Fermi National Accelerator Laboratory

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A Study of $D_s^{\pm}$ and $D^{\pm}$ Decays into Four-Body Final States, Including $\eta\pi^{\pm}$ and $\omega\pi^{\pm}$ *

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A STUDY OF $D_s^{\pm}$ AND $D^{\pm}$ DECAYS INTO FOUR-BODY FINAL STATES, INCLUDING $\eta\pi^{\pm}$ and $\omega\pi^{\pm}$

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ABSTRACT

We report results on $D_s^{\pm}$ decays into the final states $\pi^+\pi^-\pi^{\pm}\pi^0$ and $K^+K^-\pi^{\pm}\pi^0$ from Fermilab charm photoproduction experiment E691. For the former decay we search for $\eta\pi^{\pm}$ and $\omega\pi^{\pm}$ components, and for the latter, we measure the relative rate for decays into $\phi\pi^{\pm}\pi^0$ and non-resonant $K^+K^-\pi^{\pm}\pi^0$. We also present limits for Cabibbo-suppressed $D^{\pm}$ decays into these final states, and measure the Cabibbo-allowed decay $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^+\pi^0$.

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One of the fundamental problems of charm decay is the relative size of non-spectator decay processes. Spectator decays are those in which the light antiquark is not involved at the weak decay vertex. Two important decay modes for studying this question are $D_s^+ \to \eta\pi^+$ and $D_s^+ \to \omega\pi^+$. (Throughout the rest of this paper charge conjugate states are implicitly included). Cabibbo-favored spectator decays of the D_s^+ produce final states with an $s\bar{s}$ pair. Because of the large $s\bar{s}$ component in the η, $D_s^+ \to \eta\pi^+$ should be one of the dominant two-body decays.[1,2] The $\omega\pi^+$ decay mode is expected to be small in models dominated by spectator decays, but is predicted to be large in models which include large non-spectator amplitudes.[3,4] In this paper we report results on D_s^+ and D^+ decays into the final states $\pi^+\pi^-\pi^+\pi^0$ and $K^+K^-\pi^+\pi^0$ from the Fermilab charm photoproduction experiment E691.[5] The decays $D_s^+ \to \eta\pi^+$ and $D_s^+ \to \omega\pi^+$ are included in the four-pion sample.

More generally, although many D_s^+ decays have been measured,[6–11] a large fraction of the total decay rate is still not accounted for.[12] The normalization of the branching ratios depends on theoretical estimates of the D_s^+ production cross section in e^+e^- annihilation.[13] It is therefore important to check this normalization by measuring as large a fraction of the D_s^+ decays as possible. Many of the unseen decay modes which might be large are observable in the final states $\pi^+\pi^-\pi^+\pi^0$ and $K^+K^-\pi^+\pi^0$. We also study the Cabibbo-suppressed D^+ decay modes into these final states. Because of the similarity in the final state, we also present an observation of the Cabibbo-allowed decay $D^+ \to K^-\pi^+\pi^+\pi^0$.

The search for $\eta\pi^+$ decays was conducted using two different approaches. In the first approach, which we also used to search for $\omega\pi^+$ and non-resonant $\pi^+\pi^-\pi^+\pi^0$, we reconstruct all four of the final-state particles. To reduce background we apply cuts which have been used to observe decay modes in which all the decay products are charged.[8,9] In the analysis of $\omega\pi^+$ and non-resonant $\pi^+\pi^-\pi^+\pi^0$, we require all three charged track candidates to pass through both analysis magnets. Due to the low background in the

