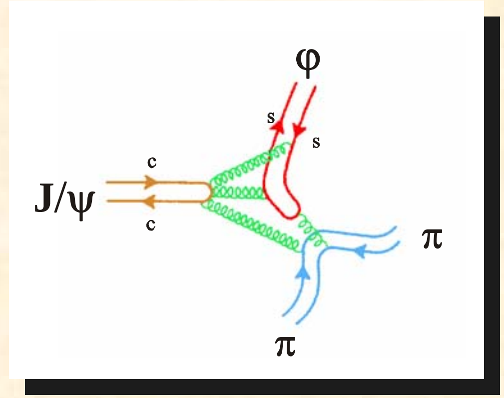
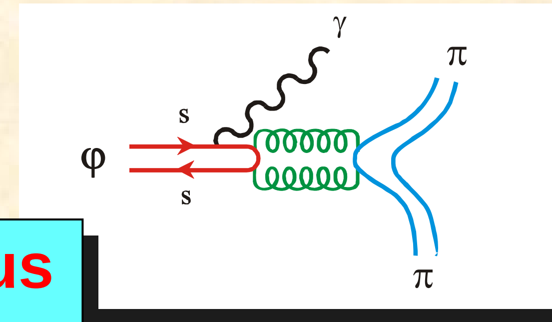
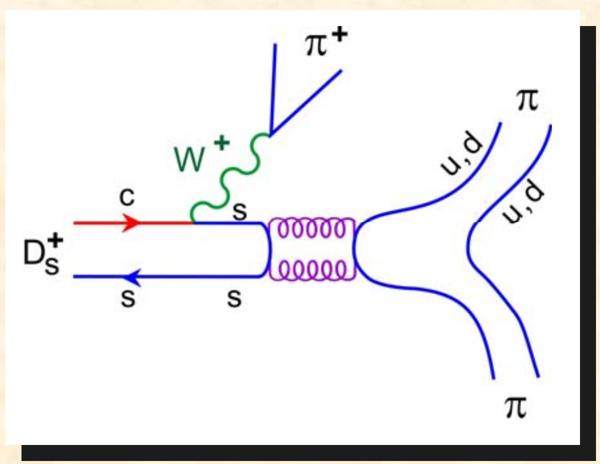


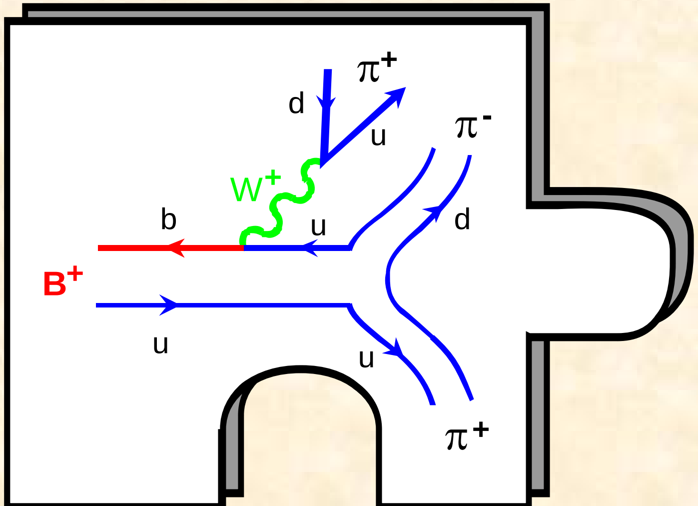


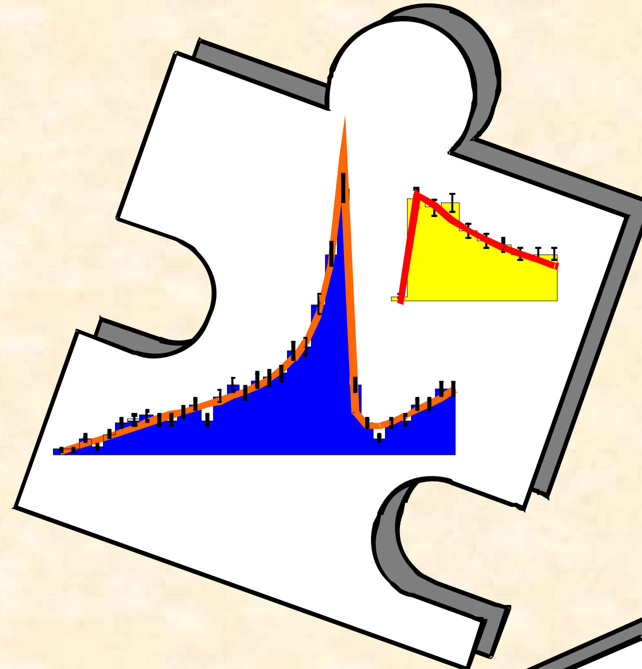
What heavy flavour decays can teach us about light quark strong physics



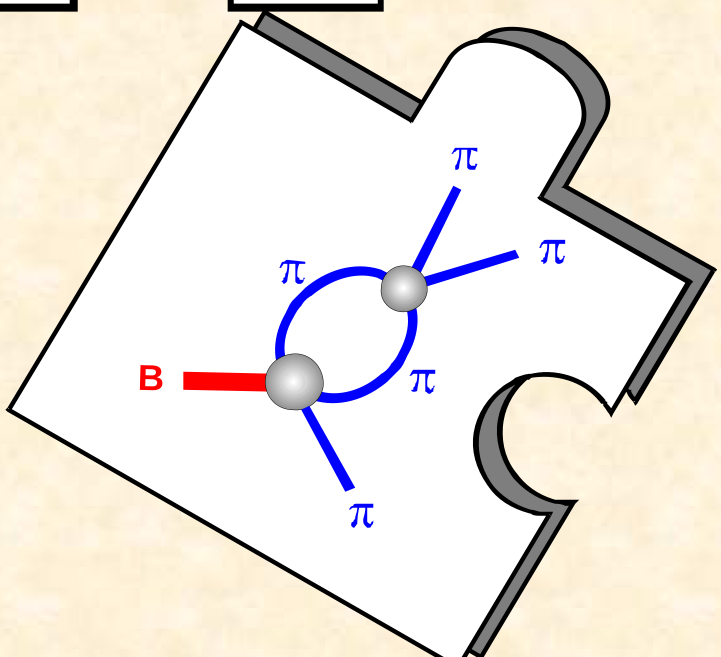
INFN Istituto Nazionale di Fisica Nucleare

