Measurement of ϕ_s at LHCb

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THE UNIVERSITY
of EDINBURGH

on behalf of:
LHCb Collaboration

2013 Phenomenology Symposium May 6-8th

Results presented in this talk:

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

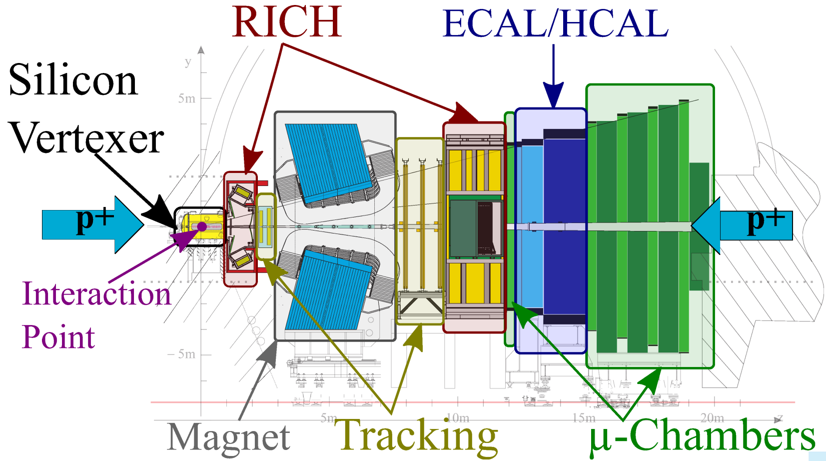
  (Commonly referred to as $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi f^0$ Analyses)

  "Measurement of $\mathcal{CP}$ violation and the B_s^0 meson decay width difference with $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi \pi^+\pi^-$ decays"
  arXiv:1304.2600 Submitted to Phys. Rev. D

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

  "First measurement of the $\mathcal{CP}$-violating phase in $B_s^0 \to \phi\phi$ decays"
  arXiv:1303.7125 Submitted to Phys. Rev. Lett.

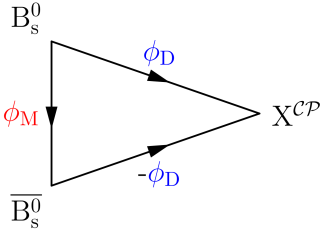
LHCb Detector



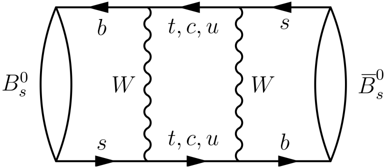
Definition of ϕ_s

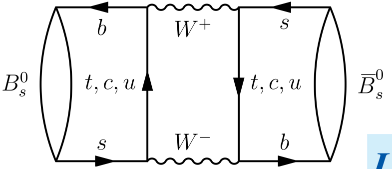
ϕ_s is defined as the phase for $\mathcal{CP}$-violation between mixing(ϕ_M) and decay(ϕ_D):

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



New physics could modify box diagrams and alter ϕ_M.

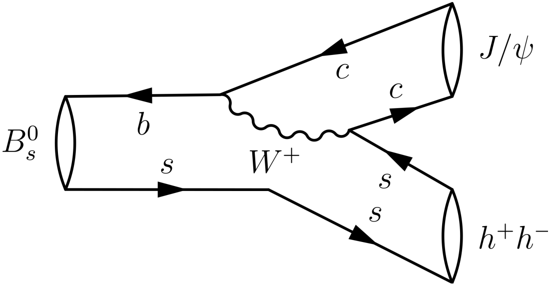




$B_s^0 \to J/\psi\ K^+K^-$ Phenomenology

$B_s^0 \to J/\psi\ K^+K^-$ and $B_s^0 \to J/\psi\ \pi^+\pi^-$ proceed via $b \to c\bar{c}s$ transition.

