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B_s Decays at the Tevatron

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We present measurements of the branching ratio and of the polarization amplitudes in charmless $B_s \to \phi\phi$ decays using data corresponding to 2.9 fb^{-1} of integrated luminosity, collected by the CDF experiment at the Tevatron. The branching ratio in $B_s \to \phi\phi$ decays is measured relative to the normalization mode $B_s \to J/\psi\phi$ be $\mathscr{B}(B_s \to \phi\phi)/\mathscr{B}(B_s \to J/\psi\phi) = [1.78 \pm 0.14(stat) \pm 0.20(syst)] \times 10^{-2}$. Using the experimental value of $\mathscr{B}(B_s \to J/\psi\phi)$ we determine the $B_s \to \phi\phi$ branching ratio

$$\mathscr{B}(B_s \to \phi\phi) = 2.40 \pm 0.21(stat) \pm 0.27(syst) \pm 0.82(BR)] \times 10^{-5}.$$

The polarization fractions are measured for the first time in this analysis and found to be:

$$\begin{aligned} |A_0|^2 &= 0.348 \pm 0.041(stat) \pm 0.021(syst) \\ |A_\parallel|^2 &= 0.287 \pm 0.043(stat) \pm 0.011(syst) \\ |A_\perp|^2 &= 0.365 \pm 0.044(stat) \pm 0.027(syst). \end{aligned}$$

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1. Introduction

B_s mesons were initially studied by the LEP experiments and then by the CLEO experiment at $\Upsilon(5S)$. More recently the KEKB accelerator has been running at $\Upsilon(5S)$ resonance as well, enabling the Belle experiment to do B_s physics. The largest B_s samples, however, are collected by the CDF and D0 experiments at the Fermilab Tevatron. To date, the Tevatron has delivered about 8 fb^{-1} of integrated luminosity while each of the two Tevatron experiments has recorded close to 7 fb^{-1} of integrated luminosity on tape. The most recent Tevatron results in B_s physics include studies of rare decays [1] like $B_s \to \mu\mu$, $B_s \to e\mu$ or $B_s \to \phi\mu\mu$, CP violation in $B_s \to J/\psi\phi$ decays [2, 3] and CP violation in inclusive semileptonic B decays [4].

In this paper we focus on studies of charmless $B_s \to \phi\phi$ decays, performed by the CDF experiment at Fermilab. We present measurements of the branching ratio [5] and of the polarization fractions [6] in these decays using data corresponding to 2.9 fb^{-1} of integrated luminosity.

Charmless B_s decays are still to be fully understood. They offer the possibility to test our current theoretical understanding and represent promising ways to search for physics beyond the Standard Model (SM). The $B_s \to \phi\phi$ decay is part of the so called $B \to VV$ family in which the initial state B-meson is a pseudo-scalar (spin 0) and the final state VV contains two vector mesons (spin 1). In the particular decay of B_s to $\phi\phi$, the final state is a CP eigenstate. Such decays can be used to measure the B_s decay width difference ($\Delta\Gamma_s$) and the phase responsible for CP violation in the interference between decays with and without mixing. To conserve the total angular momentum in $B_s \to \phi\phi$ decays, the relative orbital angular momentum between the two ϕ mesons in the final state must be either 0, 1 or 2. In the angular momentum space, there are various bases which can be used to analyze decays of pseudo-scalars to two vector mesons, but any formalism involves three independent amplitudes for the three different polarizations of the decay products in the final state. Measuring the polarization fractions amounts to an important test of the corresponding theoretical predictions.

Within the SM, the dominant process that contributes to the $B_s \to \phi\phi$ decay is the $b \to s\bar{s}s$ penguin digram shown in figure 1. The same penguin amplitude appears in other $B \to VV$ processes which exhibit significant discrepancies between the measured polarization fractions and the SM predictions. Explanations involving both new physics scenarios as well as newly accounted SM effects have been suggested to explain the observations. However, none of the existing scenarios is convincing enough. To solve this "polarization puzzle" it is important to study as many $B \to VV$ decays as available. The first polarization analysis of $B_s \to \phi\phi$ decays, performed by the CDF experiment is presented here together with an updated measurement of the $B_s \to \phi\phi$ branching fraction.

