FERMILAB-Conf-99/286-E

An Updated Measurement of sin(2β) at CDF

F. Bedeschi

I.N.F.N.-Sezione di Pisa, via Livornese 1291
I-56010 S. Piero a Grado (PI), Italy

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

November 1999

Published Proceedings of the *13th Les Rencontres de Physique de la Valle d'Aosta: Results and Perspectives in Particle Physics*, La Thuile, Valle d'Aoste, Italy, February 28-March 6, 1999

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Distribution

Approved for public release; further dissemination unlimited.

Copyright Notification

This manuscript has been authored by Universities Research Association, Inc. under contract No. DE-AC02-76CH03000 with the U.S. Department of Energy. The United States Government and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government Purposes.

AN UPDATED MEASUREMENT OF $sin(2\beta)$ AT CDF

Franco Bedeschi,
INFN - Sezione di Pisa, via Livornese 1291,
I-56010 S. Piero a Grado (PI), Italy

Abstract

We report an updated direct measurement of the Standard Model CP violation parameter $sin(2\beta)$ using the CDF Detector at Fermilab. We use the entire Run-I data sample of 110 pb^{-1} of proton-antiproton collisions at $\sqrt{s} = 1.8$ TeV.

In this analysis, we have combined three tagging methods: a same-side tag, a soft-lepton tag, and a jet-charge tag, and also added events that have less precise lifetime information because they are not fully contained within the acceptance of the SVX. The signal sample consists of ~ 400 $B \rightarrow J/\psi K_S^0$ events. A maximum likelihood fitting method is used to measure $sin(2\beta) = 0.79^{+0.41}_{-0.44}$ (stat.+syst.). We calculate a 93% Feldman-Cousins confidence interval of $0 < sin(2\beta) < 1$. This measurement is the best direct indication for CP violation in the neutral B meson sector to date. The $sin(2\beta)$ value is consistent with the Standard Model prediction of large CP symmetry violation in the b quark system.

1 Introduction

The first observation of CP nonconservation in the neutral kaon system was in 1964 (1). To date, CP violation has not been directly observed in any other system. Previously reported work searching for CP violation in the decay $B \to J/\psi K^0_S$ has been reported by the OPAL Collaboration (2) and CDF (3). This paper reports a direct measurement of $\sin 2\beta$ that is the best evidence for CP violation in the neutral B meson system to date.

Within the framework of the Standard Model, CP violation arises through a non-trivial phase in the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix. The CKM matrix V is a unitary matrix which rotates the electroweak eigenstates into the mass eigenstates:

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

The second matrix is the Wolfenstein parameterization (4). Imposing the condition of unitarity, $V^\dagger V = 1$, yields a number of relations between entries of the matrix. The most useful of these relations is:

$$V^*_{tb}V_{td} + V^*_{cb}V_{cd} + V^*_{ub}V_{ud} = 0. \quad (2)$$

This condition can be displayed graphically as a triangle in the imaginary (ρ-η) plane. Dividing the base by $V_{cd}V^*_{cb}$ to make it unit length leaves the “unitarity triangle” which is shown in Fig. 1. The Standard Model can accommodate CP violation as long as η is nonzero.

CP violation manifests itself as an asymmetry in the decay rate of particle versus antiparticle:

$$A_{CP} = \frac{N(\overline{B^0} \to J/\psi K^0_S) - N(B^0 \to J/\psi K^0_S)}{N(\overline{B^0} \to J/\psi K^0_S) + N(B^0 \to J/\psi K^0_S)} \quad (3)$$

where $N(\overline{B^0} \to J/\psi K^0_S)$ is the number of events decaying to $J/\psi K^0_S$ which were produced as $\overline{B^0}$ and $N(B^0 \to J/\psi K^0_S)$ is the number of events decaying to $J/\psi K^0_S$ which were produced as B^0. The asymmetry can be either a time dependent or time-integrated quantity. 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 β is the angle of the unitarity triangle shown in Fig. 1, t is the proper decay time of the B meson and Δm_d is the mass difference between the heavy and light B meson states. Based

