Measurement of the $B_s^0$ mixing phase at LHCb

Sevda Esen

Physikalisches Institut Heidelberg
On behalf of the LHCb collaboration

November 18th, 2014

CERN LHC Seminar
Introduction: What is missing in Standard Model

- matter and anti-matter asymmetry
- why is the universe made of matter?
- not enough CP violation
- Are there other sources of CPV?

Presence of dark matter in the universe
- what is dark matter made of?
Flavor physics in the LHC era

High energy frontier

ATLAS & CMS

Direct searches $\rightarrow$ few TeV

Higgs discovery!

Precision frontier

LHCb

Indirect searches $\rightarrow$ O(100 TeV)

Quantum loop corrections
**CP violation in SM**

- Violation of combined Charge and Parity symmetry
- Discovered in the weak interaction in 1964
- accommodated in CKM mechanism $\Rightarrow$ small

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

*only source of CPV in SM*
Probes for new physics in $B^0_s$ mixing

\[
\frac{i}{\hbar} \frac{d}{dt} \begin{bmatrix} \vert B^0_s(t) \rangle \\ \vert \bar{B}^0_s(t) \rangle \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{11} \end{bmatrix} - \frac{i}{2} \begin{bmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{11} \end{bmatrix} \begin{bmatrix} \vert B^0_s(t) \rangle \\ \vert \bar{B}^0_s(t) \rangle \end{bmatrix}
\]

Mass eigenstates mixtures of weak states

\[
\vert B^0_{sH} \rangle = p \vert B^0_s \rangle - q \vert \bar{B}^0_s \rangle \quad \vert B^0_{sL} \rangle = p \vert B^0_s \rangle + q \vert \bar{B}^0_s \rangle
\]

- mass difference: $\Delta m_s = M_H - M_L \approx 2|M_{12}|$
  \(\Rightarrow\) rate of mixing diagram

- decay width difference:
  \(\Delta \Gamma_s = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\phi_{12}\)

- Mixing phase: $\phi_M = \text{arg}(M_{12})$
  \(\Rightarrow\) time dependent CP violation


S. Esen - Heidelberg

$B^0_s$ mixing phase at LHCb

November 18th, 2014 5 / 31
(1) CPV in decay:
\[ P(B \to f) \neq P(\bar{B} \to \bar{f}) \]

(2) CPV in mixing
\[ P(B \to \bar{B}) \neq P(\bar{B} \to B) \]

(3) CPV in the interference of decay and mixing
\[ P(B \to f) \neq P(B \to \bar{B} \to f) \]

Phase difference: \[ \phi_s = \phi_M - 2\phi_{\text{dec}} \]

More on CPV in mixing see:
Cern Seminar by M. Vesterinen
Sept. 30
CPV in the interference of decay and mixing

\( \phi_s \): relative phase between interfering
\( A(B_s^0 \to J/\psi h^+ h^-) \) and \( A(\bar{B}_s^0 \to \bar{J}/\psi h^+ h^-) \)

\( \phi_s \) is sensitive to new physics in \( B_s^0 \) mixing
\( \phi_s = \phi_s^{SM} + \Delta \phi_s \Rightarrow \Delta \phi_s = \arg(M_{12}/M_{12}^{SM}) \)

CP violation in decay given by:
\[
\lambda = \frac{q}{p} \frac{\bar{A}(\bar{B}_s^0 \to f_{CP})}{A(B_s^0 \to f_{CP})}, \text{ with } \phi_s = -\arg(\lambda)
\]

only if one dominant amplitude
\( +\Delta \phi_s^{pen} \) for penguin amplitude
Decay Channels to measure $\phi_s$

- $B_s^0 \rightarrow J/\psi K^+ K^-$: benchmark mode
- $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$: dominantly CP-odd

- $B_s^0 \rightarrow D_s^- D_s^+$: pure hadronic final state

- $B_s^0 \rightarrow \phi \phi$: pure penguin decay

* to estimate penguin contribution $B^0 \rightarrow J/\psi \rho$: tree + penguin
Status as of early 2014

- Atlas, D0 and CDF: $B_s^0 \to J/\psi K^+ K^-$
- LHCb: $B_s^0 \to J/\psi K^+ K^-$ and $B_s^0 \to J/\psi \pi^+ \pi^-$
Key ingredients

