Measurements of the $\mathcal{CP}$ violating phase ϕ_s at LHCb

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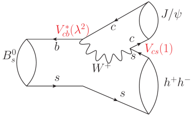
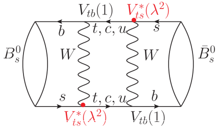
Violation of the $\mathcal{CP}$ symmetry

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

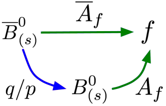
$\mathcal{CP}$V in decay
(Direct $\mathcal{CP}$ violation)
$\phi_D = \arg(V_{cs}V_{cb}^*)$



$\mathcal{CP}$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



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

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

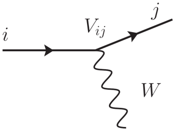
$$\phi_s^{SM} = \phi_M - 2\phi_D \to \phi_s^{c\bar{c}s} = -2\arg(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}) = -2\beta_s$$

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

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



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

$\lambda \approx 0.22$

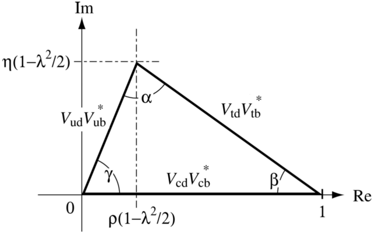
[PRL 53 (1984) 1802]

Unitary triangles

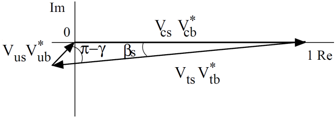
[PRL 10 (1963) 531]

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

Triangle (db)



Triangle (sb)



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

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

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

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

"Golden" mode

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

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

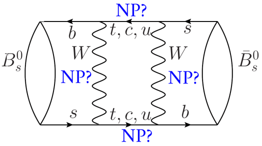
Introduction to ϕ_s

- SM prediction is very small and precise:

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

[CKMFitter, PRD 84 (2011) 033005]
*Ignoring subleading penguin contributions

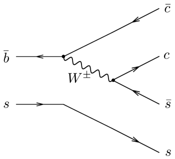
- If new particles contribute to "box" diagrams, then value of ϕ_M will be different than SM prediction

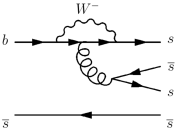


$$\phi_M = \phi_M^{SM} + \Delta\phi_M^{NP}$$
$$\phi_s^{c\bar{c}s} = \phi_M - 2\phi_D = -2\beta_s + \Delta\phi_M^{NP}$$

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

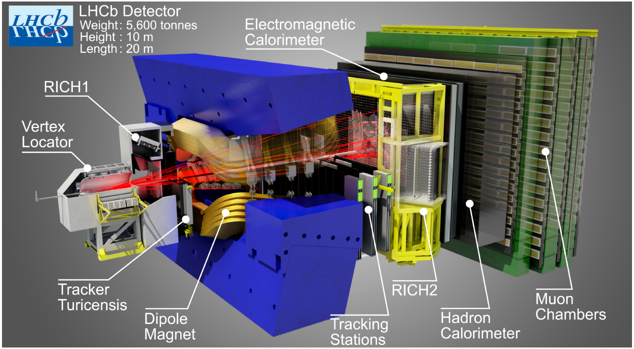
- ϕ_s is measured by LHCb in the different processes:
  - $b \to c\bar{c}s$ transition
    $B_s^0 \to J/\psi KK$, $B_s^0 \to J/\psi\pi\pi$
    $B_s^0 \to \psi(2S)\phi$, $B_s^0 \to D_s D_s$
    $B_s^0 \to \eta_c\phi$, $B_s^0 \to J/\psi\eta$ (with large statistics)
  - $b \to s\bar{s}s$ transition
    $B_s^0 \to \phi\phi$
    $B_s^0 \to \phi\pi\pi$ (with large statistics)





Large Hadron Collider beauty Detector

[JINST 3 (2008) S08005]



