Measurement of the $CP$-violating phase $\phi_s$ at LHCb

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**CP-violation in $B_s^0$ mixing and decays, $\phi_s$**

\[
\phi_s = \phi_M - 2\phi_D
\]

- $\phi_s = -\arg(\lambda_f)$, $\lambda_f = \frac{q \bar{A}_f}{p A_f}$ is a mixing-induced CPV phase in $B_s^0$ decays
- Assuming only SM tree level contribution, $\phi_s^{SM} = -2\beta_s$ - angle in $B_s^0$ system analogous to $\beta$ in $B^0$ system
- Possibility measurement in interference between $B_s^0$ mixing and decay.
  - via $b \to c\bar{c}s$ transitions, with decays like $B_s^0 \to J/\psi h^+h^-(h = K, \pi)$

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**CP-violation in $B_s^0$ mixing and decays, $\phi_s$**

- $\phi_s$ is sensitive to New Physics in $B_s^0$ mixing,
- $\phi_s^{\text{SM}}$ determined via global fit to CKM matrix

\[
\phi_s^{\text{SM}} = -0.0368^{+0.0010}_{-0.0008} \text{ rad} \quad \text{[CKMFitter], no penguins}
\]

- If $\phi_s^{\text{exp}} \neq \phi_s^{\text{SM}}$, NP is found!

**Golden mode:**

$B_s^0 \to J/\psi(\to \mu\mu)\phi(KK)$

+ smaller weak exchange and penguin annihilation diagrams
Status of $\phi_s$ before Spring 2019

- World average dominated by LHCb
- Results consistent with SM-based global fits to data, but still room for NP

$\phi_s^{SM} = -0.0368^{+0.0010}_{-0.0008}$ rad [CKMFitter]

$\phi_s^{exp} = -0.021 \pm 0.031$ rad [HFLAV]
\[
\phi_s \text{ in } B_s^0 \rightarrow J/\psi K^+ K^- \text{ and } B_s^0 \rightarrow J/\psi \pi^+ \pi^-
\]

- Relatively large BF, $\mathcal{O}(10^{-3})$
- The final state is a mixture of CP-even ($L=0,2$) and CP-odd ($L=1+S$-wave) components
  - Allow to obtain $\Gamma_s = \frac{\Gamma_H + \Gamma_L}{2}$,
  - $\Delta \Gamma_s = \Gamma_L - \Gamma_H$ and $\Delta m_s = m_H - m_L$

- $H$ : Heavy mass eigenstate
- $L$ : Light mass eigenstate

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Key ingredients

Definition of time-dependent CP asymmetry

\[ A_{\text{CP}} \equiv \frac{\Gamma(B(t) - f) - \Gamma(B(t) - f)}{\Gamma(B(t) - f) + \Gamma(B(t) - f)} \approx \eta_f \sin(\phi_s) \sin(\Delta (m_s, t)) \]

Experimentally it becomes

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

Critical requirements

- Excellent decay-time resolution \( \sigma_t \ll T \), \( B_s^0 \) oscillations fast \( T \approx 350 \text{ fs} \)
- CP eigenvalue of the final state \( \eta_f \Rightarrow \) angular analysis disentangles CP-odd and even mixture of the final states
- Tagging of meson flavor at production: probability of wrong tag \( \omega \)
- Reliable modeling of decay-time efficiency \( \epsilon(t) \) and angular efficiency \( \epsilon(\Omega) \)

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New \( B_s^0 \rightarrow J/\psi K^+K^- \) \([\text{arXiv:1906.08356}]\) and \( B_s^0 \rightarrow J/\psi \pi^+\pi^- \) \([\text{PLB 797(2019) 134789}]\)

Run-II LHCb measurements with 2015 (0.3 fb-1) and 2016 (1.6 fb-1) datasets

**Analysis strategy**

- Combinatorial background suppressed with a BDT using kinematic variables
- Background subtracted using \( sPlot \) with \( B_s^0 \) candidate masses
- Careful study of decay-time resolution and efficiencies, angular efficiencies and flavor tagging
- \( sFit \) to 3 helicity angles and \( B_s^0 \) candidates decay time+ (\( m_{\pi\pi} \) for \( B_s^0 \rightarrow J/\psi \pi^+\pi^- \))

