Results on CP Violation in $B_s$ Mixing
[measurements of $\phi_s$ and $\Delta\Gamma_s$]

Presentation on behalf of LHCb Collaboration
Rencontres de Moriond, La Thuile, 3-10 March 2012
This talk presents new LHCb results since 2011 summer conferences

- Using the full 1 fb$^{-1}$ of data from 2011 (was 0.37 fb$^{-1}$)

- CPV phase $\phi_s$, $\Delta\Gamma_s$ and other quantities from $B_s \rightarrow J/\psi \Phi$
  - LHCb-CONF-2012-002
  - arXiv:1112.3183v2 to be published in PRL

- $\phi_s$ from $B_s \rightarrow J/\psi \pi\pi$
  - LHCb-PAPER-2012-006 to be submitted to PLB

- Resolution of the “two fold ambiguity” for $\phi_s$ & $\Delta\Gamma_s$
  - arXiv:1202.4717v2 submitted to PRL
These new results are due to

- Excellent running of detector
- Excellent running of LHC
- Efforts of all the people
LHCb is a forward spectrometer

2 < \eta < 5

Optimised for \( b \) and \( c \) physics

Precise tracking and decay vertex finder

Good particle ID
Experimental phenomenology of CP Violating phase $\phi_s$
Measure relative phase difference $\phi_s = \phi_M - 2\phi_D$ between two “legs”.

In SM & normal conventions & ignoring penguins

- $\phi_D \sim 0$
- $\phi_s^{SM} \sim \phi_M$

- is predominantly determined by $\arg(V_{ts})$
- is predicted to be small $\sim -0.04$


New Physics (NP) can add large phases:

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

1] The term $\phi_s$ is overloaded. It is also used for $\arg(M_{12}/\Gamma_{12})$
2] $\phi_s = -2 \arg(V_{ts} V_{tb}^* / V_{cs} V_{cb}^*)$
The signals

- $B_s \to J/\psi \Phi$ and $B_s \to J/\psi \pi \pi$ are very clean decays

$$B_s^0 \left\{ \begin{array}{c}
  b \\
  \bar{s}
\end{array} \right\} \to J/\psi \phi \mu^+ \mu^- \pi^+ \pi^-$$
Straightforward differential decay rates for $B_s \rightarrow J/\psi \pi\pi$

$$
\Gamma (B_s^0 \rightarrow J/\psi f_0) = N_f e^{-\Gamma_{st}} \left\{ e^{\Delta \Gamma_{st}/2} (1 + \cos \phi_s) + e^{-\Delta \Gamma_{st}/2} (1 - \cos \phi_s) \\
- \sin(\phi_s) \sin(\Delta m_s t) \right\},
$$

$$
\Gamma (B_s^0 \rightarrow J/\psi f_0) = N_f e^{-\Gamma_{st}} \left\{ e^{\Delta \Gamma_{st}/2} (1 + \cos \phi_s) + e^{-\Delta \Gamma_{st}/2} (1 - \cos \phi_s) + \sin(\phi_s) \sin(\Delta m_s t) \right\}.
$$

- Signal is sinusoidal time distribution
  - Amplitude proportional to $\sin(\phi_s)$
  - Opposite sign for $B$ and $\bar{B}$ → must tag
  - Diluted by wrong tagging probability $\omega_{\text{tag}}$
  - Diluted by detector resolution $\sigma_t$

- Fundamentally we measure:
  $$\sin(\phi_s) \times D(\sigma_t) \times (1 - 2\omega_{\text{tag}}) \times \sin(\Delta m_s t)$$
Decay time resolution

\[ \sin(\phi_s) \times D(\sigma_i) \times (1 - 2\omega_{\text{tag}}) \times \sin(\Delta m_s t) \]

Need good proper time resolution w.r.t. sinusoid period ~ 350fs

- We measure from data using prompt J/ψ which decay at t=0
- width ~ 45fs
- In analysis we actually use a resolution estimated per-event

