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Measurements of the CP-Violation Parameter $\sin(2\beta)$ in $B^0 \to J/\psi\, K^0_S$ Decays

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In the $110\,\mathrm{pb}^{-1}$ Run I data sample, using three complementary flavor-tagging algorithms CDF has made a new measurement of the CP-violating asymmetry $\sin(2\beta) = 0.79^{+0.41}_{-0.44}$. This corresponds to the limit $\sin(2\beta) > -0.08$ at 95% confidence level. This result agrees well with predictions from indirect constraints based on fits of elements of the CKM matrix.

I. INTRODUCTION

Since its discovery in 1964, [1] CP violation has been observed only in decays of K^0_L mesons. In the Standard Model, CP violation is explained by the Cabibbo-Kobayashi-Maskawa (CKM) mechanism [2] which posits that the weak-interaction eigenstates of the quarks are mixtures of the mass eigenstates. Therefore, a rotation matrix is included in the weak-interaction Lagrangian.

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

This CKM matrix must be unitary to preserve probability. Because it is unitary, the CKM matrix can be described by four parameters, most simply as three angles and one non-trivial phase. It is the existence of this phase that leads to CP violation, and the Standard Model thus predicts significant CP-violating effects in the decays of neutral B mesons. In order to test whether the CKM mechanism is a correct and complete description of the origin of CP violation in weak decays, it is necessary to measure CP-violating asymmetries in a variety of B-meson decays, to verify that those asymmetries depend on the quark transitions in the expected way, and to test the unitarity of the CKM matrix. The unitarity of the matrix implies that the inner product of any two rows or any two columns vanishes. The most important of these relations is

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

This may be represented by a triangle in the complex plane where, by convention, V_{cd} and V_{cb} are taken to be real. In order to test this unitarity condition, it is necessary to over-constrain the triangle and measure both the length of the sides and the angles between them. These angles are conventionally known as α, β, and γ. β is defined as

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

One way to induce CP violation in B decays is via B^0-$\overline{B}^0$ flavor oscillations which occur via the well-known box diagram. In these oscillations, a particle that is created as, for example, a B^0 can decay as a $\overline{B}^0$ with a probability $P_{\mathrm{mix}}(t) = 1 - \cos(\Delta m\, t)$. If f is a CP eigenstate, then the decay of a B^0 to f can occur in two ways, either directly or after the B^0 has oscillated into a $\overline{B}^0$. The amplitudes of these processes interfere, leading to an net asymmetry which is a function of the decay time and can be expressed as

$$A(t) = \frac{N[\overline{B}^0 \to f](t) - N[B^0 \to f](t)}{N[\overline{B}^0 \to f](t) + N[B^0 \to f](t)} = \mathcal{A}_{CP} \sin(\Delta m\, t) \tag{4}$$

where $N[\overline{B}^0 \to f](t)$ is the number of particles created as a $\overline{B}^0$ at time $t = 0$ that decay to f at proper time t. In the case of the CP eigenstate $f = J/\psi\, K^0_S$, the CP-violating amplitude is $\mathcal{A}_{CP} = \sin(2\beta)$. Therefore, beyond the requirements of a sufficiently large data sample and adequate reconstruction precision, measurement of a CP-violating asymmetry relies most heavily on flavor tagging, the ability to determine whether a particle that decayed as $J/\psi\, K^0_S$ was produced as a B^0 or as a $\overline{B}^0$.

