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Light mesons from decays of τ leptons and D mesons

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$\boxed{\textsf{Outline}}$

- **light mesons and τ^- semileptonic decays : the $\tau^- \to \nu_\tau[3\pi]^-$ case.**

- **light mesons and charm decays: results on $D \to \pi^+\pi^-\pi^+$ decay from Fermilab-E791**

- **conclusions and prospects**

Light mesons and τ^- semileptonic decays: the $\tau^- \to \nu_\tau[3\pi]^-$ case

The structure of $[3\pi]^-$ final states from large and clean samples of τ^- decays is a powerful tool for studying the $\mathbf{a_1(1260)}$

extraction of $\mathbf{a_1(1260)}$ parameters suffer from theoretical ambiguities in the treatment of broad resonances

an additional complication: non resonant backgrounds in hadronic interactions and in τ^- decays (Z-graphs)

General formalism

- $d\Gamma(\tau^- \to \nu_\tau [3\pi]^-) = \frac{1}{4m_\tau} G_F^2 V_{ud} L^{\mu\nu} J_\mu J_\nu^* d\phi_4$

  $L^{\mu\nu} \Rightarrow$ **lepton tensor for weak decay**

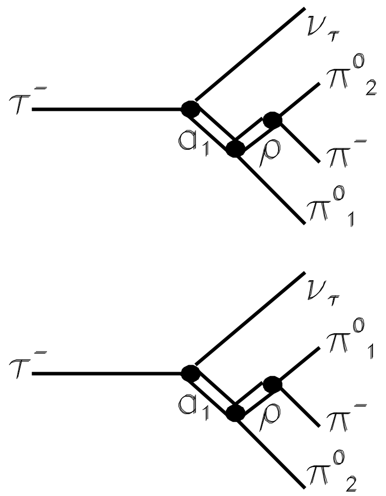
  $J^\mu \Rightarrow$ **hadronic weak current**

- $J_\mu = < 3\pi \mid \bar{d}\gamma_\mu u \mid 0 > + < 3\pi \mid \bar{d}\gamma_5\gamma_\mu u \mid 0 >$

- **a general assumption : the $[3\pi]^-$ system is mostly a $\mathbf{J^P = 1^+}$ with a small $\mathbf{0^-}$ component.**

- **dynamics expected to be dominated by resonance production. The $\mathbf{a_1(1260)}$ is the lowest lying axial vector meson**

The decay $\tau^- \rightarrow \nu_\tau \pi^- \pi^0 \pi^0$



$$\mathcal{A} = f(W \to a_1) \times g(a_1 \to \rho\pi) \times B(s) \times \sum c_i \mathcal{A}_i$$

$$B(s) = \frac{1}{s - m^2_{a_1}(s) + i m_0 \Gamma^{a_1}_{tot}(s)}$$

$$m^2_{a_1}(s) = \frac{1}{\pi} \int_{s_{min}}^{\infty} ds' m_0 \Gamma^{a_1}_{tot}(s)$$

$\Gamma^{a_1}_{tot}(s) \Rightarrow$ **model dependent off shell effects**

$\sum c_i \mathcal{A}_i \Rightarrow$ **$\mathbf{a_1}$ resonant substructure**

f, $g \Rightarrow$ **energy dependent form factors**

CLEO analysis of the decay $\tau^- \to \nu_\tau \pi^- \pi^0 \pi^0$ **:** $\pi^- \pi^0 \pi^0$ **final state from** $a_1(1260) \to \rho^-(770)\pi^-$**,** $\rho^-(1450)\pi^-$**,** $\sigma\pi^-$ **and** $f_0(1370)\pi^-$

Data from CLEO

Dalitz plots in bins on $\mathbf{M_{3\pi}}$

Data from CLEO

$\pi^-\pi^0\pi^0$ mass spectrum and $\Gamma_{tot}^{a_1}(s)$

measured a_1 parameters

	M_0(MeV)	Γ_0(MeV)
CLEO		
Fit 1	$1331 \pm 10 \pm 3$	$814 \pm 36 \pm 13$
Fit 2	1285 ± 7	619 ± 21
Fit 3	1298 ± 7	1200 ± 100
DELPHI		
Fit 1 (KS)	$1255 \pm 7 \pm 6$	$587 \pm 27 \pm 21$
Fit 2 (IMR)	$1207 \pm 5 \pm 8$	$478 \pm 3 \pm 15$
Fit 3	$1196 \pm 4 \pm 5$	$425 \pm 14 \pm 18$
OPAL		
Fit 1 (KS)	$1262 \pm 9^{+6}_{-7}$	$621 \pm 32^{+16}_{-57}$
Fit 2 (IMR)	$1210 \pm 7^{+2}_{-1}$	$457 \pm 15^{+7}_{-16}$
ARGUS		
Fit 1 (KS)	1274 ± 7	594 ± 23
Fit 2 (IMR)	1211 ± 5	446 ± 23

