

# A Measurement of $CP$ Violating Asymmetries in $B^0 \rightarrow f_0(980)K_s^0$ Decays

The *BABAR* Collaboration

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## Abstract

We present preliminary measurements of the  $CP$ -violating asymmetries in the decay  $B^0 \rightarrow f_0(980)(\rightarrow \pi^+\pi^-)K_s^0$ . The results are obtained from a data sample of  $209 \times 10^6 \Upsilon(4S) \rightarrow B\bar{B}$  decays collected with the *BABAR* detector at the PEP-II asymmetric-energy  $B$  Factory at SLAC. From a time-dependent maximum-likelihood fit we measure the mixing-induced  $CP$  violation parameter  $S = -0.95_{-0.23}^{+0.32} \pm 0.10$  and the direct  $CP$  violation parameter  $C = -0.24 \pm 0.31 \pm 0.15$ , where the first errors are statistical and the second systematic.

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# 1 Introduction

In the Standard Model (SM),  $CP$  violation arises from a single phase in the three-generation Cabibbo-Kobayashi-Maskawa quark-mixing matrix [1]. Possible indications of physics beyond the SM may be observed in time-dependent  $CP$  asymmetries of  $B$  decays dominated by penguin-type diagrams to states such as  $\phi K^0$ ,  $\eta' K^0$ ,  $K^+ K^- K^0$ , and  $f_0(980) K^0$  [2]. Neglecting CKM-suppressed amplitudes, these decays carry the same weak phase as the decay  $B^0 \rightarrow J/\psi K^0$  [3]. As a consequence, their mixing-induced  $CP$ -violation parameter is expected to be  $-\eta_f \times \sin 2\beta = -\eta_f \times 0.74 \pm 0.05$  [4] in the SM, where  $\beta \equiv \arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$  and  $\eta_f$  is the  $CP$  eigenvalue of the final state  $f$ , which is  $+1$  for  $f_0(980)K_s^0$ . There is no direct  $CP$  violation expected in these decays since they are dominated by a single amplitude in the SM. Due to the large virtual masses occurring in the penguin loops, additional diagrams with non-SM heavy particles in the loops and new  $CP$ -violating phases may contribute. Measurements of  $CP$  violation in these channels and their comparisons with the SM expectation are therefore sensitive probes for physics beyond the SM.

We present the preliminary results of an update of a measurement [5] of  $CP$ -violating asymmetries in the penguin-dominated decay  $B^0 \rightarrow f_0 K_s^0$ † from a time-dependent maximum-likelihood analysis. We restrict the analysis to the region of the  $\pi^+ \pi^- K_s^0$  Dalitz plot that is dominated by the  $f_0$  and we refer to this as the quasi-two-body (Q2B) approach. Effects due to the interference between the  $f_0$  and the other resonances in the Dalitz plot are taken as systematic uncertainties.

The structure of the scalar meson  $f_0$  has been discussed for decades and is still obscure. There were attempts to interpret it as  $K\bar{K}$  molecular states [6], four-quark states [7] and normal  $q\bar{q}$  states [8]. However, recent studies of  $\phi \rightarrow \gamma f_0$  ( $f_0 \rightarrow \gamma\gamma$ ) [9, 10] and  $D_s^+ \rightarrow f_0 \pi^+$  [11] decays favor the  $q\bar{q}$  state models. In this interpretation the flavor content of the  $f_0$  is given by  $f_0 = \cos(\phi_s) s\bar{s} + \sin(\phi_s) n\bar{n}$ , with  $n\bar{n} = (u\bar{u} + d\bar{d})/\sqrt{2}$ . A mixing phase of  $\phi_s = -48^\circ \pm 6^\circ$  has been experimentally determined from  $\phi \rightarrow \gamma f_0$  decays [10]. If the assumption is true that the  $f_0$  state has a sizable content of  $s\bar{s}$ , then the decay  $B^0 \rightarrow f_0 K_s^0$  would be dominated by the penguin transition,  $b \rightarrow s\bar{s}s$  (*cf.* Fig. 1(b)). Thus, we expect that a measurement of mixing-induced  $CP$  violation leads to  $S \simeq -\sin 2\beta$ , where  $S$  is the coefficient of the sine modulation term[2].

