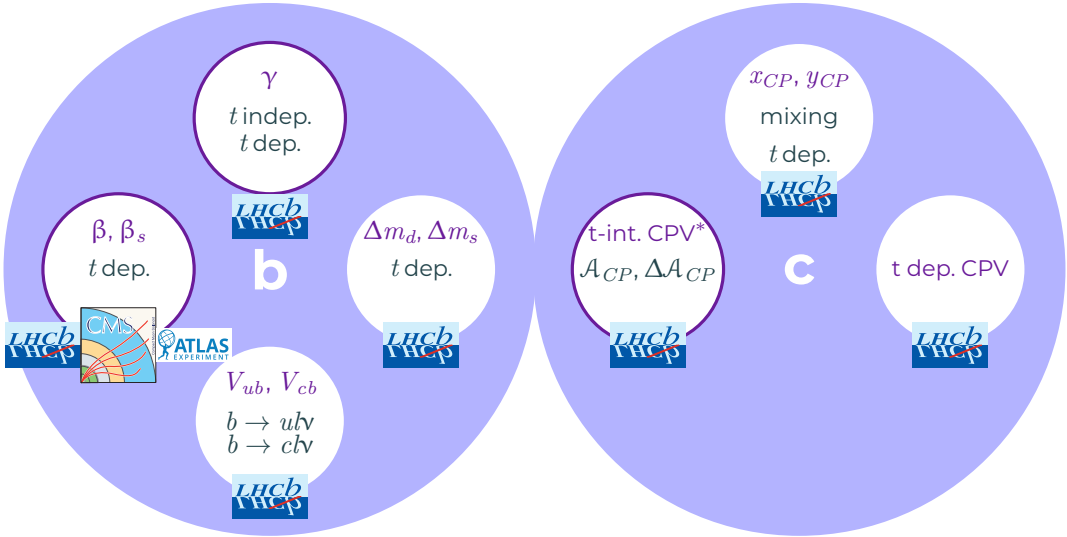
New CP-violation measurements at LHC

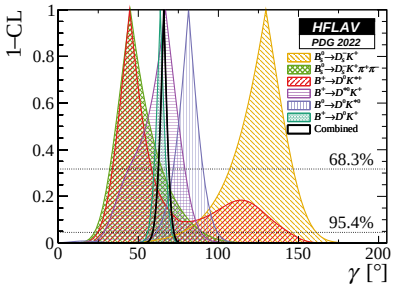
Valeriia Lukashenko
Nikhef, KINR on behalf of LHCb, ATLAS and CMS collaborations
FPCP 2023

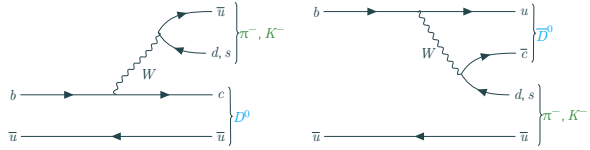
Overview

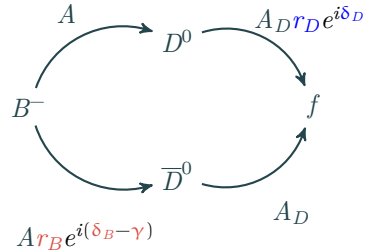


*Does not include "Search for CPV in $D^+_{(s)} \to K^+K^-K^+$" arXiv:2303.04062 and "Search for CPV in $D^0 \to \pi^+\pi^-\pi^0$" in preparation - see Serena Maccolini talk

γ update from LHCb







arXiv:2206.07501

$\gamma^{HFLAV} = (65.9^{+3.3}_{-3.5})^\circ$ [a]

$\gamma^{CKM\ Fitter} = (65.5^{+1.3}_{-1.2})^\circ$ [b] - SM

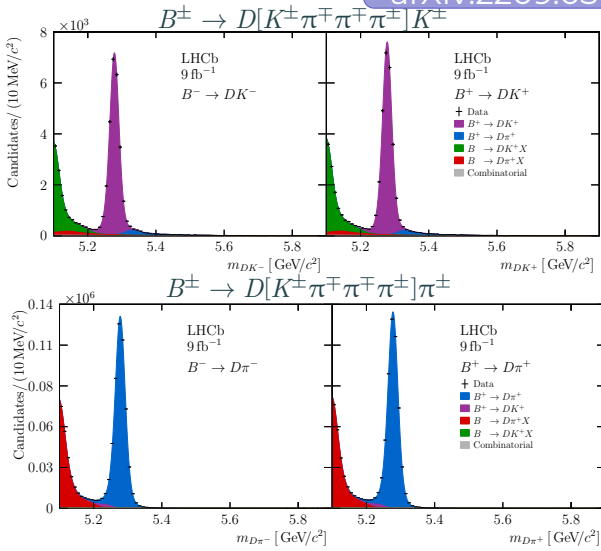
[a] arXiv:2206.07501

[b] CKM Fitter 2021, Eur. Phys. J. C (2005) 41: 131

γ from $B^{\pm} \to D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]h^{\pm}$ where $D = D^0, \overline{D}^0$ with 9 fb^{-1}

arXiv:2209.03692

- 4 bins in strong-phase difference δ_D between D^0 and $\overline{D}^0$ decays
- Like Sign Kaons - Cabbibo favored
  Opposite Sign Kaon - double Cabbibo suppressed



