Determination of the phase ϕ_s at LHCb

V. Batozskaya[1] on behalf of LHCb collaboration

[1]National Centre for Nuclear Research, Warsaw, Poland

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Outline

$\mathcal{CP}$ Violation

- CKM matrix
- Introduction to ϕ_s

LHCb Detector

ϕ_s measurement

- Analysis method
- $B_s^0 \to J/\psi K^+K^-$
- $B_s^0 \to J/\psi \pi^+\pi^-$
- $B_s^0 \to \psi(2S)\phi$
- $B_s^0 \to J/\psi KK$ HM

Experimental results

ϕ_s in future

- $B_s^0 \to \eta_c\phi$

Conclusion

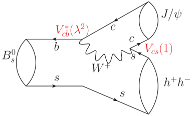
Violation of the $\mathcal{CP}$ symmetry

- Main interest in the measurement of the phase ϕ_s in $b \to c\bar{c}s$ processes, $\phi_s^{c\bar{c}s}$:

$\mathcal{CP}$V in decay

(Direct $\mathcal{CP}$ violation)

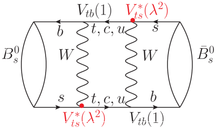
$\phi_D = \arg(V_{cs}V^*_{cb})$



$\mathcal{CP}$V in mixing

(Indirect $\mathcal{CP}$ violation)

$\phi_M = 2\arg(V_{ts}V^*_{tb})$



$\mathcal{CP}$V in interference

between direct decays and decays with mixing

$$\begin{tikzcd}\overline{B}^0_{(s)} \arrow[r, "\overline{A}_f"] \arrow[d, bend right, "q/p"'] & f \\ B^0_{(s)} \arrow[ur, bend right, "A_f"'] & \end{tikzcd}$$

$$|\lambda_f| \equiv \left|\frac{q}{p}\frac{\bar{A}_f}{A_f}\right| \approx 1$$

$$\phi_s \equiv -\arg(\lambda_f) \equiv -\arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$$

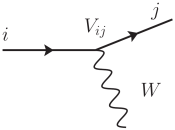
$$\phi_s^{SM} = \phi_M - 2\phi_D \to \phi_s^{c\bar{c}s} = -2\arg\left(-\frac{V_{ts}V^*_{tb}}{V_{cs}V^*_{cb}}\right) = -2\beta_s$$

CKM - quark mixing matrix

[Prog.Theor.Phys. 49 (1973) 652]

The Cabibbo-Kobayashi-Maskawa matrix is a 3 × 3 unitary matrix which consists of information about flavour changing weak decays

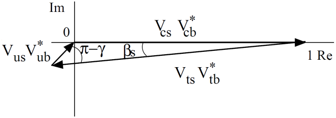
$$\begin{pmatrix} u \\ c \\ t \end{pmatrix} \leftrightarrow \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$\lambda \approx 0.22$ [PRL 53 (1984) 1802]

- 6 unitary triangles
  Triangle (sb):
  $V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$



Introduction to ϕ_s

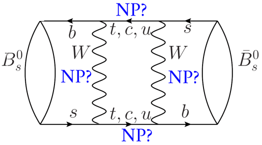
- SM prediction is very small and precise:

$$\boxed{\phi_s^{c\bar{c}s} = \text{-}2\beta_s = \text{-}0.0376^{+0.0008}_{-0.0007}\ \text{rad}}$$

[CKMFitter, PRD 84 (2011) 033005]

*Ignoring subleading penguin contributions

- If new particles contribute to "box" diagrams, then value of ϕ_M will be different than SM prediction

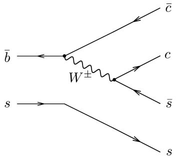


$$\phi_M = \phi_M^{SM} + \Delta\phi_M^{NP}$$
$$\phi_s^{c\bar{c}s} = \phi_M - 2\phi_D = -2\beta_s + \Delta\phi_M^{NP}$$

$\phi_s^{c\bar{c}s}$ is an excellent probe for possible NP!

