Measurement of the $D^0 \rightarrow K^-\pi^+$ Branching Fraction[a]

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The determination of the branching fraction of D^0 mesons to the simple final state, $K^-\pi^+$, is important for understanding charm decay models.[1] This branching fraction also is used to determine the production rates of charmed mesons and the ratio of D to F production in the continuum,[2] as well as in B decay. All of these measurements are important for determining whether or not the so-called charm deficit exists.[3] The updated result of the Mark III collaboration for the $D^0 \rightarrow K^-\pi^+$ branching fraction (4.2 ± 0.4%[4]) disagrees with the older results obtained by the Mark II at SPEAR (3.0 ± 0.4%[5]) and the LGW collaboration (2.4 ± 0.4%[6]). In addition, the Mark III number has changed from the value (5.4 ± 0.2%[7]) published last year. In this confused situation, it is important to obtain independent measurements.

The $D^0 \rightarrow K^-\pi^+$ branching fraction (and its charge conjugate) is measured by

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tagging a sample of the decays, $D^{+*} \rightarrow D^0\pi_s^+$ (and their charge conjugates), using the very low transverse momentum (p_t) typical of the pion produced in this decay. This method is completely different—and so has different systematics—than either the double-tag method used by Mark III or the cross-section ratio method employed by the Mark II and LGW experiments.

The D^{*+} meson is copiously produced in the fragmentation of the charmed quark in the process, $e^+e^- \rightarrow c\bar{c}$, which is 40% of the hadronic cross section. The D^* mesons from this process carry a leading quark and so have a small transverse momentum ($\approx$0.3 GeV/c) with respect to the jet axis. The data sample used for the analysis was obtained with the High Resolution Spectrometer (HRS) operating at the PEP storage ring. It corresponds to an integrated luminosity of 300 pb^{-1} taken at a center-of-mass energy of 29 GeV/c^2. The available energy, Q, in the decay, $D^{+*} \rightarrow D^0\pi_s^+$, is only 5 MeV/$c^2$ so that the maximum momentum (k) of the decay pion in the D^* center of mass is 0.039 GeV/c. Therefore, the decay can contribute, at most, 0.039 GeV/c to the transverse momentum. The low Q value also means that the fraction of the parent D^* momentum (including transverse momentum) carried by the pion is small. Specifically, the root-mean-square (rms) transverse momentum relative to the appropriate jet axis is given by

$$\langle p_{t,\pi_s}^2 \rangle = r^2 \langle p_{t,D^*}^2 \rangle + 2k^2/3, \tag{1}$$

where $\langle p_{t,D^*}^2 \rangle$ is the rms transverse momentum of the D^* and $r^2 = (m_\pi^2 + k^2)/m_{D^*}^2 = (0.072)^2$. A value of $\langle p_{t,D^*}^2 \rangle = (0.3\ \text{GeV}/c)^2$ (which is a typical value) gives $\langle p_{t,\pi_s}^2 \rangle = (0.038\ \text{GeV})^2$, which is much smaller than the $\approx$0.3 (GeV/c)^2 transverse momentum characteristic of most particles.

In practice, the width of the p_{t,π_s}^2 distribution has important contributions from the uncertainty on the determination of the jet axis. Monte Carlo simulation must be used to obtain the p_t^2 distribution expected for the pions produced in D^* decays. For this purpose, the p_t^2 distribution has been computed for a sample of Monte Carlo events that have been passed through a full detector simulation. The angular distribution of the $D^{*+} \rightarrow D^0\pi_s^+$ decay was taken to be flat, as is indicated by HRS's recent measurement.[8] The axis used to define p_t is a thrust axis computed using momentum-squared weights and using only tracks in the hemisphere opposite to the hemisphere containing the particle being plotted. The opposite hemisphere is used to minimize the dependence of the thrust axis on the decay mode of the D^0. Neutrals with energies greater than 0.5 GeV/c^2, as well as charged particles, are included in the thrust computation. FIGURE 1 shows the p_t^2 distribution from a sample of simulated pions from the decay, $D^{*+} \rightarrow D^0\pi_s^+$. The curve is a fit to two exponentials. The peak at low p_t^2 is very sharp and it is this sharp peak that is used to tag a sample of $D^{*+} \rightarrow D^0\pi_s^+$ decays independent of the decay mode of the D^0. The arrow marks the location where a particle with a typical p_t would appear.

