Heavy Flavor decays and light hadrons in the FOCUS experiment.

Hadron 2007

Frascati – October 8 - 12

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Outline

- **Introduction**
  - **Heavy Flavor** decay and **light hadron interplay**
- **Analysis**
  - **hadron dynamics study**
    - three body Dalitz plot analysis: formalism revision
      - » $\mathbf{D^+ \to K^- \pi^+ \pi^+}$ **53000 evts**
      - » $\mathbf{D^+, D_s \to \pi^+ \pi^- \pi^+}$ **1500 evts**
    - possible model independent approach
      - » $\mathbf{D^+ \to K^+ K^- \pi^+}$ **4200 evts**
  - **pentaquark search**
- **Conclusions**

Introduction
the *exegesis* of the title

- We know there is physics beyond the SM but we do not know (**yet**) what this is.
- The "search strategy" includes *also* precision measurements of the CKM matrix elements
  - Resurrection of the Dalitz plot analysis in the Heavy Flavor modern experiments
    - to study HF hadronic decays
    - to perform sophisticated studies such as CPV

$\Downarrow$

$\mathbf{B \rightarrow \rho\pi}$	α **angle**
$\mathbf{B \rightarrow D(*)K\ (*)}$	γ **angle**

The interplay…i.e, the issue

- **to go from $B \rightarrow \pi\pi\pi$ to $B \rightarrow \rho\pi$**
  - means selecting and filtering the desired states among the possible contributions, e.g. $\sigma\pi$, $f_0(980)\pi$, $\pi\pi\pi$ etc..
- **a model for D^0 decay is needed**
  - **$(K\pi)\pi$, $K(\pi\pi)$**
    - 16 states, two 'ad hoc' : σ_1, σ_2

light hadrons

Phys. Rev.Lett.95 (2005) 121802.

Phys. Rev. D73 (2006) 112009

…and the *naïve* experimentalist's question

- **In the era of precision measurements**
  - **How to deal with the underlying hadron dynamics that colors and shapes the final states ?**
    - The ππ , Kπ **S–wave** are characterized by broad, overlapping states: **unitarity** is **not** explicitly guaranteed by a simple **sum of Breit -Wigner (BW)** functions
    - σ,κ are **not simple BW's**
    - **f_0(980)** is a **Flatté**-like function, coupling to KK and ππ

.. a possible answer

a ***bridge*** of knowledge and terminology

- Many problems are already well known in nuclear and intermediate-energy physics

⇩

K-matrix

  - **a cultural bridge towards the high energy community**
  - **a common jargon**

- **Efforts made by FOCUS**
  - **apply K-matrix to the Heavy Flavor sector** …..beneficial for future B-studies

What is K-matrix?

E.P.Wigner, Phys. Rev. 70 (1946) 15

S.U. Chung et al. Ann. Physik 4 (1995) 404

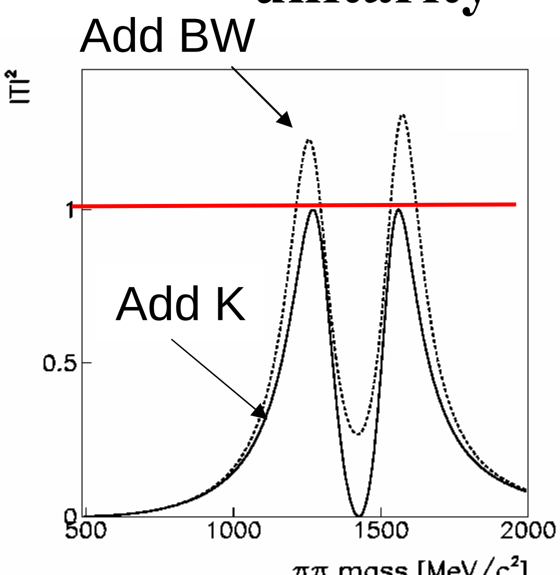
- It follows from S-matrix and, because of S-matrix unitarity, it is real

$$S = I + 2i\rho^{1/2} T \rho^{1/2}$$

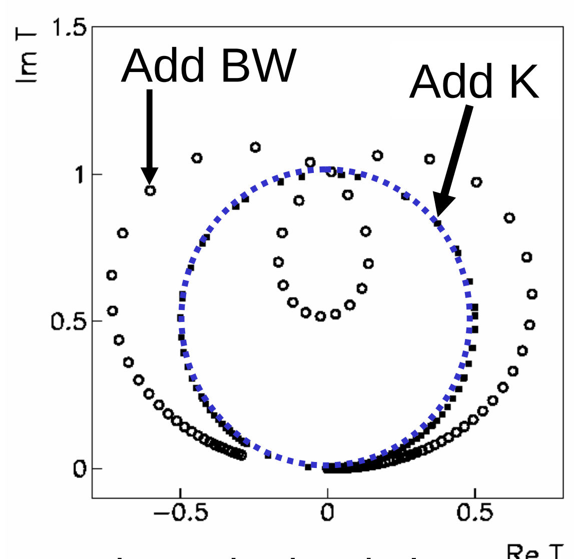
$$K^{-1} = T^{-1} + i\rho \qquad T = (I - iK \cdot \rho)^{-1} K$$

- Viceversa, any real K-matrix would generate an unitary S-matrix
- This is the real advantage of the K-matrix approach:
  - **It (heavily) simplifies the formalization of any scattering problem since the unitarity of S is automatically respected.**

- For a single-pole problem, far away from any threshold, a K-matrix amplitude reduces to the standard BW formula
    - **The two descriptions are equivalent**
- In all the other cases, the BW representation is no longer valid
    - **The most severe problem is that it does not respect unitarity**



m_A=1270 MeV, Γ_A= 180 MeV
m_B=1560 MeV, Γ_B= 160 MeV



The Unitarity circle

Adding BWs *a la* "traditional Isobar Model"

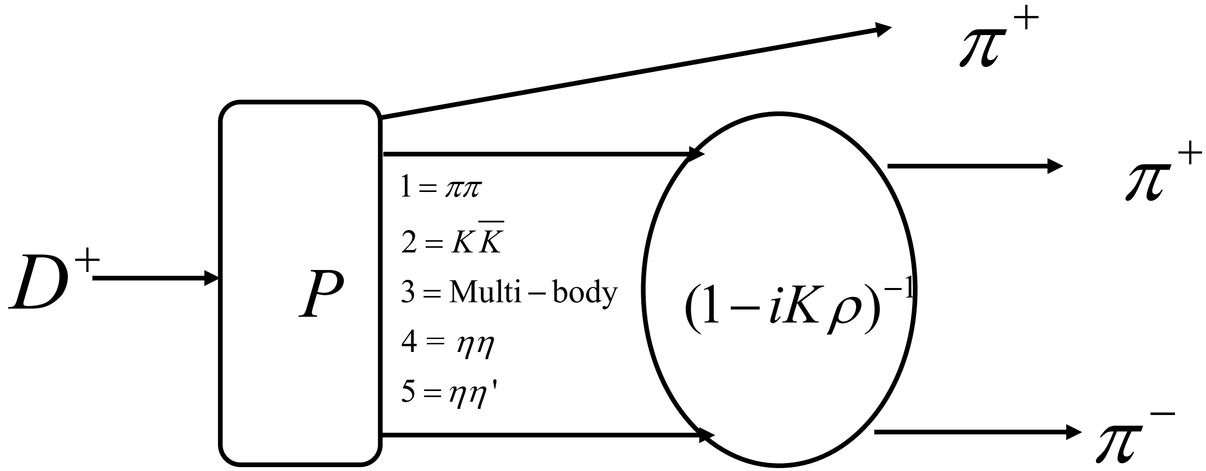
– Breaks Unitarity

– Heavily modify the phase motion!

From Scattering to Production

- Thanks to I.J.R. Aitchison (Nucl. Phys. A189 (1972) 514), the K-matrix approach can be extended to production processes
- In technical language,
  - From $$T = (I - iK \cdot \rho)^{-1} K$$
  - To $$F = (I - iK \cdot \rho)^{-1} P$$
- The P-vector describes the coupling at the production with each channel involved in the process
  - **In our case the production is the D decay**

First FOCUS study: $D^+, D_s^+ \to \pi^+\pi^-\pi^+$



$$F = (I - iK \cdot \rho)^{-1} P$$

Describes coupling of resonances to D

Comes from scattering data

Beside restoring the proper dynamical features of the resonances, K-matrix allows for the inclusion of all the knowledge coming from scattering experiments: **enormous amount of results and science!**

$\pi\pi$ S-wave scattering parametrization

"K-matrix analysis of the 00^{++}-wave in the mass region below 1900 MeV"

V.V Anisovich and A.V.Sarantsev Eur.Phys.J.A16 (2003) 229

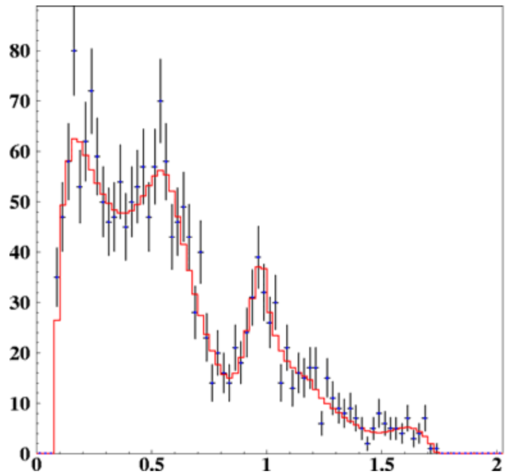
- A global fit to a rich set of the available data has been performed