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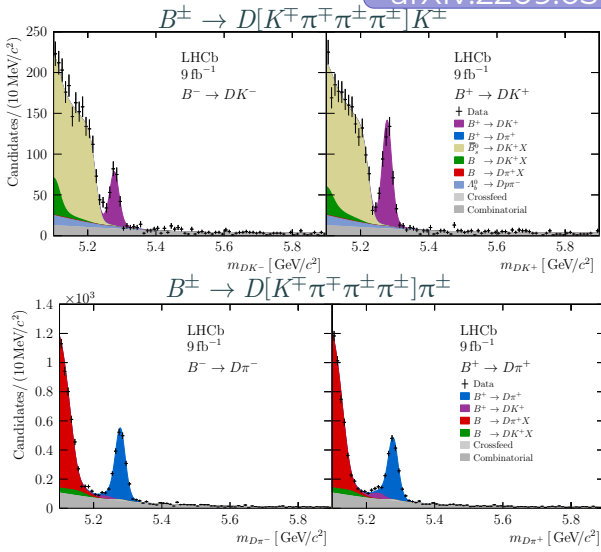


γ from $B^{\pm} \to D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]h^{\pm}$ where $D = D^0, \overline{D}^0$ with $9\ \text{fb}^{-1}$

arXiv:2209.03692

B-hadronic parameters[a]:

1

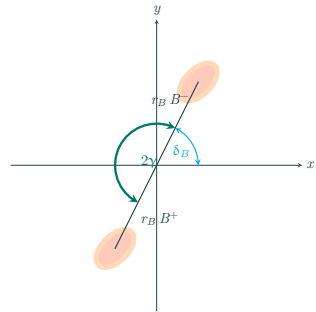
$$r_B^{DK} = (94.6^{+3.1+0.5+3.0}_{-3.0-0.5-2.3}) \times 10^{-3}$$
$$\delta_B^{DK} = (134.6^{+6.0+0.7+8.6}_{-6.0-0.7-8.7})^{\circ}$$

2

$$r_B^{D\pi} = (4.5^{+1.1+0.3+0.4}_{-1.0-0.3-0.3}) \times 10^{-3}$$
$$\delta_B^{D\pi} = (311.8^{+14.7+3.0+14.7}_{-15.0-2.3-15.0})^{\circ}$$

stat.±syst.±external (D.had.par.)

[a] D had. par. constrained from combination of LHCb, BESIII and CLEO-c results

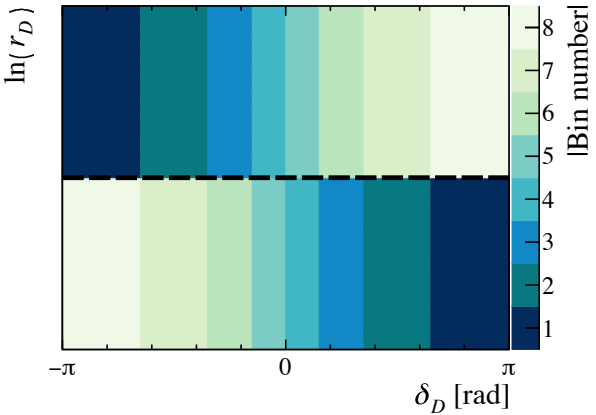


$$\gamma = (54.8^{+6.0+0.6+6.7}_{-5.8-0.6-4.2})^{\circ}$$

γ from $B^{\pm} \to D[K^+K^-\pi^+\pi^-]h^{\pm}$ and $B^{\pm} \to D[\pi^+\pi^-\pi^+\pi^-]h^{\pm}$ where $D = D^0, \overline{D}^0$ with $9\ \mathrm{fb}^{-1}$

arXiv:2301.10328

- both binned and phase-space integrated measurement ($D[\pi^+\pi^-\pi^+\pi^-]$)
- 5D phase space project onto 8 bins in strong-phase difference δ_D and ratio of amplitude magnitudes r_D between D^0 and $\overline{D}^0$ decays



δ_D and r_D binning. Labels from $-i$ to i.

γ from $B^{\pm} \to D[K^+K^-\pi^+\pi^-]h^{\pm}$ and $B^{\pm} \to D[\pi^+\pi^-\pi^+\pi^-]h^{\pm}$ where $D = D^0, \overline{D}^0$ with $9\ \mathrm{fb}^{-1}$

arXiv:2301.10328

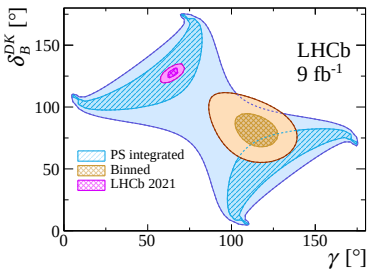
B-hadronic parameters:

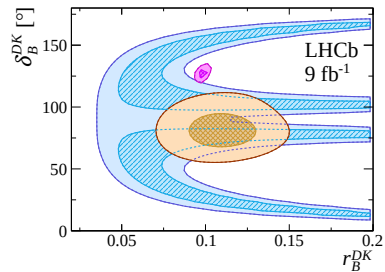
1

$$r_B^{DK} = 110^{+20}_{-20} \times 10^{-3}$$
$$\delta_B^{DK} = 81^{+14}_{-13}{}^{\circ}$$

2

$$r_B^{D\pi} = 4.1^{5.4}_{-4.1} \times 10^{-3}$$
$$\delta_B^{D\pi} = 298^{+62}_{-118}{}^{\circ}$$





$\sqrt{\text{stat.}^2 + \text{syst.}^2}$

$$\gamma = 116^{+12}_{-14}{}^{\circ}$$

LHCb 2021 from JHEP12(2021)141

Model dependent! (from arXiv:1811.08304)

Waiting for strong-phase measurement from BESIII

Updated γ and charm mixing parameters combination

Changes:

- $B^{\pm} \to D[K^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}]h^{\pm}$, arXiv:2209.03692 new
- $B^{\pm} \to D[h^+h^-\pi^0]h^{\pm}$, arXiv:2112.10617 update
- charm mix. $D^0 \to h^+h^-$, arXiv:2202.09106 new
- $D^0 \to K^+K^-$, arXiv:2209.03179 new
- charm mix. $D^0 \to K^0_s\pi^+\pi^-$, arXiv:2208.06512 new

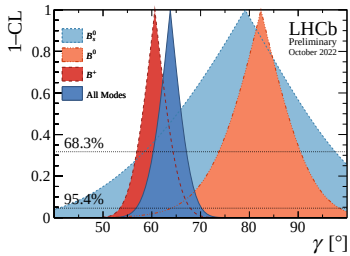
2021 Combination:

$$\gamma = (65.4^{+3.8}_{-4.2})$$

CERN-LHCb-CONF-2022-003

2022 Combination from LHCb-CONF-2022-003:

- $x = (0.389^{+0.050}_{-0.049})\%$
- $y = (0.636^{+0.020}_{-0.019})\%$
- $|q/p| = 0.995^{0.015}_{-0.016}$
- $\phi = arg(q/p) = 2.5 \pm 1.2°$
- $\gamma = (63.8^{+3.5}_{-3.7})°$



Charm CPV : CP asymmetry in $D^0 \to K^+K^-$ with $5.7\ \mathrm{fb}^{-1}$

- $\mathcal{A}_{CP}$ suppressed in SM
- Direct CP asymmetry in charm hadron decays with $D^0 \to h^+h^-$ decays
  PRL 122 (2019) 211803

see Serena Maccolini talk

$$\mathcal{A}_{CP} = \frac{|A_f|^2 - |\overline{A}_{\bar{f}}|^2}{|A_f|^2 + |\overline{A}_{\bar{f}}|^2}$$

$$\mathcal{A}_{CP} \approx a_f^d + \frac{\langle t_D \rangle}{\tau_D} \Delta Y \qquad (1)$$

direct asym. mixing asym.

CP asymmetry in $D^0 \to K^+K^-$ with $5.7\,\mathrm{fb}^{-1}$

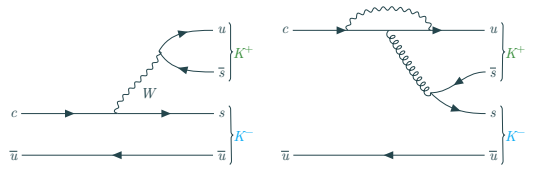
arXiv:2209.03179

- D^0 from $D^{*+} \to D^0\pi^+$, where π is tag

$$A_{CP}^{raw} = \frac{N(D^{*+} \to D^0\pi^+) - N(D^{*-} \to \overline{D}^0\pi^-)}{N(D^{*+} \to D^0\pi^+) + N(D^{*-} \to \overline{D}^0\pi^-)}$$

$$A_{CP}^{raw} = A_{CP}(K^+K^-) + A_{det}(\pi_{tag}) + A_{prod}(D^{*+})$$

- A_{det} and A_{prod} from Cabibbo favored decays $\to$ negligible A_{CP}

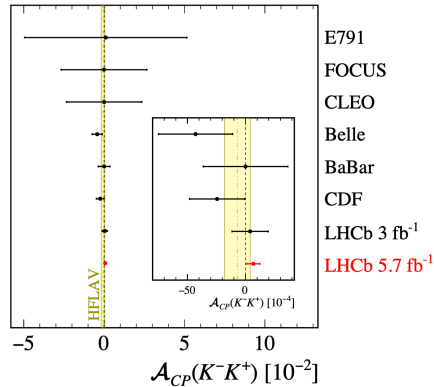


CP asymmetry in $D^0 \to K^+K^-$ with $5.7\ \mathrm{fb}^{-1}$

arXiv:2209.03179

1

$$\mathcal{A}_{CP}(K^+K^-) = [6.8 \pm 5.4 \pm 1.6] \times 10^{-4}$$



CP asymmetry in $D^0 \to K^+K^-$ with $5.7\ \mathrm{fb}^{-1}$

arXiv:2209.03179

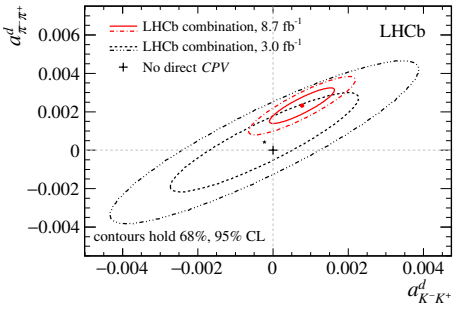
1 $\mathcal{A}_{CP}(K^+K^-) = [6.8 \pm 5.4 \pm 1.6] \times 10^{-4}$

From combination*:

1 $a^d_{K^+K^-} = (7.7 \pm 5.7) \times 10^{-4}$

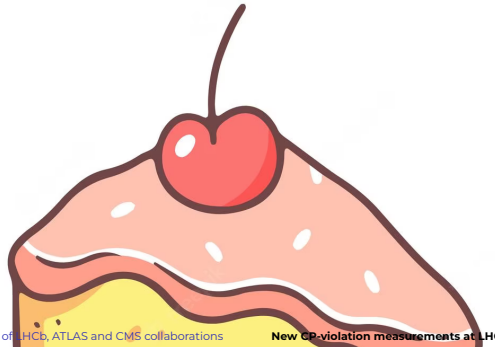
2 $a^d_{\pi^+\pi^-} = (23.2 \pm 6.1) \times 10^{-4}$ $(3.8\ \sigma)$

