Measurements of the phase ϕ_s at LHCb

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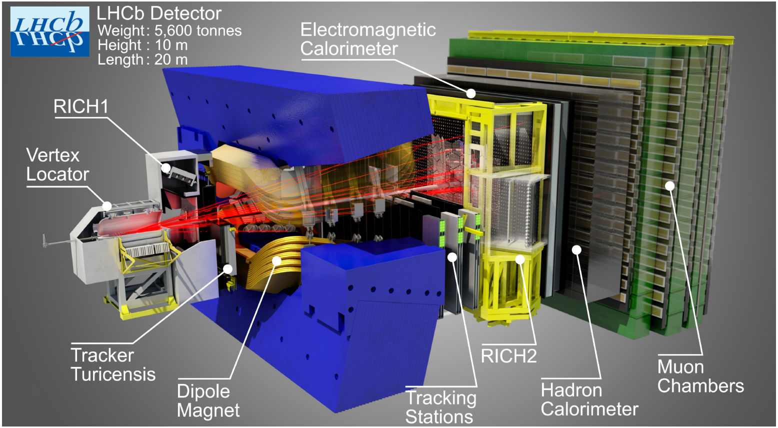
Large Hadron Collider beauty Detector [JINST 3 (2008) S08005]



- 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

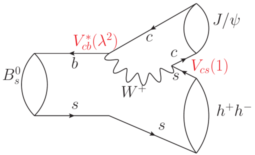
Violation of the $\mathcal{CP}$ symmetry

$\mathcal{CP}$ symmetry = $\mathcal{C}$ (charge conjugation) $\times$ $\mathcal{P}$ (parity)

Direct (in decay amplitudes)

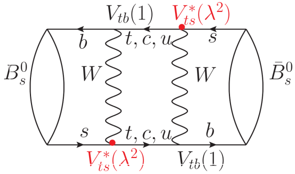
$\phi_D = \arg(V_{cs}V_{cb}^*)$

*Ignoring sub-leading penguin contributions

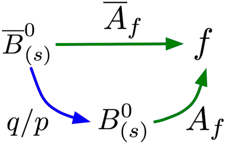


Mixing (indirect)

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



Interference between direct decays and decays with mixing



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

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

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

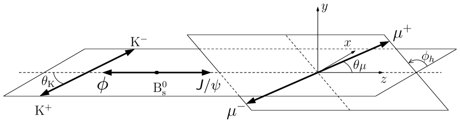
$$\phi_s^{SM} = \text{-}0.0376^{+0.0008}_{-0.0007} \text{ rad}$$ **[CKMFitter]**

$$\phi_s = \phi_s^{SM} + \Delta\phi_s + \delta_s^{NP}$$

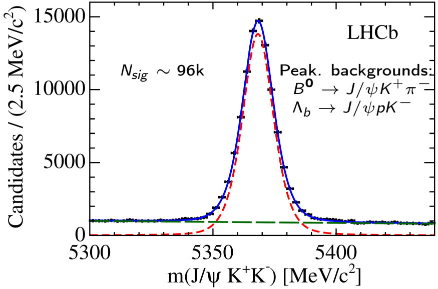
ϕ_s in $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$

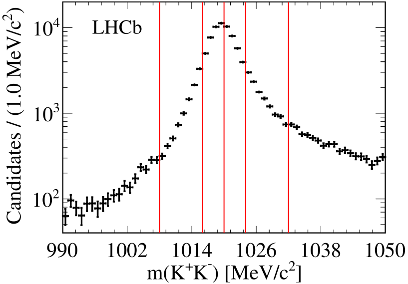
[PRL 114 (2015) 041801]

- $B_s^0 \to J/\psi\phi$ is P→VV decay ⇒ final state is an admixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd eigenstates
- Amplitudes:
  3 P-wave $(A_0, A_\perp, A_\parallel)$ + 1 S-wave (A_S)
- Time dependent angular $(\theta_K, \theta_\mu, \varphi)$ tagged $(\varepsilon\mathcal{D}^2 = (3.73 \pm 0.15)\%)$ analysis



$$\frac{d^4\Gamma(B_s^0 \to J/\psi\phi)}{dt d\Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\theta_K, \theta_\mu, \phi)$$





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

ϕ_s in $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$ [PRL 114 (2015) 041801]

