JHEP PROCEEDINGS

International Europhysics Conference on HEP

CP Violation at Belle

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Abstract: The Belle collaboration has observed a large signal for CP violation in B-meson decays. We used a data set consisting of $29.1 fb^{-1}$ recorded at the $\Upsilon(4S)$ resonance collected at the KEKB asymmetric e^+e^- collider. The data set includes 31.3 million $B\bar{B}$ pairs. The mixing-induced CP violation is measured by reconstructing CP eigenstates ($J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\eta_c K_S$, $J/\psi K_L$, and $J/\psi K^{*0}(K_S\pi^0)$) from the decay of one B meson while tagging the flavor of the accompanying B meson. From a study of the time-dependent assymetry we find $\sin 2\phi_1 = 0.99 \pm 0.14 \pm 0.06$, where the first error is statistical and the second systematical.

1. Introduction

CP violation was first observed in 1964 in the neutral K meson system by Christenson, Cronin, Fitch and Turlay[1]. In 1973, Kobayashi and Maskawa proposed a mechanism for CP violation that required at least three families of quarks[2]. In their mechanism a three by three matrix links the quark mass eigenstates to the weak eigenstates. The matrix elements in this Unitary matrix can be complex. With a three by three matrix one complex phase can not be rotated away allowing the possibility of CP violation.

From the Unitarity requirement of the CKM matrix linking the weak and mass eigenstates one can write down an equation that relates six of the matrix elements: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$. This relationship can be depicted in the complex plane as a triangle. The area of the triangle is proportional to the amount of CP violation[3].

In 1980 and 1981 Sanda, Carter and Bigi proposed a method for searching for CP violation in the B-meson system[4]. Their method utilizes the time dependent mixing of B^0 and $\bar{B}^0$ mesons, producing a time dependent asymmetry in the decay rates of the two B flavors. While elegant in nature, it has taken an additional 20 years to obtain the number of B mesons necessary to confirm CP violation in the B system.

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We utilize the method of Sanda, Carter and Bigi to measure CP asymmetry. Our data set consists of $29.1fb^{-1}$ containing 31.3×10^6 $B\bar{B}$ events collected with the Belle detector located at the KEKB e^+e^- collider. The energy of the collider is tuned to the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58GeV$). At this resonance two B mesons are produced in a coherent p-wave state. When one B decays to a known flavor eigenstate f_{tag}, B^0 or $\bar{B}^0$, at time t_{tag} the other B is projected onto the opposite b flavor eigenstate.

The method predicts a decay asymmetry when the other B decays to to a CP eigenstate f_{CP} common to both B^0 and $\bar{B}^0$. When f_{CP} is $(c\bar{c})K^{(*)0}$ the expected asymmetry is

$$A(\Delta t) = \frac{\Gamma(\bar{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\bar{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})} = -\xi_f \sin 2\phi_1 \sin \Delta m_d \Delta t, \tag{1.1}$$

where $\Gamma(\bar{B}^0 \to f_{CP})$ is the decay rate for $\bar{B}^0$ to the common CP eigenstate f_{CP} at a proper time Δt defined relative to t_{tag}, ξ_f is the CP eigenvalue of f_{CP}, Δm_d is the mass difference between the B^0 meson mass eigenstates, and ϕ_1 is one of the three angles of the Unitarity Triangle defined as $\phi_1 = \pi - \arg \frac{-V_{tb}^* V_{td}}{-V_{cb}^* V_{cd}}$[5]. Decays of the form $(c\bar{c})K^{(*)0}$ are clean to reconstruct experimentally and are expected to be easy to interpret theoretically with negligible contributions from direct CP violation and complications from strong interactions.

The time integrated asymmetry is zero requiring us to perform a time dependent measurement. This is done by giving the $\Upsilon(4S)$ a Lorentz boost in the laboratory rest frame by using asymmetric energy beams ($E_{e^-} = 8$ GeV, $E_{e^+} = 3.5$ GeV). The boost with $\beta\gamma = 0.425$ is in the z direction, defined to be along the electron beam line. We can then measure the time between the decays of the two B mesons by measuring the spacial displacement between the two vertices, $\Delta t \simeq (z_{CP} - z_{tag})/\beta\gamma c \equiv \Delta z/\beta\gamma c$.