*combining with $\Delta A_{CP} = \mathcal{A}_{CP}(K^+K^-) - \mathcal{A}_{CP}(\pi^+\pi^-)$ from previous LHCb measurement

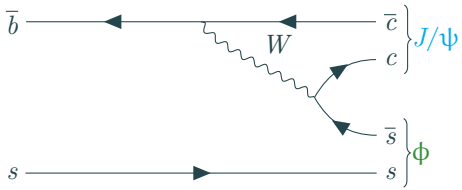


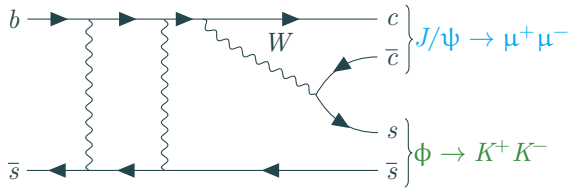
Time dependent CPV in b-sector

see Ramon Angel Ruiz Fernandez talk



Time dependent CPV in b-sector





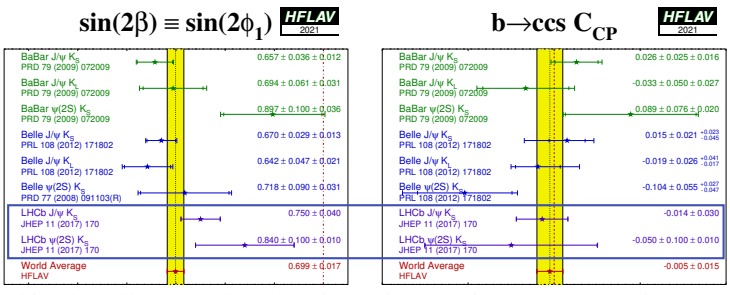
$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0_{(s)} \to f) - \Gamma(B^0_{(s)} \to f)}{\Gamma(\overline{B}^0_{(s)} \to f) + \Gamma(B^0_{(s)} \to f)} = \frac{S_f^{d(s)} \sin(\Delta m_{d(s)} t) - C_f^{d(s)} \cos(\Delta m_{d(s)} t)}{\cosh(\Delta\Gamma_{d(s)} t/2) + D_f^{d(s)} \sinh(\Delta\Gamma_{d(s)} t/2)}$$

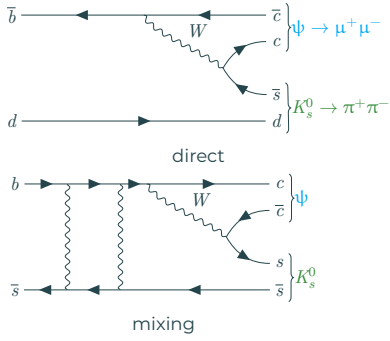
mixing induced CPV direct CPV

$sin(2\beta)$ from $B^0 \to \psi K^0_s(\pi^+\pi^-)$ with 6 fb^{-1} LHCb

$S_f \approx sin(2\beta)$

LHCb-PAPER-2023-013 in preparation





$sin(2\beta)^{HFLAV} = 0.699 \pm 0.017$ [a]

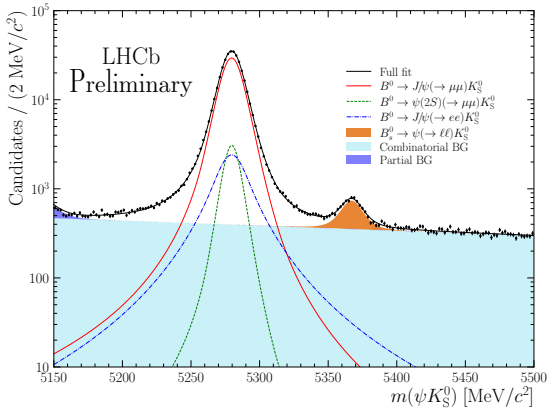
$C_{CP}^{HFLAV} = 0.005 \pm 0.015$

[a] HFLAV 2021

$sin(2\beta)$ from $B^0 \to \psi K^0_s(\pi^+\pi^-)$ with 6 fb^{-1} LHCb

LHCb-PAPER-2023-013 in preparation

- $B^0 \to J/\psi(\mu^+\mu^-)K^0_s$
  $B^0 \to \psi(2S)(\mu^+\mu^-)K^0_s$
  $B^0 \to J/\psi(e^+e^-)K^0_s$
- improvement in selection
- improvement in tagging power
- correct for detector misalignment biases



$m(\psi K^0_s)$ for *sPlot* background subtraction

$sin(2\beta)$ from $B^0 \to \psi K^0_s(\pi^+\pi^-)$ with 6 fb^{-1} LHCb

LHCb-PAPER-2023-013 in preparation

- $B^0 \to J/\psi(\mu^+\mu^-)K^0_s$
  $B^0 \to \psi(2S)(\mu^+\mu^-)K^0_s$
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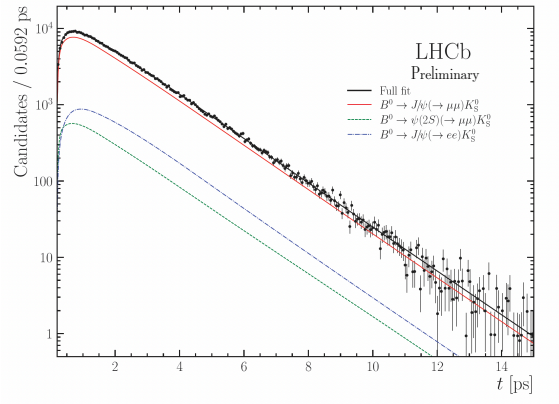