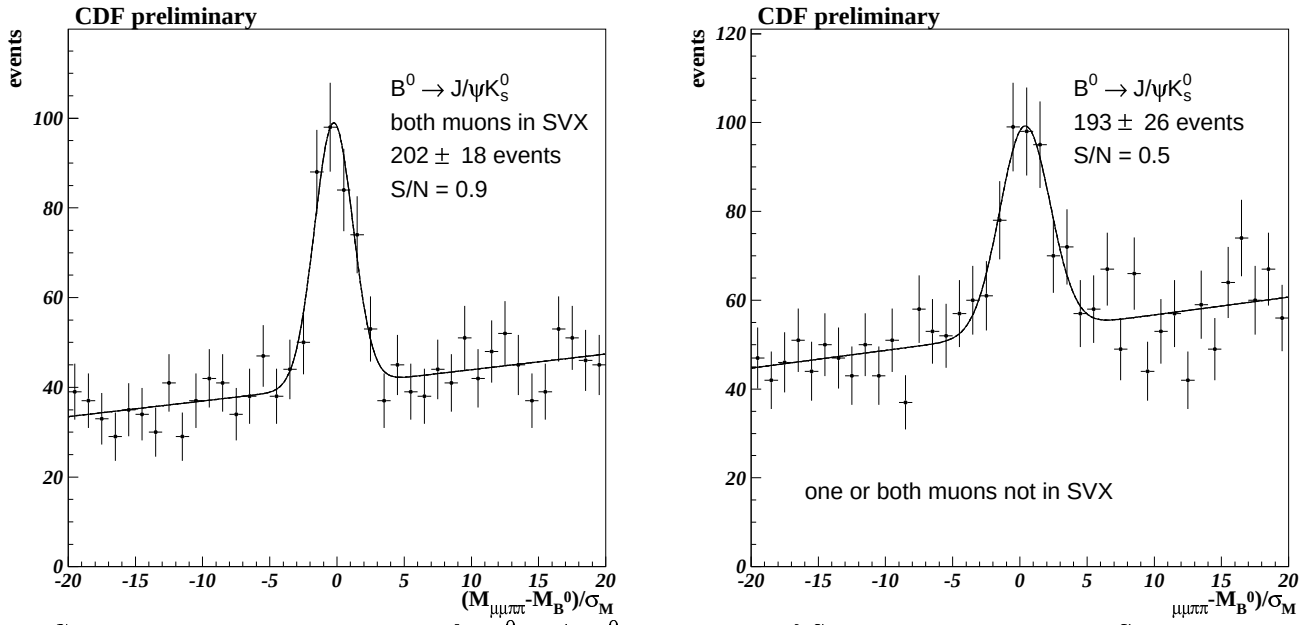

FIG. 1. Normalized mass distributions for $B^0 \to J/\psi\, K^0_S$ candidates: *Left* SVX sub-sample, *Right* non-SVX sub-sample. Fits to Gaussian signal and linear background functions are overlaid.

The first measurements of $\sin(2\beta)$ were published by CDF [3] and OPAL [4] in 1998. OPAL measured $\sin(2\beta) = 3.2^{+1.8}_{-2.0} \pm 0.5$ in the full LEP1 sample. CDF also found a result outside the physically allowed region of $|\sin(2\beta)| < 1$, measuring $\sin(2\beta) = 1.8 \pm 1.1 \pm 0.3$ which interpreted as a limit implies $\sin(2\beta) > -0.20$ at a 95% confidence level. CDF has subsequently released a new preliminary result using more tagging methods and a larger sample of $J/\psi\, K^0_S$ events. The description of the new analysis forms the balance of this report.[1]

II. EVENT SAMPLE

Three subsamples are selected from the CDF $J/\psi \to \mu^+\mu^-$ sample: a signal sample of $B^0 \to J/\psi\, K^0_S$ candidates, a sample of $B^+ \to J/\psi\, K^+$ events[2] used to determine the tagging dilutions, and a sample of inclusive $b \to J/\psi\, X$ events used to constrain the relative efficiencies for positive and negative tags. Muons are identified by the correlation of a charged particle track in the Central Tracking Chamber (CTC) with a track segment in the muon detector drift chambers which lie outside the calorimeter. The minimum momentum for muons to penetrate the calorimeter is $1.4\,\mathrm{GeV}/c$, and the efficiency of the trigger to find a muon rises from 30% at $2\,\mathrm{GeV}/c$ to a plateau value of about 90% above $3\,\mathrm{GeV}/c$. A J/ψ candidate is formed from a pair of opposite-charge muons with a mass within 5 standard deviations of the known J/ψ mass [5]. Events are classified as "SVX" events if both muons are well-reconstructed in the four-layer silicon vertex detector. These events have precise information about the location of the decay B candidates. In "non-SVX" events, one or both muons is not reconstructed in the SVX detector. Because the r.m.s. width of longitudinal distribution of interactions in the CDF detector is comparable to the length of the SVX detector, events are approximately equally distributed between the two classes. Of the non-SVX events, about 30% have one muon reconstructed in the SVX detector.

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[1] At the DPF meeting, my talk covered the published results. The new result was released after the conference. It is substantially better than the older results, and I confine my report to it since it most accurately reflects the state of knowledge about $\sin(2\beta)$.