Measured decay time of prompt events [ps]
Need to tag $B$ or $\bar{B}$ at production

$$\sin(\phi_s) \times D(\sigma_i) \times (1 - 2\omega_{tag}) \times \sin(\Delta m_s t)$$

**Same side**
- proton
- primary vertex
- signal $B_s$
- $K^+$
- $K^-$

**Opposite side**
- proton
- opposite $B$
- vertex-charge tagger from inclusive vertexing
- negative lepton taggers ($e^-, \mu^-$) from $b$-quark
- positive leptons from $b \rightarrow c \rightarrow l$ cascade
- opposite kaon tagger ($K^-$)

**LHCb preliminary**

**Event-mistag ($\omega_{tag}$)**

**Data Points**
- Mean = 0.39090
- RMS = 0.07333
- Events / 0.006

**Formulae**
- Tagging efficiency $\varepsilon_{tag} \sim 33\%$
- Effective mistag $\omega_{tag} \sim 36.8\%$
- Effective tagging power $\varepsilon_{tag}(1 - 2\omega_{tag})^2 \sim 2.3\%$
Measurements of $\phi_s$ using $B_s \rightarrow J/\psi\pi\pi$

$\sim 1.0 \text{ fb}^{-1}$


This update: LHCb-PAPER-2012-006
Previous analysis was $B_s \to J/\psi f_0(980)$

All $m(\pi\pi)$ range found to be CP-odd
(97.7\% @ 95\% C.L)
[LHCb-PAPER-2012-005]

Now use wider $M(\pi\pi)$ range hence: $B_s \to J/\psi \pi\pi\pi$
Bs → J/ψ ππ π signal

- Boosted Decision Tree selection
- Maximum likelihood fit to time and mass
- Uses Γs and ΔΓs from the Bs → J/ψΦ analysis (+correlation)
- Approx. 7400 signal events

The decay time asymmetry
B_s \rightarrow J/\psi \pi \pi \text{ final result}

\[ \phi_s = -0.02 \pm 0.17 \text{(stat.)} \pm 0.02 \text{(syst.)} \text{ rad.} \]

<table>
<thead>
<tr>
<th>Quantity (Q)</th>
<th>±ΔQ</th>
<th>+Change in ( \phi_s ) (rad)</th>
<th>−Change in ( \phi_s ) (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta )</td>
<td>4.4 \times 10^{-3}</td>
<td>0.0008</td>
<td>−0.0007</td>
</tr>
<tr>
<td>( \tau_{bkg1} ) (ps)</td>
<td>0.046</td>
<td>−0.0006</td>
<td>0.0014</td>
</tr>
<tr>
<td>( \tau_{bkg2} ) (ps)</td>
<td>0.8</td>
<td>−0.0014</td>
<td>0.0014</td>
</tr>
<tr>
<td>( f_2 )</td>
<td>0.02</td>
<td>−0.0006</td>
<td>0.0012</td>
</tr>
<tr>
<td>( N_{bkg} )</td>
<td>38</td>
<td>0.0009</td>
<td>−0.0001</td>
</tr>
<tr>
<td>( N_{\eta'} )</td>
<td>9</td>
<td>0.0006</td>
<td>0.0001</td>
</tr>
<tr>
<td>( N_{sig} )</td>
<td>105</td>
<td>0.0021</td>
<td>0.0006</td>
</tr>
<tr>
<td>( m_0 ) (MeV)</td>
<td>0.12</td>
<td>0.0012</td>
<td>−0.0004</td>
</tr>
<tr>
<td>( \sigma_1^m ) (MeV)</td>
<td>0.1</td>
<td>−0.0002</td>
<td>0.0008</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>1.1 \times 10^{-4}</td>
<td>0.0003</td>
<td>0.0003</td>
</tr>
<tr>
<td>( T ) function 5%</td>
<td>0.0005</td>
<td>0.0005</td>
<td>0.0005</td>
</tr>
<tr>
<td>( CP )-even</td>
<td>increase mistag by 2.3%</td>
<td>−0.0160</td>
<td>0</td>
</tr>
<tr>
<td>Direct ( CP )</td>
<td>free in fit</td>
<td>−0.0020</td>
<td>0</td>
</tr>
</tbody>
</table>