*	**GAMS**	$\pi p \to \pi^0\pi^0 n, \eta\eta n, \eta\eta' n$, $\lvert t\rvert<0.2$ (GeV/c^2)	
*	**GAMS**	$\pi p \to \pi^0\pi^0 n$, $0.30<\lvert t\rvert<1.0$ (GeV/c^2)	
*	**BNL**	$\pi p^- \to K\bar{K}n$	
*	**CERN-Munich**	$\pi^+\pi^- \to \pi^+\pi^-$	
*	**Crystal Barrel**	$p\bar{p} \to \pi^0\pi^0\pi^0, \pi^0\pi^0\eta, \pi^0\eta\eta$	At rest, from liquid H_2
*	**Crystal Barrel**	$p\bar{p} \to \pi^0\pi^0\pi^0, \pi^0\pi^0\eta$	At rest, from gaseous H_2
*	**Crystal Barrel**	$p\bar{p} \to \pi^+\pi^-\pi^0, K^+K^-\pi^0, K_sK_s\pi^0, K^+K_s\pi^-$	At rest, from liquid H_2
*	**Crystal Barrel**	$n\bar{p} \to \pi^0\pi^0\pi^-, \pi^-\pi^-\pi^+, K_sK^-\pi^0, K_sK_s\pi^-$	At rest, from liquid D_2
*	**E852**	$\pi^- p \to \pi^0\pi^0 n$, $0<\lvert t\rvert<1.5$ (GeV/c^2)	

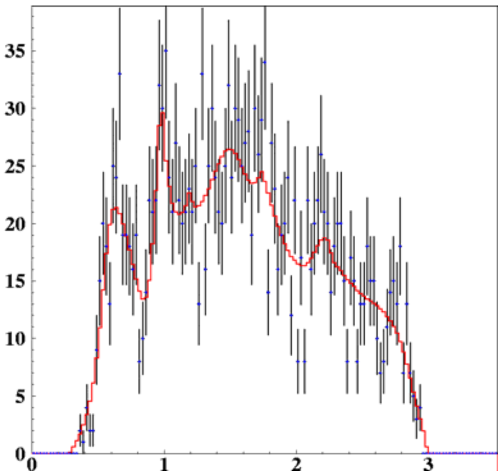
- It provided the K-matrix input to our three-pion D analysis

$D^+ \to \pi^+ \pi^- \pi^+$ K-matrix fit results

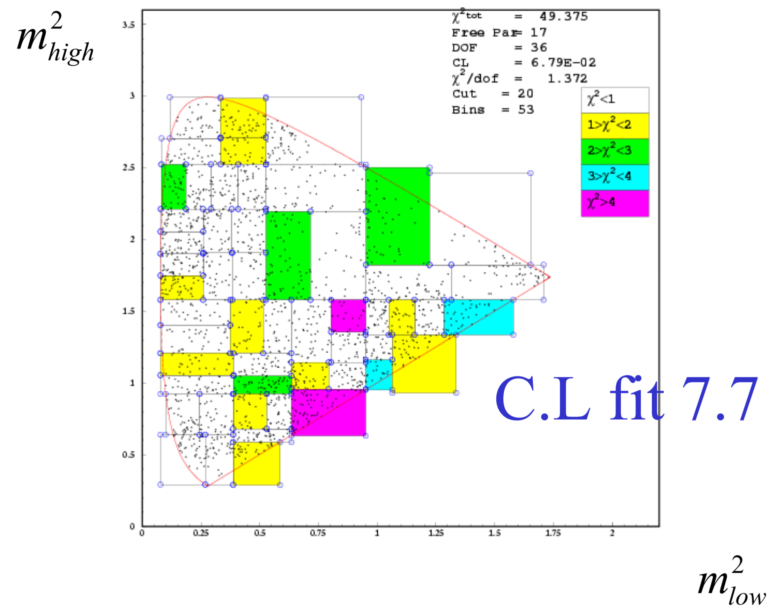
PLB 585 (2004) 200



Low mass projection



High mass projection



C.L fit 7.7 %

decay channel	fit fractions (%)	phase (deg)
$(S\text{-wave})\pi^+$	$56.00 \pm 3.24 \pm 2.08$	0(fixed)
$f_2(1275)\pi^+$	$11.74 \pm 1.90 \pm 0.23$	$-47.5 \pm 18.7 \pm 11.7$
$\rho^0(770)\pi^+$	$30.82 \pm 3.14 \pm 2.29$	$-139.4 \pm 16.5 \pm 9.9$

Reasonable fit with <u>no retuning</u> of the A&S K-matrix.
No new ingredient (resonance) required not present in the scattering!

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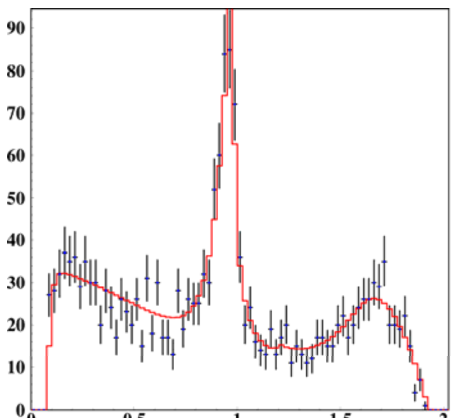
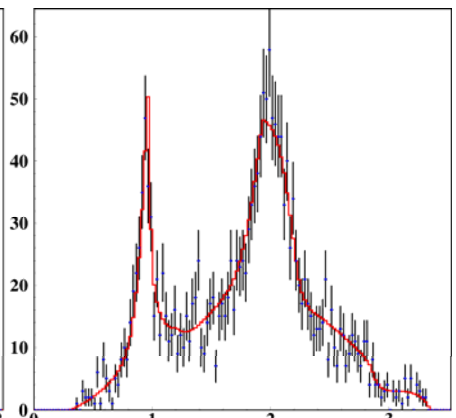
$D_s^+ \to \pi^+ \pi^- \pi^+$ K-matrix fit results

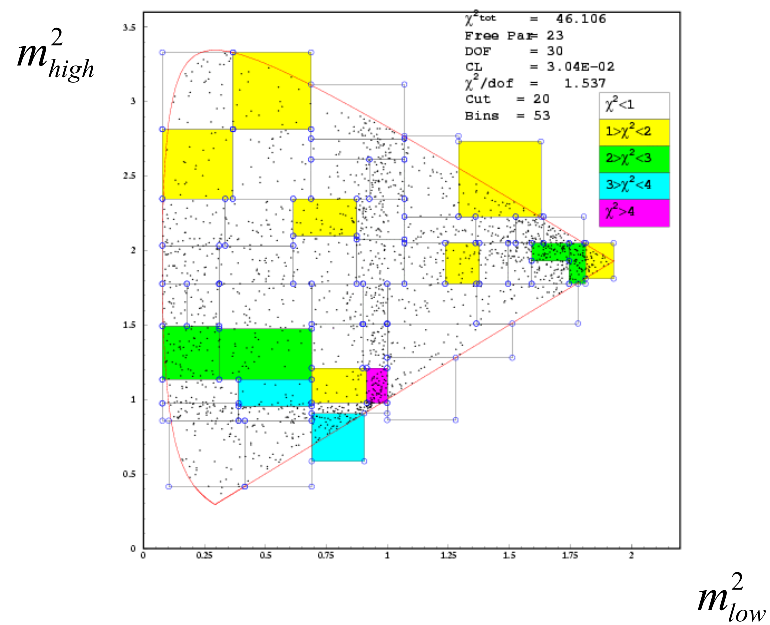


Low mass projection



High mass projection

decay channel	fit fractions (%)	phase (deg)
$(S\text{-wave})\pi^+$	$87.04 \pm 5.60 \pm 4.17$	0(fixed)
$f_2(1275)\pi^+$	$9.74 \pm 4.49 \pm 2.63$	$168.0 \pm 18.7 \pm 2.5$
$\rho^0(1450)\pi^+$	$6.56 \pm 3.43 \pm 3.31$	$234.9 \pm 19.5 \pm 13.3$



C.L fit 3 %

Yield D^+ =1527 ± 51 evts

Yield D_s =1475 ± 50 evts

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The high statistics test

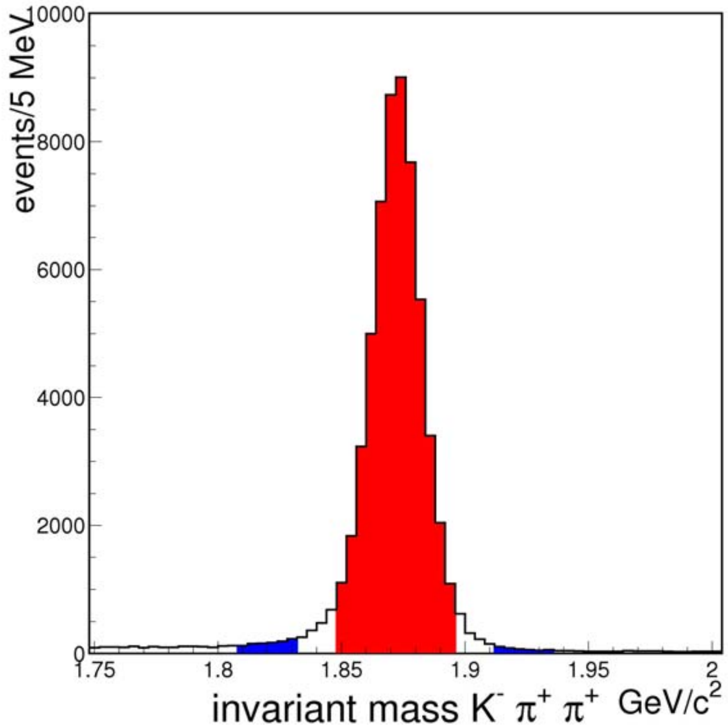
- Three-pion analysis suggested:
  - two-body dominance
  - consistency with scattering data