The data used in this analysis were accumulated with the *BABAR* detector [12] at the PEP-II asymmetric-energy  $e^+e^-$  storage ring at SLAC. The data sample consists of an integrated luminosity of  $192 \text{ fb}^{-1}$  collected at the  $\Upsilon(4S)$  resonance (“on-resonance”) corresponding to  $209 \times 10^6 B\bar{B}$  pairs, and  $11.8 \text{ fb}^{-1}$  collected about 40 MeV below the  $\Upsilon(4S)$  (“off-resonance”). In Ref. [12] we describe

†Throughout the paper  $f_0$  refer to the  $f_0(980)$  and its decay to  $\pi^+ \pi^-$ . In addition, charge conjugate decay modes are assumed unless explicitly stated.

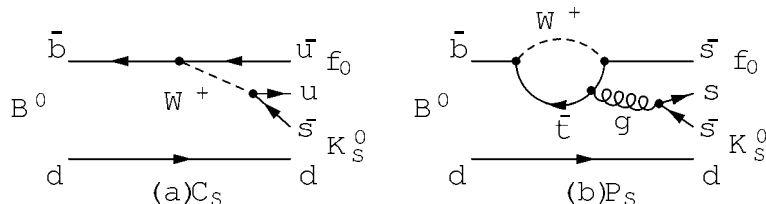


Figure 1: *The color-suppressed tree (a) and dominant gluonic penguin (b) are diagrams that could contribute to the decay  $B^0 \rightarrow f_0(980)K_s^0$ .*



the silicon vertex tracker and drift chamber used for track and vertex reconstruction, and the Cherenkov detector (DIRC), the electromagnetic calorimeter (EMC), and the instrumented flux return (IFR) used for particle identification.

If we denote by  $\Delta t$  the difference between the proper times of the decay of the fully reconstructed  $B^0 \rightarrow f_0 K_S^0$  ( $B_{\text{rec}}^0$ ) and the decay of the other meson ( $B_{\text{tag}}^0$ )<sup>||</sup>, the time-dependent decay rate  $f_{Q_{\text{tag}}}$  is given by

$$f_{Q_{\text{tag}}}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \left( 1 + Q_{\text{tag}} S \sin(\Delta m_d \Delta t) - Q_{\text{tag}} C \cos(\Delta m_d \Delta t) \right) \quad (1)$$

where  $Q_{\text{tag}} = 1(-1)$  when the tagging meson  $B_{\text{tag}}^0$  is a  $B^0(\bar{B}^0)$ ,  $\tau$  is the mean  $B^0$  lifetime, and  $\Delta m_d$  is the  $B^0\bar{B}^0$  oscillation frequency corresponding to the mass difference. The parameter  $S$  is non-zero if there is mixing-induced  $CP$  violation, while a non-zero value for  $C$  would indicate direct  $CP$  violation.

## 2 Candidate Selection

We reconstruct  $B^0 \rightarrow f_0(\rightarrow \pi^+\pi^-)K_S^0$  candidates from combinations of two tracks and a  $K_S^0$  decaying to  $\pi^+\pi^-$ . For the  $\pi^+\pi^-$  pair from the  $f_0$  candidate, we use information from the tracking system, EMC, and DIRC to remove tracks consistent with electron, kaon, and proton hypotheses. In addition, we require at least one track to have a signature in the IFR that is inconsistent with the muon hypothesis. The mass of the  $f_0$  candidate must satisfy  $0.86 < m(\pi^+\pi^-) < 1.10 \text{ GeV}/c^2$ . To reduce combinatorial background from low energy pions, we require  $|\cos\theta(\pi^+)| < 0.9$ , where  $\theta(\pi^+)$  is the angle between the positive pion direction in the  $f_0$  rest frame and the  $f_0$  flight direction in the laboratory frame. The  $K_S^0$  candidate is required to have a mass within  $10 \text{ MeV}/c^2$  of the nominal  $K^0$  mass [14] and a decay vertex separated from the  $B^0$  decay vertex by at least five standard deviations. In addition, the cosine of the angle between the  $K_S^0$  flight direction and the vector between the  $f_0$  and the  $K_S^0$  vertices must be greater than 0.99.