$\eta\pi^+$ sample, we require only two of the tracks to pass through both magnets, while the remaining track must pass through at least the upstream magnet. The three tracks must pass a minimum requirement on the product of Cherenkov probabilities for particle identification. These tracks must also form a well-constrained vertex. We also require the line-of-flight of the reconstructed D_s^+ candidate (which includes the π^0 momentum vector) to pass within 80μm of a reconstructed primary vertex candidate. Candidates which decay at least a distance 10σ downstream of the primary vertex are selected as charm candidates, where σ is the error on the distance between the primary and secondary vertices. We also demand that each of the three charged tracks pass closer to the secondary vertex than to the primary, and that no additional tracks pass within 80 μm of the secondary vertex. We reconstruct the π^0 from the decay by demanding a pair of good-quality photons which have invariant mass sufficiently near the π^0 mass. These photons leave shower profiles in an electromagnetic calorimeter[14] which are consistent with expected shapes, have transverse momentum greater than 40 MeV, are located at least 6 cm vertically from the center of the calorimeter (to avoid confusion with beam pairs), and have energy greater than 3 GeV. Neither photon can be associated with any other π^0 candidate. We also require that the energy of the π^0 be greater than 12 GeV.

The spectrum of $\pi^+\pi^-\pi^+\pi^0$ events satisfying all the above criteria is shown in Figure 1(a). A fit to this spectrum yields 12.8 ± 15.0 $D_s^+ \rightarrow \pi^+\pi^-\pi^+\pi^0$ events. We search for possible $\eta\pi^+$ and $\omega\pi^+$ components by demanding that one of the $\pi^+\pi^-\pi^0$ combinations from the charm decay candidate lie in the invariant mass ranges 536-560 GeV and 762-798 GeV, respectively. The root-mean-square resolution in 3π mass is 8 MeV at the η and 12 MeV at the ω. For $\eta\pi^+$, we also cut loosely on the π^0 energy as measured in the η rest frame, because the matrix element favors low-energy π^0's.[15] The resulting invariant mass spectra are shown in Figure 1 for $\eta\pi^+$ (b) and $\omega\pi^+$ (c). Fits to these spectra yield $2.8^{+2.1}_{-1.4}$ $\eta\pi^+$ events, and 0.0 ± 1.7 $\omega\pi^+$ events. Although there is an excess at the D_s^+ in the $\eta\pi^+$ spectrum, it has a statistical significance of only two standard deviations. The reconstruction efficiencies for these modes are $(0.08 \pm 0.02)\%$ for $\eta\pi^+$, $(0.09 \pm 0.03)\%$ for $\omega\pi^+$, and $(0.11 \pm 0.03)\%$ for $\pi^+\pi^-\pi^+\pi^0$. The Monte Carlo simulation used to determine these efficiencies includes the proper angular distributions for the η[15] and ω.[16] We normalize to $D_s^+ \to \phi\pi^+$. We thus calculate the following:

$$\Gamma(D_s^+ \to \eta\pi^+)/\Gamma(D_s^+ \to \phi\pi^+) = 1.5^{+1.1}_{-0.8} \pm 0.5 \leq 3.2$$

$$\Gamma(D_s^+ \to \omega\pi^+)/\Gamma(D_s^+ \to \phi\pi^+) = 0.0 \pm 0.3 \pm 0.1 \leq 0.5$$

$$\Gamma(D_s^+ \to \pi^+\pi^-\pi^+\pi^0\,[inclusive])/\Gamma(D_s^+ \to \phi\pi^+) = 0.7 \pm 1.7 \pm 0.2 \leq 3.3,$$

where the limits are all at the 90% confidence level.