The KEK B-factory, KEKB, has performed remarkably well. As of the conference date, peak luminosity reached $4.49 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (as of the time of writing this proceeding it has reached $5.5 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$). In addition to the $29.1fb^{-1}$ of data taken at the $\Upsilon(4S)$ resonance an additional $3.0fb^{-1}$ of data has been taken 60 MeV below the $\Upsilon(4S)$ resonance to study continuum backgrounds.

The necessary steps for making this measurement are: reconstruct $B^0 \to f_{CP}$ candidates, tag the flavor of the other B (f_{tag}), measure the vertex displacement between the two B's and thus the time between their decays, then perform a fit to extract $\sin 2\phi_1$.

2. Event Selection

Events are reconstructed with the Belle detector which is described in detail elsewhere[6]. The detector consists, from the center outward, of a three layer silicon vertex detector (SVD), a 50 layer central drift chamber (CDC), a mosaic of aerogel Cherenkov detectors for hadron identification (ACC), time-of-flight system (TOF) and a CsI(Tl) electromagnetic calorimeter (ECL). These are all inside a 1.5 Tesla superconducting coil. The iron flux return is instrumented to detect K_L showers and muons (KLM).

Electron identification is based on a combination of CDC dE/dx information, ACC response and the associated ECL shower energy and shape. Muon identification is based on the depth a particle penetrates the KLM and the scatter of KLM hits along the track.

Kaon and pions are identified by combining CDC dE/dx, TOF measurements and ACC response. Photons are identified by ECL showers not matched to a charged track and with a minimum energy of 20 MeV.

Events are first selected with a set of criteria designed to elimate non-physics backgrounds. These include requiring at least three "good" charged tracks that come from the interaction point, more than one "good" calorimenter cluster (energy greater than 100 MeV), and a balanced momentum in the center of mass. To supress continuum we require $R_2 \equiv H_2/H_0 \leq 0.5$, where H_2 and H_0 are the second and zeroth Fox-Wolfram moments[7].

We reconstruct B mesons in the following CP modes: $J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, and $\eta_c K_S$ for $\xi = -1$ and $J/\psi K_L$ for $\xi = 1$. We also use $J/\psi K^{*0}(K_S\pi^0)$ which is a mixture of CP even and CP odd final states. The CP content is determined by a full angular analysis of $B \to J/\psi K^*$ decays that excluded the K^{*0} mode. We measure the CP $\xi = -1$ fraction to be $0.19 \pm 0.04(\text{stat}) \pm 0.04(\text{syst})$[8].

We reconstruct J/ψ mesons in the e^+e^- and $\mu^+\mu^-$ channels. One lepton is required to be positively identified as an electron or muon, with the other lepton passing a lepton consistency requirement (for electrons a track that satisfies either the electron dE/dx or ECL shower energy requirements, for muons the ECL energy deposit should be consistent with a minimum ionizing particle). Electrons suffer from both final state radiation and bremsstrahlung. In order to reduce the effect of these energy losses we include every photon detected within 0.05 radians from the initial electron direction in the invariant mass calculations. We reconstruct $\psi(2S)$ in the same way. We defined J/ψ and $\psi(2S)$ candidates as lepton pairs with an invariant mass between -150 and $+36$ MeV/c^2 for dielectron and -60 and $+36$ MeV/c^2 for dimuon candidates of the J/ψ and $\psi(2S)$ masses. The asymmetric cut is to recover candidates where a radiated photon is missed. The center of mass (com) momentum of J/ψ candidates is required to be less than 2.0 GeV/c, the highest allowed momentum for a J/ψ coming from a B-meson decay.

We also reconstruct $\psi(2S)$ through the $J/\psi\pi^+\pi^-$ channel with the requirement that the $\pi^+\pi^-$ invariant mass be greater than 400 MeV/c^2. We then select $\psi(2S)$ candidates with the mass difference $M_{l^+l^-\pi^+\pi^-} - M_{l^+l^-}$ between 0.58 GeV/^{2} and 0.60 GeV/^{2} ($\pm 3\sigma$ in mass resolution). χ_{c1} is reconstructed via the $J/\psi\gamma$ channel, where the photons that are consistent with $\pi^0 \to \gamma\gamma$ are vetoed. We select χ_{c1} candidates with mass difference $M_{l^+l^-\gamma} - M_{l^+l^-}$ between 0.3850 GeV/^{2} and 0.4305 GeV/^{2}. For ψ' and χ_{c1} both leptons must be positively identified. Histograms of invariant mass spectra can be seen in Fig. 1 through Fig. 4. Note the clear signal for $B \to \chi_{c2}X$ in Fig. 4. This is the first observation of this decay.

