Suppressed $B_S^0$ decays at CDF

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We review three recent results of the CDF collaboration on $B_S^0$ suppressed decays: the first search for CP-violation in the $B_S^0 \rightarrow \phi\phi$ decay, where two CP-violating asymmetries expected to be zero in the Standard Model are measured, and the observation and the branching ratio measurements of $B_S^0 \rightarrow J/\psi f_0(980)$ and $B_S^0 \rightarrow J/\psi K^(*)$ decays.

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1. Introduction

In the past decade Tevatron experiments CDF and D0 have pioneered the physics of the $B_s^0$ meson with a broad program aimed at its exploration. Although significant samples of fully reconstructed $B_s^0$ decays have been collected allowing decisive progress on $B_s^0$ mixing, lifetime, decay width difference $\Delta \Gamma_s$ as well as CP–violation measurements, more precise investigations are ongoing. In this report, we review recent results of the CDF collaboration on $B_s^0$ suppressed decays: the first search for CP–violation in the $B_s^0 \to \phi \phi$ decay and the observation of $B_s^0 \to J/\psi f_0(980)$ and $B_s^0 \to J/\psi K^{(*)}$ decays.

Two features of the CDF II detector [1] are relevant for these measurements: the tracking and the trigger. A high resolution tracking detector provides an excellent resolution on $B$–meson decay length (30 $\mu$m) and mass, typically about 10 MeV/c$^2$ for $B \rightarrow J/\psi X$ modes, that is pivotal for the observation of $B_s^0$ suppressed modes. This is achieved by double-sided silicon microstrips arranged in five cylindrical layers and an open cell drift chamber with 96 sense wires, all immersed in a 1.4 T solenoidal magnetic field. Signals of $B \rightarrow J/\psi X$ modes are efficiently collected by a dimuon trigger [1] with a 1.5 GeV/c transverse momentum threshold, while the trigger on displaced vertex [2] allows the collection of hadronic decay modes like $B_s^0 \rightarrow \phi \phi$, through online measurement of impact parameters of charged tracks with a resolution (48 $\mu$m) comparable with offline measurements.

2. First search for CP–violation in the $B_s^0 \rightarrow \phi \phi$ decay

The $B_s^0 \rightarrow \phi \phi$ decay belongs to the class of transitions of pseudoscalar mesons into two vector particles ($P \rightarrow VV$), whose rich dynamics involves three different amplitudes corresponding to the polarization states. In the Standard Model (SM) the dominant quark level process is described by the $b \rightarrow s$ “penguin” amplitude. Hence, the possibility to access New Physics (NP) through exchange of new virtual massive particles makes the $B_s^0 \rightarrow \phi \phi$ channel attractive. Indeed, the naïve SM expectation for polarization amplitudes has shown discrepancies with measurements of similar penguin decays [3], raising considerable attention to the so–called “polarization puzzle” [4]. Moreover, having a self–conjugate final state, the $B_s^0 \rightarrow \phi \phi$ decay is sensitive to the CP–violation in the interference between decay with and without mixing. Actually, the CP–violating weak phase $\phi_{B_s^0 \rightarrow \phi \phi}$ is predicted to be extremely small in the SM and measurement of nonzero CP–violating observables would indicate unambiguously NP. The first evidence for the $B_s^0 \rightarrow \phi \phi$ decay has been reported by CDF in 2005 [6]. Using 2.9 fb$^{-1}$ of data, the branching ratio measurement was recently updated [7], $\mathcal{B}(B_s^0 \rightarrow \phi \phi) = (2.40 \pm 0.21{\text{(stat.)}} \pm 0.86{\text{(syst.)}}) \times 10^{-5}$, in agreement with the first determination. Signal candidates are reconstructed by detecting $\phi \rightarrow K^+ K^−$ decays and are formed by fitting four tracks to a common vertex. Combinatorial background is reduced by exploiting several variables sensitive to the long lifetime and relatively hard $p_T$ spectrum of $B$ mesons, while the physics background, given by $B^0 \rightarrow \phi K^*(892)^0$ decay, is estimated by simulation not to exceed a 3% fraction of the signal. Signals of $295 \pm 20$ events are obtained by fitting the mass distribution. This data sample has allowed the world’s first polarization measurement [7] by analyzing the angular distributions of decay products, expressed as a function of helicity angles, $\bar{\omega} = (\cos \vartheta_1, \cos \vartheta_2, \Phi)$. The total decay
Candidates per 0.17

