

New Measurement of the B_s^0 Mixing Phase at CDF

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The CDF collaboration presents an updated measurement of the CP-violating parameter $\beta_s^{J/\psi\phi}$ and of the decay width difference $\Delta\Gamma_s$ using approximately 6500 $B_s \rightarrow J/\psi\phi$ decays collected by the dimuon trigger and reconstructed in a data sample corresponding to 5.2 fb^{-1} of integrated luminosity. Besides exploiting the two-fold increase in the data sample with respect to the previous measurement, several improvements have been introduced in the analysis including a fully data-driven flavor tagging calibration and proper treatment of possible S-wave contributions.

We find that the CP-violating phase is within the range $\beta_s^{J/\psi\phi} \in [0.02, 0.52] \cup [1.08, 1.55]$ at 68% C.L. The decay width difference is found to be $\Delta\Gamma_s = 0.075 \pm 0.035 \text{ (stat)} \pm 0.01 \text{ (syst)} \text{ ps}^{-1}$. In addition, we present the most precise mean B_s lifetime τ_s , polarization amplitudes $|A_0|^2$, $|A_{\parallel}|^2$ and $|A_{\perp}|^2$, as well as strong phase δ_{\perp} :

$$\begin{aligned}\tau_s &= 458.6 \pm 7.6 \text{ (stat)} \pm 3.6 \text{ (syst)} \mu\text{m} \\ |A_0|^2 &= 0.524 \pm 0.013 \text{ (stat)} \pm 0.015 \text{ (syst)} \\ |A_{\parallel}|^2 &= 0.231 \pm 0.014 \text{ (stat)} \pm 0.015 \text{ (syst)} \\ \delta_{\perp} &= 2.95 \pm 0.64 \text{ (stat)} \pm 0.07 \text{ (syst)}.\end{aligned}$$

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1. Introduction

Charge-Parity (CP) violation is accommodated within the Standard Model (SM) via complex phases that enter mixing matrices which connect different family fermions. In the lepton sector the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix connects leptons from different generations, while in the quark sector, the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1] mixes quarks from different generations and introduces CP violation in the hadronic sector.

While CP violation has been well measured and found to agree with the SM expectations in Kaon and in most B-meson decays, the study of CP violation in decays of B_s mesons is still in its early stages, with the first results from $B_s \rightarrow J/\psi\phi$ decays reported by the CDF and D0 collaborations in the last couple of years [2, 3]. In these decays, CP violation occurs through the interference between the decay amplitudes with and without mixing. In the SM the relative phase between the decay amplitudes with and without mixing is $\beta_s^{SM} = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$ and it is expected to be very small [4, 5]. New physics contributions manifested in the B_s^0 mixing amplitude may alter this mixing phase by a quantity ϕ_s^{NP} leading to an observed mixing phase $2\beta_s^{J/\psi\phi} = 2\beta_s^{SM} - \phi_s^{NP}$. Large values of the observed $\beta_s^{J/\psi\phi}$ would be an indication of physics beyond the SM [5, 6, 7, 8].

The analysis presented in this paper is an update of previous CDF analyses with 1.4 fb^{-1} [2] and 2.8 fb^{-1} [9] of integrated luminosity. A combination [11] between the 2.8 fb^{-1} CDF result [9] and the corresponding one from D0 [10] led to the conclusion that, assuming the standard model predictions [8], the probability of a deviation as large as the level of the observed data is 3.4% corresponding to 2.1 Gaussian standard deviations. In that light, updated measurements from CDF and D0 were expected with more integrated luminosity. In this paper we present the 5.2 fb^{-1} $\beta_s^{J/\psi\phi}$ results from CDF [13], first presented at FPCP 2010 [14]. The D0 update was shown at ICHEP 2010 [12] and reveals an improvement of the $\beta_s^{J/\psi\phi}$ agreement with the SM expectation, at least as long as no other constraints are imposed. Adding external constraints, a 6-7.5% agreement with SM is quoted.

2. Measurement of CP violation in $B_s \rightarrow J/\psi\phi$ decays

We reconstruct $B_s \rightarrow J/\psi\phi$ decays, where the J/ψ meson decays in two opposite charge muons and the ϕ meson decays in two opposite charge kaons. Kinematic, topological and particle identification information (time of flight and energy loss) are combined into an artificial neural network optimized for $B_s \rightarrow J/\psi\phi$ candidate selection. The optimal selection is determined using pseudo-experiments in such a way that the expected statistical uncertainty on the $\beta_s^{J/\psi\phi}$ phase is minimized. We select a sample of ≈ 6500 $B_s \rightarrow J/\psi\phi$ candidates with a signal to background ratio of ≈ 1 . Figure 1 shows the $\mu^+\mu^-K^+K^-$ invariant mass distribution along with the fit projection superimposed.