- **$\tau^- \to \nu_\tau[3\pi]^-$ is a unique source of information on the $I = 1$ axial vector mesons;**
- **in spite of large and clean samples of τ^- decays, values of a_1 parameters are still uncertain, depending strongly on details of the model used for fitting the 3π spectrum;**
- **no single model provide an entirely satisfactory description of the data;**
- **dynamics of $\tau^- \to \nu_\tau[3\pi]^-$ needs to be better understood;**
- **is there a non resonant component in $\tau^- \to \nu_\tau[3\pi]^-$ decay?**
- **broad resonances : what they really are?**

Light mesons and charm decays

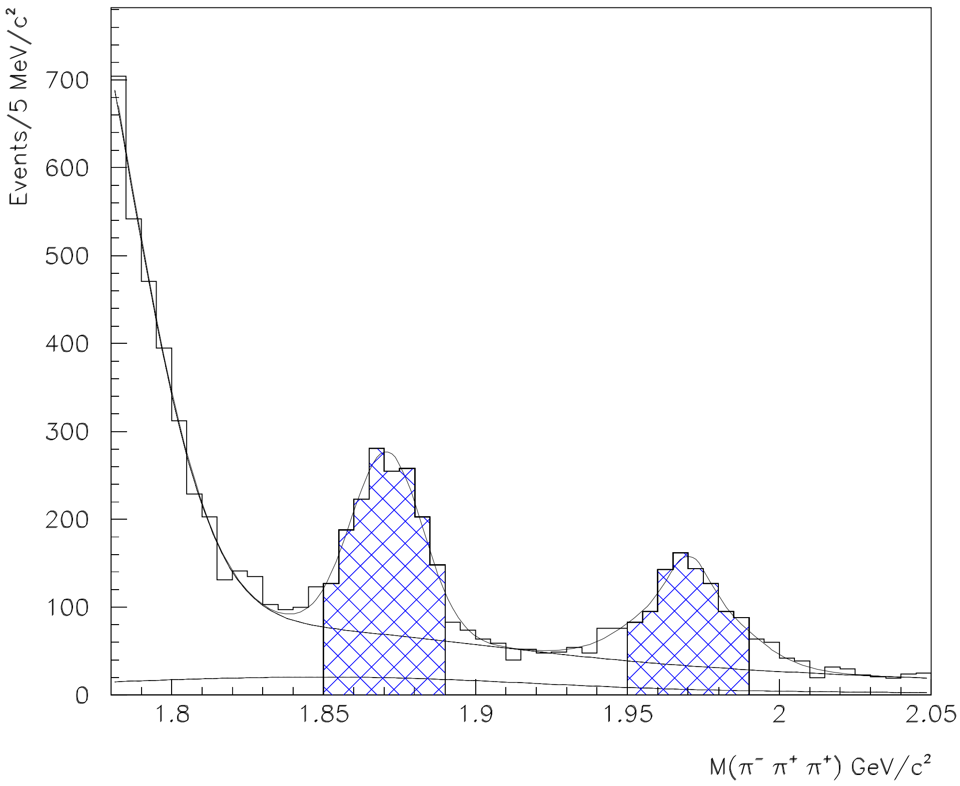
Charm decays are an excellent tool for studying light mesons

- **multibody final states exhibit a very rich resonant substructure**
- **in almost all D decays the non resonant component is very small**
- **lots of high quality data now available: high statistics with small background**
- **in D decays the initial state is always $\mathbf{J^P = 0^-}$ with a well defined mass**
- **in 3-body(4-body) final states results come from a 2-D(5-D) fit**
- **results are less model dependent**

$D \to \pi^+\pi^-\pi^+$ results from Fermilab-E791

- **The $D_s^+ \to \pi^+\pi^-\pi^+$ decay: a special tool for studying the $f_0(980)$ and $f_0(1370)$ states**

