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Measurement of the absolute branching fraction for $D^0 \to K^-\pi^+$

D.S. Akerib,[1] B. Barish,[1] M. Chadha,[1] S. Chan,[1] D.F. Cowen,[1] G. Eigen,[1] J.S. Miller,[1] C. O'Grady,[1] J. Urheim,[1] A.J. Weinstein,[1] D. Acosta,[2] M. Athanas,[2] G. Masek,[2] H. Paar,[2] A. Bean,[3] J. Gronberg,[3] R. Kutschke,[3] S. Menary,[3] R.J. Morrison,[3] S. Nakanishi,[3] H.N. Nelson,[3] T.K. Nelson,[3] J.D. Richman,[3] A. Ryd,[3] H. Tajima,[3] D. Schmidt,[3] D. Sperka,[3] M.S. Witherell,[3] M. Procario,[4] S. Yang,[4] R. Balest,[5] K. Cho,[5] M. Daoudi,[5] W.T. Ford,[5] D.R. Johnson,[5] K. Lingel,[5] M. Lohner,[5] P. Rankin,[5] J.G. Smith,[5] J.P. Alexander,[6] C. Bebek,[6] K. Berkelman,[6] D. Besson,[6] T.E. Browder,[6] D.G. Cassel,[6] H.A. Cho,[6] D.M. Coffman,[6] P.S. Drell,[6] R. Ehrlich,[6] M. Garcia-Sciveres,[6] B. Geiser,[6] B. Gittelman,[6] S.W. Gray,[6] D.L. Hartill,[6] B.K. Heltsley,[6] C.D. Jones,[6] S.L. Jones,[6] J. Kandaswamy,[6] N. Katayama,[6] P.C. Kim,[6] D.L. Kreinick,[6] G.S. Ludwig,[6] J. Masui,[6] J. Mevissen,[6] N.B. Mistry,[6] C.R. Ng,[6] E. Nordberg,[6] M. Ogg,[6*] J.R. Patterson,[6] D. Peterson,[6] D. Riley,[6] S. Salman,[6] M. Sapper,[6] H. Worden,[6] F.Würthwein,[6] P. Avery,[7] A. Freyberger,[7] J. Rodriguez,[7] R. Stephens,[7] J. Yelton,[7] D. Cinabro,[8] S. Henderson,[8] K. Kinoshita,[8] T. Liu,[8] M. Saulnier,[8] F. Shen,[8] R. Wilson,[8] H. Yamamoto,[8] B. Ong,[9] M. Selen,[9] A.J. Sadoff,[10] R. Ammar,[11] S. Ball,[11] P. Baringer,[11] D. Coppage,[11] N. Copty,[11] R. Davis,[11] N. Hancock,[11] M. Kelly,[11] N. Kwak,[11] H. Lam,[11] Y. Kubota,[12] M. Lattery,[12] J.K. Nelson,[12] S. Patton,[12] D. Perticone,[12] R. Poling,[12] V. Savinov,[12] S. Schrenk,[12] R. Wang,[12] M.S. Alam,[13] I.J. Kim,[13] B. Nemati,[13] J.J. O'Neill,[13] H. Severini,[13] C.R. Sun,[13] M.M. Zoeller,[13] G. Crawford,[14] C. M. Daubenmier,[14] R. Fulton,[14] D. Fujino,[14] K.K. Gan,[14] K. Honscheid,[14] H. Kagan,[14] R. Kass,[14] J. Lee,[14] R. Malchow,[14] F. Morrow,[14] Y. Skovpen,[14†] M. Sung,[14] C. White,[14] J. Whitmore,[14] P. Wilson,[14] F. Butler,[15] X. Fu,[15] G. Kalbfleisch,[15] M. Lambrecht,[15] W.R. Ross,[15] P. Skubic,[15] J. Snow,[15] P.L. Wang,[15] M. Wood,[15] D. Bortoletto,[16] D.N. Brown,[16] J.Fast,[16] R.L. McIlwain,[16] T. Miao,[16] D.H. Miller,[16] M. Modesitt,[16] S.F. Schaffner,[16] E.I. Shibata,[16] I.P.J. Shipsey,[16] P.N. Wang,[16] M. Battle,[17] J. Ernst,[17] H. Kroha,[17] S. Roberts,[17] K. Sparks,[17] E.H. Thorndike,[17] C.H. Wang,[17] J. Dominick,[18] S. Sanghera,[18] V. Shelkov,[18] T. Skwarnicki,[18] R. Stroynowski,[18] I. Volobouev,[18] P. Zadorozhny,[18] M. Artuso,[19] D. He,[19] M. Goldberg,[19] N. Horwitz,[19] R. Kennett,[19] G.C. Moneti,[19] F. Muheim,[19] Y. Mukhin,[19] S. Playfer,[19] Y. Rozen,[19] S. Stone,[19] M. Thulasidas,[19] G. Vasseur,[19] G. Zhu,[19] J. Bartelt,[20] S.E. Csorna,[20] Z. Egyed,[20] V. Jain,[20] and P. Sheldon[20]

