Measurement of $\phi_s$ at LHCb

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On behalf of the LHCb collaboration

EPSHEP 2013
\(B_s^0\) mixing

Phenomenological Schroedinger equation describing oscillation and decay

\[i \frac{d}{dt} \left( \frac{B_s^0}{B_s^0} \right) = \left( M - \frac{i}{2} \Gamma \right) \left( \frac{B_s^0}{B_s^0} \right)\]

\[M = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix}; \Gamma = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}\]
The mixing of $B_S^0$ states is described by the phenomenological Schrödinger equation:

\[
i \frac{d}{dt} \begin{pmatrix} B_S^0 \\ \bar{B}_S^0 \end{pmatrix} = \left( M - \frac{i}{2} \Gamma \right) \begin{pmatrix} B_S^0 \\ \bar{B}_S^0 \end{pmatrix}
\]

where

\[
M = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} \quad \text{and} \quad \Gamma = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}
\]

Mass eigenstates are not the same as flavour eigenstates, leading to a mass difference:

\[
\Delta m_s = m_H - m_L = 2|M_{12}|
\]

Decay rates are given by:

\[
\Delta \Gamma_s = \Gamma_L - \Gamma_H
\]

The phase of the mixing matrix is:

\[
\phi_M = \text{arg}(M_{12})
\]
$B_S^0$ mixing

Phenomenological Schroedinger equation describing oscillation and decay

$$i \frac{d}{dt} \begin{pmatrix} B_S^0 \\ \overline{B}_S^0 \end{pmatrix} = \left( M - \frac{i}{2} \Gamma \right) \begin{pmatrix} B_S^0 \\ \overline{B}_S^0 \end{pmatrix}$$

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix}; \Gamma = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}$$

Mass eigenstates ≠ flavour eigenstates → mass difference $\propto$ osc. frequency

$$|B_L\rangle = p|B_S^0\rangle + q|\overline{B}_S^0\rangle$$

$$|B_H\rangle = p|B_S^0\rangle - q|\overline{B}_S^0\rangle$$

$\Delta m_S = m_H - m_L = 2|M_{12}|$

$\Delta \Gamma_S = \Gamma_L - \Gamma_H$

$\phi_M = \text{arg}(M_{12})$

Dominant Feynman diagrams
(Standard Model)

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20/07/2013
Interference between mixing and decay: 
→ measure relative phase $\phi_s$

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

**CP asymmetry** (for CP eigenstates):

$$A_{CP}(t) = \frac{\Gamma(\overline{B}_s^0 (t) \to f_{CP}) - \Gamma(B_s^0 (t) \to f_{CP})}{\Gamma(\overline{B}_s^0 (t) \to f_{CP}) + \Gamma(B_s^0 (t) \to f_{CP})} = -\eta_{CP}\sin(\phi_s)\sin(\Delta m_s t)$$

**Standard Model prediction:** $\phi_s^{SM} = -0.036 \pm 0.002$ rad

$B^0_S$ mixing phase $\phi_s$

Interference between mixing and decay:
→ measure relative phase $\phi_s$

$\phi_s = \phi_M - 2\phi_D$

**CP asymmetry** (for CP eigenstates):

$$A_{CP}(t) = \frac{\Gamma(B^0_S(t) \rightarrow f_{CP}) - \Gamma(B^0_S(t) \rightarrow f_{CP})}{\Gamma(B^0_S(t) \rightarrow f_{CP}) + \Gamma(B^0_S(t) \rightarrow f_{CP})} = -\eta_{CP}\sin(\phi_s)\sin(\Delta m_s t)$$

Need excellent Flavour tagging
→ tagging power $\varepsilon D^2 \approx 3.1\%$

**Need excellent Flavour tagging**

**time-dependent analysis**
& fast $B^0_S - B^0_S$ oscillation
→ need excellent decay time resolution (45 fs)
\( B_s^0 \) mixing phase \( \phi_s \)

Interference between mixing and decay:
→ measure relative phase \( \phi_s \)

\[ \phi_s = \phi_M - 2\phi_D \]

