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PRELIMINARY RESULTS FOR TWO-PION RESONANCES IN D^+ AND $D_S^+ \to \pi^-\pi^+\pi^+$ FROM FERMILAB EXPERIMENT E-791 *

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In this paper we present preliminary results of a coherent amplitude analysis of three-pion decays of charm mesons. The analysis includes a greater number of possible resonant states than in previous analyses, and produces masses and Breit–Wigner widths of the isoscalar resonances $f_0(980)$ and $f_0(1370)$ with better precision than previous measurements. We also present preliminary results for the mass and width of the low lying $f_0(400)$, sometimes called the σ meson.

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1. Introduction

E-791 was a fixed-target experiment that ran in a negative 500 GeV/c pion beam in 1991/92 at Fermilab [1]. The beam impinged on a series of platinum and carbon targets. The spectrometer consisted of both wire chambers and silicon microstrip detectors upstream and downstream of the targets, two magnets, 35 drift chamber planes, two Čerenkov counters, electromagnetic and hadron calorimeters and two planes of scintillation counters behind thick absorbers. The experiment accumulated 50 terabytes of data, 2×10^{10} events, and reconstructed over 200 000 golden mode charm events. For the results presented in this paper, only tracking and vertex information were used in the data analysis.

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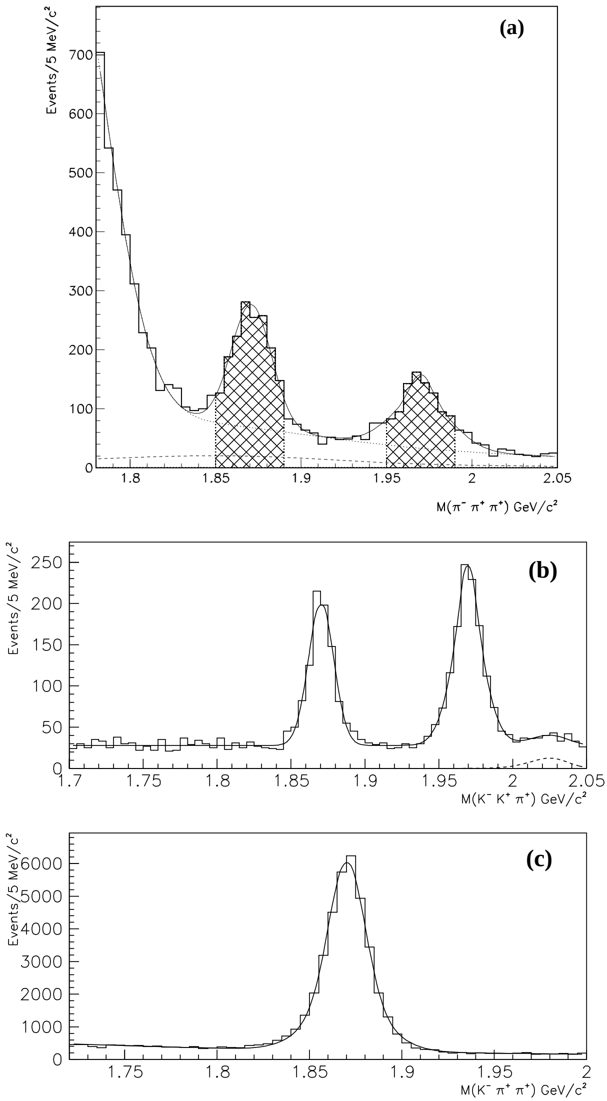

Fig. 1. (a) — the three-pion mass distribution shows clear D^+ and D_s^+ peaks. The cross-hatched areas show the signal data used in the Dalitz-plot analysis. The dashed lines show backgrounds from $D_s^+ \to \eta'\pi$ and $D^0 \to K^-\pi^+$ discussed in the text. (b) — the $D_s^+ \to \varphi\pi^+$ signal is seen as the second peak to the right of the plot. (c) — he $D^+ \to K^-\pi^+\pi^+$ signal. The normalization signals are based on the distributions in (b) and (c).

