

Measurements of the Branching Fraction and *CP*-Violating Asymmetries of $B^0 \rightarrow K_S^0 \pi^0$ Decays

The *BABAR* Collaboration

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Abstract

We present measurements of the branching fraction and time-dependent *CP*-violating (CPV) asymmetries in $B^0 \rightarrow K_S^0 \pi^0$ decays based on 227 million $\Upsilon(4S) \rightarrow B\bar{B}$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy *B* factory at SLAC. We obtain a branching fraction $\mathcal{B}(B^0 \rightarrow K^0 \pi^0) = (11.4 \pm 0.9 \pm 0.6) \cdot 10^{-6}$, the magnitude of the direct CPV asymmetry $C_{K_S^0 \pi^0} = 0.06 \pm 0.18 \pm 0.06$ and the magnitude of the CPV asymmetry in the interference between mixing and decay $S_{K_S^0 \pi^0} = 0.35_{-0.33}^{+0.30} \pm 0.04$, where the first error is statistical and the second systematic. All results are preliminary.

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1 INTRODUCTION

In the Standard Model (SM) the time-dependent CP symmetry violation in B^0 decays via $b \rightarrow s\bar{q}q$ ($q \in \{u, d, s, c\}$) transitions is governed by the Cabibbo-Kobayashi-Maskawa (CKM) phase $\beta \equiv \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$ [1]. Measurements of $\sin 2\beta$ in tree-level $b \rightarrow s\bar{c}c$ transitions have established the first experimental evidence for CP violation in the B meson system [2, 3]. The combined result of the latest measurements of $\sin 2\beta$ in these transitions is in agreement with SM predictions [4].

The measurement of $\sin 2\beta$ in decays dominated by a penguin loop-level $b \rightarrow s\bar{q}q$ transition is particularly interesting because of the sensitivity to physics beyond the Standard Model [5]. The B factory experiments have explored time-dependent CPV asymmetries in several such decays [6], namely $B^0 \rightarrow \phi K_s^0$ [7, 8], $B^0 \rightarrow \eta' K_s^0$ [7, 9], $B^0 \rightarrow K^+K^-K_s^0$ [7, 10], $B^0 \rightarrow f^0 K_s^0$ [11] and $B^0 \rightarrow K_s^0\pi^0$ [12].

In this paper we present an update of our previous measurement of CP violation in $B^0 \rightarrow K_s^0\pi^0$ decays, reported in reference [12]. The CKM and color suppression of the tree-level $b \rightarrow s\bar{u}u$ transition leads to the expectation that this decay is dominated by a top-quark-mediated $b \rightarrow s\bar{d}d$ penguin amplitude, which carries a weak phase $\arg(V_{tb}V_{ts}^*)$. If other contributions, such as the $b \rightarrow su\bar{u}$ tree amplitude, are ignored, the time-dependent CPV asymmetry is governed by $\sin 2\beta$ [13]. The bound on the deviation from $\sin 2\beta$ due to Standard Model contributions with a different weak phase is ~ 0.2 from SU(3) flavor symmetry [14] and ~ 0.1 in model-dependent QCD calculations [15].

In addition to the CPV parameters we also present an update of our previous measurement of the branching fraction of $B^0 \rightarrow K_s^0\pi^0$ [16]. Existing experimental data on branching fractions for $B \rightarrow K\pi$ decays show a small discrepancy with respect to various calculations in the literature, the so-called ‘ $K\pi$ puzzle’ [17, 15]. In particular, the ratio of the $B^0 \rightarrow K_s^0\pi^0$ branching fraction to the other $B \rightarrow K\pi$ branching fractions is about 2 standard deviations larger than inferred from isospin symmetry. Further experimental input might either resolve the puzzle or provide evidence for new physics [18].

