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MEASUREMENT OF $B^0/\overline{B}^0 \to J/\psi K_S^0$ DECAY ASYMMETRY USING SAME-SIDE B-FLAVOR TAGGING

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We present a measurement of the time-dependent asymmetry in the rate for $\overline{B}^0$ versus B^0 decays to $J/\psi K_S^0$. The data sample consists of 198 ± 17 $B^0/\overline{B}^0$ decays collected by the CDF detector in $p\overline{p}$ collisions at the Fermilab Tevatron, where the initial b flavor has been determined by a same-side flavor tagging technique. This asymmetry is interpreted in the Standard Model as a measurement of the CP-violation parameter $\sin(2\beta)$. Our analysis results in $\sin(2\beta) = 1.8 \pm 1.1(stat) \pm 0.3(syst)$.

1 Introduction

Since its discovery over thirty years ago, CP violation has remained an elusive effect experimentally observed in only a few signatures among kaon decays. The fact that it lies at or near the heart of fundamental questions in physics—including not only questions of what lies beyond the Standard Model, but also such expansive questions as the origin of the matter-antimatter asymmetry of the universe—only intensifies the precise exploitation of known signatures as well as the search for its manifestations wherever they may be found.

A popular mechanism for explaining CP violation lies in the relationship between the weak and mass eigenstates of the different generations of quarks. This relationship is parameterized in the Standard Model with the unitary Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix, [1]

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}, \tag{1}$$

where d, s, and b are the mass eigenstates and d', s', and b' are the weak interaction eigenstates. With three generations, this matrix possesses a physical complex phase capable of accommodating CP violation. It is interesting that the original 1973 proposal of a third quark generation to explain CP violation predates by a year the unexpected discovery of the charmonium states which served to complete the *second* generation.

This article concerns the extension of the search for CP violation to the third generation, a topic which has engendered considerable experimental interest. One reason for such interest is that these measurements directly address the unitarity of the CKM matrix. For instance, one of the unitary constraints can be written as follows:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0. \tag{2}$$

This equation can be represented as a triangle in the complex plane; the measurement of enough angles and sides of this triangle, thus overconstraining its construction, constitutes a fundamental test of the Standard Model understanding of CP violation.

The present analysis concerns the measurement of the angle

$$\beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \tag{3}$$

which is accessible through the relative decay rates of B^0 and $\overline{B}^0$ to the common CP eigenstate $J/\psi K_S^0$. A potentially large time-dependent asymmetry, cleanly related to this angle, arises from the interference between the direct decay path (*e.g.*, $B^0 \to J/\psi K_S^0$) and the mixed decay path (*e.g.*, $B^0 \to \overline{B}^0 \to J/\psi K_S^0$),

$$\mathcal{A}_{CP} \equiv \frac{\overline{B}^0(t) - B^0(t)}{\overline{B}^0(t) + B^0(t)} = \sin(2\beta)\sin(\Delta m_d t), \tag{4}$$

where $B^0(t)$ and $\overline{B}^0(t)$ are the numbers of decays to $J/\psi K_S^0$ at proper time t given that the produced meson (at $t = 0$) was a B^0 or $\overline{B}^0$, respectively [2]. The effect of mixing enters through Δm_d, the mass difference between the two B^0 mass eigenstates. Indirect evidence, interpreted in the light of Standard Model constraints, imply $0.30 \leq \sin(2\beta) \leq 0.88$ at 95% C.L. [3]. Thus the direct measurement of $\sin(2\beta)$ also provides a test of the Standard Model. The OPAL collaboration has reported $\sin(2\beta) = 3.2^{+1.8}_{-2.0} \pm 0.5$, also using $B^0/\overline{B}^0 \to J/\psi K_S^0$ decays[4].

This article summarizes the CDF result, which may be found in [5]. Many analysis details may also be found in [6] and [7].

