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A Reanalysis of Charmed D Meson Branching Fractions*

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Abstract

We report a new 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 poorly determined cross section (σ_D)[3][4] at the $\psi(3770)$ to convert observed charm production $(\sigma_D \cdot B_i)$ into D branching fractions (B_i). The B_i so obtained were larger than those determined using the older method. Measurements of charm production 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 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 $\mathrm{M}_X = \mathrm{M}_{\bar{X}}$. By comparing the number of observed single and double tag events, individual B_i are determined independent of $\sigma_{\psi(3770)}$. The single tags, having smaller statistical errors, largely determine the relative B_i, while the double tags establish their absolute value.

The single and double tag samples[8] include the modes $D^0 \rightarrow K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$ and $D^+ \rightarrow \bar{K}^0\pi^+$, $K^-\pi^+\pi^+$, $\bar{K}^0\pi^+\pi^0$, $\bar{K}^0\pi^+\pi^+\pi^-$. These samples differ from the original only by the addition of $D^+ \rightarrow \bar{K}^0\pi^+\pi^+\pi^-$ and the elimination of $D^+ \rightarrow K^-\pi^+\pi^+\pi^0$, which suffered from a poor signal to background ratio.[9] 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 ($1.83 \leq \mathrm{M}_X \leq 1.85$ GeV/c^2). Such backgrounds arise exclusively from sources having fitted values of $\mathrm{M}_X \sim \mathrm{M}_D$. 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.[10] An incorrectly assigned D decay can arise either from (*i*) a *single* particle being misidentified (*e.g.* $\pi^\pm \rightleftharpoons K^\pm$) or (*ii*) the loss of a *single* low energy π^0 (*e.g.* $K^-\pi^+\pi^0 \rightarrow K^-\pi^+$).

Background (*i*) arises from Cabibbo suppressed channels having the correct D momentum, but incorrect energy after $\pi^\pm \rightleftharpoons K^\pm$ 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 ($K^-\pi^+$ *vs.* $K^+\pi^-$) and the background ($K^-\pi^+$ *vs.* (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 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 ($\mathrm{M_{inv}}$) is compared with the beam energy constrained mass ($\mathrm{M_{bc}}$).[9] [11] Distributions of the difference $\Delta\mathrm{M} \equiv \mathrm{M_{bc}} - \mathrm{M_{inv}}$, 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 $K^-\pi^+\pi^0$). Requiring $|\Delta\mathrm{M}| \leq 60$ 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 $-120 \leq \Delta\mathrm{M} \leq 100$ MeV/c^2, eliminating 90% of the background with a loss of efficiency of $\leq 30\%$ for each mode. The fraction of signal events ($f_{\Delta\mathrm{M}}$) remaining after the ΔM cut for each final state is given in 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[12] and of several modes containing a single π^0 already exist;[1] no data has 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).

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] The results are summarized in Table II; a χ^2 of 3.5 for 5 and 1.8 for 3 degrees of freedom is obtained for the D^0 and D^+ fits, respectively.

The B_i so obtained are given in Table III (a). The systematic errors are calculated as before[1] with a new term $(\pm 7\%(\pm 2\%))$ for the 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 ($27700 \pm 2400 \pm 2600$ $D^0\bar{D}^0$ and $20300 \pm 2900 \pm 1100$ D^+D^-) and the integrated luminosity.[13] The branching fraction for the new channel $D^0 \to K^-\pi^+\pi^0\pi^0$ is given in Table III (b), and previous Mark III results[12][14][15] are corrected and summarized in Table III (c).

In summary, we have reevaluated the Mark III direct determination of D meson absolute branching fractions and have removed a small background present in the original analysis. The values so obtained, are reduced by 21 - 24%, but remain larger than earlier measurements employing $\sigma_{\psi(3770)}$ normalization.[2][3]

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 $B(B_{u,d} \rightarrow D^0 \text{ or } D^+) = 0.56 \pm 0.06 \pm 0.06$. Using the corrected D branching fractions, this result becomes $0.70 \pm 0.08 \pm 0.07$, which still differs significantly from the expectation of one D meson per B decay.[6][16] Recent results from ARGUS,[6] similarly corrected, give $B(B_{u,d} \rightarrow D^0 \text{ or } D^+) = 0.96 \pm 0.17 \pm 0.09$. The average[17] of these results is $0.74 \pm 0.08 \pm 0.07$. While smaller D^0 and D^+ branching fractions result in larger inclusive D production cross-sections in the e^+e^- continuum,[5] [18] the unknown contributions of D_s meson and charmed baryon production, as well as uncertainties in the knowledge of fragmentation functions, make it difficult to draw a final conclusion on the total charmed quark production.