Having identified $B_s \rightarrow J/\psi\phi$ candidates, in order to improve the analysis sensitivity to CP violation parameter $\beta_s^{J/\psi\phi}$, we need to separate B_s mesons produced as B_s^0 from the ones produced as \bar{B}_s^0 . We employ algorithms called flavor taggers which, on a candidate by candidate basis, provide the B_s production flavor (tag) along with the expected probability P that the tag is correct. Often, instead of the tagging probability, a derived quantity is quoted, the dilution: $D = 2P - 1$. A

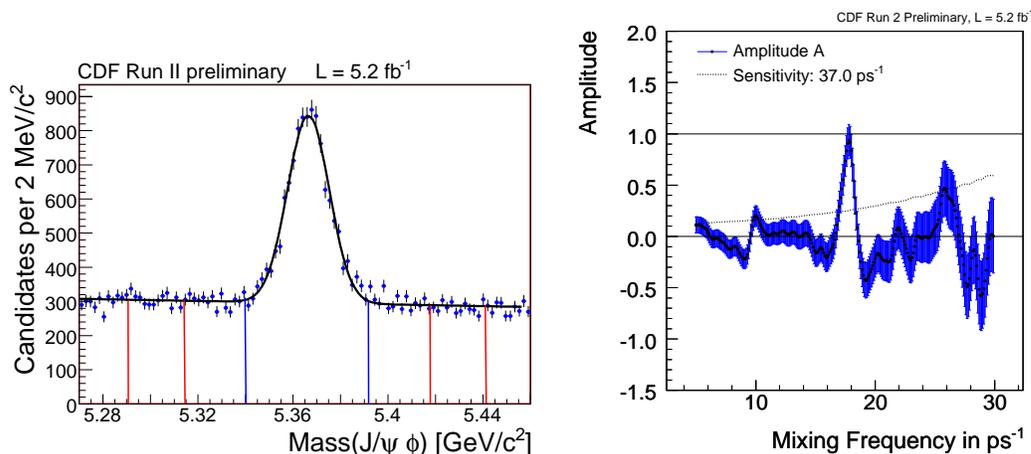


Figure 1: Left: $\mu^+\mu^-K^+K^-$ invariant mass distribution and fit projection. Right: B_s mixing amplitude scan with statistical errors only.

tagging algorithm is also characterized by its efficiency ε which is the fraction of tagged B_s mesons out of all B_s candidates. The efficiency multiplied by the squared dilution provides the tagging effectiveness: a sample of N events tagged by a tagging algorithm with efficiency ε and dilution D has the same statistical power as a sample of $\varepsilon D^2 N$ events identified with 100% efficiency and 100% tagging probability.

There are two types of flavor tagging algorithms used in this analysis. The first one takes advantage of the fact that in $p\bar{p}$ collisions at the Tevatron, b and \bar{b} quarks are dominantly produced in pairs. The opposite side tagging (OST) algorithm searches for leptons or jets opposite to the reconstructed B_s meson. The opposite side is defined as the region outside the $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ cone around the B_s flight direction, where $\Delta\eta$ and $\Delta\phi$ define the pseudo-rapidity and the azimuthal direction with respect to B_s direction. The OST algorithm uses either the lepton charge to infer the B_s production flavor or the opposite side jet which contains a displaced vertex or track and uses the sum of the jet track charges, weighted by the track momenta, to identify the B_s production flavor. The OST is calibrated on a sample of $\approx 52000 B^\pm \rightarrow J/\psi K^\pm$ decays [13]. Here, the B meson flavors at production and decay are the same. The flavor at decay is given by the kaon charge providing a straightforward way of measuring the tagging dilution. The ratio between the measured and predicted dilution is found to be 1.02 ± 0.07 which is used as a calibrating factor in the $\beta_s^{J/\psi\phi}$ measurement. The OST efficiency is $(94.2 \pm 0.4)\%$ while the average dilution is $(11.5 \pm 0.2)\%$ for a total tagging power $\varepsilon D^2 = 1.2\%$. Besides the OST we also used a flavor tagging method called same side tagging (SST). This algorithm searches for charged kaons produced during the hadronization process in which the B_s meson is formed. The charge of the kaon is used to infer the B_s flavor. The tagging dilution is determined from simulated events and calibrated in data by simultaneously measuring the B_s mixing frequency and the SST dilution scale factor using ≈ 13000 fully reconstructed $B_s \rightarrow D_s(3)\pi$ decays, where the D_s meson decays either into $\phi\pi$ or into three pions [15]. Figure 1 shows the B_s mixing amplitude as a function of the assumed oscillation frequency. The mixing amplitude is a coefficient that multiplies the mixing term $\cos(\Delta m_s t)$ which describes the B_s oscillations. Whenever the mixing frequency is fixed to a wrong value, the