The η_c is reconstructed in the $K^+K^-\pi^0$ and $K_SK^-\pi^+$ modes. As the modes are hadronic, tighter selection criteria are used. Charged kaons are required to be positively identified using combined information from CDC dE/dx, TOF, and ACC information. For the $K^+K^-\pi^0$ mode we require the invariant mass of the η_c candidate to be between 2.890 and 3.040 GeV/c^2. To suppress background from continuum we require $R_2 < 0.45$ and $|\cos\theta_{thr}| < 0.85$ where θ_{thr} is the thrust axis define by the B^0 candidate and that of the rest of the event. For the $K_SK^-\pi^-$ mode we require the invariant mass to be between 2.935 and 3.035 GeV/c^2, $R_2 < 0.40$, and $|\cos\theta_{thr}| < 0.85$.

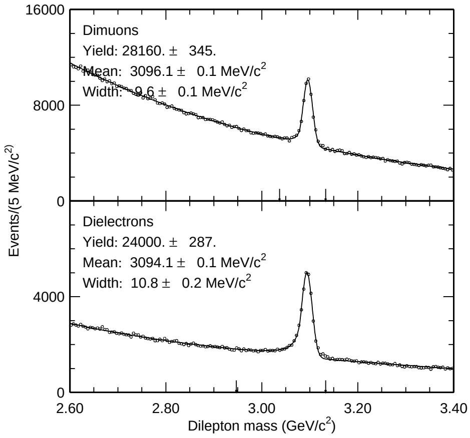

Figure 1: Dilepton invariant mass spectra in J/ψ mass region. One lepton has been positively identified while the other has passed a lepton consistency requirement.

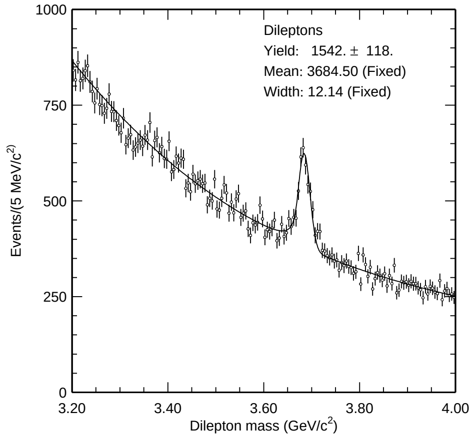

Figure 2: Dilepton invariant mass spectra in $\psi(2S)$ region. Both leptons have been positively identified.

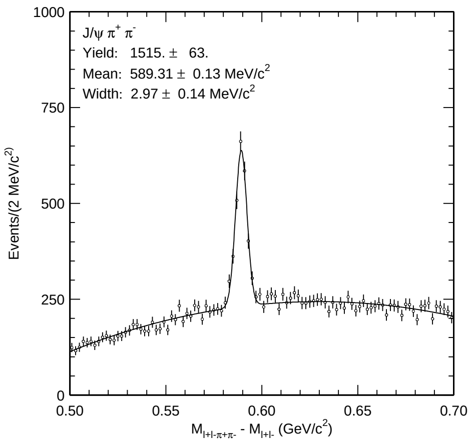

Figure 3: Invariant mass difference between $\psi(2S)$ candidate and J/ψ candidate.

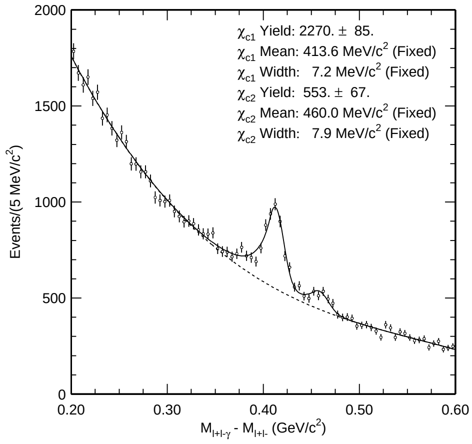

Figure 4: Invariant mass difference between χ_c candidate and J/ψ candidate.