ϕ_s = -0.058±0.049(stat)±0.006(syst) rad

Γ_s = 0.6603±0.0027(stat)±0.0015(syst) ps^{-1}

$\Delta\Gamma_s$ = 0.0805±0.0091(stat)±0.0032(syst) ps^{-1}

$\Delta m_s = 17.711^{+0.055}_{-0.057}$(stat)±0.0032(syst) ps^{-1}

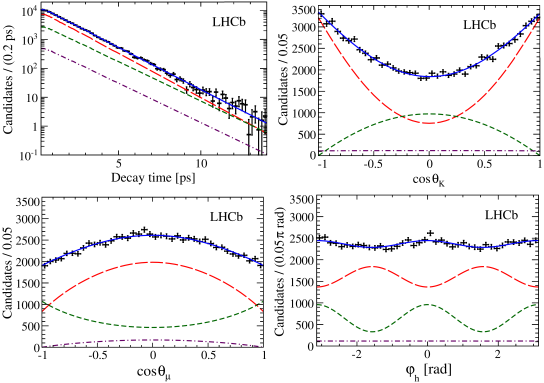
$|\lambda|$ = 0.964±0.019(stat)±0.007(syst)

Combined $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$
[PRL 114 (2015) 041801]

ϕ_s = -0.010±0.039 rad

$|\lambda|$ = 0.957±0.017

Blue: Total Red: CP-even Green: CP-odd Magenta: S-wave

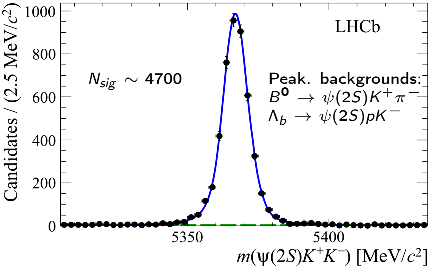


- Consistent with SM predictions
- Decay time efficiency, angular efficiency and background subtraction give dominant contribution to systematic uncertainty
- Most precise measurement of lifetime parameters from $B_s^0 \to J/\psi K^+K^-$
- ★ Most precise measurement of ϕ_s from combination of $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$

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

[PLB 762 (2016) 253-262]

- Replace $J/\psi \longrightarrow \psi(2S)$. 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 $B^0 \to \psi(2S)K^*(892)^0(\to K^+\pi^-)$ channel
- Flavour tagging efficiency is $(3.88 \pm 0.18)\%$

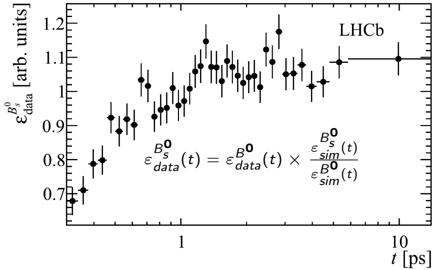


$\phi_s = 0.23^{+0.29}_{-0.28}(\text{stat})\pm 0.02(\text{syst})$ rad

$\Gamma_s = 0.668 \pm 0.011(\text{stat})\pm 0.006(\text{syst})\ \text{ps}^{-1}$

$\Delta\Gamma_s = 0.066^{+0.041}_{-0.044}(\text{stat})\pm 0.007(\text{syst})\ \text{ps}^{-1}$

$|\lambda| = 1.045^{+0.069}_{-0.050}(\text{stat})\pm 0.007(\text{syst})$

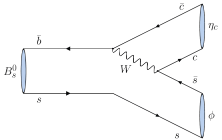


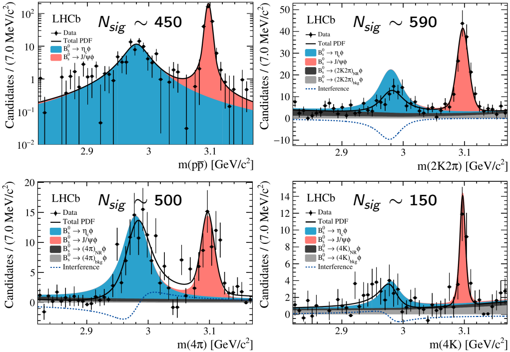
- Consistent with $B_s^0 \to J/\psi\phi$ fit results
- Limited size of data sample
- Systematic uncertainty is $< 0.2\sigma_{stat}$ except for Γ_s ($\sim 0.6\sigma_{stat}$)

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

[LHCb-PAPER-2016-056]

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





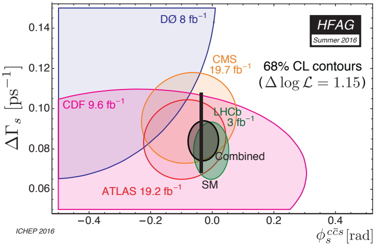
- Total decay amplitude $|A(m_i; c_k^i, \vec{x})|^2 = \sum_J |\sum_k c_k^i R_k^J(m_i; \vec{x})|^2$
- Interference between η_c and non-resonant states taken into account
- First evidence for the $B_s^0 \to \eta_c(\to p\bar{p})\pi^+\pi^-$ (decay proceeds via the $f_0(980)$ resonance)
- Expected the ϕ_s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