Total systematic error on \( \phi_s \) \( ^{-0.017}_{+0.004} \)
Measurements of $\phi_s$ using $B_s \to J/\psi\Phi$

$\sim 1.0 \text{ fb}^{-1}$

0.37 fb$^{-1}$ published result: arXiv:1112.3183 [LHCb-PAPER-2011-021]

This update: LHCb-CONF-2012-002
Decay to CP-odd and CP-even final states, need analysis of decay angle distribution

- Many larger branching fraction
  \[ \frac{J/\psi \Phi}{J/\psi \pi\pi} \approx 5 \]

- Differential cross section is “very rich”
  - 3 “P-wave” amplitudes of KK system
  - 1 “S”-wave amplitude
  - 10 terms with all interferences
..but fundamentally for $\phi_s$ we still measure:

$$\sin(\phi_s) \times D(\sigma) \times (1 - 2\omega_{tag}) \times \sin(\Delta m_s t)$$

..and because we separate the terms, we measure the lifetimes of Heavy and Light eigenstates separately:

$$\Gamma_L \ & \ \Gamma_H \ \Leftrightarrow \ \Gamma_s \ & \ \Delta\Gamma_s$$

There is a two fold ambiguity in the solutions

$$\phi_s \ \Leftrightarrow \ \pi - \phi_s$$

$$\Delta\Gamma_s \ \Leftrightarrow \ -\Delta\Gamma_s$$

+ strong phase changes
- Simple selection with kinematic cuts
- Most background removed by decay time cut $t > 0.3$ ps
- Very clean signal
- Approx. 21200 signal events
The CP-even / CP-odd separation is very clear in all distributions.
Digression: measurement of $\Delta m_s$

- The data has sinusoidal terms which measure $\Delta m_s$ independently of $\phi_s$

- We observe a central value $\Delta m_s = 17.50 \pm 0.15$ (stat) ps$^{-1}$
  - Compare to LHCb published measurement $17.63 \pm 0.11 \pm 0.02$ arXiv:1112.4311
  - This gives confidence that if there is a $\sin(\phi_s) \times \sin(\Delta m_s t)$ term we would see it.
B_s \to J/\psi \Phi : New Preliminary Results

- Maximum likelihood fit to signal + background time, angle and mass distributions.
- Constrain $\Delta m_s$ to $17.63 \pm 0.11$ ps
- “Solution-I” shown here
- $\phi_s$ uncorrelated with other quantities

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_s$ [ps$^{-1}$]</td>
<td>0.6580</td>
<td>0.0054</td>
<td>0.0066</td>
</tr>
<tr>
<td>$\Delta \Gamma_s$ [ps$^{-1}$]</td>
<td>0.116</td>
<td>0.018</td>
<td>0.006</td>
</tr>
<tr>
<td>$</td>
<td>A_\perp(0)</td>
<td>^2$</td>
<td>0.246</td>
</tr>
<tr>
<td>$</td>
<td>A_0(0)</td>
<td>^2$</td>
<td>0.523</td>
</tr>
<tr>
<td>$F_s$</td>
<td>0.022</td>
<td>0.012</td>
<td>0.007</td>
</tr>
<tr>
<td>$\delta_\perp$ [rad]</td>
<td>2.90</td>
<td>0.36</td>
<td>0.07</td>
</tr>
<tr>
<td>$\delta_\parallel$ [rad]</td>
<td>[2.81, 3.47]</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>$\delta_s$ [rad]</td>
<td>2.90</td>
<td>0.36</td>
<td>0.08</td>
</tr>
<tr>
<td>$\phi_s$ [rad]</td>
<td>-0.001</td>
<td>0.101</td>
<td>0.027</td>
</tr>
</tbody>
</table>

