Reanalysis of Charmed–D-Meson Branching Fractions

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We report a revised determination of charmed–D-meson absolute branching fractions based on complete reconstruction of $D\bar{D}$ events at the $\psi(3770)$. Two backgrounds, Cabibbo-suppressed and multi-π^0 D decays, are addressed in detail. The first measurement of the decay $D^0 \rightarrow K^-\pi^+\pi^0\pi^0$ establishes the sensitivity to hitherto unobserved multi-π^0 modes. Removal of both backgrounds reduces the values of our previously reported branching fractions by (21–24)%, leaving their ratios largely unchanged. The new values are unable to account fully for a reported deficit in charm production in B-meson decay.

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Knowledge of the decay branching fractions of charmed mesons is essential not only for a complete understanding of the weak decay of the charmed quark, but also for the study of charm production mechanisms and the production and decay of all heavier flavors. We have recently introduced a new technique[1] to directly measure D^0 and D^+ branching fractions independent of the charm production cross section. These results, based on full reconstruction of $D\bar{D}$ pairs, differ from prior results[2,3] which employed the cross section (σ_D)[3,4] at the $\psi(3770)$ to convert observed charm production $(\sigma_D B_i)$ into D branching fractions (B_i). The B_i so obtained were larger than those determined with use of the older method. Measurements of charm mesons in B-meson decay and in the e^+e^- continuum[5,6] employing the new B_i suggested that charm production was considerably smaller than expected. So motivated, we have reexamined our previous analysis and have isolated and corrected for two sources of background present in the original treatment of the data. This reanalysis results in a (21–24)% reduction in the absolute D branching fractions, but leaves the relative values essentially unchanged.

The new analysis utilizes the same data sample (9.56 pb^{-1}), particle identification, and kinematic fitting technique[7] employed in the previous work.[1] Briefly, the exclusive production of D^+D^- and $D^0\bar{D}^0$ at the $\psi(3770)$ allows the isolation of two classes of events: *single tags,* wherein only one D of a pair is reconstructed, and *double tags* wherein both D mesons are reconstructed through kinematic fitting of the reaction $e^+e^- \rightarrow X\bar{X} \rightarrow$ final state, with the mass constraint $M_X = M_{\bar{X}}$. By comparison of the number of observed single- and double-tag events, individual B_i are determined independent of σ_D. The single tags, having smaller statistical errors, largely

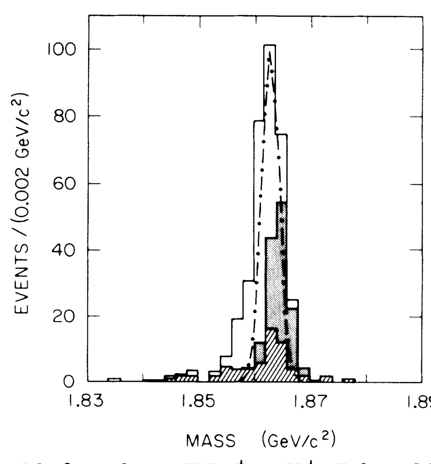

FIG. 1. M_X from fits to $K^-\pi^+$ vs $K^+\pi^-$ from Monte Carlo simulations of $K^-\pi^+$ vs $K^+\pi^-$ (dot-dashed line) and $K^-\pi^+$ vs [$\pi^+\pi^-$ (shaded area), $K^+\pi^-\pi^0$ (cross-hatched area), and K^+K^- (solid histogram)].