2 Data Sample

The sample of $B^0/\overline{B}^0 \to J/\psi K_S^0$ decays used in this analysis was collected by CDF at the Fermilab Tevatron $p\overline{p}$ collider operating at $\sqrt{s} = 1.8$ TeV. The candidates

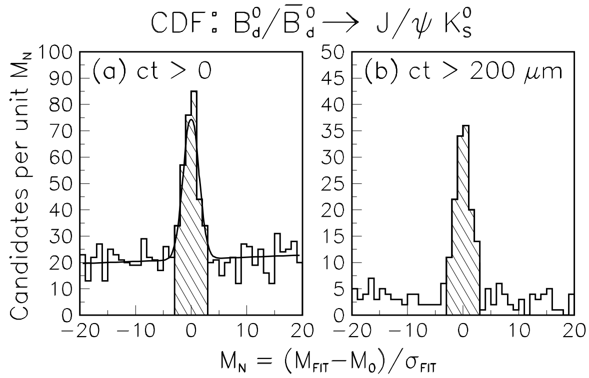

Figure 1: The normalized mass distribution of the $B^0/\overline{B}^0 \rightarrow J/\psi K_S^0$ candidates with $ct > 0$ and $ct > 200$ μm. The curve is the gaussian signal plus linear background from the full likelihood fit.

are selected from data taken in the 1992-96 run, during which CDF accumulated an integrated luminosity of 110 pb^{-1}. The J/ψ is reconstructed via its decay to two oppositely-charged muons. Both muon tracks are required to have been reconstructed in the silicon microstrip detector, thereby obtaining a precise measurement of its decay vertex. The other pairs of oppositely-charged tracks are then searched for those consistent with a $K_S^0 \rightarrow \pi^+\pi^-$ hypothesis, where the K_S^0 is significantly displaced from the J/ψ vertex, which is presumed to be the B decay vertex. Each K_S^0 candidate is then combined with the J/ψ candidate in a four-particle fit which also includes constraints pointing the K_S^0 back to the J/ψ vertex, and the $J/\psi K_S^0$ system as a whole to the primary interaction vertex. The mass calculated by the fit, M_{FIT}, has a typical resolution of $\sigma_{FIT} \sim 9$ MeV$/c^2$. The proper decay length, ct, has a typical resolution of ~ 50 μm.

Figure 1 (left) shows the distribution of positive-lifetime candidate events in normalized mass $M_N \equiv (M_{FIT} - M_0)/\sigma_{FIT}$, where M_0 is the central value of the B^0 mass peak (5.277 GeV$/c^2$). The ratio of signal to background in the signal region is approximately 1.6, where the background has been modeled as a linear distribution. The corresponding negative-lifetime distribution shows no discernible signal peak. Also shown in the plot is the result of the maximum likelihood fit, described later, which takes into account both mass and lifetime information for both positive and negative lifetimes. The fit yields 198 ± 17 mesons, with a gaussian RMS of 1.39 ± 0.11, which is similar to corresponding widths in other $B \rightarrow J/\psi K$ normalized mass distributions [6].

It is interesting to note that since the CP asymmetry varies in time as $\sin(\Delta m_d t)$, it reaches its maximum close to a proper decay length of 1000 μm. Hence it is instructive to examine the normalized mass distribution for long-lived events. Events with $ct > 200$ μm are shown in the right plot of Figure 1. The decay length requirement substantially reduces the background, and thus the measurement of the amplitude of the time-dependent CP asymmetry is largely insensitive to it.

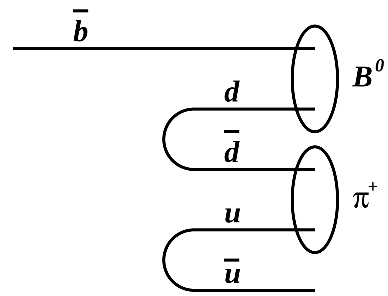

Figure 2: A simple picture of a $\overline{b}$ quark hadronizing into a B^0 meson. The "leading" pion is a π^-. The opposite correlation holds for a $\overline{B}^0$ meson.

3 Same-side Flavor Tagging

Once the sample of B's is obtained, the next step is to ascertain ("tag") whether they were B^0's or $\overline{B}^0$'s (their "flavor") when they were produced. The method used here is a "same-side" technique, *i.e.*, it aims to examine particles produced in association with the reconstructed B, in contrast with "opposite-side" techniques which attempt to identify the flavor of the other b hadron in order to infer the initial flavor of the first one. In particular, the present technique relies upon the correlation between the flavor of the reconstructed B and the charge of a nearby particle. This idea was first proposed in order to take advantage of the fact that the b quark may first hadronize to a B^{**} state, whose decay products would be the B^0 as well as the "tagging" pion [8]:

$$B^{**-} \rightarrow \overline{B}^0 \pi^- \quad (5)$$
$$B^{**+} \rightarrow B^0 \pi^+. \quad (6)$$

A $\overline{B}^0$ would thus be associated with a π^-, and a B^0 with a π^+. The same correlation is expected to exist between the B and the "leading" pion from fragmentation, as shown in Figure 2, and the present analysis utilizes both sources of correlation.