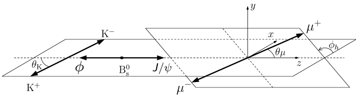
- Single-arm forward spectrometer, covering $2< \eta <5$ ($10< \theta <300$ (250) mrad)
- Momentum resolution: $\Delta p/p = 0.5\%$ at 5 GeV/c to 1.0% at 200 GeV/c
- Impact parameter resolution: 20 μm for high p_T tracks
- Decay time resolution: $\sim$ 45 fs
- Invariant mass resolution: $\sim$ 8 MeV/c^2 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

Current status of ϕ_s measurement

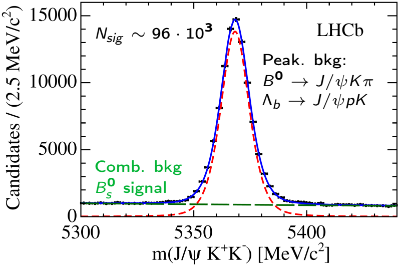
ϕ_s in $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$

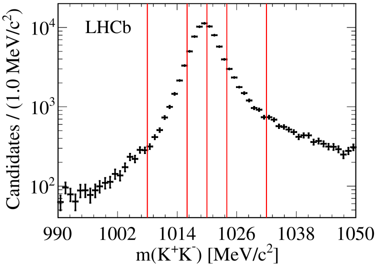
[PRL 114 (2015) 041801]

- $B_s^0 \to J/\psi\phi$ is P→VV decay ⇒ final state is an admixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd eigenstates
- Amplitudes: 3 $\mathcal{P}$-wave $(A_0, A_\perp, A_\parallel)$ + 1 $\mathcal{S}$-wave $(A_\mathcal{S})$
- Time dependent (σ_t=46 fs) angular $(\theta_K, \theta_\mu, \phi)$ tagged $(\varepsilon\mathcal{D}^2 = (3.73 \pm 0.15)\%)$ analysis



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



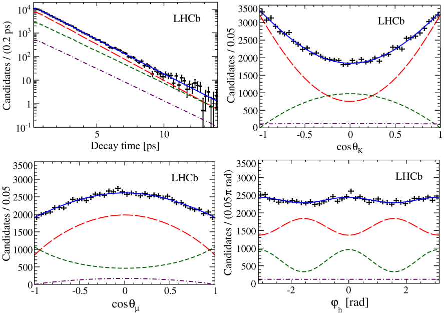


- Fit is carried out in 6 bins of $m(K^+K^-)$ region to measure $\mathcal{S}$-wave contribution

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



$$
\begin{aligned}
\phi_s &= -0.058 \pm 0.049 \pm 0.006 \text{ rad} \\
\Gamma_s &= 0.6603 \pm 0.0027 \pm 0.0015 \text{ ps}^{-1} \\
\Delta\Gamma_s &= 0.0805 \pm 0.0091 \pm 0.0032 \text{ ps}^{-1} \\
\Delta m_s &= 17.711^{+0.055}_{-0.057} \pm 0.0032 \text{ ps}^{-1} \\
|\lambda| &= 0.964 \pm 0.019 \pm 0.007
\end{aligned}
$$

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

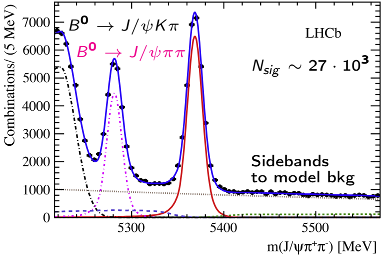
- $B_s^0 \to J/\psi K^+K^-$ is a golden channel: measurement of ϕ_s, Γ_s, $\Delta\Gamma_s$, Δm_s, $|\lambda|$
- Consistent with SM predictions, no direct $\mathcal{CP}$ violation ($|\lambda| = 1$)
- Decay time efficiency, angular efficiency and background subtraction give dominant contribution to systematic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

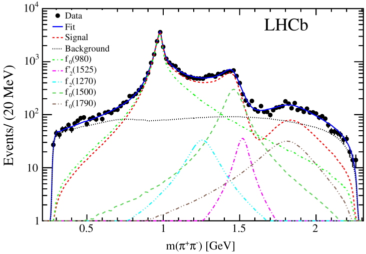
Most precise measurement of lifetime parameters to date!