(CLEO Collaboration)

[1] California Institute of Technology, Pasadena, California 91125
[2] University of California, San Diego, La Jolla, California 92093
[3] University of California, Santa Barbara, California 93106
[4] Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213
[5] University of Colorado, Boulder, Colorado 80309-0390
[6] Cornell University, Ithaca, New York 14853
[7] University of Florida, Gainesville, Florida 32611
[8] Harvard University, Cambridge, Massachusetts 02138
[9] University of Illinois, Champaign-Urbana, Illinois, 61801
[10] Ithaca College, Ithaca, New York 14850
[11] University of Kansas, Lawrence, Kansas 66045
[12] University of Minnesota, Minneapolis, Minnesota 55455
[13] State University of New York at Albany, Albany, New York 12222
[14] Ohio State University, Columbus, Ohio, 43210
[15] University of Oklahoma, Norman, Oklahoma 73019
[16] Purdue University, West Lafayette, Indiana 47907
[17] University of Rochester, Rochester, New York 14627
[18] Southern Methodist University, Dallas, Texas 75275
[19] Syracuse University, Syracuse, New York 13244
[20] Vanderbilt University, Nashville, Tennessee 37235

Abstract

Using 1.79 fb^{-1} of data recorded by the CLEO II detector we have measured the absolute branching fraction for $D^0 \to K^-\pi^+$. The angular correlation between the π^+ emitted in the decay $D^{*+} \to D^0\pi^+$, and the jet direction in $e^+e^- \to c\bar{c}$ events, is used to determine the total number of inclusive D^0 mesons produced from this source. The subsequent reconstruction of the decay chain $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$, allows a measurement of the absolute $D^0 \to K^-\pi^+$ branching fraction. Correcting for decay radiation in the final state, we find $\mathcal{B}(D^0 \to K^-\pi^+) = [3.95 \pm 0.08(\mathrm{stat.}) \pm 0.17(\mathrm{syst.})]\%$.

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*Permanent address: Carleton University, Ottawa, Canada K1S 5B6

†Permanent address: INP, Novosibirsk, Russia

A precise value for the absolute branching fraction $\mathcal{B}(D^0 \to K^-\pi^+)$ is extremely important for B and D meson experimental measurements. The $D^0 \to K^-\pi^+$ decay mode is the simplest, cleanest, and most commonly used normalizing mode for D^0 decays. Among the samples of reconstructed B mesons there are many modes which decay via $D^0 \to K^-\pi^+$ in the final state. Many of the past and current D and B branching fraction measurements are systematically limited by the precision of $\mathcal{B}(D^0 \to K^-\pi^+)$.

There have been several measurements of the absolute $D^0 \to K^-\pi^+$ branching fraction. In order to extract this branching fraction, one must first determine the total number of D^0 mesons in the event sample. To date this has been achieved by two different techniques. The first uses double tagged $D^0\bar{D}^0$ events [1], and the second uses D^0 mesons produced in $D^{*+} \to D^0\pi^+$ decays [2,3]. Once the total number of D^0 mesons is known, by reconstructing the D^0 in the decay mode of interest, one can determine the absolute branching fraction for that channel. There exists a third technique that measures the ratio of $D^0 \to K^-\pi^+$ relative to the total number of even prong decays [4,5]. The $D^0 \to K^-\pi^+$ branching fraction is then calculated using topological branching fractions measured by other experiments to correct for missing zero prong decays.

Here we use the second method. The $D^{*+} \to D^0\pi^+$ decay is a two-body process, and the small amount of energy available means that the π^+ is very soft, having a transverse momentum, $p_\perp$, relative to the D^{*+} direction which cannot exceed 40 MeV/c. This low transverse momentum provides the $D^{*+} \to D^0\pi^+$ signature. The D^0 is not reconstructed at this point, so the D^{*+} direction is not measured, however it is well approximated by the thrust axis of the event [6]. The resolution on the D^{*+} direction using this technique has been measured with the data for fully reconstructed $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ decays to be 0.080 radians full width at half maximum.