Two kinematic variables are used to discriminate between signal- $B$  decays and combinatorial background. One variable is the difference  $\Delta E$  between the measured center-of-mass (CM) energy of the  $B$  candidate and  $\sqrt{s}/2$ , where  $\sqrt{s}$  is the CM energy. The other variable is the beam-energy-substituted mass  $m_{\text{ES}} \equiv \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$ , where the  $B$  momentum  $\mathbf{p}_B$  and the four-momentum of the initial state  $(E_i, \mathbf{p}_i)$  are defined in the laboratory frame. We require  $5.23 < m_{\text{ES}} < 5.29 \text{ GeV}/c^2$  and  $|\Delta E| < 0.1 \text{ GeV}$ .

Continuum  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s, c$ ) events are the dominant background. To enhance discrimination between signal and continuum, we use a neural network (NN) to combine four variables: the cosine of the angle between the  $B_{\text{rec}}^0$  direction and the beam axis in the CM, the cosine of the angle between the thrust axis of the  $B_{\text{rec}}^0$  candidate and the beam axis, and the zeroth and second angular moments  $L_{0,2}$  of the energy flow about the  $B_{\text{rec}}^0$  thrust axis. The moments are defined by  $L_j = \sum_i p_i \times |\cos\theta_i|^j$ , where  $\theta_i$  is the angle with respect to the  $B_{\text{rec}}^0$  thrust axis of the track or neutral cluster  $i$ , and  $p_i$  is its momentum. The sum excludes the  $B_{\text{rec}}^0$  candidate. The thrust axis is defined as the direction that maximizes the sum of the longitudinal momenta of the  $B_{\text{rec}}^0$  daughters. The NN is trained with off-resonance data and simulated signal events. The final sample of signal candidates is selected with a cut on the NN output  $> -1.5$ , which retains  $\sim 97\%$  and  $52\%$  of the signal and continuum, respectively.

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<sup>||</sup>The  $B_{\text{tag}}^0$  is so called because its flavor is determined using the tagging algorithm of Ref. [13].

The signal efficiency determined from Monte Carlo (MC) simulation is  $(38.7 \pm 0.4)\%$ . MC simulation shows that 4.7% of the selected signal events are mis-reconstructed, mostly due to combinatorial background from low-momentum tracks used to form the  $f_0$  candidate. In total, 12586 on-resonance data events pass all selection criteria.

### 3 Background from other $B$ Decays

We use MC-simulated events to study the background from other  $B$  decays. The charmless decay modes are grouped into eight classes with similar kinematic and topological properties. The modes that decay to the  $\pi^+\pi^-K_S^0$  final state are of particular importance since they have signal-like  $\Delta E$  and  $m_{ES}$  distributions and their decay amplitudes interfere with the  $f_0K_S^0$  decay amplitude. Among these modes are  $\rho^0K_S^0$ ,  $f_0(1370)K_S^0$ ,  $f_2(1270)K_S^0$ ,  $K^{*+}\pi^-$  (including other kaon resonances decaying to  $K_S^0\pi^+$ ), and non-resonant  $\pi^+\pi^-K_S^0$  decays. The mode  $\rho^0K_S^0$  is particularly important because it has  $\eta_f = -1$  and thus any  $\rho^0K_S^0$  events misidentified as signal will dilute the observed CP asymmetry in our data. The inclusive charmless  $\pi^+\pi^-K_S^0$  branching fraction  $(23.4 \pm 3.3) \times 10^{-6}$  [4], together with the available exclusive measurements [4], are used to infer upper limits on the branching fractions of these decays. Along with selection efficiencies obtained from MC, these branching fractions are used to estimate the expected background. The charmed decays  $B^0 \rightarrow D^-\pi^+ \rightarrow K_S^0\pi^-\pi^+$  and  $B^+ \rightarrow \bar{D}^0\pi^+ \rightarrow K_S^0\pi^0\pi^+$  contribute significantly to the selected data sample. Each of these modes is treated as a separate class. Two additional classes account for the remaining neutral and charged  $b \rightarrow c$  decays. In the selected data sample we expect  $106 \pm 23$  charmless and  $218 \pm 93$   $b \rightarrow c$  events.

### 4 Maximum-Likelihood Fit

The time difference  $\Delta t$  is obtained from the measured distance between the  $z$  positions (along the beam direction) of the  $B_{\text{rec}}^0$  and  $B_{\text{tag}}^0$  decay vertices, and the boost  $\beta\gamma = 0.56$  of the  $e^+e^-$  system [13, 15]. To determine the flavor of the  $B_{\text{tag}}^0$  we use the tagging algorithm of Ref. [13]. This produces four mutually exclusive tagging categories. We also retain untagged events in a fifth category to improve the efficiency of the signal selection.