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

[PRD 89 (2014) 092006]

- $B_s^0 \to J/\psi\pi^+\pi^-$ is another $\bar{b} \to \bar{c}c\bar{s}$ transition
- Amplitude analysis to study resonance structure of $\pi^+\pi^-$ states
- Angular $(\theta_{\pi\pi}, \theta_{J/\psi}, \chi)$ analysis



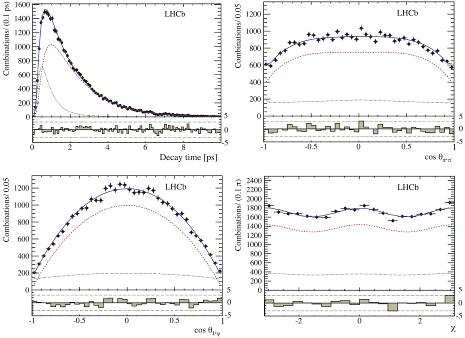


- $\mathcal{CP}$-odd state of $\pi^+\pi^-$ is >97.7% at 95% CL
- Sum over $\pi^+\pi^-$ resonant states: $\mathcal{A}(m_{\pi\pi}, \Omega) = \sum_R \sum_{\lambda=0,\parallel,\perp} A_\lambda^R(m_{\pi\pi}, \Omega)$
- Largest component in resonant states is the $f_0(980)$ with $\sim 70\%$

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

[PLB 736 (2014) 186]

Blue: Total   Red: Signal   Black: Background



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

⋆ First uncertainty is statistical, second is systematic uncertainty

Combination with $B_s^0 \to J/\psi K^+K^-$

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

[PRL 114 (2015) 041801]

- Consistent with SM predictions, no direct $\mathcal{CP}$ violation ($|\lambda_{\pi\pi}|$=1, 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!

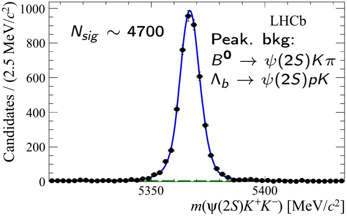
ϕ_s in $B_s^0 \to \psi(2S)(\to \mu^+\mu^-)\phi(\to K^+K^-)$

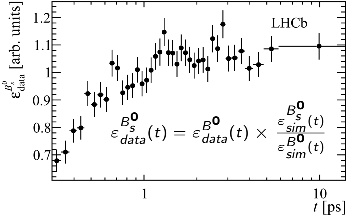
[PLB 762 (2016) 253-262]

- 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

$$\begin{aligned} \phi_s &= 0.23^{+0.29}_{-0.28} \pm 0.02 \text{ rad} \\ \Gamma_s &= 0.668 \pm 0.011 \pm 0.006 \text{ ps}^{-1} \\ \Delta\Gamma_s &= 0.066^{+0.041}_{-0.044} \pm 0.007 \text{ ps}^{-1} \\ |\lambda| &= 1.045^{+0.069}_{-0.050} \pm 0.007 \end{aligned}$$

* First uncertainty is statistical, second is systematic uncertainty



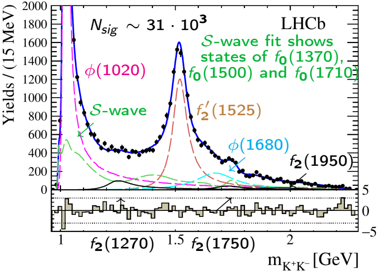


- Consistent with $B_s^0 \to J/\psi K^+K^-$ fit results
- Limited size of data sample
- Systematic uncertainty is $< 0.2\sigma_{stat}$ except for Γ_s ($\sim 0.6\sigma_{stat}$)

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



$$\begin{aligned} \phi_s &= 0.119\pm0.107\pm0.034 \text{ rad} \\ \Gamma_s &= 0.650\pm0.006\pm0.004 \text{ ps}^{-1} \\ \Delta\Gamma_s &= 0.066\pm0.018\pm0.010 \text{ ps}^{-1} \\ |\lambda| &= 0.994\pm0.018\pm0.006 \end{aligned}$$

