SLAC-PUB-3544
January 1985
(T/E)

Measurements of Cabibbo Suppressed Hadronic Decays of Charmed D^+ and D^0 Mesons*

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Abstract

Measurements of the branching ratios of ten Cabibbo suppressed hadronic weak decays of the D^+ and D^0 are presented from data collected with the Mark III detector at SPEAR. In addition to the previously observed channels $D^0 \rightarrow K^-K^+$ and $\pi^-\pi^+$, we report new measurements of $D^0 \rightarrow \pi^-\pi^+\pi^0$ and $\pi^-\pi^+\pi^-\pi^+$; and $D^+ \rightarrow \bar{K}^0K^+$, $\pi^0\pi^+$, $\bar{K}^{*0}(892)K^+$, $\phi\pi^+$, $K^-K^+\pi^+$, and $\pi^-\pi^+\pi^+$.

Submitted to *Physical Review Letters*

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* This work was supported in part by the U.S. National Science Foundation and the U.S. Department of Energy under contracts DE–AC03–76SF00515, DE–AC02–76ER01195, DE–AC03–81ER40050, and DE–AM03–76SF00034.

We present measurements of Cabibbo suppressed hadronic weak decays of the D^+ and D^0 into two, three and four-body final states. Measurements of D^+ and D^0 semileptonic branching fractions (B_e^+ and B_e^0)[1][2] as well as direct decay length measurements,[3] indicate a substantial difference between D^+ and D^0 lifetimes. The magnitudes of B_e^+ and B_e^0 suggest the presence of distinct nonleptonic processes which enhance the D^0 and suppress the D^+ width.[4] Thus, a further understanding of the D decay mechanism requires a systematic study of the hadronic decays. The measurements we report address three aspects of these decays: the contribution of Cabibbo suppressed decays to the total widths of the D^+ and D^0, the importance of interference between final state amplitudes in the D^+ decays, and the presence of non-perturbative effects in both the D^+ and D^0 decays.

The data were collected near the peak of the $\psi(3770)$ resonance with the Mark III detector at the e^+e^- storage ring SPEAR. The detector has been described in detail elsewhere.[5] The sample of events corresponds to an integrated luminosity of $8.7\,\text{pb}^{-1}$, or about 50,000 produced $D\bar{D}$ pairs.

The analyses of the Cabibbo favored D^0 decay to $K^-\pi^+$, and the suppressed decays to $\pi^-\pi^+$ and K^-K^+ proceed as follows: all charged tracks are required to originate within a fiducial volume of radius 30 mm and length 160 mm centered on the interaction point. They also must lie within the region covered by the time-of-flight (TOF) system, $|\cos\theta| \leq 0.76$ (where θ is the polar angle). The two-body decays of the D^0 produce at least one track with a large momentum ($\sim 1\,\text{GeV/c}$), for which π/K misidentification becomes significant. We therefore employ a technique which separates the signal and misidentification peaks within a single plot by taking advantage of the threshold production of the $D^0\bar{D}^0$ pairs. At threshold, the invariant mass of pairs of tracks arising from real $K^-\pi^+$ decays is insensitive to the interchange of the π and K particle assignments, while a single misidentification results in a narrow reflection peak separated by $\pm 0.120\,\mathrm{GeV/c^2}$ from the D^0 mass. Hence, for each channel, pairs of oppositely charged tracks can be arbitrarily assigned the identities of π or K. When TOF information is available, it is used to remove those pairs which are inconsistent with the desired hypothesis by requiring that neither track have a normalized weight[6] exceeding 70% for an alternate assignment of particle identities. Used in this way, the TOF information allows a greater detection efficiency for D decays than would be possible if a strict TOF requirement were imposed on each track. As D^0's produced at the $\psi(3770)$ have a unique momentum ($P_D = 0.276\,\mathrm{GeV/c}$), we require that all pairs of tracks satisfy $|P_{pair} - P_D| \leq 0.050\,\mathrm{GeV/c}$, to further reduce combinatorial background. Pairs satisfying all other cuts, but having momenta such that $0.060 \leq |P_{pair} - P_D| \leq 0.110\,\mathrm{GeV/c}$, provide a sample that is representative of the background shape through the signal region.

