We present preliminary measurements of the $CP$ asymmetry parameters in $B^0 \to K^0_S K^0_S K^0_S$ decays, reconstructing two of the $K^0_S$ into $\pi^+ \pi^-$ and one into $\pi^0 \pi^0$. In a sample of 227 $M \bar{B}B$ pairs collected by the BABAR detector at the PEP-II B-Factory at SLAC, we find the $CP$ parameters to be $S = -0.25^{+0.68}_{-0.61} \text{(stat)} \pm 0.05 \text{(syst)}$ and $C = 0.56^{+0.34}_{-0.43} \text{(stat)} \pm 0.04 \text{(syst)}$. Combining this result with the previous BABAR measurement, obtained from events with three $K^0_S$ decaying into $\pi^+ \pi^-$, we get

$$
S = -0.63^{+0.32}_{-0.28} \text{ (stat)} \pm 0.04 \text{ (syst)}
$$

$$
C = -0.10 \pm 0.25 \text{ (stat)} \pm 0.05 \text{ (syst)}
$$
Measurement of Time-dependent $CP$-Violating Asymmetries in $B^0 \to K_S^0 K_S^0 K_S^0$ Decays

The BABAR Collaboration

March 25, 2022

We present preliminary measurements of the $CP$ asymmetry parameters in $B^0 \to K_S^0 K_S^0 K_S^0$ decays, reconstructing two of the $K_S^0$ into $\pi^+\pi^-$ and one into $\pi^0\pi^0$. In a sample of 227 $B\bar{B}$ pairs collected by the BABAR detector at the PEP-II $B$ Factory at SLAC, we find the $CP$ parameters to be $S = -0.25^{+0.68}_{-0.61}\text{(stat)} \pm 0.05\text{(syst)}$ and $C = 0.56^{+0.34}_{-0.43}\text{(stat)} \pm 0.04\text{(syst)}$. Combining this result with the previous BABAR measurement, obtained from events with three $K_S^0$ decaying into $\pi^+\pi^-$, we get

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1 INTRODUCTION

In the Standard Model (SM) CP violation arises from the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [1]. Decays of $B$ mesons into charmless hadronic final states with three kaons are dominated by $b \to ss$ penguin amplitudes, while other SM amplitudes are suppressed by CKM factors [2]. Neglecting these CKM-suppressed contributions, the amplitude of time-dependent $\tau$ decays is proportional to $\sin^2 CP$ factors [2].

The time-dependent CP-violating asymmetry is obtained by measuring the proper time difference $\Delta t = t_{CP} - t_{tag}$ between a fully reconstructed neutral $B$ meson ($B_{CP}$) in the final state $K_S^0K_S^0K_S^0$, and a partially reconstructed recoil $B$ meson ($B_{tag}$). The $B_{tag}$ decay provides evidence that it decayed either as $B^0$ or $\bar{B}^0$ (flavor tag). The decay rate $f_+ (f_-)$ when the tagging meson is a $B^0(\bar{B}^0)$ is given by

$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \times \left[ 1 \pm S \sin(\Delta m_d\Delta t) \mp C \cos(\Delta m_d\Delta t) \right] ,$$

where $\tau_{B^0}$ is the neutral $B$ meson mean lifetime and $\Delta m_d$ is the $B^0-\bar{B}^0$ oscillation frequency. The parameters $C$ and $S$ describe the magnitude of CP violation in the decay and in the interference between decay and mixing, respectively. The time-dependent CP-violating asymmetry is defined as $A_{CP} \equiv (f_+ - f_-)/(f_+ + f_-)$.

