Charmless $B \to VV$ decays at LHCb

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On behalf of the LHCb collaboration

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Penguin decays
$B \to VV$ decay rate
$B_s^0 \to \phi\,\phi$
$B_s^0 \to K^* \bar{K}^*$
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In this talk...

1. Motivation
2. First measurement of the CP–violating phase in $B_s^0 \to \phi\phi$
3. First observation of the decay $B_s^0 \to K^{*0}\overline{K}^{*0}$
4. Summary

LHCb overview

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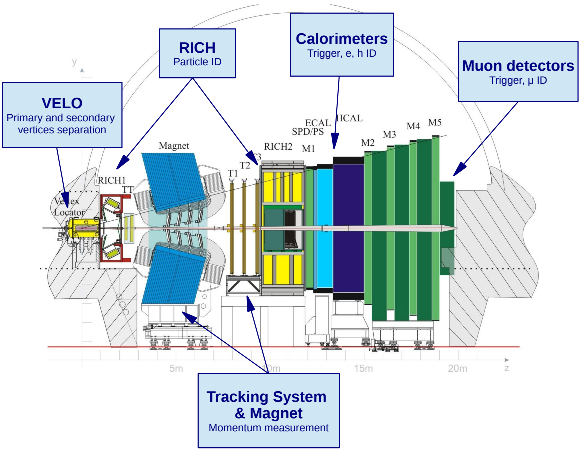

- Excellent IP and decay time resolution through the VErtex LOcator
- Excellent momentum and mass resolution
- Accurate particle ID provided by RICH detectors

Penguin decays

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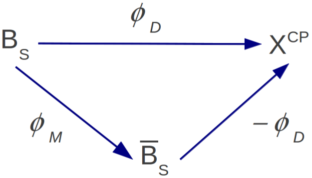
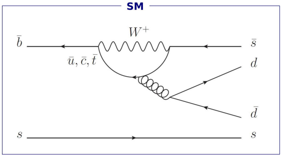
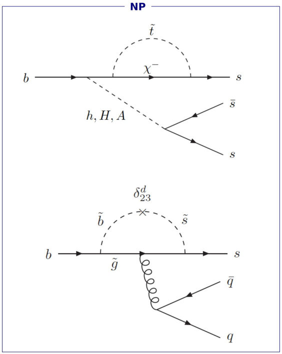
- Loops are particularly sensitive to New Physics: New heavy particles can enter them
- Deviations from the Standard Model prediction can be detected.
- Mixing induced CP–Violation: Measurement of the weak phase ϕ_s $(B_s^0 \to \phi\phi,\ B_s^0 \to K^{*0}\overline{K}^{*0})$



$$\phi_S = \phi_M - 2\,\phi_D$$





$B \to VV$ decay rate

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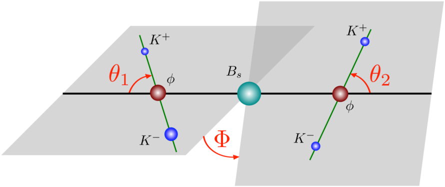
In $B \to V_1 V_2$ decays, V_1 and V_2 can have relative orbital angular momentum $L = 0, 1, 2$. The decay amplitude (*P–wave*):

$$A\left(B \to VV\right) = A_0 \cos\theta_1 \cos\theta_2 + \frac{A_\parallel}{\sqrt{2}} \sin\theta_1 \sin\theta_2 \cos\varphi + i\frac{A_\perp}{\sqrt{2}} \sin\theta_1 \sin\theta_2 \sin\varphi$$

$$\bar{A}\left(\bar{B} \to \bar{V}\bar{V}\right) = \bar{A}_0 \cos\theta_1 \cos\theta_2 + \frac{\bar{A}_\parallel}{\sqrt{2}} \sin\theta_1 \sin\theta_2 \cos\varphi - i\frac{\bar{A}_\perp}{\sqrt{2}} \sin\theta_1 \sin\theta_2 \sin\varphi$$

