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Measurement of the B_s^0 mixing phase using $B_s^0 \to \phi\phi$

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Abstract

Using 3 fb^{-1} of collision data collected by the LHCb collaboration in proton-proton collisions the B_s^0 mixing phase, ϕ_s in the $B_s^0 \to \phi\phi$ decay mode is determined to be $\phi_s = -0.17 \pm 0.15\,(\text{stat}) \pm 0.03\,(\text{syst})$. This is consistent with the Standard Model expectation that CP violation in this channel is small.

1. Introduction

In the Standard Model the decay $B_s^0 \to \phi\phi$ is forbidden at tree level and proceeds via a gluonic $b \to s\bar{s}s$ penguin process. Studies of CP violation in this channel allow to probe for new heavy particles entering into the penguin loop. In the Standard Model CP violation arises from a single phase in the Cabibbo-Kobayashi-Maskawa quark mixing matrix [1]. Interference between the B_s^0–$\overline{B}_s^0$ oscillation and decay amplitudes leads to a CP asymmetry in the decay time distributions of B_s^0 and $\overline{B}_s^0$ mesons. This gives an observable phase, ϕ_s, the value of which is dependent on the studied decay channel. For the $B_s^0 \to \phi\phi$ decay mode the value of ϕ_s is expected to be close to zero due to a cancellation of the oscillation and decay phases. A recent next-to-leading order QCD calculation gives $\phi_s = 0.01 \pm 0.02$ rad [2]. However, the value of ϕ_s can be enhanced in models of physics beyond the Standard Model [3].

The large dataset collected by the LHCb collaboration during the first LHC run has allowed to make the first point measurement of ϕ_s in this channel [4].

2. Method

The $B_s^0 \to \phi\phi$ decay is an admixture of CP eigenstates [5]. To disentangle these and measure ϕ_s a time dependent angular analysis is needed. A further complication arises since as well as the dominant the P-wave pseudoscalar to vector-vector transition constributions from processes where one or both the kaon pairs are in an S-wave configuration need to be accounted for. The possibility of direct CP violation in this decay mode is allowed for by the parameter $|\lambda| = |(q/p)(\overline{A}/A)|$, where q and p are the complex parameters relating the B_s^0 flavour and mass eigenstates, and A $(\overline{A})$ is the decay amplitude (CP conjugate decay amplitude).

To measure ϕ_s the flavour of the B_s^0 meson at production must be known. This is achieved using the opposite and same side flavour tagging algorithms described in Ref. [6] and [7]. In addition, several detector effects need to be considered. The geometry of detector leads to a non-uniform angular acceptance that is corrected for using the simulation. The cuts applied at the trigger stage (see Section 3) remove events with small decay times. The resulting angular acceptanceis corrected for using a data driven technique. This makes use of the $B_s^0 \to D_s^- \pi^+$ decay as control mode. The decay time resolution is accounted for with a per-event decay time error, used in association with a Gaussian model that is calibrated using the simulation.

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3. Dataset

The full dataset collected by LHCb is used for this analysis. This corresponds to an integrated luminosity of 2 fb^{-1} collected at centre-of mass energy of 8 TeV during 2012 and 1 fb^{-1} collected at 7 TeV during 2012.

The LHCb detector is a single arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$ [8]. Uniquely among the LHCb detectors it has the ability to identify charged hadrons using two ring imaging Cherenkov detectors. The events used in this analysis are selected by a hardware trigger, which selects hadron candidates with high transverse energy followed by a two stage software trigger.

In the subsequent offline analysis a two stage procedure is used. First, a loose cut based selection is applied which reduces the combinatorial background significantly whilst maintaining high efficiency for signal. This selects four good quality tracks with high p_T that are identified as kaons using the RICH detectors. Pairs of kaons with opposite charged are combined to form ϕ candidates and the invariant mass is required to be within 25 MeV/$/c^2$ of the nominal ϕ mass [9]. Subsequently, a Boosted Decision Tree (BDT) algorithm [10, 11] is used to provide the optimal signal-to-background for the angular analysis. The BDT is trained using simulated $B_s^0 \to \phi\phi$ decays and the far mass sidebands from the data. As input uses variables related to the event kinematics, particle identification information and isolation information. The optimal threshold for the BDT output is chosen to maximize $N_S/(N_S + N_B)$ where N_s (N_B) is the expected number of signal (background) events within ±120MeV/$/c^2$ of the B_s^0 mass.

