Measurement of the electroweak phase ϕ_s at LHCb

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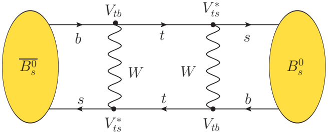
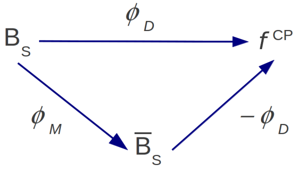
In this talk...

1. Introduction
2. $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi \pi^+\pi^-$
3. $B_s^0 \to \phi\phi$
4. Summary

Measuring ϕ_s





$$\lambda_f \equiv \left|\frac{q}{p}\right| \left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| e^{-i\phi_s}$$

CP violation parameter λ_f contains

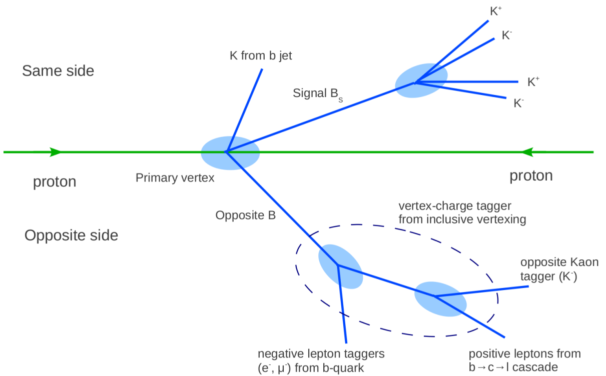
- CP violation in mixing
- CP violation in decay
- CP violation in the interference between "mixed" and "unmixed" decays

$$\phi_s = \phi_M - 2\phi_D$$

Measuring ϕ_s: Analysis

To measure ϕ_s, sensitivity to amplitude oscillation with the time is needed.

- Excellent decay time resolution
- Flavour tagging: "Opposite–Side" (OS) and "Same–Side–Kaon" (SSK) taggers.

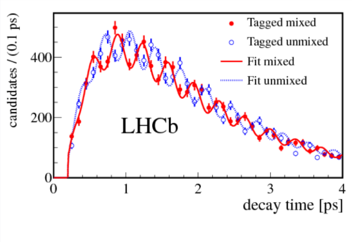


Measuring ϕ_s: Analysis

To measure ϕ_s, sensitivity to amplitude oscillation with the time is needed.

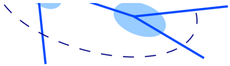
- Excellent decay time resolution

Δm_s measurement from $B_s^0 \to D_s^- \pi^+$ analysis (1/fb)

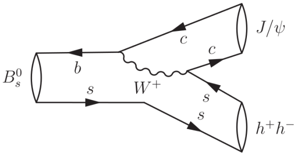


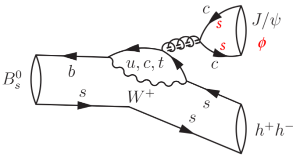
$$\Delta m_s = 17.768 \pm 0.023(\text{stat}) \pm 0.006(\text{syst})\ \text{ps}^{-1}$$

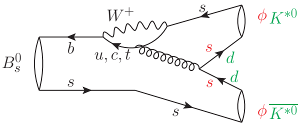
[New J. Phys. 15 (2013) 053021]



Measuring ϕ_s: Decay modes







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

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

- dominated by tree level amplitude
- sensitive to non–SM CP violation induced by mixing
- In SM[1] [CKMfitter Phys. Rev. D **84** 033005 (2011)]

$$\phi_s^{c\bar{c}c} \approx -2\beta_s = -0.0363^{+0.0016}_{-0.0015}$$

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

$B_s^0 \to K^{*0}(K^+\pi^-)\overline{K}^{*0}(K^-\pi^+)$

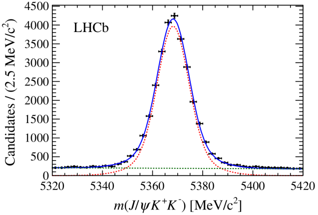
- pure penguin transitions
- sensitive to non–SM CP violation induced by mixing and/or decay
- In SM [Phys. Rev. D **80** 114026 (2009), Phys. Rev. Lett. **100** 031802 (2008)]

