Time-dependent CP violation in $B_s^0$ decays at LHCb

Emmy Gabriel (University of Edinburgh) on behalf of the LHCb Collaboration

FPCP May 6-10 2019
Victoria, Canada
The Standard Model (SM) fails to explain the matter-antimatter difference observed in our universe. Looking for new sources of CP violation (CPV) can help explain this asymmetry.

$B^0_s$ mixing provides a sensitive probe to new physics. Measurement of the CP violation phase, $\phi^{c\bar{c}s}_s = -2\beta_s$, allows for precision SM tests.
Motivation

- \( \phi_s^{c\bar{c}s} = -2\beta_s \) measured in \( B_s^0 \) decays. Dependent on the CKM angle \( \beta_s \).
- Analogous to CKM angle \( \beta \) in the \( B^0 \) system.

\( \phi_M = 2\text{arg}(V_{ts}V_{tb}^*) \)

\( \beta_s \equiv \text{arg}\left( \frac{-V_{ts}V_{tb}^*}{V_{ts}V_{tb}} \right) \)

\( \phi_s \equiv \phi_{\text{mix}} - 2\phi_{\text{dec}} \)

Interference between mixing and decay allows measurements of \( \phi_s \).
• Run 1 + 2015 + 2016 data  
  [3.2 fb⁻¹] [0.3 fb⁻¹] [1.6 fb⁻¹]

Decay dominated by a penguin loop:  
→ Enhanced sensitivity to New Physics

• 2015 + 2016 data  
  [0.3 fb⁻¹] [1.6 fb⁻¹]

Two analyses on $B^0_s \rightarrow J/\psi h^+ h^-$:  
• $h^+ h^- = K^+ K^-$ ($\phi$ mass region)  
  [0.99, 1.05] GeV/c²  
• $h^+ h^- = \pi^+ \pi^-$

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Emmy Gabriel

FPCP 2019, Victoria
What do we want to measure?

Time-dependent angular analysis used to disentangle CP-even and CP-odd final states.

Simultaneous fit to the decay-time and three helicity angles performed to extract the fit parameters.

$B_s^0 \rightarrow J/\psi K^+ K^-$

Measure

$\Delta \Gamma_s$

and

$\Gamma_s - \Gamma_d$

$b \rightarrow c\bar{c}s$
transition:
CPV phase

$\phi^{c\bar{c}s}_s$

Measure

$\Gamma_H - \Gamma_d$
(final state is 97.7% CP-odd)

$B_s^0 \rightarrow J/\psi \pi^+ \pi^-$

$B_s^0 \rightarrow \phi \phi$

$b \rightarrow s\bar{s}s$
transition:
CPV phase

$\phi^{s\bar{s}s}_s$

Direct CPV parameter
SM predictions: $\phi^{sss}_s$ in context of QCD factorisation close to zero by SM, with errors of $\sim 2\%$.

Certain BSM scenarios allow for significant CPV in $b \to s\bar{s}s$ penguin decays.

SM prediction: $\phi^{c\bar{c}s}_s$ SM $= -36.9^{+1.0}_{-0.7}$ [mrad]

Experimental status: HFLAV 2018

arXiv:0810.0249

Analysis ingredients

1. Selection
2. Decay-time resolution
3. Angular selection efficiency
4. Decay-time efficiency
5. Flavour tagging
Analysis ingredients

1. Selection
2. Decay-time resolution
3. Angular selection efficiency
4. Decay-time efficiency
5. Flavour tagging
Signal selection

\[ B_s^0 \rightarrow \phi\phi \]
LHCb-PAPER-2019-019

\[ B_s^0 \rightarrow J/\psi K^+ K^- \]
LHCb-PAPER-2019-013

\[ B_s^0 \rightarrow J/\psi \pi^+ \pi^- \]
arXiv:1903.05530

Neural network trained to remove background.