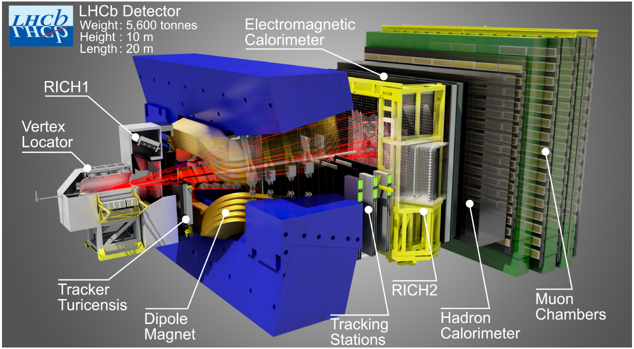
- ϕ_s is measured by LHCb in the different decay modes

$B_s^0 \to J/\psi KK$, $B_s^0 \to J/\psi\pi\pi$
$B_s^0 \to \psi(2S)\phi$, $B_s^0 \to D_s D_s$
$B_s^0 \to \eta_c\phi$ (with large statistics)



Large Hadron Collider beauty Detector

[JINST 3 (2008) S08005]



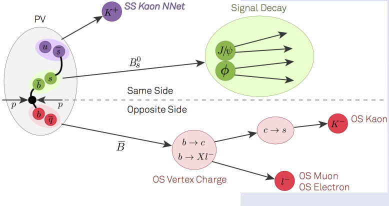
- Single-arm forward spectrometer, covering $2< \eta <5$ ($10< \theta <300$ (250) mrad)
- Momentum resolution: $\Delta p/p = 0.5\%$ at 5 GeV/c to 1.0% at 200 GeV/c
- Impact parameter resolution: 20 μm for high p_{T} tracks
- Decay time resolution: $\sim$ 45 fs
- Invariant mass resolution: $\sim$ 8 MeV/c^2 for $B \to J/\psi X$ decays with J/ψ mass constraint
- $\mathcal{L} = 3$ fb^{-1} collected in Run I at $\sqrt{s} =$ 7-8 TeV

Analysis method

Time dependent angular flavour tagged analysis:

$$\frac{d^4\Gamma(B_s^0 \to J/\psi\phi)}{dt d\Omega} \propto \sum_{k=1}^{N} h_k(t) f_k(\theta_K, \theta_l, \phi)$$

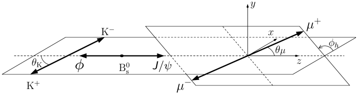
- $h_k(t)$ time dependent part: $\phi_s, \Delta\Gamma_s, \Gamma_s, \Delta m_s, A_i, \delta_i (i = 0, \perp, \parallel, S)$
- $f_k(\Omega)$ angular dependent part: θ_K, θ_l, ϕ
- Flavour tagging is determined using two algorithms:
  - Same Side - charge kaon which is correlated with B_s^0
  - Opposite Side - charge lepton or kaon from second B decay
  - Self tagging decays to calibrate the algorithms: $B^+ \to J/\psi K^+$ for OS and $B_s^0 \to D_s^- \pi^+$ for SS
  - Estimation of the algorithm efficiency:
    - tagging efficiency ε_{tag} and corrected mistag probability ω
    - total efficiency $\varepsilon_{eff} = \varepsilon_{tag}(1\text{-}2\omega)^2 = (3.73 \pm 0.15)\%$ for $B_s^0 \to J/\psi\phi$

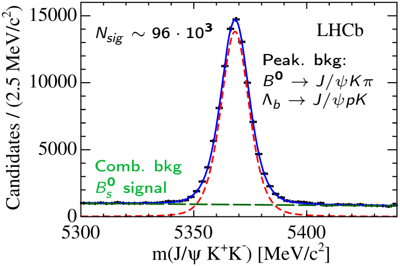


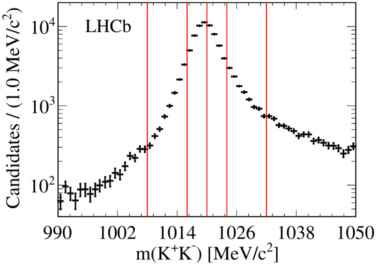
ϕ_s in $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$

