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Search for CP violation in D^0 decay

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Abstract

Using data taken with the CLEO II detector, we have searched for evidence of CP violation in the charm system. We look for asymmetries in the number of decays of D^0's and $\bar{D}^0$'s to the CP eigenstates $K^0_S\phi$, $K^0_S\pi^0$ and K^+K^-. Confidence intervals (90%) on these asymmetries are found to be $-0.115<A<0.105$, $-0.060<A<0.038$ and $-0.036<A<0.178$ respectively.

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I. INTRODUCTION

To date, the only experimental evidence for CP violation is found in the kaon system. Here we report on a search for CP violation in the charm system. We look for an asymmetry in the decay rates of D^0 and $\bar{D}^0$ mesons to CP eigenstates. This asymmetry is defined as:

$$A = \frac{\Gamma(D^0) - \Gamma(\bar{D}^0)}{\Gamma(D^0) + \Gamma(\bar{D}^0)} = \frac{N(D^0) - N(\bar{D}^0)}{N(D^0) + N(\bar{D}^0)}$$

where $\Gamma(D^0)$ and $\Gamma(\bar{D}^0)$ are the partial decay widths of the D^0 and $\bar{D}^0$ into the same CP eigenstate and $N(D^0)$ and $N(\bar{D}^0)$ are the numbers of D^0 and $\bar{D}^0$ which we observe. This assumes equal production of D^0 and $\bar{D}^0$ and equal detection efficiencies.

In this paper, we study decays to the following CP eigenstates; $K^0_S\phi$, $K^0_S\pi^0$ and K^+K^-. We use the fact that for the decay modes

$$D^{*+} \to D^0 + \pi^+$$

and

$$D^{*-} \to \bar{D}^0 + \pi^-$$

the charge of the pion tags the flavor of the $D^0(\bar{D}^0)$.

Table I shows what is currently known. Within the standard model, the asymmetry for the $D^0 \to K^+K^-$ mode is at most a few times 10^{-3} [1]. CP asymmetries on the percent level are quite conceivable for the $D^0 \to K^0_S\pi^0$ and $D^0 \to K^0_S\phi$ modes with contributions from new physics [1]. Recent publications from the E691 collaboration [2] and the E687 collaboration [3] report that upper limits on the CP asymmetry for the K^+K^- mode are 0.45 and -0.11< A <0.16, respectively, at the 90% confidence level. We know of no published experimental upper limits for the $D^0 \to K^0_S\phi$ and $D^0 \to K^0_S\pi^0$ modes.

TABLE I. The present theory and experiments

Channel	Experimental Asymmetry	Experimental UL(@90%CL)	Theory [1] Standard Model	New Physics
$D^0 \to K^0_S\phi$				$O(10^{-2})$
$D^0 \to K^0_S\pi^0$				$O(10^{-2})$
$D^0 \to K^+K^-$	0.20±0.15	0.45 [2]	$O(10^{-3})$	$O(10^{-2})$
	0.024±0.084	-0.11 <A<0.16 [3]		

II. THE ANALYSIS

A. Data Sample

We use 2,772 pb^{-1} of data taken with the CLEO II detector at the Cornell Electron Storage Ring. These data were taken on and just below the $\Upsilon(4S)$ resonance.

B. The Initial Selection

In this analysis, we first reconstruct the D^0 and $\bar{D}^0$ decays as described in the following sections. We then combine the D candidate with a soft pion to reconstruct $D^{*\pm} \rightarrow \overset{(-)}{D^0} \pi^{\pm}$. In this reconstruction, combinatorics are the dominant source of background. The background consists either of a correctly reconstructed D combined with a random pion or an incorrectly reconstructed D combined with the correct slow pion. In order to minimize the combinatorial background we use a mass difference cut of $|M_{D^{*+}} - M_{D^0}| < 2.5\sigma$ from the nominal difference. Kinematic constraints require that the momentum of the charged pion produced in the D^* decay be less than 0.45 GeV/c. This pion is denoted as the soft pion.

