

The measurement of $\sin(2\beta)$

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ABSTRACT: Since the first observation in 1964, CP violation remains one of the most elusive aspects of the standard model. The CDF collaboration has reported the first evidence of CP violation in the B system using the world's largest sample of $B \rightarrow J/\psi K_S^0$ decays. The direct measurement of $\sin(2\beta) = 0.79_{-0.44}^{+0.41}$ (combined statistical and systematic error) agrees with the standard model predictions. New data collected from the B-factories and from the upgraded experiments at the Tevatron should allow a more precise measurement of $\sin 2\beta$ in the near future.

1. Introduction

The violation of invariance under charge-conjugation and parity (CP) transformations was first observed in the neutral Kaon system in 1964 [1]. In the standard model with three generations of fermions, CP violation arises from a single complex phase in the mixing matrix for quarks. The CKM matrix, V_{CKM} , is a unitary matrix [2] that transforms the mass eigenstates to the weak eigenstates:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

It is useful to express the CKM matrix in terms of the four Wolfenstein [3] parameters: λ , A , ρ and η . The sine of the Cabibbo angle, λ , is measured in semileptonic kaon decays, $\lambda = |V_{us}| = 0.2196 \pm 0.0023$, and plays the role of an expansion parameter. A can be determined in $b \rightarrow c$ decays since $A = V_{cb}/\lambda^2$. Only λ and A are measured precisely while η and ρ must still be determined. The parameter η represents the CP-violating phase and must be different from zero to accommodate CP violation in the standard model.

The condition of unitarity between the first and third columns:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

can be represented geometrically as a triangle in the ρ - η plane. The apex of the triangle has coordinates (ρ, η) as shown in figure 1. The three angles of the unitarity triangle are :

$$\alpha = \arg \left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right]$$

$$\beta = \arg \left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right]$$

$$\gamma = \arg \left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right]$$

Measurements of weak decays of B hadrons determine the magnitudes of the three sides while CP asymmetries in B meson decays determine the three angles. The goal of B physics in the next decade is to measure both the sides and angles of the unitarity triangle and test consistency within the standard model.

2. CP violation in the neutral B meson system

The neutral b meson system, $B^0(\bar{b}d)$, is not an eigenstate of CP. The standard phase space convention defines:

$$CP|B^0\rangle = -|\bar{B}^0\rangle$$

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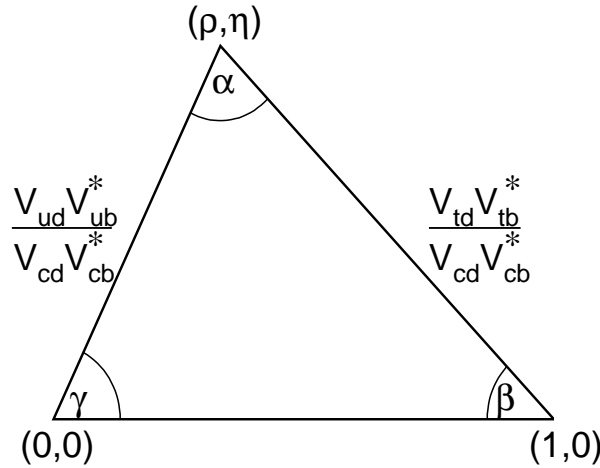


Figure 1: The unitary triangle in the complex $\rho - \eta$ plane.

Similarly to the neutral K mesons, the mass eigenstates of the neutral B system are not the flavor eigenstates. The mass eigenstates are called heavy and light and they are denoted by B_H and B_L :

$$\begin{aligned} |B_L\rangle &= p|B^0\rangle + q|\bar{B}^0\rangle \\ |B_H\rangle &= p|B^0\rangle - q|\bar{B}^0\rangle \end{aligned}$$

with $\Delta m_d = M_H - M_L$ and $\Delta\Gamma = \Gamma_H - \Gamma_L$ the mass and width difference respectively. While the two neutral K mesons have very different lifetimes, the lifetime difference in the neutral B system is negligible. Therefore the flavour of the B meson at production must be determined by tagging.

The possible manifestation of CP violation can be classified according to three main categories: CP violation in the decays, CP violation in mixing and CP violation in the interference between decays with and without mixing.

CP violation in the decays can occur both in charged and neutral decays when the amplitude for a decay and its CP conjugate mode have different magnitude. This is often called direct CP violation and can be studied by comparing the decay rates $\Gamma(B \rightarrow f)$ with $\Gamma(\bar{B} \rightarrow \bar{f})$, where f and \bar{f} are CP-conjugate final states. If A and \bar{A} are the amplitudes for the process $B \rightarrow f$ and $\bar{B} \rightarrow \bar{f}$, we have CP violation in the decay if

$$\left| \frac{A}{\bar{A}} \right| \neq 1.$$

If this condition is met the CP asymmetry A_{CP} can be defined as :

$$A_{CP} = \frac{\Gamma(\bar{B} \rightarrow \bar{f}) - \Gamma(B \rightarrow f)}{\Gamma(\bar{B} \rightarrow \bar{f}) + \Gamma(B \rightarrow f)}$$

Since in the standard model the amplitude for a decay and its CP conjugate differ at most by a phase factor, we can observe CP violating effects only if there are at least two interfering amplitudes. In the case of the decay $\bar{B}^0 \rightarrow K^-\pi^+$ such interference can be provided by the tree and the penguin contributions.

