Determination of the CP-violating phase in $B_s^0 \rightarrow J/\psi \phi$ decays at LHCb

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On behalf of the LHCb collaboration

Lake Louise Winter Institute
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Overview

1. The roadmap to $\phi_s$ using $B_s \rightarrow J/\psi\phi$
2. Alternative routes to $\phi_s$
3. Related measurements in $B_s^0$ sector
4. Summary

Full details in LHCb roadmap: B. Adeva et al arXiv:0912.4179

- K. Akiba for details of LHCb 2009 results
- H. Skottowe for $B_d \rightarrow K^*\mu\mu$
What is $\phi_s$?

- $B_s^0 \rightarrow J/\psi \phi$ dominated by $b \rightarrow c \bar{c} s$ tree-level transitions.
  - Small penguin pollution, $\delta P$.

- Interference between $B_s^0$ decay to $J/\psi \phi$ either directly or via mixing gives rise to a CP violating phase $\phi_s^{J/\psi \phi} = \Phi_M - 2\Phi_D$

- SM prediction:
  $\phi_s^{J/\psi \phi} = -2\beta_s + \delta P = -0.037 \pm 0.002 + \delta P$
New physics in $\phi_s$

- New particles in the $B_s^0 - \bar{B}_s^0$ box diagrams can significantly modify
  $\phi_{s,SM} \rightarrow \phi_{s,SM} + \phi_s$.

- Tevatron currently $\sim 2.1\sigma$ from SM. See talk this week from E Pueschel for details.
Measuring $\phi_s$ using $B_s \rightarrow J/\psi(\mu\mu)\phi(KK)$

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

- **Angular analysis** using transversity angles $\theta, \varphi, \psi$

- Unbinned negative log-likelihood fit to statistically disentangle final state.

- **6 observables**: $\theta, \varphi, \psi, c\tau, m_{B_s}$, initial flavour tag

- **8 physics parameters**: $\phi_s, \bar{\Gamma}_s, \Delta\Gamma_s, \Delta m_s, \delta_\parallel, \delta_\perp, |A_\parallel|^2, |A_\perp|^2$

- Many **detector parameters**: time and mass resolutions...
$B_s^0 \rightarrow J/\psi \phi$ differential decay rate

$$\frac{\partial^4 \Gamma(B_s^0 \rightarrow J/\psi \phi)}{\partial t \, \partial \cos \theta \, \partial \phi \, \partial \cos \psi} \propto \sum_{k=1}^{6} h_k(t) f_k(\theta, \psi, \phi)$$

<table>
<thead>
<tr>
<th>$k$</th>
<th>$h_k(t)$</th>
<th>$\bar{h}_k(t)$</th>
<th>$f_k(\theta, \psi, \phi)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$</td>
<td>A_0(t)</td>
<td>^2$</td>
</tr>
<tr>
<td>2</td>
<td>$</td>
<td>A_{</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$</td>
<td>A_{\perp}(t)</td>
<td>^2$</td>
</tr>
<tr>
<td>4</td>
<td>$\Im{A_{</td>
<td></td>
<td>}^*(t)A_{\perp}(t)}$</td>
</tr>
<tr>
<td>5</td>
<td>$\Re{A_0^*(t)A_{</td>
<td></td>
<td>}(t)}$</td>
</tr>
<tr>
<td>6</td>
<td>$\Im{A_0^*(t)A_{\perp}(t)}$</td>
<td>$\Im{\bar{A}<em>0^*(t)\bar{A}</em>{\perp}(t)}$</td>
<td>$\frac{1}{\sqrt{2}} \sin 2\psi \sin 2\theta \cos \phi$</td>
</tr>
</tbody>
</table>

![Graphs showing cosθ, ψ, and cosψ distributions](image_url)
Landmarks on the road to $\phi_s$

- **Propertime resolution** is good ($\sim 40\text{fs}$) $\Rightarrow$ resolve fast $B_s$ oscillations.

- Fit for res with $B_s^0 \rightarrow J/\psi \phi$ and check with control channels (i.e., $B_d \rightarrow J/\psi K^*$).

- **Large signal yield**

  - Signal events in $2fb^{-1}$: 117k
  - $B/S$(long-lived): $\sim 0.5$
  - $B/S$(prompt $J/\psi$): $\sim 1.6$

- Prompt bkg has $c\tau \sim 0\text{ ps}$ so "easy" to isolate.

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
Landmarks: first $\phi$ mass peak from LHCb!

