Hadronic Decays of Charm

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Abstract. Recent hadronic charm decay results from fixed-target experiments are presented. New measurements of the $D^0 \to K^-K^+K^-\pi^+$ branching ratio are shown as are recent results from Dalitz plot fits to $D^+ \to K^-K^+\pi^+$, $\pi^+\pi^-\pi^+$, $K^-\pi^+\pi^+$, $K^+\pi^-\pi^+$ and $D_s^+ \to \pi^+\pi^-\pi^+$, $K^+\pi^-\pi^+$. These fits include measurements of the masses and widths of several light resonances as well as strong evidence for the existence of two light scalar particles, the $\pi\pi$ resonance σ and the $K\pi$ resonance κ.

INTRODUCTION

Hadronic decays of charm are rich in information about QCD. For instance, the suppression of $D^0 \to \pi^+\pi^-$ relative to $D^0 \to K^-K^+$ proved the importance of final state interactions in charm decays. Also, hadronic decays give rise to the $2.5\times$ difference between the D^+ and D^0 lifetimes. Hadronic decays can provide information on relative strengths of decay diagrams (spectator, exchange, annihilation, etc.). Spectator diagrams are believed to be responsible for the vast majority of the charm decay rate. In a spectator diagram, the charm quark decays while the other quark in the meson is a spectator. By contrast, exchange and annihilation diagrams require a connection between the charm quark and the other quark in the meson and are therefore suppressed. Determining the contributions of these diagrams is an interesting open question in charm physics.

More recently, charm has been used to investigate the light resonances which are products of charm decays. Although very high statistics scattering experiments have been performed for many years to investigate these resonances, many parameters are still virtually unknown. Charm offers a unique way to investigate these resonances by nature of its low background and well defined initial state (pseudoscalar meson).

Experimentally, hadronic decays can be investigated by comparing branching ratios and by analyzing the resonant structure of multibody decays. The results presented here come from the Fermilab experiments E791 and FOCUS. E791 (FOCUS) ran in 1991 (1996–7) with a 500 GeV/c^2 π^- beam (180 GeV photon beam) on five (four) targets.

BRANCHING RATIO MEASUREMENTS

Calculations of charm *quark* decay rates via the weak interaction have been possible for many years. Unfortunately, only charm *hadron* decay rates (which are affected by the strong force) can be measured by experiments. The strong force is even more intimately involved when the charm particle decays into hadrons. Thus, deviations from the naïve weak prediction for a given decay can provide insight into the nature of the strong force.

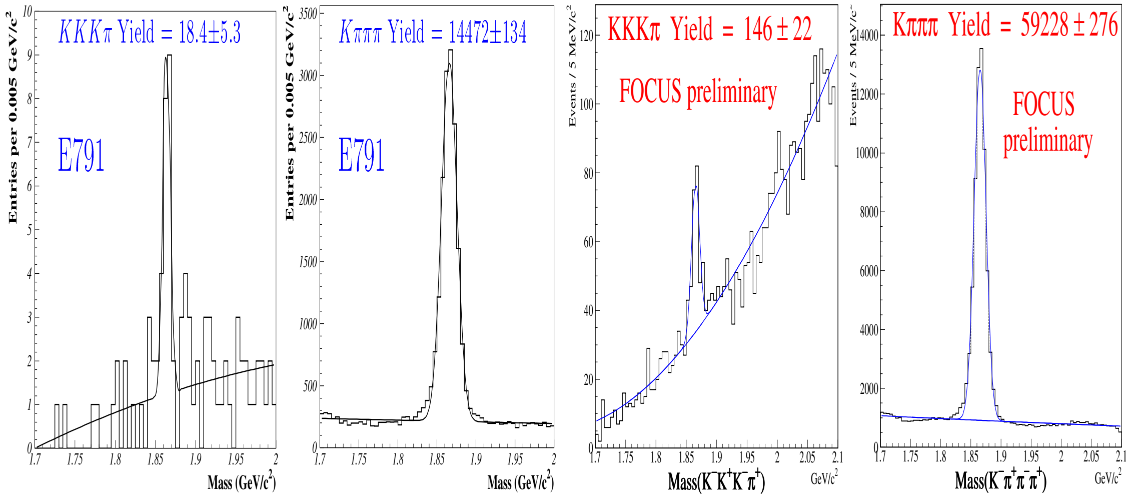

FIGURE 1. E791 and FOCUS signals from $D^0 \to K^-K^+K^-\pi^+$ and $D^0 \to K^-\pi^+\pi^-\pi^+$ decays.