Boosted decision tree trained to remove background events.

\[ \Lambda_b^0 \rightarrow J/\psi pK \] background subtracted using negative weighted MC.

Wrong sign \((\pi^\pm \pi^\mp)\) combination used to determine combinatorial background shape.

~8500 signal events.

~117 000 signal events.

~33 500 signal events.
Analysis ingredients

1. Selection
2. Decay-time resolution
3. Angular selection efficiency
4. Decay-time efficiency
5. Flavour tagging
Decay-time resolution

Necessary to resolve the fast flavour oscillations induced by $B_s^0 - \bar{B}_s^0$ mixing.

Decay-time resolution of ~41-45 fs reached at LHCb.

$B^0_s \rightarrow \phi\phi$
LHCb-PAPER-2019-019

$B^0_s \rightarrow J/\psi K^+ K^-$
LHCb-PAPER-2019-013

$B^0_s \rightarrow J/\psi \pi^+ \pi^-$
arXiv:1903.05530

Decay-time resolution calibrated on prompt pseudo-2-body samples.

Prompt $J/\psi$ sample used to calibrate the decay-time resolution.
Analysis ingredients

1. Selection
2. Decay-time resolution
3. Angular selection efficiency
4. Decay-time efficiency
5. Flavour tagging
Angular efficiency

Need to account for non-uniform selection efficiency in decay angles as a result of detector acceptance and kinematic selection.

- Simulated events with same selection as data events to determine the efficiency correction.
- Similar procedure for \( B_s^0 \rightarrow J/\psi h^+ h^- \) decays.
Analysis ingredients

1. Selection
2. Decay-time resolution
3. Angular selection efficiency
4. Decay-time efficiency
5. Flavour tagging
Decay-time efficiency

$B_s^0 \rightarrow \phi \phi$

LHCb-PAPER-2019-019

$B_s^0 \rightarrow J/\psi \pi^+ \pi^-$

arXiv:1903.05530

$B_s^0 \rightarrow J/\psi K^+ K^-$

LHCb-PAPER-2019-013

Run 1: $B_s^0 \rightarrow D_s^- \pi^+$

Run 2: $B^0 \rightarrow J/\psi K^{*0}$

$B^0 \rightarrow J/\psi K^{*0}$ used as control mode.

Different control samples used in Run 1 and Run 2 due to difference in the High Level Trigger (HLT).
Analysis ingredients

1. Selection
2. Decay-time resolution
3. Angular selection efficiency
4. Decay-time efficiency
5. Flavour tagging
Flavour tagging

- **Aim:** tag the flavour of the B meson at production.
- **Precision of** \( \phi_s \) **measurement scales with the tagging power.**
- **Tagging algorithms calibrated using modes with known flavour. E.g.** \( B^+ \rightarrow J/\psi K^+ \), \( B_s^0 \rightarrow D_s^- \pi^+ \).

\[ \epsilon = \text{tagging efficiency} \]
\[ D = \text{dilution factor} \]

**Tagging power achieved:**

- \( B_s^0 \rightarrow J/\psi \pi^+ \pi^- \)
  \[ \epsilon D^2 = 5.06 \pm 0.38\% \]
  \[ \text{arXiv:1903.05530} \]

- \( B_s^0 \rightarrow J/\psi K^+ K^- \)
  \[ \epsilon D^2 = 4.73 \pm 0.34\% \]
  \[ \text{LHCb-PAPER-2019-013} \]

- \( B_s^0 \rightarrow \phi \phi \)
  \[ \epsilon D^2 = 5.74 \pm 0.43\% \]
  \[ \text{LHCb-PAPER-2019-019} \]
Analysis ingredients

1. Selection
2. Decay-time resolution
3. Angular selection efficiency
4. Decay-time efficiency
5. Flavour tagging
Simultaneous fit to decay time and helicity angles.

