Due to flavor changing couplings to common states, the time evolution of the meson $B_S$ and $\bar{B}_S$ is described by the superposition of $B_H$ and $B_L$ states, with masses $m_S \pm \Delta m_S/2$ and lifetimes $\Gamma_S \pm \Delta \Gamma_S/2$.

These states deviate from defined values $CP = \pm 1$, as described in the SM by the mixing phase $\varphi_S$:

$$\varphi_S = -2\beta_S,$$

$$\beta_S = \text{arg}\left[-\frac{(V_{ts}V_{tb}^*)}{(V_{cs}V_{cb}^*)}\right].$$

SM prediction (fit): $\varphi_S = -0.0368 \pm 0.0018 \text{ rad}$

$$\Delta \Gamma_S = 0.082 \pm 0.021 \text{ ps}^{-1}$$

New Physics might add an additional contribution to $\varphi_S$, and might change the ratio $\Delta \Gamma_S/\Delta m_S$. 

\[ \begin{vmatrix} V_{us}V_{ub}^* \\ V_{cs}V_{cb}^* \end{vmatrix} = (\bar{\rho}, \bar{\eta}) \]

\[ \begin{vmatrix} V_{ts}V_{tb}^* \\ V_{cs}V_{cb}^* \end{vmatrix} = (0, 0) \]

\[ (1, 0) \]
In general, the decay to a final state that is coupled to $B_S$ and/or $\bar{B}_S$ exhibits fast oscillations driven by $\Delta m_S$. Interference between amplitudes for both states generates $CP$ violation, and conveys information on $\phi_s$.

If $B$ / $\bar{B}$ flavor at production is not determined (not tagged), the fast oscillations cannot be observed, but interference terms remain if the final state is described by a superposition of amplitudes of different $CP$.
Angular correlations and \( CP \)

In the decay \( B_S (\bar{B}_S) \rightarrow J/\psi \phi \rightarrow l^+ l^- K^+ K^- \) different components in the angular-distributions amplitudes correspond to \( CP = +1 \) or \( -1 \).

The “transversity angles” are used to describe the angular distributions:

In the \( J/\psi \) (or \( \phi \)) rest frames, the direction of \( \phi \) (opposite to \( J/\psi \)) defines the \( x \) axis, and the \( xy \)-plane is defined by the \( K^+ K^- \) decay plane, with \( K^+ \) oriented towards positive \( y \); \( \theta_T \) and \( \phi_T \) are the polar angles of \( l^+ \), \( \psi_T \) is the angle between \( K^+ \) and \( x \)-axis.
## Angles and time dependent distributions

Different decay amplitudes correspond to angular amplitudes of defined $CP$. The overall time- and angle-dependent probability is:

\[
\frac{d^4 \Gamma}{dt \, d\Omega} = \sum_k \mathcal{O}^{(k)}(t) g^{(k)}(\theta_T, \psi_T, \varphi_T)
\]

<table>
<thead>
<tr>
<th>$k$</th>
<th>$\mathcal{O}^{(k)}(t)$</th>
<th>$g^{(k)}(\theta_T, \psi_T, \varphi_T)$</th>
<th>$CP$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\frac{1}{2}</td>
<td>A_0(0)</td>
<td>^2 \left[ (1 + \cos \phi_s) e^{-\Gamma_L^{(s)} t} + (1 - \cos \phi_s) e^{-\Gamma_H^{(s)} t} \right]$</td>
</tr>
<tr>
<td>2</td>
<td>$\frac{1}{2}</td>
<td>A_{\parallel}(0)</td>
<td>^2 \left[ (1 + \cos \phi_s) e^{-\Gamma_L^{(s)} t} + (1 - \cos \phi_s) e^{-\Gamma_H^{(s)} t} \right]$</td>
</tr>
<tr>
<td>3</td>
<td>$\frac{1}{2}</td>
<td>A_{\perp}(0)</td>
<td>^2 \left[ (1 - \cos \phi_s) e^{-\Gamma_L^{(s)} t} + (1 + \cos \phi_s) e^{-\Gamma_H^{(s)} t} \right]$</td>
</tr>
<tr>
<td>4</td>
<td>$\frac{1}{2}</td>
<td>A_0(0)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>$\frac{1}{2}</td>
<td>A_{\parallel}(0)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>$\frac{1}{2}</td>
<td>A_0(0)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>$\frac{1}{2}</td>
<td>A_S(0)</td>
<td>^2 \left[ (1 - \cos \phi_s) e^{-\Gamma_L^{(s)} t} + (1 + \cos \phi_s) e^{-\Gamma_H^{(s)} t} \right]$</td>
</tr>
<tr>
<td>8</td>
<td>$-\frac{1}{2}</td>
<td>A_S(0)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>$\frac{1}{2}</td>
<td>A_S(0)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>$-\frac{1}{2}</td>
<td>A_0(0)</td>
<td></td>
</tr>
</tbody>
</table>