2. Measurement of the $B_s \to \phi\phi$ Branching Ratio

The $B_s \to \phi\phi$ decay was first observed by the CDF experiment in 2005 [7] using a data sample corresponding to 180 pb^{-1} of integrated luminosity. The first measurement of the branching ratio $\mathscr{B}(B_s \to \phi\phi)$ was performed with 8 signal events and found to be $[1.4 \pm 0.6(stat.) \pm 0.6(syst.)] \times 10^{-5}$. The analysis was updated in 2009 with a data sample corresponding to 2.9 fb^{-1} of integrated luminosity. The data were collected by a trigger which requires two tracks displaced with respect to

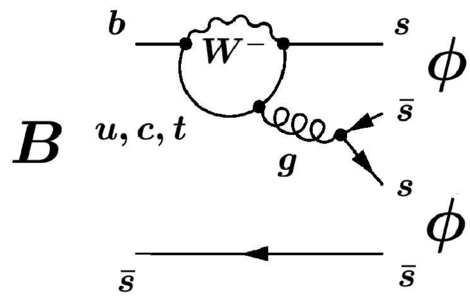

Figure 1: Main penguin diagram that contributes to the $B_s \to \phi\phi$ decay.

the primary vertex to enhance the contribution from long lived B mesons and suppress backgrounds. From the same dataset, $B_s \to J/\psi\phi$ decay are reconstructed as well and used as a normalization mode. This normalization mode was chosen because it has a topology similar to the $B_s \to \phi\phi$ decay and so, the measured branching ratio will be free of uncertainties from B_s and B_d production cross sections, as it would not be using a similar B_d penguin decay (e. g. $B_d \to \phi K^*$).

The $B_s \to \phi\phi$ decays are reconstructed from to two $\phi(1020)$ vector mesons where each ϕ meson is reconstructed from the decay $\phi \to K^+K^-$. Similarly, $B_s \to J/\psi\phi$ decays are reconstructed from a J/ψ and a ϕ meson, where the J/ψ decays to $\mu^+\mu^-$ and the ϕ meson decays to K^+K^-. Both B_s decays described above lead to four particles in the final state and all four particles come from one potentially displaced vertex. The $B_s \to J/\psi\phi$ is important on its own because it may improve the measurement of CP violation previously performed with a sample collected with a di-muon trigger [2]. The displaced track trigger may add about 25% more $B_s \to J/\psi\phi$ events which are unique to this independent dataset.

The events are selected according to an optimization procedure designed to maximize the ratio $S/\sqrt{(}S+B)$, where S is the number of signal events and B is the number of background events under the mass signal peak. This figure of merit ensures minimal statistical uncertainty on the branching ratio measurement and it was verified to also optimize the uncertainty on the polarization fraction measurement described in the following section. The signal events are simulated while the background events are chosen from the B_s mass sidebands. The variables used for the signal selection are chosen based on their discriminating power between signal and background. They are verified to be un-correlated and to exhibit good agreement between data and simulation. The most important variables used for the selection of both $B_s \to \phi\phi$ and $B_s \to J/\psi\phi$ decays are the transverse decay length of the B vertex projected along the B transverse momentum, the impact parameter of the B meson, the quality of the four-track vertex fit and transverse momenta of final state particles. In particular, for the $B_s \to J/\psi\phi$ decays, one of the two muons from J/ψ is required to be identified by the CDF muon systems.

Apart from the combinatorial background which is suppressed by the optimization procedure described above, other physics backgrounds are present in this analysis. These physics backgrounds come from real B decays which are misreconstructed as either $B_s \to \phi\phi$ or $B_s \to J/\psi\phi$. In the case of $B_s \to J/\psi\phi$ decays, the main background is $B^0 \to J/\psi K^{*0}$, where $K^{*0} \to K^+\pi^-$. When the pion from K^{*0} decay is identified as a kaon, the misreconstructed K^{*0} falls in the ϕ mass

