Study of the $D_s^+ \to \pi^-\pi^+\pi^+$ decay and measurement of f_0 masses and widths.

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From a sample of 848 $\pm$ 44 $D_s^+ \to \pi^-\pi^+\pi^+$ decays, we find $\Gamma(D_s^+ \to \pi^-\pi^+\pi^+)/\Gamma(D_s^+ \to \phi\pi^+) = 0.245 \pm 0.028^{+0.019}_{-0.012}$. Using a Dalitz plot analysis of this three body decay, we find significant contributions from the channels $\rho^0(770)\pi^+$, $\rho^0(1450)\pi^+$, $f_0(980)\pi^+$, $f_2(1270)\pi^+$, and $f_0(1370)\pi^+$. We also present the values obtained for masses and widths of the resonances $f_0(980)$ and $f_0(1370)$.

The charm meson decay $D_s^+ \to \pi^-\pi^+\pi^+$ and its charge conjugate (implicit throughout this paper) is Cabibbo-favored but has no strange meson in the final state. The decay can proceed via spectator amplitudes, producing intermediate resonant states with hidden strangeness, e.g. $D_s^+ \to f_0(980)\pi^+$, with $s\bar{s}$ quarks in the $f_0(980)$. Also, the decay can proceed via W-annihilation amplitudes, producing intermediate states with no strangeness, e.g. $D_s^+ \to \rho^0\pi^+$. A W-annihilation amplitude could also produce the intermediate state $D_s^+ \to f_0(1370)\pi^+$, assuming the $f_0(1370)$ consists mostly of $u\bar{u}$ and $d\bar{d}$ quarks as predicted by the simple quark model [1]. To determine the relative importance of these different decay mechanisms, one can use an amplitude analysis. Such an analysis is also able to determine the masses and decay widths of the intermediate states.

In general, scalar resonances have large decay fractions in the 3-body decays of D-mesons, and such decays provide a relatively clean laboratory in which to study the properties of the scalars. In particular, isoscalar intermediate states are dominant in $D_s^+ \to \pi^-\pi^+\pi^+$ decays [2,3]. The largest contribution to this final state comes from the decay involving the scalar meson $f_0(980)$ whose nature is a long-standing puzzle. It has been described as a $q\bar{q}$ state , a $K\bar{K}$ molecule, a glueball, and a 4-quark state [4].

In this paper we extend the reach of previous studies using the larger data sample from Fermilab experiment E791. We present an amplitude analysis which includes a greater number of possible resonant states, and we measure the masses and widths of the scalar resonances $f_0(980)$ and $f_0(1370)$ with improved precision. Taken together with the results of the companion analysis [5], these results provide new insight into the characteristics of scalar mesons and their importance in charm meson decay.

The data were produced by 500 GeV/c π^- interactions in five thin foils (one platinum, four diamond) separated by gaps of 1.34 to 1.39 cm. The detector, the data set, the reconstruction, and the resulting vertex resolutions have been described previously [6]. After reconstruction, events with evidence of well-separated production (primary) and decay (secondary) vertices were retained for further analysis. For this analysis all charged particles are taken to be pions; i.e., no direct use is made of particle identification.

We require a candidate's secondary vertex position to be cleanly separated from the event's primary vertex position and from the closest target material. The sum of the momentum vectors of the three tracks from this secondary vertex must point to the primary vertex. The candidate's daughter tracks must pass closer to the secondary vertex than to the primary vertex, and must not point back to the primary vertex. The resulting invariant mass spectrum is shown in Figure 1.