Notice the presence of strong phases $\delta_X$
The measurement of ATLAS

• Analysis using data collected in 2011 (4.7 fb$^{-1}$).
• Trigger selection based in di-muon and single-muon triggers ($p_T$ threshold 4 GeV or higher)

• Offline selection based on $J/\psi$ and $\phi$ invariant masses, $\chi^2$/NDF < 3 in fit to decay vertex, $|\eta|<2.5$ for all tracks, $p_T > 0.5$ GeV for kaon candidates.
• Decay time computed in the plane normal to collision axis.
• Average number of primary interactions 5.6, wrong association to primary vertex is $< 1\%$ and effects are negligible.

• Acceptance computed on large samples of signal and background channels (e.g.: $B^0 \rightarrow J/\psi K^0*$, $b\bar{b}
\rightarrow J/\psi X$, $p\bar{p} \rightarrow J/\psi X$).
• Efficiency via data-driven procedures.
Maximum likelihood fit

\[ \ln \mathcal{L} = \sum_{i=1}^{N} \left\{ w_i \cdot \ln(f_s \cdot \mathcal{F}_s(m_i, t_i, \Omega_i)) + f_s \cdot f_{B^0} \cdot \mathcal{F}_{B^0}(m_i, t_i, \Omega_i) 
\]
\[ + (1 - f_s \cdot (1 + f_{B^0})) \mathcal{F}_{bkg}(m_i, t_i, \Omega_i) \right\} + \ln P(\delta_\perp) \]

Terms describing:

- the signal (the 10 terms discussed above), with relative amplitude described by the parameter \( f_s \).
- The background due to \( B^0 \rightarrow J/\psi K^{*0} \) and \( B^0 \rightarrow J/\psi K\pi \) (non resonant), described by the parameter \( f_{B^0} \), constrained by known branching fractions and acceptance (11% of signal amplitude)
- The prompt and non-prompt combinatorial background described with empirical angular distribution. (No \( K-\pi \) discrimination.)
- \( w_i \) describes a small trigger inefficiency (~1%).
- \( P(\delta_\perp) \) is discussed below.
Result of the fit:
projection on $B_s$ mass and proper decay time
Result of the fit: projection on transversity angles

Mass projection for proper decay-time larger than 0.3 ps
### Systematic uncertainties

These are calculated with different techniques, including:

- changes in detector simulation (alignment),
- data based studies (efficiency),
- pseudo-experiments Monte Carlo (mass models, background angles)
- and variations in analysis methods and assumptions.

| Systematic                          | $\phi_s$ (rad) | $\Delta \Gamma_s$ (ps$^{-1}$) | $\Gamma_s$ (ps$^{-1}$) | $|A_{||}(0)|^2$ | $|A_0(0)|^2$ | $|A_S(0)|^2$ |
|-------------------------------------|----------------|-------------------------------|------------------------|----------------|-------------|-------------|
| Inner Detector alignment            | 0.04           | < 0.001                       | 0.001                  | < 0.001        | < 0.001     | < 0.01      |
| Trigger efficiency                  | < 0.01         | < 0.001                       | 0.002                  | < 0.001        | < 0.001     | < 0.01      |
| Signal mass model                   | 0.02           | 0.002                         | < 0.001                | < 0.001        | < 0.001     | < 0.01      |
| Background mass model               | 0.03           | 0.001                         | < 0.001                | 0.001          | < 0.001     | < 0.01      |
| Resolution model                    | 0.05           | < 0.001                       | 0.001                  | < 0.001        | < 0.001     | < 0.01      |
| Background lifetime model           | 0.02           | 0.002                         | < 0.001                | < 0.001        | < 0.001     | < 0.01      |
| Background angles model             | 0.05           | 0.007                         | 0.003                  | 0.007          | 0.008       | 0.02        |
| $B^0$ contribution                  | 0.05           | < 0.001                       | < 0.001                | < 0.001        | 0.005       | < 0.01      |
| **Totals**                          | 0.10           | 0.008                         | 0.004                  | 0.007          | 0.009       | 0.02        |
Symmetries in likelihood, parameters determination

The term describing $B_S \rightarrow J/\psi \phi$ is invariant under the transformations:

$$\{\phi_s, \Delta \Gamma_s, \delta_\perp, \delta_\parallel\} \rightarrow \{\pi - \phi_s, -\Delta \Gamma_s, \pi - \delta_\perp, 2\pi - \delta_\parallel\}$$

$$\{\phi_s, \Delta \Gamma_s, \delta_\perp, \delta_\parallel\} \rightarrow \{-\phi_s, \Delta \Gamma_s, \pi - \delta_\perp, 2\pi - \delta_\parallel\}$$

with the latter characteristic of untagged analyses.

