$B_s^0 \rightarrow J/\psi \, K^+K^-$ and other time-dependent analyses at LHCb

Katya Govorkova
on behalf of the LHCb Collaboration

Implications Workshop
16 October 2019
\[\sin(2\beta)\]

- \(B^0 \rightarrow \psi(2S) K_s\)
  - Run1 JHEP 11 (2017) 170
- \(B^0 \rightarrow J/\psi K_s\)
  - Run1 PRL 115 (2015) 031601
- \(B^0 \rightarrow D^+ D^-\)
  - Run1 PRL 117 (2016) 261801
- \(B^0 \rightarrow D^{\ast\pm} D^{\mp}\)
  - Run1+2 LHCb-PAPER-2019-036 in preparation

\[\phi_s\] from penguins

- \(B_s^0 \rightarrow (K^+\pi^-)(K^-\pi^+)\)
  - Run1 JHEP 03 (2018) 140
- \(B_s^0 \rightarrow \phi \phi\)
  - Run1+2(15,16) arXiv:1907.10003
- \(B_s^0 \rightarrow \phi \gamma\)
  - Run1 PRL 123 (2019) 081802

\[\gamma\]

- \(B_s^0 \rightarrow D_s^{\ast\mp} K^\pm\)
  - Run1 JHEP 06 (2015) 130
- \(B_s^0 \rightarrow D_s K\)
  - Run1 JHEP 03 (2018) 059
- \(B^0 \rightarrow D^{\mp} \pi^\pm\)
  - Run2(15+16) JHEP 06 (2018) 084

\[\alpha\]

- \(B^0_{(s)} \rightarrow h^\pm h^{\mp}\)
  - Run1 PRD 98 (2018) 032004

\[\phi_s\]

- \(B_s^0 \rightarrow D_s D_s\)
  - Run1 PRL 113 (2014) 211801
- \(B_s^0 \rightarrow \psi(2S) \phi\)
  - Run1 PHYS. LETT. B762 (2016) 253
- \(B_s^0 \rightarrow J/\psi K^+ K^-\) high mass
  - Run1 JHEP 08 (2017) 037
- \(B_s^0 \rightarrow J/\psi K^+ K^-\)
  - Run2(15+16) EPJC 79 (2019) 706
- \(B_s^0 \rightarrow J/\psi \pi^+ \pi^-\)
  - Run2(15+16) to appear in PLB 797 (2019)

*incomplete overview
Tree dominated decays of $B^0_\text{(s)} \left( \bar{B}^0_\text{(s)} \right)$ via $b \to c\bar{c}s$ transition
CP violation in interference between direct decay and decay after mixing
Example of time-dependent CPV

Tree dominated decays of $B^0_{(s)} (\bar{B}^0_{(s)})$ via $b \rightarrow c\bar{c}s$ transition

CP violation in interference between direct decay and decay after mixing

$\phi_{d/s} = \phi_{\text{mix}} - 2\phi_{\text{dec}}$

+ Weak phase
Tree dominated decays of $B^0_s (\bar{B}^0_s)$ via $b \to c\bar{c}s$ transition

CP violation in interference between direct decay and decay after mixing

$$\phi_{d/s} = \phi_{\text{mix}} - 2\phi_{\text{dec}}$$
Tree dominated decays of $B^0_{(s)} (\bar{B}^0_{(s)})$ via $b \to c\bar{c}s$ transition
CP violation in interference between direct decay and decay after mixing

$\phi_{d/s} = \phi_{\text{mix}} - 2\phi_{\text{dec}}$
Measurement of CP violation

Master equations for time-dependent decay rates of neutral mesons

\[
\frac{d\Gamma_{B_s^0 \rightarrow f}(t)}{dt} e^{-\Gamma_{s}t} = \frac{1}{2} |A_f|^2 (1 + |\lambda_f|^2) \left[ \cosh \left( \frac{\Delta \Gamma_{s}t}{2} \right) + A_f \Delta \Gamma \sinh \left( \frac{\Delta \Gamma_{s}t}{2} \right) + C_f \cos (\Delta m_s t) - S_f \sin (\Delta m_s t) \right]
\]

\[
\frac{d\bar{\Gamma}_{B_s^0 \rightarrow f}(t)}{dt} e^{-\bar{\Gamma}_{s}t} = \frac{1}{2} |A_f|^2 \left| \frac{p}{q} \right|^2 (1 + |\lambda_f|^2) \left[ \cosh \left( \frac{\Delta \Gamma_{s}t}{2} \right) + A_f \Delta \Gamma \sinh \left( \frac{\Delta \Gamma_{s}t}{2} \right) - C_f \cos (\Delta m_s t) + S_f \sin (\Delta m_s t) \right]
\]

where CP violation parameters

\[
A_f^{\Delta \Gamma} = \frac{-2 \Re(\lambda_f)}{1 + |\lambda_f|^2}
\]

\[
C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}
\]

\[
S_f = \frac{2 \Im(\lambda_f)}{1 + |\lambda_f|^2}
\]
Master equations for time-dependent decay rates of neutral mesons

\[
\begin{align*}
\frac{d\Gamma_{B^0_s \to f}(t)}{dt} e^{-\Gamma_{st}} &= \frac{1}{2} |A_f|^2 (1 + |\lambda_f|^2) \left[ \cosh \left( \frac{\Delta \Gamma_{st}}{2} \right) + A_f^\Delta \Gamma \sinh \left( \frac{\Delta \Gamma_{st}}{2} \right) + C_f \cos (\Delta m_s t) - S_f \sin (\Delta m_s t) \right] \\
\frac{d\Gamma_{\bar{B}^0_s \to f}(t)}{dt} e^{-\Gamma_{st}} &= \frac{1}{2} |A_f|^2 \left| \frac{p}{\bar{q}} \right|^2 (1 + |\lambda_f|^2) \left[ \cosh \left( \frac{\Delta \Gamma_{st}}{2} \right) + A_f^\Delta \Gamma \sinh \left( \frac{\Delta \Gamma_{st}}{2} \right) - C_f \cos (\Delta m_s t) + S_f \sin (\Delta m_s t) \right]
\end{align*}
\]