**CP asymmetry** (for CP eigenstates):

\[
A_{CP}(t) = \frac{\Gamma(B_s^0(t) \to f_{CP}) - \Gamma(B_s^0(t) \to f_{\overline{CP}})}{\Gamma(B_s^0(t) \to f_{CP}) + \Gamma(B_s^0(t) \to f_{\overline{CP}})} = -\eta_{CP}\sin(\phi_s)\sin(\Delta m_s t)
\]

**New Physics:** \( \phi_s = \phi_{s}^{SM} + \phi_{s}^{NP} \)
\[ \Delta m_s \text{ from } B_{s}^{0} \rightarrow D_{s}^{-} \pi^{+} \]

- High statistics (~34k signal candidates)
- Fit to 5 different \( D_s^- \) decay modes
- Very low background


<table>
<thead>
<tr>
<th>Decay Mode</th>
<th># candidates</th>
<th>Signal fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D_s^- \rightarrow \phi \pi^- )</td>
<td>14691</td>
<td>0.8337 ± 0.0081</td>
</tr>
<tr>
<td>( D_s^- \rightarrow K^* K^- )</td>
<td>10866</td>
<td>0.8573 ± 0.0088</td>
</tr>
<tr>
<td>( D_s^- \rightarrow K^- K^+ \pi^- \text{n.r.} )</td>
<td>11262</td>
<td>0.5952 ± 0.0093</td>
</tr>
<tr>
<td>( D_s^- \rightarrow K^- \pi^+ \pi^- )</td>
<td>4288</td>
<td>0.4366 ± 0.0137</td>
</tr>
<tr>
<td>( D_s^- \rightarrow \pi^- \pi^+ \pi^- )</td>
<td>6674</td>
<td>0.5990 ± 0.0081</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>47781</strong></td>
<td><strong>0.7144 ± 0.0040</strong></td>
</tr>
</tbody>
</table>

\( \Delta m_s \) is a measure of the difference in the mass of the \( B_s^0 \) and \( B_s^- \) mesons, which is used to extract the CKM matrix elements and test the unitarity of the quark mixing matrix.
\[ \Delta m_s \text{ from } B_s^0 \rightarrow D_s^- \pi^+ \]

- High statistics (~34k signal candidates)
- Fit to 5 different \( D_s^- \) decay modes
- Very low background


Uses flavour tagging:
- same side (LHCb-CONF-2012-033)

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

World’s most precise measurement

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Measuring $\phi_s$

- $B_s^0 \rightarrow J/\Psi \phi$

- $B_s^0 \rightarrow J/\Psi \pi^+ \pi^-$

- $B_s^0 \rightarrow \phi \phi$
Measuring $\phi_s$

- $B_s^0 \rightarrow J/\Psi \phi$
- $B_s^0 \rightarrow J/\Psi \pi^+ \pi^-$
- $B_s^0 \rightarrow \phi \phi$
$B_s^0 \rightarrow J/\psi \phi$

High statistics (≈27k signal events)
Low bkg (narrow $J/\psi$ resonance + cut on $B_s^0$ decay time)
$B_s^0 \rightarrow J/\psi \phi$

No CP eigenstate
→ need angular analysis
in three decay angles


High statistics (~27k signal events)
Low bkg (narrow $J/\psi$ resonance + cut on $B_s^0$ decay time)
\[ B_s^0 \to J/\psi \phi \]

High statistics (~27k signal events)
Low bkg (narrow \( J/\psi \) resonance + cut on \( B_s^0 \) decay time)

No CP eigenstate
→ need angular analysis in three decay angles

This way we can fit for \( \Delta \Gamma_s \)
Unbinned maximum likelihood fit in 6 dimensions
- Invariant mass
- Three decay angles
- Decay time
- Tagging decision

Take $\Delta m_s$ from $B_s^0 \to D_s^- \pi^+$

Allow for direct CP-violation

Use opposite and same side flavour tagger
- $\varepsilon D_{OST}^2 = 2.29 \pm 0.06\%$
- $\varepsilon D_{SST}^2 = 0.89 \pm 0.17\%$

Data
- Total fit
- CP-even
- CP-odd
- S-wave
Ambiguity

2-fold ambiguity \((\phi_s, \Delta \Gamma_s) \leftrightarrow (\pi - \phi_s, -\Delta \Gamma_s)\)

Resolve ambiguity:
Look at strong phase difference between p- and s-wave in bins of \(K^+K^-\) mass

only \(\Delta \Gamma_s > 0\) fits expectation

\(1\text{fb}^{-1}\)

