Mixing and CPV in the B system

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On behalf of the LHCb collaboration,
PLHC, Vancouver, 4-9 June 2012.
Main results to be presented

Results presented are based on the full 2011 dataset of ~1 fb\(^{-1}\) collected with the LHCb detector

• Measurement of \(\Phi_s\) in \(B_s \rightarrow J/\psi\pi\pi\) decays (LHCb-PAPER-2012-006, \texttt{arXiv:1204.5675}) – 26/3/2012,

• Time-dependent angular analysis of \(B_s \rightarrow J/\psi\phi\) decays (LHCb-CONF-2012-002) – 5/3/2012,

• Determination of the sign of the decay width difference in the \(B_s\) system (LHCb-PAPER-2011-028, \texttt{arXiv:1202.4717}) – 22/2/2012,

• Measurement of the polarization amplitudes and triple product asymmetries in the \(B_s \rightarrow \phi\phi\) decay (LHCb-PAPER-2012-004, \texttt{arXiv:1204.2813}) – 10/4/2012.
The LHCb detector

- Smooth running of the detector thanks to the 804 members,
- All possible thanks to high beam quality provided by the LHC.
- 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,
- High muon reconstruction efficiency from muon stations,
- Accurate momentum resolution from tracking stations ($\delta p/p = 0.35\%-0.55\%$).
In this presentation, $\Phi_s$ is used to denote the CP violation interference between mixing and decay:

I.e. \[ \Phi_s = \Phi_M - 2\Phi_D \]

Mode can still be sensitive to CP in mixing interference even if no direct CP in mixing and decay individually.

In SM, $\Phi_s$ in $b\to c\bar{c}s$ transitions is predicted to be $-0.04$ Charles et al. (2011) Phys. Rev D84 033005

Experimentally, penguin pollution understood with $B_s \to J/\psi K^*$

In progress, decay already seen at LHCb (LHCb-CONF-2011-025)
**Φ_s in B_s -> J/ψππ decays**


Previous study using $B_s \rightarrow J/\psi f_0(980)$ decays with 0.41 fb$^{-1}$ of LHCb data: Phys. Lett. **B707** 497 (2012)

$m(\pi\pi)$ in range $775 < m(\pi\pi) < 1500$ MeV found to be CP-odd

0.975 @ 95% confidence level (LHCb-PAPER-2012-005)

Found from Dalitz analysis of resonance structure (see additional information)

⇒ Allows for greater number of events (7421±105 signal candidates from 1.0 fb$^{-1}$) to be studied for $Φ_s$ analysis
Sample all CP-odd
⇒ Maximum likelihood fit to mass and time only
Major peaking backgrounds: $B^0\rightarrow J/\psi K\pi$ (blue), $B^0\rightarrow J/\psi\pi\pi$ (purple)
Decay time distribution: Signal (dashed), background (shaded)

Tagged decay rate:

$$\Gamma \left( B^0_s \rightarrow J/\psi f_{\text{odd}} \right) = \frac{N}{2} e^{-\Gamma_{st}} \left\{ e^{\Delta \Gamma_{st}/2} (1 + \cos \phi_s) + e^{-\Delta \Gamma_{st}/2} (1 - \cos \phi_s) \right\} \pm \sin \phi_s \sin (\Delta m_s t),$$

Main $\Phi_s$ sensitivity

Untagged decay rate:

$$\Gamma \left( B^0_s \rightarrow J/\psi f_{\text{odd}} \right) + \Gamma \left( \bar{B}^0_s \rightarrow J/\psi f_{\text{odd}} \right) = N e^{-\Gamma_{st}} \left\{ e^{\Delta \Gamma_{st}/2} (1 + \cos \phi_s) + e^{-\Delta \Gamma_{st}/2} (1 - \cos \phi_s) \right\}$$
Important to understand time resolution and acceptance

Data driven methods for time resolution and acceptance. Prompt $J/\Psi \rightarrow \mu \mu$ used to find resolution, acceptance found from $B^0 \rightarrow J/\psi K^*$

$\Gamma_S$ & $\Delta \Gamma_S$ (and associated correlation) taken from $B_S \rightarrow J/\psi \Phi$ analysis (LHCb-CONF-2012-002)

Major systematics from signal yield and background lifetime parameters

Result:

\[ \phi_s = -0.019^{+0.173+0.004}_{-0.174-0.003} \]