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Table I. Signal Events Removed by the ΔM Cut

Double Tag Combination			$f_{\Delta \mathrm{M}}$	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

Table II. Comparison of Observed Numbers of Events

and the Predictions from the Fit (in parenthesis)

D^0 Tags	$K^+\pi^-$	$K^+\pi^-\pi^0$	$K^+\pi^-\pi^-\pi^+$
$K^-\pi^+$	15 ± 5 (20 ± 2)	50 ± 7 (45 ± 4)	36 ± 6 (41 ± 4)
$K^-\pi^+\pi^0$	–	28 ± 8 (27 ± 3)	50 ± 9 (46 ± 4)
$K^-\pi^+\pi^+\pi^-$	–	–	20 ± 5 (16 ± 2)
Single Tags	963 ± 37 (949 ± 36)	1035 ± 64 (1065 ± 58)	1022 ± 55 (1028 ± 52)

D^+ Tags	$K^0\pi^-$	$K^+\pi^-\pi^-$	$K^0\pi^-\pi^0$	$K^0\pi^-\pi^-\pi^+$
$K^-\pi^+\pi^+$	11 ± 4 (9 ± 1)	31 ± 6 (33 ± 5)	13 ± 5 (9 ± 2)	7 ± 4 (9 ± 2)
Single Tags	161 ± 14 (163 ± 14)	1175 ± 42 (1172 ± 42)	160 ± 32 (169 ± 35)	168 ± 27 (162 ± 29)

Table III. D^0 and D^+ Branching Fractions

Decay Mode	Branching Fraction (%)
(a) Results of Global Fits	
$D^0 \to K^-\pi^+$	$4.2 \pm 0.4 \pm 0.4$
$D^0 \to K^-\pi^+\pi^-\pi^+$	$9.1 \pm 0.8 \pm 0.8$
$D^0 \to K^-\pi^+\pi^0$	$13.3 \pm 1.2 \pm 1.3$
$D^+ \to K^-\pi^+\pi^+$	$9.1 \pm 1.3 \pm 0.4$
$D^+ \to \bar{K}^0\pi^+$	$3.2 \pm 0.5 \pm 0.2$
$D^+ \to \bar{K}^0\pi^+\pi^0$	$10.2 \pm 2.5 \pm 1.6$
$D^+ \to \bar{K}^0\pi^+\pi^-\pi^+$	$6.6 \pm 1.5 \pm 0.5$
(b) New Double Tag Measurement	
$D^0 \to K^-\pi^+\pi^0\pi^0$	$14.9 \pm 3.7 \pm 3.0$
(c) 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.
$D^+ \to K^+\bar{K}^0$	$1.01 \pm 0.32 \pm 0.17$
$D^+ \to \pi^+\pi^-\pi^+$	$0.38 \pm 0.15 \pm 0.09$
$D^+ \to K^-K^+\pi^+_{\text{non-res}}$	$0.54 \pm 0.25 \pm 0.09$
$D^+ \to \phi\pi^+$	$0.77 \pm 0.22 \pm 0.11$
$D^+ \to K^+\bar{K}^{*0}$	$0.44 \pm 0.20 \pm 0.10$

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10. The presence of at least one correctly identified D meson in the event is sufficient to influence the equal mass hypothesis in the kinematic fit, weakening the rejection power of the fit to backgrounds. Decays with two or more erroneous assignments are adequately rejected.
11. In channels that contain π^0's, a 1C fit to the π^0 mass is first performed on the two photons. Fits with $\chi^2 \leq 4$ and fitted photon energies ≥ 40 MeV/c^2 are retained.

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13. 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].