**Total fit**
- CP-even P-wave
- CP-odd P-wave
- S-wave combined with double S-wave

S-wave component stems from the $f^0(980)$ resonance (close to the $\phi(1020)$ in mass)

Fit projections

$B^0_s \rightarrow \phi\phi$

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Simultaneous fit to decay time and helicity angles in 6 $m(K^+K^-)$ bins.

Fit binned in $m(K^+K^-)$ to control interference between S-wave and P-wave contributions.
Fit projections

$B^0_s \rightarrow J/\psi \pi^+ \pi^-$

Simultaneous fit to decay time, helicity angles and $m(\pi^+ \pi^-)$.

Yields/ (15 MeV)

Yields/ (0.1 ps)

Yields/ (0.1 rad)

Yields/ (0.05 ps)

Data and fit

$f_0(980)$

$f_0(1500)$

$f_0(1790)$

$f_2(1270)$

$f'_2(1525)$

NR
Results

\( B^0_s \to \phi \phi \)

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Polarisation independent fit

\[ \phi^{ss} = -0.073 \pm 0.115 \pm 0.027 \text{ [rad]} \]

\[ |\lambda| = -0.99 \pm 0.05 \pm 0.01 \]

Most precise measurements to date in this decay mode. Measurements dominated by statistical error.

Results in agreement with SM predictions.

Assumptions (due to limited statistics):
- \( \phi_s,0 \) is CP conserving
- No direct CPV

Polarisation dependent fit

\[ B^0_s \to \phi \phi \]

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\[ \phi_{s,\parallel} = 0.014 \pm 0.055 \pm 0.011 \text{ [rad]} \]

\[ \phi_{s,\perp} = 0.044 \pm 0.059 \pm 0.019 \text{ [rad]} \]

Stay tuned for update full Run 2 data result!
Results

\[ B_s^0 \rightarrow J/\psi K^+ K^- \]
LHCb-PAPER-2019-013

\[ \phi_s^{c\bar{c}s} = -0.083 \pm 0.041 \pm 0.006 \text{ [rad]} \]

\[ |\lambda| = 1.012 \pm 0.016 \pm 0.006 \]

\[ \Gamma_s - \Gamma_d = -0.0041 \pm 0.0024 \pm 0.0015 \text{ [ps}^{-1}\text{]} \]

\[ \Delta \Gamma_s = -0.0772 \pm 0.0077 \pm 0.0026 \text{ [ps}^{-1}\text{]} \]

\[ B_s^0 \rightarrow J/\psi \pi^+ \pi^- \]
arXiv:1903.05530

\[ \phi_s^{c\bar{c}s} = -0.057 \pm 0.060 \pm 0.011 \text{ [rad]} \]

\[ |\lambda| = 1.01^{+0.08}_{-0.06} \pm 0.03 \]

\[ \Gamma_H - \Gamma_d = -0.050 \pm 0.004 \pm 0.004 \text{ [ps}^{-1}\text{]} \]

Most precise single measurement of \( \phi_s^{c\bar{c}s} \), \( \Delta \Gamma_s \) and \( \Gamma_s - \Gamma_d \).

All results are in agreement with SM predictions.
Combination

LHCb have performed many analyses measuring $\phi_s^{c\bar{c}s}$.

LHCb Run 1 analyses

1. $B_s^0 \rightarrow \psi(2S)\phi$
2. $B_s^0 \rightarrow D^+_s D^-_s$
3. $B_s^0 \rightarrow J/\psi K^+ K^-$ (high mass range)
4. $B_s^0 \rightarrow J/\psi K^+ K^-$
5. $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$

![Graph showing the combination of LHCb Run 1 analyses with data from ATLAS, CMS, CDF, and D0 experiments.](image)
Combination

LHCb have performed many analyses measuring $\phi_s^{c\bar{c}s}$.