In this paper we present the sample of charm mesons that decay into $\pi^-\pi^+\pi^+$ modes, and the subsequent subchannel Dalitz-plot analysis. Motivated by a desire to gain a better understanding of low mass two-pion states [2], we study the three-pion distributions in both D^+ and D_s^+ events to search for two-pion resonances. The sample of events used in this analysis is displayed in Fig. 1.

Recently, calculations on the lattice have given some insight into the possible structure of four quark states [3]. In particular, the $f_0(980)$, seen in our analysis is proposed as a candidate for the non-exotic $q^2\overline{q}^2$ bound state. The f_0 mesons have also at times been thought to be $q\overline{q}$ states, glueballs, multiquark states, or $K\overline{K}$ molecules [4].

2. Branching ratio analysis

We begin the analysis of these three-pion decay modes with the branching ratios. These are measured by comparing the three pi signals to more copious D^+ and D_s^+ decays. The normalization signals are taken from the $D^+ \to K^-\pi^+\pi^+$ and $D_s^+ \to \varphi\pi^+$ modes respectively, also shown in Fig. 1.

The signal events are identified by event topology and momentum conservation. The decay vertex must be at least 8σ from the production vertex. There are no Čerenkov cuts. In Table I we give the size of the event sample for each decay mode, including the normalization signals. The resulting relative branching ratios and associated errors are also given in this table. Estimates of backgrounds and shapes are taken from data and a Monte Carlo

TABLE I

Event rates and branching ratios for D^+ and D_s^+ decays

Decay mode	Number of events	Branching ratio	Errors (stat. & syst.)
$D^+ \to \pi^-\pi^+\pi^+$	1240 ± 51	0.0329	$\pm 0.0015^{+0.0016}_{-0.0026}$
$D^+ \to K^-\pi^+\pi^+$	35400 ± 356		
$D_s^+ \to \pi^-\pi^+\pi^+$	858 ± 49	0.247	$\pm 0.028^{+0.019}_{-0.012}$
$D_s^+ \to \varphi\pi^+$, $\varphi \to K^+K^-$	1038 ± 44		

model. As can be seen in the distribution shown on the left of Fig. 1, the $D^+ \to K^-\pi^+\pi^+$ reflection produces a high mass tail that lies under the signal peaks. The $D^0 \to K^-\pi^+$ associated with an uncorrelated $\pi^\pm$ adds to this background. There are also combinatorial backgrounds with no charm vertex. Finally, the η' decay in which the subsequent [γ] is missed, forms a troublesome 3π background, which has a ρ in the final state.

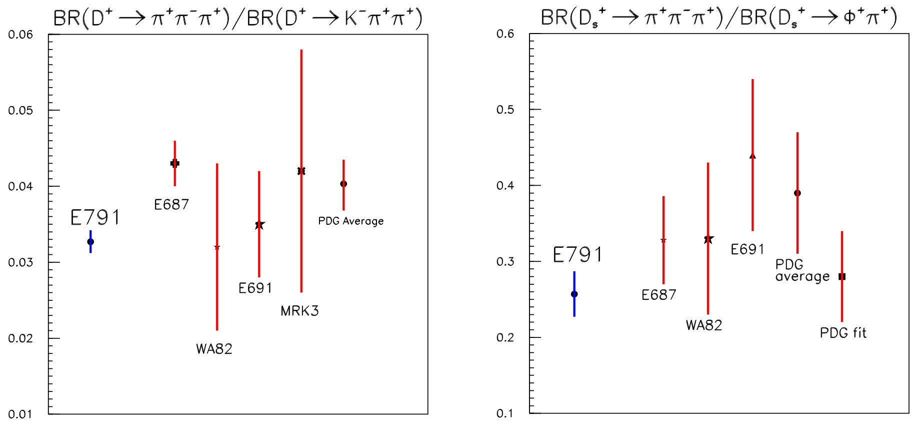

Fig. 2. Relative ranching ratios for charm meson decay as measured by E-791, compared to previous measurements and PDG values.

Part of the protocol for the branching ratio analysis requires that the same cuts be applied to both the signal and normalization events. Relative efficiencies are derived from a full E-791 Monte Carlo simulation, corrected for production x_F, p_{T}^2 distributions and resonant decay structure. Systematic uncertainty is estimated using varied cuts and fit functions.