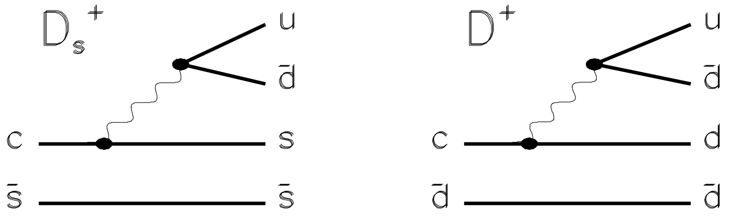
- **The $D^+ \to \pi^+\pi^-\pi^+$ decay: evidence for a new resonance : the σ meson**

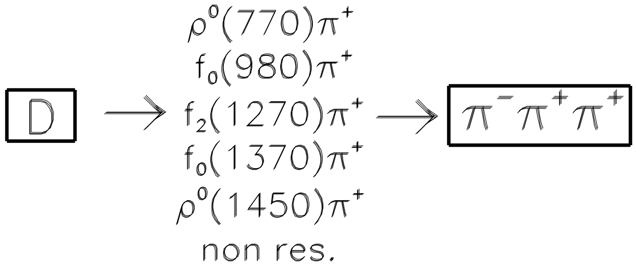


The $\pi^+\pi^-\pi^+$ invariant mass spectrum

1170±65 D^+ events

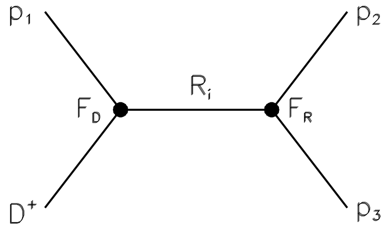
848±44 D_s^+ events


D_s^+
u
$\bar{d}$
c
s
$\bar{s}$
$\bar{s}$
D^+
u
$\bar{d}$
c
d
$\bar{d}$
$\bar{d}$


D
$\rho^0(770)\pi^+$
$f_0(980)\pi^+$
$f_2(1270)\pi^+$
$f_0(1370)\pi^+$
$\rho^0(1450)\pi^+$
non res.
$\pi^-\pi^+\pi^+$

$\boxed{\text{The formalism}}$

- **Signal amplitude: a coherent sum of individual amplitudes for each possible intermediate state**
- **amplitudes must only satisfy the constraints of Lorentz invariance and angular mometum conservation ⇒ Born term amplitudes**
- **amplitudes are a product of a relativistic Breit-Wigner, a spin amplitude and energy dependent form factors**
- **each amplitudes is multiplyied by a complex coefficient ⇒ final state interactions**



$$\mathcal{A}_i = \frac{F_D \times F_R^i}{s - m_{0i}^2 + i m_{0i} \Gamma_i^{tot}(s)} \times \mathcal{M}_i^J$$

$$\Gamma_i^{tot}(s) = \Gamma_0 \, \frac{m_0}{\sqrt{s}} \, \left(\frac{p^*}{p_0^*}\right)^{2J+1} \, \omega(s)$$

$$\mathcal{A} = a_0 e^{i\delta_0} \mathcal{A}_0 + \sum_j a_j e^{i\delta_j} \mathcal{A}_j$$

F_D, F_R^i are the Blatt-Weisskopf damping factors.

$$\boxed{D_s^+ \to \pi^+\pi^-\pi^+}$$

- **channels allowed in the fit:** $f_0(980)\pi^+$, $f_0(1370)\pi^+$, $f_2(1270)\pi^+$, $\rho^0(770)$, $\rho^0(1450)\pi^+$ **and non resonant**

