FERMILAB-CONF-10-560-E

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Measurement of β_s at CDF

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The latest results for the measurement of the *CP* violating phase β_s in $B_s^0 \to J/\psi\phi$ decays, from 5.2 fb^{-1} integrated luminosity of CDF data are presented. For the first time, this measurement includes the contribution of $B_s^0 \to J/\psi K^+K^-$ or $B_s^0 \to J/\psi f_0$ events to the signal sample, where the f_0 and non-resonant K^+K^- are *S*-wave states. Additional improvements to the analysis include more than doubling the signal sample, improved selection and particle ID, and fully calibrated flavour tagging for the full dataset. Additionally, the world's most precise single measurements of the B_s^0 lifetime, τ_s, and width difference, $\Delta\Gamma_s$ are given.

Flavor Physics and CP Violation - FPCP 2010
May 25-29, 2010
Turin, Italy

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1. Introduction

The study of neutral B meson properties can provide important tests of the Standard Model (SM) including constraints on parameters of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. While the B^0 system has been thoroughly investigated by B factories, precision measurements in the B_s^0 system are a more recent development, driven largely by the Tevatron experiments. The $B_s^0 - \bar{B}_s^0$ system has the potential to yield indirect observations of New Physics (NP), through the presence of non-SM particles in second order weak interaction processes such as flavour mixing. The golden mode for this measurement is $B_s^0 \to J/\psi\phi$. The $J/\psi\phi$ final state is common to B_s^0 and $\bar{B}_s^0$ decays; CP violation occurs in the mixing through interference between decays with and without B_s^0 mixing. The phase, β_s, between these two amplitudes is predicted to be close to zero in the SM [1], so a significant excess would be a clear indication of evidence for NP in this channel.

The updated measurement is of particular interest as a published CDF $B_s \to J/\psi\phi$ analysis and a recent update showed deviations from the Standard Model expected value of approximately 2 σ [2, 3], and a similar effect was seen in a recent combined Tevatron result [4].

2. Neutral B_s^0 system phenomenology

The flavour eigenstates of B_s^0 mesons in the SM are not the same as the mass eigenstates, leading to oscillations between $|B_s^0\rangle = (\bar{b}s)$ and $|\bar{B}_s^0\rangle = (b\bar{s})$ via the second order weak interactions. The phenomenology of this weak mixing is described by the CKM matrix. The time evolution of the $B_s^0 - \bar{B}_s^0$ system is governed by the Schrödinger equation

$$i\frac{d}{dt}\begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix} = \mathscr{H}\begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix} \equiv \left[\begin{pmatrix} M_0 & M_{12} \\ M_{12}^* & M_0 \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_0 & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_0 \end{pmatrix}\right]\begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix} \tag{2.1}$$

where the M and Γ matrices describe the mass and decays of the system. The mass eigenstates can be obtained by diagonalising $\mathscr{H}$, giving:

$$|B_s^H\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle \tag{2.2}$$

and

$$|B_s^L\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle \tag{2.3}$$

where $|q/p| = 1$ in the case of no CP violation in mixing (as opposed to between decays with and without mixing), as predicted in the $J/\psi\phi$ channel. The indices H and L label the heavy and light eigenstates respectively. The mass difference, Δm_s, between the heavy and light states is proportional to the frequency of B_s^0 mixing and is approximately equal to $2|M_{12}|$. The mass eigenstates have a small but non negligible lifetime difference, which can be described in terms of the decay width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos(2\phi_s)$ where the CP violating phase is defined as $\phi_s = arg(-M_{12}/\Gamma_{12})$ and the mean decay width $\Gamma_s = 1/\tau_s$. The SM predicts ϕ_s^{SM} to be of order 0.004, and it would be expected to increase in the presence of NP. The mixing frequency, Δm_s has been well determined by CDF, a 5σ observation of mixing with $\Delta m_s = 17.77 \pm 0.10$ (stat.) $\pm$ 0.07 (syst.)ps^{-1} was published in 2006 [5].

