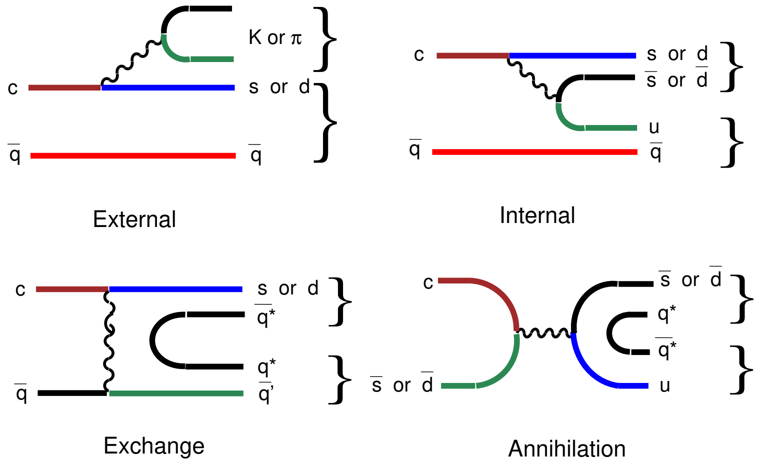
Light Scalar Meson Spectroscopy at E791

- **Hadronic decays of charm mesons - Light meson spectroscopy**
- **The E791 experiment**
- **Analysis Model**
- **Results**
  - $D_s^+ \rightarrow \pi^-\pi^+\pi^+$ [1]
  - $D^+ \rightarrow K^-\pi^+\pi^+$
  - $D^+ \rightarrow \pi^-\pi^+\pi^+$ [2]
- **Other results.**
- **Summary**

[1] E. Aitala *etal* , PRL **86** 765-769. hep-ex/0007027
[2] E. Aitala *etal* , PRL **86** 770-774. hep-ex/0007028

HQ Physics: Decay Dynamics

Hadronic decays (which are mostly quasi 2 body) provide information on decay mechanisms:



Decays of Charmed Mesons to Two Meson States

So far little evidence for annihilation diagram exists.

NOTE Decay products most likely $q\bar{q}$.

For example:

- Lifetimes:
  Destructive interference between "Internal" and "External" is probably what makes $\tau_{D^+} \approx 2.5 \times \tau_{D^\circ}$.
- Branching Fractions:

$$\boxed{D_s^+ \rightarrow \rho\pi \text{ (or } 3\pi) \Rightarrow \text{"annihilation" only possibility.}}$$

LQ Physics: Powerful New Tool for LQ Spectroscopy

- Decay products have $J = 0$
  $\Rightarrow$ greatly simplifies analysis

  (BUT weak decay $\Rightarrow$ P & I undefined)

- Can study all varieties of meson:
  - Hadronic final states most likely $q\overline{q}$.
  - Decays to η, η' or to $K^\circ\overline{K^\circ}$ can involve gluonic systems too.

- Decays are dominantly "quasi 2 body"
  $\Rightarrow$ use isobar analysis with little "non resonant" background.

- Decays of type $D(D_s) \longrightarrow 0^-0^+$ (J^P) seem to be favoured (why?)
  $\Rightarrow$ good, clean source of scalar states.

High quality charmed particle decay data now available - studies can become even more sophisticated.

Where LQ Meson work Has been done

"Peripheral model" extrapolations:

$\pi^-\pi^+ \longrightarrow \pi^-\pi^+,\ \pi^\circ\pi^\circ$	**(πN collision expts.)**
$\pi^-\pi^+ \longrightarrow K^-K^+,\ K^\circ K^\circ$	"
$\pi^-\pi^+ \longrightarrow \eta\eta,\ \eta\eta'$	"
$K^-\pi^+ \longrightarrow K^-\pi^+$	**(K^-p, LASS)**
K^-"K^+"$\longrightarrow K^-K^+,\ K^\circ K^\circ$	"

$p\overline{p}$ annihilations (LEAR - at rest):

$p\overline{p} \longrightarrow 3\pi^\circ,\ 5\pi^\circ$ $\pi^\circ\pi^\circ\eta,\ \eta\eta\pi^\circ,\ \eta\eta'\pi^\circ$	**Crystal Barrel $p\overline{p}$ states:** **$J^{PC} = 0^{-+}, 1^{++}, 2^{++}$)** **FNAL E760 - higher p**

ϕ c.f. ω ($s\overline{s}$ content):

$J/\psi \longrightarrow \phi\pi\pi,\ \phi K\overline{K}$ $\omega\pi\pi,\ \omega K\overline{K}$	**(Mark II, III)**

Rich gluon content:

$J/\psi \rightarrow \gamma\pi\pi,\ \gamma K\overline{K},\ \gamma\eta\eta,\ \gamma\eta\eta'$	**(Mark III)**
$pp \rightarrow pp + X_{central}$	**(WA76, WA102)**
$\psi' \longrightarrow J/\psi\pi\pi$ $Y' \rightarrow Y\pi\pi,\ Y'' \rightarrow Y\pi\pi$	**(Mark III)**

Suppressed gluon content:

$\gamma\gamma \rightarrow \pi\pi,\ K\overline{K}$	**(TPC)**

Some Scalar Issues

Too Many $f_\circ$'s:

There are at least 7 reported $f_\circ$'s. Some of these are likely to be glueballs or mixed states.

One of them - $f_J(1710)$ - might be spin 2.

How many scalar nonets are there?

Are there any?

Are $f_\circ(980), a_\circ(980)$ and $K_\circ(1410)$ the lowest mass scalars?
OR Are there lower mass states: σ or κ??

What are they?

$q\overline{q}$, $qq\overline{qq}$, glueballs, mixed, . . . ?

- In any event, it seems very important to understand where the σ (chiral partner of the pion) is.
- Any help understanding the low mass scalars is worthwhile.

The E791 Experiment

- **Fixed target $\pi^- N$ at 500 GeV/c, $\sqrt{s} \sim 40$ GeV.**
  - **one Pt and four C target foils ~ 1.5 mm thick**
- **Very loose trigger requiring single particle interaction, E_T in calorimeter**
  - **2×10^{10} triggers recorded**
  - **$\sim$ 25,000 exabyte tapes**
- **Silicon strip detectors upstream and downstream used to detect decay vertices**
  - **charmed hadrons usually decay in gaps between foils**
- **Took data 9/91-1/92, largest, minimal bias trigger full reconstructed charm sample until last year:**

$$
\begin{array}{ll}
D^{\pm} \longrightarrow K^- \pi^+ \pi^+ & \mathbf{70K} \\
D^{\circ} \longrightarrow K^- \pi^+ & \mathbf{50K} \\
D^{\circ} \longrightarrow K^- \ell^+ \nu_\ell & \mathbf{40K} \\
D_s^+ \longrightarrow K^- K^+ \pi^+ & \mathbf{30K}
\end{array}
$$

NOTE - *No π°, η nor η' channels were studied.*

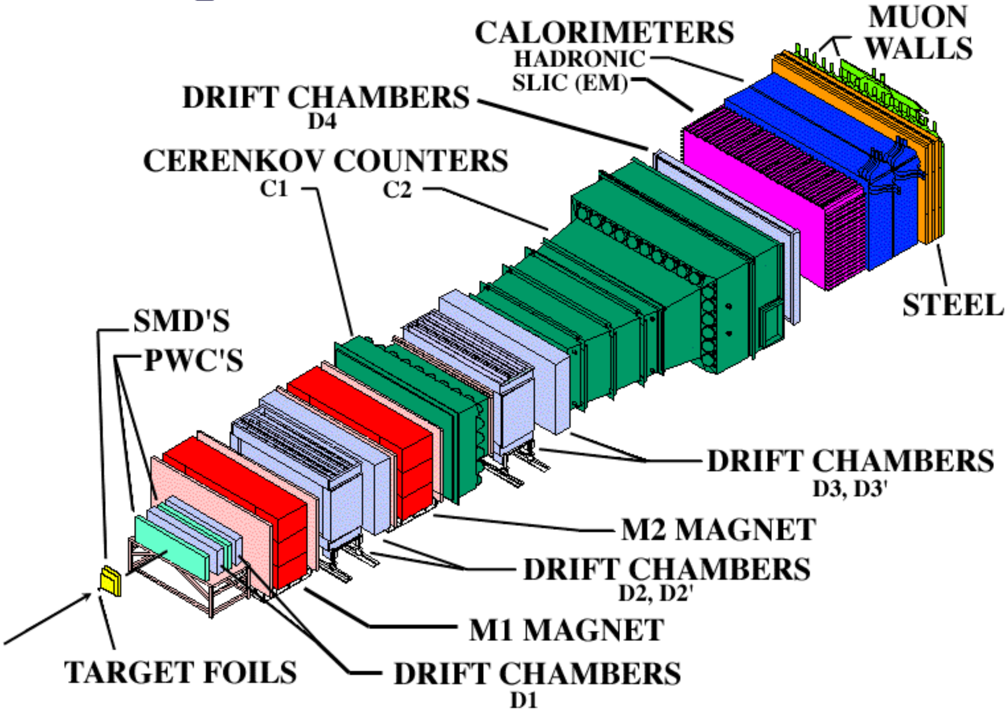
Recently superceded by FOCUS (FNAL E831) with $> 10^6$ reconstructed charm decays.
Babar and Belle rapidly catching up.

E791 Collaboration approximately 70 physicists

Brazil:	**Centro Brasileiro De Pesquisas Fisicas**
Israel:	**Tel Aviv**
Mexico:	**CINVESTAV (Mexico City)**
Uruguay:	**Universidad de la Republica, Montevideo**
USA:	**U.C. Santa Cruz, U. of Cincinnati, Fermilab, Illinois Institute of Technology, Kansas State U., U. of Mississippi, Ohio State U., U. of South Carolina, Stanford, Tufts, U. of Wisconsin, Yale**

Published 29 papers in PRL, PRD, PL, NPB with three more in process.

E-791 Spectrometer



<u>Vertex Region:</u> Silicon μ-strip detectors - 6 planes upstream and 17 downstream of target.

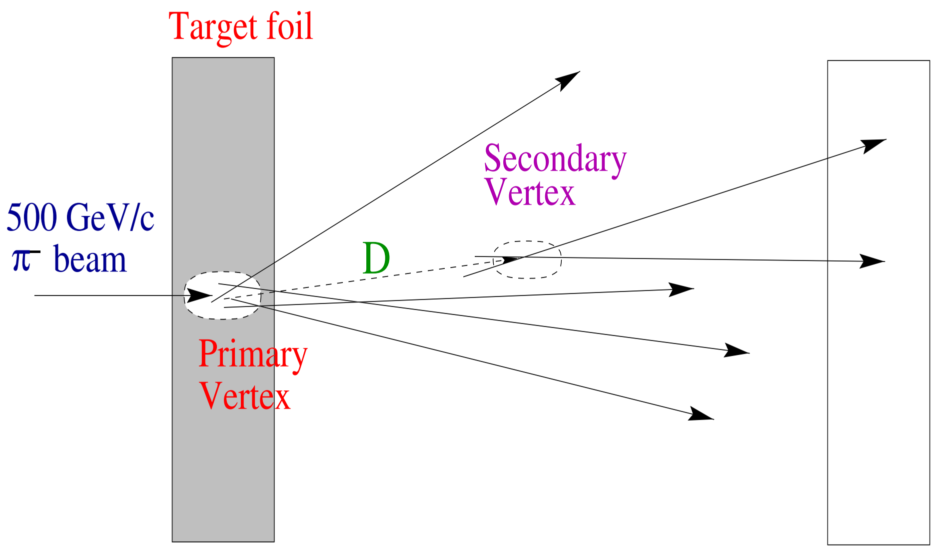
<u>Tracking:</u> 45 planes of drift/proportional wire chambers, 2 large aperture dipole magnets with p_T kicks $+212$ and $+\ 320$ MeV/c.

<u>$p/K/\pi$ Separation:</u> Two threshold Cherenkov detectors spanning momentum range 6-60 GeV/c.

<u>Calorimetry:</u> Pb/liquid-scintillator (20 radiation lengths)
Fe/plastic-scint. (6 interaction lengths)

<u>μ Identification:</u> Steel absorber. Two walls of scintillation counters segmented in x and y; the y wall was instrumented with TDC's.