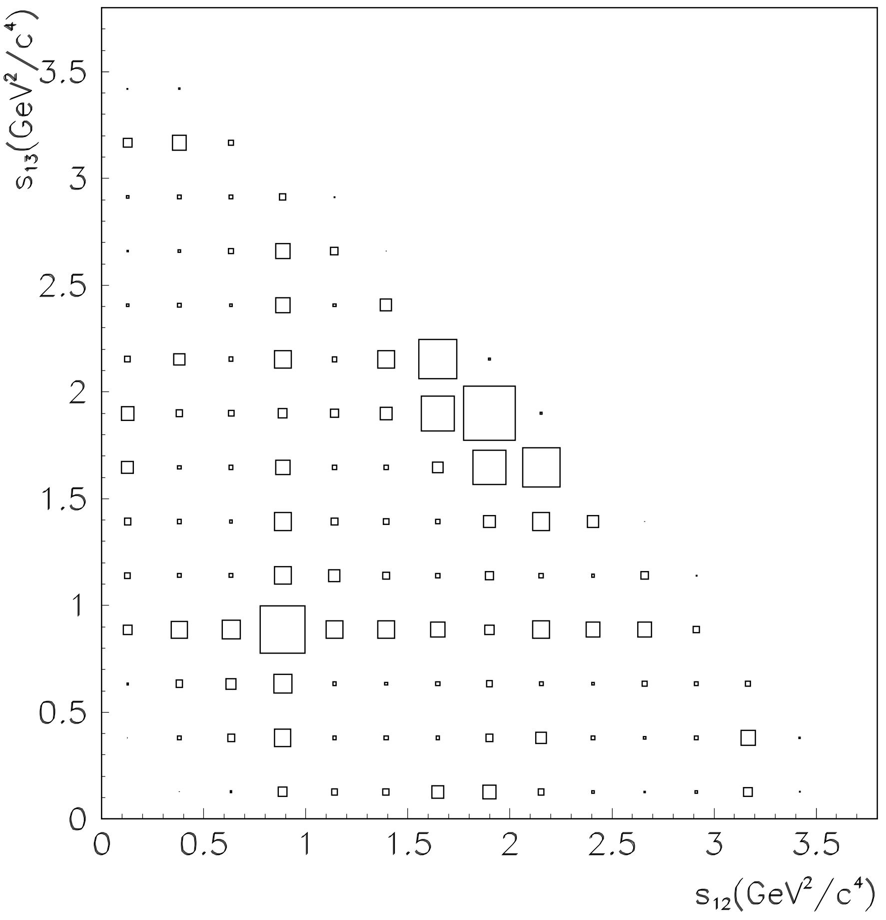
- **coupled channel Breit-Wigner for** $f_0(980)$**:**

$$BW_{f_0(980)} = \frac{1}{s - m_0^2 + im_0(\Gamma_K + \Gamma_\pi)}$$

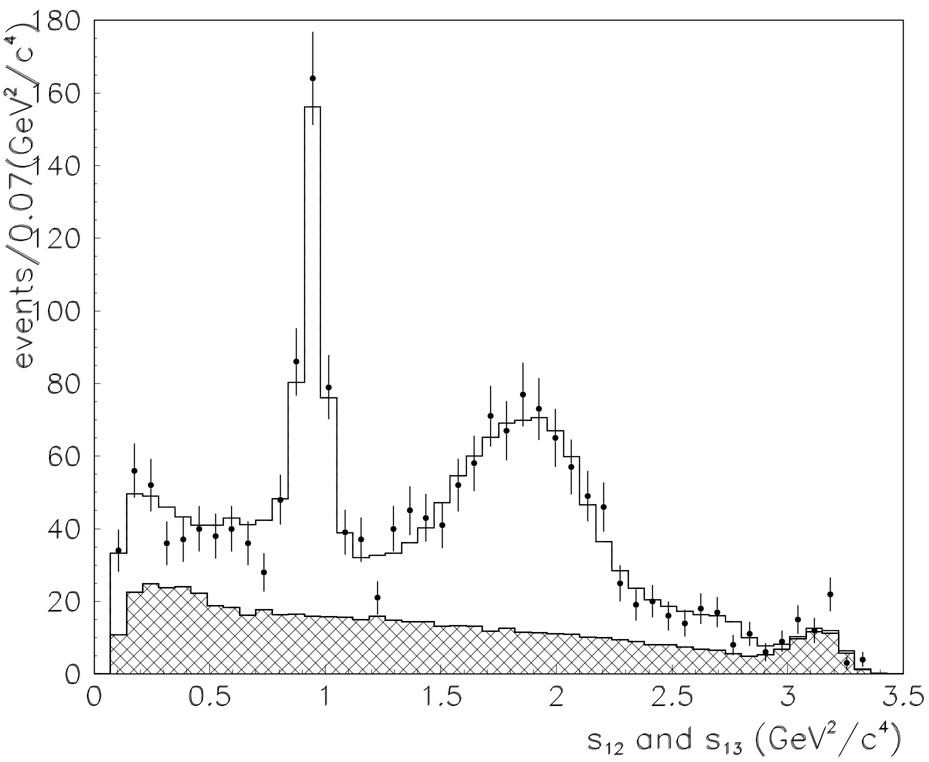
$$\Gamma_K = \frac{g_K}{2}\left(\sqrt{s/4 - m_{K^+}^2} + \sqrt{s/4 - m_{K^0}^2}\right)$$

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

- g_π, g_K **and** m_0, **for the** $f_0(980)$, **and** Γ_0 **and** m_0, **for the** $f_0(1370)$, **are floating parameters**