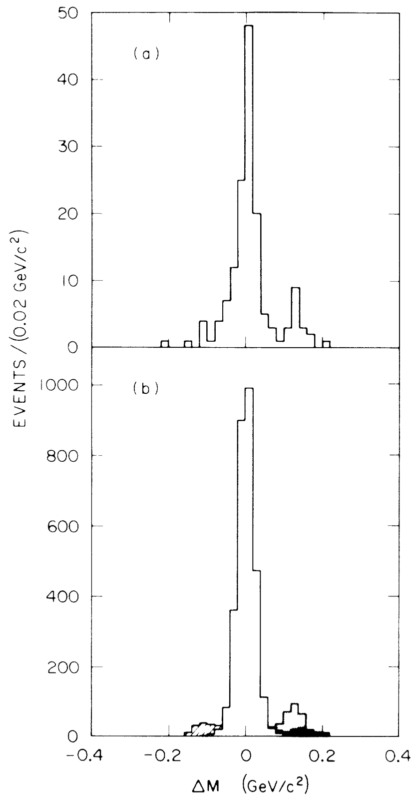

FIG. 2. ΔM for (a) original data, and (b) Monte Carlo simulations of the signal ($K^-\pi^+$ vs $K^+\pi^-$) and the backgrounds [$K^-\pi^+$ vs $\pi^-\pi^+$ (cross hatched), $K^-\pi^+$ vs $K^+\pi^-\pi^0$ (solid), and $K^-\pi^+$ vs K^-K^+ (shaded)]. The relative size of signal and background in (b) reflect that which is expected in the data.

determine the relative B_i, while the double tags establish their absolute value.

The single- and double-tag samples include the modes $D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$ and $D^+ \to \bar{K}^0\pi^+$, $K^-\pi^+\pi^+$, $\bar{K}^0\pi^+\pi^0$, $\bar{K}^0\pi^+\pi^+\pi^-$. These samples differ from the original only by the addition of $D^+ \to \bar{K}^0\pi^+\pi^+\pi^-$ and the elimination of D^+

TABLE I. Signal events removed by the ΔM cut.

Double-tag combination	$f_{\Delta M}$	Predicted loss	Observed loss
$K^-\pi^+$ vs $K^+\pi^-$	0.95	6 ± 2	11 ± 4
$K^-\pi^+$ vs $K^+\pi^-\pi^0$	0.66	48 ± 6	50 ± 8
$K^-\pi^+$ vs $K^+\pi^-\pi^-\pi^+$	0.92	11 ± 2	13 ± 5
$K^-\pi^+\pi^0$ vs $K^+\pi^-\pi^0$	0.51	49 ± 9	34 ± 14
$K^-\pi^+\pi^0$ vs $K^+\pi^-\pi^-\pi^+$	0.67	40 ± 6	53 ± 10
$K^-\pi^+\pi^+\pi^-$ vs $K^+\pi^-\pi^-\pi^+$	0.91	2 ± 1	1 ± 3
$K^-\pi^+\pi^+$ vs $K^0\pi^-$	0.93	2 ± 1	2 ± 1
$K^-\pi^+\pi^+$ vs $K^+\pi^-\pi^-$	0.94	4 ± 1	8 ± 3
$K^-\pi^+\pi^+$ vs $K^0\pi^-\pi^0$	0.72	6 ± 2	4 ± 4
Totals		168 ± 13	176 ± 21

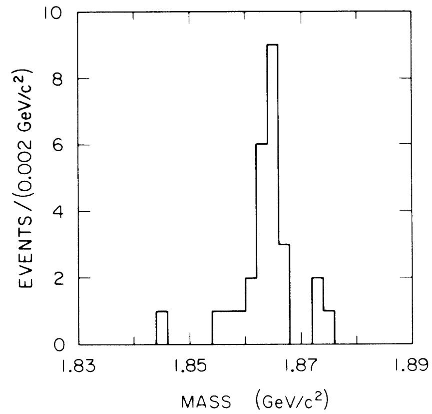

FIG. 3. Fitted mass M_X for $K^+\pi^-$ vs $K^-\pi^+\pi^0\pi^0$.

$\to K^-\pi^+\pi^+\pi^0$, which suffered from a poor signal-to-background ratio. The focus of the reanalysis is the determination of those backgrounds in the double-tag sample which are not subtracted by the previous procedure utilizing the low-mass sideband region ($1.83 \le M_X \le 1.85$ GeV/c^2). Such backgrounds arise exclusively from sources having fitted values of $M_X \sim M_D$. Extensive Monte Carlo studies of the fitting procedure for double tagging indicate that the principal background after the sideband subtraction is true $D\bar{D}$ pairs in which the decay products of one D are correctly identified, and those of the second are not. An incorrectly assigned D decay can arise either from (i) a *single* particle being misidentified (e.g., $\pi^\pm \rightleftarrows K^\pm$) or (ii) the loss of a *single* low-energy π^0 (e.g., $K^-\pi^+\pi^0 \to K^-\pi^+$).