\(\Delta \Gamma_s < 0\)
\(\Delta \Gamma_s > 0\)

\(1\text{fb}^{-1}\)

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Fit results

\[ \phi_s = 0.07 \pm 0.09 \text{ (stat)} \pm 0.01 \text{ (syst) rad} \]
\[ \Gamma_s = 0.663 \pm 0.005 \text{ (stat)} \pm 0.006 \text{ (syst) ps}^{-1} \]
\[ \Delta \Gamma_s = 0.100 \pm 0.016 \text{ (stat)} \pm 0.003 \text{ (syst) ps}^{-1} \]

Dominant systematics:
angular and decay time acceptance

Measuring $\phi_s$

- $B_s^0 \rightarrow J/\Psi \phi$
- $B_s^0 \rightarrow J/\Psi \pi^+ \pi^-$
- $B_s^0 \rightarrow \phi \phi$
$B_s^0 \rightarrow J/\psi \pi^+ \pi^-$

- Final state is purely CP-odd (> 98% see Phys.Rev D 86, 052006 (2012))
  → no angular analysis needed
- $\Gamma_s$ and $\Delta \Gamma_s$ constrained to values from $B_s^0 \rightarrow J/\psi \phi$
- Signal yield is $\sim 1/3$ of $B_s^0 \rightarrow J/\psi \phi$

$f_0(980)$
$f_2(1270)$
$f_0(1370)$

1 fb$^{-1}$
\[ B_s^0 \rightarrow J/\psi \pi^+ \pi^- \]

- Final state is purely CP-odd ( > 98% see Phys.Rev D 86, 052006 (2012)) → no angular analysis needed
- \( \Gamma_s \) and \( \Delta \Gamma_s \) constrained to values from \( B_s^0 \rightarrow J/\psi \phi \)
- Signal yield is \( \sim 1/3 \) of \( B_s^0 \rightarrow J/\psi \phi \)

\[ \phi_s = -0.14^{+0.17}_{-0.16} \pm 0.01 \text{ rad} \]
Measuring $\phi_s$

- $B_s^0 \rightarrow J/\Psi \phi$
- $B_s^0 \rightarrow J/\Psi \pi^+ \pi^-$
- $B_s^0 \rightarrow \phi \phi$
Simultaneous fit to $B_s^0 \rightarrow J/\psi \phi$ and $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$

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

- $B_s^0 \rightarrow J/\Psi \phi$

- $B_s^0 \rightarrow J/\Psi \pi^+ \pi^-$

- $B_s^0 \rightarrow \phi \phi$
\[
B_s^0 \rightarrow \phi \phi
\]

- Pure penguin mode \( \rightarrow \) small statistics
- Similar CKM phases as \( B_s^0 \rightarrow J/\psi \phi \)
- SM expectation for CPV phase very small: \( |\phi_s^{\bar{s}s}| < 0.02 \)
- Requires also tagged, time-dependent, angular analysis
$B_s^0 \rightarrow \phi \phi$

- Pure penguin mode $\rightarrow$ small statistics
- Similar CKM phases as $B_s^0 \rightarrow J/\psi \phi$
- SM expectation for CPV phase very small: $|\phi_s^{\bar{s}s\bar{s}}| < 0.02$
- Requires also tagged, time-dependent, angular analysis

880 $\pm$ 31 signal candidates

$1\text{fb}^{-1}$

$\phi$-wave

CP-even
CP-odd
S-wave

**$B_{s}^{0} \rightarrow \phi\phi$**

*Phys. Rev. Lett. 110, 241802 (2013)*

- Pure penguin mode $\rightarrow$ small statistics
- Similar CKM phases as $B_{s}^{0} \rightarrow J/\psi\phi$
- SM expectation for CPV phase very small: $|\phi_{s}^{s\bar{s}s}| < 0.02$
- Requires also tagged, time-dependent, angular analysis

- Likelihood shows non-parabolic behaviour
- Use Feldman Cousins method to provide 68% C.L. interval
- P-value of SM hypothesis is 16%