2 THE BABAR DETECTOR AND DATASET

The results are based on a sample of 226.6 ± 2.5 million $\Upsilon(4S) \rightarrow B\bar{B}$ decays collected in 1999-2004 with the BABAR detector at the PEP-II e^+e^- energy-asymmetric collider at the Stanford Linear Accelerator Center. The BABAR detector, fully described in [19], provides charged particle tracking through a combination of a five-layer double-sided silicon micro-strip detector (SVT) and a 40-layer central drift chamber (DCH), both operating in a 1.5 T magnetic field. Charged kaon and pion identification is achieved through measurements of particle energy-loss (dE/dx) in the tracking system and Cherenkov angle (θ_c) in a detector of internally reflected Cherenkov light (DIRC). A segmented CsI(Tl) electromagnetic calorimeter (EMC) provides photon detection and electron identification. Finally, the instrumented flux return (IFR) of the magnet allows discrimination of muons from pions.

3 ANALYSIS METHOD

At the $\Upsilon(4S)$ resonance, time-dependent CPV asymmetries are measured by reconstructing the distribution of the difference of the proper decay times, $\Delta t \equiv t_{CP} - t_{\text{tag}}$, where the t_{CP} refers to the decay time of the signal B^0 and t_{tag} to the other B (B_{tag}). If B^0 and \bar{B}^0 decay to a common CP eigenstate f , the Δt distribution follows

$$\mathcal{P}_{\bar{B}^0}^{B^0}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \times [1 \pm (S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t))] , \quad (1)$$

where the upper (lower) sign corresponds to B_{tag} decaying as B^0 (\bar{B}^0), τ is the B^0 lifetime averaged over the two mass eigenstates, Δm_d is the mixing frequency, C_f is the magnitude of direct CP violation and S the magnitude of CP violation in the interference between mixing and decay. For the case of pure penguin dominance, we expect $S_{K_S^0 \pi^0} = \sin 2\beta$, and $C_{K_S^0 \pi^0} = 0$.

We search for $B^0 \rightarrow K_S^0 \pi^0$ decays in $B\bar{B}$ candidate events selected using charged particle multiplicity and event topology [20]. We reconstruct $K_S^0 \rightarrow \pi^+ \pi^-$ candidates from pairs of oppositely charged tracks. The two-track combinations must form a vertex with a χ^2 consistency larger than 0.001, a $\pi^+ \pi^-$ invariant mass within 11.2 MeV/ c^2 ($\sim 3.5\sigma$) of the nominal K_S^0 mass [4] and a reconstructed decay length greater than five times its uncertainty. We form $\pi^0 \rightarrow \gamma\gamma$ candidates with an invariant mass $110 < m_{\gamma\gamma} < 160$ MeV/ c^2 from pairs of photon candidates in the EMC that are isolated from any charged tracks, carry a minimum energy of 50 MeV, and have the expected lateral shower shapes. $B^0 \rightarrow K_S^0 \pi^0$ candidates are reconstructed from $K_S^0 \pi^0$ combinations and constrained to originate from the e^+e^- interaction point using a geometric fit. We require that the χ^2 consistency of the fit, which has one degree of freedom, be larger than 0.001.

For each B candidate we compute two independent kinematic variables, namely the invariant mass m_B and the missing mass $m_{\text{miss}} = |q_{e^+e^-} - \hat{q}_B|$, where $q_{e^+e^-}$ is the four-momentum of the initial e^+e^- system and \hat{q}_B is the four-momentum of the $B^0 \rightarrow K_S^0 \pi^0$ candidate after a mass constraint on the B^0 is applied. Compared to the kinematic variables $\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$ and $m_{\text{ES}} = \sqrt{\frac{1}{4}s - p_B^{*2}}$ (where $\sqrt{s} = |q_{e^+e^-}|$ and the asterisk denotes the center of momentum frame) that are traditionally used to select B decays in *BABAR*, the present combination of variables exhibits a smaller correlation and a better background suppression, in particular for modes with a relatively poor B energy resolution. We select candidates with m_B within 150 MeV/ c^2 of the nominal B^0 mass [4] and $5.11 < m_{\text{miss}} < 5.31$ GeV/ c^2 , which includes a sideband region for background characterization.