C. Measurement

1. $D^0(\bar{D}^0) \rightarrow K_S^0 + \phi$

Candidate K_S^0 mesons are required to lie within 3σ of the nominal K_S^0 mass and have a decay vertex displaced at least 1mm from the beam position. We reconstruct the ϕ via its K^+K^- decay mode. We require that the normalized difference between the expected and measured dE/dx for the kaon hypothesis be within 2σ for both tracks. We also apply optimized track quality cuts to both kaon candidate tracks. We select candidate ϕ decays in the mass range $1.012 < M_\phi < 1.028$ GeV/c^2 (Figure 1).

The contribution from non-resonant $K_S^0 K^+ K^-$ in the signal region is removed by subtracting the $D^0(\bar{D}^0)$ content of the ϕ sideband. We select ϕ sideband events in the mass range $1.000 < M_\phi < 1.008$ GeV/c^2 and $1.032 < M_\phi < 1.040$ GeV/c^2 (Figure 1). The scale factor between the ϕ sideband regions and the ϕ signal region is unity since we have assumed a linearly falling background.

Using these cuts and ϕ sideband subtraction we obtain the D^0 and $\bar{D}^0$ mass spectra shown in Figures 2 and 3. There is no D^0 momentum cut. The background is fit with a Chebyshev polynomial of order 3 using the combined D^0 and $\bar{D}^0$ mass distributions. We exclude the peak region in this background fit. We then count the number of events in the signal region and subtract the integral of the fitted background in the same region. The signal region is defined to be within 3σ of the fitted mass, determined using a Gaussian fit to the sum of the D^0 and $\bar{D}^0$ mass distributions. For this channel the signal region is between 1.85 and 1.89 GeV/c^2. The number of events in the D^0 signal region is 143 and the number in the $\bar{D}^0$ signal region is 146. The integral of the fitted background in the same region is 12±3. Finally, we obtain $N_{K_S^0\phi}$= 131±12 for $D^0 \rightarrow K_S^0\phi$ and $\bar{N}_{K_S^0\phi}$= 134±13 for $\bar{D}^0 \rightarrow K_S^0\phi$.

2. $D^0(\bar{D}^0) \rightarrow K_S^0\pi^0$

We next consider the mode $D^0(\bar{D}^0) \rightarrow K_S^0\pi^0$. We detect π^0's by their decays to $\gamma\gamma$. Candidate π^0's are formed by taking two photon combinations which appear as clusters in the CsI calorimeter. The energy of the clusters has to be at least 30 MeV and the di-photon combination must have at least one photon in the highest resolution portion of the calorimeter ($|\cos(\theta)| < 0.71$). We reject all photons matched to charged tracks in the central detector. We require that the momentum of the di-photon combination be greater than 0.2 GeV/c and that the mass of this combination be within 2σ of the pion mass.

In addition to the K_S^0 cuts used previously, we require that the cosine of the angle between the K_S^0 in the D^0 rest frame and the D^0 laboratory momentum be less than 0.8. Since the D^0, K_S^0 and π^0 are spin-less, the D^0 decays isotropically, whereas the background peaks at $\cos\theta_{K_S^0} \approx 1.0$. We also impose a D^0 momentum cut of $P_{D^0} > 1.7$ GeV/c which reduces the combinatoric background.

Using these cuts we obtain the D^0 and $\bar{D}^0$ mass spectra shown in Figures 4 and 5. We use the same method as for the $K_S^0\phi$ channel to calculate the asymmetry. For this channel the signal region is between 1.80 and 1.92 GeV/c^2. The number of events in the D^0 signal region is 773 and the number in the $\bar{D}^0$ signal region is 796. The integral of the fitted background in the same region is 78±9. We find $N_{K_S^0\pi^0} = 695\pm29$ for $D^0 \to K_S^0\pi^0$ and $\bar{N}_{K_S^0\pi^0} = 718\pm30$ for $\bar{D}^0 \to K_S^0\pi^0$.

3. $D^0(\bar{D}^0) \to K^+K^-$

The potentially major source of background for $D^0(\bar{D}^0) \to K^+K^-$ comes from the Cabibbo favored decay where the $\overset{(-)}{D^0}$ decays to $K^\mp\pi^\pm$ and we misidentify a π^+ as a K^+ or a π^- as a K^-. While these events lie above the signal region, they can make background subtraction more difficult.