The $D_s^+ \to \pi^+\pi^-\pi^+$ Dalitz plot



The $M^2_{\pi^-\pi^+}$ projection (2 entries/event)

$\mathbf{f_0(980)}$ - coupled channel BW

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

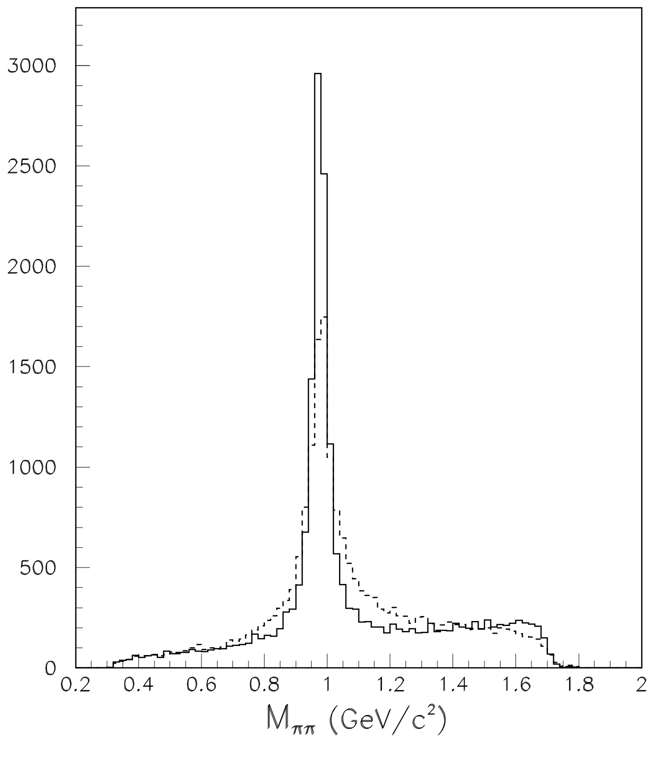
$\mathbf{f_0(980)}$ - standard BW

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

$\mathbf{f_0(1370)}$

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

- g_π **and** g_K **are much smaller than WA76 results** $(g_\pi = 0.28 \pm 0.04$**,** $g_K = 0.56 \pm 0.18)$
- **our value of** g_K **is consistent with zero** $\Rightarrow$ **small** $\mathbf{f_0(980)}$ **coupling to KK**
- **fit with a standard BW for the** $\mathbf{f_0(980)}$ **is nearly as good as the fit with coupled channel BW**
- **The channel** $f_0(980)\pi^+$ **correspond to approximately 57% of the** $D_s^+ \to \pi^+\pi^-\pi^+$ **decay rate**
- **the** $\mathbf{f_0(980)}$ **is narrow, most likely a** $s\bar{s}$ **state**



$M_{\pi\pi}$ **projection from simulated** $D_s^+ \to f_0(980)\pi^+$ **samples. Solid line uses E791 values for** $f_0(980)$ **parameters, dashed line uses WA76 values**

$\boxed{D^+ \to \pi^+\pi^-\pi^+}$

- **fitting the data using the same model as for the $D_s^+ \to \pi^+\pi^-\pi^+$ Dalitz plot: very poor fit (CL = 0.0005%). The disagreement is mostly at low $M^2_{\pi\pi}$ mass.**

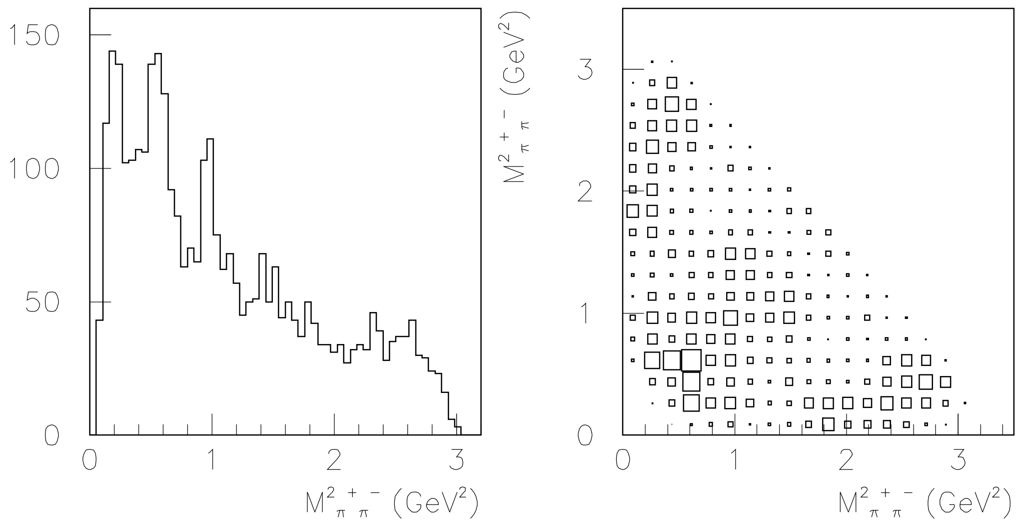
- **inclusion of an additional amplitude, a s-wave BW with floating mass and width: a much better fit with CL $\simeq$ 76%**