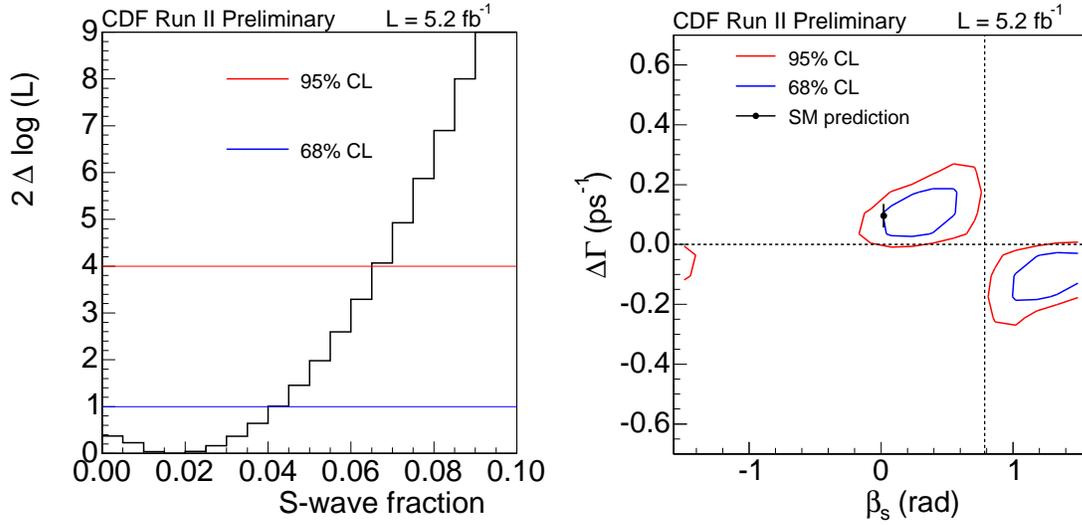


Figure 2: Left: Likelihood profile of the S-wave fraction. Right: 68% and 95% confidence regions in the $\beta_s^{J/\psi\phi} - \Delta\Gamma$ plane.

mixing amplitude is consistent with zero. When the oscillation frequency reaches the true value, the amplitude becomes inconsistent with zero. If the tagging algorithm provides accurate predicted dilution, then, the amplitude is consistent with one. Figure 1 shows that at $\Delta m_s = 17.79 \pm 0.07$ the amplitude is indeed consistent with unity: $A = 0.94 \pm 0.15$ (stat) ± 0.07 (syst). This value is used as a dilution scale factor in the $\beta_s^{J/\psi\phi}$ measurement. The SST efficiency is (52.2 \pm 0.7)% and the average dilution is (27.5 \pm 0.3)%. Accounting for the dilution calibration factor we find the total SST power to be (3.5 \pm 1.4)%. It is worth noting that the measured oscillation frequency is consistent with the previous CDF [16] and D0 [17] mixing measurements.

Another important component in this analysis is the statistical separation of CP even and CP odd $J/\psi\phi$ final states. While the B_s meson has spin 0, the final states J/ψ and ϕ have spin 1. Consequently, the total angular momentum in the final state can be either 0, 1 or 2. States with angular momentum 0 and 2 are CP even while the state with angular momentum 1 is CP odd. Angular distributions of the final muons and kaons from J/ψ and ϕ decays can be used to statistically separate the CP eigenstates. There are three angles that completely define the directions of the four particles (μ^+, μ^-, K^+, K^-) in the final state. We use the angles $\vec{\rho} = \{\cos \theta_T, \phi_T, \cos \psi_T\}$ defined in the transversity basis introduced in Ref. [19]. The detector acceptance is not flat in these angles. Corrections are introduced in the maximum likelihood fit to account for such effects. The correction method is validated by measuring the lifetime and polarization amplitudes in $B^0 \rightarrow J/\psi K^{*0}$ decays [20].