CP violation in mixing can occur when two neutral mass eigenstates cannot be chosen to be CP eigenstates. This is also called indirect CP violation and it is measured by the parameter ϵ in kaon decays. Mixing provides an interfering amplitude that can potentially produce CP violation. For example, CP violation in the kaon system is largely due to mixing. The condition for CP violation in mixing is that

$$\left| \frac{q}{p} \right| \neq 1$$

In the neutral B system, indirect CP violation is expected to be small, of $\mathcal{O}(10^{-4})$.

CP violation in the interference between decays with and without mixing can occur when there are CP final states, f_{CP} , that are common to B^0 and \bar{B}^0 . In these cases the process $B^0 \rightarrow \bar{B}^0 \rightarrow f_{CP}$ can interfere with the direct decay $B^0 \rightarrow f_{CP}$. Let us assume that the final

state f_{CP} is an eigenstate of CP with eigenvalues $\eta_{CP} = \pm 1$. CP violation produces a non exponential decay probability:

$$\begin{aligned} |A(B^0(t) \rightarrow f_{CP})|^2 &\approx \\ &e^{-\Gamma t} [1 - \eta_{CP}(f) \sin(\Delta m_d t) \sin 2(\phi_M - \phi_D)] \\ |A(\bar{B}^0(t) \rightarrow f_{CP})|^2 &\approx \\ &e^{-\Gamma t} [1 + \eta_{CP}(f) \sin(\Delta m_d t) \sin 2(\phi_M - \phi_D)] \end{aligned}$$

where ϕ_M and ϕ_D are the mixing phase and the direct weak phase respectively.

The CP asymmetry as a function of time is defined as:

$$\begin{aligned} A_{CP}(t) &= \frac{\frac{d\Gamma}{dt}(\bar{B}^0 \rightarrow f_{CP}) - \frac{d\Gamma}{dt}(B^0 \rightarrow f_{CP})}{\frac{d\Gamma}{dt}(\bar{B}^0 \rightarrow f_{CP}) + \frac{d\Gamma}{dt}(B^0 \rightarrow f_{CP})} \\ &= \eta_{CP}(f) \sin 2(\phi_M - \phi_D) \sin \Delta m_d t \end{aligned}$$

We can also compute the time integrated asymmetry as:

$$A_{CP} = \eta_{CP}(f) \frac{x_d}{1 + x_d^2} \sin 2(\phi_M - \phi_D)$$

where $x_d = \Delta m_d / \tau(B^0) = 0.732 \pm 0.032$ [6] is the $B^0 - \bar{B}^0$ mixing parameter. Such a time integrated asymmetry can be measured in a hadron collider where the B mesons are produced uncorrelated. At a B-factory operating at the $\Upsilon(4S)$ the B mesons are produced as a B^0 and a \bar{B}^0 in a correlated $C=-1$ quantum state. Therefore, the time integrated CP asymmetry vanishes since the two B mesons evolve coherently; until one of them decays, we always have a B^0 and a \bar{B}^0 . At a B-factory operating at the $\Upsilon(4S)$, it is crucial to measure the CP asymmetry as a function of the time difference, $\delta t = t_{CP} - t_{tag}$, between the B decaying into a CP eigenstate and the tagged B final state. At the Tevatron the B mesons are produced incoherently and the asymmetry can be measured either as a time dependent or a time integrated quantity. The time dependent analysis is more powerful. First, there is more statistical power in the time dependent asymmetry; decays at low lifetime exhibit a small asymmetry because there has not been enough time for mixing to generate the interference which leads to CP violation. In fact $A_{CP}(t)$ has a maximum at $t \approx 2.2$ lifetimes. Moreover, a substantial fraction of the combinatorial background occurs at short proper time.

3. Determination of $\sin 2\beta$

The angle β can be determined by studying different types of b decay modes. The best determination of $\sin 2\beta$ can be achieved by studying color suppressed decays such as $b \rightarrow c\bar{c}s$. The golden mode is the decay $B^0/\bar{B}^0 \rightarrow J/\psi K_s^0$. The dominant penguin contribution has the same weak phase as the tree amplitude [11]. The only term with a different weak phase is suppressed by $\mathcal{O}(\lambda^2)$. Therefore the extraction of β from the measurement of the asymmetry in $B^0/\bar{B}^0 \rightarrow J/\psi K_s^0$ suffers negligible theoretical uncertainties.

