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Measurement of $\sin 2\beta$ in $B^0 \to \phi K_S^0$

The *BABAR* Collaboration

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Abstract

We present a preliminary measurement of the time-dependent CP-violating asymmetry in the neutral B decay $B^0 \to \phi K_S^0$, with $\phi \to K^+K^-$ and $K_S^0 \to \pi^+\pi^-$. The measurement uses a data sample of about 87 million $\Upsilon(4S) \to B\overline{B}$ decays collected between 1999 and 2002 with the *BABAR* detector at the PEP-II asymmetric-energy B Factory at SLAC. In this sample we study events in which the CP final state is fully reconstructed and the flavor of the other neutral B meson is determined from its decay products. The amplitude of the CP-violating asymmetry $\sin 2\beta$ is derived from the decay-time distributions. We measure $\sin 2\beta = -0.19^{+0.52}_{-0.50}(\mathrm{stat}) \pm 0.09(\mathrm{syst})$.

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1 Introduction

Recent measurements of the CP-violating asymmetry parameter $\sin 2\beta$ by the *BABAR* [1] and Belle [2] collaborators established CP violation in the B^0 system. These measurements, as well as the updated measurement of $\sin 2\beta = 0.741 \pm 0.067(stat) \pm 0.033(syst)$ by *BABAR* [3] reported at this conference, are consistent with the Standard Model expectation based on measurements and theoretical estimates of the Cabbibo-Kobayashi-Maskawa quark-mixing matrix [4].

Charmless hadronic B meson decays provide important information for the study of CP violation effects. The charmless B meson decays into final states with a ϕ meson are interesting because they are dominated by $b \to s\bar{s}s$ gluonic penguins (Figure 1), with a smaller contribution from electroweak penguins, while other Standard Model contributions are highly suppressed. These decays allow the extraction of the CP-violating parameter $\sin 2\beta$. Comparison of the value of $\sin 2\beta$ obtained from these modes with that from charmonium modes probe for new physics participating in penguin loops [5, 6]. The predicted deviation of the effective $\sin 2\beta$ for the ϕK^0_S mode from $\sin 2\beta$ in the Standard Model is smaller than 4% [5, 7]. In this analysis we probe for sizable deviations which are possible in many scenarios beyond the Standard Model.

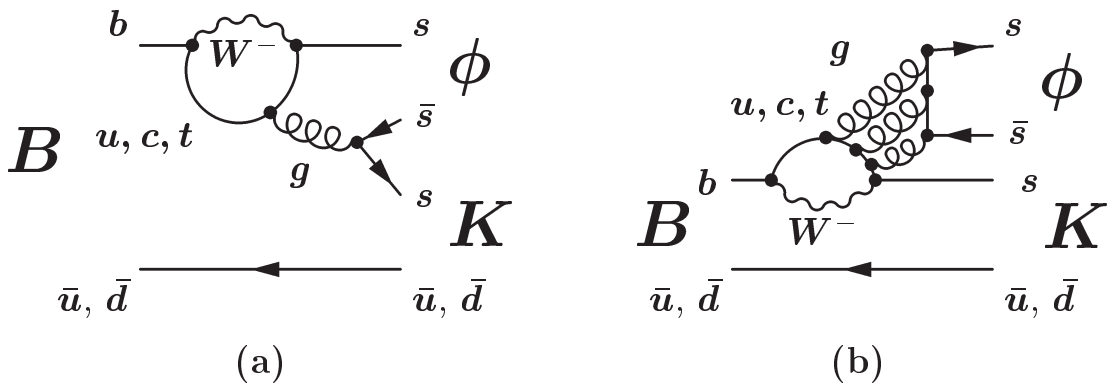

Figure 1: Quark-level diagrams describing the decays $B \to \phi K$: (a) internal penguin, (b) flavor-singlet penguin.

The decay of neutral B mesons to the CP = -1 final state ϕK^0_S has been observed by *BABAR* in a sample of about 45 million B mesons with a branching fraction of $BF(B^0 \to \phi K^0) = (8.1^{+3.1}_{-2.5} \pm 0.8) \times 10^{-6}$ [8]. The channel $B^+ \to \phi K^+$, which is used as control channel for the time-dependent analysis, was also observed with a branching fraction of $(7.7^{+1.6}_{-1.4} \pm 0.8) \times 10^{-6}$ [8].