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16. The naive spectator model predicts ~ 1.15 charmed particles per $B_{u,d}$ decay. Theoretical uncertainties in the validity of the spectator picture, incomplete measurements of B decay into $c\bar{c}$ bound states, D_s and its excited states, and charmed baryons, may lead to large uncertainties in the actual expectation for $B(B \to D + X)$.

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FIGURE CAPTIONS

1. M$_X$ from fits to $K^-\pi^+$ *vs.* $K^+\pi^-$ from Monte Carlo simulations of

   (a) $K^-\pi^+$ *vs.* $K^+\pi^-$,

   (b) $K^-\pi^+$ *vs.* ($\pi^+\pi^-$ (shaded), $K^+\pi^-\pi^0$ (cross-hatched), and K^+K^-(solid)).

2. ΔM for (a) the original data, and (b) Monte Carlo simulations of :

   (i) the signal ($K^-\pi^+$ *vs.* $K^+\pi^-$), and

   (ii) 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.

3. Fitted mass M$_X$ for $K^+\pi^-$ *vs.* $K^-\pi^+\pi^0\pi^0$.

4. The mass M$_X$ for double tags:

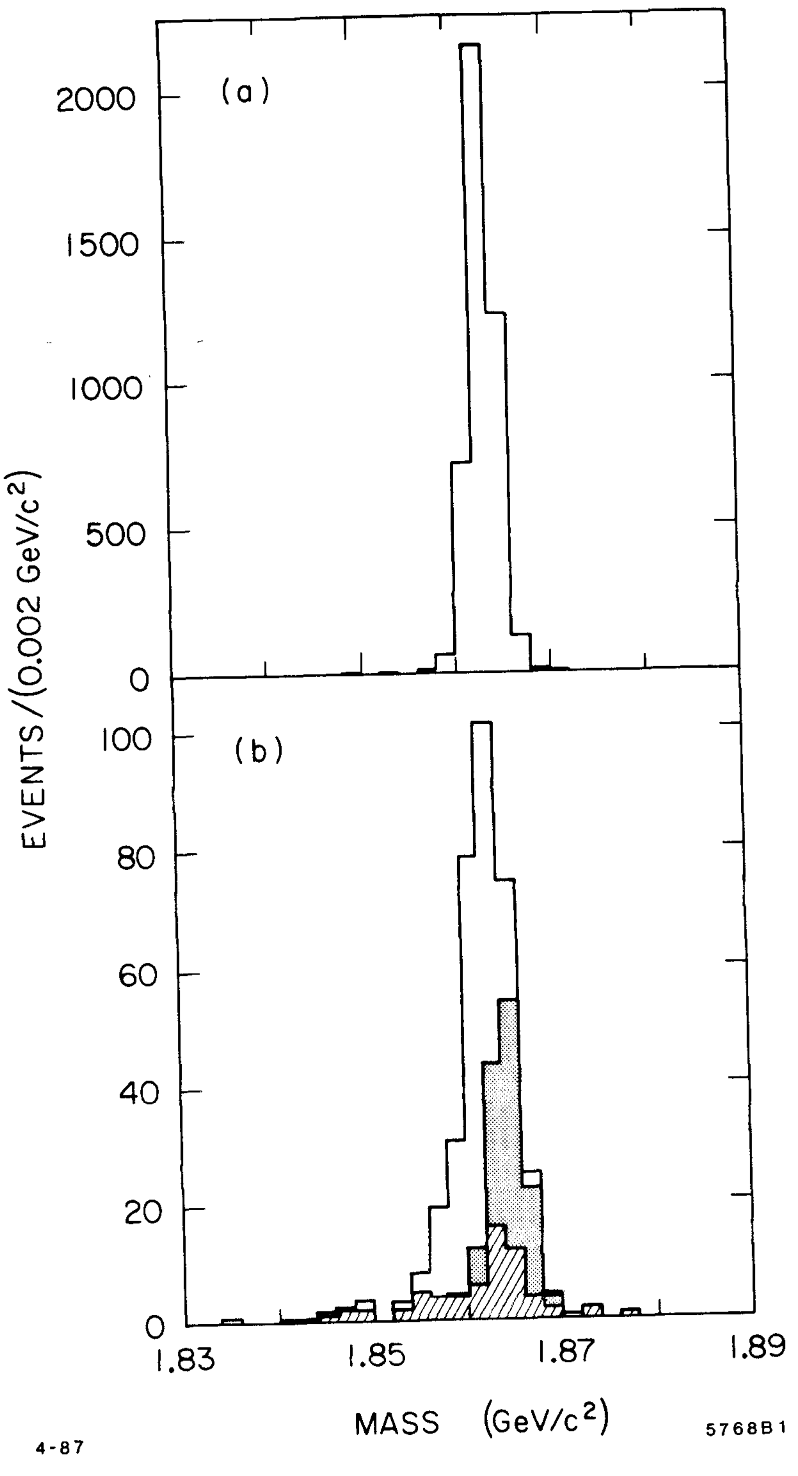
   (a) $K^-\pi^+$ *vs.* $K^+\pi^-$, (b) $K^-\pi^+$ *vs.* $K^+\pi^-\pi^-\pi^+$,

