Light Scalar Mesons Spectroscopy From Heavy Flavor Decay

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(for the E791 Collaboration)

Flavor Physics and CP Violation, Philadelphia 2002

E791 Dalitz Plot Analyses

Results for Scalar States

★ From $D_s^+ \to \pi^-\pi^+\pi^+$ decays:

▷ New mass and width measurements for $f_0(980)$ and $f_0(1370)$

PRL 86, 765 (2001)

★ From $D^+ \to \pi^-\pi^+\pi^+$ decays:

▷ Evidence of a low mass, large width σ

PRL 86, 770 (2001)

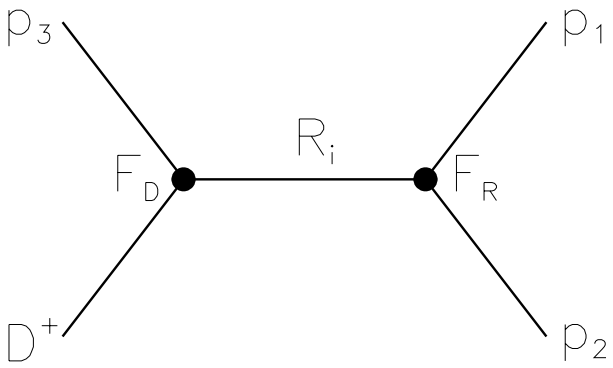
★ From $D^+ \to K^-\pi^+\pi^+$ decays :

▷ Evidence of a low mass, large width κ

▷ New mass and width measurements for $K_0^*(1430)$

hep-ex/020418

The Analysis Formalism



- **Each individual amplitude must satisfy Lorentz invariance and angular momentum conservation**

$$\mathcal{A}_i = F_D \times F_{R_i} \times BW_i \times \mathcal{M}_i^J$$

F_D, F_{R_i}: Blatt-Weisskopf damping factors

$\mathcal{M}_i^J$: Angular function

$$BW_i = \frac{1}{m_{0i}^2 - m_{12}^2 - i m_{0i} \Gamma_i(m_{12})}$$

- **Signal Amplitude: coherent sum of individual amplitudes**

$$\mathcal{A} = a_{nr} e^{i\delta_{nr}} + \sum_j a_j e^{i\delta_j} \mathcal{A}_j$$

The Fit Procedure

- **Objectives**
  - ▷ **Determine the contributing channels, their levels and relative phases:**

    a_i **and** δ_i **as floating parameters**

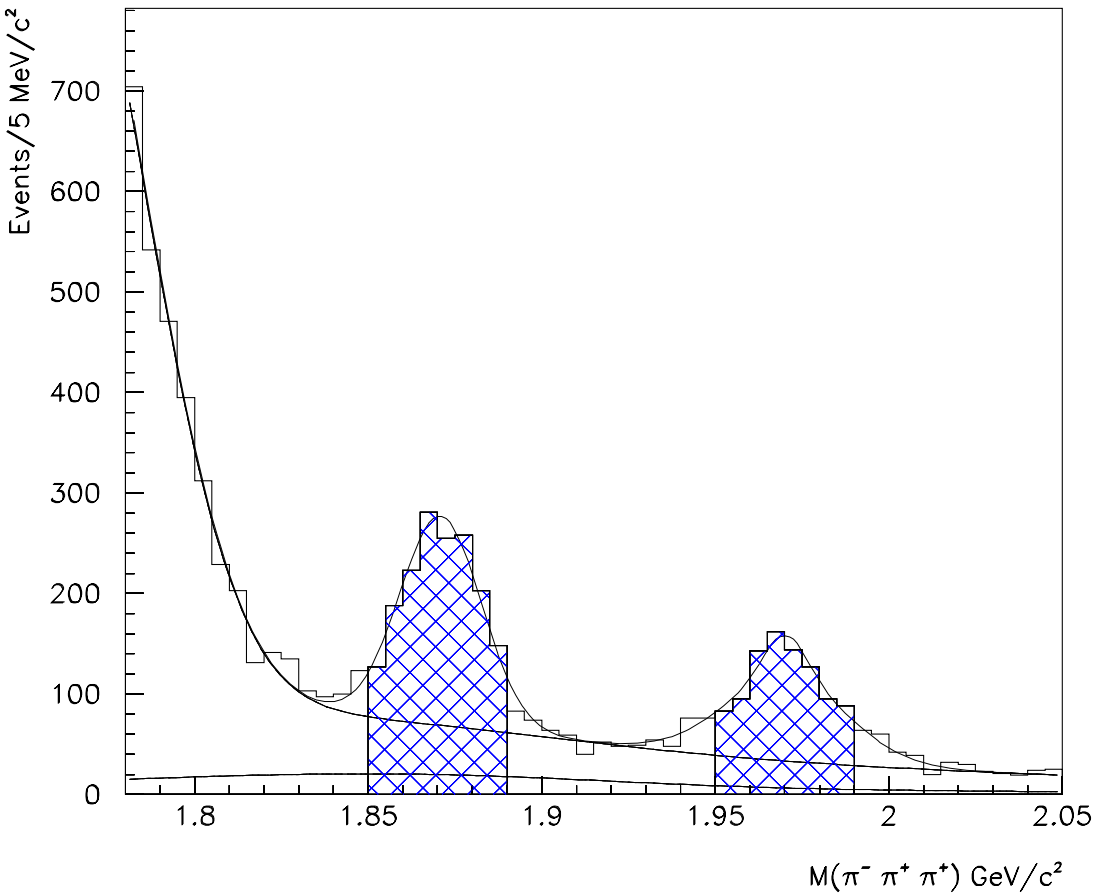
  - ▷ **We included the possibility of measuring resonance parameters**