To discriminate jet-like $e^+e^- \rightarrow q\bar{q}$ events (with $q \in \{u, d, s, c\}$) from the more uniformly-distributed $B\bar{B}$ events we exploit the ratio L_2/L_0 of two Legendre moments defined as $L_j \equiv \sum_i |\mathbf{p}_i^*| |\cos \theta_i^*|^j$, where \mathbf{p}_i^* is the momentum of particle i in the e^+e^- rest frame and θ_i^* is the angle between \mathbf{p}_i^* and the thrust axis of the B^0 candidate. We require $L_2/L_0 < 0.55$, which suppresses the background by more than a factor 3 at the cost of approximately 10% in signal efficiency. Finally, we require $|\cos \theta_B^*| < 0.9$, where θ_B^* is the angle between the B^0 candidate momentum and the e^+ momentum in the e^+e^- rest frame. For B candidates the distribution of θ_B^* follows $\mathcal{P}(\cos \theta_B^*) = 1 - \cos^2 \theta_B^*$, whereas for continuum events it is

nearly flat. After all selections the average candidate multiplicity in events with at least one candidate is ~ 1.007 . We select the candidate with the smallest χ^2 on the π^0 mass as computed in the B^0 candidate vertex fit.

For each $B^0 \rightarrow K_s^0 \pi^0$ candidate we examine the remaining tracks and neutral candidates in the event to determine the decay vertex position and the flavor of B_{tag} . Using a neural network based on kinematic and particle identification information [21] each event is assigned to one of five mutually exclusive tagging categories, designed to combine flavor tags with similar performance and Δt resolution. We parameterize the performance of this algorithm in a data sample (B_{flav}) of fully reconstructed $B^0 \rightarrow D^{(*)-} \pi^+ / \rho^+ / a_1^+$ decays. The average effective tagging efficiency obtained from this sample is $Q = \sum_c \epsilon_S^c (1 - 2w^c)^2 = 0.288 \pm 0.005$, where ϵ_S^c and w^c are the efficiencies and mistag probabilities, respectively, for events tagged in category $c \in \{1 \cdots 5\}$. For the background the fraction of events (ϵ_B^c) and the asymmetry in the rate of B^0 versus \bar{B}^0 tags in each tagging category are extracted from a fit to the data.

To compute the proper time difference Δt the B_{tag} vertex is inclusively reconstructed from the remaining charged particles in the event using the trajectory derived from the reconstruction of the B_{CP} candidate as a seed [20]. The time difference Δt and its uncertainty are extracted with a global fit to the $\Upsilon(4S) \rightarrow B^0 \bar{B}^0$ decay tree that takes the information on the beam energy and the position of the interaction point (IP) into account. The position and size of the interaction region are determined on a run-by-run basis from the spatial distribution of vertices from two-track events. The uncertainty in the IP position follows from the size of the interaction region (about $200 \mu\text{m}$ horizontal and $4 \mu\text{m}$ vertical).

Without additional constraints the single K_s^0 trajectory emerging from the $B^0 \rightarrow K_s^0 \pi^0$ decay vertex provides insufficient information on the B^0 vertex position for a meaningful Δt measurement. To obtain the required resolution we constrain the sum of the two B lifetimes in the $\Upsilon(4S) \rightarrow B^0 \bar{B}^0$ fit ($t_{CP} + t_{\text{tag}}$) to be equal to $2 \tau_{B^0}$ with an uncertainty $\sqrt{2} \tau_{B^0}$. We have verified in a Monte Carlo simulation that this procedure leads to an unbiased estimate of Δt .

For the $\sim 40\%$ of events in which each of the two pion candidates from the K_s^0 decay does not have at least 4 SVT hits or for which $\sigma(\Delta t) > 2.5 \text{ ps}$ or $\Delta t > 20 \text{ ps}$, the Δt information is not used. However, since C can also be extracted from flavor tagging information alone, these events still contribute to the measurement of C .

We extract the signal yield and CPV parameters from an unbinned maximum-likelihood fit to m_B , m_{miss} , L_2/L_0 , $\cos \theta_B^*$, Δt and the flavor tag variables. Exploiting sideband regions in data for the background and Monte Carlo simulation for the signal, we have verified that with the selection presented above these observables are sufficiently independent that we can construct the likelihood from the product of one dimensional probability density functions (PDFs). The PDFs for signal events are parameterized from either more copious fully-reconstructed B decays in data or from simulated events. For background PDFs we select the functional form from data in the sideband regions of the other observables, in which backgrounds dominate. We include these regions in the fitted sample and simultaneously extract the parameters of the background PDFs along with the CPV measurements.