Event cuts are applied to reduce the background due to events with a poorly determined thrust axis or evidence of hard gluon emission. The following cuts are used: (1) $N_{ch} > 5$, (2) $E_{ch}/E_{cm} < 0.25$, (3) $E_{tot}/E_{cm} > 0.50$, (4) $|T_z| < 0.5$, (5) $T > 0.90$, and (6) $\hat{T}_+ \cdot \hat{T}_- < -0.98$, where T is the thrust, T_z is the z component of the overall thrust axis, and $\hat{T}_+$ and $\hat{T}_-$ are the directions of the thrust axis computed independently in each hemisphere. The segregation of the tracks into two hemispheres, though, is done on the basis of the overall thrust direction. Cuts 1–3 serve to select a clean sample of hadronic events. Cuts 5 and 6 reject gluon radiation and b jets, whereas cut 4 restricts the sample to events where both the charged and neutral particles are well measured.

FIGURE 2 shows the p_t^2 distribution for the data in two x_F regions ($x_F = 2p_\parallel/E_{cm}$): (a) $0.03 < x_F < 0.06$ and (b) $0.07 < x_F < 0.1$. The sharp low p_t^2 structure is apparent in region a, but it is absent from region b. The curve in region b is a fit to a single exponential, whereas the curve in region a includes a signal term as described below. The x_F range of region b implies a D^* momentum that is typically above the beam energy; no signal is expected and none is seen. Particles with x_F below 0.03 are excluded because contributions from the decay chain, $B \rightarrow D^*X$, $D^* \rightarrow D^0\pi$, and

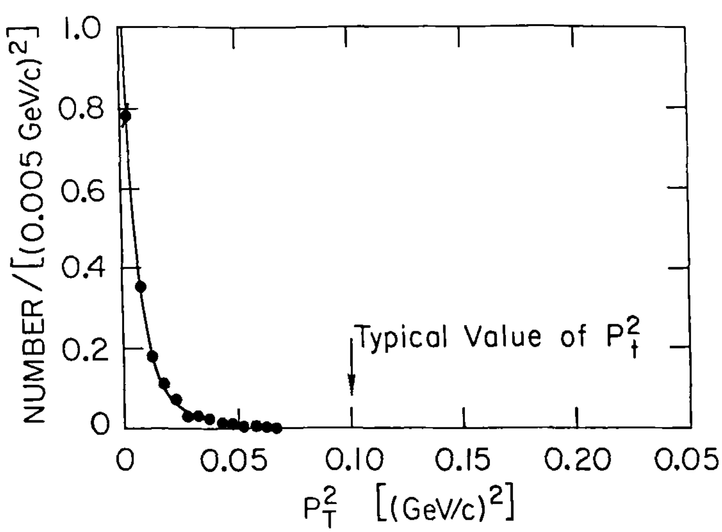

FIGURE 1. p_t^2 plots for a sample of simulated pions from the decay, $D^{*+} \rightarrow D^0\pi_s^+$. The curve is a fit to two exponentials as described in the text.

kinematic effects due the decay of fast particles complicate the shape of the p_t^2 distribution in this region.