Decay dominated by tree level diagram:



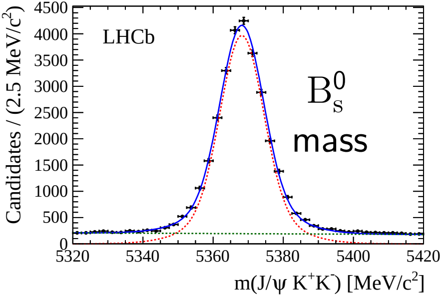
In Standard Model
(ignoring penguin pollution)

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

$\approx -0.0364 \pm 0.0016$ rad

arXiv 1106.4041

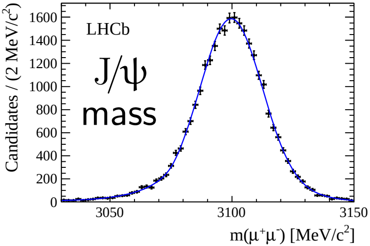
$B_s^0 \to J/\psi\ K^+K^-$ Data

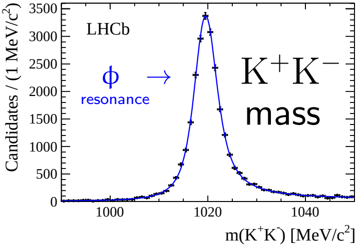


Analysed $1.0\,\text{fb}^{-1}$ of data from LHCb in 2011.

Still another $2\,\text{fb}^{-1}$ on disk from 2012 to be analysed.

$N \approx 27,600$ Signal events



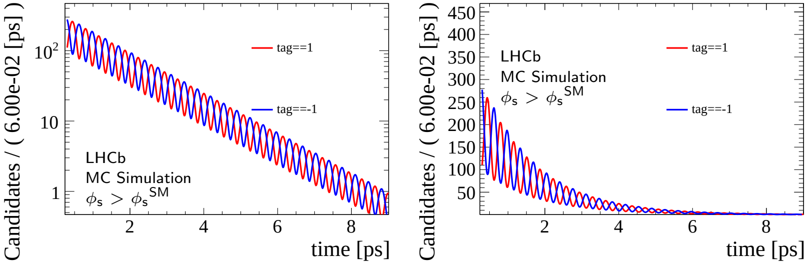


Fitting for ϕ_s

Terms sensitive to ϕ_s in the PDF take the form:

$$D_{\text{tagging}}\left(\omega_{\text{mistag}}\right) D_{\text{time-res}}\left(\sigma_t\right) \sin\left(\phi_s\right) \sin\left(\Delta m t\right)$$

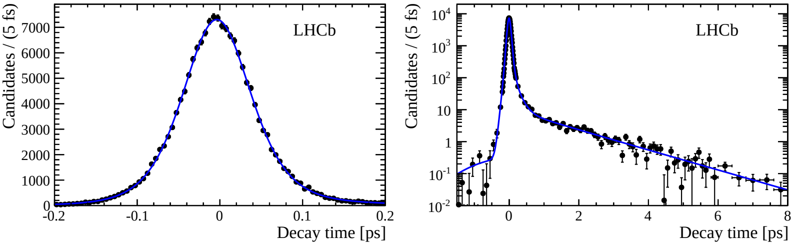
Oscillations in numbers of tagged events with time as below:



Time Resolution

Time Resolution (σ_t) calculated from fit to prompt J/ψ background. $\sigma_t = 45$fs for $B_s^0 \to J/\psi\, K^+K^-$.

Peak at t=0 composed of real J/ψ from IP + 2 random tracks, passing all of the selection cuts.



Flavour Tagging at Production (t=0)

To fit for ϕ_s we need to determine the flavour of B_s^0 meson at production.

i.e. Identify whether the signal meson was B_s^0 or $\overline{B_s^0}$ at t=0.

Flavour tagging at LHCb is discussed in more detail in a talk in Tuesday's parallel session by Katharina Kreplin.