■ Theoretical time dependent CP asymmetry

\[ A_{CP}(t) = \frac{\Gamma(\bar{B}_s^0 \rightarrow f) - \Gamma(B_s^0 \rightarrow f)}{\Gamma(\bar{B}_s^0 \rightarrow f) + \Gamma(B_s^0 \rightarrow f)} = \eta_f \sin \phi_s \sin(\Delta m_s t) \]

■ Experimentally

\[ A_{CP} \approx (1 - 2w) e^{-\frac{1}{2} \Delta m_s^2 \sigma_t^2} \eta_f \sin \phi_s \sin(\Delta m_s t) \]

■ \(w\) Probability of getting the initial flavor wrong
■ \(\sigma_t\) Decay time resolution
■ \(\eta_f\) CP eigenvalue → angular analysis

■ Minimum requirements:

■ excellent decay time resolution
■ good flavor tagging
■ large statistics
LHCb experiment

Momentum resolution:
$\sigma_p/p: 0.4\% - 0.6\%$

Time resolution:
40-50 fs

Mass resolution:
$8\text{ MeV}/c^2$ for $B \rightarrow J/\psi X$ decays

Particle identification:
$\varepsilon(\mu) = 97\%, \text{ mis-id: 0.7\%}$
$\varepsilon(K) > 90\%, \text{ mis-id: 5\%}$

Data set in run I:
2010: 37 pb$^{-1}$ @ 7 TeV
2011: 1 fb$^{-1}$ @ 7 TeV
2012: 2 fb$^{-1}$ @ 8 TeV

All results shown today are with 3fb$^{-1}$
$B^0_s \to J/\psi K^+K^-$

- Theoretically clean, tree dominating decay
- Precise SM prediction:
  $\phi_s = (-0.036 \pm 0.002) \text{rad}$
- Signal: $95690 \pm 350$ events

- Background:
  - combinatorial
  - peaking:
    - $\Lambda^0_b \to J/\psi p K^-$: 4800 evt.
    - $B_d \to J/\psi K^+\pi^-$: 1700 evt.
Background subtraction

Background events subtracted statistically

⇒ avoid parametrization in multiple dimensions

- Combinatorial background:
  - discriminating variable: $J/\psi K^+ K^-$ mass
  - assign a signal weight to each event
- Peaking backgrounds:
  - MC events re-weighted to match data
  - added to data with negative weights

![Graph](attachment:image.png)
Angular analysis of $B_s^0 \rightarrow J/\psi K^+ K^-$

$P \rightarrow VV$ final state

$K^+ K^-$ in P-wave: 0 (CP even), $\parallel$ (CP even), $\perp$ (CP odd)

$K^+ K^-$ in S-wave: CP odd

Mixture of CP-even and -odd
⇒ need angular analysis to disentangle
⇒ have access to both $\Gamma_s$ and $\Delta \Gamma_s$

Use of helicity angles: $\Omega(\theta_\mu, \theta_K, \phi_h)$
\( B^0_s \rightarrow J/\psi K^+ K^- \) Fit Model

simultaneous fit in:
- six bins of \( m(K^+ K^-) \) to account for S-wave

Acceptance

- Angular acceptance
  - detector acceptance and event selection
  - based on data corrected simulation

- Time acceptance:
  - selection, reconstruction
  - obtained from data
$B_s^0 \rightarrow J/\psi K^+ K^-$ time resolution

calibration with prompt $J/\psi$

$\sigma(z) \sim 100 \mu m$

$\sigma(z) 300 \mu m$

$K^+$

$\phi$

$K^-$

$\mu^+$

$\mu^-$

$J/\psi$

$S. Esen - Heidelberg$

$B_s^0$ mixing phase at LHCb

November 18th, 2014

$t = d \times m_B/p_B$

c.f. oscillation period $\sim 350$ fs

- $\sigma_t$ per-event decay time error
- average $\sim 45$ fs $\Rightarrow$ dilution factor $e^{-\frac{1}{2} \Delta m_s^2 \sigma_t^2} = 0.73$
\( B_s^0 \rightarrow J/\psi K^+ K^- \) Flavor tagging

need to resolve fast oscillations of \( B_s^0-\bar{B}_s^0 \)

b quarks are produced in pairs:

- **Same-side tagging:**
  
  Use charge of kaon produced in the fragmentation

- **Opposite-side tagging:**
  
  Use charge of final state particles of other B

\begin{align*}
\text{total tagging power: } & \epsilon(1 - w)^2 = (3.73 \pm 0.15)\% \\
\star & 20\% \text{ improvement compare to } 1\text{fb}^{-1} \text{ analysis}
\end{align*}
\( \mathcal{B}_s^0 \rightarrow J/\psi K^+ K^- \) results arXiv:1411.3104

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi_s ) [rad]</td>
<td>(-0.058 \pm 0.049 \pm 0.006)</td>
</tr>
<tr>
<td>(</td>
<td>\lambda</td>
</tr>
<tr>
<td>( \Delta \Gamma_s ) [ps(^{-1})]</td>
<td>(0.0805 \pm 0.0091 \pm 0.0033)</td>
</tr>
<tr>
<td>( \Gamma_s ) [ps(^{-1})]</td>
<td>(0.6603 \pm 0.0027 \pm 0.0015)</td>
</tr>
<tr>
<td>( \Delta m_s ) [ps(^{-1})]</td>
<td>(17.711 \pm 0.055 \pm 0.011)</td>
</tr>
</tbody>
</table>

\[\text{Candidates / (0.2 ps)}\]

\[\text{LHCb}\]

\[\text{Decay time [ps]}\]

\[\text{Candidates / (0.05 \pi \text{ rad})}\]

\[\text{LHCb}\]

\[\phi_{\theta} \text{ vs. } \cos \theta_{\mu}\]

\[\phi_{\theta} \text{ vs. } \cos \theta_{K}\]

\[\text{B}_s^0 \text{ mixing phase at LHCb}\]

November 18\(^{th}\), 2014
For non-negligible penguin contributions

- size of pollution could be different for 3 P-wave and the S-wave states
- CPV might be polarization dependent
- complicates the search for NP effects

We measure:

\[
\lambda_f = \frac{q}{p} \frac{\bar{A}_f}{A_f} = |\lambda_f| e^{-i\phi_f}
\]

for each \( f = 0, \parallel, \perp, S \)

assume zero CPV in mixing

| \( \phi_s^0 \) [rad] | \(-0.045 \pm 0.053 \pm 0.007\) |
| \( \phi_s^\parallel - \phi_s^0 \) [rad] | \(-0.018 \pm 0.043 \pm 0.009\) |
| \( \phi_s^\perp - \phi_s^0 \) [rad] | \(-0.014 \pm 0.035 \pm 0.006\) |
| \( \phi_s^S - \phi_s^0 \) [rad] | \(0.015 \pm 0.061 \pm 0.021\) |

| \( |\lambda^0|\) | \(1.012 \pm 0.058 \pm 0.013\) |
| \( |\lambda^\parallel/\lambda^0|\) | \(1.02 \pm 0.12 \pm 0.05\) |
| \( |\lambda^\perp/\lambda^0|\) | \(0.97 \pm 0.16 \pm 0.01\) |
| \( |\lambda^S/\lambda^0|\) | \(0.86 \pm 0.12 \pm 0.04\) |

e.g., Bhattacharya, Datta, Int. J. Mod, Phys. A28(2013) 1350063
$B^0_s \rightarrow J/\psi \pi^+ \pi^-$

- 27100 ± 200 signal events
- Effective time resolution: 40.3 fs
- Effective tagging power: (3.89 ± 0.25)%

- from the amplitude analysis
  2.3% CP even @ 95% CL
- largest component $f_0(980)$
$\mathcal{B}_s^0 \rightarrow J/\psi \pi^+ \pi^-$ Phys. Lett. B 736 (2014) 186

* 6 dimensional fit: $m_{\pi\pi}$, $m_{J/\psi \pi \pi}$, $t$ and $\Omega$

Results:

$\phi_s = 0.070 \pm 0.068 \pm 0.008$ rad

$|\lambda| = 0.89 \pm 0.05 \pm 0.01$
\[ B_s^0 \rightarrow J/\psi K^+ K^- \quad \text{and} \quad B_s^0 \rightarrow J/\psi \pi^+ \pi^- \] Combination

under the assumptions:
- both decays proceed dominantly via \( b \rightarrow c\bar{c}s \)
  \[ \Rightarrow \text{CPV in decay same} \]
- ratio between penguin and tree diagrams is the same

\[
\begin{array}{ccc}
B_s^0 \rightarrow J/\psi K^+ K^- & B_s^0 \rightarrow J/\psi \pi^+ \pi^- & \text{Combined} \\
\phi_s [\text{rad}] & -0.058 \pm 0.049 \pm 0.006 & 0.070 \pm 0.068 \pm 0.008 & -0.010 \pm 0.039 \\
|\lambda| & 0.964 \pm 0.019 \pm 0.007 & 0.89 \pm 0.05 \pm 0.01 & 0.957 \pm 0.017
\end{array}
\]

* correlations between common parameters are accounted for
$B_s^0 \rightarrow D^- D_s^+$

- another decay with $b \rightarrow c\bar{c}s$ transition ➞ measurement of $\phi_s$ in a hadronic final state
- just CP-even ➞ no angular analysis
- what about the penguin?

3345 ± 62 events in 3 fb$^{-1}$

Control channel: $B_s^0 \rightarrow D^- D_s^+$

21320 ± 148 events
\[ \mathcal{B}_s^0 \rightarrow D_s^- D_s^+ \]

- background subtracted decay time fit
- per-event decay time resolution
- effective resolution: 54 fs
- flavor tagging
  - effective tag. pow.: \((5.33 \pm 18 \pm 17)\%\)

\[ \varepsilon(t) = \varepsilon_{D_sD}(t) \times \frac{\varepsilon_{DsDs}^\text{sim}(t)}{\varepsilon_{DsD}^\text{sim}(t)} \]

Results:

\[ \phi_s = 0.02 \pm 0.17(\text{stat}) \pm 0.02(\text{syst}) \text{ rad} \]
\[ |\lambda| = 0.91^{+0.18}_{-0.17}(\text{stat}) \pm 0.02(\text{syst}) \]

\( \Rightarrow \) consistent with other measurements
\( \Rightarrow \) consistent with no CPV in decay
$\phi_s - \Delta \Gamma_s$ world average

68% CL contours ($\Delta \log \mathcal{L} = 1.15$)

- DØ 8 fb$^{-1}$
- CMS 20 fb$^{-1}$
- CDF 9.6 fb$^{-1}$
- LHCb 3 fb$^{-1}$
- ATLAS 4.9 fb$^{-1}$
- Combined SM

S. Esen - Heidelberg

B$^0_s$ mixing phase at LHCb

November 18th, 2014
Side note: $\phi_s$ in $B_s^0 \to \phi\phi$ Phys. Rev. D 90 (2014) 052011

- forbidden at tree level in SM sensitivity to NP in decay
- gluonic $b \to s\bar{s}s$ transition

$\phi_s^{s\bar{s}s} < 0.02$ rad

$\phi_s = -0.17 \pm 0.15(stat) \pm 0.03(syst)$ rad

$|\lambda| = 1.04 \pm 0.07 \pm 0.03(syst)$

$\Rightarrow$ agreement with prediction

$\Rightarrow$ no evidence of CPV in decay or mixing
Penguin Pollution in $\phi_s$

What we really measure:
$$\phi_s = \phi_{SM} + \Delta\phi_{NP} + \Delta\phi_{pen}$$

- doubly Cabibbo suppressed
- non-perturbative hadronic enhancements?

Control penguins via flavor symmetry:
- use U-spin-related modes
  $\Rightarrow$ with increased relative penguin influence
- can extract $\Delta\phi_{pen}$
  $\Rightarrow$ with problem of dependence on SU(3) breaking
- Useful modes: $B_s^0 \rightarrow J/\psi K^*$ and $B^0 \rightarrow J/\psi \rho$
$B^0 \rightarrow J/\psi\pi^+\pi^-$

17650 ± 200 signal events

- from amplitude analysis
- 65% of signal from $B^0 \rightarrow J/\psi\rho$
$B^0 \rightarrow J/\psi \pi^+ \pi^-$ arXiv:1411.1634

- using $B^0 \rightarrow J/\psi \rho$ events:
  
  \[ 2\beta_{J/\psi \rho} = (41.7 \pm 9.6^{+2.8}_{-6.3})^\circ \]