Cabibbo suppressed modes such as $b \rightarrow c\bar{c}d$ can also be used to determine $\sin 2\beta$. The tree amplitude for $B^0/\bar{B}^0 \rightarrow D\bar{D}$ is proportional to $-\sin 2\beta$. The contribution of penguin graphs with different weak phases is potentially significant in these decay modes since the tree contribution is Cabibbo suppressed. A determination of the possible phase shift due to the penguin contribution will be highly model dependent and have large theoretical uncertainties since it will be dominated by low energy hadronic effects. Progress on measuring β through these decays will be possible only by comparing a variety of final states.

In penguin dominated modes such as $b \rightarrow s\bar{s}s$ or $b \rightarrow d\bar{d}s$ the tree contribution is absent or is both Cabibbo and color suppressed. Predictions can be obtained for a few modes such as $B \rightarrow \phi K_s^0$ but the theoretical status is unclear.

At hadron colliders the golden mode $B \rightarrow J/\psi K_s^0$ is especially interesting experimentally because the $J/\psi \rightarrow \mu^+ \mu^-$ decay mode gives a unique signature and allows for a powerful trigger. Therefore the decay $B^0 \rightarrow J/\psi K_s^0$ can be reconstructed with an excellent signal to background ratio. The interference of the direct decays $B^0 \rightarrow J/\psi K_s^0$ versus $B^0 \rightarrow \bar{B}^0 \rightarrow J/\psi K_s^0$ gives rise to a CP asymmetry that measures $\sin 2\beta$:

$$A_{CP}(t) = \frac{\bar{B}^0(t) - B^0(t)}{\bar{B}^0(t) + B^0(t)} = \sin 2\beta \sin \Delta m_d t$$

The time integrated asymmetry is:

$$A_{CP} = \frac{x_d}{1 + x_d^2} \sin 2\beta$$

To measure the asymmetry we have to identify the flavor of the B meson at the time of production. The tagging algorithms are evaluated in terms of efficiency ϵ for assigning a flavor tag and the probability that the tag is correct. The quality of the tag is evaluated by defining the tagging dilution as $D = (N_R - N_W)/(N_R + N_W)$ where $N_R(N_W)$ is the number of right (wrong) tags. The observed asymmetry is reduced with respect to the true asymmetry by the dilution D : $A_{CP}^{obs} = DA_{CP}$. Therefore, the maximum sensitivity can be achieved when the dilution is large. A perfect tagging algorithm will have a dilution $D = 1$. The statistical uncertainty on $\sin 2\beta$ is inversely proportional to $\sqrt{\epsilon D^2}$ and to $\sqrt{S^2/(S + N_{bck})}$ where S is the number of signal events and N_{bck} is the number of background events within three standard deviations of the B mass. Therefore the data sample should be chosen to maximize the signal and minimize the background.

Searches for a CP violating asymmetry using $J/\psi K_S^0$ samples have been performed by the OPAL [4] and by the CDF [10] collaborations which have reported $\sin 2\beta = 3.8_{-2.0}^{+1.8} \pm 0.5$ and $\sin 2\beta = 1.8 \pm 1.1 \pm 0.3$ respectively.

By combining indirect measurements it is possible to constrain the value of $\sin 2\beta$. Currently several analysis find that the standard model prefers large positive values of $\sin 2\beta$. One recent global fit finds $\sin 2\beta = 0.75 \pm 0.09$ [5].

4. The CDF Detector

The CDF detector is described in detail elsewhere [7]. The measurement of the CP asymmetry requires reconstruction of the decay mode $B^0/\bar{B}^0 \rightarrow J/\psi K_S^0$ with good signal over background, the measurement of the proper time t , and the determination of the B flavor at production. The crucial detector features to achieve these requirements include a four layer silicon microstrip detector (SVX), a large volume drift chamber, and excellent electron and muon identification. The SVX measures the impact parameter, d , of charged tracks with a resolution that allows the precise determination of the B meson proper decay time t . The impact parameter resolution for charged tracks is $\sigma_d = (13 + 40/P_T)$

μm , where P_T is the magnitude of the component of the momentum of the track transverse to the beam line in units of GeV/c.

The CTC has a radius of 1.4 m and is operating in a 1.4 T axial magnetic B field. The CTC provides excellent track reconstruction efficiency and good momentum resolution, $(\delta P_T/P_T)^2 = (0.0066)^2 \oplus (0.0009)^2$, which allows B meson reconstruction with a mass resolution of $\approx 10 \text{ MeV}/c^2$. Electron (e) and (μ) detectors in the central rapidity region ($|y| < 1$) allow B meson detection and provide triggers using semileptonic B decays or $B \rightarrow J/\psi X$ and $J/\psi \rightarrow \mu^+\mu^-$.

