Measurement of CP Violation in the $B_s$ System

Kristof De Bruyn
On behalf of the LHCb Collaboration

BEACH 2014
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The LHCb Detector

- Good impact parameter resolution to identify secondary vertices: $20 \, \mu m$
- Decay time resolution: $40 \, fs$ ($B^0_s \rightarrow J/\psi\pi^+\pi^-$)
- Invariant mass resolution: $8 \, MeV/c^2$ ($B \rightarrow J/\psi X$) and $22 \, MeV/c^2$ ($B \rightarrow hh$)
- Excellent particle identification: 95% $K$ ID efficiency (5% $\pi \rightarrow K$ mis-ID)
- Versatile & efficient trigger for $b$- and $c$-hadrons and forward EW signals

Forward arm spectrometer to study $b$- and $c$-hadron decays
- Pseudo-rapidity coverage: $2 < \eta < 5$
Measuring CP Violation: Interfering Paths

Mixing-Induced CP Violation:

- Interference between direct decay and decay after mixing
- Key Measurements: $\phi_s$ from $B_s^0 \rightarrow J/\psi h^+ h^-$; $\gamma$ from $B_s^0 \rightarrow D_s^\mp K^\pm$

New Results on CP Violation in the $B_s$ System:

- ✓ Measurement of the CP violating phase in $B_s^0 \rightarrow \phi\phi$ (3 fb$^{-1}$ – Full Run 1)
- ✓ Update on measurement of $\phi_s$ from $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ (3 fb$^{-1}$ – Full Run 1)
- × Update on the measurement of $\gamma$ from $B_s^0 \rightarrow D_s^\mp K^\pm$ (1 fb$^{-1}$ – 2011 Only)

→ [See Talk by Alexis Vallier]
Measurement of the CP violating phase in $B_s^0 \rightarrow \phi \phi$
Introduction to $B_s^0 \to \phi\phi$

**Excellent probe to Search for New Physics**

- Originates from $\bar{b} \to \bar{s}s\bar{s}$ transition
- Forbidden at tree level
- Standard Model: Dominant contribution from gluonic penguins
  - Objective: Mixing-induced CP violation
  - Parametrised by

$$\lambda \equiv \frac{q}{p} \frac{A(B_s^0 \to \phi\phi)}{A(B_s^0 \to \phi\phi)} = |\lambda| e^{i\varphi_s}$$

*[Note: $\varphi_s \neq \phi_s(B_s^0 \to J/\psi h^+h^-)]$

- SM prediction:

$$\varphi_s \approx \left( S_{\phi\phi} \equiv \frac{2 \text{Im}[\lambda]}{1 + |\lambda|^2} \right) \leq 0.02$$

*[M. Bartsch et al., arxiv:0810.0249]*
$B_s^0 \rightarrow \phi \phi$ at LHCb: Selection

**Selection:**

- Reconstructed as $B_s^0 \rightarrow \phi \phi \rightarrow K^+ K^- K^+ K^-$
- Trigger: Topological $b$-decay $||$ large $p_T$ $K$’s from $\phi$
- Selection based on Boosted Decision Tree trained on Simulation (Signal) and Data (Background)
- Different trainings for 2011 and 2012 data
- Event Yield: $1185 \pm 35$ (2011) & $2765 \pm 57$ (2012)

**Four Kaon Invariant Mass:**

- $B_s^0 \rightarrow \phi \phi$ Signal
- $B^0 \rightarrow \phi K^{*0}$ Peaking Background (From Simulation)
- $\Lambda_b^0 \rightarrow \phi p K^-$ Peaking Background (From Data)
- Combinatoric Background
$B_s^0 \rightarrow \phi\phi$ at LHCb: Angular Analysis

Angular Decomposition:

- $B_s^0 \rightarrow \phi\phi$ is a Vector-Vector final state
  ⇒ Three components $A_0$, $A_\parallel$ & $A_\perp$

- Non-resonant $K^+ K^- K^+ K^-$ final states:
  S-wave $A_S$ and double S-wave $A_{SS}$

- Total decay amplitude: 15 contributions
**Time Resolution**
- Using per-event resolution model
- Effective resolution:
  - 41.4 fs (2011) and 43.9 fs (2012)
- Difference due to independent selection

**Flavour Tagging**
- Including Opposite Side (OS) and Same Side Kaon (SSK) tagging

### Dataset

<table>
<thead>
<tr>
<th>Dataset</th>
<th>$\epsilon D^2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011 Total</td>
<td>5.33 ± 0.37</td>
</tr>
<tr>
<td>2012 Total</td>
<td>5.44 ± 0.30</td>
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</table>