In order to extract the number of $D^{*+} \rightarrow D^0\pi_s^+$ decays from the p_t^2 distribution, a fit is performed to the shape of the signal as determined from the Monte Carlo simulation of FIGURE 1 and a smooth background term. The shape of the signal is represented by two exponentials that are fit to the Monte Carlo spectrum of $D^{*+} \rightarrow D^0\pi_s^+$ decays. A fit to the following form,

$$F(p_t^2) = N_0 \cdot (e^{-B_1 p_t^2} + Ce^{-B_2 p_t^2}) \quad (2)$$

(where N_0 is a normalization factor chosen so that the integral over p_t^2 is 1.0), yields $B_1 = 179.0$, $B_2 = 63.1$, and $C = 0.191$. The result of the fit is the curve shown in FIGURE 1. An exponential plus a constant term is used for the background. The data points are

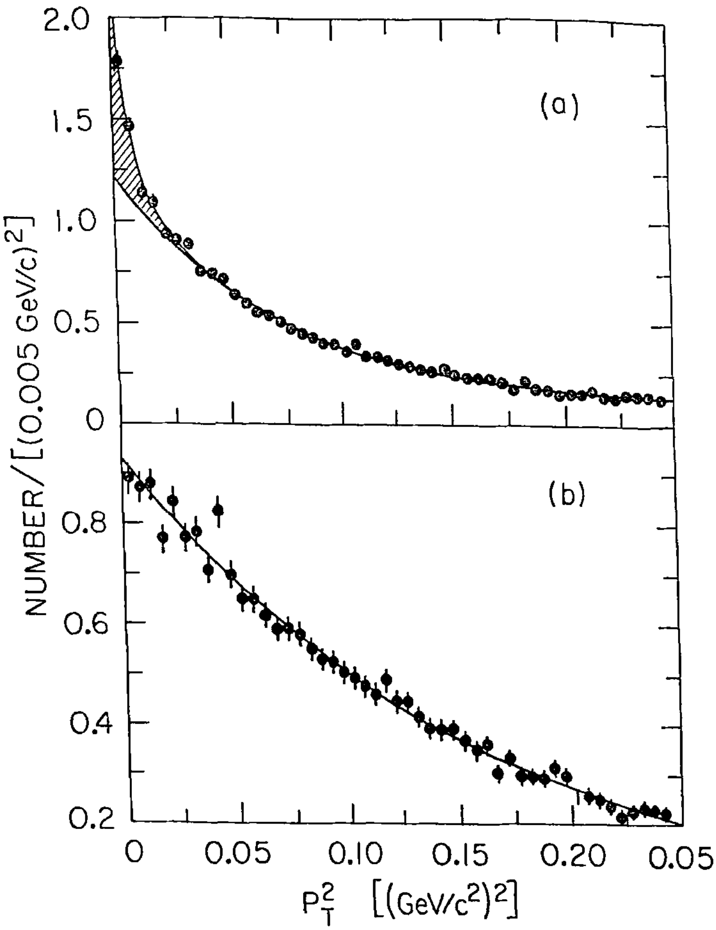

FIGURE 2. The p_t^2 distribution for the data in two x_F regions ($x_F = 2p_\parallel/E_{cm}$): (a) $0.03 < x_F < 0.04$ and (b) $0.07 < x_F < 0.1$. The curves are results of fits described in the text. The crosshatched region indicates the size of the signal.

fit for the normalization of the signal together with the shape and normalization of the background as follows:

$$dN/dp_a^2 = N_S \cdot F(p_t^2) + N_B \cdot (e^{-Bp_t^2} + K), \quad (3)$$

where N_S is the number of D^* decays and N_B is the background normalization. The curves in FIGURE 2 are the result of this fit. The cross-hatching indicates the signal. The fit yields $B = 10.6$ (GeV/c)$^{-2}$ and $K = 0.043$. Note that in determining the branching fraction, only particles with $p_t^2 < 0.01$ (GeV/c)^2 are used because the determination of the D^* contribution to this limited region is less sensitive to possible systematic errors in the fitting procedure than the total number. In particular, the number with $p_t^2 < 0.01\ (\mathrm{GeV}/c)^2$ is insensitive to the exact shape used for $F(p_t^2)$. The fit yields $N(p_t^2 < 0.01) = 1584 \pm 110$ for the number of π_s particles contributing to this low p_t^2 region. The ratio of signal to noise in the $p_t^2 < 0.01\ (\mathrm{GeV}/c)^2$ region is about one to three.