[PRL 114 (2015) 041801]

- P→VV decay ⇒ final state is an admixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd eigenstates
- Amplitudes: 3 $\mathcal{P}$-wave $(A_0, A_\perp, A_\parallel)$ + 1 $\mathcal{S}$-wave $(A_\mathcal{S})$





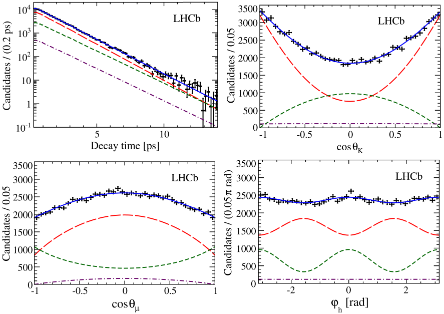


- Fit is carried out in 6 bins of $m(K^+K^-)$ region to measure $\mathcal{S}$-wave contribution

ϕ_s in $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$

[PRL 114 (2015) 041801]

Blue: Total Red: $\mathcal{CP}$-even
Green: $\mathcal{CP}$-odd Magenta: $\mathcal{S}$-wave



$$
\begin{aligned}
\phi_s &= -0.058\pm0.049\pm0.006 \text{ rad}\\
\Gamma_s &= 0.6603\pm0.0027\pm0.0015 \text{ ps}^{-1}\\
\Delta\Gamma_s &= 0.0805\pm0.0091\pm0.0032 \text{ ps}^{-1}\\
\Delta m_s &= 17.711^{+0.055}_{-0.057}\pm0.0032 \text{ ps}^{-1}\\
|\lambda| &= 0.964\pm0.019\pm0.007
\end{aligned}
$$

$\star$ First uncertainty is statistical, second is systematic uncertainty

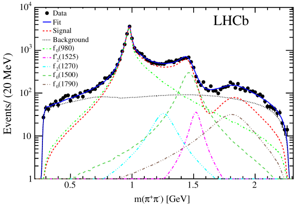
- $B_s^0 \to J/\psi K^+K^-$ is a golden channel: measurement of ϕ_s, Γ_s, $\Delta\Gamma_s$, Δm_s, $|\lambda|$
- Consistent with SM predictions, no direct $\mathcal{CP}$ violation ($|\lambda| = 1$)
- Decay time efficiency, angular efficiency and background subtraction give dominant contribution to systematic uncertainty
- No polarisation-dependent $\mathcal{CP}$ violation observed (see backups)

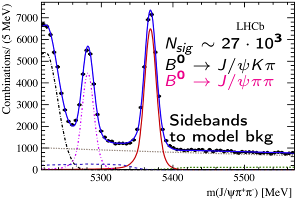
Most precise measurement of lifetime parameters to date!

ϕ_s in $B_s^0 \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$

[PRD 89 (2014) 092006]

- Amplitude analysis to study resonance structure of $\pi^+\pi^-$ states ⇒ $\mathcal{CP}$-odd state of $\pi^+\pi^-$ is >97.7% at 95% CL
- Largest component in resonant states is the $f_0(980)$ with $\sim$ 70%





$$\phi_s = 0.070 \pm 0.068 \pm 0.008 \text{ rad}$$
$$|\lambda| = 0.89 \pm 0.05 \pm 0.01$$

Combination with $B_s^0 \to J/\psi\phi$

$$\phi_s = -0.010 \pm 0.039 \text{ rad}$$
$$|\lambda| = 0.957 \pm 0.017$$

⋆ First uncertainty is statistical, second is systematic uncertainty

- Consistent with SM predictions; no direct $\mathcal{CP}$ violation assumed equal for all $\pi^+\pi^-$ states
- Main contribution to systematic uncertainty from known $\pi^+\pi^-$ resonance model

Most precise $\phi_s^{c\bar{c}s}$ measurement from combination of $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$ to date!