[2] Unless otherwise stated, a reference to a charge-specific state implies the charge-conjugate state as well.

A $K^0_S \to \pi^+\pi^-$ candidate is formed from an opposite-charge pair of tracks that are assumed to be pions. Since the K^0_S lifetime is large, the intersection of the tracks is required to be a significant distance from the beamline. To reduce background, the transverse momentum of the candidate p_T is required to exceed $700\,\mathrm{MeV}/c$. The J/ψ and K^0_S candidates are combined to form a B^0 candidate with the $\mu^+\mu^-$ and $\pi^+\pi^-$ pairs constrained to the appropriate masses and the B^0 and K^0_S momenta constrained to be along the line joining the origin and decay points of the particles. The confidence level of the kinematic fit is required to exceed 0.1%. The normalized B mass is given by $M_N = (M - M_B)/\sigma_{fit}$, where M is the candidate mass returned by the fit, M_B is the known B^0 mass [5], and σ_{fit} is the resolution returned by the fit which is typically about $10\,\mathrm{MeV}/c^2$. Fig. 1 shows the normalized mass distribution for $B^0 \to J/\psi\, K^0_S$ candidates in both the SVX and non-SVX sub-samples. The likelihood fit used to determine $\sin(2\beta)$ includes Gaussian signal and linear background functions for the mass distribution and return 202 ± 18 SVX events and 193 ± 26 non-SVX events. Although there are some technical differences in the selection criteria, the former sample is very similar to that used in [3].

The criteria for selecting $B^+ \to J/\psi\, K^+$ events are similar. Any charged-particle track with $p_T > 2\,\mathrm{GeV}/c$ is considered as a K^+ candidate. The inclusive J/ψ sample in which the B candidates are found contains J/ψ mesons arising both from B-decay and prompt-production mechanisms. Therefore, to select $b \to J/\psi\, X$ events for tagging studies, SVX events are selected in which the decay point of the J/ψ is a significant distance from the beamline.

III. TAGGING

In order to observe CP violation, it is necessary to know whether a particle decayed as a B^0 or as a $\overline{B}^0$. This can be known on a statistical basis by determining the flavor (*i.e.* b or $\bar{b}$) at production. Given the flavor at production, the probabilities can be calculated from the known B^0-$\overline{B}^0$ oscillation frequency $\Delta m_d = 0.47 \pm 0.02\,\mathrm{ps}^{-1}$ [5] and the measured decay time. The determination of the production flavor is usually referred to as "flavor tagging." The effectiveness of a tagging method can be characterized by two properties: the efficiency ϵ, which is the fraction of events in which one is able to make a tag, and the dilution D, which is the difference in the fraction of events in which that tag is correct or incorrect, *i.e.* $D = (R - W)/(R + W)$ where R and W are the number of right and wrong tags, respectively. The dilution parameter is so named because it describes how the measured asymmetry amplitude is reduced from the true value in Eq. 4:

$$\mathcal{A}_{meas} = D\mathcal{A}_{CP} \tag{5}$$

The expected statistical uncertainty on a measurement of $\mathcal{A}_{CP}$ is then given by

$$\delta\mathcal{A}_{CP} \sim \frac{1}{\sqrt{N\epsilon D^2}} \tag{6}$$

where N is the number of $J/\psi\, K^0_S$ events. Since it multiplies the sample size in the determination of the uncertainty, ϵD^2, is the effective tagging power, and it is the quantity to be optimized for any tagging procedure.

One way to tag the flavor of the B decaying to $J/\psi\, K^0_S$ is to determine the flavor of the away-side B hadron. Because the b and $\bar{b}$ quarks hadronize incoherently in $p\bar{p}$ collisions, the efficiency and dilution of an opposite-side tagging method can be measured in $B^+ \to J/\psi\, K^+$ events which have similar kinematics to the $J/\psi\, K^0_S$ signal sample and have a known flavor. Two opposite-side tagging methods are used: jet-charge (JETQ) and soft-lepton (SLT). The soft-lepton tag takes advantage of the large semileptonic branching ratio of bottom hadrons. Although the lepton threshold of $2\,\mathrm{GeV}/c$ for muons and $1\,\mathrm{GeV}/c$ for electrons limits the acceptance for leptons from B decay, it more severely suppresses the leptons from the $b \to c \to \ell$ sequential decay chain. The mixing of opposite-side B^0 and B^0_s mesons also reduces the dilution of the soft lepton tag, and the efficiency of opposite-side tags is somewhat limited by the weak rapidity correlation of the b and $\bar{b}$ hadrons produced in $p\bar{p}$ collisions. In this analysis, the efficiency and dilution are measured by finding the number of events in the reference sample with the correct charge correlation ($J/\psi\, K^+$, ℓ^-), the number with the incorrect correlation ($J/\psi\, K^+$, ℓ^+), and the number that are not tagged. Fig. 2