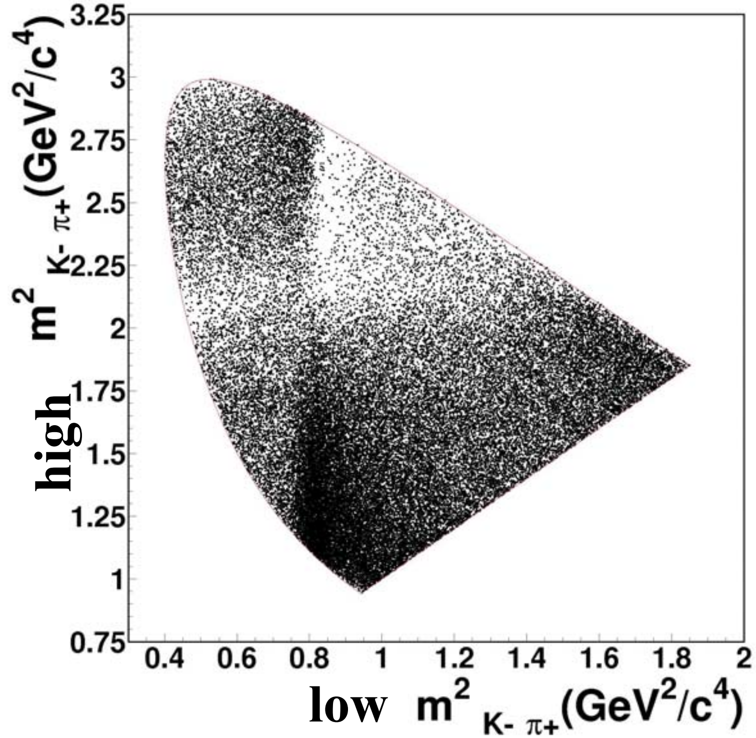
- It was important (mandatory) to **test** the formalism **@ high statistics**
  - **$D^+ \to K^- \pi^+ \pi^+$ channel**

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

53653 evts…another story!

Phys. Lett. B 653 (2007) 1.





The Kπ S-wave scattering parametrization

(Mike Pennington)

- two isospin states (I=1/2 and I=3/2) ⟺ two K-matrices

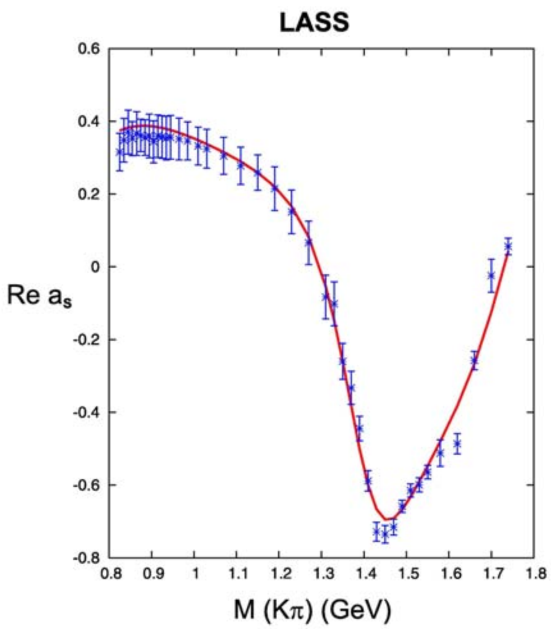
  fit S-wave $K^- \pi^+ \to K^- \pi^+$ LASS data above 825 MeV

  Nucl. Phys,.B 296 (1988) 493

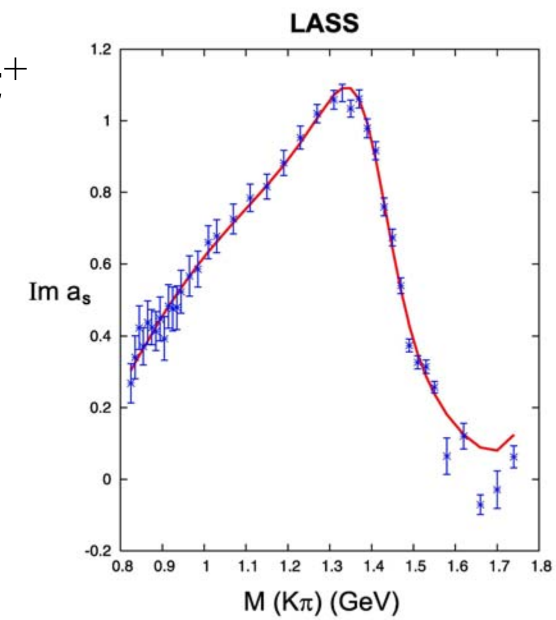
  and $K^- \pi^- \to K^- \pi^-$ scattering from Estabrooks *et al*

  Nucl. Phys,.B 133 (1978) 490

- extrapolate down to Kπ threshold according to dispersive analysis consistent with ChPT (Buttiker et al, Eur.Phys.J C33 (2004) 409).



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



I=1/2 K-matrix

1 pole -2 channels (Kπ -Kη’)

$$K_{11}=\left(\frac{s-s_{01/2}}{s_{norm}}\right)\left(\frac{g_1\cdot g_1}{s_1-s}+C_{110}+C_{111}\tilde{s}+C_{112}\tilde{s}^2\right)$$

$$K_{22}=\left(\frac{s-s_{01/2}}{s_{norm}}\right)\left(\frac{g_2\cdot g_2}{s_1-s}+C_{220}+C_{221}\tilde{s}+C_{222}\tilde{s}^2\right)$$

$$K_{12}=\left(\frac{s-s_{01/2}}{s_{norm}}\right)\left(\frac{g_1\cdot g_2}{s_1-s}+C_{120}+C_{121}\tilde{s}+C_{122}\tilde{s}^2\right)$$

$\mathbf{g_1}$,$\mathbf{g_2}$: real couplings of the $\mathbf{s_1}$ pole to the first and second channel

$\mathbf{s_{01/2}}$ =0.23 GeV^2 is the Adler zero position in the I=1/2 ChPT elastic scattering amplitude

$s = m^2(K\pi)$

$s_{norm} = m^2_K + m^2_\pi$

$\tilde{s} = s/s_{norm} - 1$

Table 1
Values of parameters for the $I = 1/2$ K-matrix

Pole (GeV^2)	Coupling (GeV)	C_{11i}	C_{12i}	C_{22i}
$s_1 = 1.7919$				
	$g_1 = 0.31072$			
	$g_2 = -0.02323$			
		$C_{110} = 0.79299$	$C_{120} = 0.15040$	$C_{220} = 0.17054$
		$C_{111} = -0.15099$	$C_{121} = -0.038266$	$C_{221} = -0.0219$
		$C_{112} = 0.00811$	$C_{122} = 0.0022596$	$C_{222} = 0.00085655$

S-matrix pole : $E = M - i\Gamma/2 = 1.408 - i0.110$ GeV

I=3/2 K-matrix

1 channel scalar function

$$K_{3/2} = \left(\frac{s - s_{03/2}}{s_{norm}} \right) \left(D_{110} + D_{111}\tilde{s} + D_{112}\tilde{s}^{2} \right)$$

$\mathbf{s_{03/2}}$ =0.27 GeV^2 is the Adler zero position in the I=3/2 ChPT elastic scattering amplitude

s = m^2(Kπ)
s_{norm} = $m^2_K + m^2_\pi$
$\tilde{s}$ = s/s_{norm}-1

$$D_{110} = -0.22147$$
$$D_{111} = 0.026637$$
$$D_{112} = -0.00092057$$

P and F-vectors

- P-vectors
  - initial coupling $D^+ \to (K^- \pi^+) \pi^+_{\text{spectator}}$ need not be real

$$(P_{1/2})_{1=K\pi} = \frac{\beta g_1 e^{i\theta}}{s_1 - s} + (c_{10} + c_{11}\hat{s} + c_{12}\hat{s}^2)e^{i\gamma_1}$$

$$\hat{s} = s - s_c$$

$$s_c = 2 \text{ GeV}^2$$

$$(P_{1/2})_{2=K\eta'} = \frac{\beta g_2 e^{i\theta}}{s_1 - s} + (c_{20} + c_{21}\hat{s} + c_{22}\hat{s}^2)e^{i\gamma_2}$$

$$P_{3/2} = (c_{30} + c_{31}\hat{s} + c_{32}\hat{s}^2)e^{i\gamma_3}$$

…and F-vectors

β, θ, c_{ij} , γ_i are the free parameters, all the others are fixed to scattering