Previous study: $\phi_s = -0.44 \pm 0.44 \text{ (stat)} \pm 0.02 \text{ (syst)}$
Tagged time-dependent measurement of $\Phi_s$ in $B_s \rightarrow J/\Psi \Phi$ decays
LHCb-CONF-2012-002

Measurement based on a sample of $\sim 21200$ events from 1.0 fb\(^{-1}\) at LHCb
Update of previous analysis based on 370 pb\(^{-1}\)
LHCb collaboration (2011) PRL 108, 101803

Mixture of CP-odd and CP-even components in the final state => full angular analysis in transversity basis is employed

$J/\Psi$ rest frame

$\Phi$ rest frame
Mixing & CPV in B System - Sean Benson

For $\Phi_s$ measurements mainly sensitive to $\sin \Phi_s \sin \Delta m_s t$ terms

PDF also allows fitting for $\Delta \Gamma_s$ and $\Delta m_s$.

NOTE: There is an ambiguity $\Phi_s \rightarrow \pi - \Phi_s$.

$\Delta \Gamma_s \rightarrow - \Delta \Gamma_s$ + strong phase changes
Analysis requires good understanding of time and angular acceptances

Effective tagging efficiency:
\[ \varepsilon_{\text{tag}} D^2 = (2.29 \pm 0.27)\% \]

where \[ D = (1 - 2\omega_{\text{mistag}}) \]

(For more tagging info, see additional slides or talk on Monday)

Time resolution of \( \sim 45 \) fs

Resolution found from fits to prompt \( J/\Psi \rightarrow \mu \mu \) candidates
Comparison:

Results:

\[
\phi_s = -0.001 \pm 0.101 \text{ (stat) } \pm 0.027 \text{ (syst) rad,}
\]

\[
\Gamma_s = 0.6580 \pm 0.0054 \text{ (stat) } \pm 0.0066 \text{ (syst) ps}^{-1}
\]

\[
\Delta \Gamma_s = 0.116 \pm 0.018 \text{ (stat) } \pm 0.006 \text{ (syst) ps}^{-1}
\]

\[
\phi_s = -0.002 \pm 0.083 \text{(stat)} \pm 0.027 \text{(syst)}
\]

Combination with LHCb measurement of $\Phi_s$ in $B_s \rightarrow J/\psi \pi \pi$:

Comparison:
Sign of the $\Delta \Gamma_s$ in the $B_s$ system

As mentioned earlier, two ambiguous solutions:
$\Phi_s \rightarrow \pi - \Phi_s$
$\Delta \Gamma_s \rightarrow - \Delta \Gamma_s +$ strong phase changes

Solved using P-wave $\leftrightarrow$ S-wave interference
Principle described in Xie et al. (2009) JHEP 0909:074

KK P-wave: $\phi$ meson spin-1
=> Amplitude described by Breit-Wigner
  (rapid phase increase across $\phi$ mass region)

KK S-wave:
  Amplitude described by Flatté function
  (approx. flat across $\phi$ mass region)

=> Rapid decrease in difference between S-wave and P-wave
Data split into 4 bins by $m_{KK}$

In each bin, measure $\delta_{s\perp} \equiv \delta_{s} - \delta_{\perp}$ along with fraction of S-wave ($F_{S}$)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Solution I</th>
<th>Solution II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_{s}$ (rad)</td>
<td>0.167 ± 0.175</td>
<td>2.975 ± 0.175</td>
</tr>
<tr>
<td>$\Delta \Gamma$ (ps$^{-1}$)</td>
<td>0.120 ± 0.028</td>
<td>−0.120 ± 0.028</td>
</tr>
<tr>
<td>$F_{S;1}$</td>
<td>0.283 ± 0.113</td>
<td>0.283 ± 0.113</td>
</tr>
<tr>
<td>$F_{S;2}$</td>
<td>0.061 ± 0.022</td>
<td>0.061 ± 0.022</td>
</tr>
<tr>
<td>$F_{S;3}$</td>
<td>0.044 ± 0.022</td>
<td>0.044 ± 0.022</td>
</tr>
<tr>
<td>$F_{S;4}$</td>
<td>0.269 ± 0.067</td>
<td>0.269 ± 0.067</td>
</tr>
<tr>
<td>$\delta_{s\perp;1}$ (rad)</td>
<td>−0.46 ± 0.35</td>
<td>−2.68 ± 0.42</td>
</tr>
<tr>
<td>$\delta_{s\perp;2}$ (rad)</td>
<td>−2.92 ± 0.15</td>
<td>−0.22 ± 0.13</td>
</tr>
<tr>
<td>$\delta_{s\perp;3}$ (rad)</td>
<td>−3.25 ± 0.16</td>
<td>0.11 ± 0.16</td>
</tr>
<tr>
<td>$\delta_{s\perp;4}$ (rad)</td>
<td>−4.11 ± 0.28</td>
<td>0.97 ± 0.43</td>
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⇒ Solution I is selected, $\Delta \Gamma_{S} > 0$
⇒ Heavy $B_{s}$ mass eigenstate lives longer