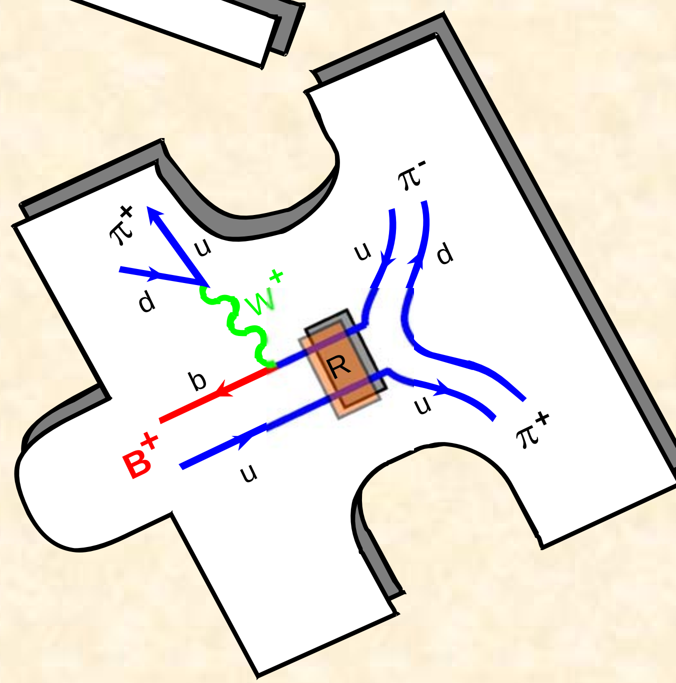
Physics Puzzle



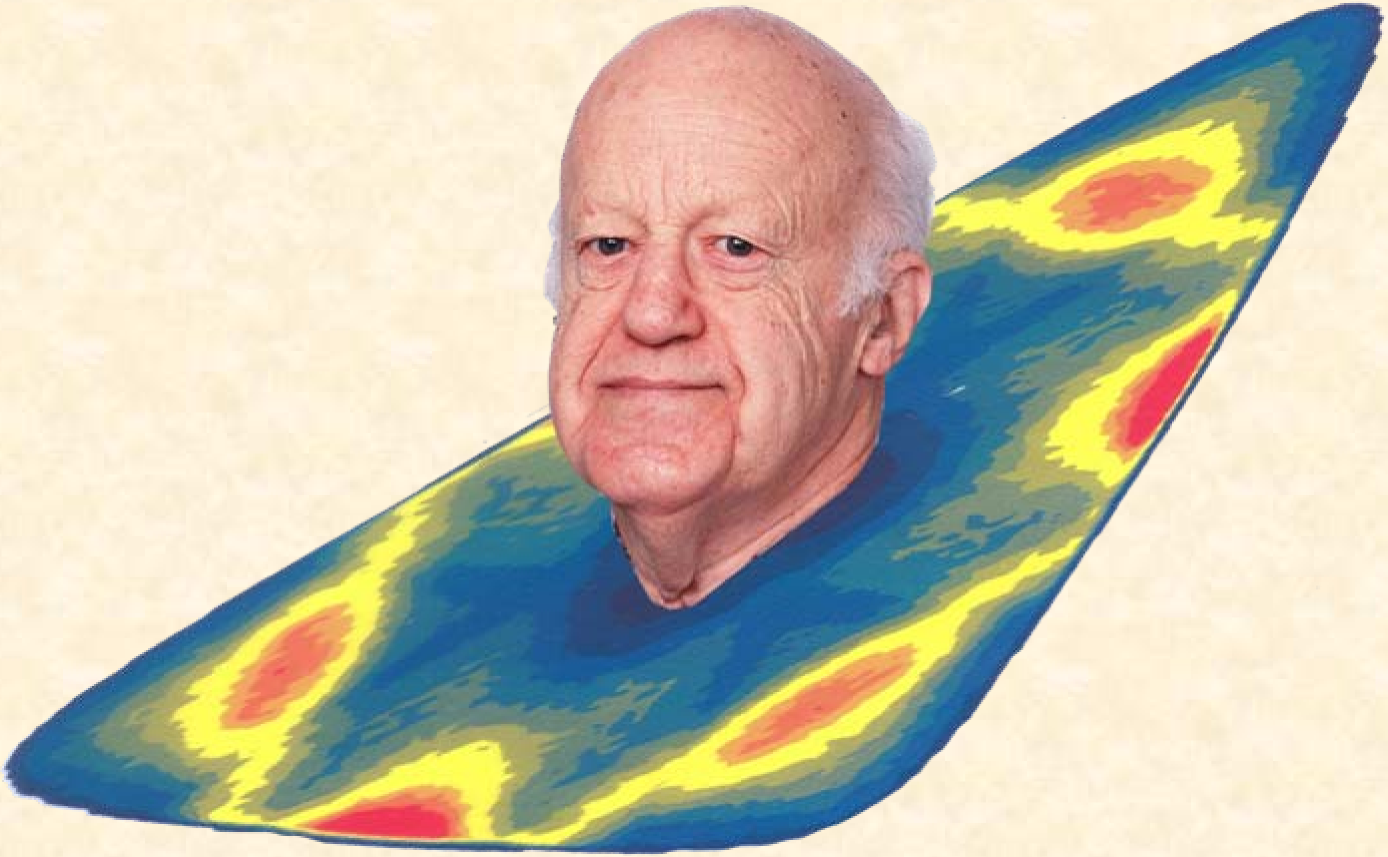


~~CP~~

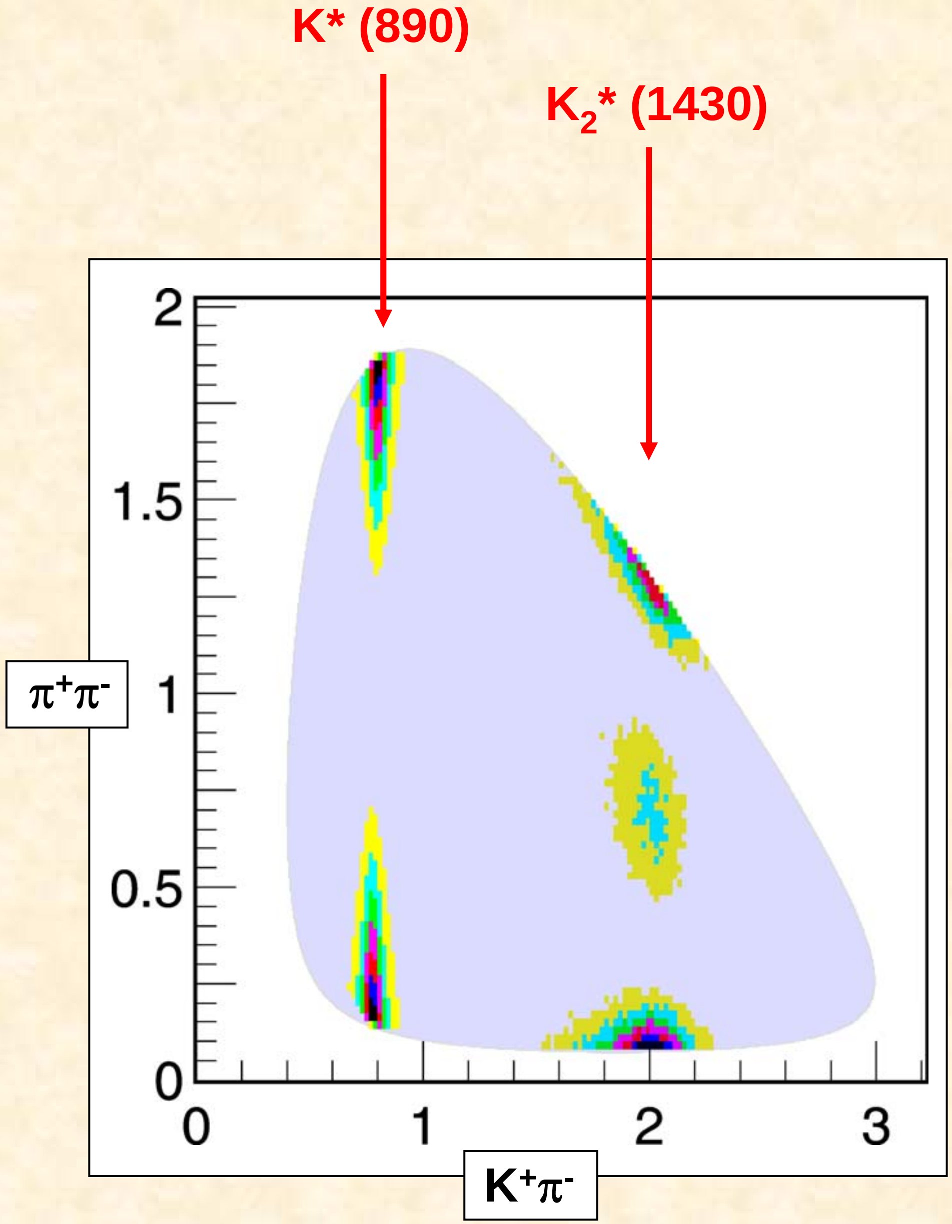




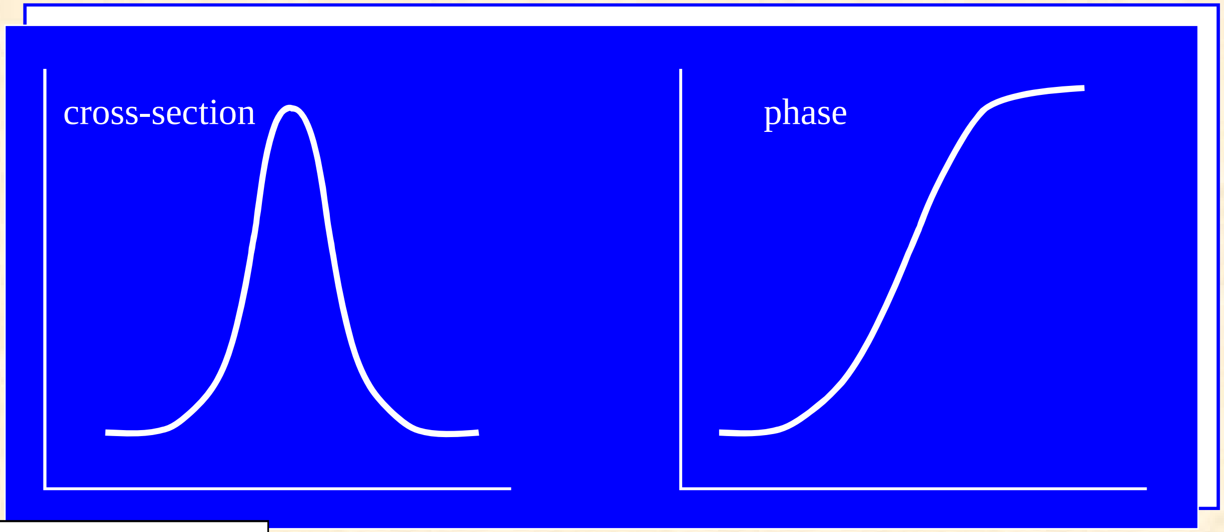
Dalitz Analysis

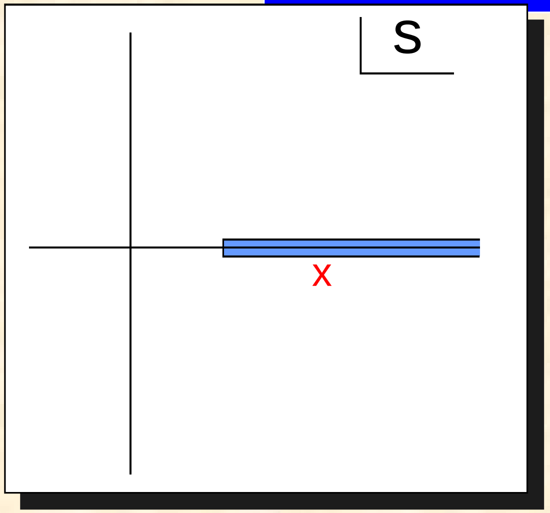


$D^+ \longrightarrow K^+\pi^+\pi^-$



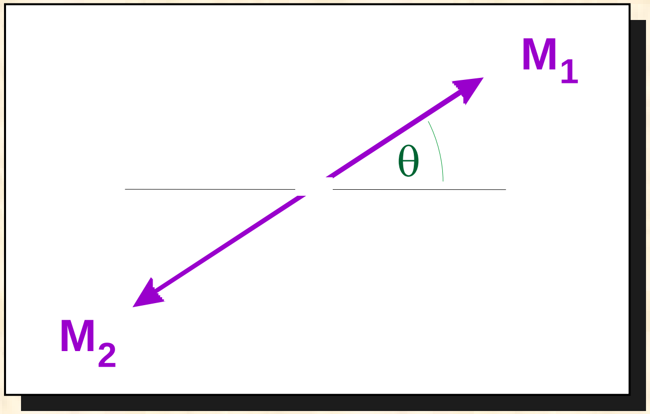
Hadron states

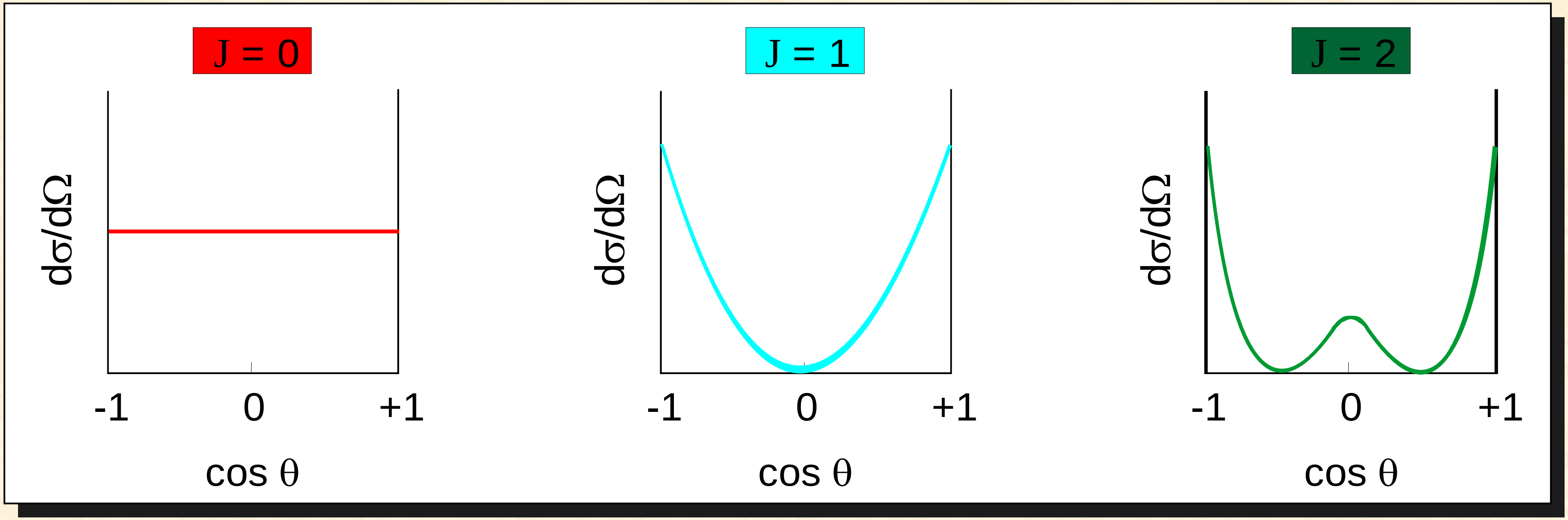




$$\frac{1}{M^2 - s - iM\Gamma}$$

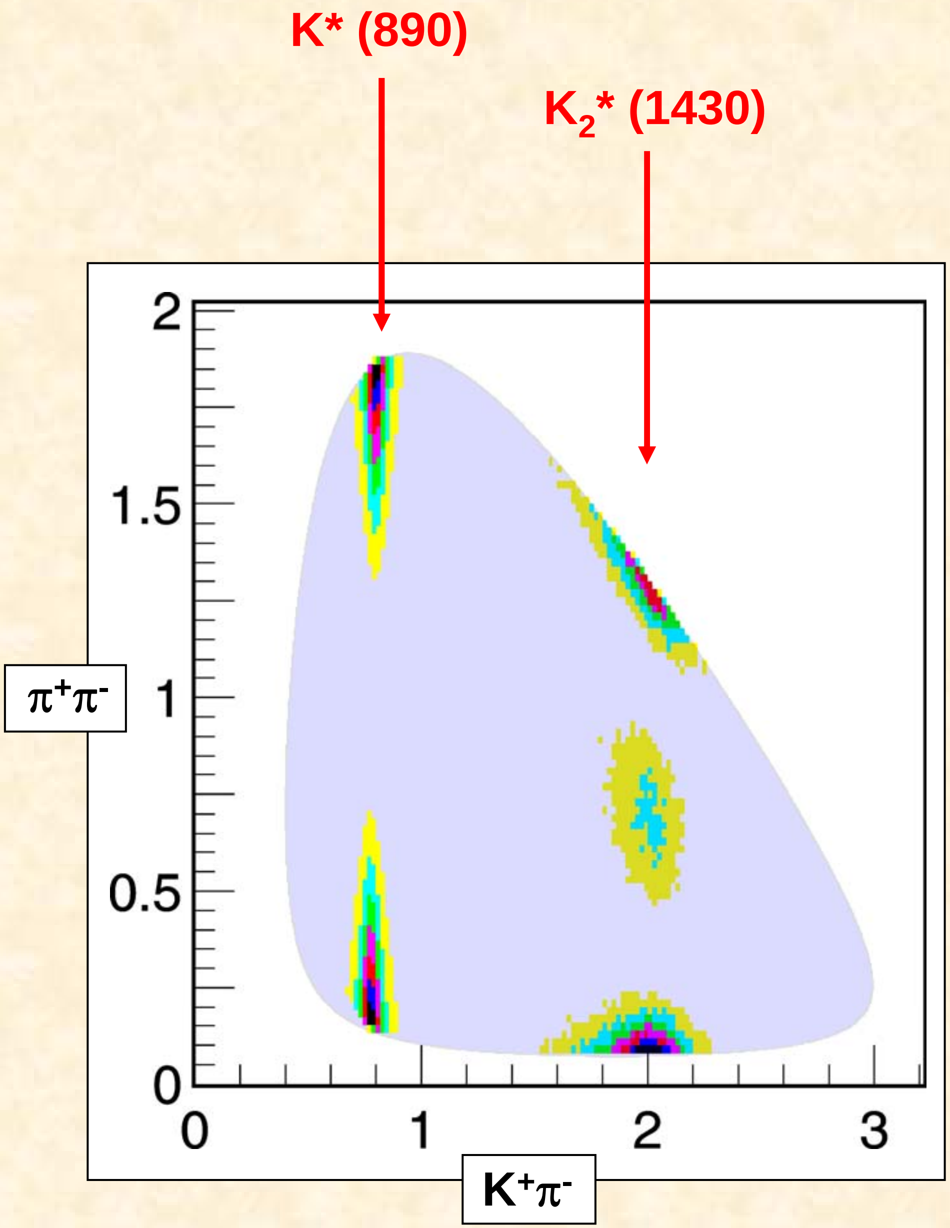
SPIN ANALYSIS



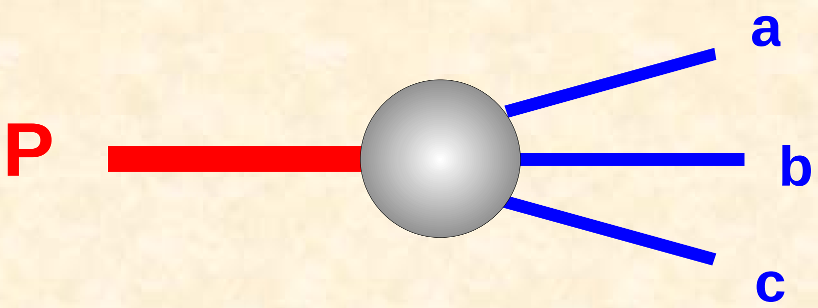


Spectroscopy: interplay of poles & zeros

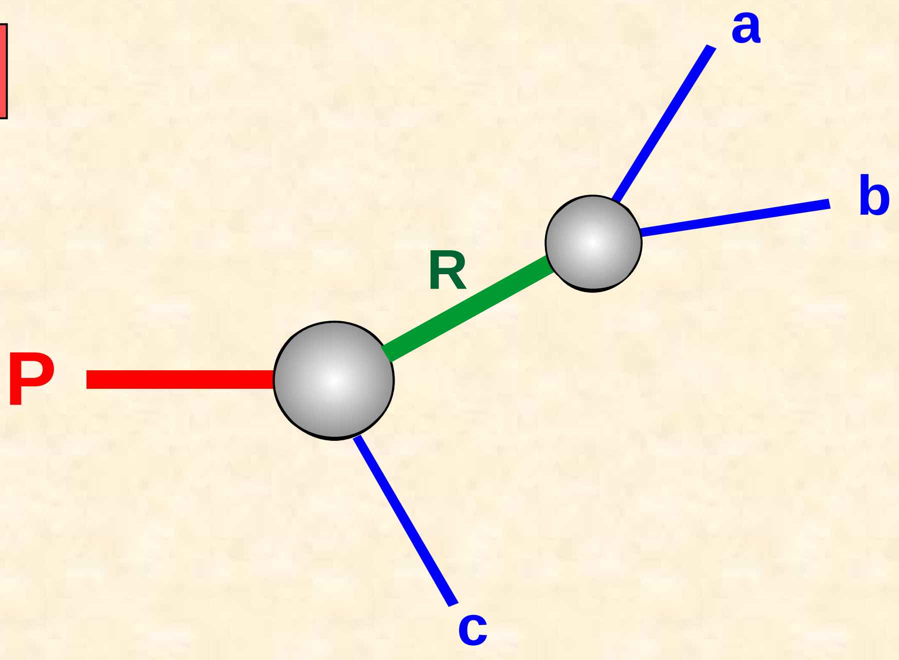
$D^+ \longrightarrow K^+\pi^+\pi^-$



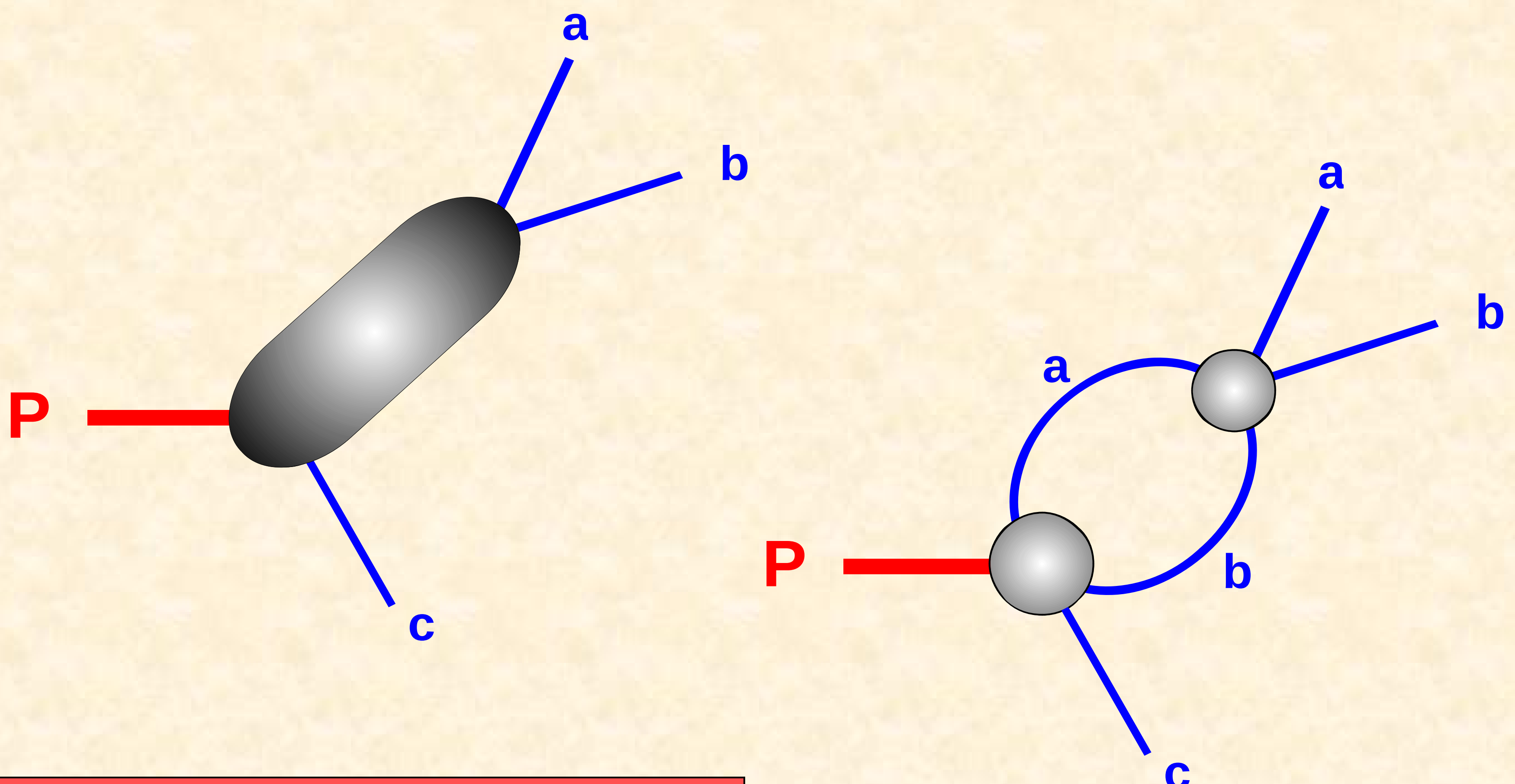
P ⟶ a b c



isobar picture

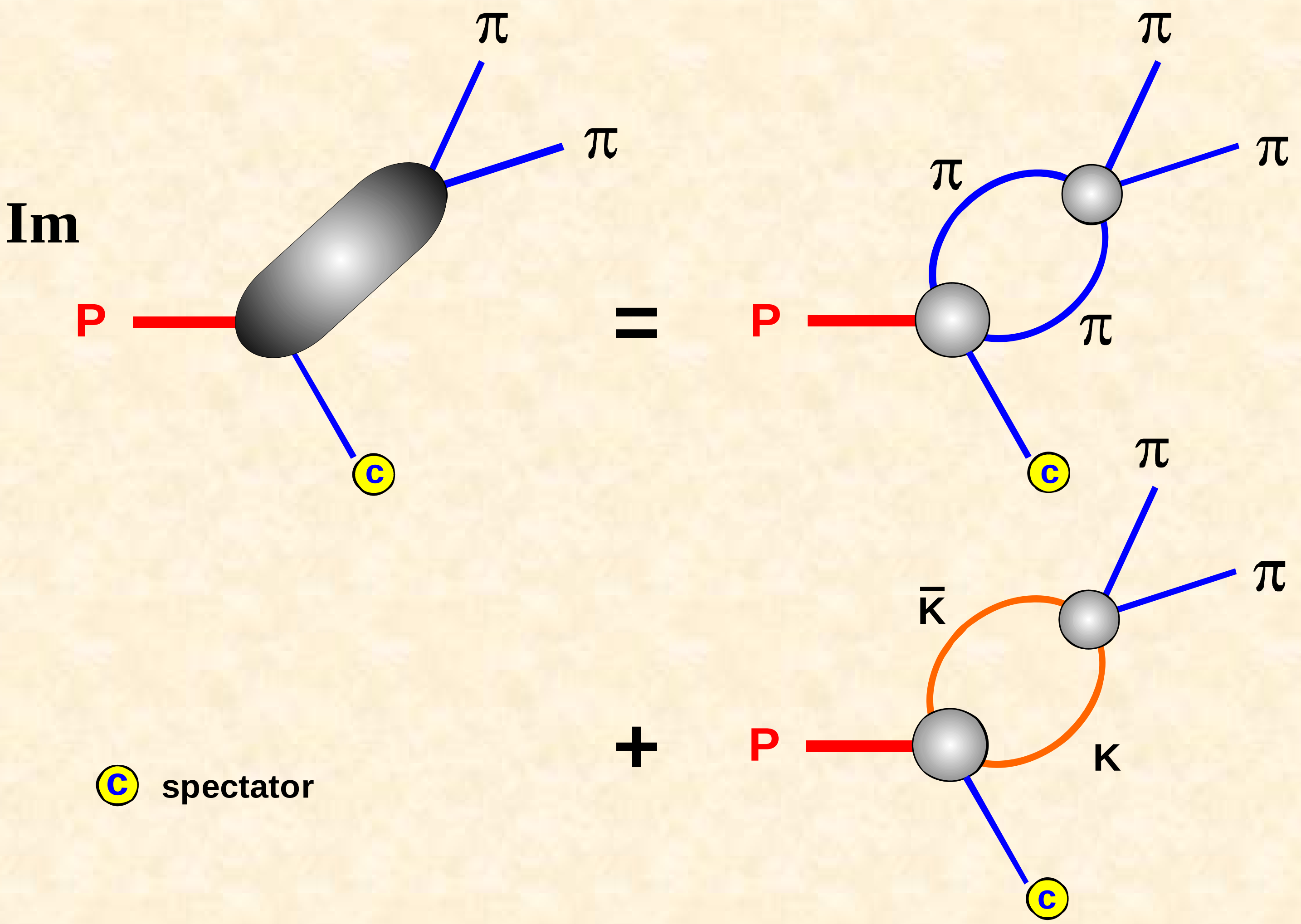


P ⟶ a b c



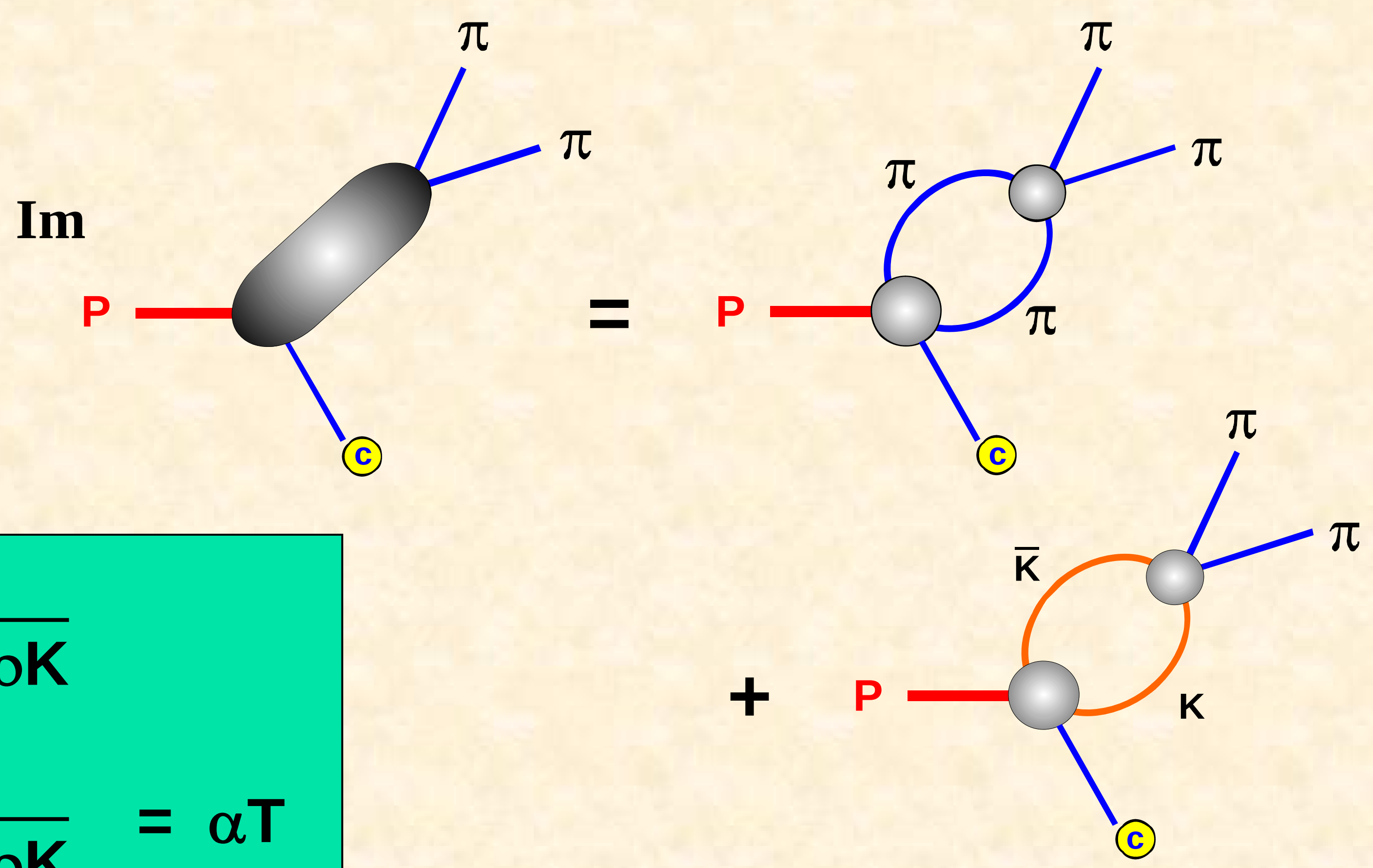
unitarity connects to hadronic scattering

Unitarity for P $\longrightarrow$ ππ (c)



c spectator

UNITARITY : decays in spectator picture



$$T = \frac{K}{1 - i\rho K}$$

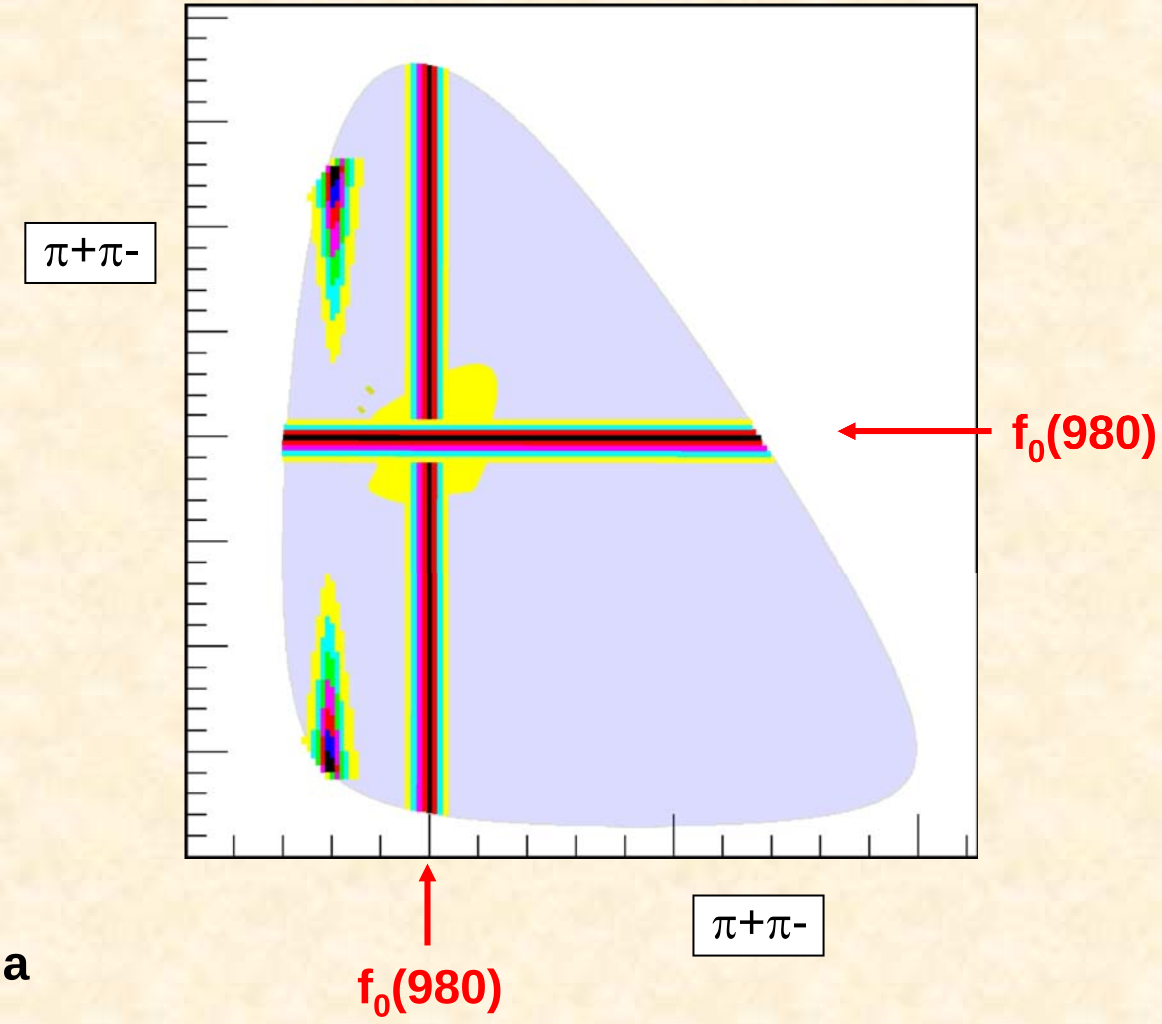
$$F = \frac{P}{1 - i\rho K} = \alpha T$$