   (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.* $K^0\pi^-\pi^-\pi^+$.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(b)
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1500
1000
500
0
100
80
60
40
20
0
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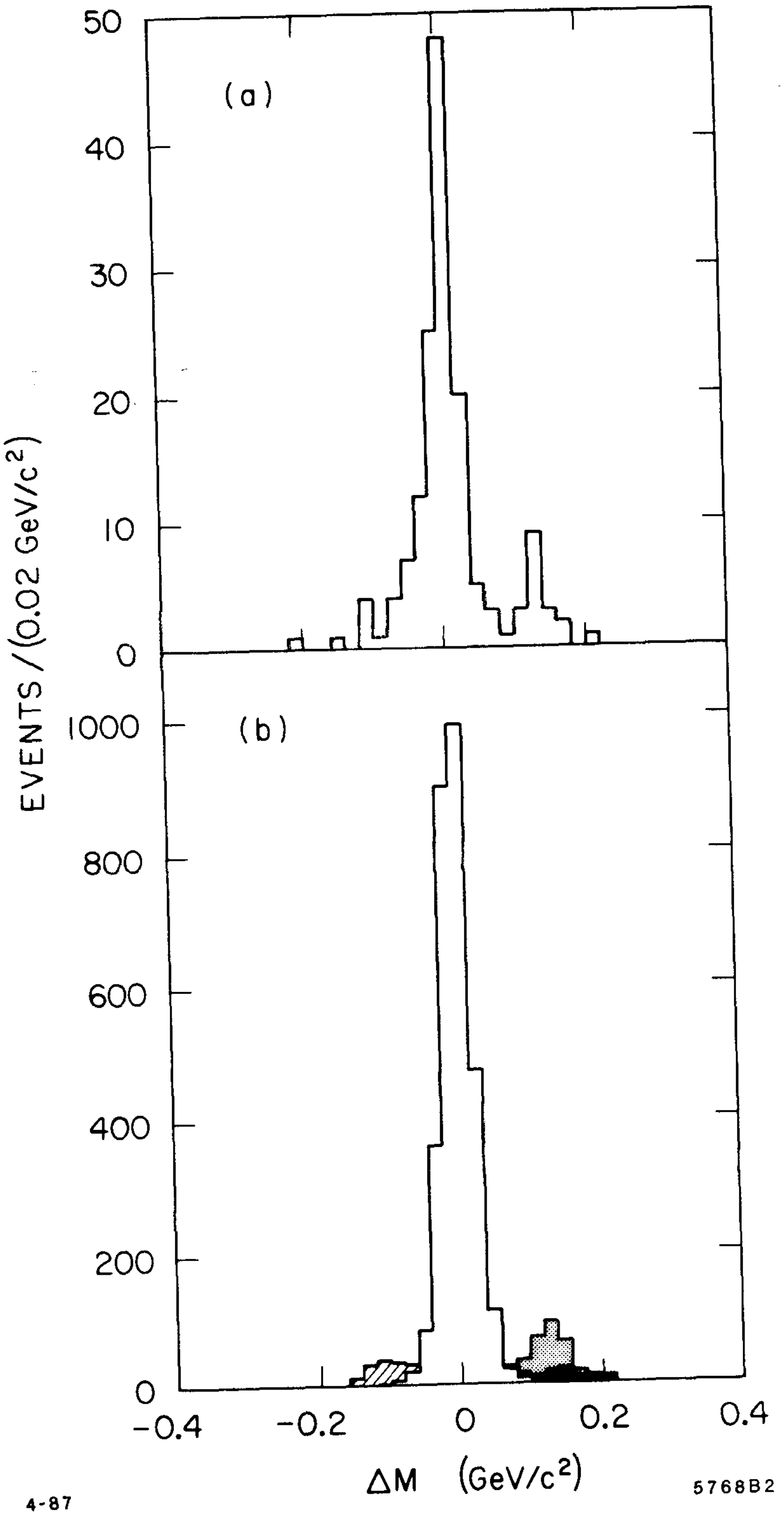
1.85
1.87
1.89
MASS (GeV/c^2)
4-87
5768B1