$D^0 \to K^-K^+K^-\pi^+$ branching ratio

The decays $D^0 \to K^-K^+K^-\pi^+$ and $D^0 \to K^-\pi^+\pi^-\pi^+$ are both Cabibbo favored decays. A Cabibbo-favored hadronic $D^0(c\bar{u})$ decay produces one s quark from the charm, one $\bar{u}$ spectator quark, and a u and $\bar{d}$ quark from the virtual W. If both decay modes were entirely non-resonant, forming the $K^-\pi^+\pi^-\pi^+$ final state would require popping $u\bar{u}d\bar{d}$ from the vacuum while $K^-K^+K^-\pi^+$ would require $u\bar{u}s\bar{s}$ and the branching ratio between $D^0 \to K^-K^+K^-\pi^+$ and $D^0 \to K^-\pi^+\pi^-\pi^+$ could be used to determine the $s\bar{s}$ suppression relative to $d\bar{d}$. Multi-body charm decays generally proceed through resonances, however, which complicates the issue. Even in this case, one can note that the $D^0 \to K^-\pi^+\pi^-\pi^+$ decay can occur through resonances using only the four quarks from the decay, *e.g.* $\overline{K}^*(892)^0(s\bar{d})\ \rho(770)^0(u\bar{u})$, while the $D^0 \to K^-K^+K^-\pi^+$ decay requires either an $s\bar{s}$ pair from the vacuum or a final state interaction which couples $\pi\pi$ to $K\overline{K}$. The recent E791 result contains some of these speculations [1]. Signals for these two modes from E791 and FOCUS are shown in Fig. 1. E791 finds $\mathrm{BR}\left(\frac{D^0 \to K^-K^+K^-\pi^+}{D^0 \to K^-\pi^+\pi^-\pi^+}\right) = 0.0054 \pm 0.0016 \pm 0.0008$, significantly higher than the E687 measurement of $0.0028 \pm 0.0007 \pm 0.0001$ [1, 2]. The preliminary FOCUS result is much closer to the E687 result at 0.00306 ± 0.00047 (statistical error only).

DALITZ PLOT ANALYSES

Multibody decays of charm particles can occur through various strong resonances which can interfere with each other. In a three-body decay, a "Dalitz" plot can be constructed to show the effect of these resonances and their interferences by plotting the squared invariant mass of two combinations of the final state particles against each other. In the absence of interference, how a resonance appears on the Dalitz will depend on its mass and width (a relativistic Breit-Wigner) as well as on its spin (Legendre polynomials).