Figure 1 and 2 shows the invariant mass of the four kaons for the data collected in 2011 and 2012 respectively. There is a clear signal peak. The remaining background is mainly combinatorial in nature with small contributions from the decays $B^0 \to \phi K^*$ and $\Lambda_b^0 \to \phi p K^-$ decays with misidentified hadrons. The fit gives a total of 3950 ± 67 signal candidates.

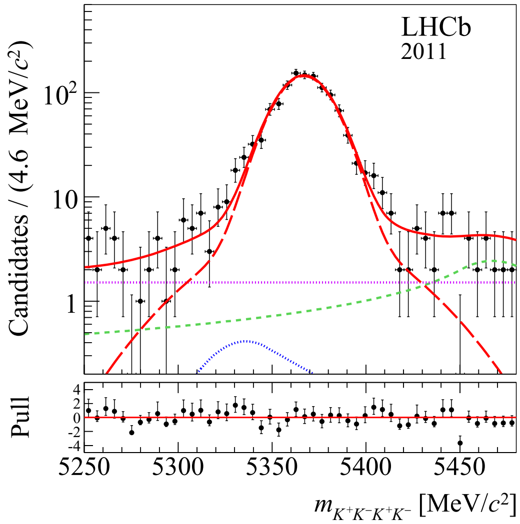

Figure 1: Four kaon invariant mass for selected candidates in the 2011 dataset. The total fitted function is shown in solid red together with the fitted signal (dotted red), combinatorial background (dotted magenta), $B^0 \to \phi K^*$ background (solid blue) and the $\Lambda_b^0 \to \phi p K^-$ background (dotted green).

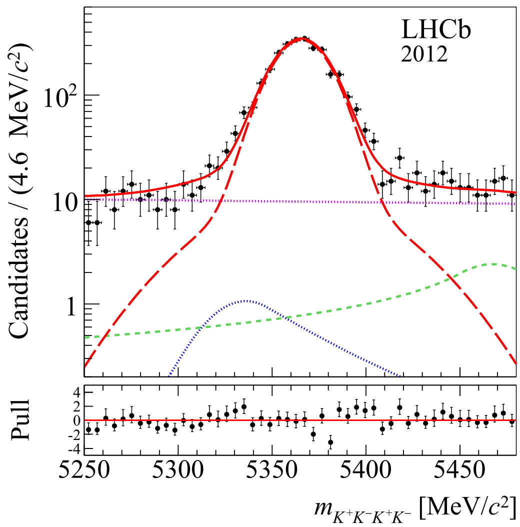

Figure 2: Four kaon invariant mass for selected candidates in the 2012 dataset. The total fitted function is shown in solid red together with the fitted signal (dotted red), combinatorial background (dotted magenta), $B^0 \to \phi K^*$ background (solid blue) and the $\Lambda_b^0 \to \phi p K^-$ background (dotted green) .

4. Results

To determine the CP violating parameters, polarization amplitudes and corresponding strong phases, an unbinned maximum likelihood fit in the decay angles and decay time is made to the data. In this fit background is subtracted using the *sPlot* [12] technique with the mass as the control variable. The main systematic uncertainties on the result arise from the modelling of the time and angular acceptances of the detector. The scan of the natural logarithm of the likelihood for the ϕ_s parameter is shown in Fig. 3. It can been seen that the likelihood behaves parabolically in the region of the minima.

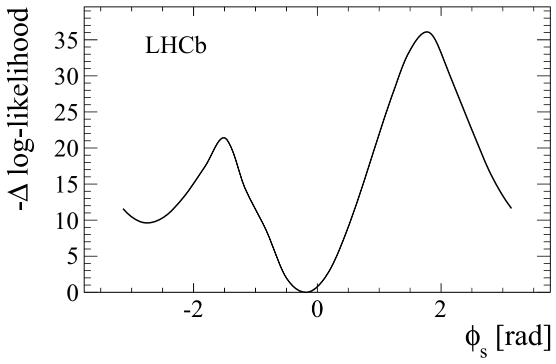

Figure 3: Profile log-likelihood for the ϕ_s parameter.

Including systematic uncertainties the results are:

$$\phi_s = -0.17 \pm 0.15\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})\,\mathrm{rad}$$

and

$$|\lambda| = 1.04 \pm 0.07\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})\,\mathrm{rad}$$

These measurements are consistent with the Standard Model predictions of negligible CP violation in this mode.

