Search for $CP$ violation in the $B_S^0 - \bar{B}_S^0$ system

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Abstract. We present studies from the LHCb experiment leading to the measurement of the weak phase $\phi_s$. At first, flavor tagging is established by measuring the $B_S^0$ oscillation frequency $\Delta m_s$. Then, flavor tagging is used to perform a measurement of the well known CKM angle $\sin 2\beta$ in $B^0 \rightarrow J/\psi K_S^0$, before we constrain $\phi_s$ through an amplitude analysis of $B_S^0 \rightarrow J/\psi \phi$ decays. These studies use about 35 pb$^{-1}$ of data taken in 2010. In addition, we present the measurement of $\mathcal{B}(B^+ \rightarrow J/\psi \pi^+)/\mathcal{B}(B^0 \rightarrow J/\psi K^0)$ and the first observation of $B_S^0 \rightarrow J/\psi f_2(1525)$.

Keywords: CP violation, CKM angle $\beta$, $\phi_s$, $\Delta m_s$, new physics

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INTRODUCTION

Decays of neutral $B$ mesons provide a unique laboratory to study $CP$ violation originating from a weak phase in the CKM matrix. The relative phase between two amplitudes, direct decay and decay after mixing, gives rise to time-dependent $CP$ violation. The decay $B^0 \rightarrow J/\psi \phi$ is considered the golden mode for measuring this type of $CP$ violation in the $B_S^0$ system. In the Standard Model, the $CP$ violating phase in this decay is predicted to be $\phi_s \approx -2\beta_s$, where $\beta_s = \arg(-V_{ts}^* V_{ub}/V_{ts} V_{ub}^*)$. Indirect measurements show $2\beta_s$ is small, $2\beta_s = (0.0363 \pm 0.0017)$ rad [1]. But new contributions to $B^0_S - \bar{B}_S^0$ mixing may alter the expected value of $\phi_s$ [2, 3]. Previous constraints on $\phi_s$ at the 0.5 rad level have been reported by the Tevatron experiments CDF [4] and D0 [5]. The precise determination of $\phi_s$ is one of the key goals of the LHCb experiment [6]. In this letter we present a series of measurements leading the way to a measurement of $\phi_s$.

CONSTRAINTS ON $\phi_s$

We first present [7] a measurement of the mixing frequency $\Delta m_s$ of the $B_S^0$ system, using about 1350 $B_S^0$ signal candidates reconstructed in 36 pb$^{-1}$ collected in 2010 through their decays $B_S^0 \rightarrow D^- \pi$ and $B_S^0 \rightarrow D^- 3\pi$, where $D^- \rightarrow K^- K^+ K^-$, $3\pi$ is sufficient to resolve the fast oscillations in $B_S^0$ mixing. It also establishes the flavor tagging algorithms required to identify the $B_S^0$ flavor at production time. The effective tagging efficiency is $\epsilon_{\text{eff}} = 3.8 \pm 2.1$(stat)%. Figure 1 shows the result of an amplitude scan, converging to $\Delta m_s = 17.63 \pm 0.11$(stat) $\pm 0.04$(syst) ps$^{-1}$, which is compatible with the Tevatron measurements and of similar precision.

We then [8] make use of the flavor tagging algorithms to repeat the measurement of the CKM angle $\sin 2\beta$, which was determined by the B factories to amazing precision: $\sin 2\beta = 0.673 \pm 0.023$ [9]. In 35 pb$^{-1}$ we find about 280 tagged $B^0 \rightarrow J/\psi K_S^0$ decays, considered the golden channel for this measurement. A maximum likelihood fit to the decay time distribution and the $B^0$ invariant mass, simultaneously fitting tagged and untagged samples, reports $\sin 2\beta \approx S = 0.53^{+0.26}_{-0.25}$(stat) $\pm 0.05$(syst). The systematic uncertainty is dominated by that on the flavor tagging. Although not yet competitive with the result of the B-factories a very precise measurement will be possible with the data that LHCb will collect over the coming few years. Figure 1 shows the time dependent raw asymmetry of $B^0$ and $\bar{B}_S^0$ decaying into $J/\psi K_S^0$, the amplitude of which is proportional to $S$.

