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

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Implications of LHCb measurements and future prospects
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Outline

- Introduction
- Measurements
- Ongoing work
- Conclusion
Measurements of $\phi_s$

CP violation in the interference between “mixed” and “unmixed” decays

$$\lambda_f \equiv \frac{q}{p} \frac{\bar{A}_f}{A_f} \equiv \eta_f \frac{q}{p} \frac{\bar{A}_f}{A_f} e^{-i\phi_s}$$

CP-violation parameter $\lambda_f$ contains

- CP violation in mixing
- CP violation in decay
- CP violation in interference between “mixed” and “unmixed” decays

$\phi_s$ is sensitive to physics beyond the Standard Model that affects the loops in mixing and/or decay
Analysis methods

\( B^0_s \rightarrow f \)

\( \overline{B}^0_s \rightarrow f \)

\( \phi_s \) is determined from decay-time distributions

- amplitude of oscillations
- relative contributions of heavy and light \( B^0_s / \overline{B}^0_s \) eigenstates to exponential decay

→ see also talk by R. Knegjens on effective lifetimes

Use decay-angle distributions (and \( h^+ h^- \) invariant masses)

to separate contributions from intermediate resonant and polarization states

\( B^0_s \rightarrow J/\psi K^+ K^- \) (PRD 87 (2013) 112010)
Decays

\[ B_s^0 \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) \phi (\rightarrow K^+ K^-) \]
\[ B_s^0 \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) f_0 (\rightarrow \pi^+ \pi^-) \]
- dominated by tree-level amplitude
- sensitive to non-Standard Model CP violation induced by mixing
- \( \phi_s^{c\bar{c}s} \approx -2\beta_s = -0.0363^{+0.0016}_{-0.0015} \) in SM

\[ B_s^0 \rightarrow \phi (\rightarrow K^+ K^-) \phi (\rightarrow K^+ K^-) \]
\[ B_s^0 \rightarrow K^{*0} (\rightarrow K^+ \pi^-) \bar{K}^{*0} (\rightarrow K^- \pi^+) \]
- sensitive to non-Standard Model CP violation induced by mixing and/or decay
- \( \phi_s^{\phi \phi} \approx 0 \) and \( \phi_s^{K^* K^*} \approx 0 \) in SM

also expected:
\[ B_s^0 \rightarrow \psi(2S) \phi; B_s^0 \rightarrow J/\psi \eta^{(')}; B_s^0 \rightarrow D_s^+ D_s^- \]
Outline

- Introduction

- Measurements
  - \( B^0_s \to J/\psi K^+ K^- \) and \( B^0_s \to J/\psi \pi^+ \pi^- \)
  - \( B^0_s \to \phi \phi \)
  - \( B^0_s \to K^{*0} \overline{K}^{*0} \)

- Ongoing work

- Conclusion
$B_s^0 \rightarrow J/\psi h^+h^-$

Resonant components

$B_s^0 \rightarrow J/\psi K^+K^-$  (PRD 87 (2013) 072004)

$B_s^0 \rightarrow J/\psi \pi^+\pi^-$  (PRD 86 (2012) 052006)

**$\phi_s$ analysis:**

0.99–1.05 GeV/$c^2$ $K^+K^-$-mass window

- mass region dominated by $\phi(1020)$
- small S-wave component

0.60–2.40 GeV/$c^4$ $\pi^+\pi^-$-mass window

- mass region dominated by $f_0(980)$
- fraction of CP-odd components $> 0.977$ at 95% C.L.
**B^0_s → J/ψ h^+ h^-**

Analysis on 1 fb\(^{-1}\) of data from 2011 (update with full 3 fb\(^{-1}\) planned)

\[
\begin{align*}
B^0_s &\rightarrow J/ψ K^+ K^- \\
\approx 28,000 \text{ signal events} \\
φ^{c̅c̅}\_s &= 0.07 \pm 0.09 \pm 0.01 \text{ rad} \\
ΔΓ_s &= 0.100 \pm 0.016 \pm 0.003 \text{ ps}^{-1} \\
Γ_s &= 0.663 \pm 0.005 \pm 0.006 \text{ ps}^{-1}
\end{align*}
\]

- Assume \(φ_s\) does not depend on decay channel (or intermediate state)
- Combination for \(B^0_s \rightarrow J/ψ h^+ h^-\) channels gives

\[
\begin{align*}
φ^{c̅c̅}\_s &= 0.01 \pm 0.07 \pm 0.01 \text{ rad} \\
ΔΓ_s &= 0.106 \pm 0.011 \pm 0.007 \text{ ps}^{-1} \\
Γ_s &= 0.661 \pm 0.004 \pm 0.006 \text{ ps}^{-1}
\end{align*}
\]
Analysis on 1 fb\(^{-1}\) of data from 2011 (update with full 3 fb\(^{-1}\) planned)