$\Delta \Gamma_{S} < 0$
$\Delta \Gamma_{S} > 0$

4.7σ negative trend
Polarization amplitudes and triple product asymmetries in the $B_s\rightarrow\phi\phi$ decay  

$B_s\rightarrow\phi\phi$ a pure penguin $P\rightarrow VV$ decay

Sensitive to new physics in mixing and decay

801±29 events observed in 1.0 fb$^{-1}$ LHCb data

Results presented based on time-integrated angular analysis

Very clean signal for hadronic mode at a hadronic collider!!!!
Principle: Through CPT theorem, T violation equivalent to CP violation
⇒ Look at observables in P->VV decays, corresponding to T-odd triple products

Consider $B_s \rightarrow \phi\phi$ decay:

We look at observables:

\[ U = \sin(2\Phi) / 2 \]
\[ V = \text{sign}(\cos\theta_1 \cos\theta_2) \sin\Phi \]

Related to T-odd triple products

which then pick out CP-even - CP-odd interference terms from decay rate
(see additional information)
Polarization amplitudes and strong phase difference measured from time-integrated PDF

\[
\frac{d\Gamma}{d\omega} = 4|A_0|^2\tau_L \cos^2 \theta_1 \cos^2 \theta_2 + |A_\parallel|^2\tau_L \sin^2 \theta_1 \sin^2 \theta_2(1 + \cos 2\Phi) \\
+ |A_\perp|^2\tau_H \sin^2 \theta_1 \sin^2 \theta_2(1 - \cos 2\Phi) \\
+ \sqrt{2}|A_0||A_\parallel|\cos(\delta_\parallel)\tau_L \sin \theta_1 \sin 2\theta_2 \cos \Phi
\]

Lifetimes constrained from $B_s \rightarrow J/\psi \phi$ measurements of $\Gamma_s$ & $\Delta\Gamma_s$

\[
|A_0|^2 = 0.365 \pm 0.022 \text{ (stat)} \pm 0.012 \text{ (syst)} \\
|A_\perp|^2 = 0.291 \pm 0.024 \text{ (stat)} \pm 0.010 \text{ (syst)} \\
\cos(\delta_\parallel) = -0.844 \pm 0.068 \text{ (stat)} \pm 0.029 \text{ (syst)}
\]
Triple products asymmetries measured from U & V observables to be:

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

$$A_V = 0.010 \pm 0.036 \text{ (stat)} \pm 0.018 \text{ (syst)}$$

Result consistent with hypothesis of CP conservation

Main systematics from angular and time acceptances

Assumed no S-wave (2% contribution for systematic in polarization amplitudes), found to be negligible from data

Uniform time acceptance assumed
LHCb has presented the most accurate measurements of CP in the B_s system with the 2011 1 fb⁻¹ dataset:

- In the B_s→J/Ψφ decay, we measure:
  \[ \phi_s = -0.019^{+0.173+0.004}_{-0.174-0.003} \]
  \[ \Delta\Gamma_s > 0 \quad 4.7\sigma \]
  \[ |A_0|^2 = 0.365 \pm 0.022 \text{ (stat)} \pm 0.012 \text{ (syst)} \]
  \[ |A_\perp|^2 = 0.291 \pm 0.024 \text{ (stat)} \pm 0.010 \text{ (syst)} \]
  \[ \cos(\delta_{\perp}) = -0.844 \pm 0.068 \text{ (stat)} \pm 0.029 \text{ (syst)} \]
  \[ A_U = -0.055 \pm 0.036 \text{ (stat)} \pm 0.018 \text{ (syst)} \]
  \[ A_V = 0.010 \pm 0.036 \text{ (stat)} \pm 0.018 \text{ (syst)} \]

- In the B_s→J/ψππ decay, we measure:
  \[ \phi_s = -0.002 \pm 0.083 \text{ (stat)} \pm 0.027 \text{ (syst)} \]

- The combination of the two results is therefore:

- The decay width difference has been resolved to be:
  \[ \Delta\Gamma_s > 0 \quad 4.7\sigma \]