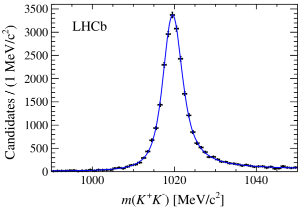
$$\phi_s^{s\bar{s}s} \approx 0$$

[1] *See talk by Carlos Vázquez @ Red de Física de Flavour*

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

Analysis based in 1/fb of data from 2011 ($\sim$ 28K candidates)





Phenomenology:

- Predominantly via $B_s^0 \to J/\psi\phi$ with $\phi \to K^+K^-$, i.e. *P–wave*
- Small component with K^+K^- in *S–wave* configuration
- 4 amplitudes: three *P–wave*, A_0, $A_\parallel$, $A_\perp$, and one *S–wave*, A_s
- Final state is a mixture of CP–even (0, $\parallel$) and CP–odd ($\perp$,S) eigenstates

[Phys. Rev. D **87** 112010]

$B_s^0 \to J/\psi K^+K^-$: Angular analysis

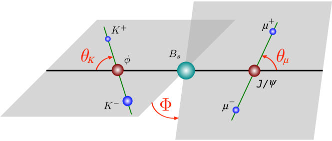
Time–dependent angular analysis needed to disentangle $CP = \pm 1$ states and measure ϕ_s

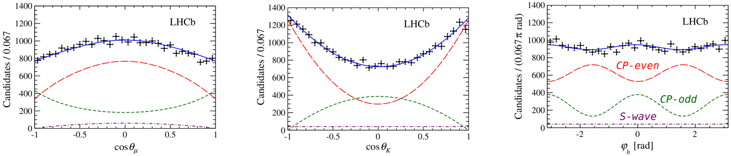
$$\frac{d^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{d\Omega dt} \propto \sum_{i=1}^{10} K_i(t) f_i(\Omega)$$

$$K_i(t) = N_i e^{-\Gamma_s t}[\pm c_i \cos(\Delta m_s t) \pm d_i \sin(\Delta m_s t) + a_i \cosh(\frac{1}{2}\Delta\Gamma_s t) + b_i \sinh(\frac{1}{2}\Delta\Gamma_s t)]$$

where N_i, a_i, b_i, c_i, d_i are functions of

- $|A_0|^2$, $|A_\parallel|^2$, $|A_\perp|^2$, $|A_S|^2$
- $\delta_\parallel$, $\delta_\perp$, δ_s $(\delta_0 = 0)$
- ϕ_s



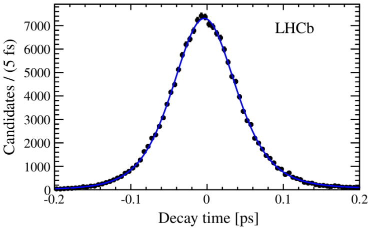


$B_s^0 \to J/\psi K^+ K^-$

Decay time resolution

Per–event decay time error, with scale factor calibrated using real J/ψ from the PV plus 2 random kaons.

$\sigma_t^{eff} = 45$ fs $\quad (<< 2\pi/\Delta m_s)$



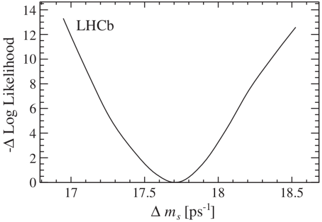
Flavour Tagging

"Same–Side–Kaon" and "Opposite–Side" taggers are used, giving a combined tagging power of $\epsilon_{tag}(1-2\omega)^2 = 3.13\%$

Unconstrained fit of Δm_s agrees with the $B_s^0 \to D_s \pi$ result from LHCb

Acceptance

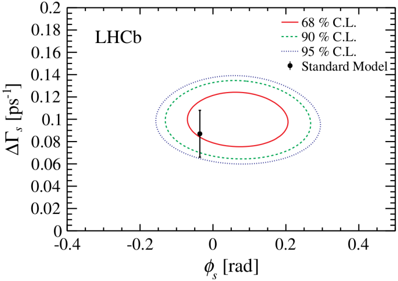
Angular acceptance parametrized using simulated events.
Decay time acceptance characterized using data driven methods (also $\tau > 0.3$ ps)



[Phys. Rev. D **87** 112010]

$B_s^0 \to J/\psi K^+ K^-$: Results

[Phys. Rev. D **87** 112010]



World most precise measurements! Results compatible with the SM prediction.

$$\begin{aligned} \phi_s &= 0.07 \pm 0.09 \text{ (stat)} \pm 0.01 \text{ (syst) rad} \\ \Gamma_s &= 0.663 \pm 0.005 \text{(stat)} \pm 0.006 \text{(syst) ps}^{-1} \\ \Delta\Gamma_s &= 0.100 \pm 0.016 \text{(stat)} \pm 0.003 \text{(syst) ps}^{-1} \end{aligned}$$

Dominant systematic uncertainties from the angular acceptance and the decay time resolution.