5. The CDF Data Sample

CDF exploits the large B cross section at the Tevatron to obtain a large sample of $J/\psi K_S^0$ decays to measure $\sin 2\beta$. The analysis reported here uses the entire Run I data sample of 110 pb^{-1} and is described in detail in [8]. The J/ψ sample is identified by selecting two oppositely charged muon candidates, each with $P_t > 1.4 \text{ GeV}/c$. A J/ψ candidate is defined as a $\mu^+\mu^-$ pair within $\pm 5\sigma$ of the world average mass of $3.097 \text{ GeV}/c^2$, where σ is the mass uncertainty for each event. The K_S^0 candidates are found by matching oppositely charged tracks assumed to be pions. The K_S^0 candidates are required to have $P_T(K_S^0) > 700 \text{ MeV}/c$ and to travel a significant distance $L_{xy} > 5\sigma$ from the primary vertex, where L_{xy} is the 2-dimensional flight distance in the plane perpendicular to the direction of the beam. The $\mu^+\mu^-$ and $\pi^+\pi^-$ are constrained to the appropriate masses and separate decay vertices. A K_S^0 candidate is constrained to point back to the B^0 meson decay point, and the B^0 meson candidate is constrained to point back to the primary vertex. In order to further improve the signal-to-background ratio, B candidates are required to have $P_T(B)$ above $4.5 \text{ GeV}/c$.

The data are divided into two samples which are called SVX and the non-SVX samples. The SVX sample requires both muon candidates to be well measured by the silicon vertex detectors. The two dimensional flight distance, measured in the plane perpendicular to the beam, can be used to calculate the proper decay time ct , which is the projection of the displacement along the

B momentum. The B candidates in this sample have a precise proper decay time resolution of $\sigma_{ct} \approx 60 \mu\text{m}$. The non-SVX sample contains events in which one or both of the muon candidates are not measured in the silicon vertex detector. B candidates in this sample have low proper decay time resolution of $\sigma_{ct} \approx 300 - 900 \mu\text{m}$. The lifetime information for both the SVX and the non-SVX B candidates is used to evaluate the asymmetry as a function of proper time in order to reduce the statistical uncertainty in $\sin 2\beta$.

The $J/\psi K_S^0$ mass from the vertex and mass-constrained fit is used to define the normalized mass $M_N = (m_{\mu\mu\pi\pi} - M_0)/\sigma_{fit}$. The uncertainty in the fit, σ_{fit} , is typically $\approx 10 \text{ MeV}/c^2$, and the world average neutral B^0 mass, M_0 is $5.2792 \text{ GeV}/c^2$. The normalized mass distributions for the SVX and non-SVX samples are shown in figure 2. The SVX sample and the non-SVX sample contain 202 ± 18 and 193 ± 26 events respectively. The event yields are extracted from an unbinned likelihood fit. The total sample of $J/\psi K_S^0$ is 395 ± 26 events is used in this analysis. The SVX subsample was used for a previous measurement of $\sin 2\beta$ [10].

6. Flavor tagging

In order to observe the CP asymmetry, A_{CP} , we must determine the b flavour at production by establishing whether the B meson contains a b or \bar{b} quark. Since the error on $\sin 2\beta$ depends on $1/\sqrt{\epsilon D^2 N}$, we can improve the statistical reach by using several taggers. CDF has studied three tagging algorithms to measure Δm_d in $B^0 - \bar{B}^0$ oscillations. CDF measures $\Delta m_d = 0.495 \pm 0.026 \pm 0.025 \text{ ps}^{-1}$, which agrees well with the world average[6]. Two are opposite side tag algorithms and one is a same side tag algorithm. The dilution parameters for all tagging algorithms are measured on calibration samples. At the Tevatron the strong interaction creates $b\bar{b}$ pairs at sufficiently high energy that the B mesons are largely uncorrelated. For example, the b quark could hadronize as a \bar{B}^0 while the \bar{b} could hadronize as a B^+ , B^0 , or B_s^0 meson. Therefore we can use a sample of 998 ± 51 $B^\pm \rightarrow J/\psi K^\pm$ decays to measure the tagging

dilutions for the opposite side algorithms. The performance of the same side tagging methods is evaluated by tagging $B \rightarrow \nu \ell D^{(*)}$ decays and by measuring the time dependence of $B^0 \bar{B}^0$ oscillations in this high statistics sample ($\approx 6,000$ events) and in a lower statistics sample of $B \rightarrow J/\psi K^{*0}$ (≈ 450 events). In the mixing case, the measured asymmetry A_{mix} is given by:

$$\begin{aligned} A_{mix}(t) &= \frac{N_{unmixed}(t) - N_{mixed}(t)}{N_{unmixed}(t) + N_{mixed}(t)} \\ &= D \cos(\Delta m_d t) \end{aligned}$$

where $N_{unmixed}(t)$ and $N_{mixed}(t)$ are the number of candidates with same or opposite b flavor. CDF has used the measurements of $B^0 - \bar{B}^0$ mixing to determine D for the three different tagging methods used in this analysis.