We obtain the PDF for the Δt of signal decays from the convolution of Eq. 1 with a resolution function $\mathcal{R}(\delta t \equiv \Delta t - \Delta t_{\text{true}}, \sigma_{\Delta t})$. The resolution function is parameterized as

the sum of a ‘core’ and a ‘tail’ Gaussian, each with a width and mean proportional to the reconstructed $\sigma_{\Delta t}$, and a third Gaussian centered at zero with a fixed width of 8 ps [20]. We have verified in simulation that the parameters of $\mathcal{R}(\delta t, \sigma_{\Delta t})$ for $B^0 \rightarrow K_S^0 \pi^0$ decays are similar to those obtained from the B_{flav} sample, even though the distributions of $\sigma_{\Delta t}$ differ considerably. We therefore extract these parameters from a fit to the B_{flav} sample. We find that the Δt distribution of background candidates is well described by a delta function convolved with a resolution function with the same functional form as used for signal events. The parameters of the background function are determined in the fit.

To extract the yield and the CPV asymmetries we maximize the logarithm of the extended likelihood

$$\begin{aligned} \mathcal{L}(S_f, C_f, N_S, N_B, f_S, f_B, \vec{\alpha}) &= \frac{e^{-(N_S+N_B)}}{(N_S + N_B)!} \times \\ &\prod_{i \in I} [N_S f_S \epsilon_S^c \mathcal{P}_S(\vec{x}_i, \vec{y}_i; S_f, C_f) + N_B f_B \epsilon_B^c \mathcal{P}_B(\vec{x}_i, \vec{y}_i; \vec{\alpha})] \times \\ &\prod_{i \in II} [N_S (1 - f_S) \epsilon_S^c \mathcal{P}'_S(\vec{x}_i; C_f) + N_B (1 - f_B) \epsilon_B^c \mathcal{P}'_B(\vec{x}_i; \vec{\alpha})], \end{aligned}$$

where I (II) is the subset of events with (without) Δt information. The probabilities \mathcal{P}_S and \mathcal{P}_B are products of PDFs for signal (S) and background (B) hypotheses evaluated for the measurements $\vec{x}_i = \{m_B, m_{\text{miss}}, L_{12}/L_{10}, \cos \theta_B^*, \text{tag}, \text{tagging category}\}$ and $\vec{y}_i = \{\Delta t, \sigma_{\Delta t}\}$. Along with the CPV asymmetries S_f and C_f , the fit extracts the yields N_S and N_B , the fractions of events with Δt information f_S and f_B , and the remaining parameters, collectively denoted by $\vec{\alpha}$. These include all parameters of background PDFs and some parameters of the signal PDFs, such as the mean values of m_B and m_{miss} .

4 RESULTS

Fitting the data sample of 9726 $B^0 \rightarrow K_S^0 \pi^0$ candidates, we find $N_S = 300 \pm 23$ signal decays with

$$S_{K_S^0 \pi^0} = 0.35_{-0.33}^{+0.30} (\text{stat}) \pm 0.04 (\text{syst})$$

and

$$C_{K_S^0 \pi^0} = 0.06 \pm 0.18 (\text{stat}) \pm 0.06 (\text{syst}).$$

The total detection efficiency for $B^0 \rightarrow K_S^0 \pi^0$ decays with $K_S^0 \rightarrow \pi^+ \pi^-$ and $\pi^0 \rightarrow \gamma \gamma$ is $0.34 \pm 0.02\%$. With the K_S^0 and π^0 branching fractions taken from [4] and assuming equal production of charged and neutral B mesons at the $\Upsilon(4S)$ resonance, we obtain a branching fraction

$$\mathcal{B}(B^0 \rightarrow K^0 \pi^0) = (11.4 \pm 0.9 (\text{stat}) \pm 0.6 (\text{syst})) \times 10^{-6}.$$

The evaluation of the systematic uncertainties is described below.