The data used for this analysis consist of 1.79 fb^{-1} of e^+e^- collisions recorded with the CLEO II detector at the Cornell Electron Storage Ring (CESR). The CLEO II detector has been described in detail elsewhere [7]. Data were recorded on the $\Upsilon(4S)$ resonance and the nearby continuum. There are two sources of D^{*+} mesons at the $\Upsilon(4S)$ energy; continuum $e^+e^- \to c\bar{c}$ reactions and $B \to D^{*+}X$ decays. Since $\Upsilon(4S) \to B\bar{B}$ decays are spherical in topology the thrust axis no longer approximates the D^{*+} direction. To eliminate $B \to D^{*+}X$ decays, we require that the π^+ have a momentum greater than 225 MeV/c, which selects $D^{*+} \to D^0\pi^+$ decays where the parent D^{*+} momentum is too large to have come from a B decay. This cut retains over 40% of the $D^{*+} \to D^0\pi^+$ decays in continuum events. We also require that the thrust [6], T, value be greater than 0.75 to reduce combinatorial background from $\Upsilon(4S)$ decays and to ensure a well defined thrust axis. To minimize systematic errors from modeling of the detection efficiency we also require that the thrust axis have a polar angle with respect to the beam axis of greater than 45 degrees. This selects events with the thrust axis pointing into the barrel portion of the detector.

Previous measurements have used the $p_\perp^2 = p_\pi^2 \sin^2\alpha$ distribution to determine the total number of $D^{*+} \to D^0\pi^+$ decays, where α is the angle between the pion and the thrust axis and p_π is the magnitude of the π^+ momentum in the lab frame. We adopt a slightly different approach by dividing the data sample into eight 25 MeV/c slices in p_π. The $p_\perp^2$ and $\sin^2\alpha$ distributions then contain essentially the same information. We use the $\sin^2\alpha$ distribution to determine the number of $D^{*+} \to D^0\pi^+$ since it has the same range for all pion momentum slices.

In Figure 1 we show the $\sin^2\alpha$ distributions for pions in the eight momentum slices from 225 to 425 MeV/c. A clear peak from $D^{*+} \to D^0\pi^+$ decays is observed near zero. The histogram is the result of a fit to a signal shape obtained from a Monte Carlo simulation and a background function which is described below. When fitting the data we only fit the region $0 < \sin^2\alpha < 0.9$, and exclude the region $0.9 < \sin^2\alpha < 1$, since it has larger backgrounds and is far from the signal region so has no influence on the extracted yields. The peaking at $\sin^2\alpha \sim 1$ is due to tracks which are randomly distributed in $\cos\alpha$. The $D^{*+} \to D^0\pi^+$ yields obtained from each fit are given in the second column of Table I.

The predicted signal shape is sensitive to the fragmentation distribution of the D^{*+} mesons and the alignment of the D^{*+} spin relative to its momentum vector [8]. We have measured these production characteristics of D^* mesons in data using fully reconstructed $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ events. These measurements are then used to generate D^{*+} mesons in our Monte Carlo with the correct fragmentation and spin alignment. Varying the production parameters changes the yield of D^{*+} mesons by less than $\pm 1\%$. The background curve shown in Figure 1 is determined by studying background distributions in the data and Monte Carlo as described below. The functional form, $F = a_0/(1 + a_1\sin^4\alpha + a_2\sin^6\alpha) + a_3/\sqrt{1-\sin^2\alpha}$, is found to model the background well in all eight momentum slices for both the data and Monte Carlo distributions.

We look for sources of background that would peak at low $\sin^2\alpha$ by using the charge of the pion track in the low $\sin^2\alpha$ region to determine the charge of the $D^{*\pm}$ in one hemisphere. The other hemisphere should then contain charm of the opposite flavor. If this charm quark fragments as a charged D^*, the π from its decay will have opposite charge to the one used for tagging. Thus a sample of charged tracks in the opposite hemisphere with the same sign as the tagged pion will have no contributions from $D^{*-} \to D^0\pi^-$ (if the tagged pion is a π^+), but could have contributions from other charm processes such as $\Sigma_c \to \Lambda_c\pi$ decays. We use a sideband in the tagged $\sin^2\alpha$ distribution to predict the shape and normalization of the contribution due to background tracks at small $\sin^2\alpha$ in our tagged sample. Figure 2 shows the background subtracted $\sin^2\alpha$ distribution for tracks between 225-425 MeV/c in the opposite hemisphere opposite for approximately 150000 tagged $D^{*+} \to D^0\pi^+$ events. We see no evidence of a peak at $\sin^2\alpha \sim 0$. The overlaid curve shows the result of a fit to our background function. We also looked at pions from fully reconstructed $\eta \to \pi^+\pi^-\pi^0$ and $\omega \to \pi^+\pi^-\pi^0$ decays in the data. The $\sin^2\alpha$ distribution for these pions fits to the background function and is well reproduced by the Monte Carlo. We also study Monte Carlo continuum events, in which the slow pions from D^{*+} decays have been removed. For these events there is no peaking at low $\sin^2\alpha$.