As shown below, the fit to the data favors values of $\phi_s$ close to 0 ($\pi$), for which an untagged analysis is scarcely sensitive to the phase $\delta_\perp$.

We therefore proceed as follows:

- we constrain the value of $\delta_\perp$ to $2.95 \pm 0.39$ rad as recently measured (LHCb) [or its complement to $\pi$]. [Ref.s in slide n. 16]
- the four minima of the likelihood do not overlap, only one of them is compatible with previous measurements, and we show below the result for that minimum.
## Result of likelihood fit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Statistical uncertainty</th>
<th>Systematic uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_s (\text{rad})$</td>
<td>0.22</td>
<td>0.41</td>
<td>0.10</td>
</tr>
<tr>
<td>$\Delta \Gamma_s (\text{ps}^{-1})$</td>
<td>0.053</td>
<td>0.021</td>
<td>0.008</td>
</tr>
<tr>
<td>$\Gamma_s (\text{ps}^{-1})$</td>
<td>0.677</td>
<td>0.007</td>
<td>0.004</td>
</tr>
<tr>
<td>$</td>
<td>A_0(0)</td>
<td>^2$</td>
<td>0.528</td>
</tr>
<tr>
<td>$</td>
<td>A_{\parallel}(0)</td>
<td>^2$</td>
<td>0.220</td>
</tr>
<tr>
<td>$</td>
<td>A_S(0)</td>
<td>^2$</td>
<td>0.02</td>
</tr>
</tbody>
</table>

### Correlation coefficients

|          | $\phi_s$ | $\Delta \Gamma_s$ | $\Gamma_s$ | $|A_0(0)|^2$ | $|A_{\parallel}(0)|^2$ | $|A_S(0)|^2$ |
|----------|----------|-------------------|------------|--------------|------------------------|--------------|
| $\phi_s$ | 1.00     | -0.13             | 0.38       | -0.03        | -0.04                  | 0.02         |
| $\Delta \Gamma_s$ | 1.00 | 1.00              | -0.60      | 0.12         | 0.11                   | 0.10         |
| $\Gamma_s$ |       |                   | 1.00       | -0.06        | -0.10                  | 0.04         |
| $|A_0(0)|^2$ |         |                   |            | 1.00         | -0.30                  | 0.35         |
| $|A_{\parallel}(0)|^2$ |       |                   |            |              | 1.00                   | 0.09         |
| $|A_S(0)|^2$ |         |                   |            |              |                        | 1.00         |
Likelihood profiles in the $\phi_s \times \Delta \Gamma_s$ plane

$\Delta \Gamma_s$ constrained to 2.95 $\pm$ 0.39 rad
$\Delta \Gamma_s$ constrained to $>$ 0

$\sqrt{s} = 7$ TeV
$\int L \, dt = 4.9$ fb$^{-1}$

$\text{ATLAS Preliminary}$

(Statistical errors only)

Agreement with the SM prediction
Comparison with other experiments

See reference listed in slide n. 16 for details concerning contour plots from other experiments.
Conclusions

From 4.9 fb-1 collected by ATLAS in 2011, decay time and angular distributions have been studied in a sample of 22000 $B_S \rightarrow J/\psi \phi$ events. Without flavor tagging, and assuming $\delta_{\perp} = 2.95 \pm 0.39$ rad, the preliminary result is:

\[
\phi_s = 0.22 \pm 0.41 \text{ (stat.)} \pm 0.10 \text{ (syst.)} \text{ rad}
\]
\[
\Delta \Gamma_s = 0.053 \pm 0.021 \text{ (stat.)} \pm 0.008 \text{ (syst.)} \text{ ps}^{-1}
\]
\[
\Gamma_s = 0.677 \pm 0.007 \text{ (stat.)} \pm 0.004 \text{ (syst.)} \text{ ps}^{-1}
\]
\[
|A_0(0)|^2 = 0.528 \pm 0.006 \text{ (stat.)} \pm 0.009 \text{ (syst.)}
\]
\[
|A_{\parallel}(0)|^2 = 0.220 \pm 0.008 \text{ (stat.)} \pm 0.007 \text{ (syst.)}
\]
References

- Strong phases and sign of $\Delta \Gamma_s$: LHCb Collaboration, PRL 108, 241801 (2012)
- Previous measurements in $\phi_s \times \Delta \Gamma_s$:
  - CDF Collaboration: CDF-Public-Note-10778
  - D0 Collaboration: PRD85, 032006 (2012)
  - Plot in slide n. 14 modified from: P. Clarke, Moriond EW 2012.
ADDITIONAL SLIDES
Mass distribution $J/\psi (\mu^+\mu^-)$ and $\phi (K^+K^-)$ for $B_S$ candidates with $5317 < m < 5417$ MeV.