The full angular and time dependent equations for the measurement of $B_s^0 \to J/\psi\phi$, including the addition of the S-wave KK component are detailed in [6].

3. *CP* violation in $B_s \to J/\psi\phi$

The relative phase, β_s, between decays of a B_s^0 meson to $J/\psi\phi$ directly, and after mixing to $\bar{B}_s^0$, is defined in the SM as

$$\beta_s^{SM} = arg\left(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \approx 0.02 \tag{3.1}$$

A New Physics phase, contributing to the weak mixing diagrams in the neutral B_s^0 system would introduce a new physics phase ϕ_s^{NP} to β_s such that the measured value would be $2\beta_s = 2\beta_s^{SM} - \phi_s^{NP}$. The same NP phase would enhance ϕ_s, giving $\phi_s = \phi_s^{SM} + \phi_s^{NP}$. As both β_s^{SM} and ϕ_s^{SM} are predicted to be close to zero, the NP phase would dominate, and the measured phase would be $2\beta_s \approx -\phi_s \approx \phi_s^{NP}$. This approximation is valid given the current experimental resolution, but future high precision measurements may be able to distinguish between these quantities.

3.1 Experimental strategy

The decay $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$ is fully reconstructed from events which pass the di-muon trigger. A Neural Network (NN) selection procedure is used to reconstruct $\sim$ 6500 signal events in 5.2 $^{-1}$ of data. For this updated analysis, rather than using a standard $S/\sqrt{(S+B)}$ figure of merit, the NN cut is optimised by selecting the cut value which minimises the statistical error on β_s in pseudo experiments. This, along with a full re-calibration of particle identification information from dE/dx and Time of Flight (TOF), has lead to a $B_s^0 \to J/\psi\phi$ signal yield of more than twice that in the previous 2.8 fb^{-1} data sample [3]. Figure 1 shows the $B_s^0 \to J/\psi\phi$ mass distribution after selection.

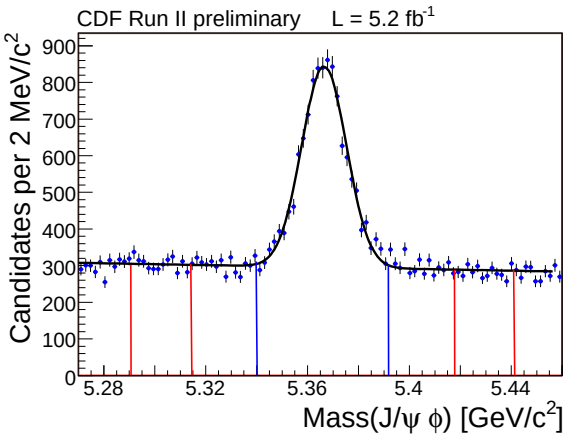

Figure 1: B_s^0 mass distribution for CDF 5.2 fb $^{-}$1 data sample, fitted with a single Gaussian for the signal and a 1st order polynomial to describe the background component.

The final state is an admixture of *CP* odd and even states, which can be separated according to their angular momentum. The total angular momentum of the $J/\psi\phi$ state can be $L = 0$, 1, or 2, and the *CP* of the state is $(-1)^L$, so the $L = 0, 2$ states are *CP* even, and the $L = 1$ state is *CP* odd. These *CP* states can be separated using the angular distribution of the four final state particles, the muons and kaons from the decay of the J/ψ and ϕ. The transversity basis [7] is used to define

the angular dependence of the final state, where the relative directions of the four particles can be described in terms of three transversity angles, $\{\cos\theta_T, \phi_T, \cos\psi_T\}$ which are defined by the direction of the decaying J/ψ and ϕ mesons. In the transversity basis, the decay amplitude can be separated into three components which represent different linear polarisation states. The *CP* even states correspond to the vector mesons either being longitudinally polarised, or transverse to their direction of motion and parallel to each other (0, $\|$), for the *CP* odd state the mesons are transversely polarised with respect to their direction of motion, and perpendicular to each other ($\perp$). The amplitudes of these states are $A_0, A_\|$ and $A_\perp$ respectively. The use of the transversity basis to separate the *CP* odd and even states in this way means that the measurement is sensitive to the *CP* violating phase with or without flavour tagging information for the initial state.