shows the $\mu^+\mu^-K^+$ mass distributions for $J/\psi K^+$ and $J/\psi K^-$ events with correct and incorrect soft-lepton tags and without a tag. The distributions are fit simultaneously to a Gaussian signal distribution for which only the normalization is allowed to vary between the three samples and to linear background distributions for each sample. The charge-average efficiency is $6.5 \pm 1.0\%$ and the dilution is $62.5 \pm 14.6\%$. In the actual fit for $\sin(2\beta)$ (see Sec. IV), the efficiency and dilution are measured separately from B^+ and B^- samples.

The Jet-Charge (JETQ) tagging method uses a momentum-weighted sum of tracks in a jet, presumed to be from a b hadron, opposite the B^0 signal candidate. With the soft-lepton tag, this method has been used by CDF in inclusive lepton samples to measure Δm_d [6]. The jet is reconstructed using charged tracks with a modified version of the JADE algorithm. In Ref. [6], the track charges are weighted by the component of the track momentum momentum along the jet axis. However, the B mesons in the CP sample are at considerably lower momentum. The algorithm has been optimized for the $J/\psi K^0_S$ kinematic region, and the definition of jet charge is:

$$Q_{\rm jet} = \frac{\sum_i q_i p_{T,i}(2-T_i)}{\sum_i p_{T,i}(2-T_i)} \tag{7}$$

where the sum is over the tracks in the jet, q_i is the charge of a track, and $p_{T,i}$ is its momentum transverse to the beamline. $2-T_i$ is a track displacement factor to give greater weight to tracks that are displaced from the beamline as would be the case for B daughters. For tracks reconstructed in the SVX, T_i is the χ^2 probability that a track is consistent with being prompt: $T_i = \mathrm{erfc}(d_i/\sigma_i)$ where d_i is the measured track impact parameter and σ_i is its resolution. For non-SVX tracks, T_i is set to 1. An event is considered tagged if $|Q_{\rm jet}|$ exceeds 0.2. A positive value of $Q_{\rm jet}$ has the same interpretation as a positive lepton tag, *i.e.* the signal $J/\psi K^0_S$ was produced as a $\overline{B}^0$. The efficiency and dilution of the jet-charge tag are measured in the same fashion as for the lepton tag, and the results are shown in Fig. 2. Because the lepton will tend to be the leading particle in a B decay, the two methods can have substantial correlation. However, the dilution of the lepton tag is significantly better than for the jet-charge tag. Therefore, to eliminate the correlation, events with lepton tags are excluded from consideration for jet-charge tagging. The average efficiency of the jet-charge tag is $44.9 \pm 2.2\%$, and the dilution is $21.7 \pm 6.6\%$.

The third tagging method used in this analysis is an extension of the Same-Side Tag (SST) used in Ref. [3]. The

