CP violation and mixing of B mesons at CDF

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We report recent studies of CP-violation and mixing in neutral B mesons from the CDF experiment at the Fermilab Tevatron Collider. Results of a direct measurement of the CP-violation parameter $\sin 2\beta$ using $B^0 \rightarrow J/\psi K^0_S$ with multi flavor tagging algorithms, a search for $B^0_s - \overline{B^0_s}$ mixing using semileptonic decays, and the updated precision measurements of the $B^0 - \overline{B^0}$ mixing parameter will be presented. The prospects for B physics with the upgraded CDF detector in the next Tevatron Collider run will also be discussed.

1. INTRODUCTION

The experimental determination of the CKM matrix provides a fundamental test of the Standard Model. Using the Wolfenstein parameterization [1] the matrix can be written as:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Two of the four free parameters, $\lambda = \sin\Theta_c = 0.2196 \pm 0.0023$ and $A = 0.819 \pm 0.035$, are known quite well, but no direct measurements of ρ and η exist to date. It is believed that the non-zero phase η/ρ is the source of CP violation. One of the major goals of heavy flavor physics is to determine the values of ρ and η.

The constraints on the CKM matrix can be graphically represented by the so-called unitarity triangle. Figure 1 shows the triangle derived using the unitary condition $V^*_{ud}V_{td} + V^*_{us}V_{ts} + V^*_{ub}V_{tb} = 0$. The angle β can be determined by measuring the asymmetry in the decay ratio $B^0/\overline{B^0} \rightarrow J/\psi K^0_S$. The side $\frac{V_{td}}{V_{ts}}$ in the triangle can be determined from measurements of the $B^0 - \overline{B^0}$ and $B^0_s - \overline{B^0_s}$ mixing parameters Δm_d and Δm_s. In this talk, we will concentrate on recent CDF measurements of $\sin 2\beta$ and $B^0_s - \overline{B^0_s}$ mixing. We will describe B flavor tagging methods, CP violation, and mixing results using data taken between 1992 and 1995 at the Tevatron (Run I), and prospects for future measurements at the Tevatron (Run II) that are projected to begin in CY 2001.

2. B FLAVOR TAGGING AT CDF

Three tagging algorithms were explored by CDF to determine the flavor of the B meson at the time of production. The soft lepton tagging (SLT) algorithm uses the charge information from leptons produced from semileptonic decays, $b \rightarrow \ell^- X$ and $\overline{b} \rightarrow \ell^+ X$,

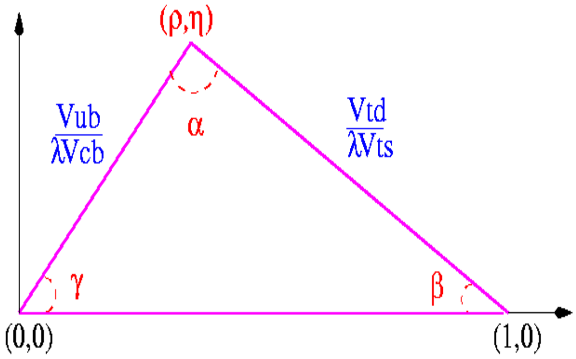

Figure 1. CKM unitarity triangle.

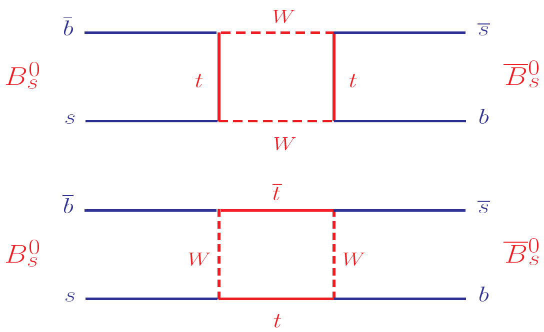

Figure 2. Box diagram for $B_s^0 - \overline{B_s^0}$ mixing.

to identify the B meson flavor. In jet-charge tagging (JetQ), the weighted sum of the charges of tracks recoiling against a B meson is used. In same side tagging (SST), the correlation between the B meson flavor and charged tracks from b quark fragmentation is used.