Finally, we perform [10] an untagged angular analysis of $B^0 \rightarrow J/\psi K^{*0}$ and $B_S^0 \rightarrow J/\psi \phi$ decays. This gives access to the decay amplitudes for both final states, as well as the lifetime and lifetime difference $\Delta \tau_S$ for $B_S^0 \rightarrow J/\psi \phi$. Due to the forward geometry of the LHCb detector, the reconstruction efficiency for these decays is a non-trivial function

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1 on behalf of the LHCb collaboration
of the decay angles. Then we add [11] the flavor tagging information to the measurement. In the 36 pb\(^{-1}\) of 2010 we find approximately 760 \(B^0\) \(\to J/\psi\phi\) events. We extract constraints on \(\phi\), through a maximum likelihood fit to the decay time distribution, the \(B^0\) invariant mass, and three decay angles. The data sample is too small to allow for meaningful point estimates. Instead we perform a Feldman-Cousins analysis which gives contours in the \(\Delta\Gamma_s - \phi_s\) plane (Figure 2) that have frequentist coverage. We observe a deviation from the Standard Model of 1.2\(\sigma\), and constrain \(\phi_s \in [-2.7, -0.5]\) rad at the 68.3% confidence level.

**ANALYSIS OF \(B^0_s \to J/\psi (KK, \pi\pi)\)**

Following our recent first observation of the \(B^0_s \to J/\psi f_0\) decay [12], we update [13] the analysis of the \(B^0_s \to J/\psi \pi\pi\) final state with a larger dataset of 162 pb\(^{-1}\), coming mostly from the first period of the 2011 run. We also show that the \(f_0\) resonance is consistent with being purely \(S\)-wave, making \(J/\psi f_0\) a pure \(CP\) odd eigenstate. This will allow for a measurement of \(\phi_s\) in \(B^0\) \(\to J/\psi f_0\) decays without the need of an amplitude analysis. We measure the ratio of rates in a \(\pm90\) MeV/\(c^2\) mass window around the \(f_0(980)\), \(R_{\text{effective}}^{f_0} = \mathcal{B}(B^0_s \to J/\psi f_0, f_0 \to \pi\pi)/\mathcal{B}(B^0_s \to J/\psi \phi, \phi \to KK)\), to be \(R_{\text{effective}}^{f_0} = (21.7 \pm 1.1\) (stat) \(\pm 0.7\) (syst)\) \%. We extend our analysis to the \(B^0_s \to J/\psi K^+K^-\) final state. In the \(K^+K^-\) invariant mass spectrum we for the first time observe, in addition to the \(\phi(1020)\) component, a structure that we identify as the spin-2 \(f_2^2(1525)\). An angular analysis confirms, that the data are consistent with the spin-2, and inconsistent with the spin-0 hypothesis. The \(B^0_s \to J/\psi f_2^2\) mode can also be used to measure \(\phi_s\), although here a transversity analysis would be required as in \(J/\psi \phi\). It is also
possible that this mode could be used to resolve ambiguities in $\phi$, if the interference with non-resonant $J/\psi K^+K^-$ is significant. Figure 3 shows both the $J/\psi K^+K^-$ and the $K^+K^-$ invariant mass spectra for this first observation. We measure $B_{\text{effective}}^{J/\psi} = (19.4 \pm 1.8 \text{(stat)} \pm 1.1 \text{(syst)})\%$ in a $\pm 125 \text{MeV}/c^2$ mass window around the $f_2'$.  

**MEASUREMENT OF $B(B^+ \rightarrow J/\psi \pi^+)/B(B^+ \rightarrow J/\psi K^+)$**

We also analyze [14] the $B^+ \rightarrow J/\psi \pi^+$ and $B^+ \rightarrow J/\psi K^+$ decay channels, of which the latter plays an important role in the calibration of the flavor tagging algorithms. In 37 $\text{pb}^{-1}$ we measure the ratio of their branching fractions to be 

$$B(B^+ \rightarrow J/\psi \pi^+)/B(B^+ \rightarrow J/\psi K^+) = (3.94 \pm 0.39 \text{(stat)} \pm 0.17 \text{(syst)}) \times 10^{-2}.$$  

This result has a precision comparable to the present world average [15], but is lower by 2.2$\sigma$.

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