The same side tagging method or SST [13] relies on the correlation between the B flavor and the charge of a nearby particle. Such a correlation can arise from the fragmentation processes which form a B meson from a \bar{b} quark as illustrated in figure 3 and from the decay of an excited B meson state (B^{**}). In the fragmentation a \bar{b} quark forming a B^0 can combine with a d in the hadronization leaving a \bar{d} which can form a π^+ with a u quark from the sea. The excited B state will decay $B^{**+} \rightarrow B^{(*)0} \pi^+$. Therefore in both cases a B^0 (\bar{B}^0) meson is associated with a positive (negative) particle respectively. The effectiveness of this method has been demonstrated by tagging $B \rightarrow \nu \ell D^{(*)}$ decays and observing the time dependence of the $B^0 - \bar{B}^0$ oscillations. The SST method selects a single charged particle as a flavor tag from those within an $\eta - \phi$ cone of half-angle 0.7 around the B direction. The pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$; θ is the polar angle relative to the proton beam direction, and ϕ is the azimuthal angle around the beam line. The tag must have $P_T(\text{tag}) > 400 \text{ MeV}/c$. It must be reconstructed in the SVX and have impact parameter within $3 \sigma_d$ of the primary vertex, where σ_d is the error on the impact parameter. If there is more than one track candidate, we select as the flavor tag the one with the smallest P_T^{rel} , where P_T^{rel} is the component of the track momentum with respect to the momentum of the combined B+track system. The dilution of the SST sample was measured, us-

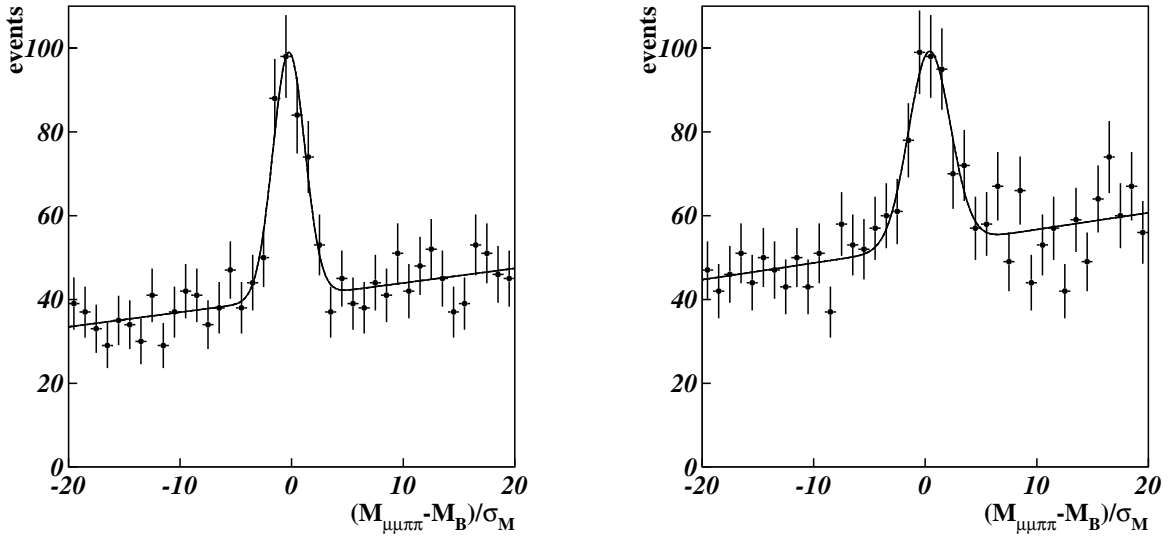


Figure 2: Left: Normalized mass for the $J/\psi K_S^0$ candidates where both muons have high precision decay length measurements in the silicon vertex detector. Right: Normalized mass for the $J/\psi K_S^0$ where either one or both muons are not measured in the silicon vertex detector.

ing the SVX sample, to be $D = (16.6 \pm 2.2) \%$. This dilution was obtained by measuring D in the large $B \rightarrow \ell D^{(*)} X$ data sample used in the mixing analysis. A Monte Carlo simulation was used to extrapolate from the momentum range of B mesons in semileptonic decays, which have an average P_T of 21 GeV/c, to the lower B momentum of the $B \rightarrow J/\psi K_S^0$ sample with an average P_T of 12 GeV/c. When using the non-SVX sample, the SST tagging algorithm is modified by dropping the SVX information for all candidate tagging tracks and therefore increasing the geometric acceptance. A dilution scale factor f_D is defined by $D_{non-SVX} = f_D D_{SVX}$. The scale factor is measured in the $B^\pm \rightarrow J/\psi K^\pm$ sample to be 1.05 ± 0.17 , yielding a dilution in the non-SVX sample $D = (17.4 \pm 3.6) \%$.