**Time Acceptance**
- Determined from topologically similar $B_s^0 \rightarrow D_s^- (\rightarrow K^+ K^- \pi^-) \pi^+$ decays

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Measurement of CP Violation in the $B_s$ System  
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CP Violating Phase

\[
\varphi_s = -0.17 \pm 0.15 \text{ (stat)} \pm 0.03 \text{ (syst)} \text{ rad}
\]

\[
|\lambda| = 1.04 \pm 0.07 \text{ (stat)} \pm 0.03 \text{ (syst)}
\]

- Compatible with SM prediction
- No indication for direct CP violation

Angular Analysis

\[
|A_0|^2 = 0.364 \pm 0.012 \text{ (stat)} \pm 0.009 \text{ (syst)}
\]

\[
|A_\perp|^2 = 0.305 \pm 0.013 \text{ (stat)} \pm 0.005 \text{ (syst)}
\]

\[
\delta_1 \equiv \delta_\perp - \delta_0 = 0.13 \pm 0.23 \text{ (stat)} \pm 0.05 \text{ (syst) rad}
\]

\[
\delta_2 \equiv \delta_\perp - \delta_0 = 2.67 \pm 0.23 \text{ (stat)} \pm 0.07 \text{ (syst) rad}
\]
Triple Product Asymmetries: Alternative Tests of CP violation

- Quantity odd under Time reversal
- Time integrated quantity \( \Rightarrow \) Reduce problem to counting experiment
- SM expectation: \( A_{U,V} \approx 0 \)

Definition:

\[
A_U \equiv \frac{\Gamma(U > 0) - \Gamma(U < 0)}{\Gamma(U > 0) + \Gamma(U < 0)} = -0.003 \pm 0.017 \text{ (stat)} \pm 0.006 \text{ (syst)}
\]

\[
A_V \equiv \frac{\Gamma(V > 0) - \Gamma(V < 0)}{\Gamma(V > 0) + \Gamma(V < 0)} = -0.017 \pm 0.017 \text{ (stat)} \pm 0.006 \text{ (syst)}
\]

where

\[
U \equiv \sin(\Phi) \cos(\Phi), \quad V \equiv \sin(\pm\Phi)
\]
Update on measurement of $\phi_s$ from $B^0_s \rightarrow J/\psi\pi^+\pi^-$
Introduction to $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$

$B_s^0 - \bar{B_s}^0$ mixing $\phi_s$

- One of the CKM angles ⇒ Important test of the Standard Model

$$\phi_s^{\text{SM}} = -0.0364 \pm 0.0016 \text{ rad}$$

- Small magnitude offers excellent probe to search for New Physics

$$\phi_s = \phi_s^{\text{SM}} + \phi_s^{\text{NP}}$$

- Experimentally accessible through CPV in $B_s^0 \rightarrow J/\psi \phi$ and $B_s^0 \rightarrow J/\psi f_0(980)$
- Extended scope: $B_s^0 \rightarrow J/\psi K^+ K^-$ and $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$

Current Status:

- LHCb 1 fb$^{-1}$ result: [arxiv:1304.2600]

$$\phi_s = 0.01 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (syst) rad}$$

$$\Gamma_s = 0.661 \pm 0.004 \text{ (stat)} \pm 0.006 \text{ (syst) ps}^{-1}$$

$$\Delta \Gamma_s = 0.106 \pm 0.011 \text{ (stat)} \pm 0.007 \text{ (syst) ps}^{-1}$$

- World Average: [HFAG – PDG 2014]

$$\phi_s = 0.00 \pm 0.07$$
$B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ at LHCb: Selection

**Selection:**

- Reconstructed as $B_s^0 \rightarrow J/\psi \pi^+ \pi^- \rightarrow \mu^+ \mu^- \pi^+ \pi^-$
- Trigger: Muons from $J/\psi \rightarrow \mu^+ \mu^-$
- Selection based on Boosted Decision Tree trained on Simulation (Signal) and Data (Background)
- Event Yield: 27 100 ± 200 Signal candidates
- Signal purity in ±20 MeV mass window around $B_s^0$ peak: 79.6%

**Invariant Mass:**

- $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ Signal
- $B_d^0 \rightarrow J/\psi \pi^+ \pi^-$ Signal
- $B^- \rightarrow J/\psi K^-$ (From Simulation)
- $B_d^0 \rightarrow J/\psi K^\mp \pi^\pm$ Reflection (From Simulation)
- Other misreconstructed decays (From Simulation)
- Combinatoric Background (From Like-Sign)
CP Content and Decomposition of $J/\psi\pi^+\pi^-$ Final State:

- Focus on ±20 MeV mass window around $B^0_s$ peak
- Included Modes: $f_0(980)$ (Dominant), $f_0(1500)$, $f_0(1790)$, $f_2(1270)$, $f_2'(1525)$
- CP-even contributions < 2.3% at 95% C.L.

