Time Integrated Analysis of $B^0_s \rightarrow \phi\phi$
at LHCb

Dean Lambert
on behalf of the LHCb Collaboration

Rencontres de Moriond 2012
Contents

- Angular Analysis
- Triple Product Asymmetries
Motivation

- The decay $B_s^0 \rightarrow \phi\phi$ proceeds via a Flavour Changing Neutral Current (FCNC) process.
- FCNCs or B flavour mixing allow possible new physics contributions in loop diagrams.
- $CP$ violating phase $\Phi_{\phi\phi}$ accessible, larger dataset needed.
- Using smaller dataset can measure $T$-violating “triple products”, which do not rely on flavour tagging/time.
Analysis presented uses entire dataset collected by LHCb during 2011, 1.0fb$^{-1}$.
Reconstruct as $B_{s}^{0} \rightarrow \phi(\rightarrow K^{+}K^{-})\phi(\rightarrow K^{+}K^{-})$.

Figure: $B_{s}^{0}$ mass distribution after full offline selection. Fits to a double Gaussian signal(red) and exponential background(blue dotted) are superimposed.

801 $\pm$ 29 events observed.
LHCb-Paper-2012-04
In the Standard Model, the flavour-changing neutral current (FCNC) decay $B^0_s \to \pi^0$ proceeds via a $\bar{c}b \to \bar{s}s\bar{s}$ penguin process. Studies in this mode provide powerful tests for the presence of contributions from new physics processes beyond the Standard Model [1].

The $B^0_s \to \pi^0$ decay is a pseudoscalar to vector-vector transition. As a result, there are three possible spin configurations allowed by angular momentum conservation. These manifest themselves as three helicity states, with amplitudes denoted $H^{+1}$, $H^0$, and $H^{-1}$.

It is convenient to define linear polarization amplitudes, which are related to the helicity amplitudes through the following transformations:

$$A_0 = H^0$$
$$A_\perp = H^{+1} - H^{-1}$$
$$A_\parallel = H^{+1} + H^{-1}.$$ 

The final states are a mixture of $CP$-even and $CP$-odd eigenstates. These are described by the $CP$-even longitudinal ($A_0$) and parallel ($A_\parallel$) components together with the $CP$-odd perpendicular component ($A_\perp$). Due to the V-A nature of the weak interaction, the longitudinal component is expected to be dominant [2–4]. However, roughly equal longitudinal and transverse components are found in measurements of $B^+\to\pi^0\pi^0$ and $B^0\to\pi^0\pi^0$ decays [5–7] at the B-factories. Several explanations, such as large contributions from penguin annihilation effects [8] or final state interactions [9], have been proposed to explain this discrepancy. More recent theoretical predictions, where phenomenological parameters are adjusted to account for the data, give a longitudinal fraction $f_L = |A_0|^2$ in the range 40–70% [2, 3].

\[
\begin{align*}
\theta_1 & \quad \phi \\
\theta_2 & \quad \phi
\end{align*}
\]

Figure 1: Decay angles defined in the helicity frame for the $B^0_s \to \pi^0\pi^0$ mode.

- P→VV decay, spin 0 B meson decays to two particles of spin 1.
- Therefore there are 3 possible spin configurations allowed by conservation of orbital angular momentum.
- These correspond to 3 linear polarisation amplitudes, $|A_0|$, $|A_\perp|$, $|A_\parallel|$. 

\[
\begin{align*}
K^+ & \quad \phi \\
K^- & \quad \phi \\
K^+ & \quad \phi \\
K^- & \quad \phi
\end{align*}
\]
“Polarisation Puzzle”

- Due to V-A nature of the weak interaction, $f_L \gg f_T$.
- Experimentally confirmed by the B-factories in tree dominated processes e.g. $B^0_d \rightarrow \rho^+ \rho^-$.
- However in decays such as $B^0_d \rightarrow \phi K^*(892)$ it was found $f_L \approx f_T$.
- This is sometimes known as the “polarisation puzzle.”

\[
    f_L = \frac{|A_0|^2}{|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2}, \quad f_T = \frac{|A_\perp|^2 + |A_\parallel|^2}{|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2}.
\]
Angular Analysis Results

Figure: Angular distributions (points) and fit projections for signal (red) and background (blue).