The opposite side tagging algorithms identify the flavor of the *opposite* B in the event at the time of production. CDF employs two opposite side tagging methods: soft lepton tag (SLT) and jet-charge tag (JETQ).

The soft lepton tag [14] associates the charge of the lepton (e or μ) from semileptonic decays with the flavor of the parent B meson as $b \rightarrow \ell^-$. Since we are tagging the opposite B meson, its flavor is anti-correlated with the flavor of the B-

meson that decays to $J/\psi K_S^0$. Hence a $\ell^- (\ell^+)$ tags a $B^0 (\bar{B}^0)$ decaying as $B \rightarrow J/\psi K_S^0$. A soft muon tag is defined as an identified muon with $P_T > 2$ GeV/c; the muon selection is similar to that for $J/\psi \rightarrow \mu^+ \mu^-$. A soft electron tag is defined as a charged track reconstructed in the Central Tracking Chamber (CTC) with $P_T > 1$ GeV/c and extrapolated into the electromagnetic calorimeter. The position information from proportional chambers in the central calorimeter is required to match the CTC track, and the shower profile and pulse height must be consistent with an electron. The electron candidate's CTC track must have a dE/dx deposition consistent with an electron. A dilution of the SLT tagging method is measured by applying the SLT algorithm to the $B^\pm \rightarrow J/\psi K^\pm$ data sample. We find $D = (62.5 \pm 14.6) \%$.

The other opposite side method, "Jet charge" or JETQ, tags the b flavor by measuring the average charge of the opposite side jet. If a soft lepton is not found we calculate Q_{jet} as:

$$Q_{jet} = \frac{\sum_i q_i P_{T_i} (2 - (T_p)_i)}{\sum_i P_{T_i} (2 - (T_p)_i)}$$

where q_i and P_{T_i} are the charge and transverse momentum of track i in the jet. The quantity T_p is the probability that track i originated from

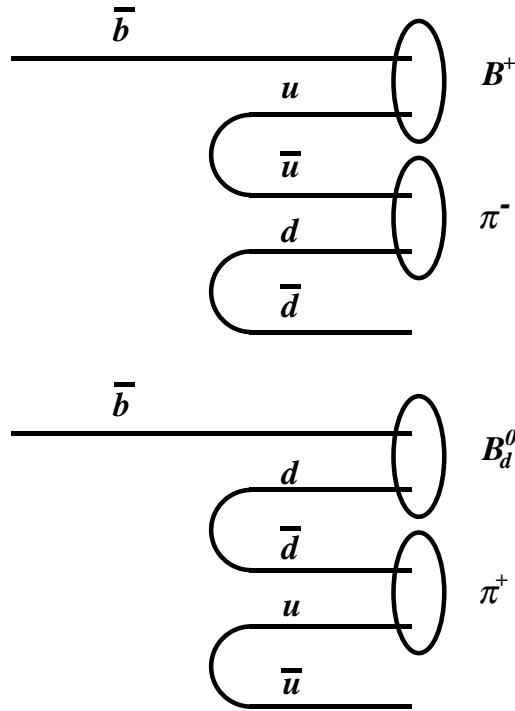


Figure 3: The same side flavour tag method is based on the correlation between the b flavor and the charge of particles produced in the b quark fragmentation.

the $p\bar{p}$ interaction point. Tracks displaced from the primary vertex are characterized by $T_P \approx 0$. Therefore, displaced tracks from B decays will have a larger weight in the sum than tracks from the primary interaction. For b quark jets, the jet charge has on average the same sign as the b quark charge. The algorithm was optimized by maximizing ϵD^2 on a sample of $B^\pm \rightarrow J/\psi K^\pm$ events generated by a Monte Carlo program. The jet is formed by clustering charged tracks with $P_T > 0.40$ GeV/c around a seed track of $P_T > 1.75$ GeV/c until the mass of the cluster is approximately equal to the mass of the B meson. Tracks within $\Delta R < 0.7$ are excluded to avoid overlap with SST tags. The B^0 meson decay products are explicitly excluded from the jet. If several jet candidates are found, we select the cluster which is most likely to be a b jet based on impact parameter and cluster transverse momentum. A B^0 (\bar{B}^0) is selected by $Q_{jet} < -0.2$ (> 0.2). If the jet charge $|Q_{jet}| < 0.2$, then the jet is considered untagged. The dilution $D =$

$(23.5 \pm 6.9) \%$ is found by applying the JETQ algorithm to the $B^\pm \rightarrow J/\psi K^\pm$ data sample.