Including the LHCb Run 2 analyses

$B_s^0 \rightarrow J/\psi K^+ K^-$
LHCb-PAPER-2019-013

$B_s^0 \rightarrow J/\psi \pi^+ \pi^-$
arXiv:1903.05530

$\phi_s^{c\bar{c}s} = -0.040 \pm 0.025$ [rad]
$|\lambda| = 0.991 \pm 0.010$
$\Delta \Gamma_s = 0.0816 \pm 0.0048$ [ps$^{-1}$]
$\Gamma_s - \Gamma_d = -0.0024 \pm 0.0018$ [ps$^{-1}$]

Preliminary ATLAS result:
ATLAS-CONF-2019-009
Conclusion

• The latest CP violation measurements presented have made a tremendous improvement in the experimental precision.

• Currently LHCb is producing some of the world’s most precise $\phi_s$ measurements.

• With the ongoing upgrade and more Run 2 data to analyse, the statistical precision of these measurements will increase further.

arXiv:1808.08865
Thank you for your attention.
Questions?
Backup
Run 1 results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_s$ (ps$^{-1}$)</td>
<td>$0.6603 \pm 0.0027 \pm 0.0015$</td>
</tr>
<tr>
<td>$\Delta \Gamma_s$ (ps$^{-1}$)</td>
<td>$0.0805 \pm 0.0091 \pm 0.0032$</td>
</tr>
<tr>
<td>$</td>
<td>A_{\perp}</td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
</tr>
<tr>
<td>$\delta_{\parallel}$ (rad)</td>
<td>$3.26^{+0.10+0.06}_{-0.17-0.07}$</td>
</tr>
<tr>
<td>$\delta_{\perp}$ (rad)</td>
<td>$3.08^{+0.14}_{-0.15} \pm 0.06$</td>
</tr>
<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 m_s$ (ps$^{-1}$)</td>
<td>$17.711^{+0.055}_{-0.057} + 0.011$</td>
</tr>
</tbody>
</table>

Run 1 results

$\phi_s = 70 \pm 68 \pm 8$ mrad

$|\lambda| = 0.89 \pm 0.05 \pm 0.01$
$B^0_s \rightarrow \phi \phi$

Phys. Rev. D 90, 052011

Run 1 results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best fit value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_s$ (rad)</td>
<td>$-0.17 \pm 0.15$</td>
</tr>
<tr>
<td>$</td>
<td>\lambda</td>
</tr>
<tr>
<td>$</td>
<td>A_{\perp}</td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
</tr>
<tr>
<td>$\delta_1$ (rad)</td>
<td>$0.13 \pm 0.23$</td>
</tr>
<tr>
<td>$\delta_2$ (rad)</td>
<td>$2.67 \pm 0.23$</td>
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<tr>
<td>$\Gamma_s$ (ps$^{-1}$)</td>
<td>$0.662 \pm 0.006$</td>
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<tr>
<td>$\Delta \Gamma_s$ (ps$^{-1}$)</td>
<td>$0.102 \pm 0.012$</td>
</tr>
<tr>
<td>$\Delta m_s$ (ps$^{-1}$)</td>
<td>$17.774 \pm 0.024$</td>
</tr>
</tbody>
</table>
### Predictions