$\phi_{s}^{s\bar{s}s} \in [-2.46, -0.76]$ rad

**First constraints on $\phi_{s}$ from a pure penguin mode**
• LHCb showed the most accurate measurements of the CP violating phase $\phi_s$
• A combination of the modes $B_s^0 \rightarrow J/\psi\phi$ and $B_s^0 \rightarrow J/\psi\pi^+\pi^-$ gives:

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

• First constraints on $\phi_s$ from a pure penguin mode ($B_s^0 \rightarrow \phi\phi$)

\[
\phi^s_s^s \in [-2.46, -0.76] \text{ rad, at 68\% C.L.}
\]

• Future
  – Analysis of 2012 data in progress (soon 3x statistics)
  – Improvements of flavour tagging algorithms
Backup
Flavour Tagging

Tagging efficiency

\[ \varepsilon = \frac{\text{# tagged candidates}}{\text{# all candidates}} \]

Mistag probability

\[ \omega = \frac{\text{# tagged wrong}}{\text{# tagged}} \]

Dilution

\[ D = (1 - 2\omega) \]

- **Opposite side taggers**
  - exploits \( b\bar{b} \) pair production by partially reconstructing the second B-hadron in the event
- **Same side kaon tagger**
  - exploits hadronization of signal \( B_s \)-meson
- **Combined tagging power (in \( B_s^0 \rightarrow D_s^-\pi^+ \))**
  - \( \varepsilon D^2 = 3.5 \pm 0.5\% \)
$B_s^0 \rightarrow J/\psi\phi$ mass plots

Figure 4: Invariant mass distribution of the selected $B_s^0 \rightarrow J/\psi K^+K^-$ candidates. The mass of the $\mu^+\mu^-$ pair is constrained to the $J/\psi$ mass [7]. Curves for the fitted contributions from signal (dotted red), background (dotted green) and their combination (solid blue) are overlaid.

Figure 5: Background subtracted invariant mass distributions of the (a) $\mu^+\mu^-$ and (b) $K^+K^-$ systems in the selected sample of $B_s^0 \rightarrow J/\psi K^+K^-$ candidates. The solid blue line represents the fit to the data points described in the text.
$B_s^0 \rightarrow J/\psi \phi$ decay time resolution

Figure 6: Decay time resolution, $\sigma_t$, for selected $B_s^0 \rightarrow J/\psi K^+K^-$ signal events. The curve shows a fit to the data of the sum of two gamma distributions with a common mean.

Figure 7: Decay time distribution of prompt $J/\psi K^+K^-$ candidates. The curve (solid blue) is the decay time model convolved with a Gaussian resolution model. The decay time model consists of a delta function for the prompt component and two exponential functions with different decay constants, which represent the $B_s^0 \rightarrow J/\psi K^+K^-$ signal and long-lived background, respectively. The decay constants are determined from the fit. The same dataset is shown in both plots, on different scales.

- Use per-event error estimate
- Calibrated on data
- Effective resolution $\approx 45 \text{ fb}^{-1}$
$B_s^0 \rightarrow J/\psi\phi$ acceptances

Figure 8: $B_s^0$ decay time trigger-acceptance functions obtained from data. The unbiased trigger category is shown on (a) an absolute scale and (b) the biased trigger category on an arbitrary scale.

Figure 9: Angular acceptance function evaluated with simulated $B_s^0 \rightarrow J/\psi\phi$ events, scaled by the mean acceptance. The acceptance is shown as a function of (a) $\cos\theta_K$, (b) $\cos\theta_\mu$ and (c) $\varphi_h$, where in all cases the acceptance is integrated over the other two angles. The points are obtained by summing the inverse values of the underlying physics PDF for simulated events and the curves represent a polynomial parameterisation of the acceptance.
Use per event mistag probability estimate $\eta$

$$
\omega = p_0 + \frac{\Delta p_0}{2} + p_1 \cdot (\eta - \langle \eta \rangle) \\
\bar{\omega} = p_0 - \frac{\Delta p_0}{2} + p_1 \cdot (\eta - \langle \eta \rangle)
$$

Calibrated on data separately for $B$ and $\bar{B}$

Figure 10: Average measured wrong-tag probability ($\omega$) versus estimated wrong-tag probability ($\eta$) calibrated on $B^+ \to J/\psi K^+$ signal events for the OS tagging combinations for the background subtracted events in the signal mass window. Points with errors are data, the red curve represents the result of the wrong-tag probability calibration, corresponding to the parameters of Table 3.
$B^0_s \rightarrow J/\psi \phi$ Flavour Tagging

Use per event mistag probability estimate $\eta$

![Graph showing distributions of the estimated wrong-tag probability, $\eta$, for $B^0_s \rightarrow J/\psi K^+ K^-$ signal events obtained using the sPlot method on the $J/\psi K^+ K^-$ invariant mass distribution. Both the (a) OS-only and (b) SSK-only tagging categories are shown.]