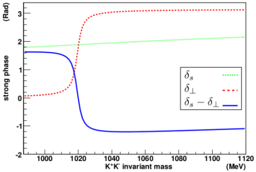
$B_s^0 \to J/\psi K^+K^-$: Resolving the sign of $\Delta\Gamma_s$

Decay rates invariant under [Phys. Rev. D **87** 112010]

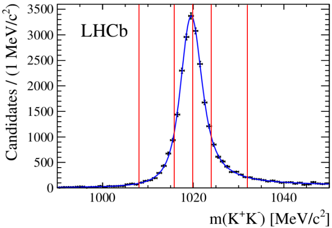
$$(\phi_s, \Delta\Gamma_s, \delta_0, \delta_\parallel, \delta_\perp, \delta_s) \leftrightarrow (\pi - \phi_s, -\Delta\Gamma_s, -\delta_0, -\delta_\parallel, \pi - \delta_\perp, -\delta_s)$$

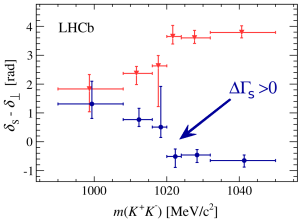
Physical solution:

- *P–wave* phases increase with m_{KK}
- *S–wave* phase varies slowly
- $\delta_\perp - \delta_s$ decreases with m_{KK}



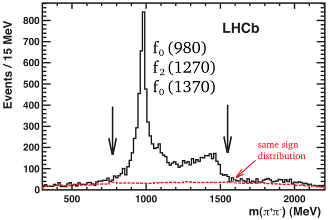
Perform the analysis in 6 bins of m_{KK} $\Rightarrow$ $\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H > 0$





$B_s^0 \to J/\psi\,\pi^+\pi^-$

Update of a previous measurement [Phys. Lett. B **713** (2012) 378]
Analysis based in 1/fb of data from 2011



Phenomenology:

- Predominantly via $B_s^0 \to J/\psi X$, with $X \equiv f_0(980), f_2(1270), f_0(1370)$
- Analysis of resonance structure shows that the decay mode is $> 97.5\%$ CP–odd at 95% CL
- No need for angular analysis!

$B_s^0 \to J/\psi\,\pi^+\pi^-$

Measuring ϕ_s at LHCb

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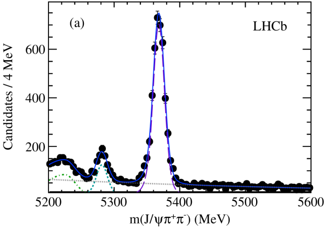
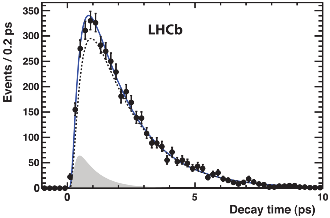
ϕ_s is measured through a maximum likelihood fit to $J/\psi\pi\pi$ invariant mass and decay time.

[Phys. Rev. D **87** 112010]





- Flavour tagging (OS + SSK): $\epsilon(1-2\omega)^2 = 3.37\%$
- Decay time resolution from prompt $J/\psi\pi^+\pi^-$
- Decay time acceptance determined from $B^0 \to J/\psi K^{*0}$ data
- Γ_s and $\Delta\Gamma_s$ fixed to the values measured in $B_s^0 \to J/\psi\,K^+K^-$

