An Updated Measurement of the B_s^0 Mixing Phase $\sin(2\beta_s)$ at CDF

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The phase of B_s^0 mixing (β_s) is extremely sensitive to new physics amplitudes and is still largely unconstrained experimentally. CDF reports the latest update of the $\sin(2\beta_s)$ measurement using $B_s^0 \to J/\psi\phi$ decays reconstructed in 5.2 fb^{-1} of data.

1 Introduction

The decay $B_s^0 \to J/\psi\phi$ presents a theoretically clean system in which to attempt indirect detection of new physics. The B_s^0 meson can decay directly to the $J/\psi\phi$ final state, as shown in the left diagram in Fig. 1. It can also mix into a $\bar{B}_s^0$ meson via a box diagram, as shown in the right diagram in Fig. 1, before decaying to the final state.

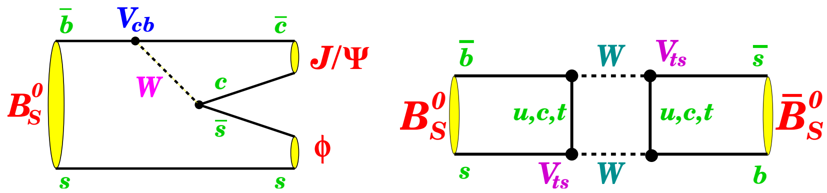

Figure 1: The B_s^0 meson can decay to $J/\psi\phi$ directly (left), or can mix to a $\bar{B}_s^0$ meson before decaying (right).

The mixing box diagram presents an interfering amplitude that can produce CP violation in this system, as well as providing a loop diagram in which new physics could participate. Should a non-standard model heavy particle be exchanged in the mixing box diagram, the CP violation produced by the interference between the direct decays and decays via mixing could be altered from the standard model expectation [1].

Neutral meson mixing occurs when a meson's mass and flavor eigenstates are not identical. This introduces several observables, including Δm_s, the mass difference between the mass eigenstates and also the mixing oscillation frequency, and $\Delta\Gamma_s$, the decay width difference between the mass eigenstates. Additionally, there exists a CP phase ϕ_s, which is expected to be close to zero in the standard model.

Although other mixing observables are measured, the determination of the CP violating phase β_s is the primary goal of this analysis. The phase is associated with the CP violation that occurs in the interference between the direct decay and decay via mixing amplitudes in

$B_s^0 \to J/\psi\phi$ decays. The phase β_s is defined in terms of elements of the Cabibbo-Kobayashi-Maskawa matrix as $\beta_s \equiv arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$, the smallest angle of the unitarity triangle produced by the second and third columns of the CKM matrix. The phase is expected to be quite small in the standard model, $\beta_s \approx 0.02$. Should new physics contributions produce an additional large CP violating phase, ϕ_s^{NP}, the new phase would dominate both β_s and ϕ_s.

2 Analysis Strategy

The decay $B_s^0 \to J/\psi\phi$ is a pseudoscalar decay to two vector particles. The angular momenta of the vector particles sum to produce three angular momentum final states. Two of the angular momentum states, the S and D waves, are CP even, while the P wave is CP odd. An angular analysis is required to determine the relative proportion of CP even to CP odd in the final state and measure β_s. This is done using the transversity basis, which describes a set of CP pure final state amplitudes. Three transversity angles, θ, ϕ, and ψ are also defined [2]. The linear polarization of the vector particles produce the time dependent amplitudes $A_\perp(t)$, $A_{||}(t)$, and $A_0(t)$. The amplitudes $A_\perp(t)$ and $A_{||}(t)$ are transversely polarized and CP odd and even, respectively, while $A_0(t)$ is longitudinally polarized and CP even. Information about the initial amplitudes is encoded in the strong phases $\delta_{||} \equiv (A_{||}(0)A_0^*(0))$ and $\delta_\perp \equiv (A_\perp(0)A_0^*(0))$.

