Measurement of $\phi_s$ at LHCb using $B_s^0 \rightarrow J/\psi \phi$ and $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$

Greig Cowan, on behalf of the LHCb collaboration

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**LHCb detector**

**VELO**  
Primary vertices  
Impact parameter

**RICHES**  
K, pi particle ID

**E/HCAL**  
Trigger, p, e, gamma PID

**MUONS**  
Trigger and PID

**TRACKER**  
P of charged particles

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**LHCb Preliminary**

- All triggers
- Muon + track
- Di-muon
- Topological
- Drell - Yan
- $\Psi, \psi J/\psi$

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**IP resolution vs $1/p_T$**

$\sqrt{s} = 7$ TeV  
2011 Data

$\sigma = 13.2 + 24.7/p_T \, \text{um}$

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**Efficiency vs $P_T$**

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LHCb-PUB-2012-017
**CP-violation in the $B_s^0$ system**

- Interference between $\bar{b} \to \bar{c}c\bar{s}$ either directly or via mixing gives rise to a CP-violating phase

\[
\phi_s^{SM} = -2\beta_s + \delta P = -0.036 \pm 0.002 \text{ rad} + \delta P
\]

- $\bar{b} \to \bar{c}c\bar{s}$ dominated by tree-level transitions, $\Phi_D = \text{arg}(V_{cs}V_{cb}^*)$.
  - Small penguin pollution, $\delta P \sim 10^{-3} - 10^{-4}$.

- Mixing phase $\Phi_M = 2 \text{arg}(V_{ts}V_{tb}^*) \approx -2\beta_s$.
  - New physics can modify: $\phi_s \to \phi_s^{SM} + \phi_s^{NP}$.
Measuring $\phi_s$ using $B_s \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$

- $P \rightarrow VV$: final state is admixture of CP-odd ($\ell = 1$) and CP-even ($\ell = 0, 2$) with different lifetimes.
- $3$ $K^+K^-$ P-wave, 1 S-wave

Unbinned log-likelihood fit to statistically disentangle final states.

\[
\text{CP}|J/\psi\rangle_{\ell} = \eta_f |J/\psi\rangle_{\ell} = (-1)^\ell |J/\psi\rangle_{\ell}
\]

Angular analysis $\Omega = (\theta, \varphi, \psi)$

\[
S(\lambda, m, t, \Omega) = G(m) \cdot \epsilon(t, \Omega) \cdot \left( \frac{1 + qD}{2} \cdot s(\lambda, t, \Omega) + \frac{1 - qD}{2} \cdot \bar{s}(\lambda, t, \Omega) \right) \otimes R_t
\]

- Acceptance, flavour tagging, time resolution.
- Physics: $\lambda = (\phi_s, \Gamma_s, \Delta \Gamma_s, \Delta m_s, \delta_{||}, \delta_{\perp}, \delta_S, |A_{||}|^2, |A_{\perp}|^2, |A_S|^2)$
$B^0_s \rightarrow J/\psi \phi$ analysis of 1 fb$^{-1}$

**Selection**

- Di-muon trigger: $p_T > 0.5$ GeV/c.
- Simple kinematic selection: $\sim 21200$ candidates

**Decay time resolution**

- Use prescaled sample of prompt-$J/\psi$ events to extract resolution scale factor.

\[ \langle \sigma_{\text{eff}} \rangle \approx 45 \text{ fs} \]

\[ \langle \sigma_m \rangle \approx 7 \text{ MeV} \]

Suppress background: $t > 0.3$ ps
Angular acceptance

- Angular acceptance of $\pm 5\%$ due to detector geometry ($10 < \Theta < 400\, \text{mrad}$) and implicit momentum cuts on final state particles.
- Evaluate using MC.
- Apply to fit via angular “moments” of the PDF or 3D analytic parameterisation of orthogonal polynomials.
Flavour tagging

- Sensitivity to $\phi_s$ comes from events tagged as $B_s^0$ or $\bar{B}_s^0$.
- Specialised tagging algorithms analyse event to determine initial flavour (talk from S. Vecchi).
- Effective OS tagging efficiency of $\varepsilon_{\text{tag}}D^2 = (2.29 \pm 0.27)\%$

**OS calibration:**

$$\omega = p_0 + p_1(\eta_c - \langle \eta_c \rangle)$$

![Graph showing $B^+ \rightarrow J/\psi K^+$ decay]