coupling function

c spectator

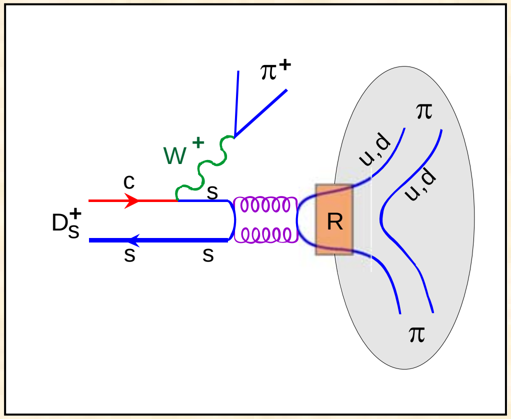
$D_s^+ \longrightarrow \pi^+\pi^+\pi^-$

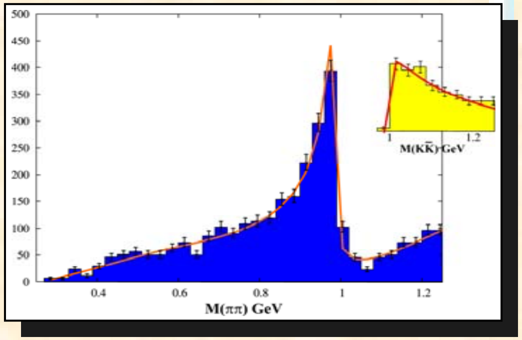
E791

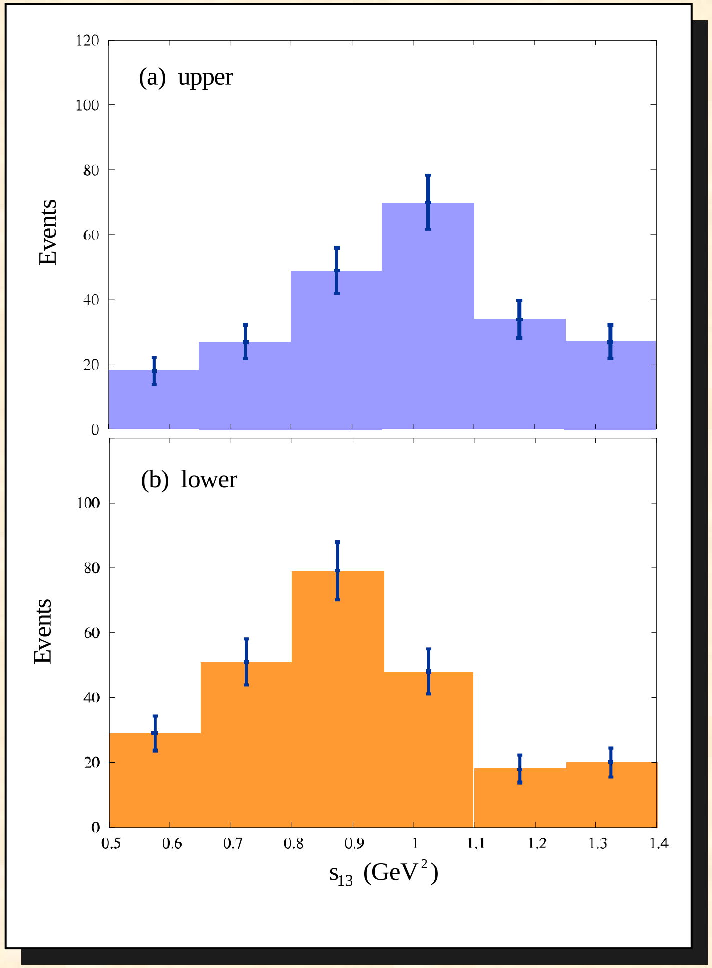


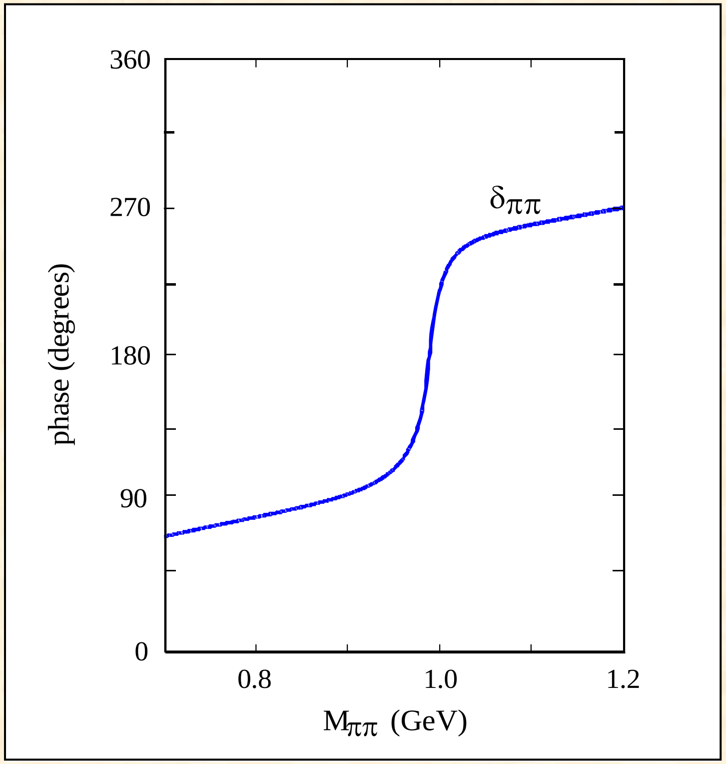
Bediaga & Miranda

$D_s^+ \longrightarrow \pi^+\pi^+\pi^-$



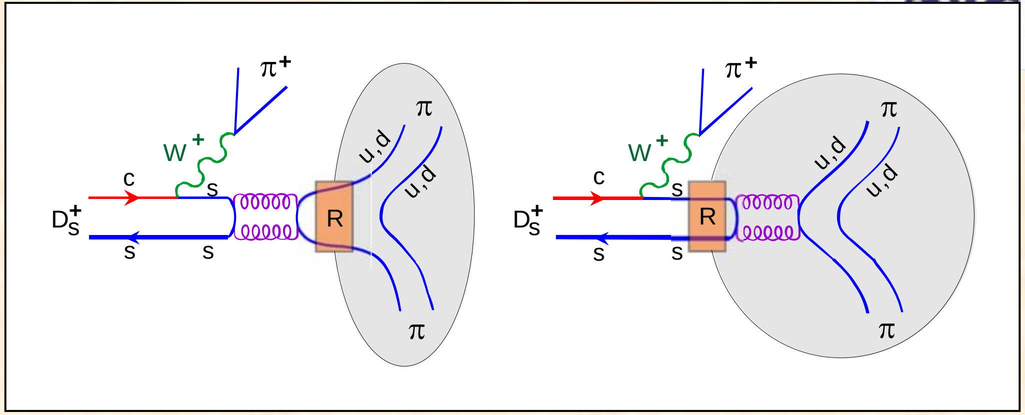


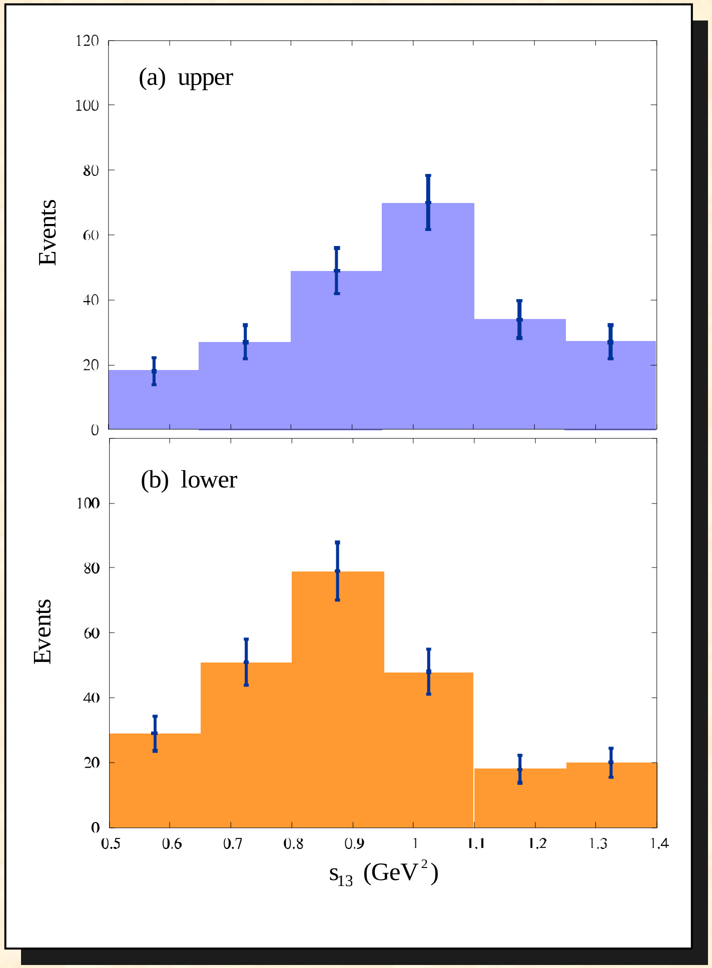


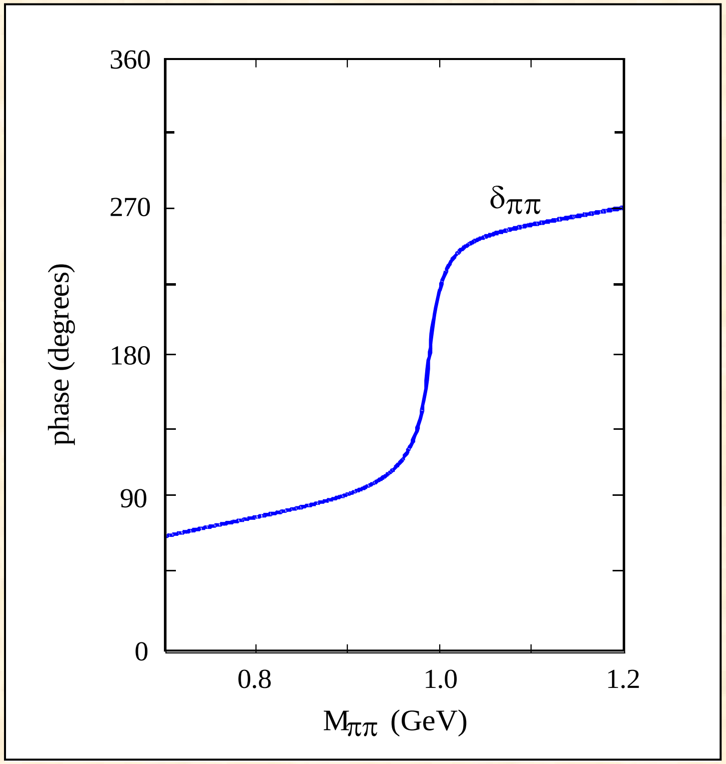


Bediaga & Miranda

$D_s^+ \longrightarrow \pi^+\pi^+\pi^-$

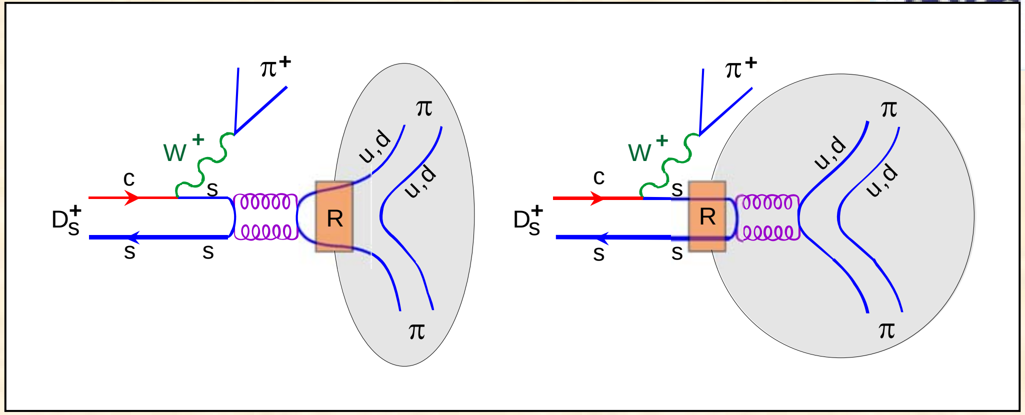


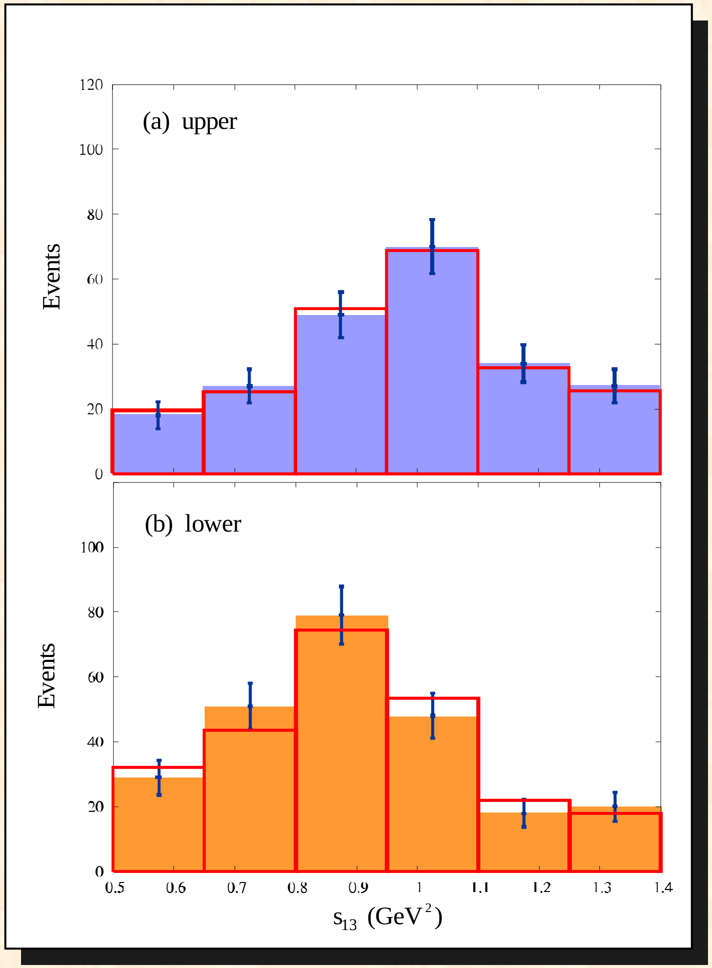


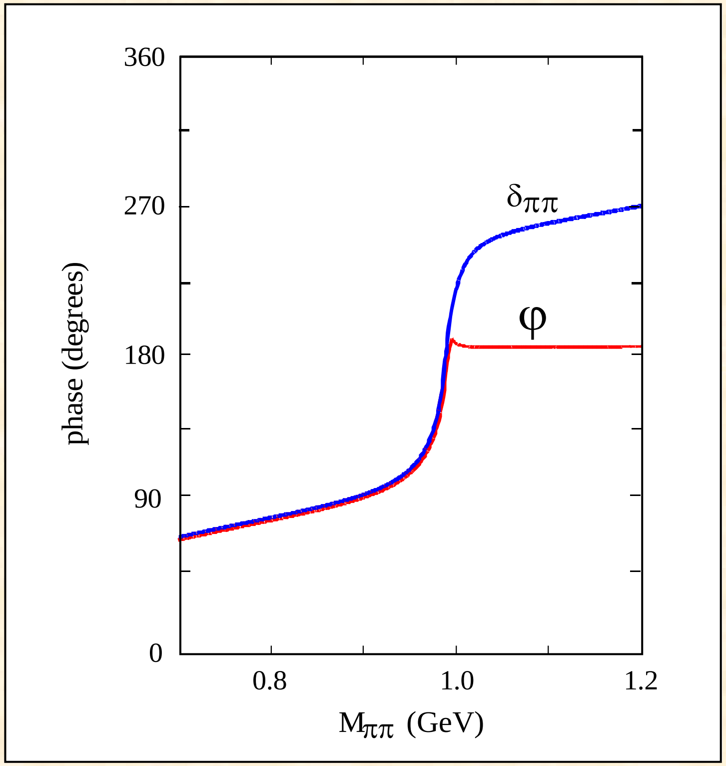


Bediaga & Miranda

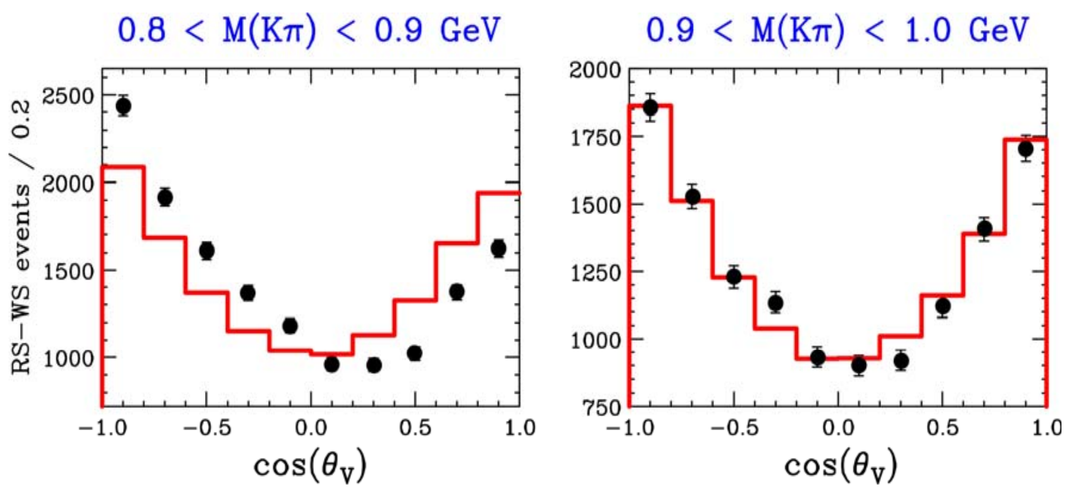
$D_s^+ \longrightarrow \pi^+\pi^+\pi^-$





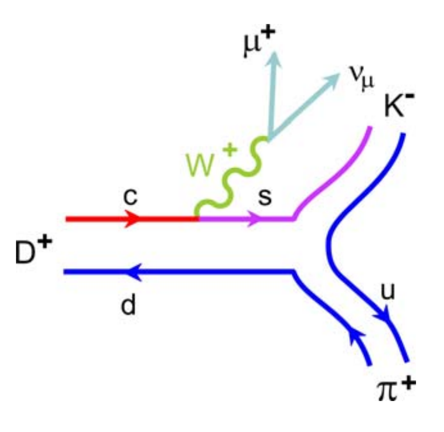


$D^+ \longrightarrow (K^-\pi^+)\mu^+\nu_\mu$

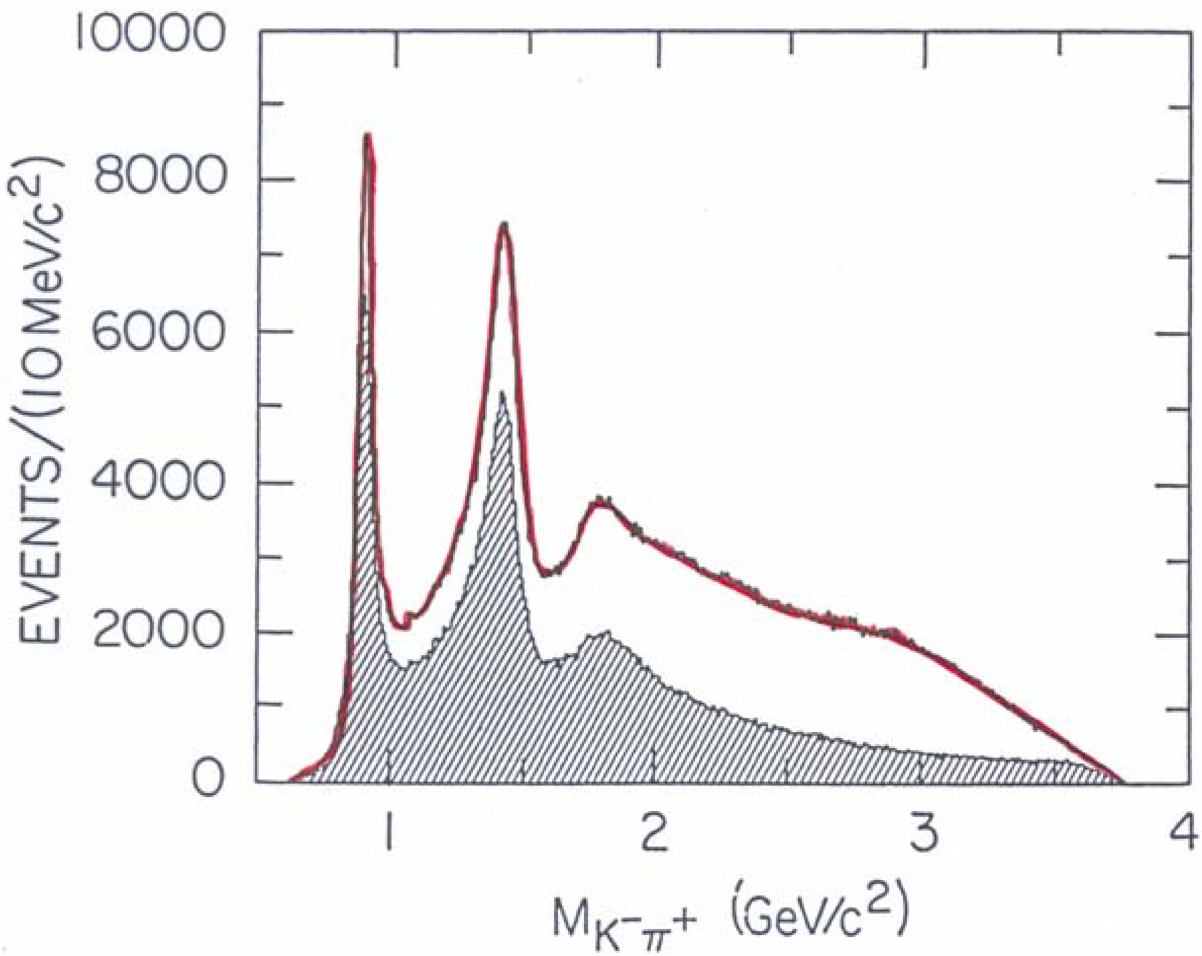


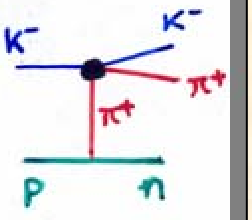
$$\mathcal{F}(D \to (K\pi)\mu\nu; s) \;=\; \mathcal{F}_{sl}^{1/2}(s) \;+\; \mathcal{F}_{sl}^{3/2}(s)$$

$$\mathcal{F}_{sl}^{I}(s) \;= |\,\mathcal{F}_{sl}^{I}(s)\,|\; \exp\left[i\delta^{I}(s)\right]$$

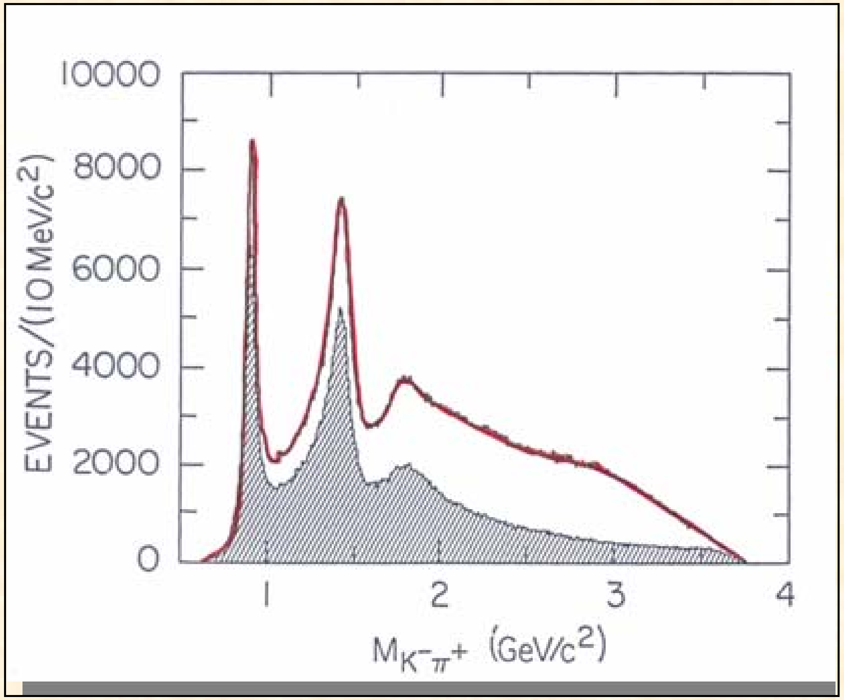


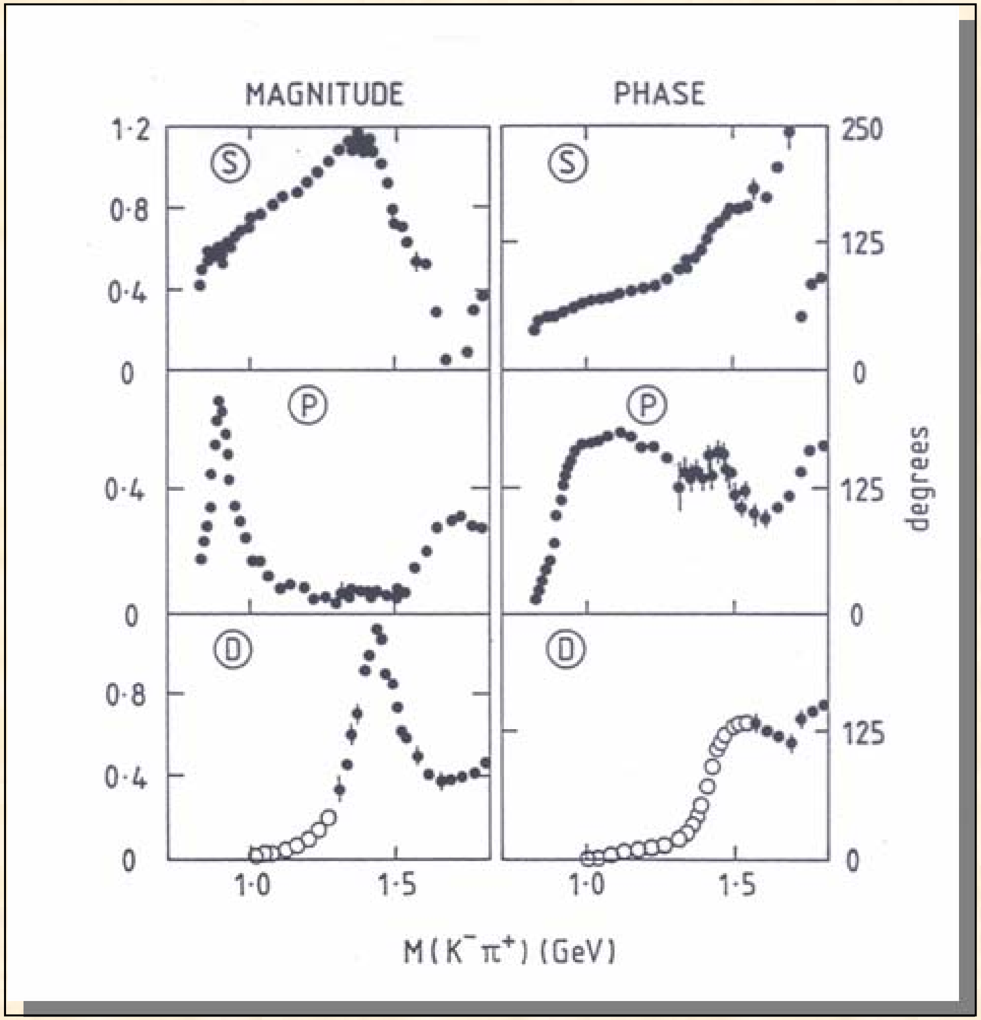
LASS: $K^- p \longrightarrow K^- \pi^+ n$

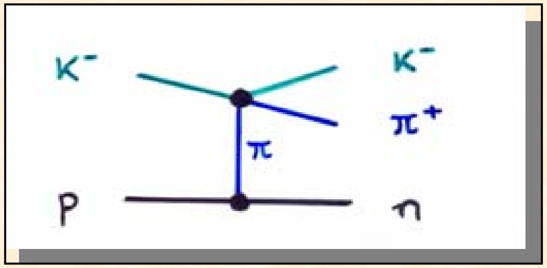


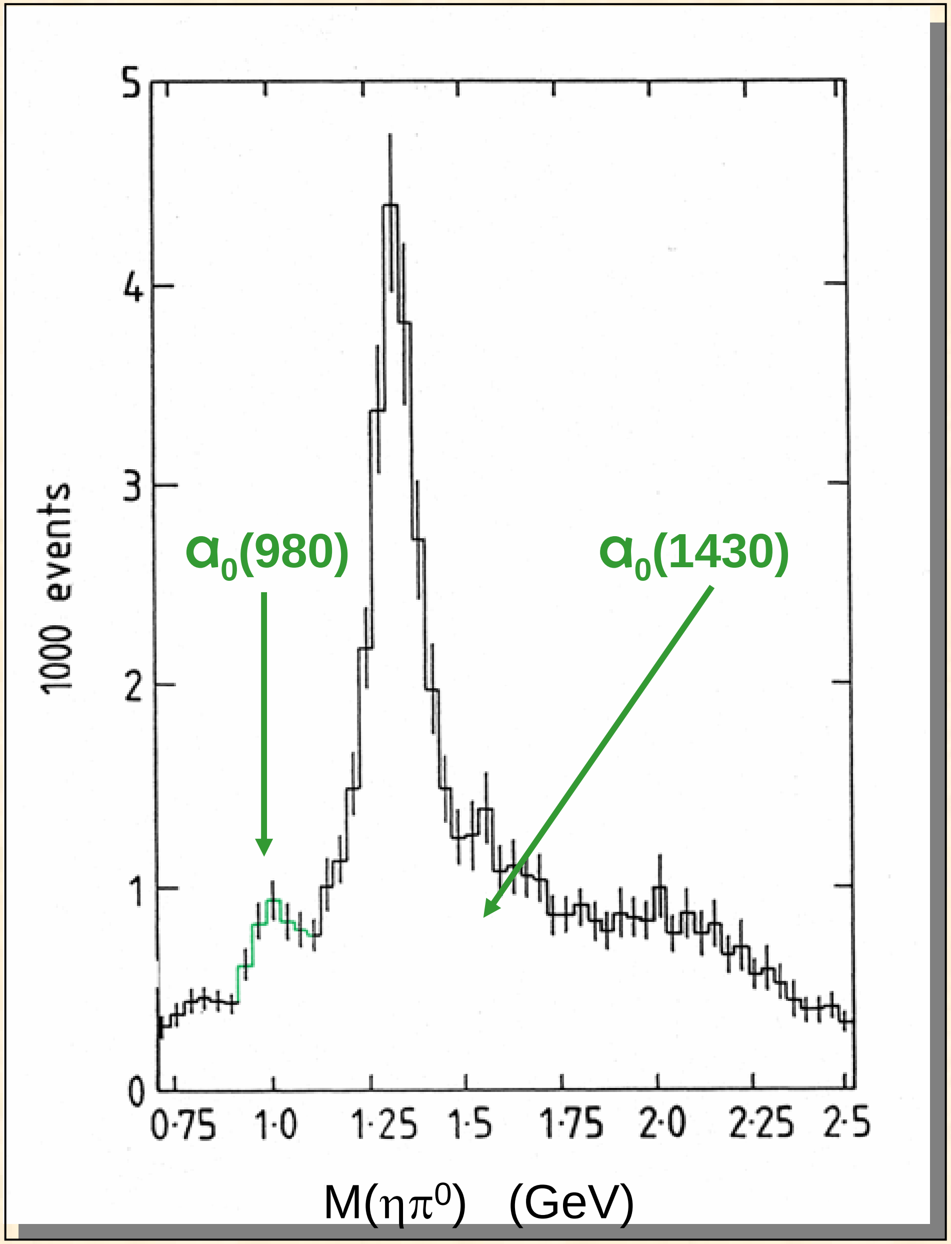


LASS: $K^- p \longrightarrow K^- \pi^+ n$







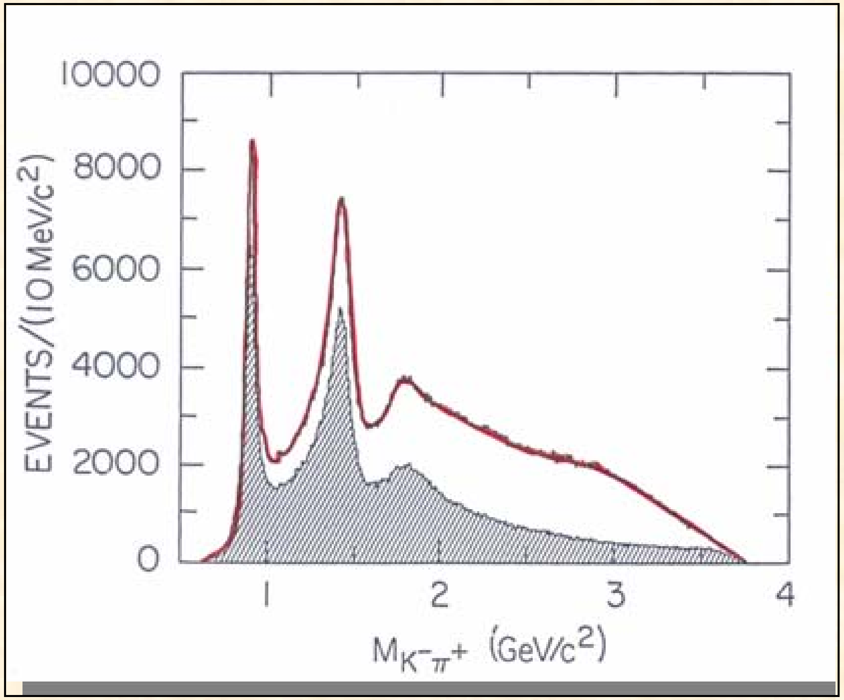


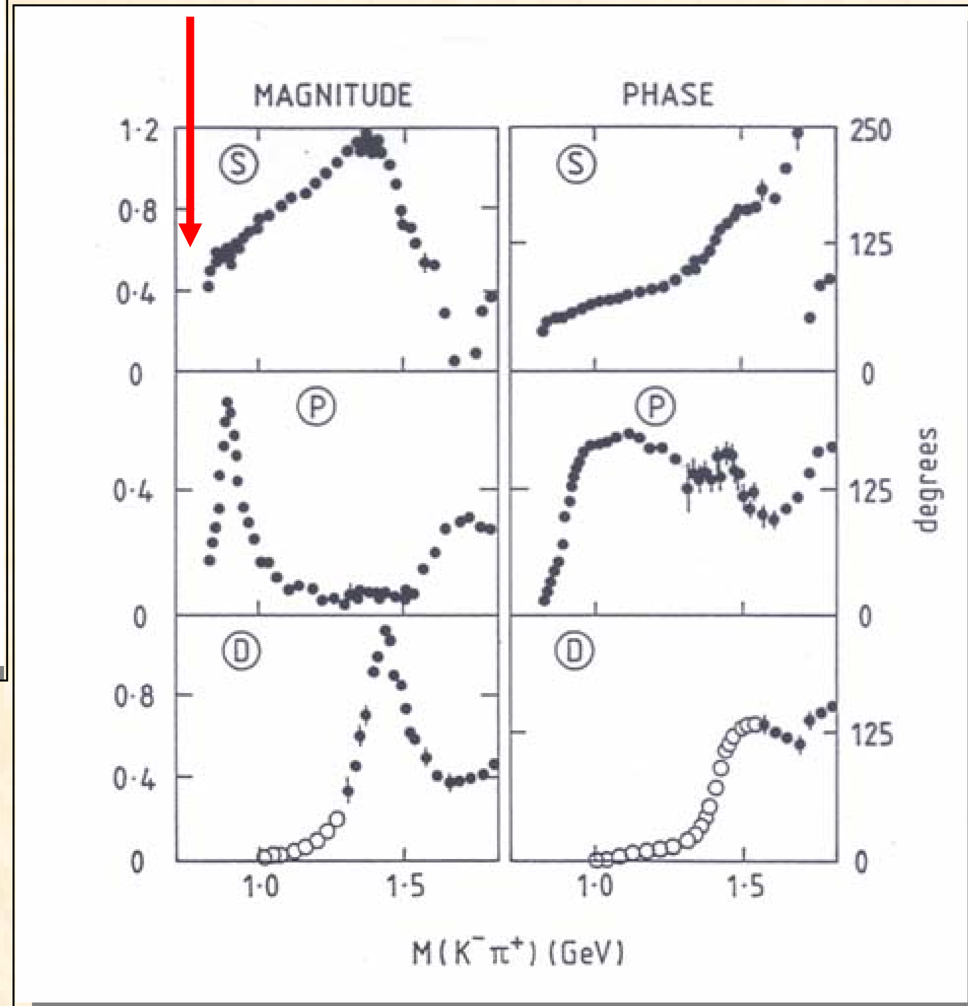
GAMS

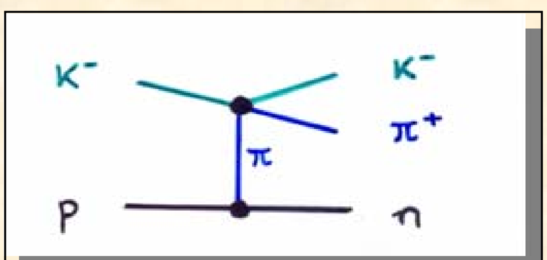
$$\pi^- p \longrightarrow (\eta\pi^0)n$$