|          | $\Gamma_s$ | $\Delta \Gamma_s$ | $|A_\perp|^2$ | $|A_0|^2$ | $\phi_s$ |
|----------|------------|-------------------|--------------|-----------|---------|
| $\Gamma_s$ | 1.00       | -0.38             | 0.39         | 0.20      | -0.01   |
| $\Delta \Gamma_s$ | 1.00       | -0.67             | 1.00         | 0.63      | -0.01   |
| $|A_\perp(0)|^2$ | 1.00       | -0.53             | 1.00         | -0.53     | -0.01   |
| $|A_0(0)|^2$ | 1.00       |                   | 1.00         | 1.00      | -0.02   |
| $\phi_s$  |            |                   |              |           | 1.00    |

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$B_s \rightarrow J/\psi \Phi$ : New Preliminary Results 1.0 fb$^{-1}$

$\Gamma_s = 0.6580 \pm 0.0054$(stat.) $\pm 0.0066$(syst.) ps$^{-1}$

$\Delta \Gamma_s = 0.116 \pm 0.018$(stat.) $\pm 0.006$(syst.) ps$^{-1}$

$\phi_s = -0.001 \pm 0.101$(stat.) $\pm 0.027$(syst.) rad
### Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Gamma_s$ [ps$^{-1}$]</th>
<th>$\Delta\Gamma_s$ [ps$^{-1}$]</th>
<th>$A_{\perp}^2$</th>
<th>$A_{0}^2$</th>
<th>$F_S$</th>
<th>$\delta_{\parallel}$ [rad]</th>
<th>$\delta_{\perp}$ [rad]</th>
<th>$\delta_s$ [rad]</th>
<th>$\phi_s$ [rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description of background</td>
<td>0.0010</td>
<td>0.004</td>
<td>-</td>
<td>0.002</td>
<td>0.005</td>
<td>0.04</td>
<td>0.04</td>
<td>0.06</td>
<td>0.011</td>
</tr>
<tr>
<td>Angular acceptances</td>
<td>0.0018</td>
<td>0.002</td>
<td>0.012</td>
<td>0.024</td>
<td>0.005</td>
<td>0.12</td>
<td>0.06</td>
<td>0.05</td>
<td>0.012</td>
</tr>
<tr>
<td>$t$ acceptance model</td>
<td>0.0062</td>
<td>0.002</td>
<td>0.001</td>
<td>0.001</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$z$ and momentum scale</td>
<td>0.0009</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Production asymmetry ($\pm$ 10%)</td>
<td>0.0002</td>
<td>0.002</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.008</td>
</tr>
<tr>
<td>CPV mixing &amp; decay ($\pm$ 5%)</td>
<td>0.0003</td>
<td>0.002</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.020</td>
</tr>
<tr>
<td>Fit bias</td>
<td>-</td>
<td>0.001</td>
<td>0.003</td>
<td>-</td>
<td>0.001</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.005</td>
</tr>
<tr>
<td>Quadratic sum</td>
<td>0.0066</td>
<td>0.006</td>
<td>0.013</td>
<td>0.024</td>
<td>0.007</td>
<td>0.13</td>
<td>0.07</td>
<td>0.08</td>
<td>0.027</td>
</tr>
</tbody>
</table>

- **Note:** Tagging and resolution parameters floated in fit within uncertainties, hence not explicitly included in systematics
$B_s \rightarrow J/\psi \Phi$ and $B_s \rightarrow J/\psi \pi \pi$ combined prelim. result

- Used a simultaneous fit to both datasets, taking all common parameters and correlations into account.
- Used largest syst. error.

$$\phi_s = -0.002 \pm 0.083{\text{(stat.)}} \pm 0.027{\text{(syst.)}} \text{ rad}$$
Resolving the ambiguous solution