Part I: Fitting of the Dalitz Plane
\( B_s^0 \rightarrow J/\psi \pi^+ \pi^- \) at LHCb: Angular Analysis

**Part II: Angular Decomposition:**

- Disentangle CP-even and CP-odd contributions

---

**Signal**

**Background**

**Total**
**Time Resolution**

- Using per-event resolution model
- Effective resolution: 40.3 fs

**Flavour Tagging**

- Including Opposite Side (OS) and Same Side Kaon (SSK) tagging
- Tagging power \( \epsilon_{\text{tag}} D^2 = (3.89 \pm 0.25)\% \)

**Time Acceptance**

- Determined from \( B^0_d \rightarrow J/\psi K^{*0} (\rightarrow K^+ \pi^-) \) decays
- Difference with \( B^0_s \rightarrow J/\psi \pi^+ \pi^- \) corrected using Simulation

*Figure showing decay time distribution and efficiency ratio for different decay modes.*

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\( \phi_s \) from \( B_s^0 \rightarrow J/\psi \pi^+ \pi^- \): Results

Fit Assumptions

- 1 fb\(^{-1}\) result from \( B_s^0 \rightarrow J/\psi K^+ K^- \) at LHCb

\[
\begin{align*}
\Gamma_s &= 0.663 \pm 0.005 \text{ (stat)} \pm 0.006 \text{ (syst)} \text{ ps}^{-1} \\
\Delta \Gamma_s &= 0.100 \pm 0.016 \text{ (stat)} \pm 0.003 \text{ (syst)} \text{ ps}^{-1}
\end{align*}
\]

Results

\[
\begin{align*}
\phi_s &= 0.070 \pm 0.068 \text{ (stat)} \pm 0.008 \text{ (syst)} \text{ rad} \\
|\lambda| &= 0.89 \pm 0.05 \text{ (stat)} \pm 0.01 \text{ (syst)}
\end{align*}
\]

- Compatible with the SM
Preliminary Update on $\Delta \Gamma_s - \phi_s$ from $B_s^0 \to J/\psi h^+ h^-$

$B_s^0 \to \phi \phi$

$B_s^0 \to J/\psi \pi^+ \pi^-$

LHCb $J/\psi$ KK 1 fb$^{-1}$, $J/\psi \pi \pi$ 3 fb$^{-1}$ + CDF 9.6 fb$^{-1}$ + D0 8 fb$^{-1}$ + ATLAS 4.9 fb$^{-1}$ + CMS 20 fb$^{-1}$

68% CL contours ($\Delta \log L = 1.15$)

DISCLAIMER: Not an official result

Kristof De Bruyn (Nikhef)
Conclusion

- LHCb has produced many first and world’s best CP asymmetry measurements, in many different $B$ decay modes.

- Discussed recent updates in $B_s^0 \rightarrow \phi\phi$ and $B_s^0 \rightarrow J/\psi\pi^+\pi^-$

\[
\phi_{s}^{\phi\phi} = -0.17 \pm 0.15 \text{ (stat)} \pm 0.03 \text{ (syst) rad}
\]
\[
\phi_{s}^{J/\psi\pi^+\pi^-} = 0.070 \pm 0.068 \text{ (stat)} \pm 0.008 \text{ (syst) rad}
\]

- Most of the LHCb results are limited by their statistical uncertainty.