    unconstrained m_0 , Γ_0

- **Unbinned Maximum Likelihood Fit to the Dalitz plot distribution**
  - ▷ **Probability distribution functions for Signal and Background**
  - ▷ **Minimizing** $\boxed{fcn = -2\log\mathcal{L}}$

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

Dalitz Plot Analyses

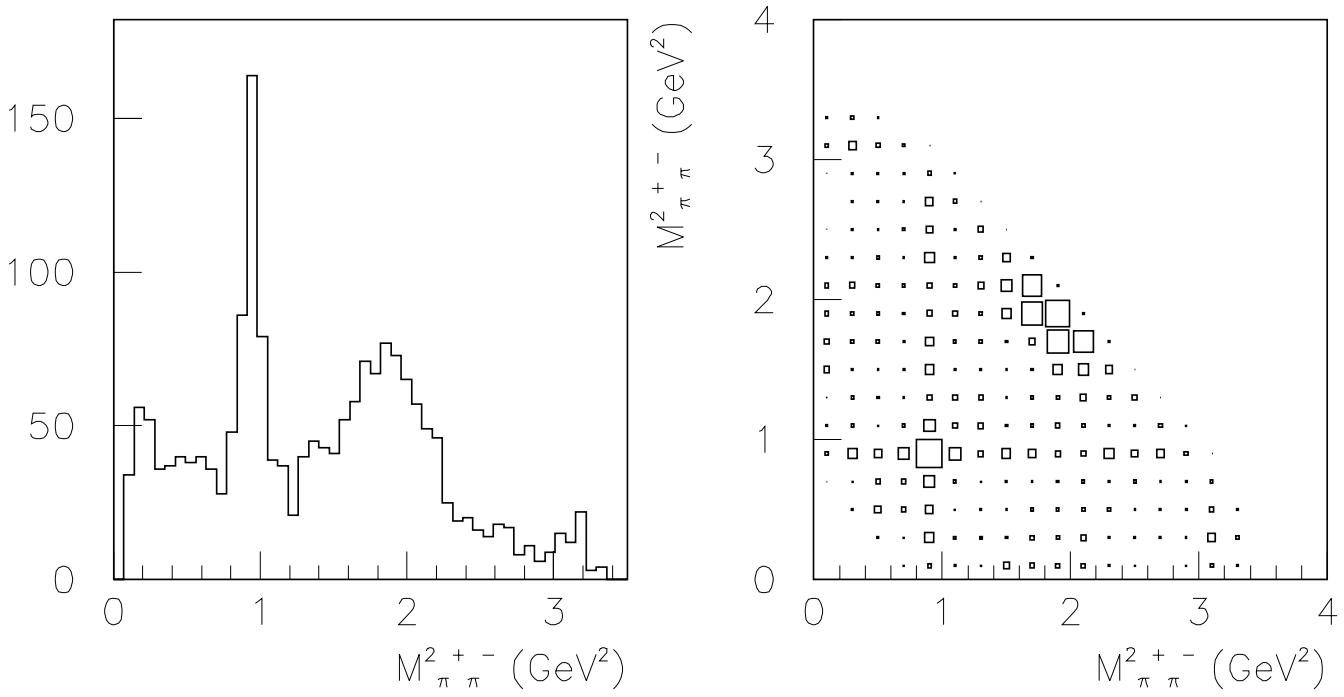


$\pi^-\pi^+\pi^+$ Invariant Mass :