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

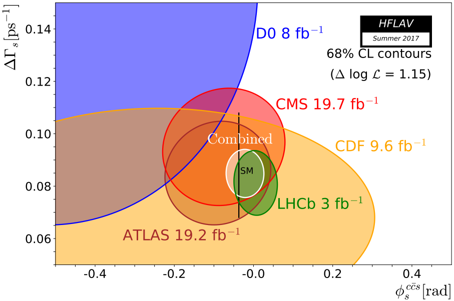
$$\begin{aligned} \phi_s &= -0.025\pm0.045\pm0.008 \text{ rad} \\ \Gamma_s &= 0.6588\pm0.0022\pm0.0015 \text{ ps}^{-1} \\ \Delta\Gamma_s &= 0.0813\pm0.0073\pm0.0036 \text{ ps}^{-1} \\ |\lambda| &= 0.978\pm0.013\pm0.003 \end{aligned}$$

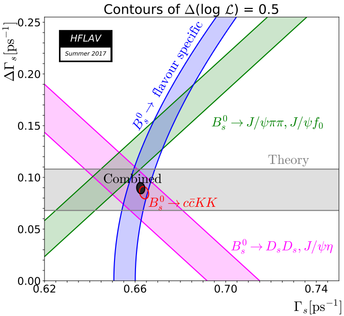
* First uncertainty is statistical, second is systematic uncertainty

- 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, Γ_s and $\Delta\Gamma_s$ experimental measurements

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





HFLAV combination

$\phi_s^{c\bar{c}s}$ = -0.021±0.031 rad

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

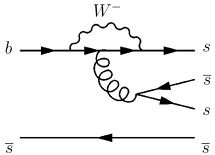
Γ_s = 0.6640±0.0020 ps^{-1}

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

Measurement of ϕ_s in charmless B_s^0 decays

ϕ_s in $B_s^0 \to \phi(\to K^+K^-)\phi(\to K^+K^-)$

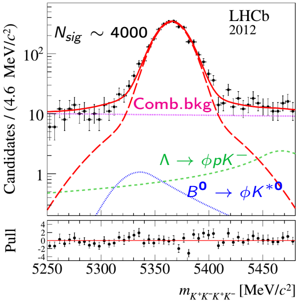
[PRD 90 (2014) 052011]



- $b \to s\bar{s}s$ penguin process is sensitive to NP on the loops
- P→VV + P→VS and P→SS due to proximity to $f_0(980)$ resonance ⇒ angular analysis
- Amplitudes:
  3 $\mathcal{CP}$-even $(A_0, A_\parallel, A_{\mathcal{SS}})$ + 2 $\mathcal{CP}$-odd $(A_\perp, A_\mathcal{S})$

$|\phi_s^{s\bar{s}s}|^{SM} < 0.02$ rad

[NPB 774 (2007) 64-101]
[arXiv:0810.0249]
[PRD 80 (2009) 114026]



$$\phi_s^{s\bar{s}s} = -0.17 \pm 0.15 \pm 0.03$$
$$|\lambda| = 1.04 \pm 0.07 \pm 0.03$$

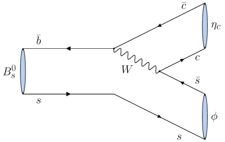
* First uncertainty is statistical, second is systematic uncertainty

- Consistent with SM predistions, no $\mathcal{CPV}$ in $b \to s\bar{s}s$ decay amplitude
- Fraction of $\mathcal{S}$-wave is found to be consistent with zero
- Most significant systematics arise from the angular and decay time acceptance

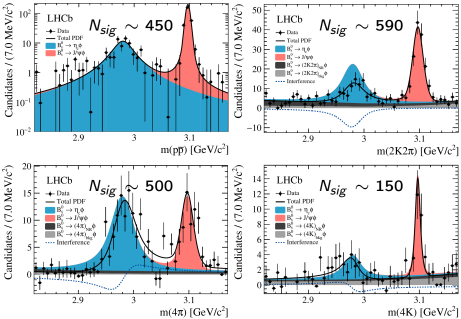
Future contributions to the measurement of ϕ_s