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Background subtraction

Boosted decision tree is trained to select signal candidates

- $\Lambda^0_b \rightarrow J/\psi p K$ subtracted with negative MC weights, $B^0 \rightarrow J/\psi K^+ \pi^-$ negligible
- Mass fit: combinatorial background (exp,) and signal $B^0_s \rightarrow J/\psi K^+ K^-$

$\Lambda^0_b \rightarrow J/\psi p K$ and $B^0_s \rightarrow J/\psi \eta^*( \rightarrow \rho^0 \gamma)$ using MC shaped
- Combinatorial background estimated using wrong sign (WS) $J/\psi \pi^\pm \pi^\pm$ data

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Decay-time resolution

- Pre-candidate decay-time error $\sigma_t$ is calibrated using prompt $J/\psi$ sample formed from $J/\psi$ and two kaons (pions) from PV

\[ \sigma_{\text{eff}}(B_s^0 \rightarrow J/\psi K^+ K^-) = 45.5 \text{ fs} \]

- Impact of decay-time resolution, $\Delta m_s \approx 17.7 \text{ ps}^{-1}$
  - If $\sigma_{\text{eff}} = 45 \text{ fs}$, dilution factor $e^{\frac{1}{2} \Delta m_s \sigma_t^2} = 0.73$
  - If $\sigma_{\text{eff}} = 90 \text{ fs}$, dilution factor $e^{\frac{1}{2} \Delta m_s \sigma_t^2} = 0.28$

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Decay-time efficiency

- Use $B^0 \rightarrow J/\psi K^{*0}(892)$ as control channel, fit simultaneously $B^0$ data, simulation and $B_s^0$ simulation

$$\epsilon_{data}^{B_s^0}(t) = \epsilon_{data}^{B^0}(t) \times \frac{\epsilon_{MC}^{B_s^0}(t)}{\epsilon_{MC}^{B^0}(t)}$$

- Method validated with $B^+ \rightarrow J/\psi K^+$
  - $\Gamma_u - \Gamma_d = -0.0478 \pm 0.0013 \text{ ps}^{-1}$ (stat. only) vs. $(\Gamma_u - \Gamma_d)_{PDG} = -0.0474 \pm 0.0023 \text{ ps}^{-1}$

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Angular and $m_{\pi\pi}$ efficiency

- Kinematic selection and detector acceptance can cause non uniform efficiency as function of decay angles and $m_{\pi\pi}$ ($B^0_s \to J/\psi \pi^+ \pi^-$)

- Efficiencies obtained from simulation and corrected to match the data
  - Method $B^0_s \to J/\psi K^+ K^-$ validated on $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^* \pi^+$ data, good agreement are found
Angular and $m_{\pi\pi}$ efficiency

Angular and $m_{\pi\pi}$ efficiency obtained with $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ simulation

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

[PLB 797(2019) 134789]
Flavour tagging

- Tagging power $\epsilon_{\text{tag}}(1 - 2\omega)^2$ is used to estimate the performance of flavor tagging.
- More tagging power = better exploitation of data.

$$\epsilon_{\text{tag}}(1 - 2\omega)^2 = 4.73 \pm 0.34\%$$

$$\epsilon_{\text{tag}}(1 - 2\omega)^2 = 5.06 \pm 0.38\%$$
## Systematics for $B^0_s \to J/\psi K^+K^-$