The next step is to find out how many of the tagged $D^{*+} \rightarrow D^0\pi_s{}^+$ decays are followed by a $D^0 \rightarrow K^-\pi^+$ decay. This is done using the standard $D^* - D$ mass difference trick.[9] A sample of $K^-\pi^+$ candidates is selected by the following cuts: (1) $0.143 < \delta = M_{K\pi\pi} - M_{K\pi} < 0.148$, (2) $|\cos\theta_{\mathrm{hel}}| < 0.8$, and (3) $p_t^2 < 0.01\ (\mathrm{GeV}/c)^2$, where θ_{hel} is the helicity angle of the $K\pi$ system. The helicity angle cut is applied to suppress combinatorial background and the p_t^2 cut restricts the sample to tagged D^* decays. FIGURE 3 shows the $K^-\pi^+$ mass spectrum for pairs of particles selected by these cuts. The number of fully reconstructed decay chains ($D^{*+} \rightarrow D^0\pi_s{}^+$, $D^0 \rightarrow K^-\pi^+$) with $p_{t,\pi_s}^2 < 0.01\ (\mathrm{GeV}/c)^2$ is determined by fitting the $K^-\pi^+$ effective mass distribution of FIGURE 3 to a Gaussian for the signal plus a linear background. Only the mass spectrum in the region between 1.7 and 2.3 GeV/c^2 is fit to avoid the reflection due to the decay mode, $D^0 \rightarrow K^-\rho^+$, that populates the region from 1.6–1.7 GeV/c^2. The result is not too sensitive to the upper bound on the fitting region, which is varied to check systematics. The fit yields a width of 24 MeV/c^2, a D mass of 1.863 GeV/c^2, and a total of 56 ± 9 $D^0 \rightarrow K^-\pi^+$ decays.

By running Monte Carlo events through the same procedure applied to the data, it is observed that the efficiency for finding the $K^-\pi^+$ (given that the π_s has been seen) is 0.79. Combining this with the number of tagged $D^{*+} \rightarrow D^0\pi_s{}^+$ decays and the number of tags in which the decay, $D^0 \rightarrow K^-\pi^+$, is observed, $\mathrm{Br}(D^0 \rightarrow K^-\pi^+) = 4.5 \pm 0.8 \pm 0.5$ is found. The first error is statistical and the second is systematic.

There are three contributions to the systematic error: (1) determination of the $D^0 \rightarrow K^-\pi^+$ finding efficiency and background, (2) bias introduced by the event

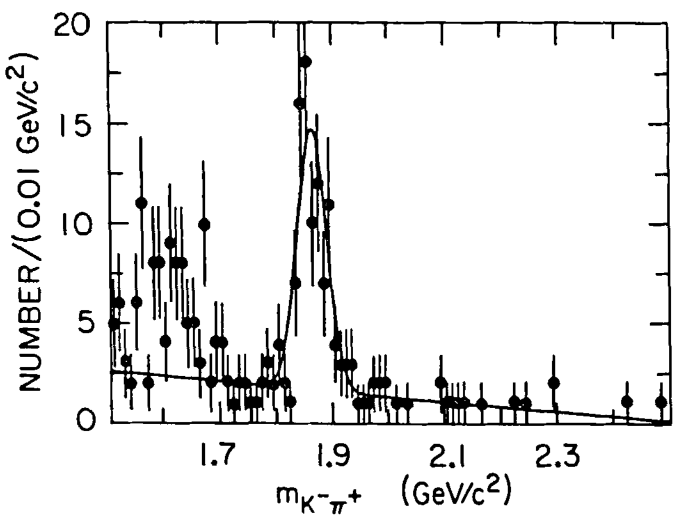

FIGURE 3. The $K^-\pi^+$ invariant mass plot for particle pairs selected on the $D^* - D$ mass cut, the helicity cut, and the p_t^2 cut as described in the text.

selection cuts, and (3) errors in the p_t^2 distribution fitting procedure—in particular, uncertainties in the assumed shapes of the signal and background used to fit the p_t^2 distribution.