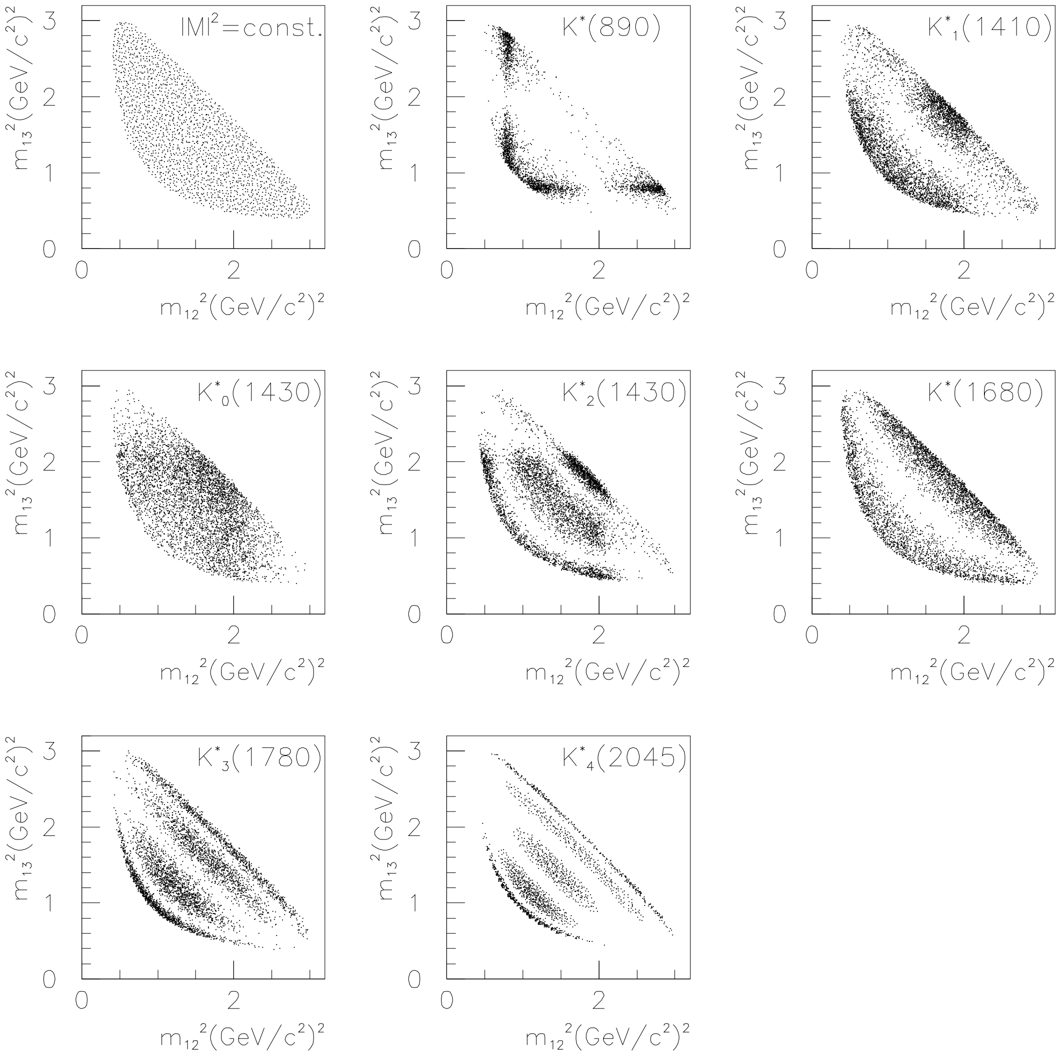
Charm in Hadron Environment



Variable	Typical Value
Vertex resolution $\sigma_{\parallel} \times \sigma_{\perp}$	$350 \times 6\ \mu$m
D meson mean momentum	$70\ GeV/c$
D° pathlength	5 mm
$\Delta_{\mathrm{prim}} = \left(z_{\mathrm{sec}} - z_{\mathrm{prim}}\right) / \sqrt{\left(\sigma_{\parallel}^2\right)_{\mathrm{sec}} + \left(\sigma_{\parallel}^2\right)_{\mathrm{prim}}}$	$8 - 20$
Δp_T($\perp$ to charm line-of-flight)	$< 250 MeV/c$
$\Delta_z(\mathrm{target}) = \left(z_{\mathrm{target\ edge}} - z_{\mathrm{sec}}\right) / \sigma_{\mathrm{sec}}$	> 5
DIP (impact par. wrt primary vertex)	$< 60\ \mu$m
χ^2_{track}	< 5
lifetime $\equiv \left(z_{\mathrm{sec}} - z_{\mathrm{prim}}\right) \times \frac{m_D}{p}$	$< 5ps$

Isobar Model

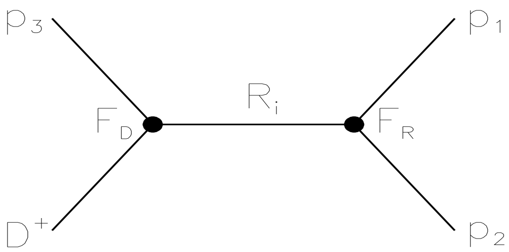
Each decay is defined by coordinates in Dalitz plot (s_{12}, s_{13}).



Fit density to extract physics:

- Definite spin $\longrightarrow$ resonances interfere.
- Non D background is incoherent.

Isobar Model



- **The amplitude for each isobar must satisfy Lorentz invariance, conserve total spin and (if appropriate) be Bose symmetrized.**

$$\begin{aligned}\mathcal{A}_R &= F_D(q, r_D) F_R(p, r_R) \times BW_R(s_{12}) \\ & \quad \times \; (-1)^J |\vec{p}|^J |\vec{q}|^J P_J(\cos\theta)\end{aligned}$$

where

F_D, F_R		Blatt-Weisskopf form factors
$\vec{p}$ $(\vec{p}_R)$		$\vec{p}_1$ in 12 CMS (value at $s_{12} = s_R$)
$\vec{q}$		$\vec{p}_3$ in D CMS
θ		$\cos^{-1}(\hat{p}\cdot\hat{q})$
BW_R	$=$	$[s_R - s_{12} - i m_R \Gamma(s_{12})]^{-1}$

- **The decay amplitude: coherent sum of individual modes**

$$A_S(s_{12}, s_{13}) = a_{\rm NR} \; + \; \sum_R a_R e^{i\delta_R} \mathcal{A}_R$$

where a, δ are found empirically and $a_{\rm NR}$ corresponds to non-resonant decay to three particles.

Isobar Model (II)

- **In decays to final states where 2&3 are identical (*e.g.* $\pi^-\pi^+\pi^+$ or $K^-\pi^+\pi^+$ A_S) must be Bose symmetrized:**

$$A_S(s_{12}, s_{13}) \;\longrightarrow\; A_S(s_{12}, s_{13}) \;+\; A_S(s_{13}, s_{12})$$

- **The BW used had mass dependent width**

$$\Gamma(s_{12}) = \left[\frac{F_R(p, r_R)}{F_R(p_R, r_R)}\right]^2 \left(\frac{p}{p_R}\right)^{2J+1} \sqrt{\frac{s_R}{s_{12}}}\Gamma_\circ$$

- **Blatt-Weisskopf damping factors were:**

$$\begin{aligned} F_X &= 1 & J = 0 \\ &= (1 + r_X^2 p^2)^{-1/2} & J = 1 \\ &= (9 + r_X^2 p^2 + r_X^4 p^4)^{-1/2} & J = 2 \end{aligned}$$

where r_X is the "radius" of X.

- **Values usually taken (*Argus, PLB308, 435 1993*) for radii are**

$$r_D = 3.0\ GeV/c \;\;;\;\; r_{\rho,K^*} = 1.5\ GeV/c$$

- Efficiency $\epsilon(s_{12}^2, s_{13}^2)$ was determined at each point in Dalitz Plot using large MC samples.

- Background distribution ($\mathcal{P}_B(s_{12}, s_{13})$) modelled for events under D mass peak:
  - non charm sources - from D signal sidebands
  - other charm sources - from MC

- D mass shape $S(M_D)$ was folded onto Dalitz Plot (fuzzy boundary).
  $\Rightarrow$ all p, q, θ computed with M_D for event.

$\Rightarrow$ PDF for Dalitz plot:

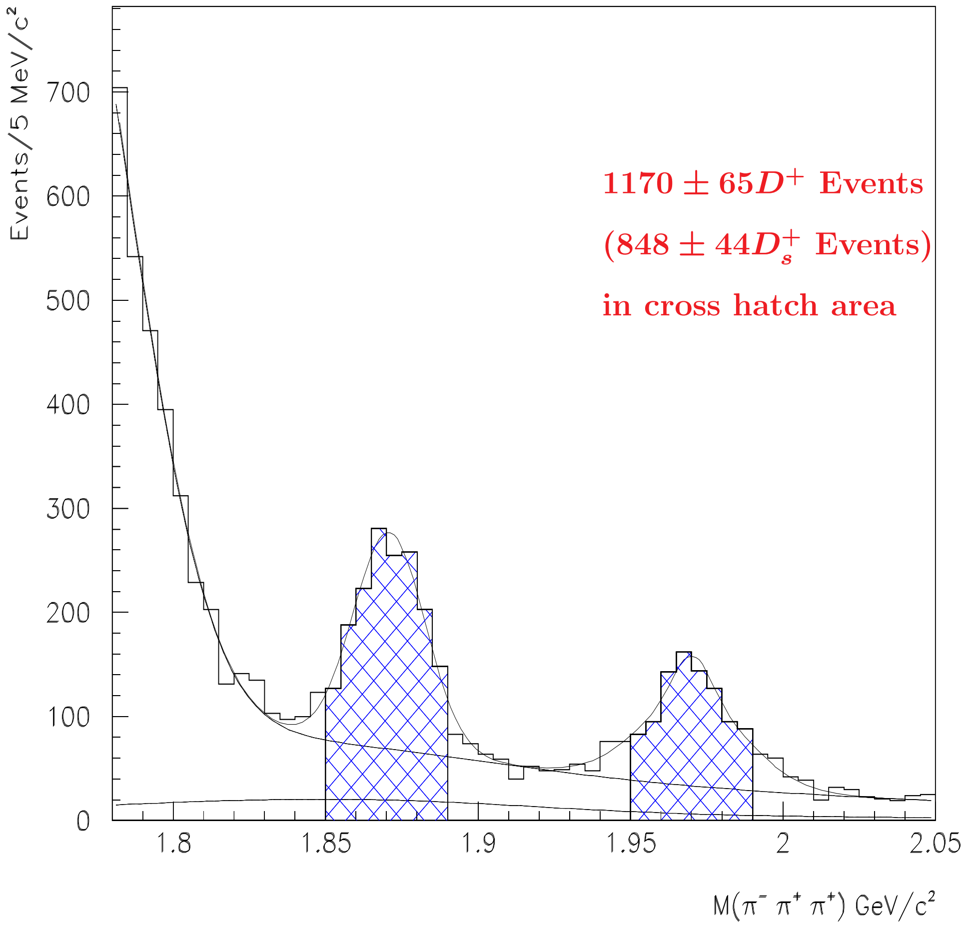
$$\mathcal{P}(s_{12}, s_{13}, M_D) = S \times [f\mathcal{P}_B/N_B + \epsilon(1-f)|A_S|^2/N_S]$$

where

$$\begin{aligned} N_B &= \int dM_D S(M_D) \int ds_{12} ds_{13} \mathcal{P}_B^2 \\ N_S &= \int dM_D S(M_D) \int ds_{12} ds_{13} \epsilon |A_B|^2 \end{aligned}$$

f is fraction of background

Decays $D^+(D_s^+) \to \pi^-\pi^+\pi^+$



Event Selections:

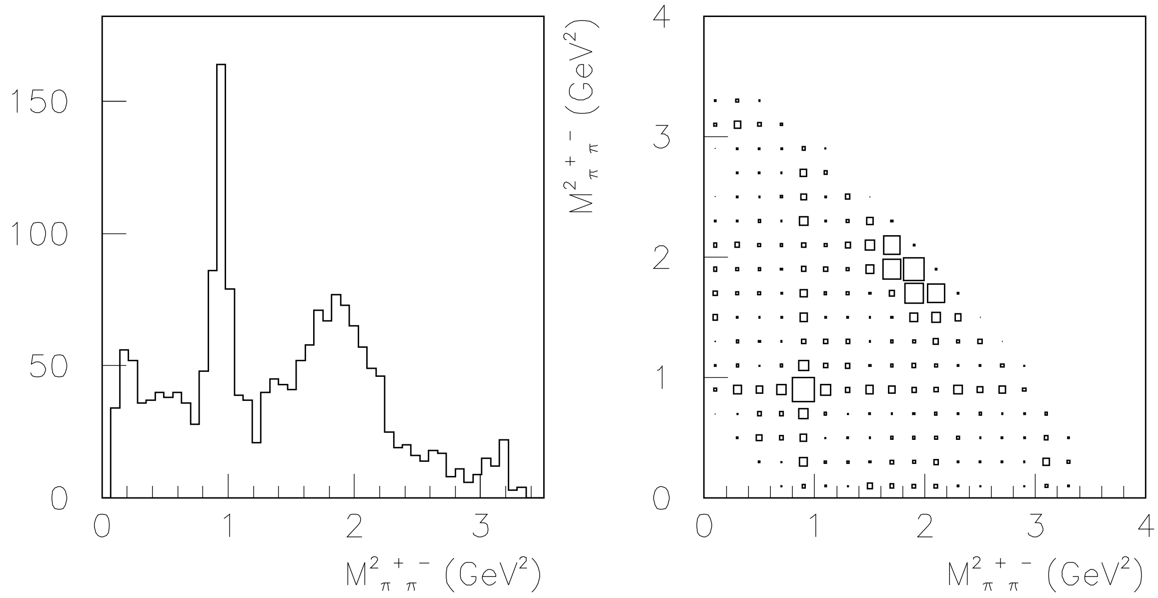
3 track-good vertex
$\Delta p_T < 250$ GeV/c
$\Delta z_{\text{prim}} > 8\sigma$
$\Delta z_{\text{target}} > 4\sigma$
$DIP < 40\ \mu$m
Cuts on unique vertex

Backgrounds:

Charm sources - modelled by MC:

$D^\circ \to K^-\pi^-\pi^+$
$D_s^+ \to \eta'(\to \pi^+\pi^-\gamma)\pi^+$
$D^\circ \to K^-\pi^+$ (extra π)
Combinatorial - modelled from side bands.