We fit the spectrum of Figure 1 as the sum of D^+ and D_s^+ signals plus background. To account for the signal's non Gaussian tails, we model each signal as the sum of two Gaussian distributions with the same centroid but different widths. We model the background as the sum of four components: a general combinatorial background, the reflection of the $D^+ \to K^-\pi^+\pi^+$ decay, reflections of $D^0 \to K^-\pi^+$ plus one extra track (mostly from the primary vertex), and $D_s^+ \to \eta'\pi^+$ followed by $\eta' \to \rho^0(770)\gamma$, $\rho^0(770) \to \pi^+\pi^-$. The $D^+ \to K^-\pi^+\pi^+$ reflection is located below 1.85 GeV/c^2 in the $\pi^-\pi^+\pi^+$ spectrum. The other charm backgrounds populate the whole $\pi^-\pi^+\pi^+$ spectrum. We use Monte Carlo (MC) simulations to determine the shape of each identified charm background in the $\pi^-\pi^+\pi^+$ spectrum. We assume that the combinatorial background falls exponentially with mass. The levels of $D^0 \to K^-\pi^+$ and $D_s^+ \to \eta'\pi^+$ backgrounds are determined using charm signal rates measured in our total event sample and branching ratios taken from the compilation by the Particle Data Group [1]. The parameters describing the combinatorial background and the level of the $D^+ \to K^-\pi^+\pi^+$ reflection are determined from fitting the $\pi^-\pi^+\pi^+$ distribution. The mass (centroid) and both Gaussian widths for each signal float in our fit. The fit converges to 1172 ± 61 D^+ events and 848 ± 44 D_s^+ events. The D_s^+ signal is used for the measurement of the decay rate $\Gamma(D_s^+ \to \pi^-\pi^+\pi^+)$ relative to $\Gamma(D_s^+ \to \phi\pi^+)$ and for an amplitude analysis of the D_s^+ Dalitz plot.

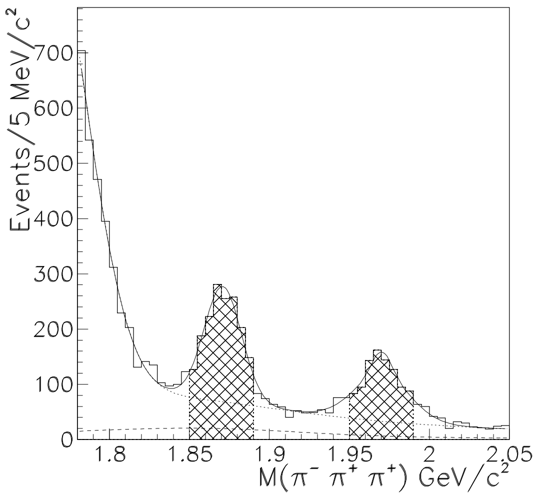

FIG. 1. The $\pi^-\pi^+\pi^+$ effective-mass spectrum. The dotted line represents the $D^0 \to K^-\pi^+$ plus $D_s^+ \to \eta'\pi^+$ and the dashed line is the total backgound. Events in the hatched areas at the D_s mass are used for the D_s Dalitz plot analysis in this Letter. The hatched area at the D^+ mass is used for the analysis in the following companion paper [5].

To minimize systematic effects when calculating the ratio of efficiencies, we select the $D_s^+ \to \phi\pi^+$, $\phi \to K^-K^+$ signal using the same track and vertex quality criteria as for the $D_s^+ \to \pi^-\pi^+\pi^+$ decay. The number of normalization events is found to be 1038 ± 44.

We use MC simulations to correct for geometrical acceptance and detector efficiency. We measure a ratio of efficiencies $\varepsilon(D_s^+ \to \pi^-\pi^+\pi^+)/\varepsilon(D_s^+ \to \phi\pi^+) = 1.64 \pm 0.15$ with values $\varepsilon(D_s^+ \to \pi^-\pi^+\pi^+)$ and $\varepsilon(D_s^+ \to \phi\pi^+)$ of about 2% and 1%, respectively.

The branching fraction for $D_s^+ \to \pi^-\pi^+\pi^+$ relative to that for $D_s^+ \to \phi\pi^+$ is measured to be:

$$\frac{B(D_s^+ \to \pi^-\pi^+\pi^+)}{B(D_s^+ \to \phi\pi^+)} = 0.245 \pm 0.028^{+0.019}_{-0.012} . \qquad (1)$$

The first error is statistical. The second is systematic, and is dominated by uncertainties related to the signal and background shapes used in the fit, the background levels, the sample selection criteria, and by uncertainties in the MC model of D production. This value is smaller than the other experimental results: E691 [2] found $0.44\pm0.10\pm0.04$, WA82 [7] quoted $0.33\pm0.10\pm0.04$ and E687 [3] presented $0.33 \pm 0.058 \pm 0.058$. The PDG [1] presents a value of 0.28 ± 0.06 from a constrained fit.