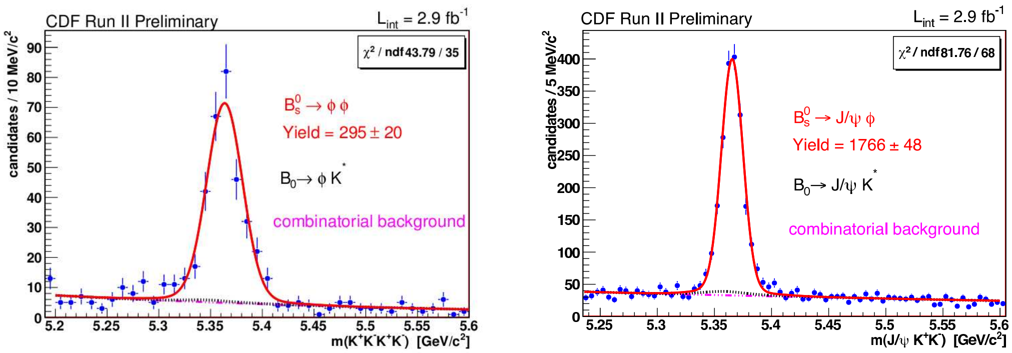

Figure 2: Left: $\phi\phi$ invariant mass. Right: $J/\psi\phi$ invariant mass. For both mass distributions physics background contributions are shown together with overlaid fits to the data.

region. The background fraction $f_{J/\psi K^{*0}} = N(B^0 \to J/\psi K^{*0})/N(B_s \to J/\psi\phi)$ is estimated using:

$$f_{J/\psi K^{*0}} = \frac{f_d}{f_s}\frac{\mathscr{B}(B^0 \to J/\psi K^{*0})}{\mathscr{B}(B_s \to J/\psi\phi)}\frac{\mathscr{B}(K^{*0} \to K^+\pi^-)}{\mathscr{B}(\phi \to K^+K^-)}\frac{\varepsilon^{J/\psi K^{*0}}(J/\psi\phi)}{\varepsilon^{J/\psi\phi}} \tag{2.1}$$

where $\varepsilon^{J/\psi K^{*0}}(J/\psi\phi)$ is the trigger and selection efficiency of the $B^0 \to J/\psi K^{*0}$ decay reconstructed as $B_s \to J/\psi\phi$ and $\varepsilon^{J/\psi\phi}$ is the trigger and selection efficiency for $\varepsilon^{J/\psi\phi}$, both determined using simulation. f_d and f_s are the production fractions of the B_d and B_s mesons. The fraction $f_{J/\psi K^{*0}}$ is found to be 0.0419 ± 0.0093. For the $B_s \to \phi\phi$ mode, the physics backgrounds come from $B^0 \to \phi K^{*0} \to K^+K^-K^+\pi^-$ and $B_s \to \bar{K}^{*0}K^{*0} \to K^-\pi^+K^+\pi^-$. Using methods similar to equation 2.1 (see equations 2 and 3 in [6]) we find that the contribution of the $B_s \to \bar{K}^{*0}K^{*0}$ is negligible and the contribution of the $B^0 \to \phi K^{*0} \to K^+K^-K^+\pi^-$ mode is about eight events.

An important step in this analysis is to measure the signal yields of both $B_s \to J/\psi\phi$ and $B_s \to \phi\phi$. After applying the optimization procedure described above, the corresponding B_s mass peaks are shown in figure 2. We find $1766 \pm 48(stat.)$ $B_s \to J/\psi\phi$ signal events and $295 \pm 20(stat.)$ $B_s \to J/\psi\phi$ signal events.

The branching ratio $\mathscr{B}$ of the decay $B_s \to \phi\phi$ normalized to the well known $\mathscr{B}(B_s \to J/\psi\phi)$ can be evaluated using the following equation:

$$\frac{\mathscr{B}(B_s \to \phi\phi)}{\mathscr{B}(B_s \to J/\psi\phi)} = \frac{N_{\phi\phi}}{N_{J/\psi\phi}} \times \frac{\mathscr{B}(J/\psi \to \mu\mu)}{\mathscr{B}(\phi \to KK)} \times \frac{\varepsilon_{TOT}^{J/\psi\phi}}{\varepsilon_{TOT}^{\phi\phi}} \times \varepsilon_{mu}^{TOT} \tag{2.2}$$

where $N_{J/\psi\phi}$ are $N_{\phi\phi}$ the numbers of $B_s \to J/\psi\phi$ and $B_s \to \phi\phi$ signal events. $\varepsilon_{TOT}^{J/\psi\phi}$ and $\varepsilon_{TOT}^{\phi\phi}$ are the combined trigger and selection efficiencies. The term ε_{mu}^{TOT} accounts for the efficiency of identifying at least one of the muons in the muon detectors. Using the above ratio, the uncertainties in the production cross section of the B mesons cancel out and several systematic effects due to detector and trigger efficiencies cancel as well, allowing a reduced systematic uncertainty in the measurement of the branching ratio.