Figure 1: Distribution of \( u \) (left) and \( v \) (right) for \( B^0_s \rightarrow \phi \phi \) candidates. Black crosses are background-subtracted data; the blue histogram represents the background.

width is composed of three polarization amplitudes: two CP-even \((A_0 \text{ and } A_{||})\) and one CP-odd \((A_{\perp})\). The measured amplitudes result in a smaller longitudinal fraction with respect to the naïve expectation, \( f_L = 0.348 \pm 0.041 \pm 0.021 \), as found in other similar \( b \rightarrow s \) penguin decays [3].

Present statistics of the \( B^0_s \rightarrow \phi \phi \) data sample are not sufficient for a suitable time-dependent analysis of mixing induced CP-violation as the case of the \( B^0_s \rightarrow J/\psi \phi \) decay. However, an investigation of genuine CP-violating observables which could reveal the presence of NP, such as triple products (TP) correlations, is accessible [8]. The TP is expressed as \( \vec{p} \cdot (\vec{\epsilon}_1 \times \vec{\epsilon}_2) \), where \( \vec{p} \) is the momentum of one of the \( \phi \) meson in the \( B^0_s \) rest frame, and \( \vec{\epsilon}_i \) are the polarization vectors of the vector mesons. There are two triple products in the \( B^0_s \rightarrow \phi \phi \) decay corresponding to interferences between CP-odd and CP-even amplitudes, one for transverse–longitudinal mixture, \( \mathcal{S}(A_0 A^*_\perp) \), and the other for the transverse–transverse term, \( \mathcal{S}(A_{||} A^*_\perp) \). These products are functions of the helicity angles: the former is defined by \( v = \sin \Phi \) for \( \cos \vartheta_1 \cos \vartheta_2 \geq 0 \) and \( v = -\sin \Phi \) for \( \cos \vartheta_1 \cos \vartheta_2 < 0 \); the latter is defined by \( u = \sin 2\Phi \). The \( u \) and \( v \) distribution for \( B^0_s \rightarrow \phi \phi \) candidates are shown in fig 1. Without distinction of the flavor of the \( B^0_s \) meson at the production time (untagged sample), the following equation defines a CP-violating asymmetry:

\[
\mathcal{A}_u = \frac{\Gamma(u > 0) + \bar{\Gamma}(u < 0) - \Gamma(u < 0) - \bar{\Gamma}(u > 0)}{\Gamma(u > 0) + \bar{\Gamma}(u > 0) + \Gamma(u < 0) + \bar{\Gamma}(u < 0)},
\]

where \( \Gamma \) is the decay rate for the given process and \( \bar{\Gamma} \) is its CP-conjugate. An equivalent definition holds for \( v \). Being proportional to \( \sin \phi_s \cos \delta_i \), where \( \delta_i \) are relative strong phases between the polarization amplitudes, in \( B^0_s \rightarrow \phi \phi \) these asymmetries are nonzero only in presence of NP [8].

The CDF collaboration has made the first measurement of \( \mathcal{A}_u \) and \( \mathcal{A}_v \) asymmetries in \( B^0_s \rightarrow \phi \phi \) using the data sample described above [9]. The asymmetries are obtained through an unbinned maximum likelihood fit. The sample is split into two subsets according to the sign of \( u \) (or \( v \)) of \( B^0_s \rightarrow \phi \phi \) candidates. The invariant mass distribution of each subset is fitted simultaneously in order to extract the signal asymmetry. The small fraction of physics background, such as \( B^0 \rightarrow \phi K^*(892)^0 \) as well as non–resonant decay \( B^0_s \rightarrow \phi K^+ K^- \) and “S–wave” contamination \( B^0_s \rightarrow J/\psi f_0(980) \), is neglected in the fit and its effect is accounted for in the assigned systematic uncertainties. Using a large sample of Monte Carlo (MC) data the detector acceptance and
the reconstruction requirements are checked against biases with a 0.2% accuracy. The background asymmetries are consistent with zero, and the final results for signal asymmetries are: $\epsilon_N = (-0.7 \pm 6.4 \text{(stat.)} \pm 1.8 \text{(syst.)})\%$ and $\epsilon_s = (-12.0 \pm 6.4 \text{(stat.)} \pm 1.6 \text{(syst.)})\%$. This measurement establishes a method to search for NP through CP–violating observables in $P \rightarrow VV$ decays without the need of tagging and time–dependent analysis, which requires high statistics samples.