To determine the number of $D^0 \to K^-\pi^+$ decays occurring in the sample of $D^{*+} \to D^0\pi^+$ decays, the slow π^+ is combined with two oppositely charged tracks. A Cabibbo favored decay of the D^0 is assumed in order to assign the K and π mass hypotheses. To minimize uncertainties due to the Monte Carlo simulation of detector efficiency, the π and K tracks are required to have momenta greater than 200 MeV/c, and that the magnitude of the cosine of each track's polar angle be less than 0.81. We select D^0 candidates which when combined with the slow pion give a mass difference, $M_{D^{*+}} - M_{D^0}$, within ± 5 MeV/c^2 of the expected value of 145.4 MeV/c^2 [9]. This loose cut ($\sim 5\sigma$) ensures that all the $D^0 \to K^-\pi^+$ events are present in the $M_{K\pi}$ distribution, which is shown in Figure 3. The D^0 signal shape is well represented by the sum of two Gaussian functions with the same mean but different widths. The background is well modelled by a second order polynomial. We find 4241 ± 82 $D^0 \to K^-\pi^+$ candidates. To account for random π, true D^0 combinations, we fit the $M_{K\pi}$ distribution from the $M_{D^{*+}} - M_{D^0}$ sidebands and normalize so that the area in the sideband region is equal to the fitted background area in the signal region. We find 33 ± 12 random combinations that fit to a D^0 signal. Subtracting these random combinations from the total yield gives 4208 ± 83 $D^0 \to K^-\pi^+$ events.

The last ingredient needed to calculate the $D^0 \to K^-\pi^+$ branching fraction is the efficiency, $\epsilon(K\pi)$, for finding the $K\pi$ tracks once the event has satisfied all the other requirements. To determine this efficiency we use a full hit-by-hit simulation of the CLEO detector to determine the efficiency. The digitized output is then processed through the same reconstruction and analysis software as the real data. The efficiencies obtained from this simulation are given in Table I.

The branching fraction is calculated using:

$$\mathcal{B}(D^0 \to K^-\pi^+) = \frac{N(D^{*+} \to D^0\pi^+,\ D^0 \to K^-\pi^+)}{N(D^{*+} \to D^0\pi^+)\epsilon(K\pi)}, \tag{1}$$

where $N(D^{*+} \to D^0\pi^+,\ D^0 \to K^-\pi^+)$ is obtained from the fit to the $M_{K\pi}$ distribution, and $N(D^{*+} \to D^0\pi^+)$ is determined by the fit to the $\sin^2\alpha$ distribution. We calculate the branching fraction for eight slices of pion momentum. The results are summarized in Table I. The χ^2 that all eight measurements arise from the weighted mean is 2.6 for 7 degrees of freedom. The low χ^2 value shows that the technique worked well over the entire pion momentum range without inducing any systematic effects. Combining all eight results we find $\mathcal{B}(D^0 \to K^-\pi^+) = (3.91 \pm 0.08 \pm 0.17)\%$, where the first error is statistical and the second is an estimate of our systematic uncertainty.

The total systematic error is obtained by summing in quadrature the errors given in Table II. The main contribution to the error is the uncertainty in $\epsilon(K\pi)$ due to our understanding of the Monte Carlo simulation of track reconstruction. To determine how well the simulation reproduces the data we compare single track efficiencies determined from the data with single track efficiencies in the Monte Carlo. These studies have a statistical precision of 2% per track and we assign a total $\pm 4\%$ uncertainty to $\epsilon(K\pi)$ from this source. In addition there is a $\pm 0.3\%$ uncertainty in the efficiency of the 200 MeV/c momentum cut on the $K\pi$ tracks. This error is estimated by varying the fragmentation function of the D^{*+} mesons in the Monte Carlo and studying the variation in acceptance. There is also a $\pm 0.7\%$ error on $\epsilon(K\pi)$ due to Monte Carlo statistics.