$\eta \to \gamma\gamma$, $\pi^0 \to \gamma\gamma$

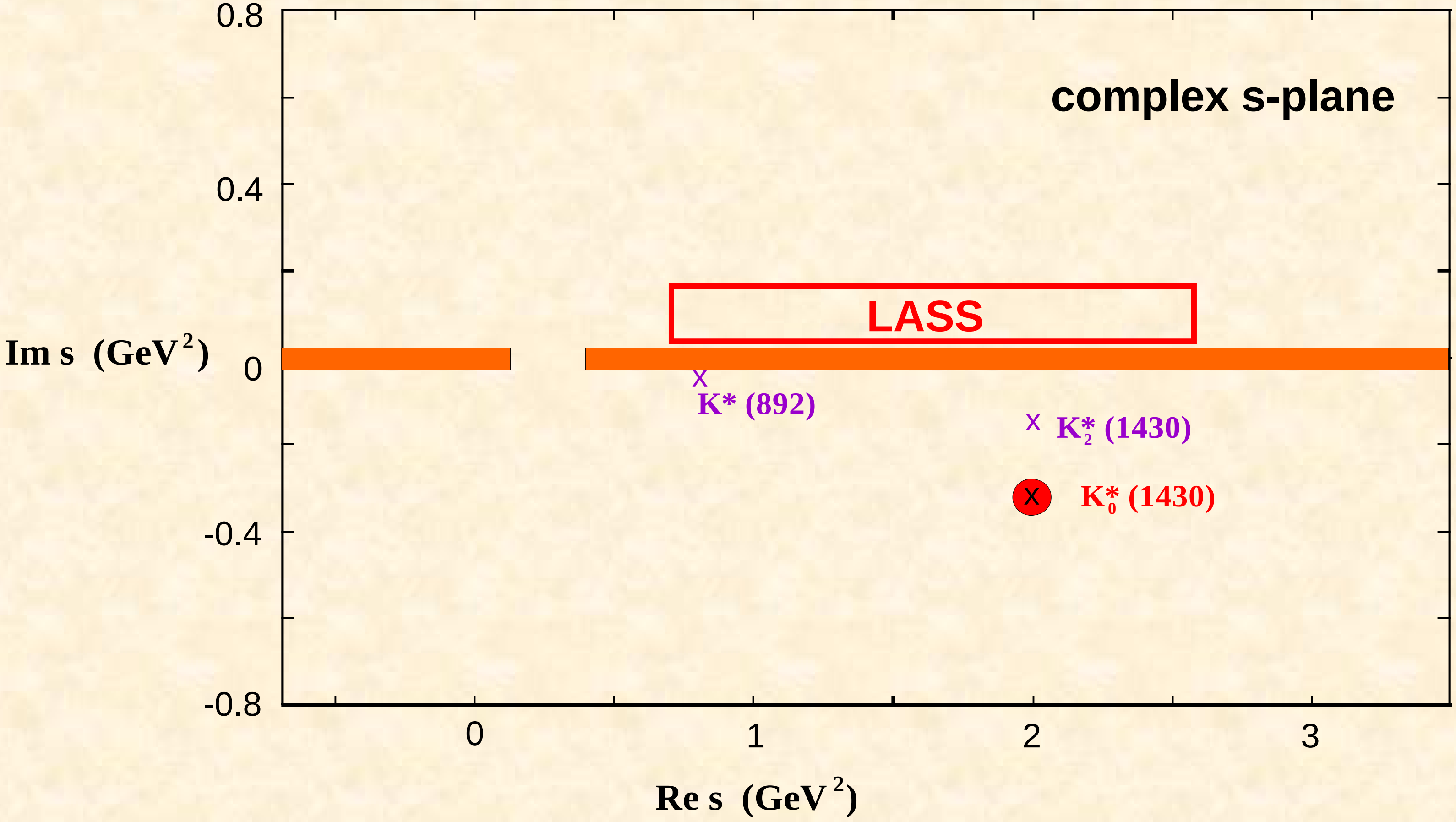
LASS: $K^-p \longrightarrow K^-\pi^+n$





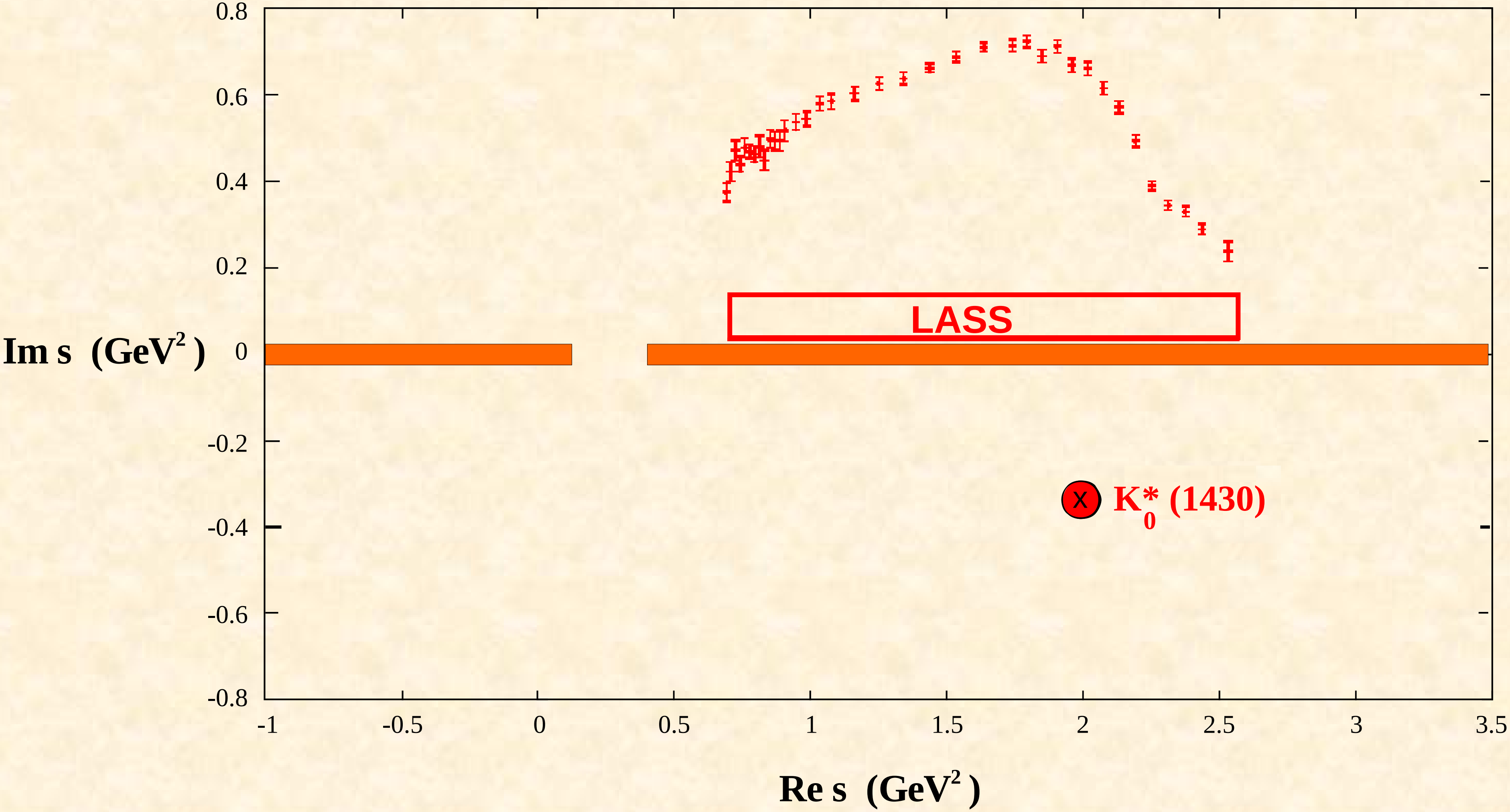


πK : $I = 1/2$, J



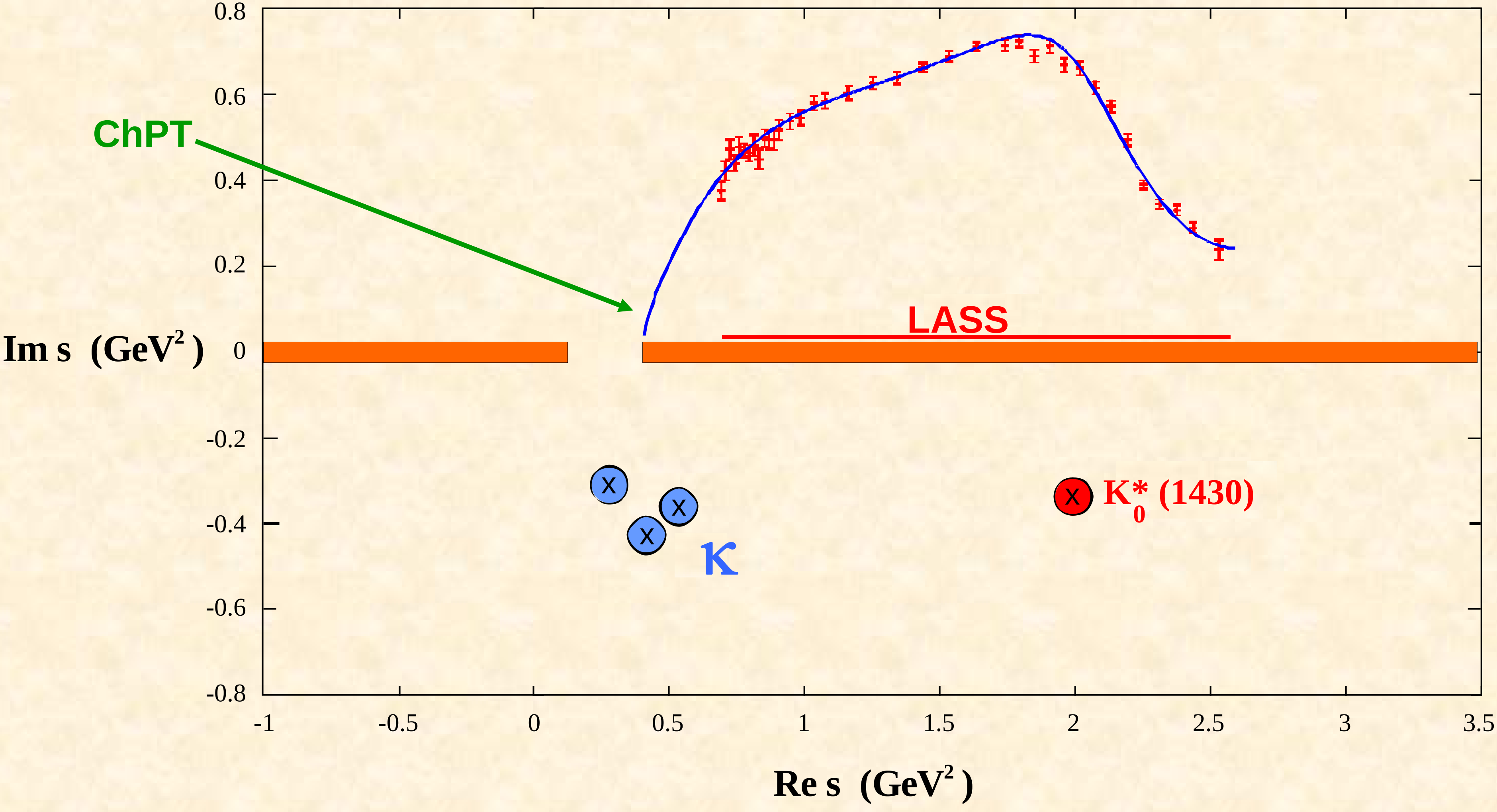
0.8
0.4
0
-0.4
-0.8
complex s-plane
LASS
Im s (GeV²)
K* (892)
K_2^* (1430)
K_0^* (1430)
0
1
2
3
Re s (GeV²)

πK : I = ½, J = 0



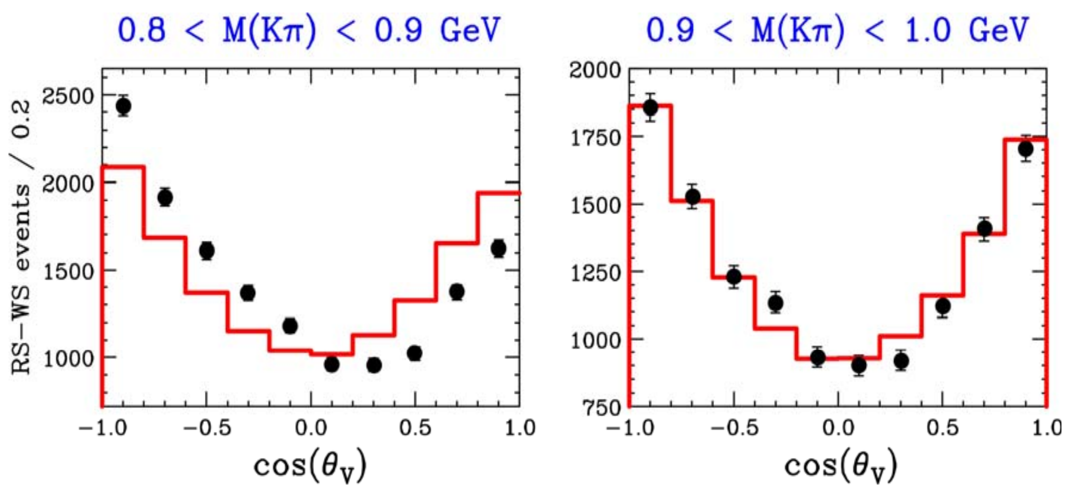
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
Im s (GeV²)
LASS
K*0 (1430)
-1
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
Re s (GeV²)

πK : I = ½, J = 0



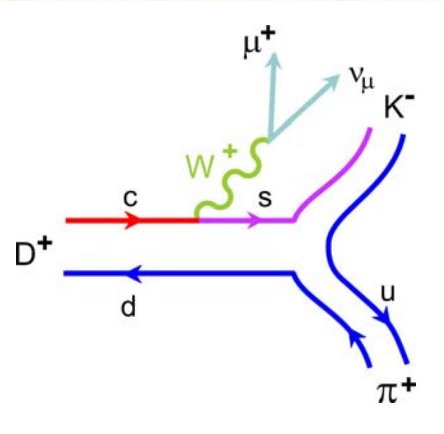
ChPT
LASS
κ
K*0 (1430)
Im s (GeV2)
Re s (GeV2)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-0.5
0
0.5
1
1.5
2
2.5
3
3.5

$D^+ \longrightarrow (K^-\pi^+)\mu^+\nu_\mu$

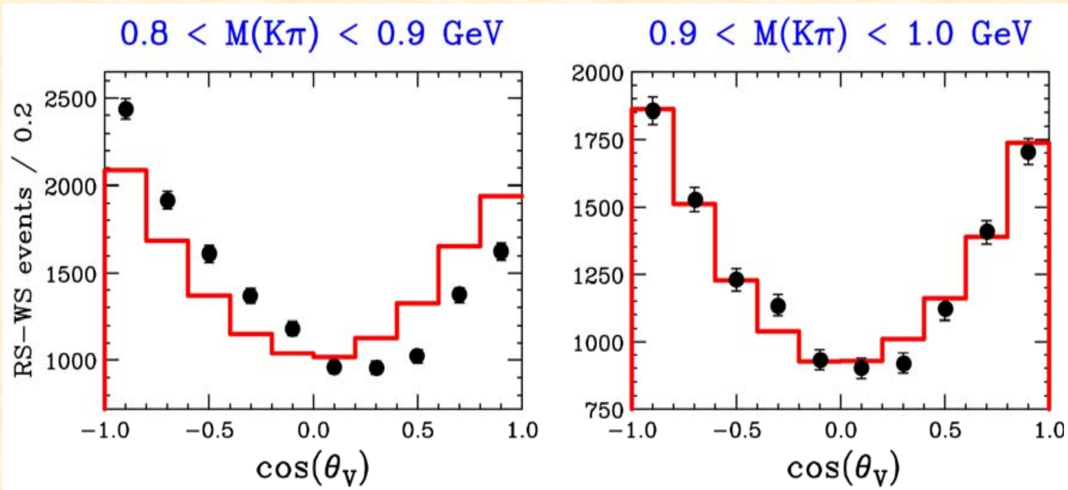


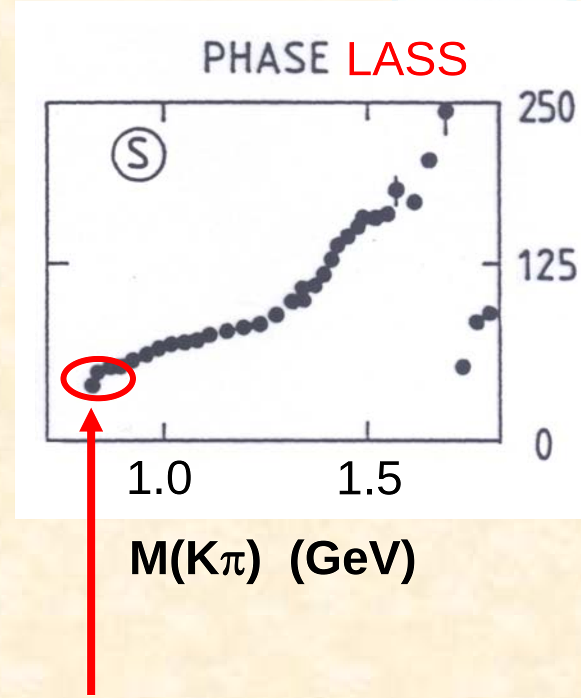
$$\mathcal{F}(D \to (K\pi)\mu\nu; s) = \mathcal{F}_{sl}^{1/2}(s) + \mathcal{F}_{sl}^{3/2}(s)$$

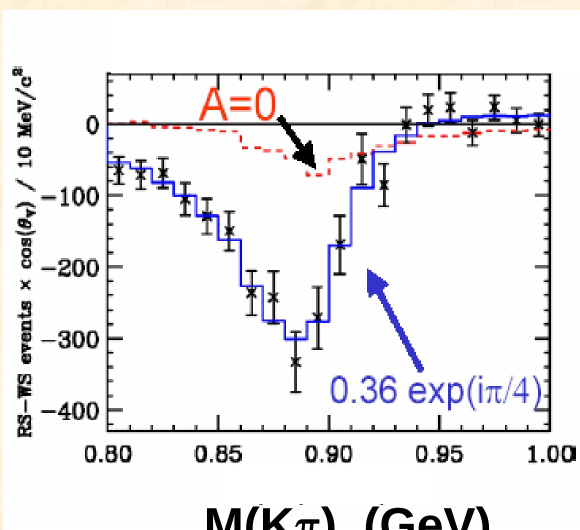
$$\mathcal{F}_{sl}^{I}(s) = |\, \mathcal{F}_{sl}^{I}(s) \,| \, \exp\left[i\delta^{I}(s)\right]$$

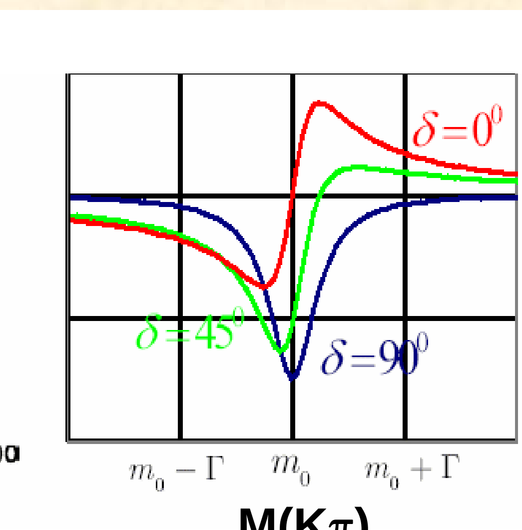


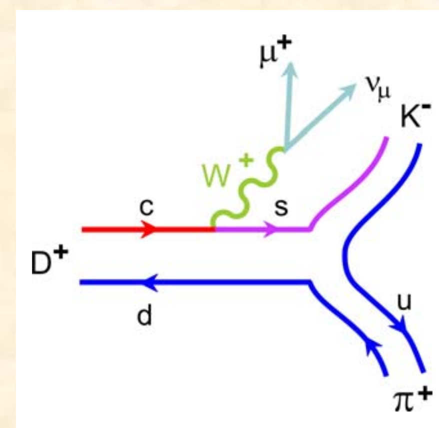
$D^+ \longrightarrow (K^-\pi^+)\mu^+\nu_\mu$





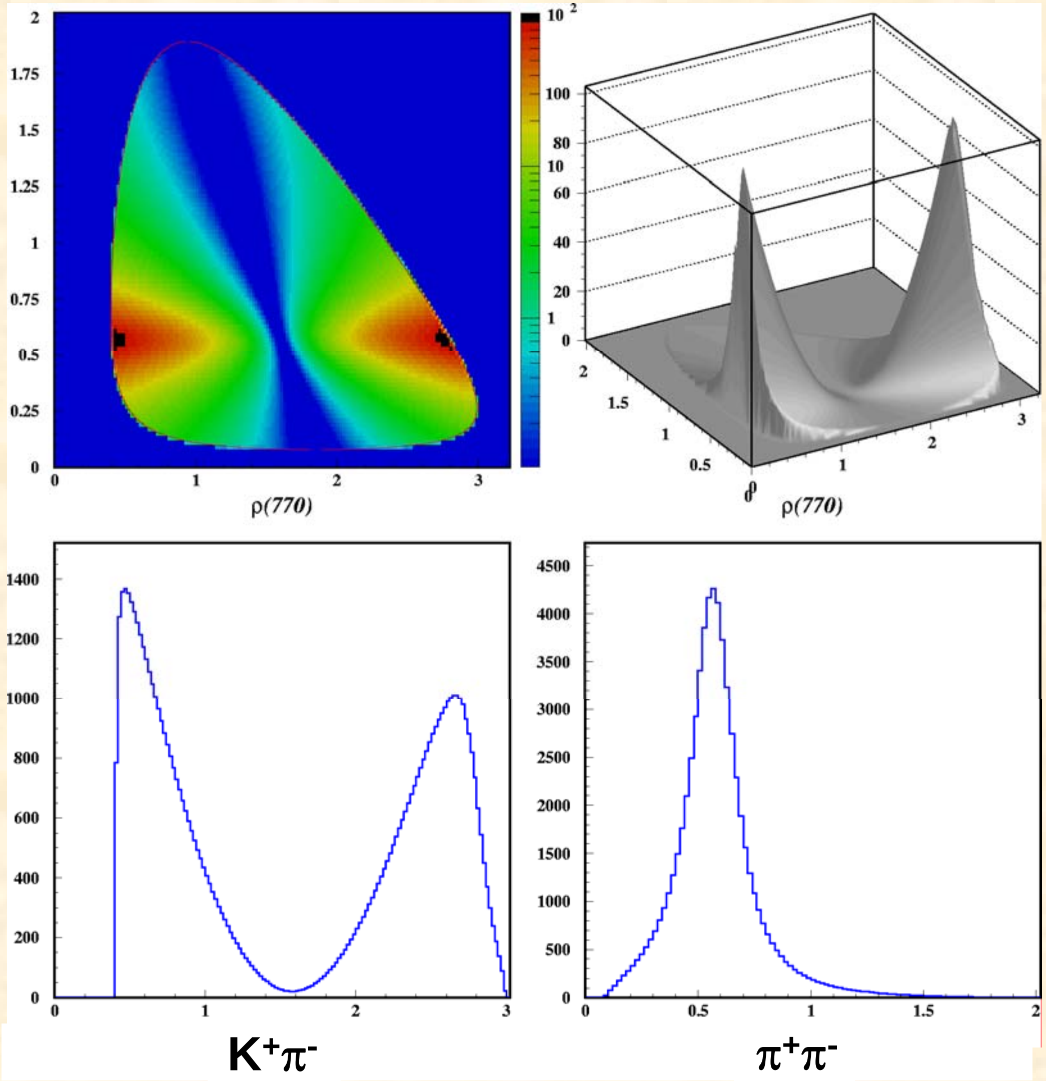






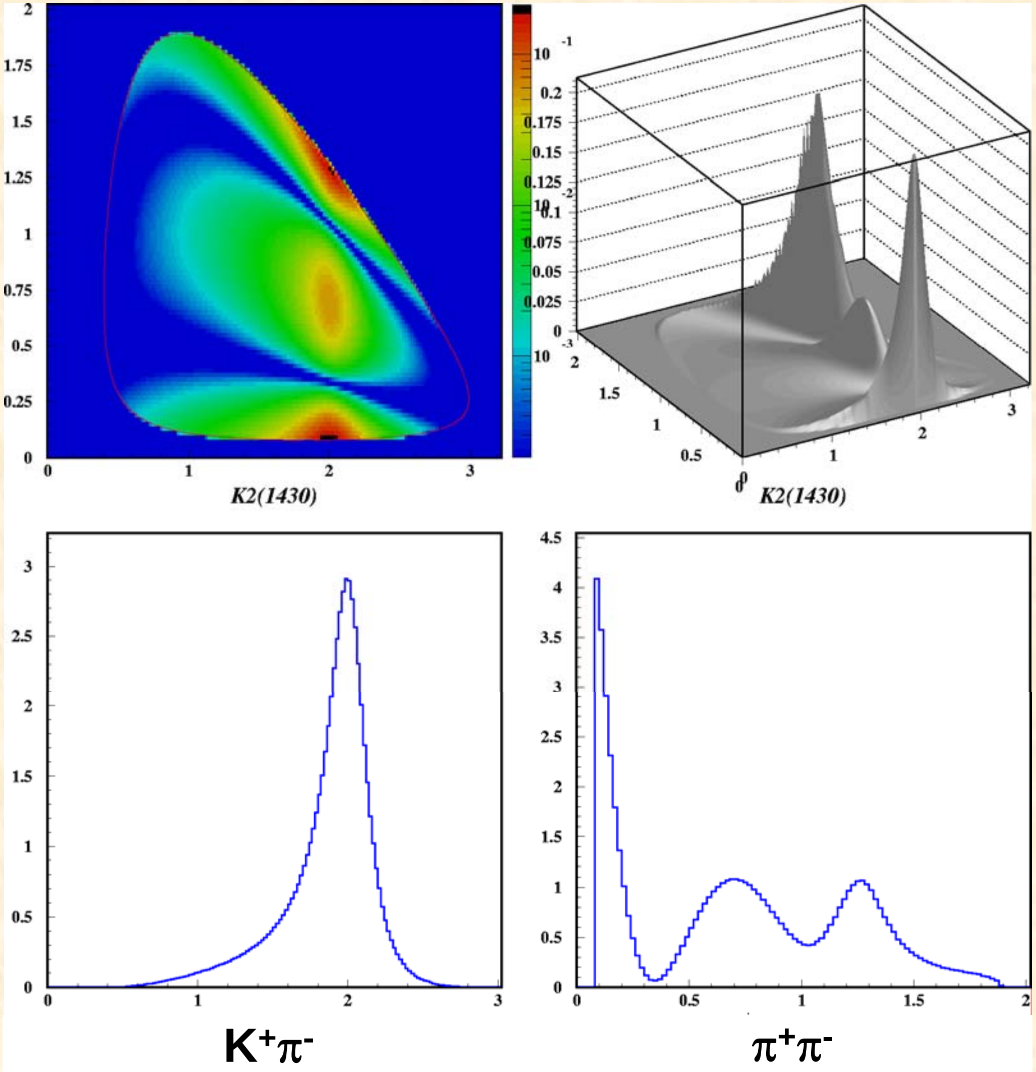
$D^+ \longrightarrow K^+\pi^+\pi^-$

ρ(770)



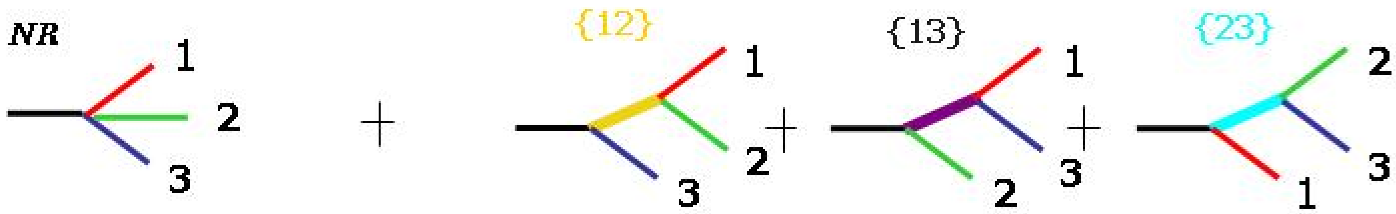
$D^+ \longrightarrow K^+\pi^+\pi^-$

$K_2^*(1430)$



“Traditional” Dalitz Plot Analyses

- The “isobar model” has been widely used, with Breit-Wigner resonant terms, over the past 15 years.