1170 ± 65 D^+ events

848 ± 44 D_s^+ events

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



Channels included :

$$D_s^+ \to \begin{matrix} \text{non-resonant} \\ \rho^0(770)\pi^+ \\ f_0(980)\pi^+ \\ f_2(1270)\pi^+ \\ f_0(1370)\pi^+ \\ \rho^0(1450)\pi^+ \end{matrix} \to \pi^-\pi^+\pi^+$$

$D_s^+ \to \pi^-\pi^+\pi^+$ Fit Approach

- **Coupled channel Breit-Wigner for $f_0(980)$**

$$BW_{f_0(980)} = \frac{1}{m_{12}^2 - m_0^2 + i m_0(\Gamma_K + \Gamma_\pi)}$$

$$\Gamma_K = g_K\sqrt{m_{12}^2/4 - m_K^2}$$

$$\Gamma_\pi = g_\pi\sqrt{m_{12}^2/4 - m_\pi^2}$$

Large uncertainties for the f_0 parameters [PDG(2000)]

- $f_0(1370)$: $m_0 = 1200$ to 1500 MeV/c^2, $\Gamma_0 = 200$ to 500 MeV/c^2
- $f_0(980)$: $m_0 = 980 \pm 10$ MeV/c^2, $\Gamma_0 = 40$ to 100 MeV/c^2

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OBTAIN f_0 PARAMETERS FROM THE FIT

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

$f_0(1370)$

$$m_0 = (1434 \pm 18 \pm 9) \ \ \mathrm{MeV/c^2}$$
$$\Gamma_0 = (172 \pm 32 \pm 6) \ \ \mathrm{MeV/c^2}$$

$f_0(980)$

$$m_0 = (977 \pm 3 \pm 2) \ \ \mathrm{MeV/c^2}$$
$$g_\pi = 0.09 \pm 0.01 \pm 0.01$$
$$g_K = 0.02 \pm 0.04 \pm 0.03$$

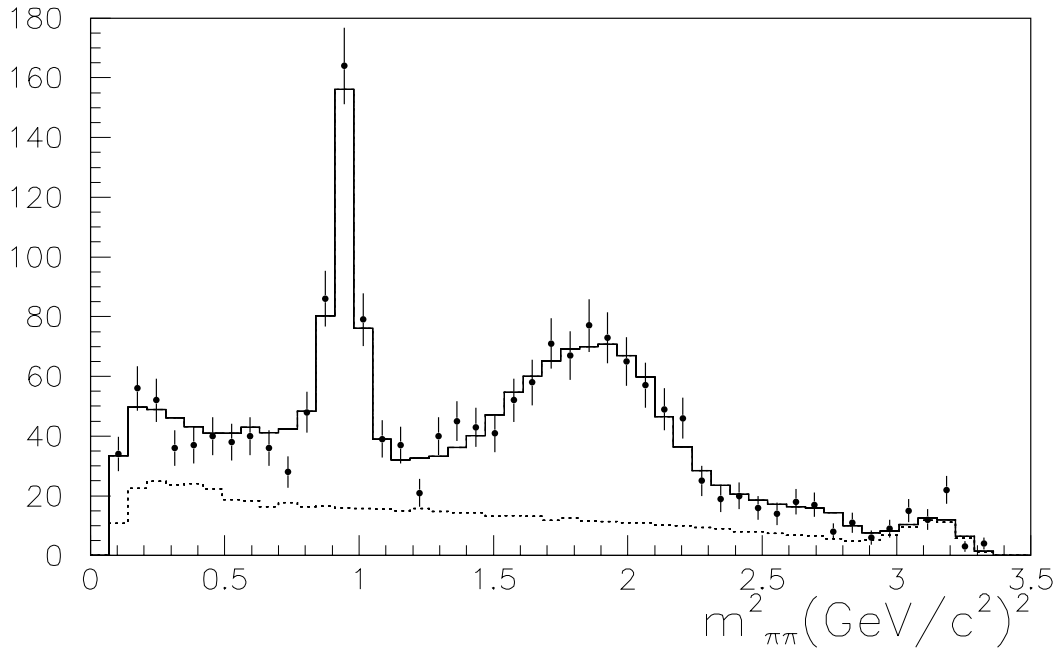
$f_0(980)$ standard BW

$$m_0 = (975 \pm 3 \pm 2) \ \ \mathrm{MeV/c^2}$$
$$\Gamma_0 = (44 \pm 2 \pm 2) \ \ \mathrm{MeV/c^2}$$