In order to select the K^+K^- decay mode and reduce the $K\pi$ background, we require that the normalized difference between the expected and measured dE/dx for the kaon hypothesis be within 3σ for both kaon tracks. We also require that the normalized dE/dx difference for the pion hypothesis be greater than 1.5σ for the kaon track with the same sign as the soft pion. This cut greatly reduces the background from the $K\pi$ modes. We also require that the cosine of the angle between the $K^\pm$ in the D^0 rest frame and the D^0 laboratory momentum be less than 0.8 and that the momentum of kaon be greater than 0.3 GeV/c. Finally, we impose a D^0 momentum cut of $P_{D^0} > 1.7$ GeV/c.

Using these cuts we obtain the D^0 and $\bar{D}^0$ mass spectra shown in Figures 6 and 7. This time, in fitting the background we include the peak around 1.98 GeV/c^2 due to the misidentified $D^0(\bar{D}^0) \to K^\mp\pi^\pm$ events. This peak is fit with $K\pi$ Monte Carlo events. Otherwise we proceed as before. For this channel the signal region is between 1.84 and 1.89 GeV/c^2. The number of events in the D^0 signal region is 449 and the number in the $\bar{D}^0$ signal region is 414. The integral of the fitted background in the same region is 165±13. We find $N_{K^+K^-} = 284\pm25$ for $D^0 \to K^+K^-$ and $\bar{N}_{K^+K^-} = 249\pm24$ for $\bar{D}^0 \to K^+K^-$.

III. SYSTEMATIC STUDIES

A. Soft pion detection efficiencies

We have searched for systematic biases which would give an asymmetry in the number of D^{*+} and D^{*-} detected. The most probable source of such a bias is a difference in the efficiencies for detecting positive and negative soft pions. We have checked for this effect in several ways.

1. Beam pipe interaction

Since the soft pions we detect have travelled through a beryllium beam pipe, a difference in the hadronic interactions for negative and positive pions would cause an asymmetry. Isospin arguments show that any such difference would come from a difference in the number of protons and neutrons in the beam pipe. We have calculated the interaction probabilities in all of the materials between the interaction part and the drift chamber and find that the difference in rates is less than 0.0004. This is negligible given the size of our statistical error.

2. Soft π detection efficiency

To look directly for differences in the reconstruction efficiencies of soft pions we use pions from K_S^0 decays. The procedure is to determine the number of π^+ and π^- bin by bin in momentum and calculate the asymmetry A defined as

$$A = \frac{N_{\pi^+} - N_{\pi^-}}{N_{\pi^+} + N_{\pi^-}}$$

where $N_{\pi^+}(N_{\pi^-})$ is the number of soft $\pi^+(\pi^-)$. This study is complicated by the non-zero lifetime of the K_S^0. We select a clean sample of K_S^0's originating from as close to the origin as possible and exclude all those decaying outside the beam pipe by requiring that the kaon decay vertex be between 5 and 35mm. We also apply a 2σ mass cut. Using these cuts we obtain the soft π momentum distributions shown in Figure 8.

From these soft π momentum distributions we calculate the bin-by-bin asymmetry shown in Figure 9. The momentum region of interest is the region between 0.10 and 0.25 GeV/c where there is some evidence of a bias. Note that while this study is insensitive to a momentum-independent asymmetry in the detection efficiencies, studies have shown that it is a good measure of asymmetries that affect only low momentum tracks. The average asymmetry in this region is -0.010 ± 0.002.

To get an accurate estimate of the systematic uncertainty this effect causes, we fold this asymmetry into the momentum spectrum of the soft pions from D^* decay for each mode. Table II shows the calculated asymmetry which could be associated with this source for each decay mode.

TABLE II. The systematic error on the asymmetry due to differences in soft pion detection efficiency.

Channel	Shift in Asymmetry A$\pm$dA
$D^0 \to K_S^0\phi$	-0.006 ± 0.007
$D^0 \to K_S^0\pi^0$	-0.006 ± 0.006
$D^0 \to K^+K^-$	-0.005 ± 0.006

We have chosen to deal with this systematic bias by correcting the central values quoted for this effect.

3. $\overset{(-)}{D^0} \to K^{\mp}\pi^{\pm}$

Another way to check for differences in the soft pion detection efficiencies might be to use soft pions from charged D^* decays where there is a Cabibbo favored neutral D decay to a $K\pi$.