The criteria for the "nearby" track are as follows: the track must lie in an $\eta - \phi$ cone of half-angle 0.7 around the B direction, where $\eta \equiv -\ln[\tan(\theta/2)]$ is the pseudorapidity, θ is the polar angle relative to the proton beam direction, and ϕ is the azimuthal angle around the beam line. The tag must also have a minimum momentum transverse to the beam, p_T, of 400 MeV$/c$, and it should

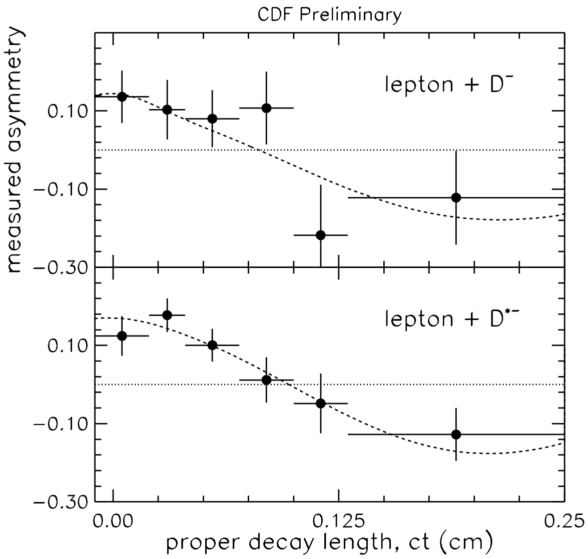

Figure 3: The measured tagging asymmetries as a function of ct for $B \to \ell D^{(*)-} X$ data (points). The dashed curve is the fit to the data, taking into account contributions to the sample from charged B's.

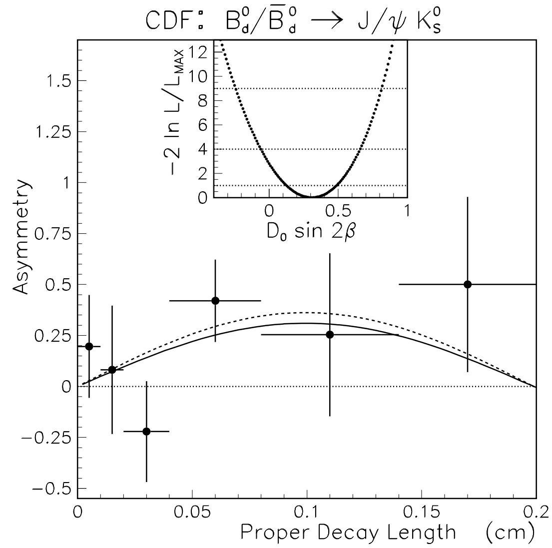

Figure 4: The sideband-subtracted tagging asymmetry as a function of the reconstructed $J/\psi K^0_S$ proper decay length (points). The dashed curve is the result of a simple binned χ^2 fit with the function $\mathcal{A}_0 \sin(\Delta m_d t)$. The solid curve is the likelihood fit result, for which the inset shows a scan through the log-likelihood function as $\mathcal{D}_0 \sin(2\beta)$ is varied about the best fit value.

be consistent with having come from the primary interaction vertex. If there is more than one "nearby" track, the one with the smallest p_T^{rel} is selected as the one tagging track, where p_T^{rel} is defined as the component of its momentum transverse to the momentum of the combined B+particle system.

The tagging algorithm, based as it is upon physical processes that happen before the B decay, should be applicable to other decay modes, and indeed, it has been applied successfully to the observation of $B^0 - \overline{B}^0$ time-dependent mixing and measurement of Δm_d using $B \to \ell D^{(*)} X$ decays [6,9], as shown in Figure 3. The algorithm has also been applied to a lower-statistics sample of $B^0 \to J/\psi K^{*0}$ decays, which are kinematically similar to the $J/\psi K^0_S$ events used in this analysis, yielding behavior consistent with mixing. The amplitude of the mixing oscillation in the $\ell D^{(*)}$ and $J/\psi K^{*0}$ data provides a direct measurement of the "dilution," $\mathcal{D}_0$, which is related to the "mistag" probability, $\mathcal{P}_{mistag}$:

$$\mathcal{D}_0 \equiv \frac{N_{RS} - N_{WS}}{N_{RS} + N_{WS}} = 1 - 2\mathcal{P}_{mistag} \tag{7}$$

where N_{RS} is the number of events with the correct sign correlation and N_{WS} the others. In the case of SST, $\mathcal{D}_0 \sim 20\%$ [6]. As noted below, knowledge of the dilution is necessary for the extraction of $\sin(2\beta)$.