The efficiencies for both $B_s \to \phi\phi$ and $B_s \to J/\psi\phi$ channels are obtained by taking the ratio between the number of simulated events that satisfy the trigger and selection criteria and the total number of generated events. The efficiency for the muon identification is determined in a different way than the trigger and reconstruction efficiencies because the simulation does not account properly for muon acceptance and the corresponding uncertainties would not cancel in the ratio of efficiencies. The muon efficiency is determined as a function of the muon momentum and it is obtained by using inclusive $J/\psi \to \mu\mu$ decays reconstructed in the same dataset where either one or both muons have been identified by the muon detectors.

The most important systematic uncertainties in this analysis are listed here. The uncertainties in the number of signal events due to variations in the fit mass range that account for the possible presence of unidentified peaking background near the signal peak and uncertainty in the shape of the combinatorial background as well as the parameterization of the signal mass peak with a single Gaussian function instead of two Gaussians, uncertainties on the physics backgrounds coming from errors on the corresponding branching ratios, uncertainties on the muon efficiency, uncertainty on the ratio of the trigger and selection efficiencies due to poor knowledge of the polarization amplitudes and the decay width difference between the B_s mass eigenstates. The total systematic uncertainty, excluding the error on the $B_s \to J/\psi\phi$ branching ratio is 11%. The final ratio of branching fractions is:

$$\frac{\mathscr{B}(B_s \to \phi\phi)}{\mathscr{B}(B_s \to J/\psi\phi)} = [1.78 \pm 0.14(stat.) \pm 0.20(syst.)] \times 10^{-2} \tag{2.3}$$

Using the experimental value of the $B_s \to J/\psi\phi$ branching ratio we obtain:

$$\mathscr{B}(B_s \to \phi\phi) = [2.40 \pm 0.21(stat.) \pm 0.27(syst.) \pm 0.82(BR)] \times 10^{-5} \tag{2.4}$$

where the last uncertainty (BR) is the dominant contribution and comes from the error on the $B_s \to J/\psi\phi$ branching ratio. We note that the world average for the $\mathscr{B}(B_s \to J/\psi\phi) = (0.93 \pm 0.33) \times 10^{-3}$ is based on a single CDF Run I measurement that assumed the ratio between the B_s^0 and B_d^0 fragmentation fractions $f_s/f_d = 0.40$. The central value of $\mathscr{B}(B_s \to J/\psi\phi)$ is scaled to reflect the current value of $f_s/f_d = 0.110/0.399 = 0.28$ [8]. Consequently, we use $\mathscr{B}(B_s \to J/\psi\phi) = (1.35 \pm 0.46) \times 10^{-3}$.

This result is compatible with the initial observation [7], with substantial improvement on the statistical uncertainty. The result is also compatible with recent theoretical calculations [9] and [10].

3. Measurement of the Polarization Amplitudes in $B_s \to \phi\phi$ Decays

As already pointed out in the Introduction, in the $B_s \to \phi\phi$ decay, the dominant diagram is the $b \to s$ penguin shown in figure 1. The same penguin amplitude is also relevant in in other processes which have shown deviations from the SM predictions. Such effects are the difference in the CP asymmetries in $B_d \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ and the potential difference between the $\sin(2\beta)$ measurements in $b \to s\bar{q}q$ and $b \to c\bar{c}s$ B^0 decays.

The decay amplitude in $B_s \to \phi\phi$ decays can be expressed in terms of three independent decay amplitudes, which correspond to the three possible relative angular momenta between the two ϕ vector mesons. In this analysis we use the helicity formalism in which the polarizations of the two vector mesons are either longitudinal with respect to the direction of motion A_0 or transverse relative to the direction of motion. There are two transverse amplitudes $A_{||}$ and $A_\perp$ corresponding to the two polarizations being parallel or perpendicular to each other. The fractions of these amplitudes can be measured from the analysis of the angular distributions of the final state particles (the decay products of the two ϕ mesons).