Each event can be tagged by two tagging algorithms, one same side and one opposite side. We use the SLT if both JETQ and SLT tags are present to avoid correlations between the two opposite side tagging algorithms. A soft lepton tag SLT can still be used as the SST track. This introduces a small overlap between the two tagging algorithms which effects only three events and does not change the final result.

A positive (+ tag) is defined as the tag of a \bar{b} quark (B^0 meson). A negative (-tag) is defined as the tag of a b quark (\bar{B}^0 meson). A null (0 tag) corresponds to an event where the flavor of the B meson was not identified. The efficiency and dilution of the tagging methods must be generalized to take into account possible detector asymmetries. For example, the CDF tracking chamber has a 1% bias due to the tilted cell geometry that favors the reconstruction of positive charge tracks at low transverse momentum. To allow for

Tagging method	ϵ	Dilution
SST SVX	35.5 ± 3.7	16.6 ± 2.2
SST non-SVX	38.1 ± 3.9	17.4 ± 3.6
SLT all	5.6 ± 1.8	62.5 ± 14.6
JETQ all	40.2 ± 3.9	23.5 ± 6.9

Table 1: Summary of the tagging algorithms performance. All numbers are in percent. The efficiencies are obtained from the $B \rightarrow J/\psi K_S^0$ sample. The dilution parameters are derived from the $B^\pm \rightarrow J/\psi K^\pm$ sample

this asymmetry, we define $\epsilon_R^+(\epsilon_W^+)$ as the fraction of B meson of type + that will be tagged as + (-). The fraction ϵ_0^+ is the fraction of B meson of type + that are not tagged. We have six parameters that account for these asymmetries: ϵ_R^+ , ϵ_W^+ , ϵ_0^+ , ϵ_R^- , ϵ_W^- and ϵ_0^- , but only four are independent since by definition $\epsilon_R^+ + \epsilon_W^+ + \epsilon_0^+ = 1$ and $\epsilon_R^- + \epsilon_W^- + \epsilon_0^- = 1$.

The performances of the individual tagging methods are comparable as summarized in table 1. The three tagging methods are combined to reduce the uncertainty in the CP asymmetry. Since the soft lepton tagging has low efficiency but high dilution, the jet charge tagging information is dropped if there is a lepton tag. This avoids correlations between SST and JETQ. Therefore a neutral B is tagged by at most two methods. We combine two tagging algorithms by defining the dilution weighted tags $\mathcal{D}_i = q_i D_i$ where $q = 1, -1, 0$ for B^0 , \bar{B}^0 and untagged events respectively. The combined dilution is:

$$\mathcal{D}_{q_1 q_2} = \frac{\mathcal{D}_1 + \mathcal{D}_2}{1 + \mathcal{D}_1 \mathcal{D}_2}$$

and the combined efficiency is:

$$\epsilon_{q_1 q_2} = \epsilon_{q_1} \epsilon_{q_2} (1 + \mathcal{D}_1 \mathcal{D}_2)$$

If the tags agree, the effective dilution is increased while if they disagree, the effective dilution is decreased. If two perfect tagging algorithms give an opposite tagging charge q ($D_1 = D_2$ and $|\mathcal{D}_1| = 1$), then the effective dilution and the combined efficiency must be zero since by definition perfect tagging algorithms cannot disagree. The combined tagging power is $\epsilon D^2 = (6.3 \pm 1.7)$ %, and the efficiency for flavor tagging a $J/\psi K_S^0$ with a least one tag is ≈ 80 %.

7. The measurement of $\sin(2\beta)$

An unbinned likelihood fit is used to determine $\sin 2\beta$. The parameters in the fit can be described as a vector with 65 components. The value of $\sin(2\beta)$ is a free parameter of the fit while the remaining 64 parameters describe other features of the data. The likelihood function is described in detail in [8]. The likelihood function is the product $\prod_i P_i$ where i runs over all selected events and P_i is the probability distribution that an event is signal or background for the normalized mass, the lifetime and the flavor tag (q_1, q_2, q_3). There is a separate set of parameters for the SVX sample and the non-SVX sample but both are part of the same fit. The P_i assume that the events are signal or background, either prompt or long lived, and therefore the P_i contains three components P_S, P_P and P_L . The fit includes the effective dilution, the normalized mass and the lifetime. Each of the components is expressed as the product of a time-function (T_S, T_P, T_L), a mass-function (M_S, M_P, M_L), and the tagging efficiency ($\epsilon_S, \epsilon_P, \epsilon_L$). The time-function T_S has a dependence on the B lifetime and the mixing parameter. The B^0 lifetime τ and the mixing parameter Δm_d are constrained to the world averages: $\tau = (1.54 \pm 0.04)$ ps and $\Delta m_d = (0.464 \pm 0.018)\hbar$ ps $^{-1}$. The prompt J/ψ background is represented by a Gaussian which depends on the proper time and its uncertainty. The long lived background function T_L has positive and negative exponentials in time which represent positive and negative long-lived background. The positive long-lived background is from real B decays while the negative component is due to non-Gaussian tails in the lifetime resolution. The signal mass function M_S is a Gaussian while the prompt and long lived mass functions are linear in mass. The tagging efficiency function for the signal is constrained by the measurement of the tagging efficiencies and dilutions. The prompt and long-lived background functions, ϵ_P and ϵ_L , give the probability of obtaining the observed combination of tags for prompt and long-lived background events.