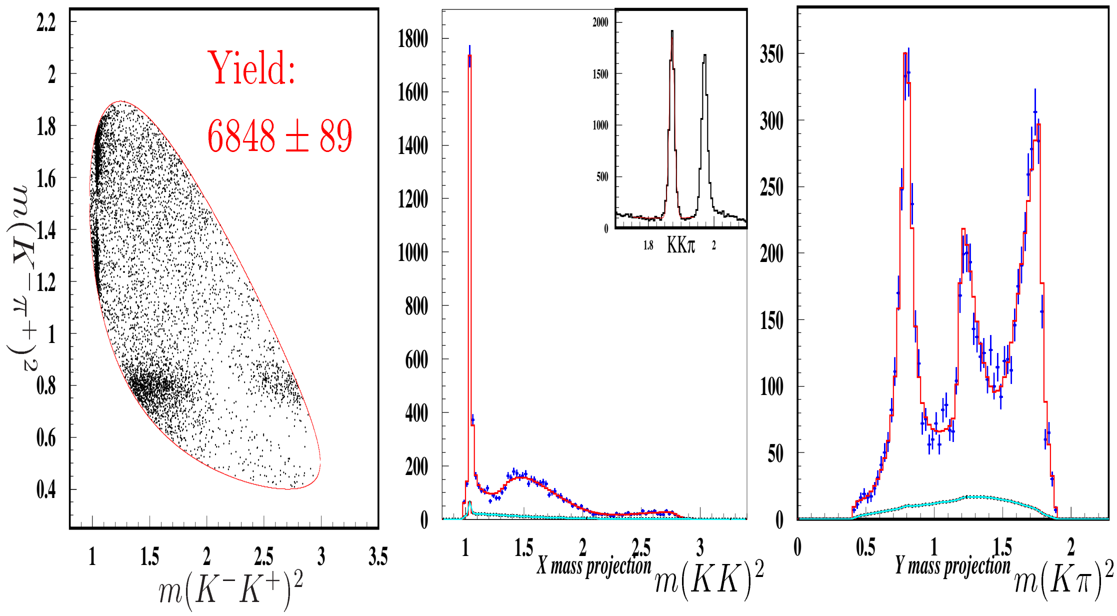

FIGURE 2. Preliminary $D^+ \to K^-K^+\pi^+$ FOCUS Dalitz plot and projections. Projections show the data background, data signal+background, and the fitted result.

Interference effects can significantly alter these shapes. Fitting a Dalitz plot to a fully coherent sum of resonances allows one to extract information about how much each resonance contributes and how each resonance interferes with other resonances. By performing a coherent Dalitz plot analysis one can extract information about weak decays and the effects of the strong force on the weak decays.

$D^+ \to K^-K^+\pi^+$ decays

FOCUS has a high statistics sample of the singly Cabibbo suppressed decay $D^+ \to K^-K^+\pi^+$. The Dalitz plot as well as projections along each axis for this mode are shown in Fig. 2. In the Dalitz plot and on the $m^2(KK)$ projection, a very clear $\phi(1020)$ can be seen. The $K^*(892)$ across the Dalitz plot and along the $m^2(K\pi)$ projection is also clear. Both contributions show a $\cos\theta$ modulation of the amplitude due to the spin-1 nature of the resonances. Distortions due to interferences are also visible. Preliminary fit results from a fully coherent analysis of the data are tabulated in Table 1. These results support the presence of significant amounts of $K^*(892)$ and $\phi(1020)$. The large contribution from the $K_0^*(1430)$ partly explains the broad enhancement at high $m^2(K\pi)$. The existance of many resonances with very different phases indicates significant interferences, as does the fact that the fit fraction sum is much greater than 100%. These interferences explain the obvious distortions seen in the Dalitz plot. Work is currently underway to investigate direct CP violation by comparing the Dalitz plots of the D^+ and D^- decays. While for two-body decays a simple branching ratio is sufficient, for multi-body modes a Dalitz plot analysis is necessary to extract all of the information on direct CP violation.

TABLE 1. Preliminary FOCUS Dalitz plot fit results for the decay $D^+ \to K^- K^+ \pi^+$. (Statistical errors only.)

Decay mode	**Fraction (%)**	**Phase (°)**
$K^*(892)K^+$	22.0 ± 1.1	0 (fixed)
$a_0(980)\pi^+$	27.8 ± 4.8	146 ± 5
$\phi(1020)\pi^+$	27.8 ± 0.9	244 ± 6
$f_2(1270)\pi^+$	0.7 ± 0.2	12 ± 7
$f_0(1370)\pi^+$	5.9 ± 1.2	60 ± 6
$K^*(1410)K^+$	8.8 ± 1.9	135 ± 6
$K_0^*(1430)K^+$	69.3 ± 6.3	63 ± 4
$\phi(1680)\pi^+$	1.5 ± 0.5	-70 ± 9
sum	163.8	

FIGURE 3. Diagram of annihilation (left) and resonance (right) contributions to $D_s^+ \to \pi^+\pi^-\pi^+$.

$D_s^+ \to \pi^+\pi^-\pi^+$ decays

Although $D_s^+ \to \pi^+\pi^-\pi^+$ is Cabibbo favored, it can only occur via a spectator diagram if it uses a resonance which couples to both $K\overline{K}$ and $\pi\pi$ or via final state interactions. It can also proceed via an annihilation diagram. These possibilities are sketched in Fig. 3. Since $\rho(770)$ does not couple to $K\overline{K}$, any $\rho(770)$ would indicate an annihilation diagram contribution or final state interactions. A resonance known to couple to $K\overline{K}$ and $\pi\pi$ is the $f_0(980)$. This mysterious state has been proposed as a four-quark state and $K\overline{K}$ molecule among other things. The presence of the $a_0(980)$ further complicates the understanding of this unique resonance. The $f_0(980)$ mass is below the $K\overline{K}$ threshold but is broad enough to have a significant branching fraction to $K\overline{K}$ even with limited phase space.