Fig. 1


(a)
(b)
EVENTS / (0.02 GeV/c²)
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20
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40
50
0
200
400
600
800
1000
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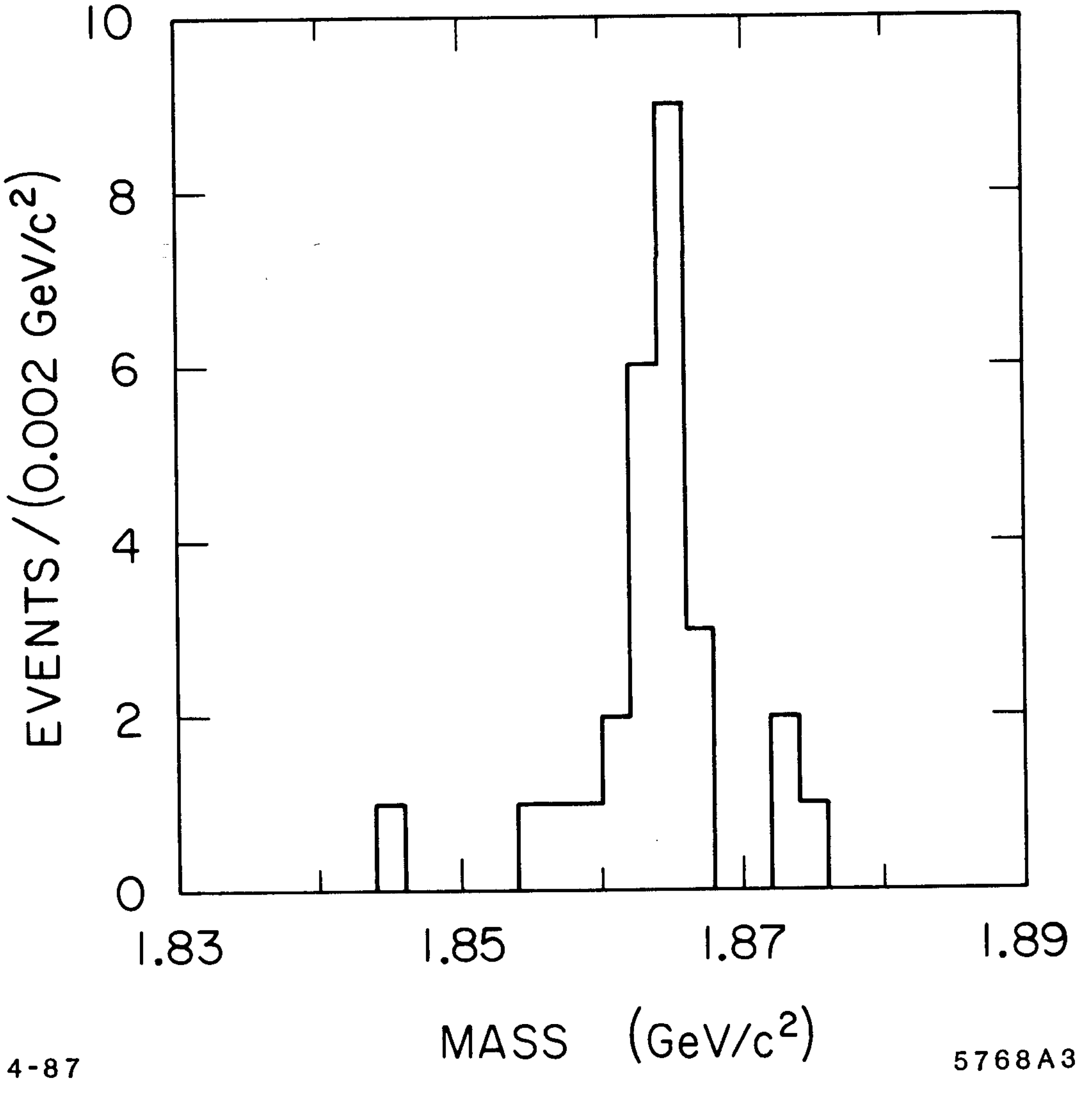
−0.2
0
0.2
0.4
ΔM (GeV/c²)
4-87
5768B2