The error in determining $N(D^{*+} \to D^0\pi^+)$ is estimated by using different $\sin^2\alpha$ signal shapes obtained with different D^{*+} production parameters. We see variations in the total yield of D^{*+} events of less than $\pm 1\%$. As a cross check the number of D^{*+} mesons is obtained without any reference to a signal shape. Using only the background function to fit the $\sin^2\alpha$ distribution away from the signal region, we then extrapolate the background function underneath the signal and subtract the estimated background. The yield obtained in this manner agrees to within $\pm 1\%$ of that obtained using the full fit to a Monte Carlo signal shape. The slow pion reconstruction efficiency cancels in Equation (1) only if the slow pion reconstruction efficiency is independent of the D^0 decay mode. Any variation would result in a *topological skew* in the final result. We check this by measuring the slow pion reconstruction efficiency in the Monte Carlo for various D^0 decay modes. There is no statistically significant variation in the slow pion efficiency. However, these studies have a statistical precision of 1%. We also study the effect of the thrust value cut by measuring the acceptance for a Monte Carlo simulation containing generic D^0 decays and $D^0 \to K^-\pi^+$ decays. This study has a statistical precision of 0.5% and the acceptance agrees within the statistical precision. Combining these estimates in quadrature we assign a total systematic error of $\pm 1.5\%$ on $N(D^{*+} \to D^0\pi^+)$.

The systematic error on $N(D^0 \to K^-\pi^+)$ is estimated to be $\pm 0.6\%$ by fitting the $M_{D^{*+}} - M_{D^0}$ distribution and comparing the yield with that obtained by fitting the $M_{K\pi}$ distribution.

Finally, the $K\pi$ daughters can radiate photons in the final state. Decay radiation will cause a loss in efficiency due to $K\pi$ combinations that no longer reconstruct to the D^0 mass. We determine the effect of decay radiation by comparing $\epsilon(K\pi)$ determined with and without radiative effects. The ratio of efficiencies with and without radiative corrections is $0.991 \pm 0.003 \pm 0.002$. The first error is due to Monte Carlo statistics and the second is our estimate of how well the Monte Carlo simulates decay radiation. This systematic error is determined by comparing measured radiative effects [10] in $K_s^0 \to \pi^+\pi^-$ decays with K_s^0 decays in the Monte Carlo. Correcting for radiative effects we find, $\mathcal{B}(D^0 \to K^-\pi^+) = (3.95 \pm 0.08 \pm 0.17)\%$ where the errors associated with the radiative corrections has been added in quadrature to the systematic error.

In conclusion, we have made the most precise measurement to date of the absolute $D^0 \to K^-\pi^+$ branching fraction. We find before radiative corrections $\mathcal{B}(D^0 \to K^-\pi^+) = (3.91 \pm 0.08 \pm 0.17)\%$, where the first error is statistical and the second is an estimate of our systematic uncertainty. This result agrees with previous measurements [1–5]. Including effects of decay radiation we find, $\mathcal{B}(D^0 \to K^-\pi^+) = (3.95 \pm 0.08 \pm 0.17)\%$ [11]. We have searched for background contributions at low $\sin^2\alpha$ in the data which would invalidate this technique; none were found.

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[11] We quote two results for $\mathcal{B}(D^0 \to K^-\pi^+)$. The radiative corrected result is the absolute branching fraction independent of experimental resolution in $M(K\pi)$. The non-radiative corrected number should be used by experimentalists with $M(K\pi)$ resolution comparable to our resolution, $\sigma(M(K\pi)) = 10$ MeV/c^2, who do not include decay radiation in their calculation of the $D^0 \to K^-\pi^+$ efficiency.