The FOCUS Dalitz plot and projections for $D_s^+ \to \pi^+\pi^-\pi^+$ are shown in Fig. 4. Clear $f_0(980)$ bands are visible in the Dalitz plot and projections. A concentration at $m^2(\pi^+\pi^-) \sim 2$ GeV/c^2 is also visible. The results of a preliminary fit to this distribution as well as E791 results [3] are shown in Table 2. Both results clearly show $f_0(980)$ dominance and no significant $\rho(770)$. Thus, this decay proceeds almost entirely through resonance modes with no evidence of an annihilation diagram contribution.

Using data, E791 and FOCUS have made measurements of the poorly measured scalars contributing to the $D_s^+ \to \pi^+\pi^-\pi^+$ decay. Although the PDG [4] lists $f_0(980)$ mass and width measurements from 1973 to the present, with 13 measurements in 1999 alone, there is still no consensus on either value. The I=0, J=0 states betweeen 1200 and 1500 MeV/c^2 are even more murky.

E791 finds a mass and width of the $f_0(1370)$ of $1434 \pm 18 \pm 9$ MeV/c^2 and $172 \pm 32 \pm 6$ MeV/c^2, respectively. FOCUS uses $S_0(1475)$ for a scalar around 1475 MeV/c^2, as seen in an E687 analysis. The preliminary mass and width are found to be 1473 ± 8 MeV/c^2

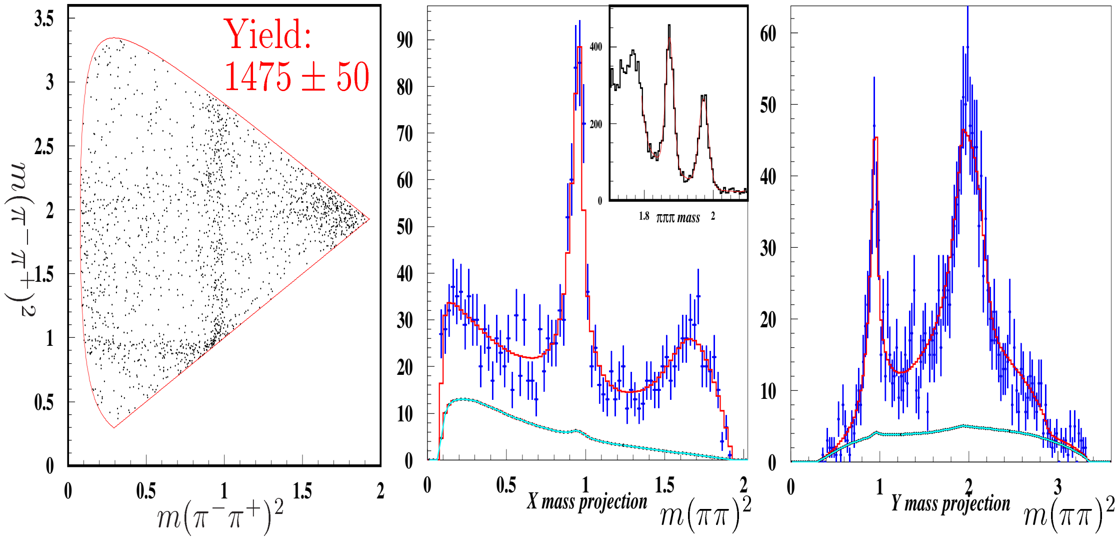

FIGURE 4. Preliminary $D_s^+ \to \pi^+\pi^-\pi^+$ FOCUS Dalitz plot and projections. Projections show the data background, data signal+background, and the fitted result.

TABLE 2. E791 [3] and preliminary FOCUS Dalitz plot fit results for the decay $D_s^+ \to \pi^+\pi^-\pi^+$. Errors on FOCUS results are statistical only.