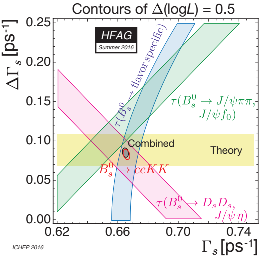
$$\mathcal{B}(B_s^0 \to \eta_c\phi) = (5.01 \pm 0.53(\text{stat}) \pm 0.27(\text{syst}) \pm 0.63(\mathcal{B})) \cdot 10^{-4}$$

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

ϕ_s and lifetime experimental measurements

- $\phi_s^{c\bar{c}s} \overset{SM}{=} -0.0376^{+0.0008}_{-0.0007}$ rad **[CKMFitter]**
- $\Delta\Gamma_s \overset{SM}{=} 0.088 \pm 0.020$ ps^{-1} **[M. Artuso et al, arXiv:1511.09466]**





HFAG combination

$\phi_s^{c\bar{c}s} = -0.030 \pm 0.033$ rad

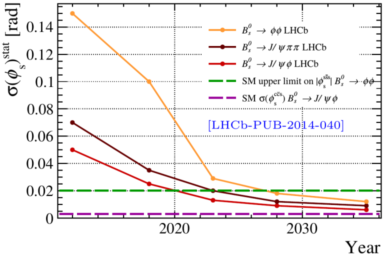
$\Delta\Gamma_s = 0.085 \pm 0.006$ ps^{-1}

$\Gamma_s = 0.6648 \pm 0.0020$ ps^{-1}

Mode	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	Exp.	Reference
$B_s^0 \to J/\psi\phi$	[-0.60,+0.12], 68% CL	$+0.068 \pm 0.026 \pm 0.009$	CDF (9.6 fb^{-1})	[PRL 109 (2012) 171802]
$B_s^0 \to J/\psi\phi$	$-0.55^{+0.38}_{-0.36}$	$+0.163^{+0.065}_{-0.064}$	D0 (8.0 fb^{-1})	[PRD 85 (2012) 032006]
$B_s^0 \to J/\psi\phi$	$-0.090 \pm 0.078 \pm 0.041$	$+0.085 \pm 0.011 \pm 0.007$	ATLAS (19.2 fb^{-1})	[JHEP 08 (2016) 147]
$B_s^0 \to J/\psi\phi$	$-0.075 \pm 0.097 \pm 0.031$	$+0.095 \pm 0.013 \pm 0.007$	CMS (19.7 fb^{-1})	[PLB 757 (2016) 97-120]
$B_s^0 \to J/\psi\phi$	$-0.058 \pm 0.049 \pm 0.006$	$+0.0805 \pm 0.0091 \pm 0.0033$	LHCb (3.0 fb^{-1})	[PRD 84 (2011) 033005]
$B_s^0 \to J/\psi\pi^+\pi^-$	$+0.070 \pm 0.068 \pm 0.008$	-	LHCb (3.0 fb^{-1})	[PLB 736 (2014) 186]
Above 2 combined	-0.010 ± 0.039 rad	-	LHCb (3.0 fb^{-1})	[PRL 114 (2015) 041801]
$B_s^0 \to \psi(2S)\phi$	$+0.23^{+0.29}_{-0.28} \pm 0.02$	$+0.066^{+0.41}_{-0.44} \pm 0.007$	LHCb (3.0 fb^{-1})	[PLB 762 (2016) 253-262]
$B_s^0 \to D_s^+ D_s^-$	$+0.02 \pm 0.17 \pm 0.02$	-	LHCb (3.0 fb^{-1})	[PRL 113 (2014) 211801]

Summary

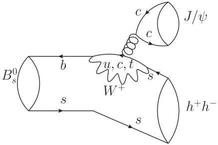
- Using Run I data the most precise measurement of ϕ_s and lifetimes in the B_s^0 system has been made at LHCb
- Many active analysis to increase accuracy of CP-violating parameters measurement:
  - $B_s^0 \to J/\psi\phi$ decay with $J/\psi \to e^+e^-$
  - $B_s^0 \to J/\psi K^+K^-$ decay above the ϕ mass region
  - ...



- Future estimations for LHCb [LHCb-PUB-2014-040]

Decay mode $\sigma_{\text{stat}}(\phi_s)$ [rad]	Run I (3 fb^{-1}) (2010-2012)	Run II (8 fb^{-1}) (2015-2018)	LHCb upgrade (+2020, 50 fb^{-1})	Theory limit
$B_s^0 \to J/\psi K^+K^-$	0.049	0.025	0.009	$\sim$0.001
$B_s^0 \to J/\psi f_0(980)$	0.068	0.035	0.012	$\sim$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



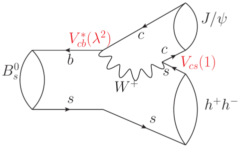
[JHEP 11 (2015) 082]

[PLB 742 (2015) 38-49]