Decay $D_s^+ \rightarrow \pi^-\pi^+\pi^+$



$$
\boxed{D_s^+} \longrightarrow
\begin{array}{c}
\textbf{non resonant} \\
\rho(770)\pi^+ \\
f_\circ(980)\pi^+ \\
f_2(1270)\pi^+ \\
f_\circ(1370)\pi^+ \\
\rho(1450)\pi^+
\end{array}
\longrightarrow \boxed{\pi^-\pi^+\pi^+}
$$

Fit Approach

- **Coupled channel Breit-Wigner for $f_\circ(980)$:**

$$\begin{aligned} BW_{f_\circ(980)}(s) &= \left[s - m_\circ^2 + i m_\circ \left(\Gamma_K + \Gamma_\pi\right)\right]^{-1} \\ \Gamma_K &= \frac{g_K}{2}\left(\sqrt{s/4 - m_K^2} + \sqrt{s - m_{K^\circ}^2}\right) \\ \Gamma_\pi &= g_\pi \sqrt{s/4 - m_\pi^2} \end{aligned}$$

- **Large uncertainties exist for the $f_\circ$ parameters (PDG)**

$$\begin{array}{lcrcrcrl} f_\circ(1370) & : & m_\circ & = & 1200 & to & 1500 & \mathrm{MeV/c^2} \\ & & \Gamma_\circ & = & 200 & to & 500 & " \\ f_\circ(980) & : & m_\circ & = & 980 & \pm & 10 & " \\ & & \Gamma_\circ & = & 40 & to & 100 & " \end{array}$$

$\Downarrow$

Obtain $f_\circ$ parameters from fit to D_s decays.

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

$f_\circ(1370)$

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

$f_\circ(980)$

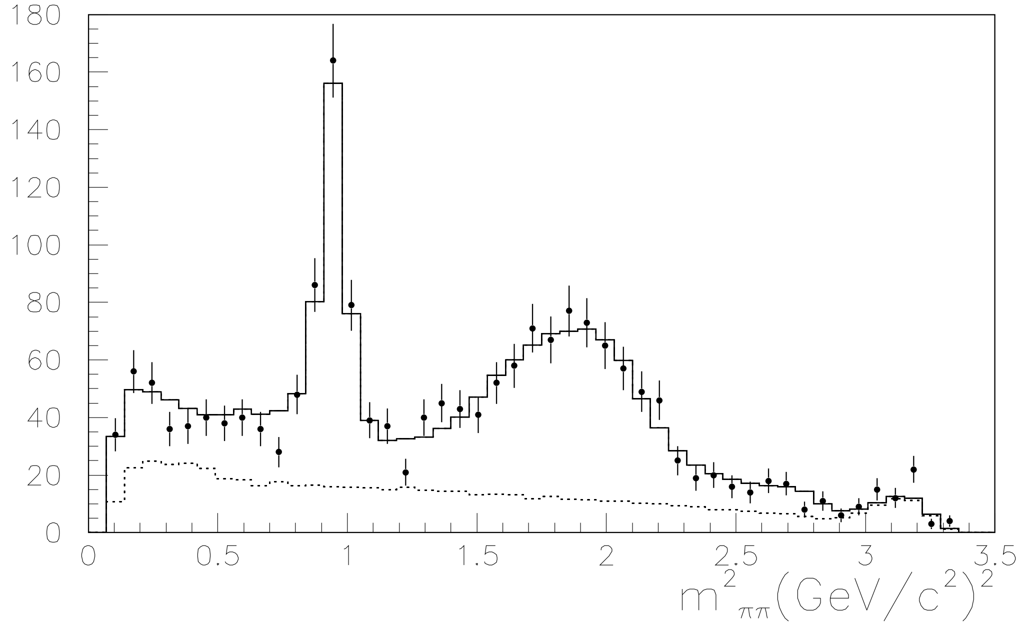
$$m_\circ = (975 \pm 3 \pm 2)\ \mathrm{MeV/c^2}$$
$$\Gamma_\circ = (44 \pm 2 \pm 2)\ \mathrm{MeV/c^{2(*)}}$$

.(*) corrected for experimental resolution.

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

Fit Quality

$$\chi^2/\text{dof} = 1.16 \quad (\text{CL} = 56\%)$$



Summary of $D_s^+ \to \pi^-\pi^+\pi^+$ Results:

- $f_\circ \pi^+$ channels dominate ($0^- \to 0^- 0^+$);
- $f_\circ(980)$ is narrow. ($\Rightarrow s\bar{s}$ state?);
- $g_K(980) \ll g_\pi$

Two Views of the $f_\circ(980)$

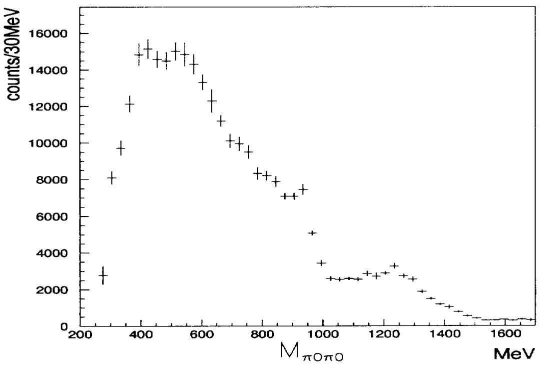


Figure 3:

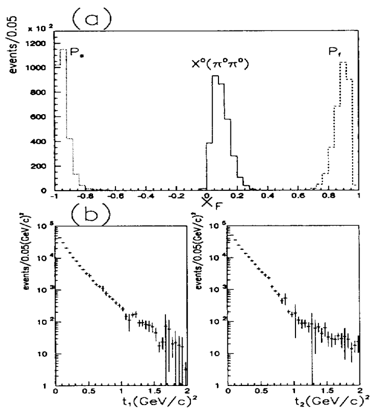
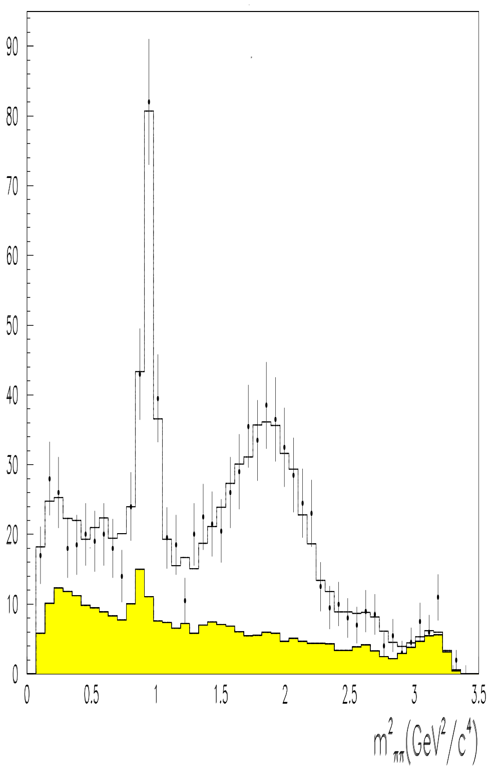


Figure 4:

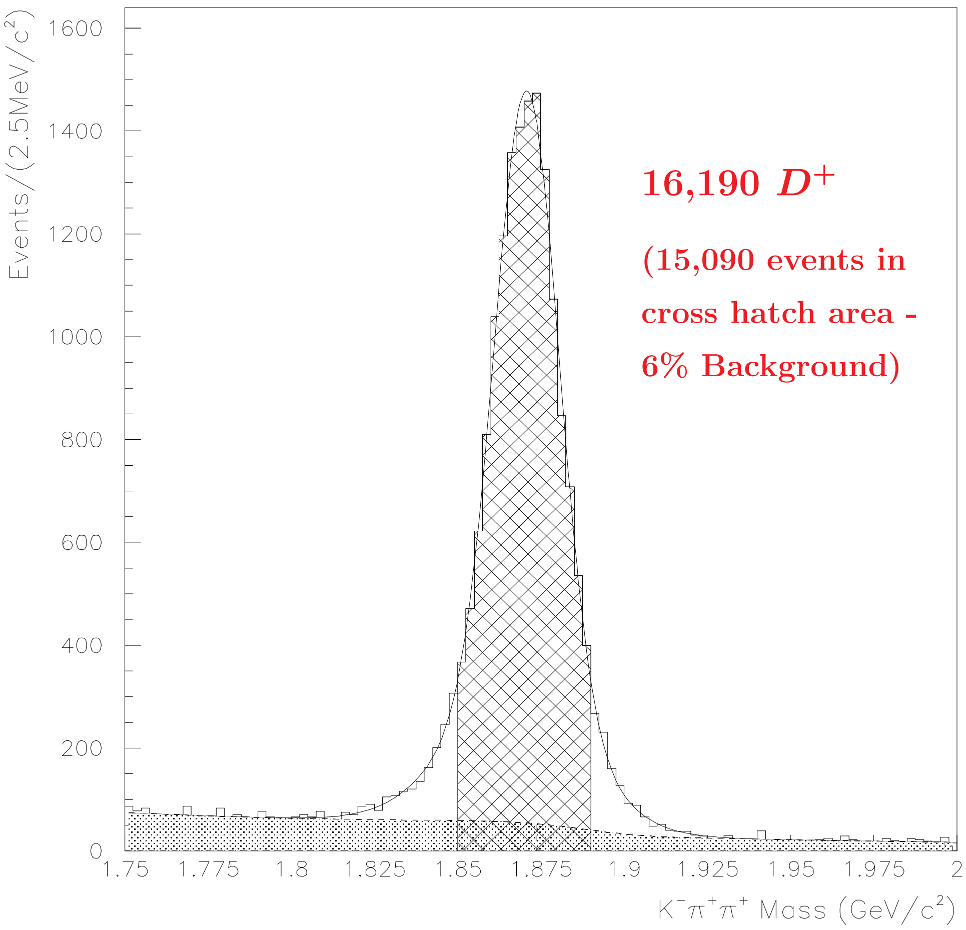
10

GAMS $\pi^\circ\pi^\circ$ s-wave
(Top Figure)



E791 $\pi^-\pi^+$ mass^2 from $D_s^+ \rightarrow \pi^-\pi^+\pi^+$ decays.

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



Event Selections:

3 tracks $|\vec{p}| < 500$ GeV/c
Cherenkov ID for K
$\Delta p_T < 250$ GeV/c
Good vertex fit
$\Delta z_{\text{prim}} > 15\sigma$
$\Delta z_{\text{target}} > 2\sigma$
$DIP < 0.004$ cm
$6 < |\vec{p}_K| < 40$ GeV/c
$p_T^2(D^+) > 0.5$ (GeV/c)^2

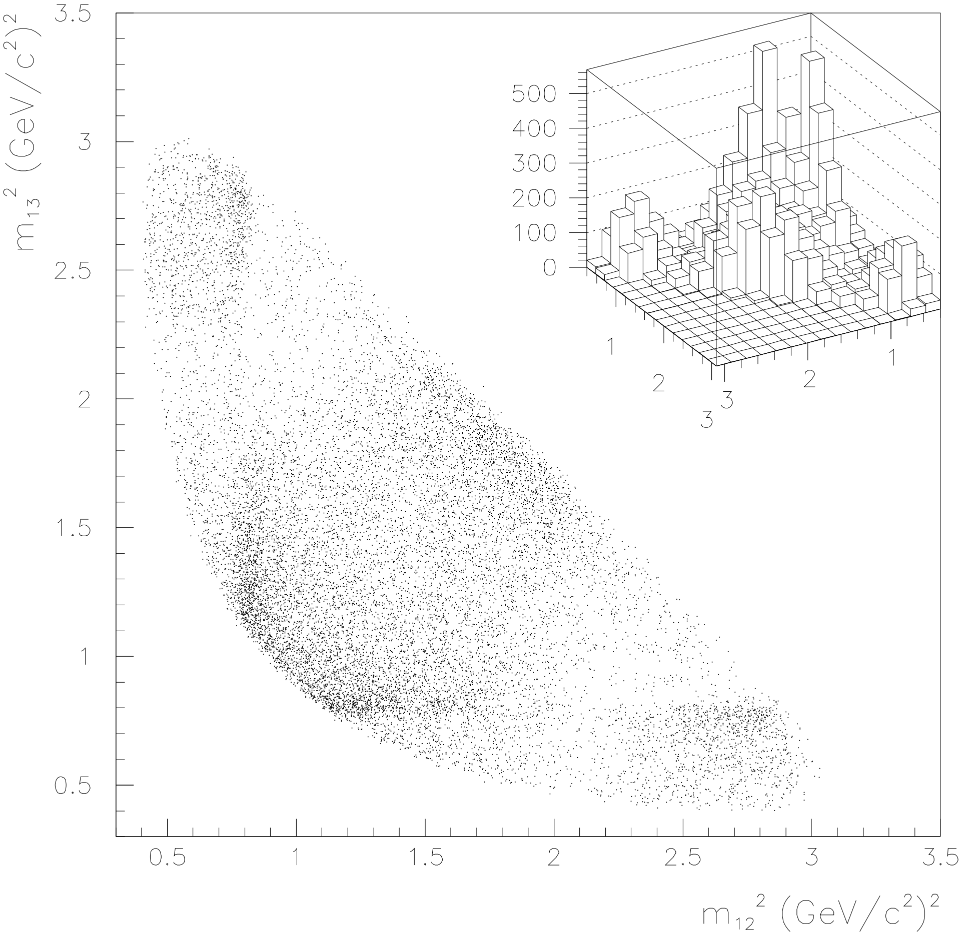
Backgrounds:

Charm sources - modelled by MC:

$D^\circ \to K^-\pi^-\pi^+\pi^+$
$D_s^+ \to \overline{K}^{*\circ}K^+$
$D_s \to \phi\pi^+$ (removed by cut on ϕ)

Combinatorial - modelled from side bands.