For $B_s^0 \to J/\psi K^+K^-$, the effective tagging efficiency is:

$\epsilon_{tag}\mathcal{D}^2 = (3.13 \pm 0.12 \pm 0.20)\,\%$ Where: $\mathcal{D} = (1 - 2\omega_{mistag})$

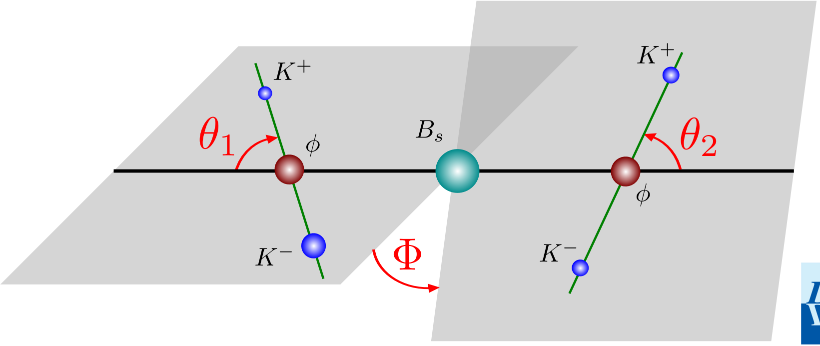
This gives us the same tagging power as a dataset containing $\epsilon_{tag}\mathcal{D}^2 \times N$ perfectly tagged events.

Angular Definitions

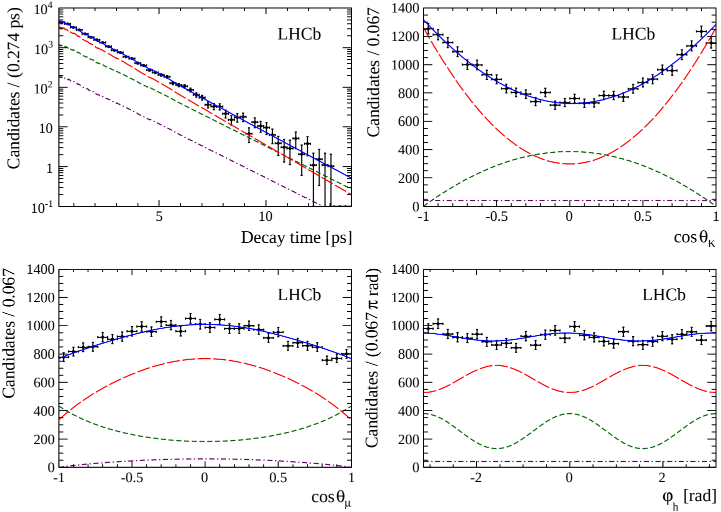
Both analyses have final states composed of $\mathcal{CP}$-Even and $\mathcal{CP}$-Odd components.

$\Rightarrow$ full angular analysis for both $B_s^0 \to \phi\phi$ and $B_s^0 \to J/\psi K^+K^-$ using the Helicity basis.

$B_s^0 \to \phi\ \phi$

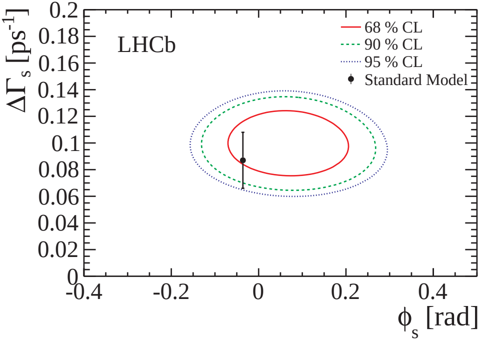


Projections



Black: Data
Red: $\mathcal{CP}$-Even
Green: $\mathcal{CP}$-Odd
Purple: S-wave
Blue: Total

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



Using the $\mathcal{S}$-Wave contribution to data the 2-fold ambiguity in $(\phi_s, \Delta\Gamma_s)$ has been resolved.

$\Delta\Gamma_s > 0$

$$\begin{aligned}
\phi_s &= 0.07 \pm 0.09 \text{ (stat)} \pm 0.01 \text{ (syst) rad}, \\
\Gamma_s \equiv (\Gamma_L + \Gamma_H)/2 &= 0.663 \pm 0.005 \text{ (stat)} \pm 0.006 \text{ (syst) ps}^{-1}, \\
\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H &= 0.100 \pm 0.016 \text{ (stat)} \pm 0.003 \text{ (syst) ps}^{-1},
\end{aligned}$$

6σ significance for $\Delta\Gamma \neq 0$!