The resulting mass distributions are shown in Figure 1. The prominent features in these plots are the signal peaks at $1.864\,\mathrm{GeV/c^2}$ and the well-separated reflection peaks arising from particle misidentification. The number of signal and background events is determined by a maximum likelihood fit. The mass and width obtained from the dominant $K^-\pi^+$ channel are used in the fits for the suppressed channels K^-K^+ and $\pi^-\pi^+$. An additional Gaussian is introduced to account for each reflection peak. For each channel the background shape (dashed curve) is derived from the adjacent momentum bands; the magnitude is allowed to vary in the fit. In the regions where both signals and reflections are absent, the background curve so derived is seen to provide an excellent representation of the data. We find $(39 \pm 12)\, \pi^-\pi^+$, $(1091 \pm 36)\, K^-\pi^+$, and $(118 \pm 15)\, K^-K^+$ events.

The relative acceptance is determined by a Monte Carlo simulation of $D\bar{D}$ production, decay and detector response. Simulated events are processed through the event reconstruction, selection and analysis programs. After corrections we find:

$$\Gamma(D^0 \to K^-K^+)/\Gamma(D^0 \to K^-\pi^+) = 0.122 \pm 0.018 \pm 0.012$$

$$\Gamma(D^0 \to \pi^-\pi^+)/\Gamma(D^0 \to K^-\pi^+) = 0.033 \pm 0.010 \pm 0.006,$$

where the errors are statistical and systematic respectively. Here, and whenever possible, we normalize ratios of Cabibbo suppressed decays to similar Cabibbo allowed modes, which permits the cancellation of many common systematic uncertainties, and provides a convenient form for comparison with theory.

The same technique is employed to analyze the decays $D^+ \to \bar{K}^0\pi^+$ and $\bar{K}^0K^+$, in which the K^0 is identified through the $K^0_S \to \pi^+\pi^-$ decay. Backgrounds from random $\pi^+\pi^-$ combinations are reduced by requiring that at least one track from a candidate K^0_S be separated from the nominal beam position in the transverse plane by $\geq 2\,\mathrm{mm}$, that the direction of the $\pi^+\pi^-$ pair align with the direction from the beam crossing point to their common vertex, and that the mass of the pair lie within $0.015\,\mathrm{GeV/c^2}$ of the K^0_S mass. Fits to the resulting mass plots (Figure 2), including signal and reflection peaks and a background term, yield: $(141 \pm 13)\, K^0_S\pi^+$ and $(31 \pm 8)\, K^0_SK^+$ events. Correcting for relative efficiency, we obtain:

$$\Gamma(D^+ \to \bar{K}^0 K^+)/\Gamma(D^+ \to \bar{K}^0 \pi^+) = 0.317 \pm 0.086 \pm 0.048.$$

The analyses of the decays $D^+ \to \pi^-\pi^+\pi^+$ and $K^-K^+\pi^+$ proceed similarly. In the $\pi^-\pi^+\pi^+$ analysis, an additional cut on the mass of each $\pi^+\pi^-$ combination is imposed to eliminate feed-down from the Cabibbo allowed channel $D^+ \to K^0_S\pi^+$ where $K^0_S \to \pi^+\pi^-$. Figure 3 shows the resulting three-body combinations. We find $(57 \pm 21)\,\pi^-\pi^+\pi^+$, $(1037 \pm 36)\,K^-\pi^+\pi^+$, and $(78 \pm 13)\,K^-K^+\pi^+$ events. The pseudoscalar-vector (PV) components ($\phi\pi^+$ and $\bar{K}^{*0}(892)K^+$) of the $K^-K^+\pi^+$ final state are isolated from the non-resonant component by additional cuts on the K^+K^- mass for the $\phi\pi^+$ decay, and the $K^-\pi^+$ mass for the $\bar{K}^{*0}K^+$ decay.[7] In the latter, a cut on the decay angular distribution[8] is also made to further reduce the overlap with the non-resonant $K^-K^+\pi^+$ component. Figure 3 also shows the $K^-K^+\pi^+$ mass *after* these cuts. There are $(22 \pm 5)\,\phi\pi^+$ events and $(19 \pm 5)\,\bar{K}^{*0}K^+$ events at the D^+ mass. We estimate by a Monte Carlo calculation that (1.0 ± 0.4) and (5.0 ± 2.0) events from non-resonant $K^-K^+\pi^+$ contaminate the $\phi\pi^+$ and $\bar{K}^{*0}K^+$ signals, respectively. Correcting for this overlap and the overall detection efficiency we find:

$$\Gamma(D^+ \to \pi^-\pi^+\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+) = 0.042 \pm 0.016 \pm 0.010$$

$$\Gamma(D^+ \to K^-K^+\pi^+)_{non-res.}/\Gamma(D^+ \to K^-\pi^+\pi^+) = 0.059 \pm 0.026 \pm 0.009$$

$$\Gamma(D^+ \to \phi\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+) = 0.084 \pm 0.021 \pm 0.011$$

$$\Gamma(D^+ \to \bar{K}^{*0}K^+)/\Gamma(D^+ \to K^-\pi^+\pi^+) = 0.048 \pm 0.021 \pm 0.011.$$

The decays $D^+ \to \pi^0\pi^+$, $D^0 \to \pi^-\pi^+\pi^0$ and $D^0 \to \pi^-\pi^+\pi^-\pi^+$ are subject to large combinatorial backgrounds when analyzed by the previous techniques.

We therefore select events in which one D meson has been identified in a Cabibbo allowed decay mode, ($1729 \pm 20\, D^+D^-$ and $3762 \pm 42\, D^0\bar{D}^0$ events) and evaluate only combinations of the charged tracks and photons belonging to the recoiling D.[9] Appropriate combinations in modes containing π^0's are fit to the two constraints of beam energy and π^0 mass, improving the resolution to about $0.003\,\mathrm{GeV/c^2}$. Combinations with $\chi^2 < 6$ are retained. The $\pi^-\pi^+\pi^-\pi^+$ mode requires only the beam energy constraint. To further reject background, a cut on total momentum is imposed in each event. Background from the Cabibbo allowed mode $K^-\pi^+\pi^0$ is eliminated by TOF cuts, and that from $\bar{K}^0\pi^0$ and $\bar{K}^0\pi^+\pi^-$, where $K_S^0 \to \pi^+\pi^-$, by cuts on the $\pi^+\pi^-$ mass. The results are shown in Figure 4. One event consistent with the decay $D^+ \to \pi^0\pi^+$ is observed yielding an upper limit (including systematic errors) of 4.2 events at 90% C.L., or a branching ratio $B(D^+ \to \pi^0\pi^+) \leq 0.53\%$. Assuming the branching ratio $B(D^+ \to \bar{K}^0\pi^+) = 2.5\%$,[10] we obtain:

$$\Gamma(D^+ \to \pi^0\pi^+)/\Gamma(D^+ \to \bar{K}^0\pi^+) < 0.21\,\mathrm{at}\ \ 90\%\,\mathrm{C.L.}$$

Fitting to $\pi^-\pi^+\pi^0$ and $\pi^-\pi^+\pi^-\pi^+$ with the expected mass resolution and a flat background, we find 10^{+4}_{-3} and 9^{+4}_{-3} events, or branching ratios $B(D^0 \to \pi^-\pi^+\pi^0) = 1.1 \pm 0.4 \pm 0.2\%$, and $B(D^0 \to \pi^-\pi^+\pi^-\pi^+) = 1.5 \pm 0.6 \pm 0.2\%$. The 10 events in the $\pi^-\pi^+\pi^0$ mode are consistent with the decay $D^0 \to \rho^0\pi^0$.

The measurements of Cabibbo suppressed branching ratios presented here provide new insights into the mechanism of nonleptonic D decays. Exact SU(3) symmetry predicts the equality of $\Gamma(D^0 \to \pi^-\pi^+)$ and $\Gamma(D^0 \to K^-K^+)$.[11] The inequality previously observed[12] is confirmed here with improved precision.