Charmonium candidates are then paired with $K_S(\pi^+\pi^-)$ candidates to form B-meson candidates. These K_S candidates are identified by a displaced $\pi^+\pi^-$ vertex and a mass within 4σ of the K^0 mass ($\sigma \approx 4\text{MeV}/c^2$). In addition, we reconstruct B mesons by combining J/ψ candidates with $K_S(\pi^0\pi^0)$, K_L, or $K^{*0}(K_S\pi^0)$ candidates. For $K_S(\pi^0\pi^0)$, all combinations of two $\gamma\gamma$ pairs with an invariant mass between 80 and 150 MeV/c^2 are tried, assuming that the photons originate from the interaction point. We then minimize the sum of χ^2's coming from fitting the pairs of photons assuming a π^0 mass, varying the decay point along the K_S flight path which is assumed to be along a line from the interaction point to the energy-weighted center of the four showers. For K_L, we define a candidate to be a shower in the ECL and/or KLM that is not matched to a charged track and has a hit pattern consistent with coming from a hadronic shower. For K^{*0}, we define a candidate as a K_S and π^0 pair with an invariant mass with in 75 MeV/c of the K^{*0} mass. Background from low momentum π^0's is reduced by requiring $\cos\theta_{K^*} < 0.8$, where θ_{K^*} is the angle between the K_S direction and the K^{*0} direction calculated in the K^{*0} rest frame.

We define B-meson candidates for all modes except $J/\psi K_L$ via two kinematic variables. The first variable is ΔE, defined as the difference between the energy of the B candidate and the beam energy in the center of mass. B candidates are required to have a ΔE consistent with zero. The exact criteria depends on the mode and is typically with ± 40 MeV (larger values for modes with π^0's). Since at the $\Upsilon(4S)$ only two B mesons are produced the B energy must match the beam energy. The second variable is the "beam constrained mass" (bc). This is the invariant mass of the B candidate where the beam energy has been used instead of the B-candidate energy. This considerably improves the mass resolution. B candidates are required to have a beam constrained mass between 5.270 and 5.280 GeV/c^2. A list of the number of candidates for each mode can be found in Table 1. Fig. 5 shows the beam constrained mass plot for the fully reconstructed candidates.

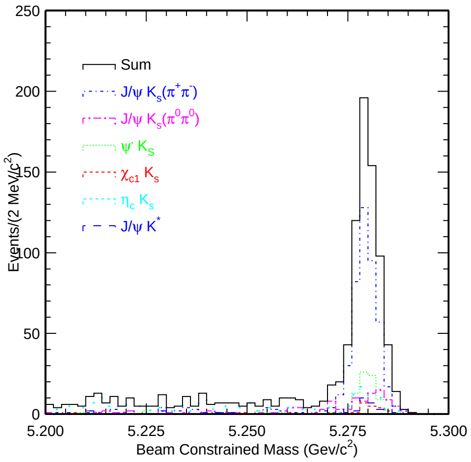

Figure 5: Beam-energy constrained mass plot for fully reconstructed modes (all but $J/\psi K_L$).

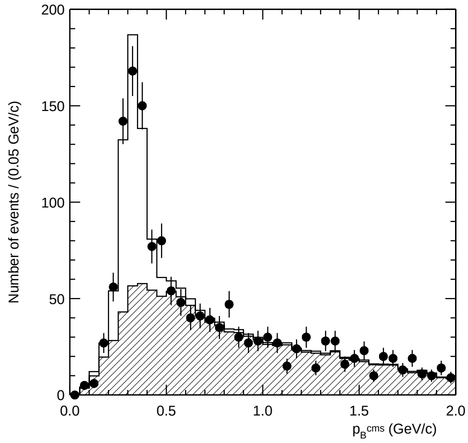

Figure 6: B-candidate momentum in center of mass rest frame for $B \to J/\psi K_L$.

