New measurement of the $B_s^0$ mixing phase and observation of suppressed $B_s^0$ decays at CDF

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Abstract. Recent CDF measurements of $B_s^0$ decay parameters are presented. The $CP$ violating phase $\beta_s$ has been measured in $B_s^0 \to J/\psi \phi$ decays using $5.2 \text{ fb}^{-1}$ integrated luminosity of CDF data. This updated $\beta_s$ 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 for this update include more than doubling the signal sample, improved selection and particle ID, and fully calibrated flavour tagging for the complete dataset. This measurement shows good agreement with the Standard Model expectation for $\beta_s$, with a significance of $<1\sigma$ for deviation from the expected value. In a related analysis, two suppressed $B_s^0$ decay channels, $B_s^0 \to J/\psi K^*0$ and $B_s^0 \to J/\psi K_s$, have been observed for the first time, in 5.9 $\text{ fb}^{-1}$ CDF data. Their branching fractions and relative branching ratios are reported. These newly observed channels have the potential for extraction of important CKM parameters including the phase $\beta_s$.

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 $B^0_s$ system are a more recent development, driven largely by the Tevatron experiments. The $B^0_s - \bar{B}^0_s$ 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 $B^0_s \to J/\psi \phi$. 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 $B^0_s$ mixing. The phase, $\beta_s$, 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 $2\sigma$ [2, 3], and a similar effect was seen in a recent combined Tevatron result [4].

The observation of previously unseen decays $B^0_s \to J/\psi K^*0$ and $B^0_s \to J/\psi K_s$ [5] is also of interest for flavour physics. The $J/\psi K_s$ final state is a $CP$ odd eigenstate, which, with sufficient statistics, could yield a measurement of the pure $B_s^{0\text{H}}$ mass eigenstate lifetime. It has been suggested [6] that this channel could also be used to extract the unitarity angle $\gamma$. The decay $B^0_s \to J/\psi K^*0$ has an admixture of $CP$ states for the final state, and could give a measurement
of the $CP$ violating phase $\beta_s$ analagously to the $B_0^0 \rightarrow J/\psi \phi$ channel. Branching ratios have been measured relative to the equivalent $B^0$ decays to the same final states.

2. New measurement of $B_0^0$ mixing phase

2.1. CP violation in $B_s \rightarrow J/\psi \phi$

The flavour eigenstates of $B^0_s$ mesons in the SM are not the same as the mass eigenstates, leading to oscillations between $|B^0_s\rangle = (b s)$ 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 $B^0_s - \bar{B}_s^0$ system is approximated by the Schrödinger equation

$$i\frac{d}{dt} \begin{pmatrix} B^0_s(t) \\ \bar{B}_s^0(t) \end{pmatrix} = \mathcal{H} \begin{pmatrix} B^0_s(t) \\ \bar{B}_s^0(t) \end{pmatrix} = \begin{pmatrix} M_0 & M_{12} \\ M_{12}^* & M_0 \end{pmatrix} \begin{pmatrix} B^0_s(t) \\ \bar{B}_s^0(t) \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_0 & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_0 \end{pmatrix} \begin{pmatrix} B^0_s(t) \\ \bar{B}_s^0(t) \end{pmatrix}$$

(1)

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

$$|B^H_s\rangle = p|B^0_s\rangle - q|\bar{B}_s^0\rangle$$

(2)

and

$$|B^L_s\rangle = p|B^0_s\rangle + q|\bar{B}_s^0\rangle$$

(3)

where $|q/p| = 1$ in the case of no $CP$ violation in mixing, as predicted in the $J/\psi \phi$ channel. The indices $H$ and $L$ label the heavy and light eigenstates respectively. The mass difference, $\Delta m_s$, between the heavy and light states is proportional to the frequency of $B^0_s$ mixing and is approximately equal to $2|\Gamma_{12}|$. The mass eigenstates have a small but non negligible lifetime difference, which can be described in terms of the decay width difference

$$\Delta \Gamma_s = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}| \cos(2\phi_s)$$

(4)

where the $CP$ violating phase is defined as $\phi_s = \text{arg}(-M_{12}/\Gamma_{12})$ and the mean decay width $\Gamma_0 = 1/\tau_s$. The SM predicts $\phi_s^{SM}$ to be of order 0.004, and it would be expected to increase in the presence of NP.

The full angular and time dependent equations for the measurement of $B^0_s \rightarrow J/\psi \phi$, including the addition of the $S$-wave $KK$ component are detailed in [8].

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

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

(5)

A New Physics phase, contributing to the weak mixing diagrams in the neutral $B^0_s$ system would introduce a new physics phase $\phi_s^{NP}$ to $\beta_s$ such that the measured value would be $2\beta_s = 2\beta_s^{SM} - \phi_s^{NP}$. The same NP phase would enhance $\phi_s$, giving $\phi_s = \phi_s^{SM} + \phi_s^{NP}$. As both $\beta_s^{SM}$ and $\phi_s^{SM}$ 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.