The symmetrized Dalitz plot of the 937 candidates with invariant mass between 1.95 and 1.99 GeV/c^2 is shown in Fig. 2. The integrated signal to background ratio is ≈ 2. The narrow horizontal and vertical bands of $s_{12} \equiv m^2(\pi_1^-\pi_2^+)$ and $s_{13} \equiv m^2(\pi_1^-\pi_3^+)$ just below 1 GeV$^2/c^4$ correspond to the $f_0(980)\pi^+$ state with constructive quantum-mechanical interference where the two bands overlap. At the upper edge of the diagonal, there is another concentration of events centered at $s_{12} \simeq s_{13} \simeq 1.8$ GeV$^2/c^4$, corresponding to the $f_2(1270)\pi^+$, $f_0(1370)\pi^+$, and $\rho^0(1450)\pi^+$.

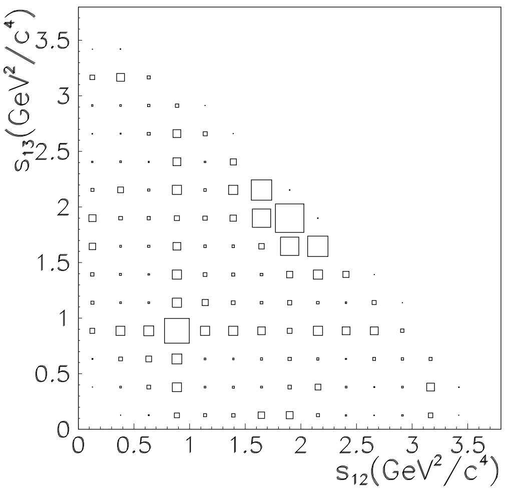

FIG. 2. The $D_s^+ \to \pi^-\pi^+\pi^+$ Dalitz plot. Since there are two identical particles, the plot is symmetrized.

We fit the distribution shown in Figure 2 to a signal probability distribution function (PDF), which is a coherent sum of amplitudes corresponding to the non-resonant decay plus five different resonant channels, and a background PDF of known shape and magnitude.

We weight the signal PDF by the acceptance across the Dalitz plot and use the measured line shape and background to determine the ratio of expected signal to background for each event in the Dalitz plot.

We assume the non-resonant amplitude to be uniform across the Dalitz plot. Each resonant amplitude, except that for the $f_0(980)$, is parameterized as a product of form factors, a relativistic Breit-Wigner function, and an angular momentum amplitude, described in the companion paper [5].

For the $f_0(980)\pi^+$ we use a coupled-channel Breit-Wigner function,

$$BW_{f_0(980)} = \frac{1}{m_{\pi\pi}^2 - m_0^2 + i m_0(\Gamma_\pi + \Gamma_K)} , \qquad (2)$$

with

$$\Gamma_\pi = g_\pi \sqrt{m_{\pi\pi}^2/4 - m_\pi^2} \qquad (3)$$

and

$$\Gamma_K = \frac{g_K}{2} \left(\sqrt{m_{\pi\pi}^2/4 - m_{K^+}^2} + \sqrt{m_{\pi\pi}^2/4 - m_{K^0}^2} \right) . \qquad (4)$$

We multiply each amplitude by a complex coefficient, $c_j = a_j e^{\delta_j}$. The fit parameters are the magnitudes, a_j, and the phases, δ_j, which accomodate the final state interactions. They are determined by the maximum-likelihood method.

Monte Carlo simulations are used to determine the shape and location of the $D^0 \to K^-\pi^+$ background in the Dalitz plot. The amount of the D^0 background is determined using both MC simulations and data. The contribution of the $D_s^+ \to \eta'\pi^+$ background is negligible. The background proportions are $12 \pm 2\%$ for $D^0 \to K^-\pi^+$ and $88 \pm 2\%$ for the combinatoric across the Dalitz plot. Verification of the background model is described in the companion paper [5].