$$F_{3/2} = (I - iK_{3/2}\rho)^{-1} P_{3/2}$$

$$(F_{1/2})_{1=K\pi} = (I - iK_{1/2}\rho)^{-1}_{1j} (P_{1/2})_j$$

…finally ready to fit $D^+ \to K^-\pi^+\pi^+$

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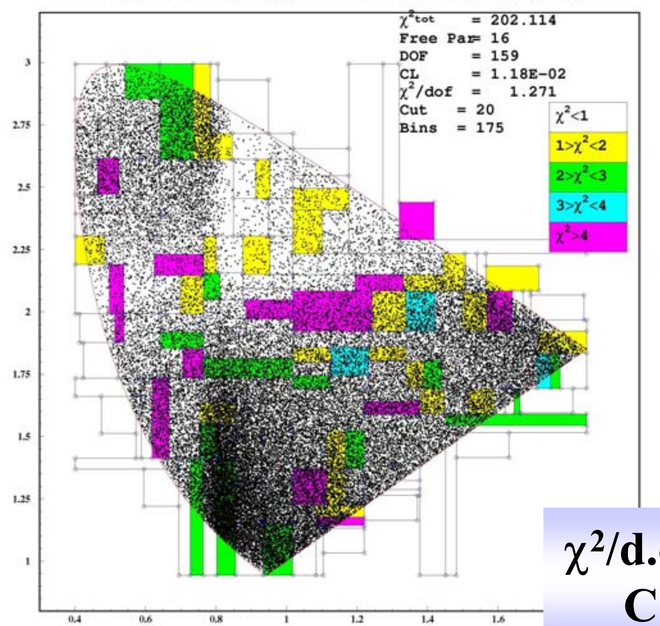
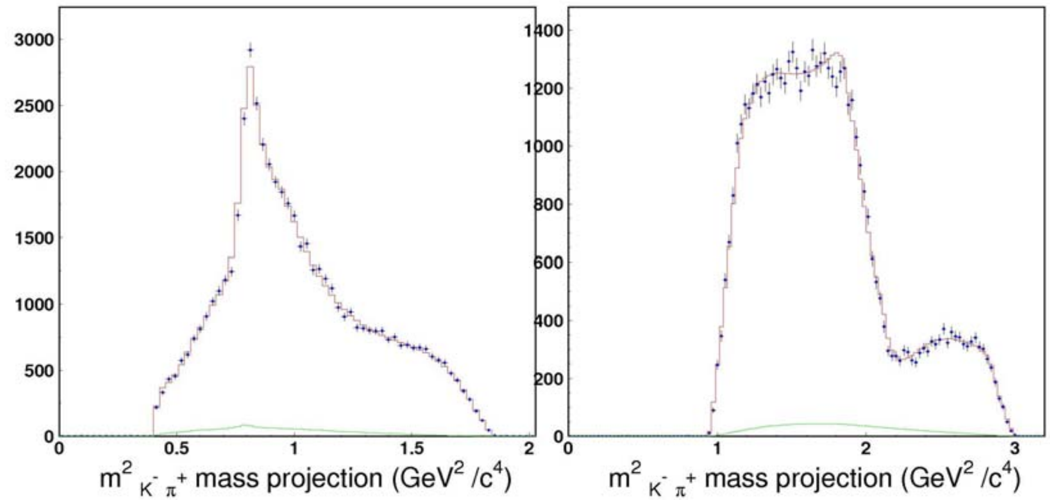




χ^2/d.o.f =1.27
C.L 1.2 %

total D decay amplitude

$$M = (F_{1/2})_1(s) + F_{3/2}(s) + \sum_n a_n e^{i\delta_n} A_n$$

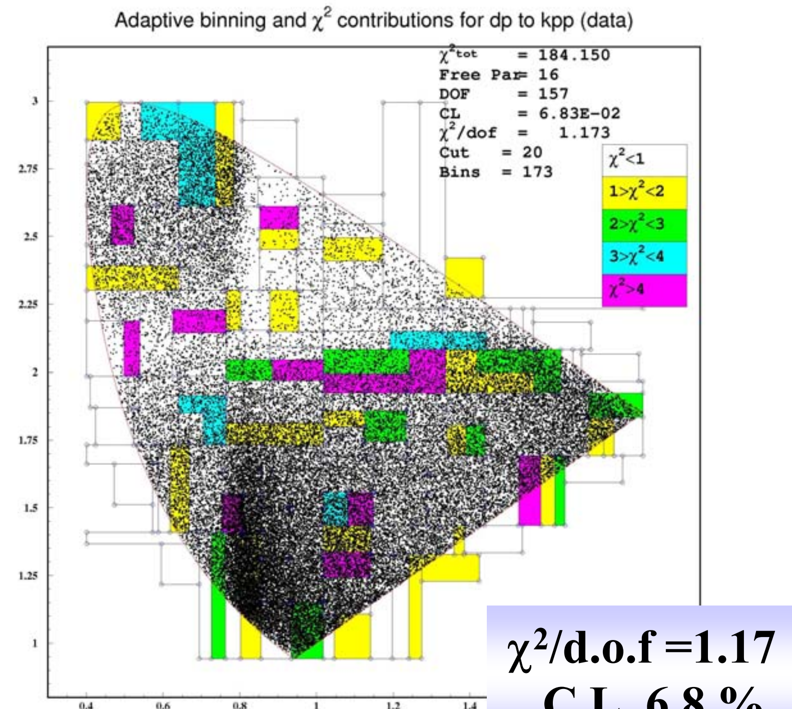
BW-like for J>0 states

coefficient	*phase (deg)*
$\beta = 3.389 \pm 0.152 \pm 0.002 \pm 0.068$	$\theta = 286 \pm 4 \pm 0.3 \pm 3.0$
$c_{10} = 1.655 \pm 0.156 \pm 0.010 \pm 0.101$	$\gamma_1 = 304 \pm 6 \pm 0.4 \pm 5.8$
$c_{11} = 0.780 \pm 0.096 \pm 0.003 \pm 0.090$	
$c_{12} = -0.954 \pm 0.058 \pm 0.0015 \pm 0.025$	
$c_{20} = 17.182 \pm 1.036 \pm 0.023 \pm 0.362$	$\gamma_2 = 126 \pm 3 \pm 0.1 \pm 1.2$
$c_{30} = 0.734 \pm 0.080 \pm 0.005 \pm 0.030$	$\gamma_3 = 211 \pm 10 \pm 0.7 \pm 7.8$
Total S-wave fit fraction $= 83.23 \pm 1.50 \pm 0.04 \pm 0.07$ %	
Isospin 1/2 fraction $= 207.25 \pm 25.45 \pm 1.81 \pm 12.23$ %	
Isospin 3/2 fraction $= 40.50 \pm 9.63 \pm 0.55 \pm 3.15$ %	

S-wave fraction
83 ±1.5 %

component	*fit fraction (%)*	*phase δ_j (deg)*	*coefficient*
$K^*(892)\pi^+$	13.61 ± 0.98	0 (fixed)	1 (fixed)
	$\pm 0.01 \pm 0.30$		
$K^*(1680)\pi^+$	1.90 ± 0.63	1 ± 7	0.373 ± 0.067
	$\pm 0.009 \pm 0.43$	$\pm 0.1 \pm 6$	$\pm 0.009 \pm 0.047$
$K_2^*(1430)\pi^+$	0.39 ± 0.09	296 ± 7	0.169 ± 0.017
	$\pm 0.004 \pm 0.05$	$\pm 0.3 \pm 1$	$\pm 0.010 \pm 0.012$
$K^*(1410)\pi^+$	0.48 ± 0.21	293 ± 17	0.188 ± 0.041
	$\pm 0.012 \pm 0.17$	$\pm 0.4 \pm 7$	$\pm 0.002 \pm 0.030$

Comparison with the isobar fit

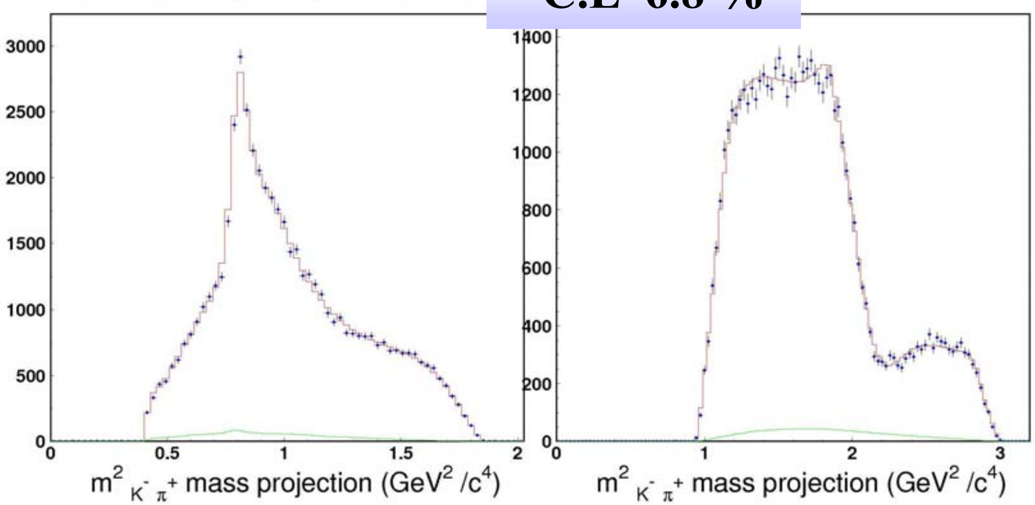


χ^2/d.o.f =1.17
C.L 6.8 %

- serves as the standard for fit quality
- requires two "ad hoc" scalars states with free masses and widths (BW) with no reference to how these states appear in other Kπ interactions (an effective data description)

k **m=856±17** **Γ=464±28**

$K_0^*(1430)$ **m=1461±4** **Γ=177±8**



- Isobar and K-matrix fits show
  - same "hot spots" in the adaptive binning scheme
  - good agreement in vector-tensor fit parameters