Mode	Relative Phase	Fraction(%)
$f_0(980)\pi^+$	0° (fixed)	$56.5 \pm 4.3 \pm 4.7$
non-resonant	$(181 \pm 94 \pm 51)^\circ$	$0.5 \pm 1.4 \pm 1.7$
$\rho^0(770)\pi^+$	$(109 \pm 24 \pm 5)^\circ$	$5.8 \pm 2.3 \pm 3.7$
$f_2(1270)\pi^+$	$(133 \pm 13 \pm 28)^\circ$	$19.7 \pm 3.3 \pm 0.6$
$f_0(1370)\pi^+$	$(198 \pm 19 \pm 27)^\circ$	$32.4 \pm 7.7 \pm 1.9$
$\rho^0(1450)\pi^+$	$(162 \pm 26 \pm 17)^\circ$	$4.4 \pm 2.1 \pm 0.2$

Fit Quality

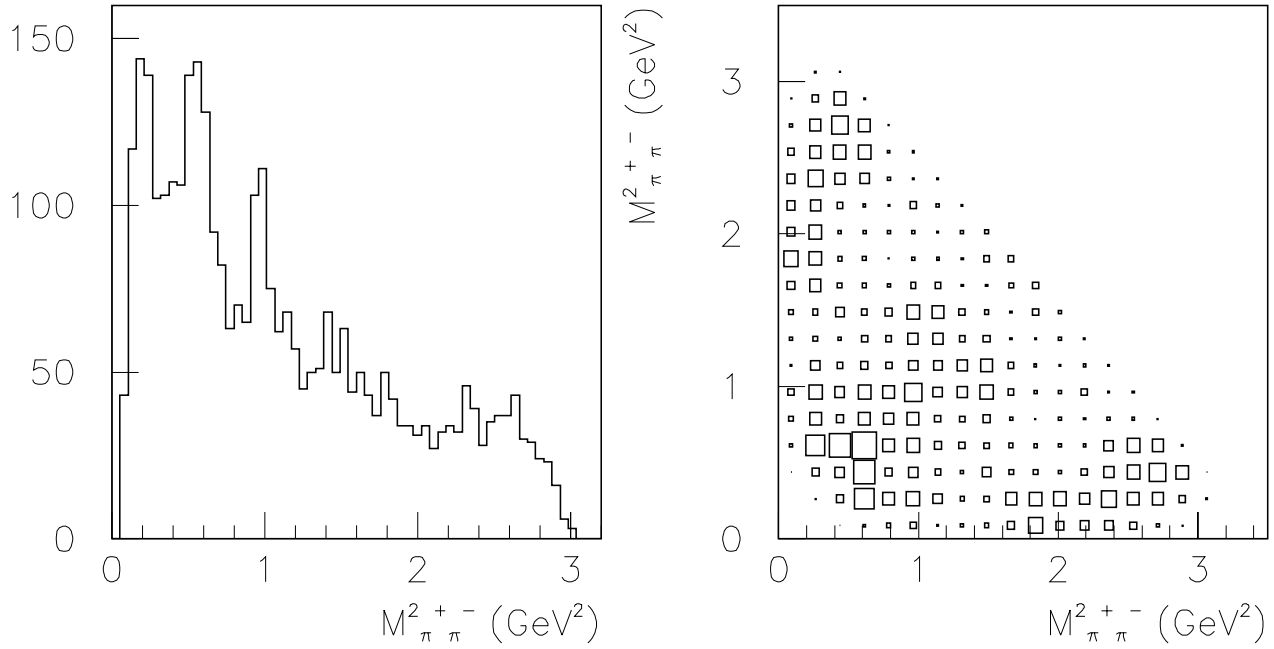
$$\chi^2/\text{dof} = 1.05 \rightarrow CL = 35\%$$



Summary of $D_s^+ \rightarrow \pi^-\pi^+\pi^+$ results

- Dominance of the $f_0\pi^+$ channels
- $f_0(980)$ is narrow
- g_K is compatible with zero
  $\Rightarrow$ small $f_0(980)$ coupling to KK

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



What is the origin of the low mass peak?