Figure 1 shows the so called s-Plot distributions [22] of the reconstructed mass and missing mass for signal $B^0 \rightarrow K_S^0 \pi^0$ candidates. The s-Plots are a statistical tool to extract the distribution of a particular discriminating variable by weighting events with their signal likelihood based on other discriminating variables. For comparison, figure 2 shows the unweighted distributions for a subsample enhanced in signal purity by selecting on L_2/L_0 and m_{miss} . The dashed and solid curves

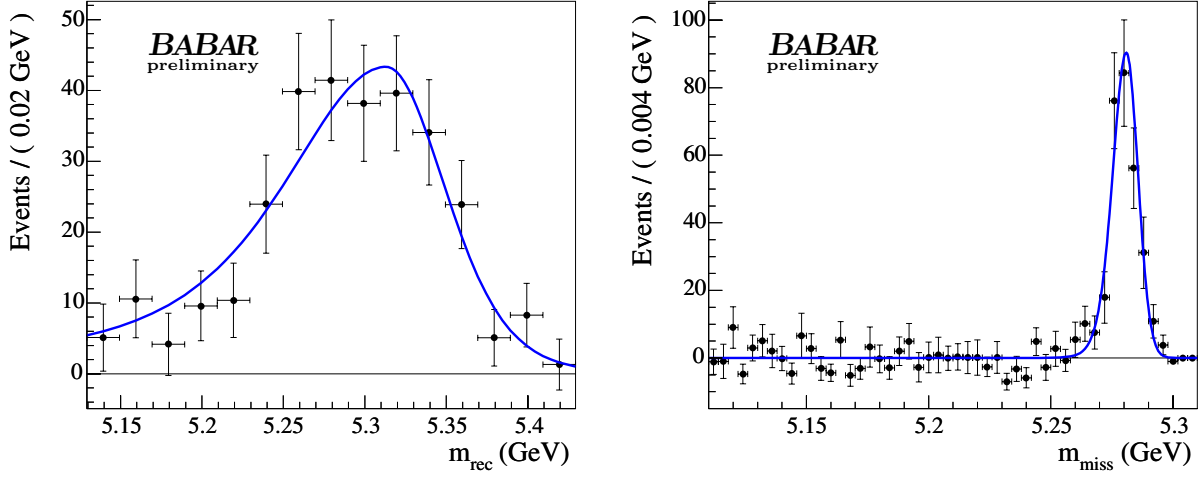


Figure 1: Signal s-Plots for reconstructed mass (left) and missing mass (right). The curve represents the PDF used for signal events in the maximum likelihood fit.

