Measurements of CP Violation in the $B_s^0$ System

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Physics laws are not invariant for mirror-reversal of the spatial arrangement and replacement of all particles with antiparticles.

Who ordered this?

Not the SM – but has sufficient complexity to accommodate it, by a single complex phase in the CKM mechanism.

NP can generate additional source of CP (and flavour) violation. Multiple, precise experimental tests of the CKM paradigm can reveal early signs of new particles/couplings.
**$B_s^0$ Handles on NP**

Broad class of SM extensions can easily alter $B_s^0$ mixing dynamics.

- Mass difference sensitive to NP, but requires inputs from lattice.
- Decay with difference less sensitive to NP, but nice byproduct.
- CP-violating mixing phase $\phi_s$ very sensitive to NP. Precise prediction in the SM: $\phi_s = -0.0038 \pm 0.0010$ (arXiv:1205.1444)
**Phase Probe**

$B_s^0 \rightarrow J/\psi \phi$

Interference of mixing and decay amplitudes originates a time-dependent CP asymmetry

$$A_{CP}(t) = \frac{\Gamma(B_s^0 \rightarrow f) - \Gamma(\bar{B}_s^0 \rightarrow f)}{\Gamma(B_s^0 \rightarrow f) + \Gamma(\bar{B}_s^0 \rightarrow f)} \approx \frac{C_f \cos(\Delta m_s t) - S_f \sin(\Delta m_s t)}{\cosh(\Delta \Gamma_s t/2) + S_f' \sinh(\Delta \Gamma_s t/2)}$$

Direct probe of the mixing phase

$C_f \approx 0 \quad S_f \approx \sin \phi_s \quad S_f' \approx \cos \phi_s$

**P \rightarrow VV decay**

3 polarization amplitudes.

Have different CP parity,

have different time dependence.
Complex likelihood fit, use information from

**B mass**
Separate signal from background

**production flavour**
Distinguish B from $\bar{B}$ at the production

**decay time**
Trace the time evolution and fast $B_s$ oscillations

**decay-angles**
Disentangle CP-even/CP-odd final state
The Signal

95K signal events in the 2011+2012 data set

Low $p_T$ dimuon trigger.
Reconstruct $J/\psi \rightarrow \mu^+\mu^-$ and $\phi \rightarrow K^+K^-$

Decay time greater than 0.3 ps removes most of combinatorial background

Small contamination from misidentified decays
$\Lambda_b \rightarrow J/\psi p K$, $B^0 \rightarrow J/\psi K^*$
Flavour Tagging

Greater sensitivity to mixing phase if production flavor is known.

2 set of algorithms, re-optimized for the analysis of the 2011+2012 data:

**Opposite Side Taggers**, $\varepsilon_{\text{eff}} = 2.55\% + 15\%$ w.r.t 2011.
Calibrate mistag $\omega$ in large samples of flavour specific decays.

**Same Side Kaon Tagger**, $\varepsilon_{\text{eff}} = 1.25\% + 40\%$ w.r.t 2011.
New algorithm based on Neural Net.
Calibrate mistag $\omega$ from the fit of $B_s$ oscillation in $B_s \to D_s \pi$ decays

Tagging power: $\varepsilon_{\text{eff}} = \varepsilon (1 - 2\omega)^2$

$\varepsilon = \frac{N(\text{tagged})}{N(\text{total})}$
$\omega = \frac{N(\text{wrong tag})}{N(\text{tagged})}$
Asymmetry Dilution

The mistag probability dilutes the asymmetry by $O(75\%)$.

Decay time resolution
Measured in control sample of prompt background with real $J/\psi$. Reduce the asymmetry by $O(30\%)$. 

$\phi_s = \frac{1}{4} \pi; \Delta m_s = 17.63 \text{ ps}^{-1}$

$B_s^0$ $\bar{B}_s^0$

PRD 87, 112010 (2013)
Angular Analyses

For $K^+K^-$ around the $\phi$ mass: P-wave (3 polarization amplitudes) and S-wave ($f_0(980)$ and non-resonant)

Disentangle the amplitudes by fitting helicity angles of final state particles (muons, kaons).