The angular analysis is combined with time development and mass dependence in a multivariate likelihood fit. In the simplest case, the fit without flavour tagging information, the likelihood function has a four fold ambiguity under the transformations $\{\beta_s, \Delta\Gamma, \phi_\|, \phi_\perp\} \Leftrightarrow \{\phi/2 - \beta_s, -\Delta\Gamma, 2\pi - \phi_\|, \pi - \phi_\perp\}$ and $\beta_s \Leftrightarrow -\beta_s$, where the strong phases are defined in terms of the transversity amplitudes, $\phi_\| \equiv arg(A_\|^* A_0)$ and $\phi_\perp \equiv arg(A_\perp^* A_0)$.

3.2 Flavour tagging

By flavour tagging the initial B_s^0 meson, the time development of B_s^0 and $\bar{B}_s^0$ states can be followed separately, which removes the insensitivity to the sign of β_s and $\Delta\Gamma$. This reduces the ambiguity to two points. The flavour of the decaying B meson is tagged using a combination of opposite side (OST) and same side (SST) tagging algorithms. The OST tags on the b quark content of a B meson from the same production vertex as the candidate B_s^0, the SST tags according to the s quark content of a kaon produced with the candidate.

For this updated analysis, the SST has been re-calibrated for the full sample on data through a B_s^0 mixing measurement. This technique uses the fact that a measured mixing amplitude of ≈ 1 means that the tagger accurately assesses its performance, and an amplitude of > 1 or < 1 implies an under or over estimation of its power, respectively.

This calibration uses the modes:

$$
\begin{aligned}
B_s^0 &\to D_s^- \pi^+, D_s^- \to \phi\pi^-, \phi \to K^+K^- \\
B_s^0 &\to D_s^- \pi^+, D_s^- \to K^*K^-, K^* \to K^+\pi^- \\
B_s^0 &\to D_s^- \pi^+, D_s^- \to \pi^-\pi^-\pi^+ \\
B_s^0 &\to D_s^- \pi^+\pi^+\pi^-, D_s^- \to \phi\pi^-, \phi \to K^+K^-
\end{aligned}
$$

Of which the first channel accounts for about 50% of the statistics.

The amplitude measured for this calibration [8] is $\mathscr{A} = 0.94 \pm 0.15\ (\text{stat.}) \pm\ 0.13(\text{syst.})$, shown in Figure 2. The mixing frequency, $\Delta m_s = 17.79 \pm 0.07\ \text{ps}^{-1}$, with statistical errors only, is in good agreement with the CDF published measurement.

3.3 *S*-wave *KK* component

It has been suggested [9] that a potential contamination of the signal ϕ meson by *S*-wave f^0 or non-resonant *KK* of $\sim 10\%$ could bias the measurement of β_s towards the SM value. This updated CDF analysis includes the *S*-wave component in the full angular and time-dependent analysis. Both