The polarisation amplitudes and strong phase are measured, using the constraint $|A_\parallel|^2 = 1 - |A_0|^2 - |A_\perp|^2$.

\[
|A_0|^2 = 0.365 \pm 0.022 \text{ (stat)} \pm 0.012 \text{ (syst)}
\]

\[
|A_\perp|^2 = 0.291 \pm 0.024 \text{ (stat)} \pm 0.010 \text{ (syst)}
\]

\[
|A_\parallel|^2 = 0.344 \pm 0.024 \text{ (stat)} \pm 0.014 \text{ (syst)}
\]

\[
\cos(\delta_\parallel - \delta_0) = -0.844 \pm 0.068 \text{ (stat)} \pm 0.029 \text{ (syst)}
\]
Angular Analysis Comparison

$L = \frac{1 - f}{2}$

- LHCb
  - CDFII CL=68.3%, PRL 107 (2011)
- Beneke et al., NPB 774 (2007)
- Datta et al., EPJC 60 (2009)
- Cheng et al., PRD 80 (2009)

Scalar triple products of three momentum (e.g. \( \sin \psi = \vec{p}_1 \cdot \vec{p}_2 \times \vec{p}_3 \)) or spin vectors are odd under time reversal.

**Non-zero** triple product asymmetries can either be due to a \( T \)-violating phase or a \( T \)-conserving phase and final-state interactions.

The former case implies, assuming \( CPT \) conservation, that \( CP \) is violated.

We define our triple products as:

\[
U = \sin (2\Phi) \\
V = \sin (\pm \Phi) \\
A_u \equiv \frac{\Gamma(U > 0) - \Gamma(U < 0)}{\Gamma(U > 0) + \Gamma(U < 0)} \\
A_v \equiv \frac{\Gamma(V > 0) - \Gamma(V < 0)}{\Gamma(V > 0) + \Gamma(V < 0)}.
\]

Where positive sign in \( \sin (\pm \Phi) \) is taken if \( \cos \theta_1 \cos \theta_2 \geq 0 \).

[2] M. Gronau, J. Rosner. "TRIPLE PRODUCT ASYMMETRIES IN K,D(s) AND B(s) DECAYS."
The triple product asymmetries in this mode are measured to be:

\[ A_U = -0.055 \pm 0.036 \text{ (stat)} \pm 0.018 \text{ (syst)} \]

\[ A_V = 0.010 \pm 0.036 \text{ (stat)} \pm 0.018 \text{ (syst)} \]
Systematic Uncertainties

Systematics uncertainties are considered from several sources.

Angular Analysis:

| Source             | $|A_0|^2$ | $|A_{\perp}|^2$ | $|A_{\parallel}|^2$ | $\cos \delta_{\parallel}$ |
|--------------------|---------|---------------|-------------------|---------------------------|
| S-wave             | 0.007   | 0.005         | 0.012             | 0.001                     |
| Time acceptance    | 0.006   | 0.006         | 0.002             | 0.007                     |
| Angular acceptance | 0.007   | 0.006         | 0.006             | 0.028                     |
| Trigger category   | 0.003   | 0.002         | 0.001             | 0.004                     |
| Background model   | 0.001   | -             | 0.001             | 0.003                     |
| Total              | 0.012   | 0.010         | 0.014             | 0.029                     |

Triple Product Analysis:

<table>
<thead>
<tr>
<th>Source</th>
<th>$A_U$</th>
<th>$A_V$</th>
<th>Chosen uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular acceptance</td>
<td>0.009</td>
<td>0.006</td>
<td>0.009</td>
</tr>
<tr>
<td>Time acceptance</td>
<td>0.006</td>
<td>0.014</td>
<td>0.014</td>
</tr>
<tr>
<td>Fit model</td>
<td>0.004</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>Total</td>
<td>0.018</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Polarisation amplitudes, triple products and a strong phase have been measured, using a time integrated method, in $B_s^0 \rightarrow \phi \phi$.

