Measurements of the polarisation amplitudes and triple product asymmetries in $B_s^0 \to \phi\phi$

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Using 1 fb^{-1} of pp collision data collected at center of mass energy $\sqrt{s} = 7$ TeV during 2011 by the LHCb detector. Measurements of the triple product asymmetries, polarisation amplitudes and strong phase difference in the decay $B_s^0 \to \phi\phi$ are presented.

1 Introduction

In the Standard Model the decay $B_s^0 \to \phi\phi$ proceeds via a flavour changing neutral current process. In such processes contributions from beyond the Standard Model are possible via the introduction of new amplitudes or phases in the penguin loop. Hence studies of the polarisation amplitudes and triple product asymmetries in this mode provide important tests of the Standard Model. [1,2,3]

The decay $B_s^0 \to \phi\phi$ is a pseudoscalar to vector-vector transition. Therefore, there are three possible spin configurations of the vector mesons allowed by conservation of angular momentum. These can be written as linear polarisation states A_0, $A_\parallel$ and $A_\perp$. The final state is a superposition of CP-even and CP-odd states. The longitudinal(A_0) and parallel($A_\parallel$) components are CP-even while the perpendicular($A_\perp$) component is CP-odd.

Tree dominated decays such as $B^0 \to \rho^+\rho^-$ are prominently longitudinally polarised [4] while in penguin dominated decays such as $B^0 \to \phi K^{*0}(892)$ and $B^0 \to \rho^0 K^{*0}(892)$, roughly equal longitudinal and transverse components are observed. [5,6,7] The predictions do suffer from large hadronic uncertainties. [8,9,10]

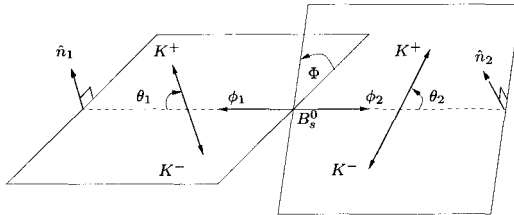To measure polarisation amplitudes, a time-integrated untagged angular analysis is per-

Figure 1: Helicity angles for the decay $B_s^0 \to \phi\phi$ where $\theta_{1,2}$ is the angle between the K^+ track momentum in the $\phi_{1,2}$ meson rest frame and the parent $\phi_{1,2}$ momentum in the B_s^0 rest frame, Φ is the angle between the two ϕ meson decay planes and $\hat{n}_{1,2}$ is the unit vector normal to the decay plane of the $\phi_{1,2}$ meson.

formed. Due to fast oscillation of the B_s^0 meson an equal number of B_s^0 and $\bar{B}_s^0$ are assumed at production. In addition, the CP violating phase is assumed to be zero, as predicted in Ref.[11]. Under these assumptions, the differential decay width is given

$$\frac{32\pi}{9}\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\Phi} = \frac{4}{\Gamma_L}|A_0|^2\cos^2\theta_1\cos^2\theta_2 + \frac{1}{\Gamma_L}|A_\parallel|^2\sin^2\theta_1\sin^2\theta_2(1+\cos 2\Phi)$$

$$+\frac{1}{\Gamma_H}|A_\perp|^2\sin^2\theta_1\sin^2\theta_2(1-\cos 2\Phi) + \frac{\sqrt{2}}{\Gamma_L}\mathrm{Im}(A_0 A_\parallel^*)\sin 2\theta_1\sin 2\theta_2\cos\Phi. \qquad (1)$$

where the helicity angles $(\theta_1, \theta_2, \Phi)$ are defined in Fig. 1 and $\Gamma_{L,H}$ are the lifetimes for the light and heavy mass eigenstates respectively. The strong phase difference $\delta_\parallel$ is defined as $\arg(A_\parallel/A_0)$.

Non zero triple product asymmetries can be due to either T violation or final state interactions. The former, assuming CPT conservation, implies CP is violated. In the decay $B_s^0 \to \phi\phi$ two triple products can be constructed, 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. These correspond to the T-odd triple products

$$\sin\Phi = (\hat{n_1}\times\hat{n_2})\cdot\hat{p_1}, \ \sin(2\Phi)/2 = (\hat{n_1}\cdot\hat{n_2})(\hat{n_1}\times\hat{n_2})\cdot\hat{p_1}, \qquad (2)$$

where $\hat{n_i}$ (i = 1,2) is a unit vector perpendicular to the ϕ decay plane and $\hat{p_1}$ is a unit vector in the direction of the ϕ momentum in the B_s^0 rest frame (see Fig. 1).

Extraction of the triple products is a simple counting experiment which does not require tagging the flavour of the B_s^0 meson or time dependence. The asymmetries are defined as

$$A_U = \frac{N_+ - N_-}{N_+ + N_-}, \ A_V = \frac{M_+ - M_-}{M_+ + M_-}, \qquad (3)$$

where N_+ (N_-) is the number of events with $U > 0$ $(U < 0)$ and M_+ (M_-) is the number of events with $V > 0$ $(V < 0)$. The dataset used for these analyses consists of 801 ± 29 $B_s^0 \to \phi\phi$ candidates in 1 fb^{-1} of data collected at the LHCb detector[12] at a centre-of-mass energy $\sqrt{s} = 7$ TeV.