Tagging power

$\varepsilon D^2_{OST} = 2.29 \pm 0.06\%$

$\varepsilon D^2_{SSST} = 0.89 \pm 0.17\%$
$B_s^0 \rightarrow J/\psi\phi$ fit results

Table 6: Results of the maximum likelihood fit for the principal physics parameters. The first uncertainty is statistical and the second is systematic. The value of $\Delta m_s$ was constrained to the measurement reported in Ref. [38]. The evaluation of the systematic uncertainties is described in Sect. 10.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_s$ [ps$^{-1}$]</td>
<td>0.663 ± 0.005 ± 0.006</td>
</tr>
<tr>
<td>$\Delta \Gamma_s$ [ps$^{-1}$]</td>
<td>0.100 ± 0.016 ± 0.003</td>
</tr>
<tr>
<td>$</td>
<td>A_\perp</td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
</tr>
<tr>
<td>$\delta_\parallel$ [rad]</td>
<td>3.30 ± 0.13 ± 0.08</td>
</tr>
<tr>
<td>$\delta_\perp$ [rad]</td>
<td>3.07 ± 0.22 ± 0.07</td>
</tr>
<tr>
<td>$\phi_s$ [rad]</td>
<td>0.07 ± 0.09 ± 0.01</td>
</tr>
<tr>
<td>$</td>
<td>\lambda</td>
</tr>
</tbody>
</table>

Table 7: Correlation matrix for the principal physics parameters.

|          | $\Gamma_s$ [ps$^{-1}$] | $\Delta \Gamma_s$ [ps$^{-1}$] | $|A_\perp|^2$ | $|A_0|^2$ | $\delta_\parallel$ [rad] | $\delta_\perp$ [rad] | $\phi_s$ [rad] | $|\lambda|$ |
|----------|-------------------------|-------------------------|-----------|--------|-------------------------|-------------------------|---------------|------------|
| $\Gamma_s$ [ps$^{-1}$] | 1.00                        | -0.39                    | 0.37       | -0.27   | -0.09                    | -0.03                    | 0.06          | 0.03       |
| $\Delta \Gamma_s$ [ps$^{-1}$] | -0.39                        | 1.00                     | -0.68      | 0.63    | 0.03                     | 0.04                     | -0.04         | 0.00       |
| $|A_\perp|^2$     | 0.37                        | -0.68                    | 1.00       | -0.58   | -0.28                    | -0.09                    | -0.04         | -0.04      |
| $|A_0|^2$         | -0.27                       | 0.63                     | -0.58      | 1.00    | -0.02                    | -0.00                    | 0.8            | -0.04      |
| $\delta_\parallel$ [rad] | -0.09                       | 0.03                     | -0.28      | -0.02   | 1.00                     | 0.32                     | -0.03         | 0.05       |
| $\delta_\perp$ [rad]  | -0.03                       | 0.04                     | -0.09      | 1.00    | 0.28                     | 1.00                     | 0.04          | 0.00       |
| $\phi_s$ [rad]     | 0.06                        | -0.04                    | -0.04      | 0.28    | 1.00                     | 0.04                     | 1.00          | 1.00       |
| $|\lambda|$        | 0.03                        | 0.00                     | 0.04       | 0.00    | 1.00                     | 1.00                     |               |            |
$B_s^0 \rightarrow J/\psi\phi$ fit results