Reconstruction of $J/\psi K_L$ candidates is a bit more difficult as the K_L momentum is not directly measured. We begin by requiring that the centroid of the K_L candidate shower be within 45° of the inferred flight direction from the two body decay $B \to J/\psi K_L$. The background is reduced through a likelihood ratio composed of the J/ψ com momentum, the angle of the K_L and its nearest neighbor charged track, the charged track multiplicity of the event, the extent the event is consistent with $B^+ \to J/\psi K^{*+}(K_L\pi^+)$, and the polar angle of the reconstructed B with respect to the z direction of the reconstructed B^0 in the com. We also remove events that are reconstructed as $B^0 \to K_S$, $J/\psi K^{*0}(K^+\pi^-, K_S\pi^0)$, $B^+ \to J/\psi K^+$, or $J/\psi K^{*+}(K^+\pi^0, K_S\pi^+)$ decays. K_L clusters that match a photon that reconstructs with another photon to form a π^0 candidate are also rejected.

Next we calculate the momentum of the B candidate in the com assuming the $B^0 \to J/\psi K_L$ hypothesis (p_B^{com}). This distribution is shown in Fig. 6. The histogram shows a fit to a combination of signal and background line shapes that were determined by a Monte Carlo simulation where the normalization and peak position were allowed to vary. For K_L candidates that contain KLM hits, the signal region is defined to be $0.2 \le p_B^{com} \le$

$0.45\text{GeV}/c$. There are 397 candidate events in this region. For K_L candidates that contain only ECL hits the signal region is $0.2 \le p_B^{com} \le 0.40\text{GeV}/c$. There are 172 events in this region. The combined fit give a total of $(346 \pm 29) J/\psi K_L$ signal events with a purity of 61%.

3. Flavor Tagging

Mode	N_{ev}	N_{bkgd}
$J/\psi(l^+l^-)K_S(\pi^+\pi^-)$	457	11.9
$J/\psi(l^+l^-)K_S(\pi^0\pi^0)$	76	9.4
$\psi(2S)(l^+l^-)K_S(\pi^+\pi^-)$	39	1.2
$\psi(2S)(J/\psi\pi^+\pi^-)K_S(\pi^+\pi^-)$	46	2.1
$\chi_{c1}(J/\psi\gamma)K_S(\pi^+\pi^-)$	24	2.4
$\eta_c(K^+K^-\pi^0)K_S(\pi^+\pi^-)$	23	11.3
$\eta_c(K_SK^-\pi^+)K_S(\pi^+\pi^-)$	41	13.6
$J/\psi(l^+l^-)K^{*0}(K_S\pi^0)$	41	6.7
Subtotal	747	58.6
$J/\psi(l^+l^-)K_L$	569	223

Table 1: The number of observed event candidates (N_{ev}) and the estimated background (N_{bkgd}) in the signal region for each f_{CP}.

Once we have our CP B-candidates we must tag the flavor of the other B meson. The tag exploits the kinematics of the $b \to c \to s$ quark decay chain that reflect the flavor of the b. We look for high momentum leptons from $b \to cl^-\bar{\nu}$, low momentum leptons from $c \to sl^+\nu$, charged kaons and Λ baryons from $c \to sX$, high momentum pions from $B \to D^{(*)}h$ where h is a π^+, ρ^+, a_1^+, etc., and slow pions from $D^{*-} \to \bar{D}^0\pi^-$.

For each of these categories tagging methods we use MC to determine a method-dependent variable that reflects if a track originated from a B^0 or $\bar{B}^0$. The particles charge, com momentum, polar angle and particle-identification probability, as well as event level properties go into determining this variable. The variables range continuously between -1 and $+1$ with a value of -1 indicating a reliably identified $\bar{B}^0$ and a value of $+1$ indicating a reliably identified B^0.

The results of the separate methods are then combined together taking into account correlations. The output of this level is a value 'q' that is -1 if the tag-side B is more B^0 like or -1 if it is more $\bar{B}^0$ like. A second value 'r' is output giving the quality of the tag, 0 if there is no flavor discrimination and 1 if there is perfect discrimination. The value r is used to divide the data into six groups according to flavor purity.