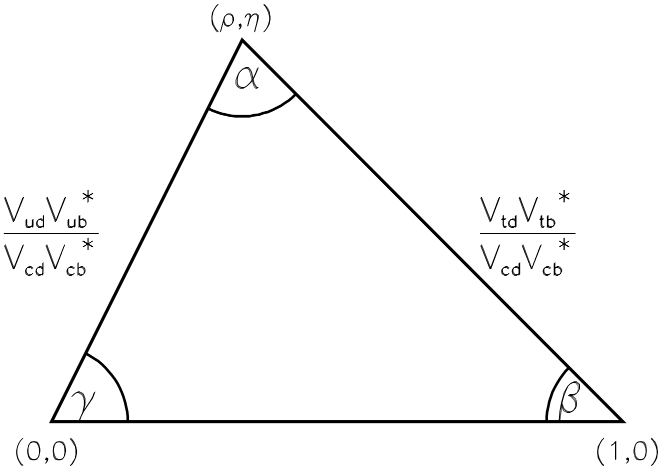

Figure 1: The unitarity triangle indicating the relationship between the CKM elements.

on global fits to indirect measurements, the Standard Model prefers a large positive value of $\sin 2\beta$. Several analyses have been performed and are in good agreement with each another 5, 6, 7, 8). One recent analysis finds $\sin 2\beta = 0.725^{+0.050}_{-0.060}$ 8).

To measure this asymmetry, the flavor of the B meson (whether it is a B^0 or a $\overline{B^0}$) must be identified (tagged) at the time of production. Unfortunately, the tagging algorithms are not perfect, and the true asymmetry is "diluted" by identifying a B^0 meson as $\overline{B^0}$ meson or vice versa. We define 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, given by $A_{CP}^{obs} = DA_{CP}$, is reduced in magnitude by this dilution parameter. The statistical uncertainty on $\sin 2\beta$ is inversely proportional to $\sqrt{\epsilon D^2}$, where the efficiency ϵ is the fraction of events that are tagged. This analysis combines three tagging algorithms in order to minimize the statistical uncertainty in the measurement.

1.1 Overview of the Analysis

This analysis builds on the work of several previous analyses using the various B enriched data sets recorded by the CDF detector. Our most recent analysis of $\sin 2\beta$ 3) used the B^0-$\overline{B^0}$ mixing analysis of Ref. 9) to establish the viability of the same-side tagging (SST) method 10). This paper reports work that uses the same algorithm. A slightly modified version of the algorithm is necessarily used for events with less precise flight path information, *i.e.* events not fully contained within the SVX detector acceptance. Furthermore, we use two additional tagging algorithms that are based on a previous B^0-$\overline{B^0}$ mixing analysis of Ref. 11). One of the algorithms used here is the same as in Ref. 11): the soft lepton tag algorithm (SLT). The other algorithm, the jet-charge tag (JETQ), is very similar to the algorithm used in the mixing analysis 11) except the acceptance cone defining the jet has been increased in size to increase the efficiency of tagging lower P_T B mesons and impact parameter weighting has been added to increase the dilution.

We reconstruct the $B \to J/\psi K^0_S$ decay mode in a manner similar to several previous analyses from CDF: a measurement of the branching ratio 12) 13) and a measurement of the B lifetime 14). The events are categorized as to how they are tagged. The JETQ and SLT tagging dilutions and efficiencies are determined from a sample of $\sim$1000 $B \to J/\psi K^\pm$ decays and a much larger sample of inclusive J/ψ events. The dilutions and efficiencies are combined for each event and a maximum likelihood fitting procedure is used to extract the result for $\sin 2\beta$. The fit includes the possibility that the tagging dilutions and efficiencies have inherent asymmetries. In addition, the backgrounds, divided into prompt and long-lived categories, are also allowed to have an asymmetry. In the end, these possible asymmetries are found not to be significant.

2 Sample Selection

Three event samples, $B \to J/\psi K^0_S$, $B \to J/\psi K^\pm$, and inclusive J/ψ decays are used in the determination of $\sin 2\beta$. The $B \to J/\psi K^0_S$ candidates form the signal sample, the $B \to J/\psi K^\pm$ is used to determine the tagging dilutions, and the inclusive J/ψ decays are used to constrain ratios of efficiencies.