We use an unbinned extended maximum-likelihood fit to extract the  $f_0K_S^0$  event yield, the CP parameters defined in Eq. (1), and the  $f_0$  resonance parameters. The likelihood function for the  $N_k$  candidates tagged in category  $k$  is

$$\mathcal{L}_k = e^{-N'_k} \prod_{i=1}^{N_k} \left\{ N_S \epsilon_k \left[ (1 - f_{\text{MR}}^k) \mathcal{P}_{i,k}^{S-\text{CR}} + f_{\text{MR}}^k \mathcal{P}_{i,k}^{S-\text{MR}} \right] + N_{C,k} \mathcal{P}_{i,k}^C + \sum_{j=1}^{n_B} N_{B,j} \epsilon_{j,k} \mathcal{P}_{i,j,k}^B \right\} \quad (2)$$

where  $N'_k$  is the sum of the signal, continuum and the  $n_B$   $B$ -background yields tagged in category  $k$ ,  $N_S$  is the number of  $f_0K_S^0$  signal events in the sample,  $\epsilon_k$  is the fraction of signal events tagged in category  $k$ ,  $f_{\text{MR}}^k$  is the fraction of mis-reconstructed signal events in tagging category  $k$ ,  $N_{C,k}$  is the number of continuum background events that are tagged in category  $k$ , and  $N_{B,j} \epsilon_{j,k}$  is the number of  $B$ -background events of class  $j$  (see section 3) that are tagged in category  $k$ . The  $B$ -background event yields are fixed parameters, with the exception of the  $D^-\pi^+$  yield. Since  $B^0 \rightarrow D^-\pi^+$  events have a characteristic distribution in  $\cos\theta(\pi^+)$ , well separated from continuum and  $f_0K_S^0$  events, the  $D^-\pi^+$  is free to vary in the fit along with the signal and continuum yields. The total likelihood  $\mathcal{L}$  is the product of the likelihoods for each tagging category.

The probability density functions (PDFs)  $\mathcal{P}_k^{S\text{-CR}}$ ,  $\mathcal{P}_k^{S\text{-MR}}$ ,  $\mathcal{P}_k^C$  and  $\mathcal{P}_{j,k}^B$ , for correctly reconstructed signal, mis-reconstructed signal, continuum background and  $B$ -background class  $j$ , respectively, are the products of the PDFs of six discriminating variables. The correctly reconstructed signal PDF is thus given by:  $\mathcal{P}_k^{S\text{-CR}} = \mathcal{P}^{S\text{-CR}}(m_{\text{ES}}) \cdot \mathcal{P}^{S\text{-CR}}(\Delta E) \cdot \mathcal{P}_k^{S\text{-CR}}(\text{NN}) \cdot \mathcal{P}^{S\text{-CR}}(|\cos\theta(\pi^+)|) \cdot \mathcal{P}^{S\text{-CR}}(m(\pi^+\pi^-)) \cdot \mathcal{P}_k^{S\text{-CR}}(\Delta t)$ , where  $\mathcal{P}_k^{S\text{-CR}}(\Delta t)$  contains the time-dependent  $CP$  parameters defined in Eq. (1), diluted by the effects of mis-tagging and the  $\Delta t$  resolution.

The fractions of mis-reconstructed signal events in each tagging category are estimated by MC simulation. The  $m_{\text{ES}}$ ,  $\Delta E$ , NN,  $|\cos\theta(\pi^+)|$ , and  $m(\pi^+\pi^-)$  PDFs for signal and  $B$  background are taken from the simulation except for the means of the signal Gaussian PDFs for  $m_{\text{ES}}$  and  $\Delta E$  as well as the mass and width of the  $f_0$ , which are free to vary in the fit. We use a relativistic Breit-Wigner function to parameterize the  $f_0$  resonance. The  $\Delta t$ -resolution function for signal and  $B$ -background events is a sum of three Gaussian distributions, with parameters determined by a fit to fully reconstructed  $B^0$  decays [13]. The continuum  $\Delta t$  distribution is parameterized as the sum of three Gaussian distributions with two distinct means and three distinct widths, which are scaled by the  $\Delta t$  per-event error. For the  $B$ -background modes that are  $CP$  eigenstates, the parameters  $C$  and  $S$  are fixed to 0 and  $\pm \sin 2\beta$ , respectively, depending on their  $CP$  eigenvalues. For continuum, four tag asymmetries and the five yields  $N_{C,k}$  are free. The signal yield,  $S$ ,  $C$ , and the  $f_0$  mass and width are among the 41 parameters that are free to vary in the fit. The majority of the free parameters are used to describe the shape of the continuum background.