The $D^0 \rightarrow K^-\pi^+$ finding efficiency as determined by Monte Carlo is discussed in a previous publication.[9] The systematic uncertainty is small compared to the statistical uncertainty and is neglected. The uncertainty in the fit for the number of $D^0 \rightarrow K^-\pi^+$ decays is checked by varying the upper bound on the fitting region and by using a flat background over a more limited mass region (e.g., 1.7–2.0 GeV/c^2). Typical variations are at the 5% level and this value is used for the systematic error on this fitting procedure. The bias due to the event selection criteria also was studied by reanalyzing the data with the thrust and the colinearity cuts removed. The result changed by $\approx$9%, which is taken to be the systematic error from this source.

The appropriate shape to fit to the data can deviate from the form assumed (see equations 2 and 3) for several reasons. For example, the low p_t^2 region can receive contributions from other relatively low Q decays such as $\Sigma^* \rightarrow \Lambda\pi$, thereby spoiling the assumed exponential behavior of the background, and the shape predicted by the Monte Carlo for the p_t^2 distribution of the slow pion from D^* decay cannot be expected to be perfect. It also is possible for kinematic effects in the decays of fast particles to lead to an enhancement at low p_t^2 when small x_F is selected.

The resulting uncertainty in the estimate of the number of D^* mesons tagged is evaluated by approximating the number of D^* decays producing pions with $p_t^2 < 0.01$ (GeV/c)^2 by extrapolation alone. A constant plus an exponential is fit to the region with $p_t^2 > 0.05$ (GeV/c)^2 and the extrapolated number is subtracted from the bins with $p_t^2 < 0.01$ (GeV/c)^2. For the full x_F range (0.03–0.06), there is only a 1.5% variation in the number obtained. For three smaller x_F regions (0.03–0.04, 0.04–0.05, and 0.05–0.06), the result is always within 4% of the number obtained with the full fit.[i]

In computing the $D^0 \rightarrow K^-\pi^+$ branching fraction, it is assumed that the entire low p_t^2 enhancement is due to the D^*. For the systematic error, a 4% difference is taken between the fitted and extrapolated numbers that occurred for the worst of the three x_F regions tried. It is worth noting that the effect of an additional source for the low p_t^2 enhancement would be to decrease the apparent branching fraction. The real branching fraction would be larger than that obtained under the presumption that only D^* decays contribute to the enhancement.

Because these sources of systematic error appear to be roughly independent, they are added in quadrature to get the overall systematic error of $\approx$11%.

[i]In the Monte Carlo sample, this procedure results in discrepancies as large as 14%. This large variation in the Monte Carlo has been traced to a kinematic effect due to the decay of particles with hard fragmentation functions, such as the D and D_s mesons. Specifically, when the LUND string fragmentation algorithm is used for the decay of the heavy mesons and particles with $0.03 < x_F < 0.06$ are selected from among these decays, a low p_t^2 enhancement arises with a width about three times that of the enhancement due to D^* decays. This enhancement is not present in that portion of the D decays that proceed through the known, measured, branching modes of the D meson. Its prominence in the Monte Carlo sample here is due to the fact that the events were generated with the small, pre–Mark III, branching fractions, thus leaving a relatively large fraction of the D decays to be handled by the string algorithm. In the data, there is no evidence for the operation of this mechanism, as is indicated by the close agreement between the number of D^* tags determined by fitting and the number found by extrapolation (1.5%).

In summary, the branching fraction for the decay, $D^0 \rightarrow K^-\pi^+$, has been measured by a new method that has different systematics than any of the previous measurements. The result of $Br(D^0 \rightarrow K^-\pi^+) = 4.5 \pm 0.8 \pm 0.5$ (where the first error is statistical and the second is systematic) confirms the most recent[4] Mark III result and is roughly 1.7σ from the Mark II result. No evidence has been found for backgrounds to the D^* in the behavior of the data and, therefore, it is assumed that the low p_t^2 enhancement is entirely due to D^* decays. The presence of undetected backgrounds in the tagged D^* sample here would imply a larger $K^-\pi^+$ branching fraction and, thus, this would more strongly disfavor the smaller branching fractions found by the Mark II and LGW experiments.

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