**arXiv:1309.2293**

<table>
<thead>
<tr>
<th></th>
<th>2003</th>
<th>2013</th>
<th>Stage I</th>
<th>Stage II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>V_{ud}</td>
<td>$</td>
<td>0.9738 ± 0.0004</td>
<td>0.97425 ± 0 ± 0.00022</td>
</tr>
<tr>
<td>$</td>
<td>V_{us}</td>
<td>(K_{L3})$</td>
<td>0.2228 ± 0.0039 ± 0.0018</td>
<td>0.2258 ± 0.0008 ± 0.0012</td>
</tr>
<tr>
<td>$</td>
<td>e_K</td>
<td>$</td>
<td>(2.282 ± 0.017) × 10^{-3}</td>
<td>(2.228 ± 0.011) × 10^{-3}</td>
</tr>
<tr>
<td>$\Delta m_d$ [ps^{-1}]</td>
<td>0.502 ± 0.006</td>
<td>0.507 ± 0.004</td>
<td>id</td>
<td>id</td>
</tr>
<tr>
<td>$\Delta m_\tau$ [ps^{-1}]</td>
<td>&gt; 14.5 [95% CL]</td>
<td>17.768 ± 0.024</td>
<td>id</td>
<td>id</td>
</tr>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>\times 10^3$ ($b\to c\ell\bar{\nu}$)</td>
<td>41.6 ± 0.58 ± 0.8</td>
<td>41.15 ± 0.33 ± 0.59</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>\times 10^3$ ($b\to u\ell\bar{\nu}$)</td>
<td>3.90 ± 0.08 ± 0.68</td>
<td>3.75 ± 0.14 ± 0.26</td>
</tr>
</tbody>
</table>

- **$\sin 2\beta$**
  - 0.726 ± 0.037

- **$\alpha$ (mod $\pi$)**
  - (85.4^{+4.0}_{-3.8})^\circ
  - (91.5 ± 2)^\circ [17]

- **$\gamma$ (mod $\pi$)**
  - (68.0^{+8.0}_{-8.6})^\circ
  - (67.1 ± 4)^\circ [17, 18]

- **$\beta_s$**
  - 0.0065^{+0.0450}_{-0.0415}
  - 0.0178 ± 0.012 [18]

- **$B(B\to \tau\nu) \times 10^4$**
  - 1.15 ± 0.23 [17]

- **$B(B\to \mu\nu) \times 10^7$**
  - 3.7 ± 0.9 [17]

- **$A^s_{SL} \times 10^4$**
  - 10 ± 140
  - 23 ± 26
  - -22 ± 52 [18]

- **$A^g_{SL} \times 10^4$**
  - -22 ± 52 [18]

- **$\bar{m}_c$**
  - 1.2 ± 0.2

- **$\bar{m}_t$**
  - 167.0 ± 5.0

- **$\alpha_s(m_Z)$**
  - 0.1172 ± 0 ± 0.00020

- **$B_K$**
  - 0.86 ± 0.06 ± 0.14

- **$f_{B_s} [\text{GeV}]$**
  - 0.217 ± 0.012 ± 0.011

- **$f_{B_d}/f_{B_s}$**
  - 1.37 ± 0.14

- **$B_{B_s}/B_{B_d}$**
  - 1.21 ± 0.05 ± 0.01

- **$\tilde{B}_{B_s}/\tilde{B}_{B_d}$**
  - 1.00 ± 0.02

- **$\bar{B}_{B_s}/\tilde{B}_{B_d}$**
  - 1.01 ± 0 ± 0.03

- **$\bar{B}_{B_s}$**
  - 0.91 ± 0.03 ± 0.12
Decay-time resolution

Run 1: $B^0_s \rightarrow D_s^- \pi^+$
Run 2: $B^0 \rightarrow J/\psi K^{*0}$

Different samples used in Run 1 and Run 2 due to difference in the Higher Level Trigger (HLT).

Want a decay-time unbiased control sample.

**Run 1:** stripping line for control sample is BDT based (same bias as our decay).

**Run 2:** completely decay-time unbiased stripping/trigger selection.
**External Inputs**

$B_s^0$ decay width, $\Gamma_s$, and decay width difference, $\Delta \Gamma_s$, Gaussian constrained to values measured in Run 1 $B_s^0 \rightarrow J/\psi \phi$ and $B_s^0 \rightarrow J/\psi \pi \pi$ combination (arXiv:1411.3104).

With enough control over the decay time acceptance, the mode could also provide an important measurement of $\Delta \Gamma_s$.

External inputs of the $B_s^0$ oscillation frequency improves the accuracy of the measurement (arXiv:1304.4741).