The selection criteria for the $B \to J/\psi K^0_S$ sample provides an optimal value of the signal-to-background ratio, which enters into the uncertainty on the final result for $\sin 2\beta$. The J/ψ is identified by requiring two oppositely charged muon candidates, with each muon having $P_T > 1.4$ GeV/c.

We divide the data into two samples, one called the SVX sample, the other the non-SVX sample. The SVX sample requires both muon candidates to be well measured with the silicon vertex detector, and is therefore a sample of B candidates with precise decay length information.

The K^0_S candidates are found by matching pairs of oppositely charged tracks, assumed to be pions. The K^0_S candidates are required to travel a significant distance from the primary vertex (beam luminous region) and to have $P_T > 700$ MeV/c in order to improve the signal-to-background ratio. The J/ψ and

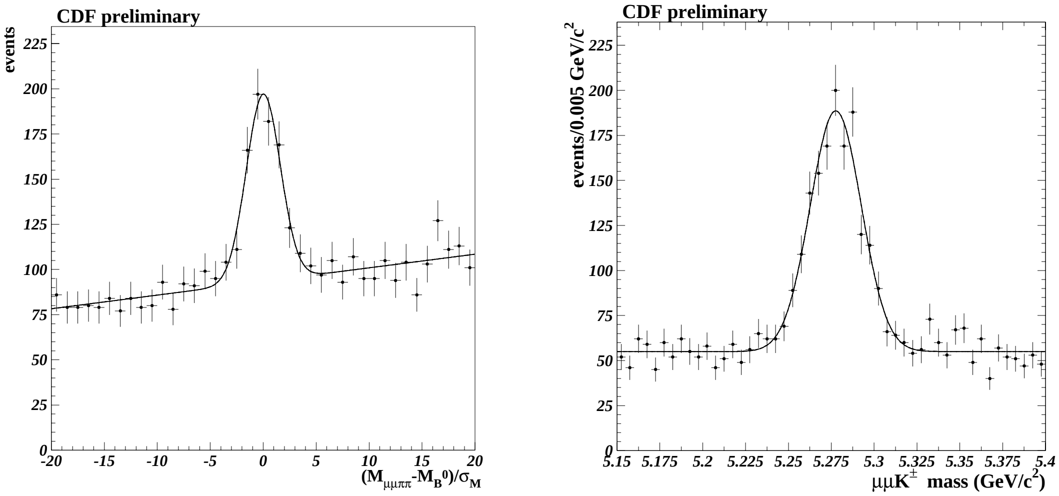

Figure 2: Left: the normalized mass distribution of the $J/\psi K_S^0$ candidates. The curve is a Gaussian signal plus linear background from the likelihood fit. Left: the mass distribution of the $J/\psi K^\pm$ control sample.

K_S^0 candidates are combined into a four particle fit to the hypothesis $B \to J/\psi K_S^0$ and the $\mu^+\mu^-$ and $\pi^+\pi^-$ are constrained to the appropriate masses and separate decay vertices. The K_S^0, J/ψ, and B are constrained to point back to their points of origin. In order to further improve the signal-to-background ratio B candidates are accepted for $P_T(B) > 4.5$ GeV/c and fit quality cuts are applied to the J/ψ, K_S^0, and B candidates.

We define a normalized mass $M_N = (m_{\mu\mu\pi\pi} - M_0)/\sigma_{\text{fit}}$, where $m_{\mu\mu\pi\pi}$ is the four-track mass coming from the vertex and mass-constrained fit of the B candidate. The uncertainty, σ_{fit}, is from the fit, typically ~ 9 MeV/c^2, and M_0 is the world average B^0 mass [15]. The decay distance projected onto the plane transverse to the beam line is used to calculate the proper decay distance ct, which is the projection of the displacement along the B momentum. The normalized mass is shown in Fig. 2. We observe a sample of 419 ± 39 events with a signal-to-noise of 0.7. The SVX sample contains 211 ± 24 events with a signal-to-noise of 0.9 and the non-SVX sample contains 218 ± 34 events with a signal-to-noise of 0.5.