The final state is identical to decays with intermediate scalar resonances, $B \to SV$, $B \to VS$ or $B \to SS$ (*S–wave*)

$$... + \frac{A_{SV}}{\sqrt{3}}(\cos\theta_1 + \cos\theta_2) + \frac{A_{SS}}{3}$$



$B \to VV$ decay rate

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Squaring the amplitude the decay rate is:

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

$f_i(\Omega)$ are angular functions and $K_i(t)$ are time dependent terms

Time dependent terms contain the interesting parameters

- Polarization fractions: $|A_0|^2$, $|A_\parallel|^2$, $|A_\perp|$
- Strong phases: $\delta_\parallel$, $\delta_\perp$
- *S–wave* parameters: $|A_{SV}|^2$, $|A_{SS}|^2$, δ_{SV}, δ_{SS}
- CP–violating phase: ϕ_S (CP eigenstates)

$B_s^0 \to \phi\phi$

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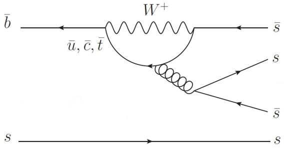
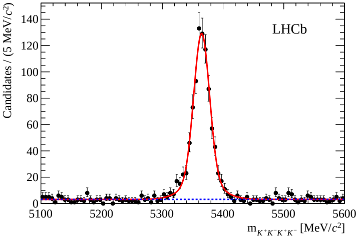
- Sensitive to CP–violation in interference between mixing and decay.
- $b \to s\bar{s}s$ transition $\Rightarrow$ SM expectation of ϕ_s is zero as cancellation of mixing and decay weak phases.
- Mixture of CP–odd and CP–even components in the final state $\to$ Time dependent angular analysis
- 801 ± 31 candidates observed in $KKKK$ final state using $1fb^{-1}$ of 2011 LHCb data.





LHCb–PAPER–2013–007, arXiv:1303.7125[hep–ex]

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

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Time dependent terms

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

were a_i, b_i, c_i, d_i depend on the strong phases $(\delta_{\parallel}, \delta_{\perp}, \delta_{SV}, \delta_{SS})$ and the weak phase ϕ_S

Analysis requirements:

- Terms of the form $\sin\phi_S \sin(\Delta m_S t)$ are the most sensitive for ϕ_S measurement $\Rightarrow$ Flavour tagging
- Angular and lifetime acceptances and resolutions.

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

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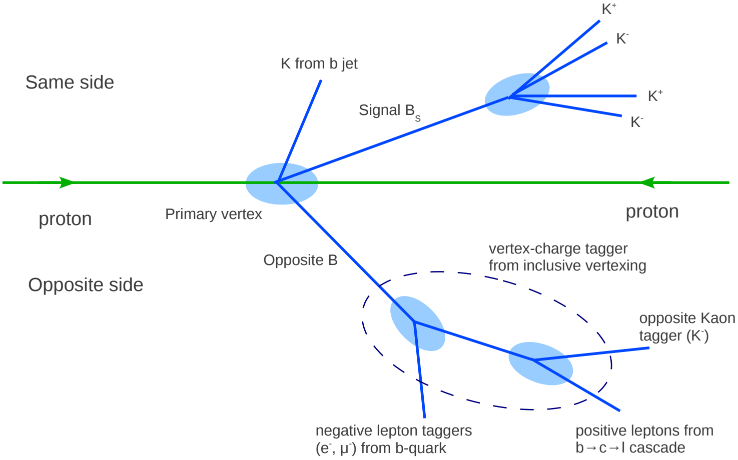
- Flavour tagging: "opposite side" and "same side kaon" taggers are used. Total tagging power $\epsilon_{tag}\mathcal{D}^2 = (3.29 \pm 0.48)\%$ where $\mathcal{D} = (1 - 2\omega_{mistag})$



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

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- Time resolution: Single gaussian convolution (39.7 fs from simulation)

- 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 used to select signal from background.

  Both acceptance functions are taken from simulation.