Because of the small energy release in the $\eta \to \pi^+\pi^-\pi^0$ decay, it is possible to perform an independent search for an $\eta\pi^+$ signal without reconstructing the π^0. The $\pi^+\pi^-$ mass from the η must be less than 0.42 GeV, and the $\pi^+\pi^-\pi^+$ mass in the $D_s^+ \to \eta\pi^+$ events must be less than 1.833 GeV. We can reduce the background substantially by exploiting the narrow allowed invariant mass range of the two charged pions from the η decay. In Figure 2(a) is shown a Monte Carlo simulation of the three-track spectrum from $D_s^+ \to \eta\pi^+$ decays where we demand that the two tracks from the η have invariant mass between 280 and 414 MeV. (At three-pion mass below 1.66 GeV we have cut even tighter on the two-pion mass, since the maximum $\pi^+\pi^-$ mass drops with lower three-pion mass). For this sample we have required that the charm candidate decay at least 14σ downstream of the primary vertex, and that the line-of-flight of the reconstructed charm candidate pass within 100μm of a reconstructed primary vertex candidate. Other requirements on the charged tracks are similar to those used in the analysis detailed above. The efficiency for detecting an $\eta\pi^+$ signal in this manner is $(1.43 \pm 0.09)\%$, more than ten times greater than the efficiency including π^0 reconstruction. The sharp edge at 1.833 GeV in the mass spectrum provides a characteristic signal of the $D_s^+ \to \eta\pi^+$ decay.

The corresponding three-pion mass spectrum from the data is shown in Figure 2(b). We performed a maximum-likelihood fit to this spectrum to search for an $\eta\pi^+$ signal. The background was parameterized using a sample of three-pion combinations that failed the requirements we demanded for the charm candidates. In the fit to Figure 2(b) we have allowed the background to have an additional multiplicative term linear in three-pion mass. The fit yields -12 ± 15 $\eta\pi^+$ events. To be conservative we use the value 0 ± 15 to calculate the upper limit described below.

The systematic error on the number of $\eta\pi^+$ decays is estimated by changing the analysis cuts, using different background shapes, and allowing for other charm decays which may cause significant structure in the three-pion spectrum. The cut on $\pi^+\pi^-$ mass suppresses feedthrough from other charm decays by a large factor. In addition, feedthrough from any non-η source would be very evident in the $\pi^+\pi^-\pi^+$ mass spectrum with no 2π mass cut. The systematic error is dominated by the error in the feedthroughs and the variation with analysis cuts, and is estimated to be ± 14 events. Most importantly, trying a wide range of background shapes caused only modest changes in the number of $\eta\pi^+$ decays. We thus obtain by this method

$$\Gamma(D_s^+ \to \eta\pi^+)/\Gamma(D_s^+ \to \phi\pi^+) = 0.0 \pm 0.5 \pm 0.5,$$

which is consistent with the result obtained by the first method. We calculate an upper limit on $D_s^+ \to \eta\pi^+$ by taking a weighted average of the two independent measurements. We have verified that the spectra of Figure 1(b) and Figure 2(b) have no events in common. The best measurement, using both modes, is

$$\Gamma(D_s^+ \to \eta\pi^+)/\Gamma(D_s^+ \to \phi\pi^+) = 0.6 \pm 0.6.$$

From this measurement we calculate the upper limit of

$$\Gamma(D_s^+ \to \eta\pi^+)/\Gamma(D_s^+ \to \phi\pi^+) \leq 1.5$$

at the 90% confidence level.

We have analyzed the spectrum of Figure 1(a) for evidence of a $D^+ \to \pi^+\pi^-\pi^+\pi^0$ signal, using similar techniques as for the D_s^+. However, in order to further reduce background, we take advantage of the long D^+ lifetime[5] and require the charm candidate to decay at least 15σ downstream of the primary vertex. We find 20.8 ± 11.9 D^+ events. Normalizing to the copious mode $D^+ \to K^-\pi^+\pi^+$, we obtain $\Gamma(D^+ \to \pi^+\pi^-\pi^+\pi^0)/\Gamma(D^+ \to K^-\pi^+\pi^+) = 0.2 \pm 0.1 \le 0.4$ at the 90% confidence level. No evidence was found for resonant substructure in this mode; we calculate $\Gamma(D^+ \to \omega\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+) = 0.01 \pm 0.04 \le 0.08$ at the 90% confidence level, and $\Gamma(D^+ \to \eta\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+) = 0.05 \pm 0.05$. Using the missing-$\pi^0$ technique, we found 23 ± 20 $D^+ \to \eta\pi^+$ events in the spectrum of Figure 2(b), corresponding to $\Gamma(D^+ \to \eta\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+) = 0.07 \pm 0.08$. As for the D_s^+, we take a weighted average of these two independent measurements and obtain $\Gamma(D^+ \to \eta\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+) = 0.06 \pm 0.04 \le 0.12$ at the 90% confidence level.