The criteria used to select the $B \to J/\psi K^\pm$ decays are the same as described for $B \to J/\psi K_S^0$ decays except for the $K^\pm$ selection. Since CDF has only limited $K^\pm$–$\pi^\pm$ separation power at high P_T, using the dE/dx information of the central tracking chamber, candidate kaons are defined as any track with $P_T > 2$ GeV/c. The $\mu^+\mu^-K^\pm$ mass distribution is shown in Fig. 2.

The inclusive $J/\psi \to \mu^+\mu^-$ sample is a superset from which the $B_d^0 \to$

$J/\psi K_S^0$ is derived. The inclusive sample is $\sim 80\%$ prompt J/ψ, and in order to enrich the sample in B decays we require a significant J/ψ travel distance from the beamline.

3 Tagging Algorithms

We have two opposite-side tagging algorithms and one same-side tagging algorithm. The same-side tagging (SST) algorithm exploits the local correlation between the B meson and the charge of nearby tracks to tag the flavor of the B. When using the SVX sample, the algorithm of Ref. 3) is used as well as the same value for tagging dilution parameter, $D = (16.6 \pm 2.2)\%$.

When using the non-SVX sample, the same-side tagging algorithm is modified slightly by dropping the SVX information for all candidate tagging tracks and loosening the track selection criteria in order to maximize the acceptance. We derive from the $B \to J/\psi K^{\pm}$ sample a dilution scale factor, f_d, which relates the SVX sample SST algorithm performance to the non-SVX sample SST algorithm. We find a value of $f_D = (104.7 \pm 16.8)\%$. Combining with the measured SST dilution for SVX tracks, we find $D = (17.4 \pm 3.6)\%$.

Opposite-side tagging refers to the identification of the flavor of the "other" B in the event at the time of production. As mentioned earlier, two algorithms are employed: soft-lepton (SLT) and jet-charge tagging (JETQ). Their tagging dilutions and efficiencies are determined using a sample of $B \to J/\psi K^{\pm}$ events and are presented in Table 1. The tagging efficiencies are stated relative to the entire sample.

The soft-lepton tagging algorithm is described in detail in Ref. 11). The SLT tagging algorithm associates the charge of the lepton (electron or muon) with the flavor of the parent B meson, which in turn is correlated with the produced flavor of the B that decays to $J/\psi K_S^0$. The dilution for soft lepton tagging is $D = (62.5 \pm 14.6)\%$ regardless of whether the muon candidates from the reconstructed $B \to J/\psi K_S^0$ are contained in the SVX.

The JETQ tagging algorithm is described in detail in Ref. 11). The jet-charge flavor tag uses a momentum-weighted charge average of particles in a b quark jet to infer the charge of the b quark. The JETQ dilution is measured to be $D = (21.5 \pm 6.6)\%$ for all events and $D = (23.5 \pm 6.9)\%$ when SLT tagged events are removed from the sample. These dilution numbers are valid regardless of whether the reconstructed B is contained in the SVX or not.

Each event will have the opportunity to be tagged by as many as two tagging algorithms: one same-side and one opposite-side. We follow the prescription

Table 1: Summary of tagging algorithms used in this analysis. The efficiencies quoted are relative to the full $J/\psi K^0_S$ sample. All numbers listed are in percent.

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

outlined in Ref. [11)], in which the SLT tag is used if both the SLT and JETQ tags are available. This is done to avoid correlations between the two opposite side tagging algorithms and because the SLT dilution is much larger than that of the JETQ algorithm.

The dilutions and efficiencies described earlier are generalized before incorporation into the analysis so as to permit possible asymmetries in the detector performance. CDF has a small bias toward reconstructing more tracks of positive charge at low transverse momentum.

In practice we use the available control samples to determine separately dilutions and efficiencies for each tag sign. The inclusive J/ψ sample is used to constrain the ratio of the efficiencies for the two signs.

These measurements are summarized in Table 2.