- Amplitude for channel {ij}:

$$\mathcal{A}_{ij} = d_0 e^{i\delta_0} + \sum_R d_R e^{i\delta_R} A(s_{ij}) \times F_0^D(q, r_D) F_J^R(p, r_R) \; M_J(p, q)$$

NR Constant — D form factor — R form factor — spin factor

- Each resonance “**R**” (mass M_R, width Γ_R) assumed to have form

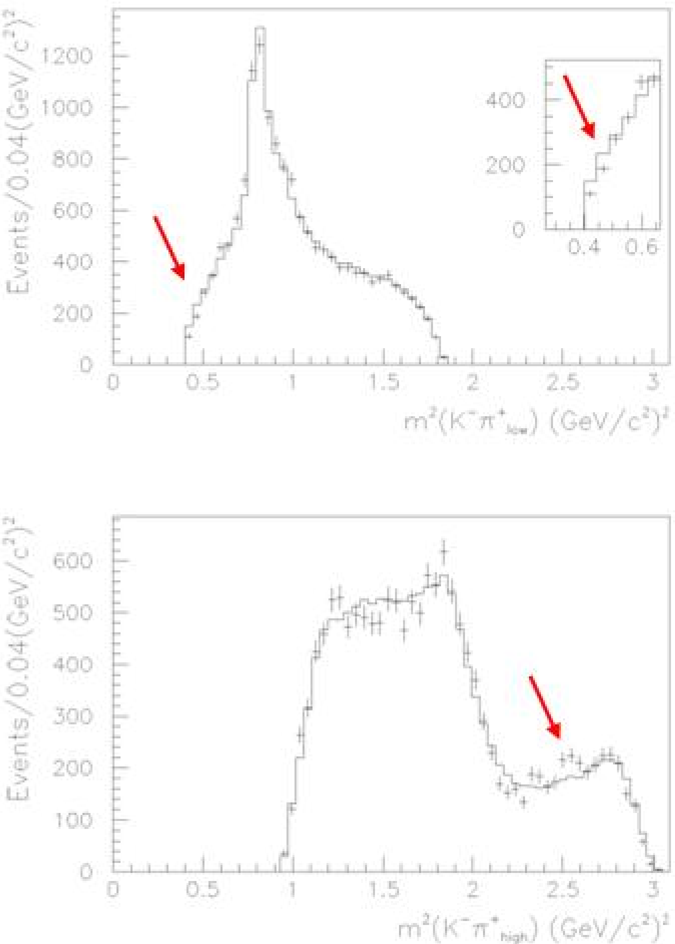
$$A_R(s_{ij}) = [m_R^2 - s_{ij} - i m_R \Gamma(p \;, r_R)]^{-1}$$

p, q are momenta in ij rest frame

r_D, r_R meson radii

Brian Meadows

E791 $D^+ \to K^-\pi^+\pi^+$



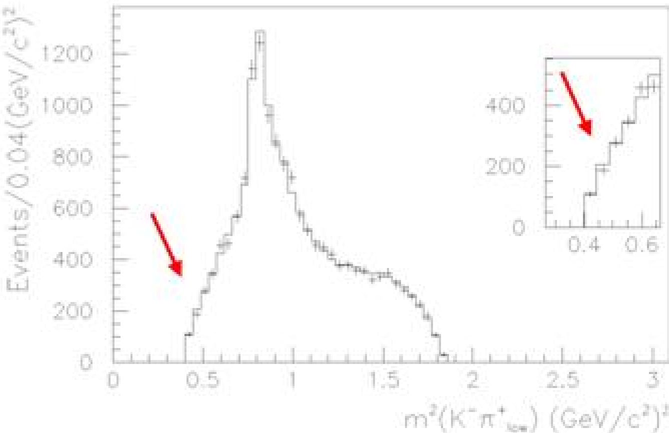
$D^+ \to$

non resonant	$90.0 \pm 2.6\%$	$0°$ (fixed)
$K^*(890)\pi^+$	$13.8 \pm 0.5\%$	$54 \pm 2°$
$K_0^*(1430)\pi^+$	$30.6 \pm 1.6\%$	$109 \pm 2°$
$K_2^*(1430)\pi^+$	$0.4 \pm 0.1\%$	$33 \pm 8°$
$K_1^*(1680)\pi^+$	$3.2 \pm 0.3\%$	$66 \pm 3°$
	~138 %	

χ^2/d.o.f. = 2.7

Brian Meadows

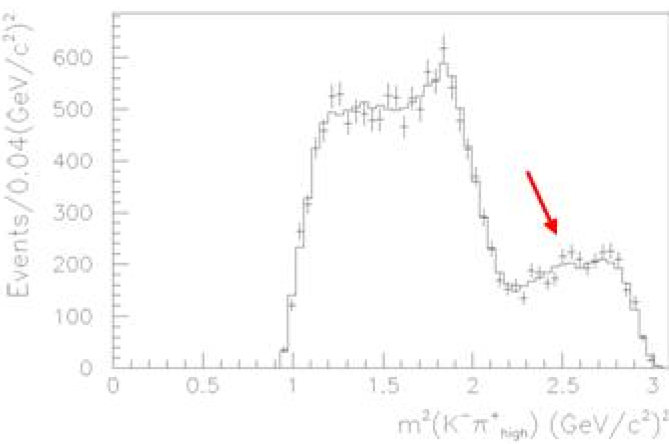
E791 $D^+ \to K^-\pi^+\pi^+$



$D^+ \to$

non resonant	$13.0 \pm 5.8 \pm 2.6\%$	$349 \pm 14 \pm 8°$
"κ"π^+	$47.8 \pm 12.1 \pm 3.7\%$	$187 \pm 8 \pm 17°$
$K^*(890)\pi^+$	$12.3 \pm 1.0 \pm 0.9\%$	$0°$ (fixed)
$K_0^*(1430)\pi^+$	$12.5 \pm 1.4 \pm 0.4\%$	$48 \pm 7 \pm 10°$
$K_2^*(1430)\pi^+$	$0.5 \pm 0.1 \pm 0.2\%$	$306 \pm 8 \pm 6°$
$K_1^*(1680)\pi^+$	$2.5 \pm 0.7 \pm 0.2\%$	$28 \pm 13 \pm 15°$

~89 %

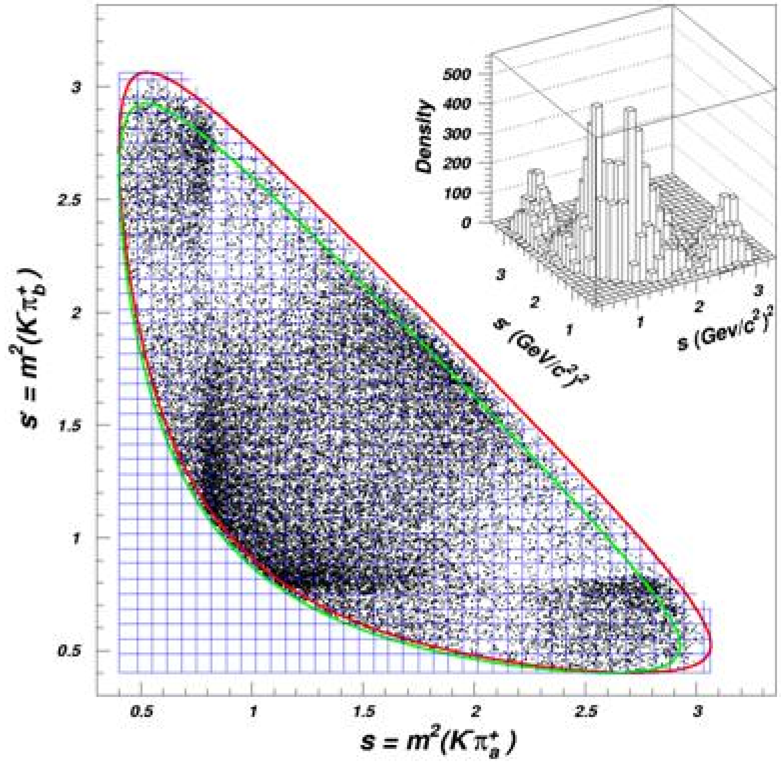


χ^2/d.o.f. = 0.73
(95 %) ← Probability

$M_\kappa = 797 \pm 19 \pm 42$ MeV/c²
$\Gamma_\kappa = 410 \pm 43 \pm 85$ MeV/c²

Brian Meadows

E791 $D^+ \to K^-\pi^+\pi^+$ Dalitz Plot



- Most interesting feature:
  - $K^*(892)$ bands dominate
  - Asymmetry in $K^*(892)$ bands

→ Interference with large s–wave component

- Also:
  - Structure at ~ 1430 MeV/c^2 mostly $K_0^*(1430)$
  - Some $K_2^*(1420)$? or $K_1^*(1410)$??
  - Perhaps some $K_1^*(1680)$?
- So

  At least the $K^*(892)$ can act as interferometer for s–wave

  Perhaps other resonances can fill in some gaps too.

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s–wave from $D^+ \to K^-\pi^+\pi^+$ Dalitz Plot?

- Divide $m^2(K^-\pi^+)$ into slices
- Find s–wave amplitude in each slice (two parameters)
  - Use remainder of Dalitz plot as an interferometer

$$\frac{d^2\Gamma}{ds_{12}ds_{13}} \propto |\mathcal{S} + (\mathcal{P} + \mathcal{D})|^2$$

- For s-wave:
  - Interpolate between (c_k, γ_k) points:

$$\mathcal{S} = \text{Interp}\left(c_k e^{i\gamma_k}\right) \times F_0^D(q, r_D) F_0^R(p, r_R)$$

S ("partial wave")

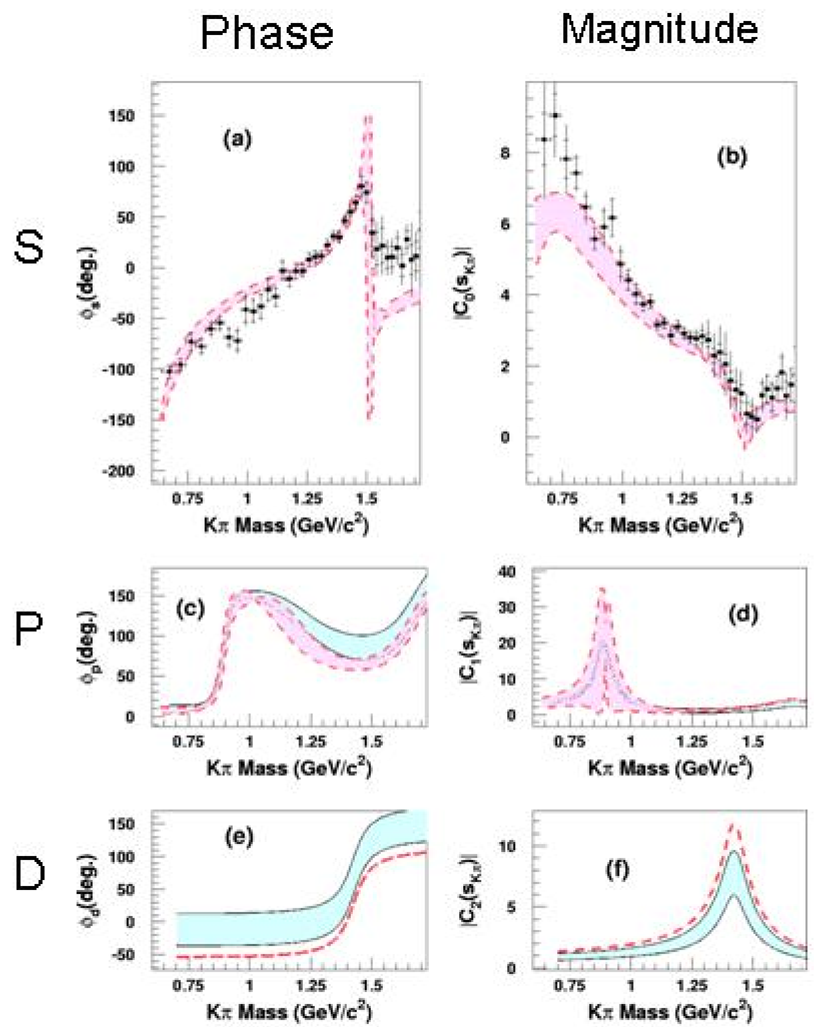
- Model P and D

Brian Meadows

Fit E791 Data for s-wave

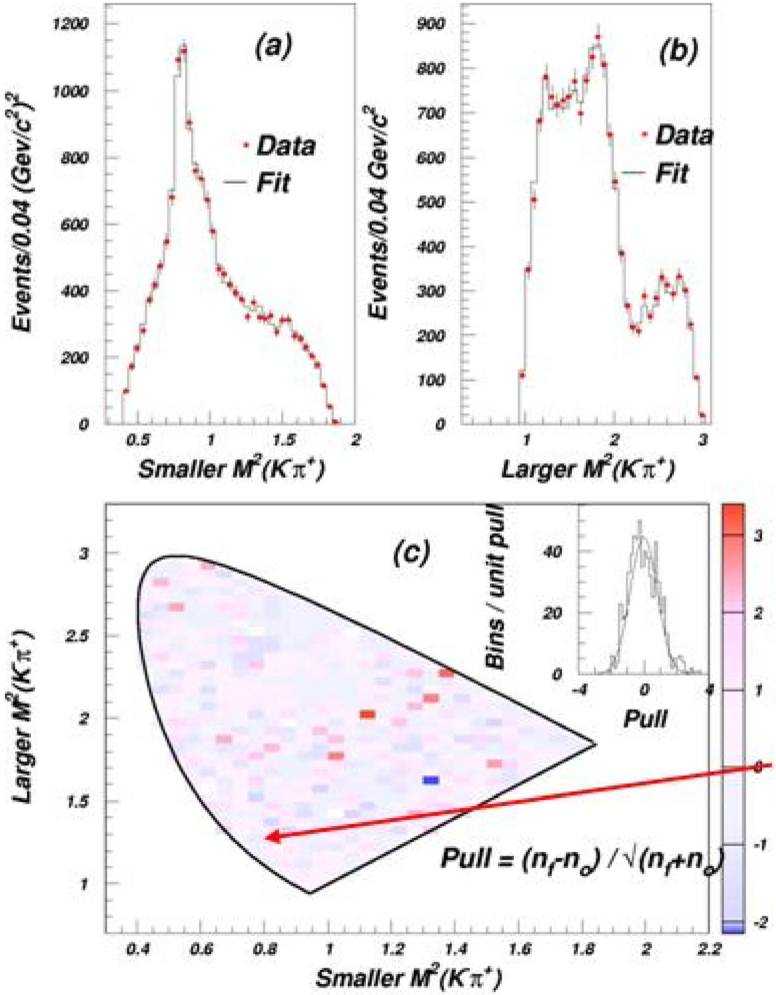
Float P and D parameters and find S:

- General appearance similar to isobar model fit:
  - Magnitudes at low mass differ
  - Phases above $K_0^*(1430)$
- **Tests with many MC samples of this size (15K events), produced to simulate the isobar model, produce similar differences in ~15% of the cases**
- Major source of systematic uncertainty:
  - Contribution of reference waves in region between $K^*(892)$ and $K^*(1680)$.



Brian Meadows

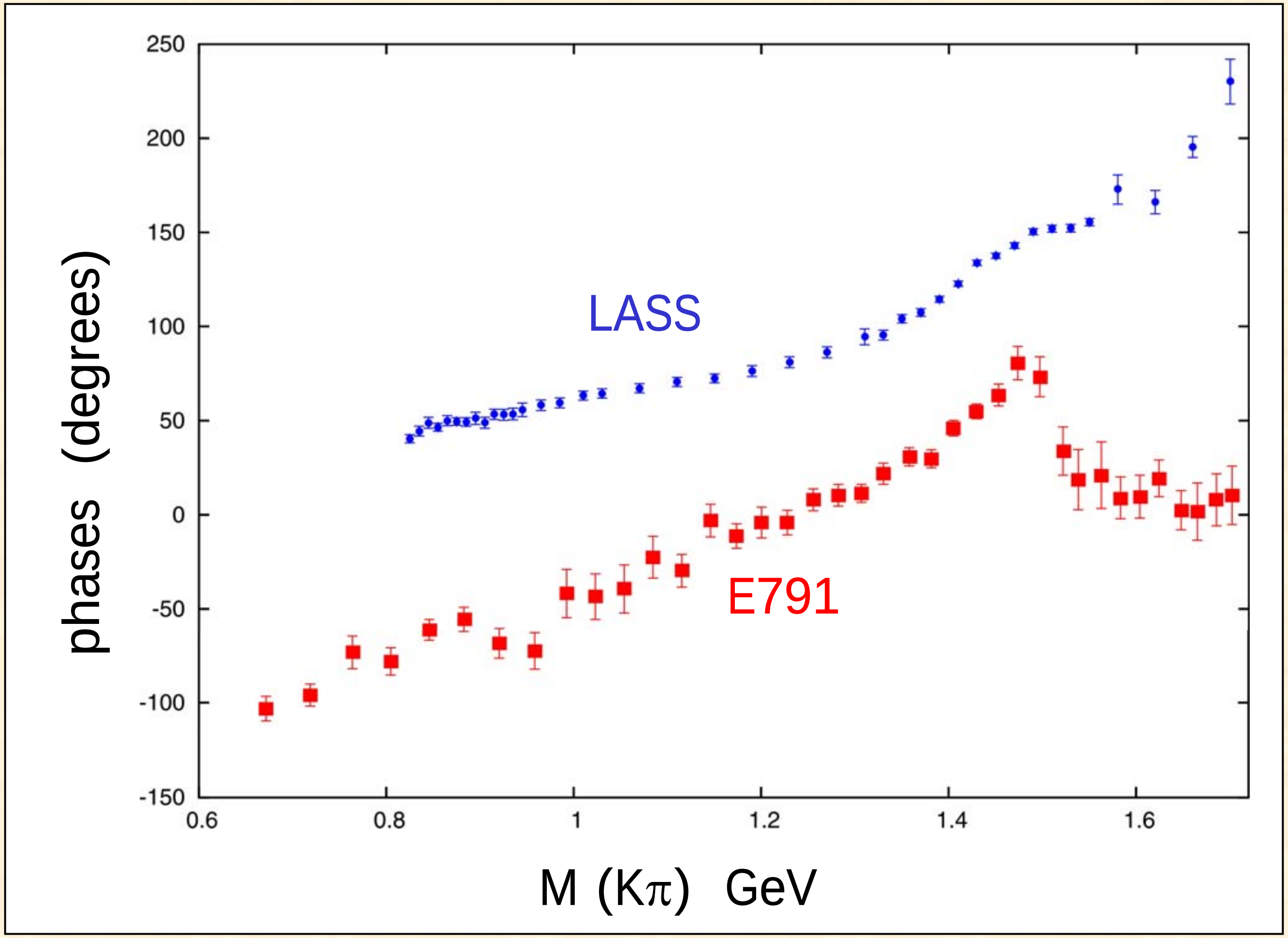
Comparison with Data



χ^2/NDF = 272/277 (48%)

Brian Meadows

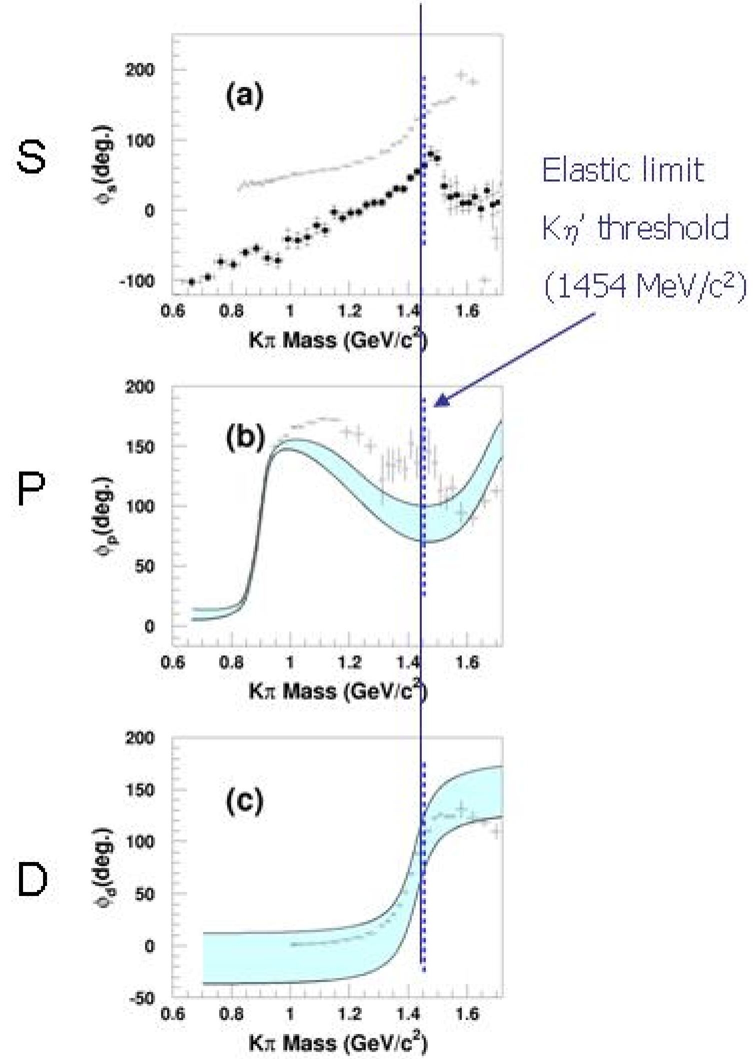
E791 v elastic scattering (LASS)



Watson Theorem - a direct test

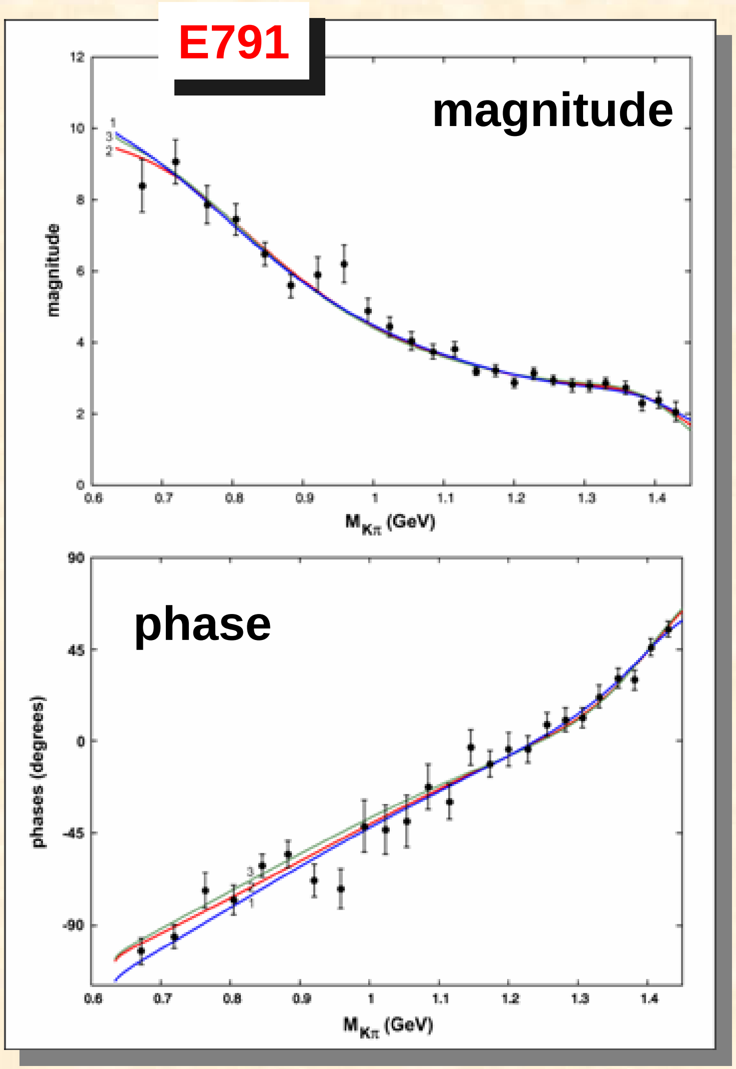
Phases for S, P and D waves are compared with those from LASS.