Decay $D^+ \rightarrow K^-\pi^+\pi^+$



$$\boxed{D^+} \longrightarrow \begin{matrix} \text{non resonant} \\ \overline{K}^{*\circ}(890)\pi^+ \\ \overline{K}^{*\circ}(1430)\pi^+ \\ \overline{K}_2^{*\circ}(1430)\pi^+ \\ \overline{K}^{*\circ}(1680)\pi^+ \\ \text{“}\kappa\text{”}\pi^+ \end{matrix} \longrightarrow \boxed{K^-\pi^+\pi^+}$$

First Approach

"Standard" Ansatz
With All Known $K\pi$ Resonances

- **Fixed resonance masses & widths at PDG values.**
- **No form factors for scalar states.**

Results

Preliminary

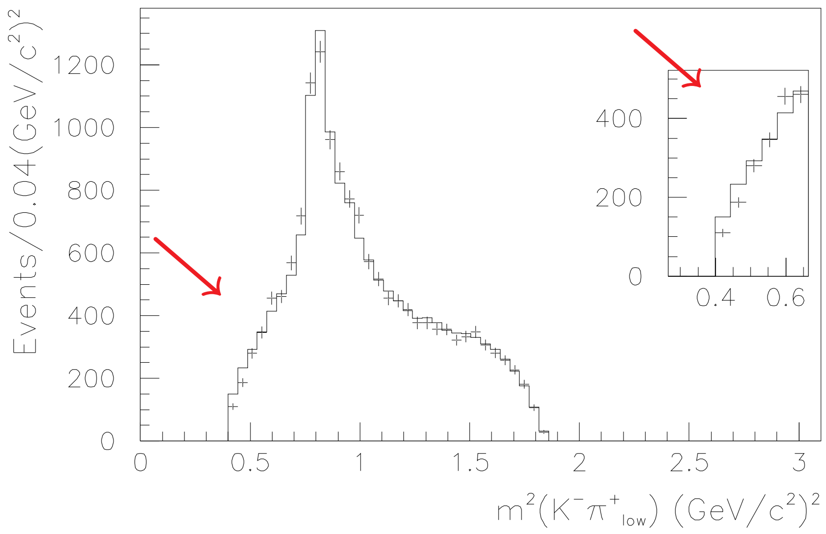
Mode	Relative Phase	Fraction (%)
Non-resonant	0° (fixed)	90.0 ± 2.6
$K^*(890)\pi^+$	$(54 \pm 2)^\circ$	13.8 ± 0.5
$K^*_\circ(1430)\pi^+$	$(54 \pm 2)^\circ$	30.6 ± 1.6
$K^*_2(1430)\pi^+$	$(33 \pm 8)^\circ$	0.4 ± 0.1
$K^*_1(1680)\pi^+$	$(66 \pm 3)^\circ$	3.2 ± 0.3

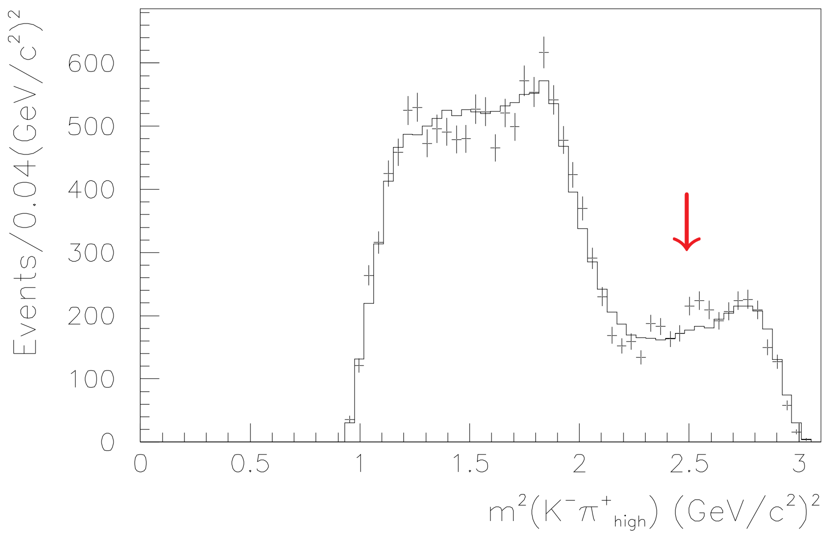
Some Problems:

- **very large non-resonant contribution unusual in D decays**
- **sum of fractions large ~140%**
- **general agreement with E691 and E687**
- **bad fit quality - mostly in low $K\pi$ mass region also at $\sim 2.5\ (\mathrm{GeV})^2$ in the other $K\pi$ mass**

"Standard" Fit Result

$$\boldsymbol{\chi^2/\mathrm{dof} = 2.7 \quad (CL = 10^{-11}}$$





FNAL E687

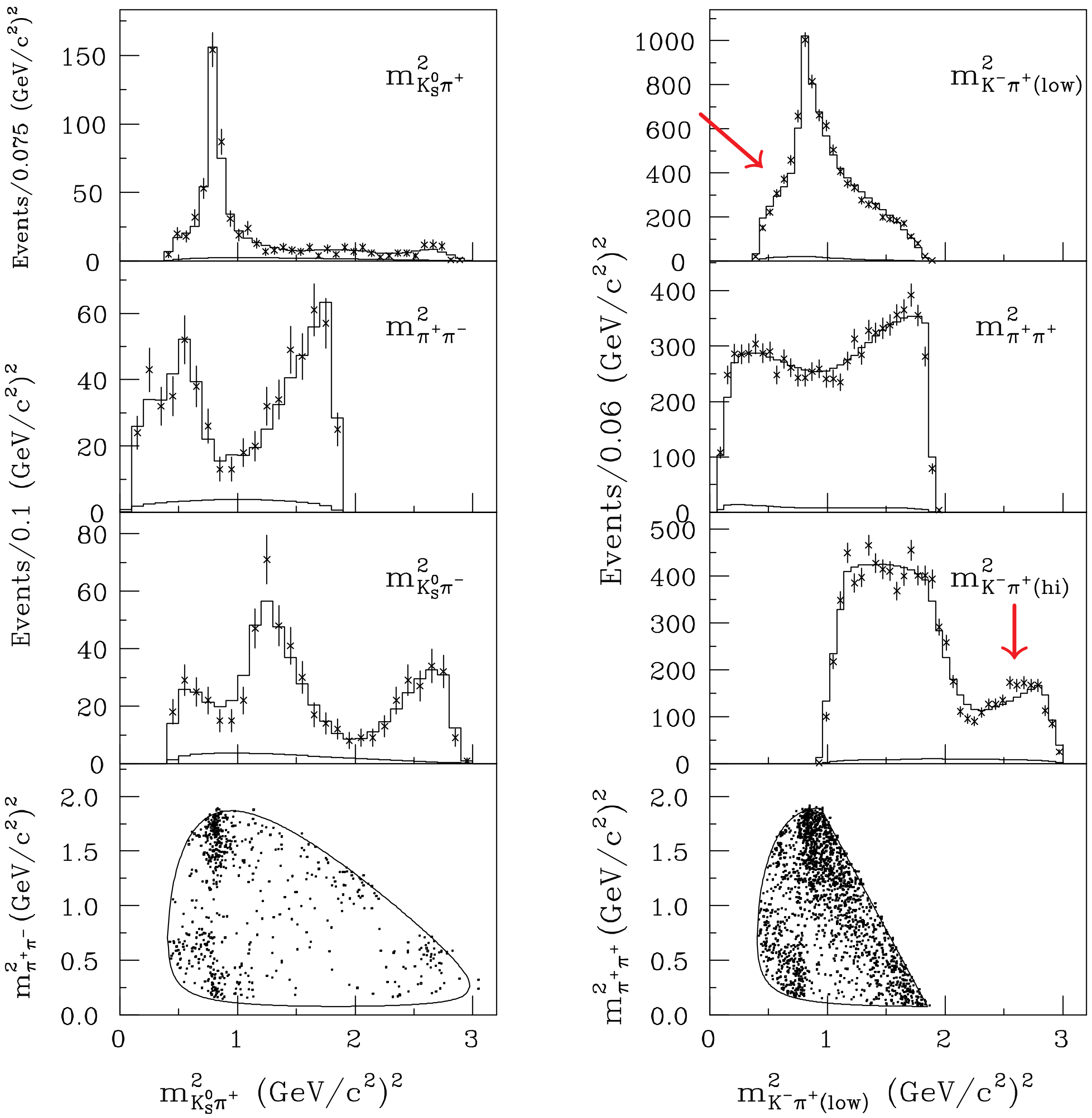
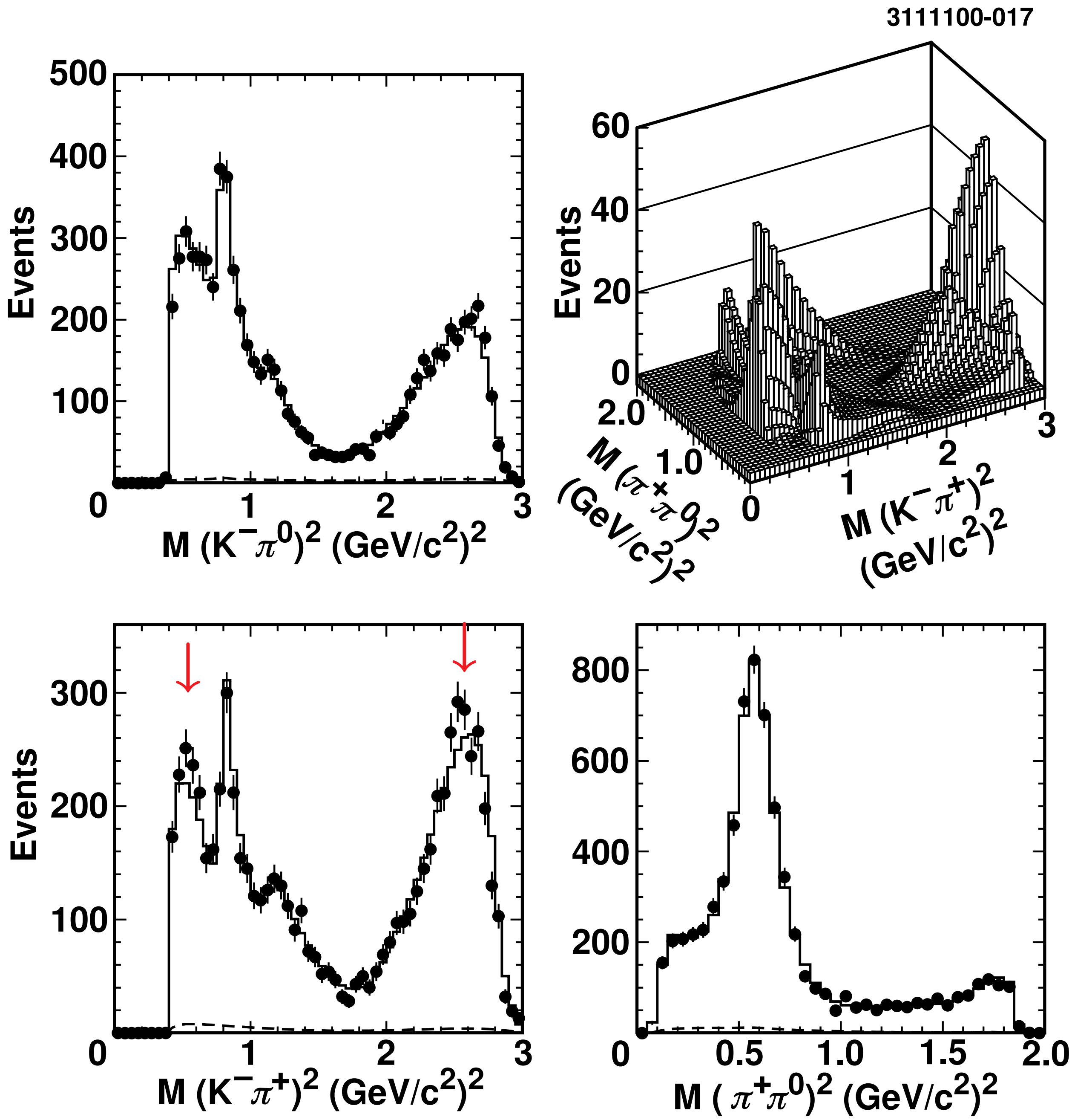


Figure 2

From *P. Fabretti, etal* **, PLB 331, 217 (1994)**

Similar problems, less statistically significant.