The incorrect flavor assignment probability w_l is determined for each bin of r from data using self-tagged decays ($B^0 \to D^{*-}l^+\nu$, $D^{(*)-}\pi^+$, and $D^{*-}\rho^+$. The values of w_l are determined by the amplitudes of the time-dependent $B^0\bar{B}^0$ mixing oscillations described by: $\frac{N_{OF}-N_{SF}}{N_{OF}+N_{SF}} = (1-2w_l)\cos(\Delta m_d \Delta t)$, where N_{OF} is the number of events with opposite flavor B's and N_{SF} is the number of events with the same flavor B's. In performing the fits, Δm_d is fixed to the world average value[10]. The total tagging efficiency is then then $\sum_l f_l(1-2w_l)^2 = 0.270 \pm 0.008(\text{stat})^{+0.006}_{-0.009}(\text{syst})$ where f_l is the fraction of events in each bin of r. A summary of f_l and w_l can be found in Table 2.

4. Vertexing

The next step is to find the time difference between the two B decays which requires us to find the vertex of the two B's. We only use tracks that have both $r-\phi$ and z hits in the same SVD layer along with one or more additional z hits in the other layers. Both vertices are required to be consistent with the interaction point profile taking into account the B meson decay length. For the f_{CP} B only the tracks that come from the charmonium candidate are used: lepton tracks for J/ψ and $\psi(2S)$ and prompt hadron tracks for η_c. The efficiency and the z vertex resolution (rms) are determined from Monte Carlo and found to be 95% and 75 μm (measured with $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^{*0}(K^+\pi^-)$ data events). For the f_{tag} B we use all tracks not associated with the f_{CP} B and not associated with a K_S decays. Tracks that contribute a large χ^2 to the vertex fit are eliminated in an iterative process. The efficiency and z vertex resolution for the f_{CP} B are 93% and 140 μm (also measured with $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^*0(K^+\pi^-)$ data events).

Once the two vertices have been found, the proper-time interval is calculated. The resolution of the proper-time interval R_{sig} is an important input in to the CP fit. It is approximated by the sum of two Gaussians, a main Gaussian that is due to the SVD vertex resolution and charm meson lifetimes, and a tail Gaussian due to poorly reconstructed tracks. The relative fractions of the two Gaussians is determined from a study of $B^0 \to D^{*-}\pi^+$, $D^{*-}\rho^+$, $D^-\pi^+$, $J/\psi K_S$, and $B^+ \to \bar{D}^0\pi^+$, $J/\psi K^+$ events. The main component fraction is 0.97 ± 0.02. The mean and errors of the Gaussians are calculated on an event-by-event basis from the vertex fit error matrices and the χ^2 of the fit. Typical values for the main (tail) component are -0.24 ps (0.18 ps) for the mean and 1.49 ps (3.85 ps) for the error.

l	r	f_l	w_l
1	0.000-0.250	0.405	$0.465^{+0.010}_{-0.009}$
2	0.250-0.500	0.149	$0.352^{+0.015}_{-0.014}$
3	0.500-0.625	0.081	$0.243^{+0.021}_{-0.030}$
4	0.625-0.750	0.099	$0.176^{+0.022}_{-0.017}$
5	0.750-0.875	0.123	$0.110^{+0.022}_{-0.014}$
6	0.875-1.000	0.140	$0.041^{+0.011}_{-0.010}$

Table 2: For each bin of ‘r’, the event fraction f_l and w_l are listed. Errors include both statistical and systematic uncertainties.

The “resolution” for background events $R_{bkg}(t)$ is also a necessary input for the CP fit. The shape is also described by a double Gaussian. The parameters are determined by studying the sidebands in M_{bc} and ΔE.

To verify our procedure for finding the vertex resolutions we measure the B meson lifetimes using the same resolutions and techniques. We find $\tau_{B^0} = 1.547 \pm 0.021$ and $\tau_{B^+} = 1.641 \pm 0.033 ps$ where the errors are statical only.

5. Fitting Procedure

We perform an unbinned likelihood fit to find $\sin 2\phi_1$. The fit includes the vertex resolutions for signal and background, mistagging fraction, CP state of B, and for $J/\psi K^*$ the transversity angle.

After vertexing we find 560 events with $q = +1$ and 577 events with $q = -1$ flavor tags. A clear asymmetry can be seen in the raw data when distributions in Δt are made for $q\xi_f = +1$ and $q\xi_f = -1$ separately as seen in Fig. 7. This in itself shows that CP symmetry is violated.

