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Measurement of CP violation in $B_s^0 \to \phi\phi$ decays

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A measurement of the CP-violating phase ϕ_s in the decay $B_s^0 \to \phi\phi$ is presented. Around 4000 signal events are selected using $3\,\mathrm{fb}^{-1}$ of proton-proton collisions at $\sqrt{s} = 7$ and $8\,\mathrm{TeV}$ collected by LHCb. CP violation in this decay may arise in the interference between the mixing of the B_s^0 meson with the $\bar{B}_s^0$ and the decay amplitudes of $B_s^0 \to \phi\phi$ and its CP-conjugate process. The final state is not a CP eigenstate, hence a decay-time-dependent angular analysis is performed, which yields a result of $\phi_s = -0.17 \pm 0.15 \pm 0.03\,\mathrm{rad}$. This is consistent with theoretical predictions.

The 15th International Conference on B-Physics at Frontier Machines at the University of Edinburgh,
14 -18 July, 2014
University of Edinburgh, UK

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PoS(Beauty2014)064

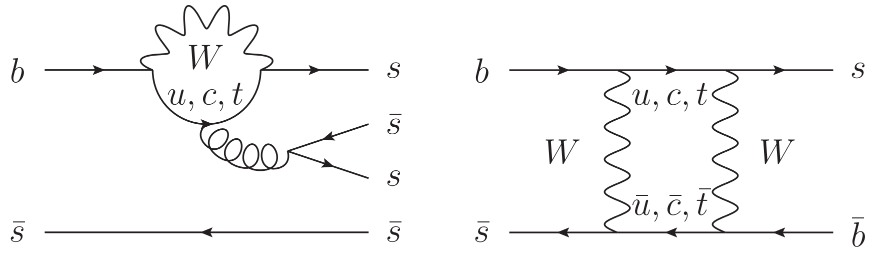

Figure 1: Left: Leading-order gluonic penguin Feynman diagram for the $B_s^0 \to \phi\phi$ decay. Right: Example Feynman diagram for $B_s^0 - \bar{B}_s^0$ mixing.

1. Introduction

The decay $B_s^0 \to \phi\phi$ is a $b \to s\bar{s}s$ flavour-changing neutral current transition, which is forbidden at tree level. The leading-order diagram contains a loop, as shown in Figure 1, making the decay amplitude sensitive to the existence of heavy particles. The final state is accessible to both B_s^0 and $\bar{B}_s^0$. Hence, CP violation would occur in the interference between $B_s^0 - \bar{B}_s^0$ mixing and the amplitudes of the decays $B_s^0 \to \phi\phi$ and $\bar{B}_s^0 \to \phi\phi$ The observable phase ϕ_s is a function of the mixing phase ϕ_M and decay phase ϕ_D. If a B_s^0 decays directly to $\phi\phi$, a phase of ϕ_D is acquired. If it first oscillates to a $\bar{B}_s^0$ before decaying, the total phase is $\phi_M - \phi_D$. The observable phase is the difference between these two paths, i.e. $\phi_s = \phi_M - 2\phi_D$. Due to a cancellation between the mixing and decay phases, ϕ_s is expected to be zero in the Standard Model. Next-to-leading order QCD calculations give $\phi_s = 0.01 \pm 0.02\,\mathrm{rad}$ [2]. Physics beyond the Standard Model may lead to larger values of ϕ_s, which motivates the measurement of CP violation in this channel.

A measurement of the parameter $|\lambda| = \left|(q/p)(\bar{A}_f/A_f)\right|$ is also made. It is a function of the decay amplitudes A_f for $B_s^0 \to \phi\phi$ and $\bar{A}_f$ for $\bar{B}_s^0 \to \phi\phi$ and the mixing amplitudes q and p. Under the assumption that $|(q/p)| = 1$, $|\lambda|$ measures direct CP violation, which occurs if $|\lambda| \neq 1$.

2. Selection and mass fit

The dataset consists of proton-proton collisions collected by the LHCb detector corresponding to an integrated luminosity of 3 fb^{-1}, split into 1 fb^{-1} at $\sqrt{s} = 7$ TeV and 2 fb^{-1} at $\sqrt{s} = 8$ TeV. The LHCb detector is a single arm forward spectrometer, covering a range in pseudorapidity $2 < \eta < 5$, designed for precision studies of heavy quark decays [3]. Event candidates are reconstructed from a $K^+K^-K^+K^-$ final state. K^+K^- pairs are reconstructed to ϕ meson candidates, which were in turn reconstructed into B_s^0 candidates.

An initial set of loose cuts was applied to the dataset. Selected kaon candidates were required to have good track quality and to have high transverse momentum. Kaon-pair invariant masses were required to be in the range $\left|m_{K^+K^-} - m_\phi\right| < 25$ MeV/c^2.