We have also analyzed the final states containing $K^+K^-\pi^+\pi^0$ for D^+ and D_s^+ decays and searched for resonant substructure. The analysis is similar to the $\eta\pi^+$ and $\omega\pi^+$ analysis described above. For the D^+ search we have demanded that the charm candidate decay a distance 20σ downstream of the primary vertex. The $K^+K^-\pi^+\pi^0$ mass spectra for non-ϕ and ϕ events are shown in Figures 3(a) and 3(b) respectively. The K^+K^- invariant mass for the events in Figure 3(b) must lie between 1.012 and 1.027 GeV. A fit to spectrum 3(a) finds 0.0 ± 5.6 D^+ events and $5.3^{+5.9}_{-5.0}$ D_s^+ events. (The curve shown in Figure 3(a) shows the background shape). The fit to the $\phi\pi^+\pi^0$ spectrum yields 11.0 ± 3.6 D_s^+ events, a 3.7σ effect, and 2.6 ± 1.6 events at the D^+. (The D^+ signal has been set to zero for the curve in Figure 3(b)). Because of the very difficult subtraction of feedthrough from other modes with $K^+K^-\pi^+\pi^0$ final states, we cannot separately measure the $K^{*+}\overline{K}^{*0}$ component. The feedthrough into the $D_s^+ \to \phi\pi^+\pi^0$ sample is 0.9 ± 0.9 events. The results for the D_s^+ modes, normalized to $D_s^+ \to \phi\pi^+$, are shown in Table 1. Because of the narrowness of the ϕ and the limit on non-resonant $K^+K^-\pi^+\pi^0$ decays, the effect of possible interference is small compared to the errors. We cannot measure the fraction of $\phi\pi^+\pi^0$ from the vector-vector mode, $D_s^+ \to \phi\rho^+$, with the present statistics. However, even if all of the decays are from this source, the branching ratio would be significantly less than the predicted ratio $B(D_s^+ \to \phi\rho^+)/B(D_s^+ \to \phi\pi^+) = 6.3$.[1] Thus the vector-vector mode seems to be overestimated in the Bauer-Stech-Wirbel model. We have also obtained limits on $D^+ \to \phi\pi^+\pi^0$ and $D^+ \to K^+K^-\pi^+\pi^0$. The limits on the D^+ channels are summarized in Table 2.

Finally, the decay mode $D^+ \to K^-\pi^+\pi^+\pi^0$ provides a large charm signal with the same topology as the D_s^+ modes discussed here. This signal is shown in Figure 4. In a forthcoming publication we will describe a detailed analysis of possible resonant substructure; for the present we quote the main result:

$$\Gamma(D^+ \to K^-\pi^+\pi^+\pi^0)/\Gamma(D^+ \to K^-\pi^+\pi^+) = 0.69 \pm 0.10 \pm 0.16.$$

This result is consistent with an earlier measurement, 0.56 ± 0.14.[17]

The best tests for the size of the weak annihilation decay are in the decay modes $D_s^+ \to \rho\pi^+$ and $\omega\pi^+$.[12] Earlier we set the experimental limit $\Gamma(D_s^+ \to \rho\pi^+)/\Gamma(D_s^+ \to \phi\pi^+) \leq 0.08$.[9] It has been argued that the weak annihilation decay could still be as large as the spectator decay for the D_s^+, because of the interference of two W-annihilation amplitudes. The predictions in that case for $\Gamma(D_s^+ \to \omega\pi^+)/\Gamma(D_s^+ \to \phi\pi^+)$ are 1[3,4] or 12,[3] both of which are ruled out by our experimental limit of 0.5. This result confirms the picture in which weak annihilation is small and does not account for the major difference between D_s^+ and D^+ lifetimes.