S-wave fraction in bins of the $K^+K^-$ invariant mass

<table>
<thead>
<tr>
<th>$m(K^+K^-)$ bin [MeV/$c^2$]</th>
<th>Parameter</th>
<th>Value</th>
<th>$\sigma_{\text{stat}}$ (asymmetric)</th>
<th>$\sigma_{\text{syst}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>990 - 1008</td>
<td>$F_S$</td>
<td>0.227</td>
<td>+0.081, −0.073</td>
<td>0.020</td>
</tr>
<tr>
<td></td>
<td>$\delta_S - \delta_{\perp}$ [rad]</td>
<td>1.31</td>
<td>+0.78, −0.49</td>
<td>0.09</td>
</tr>
<tr>
<td>1008 - 1016</td>
<td>$F_S$</td>
<td>0.067</td>
<td>+0.030, −0.027</td>
<td>0.009</td>
</tr>
<tr>
<td></td>
<td>$\delta_S - \delta_{\perp}$ [rad]</td>
<td>0.77</td>
<td>+0.38, −0.23</td>
<td>0.08</td>
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<tr>
<td>1016 - 1020</td>
<td>$F_S$</td>
<td>0.008</td>
<td>+0.014, −0.007</td>
<td>0.005</td>
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<tr>
<td></td>
<td>$\delta_S - \delta_{\perp}$ [rad]</td>
<td>0.51</td>
<td>+1.40, −0.30</td>
<td>0.20</td>
</tr>
<tr>
<td>1020 - 1024</td>
<td>$F_S$</td>
<td>0.016</td>
<td>+0.012, −0.009</td>
<td>0.006</td>
</tr>
<tr>
<td></td>
<td>$\delta_S - \delta_{\perp}$ [rad]</td>
<td>−0.51</td>
<td>+0.21, −0.35</td>
<td>0.15</td>
</tr>
<tr>
<td>1024 - 1032</td>
<td>$F_S$</td>
<td>0.055</td>
<td>+0.027, −0.025</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>$\delta_S - \delta_{\perp}$ [rad]</td>
<td>−0.46</td>
<td>+0.18, −0.26</td>
<td>0.05</td>
</tr>
<tr>
<td>1032 - 1050</td>
<td>$F_S$</td>
<td>0.167</td>
<td>+0.043, −0.042</td>
<td>0.021</td>
</tr>
<tr>
<td></td>
<td>$\delta_S - \delta_{\perp}$ [rad]</td>
<td>−0.65</td>
<td>+0.18, −0.22</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Independent measurement of $\Delta m_s$

$$\Delta m_s = 17.70 \pm 0.10\,(stat) \pm 0.01\,(syst)\,ps^{-1}$$

Better sensitivity as CDF result
$B_s^0 \rightarrow J/\psi \phi$ systematics

Table 9: Statistical and systematic uncertainties.

| Source                      | $\Gamma_s$ [ps$^{-1}$] | $\Delta \Gamma_s$ [ps$^{-1}$] | $|A_\perp|^2$ | $|A_0|^2$ | $|\delta_{\parallel}|$ [rad] | $|\delta_{\perp}|$ [rad] | $\phi_s$ [rad] | $|\lambda|$ |
|-----------------------------|-------------------------|--------------------------------|--------------|----------|----------------|----------------|-------------|----------|
| 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    |
| $B^0 \rightarrow J/\psi K^0$ 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                          | 0.0017       | 0.0114   | $+0.15$ $-0.23$ | 0.23           | 0.001       | 0.038    |

Table 10: Statistical and systematic uncertainties for S-wave fractions in bins of $m(K^+K^-)$.

