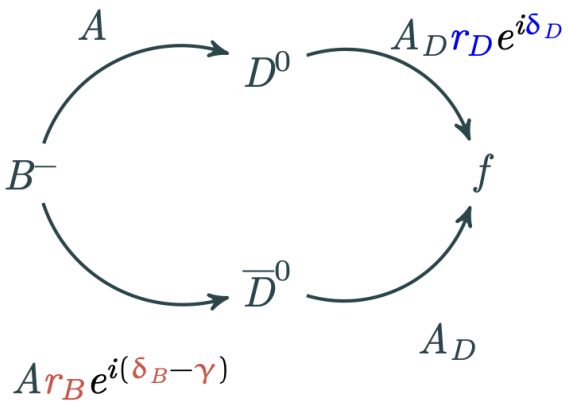


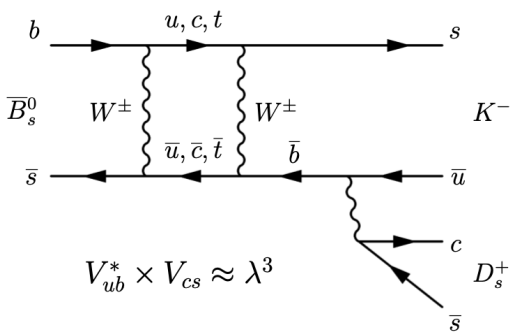
suppressed

$$|A(B^-)|^2 \propto A_D^2 + r_B^2 A_{\bar{D}}^2 + 2A_D A_{\bar{D}} r_B \cos(\delta_B - \gamma)$$

$$|A(B^+)|^2 \propto A_D^2 + r_B^2 A_{\bar{D}}^2 + 2A_D A_{\bar{D}} r_B \cos(\delta_B + \gamma)$$

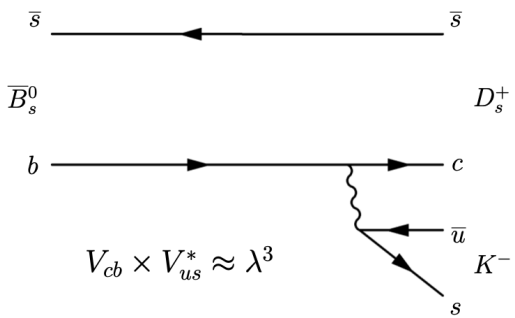


- Use final states accessible to both D and $\bar{D}$ to examine interference between $b \to c$ and $b \to u$ quark transitions
- Measurement technique depends on D-decay mode



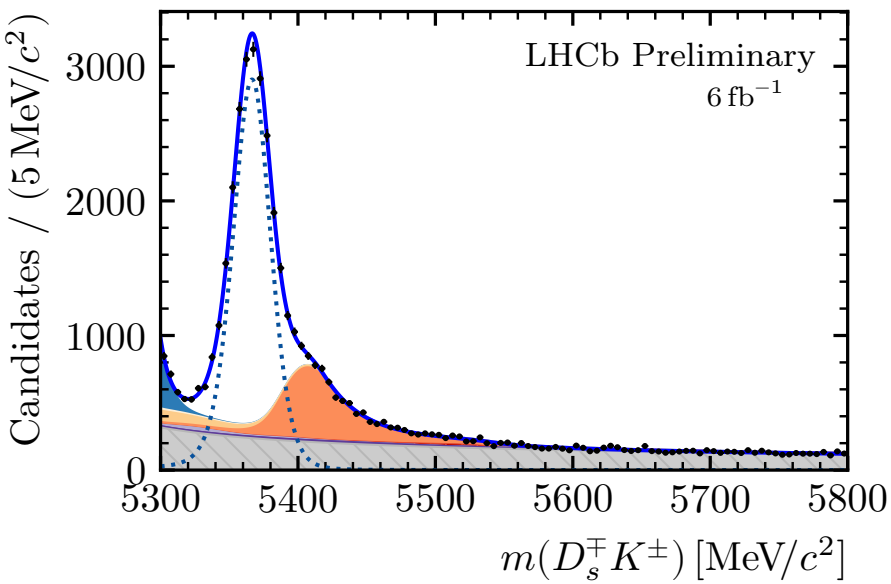
Relative phase:

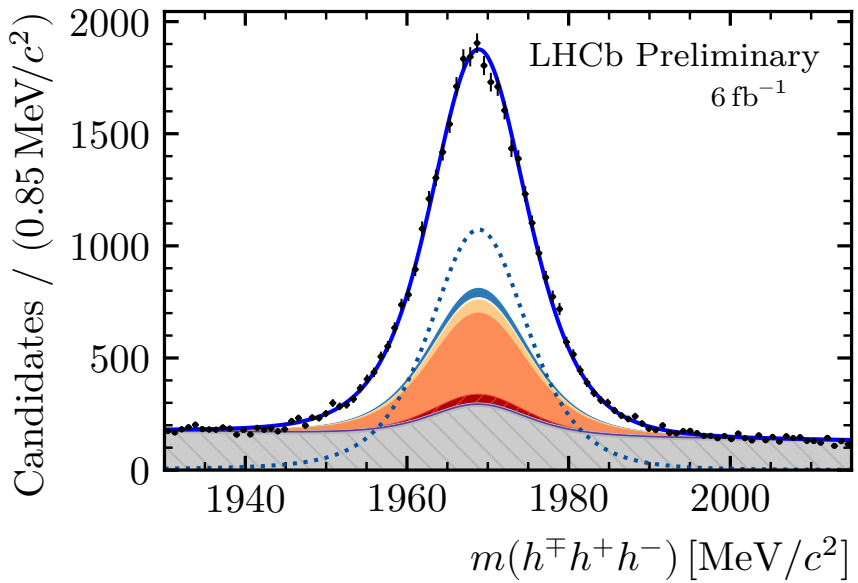
$\gamma - 2\beta_s$



γ WITH $B_s \to D_s^{\pm} K^{\mp}$ [CONF-2023-004]

- $D_s^{\pm}$ reconstructed in 5 decay modes
- Full run 2 data: 20950 ± 180 candidates
- Closely following ΔM_s analysis with $B_s \to D_s^- \pi^+$