Our limit $\Gamma(D_s^+ \to \eta\pi^+)/\Gamma(D_s^+ \to \phi\pi^+) \leq 1.5$ is consistent with the theoretical expectation that the two modes should be comparable.[1,2] Recently there have been two positive measurements of this decay mode, one published[18] and the other preliminary.[19] Although the central values are greater than the upper limit quoted here, the results are not clearly inconsistent. The errors on the ratio, and sensitivity of the results, are similar. Combining this result with our measured value of $\sigma \cdot B(D_s^+ \rightarrow \phi\pi^+)$,[7,20] we get a limit on $\sigma \cdot B(D_s^+ \rightarrow \eta\pi^+)$ of 2.5 nb, which is an order of magnitude lower than an earlier published result.[21]

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Table 1. Results for D_s^+ decays (all limits are 90% C.L.).

Decay Mode	Branching ratio, normalized to $D_s^+ \to \phi\pi^+$
$D_s^+ \to \pi^+\pi^-\pi^+\pi^0$ [*inclusive*]	≤ 3.3
$D_s^+ \to \eta\pi^+$	≤ 1.5
$D_s^+ \to \omega\pi^+$	≤ 0.5
$D_s^+ \to \phi\pi^+\pi^0$	$2.4 \pm 1.0 \pm 0.5$
$D_s^+ \to K^+K^-\pi^+\pi^0$ [*non* $-\ \phi$]	≤ 2.4

Table 2. Results for D^+ decays (all limits are 90% C.L.).

Branching ratios are calculated assuming

$B(D^+ \to K^-\pi^+\pi^+) = 9.1 \pm 1.3 \pm 0.4\,\%$.[22]

Decay Mode	Branching ratio, normalized to $D^+ \to K^-\pi^+\pi^+$	Branching ratio (%)
$D^+ \to \pi^+\pi^-\pi^+\pi^0$ [*inclusive*]	$0.2 \pm 0.1\ \leq 0.4$	≤ 3.7
$D^+ \to \eta\pi^+$	≤ 0.12	≤ 1.1
$D^+ \to \omega\pi^+$	≤ 0.08	≤ 0.8
$D^+ \to \phi\pi^+\pi^0$	≤ 0.28	≤ 2.6
$D^+ \to K^+K^-\pi^+\pi^0$ [*non* $-\ \phi$]	≤ 0.25	≤ 2.3
$D^+ \to K^-\pi^+\pi^+\pi^0$	$0.69 \pm 0.10 \pm 0.16$	$6.3 \pm 1.3 \pm 1.5$

