CP violation in the $B_s \rightarrow \phi\phi$ decay at LHCb

Sean Benson on behalf of the LHCb collaboration

IOP, 8-10 April 2013
Outline

LHCb detector

Phenomenology and New Physics

$B_s \rightarrow \phi\phi$ analysis ingredients

Results New for 2013

LHCb Detector

- LHCb is a forward arm spectrometer (pseudo-rapidity range: $2 < \eta < 5$),
- Accurate decay time resolution through vertex locator (VELO),
- Accurate particle ID provided by RICH detectors.
Why $B_s$ Physics?

Mixing

There could be new physics contributions, that would manifest as new contributions in $B_s$ mixing diagrams (arXiv:1008.1593)

Large effects are ruled out through existing measurements of $B_s \rightarrow J/\psi \phi$

Decay


Loop suppressed $\rightarrow$ need large datasets to measure

Now becoming accessible.
Why $B_s \rightarrow \phi \phi$?

$B_s \rightarrow \phi \phi$ is an example of a flavour changing neutral current interaction (FCNC) $b \rightarrow s s s \Rightarrow$ can only occur through penguin diagrams and higher orders.

Measure $\phi_s$, defined as the CP violation interference between mixing and decay:

I.e. $\phi_s = \phi_M - 2\phi_D$

$\Rightarrow B_s \rightarrow \phi \phi$ is sensitive to new physics in mixing and decay as both $B_s$ and $\bar{B_s}$ can decay to $\phi \phi$.

In $B_s \rightarrow \phi \phi$, resulting from a $b \rightarrow s \bar{s} s$ transition, the SM prediction is $0.00 \pm 0.02$ rad.
Analysis Details

$B_s \rightarrow \phi \phi$ is a $P \rightarrow VV$ decay => Final state a mixture of CP-even and CP-odd eigenstates \( \rightarrow \) need angular analysis to disentangle them.

To obtain greatest sensitivity to CP violation, need to be able to resolve $B_s$ oscillations \( \Rightarrow \) requires observation of the $B_s$ decay time.

Therefore analysis requires good understanding of efficiencies as a function of decay time and angular observables:

• Selections such as impact parameter give lower efficiency at short decay times.
• Shape of LHCb detector means high values of $|\cos \theta_i|$ are less efficient.

These are taken from simulation.
### Analysis Details

- PDF has 15 terms (6 P-wave and 9 S-wave).
- \( F(t,\cos\theta_1,\cos\theta_2,\Phi) = \sum_i K_i(t)f_i(\cos\theta_1,\cos\theta_2,\Phi) \), where:

<table>
<thead>
<tr>
<th>( i )</th>
<th>( K_i )</th>
<th>( f_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(</td>
<td>A_0(t)</td>
</tr>
<tr>
<td>2</td>
<td>(</td>
<td>A_{|}(t)</td>
</tr>
<tr>
<td>3</td>
<td>(</td>
<td>A_{\perp}(t)</td>
</tr>
<tr>
<td>4</td>
<td>(\text{Im}(A_{|}^*(t)A_{\perp}(t)))</td>
<td>(-2\sin^2\theta_1\sin^2\theta_2\sin 2\Phi)</td>
</tr>
<tr>
<td>5</td>
<td>(\text{Re}(A_{|}^*(t)A_0(t)))</td>
<td>(\sqrt{2}\sin 2\theta_1\sin 2\theta_2\cos \Phi)</td>
</tr>
<tr>
<td>6</td>
<td>(\text{Im}(A_0^*(t)A_{\perp}(t)))</td>
<td>(-\sqrt{2}\sin 2\theta_1\sin 2\theta_2\sin \Phi)</td>
</tr>
<tr>
<td>7</td>
<td>(</td>
<td>A_{SS}(t)</td>
</tr>
<tr>
<td>8</td>
<td>(</td>
<td>A_S(t)</td>
</tr>
<tr>
<td>9</td>
<td>(\text{Re}(A_S^*(t)A_{SS}(t)))</td>
<td>(\frac{8}{3}\cos\theta_1\cos\theta_2)</td>
</tr>
<tr>
<td>10</td>
<td>(\text{Re}(A_0(t)A_{SS}^*(t)))</td>
<td>(\frac{4\sqrt{2}}{3}\sin\theta_1\sin\theta_2\cos \Phi)</td>
</tr>
<tr>
<td>11</td>
<td>(\text{Re}(A_{|}(t)A_{SS}^*(t)))</td>
<td>(-\frac{4\sqrt{2}}{3}\sin\theta_1\sin\theta_2\sin \Phi)</td>
</tr>
<tr>
<td>12</td>
<td>(\text{Im}(A_{\perp}(t)A_{SS}^*(t)))</td>
<td>(\frac{8}{\sqrt{3}}\cos\theta_1\cos\theta_2(\cos\theta_1 + \cos\theta_2))</td>
</tr>
<tr>
<td>13</td>
<td>(\text{Re}(A_0(t)A_S^*(t)))</td>
<td>(\frac{4\sqrt{2}}{\sqrt{3}}\sin\theta_1\sin\theta_2(\cos\theta_1 + \cos\theta_2)\cos \Phi)</td>
</tr>
<tr>
<td>14</td>
<td>(\text{Re}(A_{|}(t)A_S^*(t)))</td>
<td>(-\frac{4\sqrt{2}}{\sqrt{3}}\sin\theta_1\sin\theta_2(\cos\theta_1 + \cos\theta_2)\sin \Phi)</td>
</tr>
<tr>
<td>15</td>
<td>(\text{Im}(A_{\perp}(t)A_S^*(t)))</td>
<td>(-\frac{4\sqrt{2}}{\sqrt{3}}\sin\theta_1\sin\theta_2(\cos\theta_1 + \cos\theta_2)\sin \Phi)</td>
</tr>
</tbody>
</table>