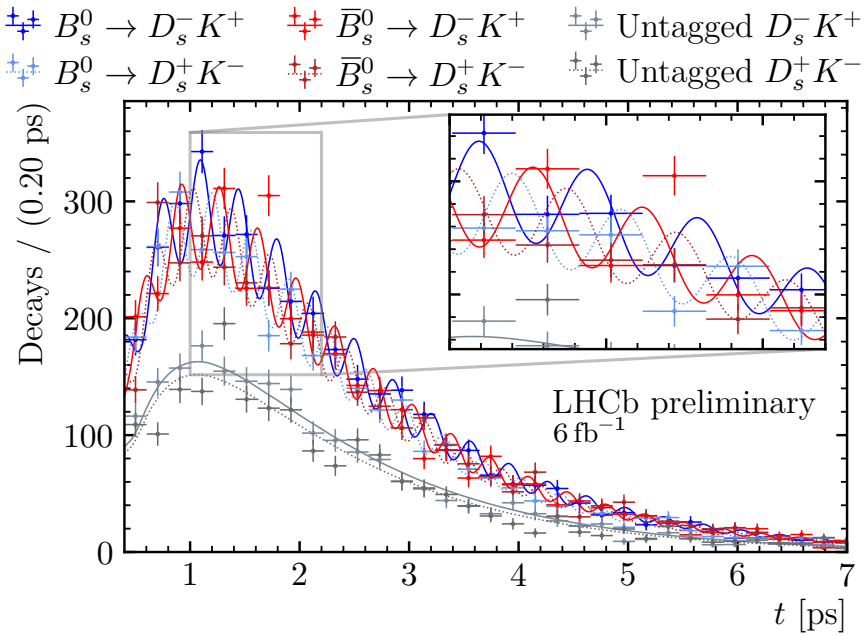


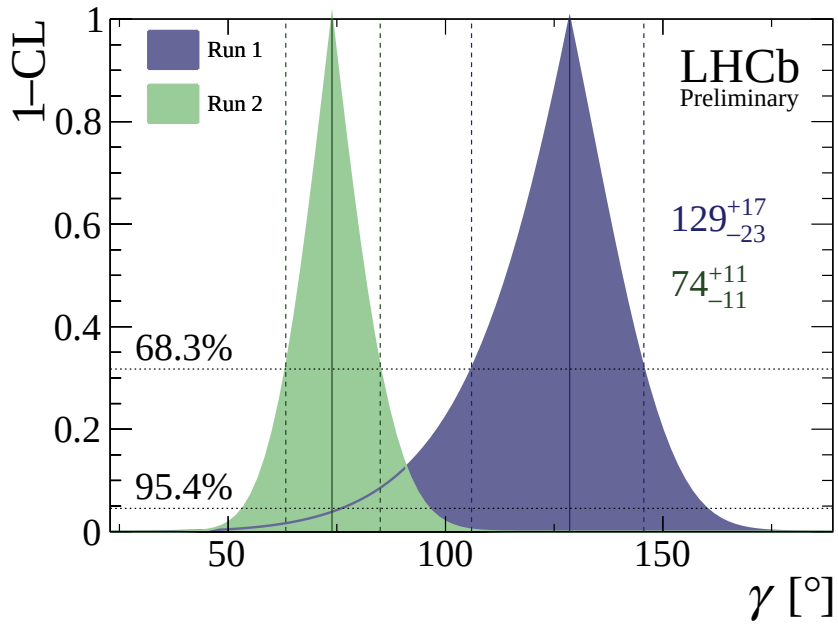


Data
$B_s^0 \to D_s^{\mp} K^{\pm}$
Combinatorial
$B^0 \to D_s^- K^+$
$B_s^0 \to D_s^- \rho^+$
$B_s^0 \to D_s^{*-} \pi^+$
$B_s^0 \to D_s^- \pi^+$
$\Lambda_b^0 \to D_s^{(*)-} p$
$B^0 \to D^- \{K^+, \pi^+\}$
$\overline{\Lambda}_b^0 \to \overline{\Lambda}_c^- \{K^+, \pi^+\}$

γ WITH $B_s \to D_s^{\pm} K^{\mp}$ [CONF-2023-004]

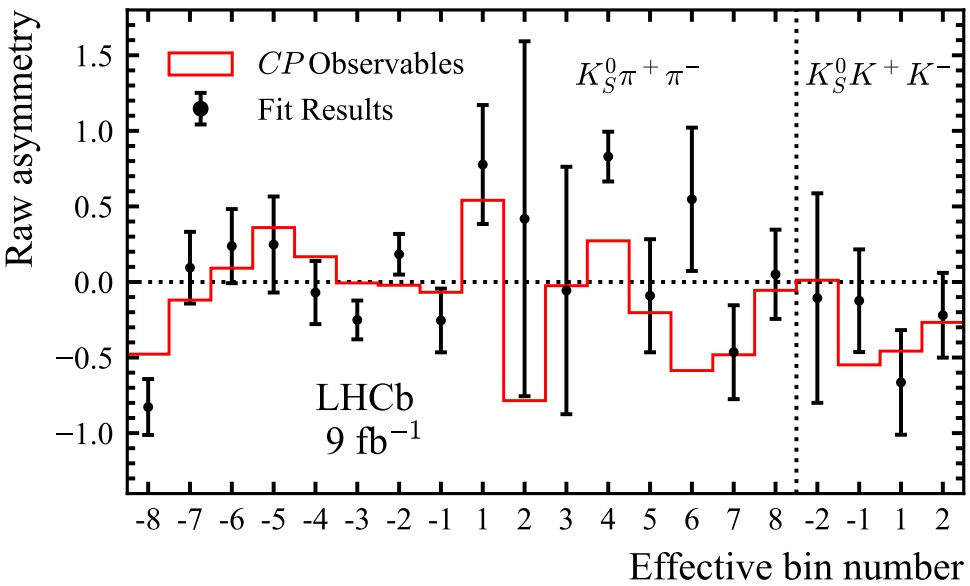
- Simultaneous decay time fit of all modes and years
- External input $-2\beta_s = (-0.031 \pm 0.018)$ rad
- Resulting for run 2: $\gamma = (74 \pm 11)^\circ$