where CP violation parameters

\[
\begin{align*}
A_f^\Delta \Gamma &= \frac{-2R(\lambda_f)}{1 + |\lambda_f|^2} \\
C_f &= \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \\
S_f &= \frac{2 \Im \lambda_f}{1 + |\lambda_f|^2}
\end{align*}
\]

experimental effects that have to be taken care of in CPV measurements

\[
pdf \propto \mathcal{E}(t) \left( \frac{d\Gamma}{dt} \otimes G(t | \sigma_t) \right) (1 - 2\omega)
\]

\[
\omega \quad \text{mistag probability of flavour tagging} \\
\mathcal{E} \quad \text{efficiency as a function of observables} \\
\sigma_t \quad \text{decay time resolution}
\]
CP-violating phase $\phi_s$

- Sensitive probe of New Physics in $B^0_s$ mixing
- Precise test of Standard Model through the measurement of $\phi_s$

\[ \phi_s^{\text{SM}} \approx -2 \arg \left( \frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*} \right) = -0.03686^{+0.00096}_{-0.00068} \text{ rad} \]

\( \text{If } \phi_s^{\text{exp}} \neq \phi_s^{\text{SM}} \)

New Physics!

\[ B_s^0 \rightarrow J/\psi K^- K^+ \text{ and other time-dependent analyses at LHCb} \]

16 October 2019
CP-violating phase $\phi_s$

- Sensitive probe of New Physics in $B^0_s$ mixing
- Precise test of Standard Model through the measurement of $\phi_s$

Access to penguin contribution with SU(3) counterparts not suppressed relative to tree level

$B^0_s \to J/\psi \bar{K}^*0$
Run1 JHEP 11 (2015) 082

$B^0 \to J/\psi \pi^+\pi^-$
Run1 PHYS. LETT. B742 (2015) 38

$B^0_s \to J/\psi K^0_s$
Run1 JHEP 06 (2015) 131

Assuming contribution from penguins is negligible

$$\phi_s^{SM} \approx -2 \arg \left( \frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*} \right) = -0.03686^{+0.00096}_{-0.00068} \text{ rad}$$

[CKM fitter]
CP-violating phase $\phi_s$

- Sensitive probe of New Physics in $B^0_s$ mixing
- Precise test of Standard Model through the measurement of $\phi_s$

$B^0_s \rightarrow D_s D_s$
Run1 PRL 113 (2014) 211801

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$B^0_s \rightarrow J/\psi K^+K^-$
Run2(15+16) EPJC 79 (2019) 706

$B^0_s \rightarrow J/\psi \pi^+\pi^-$
Run2(15+16) to appear in PLB 797 (2019)

\[
\phi_s^{SM} \approx -2 \arg \left( \frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*} \right) = -0.03686^{+0.00096}_{-0.00068} \text{ rad}
\]
Measurement of $\phi_s$ at LHCb
Measurement of $\phi_s$ at LHCb

Inside the VELO

$B^0_s$ flies $\sim 1$ cm

$p \rightarrow J/\psi \rightarrow \mu^+ \mu^-$

$B^0_s \rightarrow J/\psi K^+ K^-$ and other time-dependent analyses at LHCb
Measurement of $\phi_s$ at LHCb

Inside the VELO

$J/\psi$ is produced at the interaction point, and $B^0_s$ decays nearby.

$B^0_s$ flies ~ 1 cm

Helicity angles formalism

$B^0_s \rightarrow J/\psi K^+ K^-$ and other time-dependent analyses at LHCb

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Analyses strategy

\[ B_s^0 \rightarrow J/\psi \ K^+K^- \]
EPJC 79 (2019) 706

\[ B_s^0 \rightarrow J/\psi \ \pi^+\pi^- \]
To appear in PLB 797 (2019)

Using 2015 (0.3 fb^{-1}) and 2016 (1.6 fb^{-1}) data
measure \( \phi_s \), |\( \lambda \)| and
Analyses strategy

\[ B^0_s \rightarrow J/\psi \ K^+K^- \]
EPJC 79 (2019) 706

\[ B^0_s \rightarrow J/\psi \ \pi^+\pi^- \]
To appear in PLB 797 (2019)

Using 2015 (0.3 fb\(^{-1}\)) and 2016 (1.6 fb\(^{-1}\)) data
measure \( \phi_s \), \( |\lambda| \) and
\[ \Delta \Gamma_s \text{ and } \Gamma_s - \Gamma_{B^0} \]
to test the Heavy Quark Expansion
prediction of \( \Gamma_s / \Gamma_{B^0} = 1.0006 \pm 0.0025 \) [ref]
Analyses strategy

<table>
<thead>
<tr>
<th>$B^0_s \to J/\psi K^+ K^-$</th>
<th>$B^0_s \to J/\psi \pi^+ \pi^-$</th>
</tr>
</thead>
</table>

Using 2015 (0.3 fb$^{-1}$) and 2016 (1.6 fb$^{-1}$) data
measure $\phi_s$, $|\lambda|$ and
$\Delta \Gamma_s$ and $\Gamma_s - \Gamma_{B^0}$
to test the Heavy Quark Expansion
prediction of $\Gamma_s / \Gamma_{B^0} = 1.0006 \pm 0.0025$ [ref]

$\Gamma_H - \Gamma_{B^0}$
since the final state is almost entirely CP-odd
Analyses strategy

\[ B^0_s \rightarrow J/\psi \ K^+K^- \]