LHCb Preliminary

$\sqrt{s} = 7$ TeV Data
Projection of time dependent angular fit

Decay time $t$ [ps]

Events / 0.2 ps

Bkg

CP-even

CP-odd

S-wave (odd)

CP-even

S-wave

Bkg

CP-odd

S-wave (odd)
### Projection of time dependent angular fit

#### Preliminary

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<td>$\Gamma_s \ [\text{ps}^{-1}]$</td>
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<td>$</td>
<td>A_\perp(0)</td>
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<td>$\delta_\perp \ [\text{rad}]$</td>
<td>2.90</td>
<td>0.36</td>
<td>0.07</td>
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<tr>
<td>$\delta_\parallel \ [\text{rad}]$</td>
<td>[2.81, 3.47]</td>
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<tr>
<td>$\delta_s \ [\text{rad}]$</td>
<td>2.90</td>
<td>0.36</td>
<td>0.08</td>
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<tr>
<td>$\phi_s \ [\text{rad}]$</td>
<td>-0.001</td>
<td>0.101</td>
<td>0.027</td>
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</table>

#### Systematics

- Neglecting potential CPV in mixing and decay.
- Knowledge of angular acceptance.
- Background description.
- Decay time acceptance.

**Ongoing studies to reduce these for publication**

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**Symmetry $\Rightarrow$ two solutions**

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[Image of a graph showing projections of time dependent angular fit]
Resolving the ambiguity

\[(\phi_s, \Delta \Gamma_s, \delta_\parallel - \delta_0, \delta_\perp - \delta_0, \delta_S - \delta_0) \leftrightarrow (\pi - \phi_s, -\Delta \Gamma_s, \delta_0 - \delta_\parallel, \pi + \delta_0 - \delta_\perp, \delta_0 - \delta_S)\]

- Perform angular fit in 4 bins of \(K^+K^-\) mass.
- \(\delta_{S\perp} = \delta_S - \delta_\perp\) should fall across \(\phi(1020)\) mass.
$\phi_s$ from $B^0_s \rightarrow J/\psi \pi^+ \pi^-$

- $B^0_s \rightarrow J/\psi \pi^+ \pi^-$ is another $\bar{b} \rightarrow \bar{c}c\bar{s}$.
- Not vector-vector final state $\Rightarrow$ no complex angular analysis!
- $\pi^+ \pi^-$ is $>97.7\%$ CP-odd @ 95\% Conf. Level (see talk from C. Linn).

![LHCb plots](image-url)
$\phi_s$ from $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$

- $\Gamma_s, \Delta \Gamma_s$ constrained from $B_s^0 \rightarrow J/\psi \phi$ analysis (see talk from A. Phan on $B_s^0$ lifetimes)

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

$$\phi_s = -0.002 \pm 0.083 \pm 0.027 \text{ rad}$$
Latest $\phi_s$ combination

\[ \phi_s = -0.044^{+0.090}_{-0.085} \text{ rad}, \quad \Delta \Gamma_s = +0.105 \pm 0.015 \text{ ps}^{-1} \]
- Model independent analysis places strong constraints on size of NP in $M_{12}$.
- **Need** independent $a_{fs}^S$ measurement (see talk from M. Artuso).
- **Need** increased precision on $\phi_s$.
Summary

- Excellent detector performance:
  1. Clean signals.
  2. Decay time resolution: $\sim 45 \text{ fs}$.
  3. OS tagging: $\varepsilon_{\text{tag}} D^2 = (2.29 \pm 0.27)\%$.

- LHCb made most precise measurement of $\phi_s$ ($B^0_s \rightarrow J/\psi \phi$, $J/\psi \pi \pi$).
- First direct observation of non-zero $\Delta \Gamma_s \Rightarrow$ resolved sign ambiguity.

Lots more data on tape waiting to be analysed

Expect $> 1.5 \text{ fb}^{-1}$ by end 2012
Backup
Brief introduction to $B^0_s$-meson mixing and decay

$$i \frac{\partial}{\partial t} \left( \begin{array}{c} B^0_s(t) \\ \bar{B}^0_s(t) \end{array} \right) = \left( M - i \frac{\Gamma}{2} \right) \left( \begin{array}{c} B^0_s(t) \\ \bar{B}^0_s(t) \end{array} \right)$$

$$|B^0_{s,L}\rangle = p|B^0_s\rangle + q|\bar{B}^0_s\rangle$$
$$|B^0_{s,H}\rangle = p|B^0_s\rangle - q|\bar{B}^0_s\rangle$$