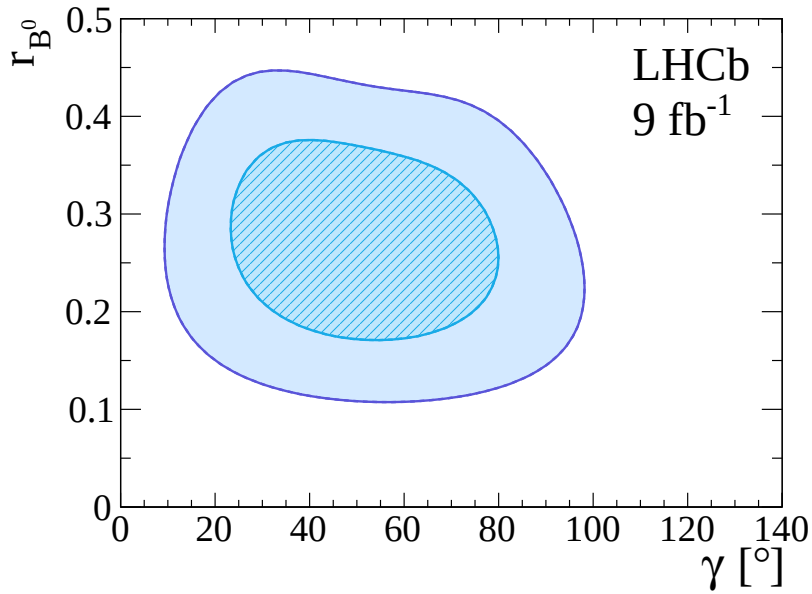




γ WITH $B^0 \to D^0(\to K_S hh)K^*$ [PAPER-2023-009]

- Branching fractions lower than in $B^\pm \to DK^\pm$, but interference is larger ($r_{B^0} \approx 3r_{B^\pm}$)
- Binned fit performed to determine the CP observables



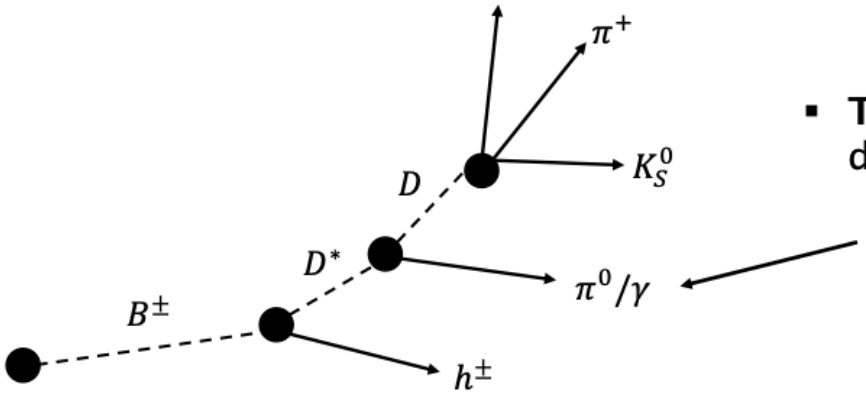


Reduces B^+/B^0 tension ⟶ $\gamma = (49^{+23}_{-18})^\circ$,

Consistent with expectations ⟶ $r_{B^0} = 0.271^{+0.068}_{-0.066}$,

$\delta_{B^0} = (236^{+19}_{-21})^\circ$.

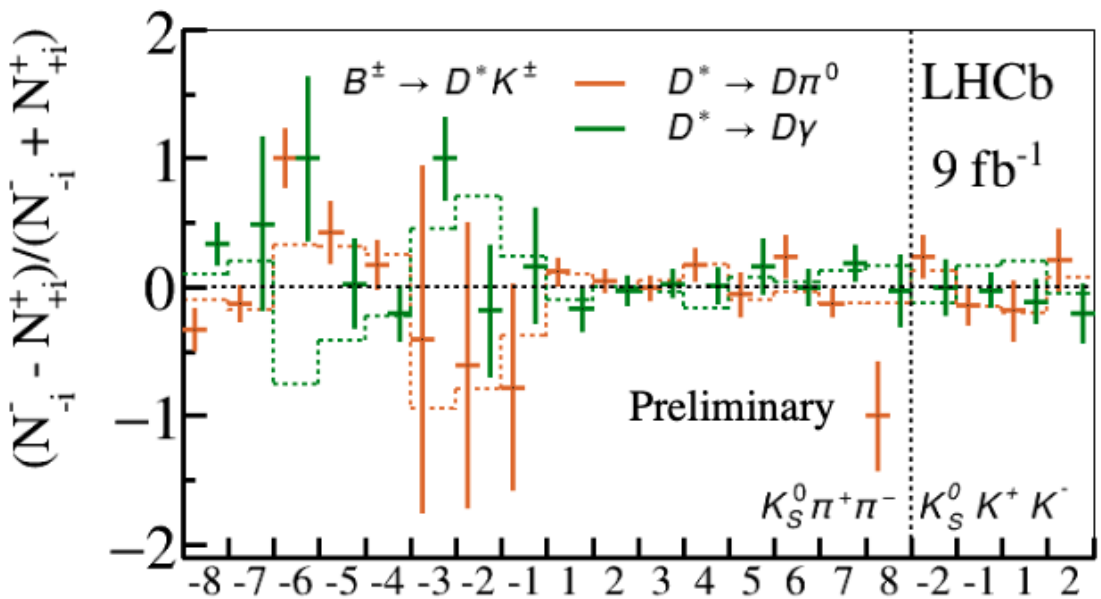
γ WITH $B^{\pm} \to D^{*}K^{\pm}$ [PAPER-2023-012] [PAPER-2023-016]