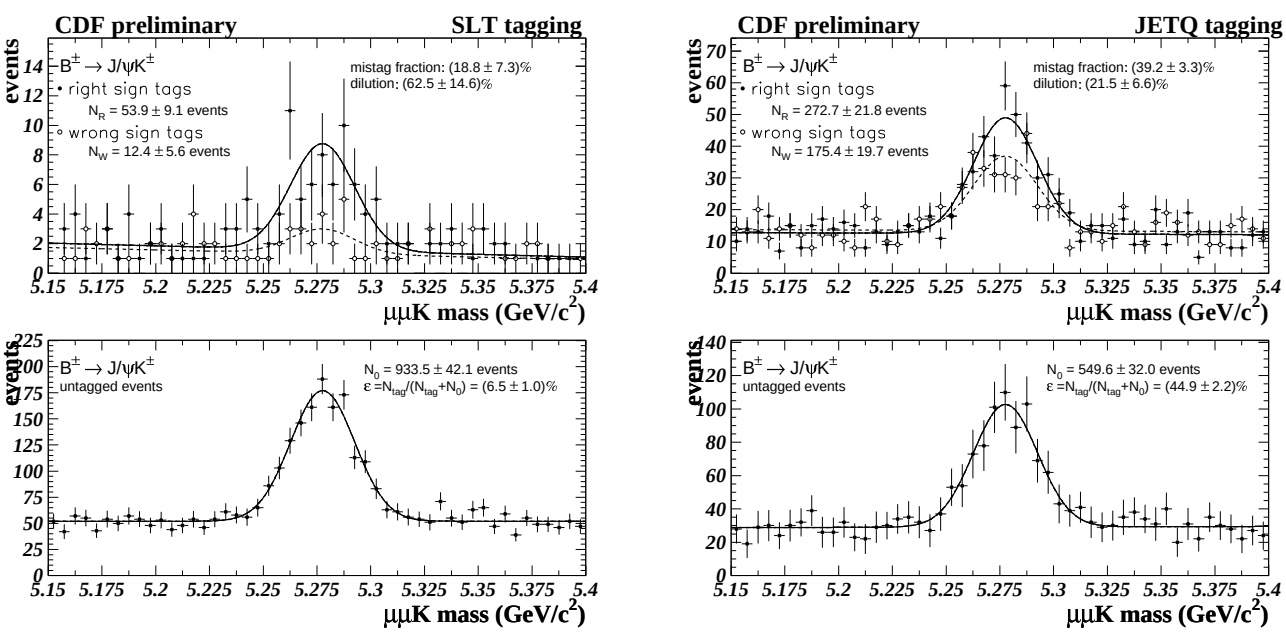

FIG. 2. Mass distributions for $B^+ \to J/\psi K^+$ candidates. Upper plots show the yield for events with correct (incorrect) tags with the solid (open) points. The lower plots show events with no tag. Fits to Gaussian signal and linear background functions are overlaid. *Left:* Soft-lepton tag. *Right:* Jet-charge tag.

SST algorithm takes advantage of a correlation in the charge of pions near B^0 mesons that arises either from decays of higher B resonances (B^{**}) or from the fragmentation process. In either case, there is a $B^0\pi^+$ or $\overline{B}^0\pi^-$ correlation. Tracks of $p_T > 400\,\mathrm{MeV}/c$ are considered if they are with in a cone $\eta^2 + \phi^2 < 1$. The tag comes from the charge of the track with the minimum momentum transverse to the B direction. Because the dilution of the same-side tag is different for B^0 and B^+, the $J/\psi\,K^+$ sample cannot be used to determine the dilution, and additional information is required. In Ref. [3], measurements from higher-momentum ℓD samples were extended to the mean momentum of the $J/\psi\,K$ samples using the Pythia [7] Monte Carlo program with parameters optimized for B production at CDF. Because the sample of SVX events in this analysis with same-side tags is nearly identical to the sample used in Ref. [3], the charge-average dilution for the same side tag for SVX events is set to have the value and uncertainty that was found in Ref. [3]: $D_{SST} = 16.6 \pm 2.2\%$. The $J/\psi\,K^+$ sample is used for two purposes in understanding the SST dilution: first for determining the ratio of dilutions for positive and negative tags and second for extending the SST method to non-SVX events. The average dilution in $J/\psi\,K^+$ SVX events is compared to the dilution with the SVX information ignored. It is found that the results are statistically consistent, but the additional uncertainty is included in the dilution for the non-SVX events.

Although the average efficiency for each tag factors out of the fit for $\sin(2\beta)$, there is a potential bias if there is a different efficiency for positive and negative tags. Therefore, for each of the three tagging methods, the ratio of efficiencies of positive (indicative of $\overline{b}$ anti-quark) to negative (b quark) tags is measured in the inclusive displaced J/ψ sample. The ratio and uncertainty are included in the fit as a constraint on systematic bias. However, no significant bias is observed.

Either a same-side tag, an opposite tag, or both can be found for any event, where as described above, the lepton tag takes precedence over the jet-charge tag. When both same- and opposite-side tags are found, the combined dilution is

$$D_{\text{combined}} = \frac{D_{OST} \pm D_{SST}}{1 \pm D_{OST} D_{SST}} \tag{8}$$

where the terms are added (subtracted) when the tags agree (disagree). Since the OST dilutions both larger than the SST dilution, D_{combined} is manifestly positive.