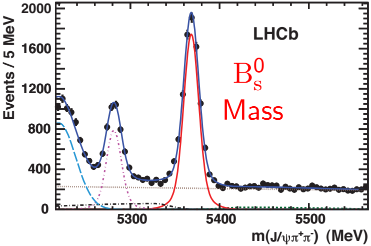
$B_s^0 \to J/\psi\, \pi^+\pi^-$ Data

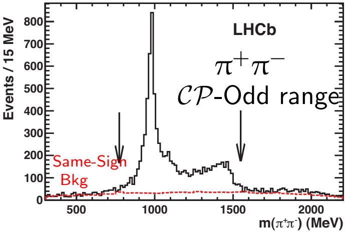
Original $B_s^0 \to J/\psi\, \pi^+\pi^-$ analysis previously published arXiv:1204.5675.

Decay mode determined to be $> 97.7\%$ $\mathcal{CP}$-Odd. ($\Rightarrow$ no need for angular analysis)

Analysis has been updated and latest tagging information is used.

$\approx 7,400$ signal events

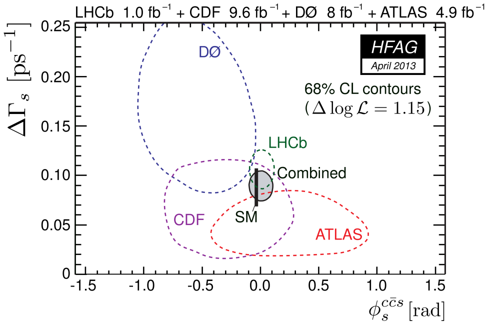




$B_s^0 \to J/\psi K^+K^- + B_s^0 \to J/\psi \pi^+\pi^-$ Combined Results

Combined result gives the most precise measurements of:

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

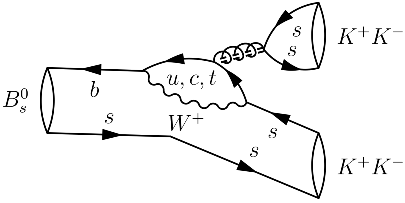


Latest HFAG Result as presented in Beauty 2013

(Without latest tagged results from ATLAS)

$B_s^0 \to \phi\,\phi$ Phenomenology

Decay proceeds via $b \to s\bar{s}s$ transition.
Dominated by penguin diagram:

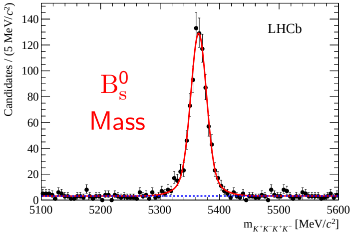


In Standard Model: $\phi_s = 0.0 \pm 0.2$rad.

arXiv 0810.0249, arXiv 0910.5237, arXiv hep-ph/0612290

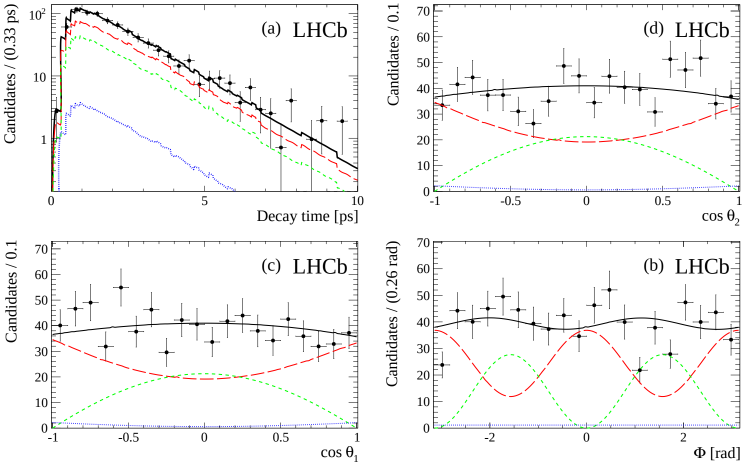
Clean Signal in purely hadronic channel:

N ≈ 900 Signal events



Time resolution in this analysis is $\sigma_t = 40$ fs.
Effective tagging power of $\epsilon_{\text{tag}}\mathcal{D}^2 = (3.29 \pm 0.48)\,\%$.