- and $2\beta$ from $B^0 \rightarrow J/\psi K_S$

- Penguin contribution:
  
  \[ \Delta 2\beta = 2\beta_{J/\psi \rho} - 2\beta_{J/\psi K_S} \]

- from SU(3) symmetry $\epsilon = \frac{|V_{us}|^2}{1-|V_{us}|^2}$
  
  the penguin shift in $\phi_s$: $\delta_P \approx -\epsilon \Delta 2\beta$
  
  $\Rightarrow [-1.05^\circ, 1.18^\circ]$ @ 95% CL
Prospects

- Additional decay modes can reduce $\phi_s$ uncertainty
  
  $B_s^0 \to J/\psi(e^+e^-)K^+K^-$
  
  $B_s^0 \to \psi(2S)K^+K^-$
  
  $B_s^0 \to J/\psi K^+K^-$ (above $\phi$ mass)

- More studies on penguin contributions

  Decays related by flavor symmetry: $B_s^0 \to J/\psi K^*, B_s^0 \to J/\psi K_S^0, B^0 \to J/\psi \omega$

- Projected sensitivity

<table>
<thead>
<tr>
<th></th>
<th>Run 1 (2010-12)</th>
<th>Run 2 (2015-17)</th>
<th>Upgrade (2019-)</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0 \to J/\psi K^+K^-$</td>
<td>0.05</td>
<td>0.025</td>
<td>0.009</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td>$B_s^0 \to J/\psi \pi^+\pi^-$</td>
<td>0.09</td>
<td>0.05</td>
<td>0.016</td>
<td>$\sim 0.001$</td>
</tr>
<tr>
<td>$B_s^0 \to \phi\phi$</td>
<td>0.18</td>
<td>0.12</td>
<td>0.026</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Summary

- LHC run I data proven to be fruitful for $\phi_s$
  - experimental $\sigma(\phi_s) < 0.038$

  \[
  \begin{align*}
  \text{SM} & \quad \phi_s^{\text{obs}} \quad \text{[rad]} \\
  \text{D0, J/ψKK} & \quad 8 \text{ fb}^{-1} \\
  \text{CDF, J/ψKK} & \quad 9.6 \text{ fb}^{-1} \\
  \text{ATLAS, J/ψKK} & \quad 4.9 \text{ fb}^{-1} \\
  \text{CMS, J/ψKK} & \quad 20 \text{ fb}^{-1} \\
  \text{LHCb, D_sD_s} & \quad 3 \text{ fb}^{-1} \\
  \text{LHCb, J/ψKK+J/ψππ} & \quad 3 \text{ fb}^{-1} \\
  \text{World average} & 
  \end{align*}
  \]

- first polarization dependent measurements
- first measurement in a purely penguin mode $B_s^0 \rightarrow \phi\phi$

- good agreement with SM overall
- expected sensitivity $\sim 0.02$ by the end of Run 2
- theory input needed for penguin pollution estimates
BACKUP
**Side note: $\phi_s$ in $B_s^0 \rightarrow \phi\phi$**

$\phi_s = -0.17 \pm 0.15 (\text{stat}) \pm 0.03 (\text{syst}) \ \text{rad}$

$|\lambda| = 1.04 \pm 0.07 \pm 0.03 (\text{syst})$

$\Rightarrow$ agreement with prediction

$\Rightarrow$ no evidence of CPV in decay or mixing
penguin amplitude not suppressed measure an effective $2\beta_{\text{eff}}$

$$\eta_f \lambda_f = |\lambda_f| e^{-i2\beta_{\text{eff}}^f} = \frac{1-a_f' e^{i\theta_f} e^{-i\gamma}}{1-a_f' e^{i\theta_f} e^{i\gamma}} e^{-i2\beta}$$

eff. penguin amplitude relative to tree amplitude: $a_f'$ and $\theta_f'$

$$\Delta 2\beta_f = 2\beta_{\text{eff}}^f - 2\beta$$

from SU(3) symmetry $\epsilon = \frac{|V_{us}|^2}{1-|V_{us}|^2}$

the penguin shift in $2\beta$: $\delta_P \approx \epsilon \Delta 2\beta_f$