Background (i) arises from Cabibbo-suppressed channels having the correct D momentum, but incorrect energy after $\pi^\pm \rightleftarrows K^\pm$ interchange. Background (ii) comes predominantly from higher-multiplicity Cabibbo-allowed channels containing one or more soft π^0's, where one π^0 is lost; the larger measurement errors for photons allow such losses to occur while still satisfying the χ^2 requirement of the kinematic fit. The M_X distributions from Monte Carlo simulations for both the signal (double-tag events $K^-\pi^+$ opposite $K^+\pi^+$) and the background [$K^-\pi^+$ opposite (K^+K^- or $\pi^+\pi^-$ or $K^+\pi^-\pi^0$)], as shown in Fig. 1, demonstrate that these backgrounds produce a peak whose mass and width are similar to those of a true signal.

Both backgrounds can be completely suppressed by our imposing a more restrictive cut on χ^2; however, such a procedure substantially reduces the efficiency for observing some final states. Therefore, an additional kinematic selection on the *individual* D mesons composing a double tag is imposed. For each D candidate, the *unfitted* invariant mass ($M_{\rm inv}$) is compared with the beam energy constrained mass ($M_{\rm bc}$).[1,8] Distributions of the different $\Delta M \equiv M_{\rm bc} - M_{\rm inv}$, are shown in Fig. 2 for the $K^-\pi^+$ mode of the original analysis and for Monte Carlo simulations of the signal ($K^-\pi^+$) and the most prominent backgrounds (K^-K^+, $\pi^-\pi^+$, and $K^-\pi^+\pi^0$).