The measurement of the time-dependent CP asymmetry in $B^0 \to \phi K^0_S$ is similar to our approach in the charmonium channels [9]. We use an extended parametrization of the likelihood describing the event yield in signal and background which is combined with the likelihood for the decay-time distributions.

2 The *BABAR* Detector and Data Set

This measurement is based on data recorded with the *BABAR* detector [10] at the PEP-II energy-asymmetric e^+e^- storage ring at SLAC. The data sample corresponds to an integrated luminosity of approximately 80 fb^{-1} that was collected at the $\Upsilon(4S)$ resonance.

The detector consists of a five-layer silicon vertex tracker (SVT), a 40-layer drift chamber (DCH), a detector of internally reflected Cherenkov light (DIRC), an electromagnetic calorimeter (EMC), assembled

from 6580 CsI(Tl) crystals, all embedded in a solenoidal magnetic field of 1.5 T and surrounded by an instrumented flux return (IFR). The performance of the detector is discussed in [9].

3 Analysis Method

3.1 Time dependent Analysis

Each candidate event consists of a fully reconstructed neutral B meson, B_{CP}, decaying into ϕK^0_S and a partially reconstructed recoil B, B_{tag}, which we examine for evidence that it decayed as B^0 or $\overline{B}^0$ (flavor tag). The decay-time distribution of B decays to a CP eigenstate with a B^0 or $\overline{B}^0$ tag can be expressed in terms of a complex parameter λ that depends on both the B^0-$\overline{B}^0$ oscillation amplitude and the amplitudes describing $\overline{B}^0$ and B^0 decays to this final state [11]. The decay rate $\mathrm{f}_+(\mathrm{f}_-)$ when the tagging meson is a $B^0(\overline{B}^0)$ is given by

$$\mathrm{f}_\pm(\,\Delta t) = \frac{\mathrm{e}^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \times \left[\, 1 \pm \frac{2\,\mathcal{I}m\lambda}{1+|\lambda|^2}\sin\left(\Delta m_d \Delta t\right) \mp \frac{1-|\lambda|^2}{1+|\lambda|^2}\cos\left(\Delta m_d \Delta t\right)\right], \tag{1}$$

where $\Delta t = t_{CP} - t_{tag}$ is the difference between the proper decay time of the reconstructed B meson (B_{CP}) and the proper decay time of the tagging B meson (B_{tag}), τ_{B^0} is the B^0 lifetime, and Δm_d is the B^0-$\overline{B}^0$ oscillation frequency. The sine term in Eq. (1) is due to the interference between direct decay and decay after flavor change, and the cosine term is due to the interference between two or more decay amplitudes with different weak phases. Evidence for CP violation can be observed as a difference between the Δt distributions of B^0- and $\overline{B}^0$-tagged events or as an asymmetry with respect to $\Delta t = 0$ for either flavor tag.

In the Standard Model and for the case that the decay proceeds purely via $b \to s\bar{s}s$ gluonic penguin transitions, $\lambda = \eta_f e^{-2i\beta}$, and the angle β of the Unitarity Triangle of the three-generation CKM matrix [12] is given as $\beta = arg\,[-V_{cd}V^\star_{cb}/V_{td}V^\star_{tb}]$.

Thus, the time-dependent CP-violating asymmetry is

$$A_{CP}(\Delta t) \;\equiv\; \frac{\mathrm{f}_+(\Delta t) - \mathrm{f}_-(\Delta t)}{\mathrm{f}_+(\Delta t) + \mathrm{f}_-(\Delta t)} = -\eta_f \sin 2\beta \sin\left(\Delta m_d\,\Delta t\right), \tag{2}$$

with CP eigenvalue $\eta_f = -1$ for ϕK^0_S, and $K^0_S \to \pi^+\pi^-$.

3.2 Reconstruction of the ϕK^0_S Final State

We fully reconstruct B meson candidates (B_{CP}) in the decay mode ϕK^0_S with $K^0_S \to \pi^+\pi^-$ and $\phi \to K^+K^-$. For the charged tracks belonging to the recoil B and to the K^0_S we require at least 12 measured drift chamber hits and a minimum transverse momentum of 0.1 GeV/c. The kaon tracks of the ϕ in addition have to originate within 1.5 cm in the transverse plane and 10 cm in beam direction from the interaction point.