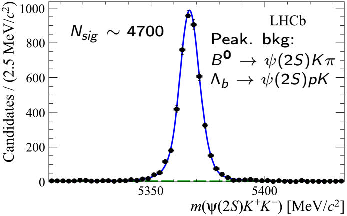
ϕ_s in $B_s^0 \to \psi(2S)(\to \mu^+\mu^-)\phi(\to K^+K^-)$

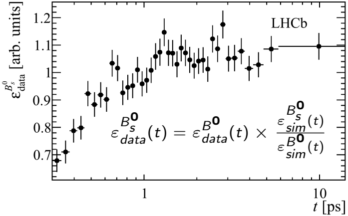
[PLB 762 (2016) 253-262]

- Replace $J/\psi \to \psi(2S)$. The B_s^0 yield is decreased by factor ~ 20
- Prompt J/ψ events are used to calibrate decay time resolution model
- Decay time efficiency is determined using control $B^0 \to \psi(2S)K^*(\to K^+\pi^-)$ channel

$$\begin{aligned}\phi_s &= 0.23^{+0.29}_{-0.28}\pm0.02 \text{ rad}\\ \Gamma_s &= 0.668\pm0.011\pm0.006 \text{ ps}^{-1}\\ \Delta\Gamma_s &= 0.066^{+0.041}_{-0.044}\pm0.007 \text{ ps}^{-1}\\ |\lambda| &= 1.045^{+0.069}_{-0.050}\pm0.007\end{aligned}$$

[*] First uncertainty is statistical, second is systematic uncertainty



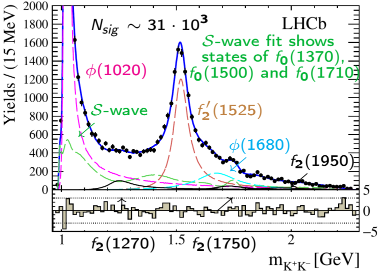


- Consistent with $B_s^0 \to J/\psi K^+K^-$ fit results
- Limited size of data sample
- Systematic uncertainty is $< 0.2\sigma_{stat}$ except for Γ_s ($\sim 0.6\sigma_{stat}$)

ϕ_s in $B_s^0 \to J/\psi K^+K^-$ in high $M(KK)$ region

[JHEP 08 (2017) 037]

- $B_s^0 \to J/\psi KK$ with $M(KK) > 1.05$ GeV higher than $M(\phi(1020))$
- Formalism of the analysis is the same as used in $B_s^0 \to J/\psi\phi$
- Decay time efficiency is determined using control $B^0 \to J/\psi K^*(\to K^+\pi^-)$ channel



$$\begin{aligned}
\phi_s &= 0.119 \pm 0.107 \pm 0.034 \text{ rad}\\
\Gamma_s &= 0.650 \pm 0.006 \pm 0.004 \text{ ps}^{-1}\\
\Delta\Gamma_s &= 0.066 \pm 0.018 \pm 0.010 \text{ ps}^{-1}\\
|\lambda| &= 0.994 \pm 0.018 \pm 0.006
\end{aligned}$$

Combination with $B_s^0 \to J/\psi\phi$

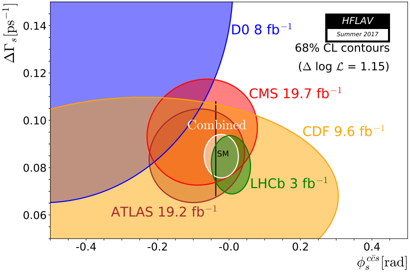
$$\begin{aligned}
\phi_s &= -0.025 \pm 0.045 \pm 0.008 \text{ rad}\\
\Gamma_s &= 0.6588 \pm 0.0022 \pm 0.0015 \text{ ps}^{-1}\\
\Delta\Gamma_s &= 0.0813 \pm 0.0073 \pm 0.0036 \text{ ps}^{-1}\\
|\lambda| &= 0.978 \pm 0.013 \pm 0.003
\end{aligned}$$