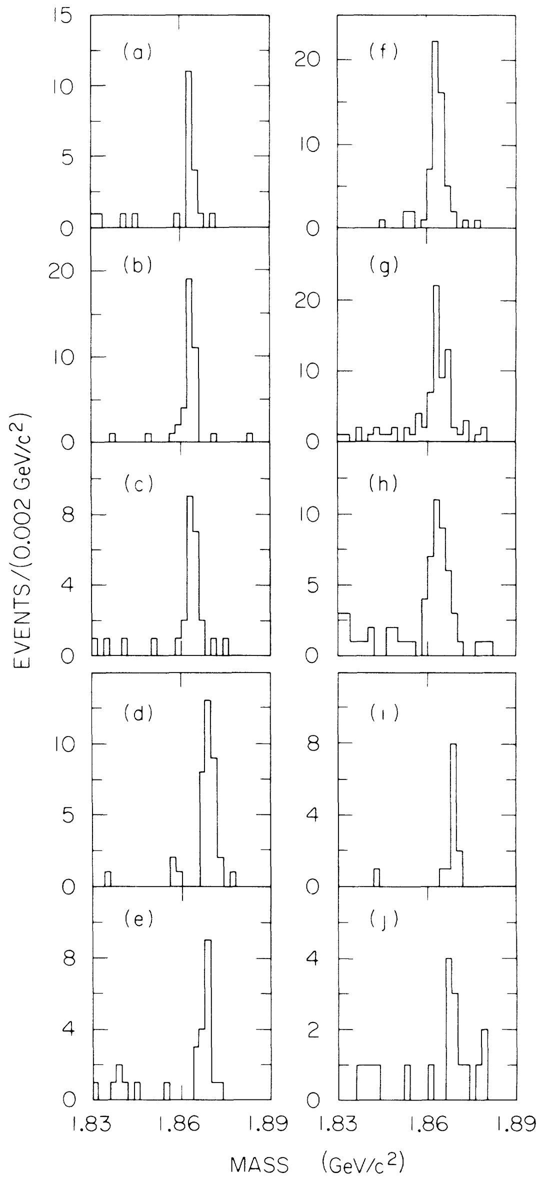

FIG. 4. Mass M_X for double tags: (a) $K^-\pi^+$ vs $K^+\pi^-$, (b) $K^-\pi^+$ vs $K^+\pi^-\pi^-\pi^+$, (c) $K^-\pi^+\pi^+\pi^-$ vs $K^+\pi^-\pi^-\pi^+$, (d) $K^-\pi^+\pi^+$ vs $K^+\pi^-\pi^-$, (e) $K^-\pi^+\pi^+$ vs $K^0\pi^-\pi^0$, (f) $K^-\pi^+$ vs $K^+\pi^-\pi^0$, (g) $K^-\pi^+\pi^+\pi^-$ vs $K^+\pi^-\pi^0$, (h) $K^-\pi^+\pi^0$ vs $K^+\pi^-\pi^0$, (i) $K^-\pi^+\pi^+$ vs $K^0\pi^-$, (j) $K^-\pi^+\pi^+$ vs $K^0\pi^-\pi^-\pi^+$.

The requirement that $|\Delta M| \leq 60$ MeV/c^2 for all modes containing only charged particles removes all background with a loss of efficiency of $\leq 5\%$ for each mode. For modes containing π^0's, the cut is widened to $-120 \leq \Delta M \leq 100$ MeV/c^2, eliminating 90% of the background with a loss of efficiency of $\leq 30\%$ for each mode. The fraction of signal events ($f_{\Delta M}$) that remain after the ΔM cut for each final state is given by a product of these efficiencies (see Table I).

To verify that the ΔM requirement provides sufficient background rejection *regardless of the source,* Monte Carlo simulations of all contributing topologies were generated and compared with the data. Measurements of many Cabibbo-suppressed decays[9] and of several modes containing a single π^0 already exist[1]; no data have heretofore been available on decays with two or more π^0's. Examination of the double tags containing candidates for $D^0 \to K^-\pi^+\pi^0$ indicates, however, the presence of an additional π^0 in a subset of events that survive the kinematic fit but fail the ΔM cut. These events, which form the largest background to $K^-\pi^+\pi^0$ in the previous analysis, arise from the multi-π^0 decay $D^0 \to K^-\pi^+\pi^0\pi^0$. We observe 24 ± 5 events with 7% efficiency in fully reconstructed $D^0\bar{D}^0$ events along with $K^+\pi^-$ (see Fig. 3).

TABLE II. D^0 and D^+ branching fractions.

Decay mode	Branching fraction (%)
Results of global fits	
$D^0 \to K^-\pi^+$	$4.2 \pm 0.4 \pm 0.4$
$D^0 \to K^-\pi^+\pi^-\pi^+$	$9.1 \pm 0.8 \pm 0.8$
$D^0 \to K^-\pi^+\pi^0$	$13.3 \pm 1.2 \pm 1.3$
$D^+ \to K^-\pi^+\pi^+$	$9.1 \pm 1.3 \pm 0.4$
$D^+ \to \bar{K}^0\pi^+$	$3.2 \pm 0.5 \pm 0.2$
$D^+ \to \bar{K}^0\pi^+\pi^0$	$10.2 \pm 2.5 \pm 1.6$
$D^+ \to \bar{K}^0\pi^+\pi^-\pi^+$	$6.6 \pm 1.5 \pm 0.5$
New double-tag measurement	
$D^0 \to K^-\pi^+\pi^0\pi^0$	$14.9 \pm 3.7 \pm 3.0$
Corrected values for previous measurements	
$D^0 \to K^-K^+$	$0.51 \pm 0.09 \pm 0.07$
$D^0 \to \pi^-\pi^+$	$0.14 \pm 0.04 \pm 0.03$
$D^0 \to \bar{K}^0\phi$	$0.86^{+0.50+0.31}_{-0.41-0.18}$
$D^0 \to \bar{K}^0K^+K^-_{\text{non-res}}$	$0.85^{+0.27+0.20}_{-0.24-0.18}$
$D^0 \to \bar{K}^0K^0$	≤ 0.460 at 90% C.L.
$D^0 \to \mu^\pm e^\mp$	≤ 0.012 at 90% C.L.
$D^+ \to K^+\bar{K}^0$	$1.01 \pm 0.32 \pm 0.17$
$D^+ \to \pi^+\pi^-\pi^+$	$0.38 \pm 0.15 \pm 0.09$
$D^+ \to K^-K^+\pi^+_{\text{non-res}}$	$0.54 \pm 0.25 \pm 0.09$
$D^+ \to \phi\pi^+$	$0.77 \pm 0.22 \pm 0.11$
$D^+ \to K^+\bar{K}^{*0}$	$0.44 \pm 0.20 \pm 0.10$