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

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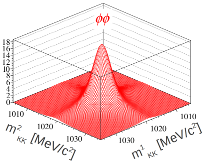
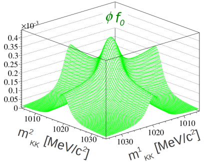
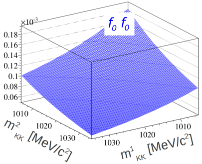
- The amplitudes A_i contain a hidden dependence on the KK invariant mass.
  - *P–wave*: Breit–Wigner shape
  - *S–wave*: Flatté model
- Since we consider a finite mass window ($\pm 15\,\mathrm{MeV}/c^2$) around the ϕ nominal mass $\Rightarrow$ Correction factor in the interference terms between different 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.







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

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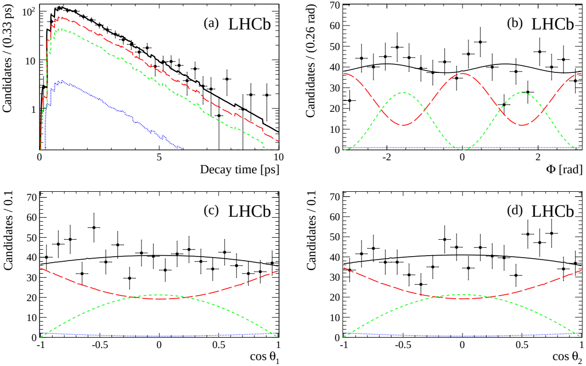

Total
CP–even
CP–odd
S–wave

- Γ_S and $\Delta\Gamma_S$ from $B_s^0 \to J/\psi\phi$ LHCB-PAPER-2013-002 in preparation.
- $\Delta m_S = (17.73 \pm 0.05) ps^{-1}$, LHCb-CONF-2011-050.

LHCb–PAPER–2013–007, arXiv:1303.7125[hep–ex]

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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

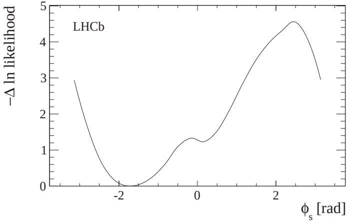
Dominant systematic uncertainties from time acceptance and *S–wave*

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%



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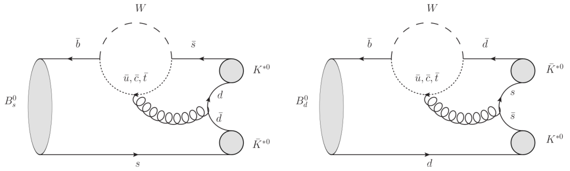
$B_s^0 \to K^{*0} \overline{K}^{*0}$

- Unobserved $b \to s$ decay
- Interesting for precision CP–violation studies, where $B^0 \to K^{*0}\overline{K}^{*0}$ is used to control theoretical uncertainties
- Theoretical prediction for its BF [Beneke, Rohrer and Yang]

$$\mathcal{B}(B_s^0 \to K^{*0}\overline{K}^{*0}) = (9.1^{+11.3}_{-6.8}) \times 10^{-6}$$

- Searched for at SLD: $\mathcal{B}(B_s^0 \to K^{*0}\overline{K}^{*0}) < 1.68 \times 10^{-3}$ (90% CL)
- Analysis based on $35pb^{-1}$ of 2010 LHCb data



LHCb Collaboration, R. Aaij et al., Phys. Lett. B709 (2012) 50

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Cut–based selection + Geometrical Likelihood (B IP, B lifetime, track IP, B p_T)

Possible peaking backgrounds under control:

- Resonant structures in KK or $\pi\pi$ spectra
- 3–body resonances ($B_s^0 \to D_s(KK\pi)\pi$)

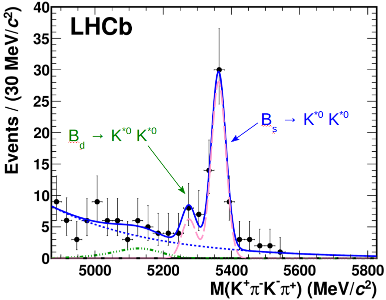
Fit model:

- B_s^0 and B^0 signals (Gaussian)
- Partially reconstructed background (ARGUS)
- Combinatorial background (Exponential)

We observe

$$N_s = 50.1 \pm 7.5$$
$$N_d = 11.2 \pm 4.3$$

Signal significance of 10.9σ



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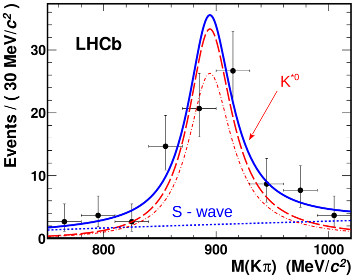
Final state contains $K\pi$ *S–wave* contributions

ML fit to $M(K^+\pi^-) \times M(K^-\pi^+)$

$$purity = (62 \pm 18)\%$$



Combinatorial background shape from the sidebands of the B_s^0 mass spectrum.

Nonresonant component (linear x phase space)

$$S(m) = (1 + bm)P(m)$$

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$B_s^0 \to K^{*0}\overline{K}^{*0}$: Branching Fraction

The BF is calculated using $B^0 \to J/\psi\, K^{*0}$ as a normalization channel using

$$\mathcal{B}\left(B_s^0 \to K^{*0}\overline{K}^{*0}\right) = \lambda_{f_L} \times \frac{\varepsilon_{B^0 \to J/\psi\, K^{*0}}}{\varepsilon_{B_s^0 \to K^{*0}\overline{K}^{*0}}} \times \frac{N_{B_s^0}}{N_{B^0}} \times \mathcal{B}_{vis}(B^0 \to J/\psi\, K^{*0}) \times \frac{f_d}{f_s} \times \left(\frac{3}{2}\right)^2$$

- $N_{B_s^0}$ and N_{B^0} are the number of candidates found for the signal and control channel
- *S–wave* contribution per K^{*0} from $B^0 \to J/\psi\, K^{*0}$ LHCb-CONF-2011-002
- Ratio of efficiencies estimated using simulation
- λ_{f_L} acceptance correction due to different polarization
- $f_s/f_d = 0.253 \pm 0.031$, LHCb collaboration, PRL 107 (2011) 211801

  (Updated measurement: LHCb, JHEP 04 (2013) 001)

$B_s^0 \to K^{*0}\overline{K}^{*0}$: Angular Analysis

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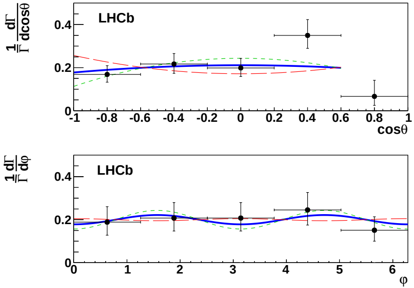
Untagged and time-integrated angular fit

Acceptance as a function of the helicity angles from simulation

S–wave contribution is neglected in the fit (systematic uncertainty)

$$|A_0|^2 = 0.30 \pm 0.12(stat) \pm 0.04(syst)$$
$$|A_\perp|^2 = 0.38 \pm 0.11(stat.) \pm 0.04(syst.)$$

Remarkable difference with its U-spin partner $B^0 \to K^{*0}\overline{K}^{*0}$ (BaBar: $|A_0|^2 = 0.80 \pm 0.13$)



$B_s^0 \to K^{*0}\overline{K}^{*0}$: Branching Fraction

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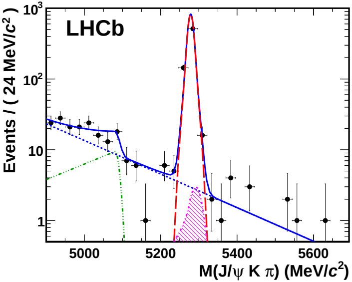