	E791		**FOCUS (preliminary)**	
Decay mode	**Fraction (%)**	**Phase (°)**	**Fraction (%)**	**Phase (°)**
$f_0(980)\pi^+$	$56.5 \pm 4.3 \pm 4.7$	0 (fixed)	94.4 ± 2.5	0 (fixed)
non-resonant	$0.5 \pm 1.4 \pm 1.7$	$181 \pm 94 \pm 51$	25.5 ± 4.4	246 ± 4
$\rho(770)\pi^+$	$5.8 \pm 2.3 \pm 3.7$	$109 \pm 24 \pm 5$		
$f_2(1270)\pi^+$	$19.7 \pm 3.3 \pm 0.6$	$133 \pm 13 \pm 28$	9.8 ± 1.2	140 ± 6
$\rho(1450)\pi^+$	$4.4 \pm 2.1 \pm 0.2$	$162 \pm 26 \pm 17$	4.1 ± 0.7	188 ± 14
$S_0(1475)\pi^+$			17.4 ± 2.2	250 ± 4
$f_0(1370)\pi^+$	$32.4 \pm 7.7 \pm 1.9$	$198 \pm 19 \pm 27$		
sum	119.3		151.2	

and 112 ± 17 MeV/c^2, respectively; quite comparable to the E791 result for $f_0(1370)$.

E791 finds slightly better fits using the WA92 coupled channel Breit-Wigner formalism to describe the $f_0(980)$. A standard relativistic Breit-Wigner is proportional to $1/(m^2 - m_r^2 + im_r\Gamma_r(m^2))$ for a resonance r with a mass and width of m_r and Γ_r, respectively and at a two-body mass-squard of m^2. In the $f_0(980)$ WA92 coupled channel formula, Γ_r is replaced with $\Gamma_r^\pi + \Gamma_r^K$ where $\Gamma_r^\pi(m^2) = g_\pi\sqrt{m_{\pi\pi}^2/4 - m_\pi^2}$ and $\Gamma_r^K(m^2) = g_K\left(\sqrt{m_{\pi\pi}^2/4 - m_{K^+}^2} + \sqrt{m_{\pi\pi}^2/4 - m_{K^0}^2}\right)$. This framework yields $M_{f_0(980)} = 977 \pm 3 \pm 2$ MeV/c^2, $g_\pi = 0.09 \pm 0.01 \pm 0.01$, and $g_K = 0.02 \pm 0.04 \pm 0.03$ from the E791 data. Fitting with a standard Breit-Wigner results in minor changes: $M_{f_0(980)} = 975 \pm 3 \pm 2$ MeV/c^2 and $\Gamma_{f_0(980)} = 44 \pm 2 \pm 2$ MeV/c^2. FOCUS finds the K-matrix framework works quite well in dealing with the coupled channel nature of the $f_0(980)$ [5, 6]. In this framework, transformed variables are used:

$m_0^2 = m_r^2 + (\gamma_{KK}/\gamma_{\pi\pi})^2(|\rho_{KK}(m_r)|/\rho_{\pi\pi}(m_r))m_r\Gamma_r$ and $\Gamma_0 = m_r\Gamma_r/(m_0\rho_{\pi\pi}(m_r)\gamma_{\pi\pi}^2)$ where $\rho_{\pi\pi}$ and ρ_{KK} are phase space terms and $\gamma_{\pi\pi}$ and γ_{KK} are coupling constants normalized to $\gamma_{\pi\pi}^2 + \gamma_{KK}^2 = 1$. In this framework, the preliminary FOCUS fits return $M_{f_0(980)} = 963 \pm 6$ MeV/c^2, $\Gamma_{f_0(980)} = 297 \pm 92$ MeV/c^2, and $\gamma_{KK}^2/\gamma_{\pi\pi}^2 = 2.09 \pm 0.53$ which translates to $M_{f_0(980)} = 982 \pm 30$ MeV/c^2 and $\Gamma_{f_0(980)} = 89 \pm 32$ MeV/c^2 for a standard Breit Wigner (errors are statistical only).