- **Peculiar distribution of the known dipion resonances with their possibles interferences?**
- **New dipion resonance with mass below the $\rho(770)$?**

Initial Approach

Same Channels used in $D_s^+ \to \pi^-\pi^+\pi^+$:

$$\boxed{D^+} \to \begin{array}{c}\text{non-resonant}\\ \rho^0(770)\pi^+\\ f_0(980)\pi^+\\ f_2(1270)\pi^+\\ f_0(1370)\pi^+\\ \rho^0(1450)\pi^+\end{array} \to \boxed{\pi^-\pi^+\pi^+}$$

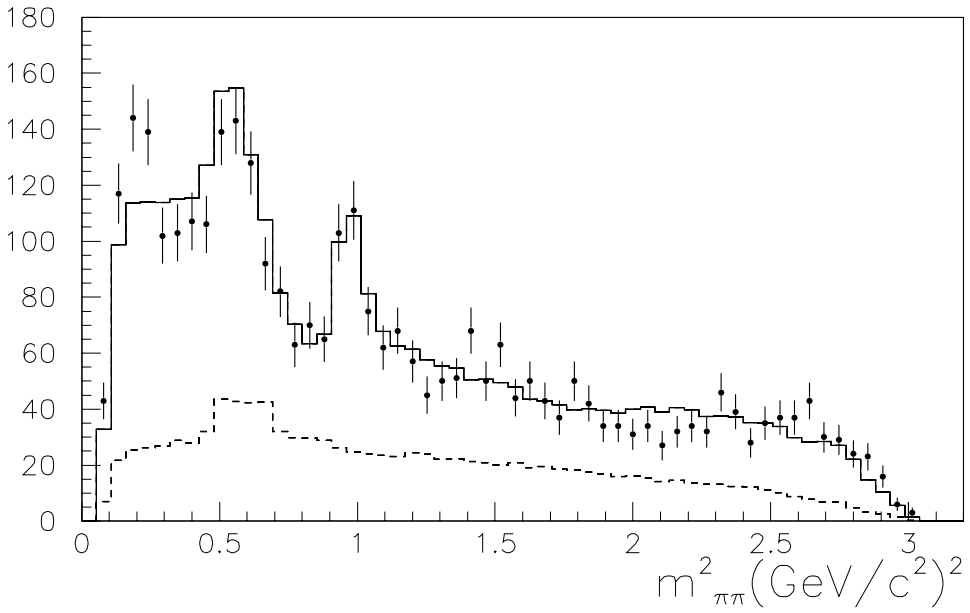
Mode	Relative Phase	Fraction(%)
$\rho^0(770)\pi^+$	0° (fixed)	20.8 ± 2.4
non-resonant	$(150 \pm 12)^\circ$	38.6 ± 9.7
$f_0(980)\pi^+$	$(152 \pm 16)^\circ$	7.4 ± 1.4
$f_2(1270)\pi^+$	$(103 \pm 16)^\circ$	6.3 ± 1.9
$f_0(1370)\pi^+$	$(143 \pm 10)^\circ$	10.7 ± 3.1
$\rho^0(1450)\pi^+$	$(46 \pm 15)^\circ$	22.6 ± 3.7

- dominant non-resonant contribution
- $\rho^0(770)\pi^+$ and $\rho^0(1450)\pi^+$ are the dominant resonant channels
- compatible with previous E687 results

Fit Quality

$$\chi^2/\mathrm{dof} = 1.5 \rightarrow CL = 10^{-5}$$

- This model, with the known resonances, failed to explain experimental data.



- We need a new dipion resonance with mass below the $\rho^0(770)$.

- The only available state is the long time expected particle σ.