The sign of $\Delta \Gamma_s$

$\sim 0.37 \, \text{fb}^{-1}$

There are two ambiguous solutions related by $\phi_s \Leftrightarrow \pi - \phi_s$ and $\Delta \Gamma \Leftrightarrow -\Delta \Gamma$

We can disambiguate using the P-Wave $\Leftrightarrow$ S-Wave interference

Similar to Babar measurement of sign of $\cos(2\beta)$, PRD 71, 032005 (2007)

**K$^+$K$^-$ P-wave:**
Phase of Breit-Wigner amplitude increases rapidly across $\phi(1020)$ mass region

$$BW(m_{KK}) = \frac{F_r F_D}{m_\phi^2 - m_{KK}^2 - im_\phi \Gamma(m_{KK})}$$

**K$^+$K$^-$ S-wave:**
Phase of Flatté amplitude for $f_0(980)$ relatively flat (similar for non-resonance)

**Phase difference between S- and P-wave amplitudes**
Decreases rapidly across $\phi(1020)$ mass region

**Resolution method:** choose the solution with decreasing trend of $\delta_s$ - $\delta_P$ vs $m_{KK}$ in the $\phi(1020)$ mass region
- Split data into 4 bins of $m_{KK}$.
- In each bin measure
  - Fraction of S-wave
  - Measure relative strong phase difference $\delta_S - \delta_{\perp}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Solution I</th>
<th>Solution II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_s$ (rad)</td>
<td>$0.167 \pm 0.175$</td>
<td>$2.975 \pm 0.175$</td>
</tr>
<tr>
<td>$\Delta\Gamma$ (ps$^{-1}$)</td>
<td>$0.120 \pm 0.028$</td>
<td>$-0.120 \pm 0.028$</td>
</tr>
<tr>
<td>$F_{S;1}$</td>
<td>$0.283 \pm 0.113$</td>
<td>$0.283 \pm 0.113$</td>
</tr>
<tr>
<td>$F_{S;2}$</td>
<td>$0.061 \pm 0.022$</td>
<td>$0.061 \pm 0.022$</td>
</tr>
<tr>
<td>$F_{S;3}$</td>
<td>$0.044 \pm 0.022$</td>
<td>$0.044 \pm 0.022$</td>
</tr>
<tr>
<td>$F_{S;4}$</td>
<td>$0.269 \pm 0.067$</td>
<td>$0.269 \pm 0.067$</td>
</tr>
<tr>
<td>$\delta_{S\perp;1}$ (rad)</td>
<td>$-0.46^{+0.35}_{-0.42}$</td>
<td>$-2.68^{+0.42}_{-0.35}$</td>
</tr>
<tr>
<td>$\delta_{S\perp;2}$ (rad)</td>
<td>$-2.92^{+0.15}_{-0.13}$</td>
<td>$-0.22^{+0.15}_{-0.13}$</td>
</tr>
<tr>
<td>$\delta_{S\perp;3}$ (rad)</td>
<td>$-3.25^{+0.18}_{-0.16}$</td>
<td>$0.11^{+0.18}_{-0.16}$</td>
</tr>
<tr>
<td>$\delta_{S\perp;4}$ (rad)</td>
<td>$-4.11^{+0.28}_{-0.43}$</td>
<td>$0.97^{+0.43}_{-0.28}$</td>
</tr>
</tbody>
</table>

Solution-I is selected [4.7σ from being flat] 
$\Delta\Gamma_s > 0$
LHC + Tevatron Results

This result 1 fb$^{-1}$

D0 8 fb$^{-1}$ [S. Burdin, EPS 2011]

CDF 10 fb$^{-1}$ [Sabato Leo talk, Lake Louise]
LHCb has presented new preliminary results using the full 2011 data (1 fb⁻¹).