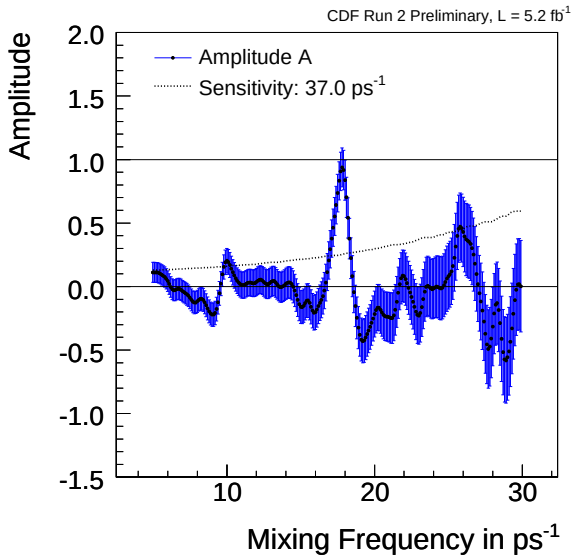

Figure 2: B_s^0 mixing amplitude scan, for calibration of SST

the f_0 and non-resonant KK components are considered flat in mass within the small selection window, and the ϕ meson mass is modelled by an asymmetric relativistic Breit Wigner; however this mass is integrated over in the fit function and is not used in the fit. The $J/\psi K^+K^-$ or $J/\psi f_0$ final state is a pure CP odd state, and thus follows the time dependence of the CP odd component of the $B_s^0 \to J/\psi\phi$ decay.

A preliminary study of the S-wave contamination of the ϕ meson signal carried out by studying the invariant KK mass distribution gives no strong indication of a large additional component, as shown in Figure 3.

4. Results

With the current data sample it is not possible to quote a point value for the phase β_s due to the symmetries in the likelihood function and the non-Gaussian error distribution. Instead the results are presented as frequentist likelihood contours; a profile-likelihood ratio ordering technique is used to ensure full coverage. Figure 4 shows the likelihood contours in the $\beta_s - \Delta\Gamma$ plane. The confidence interval for $\beta_s^{J/\psi\phi}$ at the 68 % confidence level is $[0.02, 0.52] \cup [1.08, 1.55]$ and at the 95 % confidence level, $[-\pi/2, -1.44] \cup [-0.13, 0.58] \cup [0.89, \pi/2]$.

The upper limit on the fraction of the S-wave KK (f_0) component in the $B_s^0 \to J/\psi\phi$ signal was measured to be $< 6.7\%$ at the 95% confidence level.

In the hypothesis of no CP violation ($\beta_s = 0.0$), the values of the B_s^0 lifetime, $\tau_s = 1.53 \pm 0.025$ (stat.) ± 0.01 (syst.) ps, decay width difference $\Delta\Gamma_s = 0.075 \pm 0.035$ (stat.) ± 0.01 (syst.) ps^{-1} the transversity amplitudes, $|A_{\|}|^2 = 0.231 \pm 0.014$ (stat.) ± 0.015 (syst.) and $|A_0|^2 = 0.524 \pm 0.013$ (stat.) ± 0.015 (syst.) and the strong phase $\phi_\perp = 2.95 \pm 0.64$ (stat.) ± 0.07 (syst.) from the flavour tagged fit are determined [10].