Since at first approximation $b \to s$ decays can be considered as given by a single amplitude, no direct CP violation is expected ($C \sim 0$) and $S \sim -\eta_f \sin 2\beta$, where $C$ ($S$) is the parameter for direct (mixing-induced) CP violation and $\eta_f = +1 (-1)$ corresponds to CP-even (-odd) final states. In general, a deviation from these expectations might occur without indicating the presence of physics beyond the Standard Model, since a second (CKM suppressed) part is present in the decay amplitude. The interference between these two terms can in general produce direct CP violation and introduce a nontrivial relation between $S$ and $-\eta_f \sin 2\beta$, as a function of the relative phase and size of the two amplitudes. It has been noted that for $B^0 \to K_S^0K_S^0K_S^0$ (which is a $\eta_f = +1$ state), as for the golden mode $B^0 \to \phi K_S^0$, this suppressed amplitude is a penguin contribution as well [3–5], so that the ratio of the two terms is expected to be of the order of $\lambda^2$, where $\lambda = 0.2258 \pm 0.0014$ [6] is the sine of the Cabibbo angle.

The value of $\sin 2\beta = 0.726 \pm 0.037$ determined from tree-level $b \to c\bar{c}s$ decays is in good agreement with the SM expectation [6,7]. On the other hand, $b \to s\bar{q}q$ processes are dominated by one-loop transitions, and hence may have contributions from diagrams with new heavy particles. Thus, a sizable deviation of $S$ from $-\eta_f \sin 2\beta$ would be a signal of physics beyond the Standard Model [8].

Belle and BABAR Collaboration have already reported a measurement of time-dependent CP-asymmetry in $B^0 \to K_S^0K_S^0K_S^0$ [9]. In the case of BABAR the analysis includes only $K_S^0$ decaying into $\pi^+ \pi^-$. Since this measurement might be limited in precision by the amount of data one expects to have at the end of BABAR experiment, the present work has the main purpose of improving the precision using the same dataset, but reconstructing one of the $K_S^0$ in the $\pi^0\pi^0$ decay mode. Because of the absence of charged tracks originating from the $B^0$ decay vertex, we use the vertexing technique recently developed for $B^0 \to K_S^0\pi^0$ [10].
2 THE BaBar DETECTOR

The BaBar detector is described elsewhere [11]. The components are a charged-particle tracking system consisting of a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) surrounded by a 1.5-T solenoidal magnet with an instrumented flux return (IFR), an electromagnetic calorimeter (EMC) comprised of 6580 CsI(Tl) crystals, and a detector of internally reflected Cherenkov light (DIRC) providing excellent charged $K - \pi$ separation up to a momentum of 4.5 GeV/c relevant for this analysis.

3 ANALYSIS METHOD

The $B^0 \rightarrow K_S^0 K_S^0 K_S^0$ candidate ($B_{CP}$) is reconstructed combining three $K_S^0$ candidates, two of which are reconstructed in the $K_S^0 \rightarrow \pi^+\pi^-$ mode, while the third is reconstructed in the $K_S^0 \rightarrow \pi^0\pi^0$ mode. We reconstruct $K_S^0 \rightarrow \pi^+\pi^-$ candidates from pairs of oppositely charged tracks. The two-track composites must form a vertex with a $\pi^+\pi^-$ invariant mass within 11 MeV/c² (about 4$\sigma$) of the nominal $K_S^0$ mass [12]. We form $\pi^0 \rightarrow \gamma\gamma$ candidates from pairs of photon candidates in the EMC. Each photon is required to be isolated from any charged tracks, to carry a minimum energy of $50\text{ MeV}$, and to have the expected lateral shower shape. We reconstruct $\pi^0$ pairs which form an invariant mass $480 < m_{\pi^+\pi^-} < 520 \text{ MeV/c}^2$. $B^0 \rightarrow K_S^0 K_S^0 K_S^0$ candidates are constrained to originate from the $e^+e^-$ interaction point using a geometric fit, based on a Kalman Filter [13]. We make a requirement on the consistency of the $\chi^2$ of the fit which retains 93% of the signal events, and rejects about 49% of other $B$ decays. We extract the $K_S^0 \rightarrow \pi^\pm\pi^\mp$ decay length $L_{K_S^0}$ and the invariant mass $(m_{\gamma\gamma})$ from this fit, and require $100 < m_{\gamma\gamma} < 141 \text{ MeV/c}^2$ and $L_{K_S^0}$ greater than 5 times its uncertainty.