FIGURES

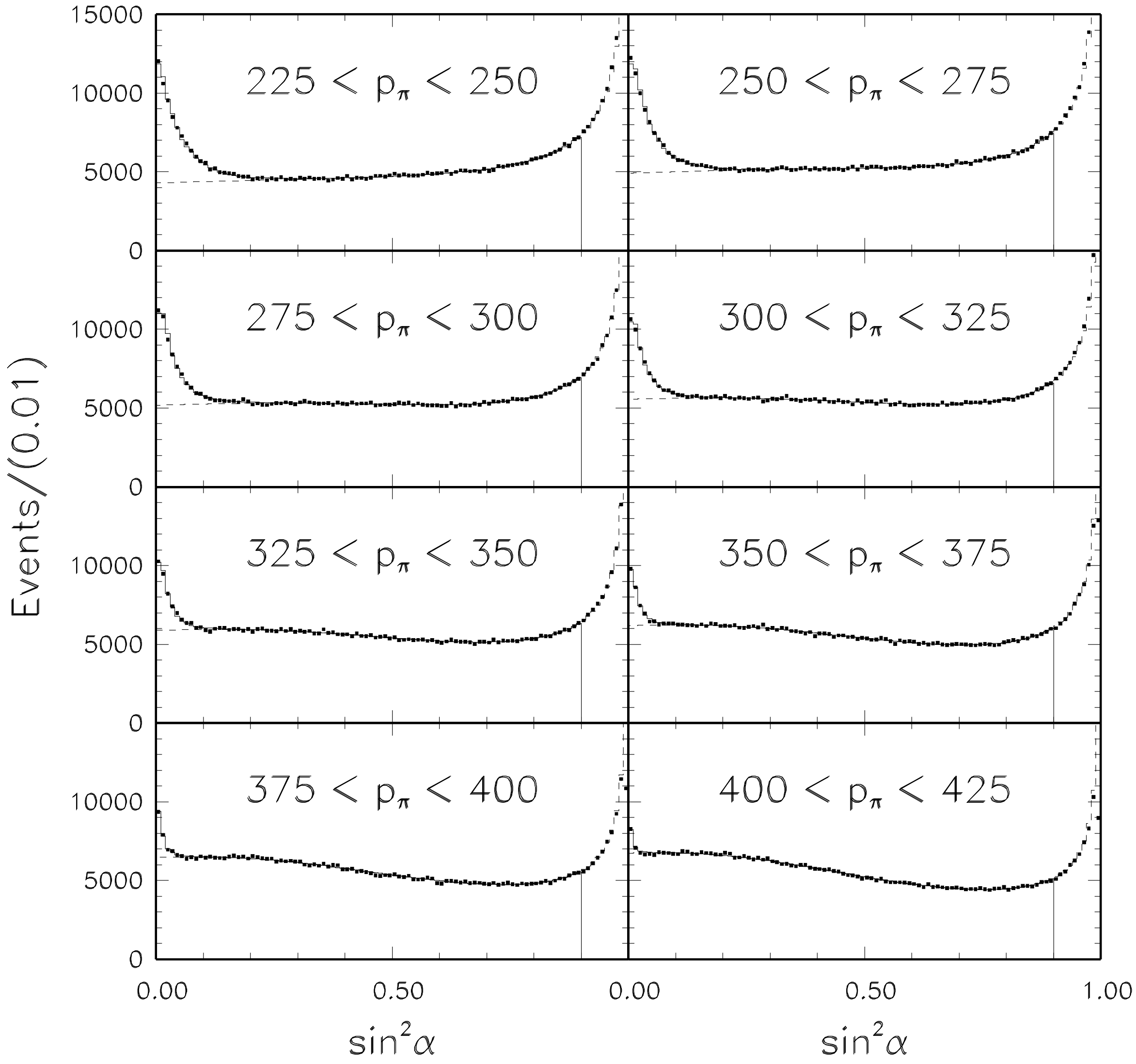

FIG. 1. The $\sin^2\alpha$ distribution for the eight 25 MeV/c momentum slices. The solid histogram is the result of a fit which includes signal and background contributions. The dashed curve in the region $\sin^2\alpha \sim 0$ shows the contribution of the background function to the fit. The vertical line marks the end of the fitted region.