2   Candidate Selection

$B_s^0 \to \phi\phi$ candidates are selected using events where both ϕ mesons decay into the final state K^+K^-. The candidate selection criteria were optimised using a data-driven approach based on
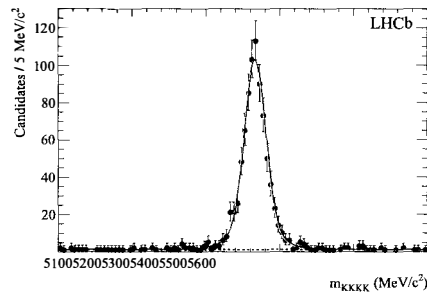

Figure 2: The $K^+K^-K^+K^-$ invariant mass distribution for selected $B_s^0 \to \phi\phi$ candidates. A fit to a double Gaussian signal component together with an exponential background (dotted line) is superimposed.

468

Table 1: Systematic uncertainties on the measured polarisation amplitudes and the strong phase difference.

Source	$|A_0|^2$	$|A_\perp|^2$	$|A_\||^2$	$\cos\delta_\|$
S-wave component	0.007	0.005	0.012	0.001
Decay time acceptance	0.006	0.006	0.002	0.007
Angular acceptance	0.007	0.006	0.006	0.028
Trigger category	0.003	0.002	0.001	0.004
Background model	0.001	-	0.001	0.003
Total	0.012	0.010	0.014	0.029

the $_s\mathcal{P}lot$ technique [13] with the invariant mass of the four-kaon system as the discriminating variable to separate signal from background. The figure of merit to be optimised is $S/\sqrt{S+B}$ where S (B) is signal (background) yield. Full details on the selection can be found in Ref. [14].

Figure 1 shows the four-kaon mass for selected events. An unbinned maximum likelihood fit is used to extract the signal yield. The signal component is modelled by two Gaussian functions with a common mean. The relative fraction and width of the second Gaussian are fixed to values obtained from simulation. Combinatoric background is modelled by an exponential function. Background from $B^0 \to \phi K^{*0}(892)$ and $B_s^0 \to K^{*0}(892)\bar{K}^{*0}(892)$ is found to be negligible in both data-driven and simulation studies. Fitting this probability density function (PDF) yields 801 ± 29 signal events.

Data-driven studies to determine contributions from S-wave final states arising from $f_0 \to K^+K^-$ and non-resonant K^+K^- yield results consistent with zero. The S-wave fraction is hence assumed to be zero in this analysis. A systematic error is assigned based on this assumption.
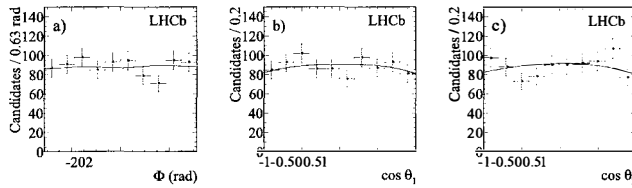
3   Results

Figure 3: Angular distributions for (a) Φ, (b) $\cos\theta_1$ and (c) $\cos\theta_2$ of $B_s^0 \to \phi\phi$ events with the fit projections for the total fitted PDF (solid line) and background component (dotted line) superimposed.

The polarisation amplitudes are determined by performing an unbinned maximum likelihood fit to the reconstructed mass and helicity angle distributions. Both the signal and background PDFs are the products of a mass component together with an angular component. The angular component of the signal is given by Eq. 1 multiplied by the angular acceptance of the detector, where the acceptance is determined using the simulation. The polarisation amplitudes are constrained such that $|A_0|^2 + |A_\||^2 + |A_\perp|^2 = 1$. The angular distributions for the background have been studied using the mass sidebands in the data, these distributions are consistent with being flat in $(\cos\theta_1, \cos\theta_2, \Phi)$. A uniform angular PDF is therefore assumed for the background and more complicated shapes are considered as part of the systematic studies. The values of $\Gamma_s = 0.657 \pm 0.009 \pm 0.008$ ps^{-1} and $\Delta\Gamma_s = 0.123 \pm 0.029 \pm 0.011$ ps^{-1} together with their correlation coefficient of -0.3, as measured by LHCb, [15] are used as a Gaussian constraint. The angular projections are shown in Fig. 3.

Table 2: Systematic uncertainties on the triple product asymmetries, A_U and A_V.

Source	A_U & A_V uncertainty
Angular acceptance	0.009
Decay time acceptance	0.014
Fit model	0.005
Total	0.018

To determine the triple product asymmetries, the dataset is partitioned according to whether U (V) is less than or greater than zero. Simultaneous fits are performed to the mass distributions for each of the two partitions. In these fits, the mean and resolution of the Gaussian signal component together with the slope of the exponential background component are common parameters. The asymmetries are left as free parameters and are fitted for directly in the simultaneous fit.

The measurements of the polarisation amplitudes and triple product asymmetries are summarised in Table 3. Several sources of systematic uncertainty are considered, summarised in Tables 1 and 2. The measured values agree well with previous measurements by the CDF collaboration. [16] The triple product asymmetries are consistent with zero and hence no indication of T-odd asymmetries are observed with the present statistics.

Table 3: Measurements of the polarisation amplitudes and triple product asymmetries in the decay $B_s^0 \to \phi\phi$.

Parameter	Measurement
$|A_0|^2$	$0.365 \pm 0.022\text{(stat.)} \pm 0.012\text{(syst.)}$
$|A_\perp|^2$	$0.291 \pm 0.024\text{(stat.)} \pm 0.010\text{(syst.)}$
$|A_\parallel|^2$	$0.344 \pm 0.024\text{(stat.)} \pm 0.014\text{(syst.)}$
$\cos(\delta_\parallel)$	$-0.844 \pm 0.068\text{(stat.)} \pm 0.029\text{(syst.)}$
A_U	$-0.055 \pm 0.036\text{(stat.)} \pm 0.018\text{(syst.)}$
A_V	$0.010 \pm 0.036\text{(stat.)} \pm 0.018\text{(syst.)}$

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