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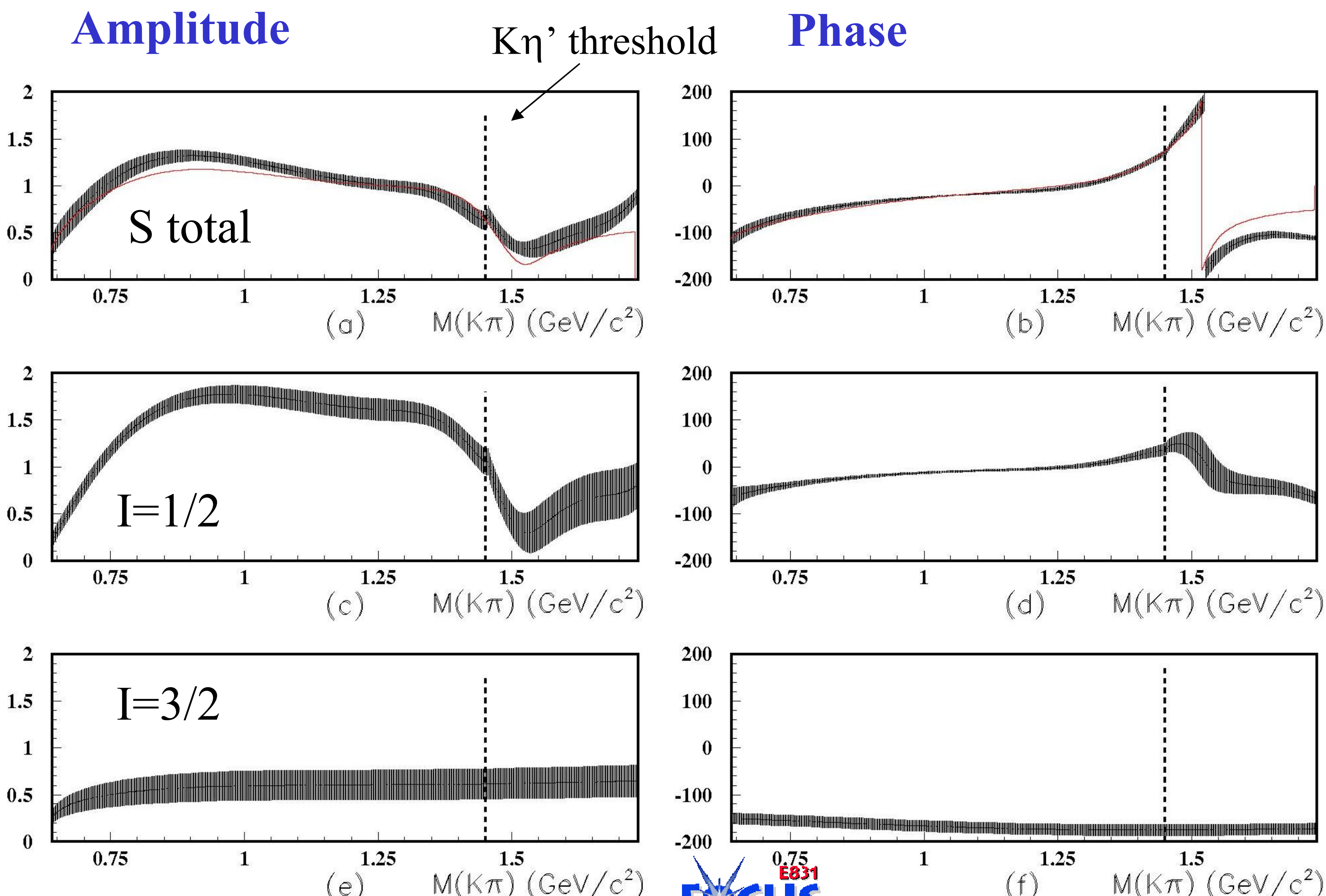
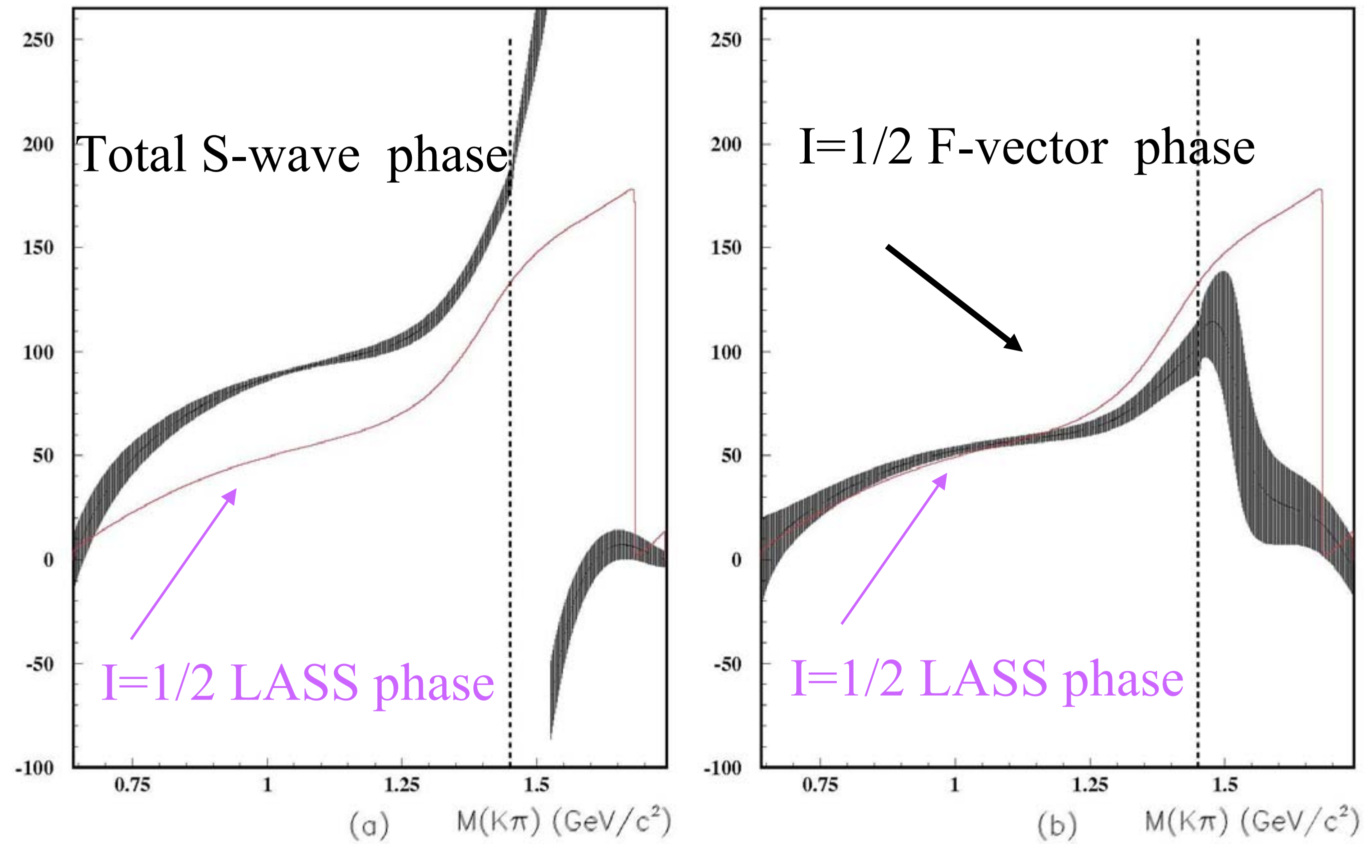
What else can we infer from F-vectors?



Phase comparison



Kη’ threshold

Results (I)

- The **first determination** in **D decays** of the **I=1/2 and I=3/2 for the S-wave Kπ** system has been performed
- The hypothesis of the **two -body dominance** is **consistent** with the **high statistics $D^+ \to K^-\pi^+\pi^+$**
- Our results show **close consistency with Kπ scattering data**, and consequently, with **Watson's theorem predictions for two-body Kπ interactions** in the low Kπ mass region where elastic processes dominate.

Results (II)

- Our K-matrix representation fits along the real energy axis inputs on scattering data and ChPT in close agreement with those used by Descotes-Genon and Moussallam (Eur. Phys. J C48 (2006) 553) that locate *k* with

mass (653 ± 15) MeV/c^2

and

width (557 ± 24) MeV/c^2

different from isobar fit parameters

- Whatever ***k* is revealed by our data**, it is the **same** as that found in **scattering data** .
  - We had reached an analougous conclusion for σ in the three pion analysis.

Results (III)

- Our K-matrix description gives a fit quality globally good.
- However it deteriorates at higher $K\pi$ mass
  - Two channels: $K\pi$ and $K\eta$':
  - **Reliable info on the former, poor constraints on the latter**

- **Improvements**: using a number of **D-decay chains** with **$K\pi$ final state interactions** and inputting all these in one **combined analysis** in which **several inelastic** channels are included in the **K-matrix formalism**.

for the future!