- **could the excess of events at low $M^2_{\pi\pi}$ be background rather than signal?**

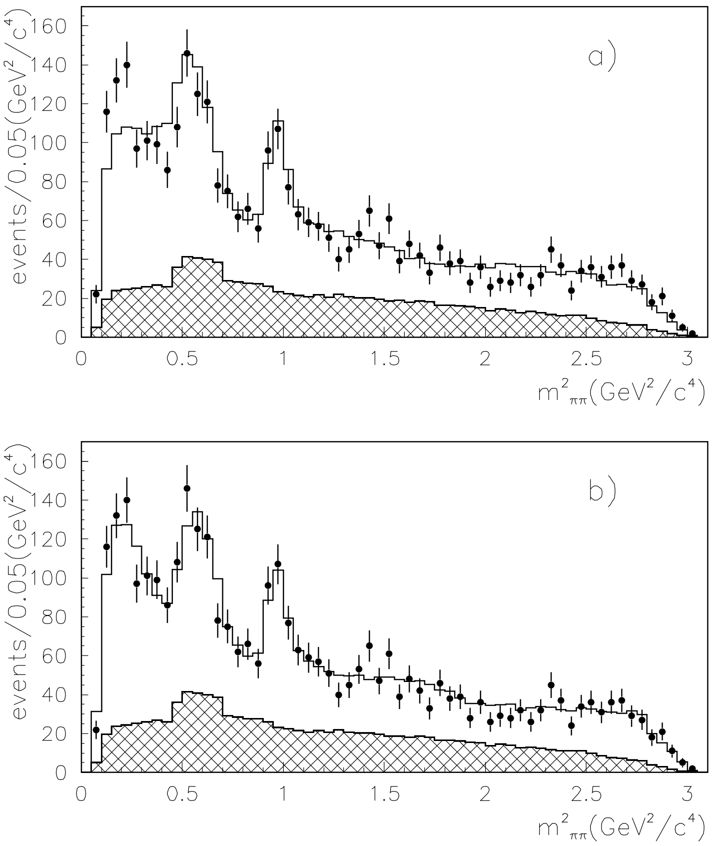
- **could it be just an accident?**

- **would this scalar state be the only possible solution?**

- **tests: vector resonance, tensor resonance, toy BW (constant phase), kinematical (Deck-like) effect, d-wave $\pi\pi$.**



The $D^+ \to \pi^+\pi^-\pi^+$ Dalitz plot



$M^2_{\pi\pi}$ projection: a) no $\sigma(500)\pi^+$ amplitude;
b) with $\sigma(500)\pi^+$ amplitude.

backgrounds

- **combinatorics $\Rightarrow$ sidebands show a flat distribution**

- $D^0 \to K^-\pi^+ \Rightarrow$ **located at the corners of the Dalitz plot**

- $D^0 \to K^-l^+\nu \Rightarrow$ **too small**

- $D_s^+ \to \eta'\pi^+$, $\eta' \to \rho^0(770)\gamma$, $\rho^0(770) \to \pi^-\pi^+ \Rightarrow$ **located at the $\rho^0(770)\pi^+$ signal region**

- $c\bar{c}$ **generic MC does not show any structure at low $M^2_{\pi\pi}$**

E791 found evidence of a new light broad scalar state

$$M = 478^{+24}_{-23} \pm 9 \text{ MeV}$$

$$\Gamma_0 = 324^{+42}_{-40} \pm 9 \text{ MeV}$$

- **signal is a 9.0 standard deviation effect**
- **no such mode was observed in $D_s^+ \to \pi^+\pi^-\pi^+$ decay $\Rightarrow$ a small $s\bar{s}$ component**
- **in $D^+ \to \pi^+\pi^-\pi^+$ this is the dominant mode: $\sim$ 44% of the total decay width $\Rightarrow$ a large $d\bar{d}$ component**