An unbinned maximum likelihood fit [18] is performed to extract the parameters of interest, $\beta_s^{J/\psi\phi}$ and $\Delta\Gamma_s$, plus additional parameters referred to as “nuisance parameters” which include the signal fraction f_s , the B_s^0 mass, the mean B_s^0 width $\Gamma \equiv (\Gamma_L + \Gamma_H)/2 = 1/\tau(B_s^0)$, the magnitudes of the polarization amplitudes in the transversity basis $|A_0|^2$, $|A_{\parallel}|^2$, and $|A_{\perp}|^2$, and the strong phases $\delta_{\parallel} \equiv \arg(A_{\parallel}A_0^*)$ and $\delta_{\perp} \equiv \arg(A_{\perp}A_0^*)$. The fit uses information on the reconstructed B_s^0 candidate mass, the B_s^0 candidate proper decay time and its uncertainty, the transversity angles $\vec{\rho}$ and tagging

information [16] P and ξ , where P is the event-by-event correct tag probability and $\xi = \{-1, 0, +1\}$ is the tag decision, in which $+1$ corresponds to a candidate tagged as B_s^0 , -1 to a \bar{B}_s , and 0 to an untagged candidate.

In this updated of the analysis we include in the maximum likelihood fit potential S-wave contributions from either $B_s \rightarrow J/\psi f_0$ with $f_0 \rightarrow K^+K^-$ or non-resonant $B_s \rightarrow J/\psi K^+K^-$ decays. While it has been suggested [21] that the S-wave contribution within ± 10 MeV around the ϕ mass may be as large as 6.3%, our analysis shows that the S-wave contribution is less than 6.7% at 95% confidence level. Figure 2 shows the likelihood profile of the S-wave fraction with a best fit value of $\approx 2\%$.

3. Results and Conclusions

Assuming no CP violation ($\beta_s^{J/\psi\phi} = 0$), the B_s decay width difference, lifetime, polarization fractions and strong phase δ_\perp are measured and found to be the most precise to date: $\Delta\Gamma_s = 0.075 \pm 0.035$ (stat) ± 0.01 (syst) ps^{-1} , $\tau_s = 458.6 \pm 7.6$ (stat) ± 3.6 (syst) μm , $|A_0|^2 = 0.524 \pm 0.013$ (stat) ± 0.015 (syst), $|A_\parallel|^2 = 0.231 \pm 0.014$ (stat) ± 0.015 (syst), $\delta_\perp = 2.95 \pm 0.64$ (stat) ± 0.07 (syst). The strong phase δ_\parallel is close to the symmetry point at π which makes the estimation of its value and uncertainty unreliable and therefore we do not provide a result for it at this point. Finally, the confidence regions in the $\beta_s^{J/\psi\phi} - \Delta\Gamma_s$ plane are presented in Figure 2. The ambiguity between the two minima could be resolved if the strong phases δ_\parallel and δ_\perp were known. Recent theoretical studies [22] suggest that the strong phases involved in $B_s^0 \rightarrow J/\psi\phi$ decays are expected to be close to the corresponding strong phases in $B^0 \rightarrow J/\psi K^{*0}$. Using this information, the preferred solution would be the one corresponding to positive $\Delta\Gamma_s$. For the SM values of $\beta_s^{J/\psi\phi}$ and $\Delta\Gamma_s$ we obtain a p-value of 0.44 which corresponds to about 0.8 standard deviations. Minimizing the likelihood function over $\Delta\Gamma_s$ as well, we find $\beta_s^{J/\psi\phi} \in ([0.02, 0.52] \cup [1.08, 1.55])$ at 68% C.L. and $\beta_s^{J/\psi\phi} \in ([-\pi/2, -1.44] \cup [-0.13, 0.68] \cup [0.89, \pi/2])$ at 95% C.L. The p-value for the SM expectations of $\beta_s^{J/\psi\phi}$ is 0.31.

We have presented an updated measurement of the CP violation parameter $\beta_s^{J/\psi\phi}$ in $B_s \rightarrow J/\psi\phi$ decays using 5.2 fb^{-1} of integrated luminosity accumulated by the CDF experiment. The updated result provides bounds on $\beta_s^{J/\psi\phi}$ which are significantly stronger than previous results. The data are consistent with the SM expectations at one standard deviation level. Due to multiple improvements to the analysis, the improvement compared to the 2.8 fb^{-1} result is better than the expectation from just scaling the previous results by the amount of additional data sample. Future analyses may add other decay modes and data from other CDF triggers. The data sample is expected to double by 2011.

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