No particle ID

- PID comes from the RICH detectors.
- $N_{signal} = 574.4 \pm 35.5$
- Now the search for $J/\psi$ begins!

With particle ID

- $m_0 = 1019.66 \pm 0.24$ MeV
- $\sigma_{Gauss} = 1.96 \pm 0.37$ MeV

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$\phi_s$ at LHCb  
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Landmarks on the road to $\phi_s$

- **Tagging** of initial $B_s$ flavour.
  - Combination of several methods: electron, muon, kaon, inclusive vertex, same side kaon.
  - Mistag $\omega \sim 33\%$, tagging power $\epsilon \sim 6\%$.
  - $B_d \rightarrow J/\psi K^*, B_u \rightarrow J/\psi K$ to calibrate the opposite side tagging. Fits can be used to extract $\omega$.
  - $B_s \rightarrow D_s \pi, B_s \rightarrow D_s \mu\nu$ to calibrate the same side tagging.

- **Angular acceptances**
  - LHCb detector geometry (20-300 mrad) distorts the $\theta, \phi, \psi$ angular distributions by $\sim 8\%$.
  - Ignoring this effect biases $|A_\perp|^2, |A_\parallel|^2$, $\phi_s$ **unbiased**
  - $B_d \rightarrow J/\psi K^*$ is a $P \rightarrow VV$ decay so use as control channel to understand acceptances.
The sensitivity of LHCb to $\phi_s$ is shown in the graph. The significance of $\phi_s$ can be estimated using the integrated luminosity $(fb^{-1})$ and various cross-sections and branching ratios. The results are as follows:

- **0.3fb$^{-1}$ at 7TeV:** LHCb should improve upon the Tevatron limit.
  - If $\phi_s \sim 0.7$ then LHCb can discover NP in $\bar{B}_s^0 - B_s^0$ mixing (i.e. establish $\phi_s \neq -2\beta_s$ at 5$\sigma$) with $0.3fb^{-1}$ of data!

- **2fb$^{-1}$ at 14TeV:** LHCb $\sigma(\phi_s) \sim$ SM value (0.036)
Alternative routes to $\phi_s$

Pure CP eigenstates:

- $B^0_s \to J/\psi f_0(980)$ where $f_0 \to \pi^+\pi^-$
- $B^0_s \to J/\psi \eta$, $B^0_s \to J/\psi \eta'$

$\Rightarrow$ No angular analysis is needed!

$$\Gamma(B^0_s \to f_{CP}) = |A_f|^2 e^{-\Gamma_{st}} \left( \cosh \frac{\Delta \Gamma_{st}}{2} - \eta_f \cos \phi_s \sinh \frac{\Delta \Gamma_{st}}{2} + \eta_f \sin \phi_s \sin(\Delta m_{st}) \right)$$

$\eta$, $\eta'$ decay modes contain $\geq 1\gamma$ $\Rightarrow$ lower reconstruction efficiency than charged particles, so consider $B_s \to J/\psi f_0$ ($\eta_f = -1$).

<table>
<thead>
<tr>
<th>Signal events in $2fb^{-1}$</th>
<th>26.1k</th>
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<tbody>
<tr>
<td>B/S(prompt $J/\psi$)</td>
<td>$\sim 0.11$</td>
</tr>
<tr>
<td>B/S($b\bar{b}$)</td>
<td>$\sim 0.21$</td>
</tr>
<tr>
<td>B/S($B^0_s \to J/\psi \eta'$)</td>
<td>$\sim 0.024$</td>
</tr>
<tr>
<td>B/S($B^+_u \to J/\psi K^+$)</td>
<td>$\sim 0.042$</td>
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- There is a non-resonant $\pi\pi$ S-wave contribution.
- With $2fb^{-1}$: $\sigma(\phi_s) = 0.044$

**CP measurements using penguins**

- $B_s^0 \rightarrow \phi\phi$ is a FCNC decay, forbidden at tree level in SM. Gluonic penguin dominates.
  
  - Similar to $B_d \rightarrow \phi K_s$ at the B factories.

\[
\Phi_{SM} = \Phi_M - 2\Phi_D = 2\text{arg}(V_{tb}V_{ts}^*) - 2\text{arg}(V_{tb}V_{ts}^*) \approx 0
\]

- Sign of NP if LHCb measures $\Phi \neq 0$!

- Angular analysis and fit like $B_s^0 \rightarrow J/\psi\phi$.