The merit of a flavor tagging algorithm is described by the tagging efficiency and dilution. Tagging efficiency is defined as the fraction of the data sample for which the tag returns a decision: $\epsilon \equiv N_{tag}/N_{total}$. The dilution, defined as $D \equiv \frac{N_{RS}-N_{WS}}{N_{RS}+N_{WS}} = 2\mathcal{P} - 1$, where N_{RS} and N_{WS} are respectively the number of correctly and incorrectly tagged events, is closely related to the probability $\mathcal{P}$ that the tag is correct. The "effective tagging efficiency" is given by the quantity ϵD^2 for any flavor tagging method. In an asymmetry measurement, the statistical power of the sample is reduced by the factor ϵD^2 : $\sigma_{\mathcal{A}_{obs}} \propto \sqrt{1/\epsilon D^2}$. Detail descriptions of the three tagging algorithms can be found in references [2] [3].

3. $B^0 - \overline{B^0}$ AND $B_s^0 - \overline{B_s^0}$ MIXING MEASUREMENTS

The process governing neutral $B_q^0 - \overline{B_q^0}$ mixing is dominated by the second-order weak interaction involving virtual top quarks, as illustrated by the box diagrams shown in Figure 2. The mass difference Δm_q between the two meson eigenstates for the $B_q^0 - \overline{B_q^0}$ system determines the mixing frequency and is predicted as a function of the CKM matrix element $\mid V_{tq} \mid$. The calculations for $B_s^0 - \overline{B_s^0}$ and $B_d^0 - \overline{B_d^0}$ mixing are very similar. A comparison of Δm_s and Δm_d cancels most of the theoretical uncertainties and results in a determination of $\mid V_{ts}/V_{td} \mid$:

$$\frac{\Delta m_s}{\Delta m_d} = \left(\frac{m_{B_s}}{m_{B_d}}\frac{\eta_s}{\eta_d}\frac{F_s}{F_d}\right)\left|\frac{V_{ts}}{V_{td}}\right|^2.$$

The QCD correction ratio $(\eta_s F_s/\eta_d F_d)$ is known to a precision of 10% [4].

The SLT and JetQ flavor tags were used successfully [2] for the measurement of Δm_d using a sample of inclusive semileptonic decays; this sample was enriched in B hadrons by requiring a lepton from $B^0 \to \ell X$ associated with a secondary vertex. The lifetime-dependent asymmetry distribution was used to extract a value of $\Delta m_d = 0.50 \pm 0.05 \pm$

0.05 ps^{-1}. The SST flavor tag was used on a sample of 6000 B^0 events in the modes $B^0 \to \ell^0 D^{(*)+} X$, and a value of $\Delta m_d = 0.471^{+0.078}_{-0.068} \pm 0.034\ ps^{-1}$ was extracted in this analysis. Averaging these with other CDF measurements [5], CDF has determined the $B^0 - \overline{B^0}$ mixing parameter to be $\Delta m_d = 0.495 \pm 0.026 \pm 0.025\ ps^{-1}$.

A search for $B^0_s - \overline{B^0_s}$ mixing was performed in a sample of B^0_s semileptonic decays reconstructed using ϕ meson - lepton correlations. The events were collected using dilepton triggers in Run I. The B_s initial production flavor was determined from the second lepton in the event. Appropriate selection cuts [6] were used to enhance signals from the decays $B^0_s \to D^-_s \ell^+ X \nu \to \phi \ell^+ X \nu$. The sample consisted of 1068 ± 70 events with a B^0_s purity of 61%, as shown in Figure 3. The amplitude fit method [7] was used to place constraints on the value of Δm_s. In this method, we fit for the normalized mixing amplitude $\mathcal{A}$ and its Gaussian error $\sigma_{\mathcal{A}}$ at each assumed Δm_s value. It is expected that $\mathcal{A} \approx 1$ if the assumed Δm_s is close to the true value and $\mathcal{A} \approx 0$ otherwise. A value of Δm_s can be excluded at 95% confidence level if $\mathcal{A} + 1.645\sigma_{\mathcal{A}} < 1$. Figure 4 shows the amplitude fit result. The dots with error bars are the fitted amplitudes and their errors. The dot-dashed lines correspond to $\mathcal{A} + 1.645\sigma_{\mathcal{A}}$ with statistical uncertainties, while the solid lines include the contribution from systematic uncertainties. The dashed line shows the expectation ($\mathcal{A} = 1$) for mixing. The highest Δm_s value below which all values are excluded with a 95% confidence level is $\Delta m_s > 6.2$ with statistical errors only and $\Delta m_s > 5.8$ with systematic errors included.