The fit yields $\sin(2\beta) = 0.79_{-0.44}^{+0.41}$ (*stat.* + *sys.*) The asymmetry is shown in figure 4 for the SVX and non-SVX events separately. The

asymmetry for the SVX events which have good ct resolution is shown as a function of the proper lifetime. The lifetime information for the non-SVX events is utilized in the fit but the time-integrated asymmetry is shown in figure 4 because the decay length information has low resolution. The data shown in figure 4 have been side-band subtracted. The curves displayed in the plot are the results of the full maximum likelihood fit using all the data. The uncertainty can be divided into statistical and systematic terms:

$$\sin(2\beta) = 0.79 \pm 0.39(\text{stat.}) \pm 0.16(\text{syst.})$$

The error is dominated by the statistical uncertainty. The systematic term is dominated by the uncertainty in the dilution parameters.

A scan of the likelihood function can be used to determine whether the CDF result supports $\sin(2\beta) > 0$. Using the Feldman-Cousins frequentist approach [12] we determine $0.0 < \sin 2\beta < 1$ at 93 % confidence level. The Bayesian method assumes a flat prior probability in $\sin(2\beta)$ and yields $\sin(2\beta) > 0$ at 95 % confidence level. Moreover if the true value of $\sin 2\beta$ is zero and a Gaussian error uncertainty 0.44 is assumed, the probability of measuring $\sin 2\beta > 0.79$ is 3.6 %. This

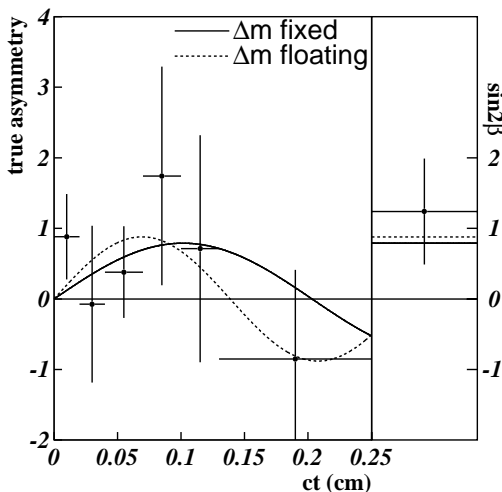


Figure 4: The true asymmetry as a function of time for $J/\psi K_S^0$ events. The data points are side-band subtracted and have been combined according to the effective dilutions for single and double tags. The time integrated asymmetry for non-SVX events are shown on the right.

is the first compelling evidence for CP violation in B meson decays.

Several checks were performed. We remove the constraint of Δm_d to the world average in the fit and measure $\sin 2\beta = 0.99_{-0.41}^{+0.44}$ and $\Delta m_d = 0.68 \pm 0.17 \text{ ps}^{-1}$. A simplified time-integrated measurement of the asymmetry yields $\sin 2\beta = 0.71 \pm 0.63$.

The same tagging analysis and fitting procedure was applied to a sample of $\approx 450 B^0 \rightarrow J/\psi K^{*0}$ events. The fit yields $\Delta m_d = 0.40 \pm 0.18 \text{ ps}^{-1}$ which is consistent with the world average $\Delta m_d = 0.464 \pm 0.018 \text{ ps}^{-1}$.

8. Summary and future prospects

The CDF measurement provides a first evidence for large CP asymmetries in the B^0 system. More precise measurements of $\sin 2\beta$ will soon be provided by the B-factories at SLAC and KEK which have recently started data taking. The CDF and D0 experiments at the Tevatron are expected to resume data taking with the upgraded Tevatron in March 2001. Run II should deliver a factor of 20 more luminosity than run I. Moreover the CDF and the D0 detectors will undergo major upgrades[15]. For CDF we project a data sample of 10,000 $J/\psi K_S^0$ events from dimuon triggers yielding an error on $\sin 2\beta$ of about ± 0.08 . CDF is considering adding a $J/\psi \rightarrow e^+e^-$ trigger which will increase the data sample by ≈ 50 %. A time of flight system which will improve flavor tagging has also been added to the run II upgrade. Moreover, the study of CP violation in B_s decays and the measurement of Δm_s will be unique to hadron colliders. Therefore, the Tevatron will continue to play a unique role in the testing of the CKM matrix.

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