The results are given in Table I. In Fig. 2 we compare to previous experiments. In particular, we can see that these measurements have smaller uncertainties than the current PDG values [4]. Our result for the BR$(D^+ \to \pi^-\pi^+\pi^+)/(D^+ \to K^-\pi^+\pi^+)$ has a two σ difference relative to that of Fermilab experiment E-687.

3. Resonant subchannel analysis

The resonant subchannel analysis is an analysis of Dalitz-plot distributions, taken as the coherent sum of amplitudes which lead to such distributions as

shown in Fig. 3. These figures show the distribution in the decay phase space for each relevant $\pi\pi$ resonance. These distributions are also Bose symmetrized, insofar as each mass is plotted twice, once for each $\pi^-\pi^+$ combination. From the figure, we see that the distributions are simplest for the spin zero states, and increase in complexity as the spin increases.

3.1. $D_s^+ \to \pi^-\pi^+\pi^+$

On the left of Fig. 4 we show the Dalitz-plot for $D_s^+ \to \pi^-\pi^+\pi^+$. The distribution has several outstanding features: there is a remarkable concentration of events at $s_{12} + s_{23}$ greater than 3.5 GeV^2. The bands corresponding to the $f_0(980)$ are clearly seen, and there is little if any non-resonant contribution.

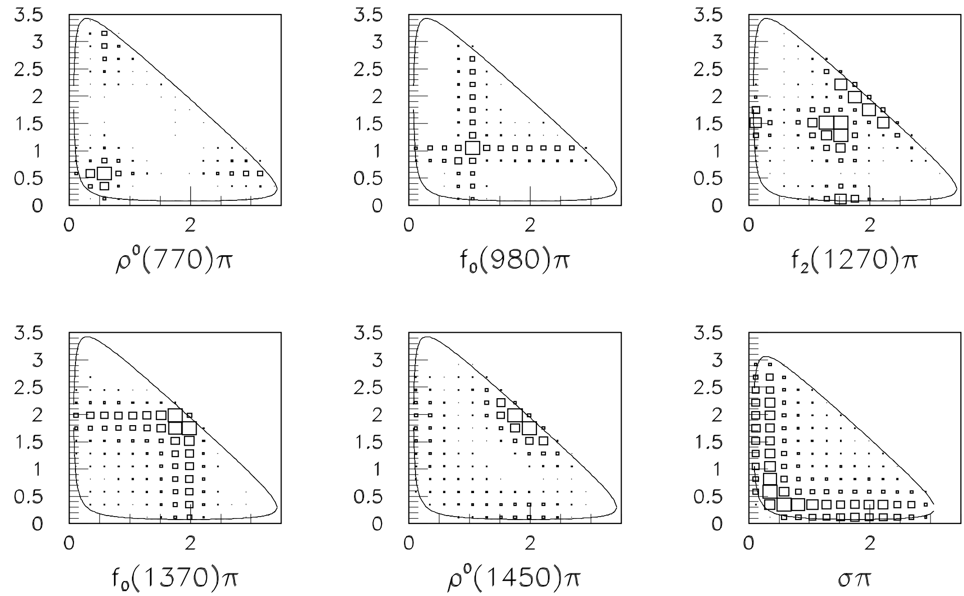

Fig. 3. Anticipated Dalitz-plot distributions for two-pion resonant states

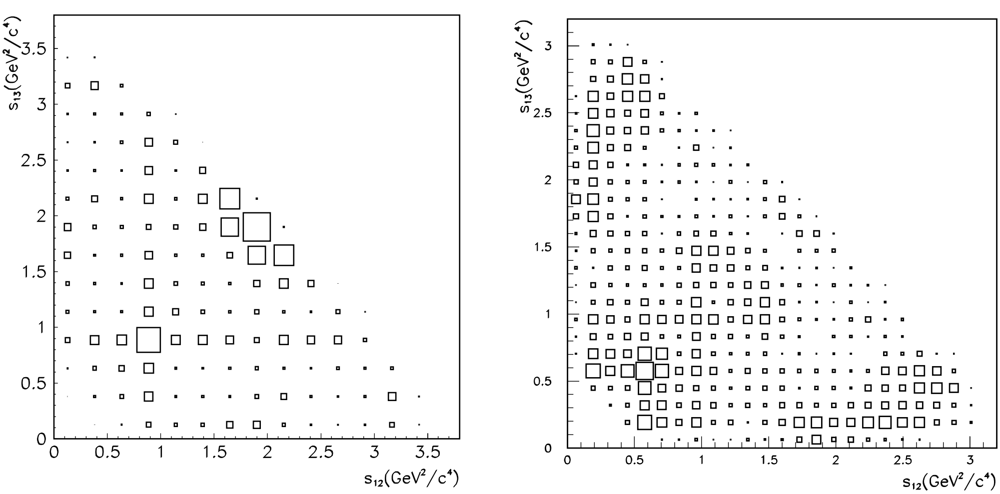

Fig. 4. Left: Dalitz-plot of data for $D_s^+ \to \pi^-\pi^+\pi^+$. Right: Dalitz-plot of data for $D^+ \to \pi^-\pi^+\pi^+$. Since there are two identical particles, the distributions have been symmetrized.

The amplitudes (a_j), phases (δ_j) and fit fractions (f_j) are given in Table II, and are defined by the relation:

$$f_j = \frac{\int ds_{12} ds_{23} \left| a_j e^{i\delta_j} \mathcal{A}_| \right|^2}{\int ds_{12} ds_{23} \left| \sum_k a_k e^{i\delta_k} \mathcal{A}_{||} \right|^2} .$$

We can see clearly the dominance of the $f_0(980)$, with substantial contribution from $f_0(1370)$. The sum of the f_j is 120%, indicating considerable interference between the resonant states. The $\rho^0(770)\pi^\pm$ has a significant

TABLE II

Amplitude, phase and fit fraction for the $D_s^+ \to \pi^-\pi^+\pi^+$ decays

Mode	Amplitude a_j	Phase δ_j (degrees)	Fraction f_j %
$f_0(980)\pi^+$	1(fixed)	0(fixed)	53.4 ±4.1 ±4.7
NR	0.11 ±0.14 ±0.04	172 ±77 ±51	0.6 ±1.6 ±1.7
$\rho^0(770)\pi^+$	0.37 ±0.07 ±0.19	97 ±22 ±5	7.2 ±2.4 ±3.7
$f_2(1270)\pi^+$	0.62 ±0.06 ±0.02	124 ±17 ±28	20.7 ±3.4 ±0.6
$f_0(1370)\pi^+$	0.79 ±0.11 ±0.03	193 ±19 ±27	33.3 ±7.5 ±1.9
$\rho^0(1450)\pi^+$	0.29 ±0.08 ±0.01	146 ±23 ±17	4.6 ±2.4 ±0.2

signal (5σ in amplitude and 3σ in fit fraction.) The $\rho^0(1450)\pi^\pm$ has a small but significant amplitude (2σ) and fit fraction (3σ). This combination of f_0 and ρ^0 states in $D_s^+ \to \pi^-\pi^+\pi^+$, when combined with the same modes for D^+ decay, and other modes such as to $K^-K^+\pi^+$ in charm meson decay, should lead to an understanding of the composition of these resonances and possible contributions of W-annihilation and final state interactions to these decays.

3.2. $D^+ \to \pi^-\pi^+\pi^+$

To the right of Fig. 4 we give the Dalitz-plot distribution for the $D^+ \to \pi^-\pi^+\pi^+$ decay mode. In this distribution we see significant evidence for a strong p-wave contribution at the $\rho^0(770)\pi^\pm$, unlike the D_s^+ Dalitz-plot. We also see an excess of events along the horizontal and vertical boundaries, $s_{12} < 0.3$ (GeV/c)^2. Angular distributions and interference make $f_2(1270)$, $f_0(1370)$ and 3π (NR) less obvious, but clearly indicated.