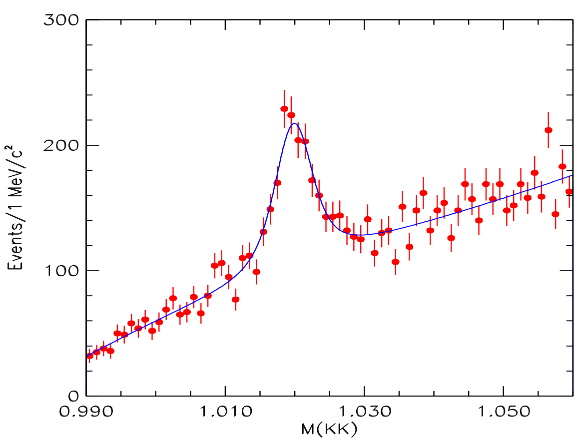

Figure 3. Invariant mass of K^-K^+ for events passing selection cuts.

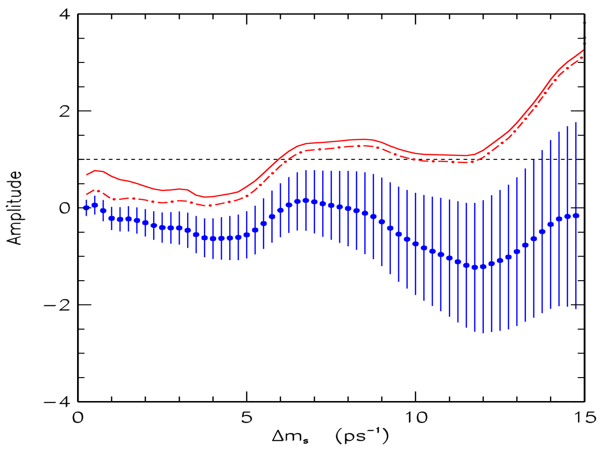

Figure 4. Measured amplitude as a function of Δm_s.

4. $\sin 2\beta$ FROM $B^0 \to J/\psi K^0_S$

CP violation is expected to manifest itself in the B^0 system as an asymmetry in particle decay rate versus antiparticle decay rate to charge-conjugate final states such as $J/\psi K^0_S$:

$$A_{CP} = \frac{N(\overline{B}^0 \to J/\psi K^0_S) - N(B^0 \to J/\psi K^0_S)}{N(\overline{B}^0 \to J/\psi K^0_S) + N(B^0 \to J/\psi K^0_S)}$$

where $N(\overline{B}^0 \to J/\psi K_S^0)$ is the number of mesons decaying to $J/\psi K_S^0$ that were produced as $\overline{B^0}$ and $N(B^0 \to J/\psi K_S^0)$ is the number of mesons decaying to $J/\psi K_S^0$ that were produced as B^0. In the Standard Model, the CP asymmetry in this decay mode is proportional to $\sin 2\beta$: $A_{CP}(t) = \sin 2\beta \sin(\Delta m_d t)$, where t is the proper decay time of the B^0 meson.

Candidate events for $B^0/\overline{B^0} \to J/\psi K_S^0$ were reconstructed by combining $J/\psi \to \mu^+\mu^-$ from a dimuon trigger sample with $K_S^0 \to \pi^+\pi^-$ [8]. In the case that both muons from the J/ψ decay were in the SVX coverage (SVX sample), precise B lifetime information was available and a more powerful time-dependent asymmetry analysis was used to extract $\sin 2\beta$. In the case that one or both muons were out of SVX coverage (non-SVX sample) and no precise lifetime information was available, a time-integrated asymmetry analysis was used. The fit to the mass distribution gives a $J/\psi K_S^0$ signal of 395 ± 31 events, as shown as in Figure 5.