However, the interpretation of the results from this check depends on the assumption that CP violation is negligible for this mode, as predicted in the standard model. If non-standard model effects contribute, then the rates for each decay may not be the same. This asymmetry measurement can therefore be interpreted either as a systematic check or as a limit on CP violation.

Given the charge of the soft pion, we consider same-sign charged tracks as pions and opposite-sign charged tracks as kaons, when finding D^0 candidates. Then, we select events by requiring the D^0 momentum be greater than 1.7 GeV/c and the kaon and pion momenta be greater than 0.3 GeV/c.

Using these cuts we can obtain the D^0 and $\bar{D}^0$ mass spectra shown in Figures 10 and 11. We use our standard fitting procedure except that we also exclude the region 1.60$\sim$1.70 GeV/c^2 from our fit. The excess of events in this region is due to feed-down from reactions such as $D^0 \to K^-\pi^+\pi^0$ where the π^0 is not used. For this channel the signal region lies between 1.835 and 1.895 GeV/c^2. The number of events in the D^0 signal region is 12280 and the number in the $\bar{D}^0$ signal region is 12190. The integral of the fitted background in the same region is 3394±58. So, we obtain $N_{K^-\pi^+}=$ 8886±125 for $D^0 \to K^-\pi^+$ and $\bar{N}_{K^+\pi^-}$=8796±125 for $\bar{D}^0 \to K^+\pi^-$. From these numbers we obtain the measured asymmetry A=0.005±0.010. Finally, after compensating for the systematic bias between the π^+ and π^- detection efficiencies, we obtain A=0.011±0.012 or $-0.009 < A < 0.030$ at the 90 % confidence level [4].

B. Monte Carlo analysis

We have also checked the analysis by generating asymmetries in the decay channels of interest in Monte Carlo. We use 21,000 D^0 decays and 20,000 $\bar{D}^0$ decays in each mode, so the generated asymmetry is 0.024. Using exactly the same cuts and procedures used in the real data analysis, we determine the asymmetries. Table III summarizes our results. It shows that the measured CP asymmetries are consistent with the generated value of 0.024 within errors.

TABLE III. The CP asymmetry check using Monte Carlo events. The generated asymmetry is 0.024.

Channel	N (D^0)	N̄ ($\bar{D}^0$)	Asymmetry
$D^0 \to K^0_S\phi$	2494±47	2449±46	0.009±0.013
$D^0 \to K^0_S\pi^0$	2679±48	2589±48	0.017±0.013
$D^0 \to K^+K^-$	2624±48	2521±47	0.020±0.013

IV. RESULTS

We have measured the asymmetries for each decay mode and have studied the major systematic effects. We find that the measured asymmetry is insensitive to the background fitting methods. The associated systematic error on the asymmetry is less than 0.001. However, to compensate the systematic bias between the π^+ and π^- detection efficiencies, we correct for the systematic asymmetry shown in table II. Table IV shows the final results. The results shown here for the $D^0 \to K^0_S\phi$ and $D^0 \to K^0_S\pi^0$ modes represent the first limits on CP violation in these channels. The $D^0 \to K^+K^-$ result is comparable to that from other experiments [3].

TABLE IV. The results

Channel	CP Asymmetry	Upper Limit [4] (@90%CL)	Previous UL(@90%CL)	Theory [1] (CP Asymmetry)
$D^0 \to K^0_S\phi$	-0.005 ± 0.067	$-0.115 < A < 0.105$		$O(10^{-2})$
$D^0 \to K^0_S\pi^0$	-0.011 ± 0.030	$-0.060 < A < 0.038$		$O(10^{-2})$
$D^0 \to K^+K^-$	0.071 ± 0.065	$-0.036 < A < 0.178$	0.45 [2]	$O(10^{-3} \sim 10^{-2})$
			$-0.11 <$A< 0.16 [3]	
Combined	0.002 ± 0.025	$-0.039 < A < 0.044$		

V. CONCLUSION

We have searched for evidence of CP violation in the D^0 system using 2,772 pb^{-1} of data. We have set new upper limits for the CP asymmetry in D^0 decays to $K^0_S\phi$, $K^0_S\pi^0$ and K^+K^-.