- 880 ± 31 signal events
- \(\phi_s^{\phi\phi} \in [-2.46, -0.76] \text{ rad (68% C.L.)}\)
  
  \[ F_L = 0.329 \pm 0.033 \pm 0.017 \]
  
  \[ F_\perp = 0.358 \pm 0.046 \pm 0.018 \]
  
  \[ \delta_1 = +2.19 \pm 0.44 \pm 0.12 \]
  
  \[ \delta_2 = -1.47 \pm 0.48 \pm 0.10 \]
$B_S^0 \rightarrow K^*0 \bar{K}^*0$

Analysis on 35 pb$^{-1}$ of data from 2010
(update with 1 fb$^{-1}$ (2011) planned, working on time-dependent analysis with 3 fb$^{-1}$)

- first observation
- angular analysis
- 50 ± 8 signal events
- $F_L = 0.31 \pm 0.12 \pm 0.04$
- $F_\perp = 0.38 \pm 0.11 \pm 0.04$

Update will also contain triple-product asymmetries
Outline

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- Ongoing work
  - Flavour tagging
  - Invariant $h^+h^-$-mass modelling
  - Polarization-dependent CP violation
- Conclusion
Flavour tagging

Improving several experimental aspects – one example is flavour tagging

- Can we increase the effective fraction of perfectly tagged events ($\varepsilon\langle D^2 \rangle \approx 3\%$)?
- Statistical uncertainty on $\phi_s$ approximately proportional to $1/\sqrt{\varepsilon\langle D^2 \rangle}$
- Improvements for both same-side and opposite-side tagging

- neural net-based algorithms
- reoptimization
Invariant $h^+h^-$-mass modelling

In addition to decay time and decay angles, should we also model the $h^+h^-$ mass(es)?

- $B_s^0 \rightarrow J/\psi K^+K^-$ analysis is done in $\phi(1020)$ region (in bins of the $K^+K^-$ mass)
- What would we gain by modelling the $K^+K^-$ mass distribution?
- What would we learn from other resonances?
- Modified time-dependent Dalitz analysis with time, helicity angles and $m_{ KK}$ described by Zhang and Stone (PLB 719 (2013) 383)

Should the model also depend on orbital angular momenta? (barrier factors, momentum dependence of wave function)
We usually only consider dominant (Standard Model) amplitudes:

- **tree-level** for $B_s^0 \rightarrow J/\psi h^+h^-$
- $O(\lambda^2)$ for $B_s^0 \rightarrow \phi \phi$ and $B_s^0 \rightarrow K^{*0} \overline{K}^{*0}$ (where $\lambda \equiv |V_{us}|$)

But CP violation is small... For a precise measurement we may also have to consider suppressed penguin amplitudes ($\rightarrow O(\lambda^4)$ in Standard Model)

And contributions with new weak phases may be introduced in the decay

Previous measurements assumed that CP violation is the same for all polarization (and resonant) states

A consequence of multiple amplitudes is that (in general) CP violation depends on the intermediate state
Polarization-dependent CP violation

**Corrections to $\phi_s$**

CP-violation parameter $\lambda_k$ depends on intermediate state $k$:

$$
\lambda_k \equiv \frac{q}{p} \frac{\bar{A}_k}{A_k} \approx \eta_k e^{-i \phi_s^{\text{dom}}} \frac{1 + r R_k e^{i \delta_k} e^{i \theta}}{1 + r R_k e^{i \delta_k} e^{-i \theta}}
$$

where

- $\phi_s^{\text{dom}}$ is $\phi_s$ if there were only the dominant amplitudes
- $R_k e^{i \delta_k} e^{\pm i \theta}$ is the “ratio of suppressed and dominant amplitudes” for $\bar{B}_s^0$ ($B_s^0$) (with strong phase $\delta_k$ and weak phase $\theta$)
- $r$ is the magnitude of ratio of CKM elements

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**Corrections to measured $\phi_s$, polarization dependent in general**

**Constant correction to measured $\lambda_k$ if amplitudes ratio polarization independent:**

$$
R_k e^{i \delta_k} e^{\pm i \theta} \rightarrow R e^{i \delta} e^{\pm i \theta}
$$

**No correction ($\lambda \equiv \frac{1}{\eta_k} \lambda_k \approx e^{-i \phi_s^{\text{dom}}}$) if:**

- magnitude of CKM-elements ratio small: $r \rightarrow 0$
- or magnitude of amplitudes ratio small: $R_k \rightarrow 0$
- or no weak phase in ratio of amplitudes: $\theta \rightarrow 0$
Polarization-dependent CP violation
Experimental approaches