## 5 Systematic Errors

The contributions to the systematic error on the signal parameters are summarized in Table 1. To estimate the errors due to the fit procedure, we perform fits on a large number of MC samples with the proportions of signal, continuum and  $B$ -background events measured from data. Biases of a few percent observed in these fits are due to imperfections in the likelihood model such as neglected correlations between the discriminating variables of the signal and  $B$ -background PDFs and are assigned as a systematic uncertainty of the fit procedure. The error due to the fit procedure includes these biases added in quadrature with their statistical errors. The expected event yields from the  $B$ -background modes are varied according to the uncertainties in the measured or estimated branching fractions. Since  $B$ -background modes may exhibit  $CP$  violation, the corresponding  $CP$  parameters are varied within their physical ranges. We vary the parameters of the  $\Delta t$  model and tagging fractions incoherently within their errors and assign the observed changes, summed in quadrature, as a systematic error. The uncertainties due to the simulated signal PDFs are obtained from a

Table 1: Summary of systematic uncertainties.

Error Source	$S$	$C$
Fitting Procedure	0.06	0.10
$B$ -background	0.04	0.08
$\Delta t$ Model	0.01	0.01
Tagging	0.02	0.01
Signal Model	0.02	0.02
DCS Decays	0.01	0.04
$\Delta m_d$ and $\tau$	0.00	0.01
Q2B Approximation	0.04	0.07
Sub-total	0.10	0.15

control sample of fully reconstructed  $B^0 \rightarrow D^-(\rightarrow K_S^0 \pi^-) \pi^+$  decays. The systematic errors due to interference between the doubly-Cabibbo-suppressed (DCS)  $\bar{b} \rightarrow \bar{u}c\bar{d}$  amplitude with the Cabibbo-favored  $\bar{b} \rightarrow \bar{c}u\bar{d}$  amplitude for tag-side  $B$  decays have been estimated from simulation by varying freely all relevant strong phases [16]. The errors associated with  $\Delta m_d$  and  $\tau$  are estimated by varying these parameters within the errors on the world average [14].

The systematic error introduced in the Q2B approximation by ignoring interference effects between the  $f_0$  and the other resonances in the Dalitz plot is estimated from simulation by varying freely all relative strong phases and taking the largest observed change in each parameter as the error. Eleven resonances are used in this study including the three lowest lying  $\rho$  resonances,  $f_0(980)$ ,  $f_0(1370)$ ,  $f_2(1270)$ , and the  $K^{*\pm}$  and higher kaon states. In addition, a non-resonant component is allowed. The proportion of each contribution is estimated using known exclusive measurements and the inclusive  $\pi^+ \pi^- K_S^0$  rate. The systematic effects due to interference are small compared with the statistical error for  $S$  and  $C$ .

## 6 Fit Results

The maximum-likelihood fit results in the  $CP$ -violation parameters:

$$\begin{aligned} S &= -0.95_{-0.23}^{+0.32} \pm 0.10, \\ C &= -0.24 \pm 0.31 \pm 0.15, \end{aligned}$$

where the first errors are statistical and the second are systematic. The improvement in the error with respect to the previous result ( $127 \times 10^6 \Upsilon(4S) \rightarrow B\bar{B}$  decays,  $\sigma_{\text{stat}}(S) = {}_{-0.51}^{+0.56}$ ) is due mainly to the increased luminosity, but is due also to one event with large signal probability and to the proximity of the measured  $S$  and the physical limit ( $|S| \leq 1$ ). We find an  $f_0 K_S^0$  event yield of  $152.4 \pm 18.5$  which is consistent with the previously measured branching fraction [5].