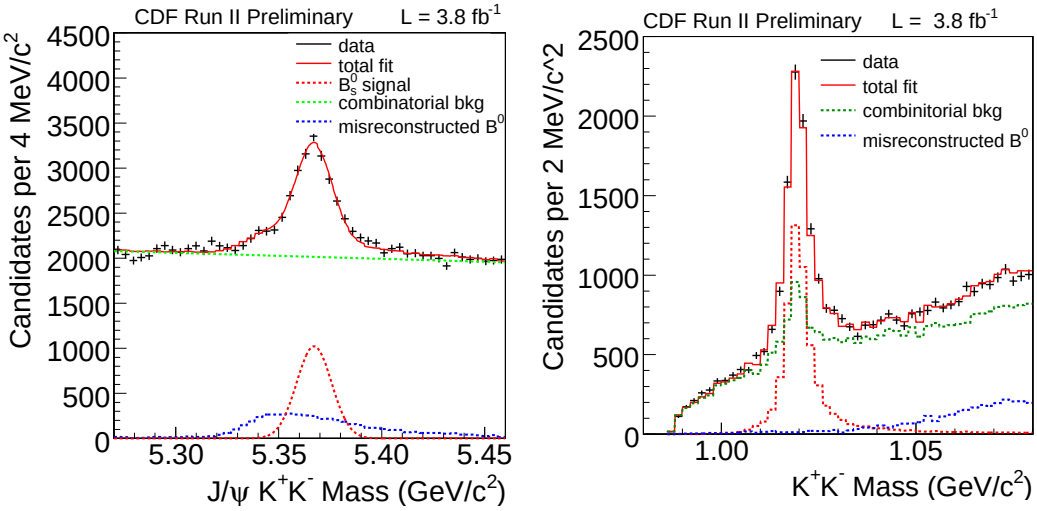

Figure 3: The B_s^0 mass is plotted (left) with a loose ϕ mass cut window, which allows contamination from $B^0 \to J/\psi K^*$ misreconstructed as $B_s^0 \to J/\psi\phi$, this reflection component is fitted with a MC template, the signal B_s^0 mass is fitted with a Gaussian and the combinatorial background with a 1st order polynomial. The invariant KK mass plot (right) is shown with the fractions of each component fixed to that found in the B_s^0 mass fit.

5. Conclusions

Previous measurements from both the CDF [3] and DØ [11] experiments, and a combined Tevatron result [4], indicated a shift of about 2 σ from the Standard Model expectation for the B_s^0 mixing phase. The new $\beta_s^{J/\psi\phi}$ measurement from the CDF experiment shows good agreement with the Standard Model expected value, with a p-value of 44%, equivalent to a deviation of 0.8 σ. These results benefit from an improved selection and particle ID to take advantage of the full available statistics, updated flavour tagging, and the inclusion of the S-wave KK component of the signal fraction in the fit. Additionally, results include the world's most precise single measurements of the B_s^0 lifetime and decay width difference in the hypothesis of no CP violation.

Future prospects for this measurement at CDF include doubling again the data sample, the potential inclusion of data from different trigger paths and the addition of other B_s^0 decay channels to the analysis as well as continuous improvements to the analysis technique.

6. Acknowledgements

The author would like to thank the University of Pittsburgh for providing funding to attend at FPCP 2010.

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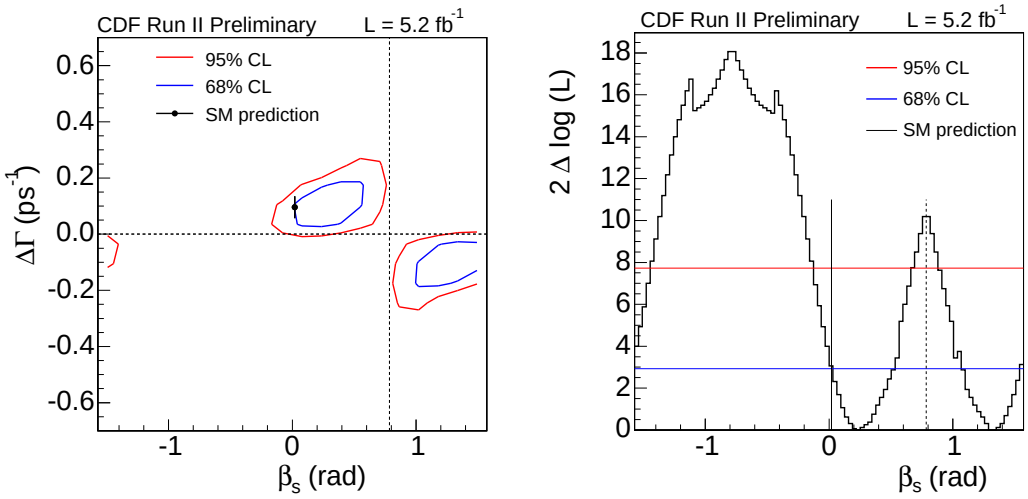

Figure 4: Confidence regions in 2-dimensions in the $\beta_s^{J/\psi\phi} - \Delta\Gamma_s$ plane, including systematics effects on the statistical uncertainties (left) and in 1-dimension for $\beta_s^{J/\psi\phi}$ (right). The SM predicted value is marked with a black point or line.

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