Table 2: The dilutions determined from the $B \to J/\psi K^\pm$ sample and the efficiency ratios determined from the inclusive J/ψ sample. D_{ave} is the average dilution.

tag	ϵ_+/ϵ_-	$D_+(\%)$	$D_-(\%)$	$D_{ave}(\%)$
$\mathrm{SST_{SVX}}$	1.031 ± 0.011	16.1 ± 5.1	17.1 ± 5.2	16.6 ± 2.2
$\mathrm{SST_{CTC}}$	1.037 ± 0.010	17.0 ± 5.7	17.8 ± 5.8	17.4 ± 3.6
SLT	0.978 ± 0.047	76.9 ± 19.6	46.4 ± 21.8	62.5 ± 14.6
JETQ	0.977 ± 0.015	20.7 ± 9.3	26.5 ± 8.3	23.5 ± 6.9

4 The Likelihood Function

We use an unbinned negative log-likelihood method to determine the best value for $\sin 2\beta$, a free parameter in the fit. The data are fit to a model which takes into account the shape of the mass and lifetime distributions. Three separate components

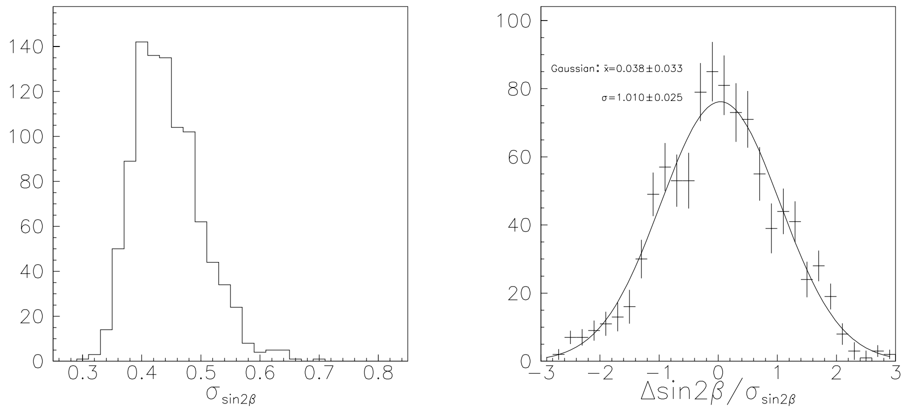

Figure 3: Left: Distribution of $\sigma_{\sin 2\beta}$ from multiple fits to Monte Carlo data generated with $\sin 2\beta = 0.5$. Right: Distribution of normalized $\sin 2\beta$ deviations, *i.e.* (fit-$\sin 2\beta - 0.5)/\sigma_{\sin 2\beta}$, and a Gaussian fit to that distribution.

are assumed to contribute to the observed distributions: signal, prompt background and long-lived background. Parameters measured with separate data sets, like dilutions and efficiency ratios, are inserted in the fit as free paramenters and constrained by adding Gaussian terms to the likelihood.

As a check of the fitting procedure we generated several sets of ~ 1000 toy Monte Carlo data samples (mass, time, tags, etc.). The number of events, SVX-non-SVX ratio, signal-background ratios, tagging efficiencies and dilutions, mass uncertainty and its scale factor, background lifetimes, time uncertainties and scale factors, and other kinematic features of the generation procedure were all tuned to be similar to the composition of the data sample. There were 202 signal, 1618 background events for SVX, and 193 signal, 2185 background events for non-SVX only.

The left plot in Fig. 3 shows the distribution of the appropriate MINOS [16] uncertainty on $\sin 2\beta$ returned from the Monte Carlo fits with generated $\sin 2\beta = 0.5$. The typical value of the uncertainty on $\sin 2\beta$ returned from these fits is ~ 0.44, though there is a long tail extending out to ~ 0.7. The right plot in Fig. 3 shows $[\sin 2\beta(\mathrm{fit}) - 0.5]/\sigma$, where σ is the uncertainty on $\sin 2\beta$ as returned by the fit.