To further test our understanding of the identification and rejection of these backgrounds, a study of the absolute number of signal events removed by the ΔM cut is presented in Table I. The loss of 176 ± 21 signal events from the original sample by the ΔM cut compares well with that predicted (168 ± 13) from Monte Carlo simulation of D background sources for all measured modes, and suggests that all significant backgrounds are now accounted for.

The fitted M_X distributions are shown in Fig. 4 after the ΔM cut. The sideband subtraction is performed as in the previous work, and combined with the single tags to perform independent fits to the D^0 and D^+ samples.[1] A χ^2 of 3.5 for five and 1.8 for three degrees of freedom is obtained for the D^0 and D^+ fits, respectively.

The B_i so obtained are given in the top part of Table

II. The systematic errors are calculated as before[1] with a new term [$\pm 7\%$ ($\pm 2\%$)] for each D^0 (D^+) mode arising from uncertainties in the efficiency of the ΔM cut. The cross sections $\sigma_{D^0} = 5.8 \pm 0.5 \pm 0.6$ nb and $\sigma_{D^+} = 4.2 \pm 0.6 \pm 0.3$ nb are obtained from the fitted number of produced events ($27\,700 \pm 2400 \pm 2600$ $D^0\bar{D}^0$ and $20\,300 \pm 2900 \pm 1100$ D^+D^-) and the integrated luminosity.[10] The branching fraction for the new channel $D^0 \to K^-\pi^+\pi^0\pi^0$ is given in the middle part of Table II, and previous Mark III results[9,11,12] are corrected and summarized in the bottom part of Table II. A new HRS measurement[13] of $B(D^0 \to K^-\pi^+) = (4.5 \pm 0.8 \pm 0.6)\%$ using daughter $\pi^\pm$ from D^* decay to tag charm offers confirming evidence for the scale of the D branching fractions reported here.

The existence of a large deficit in charm from B-meson decay was first suggested by the CLEO group based on their inclusive measurement[5,6] of $B(B_{u,d} \to D^0$ or $D^+ + X) = 0.56 \pm 0.06 \pm 0.06$. With use of the corrected D branching fractions, this result becomes $0.70 \pm 0.08 \pm 0.07$,[14] which still differs significantly from the expectation of one D meson per B decay.[6,15] Recent results from ARGUS,[16] when similarly corrected, give $B(B_{u,d} \to D^0$ or $D^+ + X) = 0.88 \pm 0.08 \pm 0.09$, in closer agreement with theoretical expectations.

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(a)Deceased.

[1]R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **56**, 2140 (1986).

[2]R. H. Schindler *et al.*, Phys. Rev. D **24**, 78 (1981).

[3]I. Peruzzi *et al.*, Phys. Rev. Lett. **39**, 1301 (1977); D. L. Scharre *et al.*, Phys. Rev. Lett. **40**, 74 (1978).

[4]R. H. Schindler *et al.*, Phys. Rev. D **21**, 2716 (1980); H. Sadrozinski, in *High Energy Physics—1980*, edited by Loyal Durand and Lee Pondrom, AIP Conference Proceedings No. 68 (American Institute of Physics, New York, 1981), p. 681. Note: As indicated in Ref. 1 there exist large differences in the measurements of σ_D in Refs. 3 and 4.

[5]D. Bortoletto *et al.*, Phys. Rev. D **35**, 19 (1987).

[6]M. D. Gilchriese, in *Proceedings of the Twenty-Second International Conference on High Energy Physics, Berkeley, California, 1986*, edited by S. Loken (World Scientific, Singapore, 1987).

[7]G. Blaylock, Ph.D. thesis, University of Illinois, Urbana, 1986 (unpublished).