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[3] P. L. Frabetti *et al*, Preprint, Fermilab-Pub-071-E (1994).
[4] We center this interval on our measured value.

FIGURES

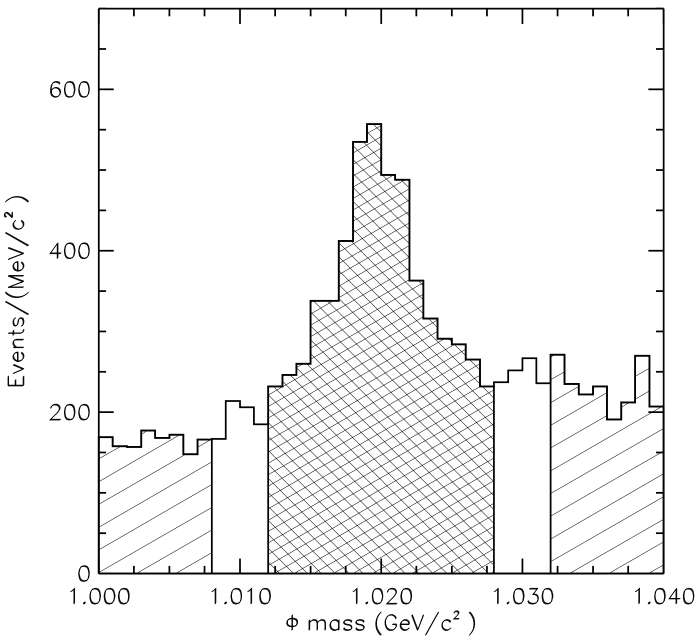

FIG. 1. ϕ mass spectrum for $\phi \rightarrow K^+K^-$. The shaded region is the signal region and the slashed region is the sideband region.

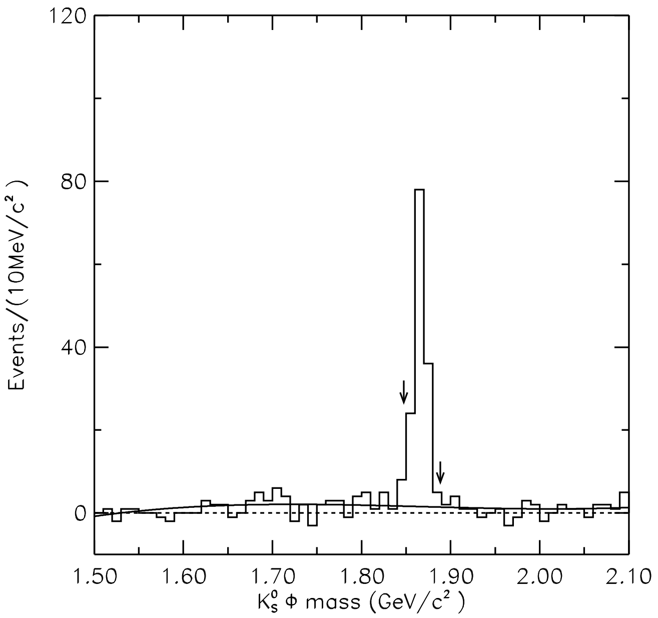

FIG. 2. The reconstructed D^0 mass spectrum for $D^0 \to K^0_S\phi$. In this D^0 mass signal, we use ϕ sideband subtraction in order to remove non-resonant $K^0_S K^+ K^-$ background. The solid curve is background and the dashed line is the zero line. The arrows show the signal region.