2.2. Experimental strategy

The decay $B^0_s \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\phi(\rightarrow K^+K^-)$ is fully reconstructed from events which pass the di-muon trigger. A Neural Network (NN) selection procedure [9] is used to reconstruct $\sim 6500$ signal events in $5.2^{-1}$ of data. The NN is trained on background events from the $B^0_s$ mass side bands, and MC signal events. The NN output for these training samples is shown in Figure 1.
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 $\beta_s$ 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 $B_s^0 \rightarrow J/\psi \phi$ signal yield of more than twice that in the previous 2.8 $fb^{-1}$ data sample [3]. Figure 1 shows the $B_s^0 \rightarrow J/\psi \phi$ mass distribution after selection.

Figure 1. [left] $B_s^0$ mass distribution for CDF 5.2 fb$^{-1}$ data sample, fitted with a single Gaussian for the signal and a line to describe the background component. [right] NN training: output for signal and background events.

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 $L = 0, 1, 2$, 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 $J/\psi$ and $\phi$. The transversity basis [10] 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 $J/\psi$ and $\phi$ 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 (⊥). 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 $\{\beta_s, \Delta \Gamma, \phi_||, \phi_\perp\} \leftrightarrow \{\pi/2 - \beta_s, -\Delta \Gamma, 2\pi - \phi_||, \pi - \phi_\perp\}$ 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 $\phi_\perp \equiv arg(A_\perp A^*_0)$.
2.3. Flavour tagging
By flavour tagging the initial $B^0_s$ meson, the time development of $B^0$ and $\bar{B}^0$ states can be followed separately, which removes the insensitivity to the sign of $\beta_s$ 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 $B^0_s$, 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 $B^0_s$ mixing measurement [11]. This technique uses the fact that a measured mixing amplitude of $\approx 1$ means that the tagger accurately assesses its performance, and an amplitude $>1$ or $<1$ implies an under or over estimation of its power, respectively.

This calibration uses the modes:

$$
B^0_s \rightarrow D^- \pi^+, D_s^- \rightarrow \phi \pi^-, \phi \rightarrow K^+ K^-
$$

$$
B^0_s \rightarrow D^- \pi^+, D_s^- \rightarrow K^+ K^-, K^* \rightarrow K^+ \pi^-
$$

$$
B^0_s \rightarrow D^- \pi^+, D_s^- \rightarrow \pi^- \pi^- \pi^+
$$

The first channel accounts for about 50% of the statistics, the yield for this channel is shown in Figure 2.

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

![Figure 2](image.png)

2.4. $S$-wave $KK$ component
It has been suggested [12] that a potential contamination of the signal $\phi$ meson by $S$-wave $f_0$ or non-resonant $KK$ of $\sim 10\%$ could bias the measurement of $\beta_s$ towards the SM value. This
latest CDF analysis includes the $S$-wave component in the full angular and time-dependent analysis. Both the $f_0$ and non-resonant $KK$ components are considered flat in mass within the small selection window, and the $\phi$ 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 $B^0_s \rightarrow J/\psi \phi$ decay.

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

![Figure 3](image_url)

**Figure 3.** The $B^0_s$ mass is plotted (left) with a loose $\phi$ mass cut window, which allows contamination from $B^0 \rightarrow J/\psi K^*$ misreconstructed as $B^0_s \rightarrow J/\psi \phi$, this reflection component is fitted with a MC template, the signal $B^0_s$ mass is fitted with a Gaussian and the combinatorial background with a line.

2.5. Results

It is currently not possible to quote a point value for the phase $\beta_s$, without adding external constraints, due to the symmetries in the likelihood function and the non-Gaussian error distribution for $\beta_s$. 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, $[−\pi/2, −1.44] \cup [−0.13, 0.68] \cup [0.89, \pi/2]$.

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

In the hypothesis of no $CP$ violation ($\beta_s = 0$), the values of the $B^0_s$ lifetime, $\tau_s = 1.53 ± 0.025$ (stat.)$± 0.01$ (syst.) ps, decay width difference $\Delta \Gamma_s = 0.075 ± 0.035$ (stat.)$± 0.01$ (syst.) ps$^{-1}$, the transversity amplitudes, $|A_\parallel|^2 = 0.231 ± 0.014$ (stat.)$± 0.015$ (syst.) and $|A_\perp|^2 = 0.524 ± 0.013$ (stat.)$± 0.015$ (syst.) and the strong phase $\phi_\perp = 2.95 ± 0.64$ (stat.)$± 0.07$ (syst.) are determined [13] from the flavour tagged fit.
3. Observation of suppressed $B^0_s$ decays
The branching ratios for the suppressed decays $B^0_s \to J/\psi K^{*0}$ and $B^0_s \to J/\psi K_0$ are measured relative to the more common $B^0$ decays in the same channels, using the relation [5]:

$$
\frac{\mathcal{B}(B^0_s \to J/\psi K)}{\mathcal{B}(B^0 \to J/\psi K)} = A_{rel} \times f_d/f_s \times \frac{N(B^0_s \to J/\psi K)}{N(B^0 \to J/\psi K)}
$$

where $K$ is $K_0^0$ or $K^{*0}$. $A_{rel}$ is the relative acceptance measured from MC and $f_d/f_s$ is the ratio of fragmentation fractions, taken from a combination of CDF measurements and PDG values.