[8]In channels that contain π^0's a 1-C fit to the π^0 mass is first performed on the two photons. Fits with $\chi^2 \le 4$ and fitted photon energies ≥ 40 MeV/c^2 are retained.

[9]R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **55**, 150 (1985).

[10]The ratio $\sigma_{D^0}/\sigma_{D^+} = 1.36 \pm 0.23 \pm 0.14$ differs little from $1.34^{+0.17}_{-0.20} \pm 0.11$ of Ref. 1. A detailed comparison with previous measurements is given in Ref. 1.

[11]R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **56**, 2136 (1986).

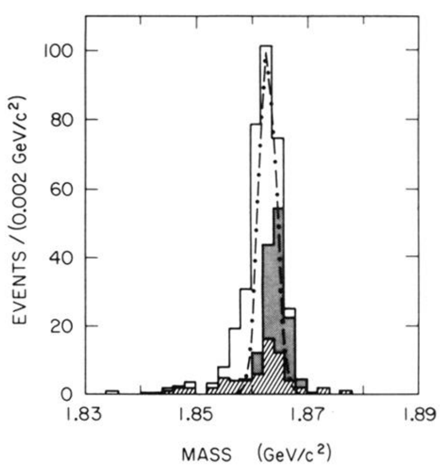
[12]J. J. Becker *et al.*, SLAC Report No. SLAC-PUB 4194, 1987 (to be published).

[13]A. Snyder, in Proceedings of the International Symposium on the Production and Decay of Heavy Flavors, Stanford, California, 1987 (to be published); Indiana University Report No. IUHEEE-87-11, 1987 (to be published).

[14]The first error is the combined statistical and systematic errors on the product branching ratios (Ref. 5), while the second error represents uncertainties from the Mark III determination of D branching fractions. In comparisons between experiments, the last error should be dropped.

[15]The naive spectator model predicts $\simeq 1.15$ charmed particles per $B_{u,d}$ decay. Uncertainties in the value of the charmed-quark mass, incomplete measurements of B decay into $c\bar{c}$ bound states, D_s and its excited states, and charmed baryons, may lead to large ($\simeq 20\%$) uncertainties in the actual expectation for $B(B \to D + X)$. Predictions for the inclusive D meson production in the e^+e^- continuum suffer from additional uncertainties in the knowledge of fragmentation functions.

[16]W. Schmidt-Parzefall, in Proceedings of the International Symposium on Lepton and Phonon Interactions at High Energies, Hamburg, West Germany, 1987 (to be published).



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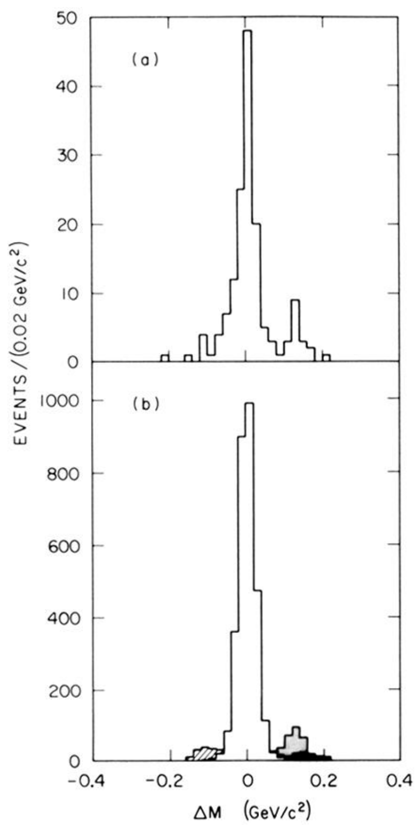

FIG. 2. ΔM for (a) original data, and (b) Monte Carlo simulations of the signal ($K^-\pi^+$ vs $K^+\pi^-$) and the backgrounds [$K^-\pi^+$ vs $\pi^-\pi^+$ (cross hatched), $K^-\pi^+$ vs $K^+\pi^-\pi^0$ (solid), and $K^-\pi^+$ vs K^-K^+ (shaded)]. The relative size of signal and background in (b) reflect that which is expected in the data.