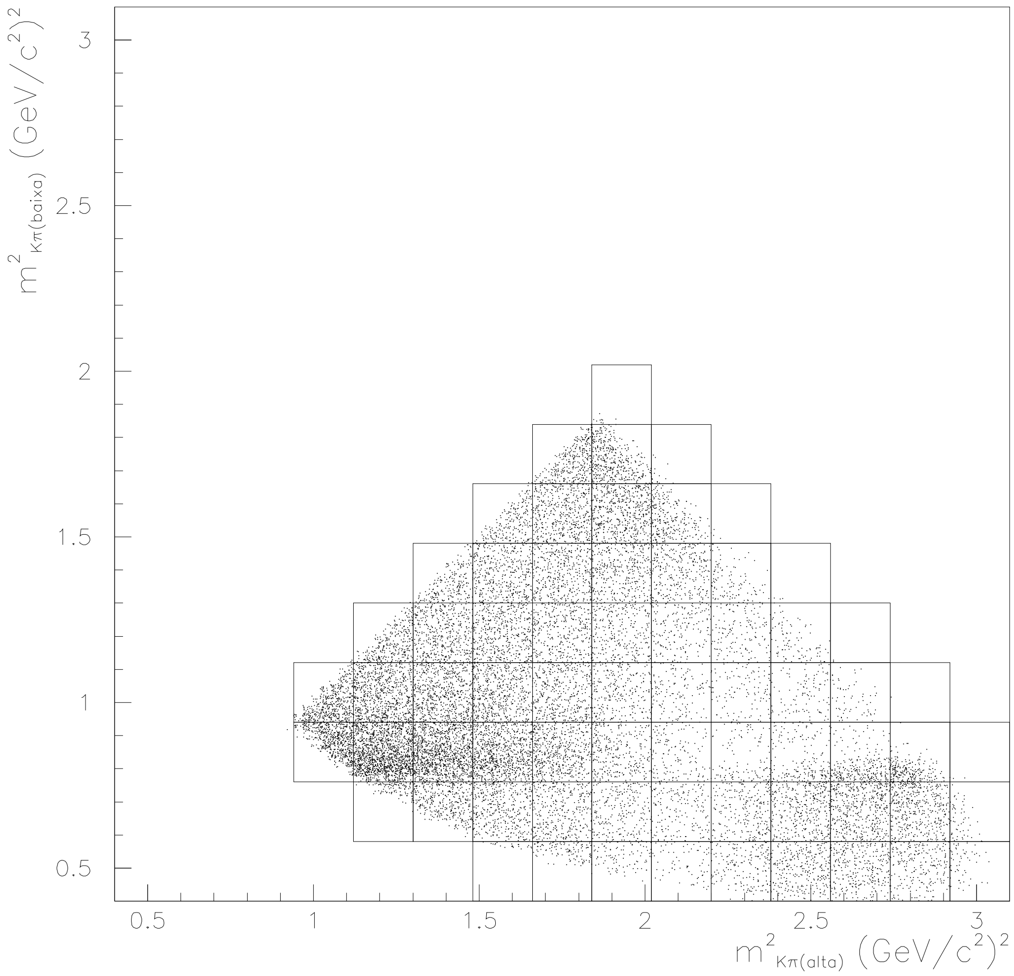
CLEO - $D^\circ \rightarrow K^-\pi^+\pi^\circ$



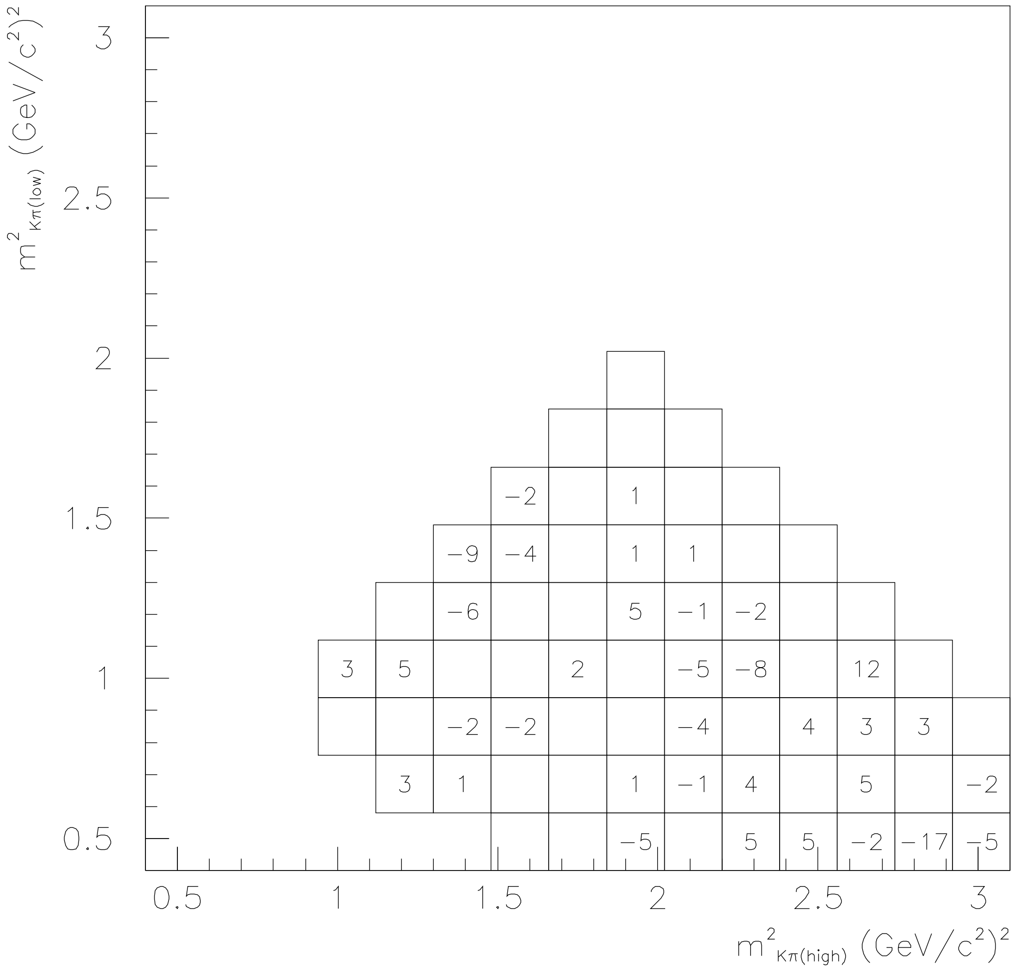
From *S. Kopp, etal* , PR D63, 092001 (2001)

A problem? Statistically significant?

Test Bins



"Standard Fit"



Contributions to χ^2 in Dalitz plot

Fit without κ

Improving Fit to $D^+ \to K^-\pi^+\pi^+$ Data

High statistical precision of data makes clear the need for a better model.

Things to try:

- Float $K^*_\circ(1430)$ mass and width
- Allow D and K^* radii to vary.
- Include Gaussian form factor for scalar states (Tornqvist).

$$F_R = 1.0 \;\longrightarrow\; F_R = \exp\left\{\frac{-p^2 r_R^2}{6}\right\}$$

More Sophisticated Model

PRELIMINARY

- New measurements for $K^*_\circ(1430)$

$$\boxed{\begin{aligned} M_{K^*_\circ(1430)} &= 1416 \pm 27\ MeV/c^2 \\ \Gamma_{K^*_\circ(1430)} &= 250 \pm 21\ MeV/c^2 \end{aligned}}$$

PDG

$$\begin{aligned} M_{K^*_\circ(1430)} &= 1412 \pm 6\ MeV/c^2 \\ \Gamma_{K^*_\circ(1430)} &= 294 \pm 23\ MeV/c^2 \end{aligned}$$

- Radii:

$$\boxed{\begin{aligned} r_D &= 0.8 \pm 1.0\ \mathrm{GeV}^{-1} \\ r_R &= 1.8 \pm 3.4\ \mathrm{GeV}^{-1} \end{aligned}}$$

More Sophisticated Model (II)

$$\boxed{\chi^2/\mathrm{dof} = 2.0 \quad (CL \sim 10^{-6})}$$

Mode	Fraction (%)
Non-resonant	89.5 ± 16.1
$K^*(890)\pi^+$	12.1 ± 3.3
$K^*_\circ(1430)\pi^+$	28.7 ± 10.2
$K^*_2(1430)\pi^+$	0.5 ± 0.3
$K^*_1(1680)\pi^+$	3.7 ± 1.9

- NR fraction still large $\sim$90%
- Sum of fractions still $\sim$135%
- Fit quality still bad
- Problem is still in same Dalitz plot region

Further Improvement

Add another (scalar) amplitude?
Let fit determine $M_\circ, \Gamma_\circ$.

Also

- **Float $K^*_\circ(1430)$ mass and width**
- **Allow D and K^* radii to vary.**
- **Include Gaussian form factor for scalar states (Tornqvist).**

$$F_R = 1.0 \;\longrightarrow\; F_R = \exp\left\{\frac{-p^2 r_R^2}{6}\right\}$$

Fit including additional scalar

PRELIMINARY

- **Scalar amplitude "κ"π**

$$\boxed{\begin{aligned} M_\kappa &= 797 \pm 19 \pm 42\ MeV/c^2 \\ \Gamma_\kappa &= 410 \pm 43 \pm 85\ MeV/c^2 \end{aligned}}$$

- **New measurements for $K^*_\circ(1430)$**

$$\boxed{\begin{aligned} M_{K_\circ(1430)} &= 1459 \pm 7 \pm 6\ MeV/c^2 \\ \Gamma_{K_\circ(1430)} &= 175 \pm 12 \pm 12\ MeV/c^2 \end{aligned}}$$

PDG

$$M_{K^*_\circ(1430)} = 1412 \pm 6\ MeV/c^2$$

$$\Gamma_{K^*_\circ(1430)} = 294 \pm 23\ MeV/c^2$$

- **Radii:**

$$\boxed{\begin{aligned} r_D &= 5.0 \pm 0.5\ \mathrm{GeV}^{-1} \\ r_R &= 1.6 \pm 1.3\ \mathrm{GeV}^{-1} \end{aligned}}$$

Fit including $\kappa\pi^+$ Amplitude (2)

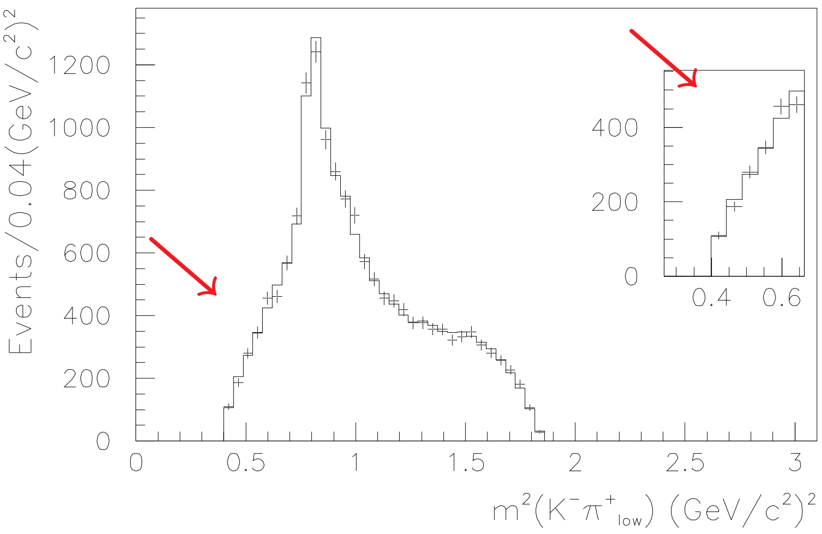
PRELIMINARY

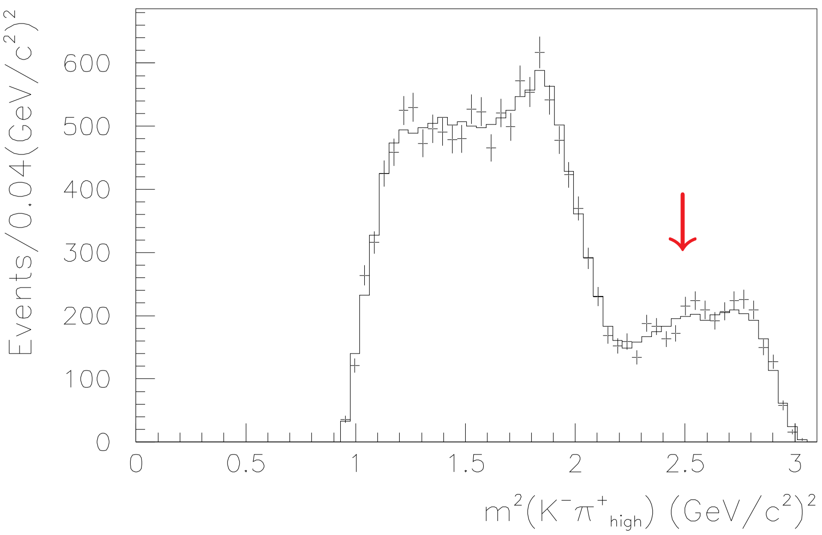
Mode	Relative Phase	Fraction (%)
Non-resonant	$(349 \pm 14 \pm 8)^\circ$	$13.0 \pm 5.8 \pm 2.6$
"κ"π^+	$(187 \pm 8 \pm 17)^\circ$	$47.8 \pm 12.1 \pm 3.7$
$K^*(890)\pi^+$	0° (fixed)	$12.3 \pm 1.0 \pm 0.9$
$K^*_\circ(1430)\pi^+$	$(48 \pm 7 \pm 10)^\circ$	$12.5 \pm 1.4 \pm 0.4$
$K^*_2(1430)\pi^+$	$(306 \pm 8 \pm 6)^\circ$	$0.5 \pm 0.1 \pm 0.2$
$K^*_1(1680)\pi^+$	$(28 \pm 13 \pm 15)^\circ$	$2.5 \pm 0.7 \pm 0.2$

- New "κ"π amplitude is dominant
- NR fraction drops to $\sim 2\sigma$
- Sum of fractions $\sim$90%
- Very good fit quality in all Dalitz plot regions
- BUT - $K_\circ(1430)$ parameters moved quite a bit.