3.1. Experimental technique
This analysis uses 5.9 fb$^{-1}$ integrated luminosity of CDF data collected with the di-muon trigger. From the enhanced sample of $J/\psi \to \mu\mu$ events, $B^0 \to J/\psi K^{*0}$ and $B^0 \to J/\psi K_0^0$ decays are reconstructed. The signal selection is optimised for these $B^0$ decays then applied to the $B^0_s$ channel. Selection for the $J/\psi K^{*0}$ channel is carried out using rectangular cuts, optimised on the quantity $S/(1.5 + \sqrt{B})$. The $J/\psi K_0^0$ channel is selected using a Neural Network (NN) as the $B^0_s$ contribution is expected to be smaller in this decay, making good combinatorial background suppression essential. In a binned likelihood fit, the $B^0$ mass distributions are modelled with a three Gaussian template taken from Monte Carlo, and an identical template is used for the $B^0_s$ mass with the mean shifted appropriately.

3.2. Results
Figure 5 shows the invariant mass distributions for the $B^0_s \to J/\psi K_0$ and $B^0_s \to J/\psi K^{*0}$ channels. The $B^0_s \to J/\psi K_0$ channel is observed with a significance of 1.72$\sigma$ over the null hypothesis, the $B^0_s \to J/\psi K^{*0}$ channel with 8.0$\sigma$.

The ratios of branching fractions for the $B^0_s$ channels with respect to the reference $B^0$ decays are:

$$
\frac{\mathcal{B}(B^0_s \to J/\psi K^{*0})}{\mathcal{B}(B^0 \to J/\psi K^{*0})} = (0.062 \pm 0.009 \text{ (stat.)} \pm 0.025 \text{ (syst.)} \pm 0.008 \text{ (frag.)})
$$
Both the CDF [3] and DØ [14] experiments have previously produced measurements of the $\text{B}^0_\text{s} \to J/\psi K^*$ component of the signal fraction in the fit. Additionally, results from the $\text{B}^0_\text{s} \to J/\psi K^*$ 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 $\sigma$.

These latest 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 $K K$ component of the signal fraction in the fit. Additionally, results from the $\beta_s$ measurement include the world’s most precise single measurements of the $\text{B}^0_\text{s}$ lifetime and decay width difference in the hypothesis of no $CP$ violation.

The observation of two suppressed $\text{B}^0_\text{s}$ decay channels opens up the possibility (in the case of sufficient statistics) of further measurements of CKM parameters, in particular the study of $\beta_s$ in the decay $\text{B}^0_\text{s} \to J/\psi K^*$, and the potential to measure individually the $CP$ odd $\text{B}^0_\text{s,0H}$ lifetime in the channel $\text{B}^0_\text{s} \to J/\psi K^*$. In the near future, each of the discussed measurements at CDF can be improved by doubling the data samples used, as the integrated luminosity delivered by the Tevatron has already surpassed 10 fb$^{-1}$.

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Figure 5. Invariant mass distribution, zoomed in signal region, for (left) $\text{B}^0_\text{s} \to J/\psi K^*0$ and (right) $\text{B}^0_\text{s} \to J/\psi K_s$.

$$\frac{\mathcal{B}(\text{B}^0_\text{s} \to J/\psi K^*_s)}{\mathcal{B}(\text{B}^0_\text{s} \to J/\psi K^*_0)} = (0.041 \pm 0.007 \text{ (stat.)} \pm 0.004 \text{ (syst.)} \pm 0.005 \text{ (frag.)})$$

From these, using the PDG values for the branching fractions of the reference $\text{B}^0$ decays, the absolute branching fractions for the $\text{B}^0_\text{s}$ decays can be calculated as:

$$\mathcal{B}(\text{B}^0_\text{s} \to J/\psi K^0) = (3.5 \pm 0.6 \text{ (stat.)} \pm 0.4 \text{ (syst.)} \pm 0.4 \text{ (frag.)} \pm 0.1 \text{ (norm)}) \times 10^{-5}$$

$$\mathcal{B}(\text{B}^0_\text{s} \to J/\psi K^{*0}) = (8.3 \pm 1.2 \text{ (stat.)} \pm 3.4 \text{ (syst.)} \pm 1.0 \text{ (frag.)} \pm 0.4 \text{ (norm)}) \times 10^{-5}(8)$$

4. Conclusions
Both the CDF [3] and DØ [14] experiments have previously produced measurements of the $\text{B}^0_\text{s}$ mixing phase $\beta_s$, independently and in a combined Tevatron result [4], which indicated a shift of about 2 $\sigma$ from the Standard Model expectation. The new $\beta_s^{J/\psi}$ 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 $\sigma$. In the near future, each of the discussed measurements at CDF can be improved by doubling the data samples used, as the integrated luminosity delivered by the Tevatron has already surpassed 10 fb$^{-1}$.  

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