Inclusion of a New State in the $D^+ \to \pi^-\pi^+\pi^+$ Decay

★ **Scalar state with unconstrained mass and width**

Candidate: the σ particle

Fit Results

$$M_\sigma = 478^{+24}_{-23} \pm 17 \ \ \mathrm{MeV/c^2}$$

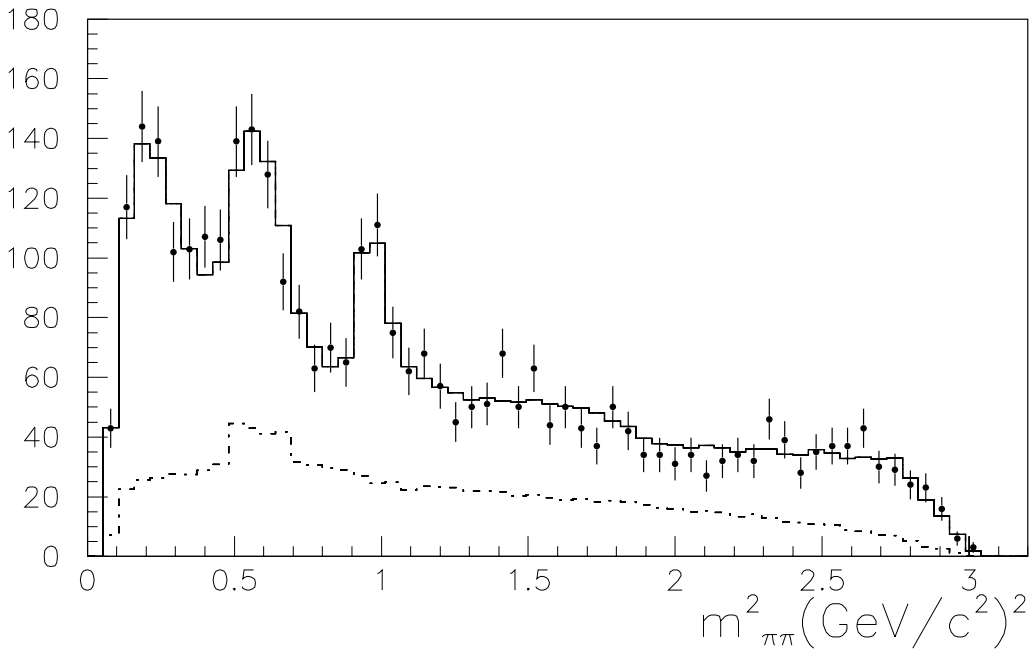
$$\Gamma_\sigma = 324^{+42}_{-40} \pm 21 \ \ \mathrm{MeV/c^2}$$

Mode	Relative Phase	Fraction(%)
$\sigma\pi^+$	$(206 \pm 8.0 \pm 5)^\circ$	$46.3 \pm 9.0 \pm 2.1$
$\rho^0(770)\pi^+$	0° (fixed)	$33.6 \pm 3.2 \pm 2.2$
non-resonant	$(57 \pm 20 \pm 6)^\circ$	$7.8 \pm 6.0 \pm 2.7$
$f_0(980)\pi^+$	$(165 \pm 11 \pm 3)^\circ$	$6.2 \pm 1.3 \pm 0.4$
$f_2(1270)\pi^+$	$(57 \pm 8 \pm 3)^\circ$	$19.4 \pm 2.5 \pm 0.4$
$f_0(1370)\pi^+$	$(105 \pm 18 \pm 1)^\circ$	$2.3 \pm 1.5 \pm 0.8$
$\rho^0(1450)\pi^+$	$(319 \pm 39 \pm 11)^\circ$	$0.7 \pm 0.7 \pm 0.3$