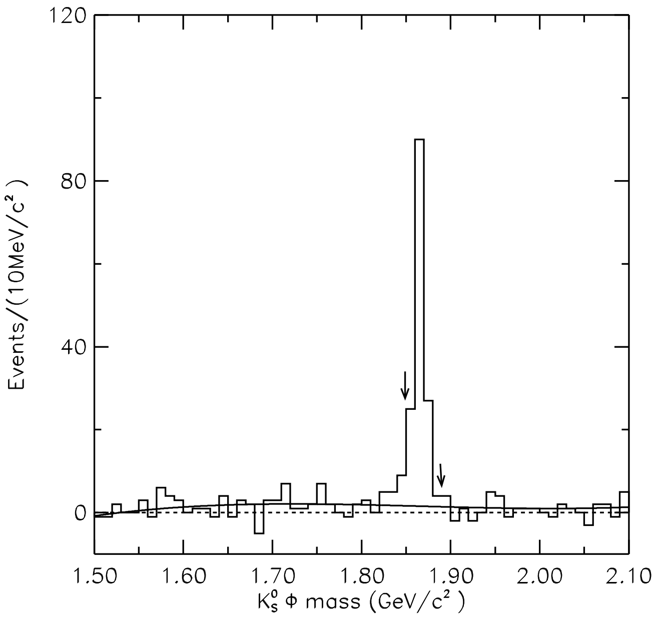

FIG. 3. The reconstructed $\bar{D}^0$ mass spectrum for $\bar{D}^0 \to K^0_S\phi$. In this $\bar{D}^0$ mass signal, we use ϕ sideband subtraction in order to remove non-resonant $K^0_S K^+ K^-$ background. The solid curve is background and the dashed line is the zero line. The arrows show the signal region.

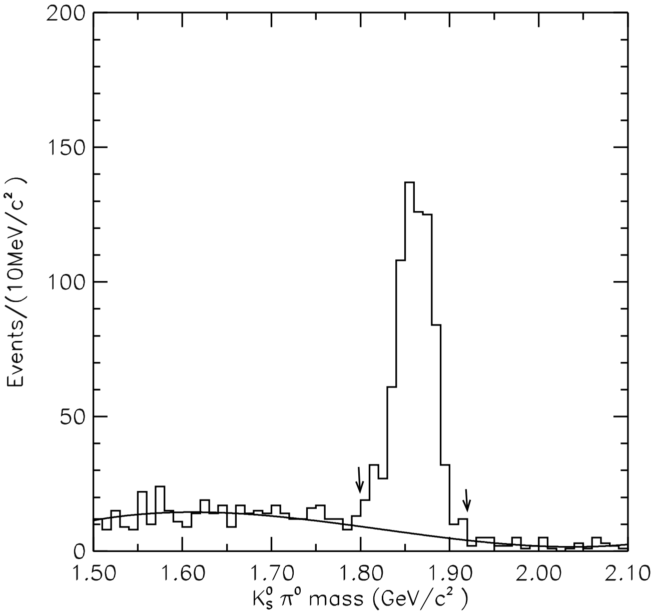

FIG. 4. The reconstructed D^0 mass spectrum for $D^0 \to K_S^0\pi^0$. The arrows show the signal region.

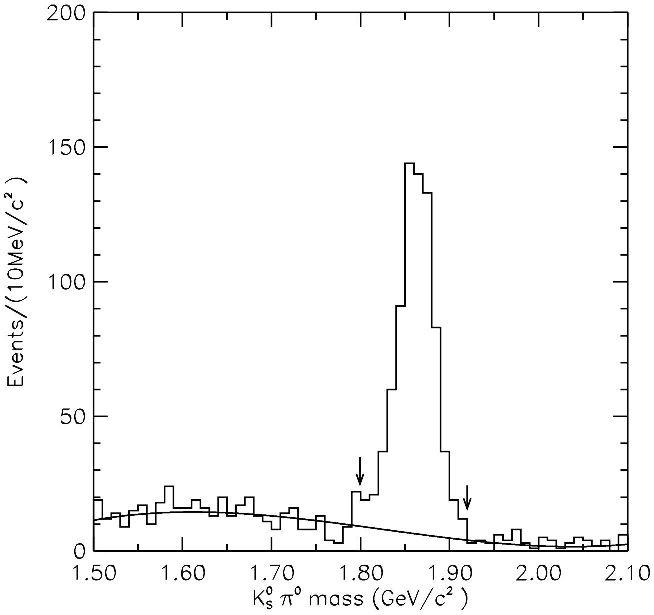

FIG. 5. The reconstructed $\bar{D}^0$ mass spectrum for $\bar{D}^0 \to K_S^0\pi^0$. The arrows show the signal region.