Taking into account the V-A nature of the weak interaction and the helicity conservation in QCD, it is expected that the dominant amplitude is the longitudinal polarization while the transverse component is suppressed by a factor of m_V/m_B [10]. This expectation is confirmed in tree-level dominated $b \to u$ transitions like $B^0 \to \rho^+\rho^-$ [11, 12], $B^+ \to \rho^0, \rho^+$ [13] and $B^+ \to \omega\rho^+$ [14], but it is not confirmed in $B \to \phi K^*$, a $\bar{b} \to \bar{s}$ decay. In this decay, the transverse polarization fraction is about equal to the longitudinal polarization [15, 16, 17]. This unexpected result is known as the "polarization puzzle". Explanations involving either new physics [18, 9] or SM corrections including either penguin annihilation [9, 10, 20] or final state interactions [21, 22, 23, 25] have been proposed. Recent work [24] based on QCD predictions finds the longitudinal polarization fraction to be in excellent agreement with our measurement if the penguin annihilation amplitude is fitted to the $B \to \phi K^*$ data.

We present the first measurement of the polarization fractions in $B_s \to \phi\phi$ decays using 2.9 fb^{-1} of CDF data. As a cross check, we also perform the polarization fractions in $B_s \to J/\psi\phi$ decays. Both measurements are performed on the data samples selected for the branching ratio measurement described in section 2. For either of the two decays, we refer to the two vector mesons as V_1 and V_2 and to their decay products as final state particles P_1 and P_2 from V_1 and P_3 and P_4 from V_2.

We use the helicity formalism to describe $B_s \to \phi\phi$ decays. The x' and x'' axes are defined as the directions of the V_1 and V_2 momenta in the rest frame of the B_s meson, respectively. We define the angle θ_1 (θ_2) as the angle between the x' (x'') axis and the P_1 (P_3) momentum vector, defined in the rest frame of V_1 (V_2). The Φ angle is defined as the angle between the decay planes of the two daughter particles. The three angles $\vec{\omega} = (\theta_1, \theta_2, \Phi)$ completely describe the directions of the final state particles. The distributions of these angles are used to separate the three amplitudes and determine their corresponding fractions. The probability distribution function (PDF) used to describe the helicity angular distribution for the signal is obtained by integrating out the time dependence. The differential decay rate as function of the helicity angles is given by:

$$\frac{d^3\Lambda(\vec{\omega})}{d\vec{\omega}} = \frac{9}{32\pi}\frac{1}{W}[F_e(\vec{\omega}) + F_o(\vec{\omega})] \tag{3.1}$$

where $F_e = \frac{2}{\Gamma_L}[|A_0|^2 f_1(\vec{\omega}) + |A_{||}|^2 f_2(\vec{\omega}) + |A_0||A_{||}|cos(\delta_{||}) f_5(\vec{\omega})]$, $F_o = \frac{2}{\Gamma_H}|A_\perp|^2 f_3(\vec{\omega})$, $W = \frac{|A_0|^2+|A_{||}|^2}{\Gamma_L} + \frac{|A_\perp|^2}{\Gamma_H}$. Here, Γ_L and Γ_H are the decays widths of the B_s mass eigenstates, f_i are functions of the helicity angles $\vec{\omega}$ and $\delta_{||}$ is a strong phase defined as $\delta_{||} = arg(A_0^* A_{||})$. The decay widths Γ_L and Γ_H are fixed to the world average. Although our trigger gives a non flat acceptance as a function of B_s proper decay time, this time-integrated approach has been verified to give biases smaller that the statistical uncertainty of the polarization fraction measurement by using simulation and the measurement of the equivalent fractions in the $J/\psi\phi$ control sample. A similar formalism is used to describe $B_s \to J/\psi\phi$ decays in the transversity basis [26]. The data samples and the optimization procedures are the same as the ones in the branching ratio measurement described in section 2.

The observables measured in this analysis are the polarization fractions $|A_0|^2$ and $|A_{||}|^2$ as well as the relative strong phase between them $\delta_{||}$. The measurement of these observables is performed