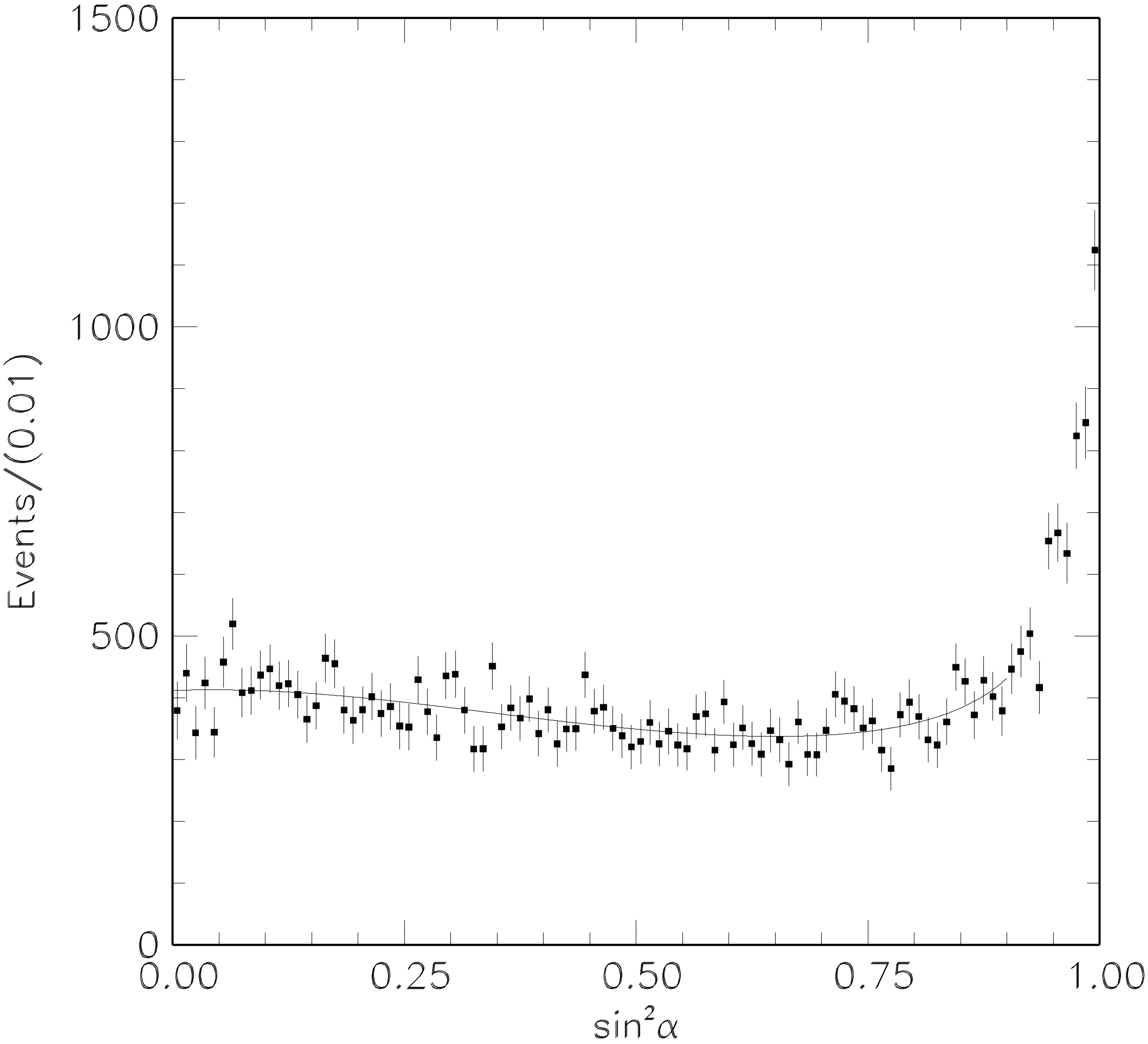

FIG. 2. The $\sin^2\alpha$ distribution for pions in the opposite jet with the same charge as the tagged pion. This plot has been background subtracted to account for the background underneath the signal in Figure 1. The curve is the result of a fit to the background function.