<table>
<thead>
<tr>
<th>Source</th>
<th>bin 1</th>
<th>bin 2</th>
<th>bin 3</th>
<th>bin 4</th>
<th>bin 5</th>
<th>bin 6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F_S$</td>
<td>$F_S$</td>
<td>$F_S$</td>
<td>$F_S$</td>
<td>$F_S$</td>
<td>$F_S$</td>
</tr>
<tr>
<td>Stat. uncertainty</td>
<td>+0.081</td>
<td>+0.030</td>
<td>+0.014</td>
<td>+0.012</td>
<td>+0.027</td>
<td>+0.043</td>
</tr>
<tr>
<td>Background subtraction</td>
<td>-0.073</td>
<td>-0.027</td>
<td>-0.007</td>
<td>-0.009</td>
<td>-0.026</td>
<td>-0.042</td>
</tr>
<tr>
<td>$B^0 \rightarrow J/\psi K^0$ background</td>
<td>0.014</td>
<td>0.003</td>
<td>0.001</td>
<td>0.002</td>
<td>0.004</td>
<td>0.006</td>
</tr>
<tr>
<td>Angular acc. reweighting</td>
<td>0.010</td>
<td>0.006</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
<td>0.018</td>
</tr>
<tr>
<td>Angular acc. statistical</td>
<td>0.004</td>
<td>0.006</td>
<td>0.004</td>
<td>0.005</td>
<td>0.006</td>
<td>0.007</td>
</tr>
<tr>
<td>Fit bias</td>
<td>0.003</td>
<td>0.003</td>
<td>0.002</td>
<td>0.001</td>
<td>0.003</td>
<td>0.004</td>
</tr>
<tr>
<td>Quadratic sum of syst.</td>
<td>0.020</td>
<td>0.009</td>
<td>0.005</td>
<td>0.006</td>
<td>0.008</td>
<td>0.021</td>
</tr>
<tr>
<td>Total uncertainties</td>
<td>-0.076</td>
<td>-0.029</td>
<td>-0.009</td>
<td>-0.011</td>
<td>-0.026</td>
<td>-0.047</td>
</tr>
</tbody>
</table>
$B_s^0 \rightarrow J/\psi \phi$ systematics

### Table 11: Statistical and systematic uncertainties for S-wave phases in bins of $m(K^+K^-)$.

<table>
<thead>
<tr>
<th>Source</th>
<th>bin 1 $\delta_S - \delta_\perp$ [rad]</th>
<th>bin 2 $\delta_S - \delta_\perp$ [rad]</th>
<th>bin 3 $\delta_S - \delta_\perp$ [rad]</th>
<th>bin 4 $\delta_S - \delta_\perp$ [rad]</th>
<th>bin 5 $\delta_S - \delta_\perp$ [rad]</th>
<th>bin 6 $\delta_S - \delta_\perp$ [rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stat. uncertainty</td>
<td>$+0.78$</td>
<td>$+0.38$</td>
<td>$+1.40$</td>
<td>$+0.21$</td>
<td>$+0.18$</td>
<td>$+0.18$</td>
</tr>
<tr>
<td>Background subtraction</td>
<td>$0.03$</td>
<td>$0.02$</td>
<td>$0.03$</td>
<td>$0.01$</td>
<td>$0.01$</td>
<td>$0.01$</td>
</tr>
<tr>
<td>$B^0 \rightarrow J/\psi K^0$ background</td>
<td>$0.08$</td>
<td>$0.04$</td>
<td>$0.08$</td>
<td>$0.01$</td>
<td>$0.01$</td>
<td>$0.05$</td>
</tr>
<tr>
<td>Angular acc. reweighting</td>
<td>$0.02$</td>
<td>$0.03$</td>
<td>$0.12$</td>
<td>$0.13$</td>
<td>$0.03$</td>
<td>$0.01$</td>
</tr>
<tr>
<td>Angular acc. statistical</td>
<td>$0.033$</td>
<td>$0.023$</td>
<td>$0.067$</td>
<td>$0.036$</td>
<td>$0.019$</td>
<td>$0.015$</td>
</tr>
<tr>
<td>Fit bias</td>
<td>$0.005$</td>
<td>$0.043$</td>
<td>$0.112$</td>
<td>$0.049$</td>
<td>$0.022$</td>
<td>$0.016$</td>
</tr>
<tr>
<td>$C_{SP}$ factors</td>
<td>$0.007$</td>
<td>$0.028$</td>
<td>$0.049$</td>
<td>$0.025$</td>
<td>$0.021$</td>
<td>$0.020$</td>
</tr>
<tr>
<td>Quadratic sum of syst.</td>
<td>$0.09$</td>
<td>$0.08$</td>
<td>$0.20$</td>
<td>$0.15$</td>
<td>$0.05$</td>
<td>$0.06$</td>
</tr>
<tr>
<td>Total uncertainties</td>
<td>$+0.79$</td>
<td>$+0.39$</td>
<td>$+1.41$</td>
<td>$+0.26$</td>
<td>$+0.19$</td>
<td>$+0.19$</td>
</tr>
</tbody>
</table>
Penguin pollution

- Angular analysis in $B_s^0 \to J/\psi K^*$ can give information about penguin contribution for $B_s^0 \to J/\psi\phi$