A boosted decision tree (BDT) event classifier [5][6] was used to improve the selection based on vertex fit quality, isolation and detachment. The choice of cut on the BDT variable was optimised by maximising signal significance $S/\sqrt{S+B}$ where S is signal yield determined using simulation and B is background yield determined using data sideband. Two peaking backgrounds —

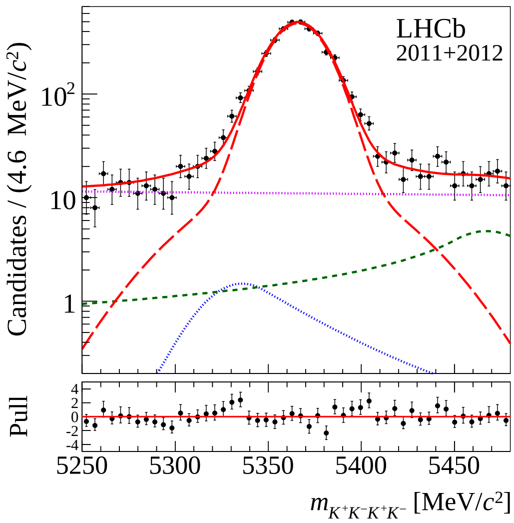

Figure 2: Fit to the $K^+K^-K^+K^-$ invariant mass spectrum. Red long-dashed line: B_s^0 peak. Green short-dashed line: $\Lambda_b \to \phi pK$. Blue dotted line: $B^0 \to \phi K^*$. Purple dotted line: combinatorial background.

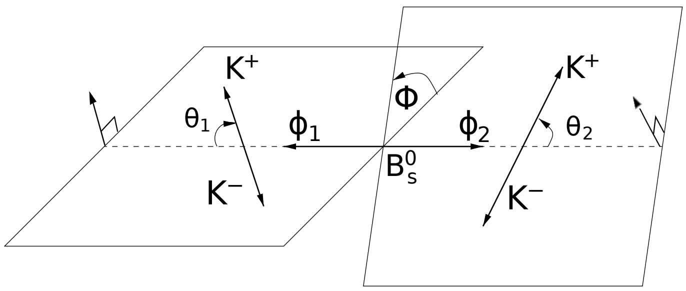

Figure 3: Decay angles for the $B_s^0 \to \phi\phi$ decay. The $K^\pm$ momenta are considered in the rest frame of the parent ϕ, and the ϕ momenta are considered in the rest frame of the B_s^0. θ is the angle between the K^+ and ϕ momenta. Φ is the angle between the two ϕ decay planes.

$\Lambda_b \to \phi K p$ and $B^0 \to \phi K^*$, both arising from misidentified hadrons — were identified and included in the mass model. From the mass fit shown in Figure 2, the $B_s^0 \to \phi\phi$ signal yield is 3950 ± 67.

3. Angular analysis

The $B_s^0 \to \phi\phi$ decay is a transition of a pseudoscalar meson to two vector mesons. As such, there are 3 possible configurations for angular momentum, ℓ. Polarisation amplitudes are assigned to each: A_0 for $\ell = 0$, $A_\perp$ for $\ell = 1$ and $A_\parallel$ for $\ell = 2$. Two amplitudes, A_0 and $A_\parallel$ are CP-even, and $A_\perp$ is CP-odd, hence the final state is a superposition of CP eigenstates. There are also contributions from decays of scalar mesons to charged kaon pairs. They are assigned the amplitudes A_S and A_{SS} for single and double S-wave, respectively. These five amplitudes depend on the decay angles θ_1,