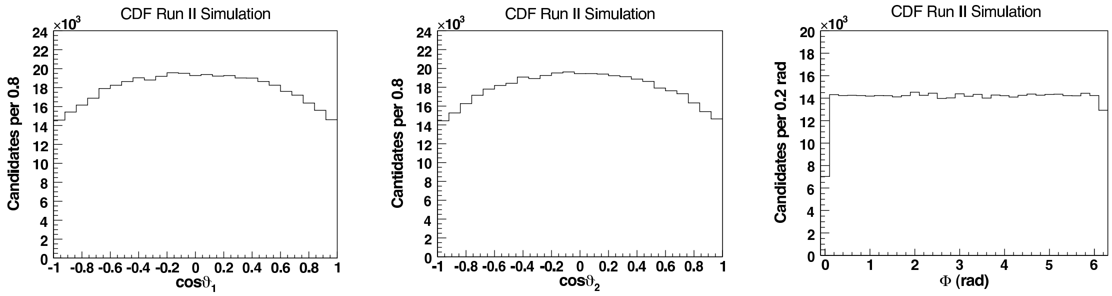

Figure 3: Detector angular acceptance projections for the helicity angles $\cos(\theta_1)$, $\cos(\theta_2)$ and Φ used for the angular analysis of $B_s \to \phi\phi$ decays.

using an unbinned maximum likelihood fit using as event-by-event inputs the reconstructed mass of the B_s candidate and the reconstructed helicity angles. The mass distribution is used in the fit to discriminate the signal from background. The angular distributions separate between the three polarization amplitudes. The signal mass distribution has a width of 20 MeV/c^2 for the $B_s \to \phi\phi$ and 10 MeV/c^2 for the $B_s \to J/\psi\phi$. In both cases the signal is parameterized with two Gaussian functions with the same mean and different resolutions. The mass background distributions are described by exponential functions. The PDFs used to describe the helicity angular distributions for the signal are described in [6]. The observed angular distributions in both helicity and transversity bases are different than the expected theoretical distributions due to detector acceptance effects. The angular acceptance is determined using simulated signal events. The projections on the helicity angles θ_1, θ_2 and Φ are shown in figure 3. The background angular distributions are determined from the B_s mass sidebands. These distributions are parameterized with empirical functions. The Φ distribution is parameterized with a constant function and the angles θ_1 and θ_2 are parameterized with functions of the form $1+B\times\cos^2(\theta)$ where B is a parameter determined by the fit. Before performing the measurement of the polarization fractions in $B_s \to \phi\phi$, several tests of the unbinned maximum likelihood fit are performed. The fit is tested on pseudo-experiments where no biases are found and the uncertainties are in the Gaussian regime. The polarization fractions are measured in $B_s \to J/\psi\phi$ decays used as a control sample:

$$|A_0|^2 = 0.534 \pm 0.019(stat.), \quad |A_{||}| = 0.220 \pm 0.025(stat.). \tag{3.2}$$

In this case the polarization fractions are found to be in good agreement with previous CDF measurements from a di-muon sample [27]. Finally, samples of $B_s \to \phi\phi$ are generated and passed through the full trigger and detector simulation and then through the analysis selection. The polarizations are measured in these samples and good agreement with the generated values is found.

Finally, we measure the polarization fractions in $B_s \to \phi\phi$ decays:

$$|A_0|^2 = 0.348 \pm 0.041(stat.), \quad |A_{||}| = 0.287 \pm 0.043(stat.). \tag{3.3}$$

The measured strong phase is $cos(\delta_{||}) = -0.91^{+0.15}_{-0.13}$. The fit projections onto the mass and helicity angles are shown in figure 4 which shows very good agreement between the data distributions and the fitting functions.

The main systematic uncertainties on the $B_s \to \phi\phi$ polarization fractions come from the dependence of the angular acceptance on the decay width difference $\Delta\Gamma_s$, uncertainties on the lifetimes