Figure 2 shows distributions of  $\Delta E$ ,  $m_{\text{ES}}$ ,  $|\cos \theta(\pi^+)|$  and  $m(\pi^+ \pi^-)$ , that are enhanced in signal content by cuts on the signal-to-continuum likelihood ratios of the other discriminating variables. The time-dependent distributions and asymmetry  $A_{B^0/\bar{B}^0} = (N_{B^0} - N_{\bar{B}^0}) / (N_{B^0} + N_{\bar{B}^0})$  in the tagged events are presented in Fig. 3.

We validated the stability of the nominal fit by testing different fit configurations where each configuration had a discriminating variable removed. As another cross-check, we allow the  $B^0$  lifetime,  $\tau_{B^0}$ , to vary. We find  $\tau_{B^0} = (1.52 \pm 0.22)$  ps, in agreement with the world average  $\tau_{B^0} = (1.536 \pm 0.014)$  ps [4], and the remaining free parameters are consistent with the nominal fit.

## 7 Summary

In summary, we have presented an updated preliminary measurement of the  $CP$ -violating asymmetries in  $B^0 \rightarrow f_0(980)(\rightarrow \pi^+ \pi^-) K_S^0$  decays. Our results for  $S$  and  $C$  are consistent with the Standard Model. The hypothesis of no mixing-induced  $CP$  violation is excluded at the  $2.3\sigma$  level.