In order to determine $\sin 2\phi_1$ we perform an unbinned maximum likelihood fit. The probability density function (PDF) for signal events for all modes except $B \to J/\psi K^{*0}$ is

$$\mathcal{P}_{signal}(\Delta t, q, w_l, \xi_f) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}}\{1 - \xi_f q(1-w_l) \times \sin 2\phi_1 \sin(\Delta m_d \Delta t)\}. \quad (5.1)$$

For $J/\psi K^{*0}$ we include the Δt and transversity angle θ_{tr}[9] in the likelihood and use the ξ_f content from the full angular analysis. The values of Δm_d and τ_{B^0} are fixed to the world averages, $\Delta m_d = 0.472\text{ps}^{-1}$ and $\tau_{B^0} = 1.55\text{ps}$[10].

For background we use

$$\mathcal{P}_{bkg}(\Delta t) = f_\tau \frac{e^{-|\Delta t|/\tau_{bkg}}}{2\tau_{bkg}} + (1-f_\tau)\delta(\Delta t), \quad (5.2)$$

where f_τ is the fraction of the background with a non-zero effective lifetime τ_{bkg} and δ is the Dirac delta function. Looking at the regions in M_{bc} and ΔE where background dominates we find that f_τ is effectively zero for all modes but $J/\psi K_L$.

For $J/\psi K_L$, the backgrounds are dominated by inclusive $B \to J/\psi X$ decays. We use Monte Carlo to determine the make up of this background and the relative amounts of the various modes that are CP eigenstates. We find 71% of the background is non-CP modes with $\tau_{bkg} = \tau_{B^0}$. Another 13% of the background is $J/\psi K^{*0}(K_L \pi^0)$. For this component we use the ξ_f content determined by the full angular analysis of $B \to J/\psi K^*$. Events with $\xi_f = +1$ make up 5% of the background while events with $\xi_f = -1$ make up 10%.

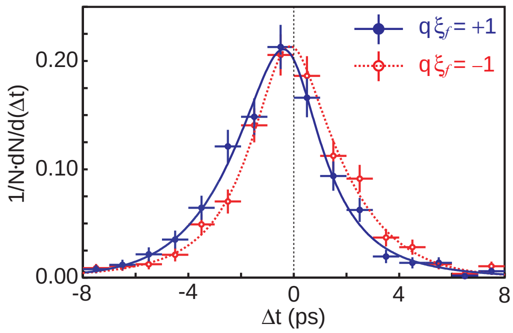

Figure 7: The Δt distribution for events with $q\xi_f = +1$ (red solid points) and $q\xi_f = -1$ (blue open points). The distribution is overlayed with the results of the global fit.

The final step is to maximize the likelihood $L = \Pi_i P_i$ where

$$P_i = \int \{f_{sig}\mathcal{P}_{sig}(\Delta t', q, w_l, \xi_f) R_{sig}(\Delta t - \Delta t') + (1-f_{sig})\mathcal{P}_{bkg}(\Delta t') R_{bkg}(\Delta t - \Delta t')\} d\Delta t', \quad (5.3)$$

where f_{sig} is the probability that an event is signal as determined by M_{bc} and ΔE for all decays except $J/\psi K_L$ where p_B^{com} is used. The only free parameter in the fit is $\sin 2\phi_1$. We find

$$\sin 2\phi_1 = 0.99 \pm 0.14(\text{stat}) \pm 0.06(\text{syst}). \quad (5.4)$$

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It is perhaps easiest to demonstrate the significance of this fit by overlaying the curve derived from this fit on top of asymmetries determined for individual bins of Δt. This is shown in Fig. 8a. In Fig. 8b and Fig. 8c are shown the corresponding asymmetries for events with $\xi_f = -1$ (all events except $J/\psi K_L$ and $J/\psi K^{*0}$) and for events with $\xi_f = +1$ ($J/\psi K_L$). The values of $\sin 2\phi_1$ determined for each of these subsets of events are 0.84 ± 0.17 and 1.31 ± 0.23 respectively, where the errors are statistical only.

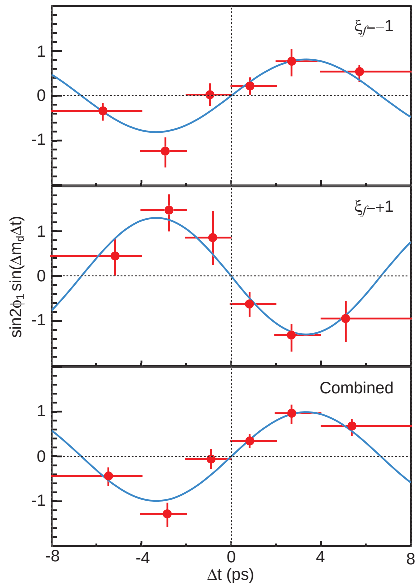

Figure 8: Time dependent asymmetry.