Projections



Points: Data

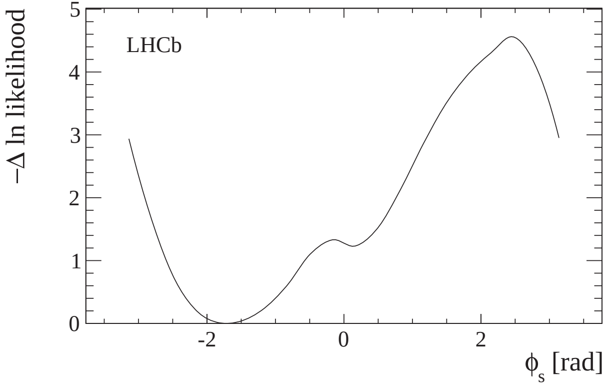
Black: Total

Red: $\mathcal{CP}$-Even

Green: $\mathcal{CP}$-Odd

Blue: S-wave

Fit Results for ϕ_s



From Plot:
$\phi_s = [-2.31, -0.92]$
$\pm 0.22\,(\text{syst})$ rad

From FC:
p-value of Standard Model hypothesis is 16%

Small Dataset $\Rightarrow$ Feldman-Cousins analysis provides coverage corrected 68% confidence limits (inc. systematics) of:

$$\phi_s = [-2.46, -0.76]\,\text{rad}$$

Summary

- Most precise measurement of ϕ_s in $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi \pi^+\pi^-$ analysis.

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

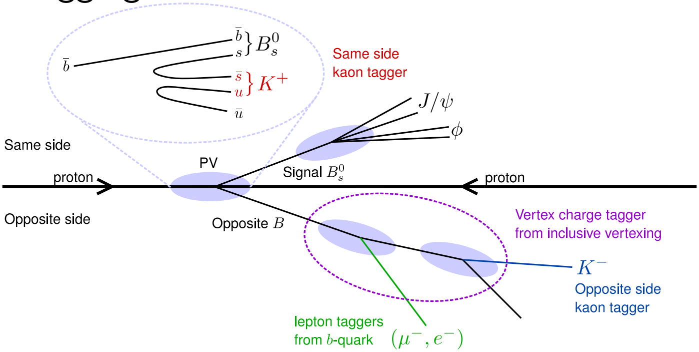
- **First** measurement of ϕ_s in $B_s^0 \to \phi\,\phi$.

$$\phi_s = [-2.46, -0.76] \text{ rad}$$

- **200% more data** recorded in 2012 yet to analyse!

Backups

Flavour Tagging



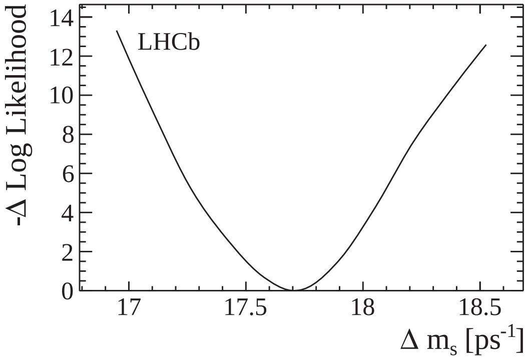
For $B_s^0 \to J/\psi\, K^+K^-$ the Effective tagging Efficiency is:
$\langle \mathcal{D}^2 \rangle = (3.13 \pm 0.12 \pm 0.20)\,\%$

Where: $\mathcal{D} = (1 - 2\omega_{\text{mistag}})$

For $B_s^0 \to J/\psi\, \pi^+\pi^-$ the Effective tagging Efficiency is:
$\langle \mathcal{D}^2 \rangle = (3.37 \pm 0.12 \pm 0.27)\,\%$

Both analyses use Opposite and Same Side Taggers

ΔLL function for Δm_s



Fitting for Δm_s in $B_s^0 \to J/\psi\,\phi$ gives a value for which is compatible with external measurements.
Evidence that flavour tagging is working and that we understand our time resolution model.