- $B^0_s \rightarrow \phi \phi$: Studying possibility to **directly measure theoretical parameters** in expressions for $\lambda_k$ (independent parameters for intermediate states)
  → talk by B. Bhattacharya on Wednesday

- $B^0_s \rightarrow J/\psi K^+K^-$: Planning to **measure observables**: independent $\lambda_k \equiv |\lambda_k| e^{-i\phi_s^k}$ for intermediate states

- Extract interesting physics from $B^0_s \rightarrow J/\psi K^+K^-$ parameters in separate analysis, using also
  - $B^0_s \rightarrow J/\psi K^{*0}$ (U-spin related) → Faller, Fleischer, Mannel, PRD 79 (2009) 014005
  - ...

- Preliminary studies on 1 fb$^{-1}$ show that $B^0_s \rightarrow J/\psi K^+K^-$ measurement is feasible:

  $\phi_s = 0.07 \pm 0.09 \quad \rightarrow \quad \left\{ \begin{array}{c}
  \phi_s^0 = \ldots \pm 0.10; \\
  \phi_s^\parallel = \ldots \pm 0.12; \\
  \phi_s^\perp = \ldots \pm 0.15 \\
  \phi_s^S = \ldots \pm 0.16
\end{array} \right.$
Conclusion

- $B_s^0 \to J/\psi h^+ h^-$ and $B_s^0 \to \phi \phi$ measurements of $\phi_s$ with 1 fb$^{-1}$ from 2011:
  - $\phi_s^{c\bar{c}s} = (0.01 \pm 0.07 \pm 0.01)$ rad
  - $\phi_s^{\phi\phi} \in [-2.46, -0.76]$ rad (68% C.L.)

updates planned with the full 3 fb$^{-1}$ data set

- $B_s^0 \to K^*^0 \overline{K}^*^0$ amplitude analysis with 1 fb$^{-1}$ planned, working on time-dependent analysis with 3 fb$^{-1}$

- Working on several experimental and modelling improvements, specifically on models which incorporate resonance- and polarization-dependent CP violation
Additional information
Products of decay amplitudes

\[ A_i(t) A_j(t) = A_i^* A_j \left( \frac{1 + |q_p|^2}{4 |q_p|^2} \right) (1 - q_{\text{flav}} C_m) e^{-\Gamma_s t} \]

\[ \times \left[ (P_{ij}^+ + P_{ij}^- C_m) \cosh \left( \frac{1}{2} \Delta \Gamma_s t \right) + q_{\text{flav}} (P_{ij}^- + P_{ij}^+ C_m) \cos (\Delta m_s t) \right. \]

\[ + \left. (P_{ij}^{\Re} D_m + P_{ij}^{\Im} S_m) \sinh \left( \frac{1}{2} \Delta \Gamma_s t \right) + q_{\text{flav}} (P_{ij}^{\Im} D_m - P_{ij}^{\Re} S_m) \sin (\Delta m_s t) \right] \]

\[ P_{ij}^+ = \frac{1}{2} \left[ 1 + \left( \frac{\bar{A}_i}{A_i} \right)^* \frac{\bar{A}_j}{A_j} \right] \quad \rightarrow \quad \frac{1}{2} \left( 1 + \left| \frac{\bar{A}_i}{A_i} \right|^2 \right) \quad \text{for } i = j \]

\[ P_{ij}^- = \frac{1}{2} \left[ 1 - \left( \frac{\bar{A}_i}{A_i} \right)^* \frac{\bar{A}_j}{A_j} \right] \quad \rightarrow \quad \frac{1}{2} \left( 1 - \left| \frac{\bar{A}_i}{A_i} \right|^2 \right) \]

\[ P_{ij}^{\Re} = \frac{1}{2} \left[ \left( \frac{\bar{A}_i}{A_i} \right)^* + \frac{\bar{A}_j}{A_j} \right] \quad \rightarrow \quad \Re \left( \frac{\bar{A}_i}{A_i} \right) \]

\[ P_{ij}^{\Im} = i \cdot \frac{1}{2} \left[ \left( \frac{\bar{A}_i}{A_i} \right)^* - \frac{\bar{A}_j}{A_j} \right] \quad \rightarrow \quad \Im \left( \frac{\bar{A}_i}{A_i} \right) \]

\[ C_m = \frac{1 - |q_p|^2}{1 + |q_p|^2} \quad D_m = - \frac{2 \Re \left( \frac{q_p}{p} \right)}{1 + |q_p|^2} \quad S_m = \frac{2 \Im \left( \frac{q_p}{p} \right)}{1 + |q_p|^2} \]

\[ \nu_N = -C_m \quad (B_s^0 - \overline{B_s^0} \text{ normalization asymmetry}) \]