*EPJC 79 (2019) 706*

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

To appear in *PLB 797 (2019)*

Using 2015 (0.3 fb\(^{-1}\)) and 2016 (1.6 fb\(^{-1}\)) data

- measure \( \phi_s \), \( |\lambda| \) and \( \Delta \Gamma_s \) and \( \Gamma_s - \Gamma_{B^0} \)
- to test the Heavy Quark Expansion prediction of \( \Gamma_s / \Gamma_{B^0} = 1.0006 \pm 0.0025 \) [ref]

\[ \Gamma_h - \Gamma_{B^0} \]

since the final state is almost entirely CP-odd

Simultaneous fit to the decay time and three helicity angles
Analyses strategy

\[ \mathcal{B}^0_s \rightarrow \psi K^+ K^- \]

*EPJC 79 (2019) 706*

\[ \mathcal{B}^0_s \rightarrow \psi \pi^+ \pi^- \]

To appear in *PLB 797 (2019)*

Using 2015 (0.3 fb\(^{-1}\)) and 2016 (1.6 fb\(^{-1}\)) data
measure \( \phi_s \), \( |\lambda| \) and
\( \Delta \Gamma_s \) and \( \Gamma_s - \Gamma_{B^0} \)
to test the Heavy Quark Expansion
prediction of \( \Gamma_s / \Gamma_{B^0} = 1.0006 \pm 0.0025 \) [ref]

Simultaneous fit to the decay time and three helicity angles
in 6 \( m(K^+ K^-) \) bins

Gamma H - Gamma B^0 since the final state is almost entirely CP-odd
Analyses strategy

$B^0_s \rightarrow J/\psi \, K^+K^-$
EPJC 79 (2019) 706

$B^0_s \rightarrow J/\psi \, \pi^+\pi^-$
To appear in PLB 797 (2019)

Using 2015 (0.3 fb$^{-1}$) and 2016 (1.6 fb$^{-1}$) data
measure $\phi_s$, $|\lambda|$ and $\Delta \Gamma_s$ and $\Gamma_s - \Gamma_{B^0}$
to test the Heavy Quark Expansion prediction of $\Gamma_s / \Gamma_{B^0} = 1.0006 \pm 0.0025$ [ref]

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

\[ \text{Yields}/(15 \text{ MeV}) \]

LHCb

Data and fit

$10^0$, $10^1$, $10^2$, $10^3$

$0.5$, $1$, $1.5$, $2$

$\phi$ contribution

Katya Govorkova

$B^0_s \rightarrow J/\psi \, K^+K^-$ and other time-dependent analyses at LHCb

16 October 2019

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Measurement of $\phi_s$

- Selection
- Decay time resolution
- Flavour tagging
- Decay time efficiency
- Selection efficiency ($\Omega$)

TD fit for

$\phi_s$ $|\lambda|$ $\Delta\Gamma_s$ $\Gamma_{s/H} - \Gamma_{B^0}$
Measurement of $\phi_s$

TD fit for

$$\phi_s \ |\lambda| \ \Delta \Gamma_s \ \Gamma_{s/H} - \Gamma_{B^0}$$

Selection

Decay time resolution

Flavour tagging

Decay time efficiency

Selection efficiency ($\Omega$)
Selection and mass fit

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

EPJC 79 (2019) 706

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

To appear in PLB 797 (2019)

Boosted decision tree is trained to select signal candidates

$$\sigma^{-1}(\phi_s) \sim \sqrt{N} Q_{\text{eff}}^{1/2} e^{-\frac{\sigma^2 \Delta m^2}{2}}$$
Selection and mass fit

\[ B^0_s \rightarrow J/\psi K^+K^- \]
\[ \text{EPJC 79 (2019) 706} \]

\[ B^0_s \rightarrow J/\psi \pi^+\pi^- \]
To appear in \[ PLB 797 (2019) \]

Boosted decision tree is trained to select signal candidates

\[ \sigma^{-1}(\phi_s) \sim \sqrt{N} Q_{\text{eff}}^{1/2} e^{-\frac{\sigma^2 \Delta m^2}{2}} \]

\[ N(B^0_s \rightarrow J/\psi K^+K^-) \approx 117 \ 000 \]

\[ N(B^0_s \rightarrow J/\psi \pi^+\pi^-) \approx 33 \ 530 \]
Measurement of $\phi_s$

TD fit for $\phi_s$, $|\lambda|$, $\Delta \Gamma_s$, $\Gamma_{s/H} - \Gamma_{B^0}$

- Selection
- Decay time resolution
- Flavour tagging
- Selection efficiency ($\Omega$)
- Decay time efficiency
Decay time resolution

\[ \sigma_{eff} = 45.5 \text{ fs} \]

\[ \sigma_{eff} = 41.5 \text{ fs} \]

\[ \sigma^{-1}(\phi_s) \sim \sqrt{N} Q_{eff}^{1/2} e^{-\frac{\sigma^2 \Delta m^2}{2}} \]

Per-candidate decay time error (\(\delta_t\)) is calibrated using prompt J/\(\psi\) sample

\[ \sigma_{eff} = \sqrt{\frac{-2}{\Delta m_s^2}} \ln D, \quad D = \sum_{i=1}^{3} f_i e^{-\sigma^2 \Delta m_s^2 / 2} \]

In each bin of \(\delta_t\) perform fit for \(\sigma_{eff}\)

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B\(^0_s\)→J/\(\psi\) K\(^+\)K\(^-\) and other time-dependent analyses at LHCb

16 October 2019
Measurement of $\phi_s$

- Selection
- Decay time resolution
- Flavour tagging
- TD fit for $\phi_s$, $|\lambda|$, $\Delta \Gamma_s$, $\Gamma_{s/H} - \Gamma_{B^0}$
- Selection efficiency ($\Omega$)
- Decay time efficiency
Selection efficiency