IV. FIT FOR $\sin(2\beta)$

A log-likelihood fitting procedure is used to find the best value of the net asymmetry amplitude, *i.e.* $\sin(2\beta)$, from the distribution for the number of positive or negative tags for the $J/\psi\,K^0_S$ signal events. For a CP-violating asymmetry induced by mixing, the tag distribution is given by:

$$h_+(t) = \tfrac{e^{-t/\tau}}{\tau}\epsilon_+[1 - \mathcal{A}_{CP} D_+ \sin(\Delta m\, t)] \tag{9}$$

$$h_-(t) = \tfrac{e^{-t/\tau}}{\tau}\epsilon_-[1 + \mathcal{A}_{CP} D_- \sin(\Delta m\, t)] \tag{10}$$

The fit sums over events and includes terms for the lifetime and normalized mass distributions for three components: signal, prompt backgrounds and long-lived backgrounds. Background asymmetries are constrained by events far from the signal peak at $M_N = 0$. The fit also includes the $J/\psi\,K^+$ and $J/\psi K^-$ yields for each of the tags to determine the dilutions and properly include their uncertainties. The B^0 lifetime and Δm, the B^0-$\overline{B}^0$ oscillation frequency, are constrained in the fit to their world-average values [5] within measured uncertainties. The mass and lifetime terms of the fit include the event-by-event measurement resolution.

The result of the fit is

$$\sin(2\beta) = 0.79^{+0.41}_{-0.44} \tag{11}$$

The projection of the fit for asymmetry as a function of lifetime is shown in Fig. 3. For display purposes, the data points are the sum of the dilutions for events in the M_N signal region after subtracting background determined

from the sideband region. The data from the non-SVX sample are shown as a single point since the decay time is poorly determined although it is included with its uncertainty in the fit. In the limit of a completely time-averaged measurement, the measured asymmetry contains an additional dilution of $D_{\rm mix} = x/(1+x^2)$, where $x = \Delta m/\Gamma = 0.73 \pm 0.04$ is the B^0-$\overline{B}^0$ oscillation parameter. The data clearly favor the positive asymmetry returned by the fit. There is also good consistency between the SVX and non-SVX samples. If Δm is allowed to float in the fit, the asymmetry does not change appreciably and the result for Δm is consistent with the known value, showing that the data are consistent with the expected oscillation frequency.

The uncertainty can be broken into two terms, a "statistical" uncertainty related only to the statistical properties of the $J/\psi\, K^0_S$ sample itself, and a "systematic" uncertainty for the dilution parameters and external inputs. In fact, such a systematic uncertainty scales with the size of the data sample since it is dominated by the statistics of the control samples. Nevertheless, such a decomposition gives a statistical uncertainty of ± 0.39 and a systematic of 0.16. Thus the uncertainty on the measurement is dominated by the number of tagged $J/\psi\, K^0_S$ events, and using $J/\psi\, K^+$ events proves to be an effective method for determination of the dilutions and should continue to be so for future measurements.

Although this measurement cannot unambiguously prove the existence of CP violation in the b system, it does show that with the Feldman-Cousins method of determining confidence intervals [8] the probability that $\sin(2\beta)$ is between 0 and 1 is 93% or $\sin(2\beta) > -0.08$ at 95% confidence level.

The CKM matrix is often approximated using the Wolfenstein parameterization [9]:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - \imath\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-\imath\eta) & -A\lambda^2 & 1 \end{pmatrix} \tag{12}$$

The unitarity condition in Eq. 2 can be represented as a triangle in the ρ-η plane. Fig. 4 shows the results of the CDF measurement as dotted lines beginning from the point $(\rho, \eta) = (1, 0)$ where β is the angle between the line and the horizontal axis. Because $\mathcal{A}_{CP}$ corresponds to $\sin(2\beta)$, there is a four-fold ambiguity in the in calculating β. The