A track is identified as a kaon based on a likelihood ratio combining the dE/dx information from the SVT and DCH below 700 MeV/c, and from DCH dE/dx and DIRC Cherenkov angle and measured Cherenkov photon number above this momentum. We define ϕ candidates as pairs of tracks with opposite charge which can be combined and fit to a common vertex and whose invariant K^+K^- mass lies within a 20 MeV/c^2 mass interval centered at the ϕ mass. In case there is no particle identification (PID) information,

the kaon hypothesis is assumed for one of the two tracks from the candidate ϕ decay. Using a relativistic Breit-Wigner function of fixed mass and width [13] convoluted with a Gaussian we obtain an invariant mass resolution of 1.1 MeV/c^2 in the ϕ signal.

Analogously to the ϕ, we construct the K_S^0 from two oppositely charged tracks which are assumed to be pions. The selection of $K_S^0 \to \pi^+\pi^-$ candidates is based on the angle α between the line connecting ϕ vertex and K_S^0-decay vertex and the momentum direction reconstructed from the pions ($\cos\alpha > 0.999$). Furthermore, we use the decay-time significance t/σ_t ($t/\sigma_t > 3$).

3.3 Event Yield Variables

The measurement of B decays at the $\Upsilon(4S)$ resonance provides kinematic constraints for the initial state. Substitution of the measured energy by the beam energy reduces the resolution of kinematic variables substantially.

Energy resolution can be expressed as:

$$\Delta E = E_B - E_{bc}\,, \tag{3}$$

with E_{bc} the beam constrained energy, which for the candidate B meson is derived as follows:

$$E_{bc} = \frac{s + 2\vec{p}_i \cdot \vec{p}_B}{2E_i}\,, \tag{4}$$

with $\sqrt{s}$ the total e^+e^- center-of-mass energy. The four momentum of the initial state is represented by $(E_i, \vec{p}_i)$, and $(E_B, \vec{p}_B)$ is the four momentum of the candidate B meson, both measured in the laboratory; E_{bc} results from the assumption that we have particle-antiparticle production. Notice that the B-candidate momentum $\vec{p}_B$ is independent of the mass values assigned to the tracks comprising the candidate B. Signal events distribute in ΔE according to a Gaussian with a mean consistent with zero (± 2 MeV). The observed width is about 17 MeV. The background shape in ΔE is parametrized by a linear function. We require $|\Delta E| < 200$ MeV.

The second kinematic quantity in our analysis is the beam-energy substituted mass m_{ES}, which is defined as:

$$m_{ES} = \sqrt{E_{bc}^2 - \vec{p}_B^{\,2}}. \tag{5}$$

Signal events are distributed Gaussian-like in m_{ES} with a mean at the B mass and a resolution of about 2.6 MeV/c^2, dominated by the beam energy spread. The background shape in m_{ES} is parametrized by a threshold (ARGUS) function [14] with a fixed endpoint given by the average beam energy. Our selection requires $m_{ES} > 5.22$ GeV/c^2.

The helicity angle θ_H of the ϕ is defined as the angle between the direction of the decay K^+ and the parent B direction in the ϕ rest frame. For pseudoscalar-vector B decay modes, angular momentum conservation results in a $\cos^2\theta_H$ distribution. In this variable the background is uniformly distributed.

Monte Carlo simulation demonstrates that contamination from other B decays is negligible. Possible (K^+K^-) S-wave contributions ($f_0(980)$) are not expected to peak under the ϕ meson [15] and are suppressed by the helicity angle which distributes uniformly for this background. However, charmless hadronic modes suffer from backgrounds due to random combinations of tracks produced in the quark-antiquark ($\bar{q}q$) continuum, where q is dominantly u, d, and s quarks. The distinguishing feature of such backgrounds is their characteristic event shape resulting from the two-jet production mechanism.

We consider the angle θ_T between the thrust axis of the B candidate and the thrust axis of the rest of the event, where the thrust axis is defined as the axis that maximizes the sum of the magnitudes of the

longitudinal momenta in the $\Upsilon(4S)$ center-of-mass system. This angle is small for continuum events where the B-candidate daugthers come from back-to-back $\bar{q}q$ jets, and is uniformly distributed for true $B\bar{B}$ events. In the event preselection we require $|\cos\theta_T| < 0.9$.