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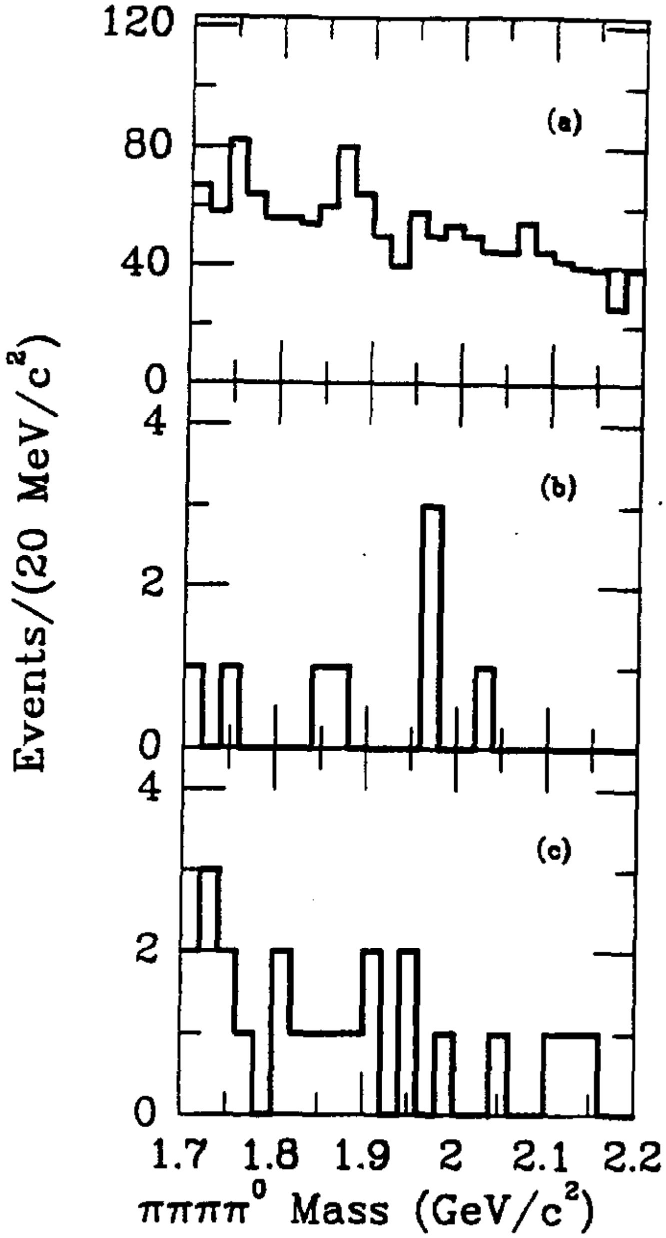
FIGURE CAPTIONS

1. The $\pi^+\pi^-\pi^+\pi^o$ mass spectra for (a) inclusive $\pi^+\pi^-\pi^+\pi^o$, (b) $\eta\pi^+$, and (c) $\omega\pi^+$ final states.

2. (a) The $\pi^+\pi^-\pi^+$ mass spectrum from a Monte Carlo simulation of $D_s^+ \to \eta\pi^+$ decay. (b) The $\pi^+\pi^-\pi^+$ mass spectrum used in the missing-π^o search for $D_s^+ \to \eta\pi^+$. The peak near 1.87 GeV corresponds to the decay $D^+ \to \pi^+\pi^-\pi^+$.[8]