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



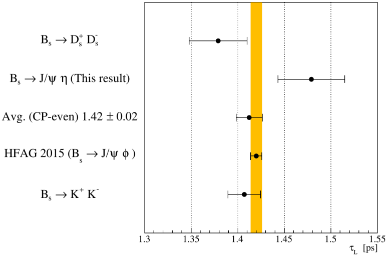
- Total decay amplitude $|A(m_i; c_k^i, \vec{x})|^2 = \sum_J |\sum_k c_k^i R_k^J(m_i; \vec{x})|^2$
- Interference between η_c and non-resonant states taken into account
- First evidence for the $B_s^0 \to \eta_c(\to p\bar{p})\pi^+\pi^-$ (decay proceeds via the $f_0(980)$ resonance)
- Expected the ϕ_s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

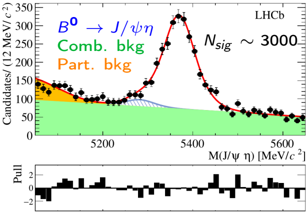
$$\mathcal{B}(B_s^0 \to \eta_c \phi) = (5.01 \pm 0.53(\text{stat}) \pm 0.27(\text{syst}) \pm 0.63(\mathcal{B})) \cdot 10^{-4}$$
$$\mathcal{B}(B_s^0 \to \eta_c \pi^+\pi^-) = (1.76 \pm 0.59(\text{stat}) \pm 0.12(\text{syst}) \pm 0.29(\mathcal{B})) \cdot 10^{-4}$$

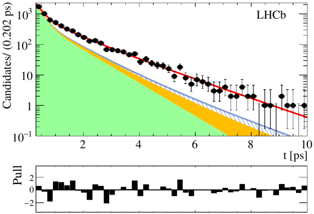
$B_s^0 \to J/\psi\eta(\to \gamma\gamma)$ lifetime efficiency

[PLB 762 (2016) 484]

- Purely $\mathcal{CP}$-even state $\Rightarrow$ no angular analysis is required
- **First step**: measure Γ_L from decay time distribution
- $\sigma_M \approx$48 MeV/c^2 $\Rightarrow$ overlapping with $B^0 \to J/\psi\eta$ component







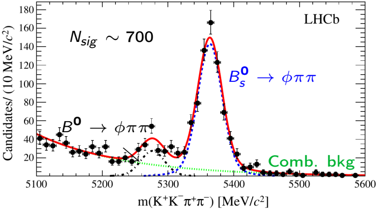
$$\tau_{\text{eff}} = 1.479 \pm 0.034(\text{stat}) \pm 0.011(\text{syst})\ \text{ps}$$

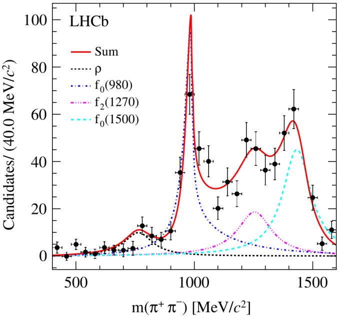
- Limited size of data sample
- Main systematic uncertainty is due to the decay time acceptance model
- Consistent with the effective lifetime determined using other B_s^0 decay modes

Observation of $B_s^0 \to \phi(\to K^+K^-)\pi^+\pi^-$

[PRD 95 (2017) 012006]

- Gluonic $b \to s$ penguin transition $\Rightarrow \mathcal{B}(B_s^0 \to \phi f_0(980))^{\text{theor}} \approx 2 \cdot 10^{-6}$
- Isospin-violating $\Delta\mathcal{I} = 1$ transition is mediated by a combination of an e/w penguin and suppressed $b \to u$ transiton
  $\Rightarrow \mathcal{B}(B_s^0 \to \phi\rho_0)^{\text{theor}} = 4.4^{+2.2}_{-0.7} \cdot 10^{-7}$
- Time dependent angular amplitude analysis, $B_s^0 \to \phi\phi$ as normalization mode