For each $B$ candidate we compute two kinematic variables, namely the invariant mass $m_B$ and the missing mass $m_{\text{miss}} = \sqrt{(q_{e^+e^-} - \vec{q}_B)^2}$, where $q_{e^+e^-}$ is the four-momentum of the initial $e^+e^-$ system and $\vec{q}_B$ is the four-momentum of the $B^0 \rightarrow K_S^0 K_S^0 K_S^0$ candidate after a mass constraint on the $B^0$ is applied. By construction the linear correlation coefficient between $m_{\text{miss}}$ and $m_B$ vanishes. This combination of variables shows smaller correlation (0.86% on reconstructed signal Monte Carlo events and 1.64% on the final data sample) and a better background suppression with respect to the equivalent kinematic variables $\Delta E$ and $m_{\text{ES}}$ used in the BaBar analysis of this mode with all $K_S^0 \rightarrow \pi^+\pi^-$ in the final state [9]. Using simulations of $B^0 \rightarrow K_S^0 K_S^0 K_S^0$ and $B^0 \rightarrow J/\psi(\rightarrow l^+l^-)K_S^0(\rightarrow \pi^0\pi^0)$ decays ($l = e, \mu$) and reconstructing $B^0 \rightarrow J/\psi(\rightarrow l^+l^-)K_S^0(\rightarrow \pi^0\pi^0)$ events on data, we determine the distribution of $m_{\text{miss}}$ and $m_B$ for signal events. We find the signal resolution for $m_B$ to be about 40 MeV/c², the distribution being asymmetric around the maximum, because of leakage effects in the EMC. The signal resolution for $m_{\text{miss}}$, about 6 MeV/c², is dominated by the beam-energy spread. We select candidates with $m_B$ within 150 MeV/c² of the nominal $B^0$ mass [12] and with $5.11 < m_{\text{miss}} < 5.31 \text{ GeV/c}^2$. The region $m_{\text{miss}} < 5.2 \text{ GeV/c}^2$ is devoid of signal and used for background characterization. Most background originates from continuum $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) events, which we suppress using both production and decay properties. To exploit the jet-like topology of continuum events, we use the angle $\theta_T$ between the thrust axis of the $B_{CP}$ candidate and the thrust axis formed from the other charged and neutral particles in the event. While $|\cos \theta_T|$ is highly peaked near 1 for $e^+e^- \rightarrow q\bar{q}$ events, it is nearly uniformly distributed for $B\bar{B}$ events. We require $|\cos \theta_T| < 0.95$. Moreover, we calculate the ratio $L_2/L_0$ of two angular moments defined as $L_j \equiv \sum_i |\vec{p_i}||\cos \theta_i^*|$, where $\vec{p}_i^*$ is the momentum of particle $i$ in the $e^+e^-$ rest frame, $\theta_i^*$ is the angle between $\vec{p}_i^*$ and the thrust axis of the $B$ candidate and the sum runs over all
reconstructed particles except for the $B$-candidate daughters. After all selection requirements are applied, the average candidate multiplicity in events with at least one candidate is approximately 1.67, coming from multiple $K^0_s \to \pi^0\pi^0$ combinations. In these cases, we select the candidate with the smallest $\chi^2 = \sum_i (m_i - m_{K^0_s})^2/\sigma_{m_i}^2$, where $m_i$ ($m_{K^0_s}$) is the measured (nominal $K^0_s$) mass and $\sigma_{m_i}$ is the estimated uncertainty on the mass of the $i$th $K^0_s$ candidate. In simulated events, this selection criterion gives the right answer about 81% of the time. The remaining uninterpreted events, coming from fake $K^0_s \to \pi^0\pi^0$ candidates, do not affect the determination of $\Delta t$ and have a small impact on the other variables used in the final fit (the largest correlation is $\sim 2.5\%$).

Events coming from $b \to c\bar{c}s$ would reduce any sensitivity to departures from the Standard Model, as this process is characterized by a Standard-Model CP asymmetry ($S \sim \sin 2\beta$ and $C \sim 0$). We therefore remove $b \to c\bar{c}s$ events by rejecting all candidates with a $K^0_sK^0_s$ mass combination within two times the experimental resolution of the $S$ mass. The contribution from $\chi_{c0}$ is found to be negligible. Combinatorics from other $B$ decays constitute a further source of background. We take this into account by adding a component in the likelihood fit (see Sec. 4), where the shape of each likelihood variable is determined from a simulation of inclusive $B$ decays.