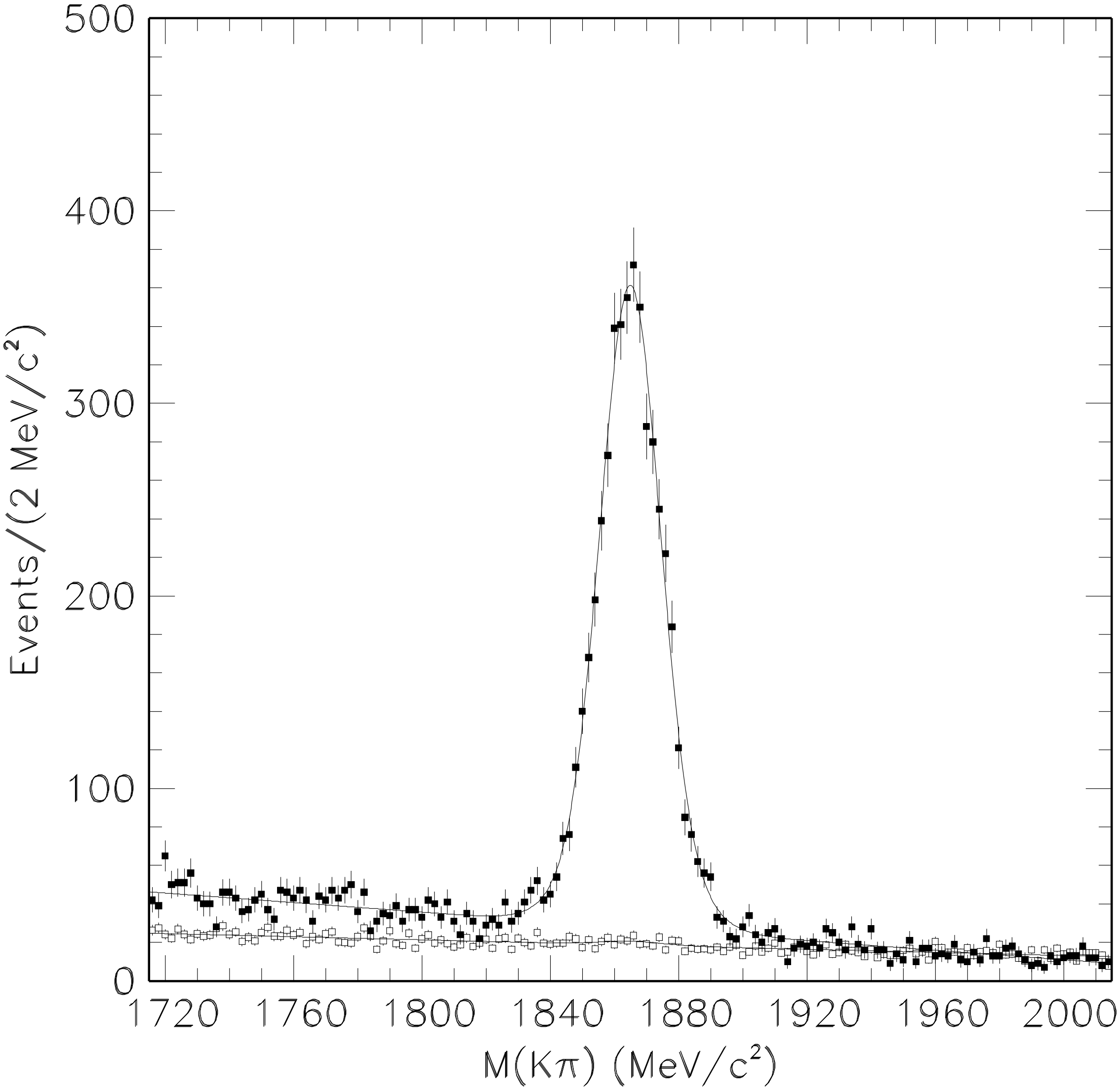

FIG. 3. The $M(K\pi)$ distribution for $K\pi$ candidates within 5 MeV/c^2 of the nominal D^{*+}-D^0 mass difference (solid points) and for $K\pi$ candidates in the sideband of the mass difference distribution (open points).

TABLES

TABLE I. Yields, efficiencies and branching ratios as a function of slow pion momentum. The errors are statistical only, the error in the last column is due to data statistics only.

p_π (MeV/c)	N($D^{*+} \to D^0\pi^+$)	N($D^0 \to K^-\pi^+$)	$\epsilon(K^-\pi^+)$ (%)	$\mathcal{B}(D^0 \to K^-\pi^+)$ (%)
225 - 250	44161 ± 611	1129 ± 44	64.6 ± 0.9	3.96 ± 0.17
250 - 275	39114 ± 562	945 ± 40	64.3 ± 0.9	3.76 ± 0.17
275 - 300	29482 ± 475	741 ± 34	64.4 ± 1.0	3.85 ± 0.18
300 - 325	21120 ± 396	528 ± 30	65.1 ± 1.1	3.85 ± 0.23
325 - 350	14973 ± 334	393 ± 25	66.0 ± 1.3	3.99 ± 0.27
350 - 375	9165 ± 267	262 ± 19	66.4 ± 1.8	4.31 ± 0.33
375 - 400	5492 ± 208	153 ± 15	68.8 ± 2.5	4.06 ± 0.42
400 - 425	2151 ± 147	57 ± 9	63.1 ± 4.4	4.20 ± 0.73
225 - 425	165658 ± 1149	4208 ± 83	64.93 ± 0.42	3.912 ± 0.082

Quantity	Possible source of systematic error	Estimate of error (%)
N($D^{*+} \to D^0\pi^+$)	signal shape	± 1.0
	topological skew	± 1.0
	thrust cuts	± 0.5
N($D^0 \to K^-\pi^+$)	fitting	± 0.6
$\epsilon(K\pi)$	Monte Carlo statistics	± 0.7
	tracking reconstruction	± 4.0
	momentum cut on $K\pi$ tracks	± 0.3
Total	summed in quadrature	± 4.4

TABLE II. Tabulation of the individual systematic errors.