Additional shape information comes from the momentum flow around the B thrust axis described through momentum weighted Legendre polynomials, L_i. The best separation between the signal and continuum events is achieved with the zeroth order ($L_0 = \sum p_i^\star$) and the second order ($L_2 = \sum p_i^\star \times \frac{1}{2}(\cos^2\theta_i^\star - 1)$) polynomials, where $p_i^\star$ and $\theta_i^\star$ are the center-of-mass momentum and angle with respect to the B_{CP} thrust axis and the sum is over all charged tracks and neutrals in the event that are not associated with the B-candidate.

The last event shape variable is the B production angle, θ_B, with respect to the beam direction in the $\Upsilon(4S)$ center-of-mass frame. In decays of a real $\Upsilon(4S)$ into two pseudoscalar B mesons, the production angle follows a $\sin^2\theta_B$ distribution, while it is approximately uniformly distributed for the continuum events.

The shape variables are strongly correlated and cannot be used independently in the likelihood calculation. A Fisher discriminant is formed as a linear combination of the shape variables $x = |\cos\theta_T|$, $\cos\theta_B$, L_0, and L_2:

$$\mathcal{F} = \sum \gamma_i x_i, \tag{6}$$

where coefficients γ_i are chosen such to make the maximum separation between the signal and continuum event distributions. The coefficients are calculated using Monte Carlo signal events and background events from data sidebands ($0.1 < \Delta E < 0.3$). For the resulting signal Fisher distribution we use a bifurcated Gaussian distribution. The background Fisher shape is described by a sum of two Gaussian distributions.

4 Tagging and Vertexing

We use a B-tagging algorithm based on multivariate techniques to determine the flavor of B_{tag} [3]. The algorithm relies on the correlation between the flavor of the b quark and the charge of the remaining tracks in the event after removal of the B_{CP} candidate. Separate neural networks are trained to identify primary leptons from semileptonic B decay, kaons, soft pions from D^* decay, and high-momentum charged particles. The outputs of each neural network are combined to produce five hierachical and mutually exclusive tagging categories. Events with an identified electron or muon, and a supporting kaon, if present are assigned to the `Lepton` category. Events with an identified kaon and a soft-pion candidate with opposite charges are assigned to the `Kaon I` category. Events with one or more kaon candidates, and no lepton or soft-pion candidates, are assigned to the `Kaon I` or `Kaon II` categories depending on the estimated mistag probability. Events with only a soft-pion candidate are assigned to the `Kaon II` category as well. The remaining events are assigned to the `Inclusive` or `Untagged` category based on estimated mistag probability.

The quality of tagging is expressed in terms of the effective efficiency $Q = \sum_c \epsilon_c(1-2w_c)^2$, where ϵ_c and w_c are the efficiency and mistag probability, respectively, for events tagged in category c. Table 1 summarizes the tagging performance in a data sample of fully reconstructed neutral B decays into $D^{(*)-}h^+$ ($h^+ = \pi^+, \rho^+, a_1^+$) and $J/\psi K^{*0}$ ($K^{*0} \to K^+\pi^-$) flavor eigenstates (B_{flav} sample). The recoil B, B_{tag}, is again partially reconstructed. We use the same tagging efficiencies and dilutions for the ϕK_S^0 channel extracted from the statistical dominant flavor sample.

The time difference Δt is obtained from the measured distance between the z positions of the B_{CP} and B_{tag} decay vertices and the known boost of the e^+e^- system. For the B_{CP} we achieve a z-vertex position resolution of better than 60 μm which compares well to the resolution obtained in the final state $J/\Psi K_S^0$. The z position of the B_{tag} vertex is determined with an iterative procedure that removes tracks with a large contribution to the total χ^2. An additional constraint is constructed from the three-momentum

Table 1: Tagging efficiency ϵ, average mistag fraction w, mistag difference $\Delta w = w(B^0) - w(\overline{B}^0)$, and effective tagging efficiency Q for signal events in each tagging category. The values are measured in the B_{flav} sample.

Category	ϵ (%)	w (%)	Δw (%)	Q (%)
`Lepton`	9.1 ± 0.2	3.3 ± 0.6	-1.5 ± 1.1	7.9 ± 0.3
`Kaon I`	16.7 ± 0.2	10.0 ± 0.7	-1.3 ± 1.1	10.7 ± 0.4
`Kaon II`	19.8 ± 0.3	20.9 ± 0.8	-4.4 ± 1.2	6.7 ± 0.4
`Inclusive`	20.0 ± 0.3	31.5 ± 0.9	-2.4 ± 1.3	2.7 ± 0.3
`Untagged`	34.4 ± 0.5			
Total Q				28.1 ± 0.7

and vertex position of the $B_{\rm CP}$ candidate, and the average e^+e^- interaction point and boost. For 98% of candidates with a reconstructed vertex the r.m.s. Δz resolution is $180\,\mu\mathrm{m}$ $(1.1\,\mathrm{ps})$. We require $|\Delta t| < 20\,\mathrm{ps}$ and $\sigma_{\Delta t} < 3.5\,\mathrm{ps}$, where $\sigma_{\Delta t}$ is the event-by-event error on Δt.