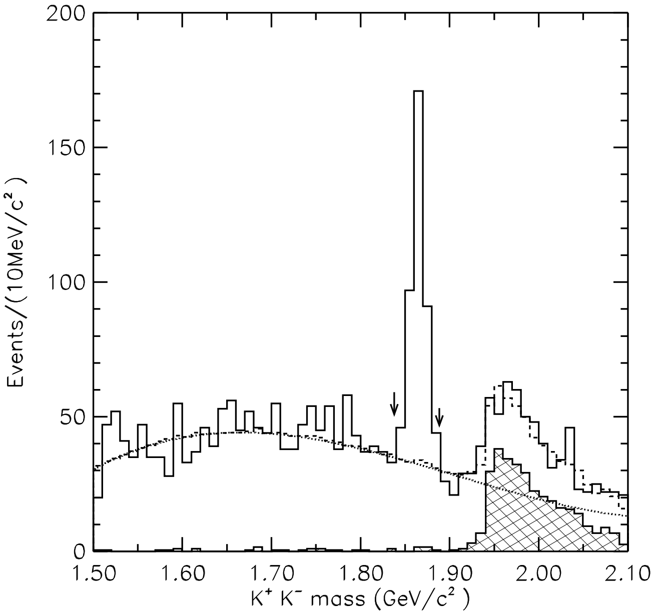

FIG. 6. The reconstructed D^0 mass spectrum for $D^0 \to K^+K^-$ and the fit to background. The dotted line is a Chebyshev polynomial of order 3 and the cross hatched region is given by $K\pi$ Monte Carlo events. The solid line is for real data. The dashed line is the sum of the Chebyshev polynomial and $K\pi$ Monte Carlo events. The arrows show the signal region.

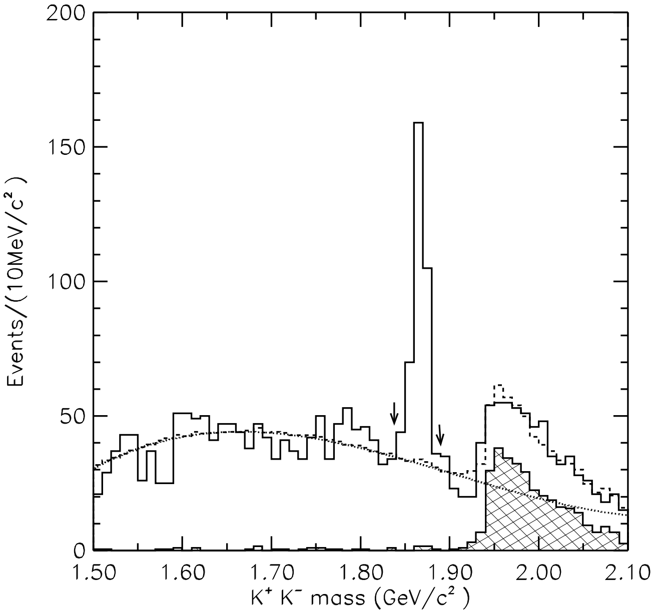

FIG. 7. The reconstructed $\bar{D}^0$ mass spectrum for $\bar{D}^0 \to K^+K^-$ analogous to FIG. 6.

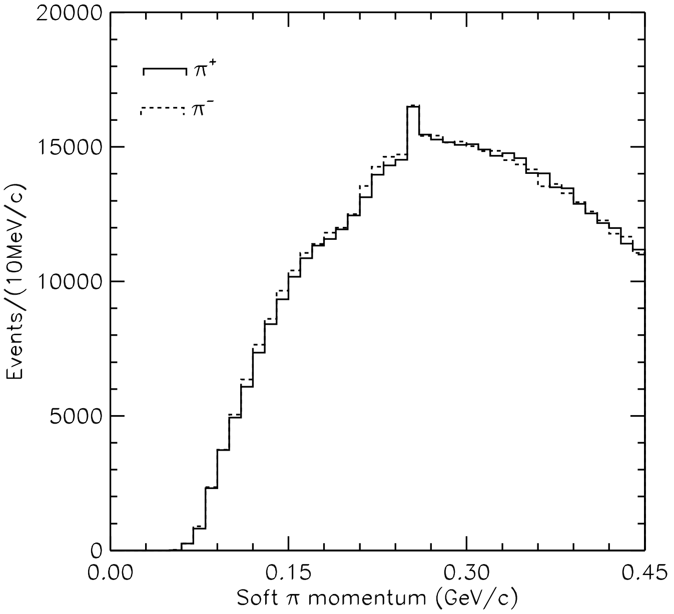

FIG. 8. The soft π momentum distributions in $K_S^0 \to \pi^+\pi^-$.

