Measurement of the phase of $B_s$ mixing with $B_s \to \phi\phi$

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On behalf of the LHCb Collaboration
Outline

• Introduction +dataset

• Time dependent analysis in $B_s \rightarrow \phi \phi$

• Triple product measurement in $B_s \rightarrow \phi \phi$

• Summary

Studies exploit full LHCb Run 1 dataset of $3\text{fb}^{-1}$
Introduction

- Observable phase $\phi_s = -2\beta_s = \Phi_M - 2\Phi_D$
  - In the Standard Model expected $\phi_s$ small for in $B_s \rightarrow \phi\phi$
  - Larger values possible in models of New Physics such as Supersymmetry and Little Higgs

Direct CP violation also possible

$$|\lambda| = \left| \frac{q}{p} \cdot \overline{A} \right|$$

$|\lambda| \neq 1$

Direct CP
Introduction: \( B_s \rightarrow \phi \phi \)

Gluonic penguin decay. \( \text{BR} \sim 2 \times 10^{-5} \)

SM cancellation between decay + mixing phases \( \phi_s \) is 0.01 with 0.02 uncertainty (arXiv:0810.0249)

Room for New Physics even if \( \phi_s \) constrained by measurements in other modes

LHCb: ideal place to measure due large dataset + hadronic trigger

Build on previous time dependent measurement using 880 events corresponding to 1fb\(^{-1}\) of data collected in 2011 [PRL 110 (2013) 241802].
Yielded 68% CL of \([-2.46, -0.76]\) rad
P + S – wave amplitudes/ strong phase
P wave three polarization amplitudes
• CP even \((A_0, A_{||})\) CP odd \((A_{\text{perp}})\)
S-wave CP odd and even components
CP violating phase \(\phi_s\)
Direct CP violation parameter \(|\lambda|\)

\[
\frac{d\Gamma}{dt\, d\cos\theta_1\, d\cos\theta_2\, d\Phi} \propto \frac{4}{3} |A(t, \theta_1, \theta_2, \Phi)|^2 = \sum_{i=1}^{15} K_i(t) f_i(\theta_1, \theta_2, \Phi)
\]

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<tr>
<th>(i)</th>
<th>(K_i)</th>
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<td>(\text{Im}(A_{\perp}(t)A_S^*(t)))</td>
<td>(-\frac{4}{3} \sqrt{2} \sin \theta_1 \sin \theta_2 \cos (\theta_1 + \cos \theta_2) \sin \Phi)</td>
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Time dependent angular analysis

Angular acceptance from simulation

Time acceptance from data
Dataset

- Full Run 1 dataset + new multi-variate selection yields 3950 signal candidates
- Around 4.5x number from previous analysis
Analysis Ingredients

Physics parameters in $\Gamma_s, \Delta \Gamma_s, \Delta m_s$ from other LHCb analyses

Unbinned maximum likelihood fit to mass, time and angles

Time resolution model from simulation. Calibrated on data $\sigma_t \sim 43$ fs

Opposite + same side tagging calibrated using $B^+ \rightarrow J/\psi K^+$ and semi-leptonic $B$ decays. See talk of M. Dorigo

Angular acceptance for signal from simulation

Time acceptance due to cuts in the trigger determined from $B_s \rightarrow D_s \pi$ data
Fit Projections

LHCb

CP Even
CP Odd
S-wave
\( \phi_s \) results

\[
\phi_s = (-0.17 \pm 0.15 \pm 0.03) \text{ rad}
\]

\[|\lambda| = 1.04 \pm 0.07 \pm 0.03\]

\[|A_0|^2 = 0.364 \pm 0.012 \pm 0.009\]

\[|A_\perp|^2 = 0.305 \pm 0.013 \pm 0.005\]

Results consistent with no CP violation and the Standard Model expectation

Main systematic uncertainties from angular and decay time acceptance.

Uncertainties due to included in \( \Gamma_s, \Delta \Gamma_s, \Delta m_s \), tagging included in the statistical uncertainty
Triple Product Asymmetries

CP-odd/CP-even interference terms \( \text{Im}(A_0^* A_\perp) + \text{Im}(A_\parallel^* A_\perp) \) are proportional to Triple products + are odd under time reversal

Sign according to \( \cos \theta_1 \cos \theta_2 \)

\[
\begin{align*}
V \sin \Phi &= (\hat{n}_{V_1} \times \hat{n}_{V_2}) \cdot \hat{p}_{V_1} \\
U \sin 2\Phi &= 2(\hat{n}_{V_1} \cdot \hat{n}_{V_2})(\hat{n}_{V_1} \times \hat{n}_{V_2}) \cdot \hat{p}_{V_1}
\end{align*}
\]

- Non-zero TPs: T violation + hence CP violation

- Extraction of TP asymmetries simple counting exercise:

\[
A_U = \frac{\Gamma(U > 0) - \Gamma(U < 0)}{\Gamma(U > 0) + \Gamma(U < 0)} \quad A_V = \frac{\Gamma(V > 0) - \Gamma(V < 0)}{\Gamma(V > 0) + \Gamma(V < 0)}
\]

- Zero in the Standard Model, non zero if weak phases of polarization amplitudes different
Triple Product results

\[ A_u = -0.003 \pm 0.017 \pm 0.006 \]
\[ A_v = -0.017 \pm 0.017 \pm 0.006 \]

- Triple products consistent with zero. Consistent with previous LHCb/CDF results, improve precision by factor of two

- Main systematics from mass model, angular and time acceptance
Summary

Full LHCb Run 1 dataset + latest flavour tagging used to make precision measurement of CP violation in $B_s \rightarrow \phi\phi$ decay

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

$$|\lambda| = 1.04 \pm 0.07 \pm 0.03$$

Updated values for triple products also given

Results consistent with Standard Model prediction of small CP violation

Expect factor of two improvement in precision with Run 2 data

Key channel for LHCb upgrade where precision will reach $\sim 0.03$ level providing high precision probe of Standard Model (theory uncertainty 0.02)
Backup
The LHCb Detector

- Muon System
- RICH Detectors
- Vertex Locator VELO
- Calorimeters
- Tracking System