The Δt resolution is dominated by the tag-side (B_{tag}), which is well under control from our flavor sample. The empirical Δt resolution function for signal candidates is parametrized by a sum of three Gaussian distributions (see Ref. [16]), with parameters determined from a fit to the flavor sample. A common parametrization is used for all tagging categories, and the parameters are determined simultaneously with the CP parameters in the maximum likelihood fit. The tagging parameters for the untagged events are fixed to $w = 0.5$ and $\Delta w = 0$. The Δt background in the ϕK^0_S channel does not show a lifetime component and is parametrized as a sum of two Gaussians, core and tail, with the tail fraction of 2%.

The parametrization of Δt is checked by measuring the lifetime in the channel ϕK^+ (180 signal events) which has a compatible Δt distribution. The obtained value agrees within 1σ with the world average [13].

4.1 Maximum Likelihood Fit

We use an unbinned extended maximum likelihood fit to extract yields and CP parameters from the ϕK^0_S (CP) sample, and simultaneously Δt resolution parameters and tagging quantities in the flavor sample. The likelihood for candidate j tagged in category c is obtained by summing the product of event yield n_i, tagging efficiency $\epsilon_{i,c}$, and probability $\mathcal{P}_{i,c}$ over the two possible signal and background hypotheses i.

$$\mathcal{L}_c = \frac{1}{N!} \exp\left(-\sum_i n_i \epsilon_{i,c}\right) \prod_j \left[\sum_i n_i \epsilon_{i,c} \mathcal{P}_{i,c}(\vec{x}_j; \vec{\alpha}_i)\right]. \tag{7}$$

The probabilities $\mathcal{P}_{i,c}$ are evaluated as the product of PDFs for each of the independent variables $\vec{x}_j = \{m_{\rm ES}, \Delta E, \mathcal{F}, \cos\theta_H, \Delta t\}$ in the CP sample, and $\vec{x}_j = \{m_{\rm ES}, \Delta E, \Delta t\}$ in the B_{flav} sample. The $\vec{\alpha}_i$ are fixed parameters that describe the expected distributions and are derived from fits to signal Monte Carlo, the $B^+ \to \phi K^+$ control channel, on-resonance sidebands, and off-resonance data. The Δt distributions of the $B_{\rm flav}$ sample evolve according to flavor oscillation in B^0 mesons. The observed amplitudes for the CP asymmetry in the CP sample and for flavor oscillation in the flavor sample are reduced by the same factor $1 - 2w$ due to flavor mistags. The total likelihood $\mathcal{L}$ is the product of likelihoods for each tagging category and the free parameters are determined by minimizing the quantity $-\ln\mathcal{L}$ [17].

The total number of ϕK^0_S candidate events in the fit region is 1352. In order to extract the event yields we perform an initial fit without tagging or Δt information. Our final CP sample is composed of 51 signal and 1301 background events distributed over the fit range. For our CP fit we fix these yields. The B_{flav} sample consists of about 26000 signal events with a purity of better than 80%.

There are 34 free variables in the fit, in agreement with the charmonium $\sin 2\beta$ fit [3], where only the parameter $\sin 2\beta$ is solely fit from the signal in $B^0 \to \phi K^0_S$ ($|\lambda| = 1$ fixed). The other parameters are the average mistag fraction w and the difference Δw between B^0 and $\overline{B}^0$ mistags for each tagging category (8), parameters for the signal Δt resolution (8), parameters for background time dependence (6), background Δt resolution (3), and mistag fractions (8). The determination of the mistag fractions and Δt resolution function parameters for the signal is dominated by the high-statistics flavor sample. We fix $\tau_{B^0} = 1.542\,\mathrm{ps}$ and $\Delta m_d = 0.489\,\mathrm{ps}^{-1}$ [13]. The largest correlation between $\sin 2\beta$ and any linear combination of the other free parameters is 2%.