In Table III are given the results of the fit for $D^+ \to \pi^-\pi^+\pi^+$ decays. It is clear that the $\sigma\pi^+$ state dominates, and that the non-resonant decay is small. The $\rho^0(1450)\pi^+$ is small when compared to $\rho^0(770)\pi^+$. The sum of the fit fractions is about 114% indicating again significant interference among

TABLE III

Amplitude, phase and fit fraction for the $D^+ \to \pi^-\pi^+\pi^+$ decays

Mode	Amplitude a_j	Phase δ_j (degrees)	Fraction f_j %
$\sigma\pi^+$	1.21 ±0.14 ±0.06	205.7 ±12.6 ±5.20	44.3 ±9.4 ±2.1
$\rho^0(770)\pi^+$	1(fixed)	0(fixed)	30.5 ±3.1 ±2.2
NR	0.57 ±0.19 ±0.09	74.5 ±17.8 ±5.8	9.9 ±7.0 ±2.7
$f_0(980)\pi^+$	0.46 ±0.05 ±0.02	163.3 ±10.3 ±3.2	6.6 ±1.3 ±0.4
$f_2(1270)\pi^+$	0.79 ±0.06 ±0.03	53.3 ±7.4 ±2.6	18.9 ±2.5 ±0.4
$f_0(1370)\pi^+$	0.29 ±0.09 ±0.03	107.1 ±17.8 ±4.7	2.5 ±1.5 ±0.8
$\rho^0(1450)\pi^+$	0.19 ±0.09 ±0.02	339.2 ±27.5 ±11.0	1.1 ±1.0 ±0.3

amplitudes. The phase difference between the $f_0(980)$ and the $f_2(1270)$ is about 110°, consistent with that found in the $D_s^+ \to \pi^-\pi^+\pi^+$ decay (124°).

4. Masses and widths

Three of the resonances used in our analysis have only poorly defined masses and widths in the PDG listings, so in our Dalitz-plot fits we allowed these to be free parameters.

From the $D_s^+ \to \pi^-\pi^+\pi^+$ events we determined the mass and width of the $f_0(980)$ to be 978 ± 4 MeV and 44 ± 5 MeV respectively, compared to the PDG values of 980 ± 10 MeV and 40 to 100 MeV for the width. We also determined the mass and width of the $f_0(1370)$ to be 1440 ± 19 MeV and 165 ± 29 MeV respectively, compared to the PDG values of 1200 to 1500 MeV for the mass, and 200 to 500 MeV for the width.

With the $D^+ \to \pi^-\pi^+\pi^+$ events we determined the mass and width of the σ resonance to be $= 486^{+28}_{-26}$, and 351^{+50}_{-43}, respectively, compared to PDG values of 400 to 1200 MeV and 600 to 1000 MeV respectively.

For the $f_0(980)$ a coupled channel analysis was performed as suggested by WA76 [5]. The fit gave the values m_0=978±5 MeV/c^2, $g_\pi = 0.083 \pm 0.022$ and $g_K = -0.03 \pm 0.03$. These values are much smaller than the WA76 results, $g_\pi = 0.28 \pm 0.04$ and $g_K = 0.56 \pm 0.18$. Our value of g_K is consistent with zero, indicating that our $f_0(980)$ can be represented by a single Breit–Wigner.

5. Is the σ an s-wave BW resonance?

Three variations of the D^+ analysis were done to determine the nature of the σ resonance. One fit was carried out using a BW profile with no phase variation, which gave a poorer fit to the Dalitz-plot distribution. Also, fits to vector and tensor BW distributions gave significantly poorer fits. The s-wave Breit–Wigner provides the best fit to the Dalitz-plot distribution, and in this sense the data favor the s-wave resonant solution.

6. Conclusions

Three of the resonances used in our analysis show sufficiently strong signals that we can allow free parameters for the masses and widths in our Dalitz-plot fits. We therefore can improve on the current PDG values for these resonances. The mass and widths are given in Section 4.

For the σ resonance, values of χ^2/DF were calculated for various BW shapes, including a vector, tensor, and a model that allowed for no phase change across the resonance. These gave inferior fits to the data when compared to the isoscalar BW for the σ. These analyses strongly support the identification of the σ as an isoscalar resonance.

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