Selection cuts:
$J/\psi$ mass within $\pm 135$-240 MeV ($\eta$ dependent),
$\phi$ mass within $\pm 11$ MeV.
Mass and proper decay-time per-candidate uncertainties

Mass and decay-time measurements enter the likelihood with event-by-event uncertainties. The distributions are extracted from data.
Pull distributions from pseudo-experiments simulation - 2
$\sqrt{s} = 7$ TeV
$\int L \, dt = 4.9$ fb$^{-1}$

$\Delta \Gamma_s [\text{ps}^{-1}]$

$\phi_s^{J/\psi \Phi}$ [rad]

**ATLAS** Preliminary

Standard Model

- ATLAS 4.9 fb$^{-1}$, 68% C.L.
- ATLAS 4.9 fb$^{-1}$, 90% C.L.

$\delta$ constrained to $2.95 \pm 0.39$ rad
$\Delta \Gamma_s$ constrained to $> 0$
ATLAS Preliminary

$\sqrt{s} = 7$ TeV
$L \, dt = 4.9 \, fb^{-1}$

$\Delta \Gamma_s [ps^{-1}]

\delta_{1} \text{ constrained to } 2.95 \pm 0.39 \text{ rad}
\Delta \Gamma_s \text{ constrained to } > 0$

$\Phi_{s}^{J/\psi \phi} [\text{rad}]$
See reference listed on slide n. 16 for details concerning contour plots from other experiments.
Likelihood fit to strong phases

<table>
<thead>
<tr>
<th>$\delta_{\text{perp}}$</th>
<th>Constrained to $2.95 \pm 0.39$ rad</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_{\text{par}}$</td>
<td>Best fit: $\pi$, $1 \sigma$ range: $3.04 - 3.24$ rad</td>
</tr>
<tr>
<td>$\delta_{\text{perp}} - \delta_{S}$</td>
<td>$0.03 \pm 0.13$ rad</td>
</tr>
</tbody>
</table>

ATLAS - 4.9 fb$^{-1}$ - Preliminary
Comparisons of recent measurements

|               | $\Gamma_s$ [ps$^{-1}$] | $\Delta \Gamma_s$ [ps$^{-1}$] | $|A_0|^2$ | $|A_{\text{par}}|^2$ | $\varphi_s$ [rad] | $|A_s|^2$ | $\delta_{\text{perp}}$ [rad] | $\delta_{\text{par}}$ [rad] | $\delta_s$ [rad] | Signal sample |
|---------------|------------------------|-------------------------------|---------|----------------------|-----------------|---------|------------------------|-----------------|---------------|---------------|
| DO (8 fb$^{-1}$, stat(+)+syst $\Delta \Gamma_s>0$ case) | 0.693 ±0.020 +0.015 | 0.179 -0.060 +0.059 | 0.565 ±0.017 | 0.249 -0.022 +0.021 | -0.56 -0.32 +0.36 | 0.173 ±0.036 effective | $\delta_{\text{par}}$ near $\pi$ | $\delta_s$ near $\pi$ | 3.15 ±0.19 | $\delta_{\text{perp}}$ = -0.20 -0.27+0.26 | ~5300 |
| CDF (10 fb$^{-1}$, unpublished) | 0.654 ±0.008 ±0.004 | 0.068 ±0.026 ±0.007 | 0.512 ±0.012 ±0.017 | 0.229 ±0.010 ±0.014 | =SM Fit:-0.2 ±0.36 | $\varphi_s$ =SM small | Appar. small | 2.79 ±0.53 ±0.15 | $\delta_s$ near $\pi$ | $\delta_{\text{perp}}$ = -0.33 ±0.13 | 11000 |
| LHCb (1 fb$^{-1}$, unpublished) | 0.6580 ±0.0054 ±0.0066 | 0.116 ±0.018 ±0.006 | 0.523 ±0.007 ±0.024 | 0.231 ±0.021 [*] | -0.001 ±0.101 ±0.027 | 0.022 ±0.012 ±0.007 | 2.90 ±0.36 ±0.07 | $\delta_s$ near $\pi$ | 2.90 ±0.33 ±0.08 | 21000 |
| ATLAS (4.9 fb$^{-1}$, preliminary) | 0.677 ±0.007 ±0.004 | 0.053 ±0.021 ±0.008 | 0.528 ±0.006 ±0.009 | 0.220 ±0.008 ±0.007 | 0.22 ±0.41 ±0.10 | 0.02 ±0.02 ±0.02 | Assum. 2.95 ±.39 | near $\pi$ | $\delta_s$ near $\pi$ | 23000 |

[*] from $|A_0|^2$ and $|A_{\text{par}}|^2$, summing stat. and syst. errors in quadrature and using quoted (negative) correlation coefficient.

See references listed on slide n. 16 for details concerning other experiments.