For each $B^0 \to K^0_sK^0_sK^0_s$ candidate we examine the remaining tracks in the event to determine the decay vertex position and the flavor of $B_{\text{tag}}$. Using a neural network based on kinematic and particle identification information [14] each event is assigned to one of seven mutually exclusive tagging categories, designed to combine flavor tags with similar performance and $\Delta t$ resolution. We parameterize the performance of this algorithm in a data sample ($B_{\text{raw}}$) of fully reconstructed $B^0 \to D^{(*)-}/rho^+/a_1^+$ decays. The average effective tagging efficiency obtained from this sample is $Q = \sum_c e^c_S (1 - 2w^c)^2 = 0.299 \pm 0.005$, where $e^c_S$ and $w^c$ are the efficiencies and mistag probabilities, respectively, for events tagged in category $c = 1, 2, \cdots, 7$. For the background, the fraction of events ($e_B^c$) 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.

The proper-time difference is extracted from the separation of the $B_{CP}$ and $B_{\text{tag}}$ decay vertices. The $B_{\text{tag}}$ vertex is reconstructed inclusively from the remaining charged particles in the event. To reconstruct the $B_{CP}$ vertex from the single $K^0_s$ trajectory we exploit the knowledge of the average interaction point (IP), which is determined on a run-by-run basis from the spatial distribution of vertices from two-track events. We compute $\Delta t$ and its uncertainty from a geometric fit to the $\Upsilon(4S) \to B^0\bar{B}^0$ system that takes this IP constraint into account. We further improve the sensitivity to $\Delta t$ by imposing a Gaussian constraint on the sum of the two $B$ decay times ($t_{CP} + t_{\text{tag}}$) to be equal to $2 \tau_{B^0}$ with an uncertainty $\sqrt{2} \tau_{B^0}$, which effectively constrains the two vertices to be near the $\Upsilon(4S)$ line of flight [10]. We have verified in a Monte Carlo simulation that this procedure provides an unbiased estimate of $\Delta t$. Details on the vertexing algorithm can be found in Ref. [13].

The per-event estimate of the uncertainty on $\Delta t$ reflects the strong dependence of the $\Delta t$ resolution on the $K^0_s$ flight direction and on the number of SVT layers traversed by the $K^0_s$ decay daughters. In about 97% of the events at least one of the two $K^0_s$ which decay into $\pi^+\pi^-$ have both pion tracks reconstructed from at least 4 SVT hits, leading to sufficient resolution for the time-dependent measurement. The average $\Delta t$ resolution in these events is about 1.0 ps. For events which fail this criterion or for which $\sigma(\Delta t) > 2.5$ ps or $\Delta t > 20$ ps, the $\Delta t$ information is not used. However, since $C$ can also be extracted from flavor tagging information alone, these events still contribute to the measurement of $C$. 

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4 MAXIMUM LIKELIHOOD FIT

We extract the results from unbinned maximum-likelihood fits to the kinematic, event shape $L_2/L_0$, $\Delta t$, and flavor tag variables. We maximize the logarithm of an extended likelihood function

$$L(S,C,N_S,N_B,N_{BB}f_S,f_B,f_{BB},\vec{a}) = e^{-(N_S+N_B+N_{BB})} \times \prod_{i \in I} \left[ N_S f_S c^S_{\Delta t}(\vec{x}_i,\vec{y}_i;S,C) + N_B f_B c^B_{\Delta t}(\vec{x}_i,\vec{y}_i;\vec{a}) + N_{BB} f_{BB} c^C_{BB} P_{BB}(\vec{x}_i,\vec{y}_i;\vec{a}) \right] \times \prod_{i \in I} \left[ N_S (1 - f_S) c^S_{\Delta t}(\vec{x}_i;C) + N_B (1 - f_B) c^B_{\Delta t}(\vec{x}_i;\vec{a}) + N_{BB} (1 - f_{BB}) c^C_{BB} P'_{BB}(\vec{x}_i;\vec{a}) \right],$$