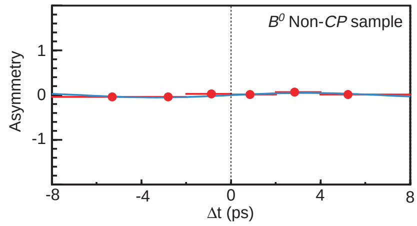

Figure 9: Time dependent asymmetry for a control sample.

A variety of check have been performed for this measurement. An obvious check is to perform the fit to a set of non-CP events that are self tagged where the expected asymmetry is zero. When we fit to a set of such events that include $B^0 \to D^{(*)-}\pi^+$, $D^{*-}\rho^+$, $J/\psi K^{*0}(K^+\pi^-)$, and $D^{*-}l^+\nu$, we find a value of 0.05 ± 0.04. The asymmetry for this control sample is shown in Fig. 9. Other checks involve breaking the event sample into different components. The results of these fits are shown in Table 3.

Sample	$\sin 2\phi_1$
$f_{tag} = B^0(q = +1)$	0.84 ± 0.21
$f_{tag} = \bar{B}^0(q = -1)$	1.11 ± 0.17
$J/\psi K_S(\pi^+\pi^-)$	0.81 ± 0.20
$c\bar{c}K_S$ except $J/\psi K_S(\pi^+\pi^-)$	1.00 ± 0.40
$J/\psi K_L$	1.31 ± 0.23
$J/\psi K^{*0}(K_S\pi^0)$	0.85 ± 1.45
All	0.99 ± 0.14

Table 3: The values of $\sin 2\phi_1$ for various subsamples. The errors are statistical only.

Source	Contribution
Vertex Algorithm	± 0.04
Flavor Tagging	± 0.03
Resolution Function	± 0.02
Background Fraction K_L	± 0.02
Background Shape	± 0.01
Δm_d and τ_{B^0} errors	± 0.01
Total	± 0.06

Table 4: Sources of Systematic Errors.

We have also performed checks where the values of Δm_d and τ_{B^0} are allowed to float. We find for the former case a value of $\sin 2\phi_1$ of 1.00 ± 0.14 with a value of Δm_d of 0.478 ± 0.057. For the latter case we find $\sin 2\phi_1 = 1.00 \pm 0.14$ with a value of τ_{B^0} of 1.66 ± 0.07 ps. We also allowed for direct CP violation. We find the fit result consistent with no direct CP violation and the value of $\sin 2\phi_1$ to be unchanged.

6. Summary

We have measured a large CP violation in the neutral B-meson system. The value is consistent with the largest value of CP violation allowed in the KM model. A value of zero is ruled out at a statistical significance of more than 6σ. In the process of performing this measurement we have also observed for the first time $B \to \chi_{c2} X$ production.

A comparison of our measurement with measurements of $\sin 2\phi_1$ from other experiments, as well as a combined value can be seen in Fig. 10[11]. It is now clear that CP violation occurs in the B-meson system as well as in the K-meson system. Kobayashi and Maskawa's model has been a stunning success in describing basic quark interactions.

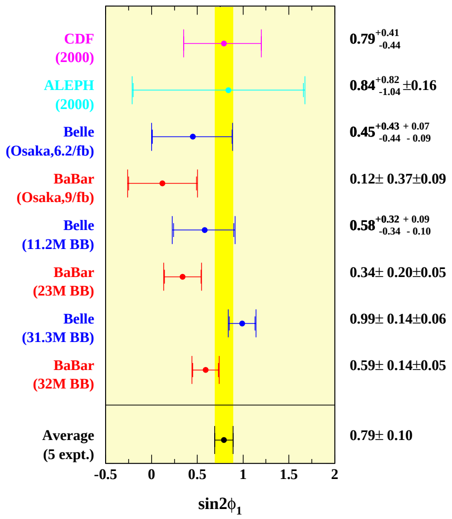

Figure 10: Comparison with other experiments.

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