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

E791 has published results for a coherent Dalitz plot analysis of $D^+ \to \pi^+\pi^-\pi^+$ [7]. In their initial fit to the Dalitz plot using all known resonances, the fit quality was very poor with a confidence level of 10^{-5}. By including a low mass scalar particle (σ) the fit was significantly improved and yielded a confidence level of 75%, providing strong evidence for the elusive light scalar. The results from both fits are tabulated in Table 3. From the fit, the σ parameters were determined to be $M_\sigma = 478^{+24}_{-23} \pm 17$ MeV/c^2 and $\Gamma_\sigma = 324^{+42}_{-40} \pm 21$ MeV/c^2. Many checks were made to validate the existence of the σ in this decay. These checks included fitting with a vector and tensor state, and fitting with no phase variation. The fit with a phase-varying scalar particle was clearly preferred.

TABLE 3. E791 Dalitz plot fit results for the decay $D^+ \to \pi^+\pi^-\pi^+$ [7]. Parameter errors from "without σ" fits are statistical only.

	Without σ: CL = 0.001%		**With σ: CL = 75%**	
Decay mode	**Fraction (%)**	**Phase (°)**	**Fraction (%)**	**Phase (°)**
$\rho(770)\pi^+$	20.8 ± 2.4	0 (fixed)	$33.6 \pm 3.2 \pm 2.2$	0 (fixed)
non-resonant	38.6 ± 9.7	150 ± 12	$7.8 \pm 6.0 \pm 2.7$	$57 \pm 20 \pm 6$
$f_0(980)\pi^+$	7.4 ± 1.4	152 ± 16	$6.2 \pm 1.3 \pm 0.4$	$165 \pm 11 \pm 3$
$f_2(1270)\pi^+$	6.3 ± 1.9	103 ± 16	$19.4 \pm 2.5 \pm 0.4$	$57 \pm 8 \pm 3$
$f_0(1370)\pi^+$	10.7 ± 3.1	143 ± 10	$2.3 \pm 1.5 \pm 0.8$	$105 \pm 18 \pm 1$
$\rho(1450)\pi^+$	22.6 ± 3.7	46 ± 15	$0.7 \pm 0.7 \pm 0.3$	$319 \pm 39 \pm 11$
$\sigma\pi^+$			$46.3 \pm 9.0 \pm 2.1$	$206 \pm 8 \pm 5$
sum	106.4		116.3	

$D^+ \to K^-\pi^+\pi^+$

The Cabibbo favored decay $D^+ \to K^-\pi^+\pi^+$ provides a very high statistics mode in which to study charm decays. Previous analyses of this decay [8, 9] have identified two mysteries in this decay. The first mystery is why there is a dominant non-resonant contribution; unique in charm decays. The second mystery is why a good fit to this Dalitz plot seems to be impossible to achieve. The E791 data sample of 15,090 events (94% signal) can be used to shed light on these mysteries. Fitting the data using all known resonances results in a large non-resonant contribution and a very poor fit (confidence level of 10^{-11}), similar to past attempts. Given the evidence for the σ in the $D^+ \to \pi^+\pi^-\pi^+$ mode, an additional scalar (κ) was added to the $D^+ \to K^-\pi^+\pi^+$ fit. This provides a dramatic reduction in the non-resonant contribution (from 91% to 13%) and a much improved fit (confidence level of 95%). The preliminary results of both fits are shown in Table 4. The preliminary κ parameters are found to be $M_\kappa = 797 \pm 19 \pm 42$ MeV/c^2 and $\Gamma_\kappa = 410 \pm 43 \pm 85$ MeV/c^2. Attempts to explain the data in other ways (*e.g.* including a vector state, tensor state, non-phase-varying state, structured non-resonant contribution) have been inadequate. Preliminary meausrements of the $K_0^*(1430)$ parameters ($M_{K_0^*(1430)} = 1459 \pm 7 \pm 6$ MeV/c^2 and $\Gamma_{K_0^*(1430)} = 175 \pm 12 \pm 12$ MeV/c^2) have also been extracted in this analysis [10].

TABLE 4. Preliminary E791 Dalitz plot fit results for the decay $D^+ \to K^-\pi^+\pi^+$. Parameter errors from "without κ" fits are statistical only.