Several distinct effects could contribute to this inequality. The long B meson lifetime[13] rules out significant contributions from the other quark sectors.[14] Quark mass effects are likely to be small.[15] Final state interactions breaking SU(3) symmetry could however account for the difference.[15] If the observed inequality is taken to reflect the scale of SU(3) violating effects, then our observation of the large ratio $\Gamma(D^+ \rightarrow \bar{K}^0 K^+)/\Gamma(D^+ \rightarrow \bar{K}^0 \pi^+)$, and the smaller $\Gamma(D^+ \rightarrow \pi^0 \pi^+)/\Gamma(D^+ \rightarrow \bar{K}^0 \pi^+)$, suggests that destructive interference between two-body D^+ decay amplitudes may contribute significantly to the difference in D^+ and D^0 lifetimes.[16] Such interference is possible in the amplitudes for both $D^+ \rightarrow \bar{K}^0 \pi^+$ and $\pi^0 \pi^+$, but not in that for $D^+ \rightarrow \bar{K}^0 K^+$. The magnitudes of the observed ratios could then be attributed to an effective enhancement of the part of the charm-changing weak Hamiltonian that transforms as a 20-plet.[17]

Previous measurements[1][10] have shown that the decay $D^0 \rightarrow \bar{K}^0 \pi^0$, which was expected to suffer strong color-suppression in the presence of hard gluon corrections to the weak Hamiltonian,[18] proceeds at a rate comparable to $D^0 \rightarrow K^- \pi^+$. The decay $D^+ \rightarrow \phi \pi^+$, also expected to be color-suppressed in this picture,[19] is found to proceed at a rate comparable to other Cabibbo suppressed D^+ decays. This suggests that color-suppression is inoperative in the D^+ system as well, and hence, that non-perturbative effects[20] which could modify the color structure in *both* D^0 and D^+ decays and thereby alter the total widths, may play a significant role.

We gratefully acknowledge the efforts of the SPEAR staff. We also wish to thank A.N. Kamal and M. Peskin for valuable theoretical discussions. One of us (N.W.) wishes to thank the Alexander von Humboldt Foundation for support.

This work was supported in part by the U.S. National Science Foundation and the U.S. Department of Energy under Contracts No.DE-AC03-76SF00515, No.DE-AC02-76ER01195, No.DE-AC03-81ER40050, and No.DE-AM03-76SF00034.

1. References

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The hypothesis could be further tested by the comparison of $\Gamma(D^+ \rightarrow \bar{K}^{*0}K^+)$ to $\Gamma(D^+ \rightarrow \bar{K}^{*0}\pi^+)$. Such a comparison also provides insight into the strength of SU (3) breaking. The measurement will appear in a subsequent paper.

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FIGURE CAPTIONS

1. Invariant mass for K^-K^+, $K^-\pi^+$, and $\pi^-\pi^+$. Here and throughout this paper, we adopt the convention that reference to a particle state also implies reference to its charge conjugate.

2. Invariant mass for $\bar{K}^0K^+$, and $\bar{K}^0\pi^+$.

3. Invariant mass for $\pi^-\pi^+\pi^+$, $K^-\pi^+\pi^+$, and $K^-K^+\pi^+$. $K^-K^+\pi^+$ events remaining after (a) K^* and (b) ϕ cuts.

4. Mass distributions employing the beam energy constraint, for $\pi^0\pi^+$, $\pi^-\pi^+\pi^0$, and $\pi^-\pi^+\pi^-\pi^+$.