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

Fit Quality with $\sigma\pi$ amplitude

$$\chi^2/\text{dof} = 0.9 \to CL = 76\%$$



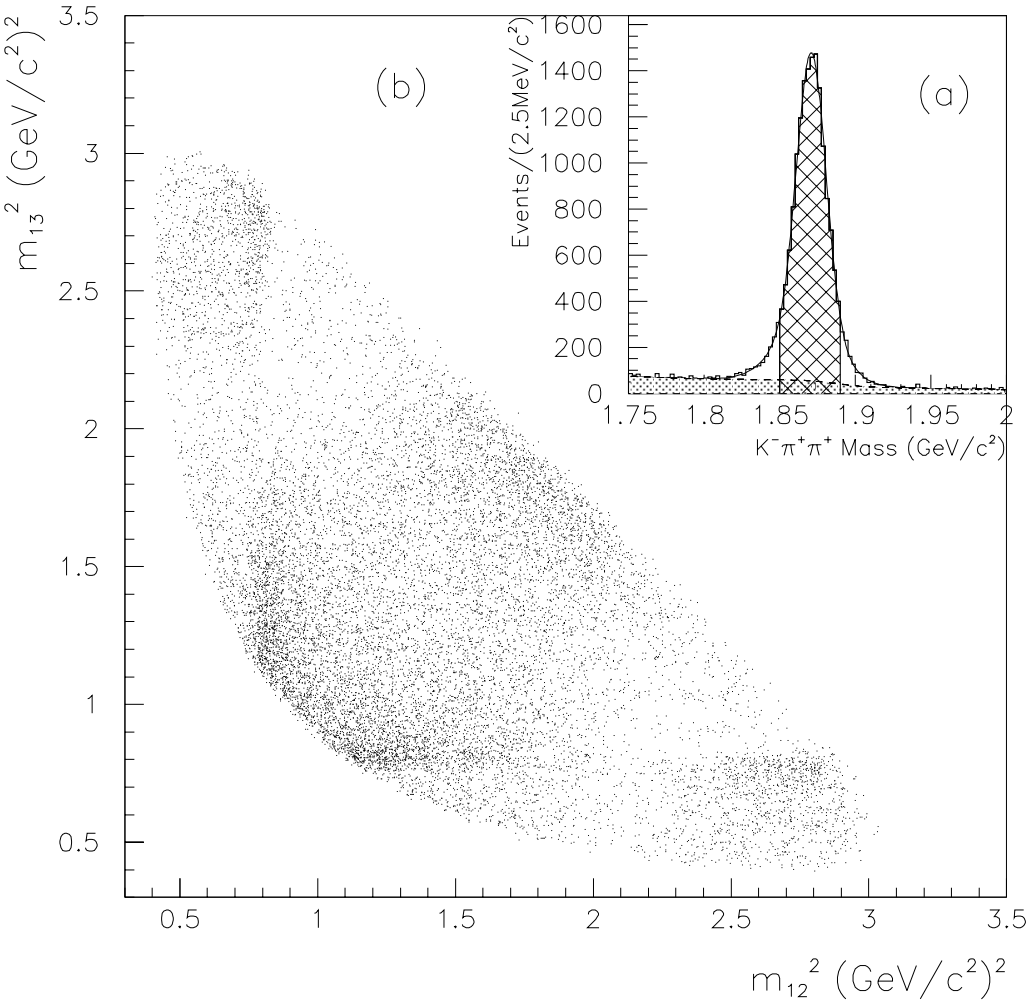
Summary of $D^+ \to \pi^-\pi^+\pi^+$ Analysis

- Model without $\sigma\pi$: high NR, bad fit quality
- σ appears with low mass, large width
- $\sigma\pi$ is the dominant channel; small NR

$\Rightarrow$ VERY GOOD DESCRIPTION AT LOW $\pi\pi$ MASS

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

15090 events inside the window



$$D^+ \to \begin{matrix} \text{non-resonant} \\ \bar{K}^*(890)\pi^+ \\ \bar{K}_0^*(1430)\pi^+ \\ \bar{K}_2^*(1430)\pi^+ \\ \bar{K}^*(1680)\pi^+ \end{matrix} \to K^-\pi^+\pi^+$$

First Approach

Conventional Model With All Known $K\pi$ Resonances

- fixed masses and widths for the resonances [PDG]

Results

Mode	Relative Phase	Fraction (%)
Non-resonant	0° (fixed)	90.9 ± 2.6
$\bar{K}^*(890)\pi^+$	$(54 \pm 2)°$	13.8 ± 0.5
$\bar{K}_0^*(1430)\pi^+$	$(54 \pm 2)°$	30.6 ± 1.6
$\bar{K}_2^*(1430)\pi^+$	$(33 \pm 8)°$	0.4 ± 0.1
$\bar{K}^*(1680)\pi^+$	$(66 \pm 3)°$	3.2 ± 0.3

- very large NR contribution
  $\Rightarrow$ unusual in D decays
- sum of the fractions $\sim 140\%$
- agreement with E691 and E687
- bad fit quality:

$$\chi^2/\text{dof} = 2.7 \rightarrow CL = 10^{-11}$$

Improving the Model

⋆ **Inclusion of an extra SCALAR STATE: unconstrained mass and width**

⋆ **Float mass and width also for $K_0^*(1430)$**

⋆ **Besides:**

⇒ **Include form-factors to account for finite size of the decaying mesons in scalar transitions using Törnqvist gaussian format**

⇒ **Radii of D and $K\pi$ resonances as two free parameters**

Fit including $\kappa\pi$ amplitude

Results:

- Scalar κ with low mass and large width

$$M_\kappa = 797 \pm 19 \pm 43 \text{ MeV}/c^2$$

$$\Gamma_\kappa = 410 \pm 43 \pm 87 \text{ MeV}/c^2$$

- New measurements for $K_0^*(1430)$ mass and width

$$M_{K_0^*(1430)} = 1459 \pm 7 \pm 5 \text{ MeV}/c^2$$

$$\Gamma_{K_0^*(1430)} = 175 \pm 12 \pm 12 \text{ MeV}/c^2$$

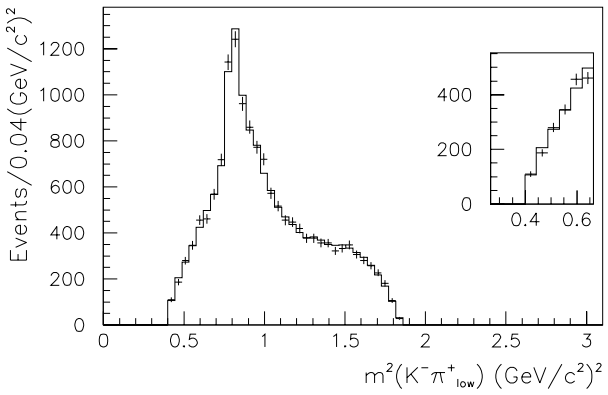
PDG(2000)

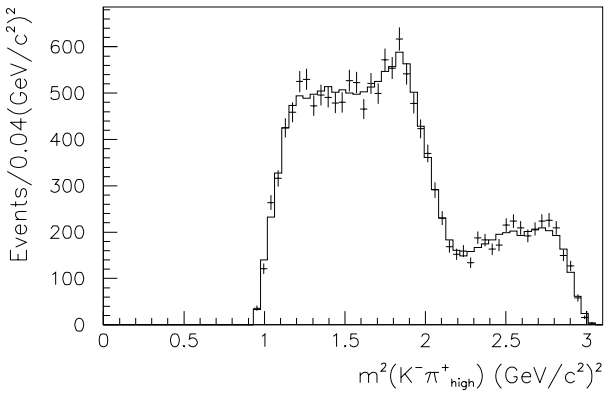
$$M_{K_0^*(1430)} = 1412 \pm 6 \text{ MeV}/c^2$$
$$\Gamma_{K_0^*(1430)} = 294 \pm 23 \text{ MeV}/c^2$$

Mode	Relative Phase	Fraction (%)
Non-resonant	$(-11 \pm 14 \pm 8)^\circ$	$13.0 \pm 5.8 \pm 4.4$
$\kappa\pi^+$	$(187 \pm 8 \pm 18)^\circ$	$47.8 \pm 12.1 \pm 5.3$
$\bar{K}^*(890)\pi^+$	0° (fixed)	$12.3 \pm 1.0 \pm 0.9$
$\bar{K}_0^*(1430)\pi^+$	$(48 \pm 7 \pm 10)^\circ$	$12.5 \pm 1.4 \pm 0.5$
$\bar{K}_2^*(1430)\pi^+$	$(-54 \pm 8 \pm 7)^\circ$	$0.5 \pm 0.1 \pm 0.2$
$\bar{K}^*(1680)\pi^+$	$(28 \pm 13 \pm 15)^\circ$	$2.5 \pm 0.7 \pm 0.2$

Fit Quality with $\kappa\pi$ amplitude

$$\chi^2/\text{dof} = 0.73 \rightarrow CL = 95\%$$





Other Studies

Checking whether other models could explain the data in a similar manner:

- **Toy Model: "Breit-Wigner" with no phase variation SQRT($|BW|^2$)**
  - **similar mass and width**
  - **unphysical fractions for κ ($283 \pm 96\%$) and NR ($127 \pm 79\%$)**
  - **worse fit quality**
- **Vector and Tensor States instead of scalar**
- **Studies of the NR amplitude in the absence of the κ**

Summary of $D^+ \to K^-\pi^+\pi^+$ Dalitz Plot Analysis

- **Fit with known resonances:**

  ⋆ Dominant NR contribution (over 90%), followed by the scalar $\bar{K}_0^*(1430)\pi^+$

  ⋆ Bad fit quality, especially at low $K\pi$ mass

- **Inclusion of a new scalar state:**

  ⋆ Evidence for a **light** and **broad** κ resonance

  ⋆ New measurement for $K_0^*(1430)$ parameters

  ⋆ The scalars appear as the main contributing states

  $\Rightarrow$ Very good description of data!

Conclusions

Dalitz Plot Analyses from E791 data provided:

- Strong evidence for the existence of $\boxed{\sigma}$
- Strong evidence for the existence of $\boxed{\kappa}$
- New measurements for $f_0(980)$, $f_0(1370)$ parameters
- New measurement for $K_0^*(1430)$ parameters

$\Downarrow$

CHARM DECAYS
AS A CLEAN LABORATORY
FOR LIGHT MESON PHYSICS

$\Rightarrow$ large and clean samples of D decays are available

$\Rightarrow$ great variety of 3 and 4-body channels to study