The measurement of $\sin(2\beta_s)$ begins with the reconstruction of $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$ events. The final state angular distributions are analyzed to extract the relative CP odd and CP even contributions. An angular analysis alone can be used to determine β_s, but sensitivity to $\sin(2\beta_s)$ is improved by taking into account whether the B meson was a B_s^0 or $\bar{B}_s^0$ at production. This requires flavor tagging algorithms that tag the B meson's initial flavor by tracks produced in association with the meson (same-side), or the decay products of the other half of the $b\bar{b}$ quark pair from which the reconstructed meson originated (opposite-side). The flavor tagging information is combined with the angular analysis into an un-binned maximum likelihood fit. The likelihood fit is used to extract all parameters of interest: most importantly $\sin(2\beta_s)$, but also $\Delta\Gamma$, the B_s^0 lifetime $\tau(B_s^0)$, the transversity amplitudes and the strong phases.

An additional consideration made in this update of the $\sin(2\beta_s)$ measurement is the possibility of the $B_s^0 \to J/\psi\phi$ signal being contaminated by non-resonant $B_s^0 \to J/\psi K^+K^-$ or $B_s^0 \to J/\psi f_0(980)$ [3]. In order to account for possible contamination, the likelihood is extended to fit for non-resonant contributions in the ϕ mass range. Both states are modeled with flat invariant mass distributions and flat phases with respect to the dominant P wave in the ϕ mass region used for the fit, an assumption that was validated with realistic Monte Carlo. A mass integration was performed over the ϕ mass window, as a K^+K^- mass-dependent fit was beyond the current scope of the analysis.

Before inclusion of non-resonant contributions, an exact symmetry under the transformation (β_s, $\Delta\Gamma$, $\delta_\perp$, $\delta_{||}$) to ($\pi/2-\beta_s$, $-\Delta\Gamma$, $\pi-\delta_\perp$, $2\pi-\delta_{||}$) is present in the likelihood. This produces an ambiguity in the measurement of β_s, with two valid solutions in the space of β_s, $\Delta\Gamma$ and the strong phases. Should a substantial non-resonant contribution exist, it would interfere with the dominant P wave and break the symmetry in the likelihood, removing the ambiguity.

3 Data Selection and Calibration

This measurement relies on CDF's tracking subsystems for mass and spatial resolution, and on the particle identification subsystems for selection and tagging. Over 5 fb^{-1} of data from a di-muon trigger were used. Backgrounds were suppressed using an artificial neural network trained on kinematic quantities such as the p_T of tracks and decay particles, and the vertex probability for decay particles. The cut on the neural network output was chosen by minimizing the β_s errors on pseudo-experiments. The final selection produced a signal sample of ∼6500 $B_s^0 \to J/\psi\phi$ events.

The flavor tagging algorithms employed in this measurement are developed on high statistics Monte Carlo samples, and their power must be calibrated to the relevant data samples. In the case of opposite side tagging, opposite side fragmentation products are used to tag the b or $\bar{b}$. The opposite fragmentation behavior is independent of the species of the reconstructed meson, and self-tagging $B^+ \to J/\psi K^+$ decays can be used to determine a tagging dilution scale factor.

The same side tracks used for tagging are dependent on the species of the associated B meson at production, thus the dilution scale factor must be determined on B_s^0 meson decays. An amplitude scan in the mixing frequency Δm_s was performed. The probability was normalized such that the amplitude should be unity at the true value of Δm_s. The measured amplitude relates the measured to the predicted tagging dilution. This measurement was performed using $B_s^0 \to D_s^- \pi^+$ and $B_s^0 \to D_s^-(3\pi)^+$ decays. The measured value of the amplitude at its maximum value is $\mathcal{A} = 0.94 \pm 0.15$ (stat) $\pm$ 0.13 (syst). The measured value of the mixing frequency is $\Delta m_s = 17.79 \pm 0.07$ ps^{-1}, well consistent with the world average.

4 Results

Fit projections were used to check the fit performance for the proper time distribution and the transversity angle distributions. The fit projection for the proper time is shown in Fig. 2. The lifetime distributions are different for the heavy and light B_s^0 mass eigenstates, enabling the measurement of $\Delta\Gamma$. The fit projections for the three transversity angles also show good agreement between the fit and the data distributions.