These are currently the most precise measurements of these parameters for this decay.

Results are consistent with earlier measurements by LHCb[3] and CDF[4].

Triple product asymmetries are consistent with no $T$-violation, hence no $CP$-violation from $CPT$.

Paper soon to be submitted to Phys. Lett. B.

[3] Study of Triple Product Asymmetries in $B_s \rightarrow \phi \phi$ decays. LHCb-CONF-2011-052.

[4] Measurement of Polarization and Search for CP-Violation in $B_s^0 \rightarrow \phi \phi$ Decays. FERMILAB-PUB-11-345-E
END.
The angular functions in the helicity basis are given

\[
\begin{align*}
    f_1(\theta_1, \theta_2, \Phi) &= 4 \cos^2 \theta_1 \cos^2 \theta_2 \\
    f_2(\theta_1, \theta_2, \Phi) &= \sin^2 \theta_1 \sin^2 \theta_2 (1 + \cos 2\Phi) \\
    f_3(\theta_1, \theta_2, \Phi) &= \sin^2 \theta_1 \sin^2 \theta_2 (1 - \cos 2\Phi) \\
    f_4(\theta_1, \theta_2, \Phi) &= -2 \sin^2 \theta_1 \sin^2 \theta_2 \sin 2\Phi \\
    f_5(\theta_1, \theta_2, \Phi) &= \sqrt{2} \sin 2\theta_1 \sin 2\theta_2 \cos \Phi \\
    f_6(\theta_1, \theta_2, \Phi) &= -\sqrt{2} \sin 2\theta_1 \sin 2\theta_2 \sin \Phi.
\end{align*}
\]
The time dependent functions are

\[ K_1(t) = \frac{1}{2} A_0^2 [(1 + \cos \phi_s) e^{-\Gamma_L t} + (1 - \cos \phi_s) e^{-\Gamma_H t} \pm 2 e^{-\Gamma_s t} \sin(\Delta m_s t) \sin \phi_s] \]

\[ K_2(t) = \frac{1}{2} A_0^2 [(1 + \cos \phi_s) e^{-\Gamma_L t} + (1 - \cos \phi_s) e^{-\Gamma_H t} \pm 2 e^{-\Gamma_s t} \sin(\Delta m_s t) \sin \phi_s] \]

\[ K_3(t) = \frac{1}{2} A_0^2 [(1 - \cos \phi_s) e^{-\Gamma_L t} + (1 + \cos \phi_s) e^{-\Gamma_H t} \mp 2 e^{-\Gamma_s t} \sin(\Delta m_s t) \sin \phi_s] \]

\[ K_4(t) = |A_\parallel| |A_\perp| [\pm e^{-\Gamma_s t} \{ \sin \delta_1 \cos(\Delta m_s t) - \cos \delta_1 \sin(\Delta m_s t) \cos \phi_s \} ] - \frac{1}{2} (e^{-\Gamma_H t} - e^{-\Gamma_L t}) \cos \delta_1 \sin \phi_s \]

\[ K_5(t) = \frac{1}{2} |A_0| |A_\parallel| \cos(\delta_2 - \delta_1) \]

\[ \left[(1 + \cos \phi_s) e^{-\Gamma_L t} + (1 - \cos \phi_s) e^{-\Gamma_H t} \pm 2 e^{-\Gamma_s t} \sin(\Delta m_s t) \sin \phi_s\right] \]

\[ K_6(t) = |A_0| |A_\perp| [\pm e^{-\Gamma_s t} \{ \sin \delta_2 \cos(\Delta m_s t) - \cos \delta_2 \sin(\Delta m_s t) \cos \phi_s \} ] - \frac{1}{2} (e^{-\Gamma_H t} - e^{-\Gamma_L t}) \cos \delta_2 \sin \phi_s \]
Angular Analysis

In order to disentangle different $CP$ states an angular analysis is needed. The time dependent differential cross section is given

$$\frac{d^4\Gamma}{d\cos\theta_1 d\cos\theta_2 d\Phi dt} \propto \sum_{n=1}^{6} K_n(t)f_n(\theta_1, \theta_2, \Phi),$$

where $K_n$ are parts describing time evolution and $f_n$ are angular distributions.