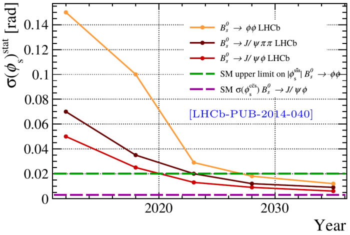




$$\mathcal{B}(B_s^0 \to \phi f_0(980)) = (1.12 \pm 0.16(\text{stat})^{+0.09}_{-0.08}(\text{syst}) \pm 0.11(\mathcal{B})) \cdot 10^{-6}$$
$$\mathcal{B}(B_s^0 \to \phi\rho^0) = (2.7 \pm 0.7(\text{stat}) \pm 0.2(\text{syst}) \pm 0.2(\mathcal{B})) \cdot 10^{-7}$$

Summary

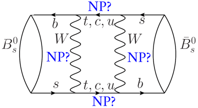
- Using Run I data the most precise measurement of ϕ_s and $\Delta\Gamma_s$ in the B_s^0 system has been made at LHCb
- Active analyses:
  - Run I: $B_s^0 \to J/\psi(\to e^+e^-)KK$, $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$
  - Run II: new modes with more data



- Future 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	$\sim$0.001
$B_s^0 \to J/\psi f_0$	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



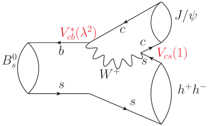
[JHEP 11 (2015) 082]
[PLB 742 (2015) 38]

Thank you for your attention!

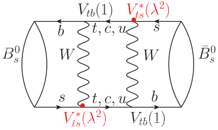
Backups

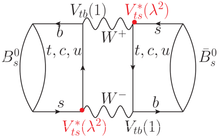
Violation of the $\mathcal{CP}$ symmetry

- 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
    $\Delta m_s = M_H - M_L \qquad \Delta\Gamma_s = \Gamma_L - \Gamma_H$
    $\Gamma_s = \frac{\Gamma_L+\Gamma_H}{2} \qquad \phi_{12} = \arg(-M_{12}/\Gamma_{12})$

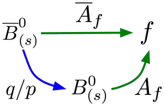




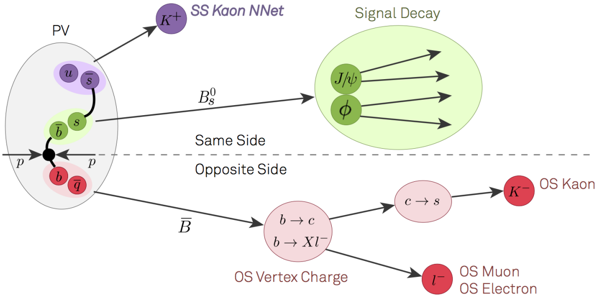
- Interference between direct decays and decays with mixing

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

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



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

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
$\lvert\lambda^0\rvert$	$1.012 \pm 0.058 \pm 0.013$
$\lvert\lambda^{\parallel}/\lambda^0\rvert$	$1.02 \pm 0.12 \pm 0.05$
$\lvert\lambda^{\perp}/\lambda^0\rvert$	$0.97 \pm 0.16 \pm 0.01$
$\lvert\lambda^{S}/\lambda^0\rvert$	$0.86 \pm 0.12 \pm 0.04$
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]	$-0.014 \pm 0.035 \pm 0.006$
$\phi_s^{S} - \phi_s^0$ [rad]	$0.015 \pm 0.061 \pm 0.021$

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

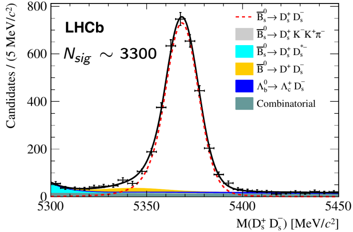
ϕ_s in $B_s^0 \to D_s^+ D_s^-$

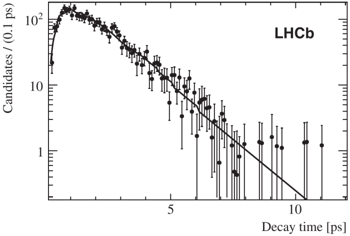
[PRL 113 (2014) 211801]

- Purely $\mathcal{CP}$-even state $\Rightarrow$ no angular analysis is required
- Candidates are reconstructed in four final states $\Rightarrow$ combinations of $D_s^\pm$ 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

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

* 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, Γ_s and $\Delta\Gamma_s$ experimental measurements

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NCBJ, Poland

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]