$B^0_s \to J/\psi \ K^+K^-$

EPJC 79 (2019) 706

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

To appear in PLB 797 (2019)

Data-driven approach using $B^0 \to J/\psi \ K^*(892)$
Method is verified with $B^0$ and $B^+$

$$
\varepsilon_{B^0_{\text{data}}}(t) = \varepsilon_{B^0_{\text{data}}}(t) \times \frac{\varepsilon_{B^0_{\text{sim}}}(t)}{\varepsilon_{B^0_{\text{sim}}}(t)}
$$
Selection efficiency

$B^0_s \to J/\psi \, K^+ K^-$

EPJC 79 (2019) 706

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

To appear in PLB 797 (2019)

Data-driven approach using $B^0 \to J/\psi \, K^*$(892)

Method is verified with $B^0$ and $B^+$

Kinematic selection and detector acceptance are causing non uniform efficiency as function of decay angles

- angular distribution in MC / expected without acceptance effect
  - fourth-order polynomial parameterisation
Measurement of $\phi_s$

TD fit for $\phi_s$, $|\lambda|$, $\Delta \Gamma_s$, $\Gamma_{s/H} - \Gamma_{B^0}$

- Selection
- Decay time resolution
- Selection efficiency ($\Omega$)
- Decay time efficiency
- Flavour tagging
Flavour tagging

\[ \mathcal{B}_s^0 \rightarrow \Upsilon K^+K^- \]
EPJC 79 (2019) 706

\[ \mathcal{B}_s^0 \rightarrow \Upsilon \pi^+\pi^- \]
To appear in PLB 797 (2019)

\[ \sigma^{-1}(\phi_s) \sim \sqrt{N} \mathcal{Q}_{\text{eff}}^{1/2} e^{-\frac{\sigma_t^2 \Delta m^2}{2}} \]

The effective tagging power is defined as \( \mathcal{Q}_{\text{eff}} = \epsilon_{\text{tag}} (1 - 2\omega)^2 \)

where \( \epsilon_{\text{tag}} \) is tagging efficiency and \( (1 - 2\omega)^2 \) is dilution

In Run1 \( \mathcal{Q}_{\text{eff}} \approx 3.73 \% \)

\[ \mathcal{Q}_{\text{eff}} = 4.73 \pm 0.34 \% \]

In Run1 \( \mathcal{Q}_{\text{eff}} \approx 3.89 \% \)

\[ \mathcal{Q}_{\text{eff}} = 5.06 \pm 0.38 \% \]
Measurement of $\phi_s$

TD fit for

$\phi_s \ |\lambda| \ \Delta\Gamma_s \ \Gamma_{s/H} - \Gamma_{B^0}$

- Selection
- Decay time resolution
- Flavour tagging
- Decay time efficiency
- Selection efficiency ($\Omega$)
Combination of LHCb results on $\phi_s$

$$\phi_s = -0.041 \pm 0.025 \text{ [rad]}$$
$$|\lambda| = 0.993 \pm 0.010$$
$$\Delta \Gamma_s = 0.0816 \pm 0.0048 \text{ [ps}^{-1}]$$
$$\Gamma_s = 0.6562 \pm 0.0021 \text{ [ps}^{-1}]$$

$\phi_s$ 0.1σ from SM
consistent with Standard Model

$\phi_s$ 1.6σ from 0
consistent with no CPV in interference between direct decay and after mixing

$|\lambda|$ consistent with 1 within 0.7σ
consistent with no direct CPV

$\Gamma_s/\Gamma_{B^0}$ consistent with HQE prediction within 1σ

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**Figure:**
- **Legend:**
  - $D_s^-D_s^+$ $3 \text{ fb}^{-1}$
  - $J/\psi K^+K^-$ $4.9 \text{ fb}^{-1}$
  - $J/\psi K^+K^-$ high mass $3 \text{ fb}^{-1}$

**Shade Colors:**
- SM
- Combined LHCb

**Contour Levels:**
- 68% CI contours ($\Delta \log L = 1.15$)

**References:**
- EPJC 79 (2019) 706

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**Note:**
- This slide summarizes the results from LHCb experiment measurements related to $\phi_s$ and their implications compared to Standard Model predictions.
The decay $B^0_s \rightarrow J/\psi \phi$ is the $B^0_s$ analogue of the decay $B^0 \rightarrow J/\psi K^0_S$, with the spectator $d$-quark replaced by an $s$-quark. However, there are four major differences:

I. $\text{V}_{ts} \neq \text{V}_{td}$. Since the spectator $d$-quark is replaced by an $s$-quark, the CKM-element responsible for the CP-asymmetry (in the Wolfenstein parameterization) is now $\text{V}_{ts}$, instead of $\text{V}_{td}$, see Fig. 4.4. In contrast to $\text{V}_{td}$, the imaginary part of $\text{V}_{ts}$ is no longer of comparable size as the real part, see Eqs. (2.10-2.11), and the predicted CP asymmetry is therefore small, $\arg(\text{V}_{ts}) \sim \eta \lambda^2$.

II. No $K$-oscillations. The final state, containing the mesons $J/\psi$ and $\phi$, is the same for the $B^0_s$ and the $\bar{B}^0_s$-meson, and hence we do not need the extra $K$-oscillation step as in the $B^0$ system.

III. $\Delta \Gamma \neq 0$. In contrast to the $B^0$ case, the $B^0_s$-system has non-vanishing $\Delta \Gamma$. This is caused by the existence of a final state common to $B^0_s$ and $\bar{B}^0_s$, with a large branching fraction around 5%, namely the CP-eigenstate $D_{\pm}^s (\ast) D_{\mp}^s (\ast)$. Since this is a CP-eigenstate with eigenvalue +1, this decay channel is only accessible for the CP-even eigenstate $B^H_s$, and not for $B^L_s$. Hence, the different lifetime for $B^H_s$ and $B^L_s$ with a predicted value of $\Delta \Gamma / \Gamma \sim 0.1$.