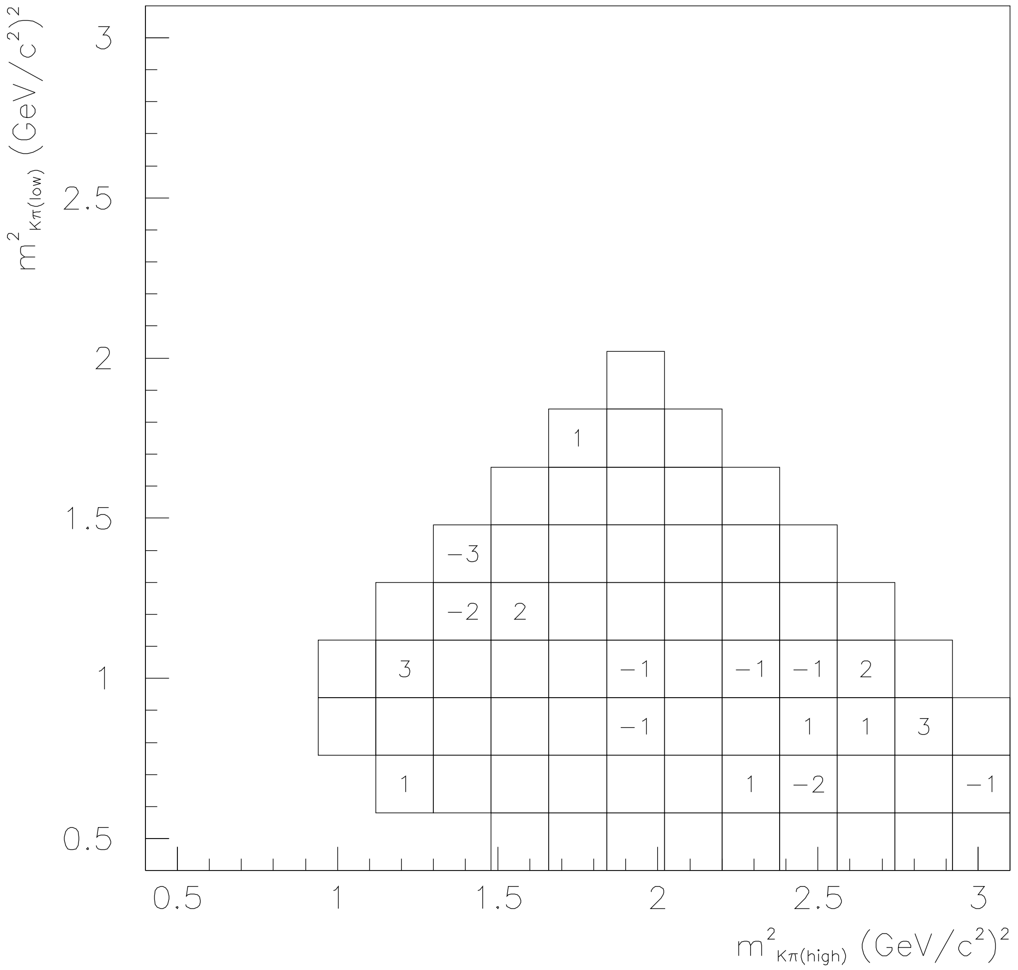
"κ" Fit Result

$$\chi^2/\mathrm{dof} = 0.73 \quad (CL = 95\%)$$





"κ" Fit

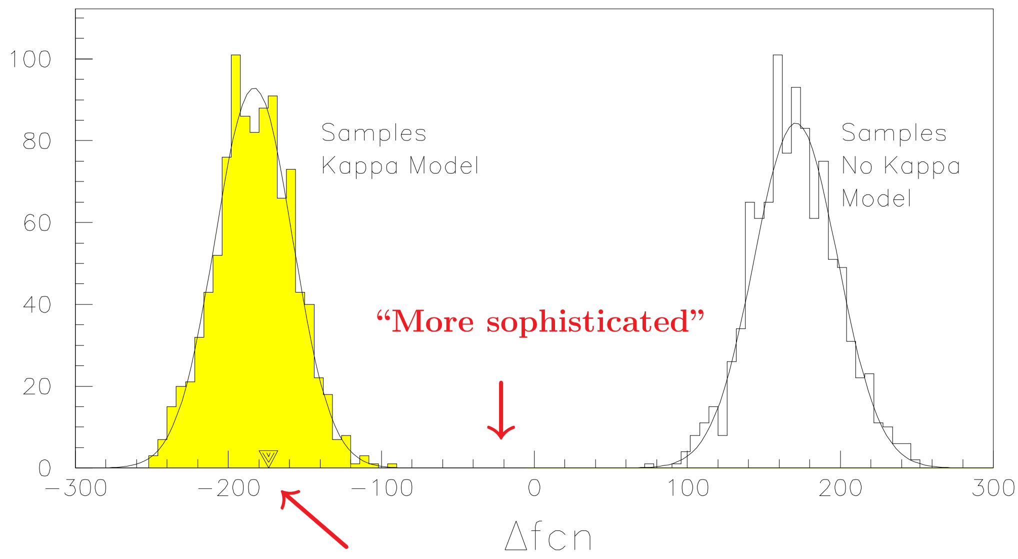


Contributions to χ^2 in Dalitz plot
Fit with "κ"

Significance of Improvement?

χ^2 test depends on bins chosen. Alternative test based on value of log-likelihood $\mathcal{L}$:

- Generate 1,000 samples using "standard" fit model: Number events fluctuates around 15,090.
  - Compute $\mathcal{L}$ with and without $\kappa\pi$ amplitude.
  - Plot difference in likelihood $\Delta\mathcal{L}$.
- Repeat with 1,000 samples generated with $\kappa\pi$ amplitude.



$\Delta\mathcal{L}$ for data $\sim 4\sigma$ from zero.

$\Rightarrow$ $\boxed{\kappa\pi \text{ is } \sim 4\sigma \text{ effect.}}$

Alternatives to Scalar Amplitude

Fit with toy model: Real "BW" - no phase variation

- **similar mass and width**
- **unphysical fractions (κ 127 $\pm$ 79% and NR 283 $\pm$ 96%)**
- **worse fit quality (CL $\sim 10^{-3}$)**

$$\boxed{\Rightarrow \text{ BW phase important.}}$$

Vector Breit-Wigner

- **Small fraction**
- **Not much improvement on standard fit ($\Delta_{\mathcal{L}} = 54$)**

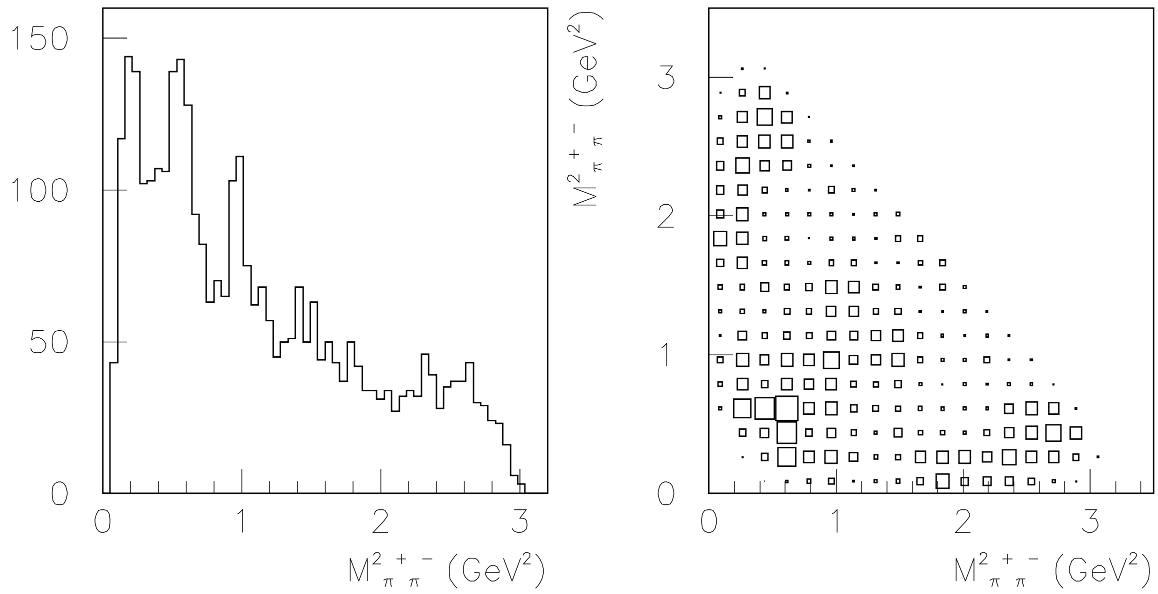
$$\boxed{\Rightarrow \text{ Probably not vector.}}$$

Other Variants

- Variations in κ parameterization
  - no form factors for $K_\circ(1430)$
  - no form factor for κ

  These altered NR and κ fractions somewhat BUT
- κ still significant.
- M_κ, Γ_κ and other parameters unchanged
- Variations in NR form
  - $A_{NR} = 1 \longrightarrow A_{NR} = e^{-\alpha(s_{12}+s_{13})}$
    $\Rightarrow$ 2σ increase in f_{NR} and decrease in f_κ;
  - Allow for $p - wave$ in NR
    $\Rightarrow$ consistent with zero.

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



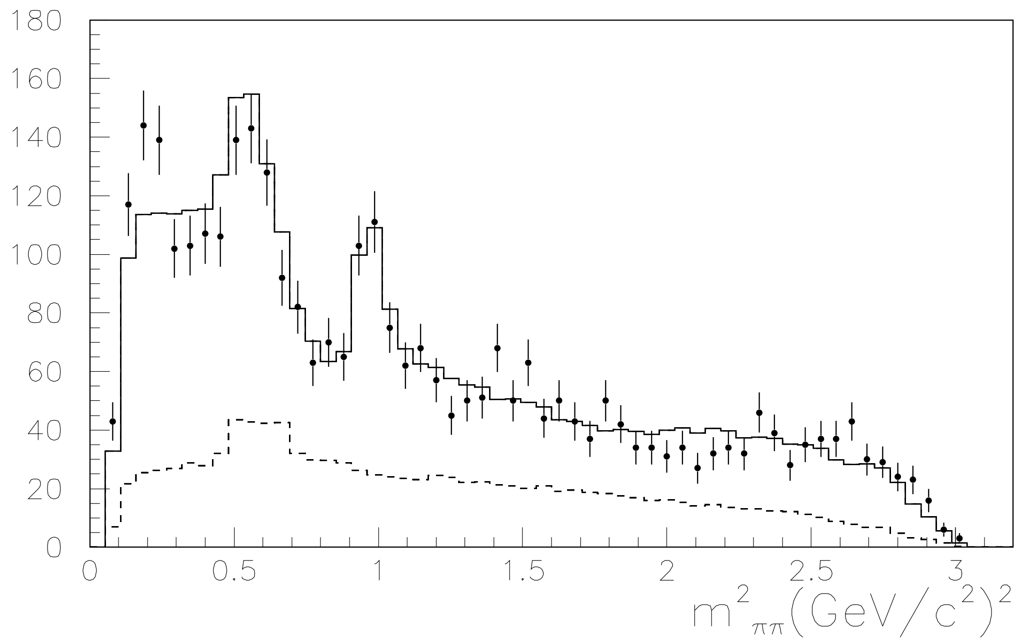
Initial Approach

USE SAME CHANNELS AS FOR D_s

- Non resonant decay is dominant.
- $\rho(1450)$ and $\rho(770)$ next and equally strong.
- Results are compatible with those of previous E687.
- Bad fit quality in low mass $\pi^+\pi^-$ region.