* First uncertainty is statistical, second is systematic uncertainty

- Combination with $B_s^0 \to J/\psi\phi$ improves a precision of the ϕ_s measurement by over 9%
- Main fractions: ∼70% $\phi(1020)$, ∼10% $f_2'(1525)$ and $\mathcal{S}$-wave each
- Largest contribution to systematic uncertainty from the resonance fit model (± 0.0236 rad)

ϕ_s experimental measurements

- $\phi_s^{c\bar{c}s} \overset{\text{SM}}{=}$ -0.0370±0.0006 rad **[CKMFitter, PRD 84 (2011) 033005]**
- $\Delta\Gamma_s \overset{\text{SM}}{=} 0.088 \pm 0.020\ \text{ps}^{-1}$ **[M. Artuso et al, arXiv:1511.09466]**



HFLAV combination

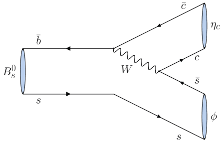
$$\phi_s^{c\bar{c}s} = -0.021 \pm 0.031\ \text{rad}$$
$$\Delta\Gamma_s = 0.085 \pm 0.006\ \text{ps}^{-1}$$
$$\Gamma_s = 0.6640 \pm 0.0020\ \text{ps}^{-1}$$

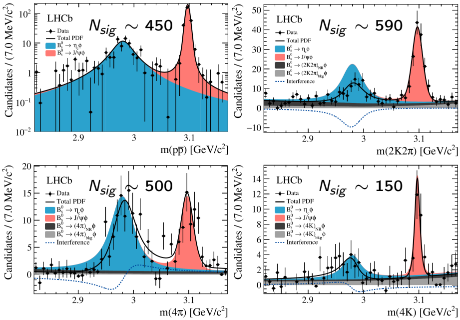
- $B_s^0 \to J/\psi KK$ gives the lowest uncertainties
- LHCb dominates world average
- Consistent with SM predictions but still a lot of window for NP

Observation of $B_s^0 \to \eta_c \phi$

[JHEP 1707 (2017) 021]

- Dominantly decay through the $b \to c\bar{c}s$ transition
- Purely $\mathcal{CP}$-even state $\Rightarrow$ no angular analysis is required
- $\eta_c \to$ into $p\bar{p}$, $2K2\pi$, 4π and $4K$ final states
- J/ψ decaying to same final states is used as normalisation



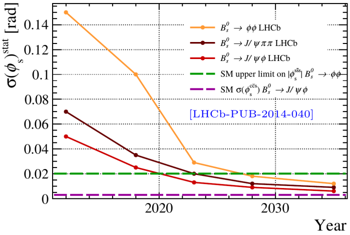


- Total decay amplitude $|A(m_i; c_k^i, \vec{x})|^2 = \sum_J |\sum_k c_k^i R_k^J(m_i; \vec{x})|^2$
- Interference between η_c and non-resonant states taken into account
- First evidence for the $B_s^0 \to \eta_c(\to p\bar{p})\pi^+\pi^-$ (decay proceeds via the $f_0(980)$ resonance)
- Expected the ϕ_s measurement with more data statistics

$$\mathcal{B}(B_s^0 \to \eta_c\phi) = (5.01 \pm 0.53(\text{stat}) \pm 0.27(\text{syst}) \pm 0.63(\mathcal{B})) \cdot 10^{-4}$$
$$\mathcal{B}(B_s^0 \to \eta_c\pi^+\pi^-) = (1.76 \pm 0.59(\text{stat}) \pm 0.12(\text{syst}) \pm 0.29(\mathcal{B})) \cdot 10^{-4}$$

Conclusion

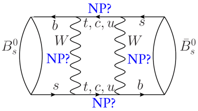
- Most precise measurement of ϕ_s in the B_s^0 system has been made at LHCb using Run I data
- Future perspectives:
  - Run I: $B_s^0 \to J/\psi(\to e^+e^-)KK$, $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$
  - Run II: new modes with more data