Decay time fit for background subtracted sample

$sin(2\beta)$ from $B^0 \to \psi K^0_s(\pi^+\pi^-)$ with 6 fb^{-1} LHCb

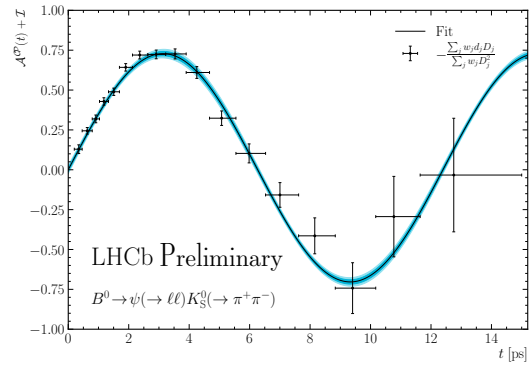
LHCb-PAPER-2023-013 in preparation

1 $S_{\psi K^0_s} = 0.7158 \pm 0.0133 \pm 0.0078$

2 $C_{\psi K^0_s} = 0.0120 \pm 0.0123 \pm 0.0029$

Statistically limited

For comparison: $sin(2\beta) = 0.699 \pm 0.017$ from HFLAV 2021

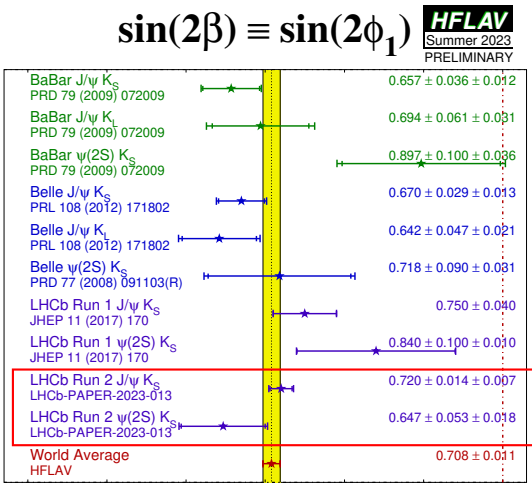


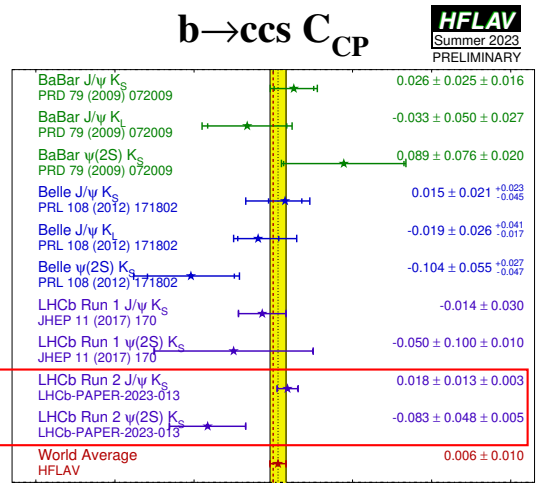
Time dependent CP-asymmetry

$sin(2\beta)$ from $B^0 \to \psi K^0_s(\pi^+\pi^-)$ with 6 fb^{-1} LHCb

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

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



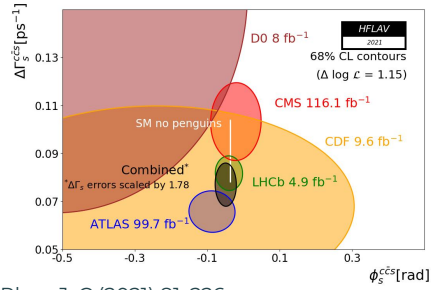


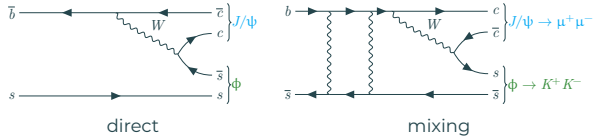
$\phi_s^{c\bar{c}s}$ in $B_s^0 \to J/\psi(\mu^+\mu^-)\phi$ with $6\ \mathrm{fb}^{-1}$ LHCb fresh for FPCP

LHCb-PAPER-2023-016 in preparation

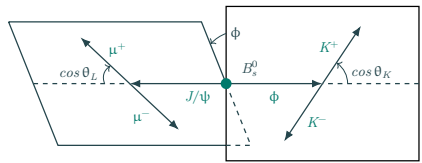
$S_f \approx sin(\phi_s)$

$\phi_s^{c\bar{c}s} \approx -2\beta_s$





- $P \to VV$: time-dependent angular decay rate



Eur. Phys. J. C (2021) 81: 226

$\phi_s^{HFLAV} = -0.049 \pm 0.019[\mathrm{rad}]$ [a]

$\phi_s^{CKM\ Fitter} = -0.036^{+0.0006}_{-0.0009}[\mathrm{rad}]$ [b] - SM

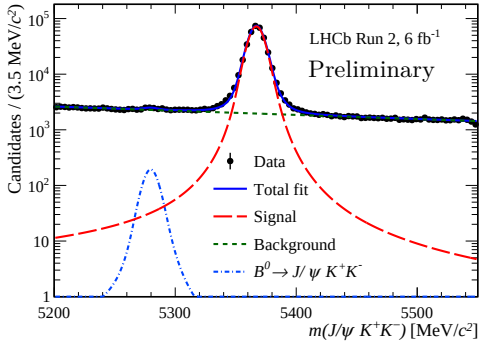
[a] Eur. Phys. J. C (2021) 81: 226

[b] CKM Fitter 2021, Eur. Phys. J. C (2005) 41: 131

$\phi_s^{c\bar{c}s}$ in $B_s^0 \to J/\psi(\mu^+\mu^-)\phi$ with $6\ \mathrm{fb}^{-1}$ LHCb fresh for FPCP