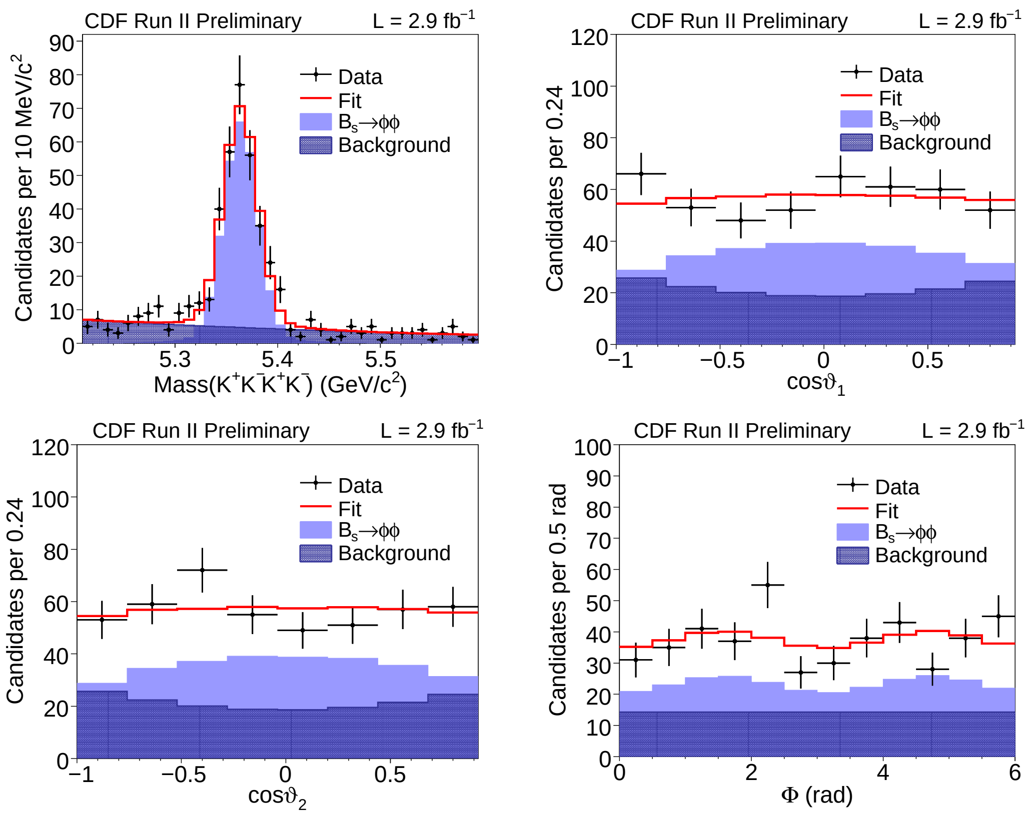

Figure 4: Fit projections for the mass component and the angular components in $B_s \to \phi\phi$ decays.

of the heavy and light B_s mass eigenstates τ_H and τ_L and the potential KK s-wave contributions to the angular distributions.

The final results, including systematic uncertainties are:

$$|A_0|^2 = 0.348 \pm 0.041(stat.) \pm 0.021(syst.) \tag{3.4}$$

$$|A_{||}|^2 = 0.287 \pm 0.043(stat.) \pm 0.011(syst.) \tag{3.5}$$

$$|A_\perp|^2 = 0.365 \pm 0.044(stat.) \pm 0.027(syst.) \tag{3.6}$$

$$cos(\delta_{||}) = -0.91^{+0.15}_{-0.13}(stat.) \pm 0.09(syst.) \tag{3.7}$$

The longitudinal and transverse polarization fractions are:

$$f_L = 0.348 \pm 0.041(stat.) \pm 0.021(syst.) \tag{3.8}$$

$$f_T = 0.652 \pm 0.041(stat.) \pm 0.021(syst.) \tag{3.9}$$

It is clear from this measurement that the SM expected amplitude hierarchy $|A_0| \gg |A_{||}| \simeq |A_\perp|$ is not valid in $B_s \to \phi\phi$ decays. Instead, the observed relation between the polarization amplitudes is given by: $|A_0| \simeq |A_{||}| \gtrsim |A_\perp|$, which is similar to the measurements for the $\bar{b} \to \bar{s}$ penguin transition of $B \to \phi K^*$ decays [15, 28, 29] which were the origin of the polarization puzzle.

We compare our results with various theoretical predictions of the polarization amplitudes. We find that our central values are consistent within the uncertainty ranges with the expectations of the QCD factorization [9], while they are not in good agreement with the expectation of perturbative QCD [10] and QCD factorization [24].

4. Conclusions

We have presented an updated measurement of the $B_s \to \phi\phi$ branching ratio using a data sample corresponding to 2.9 fb^{-1} of integrated luminosity. Using the same data sample, we measured for the first time the polarization fractions in $B_s \to \phi\phi$ decays. The measured amplitudes confirm the previously observed polarization puzzle in certain $B \to VV$ decays.

Each of the two Tevatron experiments have currently accumulated about 7 fb^{-1} of data and expect 10 fb^{-1} by the end of the Tevatron running in 2011. With a sample three times as large, CDF will improve the statistical errors on the polarization amplitudes in $B_s \to \phi\phi$ by a factor of two and will attempt to measure the decay width difference $\Delta\Gamma_s$ in this mode. Further studies of rare B_s decays and CP violation in the B_s will be improved with more data.

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