	Without κ: CL = 10^{-11}		**With κ: CL = 95%**	
Decay mode	**Fraction (%)**	**Phase (°)**	**Fraction (%)**	**Phase (°)**
NR	90.9 ± 2.6	0 (fixed)	$13.0 \pm 5.8 \pm 2.6$	$349 \pm 14 \pm 8$
$\overline{K}^*(892)\pi^+$	13.8 ± 0.5	54 ± 2	$12.3 \pm 1.0 \pm 0.9$	0 (fixed)
$\overline{K}_0^*(1430)\pi^+$	30.6 ± 1.6	54 ± 2	$12.5 \pm 1.4 \pm 0.4$	$48 \pm 7 \pm 10$
$\overline{K}_2^*(1430)\pi^+$	0.4 ± 0.1	33 ± 8	$0.5 \pm 0.1 \pm 0.2$	$306 \pm 8 \pm 6$
$\overline{K}^*(1680)\pi^+$	3.2 ± 0.3	66 ± 3	$2.5 \pm 0.7 \pm 0.2$	$28 \pm 13 \pm 15$
$\kappa\pi^+$			$47.8 \pm 12.1 \pm 3.7$	$187 \pm 8 \pm 17$
sum	138.9		88.6	

$D^+, D_s^+ \to K^+\pi^-\pi^+$

FOCUS has obtained preliminary results from Dalitz plot fits to the doubly Cabibbo suppressed decay $D^+ \to K^+\pi^-\pi^+$ and the singly Cabibbo suppressed decay $D_s^+ \to K^+\pi^-\pi^+$. The Dalitz plots and projections are shown in Fig. 5 and the fit results in Table 5. This is the first fit to the $D_s^+ \to K^+\pi^-\pi^+$ Dalitz plot. Both fit results indicate a rich resonance structure, dominated by $\rho(770)$.

TABLE 5. Preliminary FOCUS Dalitz plot fit results for $D^+ \to K^+\pi^-\pi^+$ and $D_s^+ \to K^+\pi^-\pi^+$. Statistical errors only.

	$D^+ \to K^+\pi^-\pi^+$		$D_s^+ \to K^+\pi^-\pi^+$	
Decay mode	**Fraction (%)**	**Phase (°)**	**Fraction (%)**	**Phase (°)**
$\rho(770)K^+$	51 ± 10	0 (fixed)	40 ± 4	0 (fixed)
non-resonant	9 ± 5	-6 ± 16	18 ± 4	34 ± 7
$K^*(892)\pi^+$	43 ± 7	208 ± 16	22 ± 3	163 ± 7
$f_0(980)K^+$	9 ± 5	73 ± 31		
$f_2(1270)K^+$			2 ± 1	33 ± 21
$K^*(1410)\pi^+$	12 ± 8	133 ± 23	14 ± 5	-10 ± 7
$K_0^*(1430)\pi^+$			14 ± 6	68 ± 7
$K_2^*(1430)\pi^+$	6 ± 3	48 ± 27		
$\rho(1450)K^+$	10 ± 5	247 ± 15	8 ± 2	219 ± 14
$K^*(1680)\pi^+$	22 ± 10	2 ± 20		
sum	162		118	