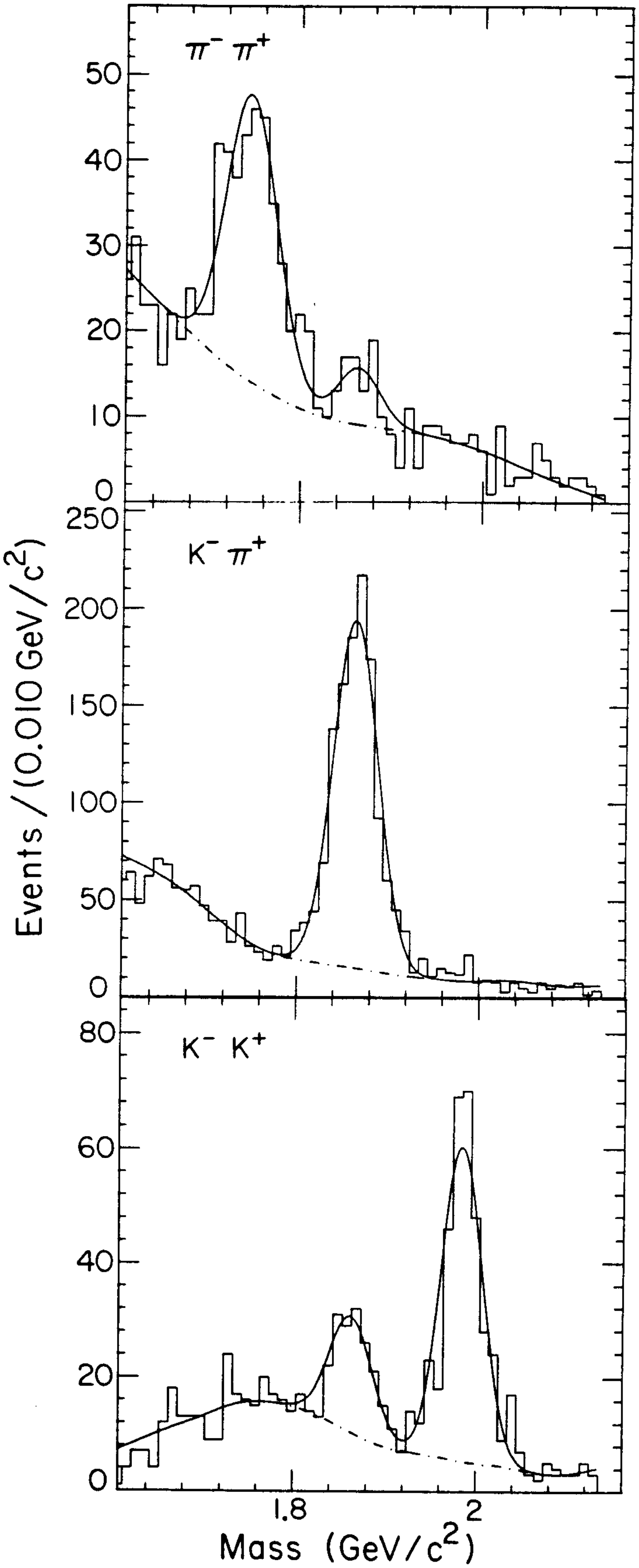
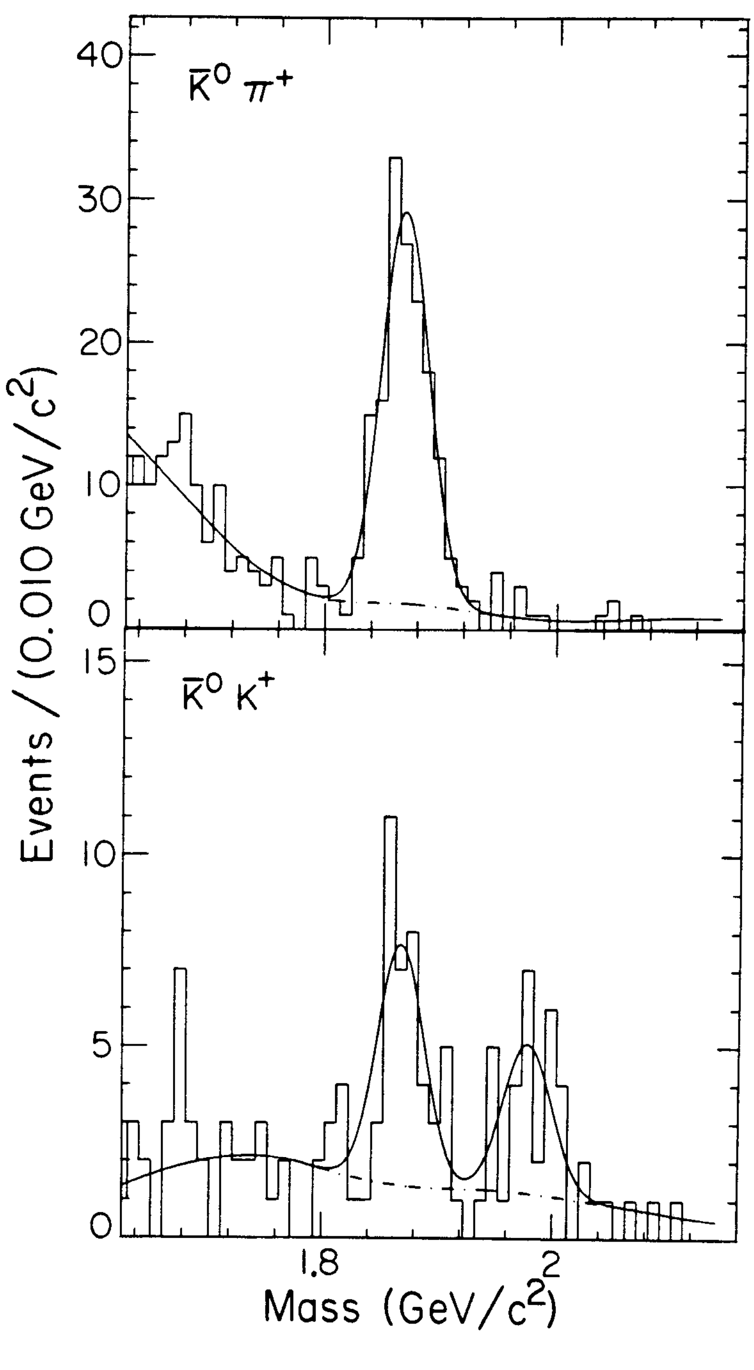