Properly describe angular acceptance with MC simulation. Deviation from uniformity within 10-20%.
Results

Analysis of 2011 data set, 27K signal events.

\[ \Gamma_s = 0.663 \pm 0.005 \pm 0.006 \text{ ps}^{-1} \]
\[ \Delta \Gamma_s = 0.100 \pm 0.016 \pm 0.003 \text{ ps}^{-1} \]

CP-violating phase:
\[ \phi_s = 0.007 \pm 0.09 \pm 0.01 \]
Consistent with the SM.
World’s best measurements.

2011+2012 results soon!
Expected resolutions
\[ \sigma(\phi_s) = 0.05 \]
\[ \sigma(\Delta \Gamma_s) = 0.009 \text{ ps}^{-1} \]
\[ \phi_s \text{ with } J/\psi \pi^+ \pi^- \]

Full 2011+2012 data set,

27100 \( B_s^0 \to J/\psi \pi^+ \pi^- \) candidates

Include the full amplitude analysis, and fit

B mass, decay time, \( m_{\pi^+ \pi^-} \) helicity angles.

Time acceptance from control sample of \( B^0 \to J/\psi K^* \) decay.

\[ \phi_s = 0.075 \pm 0.067 \pm 0.008 \]

Consistent with the SM.

Expect combination with 2011+2012 \( J/\psi \phi \)

arXiv:1405.4140
Accepted by PLB
Conclusions

CP violation in the $B_s^0$ system: rich opportunity to probe non-SM physics.

LHCb leads the effort.

Improved constraints: no anomalies but still room for NP. Measurements statistically dominated.

New update and more with 2011+2012 data coming soon!

O(30%) NP contributions still feasible
Backup
To constrain NP need to measure strength ($\Delta m_\text{s}$) and phase ($\phi_\text{s}$)

\[
\frac{\langle B^0_s|\mathcal{L}_\text{eff}|\bar{B}^0_s \rangle}{\langle B^0_s|\mathcal{L}_\text{SM}|\bar{B}^0_s \rangle} = |\Delta_s|e^{2i\phi^{\text{NP}}_s}
\]

$\Delta m_\text{s} = 17.768 \pm 0.024$ ps$^{-1}$

NJP 15 (2013) 053021
NP Bounds

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)} \]

<table>
<thead>
<tr>
<th>Bounds on ( \Lambda ) (TeV)</th>
<th>Bounds on ( c_i ) (( \Lambda = 1 ) TeV)</th>
<th>Mesons mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 10^2 - 10^5 )</td>
<td>( 10^{-11} - 10^{-7} )</td>
<td>( K^0 - \bar{K}^0 )</td>
</tr>
<tr>
<td>( 10^3 - 10^4 )</td>
<td>( 10^{-7} - 10^{-8} )</td>
<td>( D^0 - \bar{D}^0 )</td>
</tr>
<tr>
<td>( 10^2 - 10^3 )</td>
<td>( 10^{-7} - 10^{-6} )</td>
<td>( B^0 - \bar{B}^0 )</td>
</tr>
<tr>
<td>( 10^2 - 10^3 )</td>
<td>( 10^{-5} )</td>
<td>( B_s^0 - \bar{B}_s^0 )</td>
</tr>
</tbody>
</table>

### Systematics

#### Table 9: Statistical and systematic uncertainties.

| Source                                           | $\Gamma_s$ [ps$^{-1}$] | $\Delta \Gamma_s$ [ps$^{-1}$] | $|A_{\perp}|^2$ | $|A_0|^2$ | $\delta_{||}$ [rad] | $\delta_{\perp}$ [rad] | $\phi_s$ [rad] | $|\lambda|$ |
|--------------------------------------------------|-------------------------|--------------------------------|----------------|----------|-----------------|-----------------|---------------|-------------|
| Stat. uncertainty                                | 0.0048                  | 0.016                          | 0.0086         | 0.0061   | $^{+0.13}_{-0.21}$ | 0.22            | 0.091         | 0.031       |
| Background subtraction                          | 0.0041                  | 0.002                          | --             | 0.0031   | 0.03             | 0.02            | 0.003         | 0.003       |
| $B^0 \to J/\psi K^*$ background                 | --                      | 0.001                          | 0.0030         | 0.0001   | 0.01             | 0.02            | 0.004         | 0.005       |
| Ang. acc. reweighting                           | 0.0007                  | --                             | 0.0052         | 0.0091   | 0.07             | 0.05            | 0.003         | 0.020       |
| Ang. acc. statistical                           | 0.0002                  | --                             | 0.0020         | 0.0010   | 0.03             | 0.04            | 0.007         | 0.006       |
| Lower decay time acc. model                     | 0.0023                  | 0.002                          | --             | --       | --              | --              | --            | --          |
| Upper decay time acc. model                     | 0.0040                  | --                             | --             | --       | --              | --              | --            | --          |
| Length and mom. scales                          | 0.0002                  | --                             | --             | --       | --              | --              | --            | --          |
| Fit bias                                        | --                      | --                             | --             | --       | --              | --              | --            | --          |
| Decay time resolution offset                    | --                      | --                             | --             | --       | --              | --              | --            | --          |
| Quadratic sum of syst.                          | 0.0063                  | 0.003                          | 0.0064         | 0.0097   | 0.08             | 0.08            | 0.011         | 0.022       |
| Total uncertainties                             | 0.0079                  | 0.016                          | 0.0107         | 0.0114   | $^{+0.15}_{-0.23}$ | 0.23            | 0.092         | 0.038       |