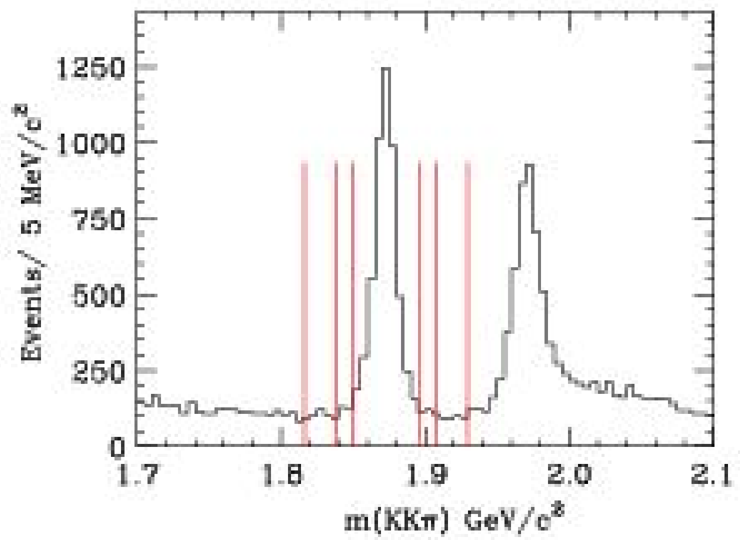
A non-parametric approach to measuring the $K^-\pi^+$ amplitudes in $D^+ \rightarrow K^-K^+\pi^+$ decay

Phys.Lett.B 648 (2007) 156

- **$D^+ \rightarrow K^-K^+\pi^+$** described by
  E687 :Phys.Lett.B 351 (1995) 591.

$$\phi\pi^+, K^+\overline{K}^{*0}(892), K^+\overline{K}_0^{*0}(1430)$$

- $\phi\pi^+$ is an important contribution BUT ϕ is very narrow and can be removed via a mass-cut **(ϕ-veto)**
  (6400 evts and 4200 m_{KK}>1050 MeV/c^2)



In the absence of K^-K^+ resonances (careful systematic check) we can write the decay amplitude in terms of $m_{K^-\pi^+}$ and the decay angle θ

⇓

one-dimensional analysis

$$A = \sum_{l}^{s,p,d\ldots} A_l(m_{K^-\pi^+}) d^l_{00}(\cos\theta)$$

Wigner *d*-matrices

- For S and P-wave only

$$I(m,\cos\theta) = |A|^2 = |S(m) + P(m)\cos\theta|^2 =$$

$$|S(m)|^2 + 2\,\mathrm{Re}\{S^*(m)P(m)\}\cos\theta + |P(m)|^2\cos^2\theta =$$

$$SS(m) + 2SP(m)\cos\theta + PP(m)\cos^2\theta$$

Apply the projector method

nearly identical to that used to determine the q^2 dependence of the helicity form factor in $D^+ \to K^-\pi^+ l^+ \nu$ (PLB 633 (2006) 183.)

Projection weighting technique

- Approach is to divide $\cos\theta$ into 20 evenly spaced angular bins
- ${}^{i}\vec{D} = ({}^{i}n_1 {}^{i}n_2 \ldots {}^{i}n_{20})$ is then a vector whose 20 components give the population in data for each of the 20 $\cos\theta$ bins: i specifies the ith $m_{K-\pi+}$ bin.
- Goal is to represent the ${}^{i}\vec{D}$ vector as a sum over the expected populations for each of the three partial waves, the ${}^{i}\vec{m}$ vectors.

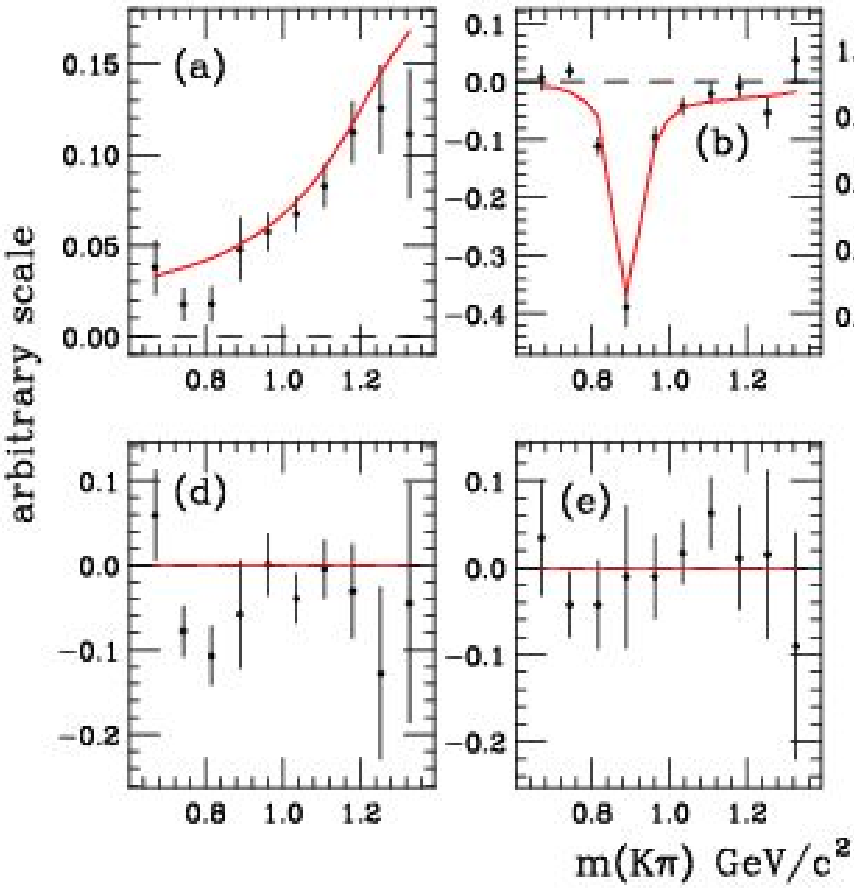
$$\{{}^{i}\vec{m}_{\alpha}\} = ({}^{i}\vec{m}_{SS}, {}^{i}\vec{m}_{SP}, {}^{i}\vec{m}_{PP})$$

  – Each ${}^{i}\vec{m}_{\alpha}$ is generated using a phase space and full simulation of the $D^+ \rightarrow K^-K^+\pi^+$ decay with one amplitude turned on and all the others shut off.

- We use a weighting technique to fit the bin populations in the data to the form

$${}^{i}\vec{D} = F_{SS}(m_i)\,{}^{i}\vec{m}_{SS} + F_{SP}(m_i)\,{}^{i}\vec{m}_{SP} + F_{PP}(m_i)\,{}^{i}\vec{m}_{PP}$$

Results (IV)



a) $S^2(m)$ direct term

b) $2S(m) \times P(m)$

c) $P^2(m)$ direct term

d) $2P(m) \times D(m)$

e) $D^2(m)$ direct term

six amplitudes:
3 direct terms:
***SS, PP and DD*.**
3 interference terms:
***SP*,*PD* and *SD* but**
amplitude ambiguity :
SD = (3 PP –SS)/2

Comparison plot is based on E687 model BUT with a much wider $K^*_0(1430)$, i.e. an *effective* Γ=500 MeV/c^2 Breit Wigner,i.e,

Kπ S-wave model not trivial

Results (V)

- **No need to assume BW, Form Factors etc..**
  - some discrepancies between our non-parametric description of the S-wave $K^-\pi^+$ amplitude and the standard BW $K_0^*(1430)$.
- **"Glitch" in the first three bins**
  - if they are deemed to be significant, one explanation would be the presence of a small D-wave component
- **$D^+ \to K^-K^+\pi^+$ is an ideal case for an analysis of this kind**
  - extend to $\mathbf{D_s^+ \to K^-K^+\pi^+}$
  - $\mathbf{D^0 \to K^+K^-\overline{K}^0}$ (emphasis on studying $m_{K\text{-}K+}$ spectrum after cuts to minimize $K^\pm\overline{K}^0$ contributions such as $a^\pm_0(980)$)
  - dipion amplitudes in **four body*** decays such as $\mathbf{D^0 \to K^-K^+\pi^-\pi^+}$ $\to \phi\pi^-\pi^+$ (dipion spectra against longitudinally and transversely polarized ϕ).

*FOCUS: **First amplitude analysis of $D^0 \to 4\pi$**

Phys.Rev.D7 (2007) 052003 **poor fit quality and model problems**

Pentaquark search in FOCUS

- 2005 Phys.Lett.B 622 (2005) 229

$$\Theta_c^0(\bar{c}uudd) \to D^{*-}p$$

$$\Theta_c^0 \to D^- p$$

no evidence of charmed pentaquark

- 2006 Phys.Lett.B 639 (2006) 604

$$\Theta^+(\bar{s}uudd) \to pK_s^0$$

no evidence of $\Theta^+ \to pK_s^0$

- 2007 arXiv: 0708.1010 [hep-ex]

φ(1860)-- (ssdd$\bar{u}$)

$$\Xi_5^{--} \to \Xi^- \pi^-$$

no evidence of $\Xi_5^- \to \Xi^- \pi^+$

- **No evidence for pentaquarks decaying to pK_s^0 in the mass range of 1470 MeV/c^2 to 2200 MeV/c^2**
  - *In contrast* 9 million $K^*(892)^+ \rightarrow K_s^0 \pi^+$
  - *0.4* million $\Sigma^*(1385)^\pm \rightarrow \Lambda^0 \pi^\pm$

similar topology and energy release

Parent particle with momenta above 25 GeV/c (good acceptance)

Natural width of 0 (15) MeV/c^2

$$\frac{\sigma(\Theta^+)\cdot BR(\Theta^+ \rightarrow pK_s^0)}{\sigma(K^*(892)^+)} < 0.00012 \ \ (0.00029) \text{ at } 95\% \text{ C.L.}$$

$$\frac{\sigma(\Theta^+)\cdot BR(\Theta^+ \rightarrow pK_s^0)}{\sigma(\Sigma^*(1385)^\pm)} < 0.0042 \ \ (0.0099) \text{ at } 95\% \text{ C.L}$$