We conclude from this and other generated samples that the fitting procedure provides a reasonably unbiased estimator of the $\sin 2\beta$ of the parent distribution, that the distribution of the difference between the fit-$\sin 2\beta$ and the $\sin 2\beta$ of the parent distribution is well approximated by a Gaussian, and that the MINOS fit-uncertainty on $\sin 2\beta$ provides a good estimate of the σ of that Gaussian.

4.1 Systematic Uncertainties

We have included the systematic uncertainties due to the B lifetime and Δm_d as constraints in the fit. We have evaluated the systematic uncertainties due to the uncertainty in the B^0 mass, trigger bias and K_L^0 regeneration. We estimate the systematic uncertainty arising from the B mass by varying it by one standard deviation and refitting. The difference between $\sin 2\beta$ from the standard fit and the $\sin 2\beta$ from the fit with the varied parameter is the systematic uncertainty from that variation. For m_{B^0}, we normalize to the world average B^0 mass, $5.2792\,\mathrm{GeV}/c^2$. We vary the B^0 mass by a value which will give us a $\pm 1\sigma$ shift in normalized mass. This value is $1\,\mathrm{MeV}/c^2$.

In our explicit handling of charge bias in the tagging algorithms, we implicitly account for any trigger bias in the algorithm in the calibration on $J/\psi K^{\pm}$, so there is no additional systematic uncertainty arising from a charge bias in the trigger. We explicitly assume that we begin with a sample which is a 50:50 mix of $B^0/\overline{B^0}$. We have verified that no trigger bias on the B hadron opposite the reconstructed $J/\psi K_S^0$ invalidates this assumption.

We have also considered the possible contamination of our data from K_L^0 regeneration from the material in the inner detector. Reconstruction of the K_L^0 as a K_S^0 would enter as the incorrect sign in the asymmetry. We calculate this effect shifts $\sin 2\beta < 0.003$.

The results of the systematic studies are shown in Table 3.

Table 3: Systematic uncertainties in the measurement of $\sin 2\beta$. The items labelled "in fit" are parameters which are allowed to float in the fit but are constrained by their measured uncertainties. The uncertainty returned from the likelihood fit includes the contributions from these sources.

parameter	$\delta \sin 2\beta$
tagging dilution	in fit
tagging efficiency	in fit
Δm_d	in fit
τ_{B^0}	in fit
m_B	± 0.013
trigger bias	negligible
K_L^0 regeneration	negligible

Many checks of the data and analysis have been performed to increase our confidence in the result. In order to check the sensitivity of the result to the dilutions,

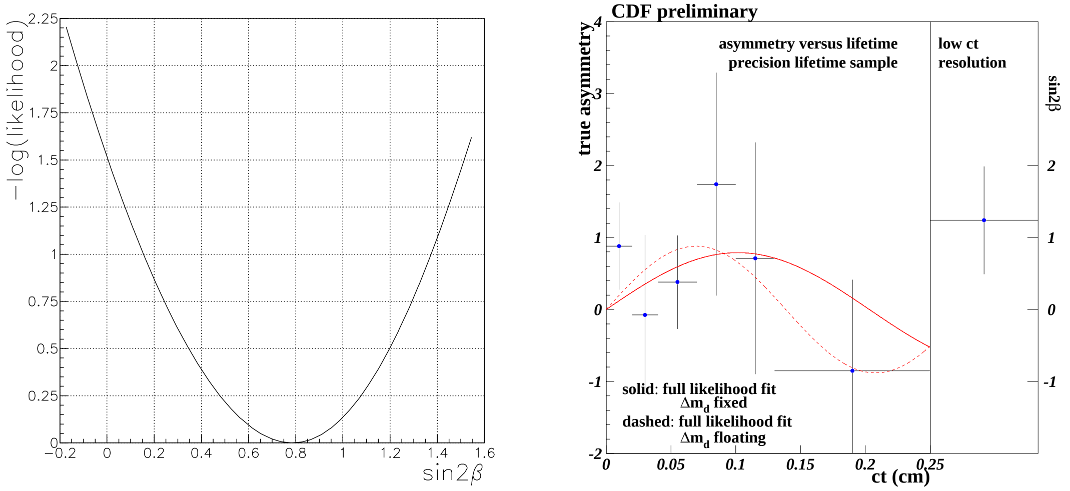

Figure 4: Left: a MINOS-style scan of the log-likelihood function. Right: the true asymmetry ($\sin 2\beta$) as a function of lifetime for $B \to J/\psi K^0_S$ events. The data points are sideband-subtracted and have been combined according to the effective dilution for single and double-tags. The non-SVX events are shown on the right.