With this, can fit for:
- Polarisation fractions \( A_i \), CP-conserving strong phases, \( \delta_i \), and CP-violating phase, \( \phi_s \)
Analysis Ingredients

Example time dependent term:

\[ \Im (A_\parallel(t) A_\perp(t)) = |A_\parallel| |A_\perp| \{ (1 - 2\omega) e^{-\Gamma_s t} [\sin \delta_1 \cos (\Delta m_s t) - \cos \delta_1 \sin (\Delta m_s t) \cos \phi_s ] - \frac{1}{2} \cos \delta_1 (e^{-\Gamma_H t} - e^{-\Gamma_L t}) \sin \phi_s \} \]

**B_s oscillation frequency**

**B_s decay rates**

**Flavour-tagging**

B_s decay rates (\( \Gamma_s = [\Gamma_H + \Gamma_L] / 2 \) & \( \Delta \Gamma_s = \Gamma_L - \Gamma_H \)): Gaussian constraints to the values measured in the B_s->J/\psi\phi decay (LHCb-PAPER-2013-002).

Time resolution: Convolve our PDF with Gaussian function of width 40fs, where the width is found from simulation.

B_s oscillation frequency: Gaussian constraint to LHCb value (LHCb-CONF-2011-050)

Flavour-tagging: Opposite side and same-side algorithms used (explained soon).
Analysis Ingredients: Flavour-tagging

Event-by-event incorrect tag probability calibrated mainly from $B^+\rightarrow J/\psi K^+$ (OS) and $B_s\rightarrow D_s\pi$ (SSK) => calibration parameters constrained in fitting.

Total tagging power = $\varepsilon(1-2\omega)^2 = (3.20\pm0.48)\%$
Results: Dataset

880 events observed in $K^+K^-K^+K^-$ final state using 1.0 fb$^{-1}$ LHCb data.

Events triggered mainly by looking for good quality tracks consistent with $\phi$ mass and exploiting general kinematics of B decays. Multivariate offline selections use kinematic variables and track quality to separate signal from background.

Low contamination from reflections from $B^0\rightarrow\phi K^*$ due to small width of the $\phi$ resonance.
Results: Projections on to Observables

- Shown below are data and corresponding fit projected on to each of the phase space observables.
- Can separate fit by CP eigenstate.

Time biasing selections cause low efficiency at short lifetimes

Projections background subtracted and include acceptances

Total CP-even CP-odd S-wave
Results: S-wave Crosscheck

Although measured in angular and time dependent fit, also possible to measure S-wave using \( m_{KK} \) lineshapes (relativistic Breit-Wigner shape for P-wave, Flatté for S-wave).

\[ \Rightarrow \text{Do a 2D fit to } m_{KK} \text{ vs. } m_{KK} \text{ as a sanity check (ignores interferences)} \]

\[
\begin{align*}
\phi & \phi \\
\frac{f_0 \phi}{f_0} & \phi \\
\Rightarrow \text{Find total S-wave fraction of } (2.12\pm1.17)\% \\
\end{align*}
\]
Results: $\phi_s$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>$\sigma_{\text{stat.}}$</th>
<th>$\sigma_{\text{syst.}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_s$ 68 % C.L: [rad]</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>

The dominant systematic uncertainties arise from time acceptance and S-wave

Statistical likelihood for $\phi_s$ shows non-parabolic behaviour $\Rightarrow$ only a 68% C.L. is quoted.

Small dataset $\Rightarrow$ Feldman Cousins analysis is used to provide a coverage corrected 68% C.L. including systematic uncertainties of $\phi_s$ in the interval [-2.46,-0.76] rad

The p-value of the Standard Model hypothesis is 16%.
Summary

- A first time-dependent tagged analysis of CP violation in the interference between mixing and decay for the $B_s\rightarrow\phi\phi$ decay yields a 68% C.L of:
  
  $[-2.46,-0.76]$ rad

- The p-value of the Standard Model hypothesis is 16%.

- Still 2$fb^{-1}$ of 2012 LHCb data yet to analyse => eager to see what awaits with the full combined 2011+2012 dataset.