where $I$ ($II$) is the subset of events with (without) $\Delta t$ information. The $N_X$ ($X$ being signal, continuum background, or $BB$ background) represent the $X$ component yield, and $f_X$ the fraction of events with $\Delta t$ information. The probabilities $P_X$ ($P'_X$) are products of PDFs for each $X$ hypotheses, evaluated for each event $i$ from the values of $\vec{x}_i = \{m_B, m_{\text{miss}}, L_2/L_0, \text{tag, tagging category} \}$ and $\vec{y}_i = \{\Delta t, \sigma_{\Delta t} \}$. The remaining parameters of the fit are denoted by $\vec{a}$. For the $B$ background events, the efficiencies and the mistag probabilities $c^S_{BB}$ and $w^c$, respectively, for the tagging category $c$, are fixed to the same values of the signal events. The observables are sufficiently uncorrelated that we can construct the likelihoods as the products of one-dimensional PDFs. The PDFs for signal are parameterized from simulations of signal events. For background PDFs we determine the functional form from data in the sideband regions of the other observables where backgrounds dominate. We include these regions in the fitted sample and simultaneously extract the parameters of the background PDFs along with the fit results. All the parameters of $BB$ background PDFs are determined using simulated samples of inclusive $B$ decays. All the parameters of the likelihood that are not determined simultaneously with $S$ and $C$ in the final fit are varied according to their uncertainties in order to estimate systematic errors.

The average $\Delta z$ resolution is dominated by the tagging vertex in the event. Thus, we can characterize the resolution with a much larger sample of reconstructed $B \rightarrow DX$ decays ($B_{\text{flav}}$ sample), which we use as signal parameterization. The amplitudes for the $B_{CP}$ asymmetries and for the $B_{\text{flav}}$ flavor oscillations are reduced by the same factor due to wrong tags. Both distributions are convoluted with a common $\Delta t$ resolution function (RF). The RF is parameterized as the sum of two Gaussians with a width proportional to the reconstructed $\sigma_{\Delta t}$, and a third Gaussian with a fixed width of 8 ps, which accounts for a small fraction of outlying events [14]. The first two Gaussians have a non-zero mean, proportional to $\sigma_{\Delta t}$, to account for the small bias in $\Delta t$ from charm decays on the $B_{\text{tag}}$ side. Backgrounds are accounted for by adding terms to the likelihood, incorporated with different assumptions about their $\Delta t$ evolution and resolution function.

The fit procedure was tested with both a parameterized simulation of a large number of data-sized experiments and a full detector simulation. The likelihood of our data fit agrees with the likelihoods from fits to the simulated data.

5 SYSTEMATIC STUDIES

We obtain systematic uncertainties in the $CP$ coefficients $S$ and $C$ due to the parameterization of PDFs for the event yield in signal and background by varying the parameters within one standard deviation (evaluated from a fit to Monte Carlo simulated events). We evaluate the uncertainties associated with the assumed parameterization of the $\Delta t$ resolution function for signal and $BB$-background, a possible difference in the efficiency between $B^0$ and $\bar{B}^0$, and the fixed values for
Δm_d and τ_B by varying the parameters within one standard deviation (extracted from a fit to the B_flav sample). The sum of the two contributions gives the total error associated with the PDF parameters. We estimate different uncertainties associated with vertexing. The first is obtained by taking the largest value of S(C)_fit − S(C)_true from fits to signal Monte Carlo events. Here the S(C)_fit represents the result of the fit to our signal Monte Carlo sample, while S(C)_true represents input values in the Monte Carlo generation. The second uncertainty is from possible SVT layers misalignment. We assign a systematic uncertainty on our knowledge of the beam spot position by shifting the beam position in the simulation by ±20 µm in the vertical direction. The sensitivity due to any calibration problems or time-dependent effects is evaluated by smearing the beam-spot position by an additional ±20µm in the vertical direction. We include an additional contribution from the comparison of the description of the RF between BC vertexing and nominal vertexing in the case of B^0 → J/ψK_S^0 events. We estimate also the errors due to the effect of doubly CKM-suppressed decays on the tag side [15]. We add these contributions in quadrature to obtain the total systematic uncertainty. The summary is reported in Table 1. The largest contribution is related to the knowledge of the PDF parameters. For reference, we note that this effect produces a systematic error of ±1.7 events on the signal yield.