we imposed alternative JETQ and SLT dilution parameters taken from our various mixing analyses that use the inclusive lepton sample 11). We observe the expected shift upward in the value of $\sin 2\beta$ and small changes in the uncertainty. The signal sample selection criteria have been varied and we find no unexpected sensitivity in the result.

4.2 Final Result

The maximum likelihood function returns a value for $\sin 2\beta$. The fit is stable and displays only a slight asymmetry in the likelihood function, indicating approximately Gaussian uncertainties. A scan through the likelihood function as $\sin 2\beta$ is varied is shown in Fig. 4. Even though asymmetric dilutions are permitted in the fit, we find no significant asymmetry. Furthermore, the background asymmetries are consistent with zero.

Using the entire data set and three tagging algorithms, we find

$$\sin 2\beta = 0.79 \begin{matrix} +0.41 \\ -0.44 \end{matrix}$$

The uncertainty can be divided into statistical and systematic terms:

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

The systematic term reflects the uncertainty in the result due to the uncertainty in the dilution parameters. Although the dilution parameters are not precisely determined, due to the limited statistics of the $B \to J/\psi K^{\pm}$ calibration sample, this uncertainty term does not dominate the overall uncertainty on $\sin 2\beta$. This is important in planning for analyses on larger data samples in the future because the uncertainty on the dilution parameters improves with increasing statistics. We conclude the uncertainty on $\sin 2\beta$ will not be dominated by the uncertainty on the dilution parameters.

The asymmetry as a function of lifetime is shown in Fig. 4 for the SVX and non-SVX events separately. The positive asymmetry preferred by the fit can be seen. The non-SVX sample contribution has been included as a single point since the decay length information is of low resolution. The full maximum likelihood fit of course uses both the SVX and non-SVX sample and treats properly the decay length and uncertainty for each event.

It is of interest to determine the quantitative statistical significance of whether this result supports $\sin 2\beta > 0.0$ and hence provides evidence for CP symmetry violation in the b quark system. We use three statistical methods to indicate the significance so as to avoid bias with choosing a particular method. We find the probability that $\sin 2\beta > 0.0$ is 95%, using a Bayesian approach, where we have assumed a flat prior distribution in $\sin 2\beta$. Using the Feldman-Cousins frequentist approach 17), we calculate our measurement excludes $\sin 2\beta < 0.0$ at the 93% CL. Finally, if the true value of $\sin 2\beta$ is zero, and the measurement uncertainty is 0.44 (Gaussian uncertainty), the probability of obtaining $\sin 2\beta > 0.79$ is 3.6%.

It is possible to remove the constraint that ties Δm_d to the world value 15) and let it be determined by the data—fitting for $\sin 2\beta$ and Δm_d simultaneously. In this case the result is $\sin 2\beta = 0.88^{+0.44}_{-0.41}$ and $\Delta m_d = 0.68 \pm 0.17\,\mathrm{ps}^{-1}$. The value of Δm_d from the fit agrees with the world value 15) at the level of $\sim 1.2\sigma$. Since one can't measure Δm_d at all in $B \to J/\psi K^0_S$ unless $\sin 2\beta$ is significantly nonzero, this agreement increases our confidence in the main result.

We have performed a time-integrated measurement to check the final result. This simplified analysis does not use the time dependence of the asymmetry and ignores the corrections applied in the full maximum likelihood fit. With just one tagging algorithm, we would simply count the number of plus and minus tags after subtracting the background and compute $\sin 2\beta$ using a single dilution. The fact that we have double-tagged events requires a special procedure. We categorize the three tagging algorithms and the non-SVX tagging algorithm into 12 unique classes. Each event can be associated with only one class (events that have the same dilution) of tag combination. The effective tagging efficiency for the entire sample, ϵD^2, is

(6.3±1.7)%. We find a value of $\sin 2\beta$ for each class and compute a weighted average from the 12 classes. Ignoring correlations in the dilution we find $\sin 2\beta = 0.71 \pm 0.63$. This value is consistent with the final result and demonstrates the improvement in the uncertainty of $\sin 2\beta$ provided by the full maximum likelihood procedure.