Results

$\chi^2/\text{dof} = 1.5 \quad (\text{CL} \sim 10^{-5})$



Mode	Relative Phase	Fraction (%)
$\rho^\circ(770)\pi^+$	0° (fixed)	20.8 ± 2.3
Non-resonant	$(150 \pm 12)^\circ$	38.6 ± 1.4
$f_\circ(980)\pi^+$	$(152 \pm 16)^\circ$	7.4 ± 4.3
$f_2(1270)\pi^+$	$(103 \pm 16)^\circ$	6.3 ± 3.3
$f_\circ(1370)\pi^+$	$(143 \pm 10)^\circ$	10.7 ± 7.7
$\rho^\circ(1450)\pi^+$	$(46 \pm 15)^\circ$	22.6 ± 2.1

Add Another Amplitude

Add $\sigma\pi^+$ amplitude - let $m_\circ$, Γ float.

Fit Results:

$$m_\sigma = (478^{+24}_{-23} \pm 17)\ \mathrm{MeV/c^2}$$
$$\Gamma_\sigma = (324^{+42}_{-40} \pm 21)\ \mathrm{MeV/c^2}$$

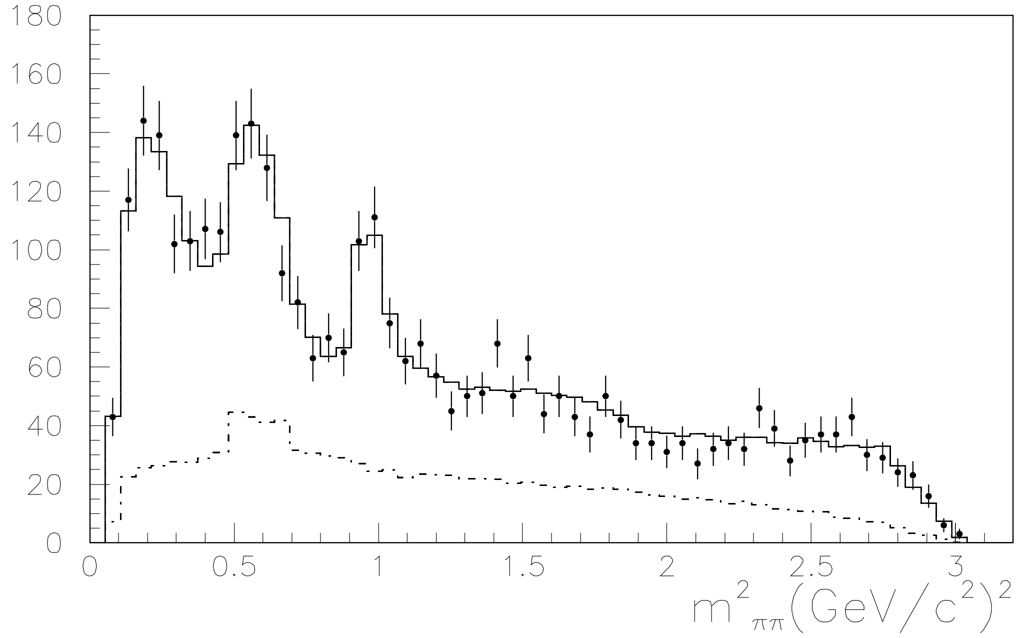
Mode	Relative Phase	Fraction (%)
$\sigma\pi^+$	$(206 \pm 8 \pm 5)^\circ$	$46.3 \pm 9.0 \pm 2.1$
$\rho^\circ(770)\pi^+$	$0^\circ(fixed)$	$33.6 \pm 3.2 \pm 2.2$
Non-resonant	$(57 \pm 20 \pm 6)^\circ$	$7.8 \pm 6.0 \pm 2.7$
$f_\circ(980)\pi^+$	$(165 \pm 11 \pm 3)^\circ$	$6.2 \pm 1.3 \pm 0.4$
$f_2(1270)\pi^+$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

Some Variations

- Toy model ("real BW") gave comparable fit BUT: $f_{NR} \rightarrow 35\%$ and $f_\sigma \rightarrow 63\%$ $\Rightarrow \sum f \rightarrow 170\%$.
  $\Rightarrow$ BW phase movement is important.
- Fit using additional vector BW for σ: $\chi^2/dof \rightarrow 1.2$; $m_\circ \rightarrow 717$, $\Gamma_\circ \rightarrow 1170$ MeV/c^2
  . $\Rightarrow$ Like a broad ρ. Poorer fit than scalar.

Fit Quality with $\sigma\pi$ Amplitude

$\chi^2/\mathrm{dof} = 0.9 \quad (\mathrm{CL} = 76\%)$ [3]

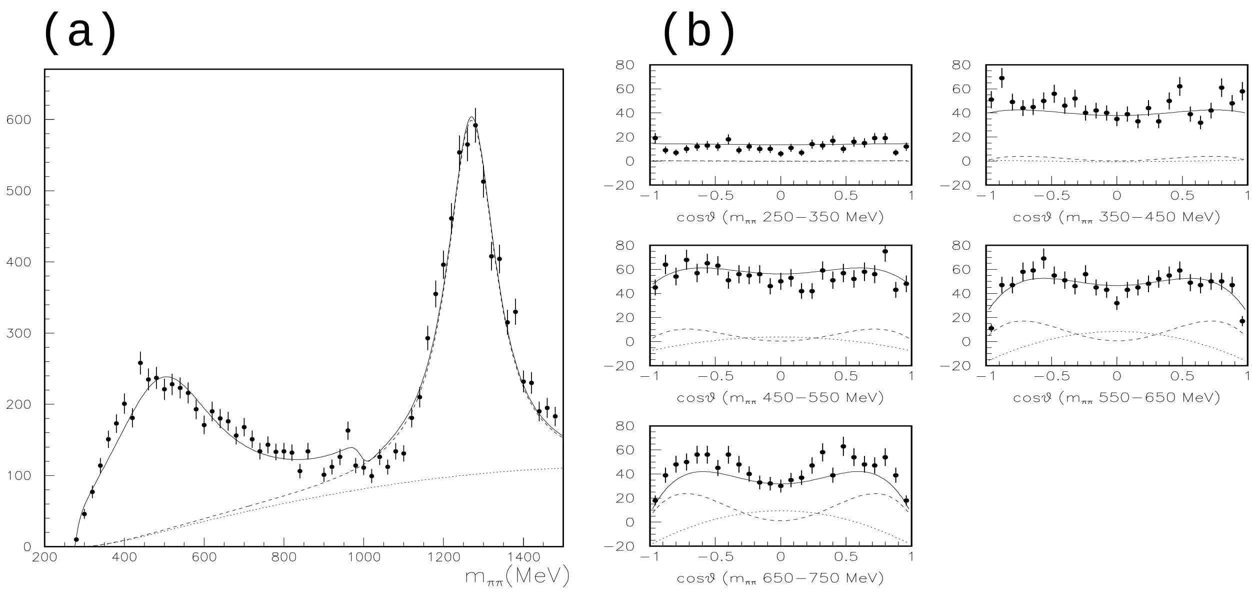


Features of this Fit

- **Model with $\sigma\pi$ has good fit quality.**
- **$\sigma\pi$ mode dominates the decay - but NR is small.**
- **$\rho(1450)\pi$ amplitude becomes negligible.**
- **σ appears at low mass (its mass was free to move higher).**

$\Rightarrow$ Good description of low mass $\pi\pi$ system.

DM2 - σ in $J/\psi \to \omega\pi\pi$ Decays?



Data from DM2 collaboration, NPB320 (1989) 1

Fit by Sigma collaboration. [4]

- **DM2 data re analyzed using a "VMW" fit to the Dalitz plot with a coherent sum of amplitudes for:**

$$\begin{aligned} J/\psi \;\to\; & f_\circ(980)(\to \pi\pi)\omega \\ & f_2(1270)(\to \pi\pi)\omega \\ & \text{“}\sigma\text{”}(\to \pi\pi)\omega \\ & b_1(\to \omega\pi)\pi \end{aligned}$$

- **Phases, amplitudes and "σ" parameters floated.**

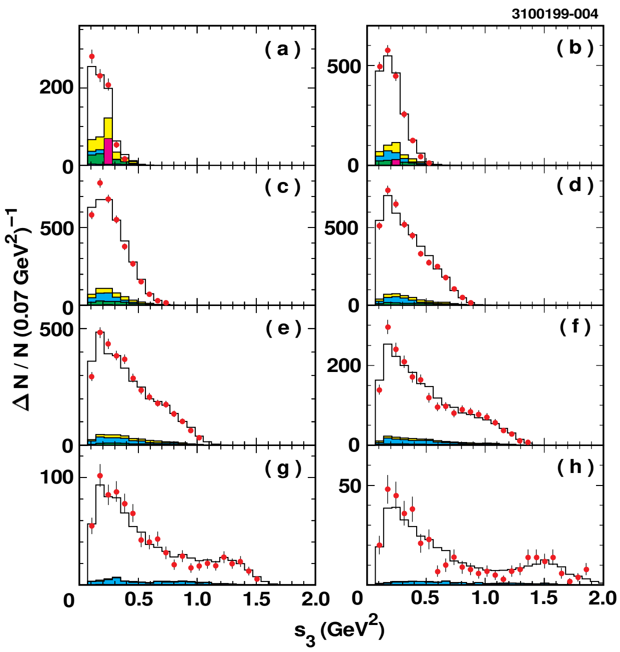
Mass and width parameters for σ:
$M = 590 \pm 10$ MeV, $\Gamma = 710 \pm 30$ MeV.

[4] M.Y. Ishida, S. Ishida, T.Ishida, T.Komada, A.M. Ma, H. Shimizu, K. Takamatsu, T. Tsuru, Tokyo Inst. Tech, Nihon U., KEK, IHEP Beijing, Yamagata U., CROSS. Reported in T. Tsuru, Soryushiron Kenkyu (Kyoto), Vol. **102** (2001), E86-E91

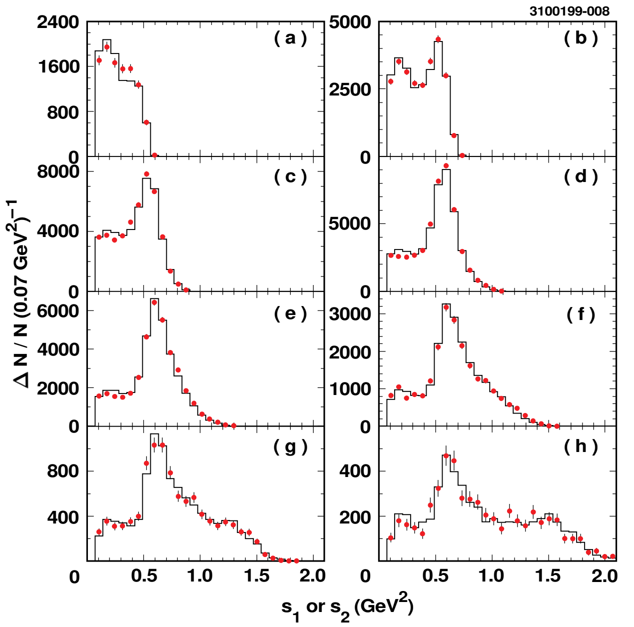
CLEO - σ in τ Decays

- **CLEO analyzed $a_1(a_1')$ decays from $\tau \to \nu_\tau\, (\pi^-\pi^\circ\pi^\circ)$.**
  - Three pions dominantly $J^P = 1^+$.
- **Fit series of Dalitz plots in 3π mass slices.**
- **Found contributions from:**

$\sigma\pi$	$\sim$16%	(8.2σ)
$\rho\pi$	$\sim$68%	(5.0σ)
$f_\circ(1370)\pi$	$\sim$4.3%	(5.4σ)
$\rho(1450)\pi$, *etc*	$\sim$1.25%	–



$M_{\pi^\circ\pi^\circ}$ from $\tau \to \nu_\tau \pi^-\pi^\circ\pi^\circ$.
Fit assumes 3π has $J^P = 1^+$.



$M_{\pi^-\pi^+}$ from $\tau \to \nu_\tau \pi^-\pi^-\pi^+$
Curve is the (isospin corrected) projection of the $\pi^\circ\pi^\circ$ fit.