- **No evidence for $\Xi_5^{--} \rightarrow \Xi^- \pi^-$ in the mass range of 1480 MeV/c^2 to 2400 MeV/c^2**
  - *In contrast* 65000 $\Xi^*(1530)^0 \rightarrow \Xi^- \pi^+$

similar topology and energy release

Parent particle with momenta above 25 GeV/c (good acceptance)
Natural width of 0 (15) MeV/c^2)

$$\frac{\sigma(\Xi_5^{--}) \cdot BR(\Xi_5^{--} \rightarrow \Xi^- \pi^-)}{\sigma(\Xi^*(1530)^0)} < 0.007 \ \ (0.019) \text{ at } 95\,\% \text{ C.L}$$

NA49: 15 $\Xi^*(1530)^0 \rightarrow \Xi^- \pi^+$ and 38 $\Xi_5^{--} \rightarrow \Xi^- \pi^-$
FOCUS results are ~4000 times larger

Conclusions

- Heavy Flavor decays are teaching us much about hadronic decay dynamics and QCD.
- Some formalism complications have already emerged expecially in the charm field others (unexpected) will only become clearer when we delve deeper into the beauty sector
  - **B_s will be a new chapter** (Ciuchini et al PLB645 (2007) 201: $B_s \to K\pi\pi$)
- There will be work for both theorists and experimentalists
  - **Synergy invaluable!**

The are no shortcuts toward ambitious and high-precision studies and NP search

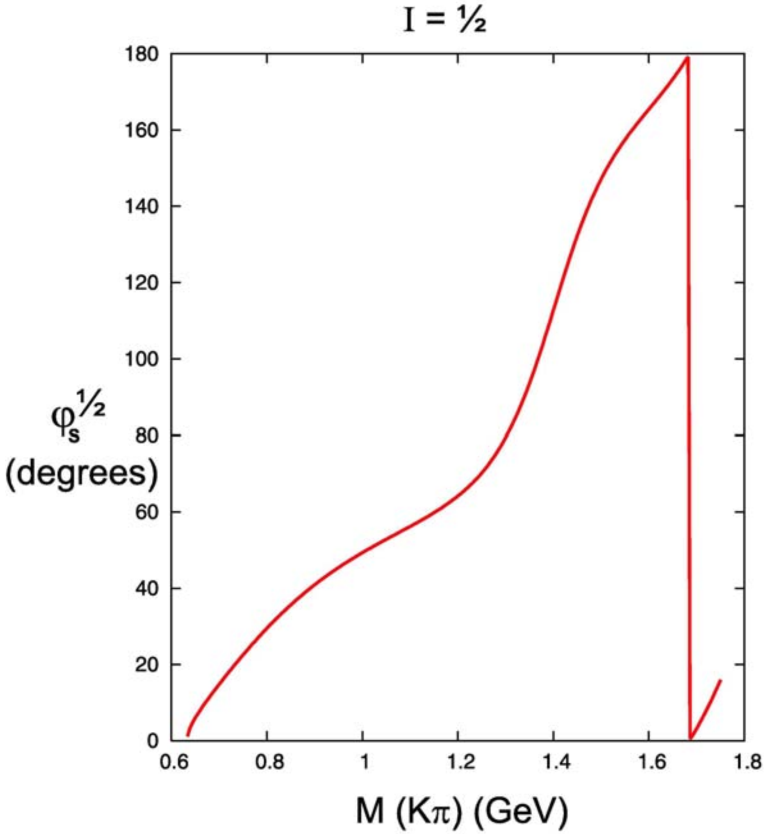
Back-up slides

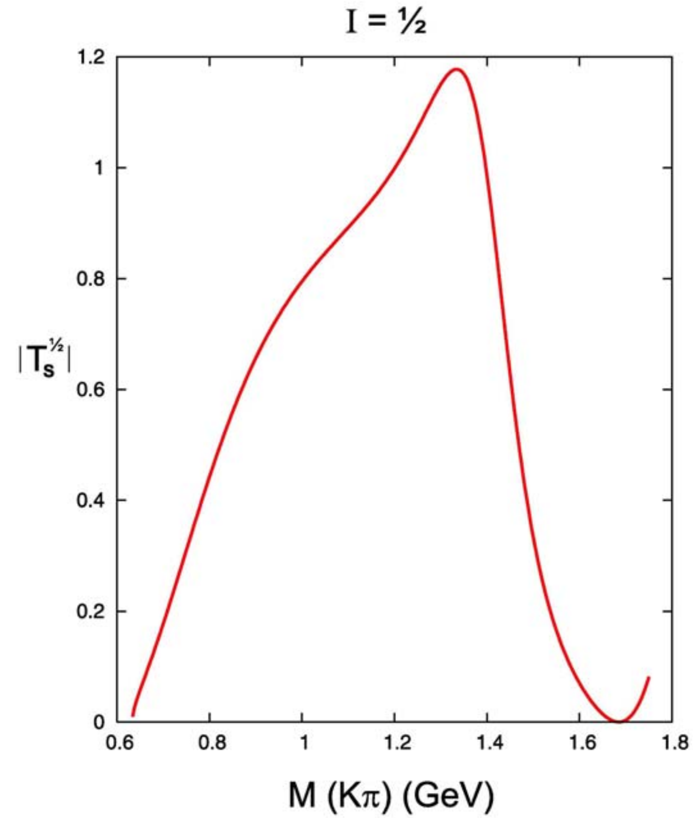
Isobar fit parameters

Table 2
Fit fractions, phases, and coefficients from the isobar fit to the FOCUS $D^+ \to K^-\pi^+\pi^+$ data. The first error is statistic, the second error is systematic from the experiment, and the third error is systematic induced by model input parameters for higher resonances

Channel	Fit fraction (%)	Phase δ_j (deg)	Coefficient
non-resonant	29.7 ± 4.5	325 ± 4	1.47 ± 0.11
	$\pm 1.5 \pm 2.1$ (see text)	$\pm 2 \pm 1.2$	$\pm 0.06 \pm 0.06$
$K^*(892)\pi^+$	13.7 ± 0.9	0 (fixed)	1 (fixed)
	$\pm 0.6 \pm 0.3$		
$K^*(1410)\pi^+$	0.2 ± 0.1	350 ± 34	0.12 ± 0.03
	$\pm 0.1 \pm 0.04$	$\pm 17 \pm 15$	$\pm 0.003 \pm 0.01$
$K^*(1680)\pi^+$	1.8 ± 0.4	3 ± 7	0.36 ± 0.04
	$\pm 0.2 \pm 0.3$	$\pm 4 \pm 8$	$\pm 0.02 \pm 0.03$
$K_2^*(1430)\pi^+$	0.4 ± 0.05	319 ± 8	0.17 ± 0.01
	$\pm 0.04 \pm 0.03$	$\pm 2 \pm 2$	$\pm 0.01 \pm 0.01$
$K_0^*(1430)\pi^+$	17.5 ± 1.5	36 ± 5	1.13 ± 0.05
	$\pm 0.8 \pm 0.4$	$\pm 2 \pm 1.2$	$\pm 0.01 \pm 0.02$
$\kappa\pi^+$	22.4 ± 3.7	199 ± 6	1.28 ± 0.10
	$\pm 1.2 \pm 1.5$ (see text)	$\pm 1 \pm 5$	$\pm 0.015 \pm 0.04$
	Mass (MeV$/c^2$)	Width (MeV$/c^2$)	
$K_0^*(1430)$	$1461 \pm 4 \pm 2 \pm 0.5$	$177 \pm 8 \pm 3 \pm 1.5$	
κ	$856 \pm 17 \pm 5 \pm 12$	$464 \pm 28 \pm 6 \pm 21$	

I=1/2 functions





- Multiplying the ${}^{i}\vec{D}$ data vector by each $\vec{m}_{\alpha}$ produces a component equation

$$\begin{pmatrix} {}^{i}\vec{m}_{SS} \cdot {}^{i}\vec{D} \\ {}^{i}\vec{m}_{SP} \cdot {}^{i}\vec{D} \\ {}^{i}\vec{m}_{PP} \cdot {}^{i}\vec{D} \end{pmatrix} = \begin{pmatrix} \vec{m}_{SS} \cdot \vec{m}_{SS} & \vec{m}_{SS} \cdot \vec{m}_{SP} & \vec{m}_{SS} \cdot \vec{m}_{PP} \\ \vec{m}_{SP} \cdot \vec{m}_{SS} & \vec{m}_{SP} \cdot \vec{m}_{SP} & \vec{m}_{SP} \cdot \vec{m}_{PP} \\ \vec{m}_{PP} \cdot \vec{m}_{SS} & \vec{m}_{PP} \cdot \vec{m}_{SP} & \vec{m}_{PP} \cdot \vec{m}_{PP} \end{pmatrix} \begin{pmatrix} F_{SS}(m_i) \\ F_{SP}(m_i) \\ F_{PP}(m_i) \end{pmatrix}$$

- The formal solution is

$$\begin{pmatrix} F_{SS}(m_i) \\ F_{SP}(m_i) \\ F_{PP}(m_i) \end{pmatrix} = \begin{pmatrix} \vec{m}_{SS} \cdot \vec{m}_{SS} & \vec{m}_{SS} \cdot \vec{m}_{SP} & \vec{m}_{SS} \cdot \vec{m}_{PP} \\ \vec{m}_{SP} \cdot \vec{m}_{SS} & \vec{m}_{SP} \cdot \vec{m}_{SP} & \vec{m}_{SP} \cdot \vec{m}_{PP} \\ \vec{m}_{PP} \cdot \vec{m}_{SS} & \vec{m}_{PP} \cdot \vec{m}_{SP} & \vec{m}_{PP} \cdot \vec{m}_{PP} \end{pmatrix}^{-1} \begin{pmatrix} {}^{i}\vec{m}_{SS} \cdot {}^{i}\vec{D} \\ {}^{i}\vec{m}_{SP} \cdot {}^{i}\vec{D} \\ {}^{i}\vec{m}_{PP} \cdot {}^{i}\vec{D} \end{pmatrix}$$