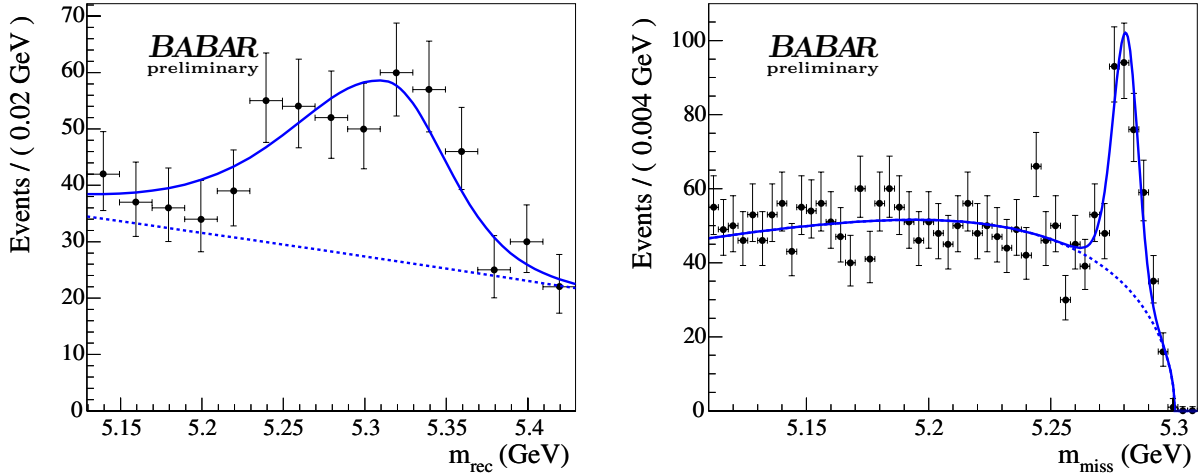


Figure 2: Distributions for the reconstructed mass of the B candidate (left) and for the missing mass (right). To enhance the sample in signal purity we required $L_2/L_0 < 0.4$ which reduces the efficiency for signal decays by $\sim 25\%$ with respect to the selection described in the text. For the m_B distribution we required in addition $m_{\text{miss}} > 5.25 \text{ GeV}/c^2$. The dashed and solid curves represent the background and signal-plus-background contributions, respectively, as obtained from the maximum likelihood fit.

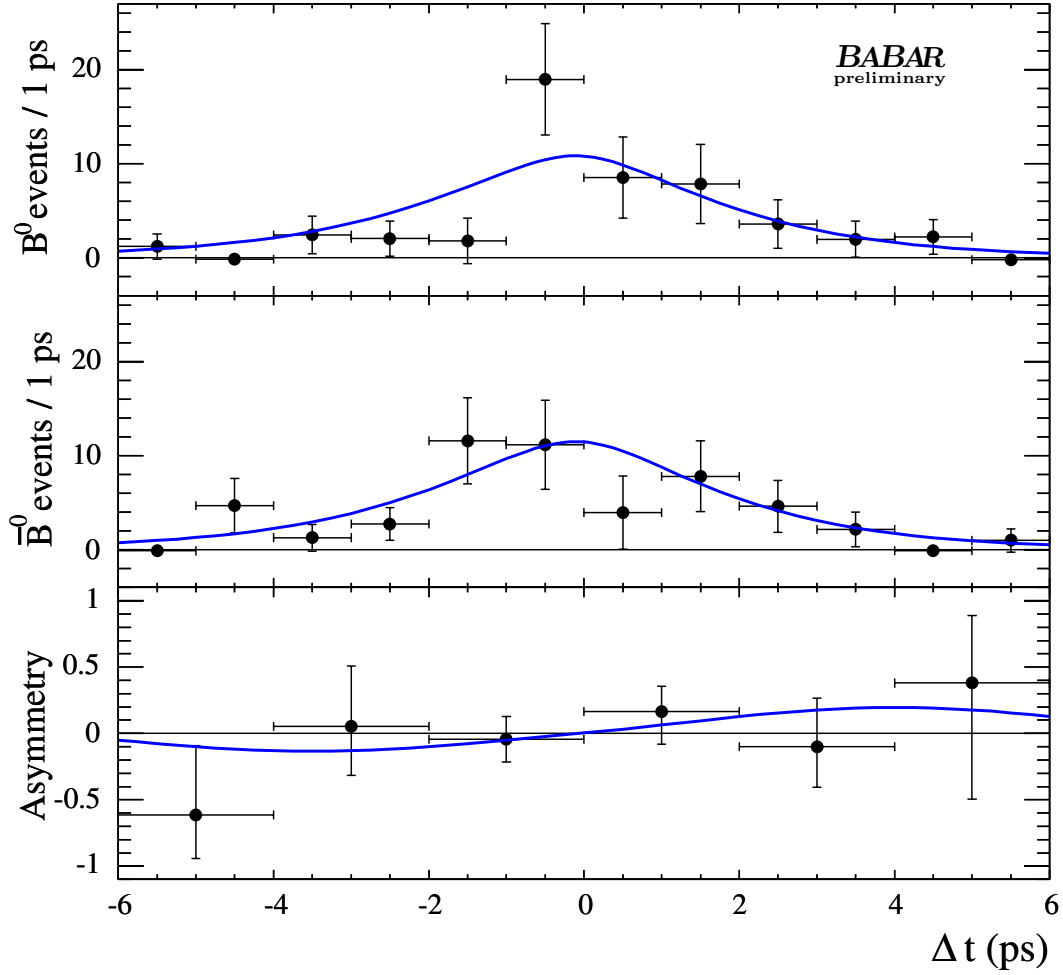


Figure 3: s-Plot distributions of Δt for signal events with B_{tag} tagged as B^0 (top) or \bar{B}^0 (center), and of the asymmetry $\mathcal{A}_{K_S^0 \pi^0}(\Delta t)$ (bottom). The curves represent the PDFs for signal decays in the likelihood fit.