The parameters of the $f_0(980)$ state, g_π, g_K, and m_0, as well as the mass and width of the $f_0(1370)$, are determined directly from the data, floating them as free parameters in the fit. The other resonance masses and widths are taken from the PDG [1]. The results of the D_s^+ Dalitz plot fit are shown in Table I. The column labeled Fit A corresponds to our best fit with all six modes. The measured values $m_0 = 977 \pm 3 \pm 2$ MeV/c^2, $g_\pi = 0.09 \pm 0.01 \pm 0.01$ and $g_K = 0.02 \pm 0.04 \pm 0.03$ have been corrected for small shifts in these parameters due to the $\pi^-\pi^+$ mass resolution in this region. This resolution is estimated to be approximately 9 MeV/c^2. We determine the shifts by folding a 9 MeV/c^2 resolution together with various g_K, g_π combinations and fitting the resulting distributions to the form in Eqns. (4)-(6).

The resolution was found to shift m_0, g_K, and g_π by -1.4 MeV, $+0.06$ and -0.006 respectively. These shifts have been included in the values quoted above and in Table I. Uncertainties in our resolution contribute to the systematic uncertainties. Our value for g_π is in very good agreement with OPAL [8] and MARKII [9] results, but WA76 [10] found a much larger value, $g_\pi = 0.28 \pm 0.04$. The values of the $f_0(980)$ mass and of g_π, as well as the magnitudes and phases of the resonant amplitudes, are relatively insensitive to the value of g_K. Both OPAL and MARKII results are also insensitive to the value of g_K. WA76, on the contrary, measured $g_K = 0.56 \pm 0.18$.

We have also fit the Dalitz plot using for the $f_0(980)$ the same Breit-Wigner function as for the other resonances. The resulting fit is nearly as good as the one using the coupled-channel Breit-Wigner function, and the fractions and phases are indistinguishable. With this parameterization we find $m_0 = 975 \pm 3$ MeV/c^2 and $\Gamma_0 = 44 \pm 2 \pm 2$ MeV/c^2, also shifted by the effect of mass resolution. For the $f_0(1370)$ we find $m_0 = 1434 \pm 18$ MeV/c^2 and $\Gamma_0 = 173 \pm 32$ MeV/c^2.

Table I shows the magnitudes (a_j) and phases (δ_j) determined from the fit, and corresponding fraction for each decay mode. The fractions are defined as

$$f_j \equiv \frac{\int ds_{12} ds_{13} \mid c_j \mathcal{A}_j \mid^2}{\int ds_{12} ds_{13} \sum_{jk} \mid c_j \mathcal{A}_j c_k^* \mathcal{A}_k^* \mid} . \tag{5}$$

The first reported error is statistical and the second is systematic, the latter being dominated by the uncertainties in the resonance parameters, in the background parameterization, and in the acceptance correction. The $f_0(980)\pi^+$ is the dominant component, accounting for nearly half of the $D_s^+ \to \pi^-\pi^+\pi^+$ decay width, followed by the $f_0(1370)\pi^+$ and $f_2(1270)\pi^+$ components. The contribution of $\rho^0(770)\pi^+$ and $\rho^0(1450)\pi^+$ components corresponds to about 10% of the $\pi^-\pi^+\pi^+$ width. We have not found a statistically significant non-resonant component. The s_{12} and s_{13} projections are nearly independent and the sum of the two is shown in Fig. 3 for Fit A.

To assess the quality of our fit absolutely, and to compare it with other possible fits, we developed a fast-MC algorithm that simulates the $D_s^+ \to \pi^-\pi^+\pi^+$ Dalitz plot from a given signal distribution, background, detector resolution and acceptance. For any given set of input parameters we calculated a χ^2 using the procedure presented in Ref. [5]. From χ^2 and the number of degrees of freedom (ν), we calculate a confidence level assuming a Gaussian distribution in χ^2/ν. The confidence level for the agreement of the projection of Fit A onto the Dalitz plot with the data of Fit A is 35%.