Parameter	Value
λ_{f_0}	0.812 ± 0.059
$N_{B_s^0}$	42.5 ± 6.7
N_{B^0}	657 ± 27
S–wave fraction	$(9.0 \pm 3.6)\%$
Efficiency ratio	0.807 ± 0.024
$\mathcal{B}(B^0 \to J/\psi K^{*0})$	$(1.33 \pm 0.06) \times 10^{-3}$
$\mathcal{B}(J/\psi \to \mu\mu)$	0.0593 ± 0.0006
$\mathcal{B}(K^{*0} \to K\pi)$	$2/3$

$$\mathcal{B}(B_s^0 \to K^{*0}\overline{K}^{*0}) = (2.81 \pm 0.46(stat) \pm 0.45(syst) \pm 0.34(f_s/f_d)) \times 10^{-5}$$

Dominant systematics arise from the trigger efficiency determination and the polarization measurement.

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- Penguin mediated $P \to VV$ decays are very sensitive to BSM physics.
- LHCb has reported first observation of $B_s^0 \to K^{*0}\overline{K}^{*0}$, measuring its branching fraction and polarization amplitudes.
- A first time–dependent tagged analysis of CP–violation in the interference between mixing and decay for the $B_s^0 \to \phi\phi$ decay has been performed:

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

- Extension of these CP–violation analyses and new ones ($B^0 \to \phi K^{*0}$, $B_{d,s} \to \rho\rho$) are expected with 2011+2012 data.
- Charmless $B \to VV$ decays are golden channels for LHCb analyses ($\sigma(\phi_S) \sim 0.02$ rad in $B_s^0 \to K^{*0}\overline{K}^{*0}$ and $B_s^0 \to \phi\phi$ expected for upgrade).

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

i	K_i	f_i
1	$\|A_0(t)\|^2$	$4\cos^2\theta_1\cos^2\theta_2$
2	$\|A_\parallel(t)\|^2$	$\sin^2\theta_1\sin^2\theta_2(1+\cos 2\varphi)$
3	$\|A_\perp(t)\|^2$	$\sin^2\theta_1\sin^2\theta_2(1-\cos 2\varphi)$
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	$\|A_{SS}(t)\|^2$	$\frac{4}{9}$
8	$\|A_{SV}(t)\|^2$	$\frac{4}{3}(\cos\theta_1+\cos\theta_2)^2$
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	$Re(A_\perp(t)A_{SV}^*(t))$	$-\frac{4\sqrt{2}}{\sqrt{3}}\sin\theta_1\sin\theta_2(\cos\theta_1+\cos\theta_2)\sin\varphi$

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

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

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

$B_s^0 \to K^{*0} \overline{K}^{*0}$ angular model

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$$
\begin{aligned}
\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\varphi} \quad \propto \quad & \frac{|A_0|^2}{\Gamma_L} \cos^2\theta_1 \cos^2\theta_2 \\
& \frac{|A_\parallel|^2}{\Gamma_L} \frac{1}{2} \sin^2\theta_1 \sin^2\theta_2 \cos^2\varphi \\
& \frac{|A_\perp|^2}{\Gamma_H} \frac{1}{2} \sin^2\theta_1 \sin^2\theta_2 \sin^2\varphi \\
& \frac{|A_0||A_\parallel|}{\Gamma_L} \frac{1}{2\sqrt{2}} \cos\delta_\parallel \sin 2\theta_1 \sin 2\theta_2 \cos\varphi
\end{aligned}
$$

where Γ_L and Γ_H are the decay widths of the light and the heavy B_s^0 mass eigenstates.

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$B_s^0 \to K^{*0} \overline{K}^{*0}$ systematics

Systematic effect	Error (%)
Trigger efficiency	11.0
Global angular acceptance	7.2
S-wave fraction	5.0
Background subtraction	4.7
$B^0 \to J/\psi\, K^{*0}$ and $J/\psi \to \mu\mu$ BR uncertainty	4.6
Selection efficiency	3.4
Total	15.9