IV. Vector-vector final state. The final state now contains two vector-particles with spin-1. As a result, the final state is not a pure CP-eigenstate, in contrast to $B^0 \rightarrow J/\psi K^0$. The spin of the final state particles $J/\psi$ and $\phi$ can be pointing parallel, $W_s u, c, t \rightarrow W_s u, c, t$.

Measurement of $\phi_s^{SS\bar{s}(d\bar{d}/\gamma)}$

Dominated by penguin $b \rightarrow ss\bar{s}(dd/\gamma)$ transition

In the first order

$$\phi_s^{SM} \propto \arg \left( \frac{V_{ts} V_{*tb}}{V_{*ts} V_{tb}} \frac{V_{*ts} V_{tb}}{V_{*ts} V_{*tb}} \right) = 0$$

$B^0_s \rightarrow (K^+ \pi^-)(K^- \pi^+)$
Run1 JHEP 03 (2018) 140

$B^0_s \rightarrow \phi \phi$
Run1+2(15,16) arXiv:1907.10003

$B^0_s \rightarrow \phi \gamma$
Run1 PRL 123 (2019) 081802
\( \phi_s \) from \( b \to s\bar{s}(\gamma) \) transition

\begin{align*}
\mathbf{B}_s^0 &\to \varphi \gamma \\
\mathbf{B}_s^0 &\to (K^+\pi^-)(K^-\pi^+) \\
\mathbf{B}_s^0 &\to \varphi \varphi
\end{align*}

- Based on Run1 (3 fb\(^{-1}\)) dataset
- Based on Run1 (3 fb\(^{-1}\)), 2015 (0.3 fb\(^{-1}\)) and 2016 (1.6 fb\(^{-1}\)) dataset

The SM predictions for the \( S, C \) and \( A \) in \( \mathbf{B}_s^0 \to \varphi \gamma \) are close to zero [ref]

\[
\begin{align*}
S_{\varphi\gamma} &= 0.43 \pm 0.30 \pm 0.11 \\
C_{\varphi\gamma} &= 0.11 \pm 0.29 \pm 0.11 \\
A_{\varphi\gamma}^\Delta &= -0.67^{+0.37}_{-0.41} \pm 0.17
\end{align*}
\]

\( f_L = 0.208 \pm 0.032 \pm 0.046 \)

Complimentary search for new \( \mathbf{B}_s^0 \) decay mode

\( \mathcal{B}(\mathbf{B}_s^0 \to \varphi\varphi) < 2.7 \times 10^{-8} \) at 90\% CL

\[
\begin{align*}
\phi_s^{s\bar{s}d} &= -0.10 \pm 0.13 \pm 0.14 \text{ [rad]} \\
|\lambda| &= 1.035 \pm 0.034 \pm 0.089 \\
\phi_s^{s\bar{s}s} &= -0.073 \pm 0.115 \pm 0.027 \text{ [rad]} \\
|\lambda| &= 0.99 \pm 0.05 \pm 0.01
\end{align*}
\]
Decays of $B^0$ dominated by tree $b \to c\bar{s}(d)$ transition

$$\sin(2\beta)^{\text{SM}} = \sin 2 \arg \left( -\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right) = 0.708^{+0.013}_{-0.010} \quad \text{[CKM fitter]}$$

**Figure 4.4:** The two interfering diagrams of the decay $B^0 \to \psi(2S) K_s$.

### Results

- $B^0 \to \psi(2S) K_s$
  - Run1: JHEP 11 (2017) 170
- $B^0 \to J/\psi K_s$
  - Run1: PRL 115 (2015) 031601
- $B^0 \to D^+ D^-$
  - Run1: PRL 117 (2016) 261801
- $B^0 \to D^{*\pm} D^{\mp}$
**B^0 \to D^*\pm D^\mp**


Based on full Run1 (3 fb^{-1}) and Run2 (6 fb^{-1}) dataset
Result is consistent with sin(2\beta) measured in b \to c\bar{c}s

B^0 \to D^*\pm D^\mp with D^*\pm \to D^0\pi^\pm and D^\mp \to K^\mp \pi^+ \pi^-

D^0 is reconstructed in two modes
studied separately
D^0 \to K^- \pi^+
D^0 \to K^- \pi^+ \pi^- \pi^+

LHCb Preliminary

D^*\!\!\to D^+

D^*\!\!\to D^-

N_{\text{sig}} \sim 6000

\begin{align*}
\text{Candidates} / (6 \text{ MeV/c}^2) & \\
\text{m}_{D^\pm D^\mp} [\text{MeV/c}^2] & \\
0 & 200 \\
200 & 400 \\
400 & 600 \\
600 & 800 \\
800 & 1000 \\
1000 & 1200 \\
\end{align*}

\begin{align*}
N_{\text{Total}} & \\
N_{B^0 \to D^*\pm D^\mp} & \\
N_{B^0 \to D^*\pm D^\mp} & \\
N_{B^0 \to D^*\pm D^\mp} & \\
N_{B^0 \to D^*\pm D^\mp} & \\
N_{\text{Comb. bkg.}} & \\
\end{align*}

\begin{align*}
N(\overline{B^0} \to D^*\pm D^\mp) & \\
N(\overline{B^0} \to D^*\pm D^\mp) & \\
N(\overline{B^0} \to D^*\pm D^\mp) & \\
\end{align*}

\begin{align*}
\text{decay time [ps]} & \\
2 & 4 & 6 & 8 & 10 \\
\end{align*}
Measurement of \( \sin(2\beta) \)

\[
B^0 \rightarrow D^* \pm D^+ \\
LHCb-PAPER-2019-036 \text{ in preparation}
\]

\[
S_{D^*D} = -0.861 \pm 0.077 \text{ (stat) } \pm 0.019 \text{ (syst)}
\]
\[
\Delta S_{D^*D} = 0.019 \pm 0.075 \text{ (stat) } \pm 0.012 \text{ (syst)}
\]
\[
C_{D^*D} = -0.059 \pm 0.092 \text{ (stat) } \pm 0.020 \text{ (syst)}
\]
\[
\Delta C_{D^*D} = -0.031 \pm 0.092 \text{ (stat) } \pm 0.016 \text{ (syst)}
\]
\[
A_{D^*D} = 0.008 \pm 0.014 \text{ (stat) } \pm 0.005 \text{ (syst)}
\]
Measurement of $\sin(2\beta)$