Expect many more updates soon!
$B_s^0 \rightarrow \phi\phi$

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

Back-up
Performance of the LHCb Detector

Data Taking

LHCb Integrated Luminosity pp collisions 2010-2012

Data taking efficiency: 93.05%
Percentage of working detector channels: ≈ 99%

Efficiencies

- Trigger efficiency:
  - Dimuon channels: ≈ 90%
  - Multibody hadronic channels: ≈ 30%
- Track reconstruction efficiency: > 96%

Resolution

- Momentum resolution:
  \( \Delta p/p = 0.4\% \) at 5 GeV/c
  \( \Delta p/p = 0.6\% \) at 100 GeV/c
- ECAL resolution: 1% ± 10%
Flavour Tagging

<table>
<thead>
<tr>
<th>Dataset</th>
<th>$\epsilon_{\text{tag}}$ (%)</th>
<th>$D$ (%)</th>
<th>$\epsilon D^2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011 OS</td>
<td>12.3 ± 1.0</td>
<td>31.6 ± 0.2</td>
<td>1.23 ± 0.10</td>
</tr>
<tr>
<td>2012 OS</td>
<td>14.5 ± 0.7</td>
<td>32.7 ± 0.3</td>
<td>1.55 ± 0.08</td>
</tr>
<tr>
<td>2011 SSK</td>
<td>40.2 ± 1.4</td>
<td>15.2 ± 2.0</td>
<td>0.93 ± 0.25</td>
</tr>
<tr>
<td>2012 SSK</td>
<td>33.1 ± 0.9</td>
<td>16.0 ± 1.6</td>
<td>0.85 ± 0.17</td>
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<tr>
<td>2011 Both</td>
<td>26.0 ± 1.3</td>
<td>34.9 ± 1.1</td>
<td>3.17 ± 0.26</td>
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<tr>
<td>2012 Both</td>
<td>27.5 ± 0.9</td>
<td>33.2 ± 1.2</td>
<td>3.04 ± 0.24</td>
</tr>
<tr>
<td>2011 Total</td>
<td>5.33 ± 0.37</td>
<td></td>
<td></td>
</tr>
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<td></td>
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Further Details on $B_s^0 \rightarrow \phi\phi$

Systematic Uncertainties

| Parameter                   | $|A_0|^2$ | $|A_\perp|^2$ | $\delta_1$ (rad) | $\delta_2$ (rad) | $\varphi_s$ (rad) | $|\lambda|$ |
|-----------------------------|----------|---------------|------------------|------------------|-------------------|-----------|
| Mass model                  | –        | –             | 0.03             | 0.04             | –                 | 0.02      |
| AA (statistical)            | 0.003    | 0.004         | 0.02             | 0.02             | 0.02              | 0.02      |
| AA (tagging)                | 0.006    | 0.002         | –                | 0.01             | –                 | 0.01      |
| Fit bias                    | –        | –             | 0.02             | –                | –                 | –         |
| Time acceptance             | 0.005    | 0.003         | 0.02             | 0.05             | 0.02              | –         |
| Peaking background          | –        | –             | 0.01             | 0.01             | –                 | 0.01      |
| Total                       | 0.009    | 0.005         | 0.05             | 0.07             | 0.03              | 0.03      |

AA = Angular Acceptance

<table>
<thead>
<tr>
<th>Source</th>
<th>$A_U$</th>
<th>$A_V$</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular acceptance</td>
<td>0.001</td>
<td>0.003</td>
<td>0.003</td>
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<tr>
<td>Time acceptance</td>
<td>0.005</td>
<td>0.003</td>
<td>0.005</td>
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<tr>
<td>Mass model</td>
<td>0.002</td>
<td>0.002</td>
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<tr>
<td>Peaking background</td>
<td>–</td>
<td>0.001</td>
<td>0.001</td>
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<tr>
<td>Total</td>
<td>0.006</td>
<td>0.005</td>
<td>0.006</td>
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</table>
### Systematic Uncertainties

<table>
<thead>
<tr>
<th>Sources</th>
<th>$\phi_s$(mrad)</th>
<th>$\lambda$</th>
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</thead>
<tbody>
<tr>
<td>Decay time acceptance</td>
<td>±0.6</td>
<td>±0.0008</td>
</tr>
<tr>
<td>Mass acceptance</td>
<td>±0.3</td>
<td>±0.0003</td>
</tr>
<tr>
<td>Background time PDF</td>
<td>±0.2</td>
<td>±0.0011</td>
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<tr>
<td>Background mass distribution PDF</td>
<td>±0.6</td>
<td>±0.0016</td>
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<tr>
<td>Resonance model</td>
<td>±6.0</td>
<td>±0.0100</td>
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<tr>
<td>Resonance parameters</td>
<td>±0.7</td>
<td>±0.0007</td>
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<tr>
<td>Other fixed parameters</td>
<td>±0.4</td>
<td>±0.0009</td>
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<tr>
<td>Production asymmetry</td>
<td>±5.8</td>
<td>±0.0017</td>
</tr>
<tr>
<td>Total</td>
<td>±8.4</td>
<td>±0.010</td>
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