[Phys. Rev. D 87, 112010]
Two solutions to the decay rates in $B_s^0 \to J/\Psi \phi$:

**Solution I**
- $\delta - \delta_0$
- $\delta_\perp - \delta_0$
- $\delta_s - \delta_0$
- $\Phi_s$
- $\Delta \Gamma_s$

**Solution II**
- $\delta_0 - \delta$
- $\pi - \delta_0 - \delta_\perp$
- $\delta_0 - \delta_s$
- $\pi - \Phi_s$
- $-\Delta \Gamma_s$

- P-wave phase ($\delta_\perp$) increases rapidly across $\phi(1020)$ mass resonance, S-wave ($\delta_s$) varies slowly.
- Measuring $\delta_s - \delta_\perp$ in bins of $M(K^+ K^-)$ resolves the ambiguity.
- LHCb results using $\mathcal{L} = 1\text{fb}^{-1}$ in 6 bins of $M(K^+ K^-)$:
  - The physical solution has to decrease in bins of $M(K^+ K^-)$.

**Solution I confirmed** $\implies$ positive $\Delta \Gamma_s$ fits expectations.
CPV in Mixing: $a^{s}_{s|l}$

Analyse $B^{0}_{s} \rightarrow D_{s}X\mu\nu$ decays (2011 data).

$$A_{\text{meas}} \equiv \frac{\Gamma[D_{s}^{-} \mu^{+}] - \Gamma[D_{s}^{+} \mu^{-}]}{\Gamma[D_{s}^{-} \mu^{+}] + \Gamma[D_{s}^{+} \mu^{-}]}$$

$$= a^{s}_{s|l} + \left[ a_{p} - a^{s}_{s|l} \right] \int_{t=0}^{\infty} e^{-\Gamma_{s} t} \cos(\Delta M_{s} t) \epsilon(t) \, dt$$

$$+ \int_{t=0}^{\infty} e^{-\Gamma_{s} t} \cosh(\frac{\Delta M_{s} t}{2}) \epsilon(t) \, dt$$

$B^{0}_{s}$ production asymmetry negligible: highly suppressed ($10^{-4}$) due to fast oscillations.

Opposite magnet polarities: cancel most of detection asymmetries of charged particles.

Using large control samples: correct for tracking (0.13%) and background asymmetries (0.05%); account for difference in trigger and PID efficiencies for $\mu^{+}$ and $\mu^{-}$.

$$a^{s}_{s|l} = (-0.06 \pm 0.50 \pm 0.36 \%)$$

World’s best measurement, consistent with SM expectation

D0 3σ deviation from SM neither ruled out nor confirmed
Full 2011+2012 data set.

Fit simultaneously the $m_{\pi^+\pi^-}$ spectrum and helicity angles.

Five interfering states. Adding also non-resonant $J/\psi\pi^+\pi^-$ describes well the data.