This new state is identified with the $\sigma(500)$ meson

Conclusions and prospects

- **semileptonic decays of τ^- offer a unique source for studies of the axial vector hadronic current, although results still suffer from the theoretical uncertainties on how to handle broad resonances**

- **using the $D_s^+ \to \pi^+\pi^-\pi^+$ decay Fermilab-E791 has studied the $f_0(980)$ and $f_0(1370)$ states. The $f_0(980)$ is a narrow state, with a small coupling to the KK channel, and likely to have a large $s\bar{s}$ component**

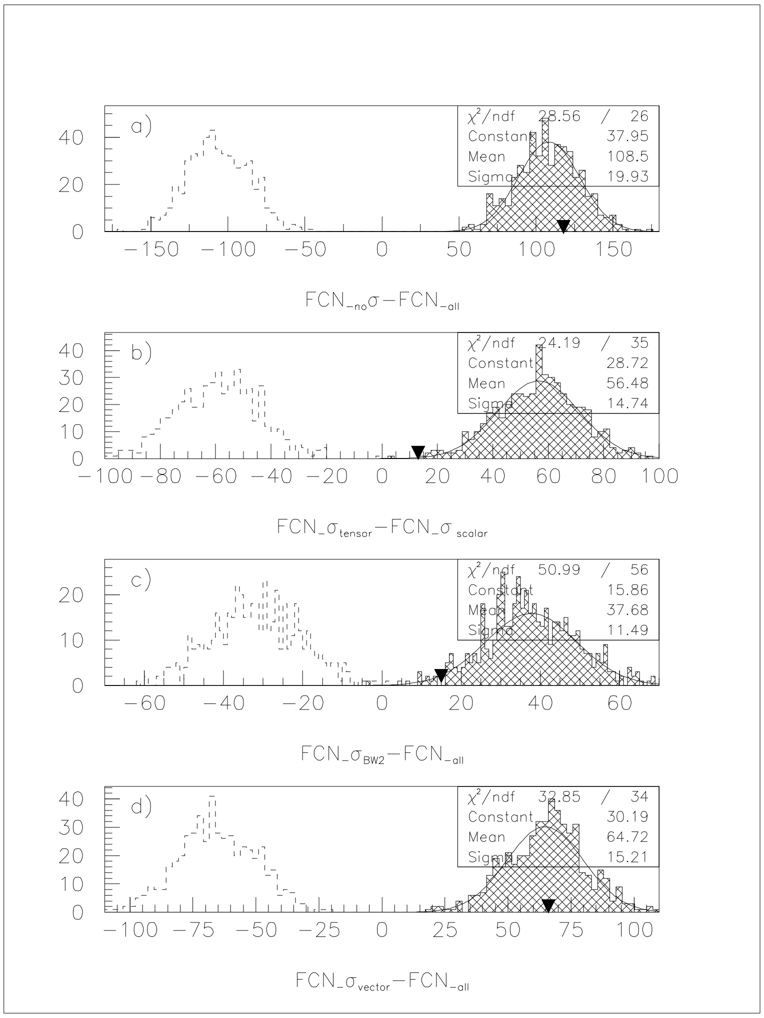
- **using the $D^+ \to \pi^+\pi^-\pi^+$ decay E791 found evidence of a new light broad sacalar resonance, identifyied with the $\sigma(500)$ meson**

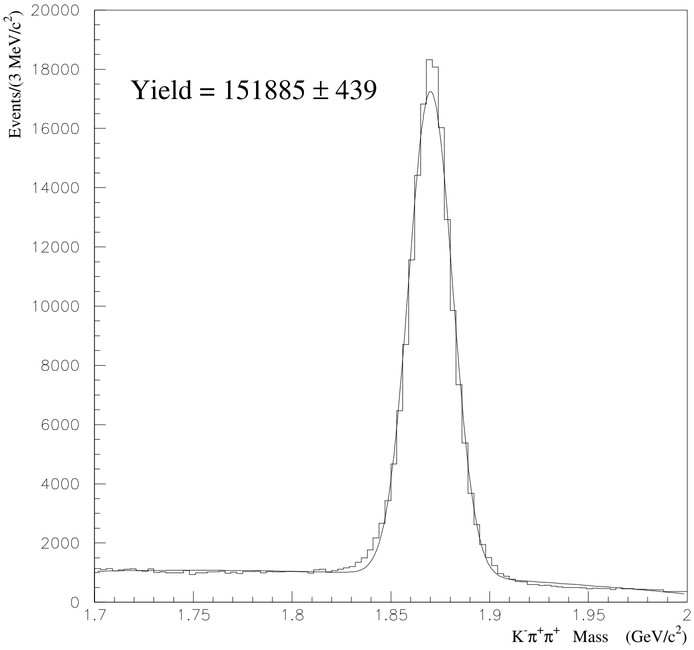
- **large samples of D decays with high purity are available. The $\sigma(500)$ state should be confirmed in other channels ($D^0 \to K3\pi$, $D^0 \to 4\pi$, $D^+ \to \pi\pi l\nu$, $D^+ \to 3\pi\pi^0$, ...)**