$B^0 \rightarrow D^{\ast\pm}D^{\mp}$


**D*+ D+ S**

- **BaBar**
  - PRD 79, 032002 (2009)
  - $-0.68 \pm 0.15 \pm 0.04$

- **Belle**
  - PRD 85 (2012) 091106
  - $-0.78 \pm 0.15 \pm 0.05$

- **Average**
  - $-0.73 \pm 0.11$

**D*+ D+ ΔS**

- **BaBar**
  - PRD 79, 032002 (2009)
  - $0.05 \pm 0.15 \pm 0.02$

- **Belle**
  - PRD 85 (2012) 091106
  - $-0.13 \pm 0.15 \pm 0.04$

- **Average**
  - $-0.04 \pm 0.11$

**D*+ D+ C**

- **BaBar**
  - PRD 79, 032002 (2009)
  - $0.04 \pm 0.12 \pm 0.03$

- **Belle**
  - PRD 85 (2012) 091106
  - $-0.01 \pm 0.11 \pm 0.04$

- **Average**
  - $0.01 \pm 0.09$

**D*+ D+ ΔC**

- **BaBar**
  - PRD 79, 032002 (2009)
  - $0.04 \pm 0.12 \pm 0.03$

- **Belle**
  - PRD 85 (2012) 091106
  - $0.12 \pm 0.11 \pm 0.03$

- **Average**
  - $0.08 \pm 0.08$

---

Marta Calvi @Beauty

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Katya Govorkova

B$^0_s \rightarrow J/\psi K^+K^-$ and other time-dependent analyses at LHCb

16 October 2019
Recent measurements of $\phi_s$
- $B_s^0 \rightarrow J/\psi K^+K^-$ \cite{EPJC 79 (2019) 706}
- $B_s^0 \rightarrow J/\psi \pi^+\pi^-$ \cite{PLB 797 (2019)}
- $B_s^0 \rightarrow (K^+\pi^-)(K^-\pi^+)$ \cite{JHEP 03 (2018) 140}
- $B_s^0 \rightarrow \phi \phi$ \cite{arXiv:1907.10003}
- $B_s^0 \rightarrow \phi \gamma$ \cite{PRL 123 (2019) 081802}

Recent measurements of $\sin(2\beta)$
- $B^0 \rightarrow D^{*\pm}D^{\mp}$ \cite{LHCb-PAPER-2019-036} in preparation

With current precision all measurements are consistent with SM

Further analysis of available dataset is in progress for most of the modes

---

**Summary and prospects**

**Figure 3.4:** Signal-yield asymmetry as a function of the decay time modulo 2π. The solid curves represent the expected sensitivity for $B_s^0 \rightarrow J/\psi K^+K^-$ from all modes combined. This will be at the same level as the current precision with integrated luminosity for individual decay modes $J/\psi\pi^+\pi^-$, $J/\psi K^+K^-$, $\psi(2S) K^+K^-$, and $D^{(*)}\pi^-$. The scaling of the asymmetry for $B_s^0 \rightarrow (K^+\pi^-)(K^-\pi^+)$ is important in LHCb Upgrade II, as shown in Fig. 3.4.

**Figure 3.5:** LHCb 300 fb$^{-1}$ simulation of the decay $B_s^0 \rightarrow J/\psi K^+K^-$. The observed signal yield asymmetry is consistent with the expected sensitivity.
Fit result $B^0_s \rightarrow J/\psi \ K^+ K^-$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_s$ [rad]</td>
<td>$-0.080 \pm 0.041 \pm 0.006$</td>
</tr>
<tr>
<td>$</td>
<td>\lambda</td>
</tr>
<tr>
<td>$\Gamma_s - \Gamma_d$ [ps$^{-1}$]</td>
<td>$-0.0041 \pm 0.0024 \pm 0.0015$</td>
</tr>
<tr>
<td>$\Delta \Gamma_s$ [ps$^{-1}$]</td>
<td>$0.0772 \pm 0.0077 \pm 0.0026$</td>
</tr>
<tr>
<td>$\Delta m_s$ [ps$^{-1}$]</td>
<td>$17.705 \pm 0.059 \pm 0.018$</td>
</tr>
<tr>
<td>$</td>
<td>A_\perp</td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
</tr>
<tr>
<td>$\delta_\perp - \delta_0$</td>
<td>$2.64 \pm 0.13 \pm 0.10$</td>
</tr>
<tr>
<td>$\delta_\parallel - \delta_0$</td>
<td>$3.061^{+0.084}_{-0.073} \pm 0.037$</td>
</tr>
</tbody>
</table>
Fit projections for $B^0_s \rightarrow J/\psi K^+ K^-$
Fit projections for $B^0_s \to J/\psi \pi^+\pi^-$
## Systematics for \( B_s^0 \rightarrow J/\psi \; K^+K^- \) Systematics