| Source                                                  | $\phi_s$  | $|\lambda|$ | $\Gamma_s - \Gamma_d$ | $\Delta\Gamma_s$ | $\Delta m_s$ | $|A_\perp|^2$ | $|A_0|^2$ | $\delta_\perp - \delta_0$ | $\delta_\parallel - \delta_0$ |
|--------------------------------------------------------|------------|-------------|------------------------|------------------|--------------|-------------|----------|--------------------------|--------------------------|
| Mass: width parametrisation                            | -          | -           | -                      | 0.0002           | 0.001        | 0.0005      | 0.0006   | 0.05                      | 0.009                    |
| Mass: decay-time & angles dependence                   | 0.004      | 0.0037      | 0.0007                 | **0.0022**       | 0.016        | 0.0004      | 0.0002   | 0.01                      | 0.004                    |
| Multiple candidates                                    | 0.0011     | 0.0011      | 0.0003                 | 0.0001           | 0.001        | 0.0001      | 0.0006   | 0.01                      | 0.002                    |
| Fit bias                                               | 0.0010     | -           | -                      | 0.0003           | 0.001        | 0.0006      | 0.0001   | 0.02                      | 0.033                    |
| $C_{Sp}$ factors                                       | 0.0010     | 0.0010      | -                      | 0.0001           | 0.002        | 0.0001      | -        | 0.01                      | 0.005                    |
| Time resolution: model applicability                   | -          | -           | -                      | -                | 0.001        | -           | -        | -                        | 0.001                    |
| Time resolution: $t$ bias                              | 0.0032     | 0.0010      | 0.0002                 | 0.0003           | 0.005        | -           | -        | 0.08                      | 0.001                    |
| Time resolution: wrong PV                              | -          | -           | -                      | -                | 0.001        | -           | -        | -                        | 0.001                    |
| Angular efficiency: simulated sample size              | 0.0011     | 0.0018      | -                      | 0.001            | 0.0004      | 0.0003      | -        | 0.04                      | 0.004                    |
| Angular efficiency: weighting                          | 0.0022     | **0.0043**  | 0.0001                 | 0.0002           | 0.001        | 0.0011      | 0.0020   | 0.01                      | 0.008                    |
| Angular efficiency: clone candidates                   | 0.0005     | 0.0014      | 0.0002                 | 0.0001           | -            | 0.0001      | 0.0002   | -                        | 0.002                    |
| Angular efficiency: $t$ & $\sigma_t$ dependence       | 0.0012     | 0.0007      | 0.0002                 | 0.0010           | 0.003        | 0.0012      | 0.0008   | 0.03                      | 0.006                    |
| Decay-time efficiency: statistical                     | -          | -           | **0.0012**             | 0.0008           | -            | 0.0003      | 0.0002   | -                        | -                       |
| Decay-time efficiency: kinematic weighting             | -          | -           | 0.0002                 | -                | -            | -           | -        | -                        | -                       |
| Decay-time efficiency: $PDF$ weighting                 | -          | -           | 0.0001                 | 0.0001           | -            | -           | -        | -                        | -                       |
| Decay-time efficiency: $\Delta\Gamma_s = 0$ simulation| -          | -           | 0.0003                 | 0.0005           | -            | 0.0002      | 0.0001   | -                        | -                       |
| Length scale                                           | -          | -           | -                      | 0.004            | -            | -           | -        | -                        | -                       |
| Quadratic sum of syst.                                 | 0.0061     | 0.0064      | 0.0015                 | 0.0026           | 0.018        | 0.0019      | 0.0024   | 0.10                      | 0.037                    |

[arXiv:1906.08356]

- Main systematic uncertainties on $\phi_s$ is flavor tagging $\sim 0.015$ rad, which incorporated in statistical
Systematics for $B_s^0 \to J/\psi \pi^+ \pi^-$

| Source                          | $\Gamma_H - \Gamma_{B^0}$ [fs$^{-1}$] | $|\lambda|$ [$\times 10^{-3}$] | $\phi_s$ [mrad] |
|--------------------------------|---------------------------------------|-------------------------------|-----------------|
| Decay-time acceptance          | 2.0                                   | 0.0                           | 0.3             |
| $\tau_{B^0}$                   | 0.2                                   | 0.5                           | 0.0             |
| Efficiency ($m_{\pi\pi}$, $\Omega$) | **0.2**                                    | 0.1                           | 0.0             |
| Decay-time resolution width    | 0.0                                   | 4.3                           | 4.0             |
| Decay-time resolution mean     | 0.3                                   | 1.2                           | 0.3             |
| Background                     | 3.0                                   | 2.7                           | 0.6             |
| Flavour tagging                | 0.0                                   | 2.2                           | 2.3             |
| $\Delta m_s$                   | 0.3                                   | 4.6                           | 2.5             |
| $\Gamma_L$                     | 0.3                                   | 0.4                           | 0.4             |
| $B_c^+$                        | 0.5                                   | -                             | -               |
| Resonance parameters           | 0.6                                   | 1.9                           | 0.8             |
| Resonance modelling            | 0.5                                   | **28.9**                     | **9.0**         |
| Production asymmetry           | 0.3                                   | 0.6                           | 3.4             |
| Total                          | 3.8                                   | 29.9                          | 11.0            |

[PLB 797(2019) 134789]

- $\Gamma_H - \Gamma_{B^0}$ mainly affected by Efficiency of $m_{\pi\pi}$ and $\Omega$, $\phi_s$ and $|\lambda|$ by resonance modeling