We perform fits excluding amplitudes with small contributions. The fit without the non-resonant amplitude is as good as Fit A, and the resulting parameters are essentially the same. When comparing Fit A with models without the $\rho^0\pi^+$ amplitudes (Table 1) we calculate $\Delta w = -2(\ln\mathcal{L}_i - \ln\mathcal{L}_A)$, where $\mathcal{L}_A$ is the likelihood of the fit with all modes, and $\mathcal{L}_i$ is the likelihood of the different models, as described in the companion paper [5]. For the model where we exclude the $\rho^0(770)\pi^+$ amplitude we have, for data, $\Delta w = 20$. In the fast-MC with all modes we have $\langle\Delta w\rangle = 37$. In the fast-MC with no $\rho^0(770)\pi^+$ we have $\langle\Delta w\rangle = -29$. We observe a similar behavior in Fit C, where we exclude the $\rho^0(1450)\pi^+$ amplitude, we have $\Delta w = 32$. In the fast-MC with all modes we have $\langle\Delta w\rangle = 30$ while with the fast-MC with no $\rho^0(1450)\pi^+$ $\langle\Delta w\rangle = -30$. In all fast-MC experiments the rms deviation for $\langle\Delta w\rangle$ is about 11 units. We conclude that the best description of our data includes both $\rho^0(770)\pi^+$ and $\rho^0(1450)\pi^+$ amplitudes.

We have also performed a fit allowing for a possible $f_0(1500)\pi^+$ channel. The contribution from this mode is negligible.

The contribution of modes having isoscalar mesons completely dominates the $D_s^+ \to \pi^-\pi^+\pi^+$ decay. The same isoscalar dominance is observed in the $D^+ \to \pi^-\pi^+\pi^+$ decay [5]. However, there is no evidence in the D_s^+ decay for a low-mass broad scalar particle as seen in the D^+ decay. If the $D_s^+ \to \pi^-\pi^+\pi^+$ decay is dominated by the Cabibbo-favored spectator mechanism, we would expect final states with a large $s\bar{s}$ content. Approximately half of the $D_s^+ \to \pi^-\pi^+\pi^+$ rate is produced via $f_0(980)\pi^+$. The $f_0(980)$ is often supposed to have a large $s\bar{s}$ component, indicating a large spectator amplitude in this decay. On the other hand, the large contribution from the intermediate state $f_0(1370)\pi^+$ indicates the presence of either W-annihilation amplitudes or strong rescattering in the final state. In fact this decay is not observed in the $D_s^+ \to K^+K^-\pi^+$ final state [11], pointing to the $f_0(1370)$ being a non-$s\overline{s}$ particle, as suggested by the naive quark model [1].

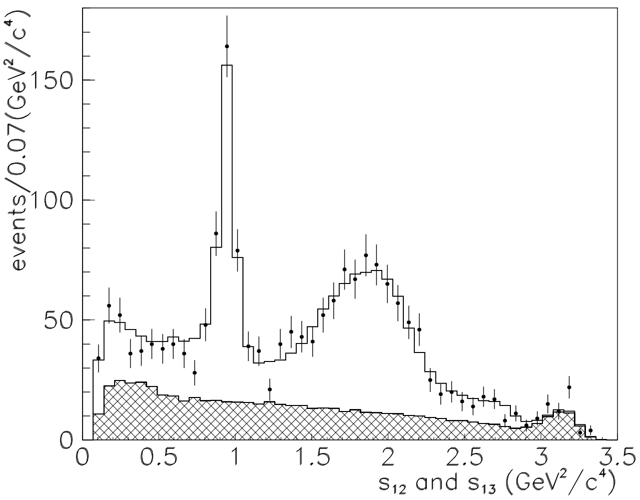

FIG. 3. s_{12} and s_{13} projections for data (dots) and Fit A (solid). The hashed area is the background distribution.