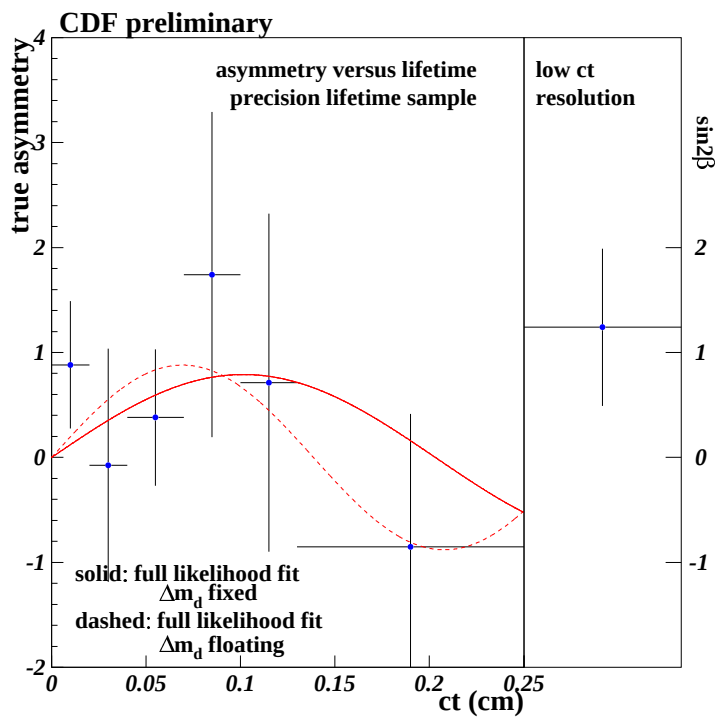

FIG. 3. Results of fit for $\sin(2\beta)$ which is the amplitude of the oscillation.

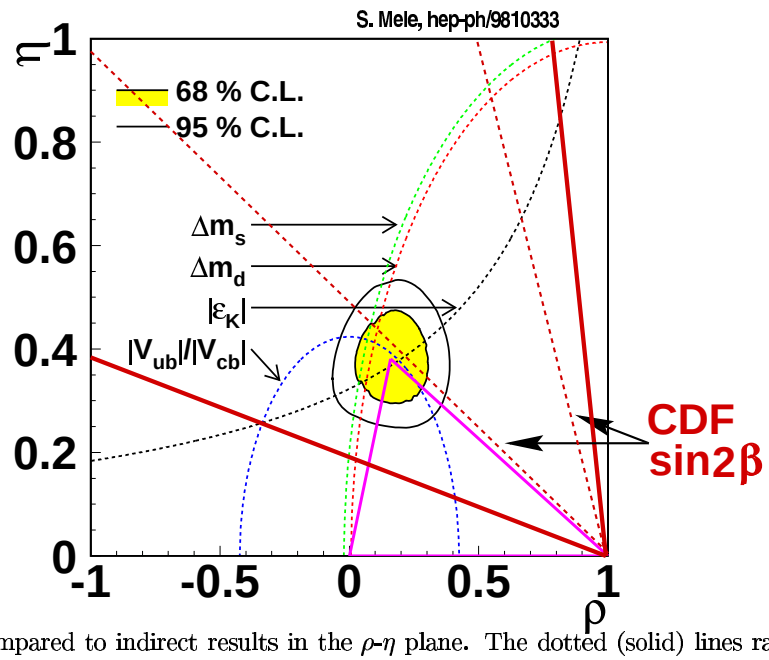

FIG. 4. CDF results compared to indirect results in the ρ-η plane. The dotted (solid) lines radiating from $(\rho, \eta) = (1, 0)$ indicate the 68% (95%) confidence interval for $\sin(2\beta)$. The egg-shaped region shows the 1σ and 2σ intervals from fits to the CKM parameters using other measurements in Ref. [10]

solutions implying $\rho > 1$ are not allowed by construction. We show the solution for $\eta > 0$ that is favored in the Standard Model by measurements of ϵ_K. The solid lines indicate the 68% confidence interval. The egg-shaped region indicates the expected interval for ρ and η based on Standard Model constraints and measurements of a variety of CKM elements.

V. CONCLUSIONS

CDF has measured a *CP*-violating asymmetry in $\overline{B}^0 \to J/\psi K^0_S$ decays to be $\sin(2\beta) = 0.79^{+0.41}_{-0.44}$ using the full Run I data sample and a combination of three tagging algorithms. Although this measurement cannot conclusively demonstrate *CP* violation in B decays, it points to an exciting future. In Run II, scheduled to begin in 2000, CDF expects to achieve and uncertainty on $\sin(2\beta)$ of 0.08. With the e^+e^- B factories also beginning operation, the next few years should lead to an unambiguous result for *CP* violation in $B^0 \to J/\psi K^0_S$ decays.

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