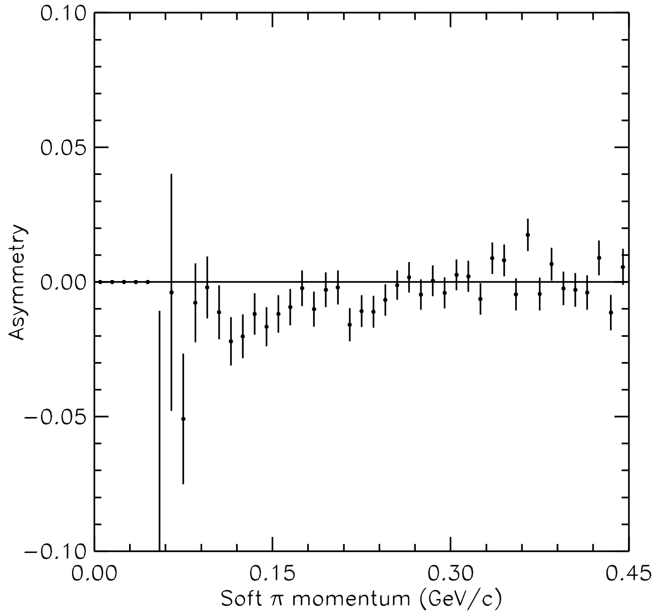

FIG. 9. The asymmetry vs. π momentum distribution in $K_S^0 \to \pi^+\pi^-$. The bin size is 10 MeV/c.

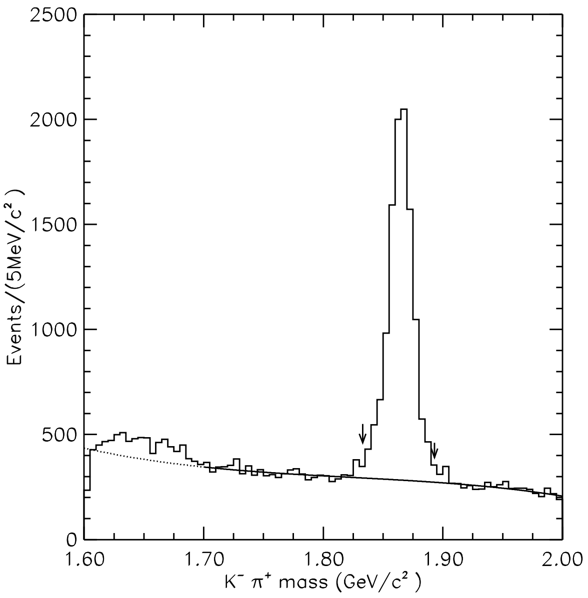

FIG. 10. The reconstructed D^0 mass spectrum for $D^0 \to K^-\pi^+$. The arrows show the signal region.

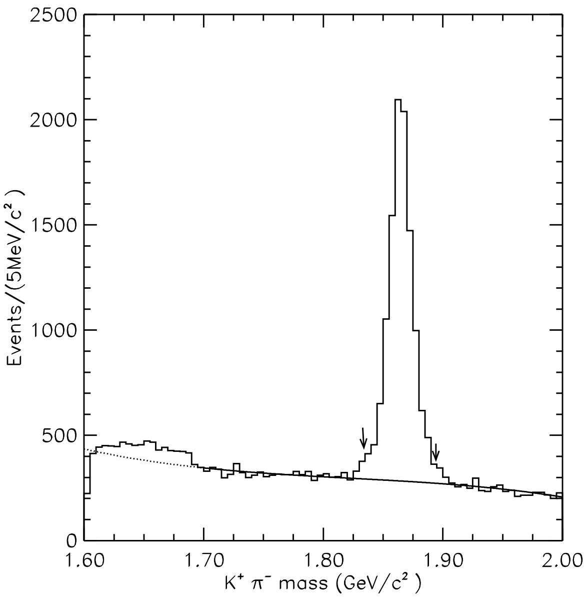

FIG. 11. The reconstructed $\bar{D}^0$ mass spectrum for $\bar{D}^0 \to K^+\pi^-$. The arrows show the signal region.