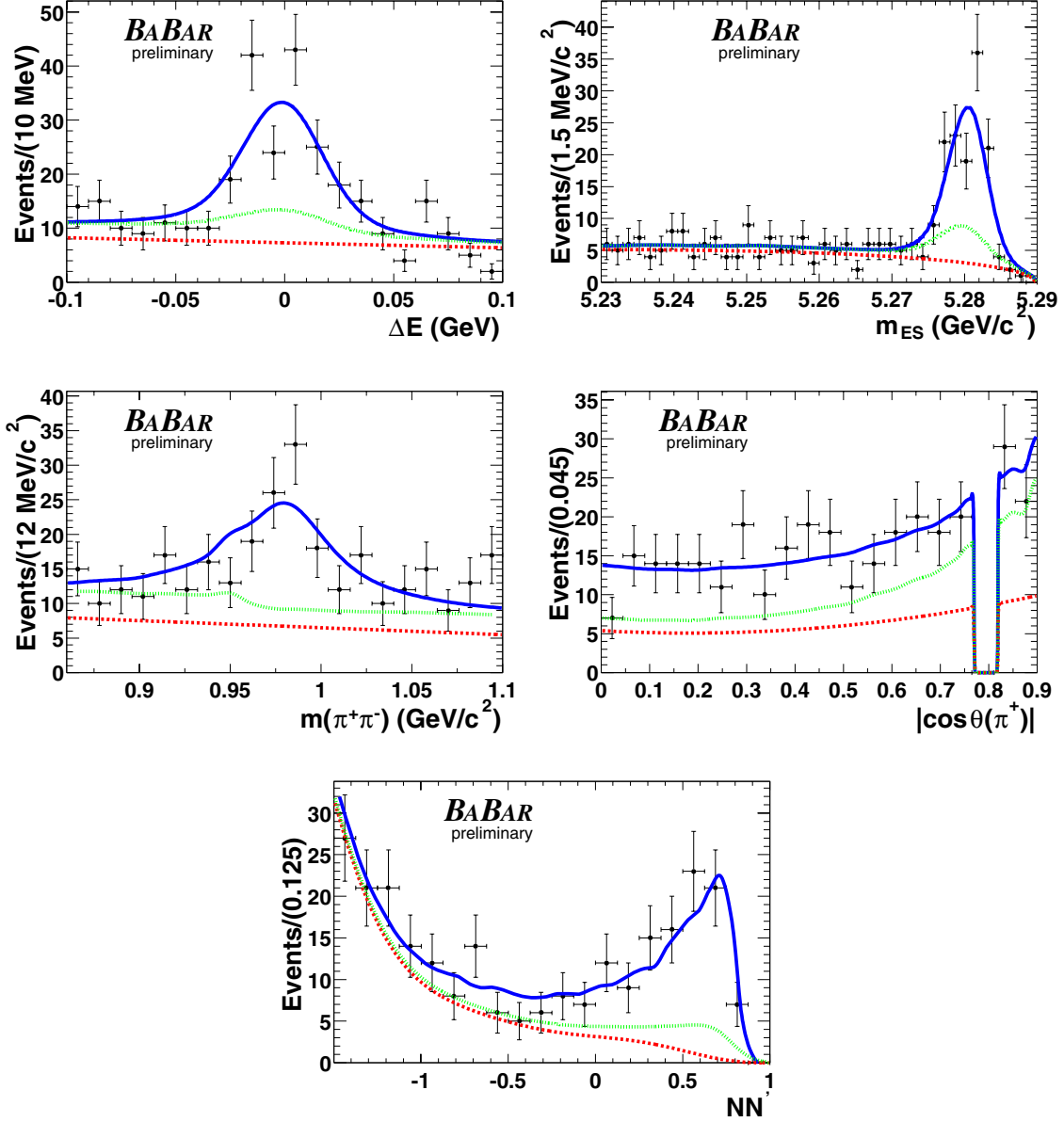


Figure 2: Distributions of (clockwise from top left)  $\Delta E$ ,  $m_{ES}$ ,  $|\cos\theta(\pi^+)|$ ,  $m(\pi^+\pi^-)$  and the NN output for samples enhanced in  $f_0K_S^0$  signal (purity is  $\sim 45\%$ .) The solid curve represents a projection of the maximum-likelihood fit result. The dashed curve represents the contribution from continuum events, and the dotted line (middle) indicates the combined contributions from continuum events and  $B$  backgrounds. For presentation purposes, the region  $0.765 < |\cos\theta(\pi^+)| < 0.81$  has been removed to suppress the contribution from  $D^-\pi^+$  events.