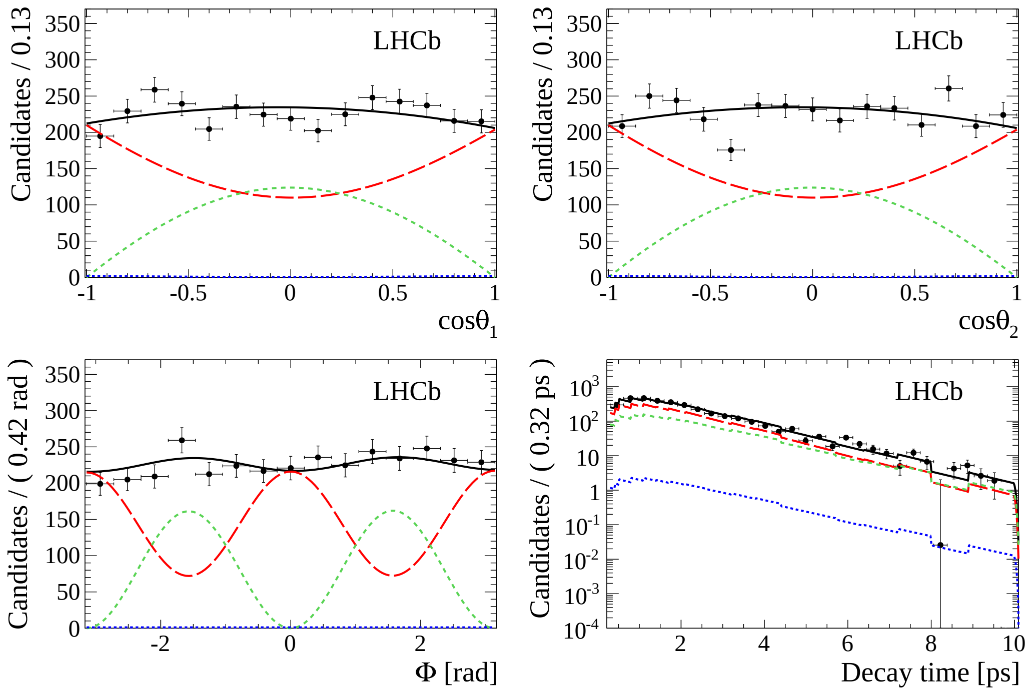

Figure 4: One-dimensional projections of the time-dependent angular fit on to t, $\cos\theta_1$, $\cos\theta_2$ and Φ. Black points are background-subtracted data obtained using the *sPlot* technique. Black solid line is the fit. Red long-dashed: CP-even *P*-wave. Green short-dashed: CP-odd *P*-wave. Blue dotted: *S*-wave.

θ_2 and Φ, defined in Figure 3. The total amplitude takes the following form:

$$\begin{aligned} A(t,\theta_1,\theta_2,\Phi) &= A_0(t)\cos\theta_1\cos\theta_2 + \frac{A_\parallel(t)}{\sqrt{2}}\sin\theta_1\sin\theta_2\cos\Phi \\ &+ i\frac{A_\perp(t)}{\sqrt{2}}\sin\theta_1\sin\theta_2\sin\Phi + \frac{A_S(t)}{\sqrt{2}}(\cos\theta_1+\cos\theta_2) + \frac{A_{SS}(t)}{3} \end{aligned} \tag{3.1}$$

The full differential decay rate can be modelled by a 15-term PDF of the form [4]:

$$\frac{\mathrm{d}^4\Gamma}{\mathrm{d}t\ \mathrm{d}\cos\theta_1\ \mathrm{d}\cos\theta_2\ \mathrm{d}\Phi} \propto \sum_{i=1}^{15} K_i(t) f_i(\theta_1,\theta_2,\Phi) \tag{3.2}$$

The CP observables ϕ_s and $|\lambda|$ are contained within the K_i terms. These can be decomposed as:

$$K_i(t) = N_i e^{-\Gamma_s t}\left[a_i\cosh(\Delta\Gamma_s t/2) + b_i\sinh(\Delta\Gamma_s t/2) + c_i\cos(\Delta m_s t) + d_i\sin(\Delta m_s t)\right] \tag{3.3}$$

where N_i are products of the absolute amplitudes $|A|$ at $t=0$. The coefficients a_i, b_i, c_i and d_i are functions of $|\lambda|$, ϕ_s and the CP-conserving strong phases δ associated with each amplitude.

A four-dimensional unbinned maximum likelihood fit is performed to the following variables: decay time, $\cos\theta_1$, $\cos\theta_2$ and Φ. One-dimensional projections of the fit onto these variables can be seen in Figure 4.

4. Results

From the results of the fit, the measured value of the observable phase is found to be $\phi_s = -0.17 \pm 0.15 \pm 0.03$ rad. The direct CP violation parameter is found to be $|\lambda| = 1.04 \pm 0.07 \pm 0.03$. The $\ell = 0$ polarisation amplitude is found to be $|A_0|^2 = 0.364 \pm 0.012 \pm 0.009$. The $\ell = 1$ polarisation amplitude is found to be $|A_\perp|^2 = 0.305 \pm 0.013 \pm 0.005$. The first uncertainties are statistical and the second systematic.

The largest constributions to the systematic uncertainties come from decay time and angular acceptance.

5. Summary and conclusions

A time-dependent angular analysis of the $B_s^0 \to \phi\phi$ decay has been performed at LHCb using the Run I dataset in order to extract a measurement of the CP violation. The measured values of ϕ_s and $|\lambda|$ are both found to be consistent with theoretical predictions of very small CP violation. The uncertainty on ϕ_s is statistically dominated. With the next additional statistics to be collected by LHCb during Run II of the LHC, a factor of 2 improvement on the precision of ϕ_s is expected. After the 2018 upgrade to the detector, the uncertainty on ϕ_s in $B_s^0 \to \phi\phi$ is expected to become comparable to theory, making this channel a high-precision test of the Standard Model.

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