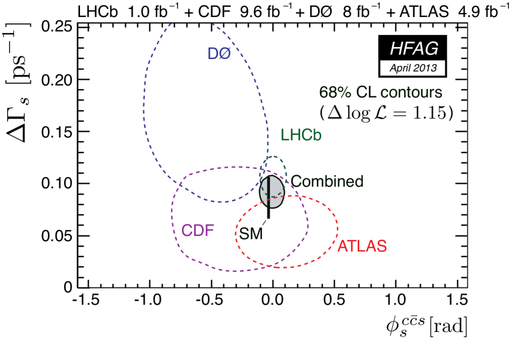
$$\boxed{\phi_s = -0.14^{+0.17}_{-0.16}(\text{stat}) \pm 0.01(\text{syst}) \quad \text{rad}}$$

$B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi \pi^+\pi^-$ combination

A simultaneous fit gives the most precise measurement of:

$$\begin{aligned}
\phi_s &= 0.01 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (syst) rad} \\
\Gamma_s &= 0.661 \pm 0.004\text{(stat)} \pm 0.006\text{(syst) ps}^{-1} \\
\Delta\Gamma_s &= 0.106 \pm 0.011\text{(stat)} \pm 0.007\text{(syst) ps}^{-1}
\end{aligned}$$

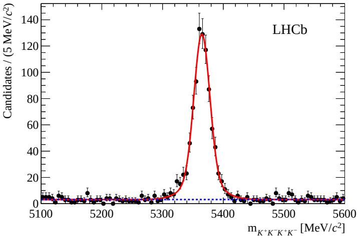
[Phys. Rev. D **87** 112010]



$B_s^0 \to \phi\phi$

[Phys. Rev. Lett. **110** 241802]

- Analysis based in 1/fb of 2011 LHCb data
- 801 ± 31 candidates observed in $KKKK$ final state



- Phenomenology (5 amplitudes):
  - *P–wave*: $B_s^0 \to \phi\phi$, with $\phi \to K^+K^-$ $(A_0, A_\parallel, A_\perp)$
  - *S–wave*: $B_s^0 \to \phi f_0$ (A_s) and $B_s^0 \to f_0 f_0$ (A_{ss})
  - Mixture of CP–odd and CP–even components in the final state $\Rightarrow$ Time dependent angular analysis needed

$B_s^0 \to \phi\phi$

[Phys. Rev. Lett. **110** 241802]

- Flavour tagging (OS + SSK): $\epsilon(1-2\omega)^2 = 3.29\%$
- Time resolution: Single gaussian convolution, from simulation:

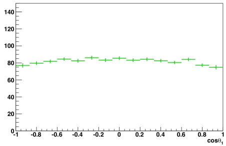
$$\sigma_t^{eff} = 39.7 \text{ fs}$$

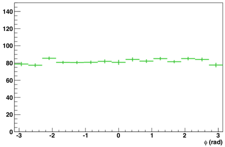
- Time and angular acceptances

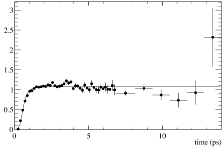
  Forward geometry of the detector and momentum cuts in the selection introduce a bias in the helicity angles ($< 20\%$).

  Biases in the decay time distribution arise from requirements in the kaons impact parameter with respect to the PV.

  Both acceptance functions are taken from simulation.

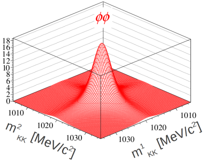




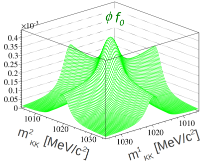


$B_s^0 \to \phi\phi$: S-P-wave coupling

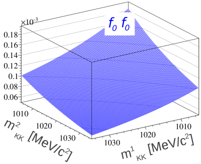
- The amplitudes A_i contain a hidden dependence on the KK invariant mass.
  - *P–wave*: Breit–Wigner shape
  - *S–wave*: Flatté model



- Since we consider a finite mass window ($\pm 15\,\mathrm{MeV}/c^2$) around the ϕ nominal mass $\Rightarrow$ Correction factor in the interference terms between different partial waves.



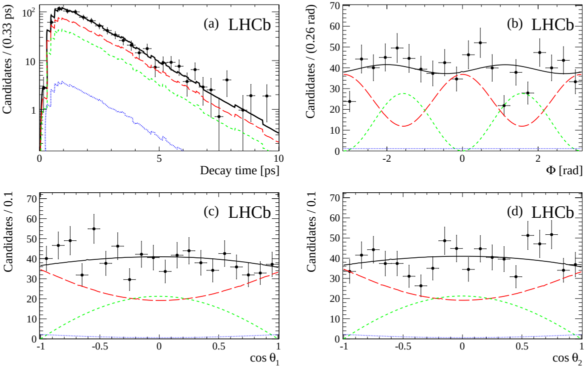
- The m_{KK} spectra were studied to crosscheck the amount of *S–wave* obtained with the angular fit.