| Source                        | \( |A_0|^2 \) | \( |A_{\perp}|^2 \) | \( \phi_s \) [rad] | \( |\lambda| \) | \( \delta_{\perp} - \delta_0 \) [rad] | \( \delta_{||} - \delta_0 \) [rad] | \( \Gamma_s - \Gamma_d \) [ps\(^{-1}\)] | \( \Delta \Gamma_s \) [ps\(^{-1}\)] | \( \Delta m_s \) [ps\(^{-1}\)] |
|-------------------------------|-------------|-----------------|-----------------|--------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Mass width parametrisation    | 0.0006      | 0.0005          | -               | -      | 0.05            | 0.009            | -               | 0.0002          | 0.001           |
| Mass factorisation            | 0.0002      | 0.0004          | 0.004           | 0.0037 | 0.01            | 0.004            | 0.0007          | 0.0022          | 0.016           |
| Multiple candidates           | 0.0006      | 0.0001          | 0.0011          | 0.0011 | 0.01            | 0.002            | 0.0003          | 0.0001          | 0.001           |
| Fit bias                      | 0.0001      | 0.0006          | 0.001           | -      | 0.02            | 0.033            | -               | 0.0003          | 0.001           |
| \( C_{SP} \) factors          | -           | 0.0001          | 0.001           | 0.0010 | 0.01            | 0.005            | -               | 0.0001          | 0.002           |
| Quadratic OS tagging          | -           | -               | -               | -      | -               | -               | -               | -               | -               |
| Time res.: statistical        | -           | -               | -               | -      | -               | -               | -               | -               | -               |
| Time res.: prompt             | -           | -               | -               | -      | -               | -               | 0.001           | -               | 0.001           |
| Time res.: mean offset        | -           | -               | 0.0032          | 0.0010 | 0.08            | 0.001           | 0.0002          | 0.0003          | 0.005           |
| Time res.: Wrong PV           | -           | -               | -               | -      | -               | 0.001           | -               | -               | 0.001           |
| Ang. acc.: statistical        | 0.0003      | 0.0004          | 0.0011          | 0.0018 | -               | 0.004            | -               | -               | 0.001           |
| Ang. acc.: correction         | 0.0020      | 0.0011          | 0.0022          | 0.0043 | 0.01            | 0.008            | 0.0001          | 0.0002          | 0.001           |
| Ang. acc.: low-quality tracks | 0.0002      | 0.0001          | 0.0005          | 0.0014 | -               | 0.002            | 0.0002          | 0.0001          | -               |
| Ang. acc.: \( t \) \& \( \sigma_t \) dependence | 0.0008      | 0.0012          | 0.0012          | 0.0007 | 0.03            | 0.006            | 0.0002          | 0.0010          | 0.003           |
| Dec.-time eff.: statistical   | 0.0002      | 0.0003          | -               | -      | -               | -               | 0.0012          | 0.0008          | -               |
| Dec.-time eff.: \( \Delta \Gamma_s = 0 \) sim. | 0.0001      | 0.0002          | -               | -      | -               | -               | 0.0003          | 0.0005          | -               |
| Dec.-time eff.: knot pos.     | -           | -               | -               | -      | -               | -               | -               | -               | -               |
| Dec.-time eff.: p.d.f. weighting | -           | -               | -               | -      | -               | -               | 0.0001          | 0.0001          | -               |
| Dec.-time eff.: kin. weighting | -           | -               | -               | -      | -               | -               | 0.0002          | -               | -               |
| Length scale                  | -           | -               | -               | -      | -               | -               | -               | 0.004           | -               |
| Quadratic sum of syst.        | 0.0024      | 0.0019          | 0.0061          | 0.0064 | 0.10            | 0.037            | 0.0015          | 0.0026          | 0.018           |
Table 5: Fit results of the resonant structure for both Solutions I and II. These results do not supersede those in Ref. [21] for the resonant fractions.

<table>
<thead>
<tr>
<th>Component</th>
<th>Fit fractions (%)</th>
<th>Transversity fractions (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Solution I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_0(980)$</td>
<td>60.09 ± 1.48</td>
<td>100</td>
</tr>
<tr>
<td>$f_0(1500)$</td>
<td>8.88 ± 0.87</td>
<td>100</td>
</tr>
<tr>
<td>$f_0(1790)$</td>
<td>1.72 ± 0.29</td>
<td>100</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>3.24 ± 0.48</td>
<td>13 ± 3</td>
</tr>
<tr>
<td>$f'_2(1525)$</td>
<td>1.23 ± 0.86</td>
<td>40 ± 13</td>
</tr>
<tr>
<td>NR</td>
<td>2.64 ± 0.73</td>
<td>100</td>
</tr>
<tr>
<td>Solution II</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_0(980)$</td>
<td>93.05 ± 1.12</td>
<td>100</td>
</tr>
<tr>
<td>$f_0(1500)$</td>
<td>6.47 ± 0.41</td>
<td>100</td>
</tr>
<tr>
<td>$f_0(1710)$</td>
<td>0.74 ± 0.11</td>
<td>100</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>3.22 ± 0.44</td>
<td>17 ± 4</td>
</tr>
<tr>
<td>$f'_2(1525)$</td>
<td>1.44 ± 0.36</td>
<td>35 ± 8</td>
</tr>
<tr>
<td>NR</td>
<td>8.13 ± 0.79</td>
<td>100</td>
</tr>
<tr>
<td>Source</td>
<td>$\Gamma_H - \Gamma_{B^0}$ [fs$^{-1}$]</td>
<td>$</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>---------------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>$t$ acceptance</td>
<td>2.0</td>
<td>0.0</td>
</tr>
<tr>
<td>$\tau_{B^0}$</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Efficiency ($m_{\pi\pi}$, $\Omega$)</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>$t$ resolution width</td>
<td>0.0</td>
<td>4.3</td>
</tr>
<tr>
<td>$t$ resolution mean</td>
<td>0.3</td>
<td>1.2</td>
</tr>
<tr>
<td>Background</td>
<td>3.0</td>
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</tr>
<tr>
<td>Flavour tagging</td>
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<td>2.2</td>
</tr>
<tr>
<td>$\Delta m_s$</td>
<td>0.3</td>
<td>4.6</td>
</tr>
<tr>
<td>$\Gamma_L$</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>$B_c^+$</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>Resonance parameters</td>
<td>0.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Resonance modelling</td>
<td>0.5</td>
<td>28.9</td>
</tr>
<tr>
<td>Production asymmetry</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3.8</strong></td>
<td><strong>29.9</strong></td>
</tr>
</tbody>
</table>
Decay time acceptance