- **other systems, like the 3π and $K\pi$ or KK, can also be studied using this technique**

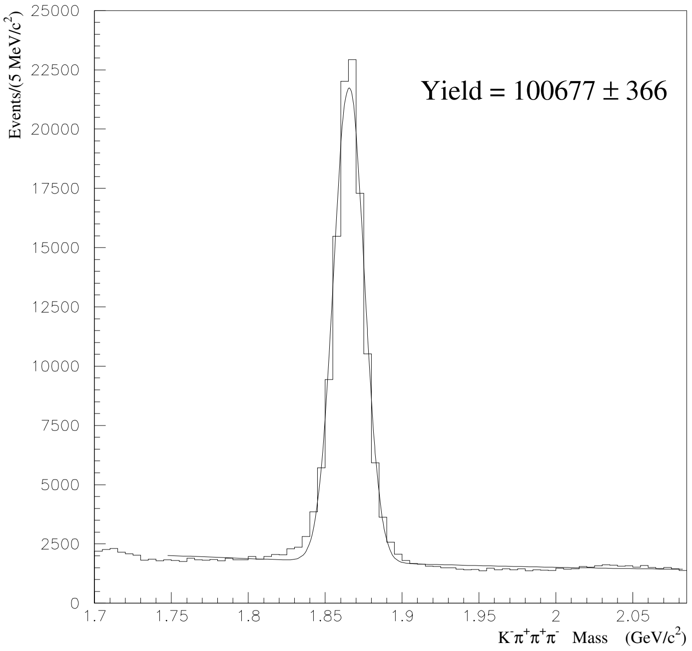
- **charm decays became a clean and complementary tool for light meson physics**

- **future B experiments should have a charm program!**


a)
χ²/ndf 28.56 / 26
Constant 37.95
Mean 108.5
Sigma 19.93
FCN_no σ − FCN_all
b)
χ²/ndf 24.19 / 35
Constant 28.72
Mean 56.48
Sigma 14.74
FCN_σ tensor − FCN_σ scalar
c)
χ²/ndf 50.99 / 56
Constant 15.86
Mean 37.68
Sigma 11.49
FCN_σ BW2 − FCN_all
d)
χ²/ndf 32.85 / 34
Constant 30.19
Mean 64.72
Sigma 15.21
FCN_σ vector − FCN_all



$D^+ \to K^-\pi^+\pi^+$ signal from Fermilab-E831



$D^0 \to K^-\pi^-\pi^+\pi^+$ signal from Fermilab-E831

mode	**phase (degree)**	**fraction(%)**
$\sigma\pi^+$	$(\mathbf{206 \pm 8.0 \pm 5})^\circ$	$\mathbf{46.3 \pm 9.4 \pm 2.1}$
$\rho^0(770)\pi^+$	$\mathbf{0^\circ}$**(fixed)**	$\mathbf{33.6 \pm 3.2 \pm 2.2}$
non-resonant	$(\mathbf{57 \pm 20 \pm 6})^\circ$	$\mathbf{7.8 \pm 6.0 \pm 2.7}$
$f_0(980)\pi^+$	$(\mathbf{165 \pm 11 \pm 4})^\circ$	$\mathbf{6.2 \pm 1.3 \pm 0.4}$
$f_2(1270)\pi^+$	$(\mathbf{57 \pm 8 \pm 3})^\circ$	$\mathbf{19.4 \pm 2.5 \pm 0.4}$
$f_0(1370)\pi^+$	$(\mathbf{105 \pm 18 \pm 1})^\circ$	$\mathbf{2.3 \pm 1.5 \pm 0.8}$
$\rho^0(1450)\pi^+$	$(\mathbf{319 \pm 39 \pm 11})^\circ$	$\mathbf{0.7 \pm 0.7 \pm 0.3}$

Results of the $D^+ \to \pi^+\pi^-\pi^+$ Dalitz plot fit

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

Results of the $D_s^+ \to \pi^+\pi^-\pi^+$ Dalitz plot fit