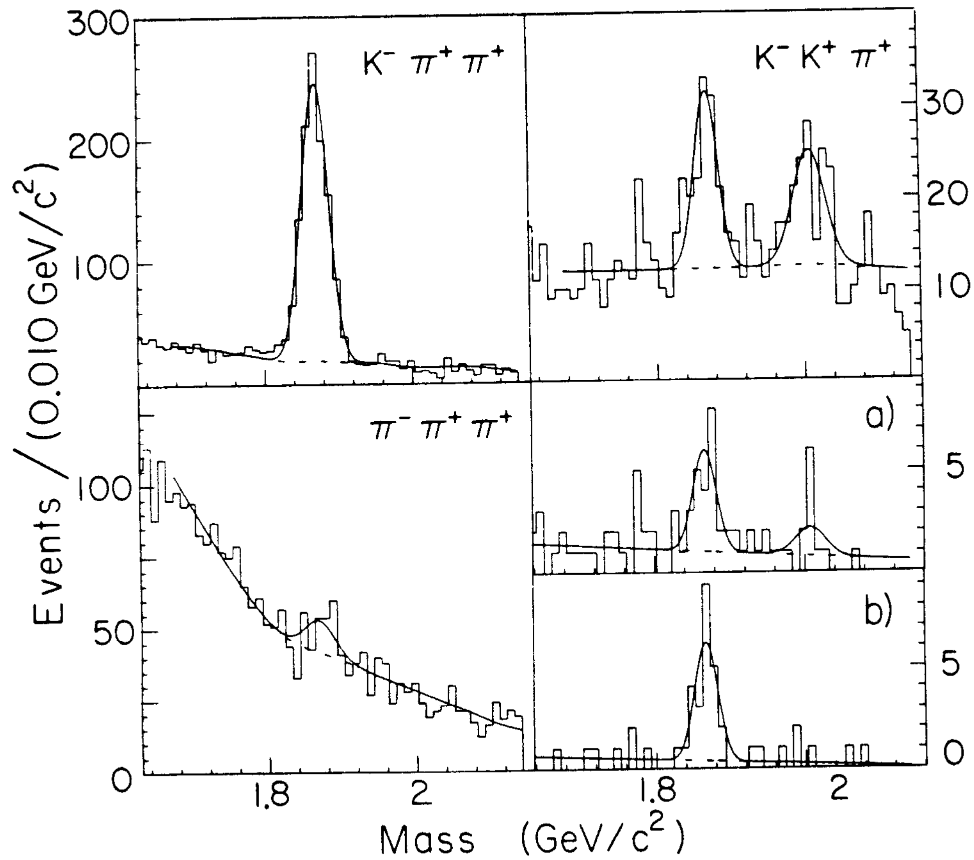