The result for the effective $\sin 2\beta$ is:

$$\sin 2\beta = -0.19^{+0.52}_{-0.50}(stat) \pm 0.09(syst) \tag{8}$$

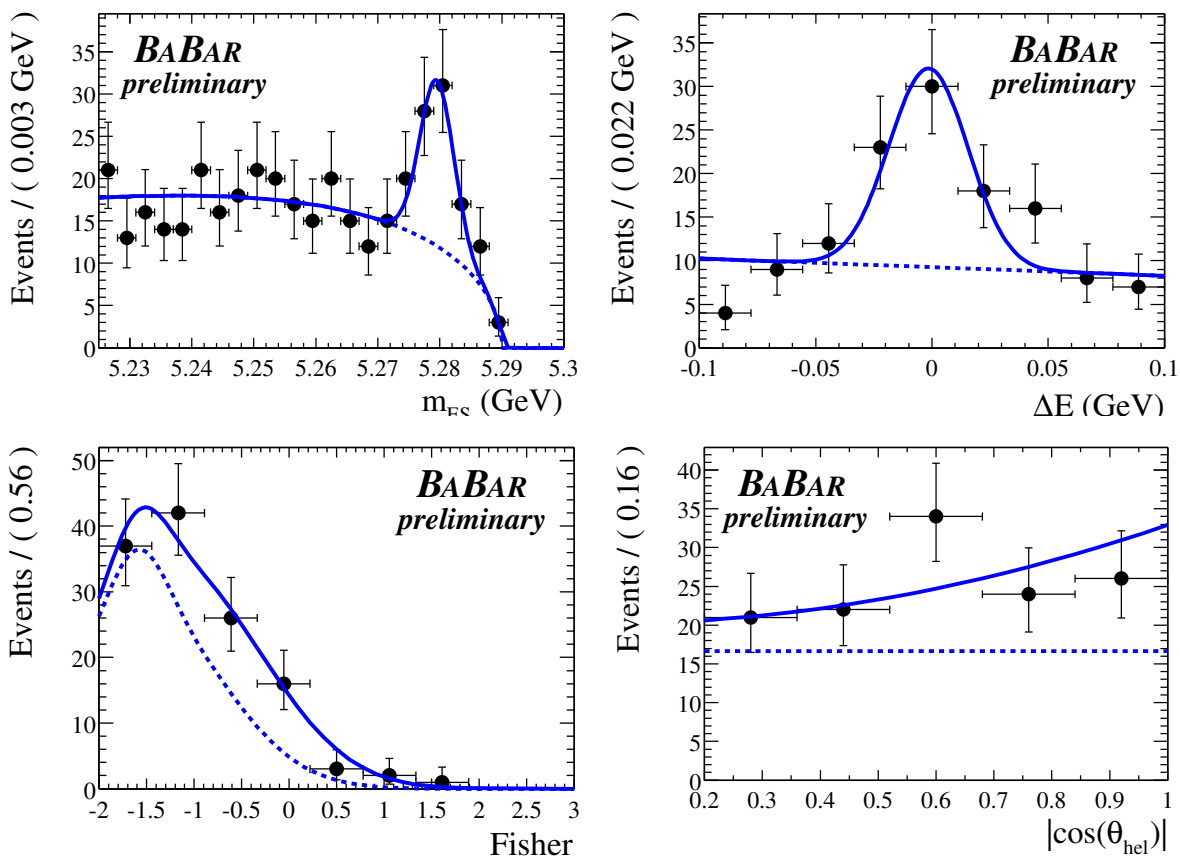

Figure 2: The distribution of the ϕK^0_S events in four fit variables with tighter selection criteria corresponding to the ranges shown (see text). The m_{ES} distribution is presented in a wider range. The solid line refers to the fit for all events, the dashed line corresponds to the expected background distribution.

Figure 2 shows the event yield variables for all events in the limited ranges $5.27 < m_{ES} < 5.3$ GeV/c^2, $|\Delta E| < 0.1$ GeV, $-2 < \mathcal{F} < 3$, and $|\cos\theta_H| > 0.2$, focussing into the signal region. Figure 3 shows the

Δt distributions for the B^0 and the $\bar{B}^0$ tagged subsets of these events with the fit superimposed.

As a consistency check we measure the CP asymmetry in the final state $B^+ \to \phi K^+$. From a sample of 180 signal events we obtain a CP asymmetry of $\sin 2\beta(\phi K^+) = 0.26 \pm 0.27$, which is consistent with the expected value of zero.