  - Estimations (only $\sigma_{\rm stat}$) for LHCb [LHCb-PUB-2014-040]

Decay mode $\sigma_{\rm stat}(\phi_s)$ [rad]	Run I (3 fb^{-1}) (2010-2012)	Run II (8 fb^{-1}) (2015-2018)	LHCb upgrade (+2020, 50 fb^{-1})	Theory limit
$B_s^0 \to J/\psi KK$	0.049	0.025	0.009	~0.001
$B_s^0 \to J/\psi f_0$	0.068	0.035	0.012	~0.01

- Penguin effects in B_s^0 mixing are under control: $\Delta\phi_s \sim 0.001 \pm 0.020$ rad … but more work still be needed for LHCb upgrade



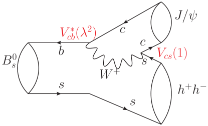
[JHEP 11 (2015) 082]
[PLB 742 (2015) 38]

Thank you for your attention!

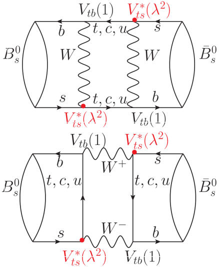
Backups

Violation of the $\mathcal{CP}$ symmetry

- Direct (in decay amplitudes):
  $\phi_D = \arg(V_{cs}V^*_{cb})$
  *Ignoring sub-leading penguin contributions



- Mixing (indirect): $\phi_M = 2\arg(V_{ts}V^*_{tb})$
  - Described by phenomenological Schrödinger equation:
    $$i\frac{d}{dt}\begin{pmatrix}|B^0_s(t)\rangle\\|\bar{B}^0_s(t)\rangle\end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\Gamma\right)\begin{pmatrix}|B^0_s(t)\rangle\\|\bar{B}^0_s(t)\rangle\end{pmatrix}$$
  - Solutions give two mass eigenstates: B_H and B_L
    $|B_L\rangle = p|B^0_s\rangle + q|\bar{B}^0_s\rangle$
    $|B_H\rangle = p|B^0_s\rangle - q|\bar{B}^0_s\rangle$
  - Mixing parameters
    $\Delta m_s = M_H - M_L$ $\Delta\Gamma_s = \Gamma_L - \Gamma_H$
    $\Gamma_s = \frac{\Gamma_L+\Gamma_H}{2}$ $\phi_{12} = \arg(-M_{12}/\Gamma_{12})$



- Interference between direct decays and decays with mixing

$$\phi_s \equiv -\arg(\lambda_f) \equiv -\arg\left(\frac{q}{p}\frac{A_f}{\bar{A}_f}\right) \neq 0 \qquad |\lambda| \equiv \left|\frac{q}{p}\frac{A_f}{\bar{A}_f}\right| \approx 1$$

$$\phi_s^{SM} = \phi_M - 2\phi_D = -2arg\left(-\frac{V_{ts}V^*_{tb}}{V_{cs}V^*_{cb}}\right) = -2\beta_s$$

$$\begin{tikzcd}
\overline{B}^0_{(s)} \arrow[rr, "\overline{A}_f"] \arrow[dr, "q/p"'] & & f \\
& B^0_{(s)} \arrow[ur, "A_f"'] &
\end{tikzcd}$$

Polarisation-dependent $\mathcal{CP}$ violation

[PRD 89 (2014) 094010]
[PRL 114 (2015) 041801]

- Results of the $B_s^0 \to J/\psi K^+K^-$ analysis are obtained with the assumption that ϕ_s and $|\lambda|$ are independent of the final state polarisation
- Condition is relaxed to allow the measurement of these parameters separately for each polarisation