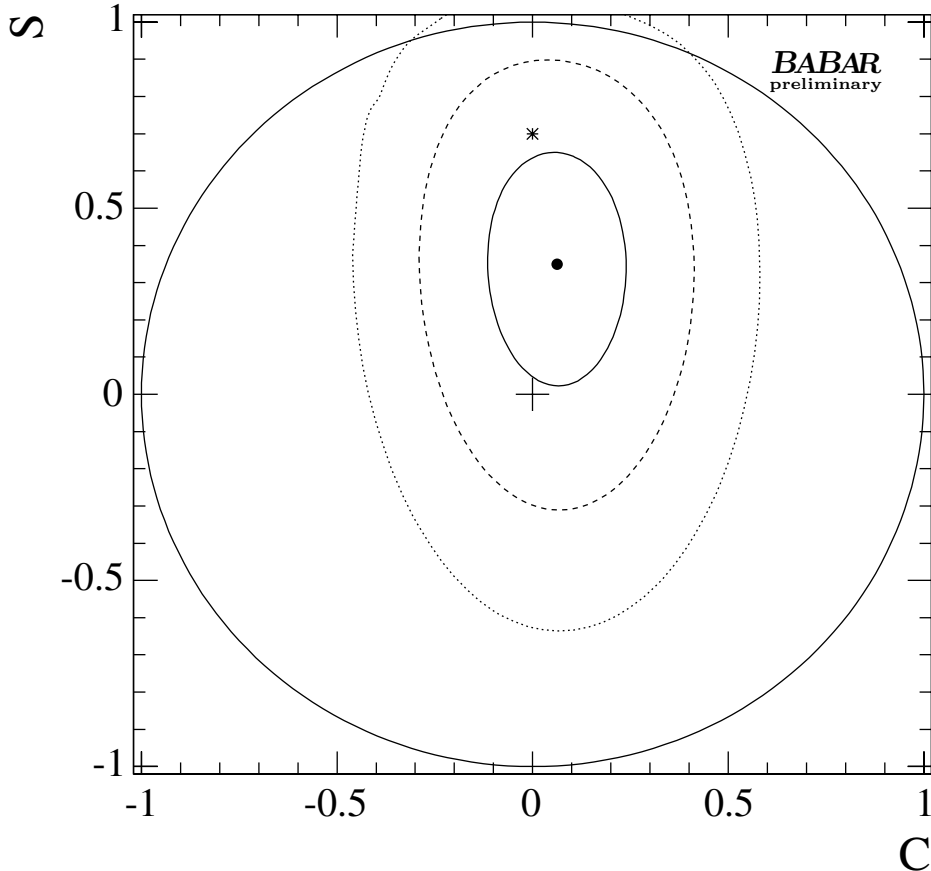


Figure 4: Contours for constant likelihood corresponding to a change in the likelihood with 1, 2 and 3 units with respect to the minimum likelihood. The enclosed regions correspond roughly to 39%, 86% and 99% confidence levels. The star represents the Standard Model prediction. The large circle represents the boundary of the physically allowed region.

indicate background and signal-plus-background contributions, respectively, as obtained from the fit, but corrected for the selection.

Figure 3 shows the s-Plot distributions of Δt for B^0 - and \bar{B}^0 -tagged events, and of the asymmetry $\mathcal{A}_{K_S^0\pi^0}(\Delta t) = [N_{B^0} - N_{\bar{B}^0}] / [N_{B^0} + N_{\bar{B}^0}]$ as a function of Δt . Figure 4 shows the contours for constant likelihood in the $S - C$ plane.