In summary, Fermilab experiment E791 has measured the branching ratio of the decay $D_s^+ \to \pi^-\pi^+\pi^+$ relative to $D_s^+ \to \phi\pi^+$ to be $0.245 \pm 0.028^{+0.019}_{-0.012}$. We measure the mass and width of the $f_0(980)$ and $f_0(1370)$. Our results for the $f_0(980)$ parameters are $g_\pi = 0.09 \pm 0.01 \pm 0.01$, $g_K = 0.02 \pm 0.04 \pm 0.03$, and $m_0 = 977 \pm 3 \pm 2$ MeV/c^2. Using the same Breit-Wigner function for the $f_0(980)$ as for the other resonances, we find $\Gamma_0 = 44 \pm 2 \pm 2$ MeV/c^2 and $m_0 = 975 \pm 3$ MeV/c^2. For the $f_0(1370)$ we find $m_0 = 1434 \pm 18 \pm 9$ MeV/c^2 and $\Gamma_0 = 173 \pm 32 \pm 6$ MeV/c^2. Finally, the fit of the Dalitz plot shows a dominant contribution from the $f_0(980)\pi^+$, significant contributions from the $f_0(1370)\pi^+$ and $f_2(1270)\pi^+$, small contribution from the $\rho^0\pi^+$ channels, and a negligible non-resonant component. The isoscalar plus π^+ components correspond to over 90% of the $D_s^+ \to \pi^-\pi^+\pi^+$ decay width.

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	Fit A Fraction(%) Magnitude Phase	Fit B Fraction(%) Magnitude Phase	Fit C Fraction(%) Magnitude Phase
$f_0(980)\pi^+$	56.5 ± 4.3 ± 4.7	58.0 ± 4.9	54.1 ± 4.0
	1(fixed)	1(fixed)	1(fixed)
	0(fixed)	0(fixed)	0(fixed)
NR	0.5 ± 1.4 ± 1.7	7.5 ± 4.8	5.0 ± 3.8
	0.09 ± 0.14 ± 0.04	0.36 ± 0.12	0.30 ± 0.12
	$(181 \pm 94 \pm 51)^\circ$	$(165 \pm 23)^\circ$	$(149 \pm 25)^\circ$
$\rho^0(770)\pi^+$	5.8 ± 2.3 ± 3.7	0	11.1 ± 2.5
	0.32 ± 0.07 ± 0.19	0	0.45 ± 0.06
	$(109 \pm 24 \pm 5)^\circ$	0	$(81 \pm 15)^\circ$
$f_2(1270)\pi^+$	19.7 ± 3.3 ± 0.6	22.2 ± 3.3	20.8 ± 3.0
	0.59 ± 0.06 ± 0.02	0.62 ± 0.06	0.62 ± 0.05
	$(133 \pm 13 \pm 28)^\circ$	$(109 \pm 11)^\circ$	$(124 \pm 11)^\circ$
$f_0(1370)\pi^+$	32.4 ± 7.7 ± 1.9	30.4 ± 6.9	34.7 ± 7.2
	0.76 ± 0.11 ± 0.03	0.72 ± 0.11	0.80 ± 0.11
	$(198 \pm 19 \pm 27)^\circ$	$(156 \pm 19)^\circ$	$(159 \pm 14)^\circ$
$\rho^0(1450)\pi^+$	4.4 ± 2.1 ± 0.2	5.8 ± 2.2	0
	0.28 ± 0.07 ± 0.01	0.32 ± 0.06	0
	$(162 \pm 26 \pm 17)^\circ$	$(144 \pm 20)^\circ$	0
$m_{f_0(980)}$ (MeV/c^2)	977 ± 3 ± 2	976 ± 3	974 ± 3
g_π	0.09 ± 0.01 ± 0.01	0.10 ± 0.01	0.09 ± 0.01
g_K	0.02 ± 0.04 ± 0.03	-0.02 ± 0.04	0.04 ± 0.04
$m_{f_0(1370)}$ (MeV/c^2)	1434 ± 18 ± 9	1401 ± 19	1406 ± 15
$\Gamma_{f_0(1370)}$ (MeV/c^2)	172 ± 32 ± 6	180 ± 34	176 ± 30
χ^2/ν	71.8/68	93.0/68	103.5/68
C.L.	35%	2%	0.4%
-2 ln$\mathcal{L}_{max}$	-3204	-3184	-3172

TABLE I. Results of the D_s Dalitz plot fits. Fit A, all resonances are allowed (systematic error follows the statistical). Fit B and Fit C do not include the $\rho^0(770)\pi^+$ and $\rho^0(1450)\pi^+$ amplitudes, respectively.