Parameter	Value
$\lvert\lambda^0\rvert$	$1.012 \pm 0.058 \pm 0.013$
$\lvert\lambda^{\parallel}/\lambda^0\rvert$	$1.02 \pm 0.12 \pm 0.05$
$\lvert\lambda^{\perp}/\lambda^0\rvert$	$0.97 \pm 0.16 \pm 0.01$
$\lvert\lambda^{\mathrm{S}}/\lambda^0\rvert$	$0.86 \pm 0.12 \pm 0.04$
ϕ_s^0 [rad]	$-0.045 \pm 0.053 \pm 0.007$
$\phi_s^{\parallel} - \phi_s^0$ [rad]	$-0.018 \pm 0.043 \pm 0.009$
$\phi_s^{\perp} - \phi_s^0$ [rad]	$-0.014 \pm 0.035 \pm 0.006$
$\phi_s^{\mathrm{S}} - \phi_s^0$ [rad]	$0.015 \pm 0.061 \pm 0.021$

No evidence for a polarisation-dependent $\mathcal{CP}$ violation in the decay.

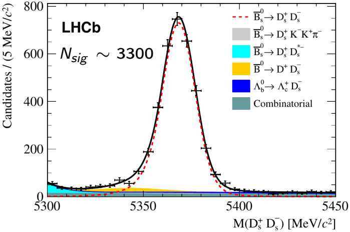
ϕ_s in $B^0_s \to D^+_s D^-_s$

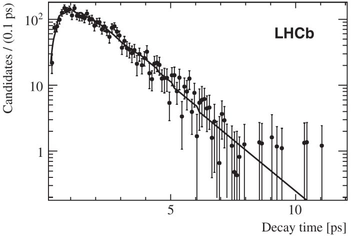
[PRL 113 (2014) 211801]

- Purely $\mathcal{CP}$-even state ⇒ no angular analysis is required
- Candidates are reconstructed in four final states ⇒ combinations of $D^{\pm}_s$ into $KK\pi$, $K\pi\pi$ and $\pi\pi\pi$
- $B^0 \to D^-(\to K^+2\pi^-)D^+_s(\to K^{\pm}\pi^+)$ is used as control channel
- Time dependent ($\sigma_t \approx$54 fs) tagged ($\varepsilon\mathcal{D}^2 = (5.33 \pm 0.18 \pm 0.17)\%$) analysis

$$\begin{aligned} \phi_s &= 0.02 \pm 0.17 \pm 0.02 \text{ rad} \\ |\lambda| &= 0.91^{+0.18}_{-0.15} \pm 0.02 \end{aligned}$$

⋆ First uncertainty is statistical, second is systematic uncertainty





- Consistent with SM predictions, no direct $\mathcal{CP}$ violation ($|\lambda|$=1)
- Systematics dominated by the decay time resolution
- Decay time uncertainty calibrated from the simulation

ϕ_s and $\Delta\Gamma_s$ experimental measurements

Mode	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	Reference
CDF (9.6 fb^{-1})			
$J/\psi\phi$	[-0.60,+0.12], 68% CL	+0.068±0.026±0.009	[PRL 109 (2012) 171802]
D0 (8.0 fb^{-1})			
$J/\psi\phi$	$-0.55^{+0.38}_{-0.36}$	$+0.163^{+0.065}_{-0.064}$	[PRD 85 (2012) 032006]
ATLAS (19.2 fb^{-1})			
$J/\psi\phi$	-0.090±0.078±0.041	+0.085±0.011±0.007	[JHEP 08 (2016) 147]
CMS (19.7 fb^{-1})			
$J/\psi\phi$	-0.075±0.097±0.031	+0.095±0.013±0.007	[PLB 757 (2016) 97-120]
LHCb (3.0 fb^{-1})			
$J/\psi KK$	-0.058±0.049±0.006	+0.0805±0.0091±0.0032	[PRL 114 (2015) 041801]
$J/\psi\pi\pi$	+0.070±0.068±0.008	-	[PLB 736 (2014) 186]
$J/\psi KK$ HM	+0.119±0.107±0.034	-	[arXiv:1704.08217]
$\psi(2S)\phi$	$+0.23^{+0.29}_{-0.28}\pm0.02$	$+0.066^{+0.41}_{-0.44}\pm0.007$	[PLB 762 (2016) 253-262]
D_sD_s	+0.02±0.17±0.02	-	[PRL 113 (2014) 211801]