Some relevant parameters

$$M_{B^0_s} = \frac{M_H + M_L}{2}, \quad \Gamma_s = \frac{\Gamma_L + \Gamma_H}{2}$$

$$\Delta m_s = M_H - M_L \approx 2M_{12}, \quad \Delta \Gamma_s = \Gamma_L - \Gamma_H \approx 2\Gamma_{12} \cos \varphi$$

$$\varphi = \text{arg} \left( -\frac{M_{12}}{\Gamma_{12}} \right)$$
## Systematics

| Source                          | $\Gamma_s$ [ps$^{-1}$] | $\Delta\Gamma_s$ [ps$^{-1}$] | $A^2_{\perp}$ | $A^2_0$ | $F_S$ [rad] | $\delta_{||}$ [rad] | $\delta_{\perp}$ [rad] | $\delta_s$ [rad] | $\phi_s$ [rad] |
|---------------------------------|------------------------|-------------------------------|----------------|---------|------------|---------------------|---------------------|-----------------|----------------|
| Description of background       | 0.0010                 | 0.004                         | -              | 0.002   | 0.005      | 0.04                | 0.04                | 0.06            | 0.011          |
| Angular acceptances             | 0.0018                 | 0.002                         | 0.012          | 0.024   | 0.005      | 0.12                | 0.06                | 0.05            | 0.012          |
| $t$ acceptance model            | 0.0062                 | 0.002                         | 0.001          | 0.001   | -          | -                   | -                   | -               | -              |
| $z$ and momentum scale          | 0.0009                 | -                             | -              | -       | -          | -                   | -                   | -               | -              |
| Prod. asymmetry (± 10%)         | 0.0002                 | 0.002                         | -              | -       | -          | -                   | -                   | -               | 0.008          |
| CPV mixing & decay (± 5%)       | 0.0003                 | 0.002                         | -              | -       | -          | -                   | -                   | -               | 0.020          |
| Fit bias                        | -                      | 0.001                         | 0.003          | -       | 0.001      | 0.02                | 0.02                | 0.01            | 0.005          |
| Quadratic sum                   | 0.0066                 | 0.006                         | 0.013          | 0.024   | 0.007      | 0.13                | 0.07                | 0.08            | 0.027          |

Neglecting potential CPV in mixing and decay.

1. Fit for $|\lambda|$ shows that $\Delta(|\lambda|^2) = \pm 5\%$ is a reasonable variation.
2. Evaluate using toys generating with $|\lambda|^2 = 0.95, 1.05$ and fitting with $|\lambda|^2 = 1$.

Knowledge of angular acceptance.
**Systematics**

| Source                                | $\Gamma_s$ [ps$^{-1}$] | $\Delta \Gamma_s$ [ps$^{-1}$] | $A^2_{\perp}$ | $A^2_0$ | $F_S$   | $\delta_{||}$ [rad] | $\delta_{\perp}$ [rad] | $\delta_s$ [rad] | $\phi_s$ [rad] |
|---------------------------------------|-------------------------|---------------------------------|----------------|---------|---------|---------------------|---------------------|-----------------|---------------|
| Description of background             | 0.0010                  | 0.004                           | -              | 0.002   | 0.005   | 0.04                | 0.04                | 0.06            | 0.011         |
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| t acceptance model                    | 0.0062                  | 0.002                           | 0.001          | 0.001   | -       | -                   | -                   | -               | -             |
| z and momentum scale                  | 0.0009                  | -                               | -              | -       | -       | -                   | -                   | -               | -             |
| Prod. asymmetry (± 10%)               | 0.0002                  | 0.002                           | -              | -       | -       | -                   | -                   | -               | 0.008         |
| CPV mixing & decay (± 5%)             | 0.0003                  | 0.002                           | -              | -       | -       | -                   | -                   | -               | 0.020         |
| Fit bias                              | -                       | 0.001                           | 0.003          | -       | 0.001   | 0.02                | 0.02                | 0.01            | 0.005         |
| Quadratic sum                         | 0.0066                  | 0.006                           | 0.013          | 0.024   | 0.007   | 0.13                | 0.07                | 0.08            | 0.027         |

**$\Delta \Gamma_s, \Gamma_s$**

1. Background description.
2. Upper decay time acceptance affects $\Gamma_s$.
3. Trigger acceptance affects $\Delta \Gamma_s$, amplitudes.