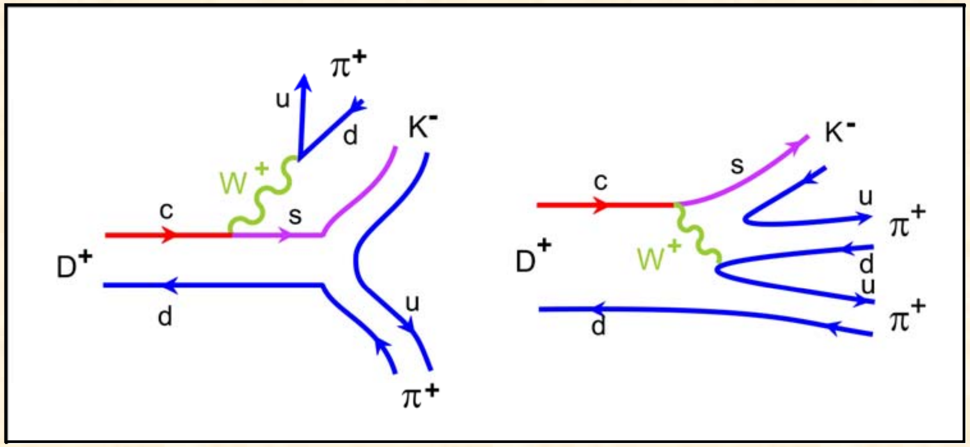
- *s*-wave phase ϕ_s for E791 is shifted by -75^0 wrt LASS.
  - ϕ_s energy dependence differs below 1100 MeV/c^2.
- ϕ_p does not match well between $K^*(892)$ and $K^*(1680)$ resonances
- ϕ_d match is excellent up to elastic limit.



Brian Meadows

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





Kπ sector

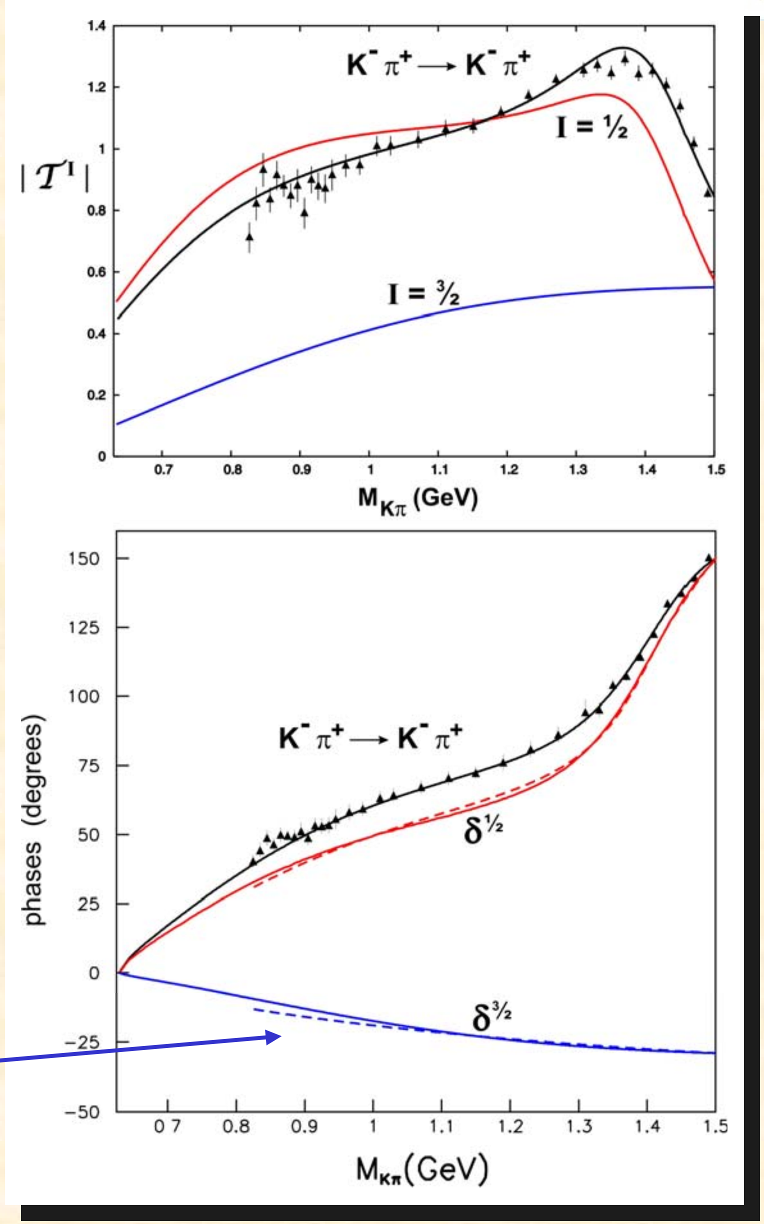
$K^- \pi^+ \longrightarrow K^- \pi^+$

$$\mathcal{T}^I(s) = \frac{1}{\rho} \sin\delta^I \exp(i\delta^I)$$

$$\rho = 2k/\sqrt{s}$$

$$\mathcal{T}(K^-\pi^+ \to K^-\pi^+; s) =$$

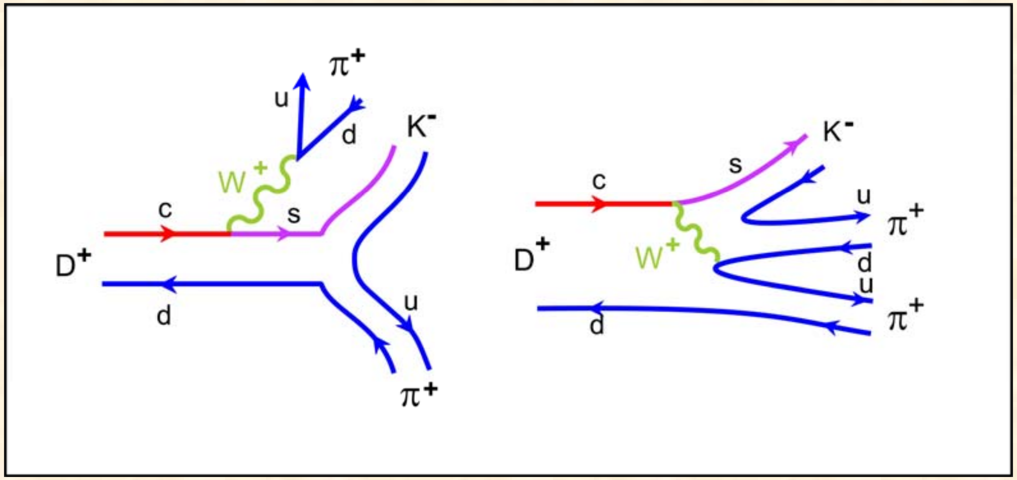
$$\frac{2}{3\rho}\left[\sin\delta^{1/2}\exp(i\delta^{1/2}) + \frac{1}{2}\sin\delta^{3/2}\exp(i\delta^{3/2})\right]$$



Descotes-Genon et al.

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

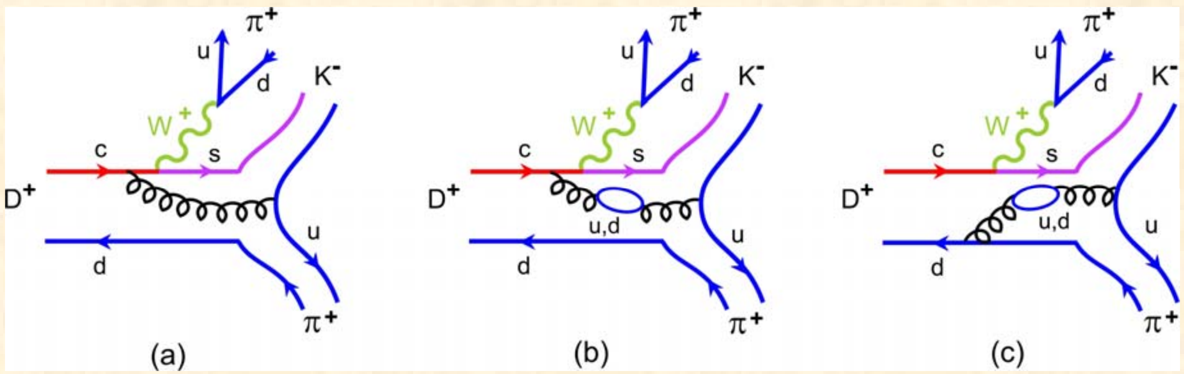
$$\mathcal{A} = \mathcal{F}^{1/2} + \mathcal{F}^{3/2}$$

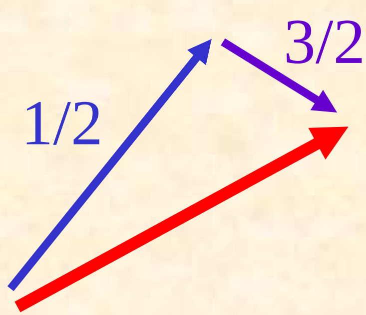


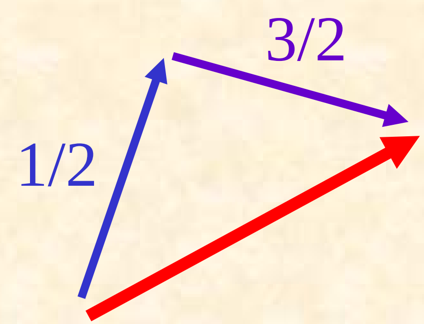
$$\mathcal{F}^I(s)_{had} = |\, \mathcal{F}^I_{had}(s)\, |\ \exp\left[i\delta^I(s) + i\beta_I\right]$$

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

$$\mathcal{A} = \mathcal{F}^{1/2} + \mathcal{F}^{3/2}$$





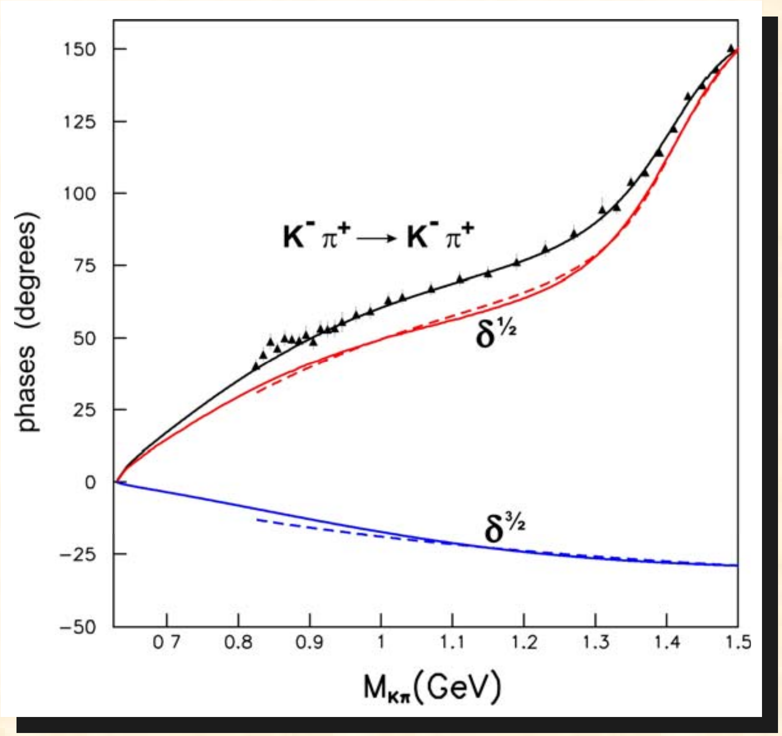


$$\mathcal{F}^I(s)_{had} = |\,\mathcal{F}^I_{had}(s)\,|\,\exp\left[i\delta^I(s) + i\beta_I\right]$$

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

$$\mathcal{F}^{1/2}(E) = \mathcal{A} \frac{\sin\left(\delta^{3/2}(E) + \beta_{3/2} - \phi(E)\right)}{\sin\left(\delta^{3/2}(E) - \delta^{1/2}(E) - \beta_{1/2} + \beta_{3/2}\right)} \exp\left[i(\delta^{1/2}(E) + \beta_{1/2})\right]$$

$$\mathcal{F}^{3/2}(E) = \mathcal{A} \frac{\sin\left(\delta^{1/2}(E) + \beta_{1/2} - \phi(E)\right)}{\sin\left(\delta^{1/2}(E) - \delta^{3/2}(E) + \beta_{1/2} - \beta_{3/2}\right)} \exp\left[i(\delta^{3/2}(E) + \beta_{3/2})\right]$$



$$\beta_{1/2} = \phi(E_r) - \delta^{1/2}(E_r) + m\pi \,, \qquad \beta_{3/2} = \phi(E_r) - \delta^{3/2}(E_r) + n\pi$$

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

$$\mathcal{F}^{1/2}(E) = \mathcal{A}\,\frac{\sin\left(\delta^{3/2}(E)+\beta_{3/2}-\phi(E)\right)}{\sin\left(\delta^{3/2}(E)-\delta^{1/2}(E)-\beta_{1/2}+\beta_{3/2}\right)}\;\exp\left[i(\delta^{1/2}(E)+\beta_{1/2})\right]$$

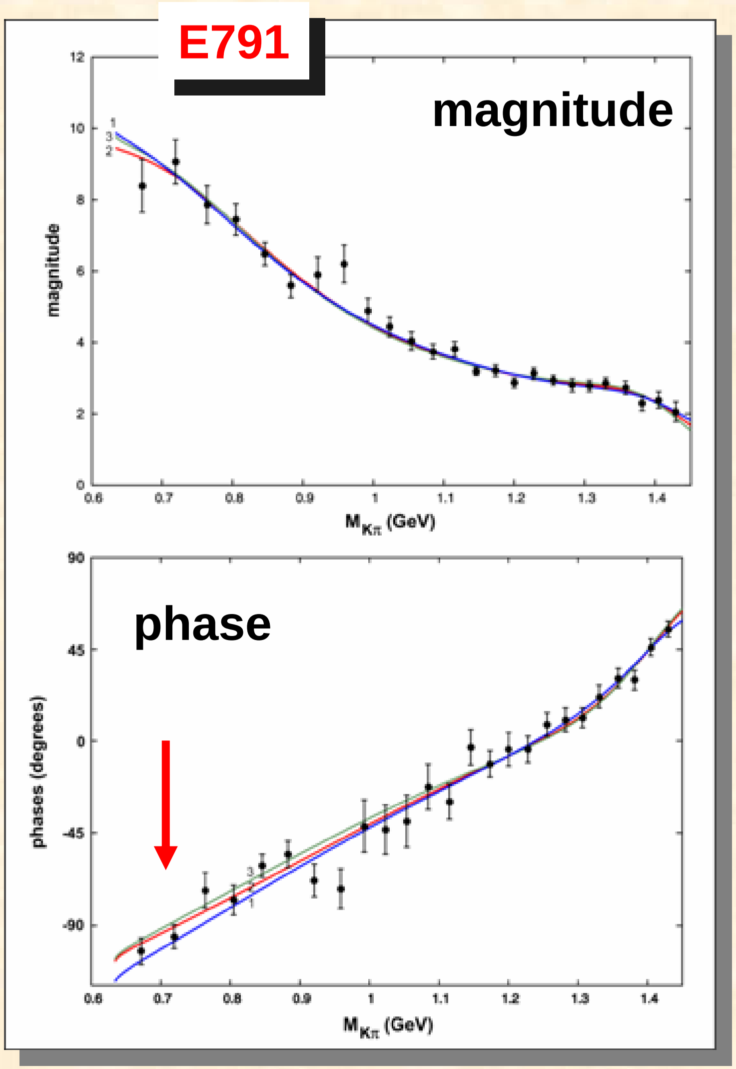
$$\mathcal{F}^{3/2}(E) = \mathcal{A}\,\frac{\sin\left(\delta^{1/2}(E)+\beta_{1/2}-\phi(E)\right)}{\sin\left(\delta^{1/2}(E)-\delta^{3/2}(E)+\beta_{1/2}-\beta_{3/2}\right)}\;\exp\left[i(\delta^{3/2}(E)+\beta_{3/2})\right]$$

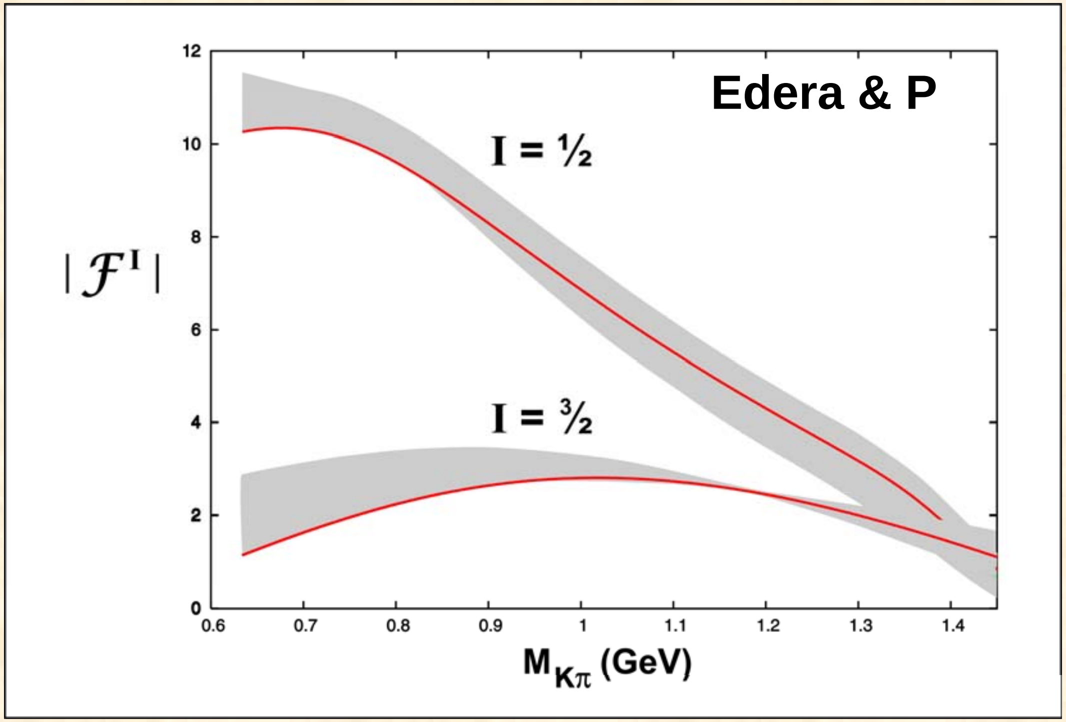
$$\beta_{1/2} = \phi(E_r) - \delta^{1/2}(E_r) + m\pi\;, \qquad \beta_{3/2} = \phi(E_r) - \delta^{3/2}(E_r) + n\pi$$

$$\mathcal{F}^{1/2}(E) = \mathcal{A}\,\frac{\sin\left(\phi(E)-\phi(E_r)-\delta^{3/2}(E)+\delta^{3/2}(E_r)\right)}{\sin\left(\delta^{1/2}(E)-\delta^{3/2}(E)-\delta^{1/2}(E_r)+\delta^{3/2}(E_r)\right)}\quad \exp\left[i(\delta^{1/2}(E)-\delta^{1/2}(E_r)+\phi(E_r))\right]$$

$$\mathcal{F}^{3/2}(E) = \mathcal{A}\,\frac{\sin\left(\delta^{1/2}(E)-\delta^{1/2}(E_r)-\phi(E)+\phi(E_r)\right)}{\sin\left(\delta^{1/2}(E)-\delta^{3/2}(E)-\delta^{1/2}(E_r)+\delta^{3/2}(E_r)\right)}\quad \exp\left[i(\delta^{3/2}(E)-\delta^{3/2}(E_r)+\phi(E_r))\right]$$

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





Scalar mesons

$f_0(980)$

$f_0(1710)$

$f_0(600)$

$f_0(1500)$

$\kappa_0^*(1430)$

$f_0(1370)$

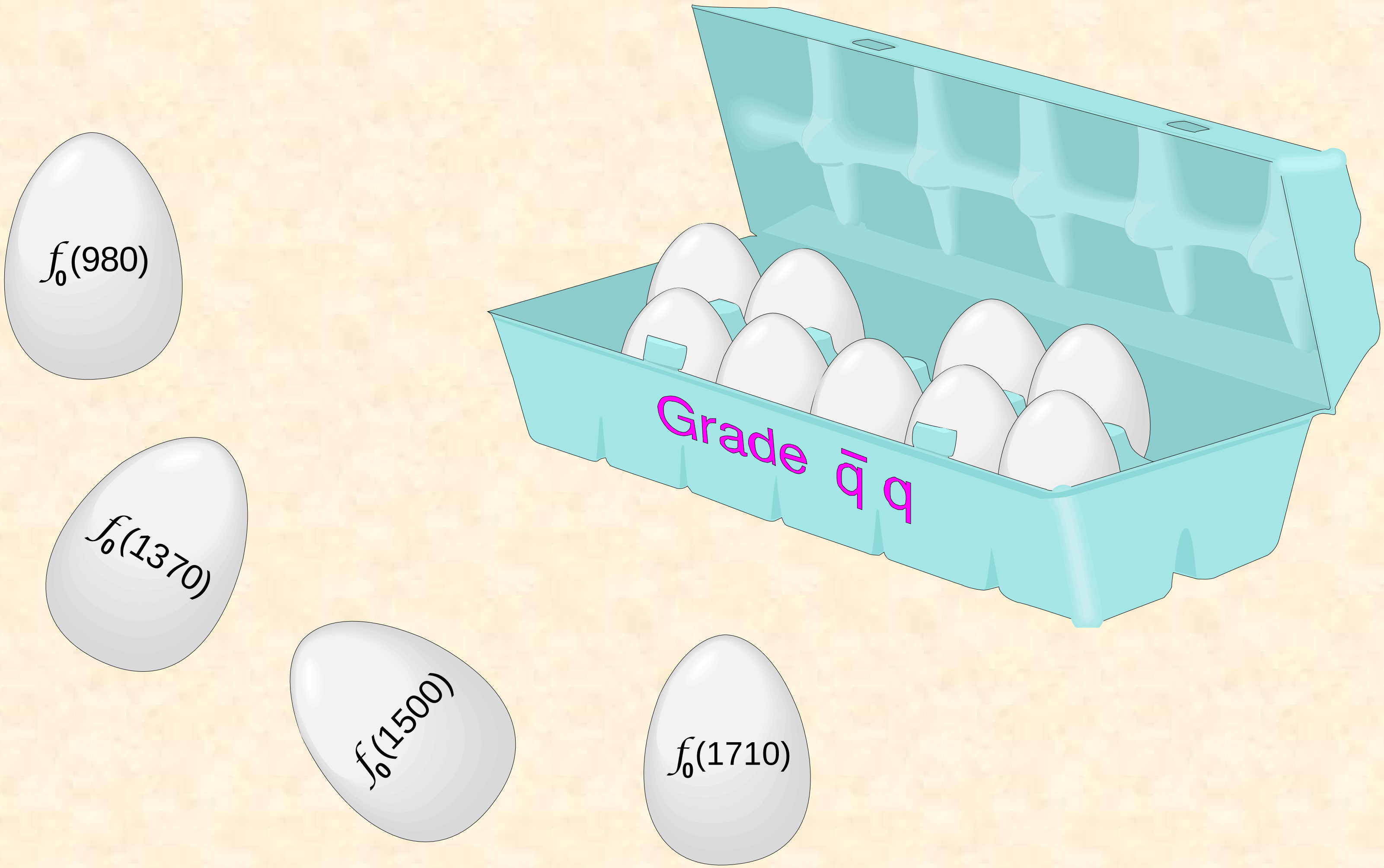
$a_0(1450)$

$a_0(980)$

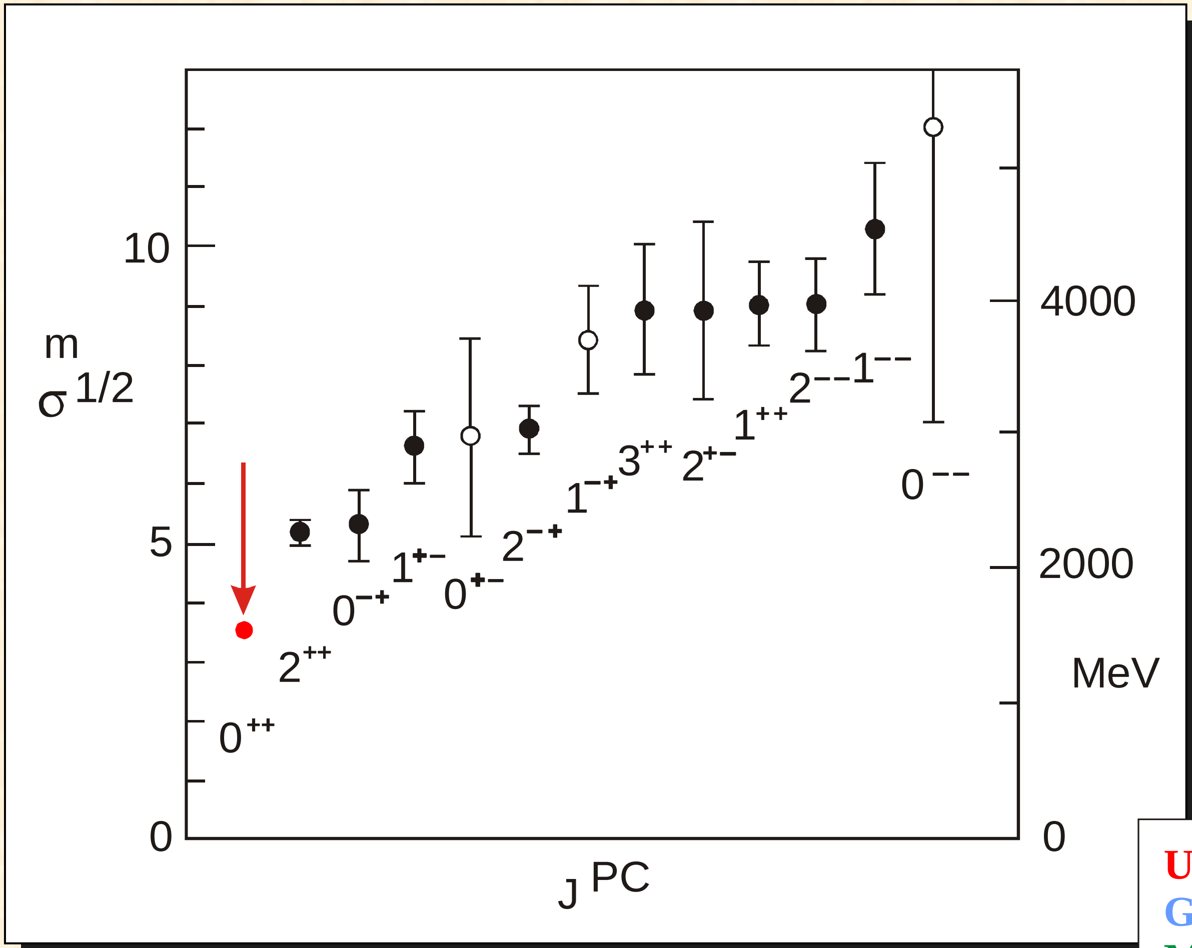
$\kappa(800)$

$\kappa_0^*(1950)$

Which f_0 is in which nonet?