LHCb-PAPER-2023-016 in preparation

- legacy analysis
  (following Eur. Phys. J. C 79, 8 (2019) pp.706)
- changed decay time resolution estimation
- correct for detector misalignment biases



$m(J/\psi K^+K^-)$ for *sPlot* background subtraction

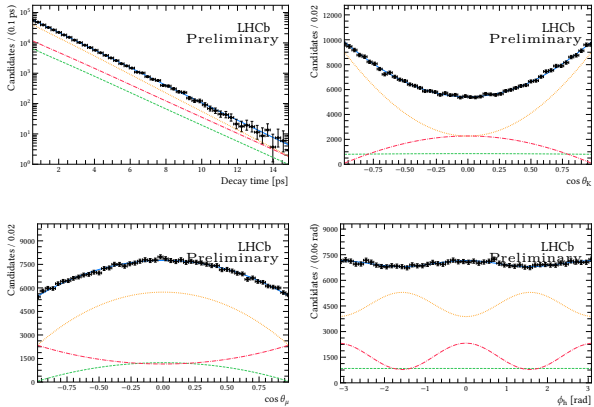
$\phi_s^{c\bar{c}s}$ in $B_s^0 \to J/\psi(\mu^+\mu^-)\phi$ with $6\,\mathrm{fb}^{-1}$ LHCb fresh for FPCP

LHCb-PAPER-2023-016 in preparation

Stat. limited (excl. $\Gamma_s - \Gamma_d$), no polarisation dependence

1. $\phi_s^{c\bar{c}s} = -0.039 \pm 0.022 \pm 0.006\,[\mathrm{rad}]$
2. $|\lambda| = 1.001 \pm 0.011 \pm 0.005\,{}^{a}$

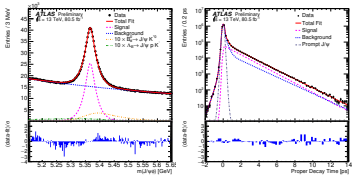
   ${}^{a}C_f = \frac{1-|\lambda|^2}{1+|\lambda|^2}$
3. $\Gamma_s - \Gamma_d = -0.0057^{+0.0013}_{-0.0015} \pm 0.0014\,[\mathrm{ps}^{-1}]$
4. $\Delta\Gamma_s = 0.0846 \pm 0.0044 \pm 0.0024\,[\mathrm{ps}^{-1}]$
5. $\Delta m_s = 17.743 \pm 0.033 \pm 0.009\,[\mathrm{ps}^{-1}]$

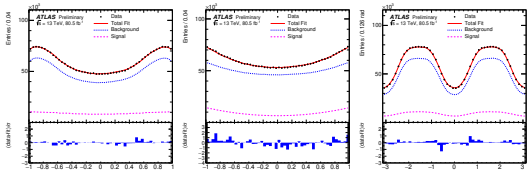


$\phi_s^{c\bar{c}s}$ in $B_s^0 \to J/\psi(\mu^+\mu^-)\phi$ with 6 fb^{-1} from ATLAS and CMS

Eur. Phys. J. C 81 (2021) 342

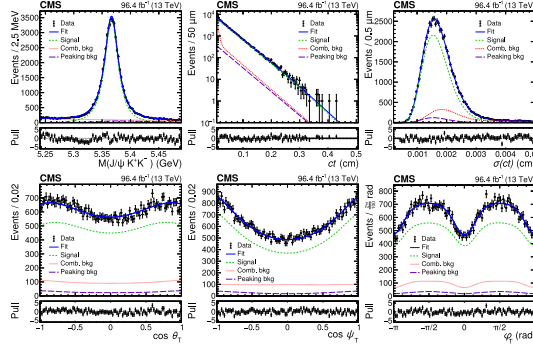
ATLAS, $\mathcal{L} = 80.5\mathrm{fb}^{-1}$ (misses 2018)





Phys. Lett. B 816 (2021) 136188

CMS, $\mathcal{L} = 96.4\mathrm{fb}^{-1}$



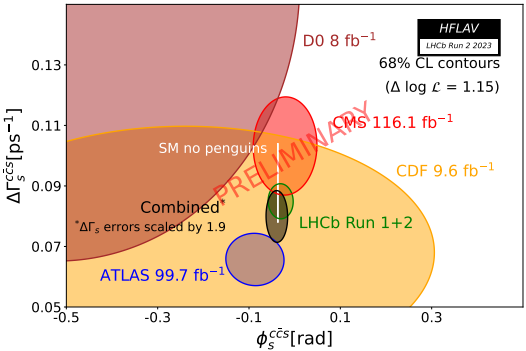
$\phi_s^{c\bar{c}s}$ HFLAV Combination fresh for FPCP

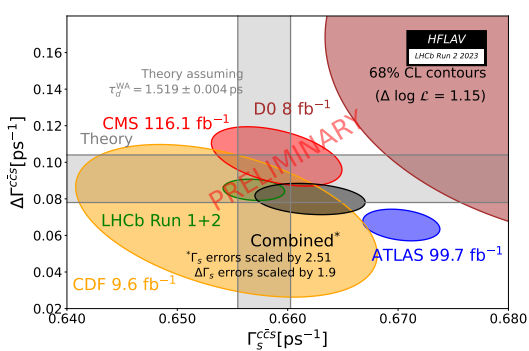
preliminary

$$\phi_s^{c\bar{c}s} = -0.049 \pm 0.019 \Rightarrow -0.039 \pm 0.016 [\text{rad}]$$

$$\Delta\Gamma_s = 0.074 \pm 0.006\ \text{ps}^{-1} \Rightarrow 0.080 \pm 0.006\ [\text{ps}^{-1}]$$

$$\Gamma_s = 0.6627 \pm 0.0036\ \text{ps}^{-1} \Rightarrow 0.6620 \pm 0.0033\ [\text{ps}^{-1}]$$