- The final result assumes no $B_s^0 \to f_0 f_0$ (SS–wave) contamination.

$B_s^0 \to \phi\phi$

[Phys. Rev. Lett. **110** 241802]



Total
CP–even
CP–odd
S–wave

- Γ_S and $\Delta\Gamma_S$ from $B_s^0 \to J/\psi\phi$, [Phys. Rev. D **87** 112010]
- $\Delta m_S = (17.73 \pm 0.05) ps^{-1}$, [LHCb-CONF-2011-050]

$B_s^0 \to \phi\phi$: Time–dependent analysis

[Phys. Rev. Lett. **110** 241802]

Parameter	Value	$\sigma_{\text{stat.}}$	$\sigma_{\text{syst.}}$
ϕ_s[rad] (68 % CL)		$[-2.37, -0.92]$	0.22
$\lvert A_0\rvert^2$	0.329	0.033	0.017
$\lvert A_\perp\rvert^2$	0.358	0.046	0.018
$\lvert A_S\rvert^2$	0.016	$^{+0.024}_{-0.012}$	0.009
δ_1 [rad]	2.19	0.44	0.12
δ_2 [rad]	-1.47	0.48	0.10
δ_S [rad]	0.65	$^{+0.89}_{-1.65}$	0.33

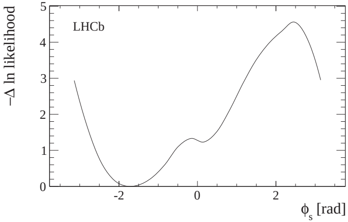
Dominant systematic uncertainties from time acceptance and *S–wave*

The likelihood profile for ϕ_S is not parabolic $\Rightarrow$ A 68% CL is quoted

$\phi_S \in [-2.46, -0.76]$ rad at 68% CL

Systematic uncertainties included

p–value of the SM hypothesis: 16%



Summary

LHCb has performed measurements of ϕ_s with 1/fb in various decay modes:

- $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi \pi^+\pi^-$: Most precise measurement to date, compatible with SM so far

$$\begin{aligned} \phi_s^{c\bar{c}c} &= 0.01 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (syst) rad} \\ \Gamma_s &= 0.661 \pm 0.004\text{(stat)} \pm 0.006\text{(syst) ps}^{-1} \\ \Delta\Gamma_s &= 0.106 \pm 0.011\text{(stat)} \pm 0.007\text{(syst) ps}^{-1} \end{aligned}$$

- $B_s^0 \to \phi\phi$: First constraint from a pure penguin mode

$$\phi_s^{s\bar{s}s} \in [-2.46, -0.76] \text{rad at 68\% CL}$$

LHCb future plans:

- Update of these analyses with 3/fb (expected $\sigma(\phi_s^{c\bar{c}c}) \sim 0.05$ rad)
- Measurement of ϕ_s in other decay modes ($B_s^0 \to K^{*0}\overline{K}^{*0}$, $B_s^0 \to \psi(2S)\phi$,...)
- Improvement of flavour tagging algorithms
- Polarization–dependent CP–violation