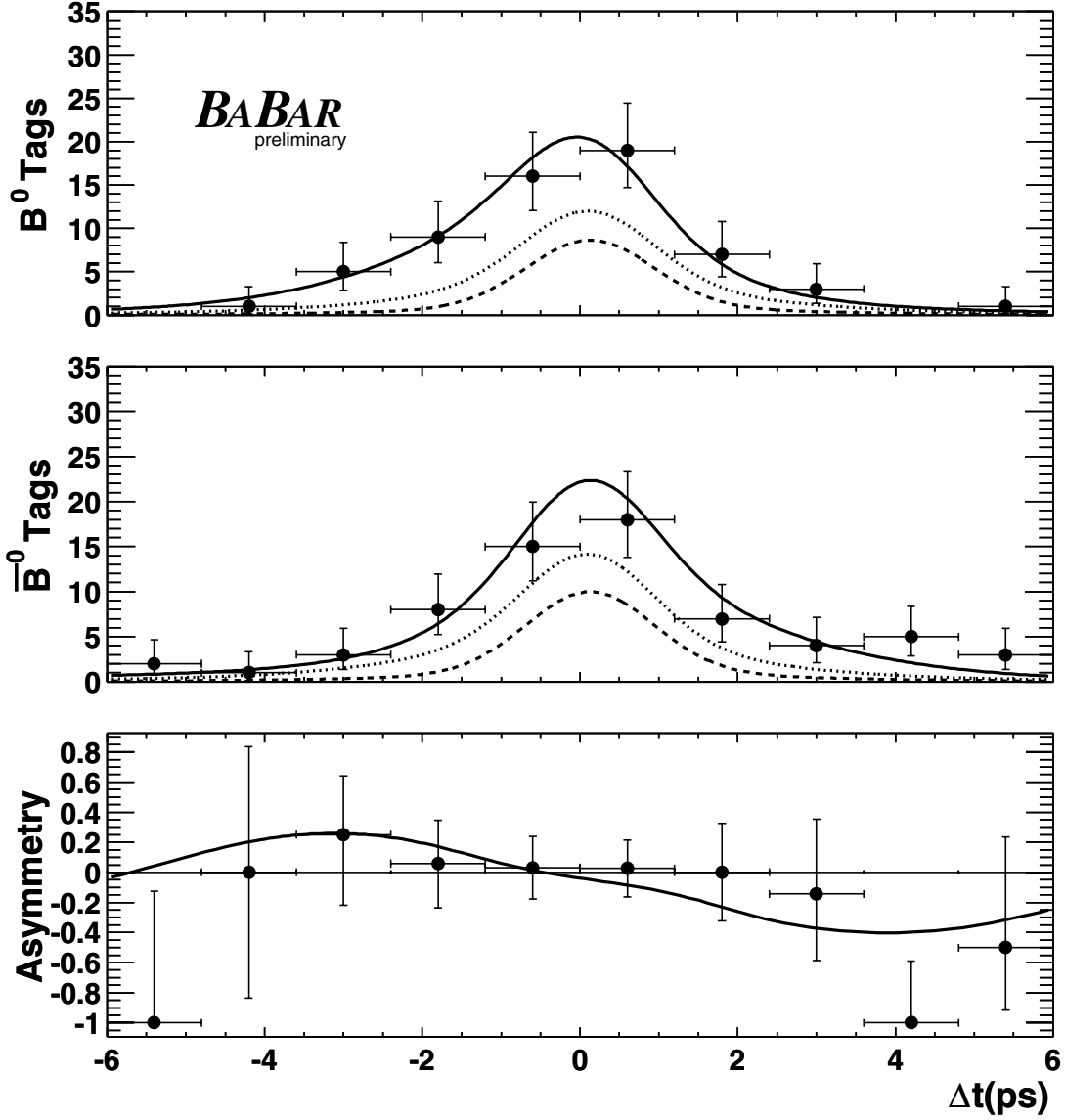


Figure 3: The signal enhanced time distributions tagged as  $B_{\text{tag}}^0$  (top) and  $\bar{B}_{\text{tag}}^0$  (middle), and the asymmetry,  $A_{B^0/\bar{B}^0}$  (bottom). The solid curve is a projection of the fit result. The dashed line is the distribution for continuum background and the dotted line is the total  $B$ - and continuum-background contribution.

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## References

- [1] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
- [2] Y. Grossman and M. P. Worah, Phys. Lett. B **395**, 241 (1997); M. Ciuchini *et al.*, Phys. Rev. Lett. **79**, 978 (1997); D. London and A. Soni, Phys. Lett. B **407**, 61 (1997).
- [3] R. Fleischer, Z. Phys. C **62**, 81 (1994); Y. Grossman, Z. Ligeti, Y. Nir and H. Quinn, Phys. Rev. D **68**, 015004 (2003).
- [4] The Heavy Flavor Averaging Group (HFAG), J. Alexander *et al.*, <http://www.slac.stanford.edu/xorg/hfag/>
- [5] *BABAR* Collaboration, B. Aubert *et al.*, hep-ex/0406040 (2004).
- [6] J. Weinstein and N. Isgur, Phys. Rev. Lett. **48**, 659 (1982); Phys. Rev. **D27**, 583 (1983); Phys. Rev. **D41**, 2236 (1990); M.P. Locher *et al.*, Eur. Phys. J. **C4** 317 (1998).
- [7] R.J. Jaffe, Phys. Rev. **D15**, 267 (1997); M. Alford and R.J. Jaffe, Nucl. Phys. **B578**, 367 (2000).
- [8] N.A. Torinqvist, Phys. Rev. Lett. **49**, 624 (1982); N.A. Tornquits and M. Roos, Phys. Rev. Lett. **76**, 1575 (1996).
- [9] F. De Fazio and M.R. Pennington, Phys. Lett. **B521**, 15 (2001); R. Delborgo, D. Liu and M.D. Scadron, Phys. Lett. **B446**, 332 (1999); T.M. Aliev *et al.*, Phys. Lett. **B527**, 193 (2002).
- [10] A.V. Anisovich, V.V. Anisovich and V.A. Nikonov, hep-ph/0011191 (2000)
- [11] F. Kleefeld *et al.*, Phys. Rev. **D66**, 034007 (2002); E. van Beveren, G. Rupp and M.D. Scadron, Phys. Lett. **B495**, 300 (2000); A. Deandrea *et al.*, Phys. Lett. **B502**, 79 (2001).

- [12] *BABAR* Collaboration, B. Aubert *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 1 (2002).
- [13] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D**66**, 032003 (2002).
- [14] Particle Data Group, K. Hagiwara *et al.*, Phys. Rev. D **66**, 010001 (2002).
- [15] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **89**, 281802 (2002).
- [16] O. Long and M. Baak, R.N. Cahn, D. Kirkby, Phys. Rev. D **68**, 034010 (2003).
- [17] E791 Collaboration, E.M. Aitala *et al.*, Phys. Rev. Lett. **86**, 765 (2001).