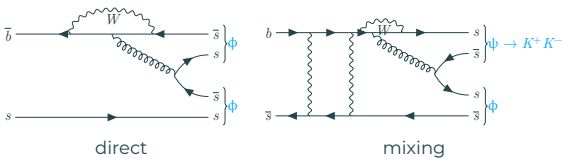


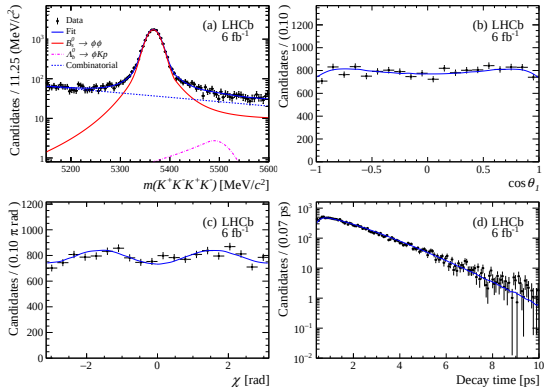


$\phi_s^{s\bar{s}s}$ from $B_s^0 \to \phi\phi$ LHCb with 6 fb^{-1}

arXiv:2304.06198

- $\phi_s^{s\bar{s}s} \neq \phi_s^{c\bar{c}s}$
- penguin mediated → sensitive to NP in loops
- $\phi_s^{s\bar{s}s} \approx 0$ in SM





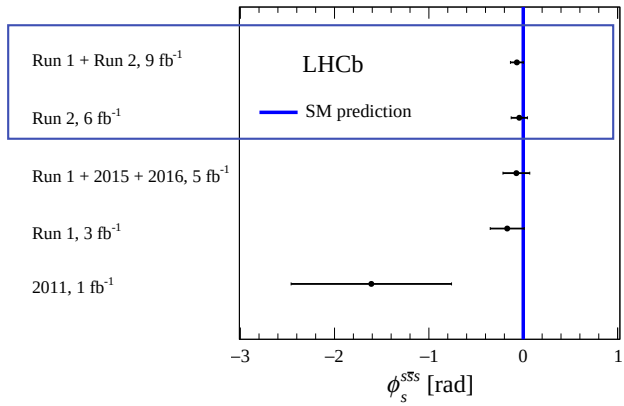
$\phi_s^{s\bar{s}s}$ from $B_s^0 \to \phi\phi$ LHCb with 6 fb^{-1}

arXiv:2304.06198

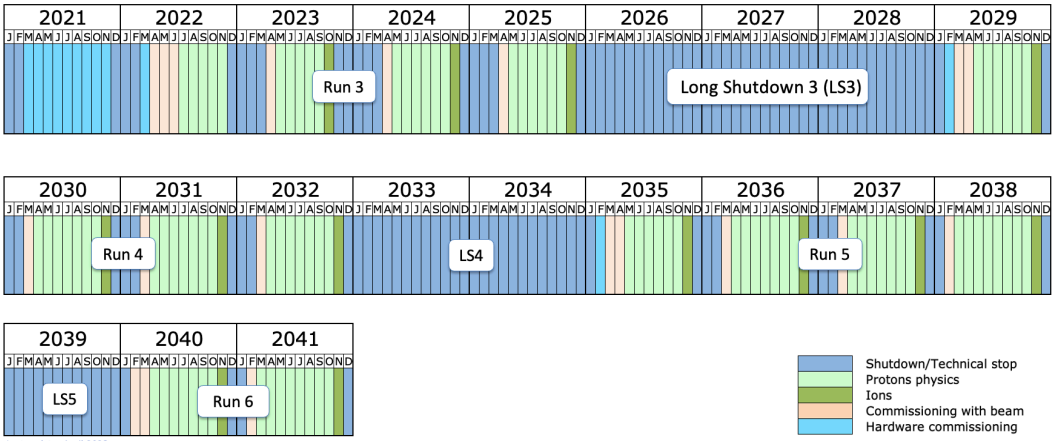
1. $\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009$ [rad]

2. $|\lambda| = 1.004 \pm 0.030 \pm 0.009$

Statistically limited, no polarisation dependence



Looking at LHC Run 3 and beyond



Looking at LHC Run 3 and beyond

LHCb now

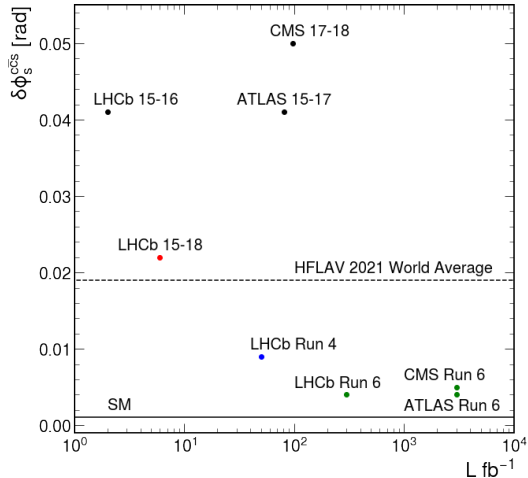
- $\delta sin2\beta \approx 0.013\,(6\,\mathrm{fb}^{-1})$
- $\delta\gamma \approx \mathcal{O}(10^\circ)$