5 Conclusion

We have presented a preliminary measurement of $\sin 2\beta$ using ~ 400 $B \to J/\psi K^0_S$ events reconstructed with the CDF detector. We find:

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

with the uncertainty dominated by the statistical contribution.

We have calculated, using three different methods, the statistical significance of whether this result supports $\sin 2\beta > 0.0$ and hence provides evidence for CP symmetry violation in the b quark system. All three methods are in good agreement. Using a Bayesian approach we a find a probability that $\sin 2\beta > 0.0$ is 95%, assuming a flat prior distribution in $\sin 2\beta$. Using the Feldman-Cousins 17) method a 93% confidence interval of $0.0 < \sin 2\beta < 1.00$ is found. If we assume the true value of $\sin 2\beta$ is zero, and our measurement uncertainty of 0.44 (Gaussian), the probability of obtaining $\sin 2\beta > 0.79$ is 3.6%. This direct measurement is the best evidence that the CP symmetry is violated in the b quark system and favors the current Standard Model expectation of a large positive value of $\sin 2\beta$ 5, 6, 7). With the accelerator and detector upgrades in progress, we anticipate an uncertainty on $\sin 2\beta$ of 0.08 or better with 2 fb^{-1} of data in Run II.

References

1. J. Christenson *et al.*, Phys. Rev. Lett. **13**, 138 (1964).

2. K. Ackerstaff *et al.*, The European Physical Journal **C5**, 379 (1998).

3. F. Abe *et al.*, Phys. Rev. Lett. **81**, 5513 (1998);
   K. Kelley, Ph.D. Dissertation, Massachusetts Institute of Technology, 1998 (unpublished).

4. L. Wolfenstein, Phys. Rev. Lett. **51**, 1945 (1983).

5. P. Paganini, F. Parodi, P. Roudeau, and A. Stocchi, Phys.Scripta **58** 556 (1998).

6. S. Mele, Phys.Rev. **D59** 113011,1999;
   CERN-EP-98-133 Aug. 1998; hep-ph/9810333
7. A. Ali and D. London, Nucl.Phys.Proc.Suppl. **54A** 297 (1997).
8. F. Parodi, P. Roudeau, A. Stocchi, LAL-99-03, Mar 1999; hep-ex/9903063
9. F. Abe *et al.*, Phys. Rev. Lett. **80**, 2057 (1998);
   F. Abe *et al.*, Phys. Rev. **D59**, 032001 (1999);
   P. Maksimović, Ph.D. Dissertation, Massachusetts Institute of Technology, 1998 (unpublished).
10. M. Gronau, A. Nippe, and J. L. Rosner, Phys. Rev **D47**, 1988 (1993); M. Gronau and J. L. Rosner, *ibid.* **D49**, 254 (1994).
11. O. Long, Ph.D. Dissertation, University of Pennsylvania, 1998 (unpublished);
    M. Peters, Ph.D. Dissertation, University of California, Berkeley, 1998 (unpublished);
    FERMILAB-Pub-99/019-E; hep-ex/9903011. Submitted to Phys. Rev. D.
12. F. Abe *et al.*, Phys. Rev. Lett. **76**, 2015 (1996).
13. F. Abe *et al.*, Phys. Rev. **D54**, 6596 (1996).
14. F. Abe *et al.*, Phys. Rev. **D57**, 5382 (1998).
15. C. Caso *et al.*, The European Physical Journal **C3**, 1 (1998).
16. F. James, *MINUIT—Function Minimization and Error Analysis*, Version 94.1, CERN Program Library Long Writeup D506, CERN, Geneva, Switzerland, 1994.
17. G. J. Feldman and R. D. Cousins, Phys. Rev. **D57**, 3873 (1998).