First step:
- Branching Fraction of $B_s^0 \to J/\psi K^*$ measured to be $4.4^{+0.5}_{-0.4} \pm 0.8 \times 10^{-5}$

*Phys. Rev. D 86 (2012) 071102*
**B_s^0 \rightarrow J/\psi \phi & B_s^0 \rightarrow J/\psi \pi^+ \pi^-** fit results

Table 12: Results of combined fit to the $B_s^0 \rightarrow J/\psi K^+ K^-$ and $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ datasets. The first uncertainty is statistical and the second is systematic.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_s$ [$\text{ps}^{-1}$]</td>
<td>$0.661 \pm 0.004 \pm 0.006$</td>
</tr>
<tr>
<td>$\Delta \Gamma_s$ [$\text{ps}^{-1}$]</td>
<td>$0.106 \pm 0.011 \pm 0.007$</td>
</tr>
<tr>
<td>$</td>
<td>A_\perp</td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
</tr>
<tr>
<td>$\delta_\parallel$ [rad]</td>
<td>$3.32 \pm 0.13 \pm 0.08$</td>
</tr>
<tr>
<td>$\delta_\perp$ [rad]</td>
<td>$3.04 \pm 0.20 \pm 0.07$</td>
</tr>
<tr>
<td>$\phi_s$ [rad]</td>
<td>$0.01 \pm 0.07 \pm 0.01$</td>
</tr>
<tr>
<td>$</td>
<td>\lambda</td>
</tr>
</tbody>
</table>

Table 13: Correlation matrix for statistical uncertainties on combined results.

|             | $\Gamma_s$ [$\text{ps}^{-1}$] $\Delta \Gamma_s$ [$\text{ps}^{-1}$] $|A_\perp|^2$ $|A_0|^2$ $\delta_\parallel$ [rad] $\delta_\perp$ [rad] $\phi_s$ [rad] $|\lambda|$ |
|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $\Gamma_s$  | 1.00            | 0.10            | 0.08            | 0.03            | -0.08           | -0.04           | 0.01            | 0.00            |
| $\Delta \Gamma_s$ | 0.10            | 1.00            | -0.49           | 0.47            | 0.00            | 0.00            | 0.00            | -0.01           |
| $|A_\perp|^2$ | 0.08            | -0.49           | 1.00            | -0.40           | 0.00            | 0.00            | 0.00            | 0.00            |
| $|A_0|^2$    | 0.03            | 0.47            | -0.40           | 1.00            | 0.00            | 0.00            | 0.00            | 0.00            |
| $\delta_\parallel$ [rad] | -0.08           | 0.00            | 0.00            | 0.00            | 1.00            | 0.00            | 0.00            | 0.00            |
| $\delta_\perp$ [rad] | -0.04           | 0.00            | 0.00            | 0.00            | 0.00            | 1.00            | 0.00            | 0.00            |
| $\phi_s$ [rad] | -0.01           | 0.00            | 0.00            | 0.00            | 0.00            | 0.00            | 1.00            | 0.00            |
| $|\lambda|$ | 0.00            | 0.00            | 0.00            | 0.00            | 0.00            | 0.00            | 0.00            | 1.00            |
Table 2: Fit results with statistical and systematic uncertainties. A 68% statistical confidence interval is quoted for $\phi_s$. Amplitudes are defined at $t = 0$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>$\sigma_{\text{stat.}}$</th>
<th>$\sigma_{\text{syst.}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_s$ [rad] (68% CL)</td>
<td>$-2.37, -0.92$</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
<td>^2$</td>
<td>0.329</td>
</tr>
<tr>
<td>$</td>
<td>A_{\perp}</td>
<td>^2$</td>
<td>0.358</td>
</tr>
<tr>
<td>$</td>
<td>A_{S}</td>
<td>^2$</td>
<td>0.016</td>
</tr>
<tr>
<td>$\delta_1$ [rad]</td>
<td>2.19</td>
<td>0.44</td>
<td>0.12</td>
</tr>
<tr>
<td>$\delta_2$ [rad]</td>
<td>-1.47</td>
<td>0.48</td>
<td>0.10</td>
</tr>
<tr>
<td>$\delta_S$ [rad]</td>
<td>0.65</td>
<td>+0.89</td>
<td>-1.65</td>
</tr>
</tbody>
</table>