3. Observation of the $B_s^0 \rightarrow J/\psi f_0(980)$ decay

The $B_s^0 \rightarrow J/\psi f_0(980)$ decay has attracted significant attention as a potential “S–wave” contamination to the $B_s^0 \rightarrow J/\psi \phi$ signal when the departure from the SM expectation of Tevatron measurement of mixed induced CP-violation was observed at level of about $1.5\sigma$ [5]. It was also suggested that enough signal of $B_s^0 \rightarrow J/\psi f_0(980)$ decays can be used to measure the CP–violating phase $\beta_s$ as well, without need of angular analysis [11]. In addition, the CP–odd nature of the $J/\psi f_0(980)$ allows for measuring the lifetime of the $B_s^0$ CP–odd eigenstate, $1/T_s^{\text{rel}}$, that is the lifetime of the heavy–mass eigenstate if CP is conserved. This year the Tevatron experiments have quickly confirmed the observations of this mode [12] from LHCb and Belle collaborations [13]. In the following we review the CDF result of the ratio of branching fractions:

$$R = \frac{\mathcal{B}(B_s^0 \rightarrow J/\psi f_0(980))\mathcal{B}(f_0(980) \rightarrow \pi^+\pi^-)}{\mathcal{B}(B_s^0 \rightarrow J/\psi \phi)\mathcal{B}(\phi \rightarrow K^+K^-)},$$

(3.1)

where $\mathcal{B}(f_0(980) \rightarrow \pi^+\pi^-)$ and $\mathcal{B}(\phi \rightarrow K^+K^-)$ are fixed to PDG values [10], while $\mathcal{B}(B_s^0 \rightarrow J/\psi f_0(980))/\mathcal{B}(B_s^0 \rightarrow J/\psi \phi)$ is measured using 3.8 fb$^{-1}$ of data collected by the dimuon trigger.

The sample selection is performed by a neural network trained to maximize the separation between signal and background events. A threshold on the output of the neural network is chosen by maximizing $\varepsilon/(2.5+\sqrt{N_b})$ [14], where $\varepsilon$ is the signal reconstruction efficiency and $N_b$ is the number of background events estimated from mass distribution sidebands. The background is dominated by a smooth combinatorial component. Physics backgrounds are studied using inclusive simulated decays of $b$–hadrons into $J/\psi$ final states (fig. 2). The most prominent physics backgrounds in the $J/\psi \pi \pi$ spectrum are $B^0 \rightarrow J/\psi K^*(892)^0$ and $B^0 \rightarrow J/\psi \pi^+\pi^-$ decays.

The ratio $\mathcal{B}(B_s^0 \rightarrow J/\psi f_0(980))/\mathcal{B}(B_s^0 \rightarrow J/\psi \phi)$ is evaluated as $N(B_s^0 \rightarrow J/\psi f_0(980))/N(B_s^0 \rightarrow J/\psi \phi)\varepsilon_{\text{rel}}$, where $N(B_s^0 \rightarrow J/\psi f_0(980))$ and $N(B_s^0 \rightarrow J/\psi \phi)$ are the number of signal events of $B_s^0 \rightarrow J/\psi f_0(980)$ and $B_s^0 \rightarrow J/\psi \phi$ respectively, extracted by performing an unbinned extended maximum likelihood fit of the candidates mass distribution in [5.26;5.5] GeV/$c^2$ (fig. 2); $\varepsilon_{\text{rel}}$ is the relative efficiency for the reconstruction of the two decays. The latter is evaluated by MC simulation, where $B_s^0 \rightarrow J/\psi \phi$ candidates are generated based on CDF preliminary results [15], while $B_s^0 \rightarrow J/\psi f_0(980)$ candidates are modeled by a Flatté distribution whose parameters are fixed to the BES experiment results [16]. We found $N(B_s^0 \rightarrow J/\psi f_0(980)) = 571 \pm 37 \text{(stat.)} \pm 25 \text{(syst.)}$ with significance much greater than $5\sigma$, and finally $R = 0.292 \pm 0.020 \text{(stat.)} \pm 0.017 \text{(syst.)}$. The measurement is in good agreement with determinations by other experiments and it is the most accurate result to date.