From an analysis of the J/ψφ channel we find:

\[ \Gamma_s = 0.6580 \pm 0.0054\text{(stat.)} \pm 0.0066\text{(syst.)} \text{ ps}^{-1} \]
\[ \Delta \Gamma_s = 0.116 \pm 0.018\text{(stat.)} \pm 0.006\text{(syst.)} \text{ ps}^{-1} \]
\[ \phi_s = -0.001 \pm 0.101\text{(stat.)} \pm 0.027\text{(syst.)} \text{ rad.} \]

From an analysis of the J/ψππ channel we find:

\[ \phi_s = -0.02 \pm 0.17\text{(stat.)} \pm 0.02\text{(syst.)} \text{ rad} \]

Combining both results we find:

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

We resolve the 2-fold ambiguity and find: \( \Delta \Gamma_s > 0 \)
Extra Information
1. CP-odd fraction: Table from LHCb-PAPER-2012-006

Table 1: Fit fractions of contributing resonances [16]. The final state helicity of the D-wave is denoted by \( \Lambda \). Only statistical errors are quoted.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Normalized fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_0(980) )</td>
<td>69.7 ± 2.3</td>
</tr>
<tr>
<td>( f_0(1370) )</td>
<td>21.2 ± 2.7</td>
</tr>
<tr>
<td>non-resonant ( \pi^+\pi^- )</td>
<td>8.4 ± 1.5</td>
</tr>
<tr>
<td>( f_2(1270), \Lambda = 0 )</td>
<td>0.49 ± 0.16</td>
</tr>
<tr>
<td>( f_2(1270), \Lambda =</td>
<td>1</td>
</tr>
</tbody>
</table>

- Upper limit on \( \rho(770) \) found to be 1.5% @ 95% C.L.
- Total is quadrature sum of \( f_2(1270) + \rho(770) \)

2. Profile Likelihood

![Figure 8](image)

Figure 8: Log-likelihood difference as a function of \( \phi_s \) for \( \overline{B}_s \rightarrow J/\psi f_{\text{odd}} \) events.
B_s \rightarrow J/\psi \Phi

Decay angle acceptances

\begin{align*}
\epsilon(\cos \theta) & \sim 5\% \text{ effects} \\
\epsilon(\psi) & \sim 5\% \text{ effects} \\
\epsilon(\cos \psi) & \sim 5\% \text{ effects}
\end{align*}

Accounted for in ML fit
This new preliminary result 1.0 fb⁻¹

\[ \Gamma_s = 0.6580 \pm 0.0054\text{(stat.)} \pm 0.0066\text{(syst.)} \text{ ps}^{-1} \]
\[ \Delta \Gamma_s = 0.116 \pm 0.018\text{(stat.)} \pm 0.006\text{(syst.)} \text{ ps}^{-1} \]
\[ \phi_s = -0.001 \pm 0.101\text{(stat.)} \pm 0.027\text{(syst.)} \text{ rad.} \]

Previous published result 0.37 fb⁻¹

arXiv:1112.3183

\[ \Gamma_s = 0.657 \pm 0.009\text{(stat.)} \pm 0.008\text{(syst.)} \text{ ps}^{-1} \]
\[ \Delta \Gamma_s = 0.123 \pm 0.029\text{(stat.)} \pm 0.011\text{(syst.)} \text{ ps}^{-1} \]
\[ \phi_s = 0.151 \pm 0.18\text{(stat.)} \pm 0.06\text{(syst.)} \text{ rad.} \]
Syst error due to possible direct CVP

- We vary $|\lambda|^2$ by 5%
- Motivated by a fit for $|\lambda|^2$ gives < 5%

$$R(t, q) \propto e^{-\Gamma_s t} \left\{ \cosh \frac{\Delta\Gamma_s t}{2} + \frac{2|\lambda|}{1 + |\lambda|^2} \cos \phi_s \sinh \frac{\Delta\Gamma_s t}{2} \right.$$  

$$\left. - \frac{2qD}{1 + |\lambda|^2} \left[ |\lambda| \sin \phi_s \sin(\Delta m_s t) + (1 - |\lambda|^2) \cos(\Delta m_s t) \right] \right\}.$$