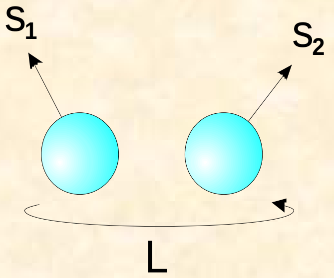
glueball spectrum in a world without quarks



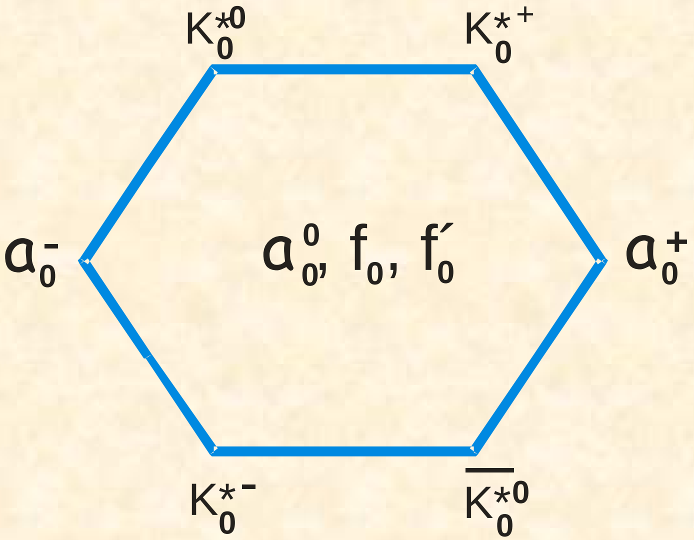
UKQCD	m =	1568 ± 89
GF11		1740 ± 71
MP		1630 ± 100
GF11 (reanal)		1648 ± 58

first find the scalar meson multiplet

$J^{PC} = 0^{++}$



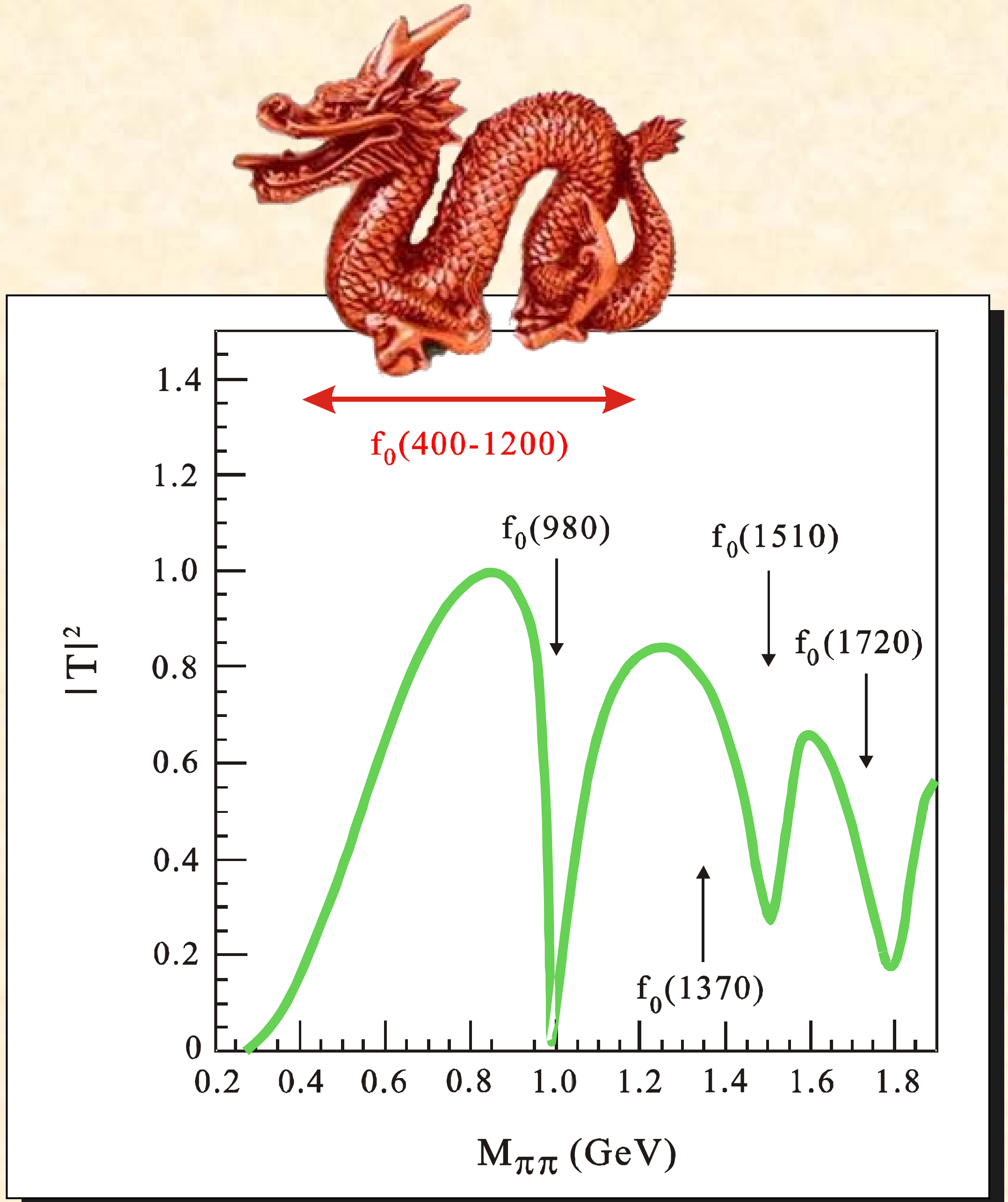
S = 1, L = 1



then find the extras

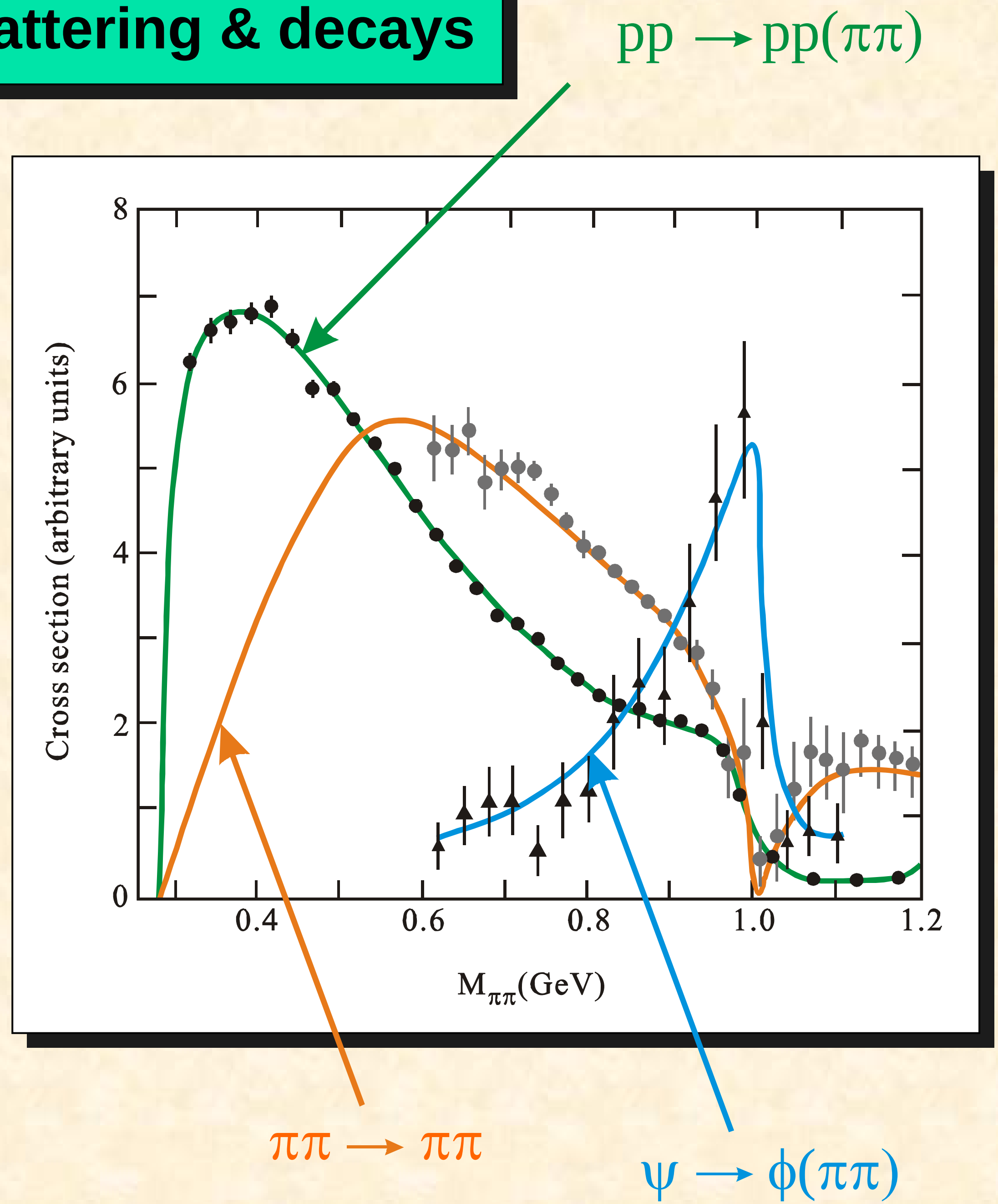
I = J = 0

Minkowski & Ochs

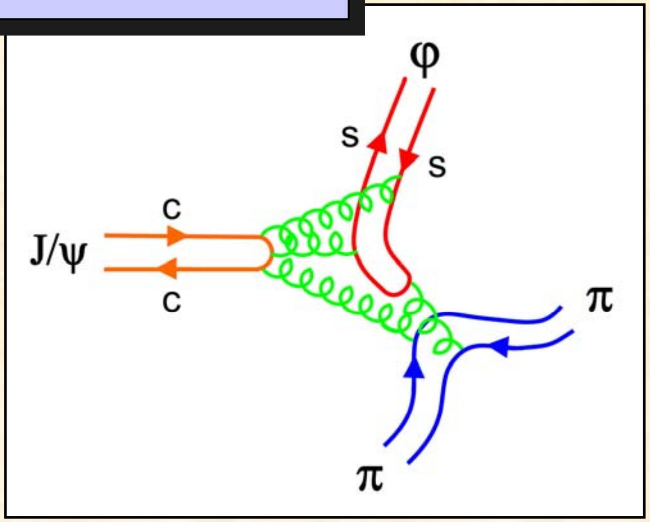


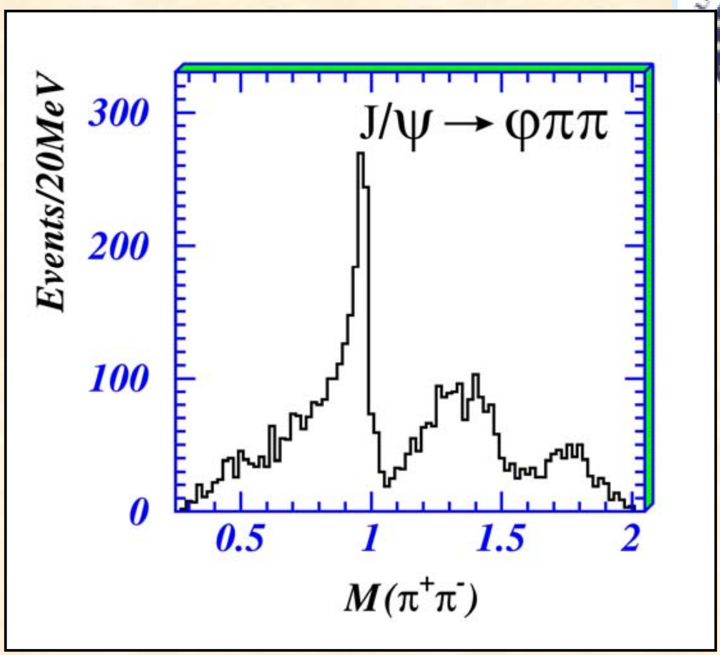
Zou

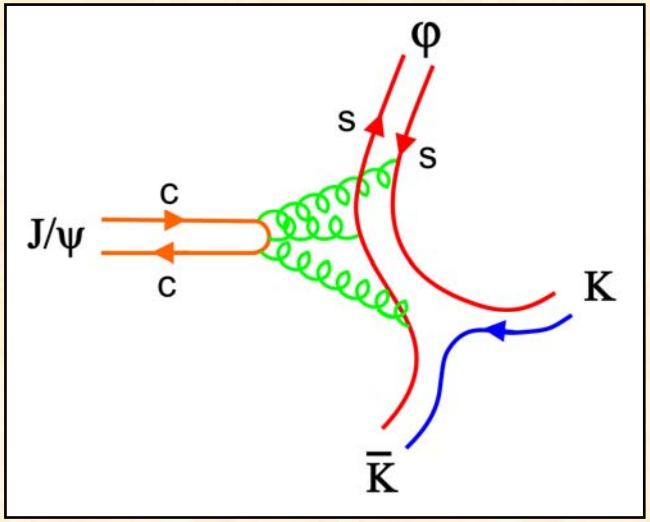
ππ sector in scattering & decays

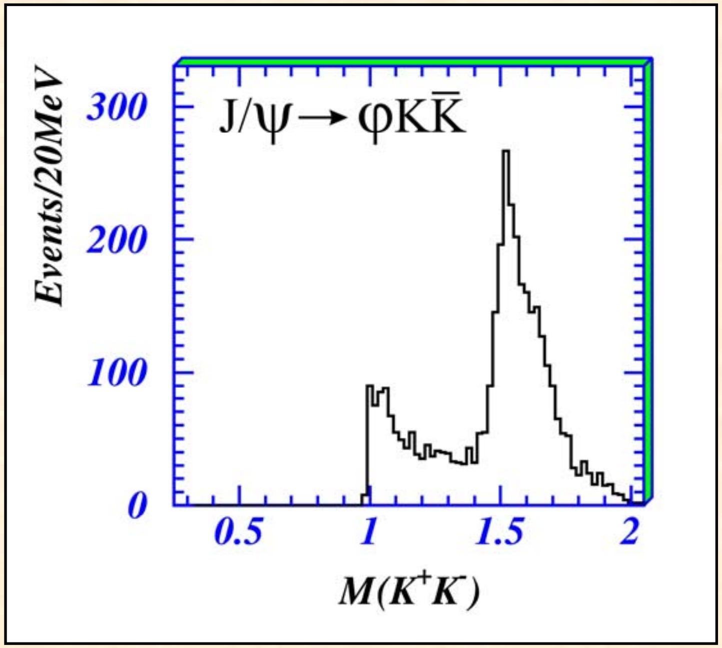


$J/\psi \longrightarrow \varphi M^+M^-$



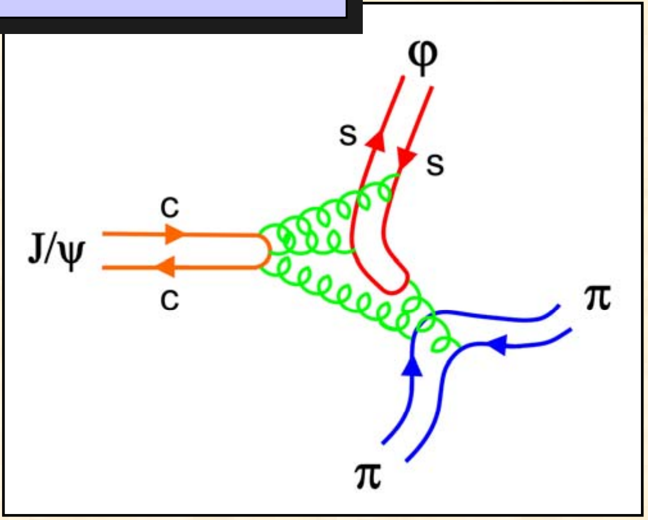


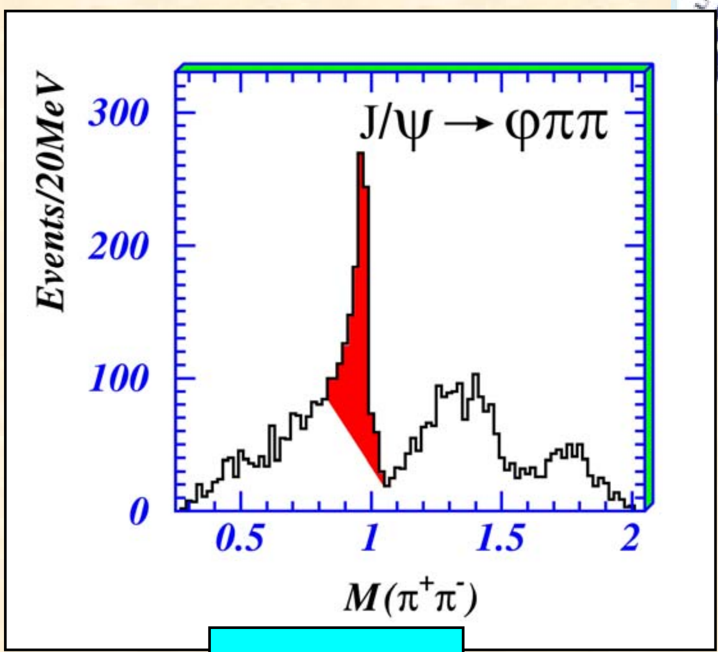




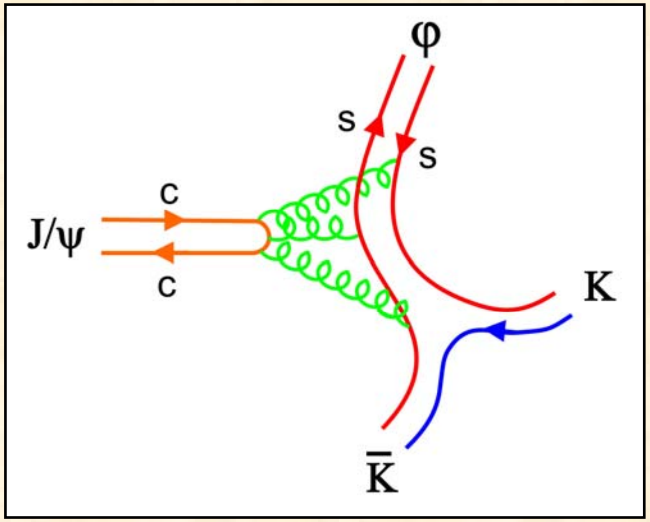
BES

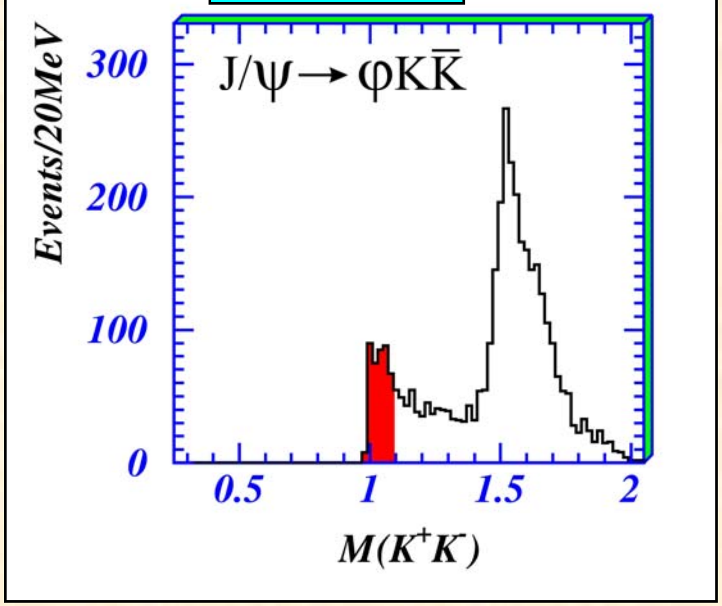
$J/\psi \longrightarrow \varphi M^+M^-$





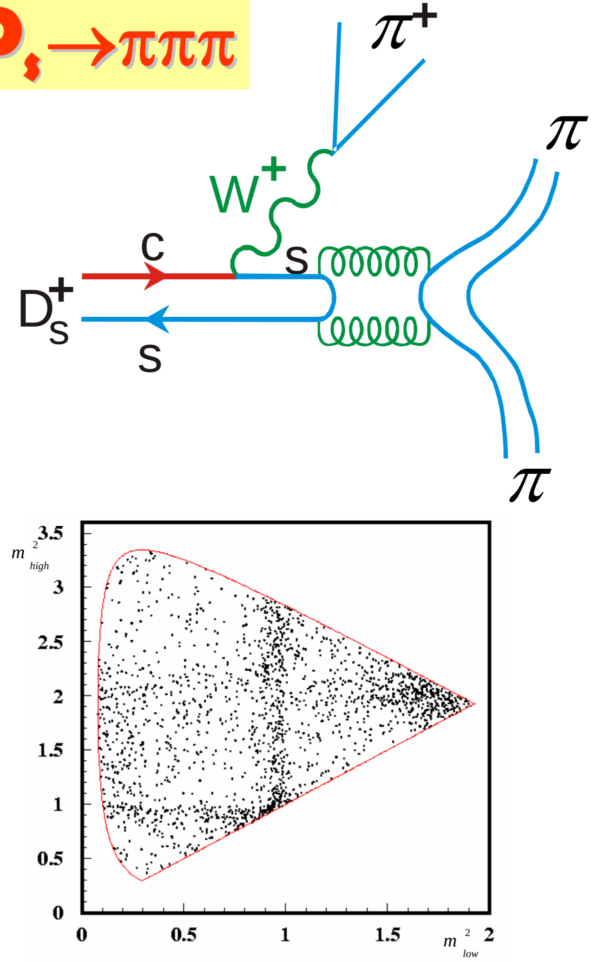
f_0 (980)



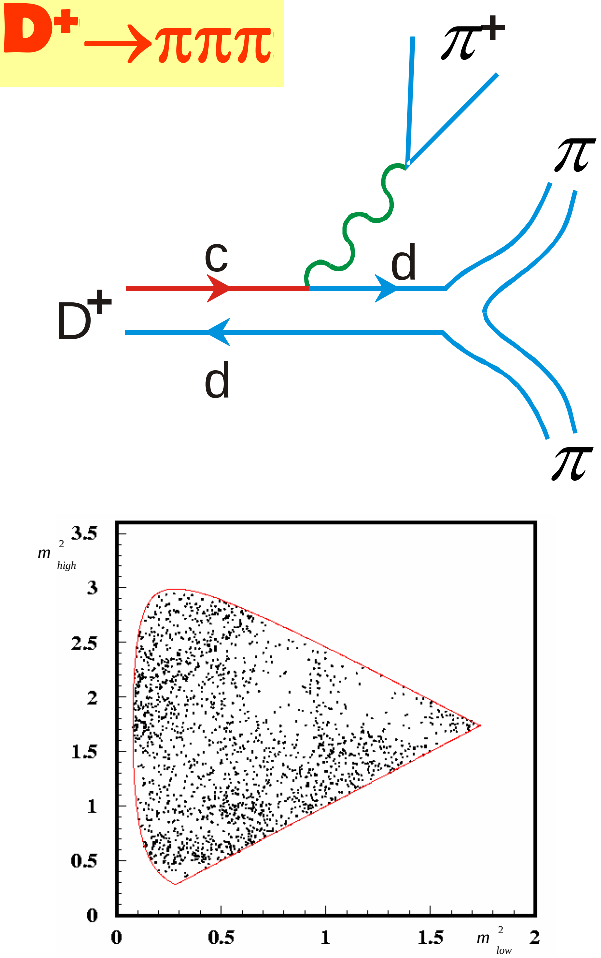


BES

$D_s \to \pi\pi\pi$

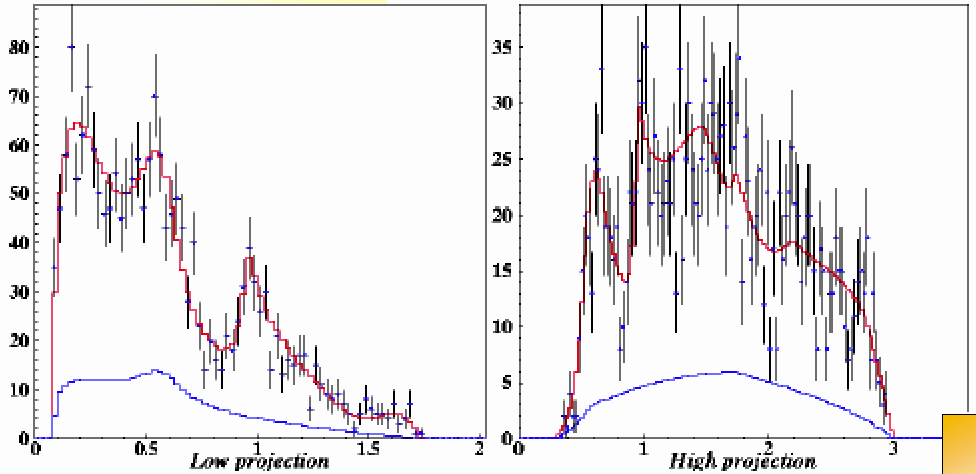


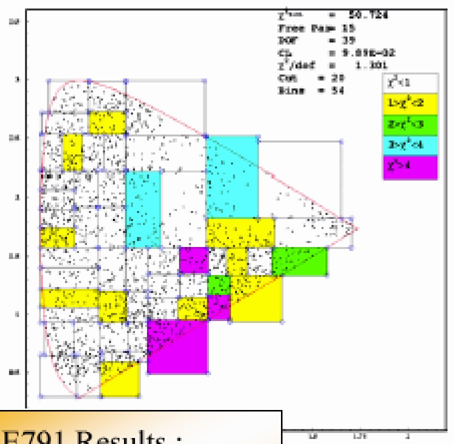
$D^+ \to \pi\pi\pi$



Preliminary

With $f_0(400)$





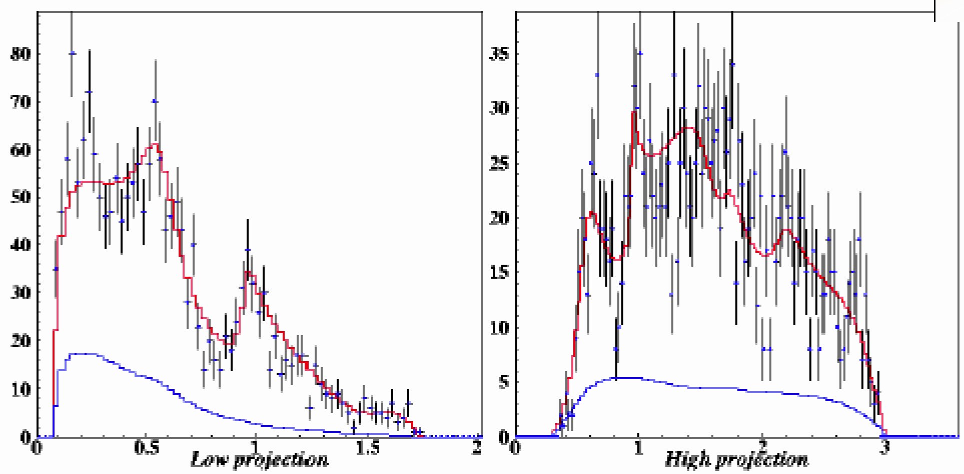
E791 Results :