\footnote{As a strong phase $\delta_1$ is not measured we use the world average value from $B^0 \rightarrow J/\psi K^{\ast0}$ decays [10].}
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4. First observation of $B_s^0 \rightarrow J/\psi K^{(*)}$ decays

The two Cabibbo–suppressed decays $B_s^0 \rightarrow J/\psi K^*(892)^0$ and $B_s^0 \rightarrow J/\psi K_S$ allow disentanglement of penguin contributions in the decays $B_s^0 \rightarrow J/\psi f$ and $B_s^0 \rightarrow J/\psi D_s^0$, respectively. The $B_s^0 \rightarrow J/\psi K^*(892)^0$ decay could be used for the measurement of $\Delta \Gamma_s$ and polarization amplitudes, and $B_s^0 \rightarrow J/\psi K_S$ for measurement of $1/T_s^{\text{odd}}$. The $B_s^0 \rightarrow J/\psi K_S$ decay can also yield information on the $\gamma$ angle of the unitarity triangle [17].

The CDF collaboration has recently reported the first observation of these modes and the measurement of their branching ratios in 5.9 fb$^{-1}$ of data selected by the dimuon trigger [18]. The sample selection was optimized maximizing the sensitivity for either finding evidence of a signal at 3$\sigma$, or excluding it at the same confidence level; for the $B_s^0 \rightarrow J/\psi K_S$ the selection is based on a neural network, while for $B_s^0 \rightarrow J/\psi K^*(892)^0$ a simpler cut–based analysis is performed, in both cases exploiting vertexing and kinematic discriminating variables. Both analyses have two common background contributions: the combinatorial background and the partially reconstructed background where $\gamma$, $\pi$ or $K$ of multibody decays are not reconstructed. Other physics backgrounds, such as $\Lambda_b \rightarrow J/\psi \Lambda$ for $B_s^0 \rightarrow J/\psi K_S$ or $B_s^0 \rightarrow J/\psi f$ for $B_s^0 \rightarrow J/\psi K^*(892)^0$, give negligible contributions. A binned maximum likelihood fit to the mass distribution of the candidates has been performed to extract the signal yields (fig. 3): $64 \pm 14 B_s^0 \rightarrow J/\psi K_S$ and $151 \pm 25 B_s^0 \rightarrow J/\psi K^*(892)^0$ signal events have been observed, both with a significance greater than 5$\sigma$. Branching fractions are normalized to rates of the corresponding favored modes, $\mathcal{B}(B_s^0 \rightarrow J/\psi K_S^0)$ and $\mathcal{B}(B_s^0 \rightarrow J/\psi K^{*0})$, and relative efficiency of reconstruction is evaluated by MC simulation. The branching ratio of the favored decays are fixed to their PDG values [10] and the fragmentation–fraction $f_s/f_d$ is fixed to the most recent CDF measurement of $f_s/(f_u + f_d)\mathcal{B}(D_s \rightarrow \phi \pi)$ [19] combined with PDG value of $\mathcal{B}(D_s \rightarrow \phi \pi)$. Finally, the measured branching ratios are $\mathcal{B}(B_s^0 \rightarrow J/\psi K^*(892)^0) = (8.3 \pm 1.2 \text{(stat.)} \pm 3.5 \text{(syst.)}) \times 10^{-5}$ and $\mathcal{B}(B_s^0 \rightarrow J/\psi K_S) = (3.5 \pm 0.6 \text{(stat.)} \pm 0.6 \text{(syst.)}) \times 10^{-5}$.
**Figure 3:** Invariant mass distribution for $J/\psi K^0_S$ (left) and for $J/\psi K\pi$ (right) with fit including the different contributions.

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