3. The $K^+K^-\pi^+\pi^o$ mass spectra for (a) non-ϕ and (b) ϕ final states.

4. The $K^-\pi^+\pi^+\pi^o$ mass spectrum.



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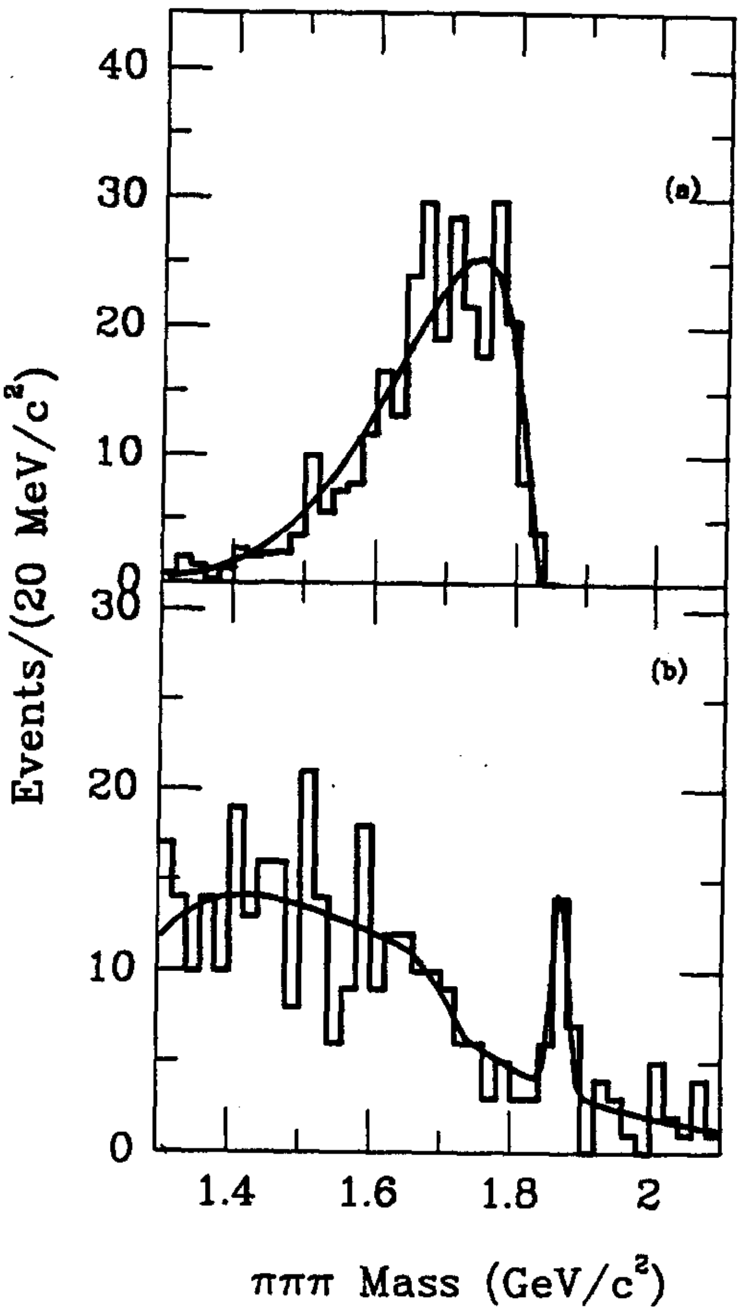
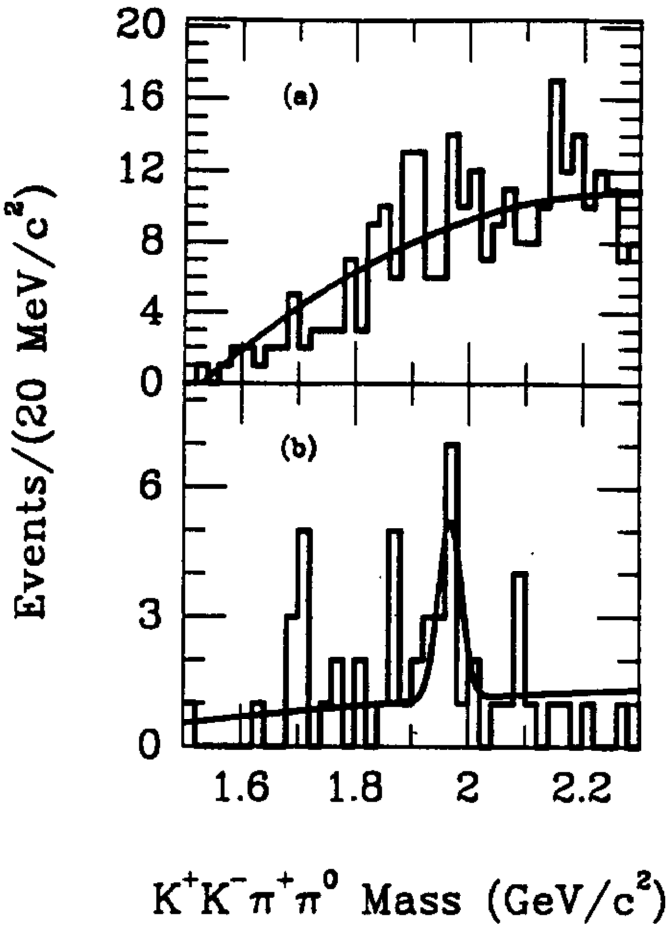
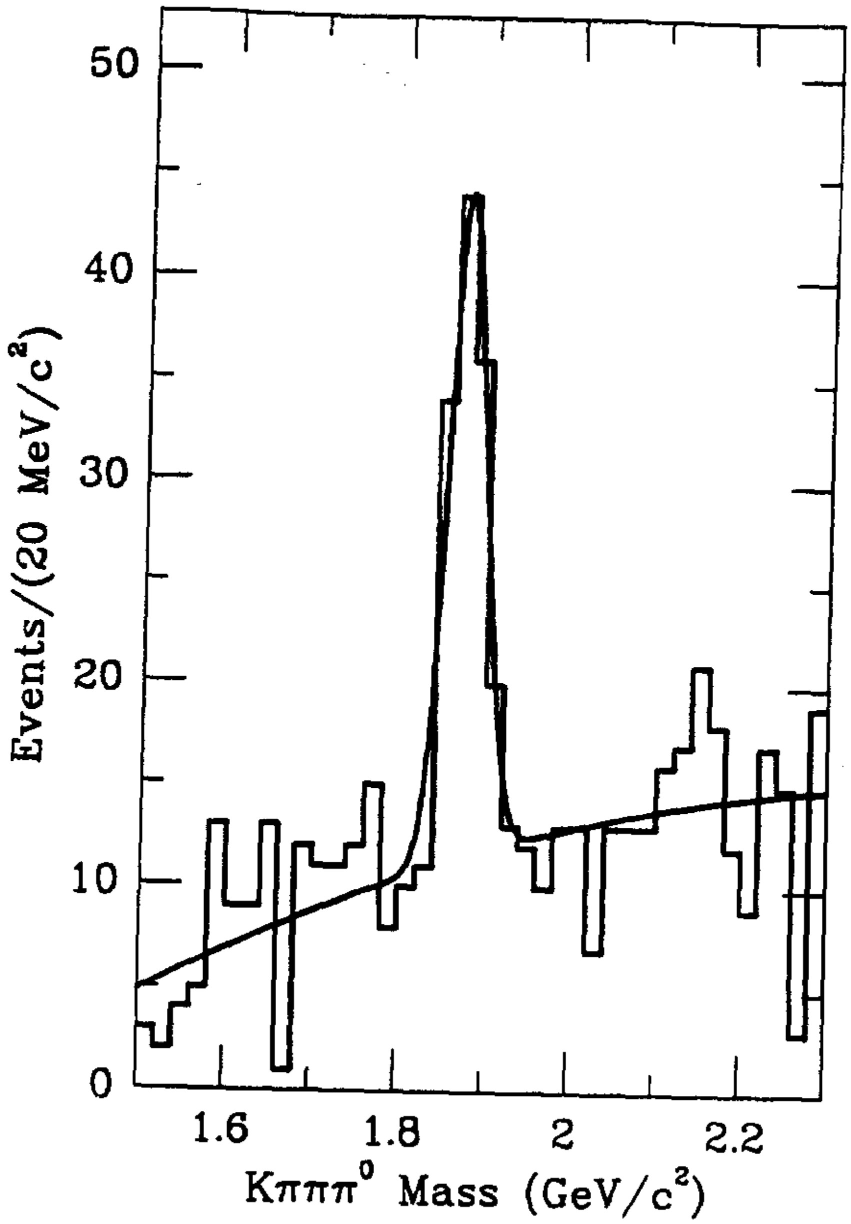


2. (a) The $\pi^+\pi^-\pi^+$ mass spectrum from a Monte Carlo simulation of $D_s^+ \to \eta\pi^+$ decay. (b) The $\pi^+\pi^-\pi^+$ mass spectrum used in the missing-π^0 search for $D_s^+ \to \eta\pi^+$. The peak near 1.87 GeV corresponds to the decay $D^+ \to \pi^+\pi^-\pi^+$.[8]



3. The $K^+K^-\pi^+\pi^0$ mass spectra for (a) non-ϕ and (b) ϕ final states.



4. The $K^-\pi^+\pi^+\pi^o$ mass spectrum.