5 VALIDATIONS AND SYSTEMATIC UNCERTAINTIES

The extraction of Δt with the IP-constrained geometric decay tree fit has been extensively tested on large samples of simulated $B^0 \rightarrow K_S^0\pi^0$ decays with different values of C and S . To evaluate uncertainties due to the use of a resolution function extracted from the B_{flav} sample we fit the

$B^0 \rightarrow K_S^0 \pi^0$ samples with a resolution function extracted from simulated $B^0 \rightarrow J/\psi K_S^0$ events. We assign a systematic uncertainty of 0.02 on $S_{K_S^0 \pi^0}$ and 0.01 on $C_{K_S^0 \pi^0}$ due to the use of the B_{flav} resolution function and other effects related to the Δt reconstruction. We evaluate the effect of a possible misalignment of the SVT by introducing misalignments in the simulation and obtain a systematic uncertainty of 0.03 on $S_{K_S^0 \pi^0}$ and 0.01 on $C_{K_S^0 \pi^0}$. We also consider large variations of the position and size of the interaction region, which we find to have negligible impact. We include a systematic uncertainty of 0.02 on both $S_{K_S^0 \pi^0}$ and $C_{K_S^0 \pi^0}$ to account for imperfect knowledge of the PDFs used in the fit. We assign a systematic uncertainty of 0.05 to $C_{K_S^0 \pi^0}$ due to possible asymmetries in the rate of B^0 versus \bar{B}^0 tags in background events.

In order to exclude any bias in the IP constraint Δt reconstruction that would be specific to data only, we examine a sample of approximately 1900 $B^0 \rightarrow J/\psi K_S^0$ decays with $J/\psi \rightarrow \mu^+ \mu^-$ and $J/\psi \rightarrow e^+ e^-$. In these events we determine Δt in two ways: by fully reconstructing the B^0 decay vertex using the trajectories of charged daughters of the J/ψ and the K_S^0 mesons, or by neglecting the J/ψ contribution to the decay vertex and using the IP constraint and the K_S^0 trajectory only. This study shows that within statistical uncertainties the IP-constrained Δt measurement is unbiased with respect to the more established technique, and that the values of $S_{J/\psi K_S^0}$ and $C_{J/\psi K_S^0}$ so obtained are consistent. In addition, we examine the pull of the Δt difference, assuming that the Δt uncertainties are fully correlated. We find that the pull distribution in the data is approximately 10% wider than that in the simulation. We therefore include an additional systematic uncertainty of 0.014 in $S_{K_S^0 \pi^0}$. Finally, we measure the B^0 lifetime in $B^0 \rightarrow K_S^0 \pi^0$ decays and in IP-constrained $B^0 \rightarrow J/\psi K_S^0$ decays and find that both agree with the world average.

The detection efficiency for signal events is calculated with a Monte Carlo simulation based on the Pythia event generator [23] and GEANT4 detector simulation [24]. The efficiency of the K_S^0 selection is calibrated with a large sample of inclusive $K_S^0 \rightarrow \pi^+ \pi^-$ decays. The $\pi^0 \rightarrow \gamma \gamma$ efficiency is calibrated with $e^+ e^- \rightarrow \tau^+ \tau^-$ events with $\tau^- \rightarrow \rho^- \nu_\tau$. The systematic uncertainty associated with the efficiency is 2.6% for K_S^0 and 3.0% for π^0 . We assign additional systematic uncertainties of 1.2% for the L_2/L_0 cut, 2.0% for the selection on m_B and a total of 2.0% for uncertainties in the signal PDFs. Finally, we include an uncertainty of 1.4% to account for unknown contributions from other $B\bar{B}$ decays and an uncertainty of 0.6% in the total number of $\Upsilon(4S) \rightarrow B\bar{B}$ decays.

6 SUMMARY

In this paper we have reported preliminary results from a measurement of the branching fraction and time-dependent CPV asymmetries of $B^0 \rightarrow K_S^0 \pi^0$ decays. The measured values of $S_{K_S^0 \pi^0}$ and $C_{K_S^0 \pi^0}$ are consistent with the Standard Model predictions. The measured branching fraction is consistent with measurements from other experiments [25].

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