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

$$\frac{d^4\Gamma\left(B_s^0 \to J/\psi\ K^+K^-\right)}{dtd\Omega} \propto \sum_{k=1}^{10} f_k\left(\Omega\right) h_k\left(t\right)$$

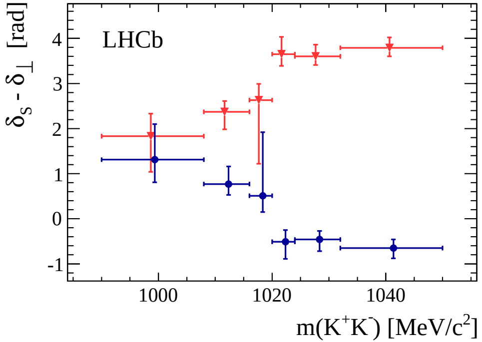
$$h_k\left(t\right) = N_k e^{\Gamma_s t}\left[a_k \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + b_k \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + c_k \cos\left(\Delta m_s t\right) + d_k \sin\left(\Delta m_s t\right)\right]$$

k	$f\left(\theta_\mu, \theta_K, \phi_h\right)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\theta_K \sin^2\theta_\mu$	$\lvert A_0(0)\rvert^2$	1	D	C	$-$S
2	$\sin^2\theta_K\left(1-\sin^2\theta_\mu\cos^2\phi_h\right)$	$\lvert A_\parallel(0)\rvert^2$	1	D	C	$-$S
3	$\sin^2\theta_K\left(1-\sin^2\theta_\mu\sin^2\phi_h\right)$	$\lvert A_\perp(0)\rvert^2$	1	$-$D	C	S
4	$\sin^2\theta_K\sin^2\theta_\mu\sin 2\phi_h$	$\lvert A_\parallel(0)A_\perp(0)\rvert$	$C\sin\left(\delta_\perp-\delta_\parallel\right)$	$S\cos\left(\delta_\perp-\delta_\parallel\right)$	$\sin\left(\delta_\perp-\delta_\parallel\right)$	$D\cos\left(\delta_\perp-\delta_\parallel\right)$
5	$\frac{1}{2}\sqrt{2}\sin 2\theta_K\sin 2\theta_\mu\cos\phi_h$	$\lvert A_0(0)A_\parallel(0)\rvert$	$\cos\left(\delta_\parallel-\delta_0\right)$	$D\cos\left(\delta_\parallel-\delta_0\right)$	$C\sin\left(\delta_\parallel-\delta_0\right)$	$-S\cos\left(\delta_\parallel-\delta_0\right)$
6	$-\frac{1}{2}\sqrt{2}\sin 2\theta_K\sin 2\theta_\mu\cos\phi_h$	$\lvert A_0(0)A_\perp(0)\rvert$	$C\sin\left(\delta_\perp-\delta_0\right)$	$S\cos\left(\delta_\perp-\delta_0\right)$	$\sin\left(\delta_\perp-\delta_0\right)$	$D\cos\left(\delta_\perp-\delta_0\right)$
7	$\frac{2}{3}\sin^2\theta_\mu$	$\lvert A_S(0)\rvert^2$	1	$-$D	C	S
8	$\frac{1}{3}\sqrt{6}\sin\theta_K\sin 2\theta_\mu\cos\phi_h$	$\lvert A_S(0)A_\parallel(0)\rvert$	$C\cos\left(\delta_\parallel-\delta_S\right)$	$S\sin\left(\delta_\parallel-\delta_S\right)$	$\cos\left(\delta_\parallel-\delta_S\right)$	$D\sin\left(\delta_\parallel-\delta_S\right)$
9	$-\frac{1}{3}\sqrt{6}\sin\theta_K\sin 2\theta_\mu\sin\phi_h$	$\lvert A_S(0)A_\perp(0)\rvert$	$\sin\left(\delta_\perp-\delta_S\right)$	$-D\sin\left(\delta_\perp-\delta_S\right)$	$C\sin\left(\delta_\perp-\delta_S\right)$	$S\sin\left(\delta_\perp-\delta_S\right)$
10	$\frac{4}{3}\sqrt{3}\cos\theta_L\sin^2\theta_\mu$	$\lvert A_S(0)A_0(0)\rvert$	$C\cos\left(\delta_0-\delta_S\right)$	$S\sin\left(\delta_0-\delta_S\right)$	$\cos\left(\delta_0-\delta_S\right)$	$D\sin\left(\delta_0-\delta_S\right)$

$$S = -\frac{2\lvert\lambda\rvert}{1+\lvert\lambda\rvert^2}\sin\left(\phi_s\right),\quad D = -\frac{2\lvert\lambda\rvert}{1+\lvert\lambda\rvert^2}\cos\left(\phi_s\right),\quad C = \frac{1-\lvert\lambda\rvert^2}{1+\lvert\lambda\rvert^2}$$