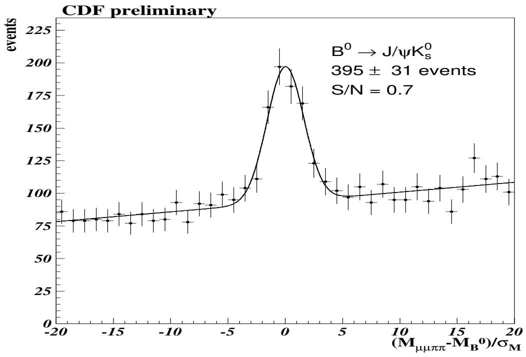

Figure 5. Nominal mass distribution for $J/\psi K_S^0$

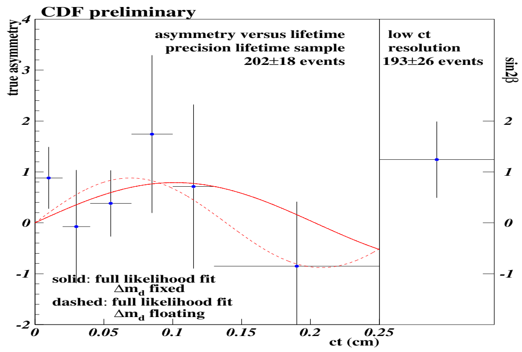

Figure 6. The true asymmetry ($\sin 2\beta$) as function of the proper decay length.

Table 1
Summary of tagging algorithms performance.

tag side	tag type	class	efficiency (%)	dilution (%)
same-side	same-side	μ_1, μ_2 in SVX	35.5 ± 3.7	16.6 ± 2.2
	same-side	μ_1 or μ_2 non-SVX	38.1 ± 3.9	17.4 ± 3.6
opposite side	soft lepton	all events	5.6 ± 1.8	62.5 ± 14.6
	jet charge	all events	40.2 ± 3.9	23.5 ± 6.9

Three tagging algorithms, SLT, JetQ, and SST, were applied to the $B^0/\overline{B^0} \to J/\psi K_S^0$ candidates to maximum the statistical power of the sample. The SLT and JetQ algorithms are very similar to the ones used in the $B^0 - \overline{B^0}$ mixing analysis, and the same algorithms were applied to both the SVX and non-SVX samples. An SST algorithm similar to that used for the $B^0 - \overline{B^0}$ mixing analysis was used on the SVX sample. Appropriate modifications have been made to validate and apply the SST tag to the non-SVX samples. The tagging dilutions and efficiencies, determined with a sample of 1000 $B^\pm \to J/\psi K^\pm$ decays and 40,000 non-prompt $J/\psi \to \mu^+\mu^-$ decays, are listed in Table 1. Tagging information is obtained for 80% of the events in $B^0/\overline{B^0} \to J/\psi K^0_S$. Each tagged event can have one or two tags. Since lepton tagging has much higher dilution than the jet charge tagging , the correlation between lepton and jet-charge tags was avoided by dropping the JetQ tag if there was a SLT tag. For double-tagged events, the correlation between the tags must be taken into account. If the tag result for an event by algorithm-i is S_i, where $S_i = +1, -1$ for B^0 and $\overline{B^0}$, then the effective dilution for two combined tags is $D_{ij} = |S_iD_i + S_jD_j|/(1 + S_iS_jD_iD_j)$. Taking into account single and double tags, a combined effective tagging efficiency $\epsilon D^2 = 6.3 \pm 1.7\%$ was obtained.

An unbinned maximum likelihood fit was used to extract $\sin 2\beta$. The fit includes the SVX and non-SVX samples and treats the decay length uncertainty and dilutions appropriately. The result for $\sin 2\beta$ is shown in in Figure 7. The left side of Figure 6 shows the asymmetry versus lifetime from the SVX sample. The solid curve shows the full likelihood fit with Δm_d fixed to the world average, and the dashed curve shows the fit with Δm_d floated. The point in the right side of the figure is the value of $\sin 2\beta$ obtained from the non-SVX sample. From the fit, we obtained a direct measurement of the CP violation parameter: $\sin 2\beta = 0.79 \pm 0.39 \pm 0.16$, where the first error is statistical and the second is systematic. The systematic error arises almost entirely from the determination of the dilution parameters with the limited sample of $B^\pm$ samples. Using this result, a 93% confidence interval of $0 < \sin 2\beta < 1.0$ is obtained using the most frequent approach advocated by Feldman and Cousins [9]. Figure 7 shows constraints on the $\rho - \eta$ values using the β values derived from this CDF $\sin 2\beta$ measurement, compared with the indirect constrains [10] from other CKM measurements.