<table>
<thead>
<tr>
<th>BR</th>
<th>$\sim 2.4 \times 10^{-5}$</th>
</tr>
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<tbody>
<tr>
<td>Signal events in $2fb^{-1}$</td>
<td>$6.2k$</td>
</tr>
<tr>
<td>B/S</td>
<td>$&lt; 0.8@90% \text{ CL}$</td>
</tr>
</tbody>
</table>

- With $10fb^{-1}$: $\sigma(\Phi) = 0.06$

N. Styles et al LHCb-PUB-2009-025
Mixing in $B_s^0 \to J/\psi \phi$ is a promising way to discover NP at the LHC.

- LHCb with $2 fb^{-1}$ (one nominal year): $\sigma(\phi_s) \sim 0.03$ rad

LHCb detector being calibrated with 2009 data.

Additional routes can be used for $\phi_s$, i.e., $B_s \to J/\psi f_0, \eta, \eta'$.

$B_s^0 \to \phi\phi$ is an alternative channel to probe NP in $\bar{b} \to \bar{s}s\bar{s}$.

LHCb is ready to start hunting down NP in the $B_s^0$ sector!
The LHCb detector

- Forward arm spectrometer. $b/\bar{b}$ production correlated in forward/backward direction.
- Lumi $\sim 10^{32} \text{cm}^{-2}\text{s}^{-1} \Rightarrow 2\text{fb}^{-1}/\text{nominal year} \Rightarrow 10^{12} b\bar{b}$ events.
- Access to $B_u, B_d, B_s, \Lambda_b$. 

See talk from Kazuyoshi Akiba for details of LHCb 2009 results
What is $\phi_s$?

\[ A(b \to \bar{c}c\bar{s}) = V_{cs}V_{cb}^*(A_T + P_c) + V_{us}V_{ub}^*P_u + V_{ts}V_{tb}^*P_t \]
\[ = V_{cs}V_{cb}^*(A_T + P_c - P_t) + V_{us}V_{ub}^*(P_u - P_t). \]
\[ V_{ts}V_{tb}^* = -V_{us}V_{ub} - V_{cs}V_{cb}. \]

- Penguin contribution ($P_u - P_t$) suppressed by factor $\lambda^2 \sim 0.05$ wrt $(A_T + P_c - P_t)$.
- So assume decays dominated by single weak phase $\Phi_D = \text{arg}(V_{cs}V_{cb}^*)$.
- $B_s^0$ mixing phase, $\Phi_M = 2\text{arg}(V_{ts}V_{tb}^*)$.
- $\phi_s^{J/\psi} = \Phi_M - 2\Phi_D = 2\text{arg}(V_{ts}V_{tb}^*) - 2\text{arg}(V_{cs}V_{cb}^*) + \delta P$
- CKM triangle:
\[ V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \quad \Rightarrow \quad \beta_s = \text{arg}\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = \eta\lambda^2 + \mathcal{O}(\lambda^4) \]

- SM prediction, $\delta P = 0$:
\[ \phi_s^{J/\psi} = -2\beta_s = -0.037 \pm 0.002 \]
New physics in $\phi_s$

- $\phi_s^\Delta$ is the same NP phase modifying other quantities, e.g.,

$$\Delta \Gamma_s = 2|\Gamma_{12}^{SM}| \cos(\phi_{s,SM}^{M/\Gamma} + \phi_s^\Delta)$$

$$\phi_{s,SM}^{M/\Gamma} = \arg\left(-\frac{M_{12}^{SM}}{\Gamma_{12}^{SM}}\right) \sim 0.0034 \neq \phi_s^{J/\psi\phi}$$
High sensitivity to small $\phi_s$ when $B/\bar{B}$ initial state determined using flavour tagging.

- 8 physics parameters that have already been well measured at the Tevatron.
- Interesting signs of new physics in value of $\phi_s$. 

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**LHCb**

**LLWI February 2010 18 / 13**
Constraints on NP in $B_s$ mixing

New Physics in $B_s - \bar{B}_s$ mixing
S-wave contribution to $B_s \rightarrow J/\psi KK$

- $B_s^0 \rightarrow J/\psi \phi$ decay rate only includes $\phi \rightarrow KK$ (P-wave) in the KK mass region.
- A 5→10% contribution from S-wave in the KK system cannot be excluded.
- S-wave has a different time and angular distribution from the P-wave.
  \[ \Rightarrow \text{4 new terms} \] in the differential decay rate.
- Ignoring 10% s-wave leads to a \[ \sim 7 \rightarrow 17\% \text{ bias on } \phi_s. \]
- Including S-wave removes bias but only increases $\sigma(\phi_s)$ by 15%.

Y. Xie et al JHEP 0909:074,2009