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Results and new LHCb combination

\[ B_s^0 \rightarrow J/\psi K^+ K^- \]  
\[ \phi_s = -0.083 \pm 0.041 \pm 0.006 \text{ rad} \]
\[ |\lambda| = 1.012 \pm 0.016 \pm 0.006 \]
\[ \Gamma_s - \Gamma_d = -0.0041 \pm 0.0024 \pm 0.0015 \text{ ps}^{-1} \]
\[ \Delta\Gamma_s = 0.077 \pm 0.008 \pm 0.003 \text{ ps}^{-1} \]

\[ B_s^0 \rightarrow J/\psi \pi^+ \pi^- \]  
\[ \phi_s = -0.057 \pm 0.060 \pm 0.011 \text{ rad} \]
\[ |\lambda| = 1.01^{+0.08}_{-0.06} \pm 0.03 \]
\[ \Gamma_H - \Gamma_{B^0} = -0.050 \pm 0.004 \pm 0.004 \text{ ps}^{-1} \]

Combination of all LHCb (Run I+II) results

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

\[ \phi_s^{\exp} = -0.021 \pm 0.031 \text{ rad} \]
\[ \Delta \Gamma_s^{\exp} = 0.0849 \pm 0.0061 \text{ ps}^{-1} \]

Reminder:
\[ \phi_s^{\SM} = -0.0368^{+0.0010}_{-0.0008} \text{ rad} \] [CKMFitter]
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HFLAV combination

$\phi_s^{\text{exp}} = -0.055 \pm 0.021 \text{ rad}$

$\Delta \Gamma_s^{\text{exp}} = 0.0764 \pm 0.0024 \text{ ps}^{-1}$

Reminder:

$\phi_s^{\text{SM}} = -0.0368^{+0.0010}_{-0.0008} \text{ rad}$ [CKMFitter]
Propects

- Include gain in trigger for $B_s^0 \rightarrow D_s^+ D_s^-$ after Upgrade 1
- Exploring new modes:
  $J/\psi (\rightarrow ee), \eta' (\rightarrow \rho^0 \gamma, \eta \pi \pi, \gamma \gamma)$
- Expect to have
  - $\sigma_{\text{stat}} \sim 4$ mrad 300 /fb ($B_s^0 \rightarrow J/\psi \phi$)
  - $\sigma_{\text{stat}} \sim 3$ mrad 300 /fb (total)
- $\phi_s$ would be statistically limited
Summary

- More precise measurement of $\phi_s$ from $b \to c\bar{c}s$ transitions using 2015-2016 data sets
- Overall picture is SM-like in $\phi_s$ measurements
  - Current results are mostly statistically dominated
  - Exploring new modes would improve our knowledge of $\phi_s$
- LHCb 300/fb data would decrease $\sigma_{\text{stat}} \sim 3$ mrad
- Analyses of 2017-2018 data sets are ongoing and significant precision improvement of $\phi_s$ measurement is expected
- Stay tuned for more results in the near future!
Backups
LHCb experiments

Decay-time resolution \( \sim 50 \) fs
IP resolution \( \sim 20 \) μm

Tracking efficiency : \( > 96 \% \)
\( \Delta p/p : 0.4 - 1.0 \% \)

Muon identification :
\( \epsilon(\mu \rightarrow \mu) \sim 97 \% \) with \( \epsilon(\pi - \mu) \sim 2 \% \)

Hadron identification :
\( \epsilon(K \rightarrow K) \sim 95 \% \) with \( \epsilon(\pi - K) \sim 10 \% \)

LHCb data set

- Run I
  - 2011 1 fb\(^{-1}\), 7 TeV
  - 2012 2 fb\(^{-1}\), 8 TeV

- Run II
  - 2015 0.3 fb\(^{-1}\), 13 TeV
  - 2016 1.6 fb\(^{-1}\), 13 TeV
  - 2017 1.7 fb\(^{-1}\), 13 TeV
  - 2018 2.1 fb\(^{-1}\), 13 TeV

[IJMPA 30, 1530022 (2015), 2008 JINST 3 S08005]
**Decay-time resolution**

- Pre-candidate decay-time error is calibrated using prompt $J/\psi$ sample formed from $J/\psi$ and two kaons (pions) from PV

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

- Fit in bins of per-event decay-time error $\delta_t$
- Method validated in MC comparing prompt and signal resolution

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**Figures**

- Left: LHCb data and fits for different decay-time regions.
- Right: Scatter plot showing normalized yield vs. decay-time error $\delta_t$.

[arXiv:1906.08356]

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