|                      | Δ S(+) | Δ S(−) | Δ C(+) | Δ C(−) |
|----------------------|--------|--------|--------|--------|
| PDF parameters       | 0.046  | 0.039  | 0.029  | 0.027  |
| vertexing method     | 0.012  | 0.012  | 0.025  | 0.025  |
| SVT alignment        | 0.004  | 0.004  | 0.008  | 0.008  |
| beam-spot            | 0.003  | 0.003  | 0.005  | 0.005  |
| data/MC RF           | 0.006  | 0.006  | 0.001  | 0.001  |
| doubly-CKM-suppressed decays | 0.001  | 0.001  | 0.011  | 0.011  |
| total errors         | 0.049  | 0.041  | 0.041  | 0.039  |

Table 1: Summary of systematic uncertainties on S and C.

6 SUMMARY OF RESULTS

In the final sample composed of 2748 B candidates we measure 41.0^{+9.2}_{−8.3} signal events, 2700 ± 56 continuum background events and 7^{+24}_{−19} B\bar{B}-background events. Assuming the world average for the branching ratio ((6.2±0.9)×10^{-6}) [9] and the reconstruction efficiency as estimated from a sample of simulated signal events, we expected 45 ± 7 events, which is in good agreement with the result. We find this preliminary result on CP parameters:

\begin{align*}
S & = -0.25^{+0.08}_{−0.06}(\text{stat}) \pm 0.05(\text{syst}) \\
C & = 0.56^{+0.34}_{−0.43}(\text{stat}) \pm 0.04(\text{syst}).
\end{align*}

Fig. 1 shows the background-subtracted distributions of m_{miss} and m_B for these events, obtained using the sPlot weighting technique [16]. Events contribute according to a weight constructed from the covariance matrix for the yields (N_S and N_B) and the probability P_S and P_B for the event, computed without the use of the variable that is being displayed. The curves represent the signal PDFs used in the fit. We combined this result with the previous BABAR measurement, obtained using B^0 → K_S^0 K_S^0 K_S^0 reconstructed from all three K_S^0 decaying into π^+π^- [9]. The combination is
obtained through a simultaneous maximum likelihood fit, which takes into account the correlations from the common $\Delta t$ PDF. The total systematic error is calculated by summing in quadrature the uncorrelated sources of errors and taking the largest contribution from the two analyses in the case of common sources of background. In this way, we obtain this preliminary result:

$$S = -0.63^{+0.32}_{-0.28} \text{(stat)} \pm 0.04 \text{(syst)}$$

$$C = -0.10 \pm 0.25 \text{(stat)} \pm 0.05 \text{(syst)}$$

In Fig. 2 we show the distributions of signal events, obtained using the sPlot weighting technique [16], in the case of $B^0 \rightarrow K^0_S K^0_S K^0_S$ with one $K^0_S$ reconstructed by $\pi^0 \pi^0$ mode (left) and for the combined fit (right). The superimposed curves represent the results of the fit in the two cases.

Considering the present uncertainty, this result agrees with Standard Model expectations. A future update of this analysis, including new data collected by BABAR, will help to understand if the present hint of pattern in the deviation of $b \rightarrow s$ penguins from the Standard Model predictions [17] is a statistical effect or a signal of new physics.

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Figure 2: Distributions of $\Delta t$ for weighted events with $B_{\text{tag}}$ tagged as $B^0$ (upper plots) or $B^0$ (middle plots), and the asymmetry (lower plots). Left plots are for the subsample with all $K^{0}_S \rightarrow \pi^0 \pi^0$, right plots are for the combined fit. The points are weighted data and the curves are the PDF projections.

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