•This solution can be written as

$$F_{SS}(m_i) = {}^i\vec{P}_{SS} \cdot {}^i\vec{D},$$

$$F_{SP}(m_i) = {}^i\vec{P}_{SP} \cdot {}^i\vec{D},$$

$$F_{PP}(m_i) = {}^i\vec{P}_{PP} \cdot {}^i\vec{D}$$

•Where the projection vectors are given by

$$\begin{pmatrix} \vec{P}_{SS} \\ \vec{P}_{SP} \\ \vec{P}_{PP} \end{pmatrix} = \begin{pmatrix} \vec{m}_{SS} \cdot \vec{m}_{SS} & \vec{m}_{SS} \cdot \vec{m}_{SP} & \vec{m}_{SS} \cdot \vec{m}_{PP} \\ \vec{m}_{SS} \cdot \vec{m}_{SS} & \vec{m}_{SP} \cdot \vec{m}_{SP} & \vec{m}_{SP} \cdot \vec{m}_{PP} \\ \vec{m}_{PP} \cdot \vec{m}_{SS} & \vec{m}_{PP} \cdot \vec{m}_{SP} & \vec{m}_{PP} \cdot \vec{m}_{PP} \end{pmatrix}^{-1} \begin{pmatrix} {}^i\vec{m}_{SS} \\ {}^i\vec{m}_{SP} \\ {}^i\vec{m}_{PP} \end{pmatrix}$$

•The various projector dot products are implemented through a weighting technique.

Example:

• to extract the term $2S(m_{K^-\pi^+})\times P(m_{K^-\pi^+})$ in the *i*th mass bin , we need the dot product

$$ {}^{i}\vec{P}_{SP} \cdot {}^{i}\vec{D} = ({}^{i}\vec{P}_{SP})_1^i n_1 + ({}^{i}\vec{P}_{SP})_2^i n_2 + \ldots + ({}^{i}\vec{P}_{SP})_{20}^i n_{20} $$

• we can do this by making a weighted histogram of $m_{K-\pi+}$ where

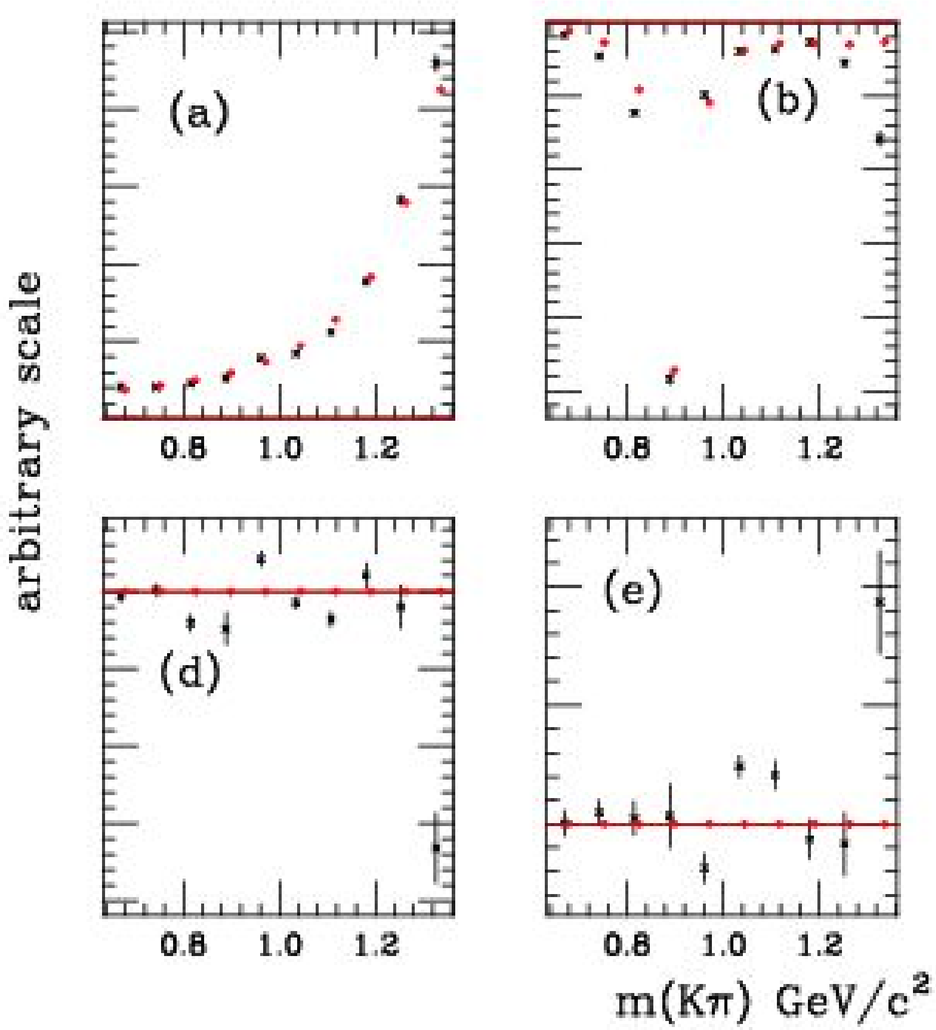
the events reconstructed in the first cosθ bin are weighted by $({}^{i}\vec{P}_{SP})_1$

the events reconstructed in the second cosθ bin are weighted by $({}^{i}\vec{P}_{SP})_2$

Systematic errors

- Model for K^-K^+ channel
  - ϕ parameters
  - potential contributions from $f_0(980)$ and $f_2(1270)$
    - varying amplitudes and phases
- Monte Carlo simulations
  - comparison of simulated and observed
    - $\cos\theta$ as a function of $m_{K-\pi+}$
    - m_{KK}, $m_{K-\pi+}$, $m_{K+\pi+}$ global mass projection (good agreement)
- Different analysis
  - three rather than five projectors (consistency)
  - different ϕ-veto cut $m_{KK} > 1050$ MeV/c^2 (1100 MeV/c^2)

The bias correction



a) $S^2(m)$ direct term
b) $2S(m) \times P(m)$
c) $P^2(m)$ direct term
d) $2P(m) \times D(m)$
e) $D^2(m)$ direct term

legenda: crosses are the reconstructed spectra, diamonds are are the actual spectra used in the simulation based on our E687 model .

- **No evidence for pentaquarks decaying to pK_s^0 in the mass range of 1470 MeV/c² to 2200 MeV/c²**

  - *In contrast* 9 million $K^*(892)^+ \rightarrow K_s^0 \pi^+$
  - *0.4* million $\Sigma^*(1385)^\pm \rightarrow \Lambda^0 \pi^\pm$

similar topology and energy release

Parent particle produced at any momenta.

Natural width of 0 (15) MeV/c²

$$\frac{\sigma(\Theta^+)\cdot BR(\Theta^+ \rightarrow pK_s^0)}{\sigma(K^*(892)^+)} < 0.0013 \ \ (0.0033) \text{ at } 95\,\% \text{ C.L}$$

$$\frac{\sigma(\Theta^+)\cdot BR(\Theta^+ \rightarrow pK_s^0)}{\sigma(\Sigma^*(1385)^\pm)} < 0.023 \ \ (0.057) \text{ at } 95\,\% \text{ C.L}$$

Parent particle with momenta above 25 GeV/c (good acceptance)

Natural width of 0 (15) MeV/c²

$$\frac{\sigma(\Theta^+)\cdot BR(\Theta^+ \rightarrow pK_s^0)}{\sigma(K^*(892)^+)} < 0.00012 \ \ (0.00029) \text{ at } 95\% \text{ C.L.}$$

$$\frac{\sigma(\Theta^+)\cdot BR(\Theta^+ \rightarrow pK_s^0)}{\sigma(\Sigma^*(1385)^\pm)} < 0.0042 \ \ (0.0099) \text{ at } 95\% \text{ C.L}$$

- **No evidence for $\Xi_5^{--} \to \Xi^- \pi^-$ in the mass range of 1480 MeV/c^2 to 2400 MeV/c^2**
  - *In contrast* 65000 $\Xi^*(1530)^0 \to \Xi^- \pi^+$

similar topology and energy release

Parent particle produced at any momenta.
Natural width of 0 (15) MeV/c^2)

$$\frac{\sigma(\Xi_5^{--}) \cdot BR(\Xi_5^{--} \to \Xi^- \pi^-)}{\sigma(\Xi^*(1530)^0)} < 0.032 \;\; (0.091) \text{ at } 95\,\%\ \text{C.L}$$

Parent particle with momenta above 25 GeV/c (good acceptance)
Natural width of 0 (15) MeV/c^2)

$$\frac{\sigma(\Xi_5^{--}) \cdot BR(\Xi_5^{--} \to \Xi^- \pi^-)}{\sigma(\Xi^*(1530)^0)} < 0.007 \;\; (0.019) \text{ at } 95\,\%\ \text{C.L}$$

NA49: 15 $\Xi^*(1530)^0 \to \Xi^- \pi^+$ and 38 $\Xi_5^{--} \to \Xi^- \pi^-$
FOCUS results are ~4000 times larger