Thanks for your attention

BACKUP

$B \to VV$ decay rate

$$\frac{d\Gamma}{\Gamma dt d\Omega} = \sum_i K_i(t) f_i(\Omega)$$

i	K_i	f_i
1	$\lvert A_0(t)\rvert^2$	$4\cos^2\theta_1\cos^2\theta_2$
2	$\lvert A_\parallel(t)\rvert^2$	$\sin^2\theta_1\sin^2\theta_2(1+\cos 2\varphi)$
3	$\lvert A_\perp(t)\rvert^2$	$\sin^2\theta_1\sin^2\theta_2(1-\cos 2\varphi)$
4	$Im(A_\parallel^*(t)A_\perp(t))$	$-2\sin^2\theta_1\sin^2\theta_2\sin 2\varphi$
5	$Re(A_0^*(t)A_\parallel(t))$	$\sqrt{2}\sin 2\theta_1\sin 2\theta_2\cos\varphi$
6	$Im(A_0^*(t)A_\perp(t))$	$-\sqrt{2}\sin 2\theta_1\sin 2\theta_2\sin\varphi$
7	$\lvert A_{SS}(t)\rvert^2$	$\frac{4}{9}$
8	$\lvert A_{SV}(t)\rvert^2$	$\frac{4}{3}(\cos\theta_1+\cos\theta_2)^2$
9	$Re(A_{SV}^*(t)A_{SS}(t))$	$\frac{8}{3\sqrt{3}}(\cos\theta_1+\cos\theta_2)$
10	$Re(A_0(t)A_{SS}^*(t))$	$\frac{8}{3}\cos\theta_1\cos\theta_2$
11	$Re(A_\parallel(t)A_{SS}^*(t))$	$\frac{4\sqrt{2}}{3}\sin\theta_1\sin\theta_2\cos\varphi$
12	$Im(A_\perp(t)A_{SS}^*(t))$	$\frac{-4\sqrt{2}}{3}\sin\theta_1\sin\theta_2\sin\varphi$
13	$Re(A_0(t)A_{SV}^*(t))$	$\frac{8}{\sqrt{3}}\cos\theta_1\cos\theta_2(\cos\theta_1+\cos\theta_2)$
14	$Re(A_\parallel(t)A_{SV}^*(t))$	$\frac{4\sqrt{2}}{\sqrt{3}}\sin\theta_1\sin\theta_2(\cos\theta_1+\cos\theta_2)\cos\varphi$
15	$Re(A_\perp(t)A_{SV}^*(t))$	$-\frac{4\sqrt{2}}{\sqrt{3}}\sin\theta_1\sin\theta_2(\cos\theta_1+\cos\theta_2)\sin\varphi$

$B_s^0 \rightarrow \phi\phi$ time–dependent terms

$$K_i(t) = N_i e^{-\Gamma_s t}[\pm c_i \cos(\Delta m_s t) \pm d_i \sin(\Delta m_s t) + a_i \cosh(\frac{1}{2}\Delta\Gamma_s t) + b_i \sinh(\frac{1}{2}\Delta\Gamma_s t)]$$

i	N_i	a_i	b_i	c_i	d_i
1	$\|A_0(0)\|^2$	1	$-\cos\phi_s$	0	$\sin\phi_s$
2	$\|A_\parallel(0)\|^2$	1	$-\cos\phi_s$	0	$\sin\phi_s$
3	$\|A_\perp(0)\|^2$	1	$\cos\phi_s$	0	$-\sin\phi_s$
4	$\|A_\parallel(0)\|\|A_\perp(0)\|$	0	$-\cos\delta_1 \sin\phi_s$	$\sin\delta_1$	$-\cos\delta_1\cos\phi_s$
5	$\|A_\parallel(0)\|\|A_0(0)\|\cos(\delta_2-\delta_1)$	1	$-\cos\phi_s$	0	$\sin\phi_s$
6	$\|A_0(0)\|\|A_\perp(0)\|$	0	$-\cos\delta_2\sin\phi_s$	$\sin\delta_2$	$-\cos\delta_2\cos\phi_s$
7	$\|A_{SS}(0)\|^2$	1	$-\cos\phi_s$	0	$\sin\phi_s$
8	$\|A_S(0)\|^2$	1	$\cos\phi_s$	0	$-\sin\phi_s$
9	$\|A_S(0)\|\|A_{SS}(0)\|$	0	$\sin(\delta_S-\delta_{SS})\sin\phi_s$	$\cos(\delta_{SS}-\delta_S)$	$\sin(\delta_{SS}-\delta_S)\cos\phi_s$
10	$\|A_0(0)\|\|A_{SS}(0)\|\cos\delta_{SS}$	1	$-\cos\phi_s$	0	$\sin\phi_s$
11	$\|A_\parallel(0)\|\|A_{SS}(0)\|\cos(\delta_2-\delta_1-\delta_{SS})$	1	$-\cos\phi_s$	0	$\sin\phi_s$
12	$\|A_\perp(0)\|\|A_{SS}(0)\|$	0	$-\cos(\delta_2-\delta_{SS})\sin\phi_s$	$\sin(\delta_2-\delta_{SS})$	$-\cos(\delta_2-\delta_{SS})\cos\phi_s$
13	$\|A_0(0)\|\|A_S(0)\|$	0	$-\sin\delta_S\sin\phi_s$	$\cos\delta_S$	$-\sin\delta_S\cos\phi_s$
14	$\|A_\parallel(0)\|\|A_S(0)\|$	0	$\sin(\delta_2-\delta_1-\delta_S)\sin\phi_s$	$\cos(\delta_2-\delta_1-\delta_S)$	$\sin(\delta_2-\delta_1-\delta_S)\cos\phi_s$
15	$\|A_\perp(0)\|\|A_S(0)\|\sin(\delta_2-\delta_S)$	1	$\cos\phi_s$	0	$-\sin\phi_s$