LHCb at $50\ \mathrm{fb}^{-1}$

- $\delta sin2\beta \approx 0.006$
- $\delta\gamma \approx 1^\circ - 4^\circ$

LHCb at $300\ \mathrm{fb}^{-1}$

- $\delta sin2\beta \approx 0.003$ $\times 4$ improv.
- $\delta\gamma \approx 0.5^\circ - 2^\circ$ $\times \mathcal{O}(5)$ improv.



arXiv:1808.08865, ATL-PHYS-PUB-2018-041, CMS-PAS-FTR-18-041

Thank you for your attention

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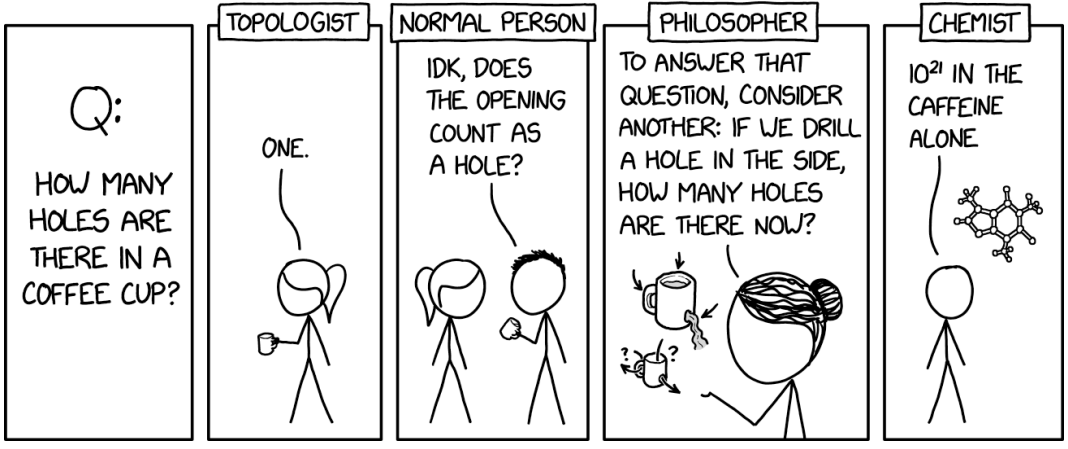

Physicist: At the Planck length, uncountably many

backup

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Corrections in the $D^0 \to K^+K^-$

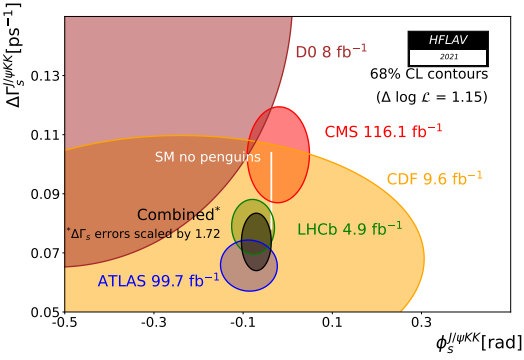
$$C_{D^+} : \mathcal{A}_{CP}(K^+K^-) = A^{raw}(K^+K^-) - A^{raw}(K^-\pi^+) + A^{raw}(K^-\pi^+\pi^+) - A^{raw}(\overline{K^0}\pi^+) + A^{raw}(\overline{K^0})$$
$$C_{D_s^+} : \mathcal{A}_{CP}(K^+K^-) = A^{raw}(K^+K^-) - A^{raw}(K^-\pi^+) + A^{raw}(\phi\pi^+) - A^{raw}(\overline{K^0}K^+) + A^{raw}(\overline{K^0})$$

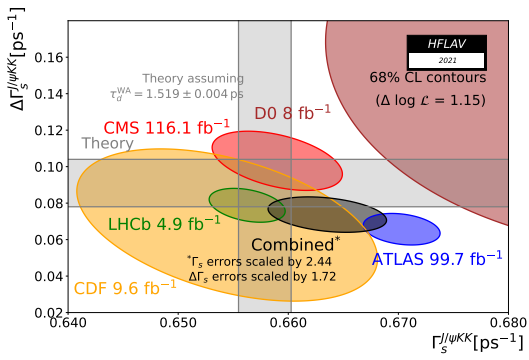
$$A^{raw}(K^-\pi^+) \approx A_P(D^{*+} - A_D K^+ + A_D(\pi^+) + A_D(\pi^+_{tag})$$
$$A^{raw}(K^-\pi^+\pi^+) \approx A_P(D^+) - A_D(K^+) + A_D(\pi^+_1) + A_D(\pi^+_2)$$
$$A^{raw}(\overline{K^0}\pi^+) \approx A_P(D^+) + A_D(\overline{K}^0) + A_D(\pi^+)$$
$$A^{raw}(\phi\pi^+) \approx A_P(D_s^+) + A_D(\pi^+)$$
$$A^{raw}(\overline{K^0}K^+) \approx A_P(D_s^+) + A_D(\overline{K}^0) + A_D(K^+)$$

$A^{raw}(\overline{K^0})$ - CPV in kaons + kaons material interactions

Decays: $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D^+ \to \overline{K}^0 pi^+$, $D_s^+ \to \phi(\to K^-K^+)\pi^+$, $D_s^+ \to \overline{K}^0 K^+$

$\phi_s^{J/\psi KK}$ HFLAV Combination 2021





new $\phi_s^{J/\psi KK}$ HFLAV Combination fresh for FPCP

preliminary

$$\phi_s^{J/\psi KK} = -0.070 \pm 0.022 \Rightarrow -0.050 \pm 0.017 [rad]$$