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

In order to resolve the 2-fold ambiguity resolution present in the $\phi_s/\Delta\Gamma_s$ plane the phase difference between the S and P-wave is used.



Blue: $\Delta\Gamma_s > 0.$

Red: $\Delta\Gamma_s < 0.$

Physical Solution (Blue) corresponds to -ve trend in $\delta_S - \delta_\perp$ across K^+K^- mass range $\Rightarrow \Delta\Gamma_s$ is $+$ve.

$B_s^0 \to J/\psi K^+K^-$ 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]	$\lvert\lambda\rvert$
Stat. 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
Ang. acc. reweighting	0.0007	–	0.0052	0.0091	0.07	0.05	0.003	0.020
Ang. acc. statistical	0.0002	–	0.0020	0.0010	0.03	0.04	0.007	0.006
Lower decay time acc. model	0.0023	0.002	–	–	–	–	–	–
Upper decay time acc. model	0.0040	–	–	–	–	–	–	–
Length and mom. scales	0.0002	–	–	–	–	–	–	–
Fit bias	–	–	0.0010	–	–	–	–	–
Quadratic sum of syst.	0.0063	0.003	0.0064	0.0097	0.08	0.07	0.009	0.022
Total uncertainties	0.0079	0.016	0.0107	0.0114	$^{+0.15}_{-0.23}$	0.23	0.091	0.038

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

Parameter	Value
Γ_s [ps^{-1}]	$0.661 \pm 0.004 \pm 0.006$
$\Delta\Gamma_s$ [ps^{-1}]	$0.106 \pm 0.011 \pm 0.007$
$\lvert A_\perp \rvert^2$	$0.246 \pm 0.007 \pm 0.006$
$\lvert A_0 \rvert^2$	$0.523 \pm 0.005 \pm 0.010$
$\delta_\parallel$ [rad]	$3.32\,^{+0.13}_{-0.21} \pm 0.08$
$\delta_\perp$ [rad]	$3.04 \pm 0.20 \pm 0.07$
ϕ_s [rad]	$0.01 \pm 0.07 \pm 0.01$
$\lvert\lambda\rvert$	$0.93 \pm 0.03 \pm 0.02$

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

	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]	$\lvert\lambda\rvert$
Γ_s [ps^{-1}]	1.00	0.10	0.08	0.03	−0.08	−0.04	0.01	0.00
$\Delta\Gamma_s$ [ps^{-1}]		1.00	−0.49	0.47	0.00	0.00	0.00	−0.01
$\lvert A_\perp\rvert^2$			1.00	−0.40	−0.37	−0.14	0.02	−0.05
$\lvert A_0\rvert^2$				1.00	−0.05	−0.03	−0.01	0.01
$\delta_\parallel$ [rad]					1.00	0.39	−0.01	0.13
$\delta_\perp$ [rad]						1.00	0.21	0.03
ϕ_s [rad]							1.00	0.06
$\lvert\lambda\rvert$								1.00

$B_s^0 \to \phi\,\phi$ Full PDF

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

$$\frac{d^4\Gamma\left(B_s^0 \to \phi\,\phi\right)}{dt\,d\Omega} \propto \sum_{i=1}^{15} K_i\,(\Omega)\,f_i\,(t)$$

Blue: P-Wave

Yellow: S-Wave $\mathcal{CP}$-Odd $+\mathcal{CP}$-Even

Red: $\phi\phi$, $f_0 f_0$ interference

Green: $\phi\phi$, ϕf_0 interference

$B_s^0 \to \phi\,\phi$ Results

Parameter	Value	$\sigma_{stat.}$	$\sigma_{syst.}$
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