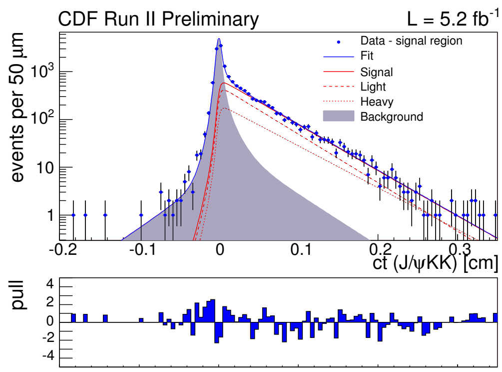

Figure 2: The B_s^0 meson's proper time fit projection. The lifetime distributions for the heavy and light mass eigenstates are denoted by the dashed red lines.

The likelihood shows biases (particularly for β_s) and non-Gaussian behaviors when β_s is allowed to float in the fit. When β_s is fixed to zero, the likelihood is well-behaved, making it possible to quote values for the remaining parameters of interest. The results are the following:

$$
\begin{aligned}
c\tau_s &= (458.7 \pm 7.5 \text{ (stat.)} \pm 3.6 \text{ (syst.)})\ \mu\text{m} \\
\Delta\Gamma &= (0.075 \pm 0.035 \text{ (stat.)} \pm 0.010 \text{ (syst.)})\ ps^{-1} \\
|A_{\parallel}(0)|^2 &= 0.231 \pm 0.014 \text{ (stat)} \pm 0.015 \text{ (stat)} \\
|A_0(0)|^2 &= 0.524 \pm 0.013 \text{ (stat)} \pm 0.015 \text{ (syst)} \\
\delta_{\perp} &= 2.95 \pm 0.65 \text{ (stat)} \pm 0.07 \text{ (syst)}.
\end{aligned}
$$

For the fit with β_s floating, a profile likelihood ordering technique was used to guarantee coverage at the 68% and 95% confidence levels. The final contour in the $\beta_s - \Delta\Gamma$ plane is shown in the left plot in Fig. 3. The p-value at the standard model point was calculated to be 44%, indicating a good consistency with the standard model expectation. The right plot in Fig. 3 shows the one dimensional β_s confidence interval. The p-value at the standard model point for this case is 31%. In both the two dimensional and one dimensional confidence regions, the two solutions for β_s are of nearly identical depth, because the measured non-resonant contamination was too small to break the symmetry of the likelihood. The non-resonant K^+K^-/f_0 fraction is measured to be less than 6.7% at the 95% confidence level.

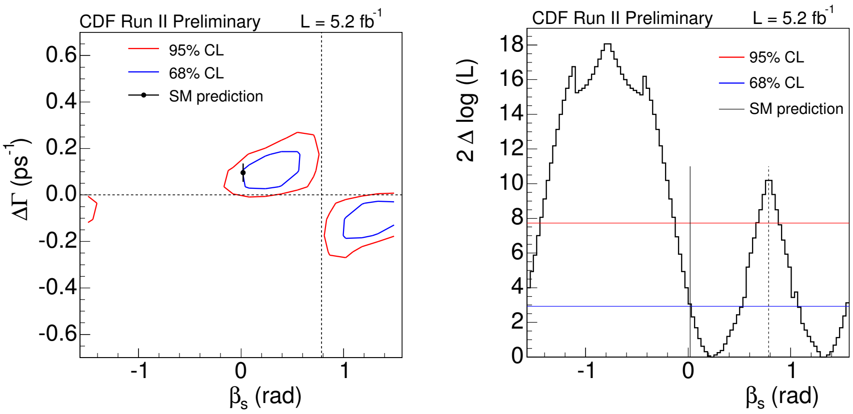

Figure 3: Confidence regions in the $\beta_s - \Delta\Gamma$ plane (left) and β_s (right).

This latest measurement of CP violation in $B_s^0 \rightarrow J/\psi\phi$ decays on 5.2 fb^{-1} of data shows improvement in the errors on β_s and the decay width difference $\Delta\Gamma$, as well as greater consistency with the standard model expectation. It is expected that CDF will double its data sample by the end of Run II, allowing an even more precise determination of $\sin(2\beta_s)$.

References

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