Decay time acceptance is approximately:

\[ \varepsilon_{\text{data}}^{B_s^0}(t) \propto \frac{N(t)}{e^{-\Gamma_d t} \otimes G(t, \sigma_t)} \]

Given a parameterisation of \( \Gamma_d \) around the used value \( \Gamma_{d0} = 1/1.520 \text{ps}^{-1} \)

\[ \varepsilon_{\text{data}}^{B_s^0}(t; \Gamma_d) \propto \frac{N(t)}{e^{-(\Gamma_{d0} + \delta \Gamma_d)t} \otimes G(t, \sigma_t)} \]

\[ \approx \frac{N(t)}{e^{-\Gamma_{d0} t} \otimes G(t, \sigma_t)} \times e^{\delta \Gamma_d t} \]

\[ = \varepsilon_{\text{data}}^{B_s^0}(t; \Gamma_{d0}) \times e^{\delta \Gamma_d t} . \]

\[ \Delta \Gamma_d^s = \Gamma_s - \Gamma_d \text{ and } \Gamma_d = \Gamma_{d0} + \delta \Gamma_d: \quad \Gamma_s = \Gamma_{d0} + \delta \Gamma_d + \Delta \Gamma_d^s \]

\[ \text{pdf}(t) \approx \varepsilon_{\text{data}}^{B_s^0}(t, \Gamma_{d0}) \times e^{\delta \Gamma_d t} \times \left[ e^{-(\Delta \Gamma_d^s + \Gamma_{d0} + \delta \Gamma_d)t} \otimes G(t, \sigma_t) \right] \]

\[ \approx \varepsilon_{\text{data}}^{B_s^0}(t, \Gamma_{d0}) \times e^{\delta \Gamma_d t} \times e^{-\delta \Gamma_d t} \left[ e^{-(\Delta \Gamma_d^s + \Gamma_{d0})t} \otimes G(t, \sigma_t) \right] \]

\[ = \varepsilon_{\text{data}}^{B_s^0}(t, \Gamma_{d0}) \times e^{-(\Delta \Gamma_d^s + \Gamma_{d0})t} \otimes G(t, \sigma_t) , \]
Signal model: Double-sided Crystal Ball function (CB2) with per-event mass error used as conditional observable

Quadratic dependence on the per-event mass error: \( \sigma = s_1 \Delta \sigma + s_2 \sigma^2 \) (\( s_1 \sim 0.8; s_2 \sim 0.05 \))
- Tails of the CB2 are fixed from the fit to MC
- Fit in 6 \( m(K^+K^-) \) bins \([990, 1008, 1016, 1020, 1024, 1032, 1050] \) MeV/\( c^2 \)

Background: Exponential for the combinatorial and gaussian for the \( B^0 \rightarrow J/\psi \ K^+K^- \) contribution

**Why?** To take into account this correlation. Mass resolution comes from the angles between muons, therefore per-candidate mass error and \( \cos(\theta_\mu) \) are highly correlated
Comparison of $\varphi_s$ sensitivity from different decay modes

$\sigma^{\text{stat}} (\varphi_s) [\text{rad}]$ vs. Integrated Luminosity [fb$^{-1}$]

$\sigma^{\text{stat}} (\varphi_s) [\text{mrad}]$ vs. Integrated Luminosity [fb$^{-1}$]

- $B_s \to J/\psi \phi$
- $B_s \to \phi \phi$
- $B_s \to K^+ \pi^- K^- \pi^+$

LHCb

- $B^0 \to \psi(2S) \phi$
- $B^0_s \to D_s^- D^+_s$
- $B^0 \to J/\psi K^+ K^-$ high mass
- $B^0 \to J/\psi \pi \pi$
- $B^0_s \to J/\psi \phi$
- $B^0_s$ all $c\bar{s}$
- $\varphi_s$ central value [CKMFitter Summer 2016]
**Opposite side tagging**

**B^{0s} \rightarrow J/\psi K^+K^-**

_EUR.PHYS.J.C 79 (2019) 706_

**B^{0s} \rightarrow J/\psi \pi^+\pi^-**

To appear in _PLB 797 (2019)_

---

In Run1 \( \epsilon_{\text{tag}} D^2 \approx 3.73 \% \)

\[ \epsilon_{\text{tag}} D^2 = 4.73 \pm 0.34 \% \]

---

In Run1 \( \epsilon_{\text{tag}} D^2 \approx 3.89 \% \)

\[ \epsilon_{\text{tag}} D^2 = 5.06 \pm 0.38 \% \]
Same side tagging

\[ B^0_s \to J/\psi K^+ K^- \]
EUR.PHYS.J.C 79 (2019) 706

\[ B^0_s \to J/\psi \pi^+ \pi^- \]
To appear in PLB 797 (2019)

In Run1 \( \varepsilon_{\text{tag}} D^2 \approx 3.73 \% \)
\[ \varepsilon_{\text{tag}} D^2 = 4.73 \pm 0.34 \% \]

In Run1 \( \varepsilon_{\text{tag}} D^2 \approx 3.89 \% \)
\[ \varepsilon_{\text{tag}} D^2 = 5.06 \pm 0.38 \% \]
Fit projections in decay time, three angles and $m(K\pi)$