Integrating over all time, assuming $\phi_s = 0$ and equal numbers of $B_s$ and $\bar{B}_s$ at production.

$$\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\Phi} \propto |A_0|^2 f_1 + |A_\parallel|^2 f_2 + |A_\perp|^2 f_3 + |A_0||A_\parallel|f_5 \cos(\delta_\parallel).$$
Triple Product Asymmetries

- TPA given \( A_{TP}^{||,0} \propto \frac{\Im(A_{\perp}A^{*,0})}{\Sigma|A_{\lambda}|^2} \).
- Without carrying out an angular fit we can calculate TP from U and V distributions.

\[
\begin{align*}
U &= \sin (2\Phi) \\
V &= \sin (\pm \Phi) \\
A_u &\equiv \frac{\Gamma(\sin 2\Phi > 0) - \Gamma(\sin 2\Phi < 0)}{\Gamma(\sin 2\Phi > 0) + \Gamma(\sin 2\Phi < 0)} \\
A_v &\equiv \frac{\Gamma(\sin(\pm \Phi) > 0) - \Gamma(\sin(\pm \Phi) < 0)}{\Gamma(\sin(\pm \Phi) > 0) + \Gamma(\sin(\pm \Phi) < 0)}.
\end{align*}
\]

Where positive sign in \( \sin (\pm \Phi) \) is taken if \( \cos \theta_1 \cos \theta_2 \geq 0 \).
Figure: $\phi$ mass distribution for the $B_s^0 \to \phi\phi$ data without a $\phi$ mass cut applied. The background has been removed using the sPlot technique. There are two entries per $B_s^0$ candidate. The red curve shows a relativistic Relativistic Breit-Wigner. The S-wave component is shown by the dotted line.
<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track $\chi^2$/ndf</td>
<td>$&lt; 5$</td>
</tr>
<tr>
<td>Track $p_T$</td>
<td>$&gt; 500$ MeV/c</td>
</tr>
<tr>
<td>Track IP $\chi^2$</td>
<td>$&gt; 21$</td>
</tr>
<tr>
<td>$\Delta \ln \mathcal{L}_{K\pi}$</td>
<td>$&gt; 0$</td>
</tr>
<tr>
<td>$</td>
<td>M_\phi - M_{\phi}^{PDG}</td>
</tr>
<tr>
<td>$p_T^{\phi_1}, p_T^{\phi_2}$</td>
<td>$&gt; 900$ MeV/c</td>
</tr>
<tr>
<td>$p_T^{\phi_1} \times p_T^{\phi_2}$</td>
<td>$&gt; 2$ GeV$/c^2$</td>
</tr>
<tr>
<td>$\phi$ vertex $\chi^2$/ndf</td>
<td>$&lt; 24$</td>
</tr>
<tr>
<td>$B_s^0$ vertex $\chi^2$/ndf</td>
<td>$&lt; 7.5$</td>
</tr>
<tr>
<td>$B_s^0$ FD $\chi^2$</td>
<td>$&gt; 270$</td>
</tr>
<tr>
<td>$B_s^0$ IP $\chi^2$</td>
<td>$&lt; 15$</td>
</tr>
</tbody>
</table>

Selection criteria for $B_s^0 \rightarrow \phi\phi$. The abbreviations IP and FD stand for Impact Parameter and Flight Distance respectively. $p_T^{\phi_1}$ and $p_T^{\phi_2}$ refer to the transverse momentum of the two $\phi$ candidates.