$B_s^0 \to J/\psi K^+ K^-$ and $B_s^0 \to J/\psi \pi^+ \pi^-$: Systematics

TABLE IX. Statistical and systematic uncertainties.

Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$\lvert A_\perp \rvert^2$	$\lvert A_0 \rvert^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$\lvert\lambda\rvert$
Statistical uncertainty	0.0048	0.016	0.0086	0.0061	$^{+0.13}_{-0.21}$	0.22	0.091	0.031
Background subtraction	0.0041	0.002	···	0.0031	0.03	0.02	0.003	0.003
$B^0 \to J/\psi K^{*0}$ background	···	0.001	0.0030	0.0001	0.01	0.02	0.004	0.005
Angular acceptance reweighting	0.0007	···	0.0052	0.0091	0.07	0.05	0.003	0.020
Angular acceptance statistical	0.0002	···	0.0020	0.0010	0.03	0.04	0.007	0.006
Lower decay-time acceptance model	0.0023	0.002	···	···	···	···	···	···
Upper decay-time acceptance model	0.0040	···	···	···	···	···	···	···
Length and momentum scales	0.0002	···	···	···	···	···	···	···
Fit bias	···	···	0.0010	···	···	···	···	···
Decay-time resolution offset	···	···	···	···	···	0.04	0.006	···
Quadratic sum of systematics	0.0063	0.003	0.0064	0.0097	0.08	0.08	0.011	0.022
Total uncertainties	0.0079	0.016	0.0107	0.0114	$^{+0.15}_{-0.23}$	0.23	0.092	0.038

$B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi \pi^+\pi^-$: Direct CP–violation

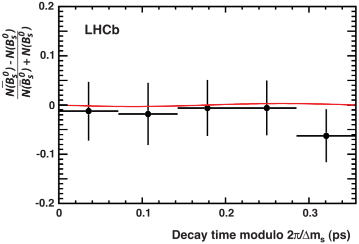
[Phys. Rev. D **87** 112010]
[Phys. Lett. B **713** (2012) 378]

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

$$|\lambda| = 0.94 \pm 0.03(\text{stat}) \pm 0.02(\text{syst})$$

- Combined $B_s^0 \to J/\psi \pi^+\pi^-$ and $B_s^0 \to J/\psi K^+K^-$

$$|\lambda| = 0.93 \pm 0.03(\text{stat}) \pm 0.02(\text{syst})$$



$B_s^0 \to J/\psi\,\pi^+\pi^-$ effective lifetime

Pure CP–odd state $\Rightarrow$ Only produced by the decay of the heavy B_s^0 mass eigenstate (no CPV)

To minimize acceptance effects we measure the lifetime relative to $B^0 \to J/\psi\,K^{*0}$

$$R(t) = R(0)e^{-t\left(1/\tau_{J/\psi f_0} - 1/\tau_{J/\psi K^{*0}}\right)}$$

Taking $\tau_{J\psi K^{*0}}$ from [PDG, Phys. Rev. D **86** 010001]

$$\tau_{J/\psi f_0} = 1.700 \pm 0.040(\text{stat}) \pm 0.026(\text{syst})\text{ps}$$

New determination from a exponential fit in [Phys. Rev. D **87** 112010]

$$\tau_{J/\psi f_0} = 1.652 \pm 0.024(\text{stat}) \pm 0.024(\text{syst})\text{ps}$$

$$\Gamma_H = 0.605 \pm 0.009(\text{stat}) \pm 0.009(\text{syst})\ \text{ps}^{-1}$$

[Phys. Rev. Lett. **109** 152002]