5. Triple Product Asymmetries

Scalar triple products of three momentum or spin vectors are odd under time reversal. Non-zero asymmetries for these observables can either be due to a CP-violating phase or a CP-conserving phase and final-state interactions. Four-body final states give rise to three independent momentum vectors in the rest frame of the decaying B_s^0 meson. For a detailed review of the phenomenology the reader is referred to Ref. [13]. In the Standard Model the Triple product asymmetries in the $B_s^0 \to \phi\phi$ decay are predicted to be negligible. Non-zero values can arise in models of physics beyond the Standard Model where the different polarization amplitudes have different weak phases. In the case of the $B_s^0 \to \phi\phi$ decay there are two observable triple products denoted $U = \sin(2\Phi)/2$ and $V = \pm\sin(\Phi)$, where the positive sign is taken if the T-even quantity $\cos\theta_1 \cos\theta_2 \geq 0$ and the negative sign otherwise.

Experimentally, the Triple Product asymmetries can be determined by a simple counting exercise that requires neither tagging nor a time dependent analysis. The asymmetry, A_U, is defined as

$$A_U = \frac{N_+ - N_-}{N_+ + N_-}\,, \tag{1}$$

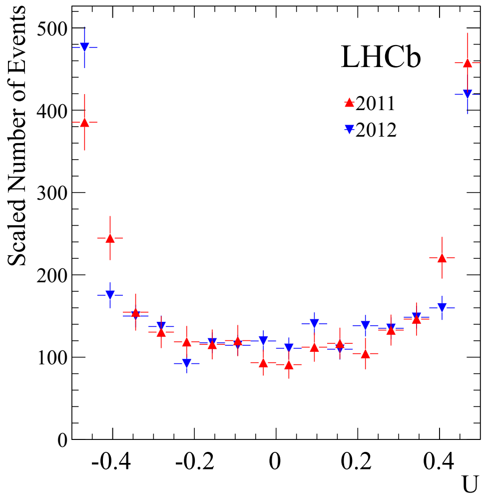

Figure 4: Background subtracted distribution of the U observables for the 2011 and 2012 dataset. The 2011 distributions are scaled to have the same area as the 2012 distributions.

where N_+ (N_-) is the number of events with $U > 0$ ($U < 0$). Similarly A_V is defined as

$$A_V = \frac{M_+ - M_-}{M_+ + M_-}\,, \tag{2}$$

where $M+$ (M_-) is the number of events with $V > 0$ ($V < 0$).

Figures 4 and 5 show the observed distributions of U and V for the 2011 and 2012 dataset. Already by eye it can be seen that these distributions are symmetric and hence the values of the asymmetries are small. The measured asymmetries are

$$A_U = -0.003 \pm 0.017\,(\mathrm{stat}) \pm 0.006\,(\mathrm{syst})$$

and

$$A_V = -0.017 \pm 0.017\,(\mathrm{stat}) \pm 0.006\,(\mathrm{syst}).$$

Both asymmetries are consistent with zero as expected in the Standard Model. They are also consistent with but more precise than previous measurements of these quantities by the LHCb [14] and CDF collaborations [15].

6. Summary

Using the dataset collected during Run 1 of the LHC a time dependent angular of the of the $B_s^0 \to \phi\phi$ decay mode has been made. The B_s^0 mixing in this channel is measured to be

$$\phi_s = -0.17 \pm 0.15\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})\,\mathrm{rad}$$

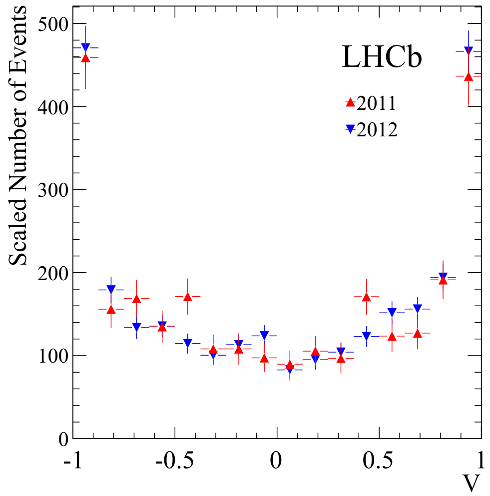

Figure 5: Background-subtracted distributions of the V observable for the 2011 and 2012 dataset. The 2011 distributions are scaled to have the same area as the 2012 distributions.

consistent with the Standard Model expectation that CP violation in this channel is small.

Further measurement of this quantity will be performed during the upcoming Run 2 of the LHC. This channel is a flagship mode for the LHCb upgrade planned for 2019. By the end of the LHCb upgrade era (2030) a precision on ϕ_s comparable to the uncertainty on the current Standard Model prediction will be achieved. This will constitute a powerful null test of the Standard Model.

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