Given the resonances composition:

- CP-odd >97.7% confirmed @ 95% C.L.
- $f_0(500)$ not observed. Stringent limit on the mixing angle between $f_0(500)$ and $f_0(980)$: $|\phi_m| < 7.7^\circ$ @ 90% C.L.
### Table of Observables

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>LHC Run 1</th>
<th>LHCb 2018</th>
<th>LHCb upgrade</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$ mixing</td>
<td>$\phi_s(B_s^0 \to J/\psi \phi) \ (\text{rad})$</td>
<td>0.05</td>
<td>0.025</td>
<td>0.009</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td></td>
<td>$\phi_s(B_s^0 \to J/\psi f_0(980)) \ (\text{rad})$</td>
<td>0.09</td>
<td>0.05</td>
<td>0.016</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td></td>
<td>$A_{sl}(B_s^0) \ (10^{-3})$</td>
<td>2.8</td>
<td>1.4</td>
<td>0.5</td>
<td>0.03</td>
</tr>
<tr>
<td>Gluonic</td>
<td>$\phi_s^{\text{eff}}(B_s^0 \to \phi \phi) \ (\text{rad})$</td>
<td>0.18</td>
<td>0.12</td>
<td>0.026</td>
<td>0.02</td>
</tr>
<tr>
<td>Penguin</td>
<td>$\phi_s^{\text{eff}}(B_s^0 \to K^{*0}K^{*0}) \ (\text{rad})$</td>
<td>0.19</td>
<td>0.13</td>
<td>0.029</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$2\beta^{\text{eff}}(B_s^0 \to \phi K_S^{0}) \ (\text{rad})$</td>
<td>0.30</td>
<td>0.20</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed</td>
<td>$\phi_s^{\text{eff}}(B_s^0 \to \phi \gamma) \ (\text{rad})$</td>
<td>0.20</td>
<td>0.13</td>
<td>0.030</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>currents</td>
<td>$\tau^{\text{eff}}(B_s^0 \to \phi \gamma)/\tau_{B_s^0}$</td>
<td>5%</td>
<td>3.2%</td>
<td>0.8%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak</td>
<td>$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{GeV}^2/c^4)$</td>
<td>0.04</td>
<td>0.020</td>
<td>0.007</td>
<td>0.02</td>
</tr>
<tr>
<td>Penguin</td>
<td>$q_0^2 A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)$</td>
<td>10%</td>
<td>5%</td>
<td>1.9%</td>
<td>$\sim 7%$</td>
</tr>
<tr>
<td></td>
<td>$A_1(K\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{GeV}^2/c^4)$</td>
<td>0.14</td>
<td>0.07</td>
<td>0.024</td>
<td>$\sim 0.02$</td>
</tr>
<tr>
<td></td>
<td>$B(B^+ \to \pi^+\mu^+\mu^-)/B(B^+ \to K^+\mu^+\mu^-)$</td>
<td>14%</td>
<td>7%</td>
<td>2.4%</td>
<td>$\sim 10%$</td>
</tr>
<tr>
<td>Higgs</td>
<td>$B(B_s^0 \to \mu^+\mu^-) \ (10^{-9})$</td>
<td>1.0</td>
<td>0.5</td>
<td>0.19</td>
<td>0.3</td>
</tr>
<tr>
<td>Penguin</td>
<td>$B(B^0 \to \mu^+\mu^-)/B(B^0 \to \mu^+\mu^-)$</td>
<td>220%</td>
<td>110%</td>
<td>40%</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>Unitarity</td>
<td>$\gamma(B \to D^{(<em>)}K^{(</em>)})$</td>
<td>7°</td>
<td>4°</td>
<td>1.1°</td>
<td>negligible</td>
</tr>
<tr>
<td>Triangle angles</td>
<td>$\gamma(B_s^0 \to D_s^{\pm}K^{\mp})$</td>
<td>17°</td>
<td>11°</td>
<td>2.4°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta(B^0 \to J/\psi K_S^{0})$</td>
<td>1.7°</td>
<td>0.8°</td>
<td>0.31°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_T(D^0 \to K^+K^-) \ (10^{-4})$</td>
<td>3.4</td>
<td>2.2</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>CP violation</td>
<td>$\Delta A_{CP} \ (10^{-3})$</td>
<td>0.8</td>
<td>0.5</td>
<td>0.12</td>
<td>-</td>
</tr>
</tbody>
</table>
Track $\sigma_{p/p}: 0.4\%-0.6\%$

Decay time resolution 40-50 fs for fully reco’d decays

PID:
$\varepsilon(\mu)=97\%$, mis-id: $0.7\%$
$\varepsilon(K)>90\%$, $\pi$ mis-id: $<5\%$