4 Tagging Asymmetry

The above same-side tagging technique tags approximately 65% of the $B^0/\overline{B}^0 \to J/\psi K^0_S$ events, which is a typical efficiency for this tagging algorithm. Figure 4 shows the sideband-subtracted asymmetry in bins of ct, where the asymmetry is calculated by counting the sideband-subtracted number of positive tags, N^+, and negative tags, N^-, in each bin:

$$\mathcal{A}(ct) = \frac{N^-(ct) - N^+(ct)}{N^-(ct) + N^+(ct)}. \tag{8}$$

The signal region has been defined as $|M_N| < 3$, and the sideband region as $3 < |M_N| < 20$, for the purposes of counting. The events in the signal region generally prefer negative tags (*i.e.*, a positive asymmetry), whereas events in the sideband regions favor positive tags (negative asymmetry). As noted before, however, the signal purity is high at large ct, and the sideband subtraction is a correspondingly small effect.

Two fits are shown in Figure 4. The dashed curve gives the results of a simple χ^2 fit of the function $\mathcal{A}_0 \sin(\Delta m_d t)$ to the binned asymmetries, where Δm_d has been fixed to its 1996 world-averaged [10] value of $0.474\ \text{ps}^{-1}$. In the absence of other charge asymmetries in the tagging, the amplitude, $\mathcal{A}_0 = 0.36 \pm 0.19$, measures $\mathcal{D}_0 \sin(2\beta)$. The amplitude of the time-dependent asymmetry is dominated by the asymmetries at large ct.

The solid curve is the result of an unbinned maximum likelihood fit which incorporates both signal and background distributions in M_N and ct. Sideband and negative-lifetime events are included to help constrain the background distributions. The likelihood function also incorporates resolution effects and corrections for systematic biases, such as the small inherent charge asymmetry favoring positive tracks resulting from the wire plane orientation in the main drift chamber. However, it is clear from the fact that the solid and dashed curves lie close to one another that these corrections do nothing dramatic; the result is dominated by the sample size. Also shown in the Figure 4 inset is the relative log-likelihood as a function $\mathcal{D}_0 \sin(2\beta)$. It is very close to parabolic, indicating gaussian errors.

Before ascribing the above asymmetry entirely to CP violation, one must eliminate other sources of charge asymmetry which could mimic the signature. The charge asymmetry of the main drift chamber has already been mentioned; it has been measured in an independent sample of inclusive $B \to J/\psi X$ decays and corrected for in the maximum likelihood fit. Backgrounds from other B decays, such as $B^0 \to J/\psi K^{*0}$, $K^{*0} \to K^0_S \pi^0$ where the π^0 has not been reconstructed, have been considered and found to be negligible. The high signal purity at large ct also limits contributions to the asymmetry from backgrounds which are present in the sidebands. In addition, the analysis has been applied to the larger samples of $B^0 \to J/\psi K^{*0}$ and $B^+ \to J/\psi K^+$ decays in order to look for systematic effects, but none have been found.

We determine the systematic uncertainty on $\mathcal{D}_0 \sin(2\beta)$ by shifting the central value of each fixed input parameter to the likelihood fit by $\pm 1\sigma$ and refitting to find the shift in $\mathcal{D}_0 \sin(2\beta)$. Varying the B^0 lifetime shifts the central value by ± 0.001. The parameterization of the intrinsic charge asymmetry of the detector is also varied, yielding a $^{+0.016}_{-0.019}$ uncertainty. The largest shift is due to Δm_d, which gives a $^{+0.029}_{-0.025}$ shift. These shifts are added in quadrature, giving $\mathcal{D}_0 \sin(2\beta) = 0.31 \pm 0.18(stat) \pm 0.03(syst)$.