π⁻ π⁺
K⁻ π⁺
K⁻ K⁺
Events / (0.010 GeV/c²)
Mass (GeV/c²)
1.8
2
0
10
20
30
40
50
250
200
150
100
60
80

Fig. 1



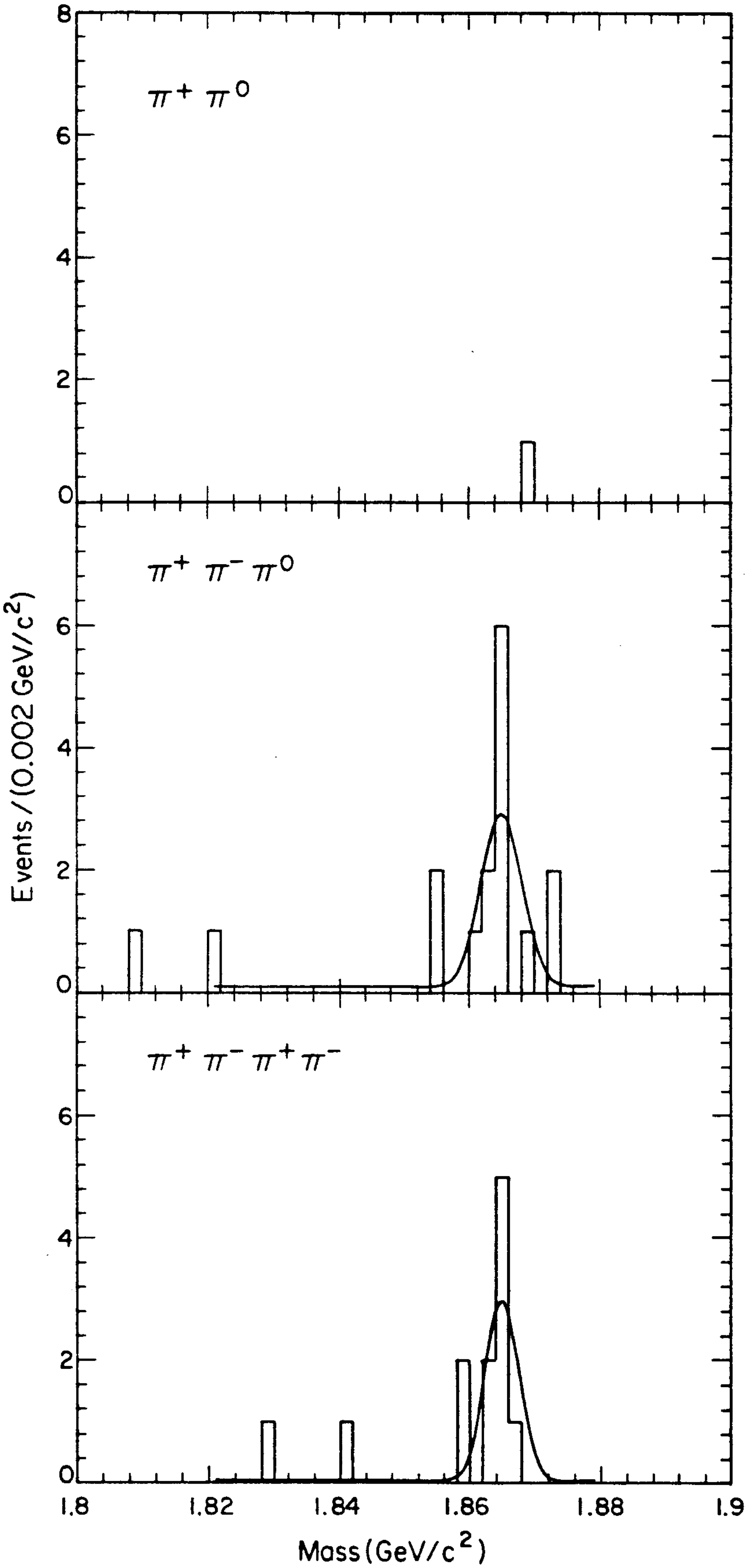
$\bar{K}^0 \pi^+$
$\bar{K}^0 K^+$
Events /(0.010 GeV/c²)
Mass (GeV/c²)
40
30
20
10
0
15
10
5
0
1.8
2

Fig. 2



K⁻ π⁺ π⁺
K⁻ K⁺ π⁺
π⁻ π⁺ π⁺
a)
b)
300
200
100
50
0
30
20
10
5
0
1.8
2
Events /(0.010 GeV/c²)
Mass (GeV/c²)

Fig. 3



π+ π0
π+ π− π0
π+ π− π+ π−
Events / (0.002 GeV/c2)
Mass (GeV/c2)
8
6
4
2
0
1.8
1.82
1.84
1.86
1.88
1.9

Fig. 4