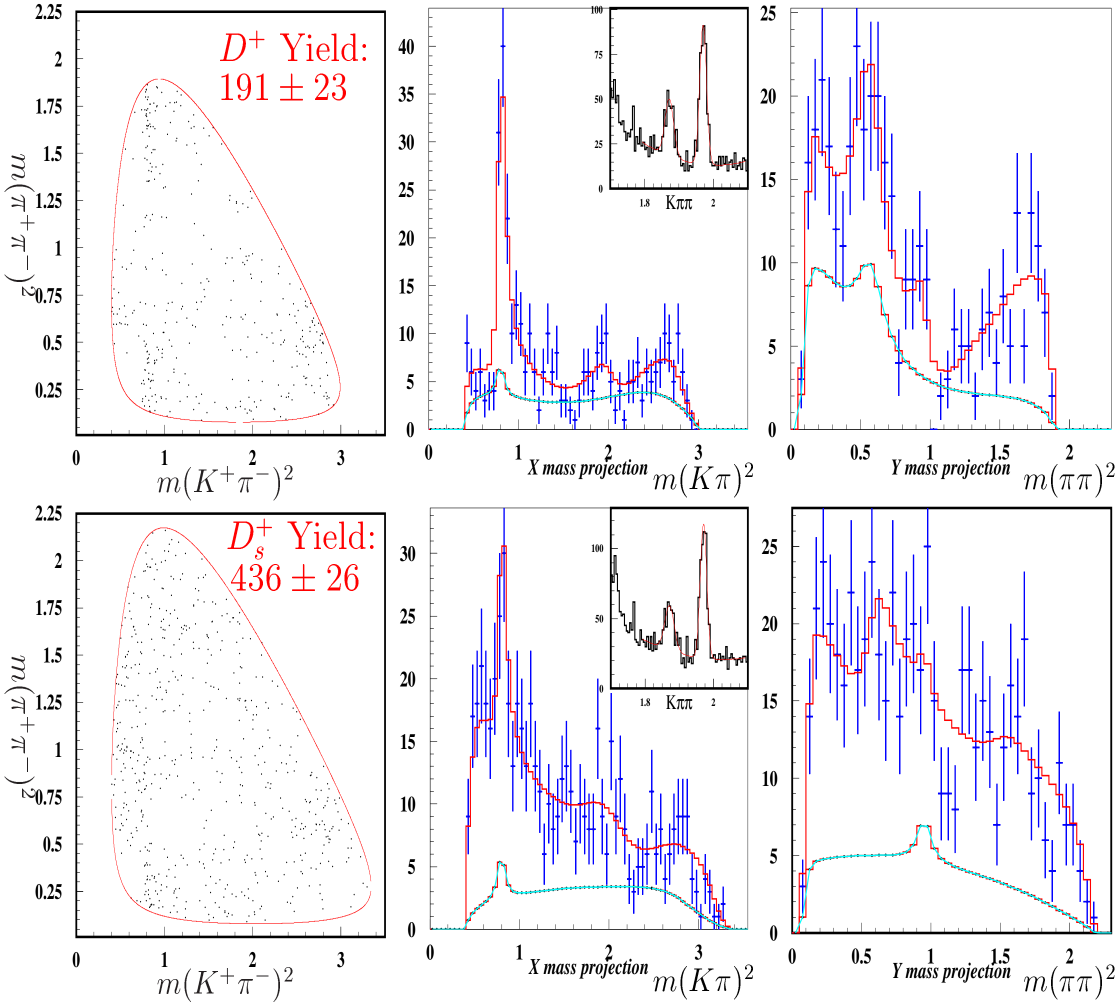

FIGURE 5. FOCUS Dalitz plots and projections for $D^+ \to K^+\pi^-\pi^+$ and $D_s^+ \to K^+\pi^-\pi^+$. Projections show the data background, data signal+background, and the fitted result.

CONCLUSION

Hadronic decays of charm provides an environment to study many aspects of high energy physics including measuring the contributions of various Feynman diagrams, studying the effect of final state interactions, searching for *CP* violation, and measuring the mass and width of light resonances. The relatively large decay rate of $D_s^+ \to \pi^+\pi^-\pi^+$ decay has been found to be due to resonances which couple simultaneously to $K\overline{K}$ and $\pi\pi$ rather than annihilation diagrams. Strong evidence for, and precise measurements of, two particles which have existed on the fringe for many years (σ and κ) are presented. Using the clean charm environment to measure light resonance parameters is a new and interesting use of charm hadronic decays. Table 6 summarizes all of the measured light resonance values described in these proceedings. The future holds the prospect of even more precise measurements of light resonances, a search for direct *CP* violation from $D^+ \to K^-K^+\pi^+$ decays, and much more information from many decay modes.

TABLE 6. Fitted masses and widths for various scalars involved in charm decays. E791 κ and $K_0^*(1430)$ results are preliminary. The FOCUS results are preliminary and errors shown are only statistical.

	E791		FOCUS	
Resonance	**Mass (MeV/c^2)**	**Γ (MeV/c^2)**	**Mass (MeV/c^2)**	**Γ (MeV/c^2)**
σ	$478^{+24}_{-23} \pm 17$	$324^{+42}_{-40} \pm 21$		
κ	$797 \pm 19 \pm 42$	$410 \pm 43 \pm 85$		
$f_0(980)$	$975 \pm 3 \pm 2$	$44 \pm 2 \pm 2$	982 ± 30	89 ± 32
$f_0(1370)/S_0(1475)$	$1434 \pm 18 \pm 9$	$172 \pm 32 \pm 6$	1473 ± 8	112 ± 17
$K_0^*(1430)$	$1459 \pm 7 \pm 6$	$175 \pm 12 \pm 12$		

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