5 Extracting $\sin(2\beta)$

As mentioned above, the dilution $\mathcal{D}_0$, which reduces the amplitude of the CP asymmetry, can be measured in other data samples, including that of $B^0 \to J/\psi K^{*0}$ decays and the much larger $B \to \ell D^{(*)} X$ sample. These different dilution measurements can be extrapolated to the kinematic range appropriate for the $J/\psi K^0_S$ data and then combined. The extrapolation is performed with a Monte Carlo simulation based upon a version of the PYTHIA event generator tuned to CDF data [6,11]; the necessary adjustments to the different dilutions are on the 10% level at most, and it is found that the appropriate dilution for the $J/\psi K^0_S$ data is $\mathcal{D}_0 = 0.166 \pm 0.018 \pm 0.013$. The first uncertainty is due to the uncertainties in the contributing dilution measurements. The second uncertainty is due to the Monte Carlo extrapolation and is calculated by varying parameters of the Monte Carlo model.

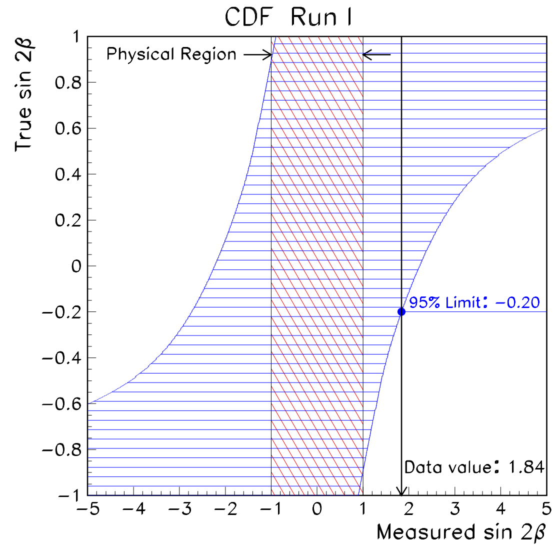

Figure 5: 95% confidence belts for the $\sin(2\beta)$ result. The vertical line represents the actual measurement of $\sin(2\beta)$, and its intersection with the confidence belts gives the confidence interval.

Using this value of $\mathcal{D}_0$, it is found that

$$\sin(2\beta) = 1.8 \pm 1.1(stat) \pm 0.3(syst), \qquad (9)$$

where the dilution uncertainty has been added to the systematic uncertainty. The central value is unphysical since the amplitude of the measured raw asymmetry exceeds the measured dilution.

The result may be phrased in terms of confidence intervals. The present analysis follows the frequentist construction of [12], which gives proper confidence intervals even for measurements in the unphysical region, as is the case here. The confidence interval is shown in Figure 5. It is found that the measurement corresponds to an exclusion of values of $\sin(2\beta)$ below -0.20 at 95% C.L. It can also be seen from the Figure that if the true value of $\sin(2\beta)$ was 1, the median expectation of an exclusion for this analysis technique in the 1992-96 CDF data would be for $\sin(2\beta) < -0.89$ at 95% C.L. This expectation of a limit is a measure of experimental sensitivity. The fact that the present limit is higher reflects the unphysical value that was actually measured.

It is interesting to note that since this result has been obtained using only a single tagging algorithm, then as long as $\mathcal{D}_0 \neq 0$, the exclusion of $\sin(2\beta)$ from this result is independent of the actual value of $\mathcal{D}_0$. Given that $\mathcal{D}_0 > 0$, the same prescription as above for calculating limits yields an exclusion of negative values of $\sin(2\beta)$ at 90% C.L.

6 Conclusion

This article summarizes the CDF result on $\sin(2\beta)$, finding the value

$$\sin(2\beta) = 1.8 \pm 1.1(stat) \pm 0.3(syst) \quad (10)$$

using only a single-track same-side flavor tagging algorithm on a sample of 198 ± 17 $B^0/\overline{B}^0 \rightarrow J/\psi K^0_S$ decays. This measurement corresponds to an exclusion of values of $\sin(2\beta) < -0.20$ at 95% C.L. This result establishes the feasibility of measuring CP asymmetries in B decays at a hadron collider. Upgrades to the Tevatron collider and to the CDF detector, as well as the application of other tagging methods, should reduce the uncertainty on $\sin(2\beta)$ to about 0.08, or by more than an order of magnitude.

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