5. SUMMARY AND RUN II PROSPECTS

Measurements of $B^0 - \overline{B^0}$ and $B^0_s - \overline{B^0_s}$ mixing and the CP violation parameter $\sin 2\beta$ provide important constraints on the CKM matrix. CDF in Run I demonstrated its ability to play a key role in these measurements. We have a precise measurement of the $B^0 - \overline{B^0}$ mixing parameter $\Delta m_d = 0.495 \pm 0.026 \pm 0.025$ ps^{-1} and a competitive limit on the $B^0_s - \overline{B^0_s}$ mixing parameter $\Delta m_s > 5.8$. We have a first indication of CP violation in the B^0 system from a measurement of $\sin 2\beta = 0.79 \pm 0.39 \pm 0.16$ using 400 $B^0/\overline{B^0} \to J/\psi K^0_S$ events.

We are upgrading our detector to fit into the Tevatron Run II environment and to improve tracking and particle identification capability. We will have a longer SVX II detector with five double sided silicon layers. We will have Intermediate Silicon Layers (ISL) to provide forward tracking in the region of $|\eta| < 2$. We will have a faster tracking chamber with stronger stereo capability. To reduce effects from multiple scattering, a silicon layer (L00) very close to the beam pipe is being built. The TOF system [11], which has a much improved $K - \pi$ separation ability as shown in Figure 8, is being added to the CDF system. We expect an increased flavor tagging efficiency from $\epsilon D^2 \approx 6.7\%$

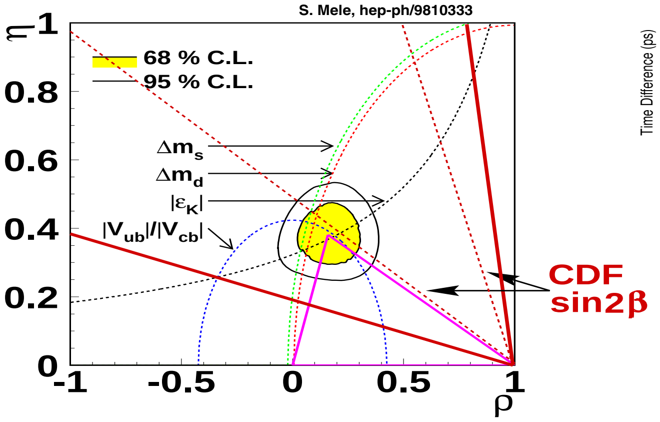

Figure 7. The measurement of $\sin 2\beta$ translates into two results (dotted lines) and one sigma bound (solid lines) on β. One sigma constrains (shaded area) from indirect measurements is also shown.

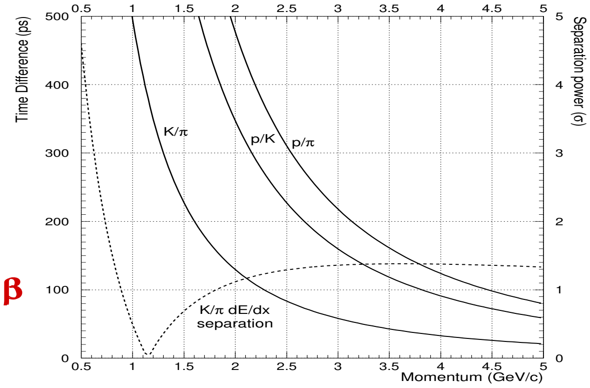

Figure 8. Time difference as function of momentum between K/π, p/π and K/p for the CDF TOF system. The dashed line show the K/π separation power from the dE/dx using Central Outer Tracker.

in Run I to 9.1% in Run II with improved tracking and particle identification capability. For a total luminosity of 2 fb^{-1} from Run II, 10,000 events of $B^0/\overline{B^0} \to J/\psi K^0_S$ and 20,000 events of $B_s \to D_s\pi + D_s\pi\pi\pi$ will be available. An improved measurement with reduced error of 0.08 on $\sin 2\beta$ and a 5σ significance observation of $B^0_s - \overline{B^0_s}$ mixing, if $x_s \equiv \Delta m_s \tau < 42$, are within CDF's reach in Run II. We are looking forward to an exciting future where CDF at the Tevatron will play a crucial, unique role in the determination of the CKM matrix.

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