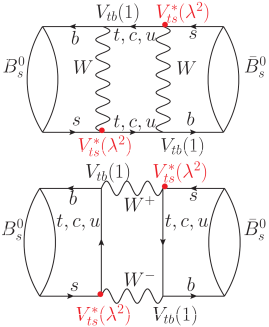
Thank you for your attention

Backups

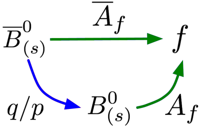
Violation of the $\mathcal{CP}$ symmetry



- **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:
    $$i\frac{d}{dt}\begin{pmatrix}|B_s^0(t)\rangle\\|\bar{B}_s^0(t)\rangle\end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\Gamma\right)\begin{pmatrix}|B_s^0(t)\rangle\\|\bar{B}_s^0(t)\rangle\end{pmatrix}$$
  - Solutions give two mass eigenstates: B_H and B_L
    $|B_L\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle$
    $|B_H\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$
  - Mixing parameters
    $\Delta m_s = M_H - M_L$ $\quad \Delta\Gamma_s = \Gamma_L - \Gamma_H$
    $\Gamma_s = \frac{\Gamma_L+\Gamma_H}{2}$ $\quad \phi_{12} = \arg(-M_{12}/\Gamma_{12})$
- **Interference** between direct decays and decays with mixing
  $\phi_s \equiv -\arg(\lambda_f) \equiv -\arg\left(\frac{q}{p}\frac{A_f}{\bar{A}_f}\right) \neq 0$ $\qquad |\lambda| \equiv \left|\frac{q}{p}\frac{A_f}{\bar{A}_f}\right| \approx 1$

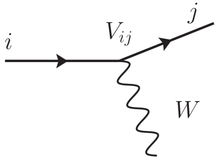


$$\phi_s^{SM} = \phi_M - 2\phi_D = -2arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -2\beta_s$$
ϕ_s^{SM} = -0.0376$^{+0.0008}_{-0.0007}$ rad **[CKMFitter]**

CKM - quark mixing matrix

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

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



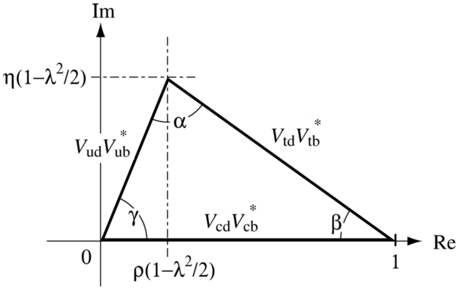
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}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

$\lambda \approx 0.22$

Unitarity triangles

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

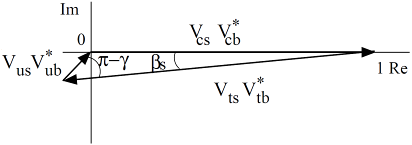
Triangle (db)



$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$\beta = arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

Triangle (sb)



$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

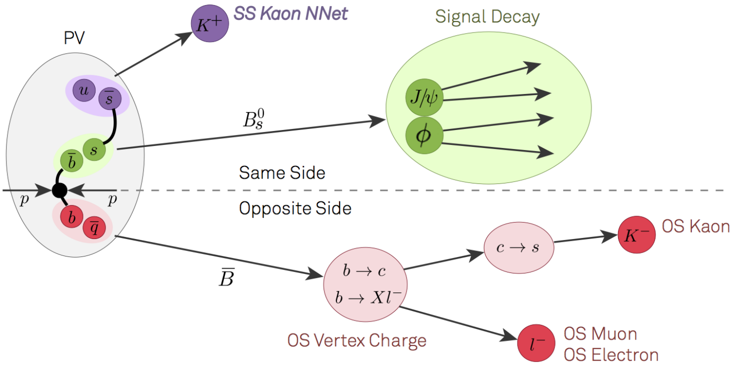
$$\boxed{\beta_s = arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)}$$

"Golden" mode

$B^0 \to J/\psi K_S$: $(\bar{b}d) \to (c\bar{c})(d\bar{s})$

$B_s^0 \to J/\psi\phi$: $(\bar{b}s) \to (c\bar{c})(s\bar{s})$

Flavour tagging of initial B_s^0



- In LHCb is used two types of tagging:
  - Same Side - charge kaon which is correlated with B_s^0
  - Opposite Side - charge lepton or kaon from second B decay
- To calibrate the tagging algorithm similar and self tagging decays to signal are used: $B^+ \to J/\psi K^+$ for OS and $B_s^0 \to D_s^- \pi^+$ for SS
- Estimated the efficiency of the algorithm:
  - tagging efficiency ϵ_{tag} and corrected mistag probability ω
  - total efficiency $\epsilon_{eff} = \epsilon_{tag}(1\text{-}2\omega)^2 = (3.73 \pm 0.15)\%$ for $B_s^0 \to J/\psi\phi$