*Data and fit from CLEO collaboration, PRD***61** *012002 (2000) 1*

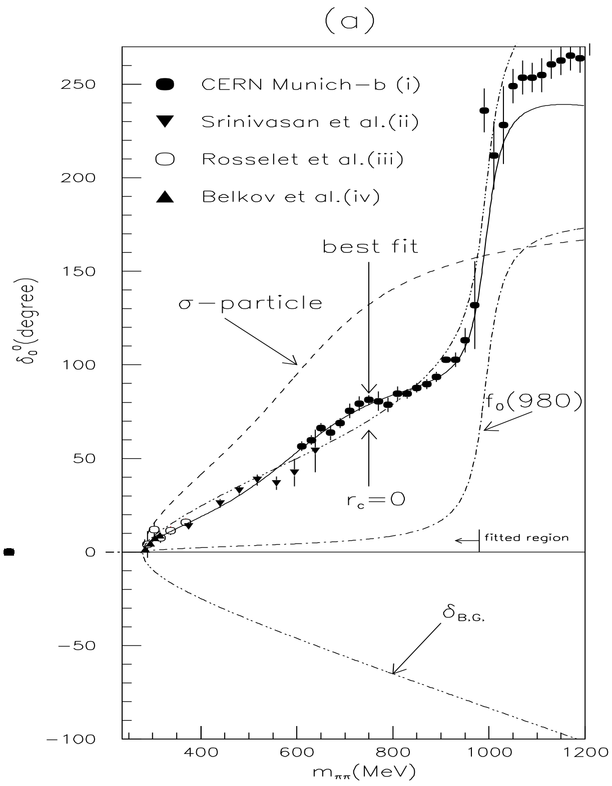
σ required (8.2σ effect)
Treated as a BW:
$M = 555$ MeV; $\Gamma = 540$ MeV.

Similar "σ" fits have also been made to other channels where $\pi^+\pi^-$ or $\pi^\circ\pi^\circ$ broad mass enhancements below 1 GeV/c^2 were observed:

$$\begin{aligned} pp &\rightarrow p_f\pi^\circ\pi^\circ p_{recoil} \\ \Upsilon' &\rightarrow \Upsilon\pi\pi \end{aligned}$$

σ and $\pi\pi$ Scattering?

- If σ exists, it must be seen in the $I = 0$ elastic phase shift $\delta^\circ_\circ$.
- Problem: $\delta^\circ_\circ$ rises only $\sim 250^\circ$ from threshold to $K\overline{K}$ threshold (elastic limit).
  - not enough for an elastic resonance below $f_\circ(980)$.
- "Sigma collaboration" fits to model with background with negative phase - repulsive core - below $K\overline{K}$ threshold.



Background phase $\delta^\circ_B = r_c|\vec{p}|$. ($r_c$ is unknown radius of repulsive core).

Argue that repulsive core is analogous to $\delta^2_\circ$ phase behaviour

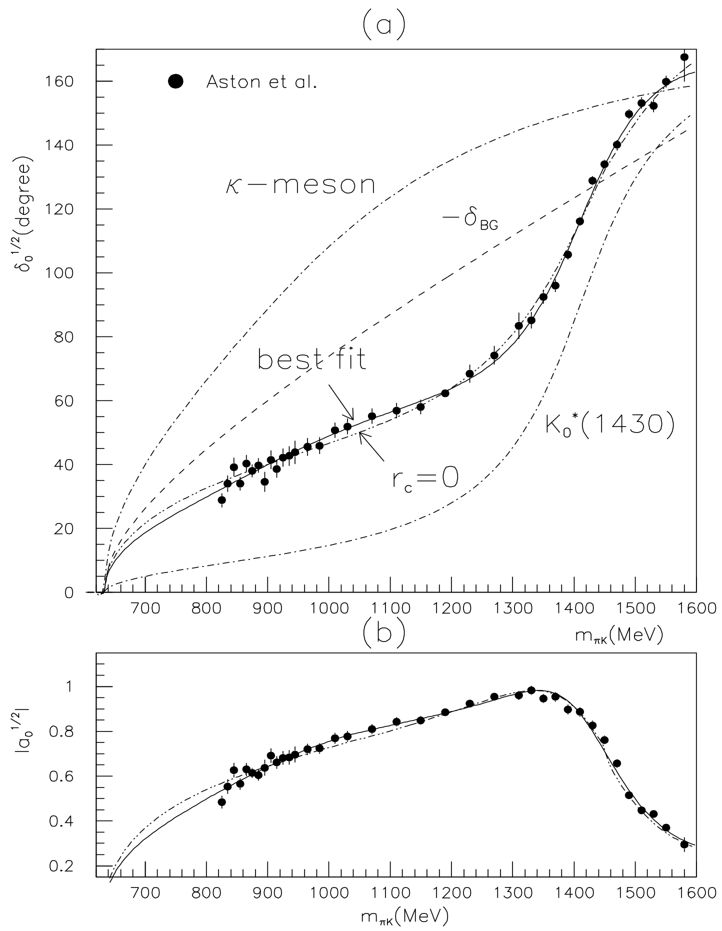
$\Rightarrow$ coming from CA contact term.

Include poles for $f_\circ(980)$ and σ.

σ parameters:
$M = 585 \pm 20$ MeV; $\Gamma = 385 \pm 70$ MeV;
$r_c = 3.03 \pm 0.35$ GeV^{-1}

κ and $K\pi$ Scattering?

- **Elastic limit is $K\eta'$ threshold at $\sim \sqrt{s} = 1450$ MeV.**
- **SIMILAR PROBLEM: $\delta_{\circ}^{\frac{1}{2}}$ rises only $\sim 160^{\circ}$ from threshold through $K_{\circ}(1430)$.**



"Sigma collaboration" fits similar model with repulsive background.

include two poles - κ and $K_{\circ}(1430)$.

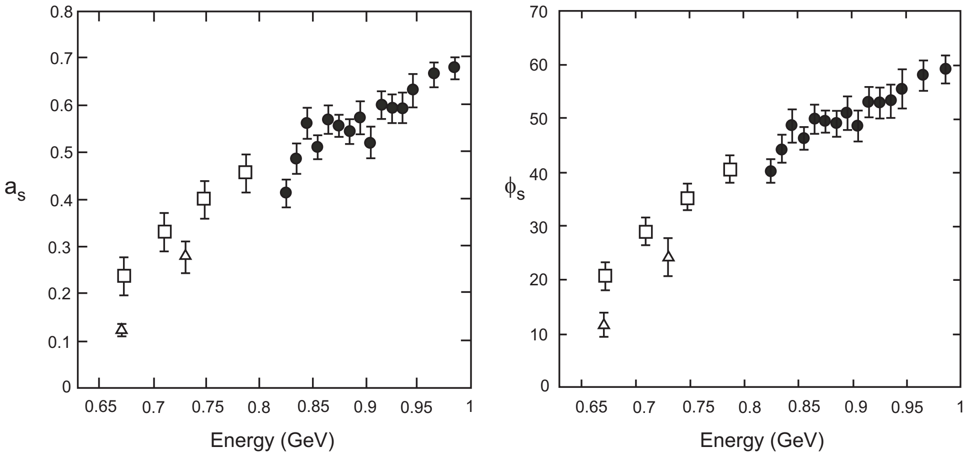
κ parameters:

$$M_{\kappa} = 905^{+65}_{-30}\ \text{MeV};\quad \Gamma_{\kappa} = 545^{+235}_{-110}\ \text{MeV};$$

$$r_c = 3.03 \pm 0.35\ \text{GeV}^{-1}$$

“There is no κ”

- **Eloquently stated - Pennington and Cherry (PC)** [5]**:**
  “Whether a state exists in the spectrum of hadrons is not a matter of ability to fit data along the real energy axis, but is completely specified by the number of poles in the complex energy plane.”
- **PC make a “model independent” analysis of the LASS data from 825 to 2000 MeV/c^2.**
  Conclusion: There is only one pole - $K_\circ(1430)$ - in the $T_{K\pi}$ matrix in this range.
- **Do allow possibility of a pole “considerably below” 825 MeV/c^2 (the LASS data cutoff).**

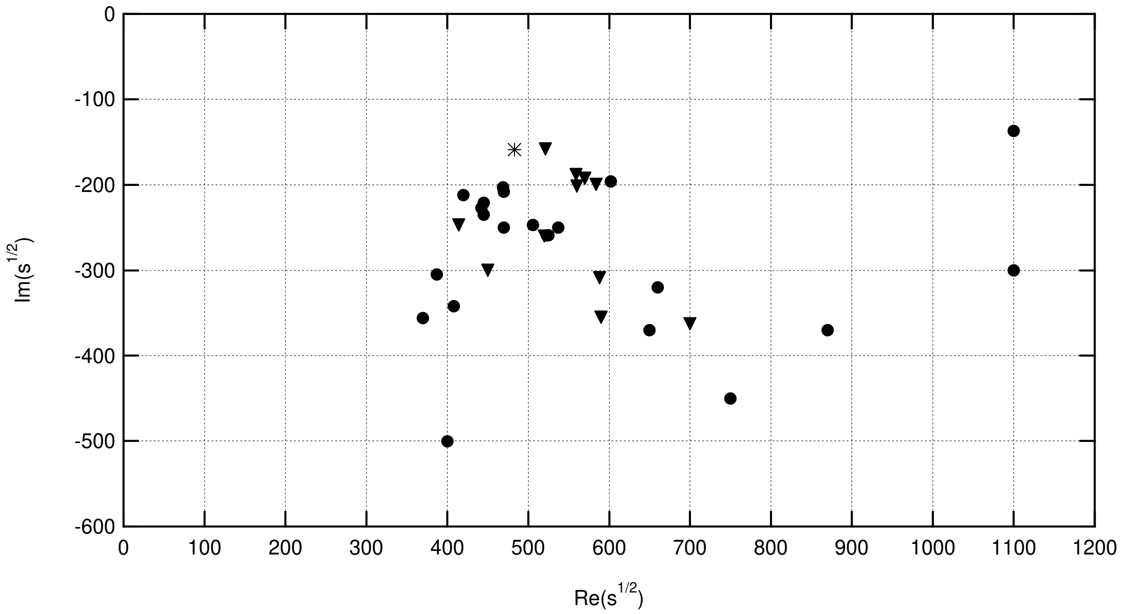


LASS s-wave amplitude $a_\circ^{1/2}$ (left) and phase $\delta_\circ^{1/2}(s_{K\pi})$ (right) below 1 GeV/c^2. Extensions below measured range shown as triangles (LASS) & squares (Pennington/Cherry).

Technical issues raised, but this analysis reveals Need to measure $\delta_\circ^{\frac{1}{2}}(s_{K\pi})$ for $\sqrt{s}_{K\pi} < 825$ MeV/c^2.
$\Rightarrow$ (BaBar)

[5]N. Cherry, M. Pennington NP **A688** 823 (2001)

"What they say about σ"



- $f_\circ(400 - 1200)$ or σ (PDG)
- Quantum fluctuation of the chiral order parameter (H. Kunihiro)
- Chiralon (S. and M. Ishida - sigma collaboration.)
- $\pi\pi$ correlation or bound state (Oller).
- Gluonium-$q\bar{q}$ mixed state (Narison).
- 4-quark state (Shechter, Jaffe, Tuan).
- The eye witness of confinement (Gribov).
- Sister of Yukawa's pion (unattributed?).
- Higgs of strong interactions - it gives light constituent quarks most of their mass.

Summary

- D_s decays to $f_\circ\pi$ states:
  Improved parameters for $f_\circ(980)$:

$$\begin{aligned} m_\circ &= (977 \pm 3 \pm 2)\ \mathrm{MeV/c^2} \\ g_\pi &= 0.09 \pm 0.01 \pm 0.01 \\ g_K &= 0.02 \pm 0.04 \pm 0.03 \end{aligned}$$

  BW parameters:

$$\begin{aligned} m_\circ &= (975 \pm 3 \pm 2)\ \mathrm{MeV/c^2} \\ \Gamma_\circ &= (44 \pm 2 \pm 2)\ \mathrm{MeV/c^2} \end{aligned}$$

  Improved parameters for $f_\circ(1370)$:

$$\begin{aligned} m_\circ &= (1434 \pm 18 \pm 9)\ \mathrm{MeV/c^2} \\ \Gamma_\circ &= (172 \pm 32 \pm 6)\ \mathrm{MeV/c^2} \end{aligned}$$

- $D_s \to \rho\pi$, $D_s \to \rho(1450)\pi$ and $D_s \to NR$ modes are insignificant - no compelling evidence for annihilation decay process.

- Inclusion of an s-wave "σ"π amplitude in $D^+ \to \pi^-\pi^+\pi^+$ decay provides significantly improved fit to E791 data. It greatly reduces NR decay and dominates. s-wave BW parameters for "σ":

$$\begin{aligned} m_\circ &= (478^{+24}_{-23} \pm 17)\ \mathrm{MeV/c^2} \\ \Gamma_\circ &= (324^{+42}_{-40} \pm 21)\ \mathrm{MeV/c^2} \end{aligned}$$

- **Inclusion of an s-wave "κ"π amplitude in $D \rightarrow K^-\pi^+\pi^+$ decay provides significant improvement in fit to E791 data. It reduces NR decay and dominates.**

- **Improved parameters for "$K_\circ(1430)$":**

$$\begin{aligned} m_\circ &= (1459 \pm 7 \pm 17)\ \mathrm{MeV/c^2} \\ \Gamma_\circ &= (175 \pm 23 \pm 21)\ \mathrm{MeV/c^2} \end{aligned}$$

s-wave BW parameters for "κ":

$$\begin{aligned} m_\circ &= (478^{+24}_{-23} \pm 17)\ \mathrm{MeV/c^2} \\ \Gamma_\circ &= (324^{+42}_{-40} \pm 21)\ \mathrm{MeV/c^2} \end{aligned}$$

- **Though evidence for σ and κ signals with similar parameters is accruing from several sources, it is unlikely the debate on the existence, let alone the nature, of these states will be settled very soon.**