Fig. 2


10
8
6
4
2
0
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1.85
1.87
1.89
MASS (GeV/c²)
4-87
5768A3

Fig. 3

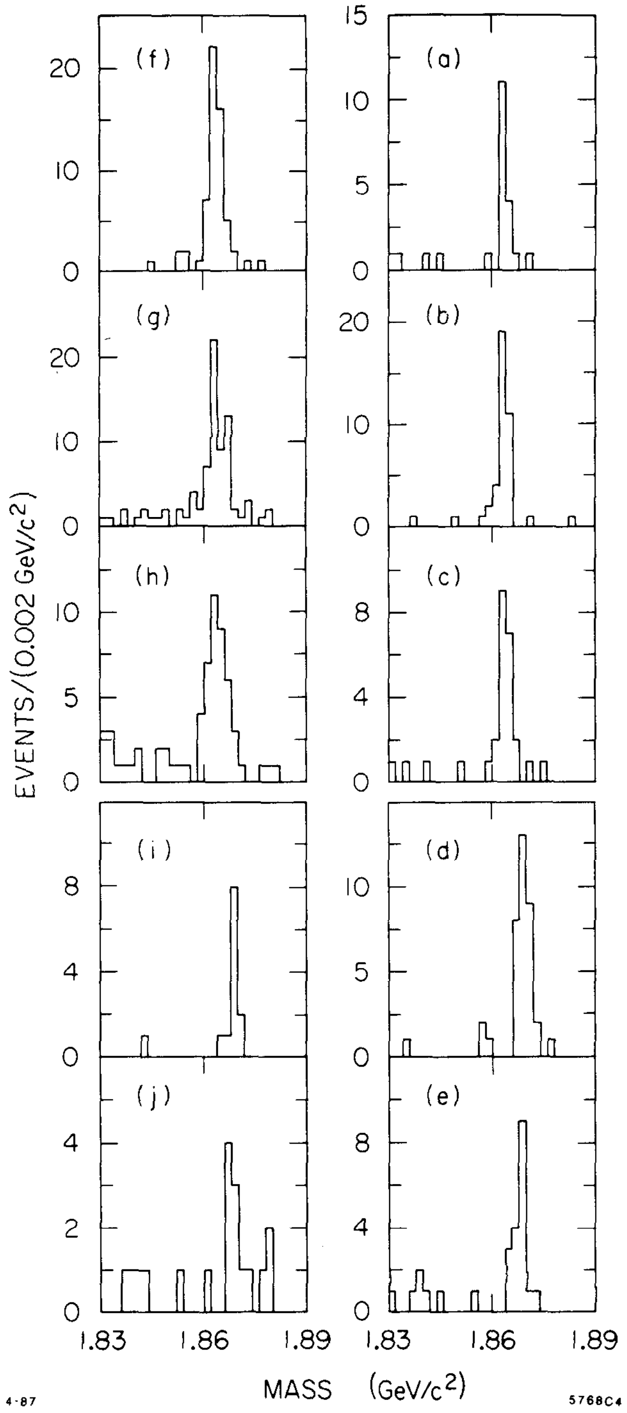
(f)
(g)
(h)
(i)
(j)
(a)
(b)
(c)
(d)
(e)
20
10
0
5
8
4
2
15
EVENTS/(0.002 GeV/c^2)
1.83
1.86
1.89
MASS (GeV/c^2)
4-87
5768C4

Fig. 4