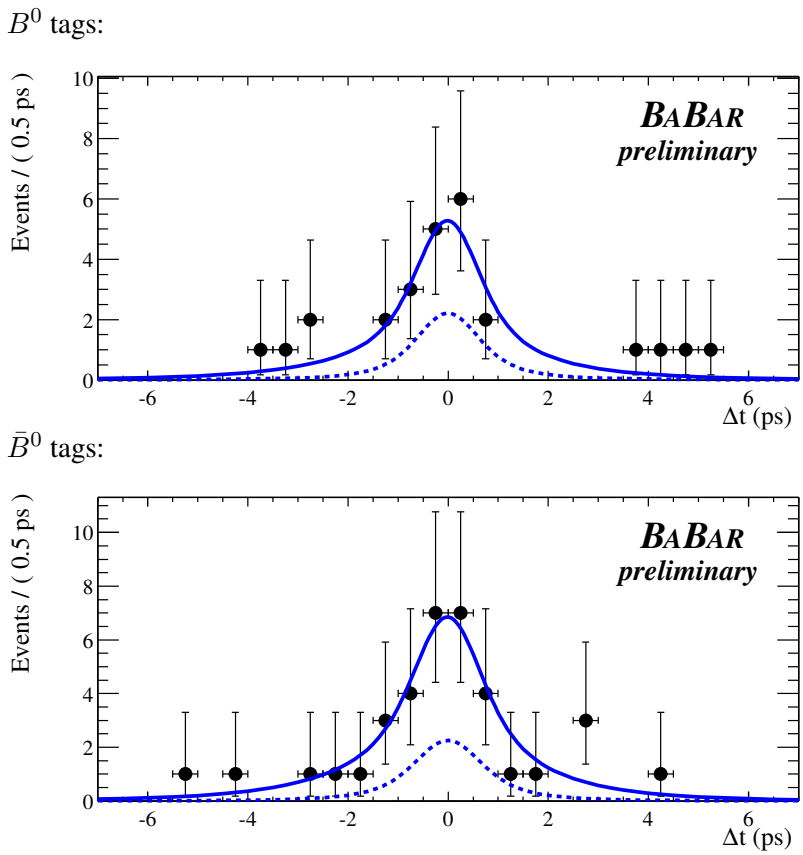

Figure 3: Time distributions for B^0 and $\bar{B}^0$ tags. The solid line refers to the fit for all events, the dashed line corresponds to background.

Repeating the fit with all parameters except $\sin 2\beta$ fixed to their values at the maximum likelihood, we attribute a total contribution in quadrature of 0.01 to the error on $\sin 2\beta$ due to the combined statistical uncertainties in mistag rates, Δt resolution, and background parameters.

The fit is repeated on generated datasets based on the probability density functions for signal and background shapes. We do not observe a bias in the refit value of $\sin 2\beta$.

We consider systematic uncertainties due to the event yield determination in ϕK^0_S (0.02), limited Monte Carlo statistics (0.02), composition and CP asymmetry in the background in the CP events (0.03), the assumed parametrization of the Δt resolution function (0.02), due in part to residual uncertainties in the Silicon Vertex Tracker alignment, and the fixed values for Δm_d and τ_B (0.006).

Furthermore, we explore the sensitivity to the parameter $|\lambda|$ in our limited sample. It turns out that the fit is not simultaneously sensitive to both $\sin 2\beta$ and $|\lambda|$. Therefore, we scan for the value of $|\lambda|$ over a wide range ($|\lambda| = 0...3$) but do not observe a strong variation of the central value of $\sin 2\beta$. We attribute an additional conservative error of 0.08 to our value of $\sin 2\beta$, which is the maximum variation observed in the scan.

5 Conclusions

We measure the preliminary effective value of the time-dependent CP asymmetry $\sin 2\beta = -0.19^{+0.52}_{-0.50}(stat)$ $\pm 0.09(syst)$ in the decay of neutral B^0_d mesons into the final state ϕK^0_S, $K^0_S \to \pi^+\pi^-$. The deviation of this value from the updated *BABAR* value presented at this conference, $\sin 2\beta = 0.741 \pm 0.067(stat) \pm 0.033(syst)$, is about two standard deviations. The measurement will, for some time, be dominated by the statistical uncertainty.

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