- **Two separate measurements** with the same decay chain but different techniques
  - The neutral particle can be reconstructed or not [14]
  - Negligible overlap between the analyses

$$CP(\pi^0) = -1 \;\&\; CP(\gamma) = 1$$

- Introduces phase shift of $\pi \to \mathcal{A}(\pi^0) = -\mathcal{A}(\gamma)$



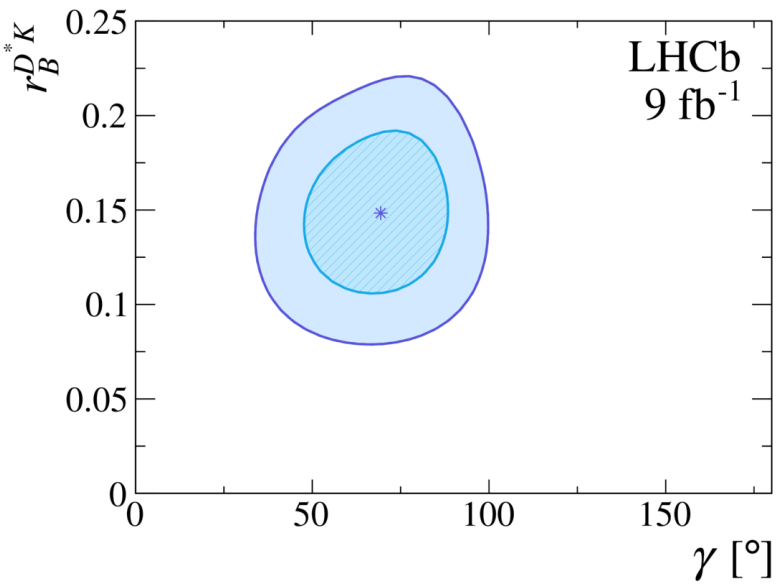
γ WITH $B^{\pm} \to D^{*}K^{\pm}$ [PAPER-2023-012] [PAPER-2023-016]

Fully reconstructed:

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

$$r_B^{D^*K} = 0.15 \pm 0.03$$

$$\delta_B^{D^*K} = (311 \pm 15)^{\circ}$$

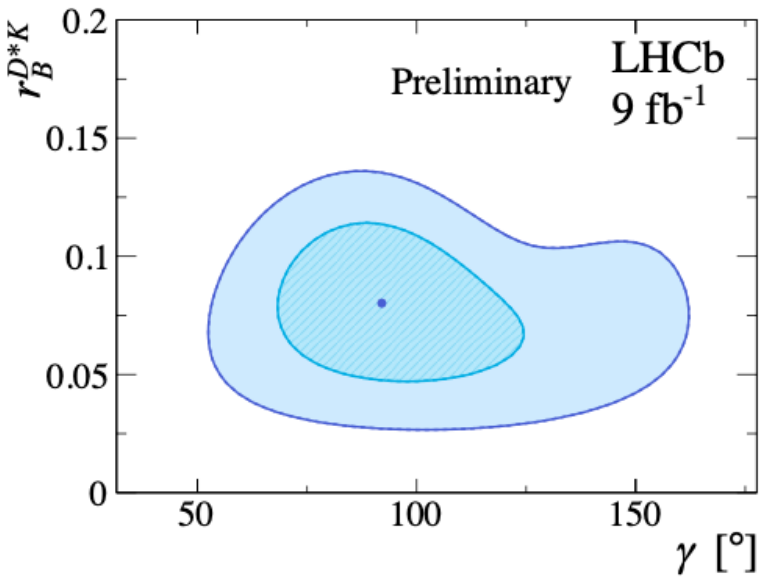


Partially reconstructed:

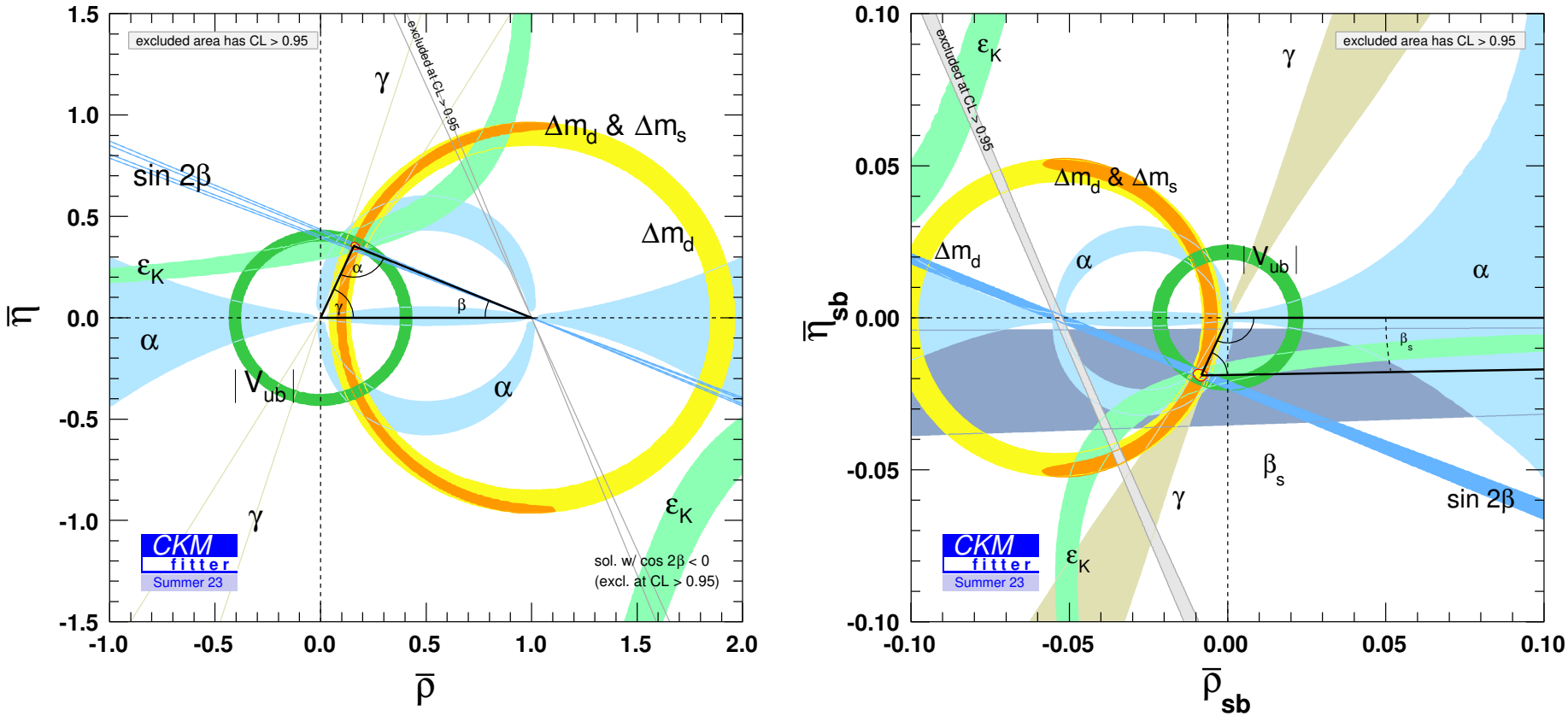
$$\gamma = (92^{+21}_{-17})^{\circ}$$

$$r_B^{D^*K} = 0.080^{+0.022}_{-0.023}$$

$$\delta_B^{D^*K} = \left(310^{+15}_{-20}\right)^{\circ}$$



Putting all together



The SM mechanism of CP Violation (still) gives an accurate picture of nature: no clear indication of NP

Pleasant Dreams!

- LHCb discovers New Physics

Implications workshop, Oct. 18, 2013 33

BACKUP

Prospects [LPCC-2018-06, Feb 25, 2019]

Observable	Current LHCb	LHCb 2025	Upgrade II
EW Penguins			
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [5]	0.025	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [6]	0.031	0.008
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	0.02, 0.02, 0.05
CKM tests			
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [7]	4°	1°
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [8]	1.5°	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$	0.04 [9]	0.011	0.003
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [10]	14 mrad	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [11]	35 mrad	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [12]	39 mrad	11 mrad
a^s_{sl}	33×10^{-4} [13]	10×10^{-4}	3×10^{-4}