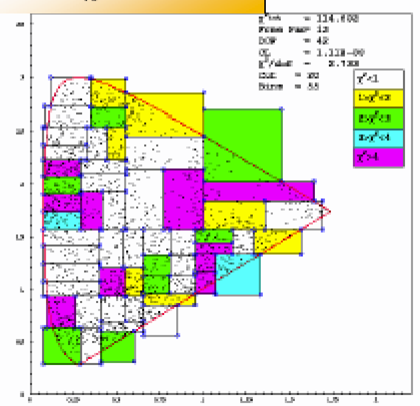
$$m = 478^{+24}_{-23} \pm 17\,MeV$$

$$\Gamma = 324^{+42}_{-40} \pm 21\,MeV$$

C.L. ~ 1 0%

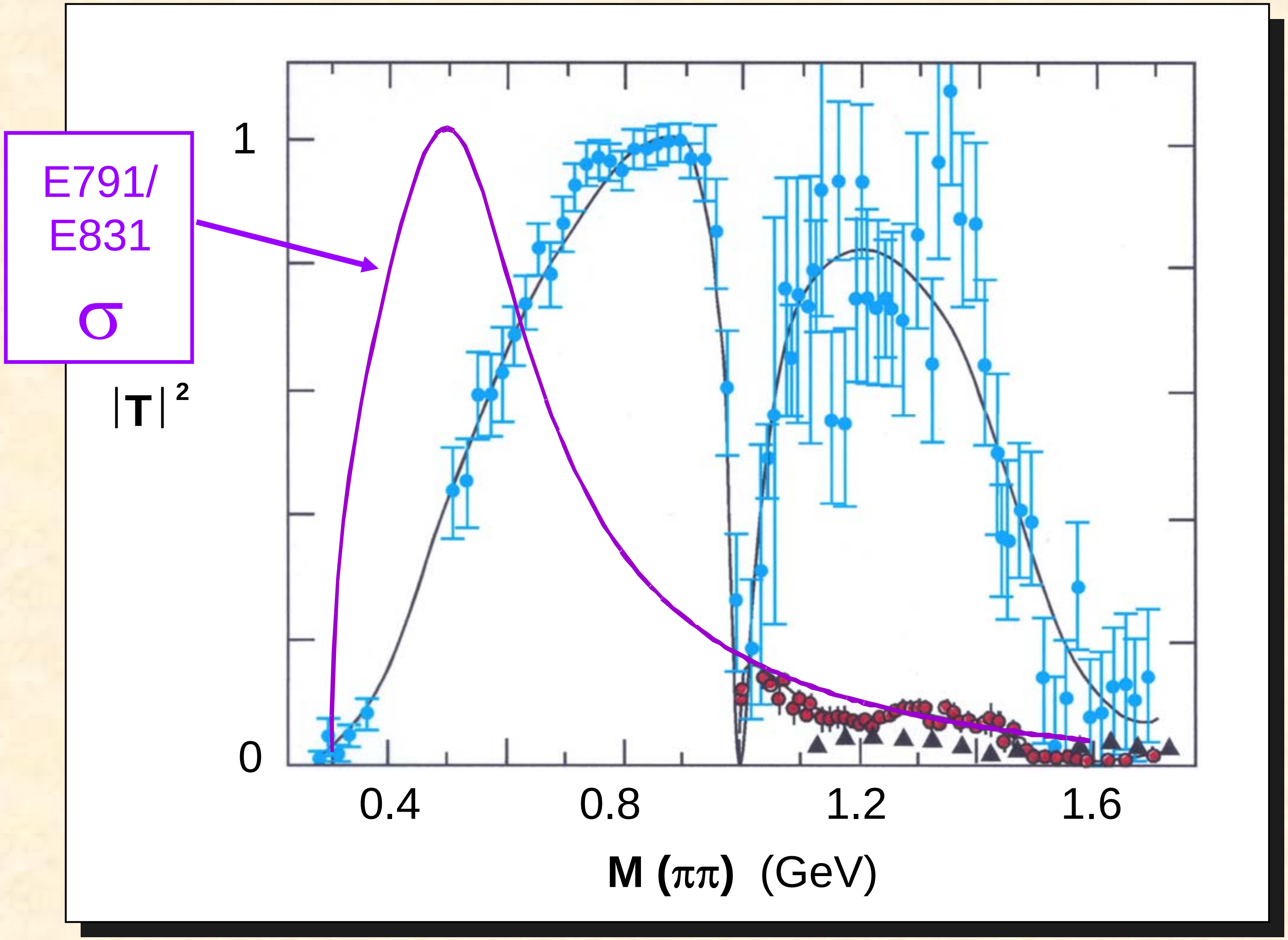
Without $f_0(400)$





~ 10^{-8} %

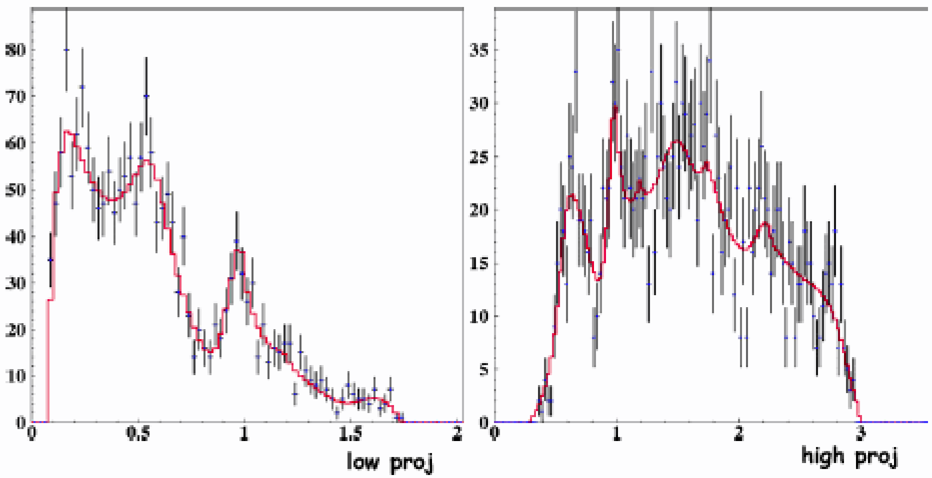
I = J = 0

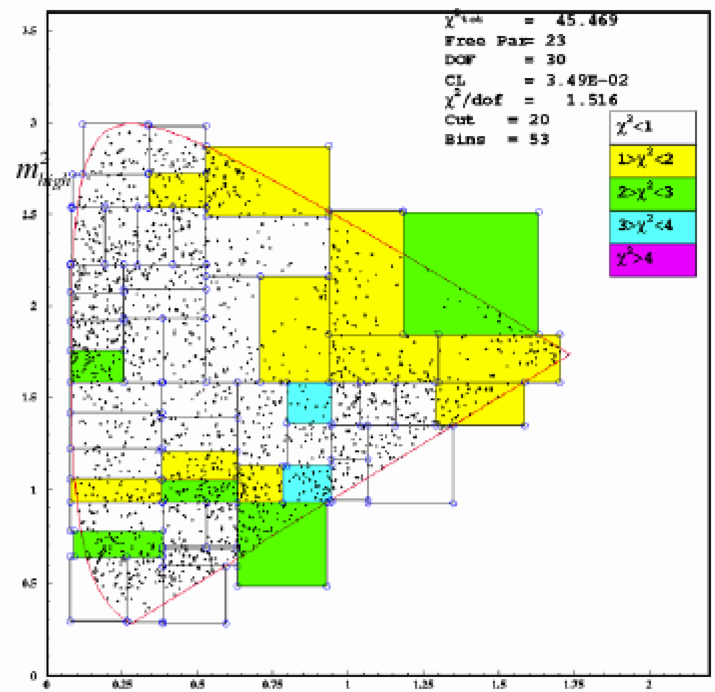


● ππ → ππ ● ππ → $K\bar{K}$ ▲ ππ → ηη

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

preliminary





m^2_{low}

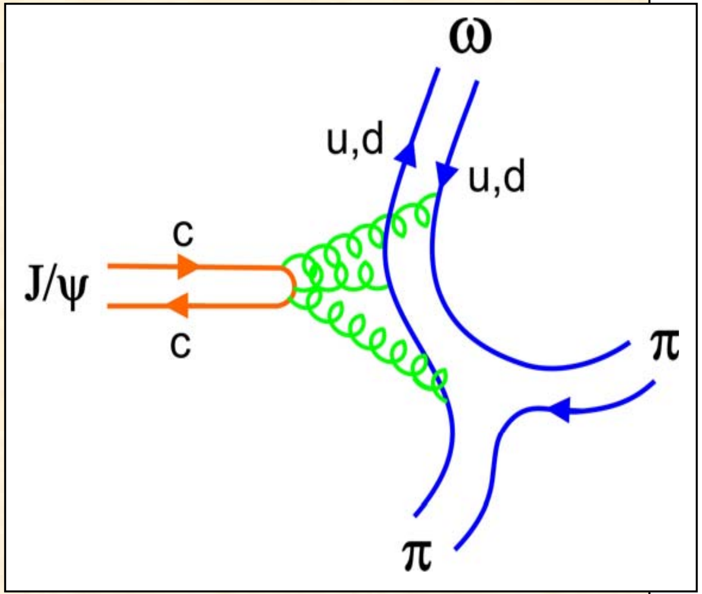
fit fractions		phases
Γ Swave	= 0.6647 ± 0.0416	(101.8 ± 22.5)
Γ ρ(770)	= 0.2116 ± 0.0436	(0.0 ± 0.0)
Γ f_2(1275)	= 0.1143 ± 0.0142	(-113.0 ± 9.0)

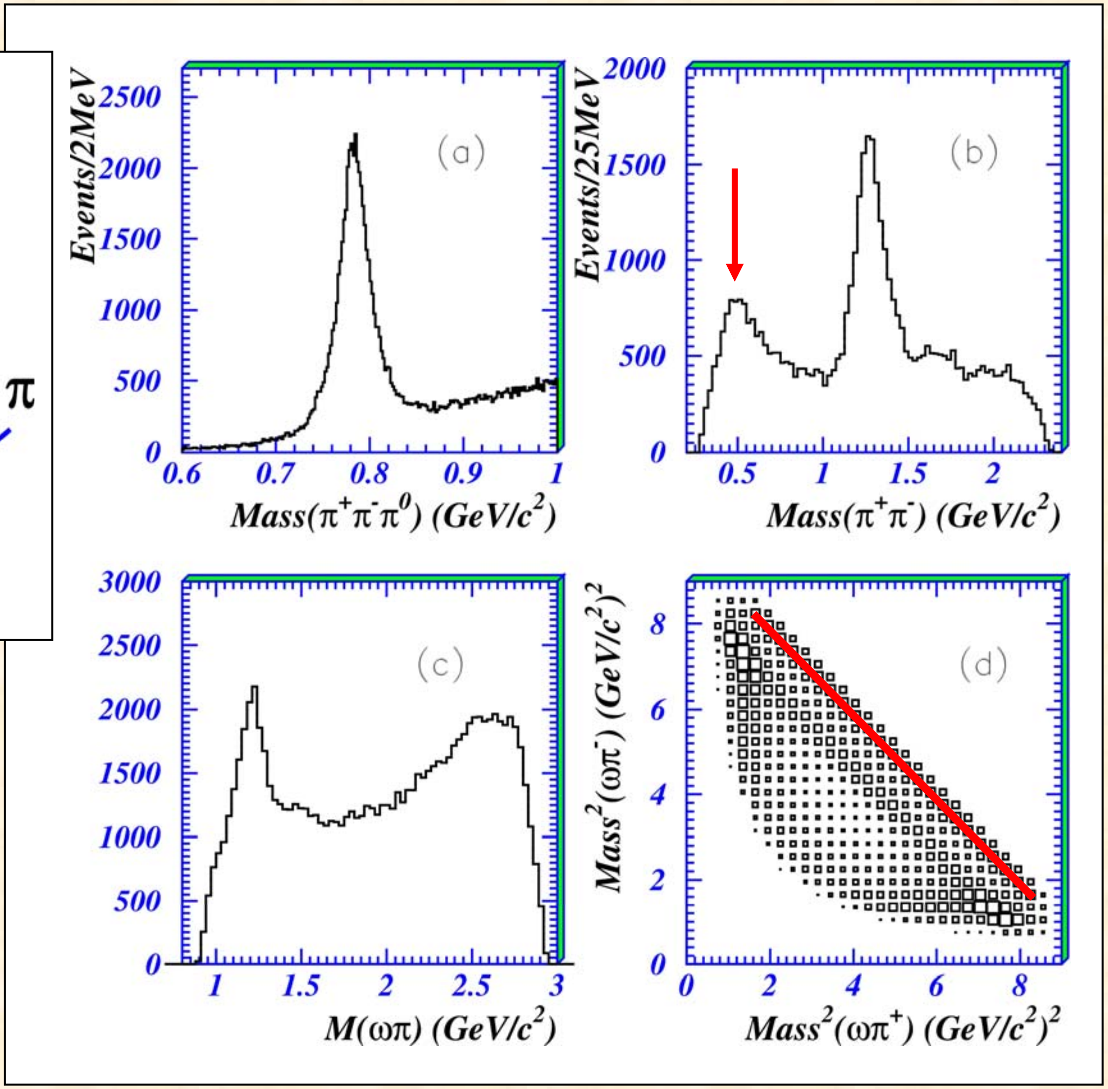
$$\sum_r f_r \sim 99\%$$

E831 FOCUS

$J/\psi \longrightarrow \omega\, \pi^+\pi^-$

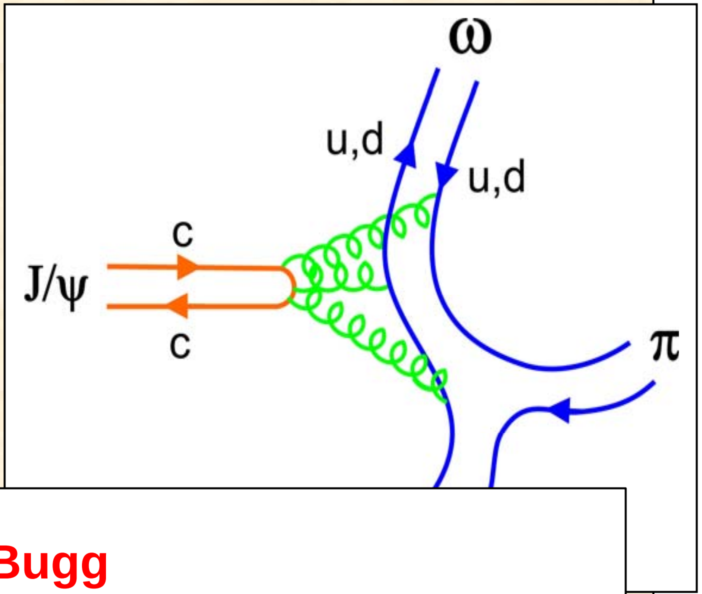
BES



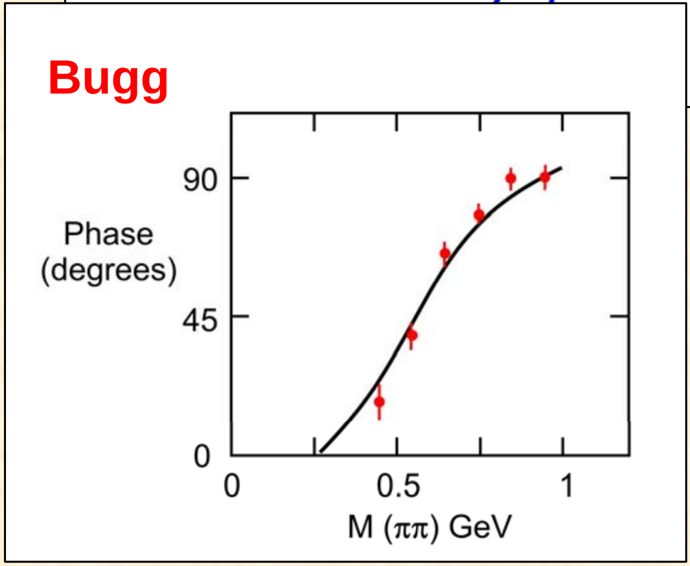


J/ψ ⟶ ω π⁺π⁻

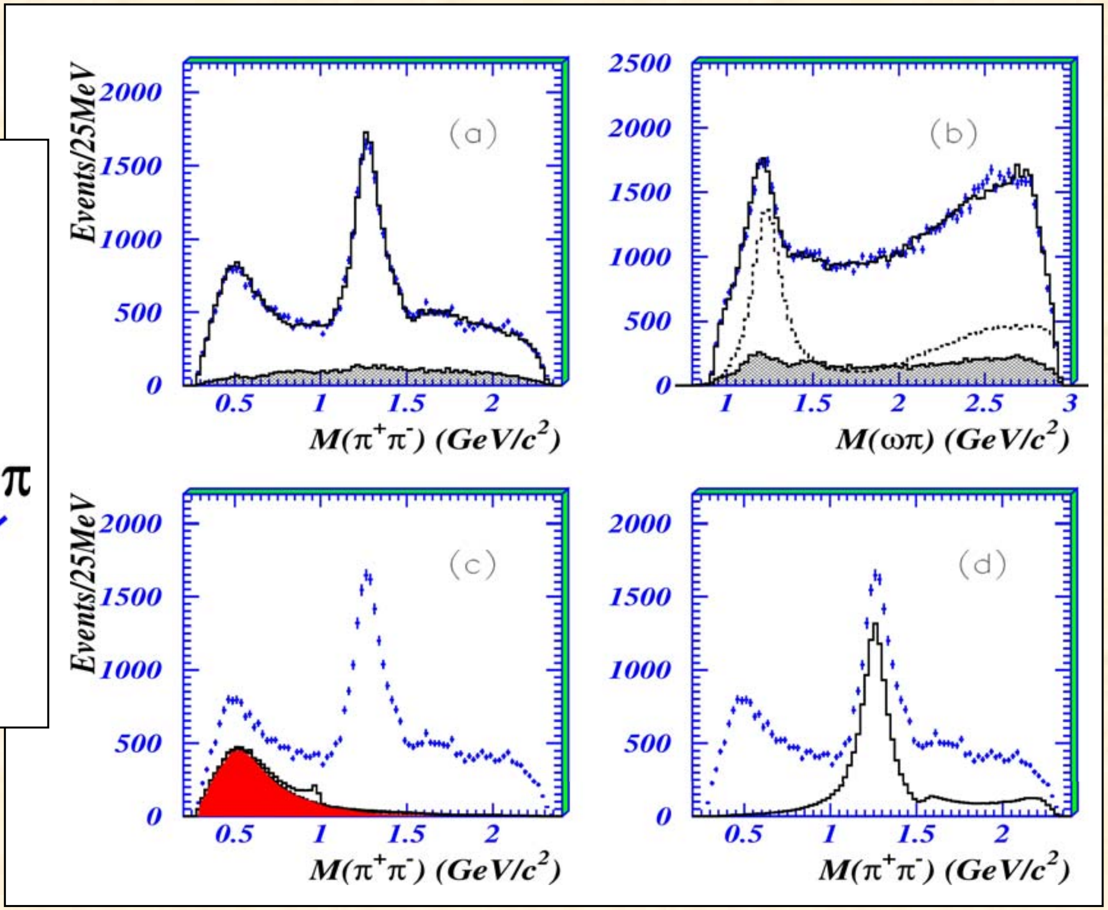
BES



ω
u,d
u,d
c
J/ψ
c
π

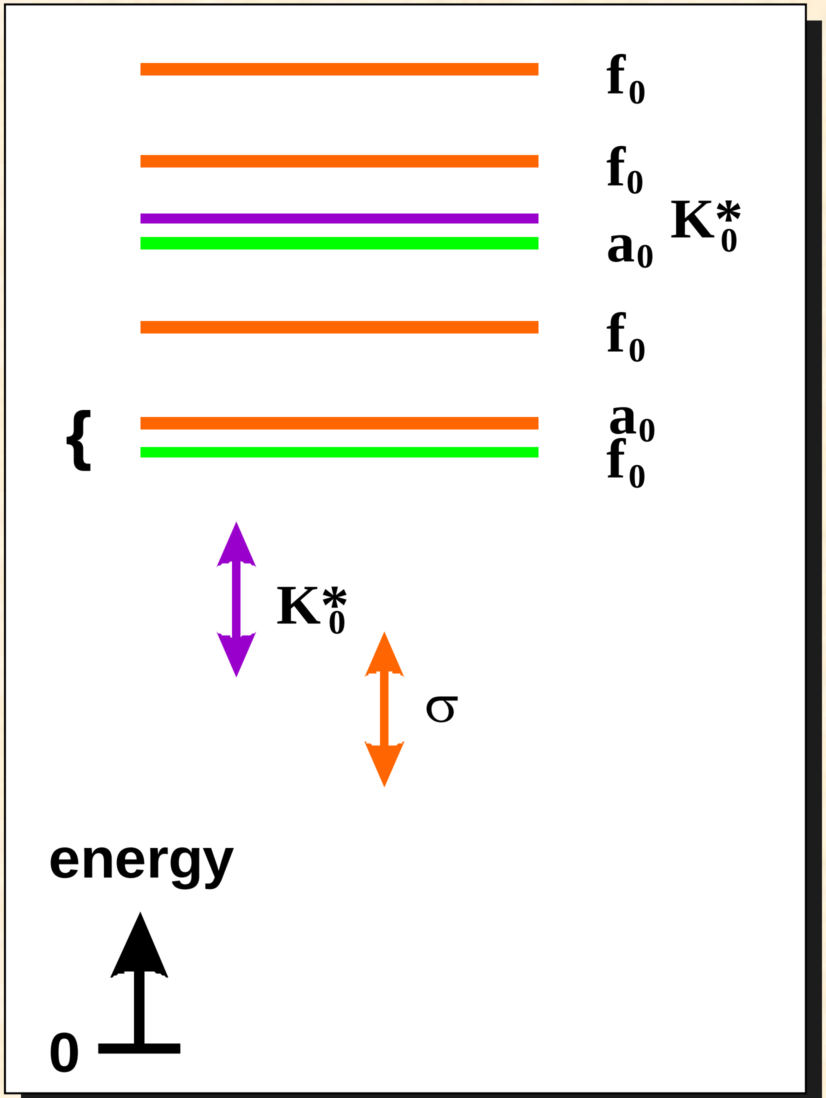


Bugg
Phase (degrees)
90
45
0
0
0.5
1
M (ππ) GeV

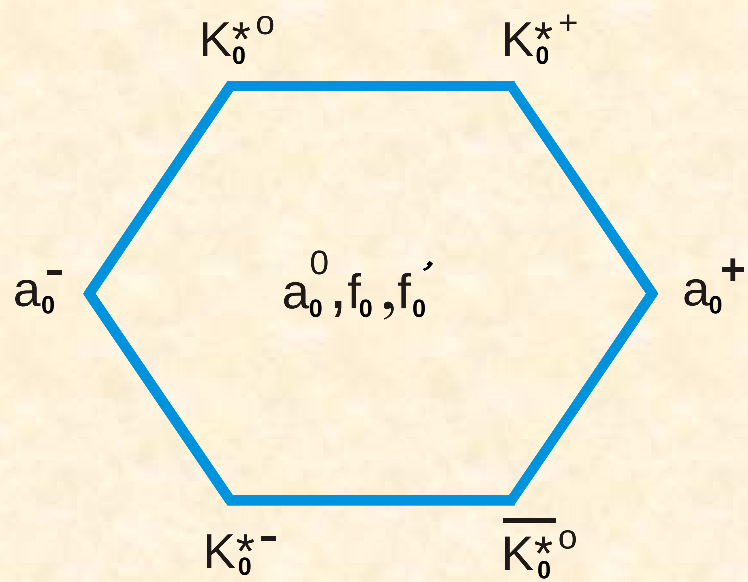


Events/25MeV
(a)
(b)
(c)
(d)
M(π⁺π⁻) (GeV/c²)
M(ωπ) (GeV/c²)

Scalar multiplet



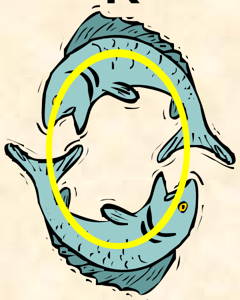
$$J^{PC} = 0^{++}$$



quark model = hadron world?

φ

+

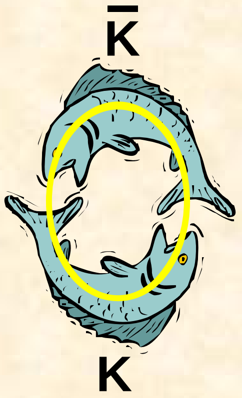


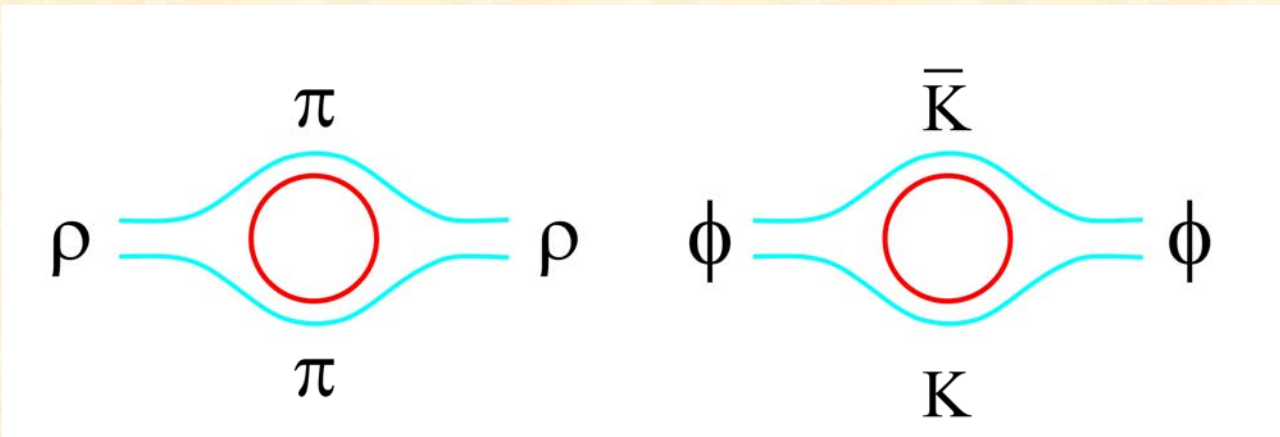
$$\frac{1}{m_0^2 - s} \longrightarrow \frac{1}{M^2 - s - iM\Gamma}$$

quark model = hadron world?

φ

+ $\frac{1}{N_c}$

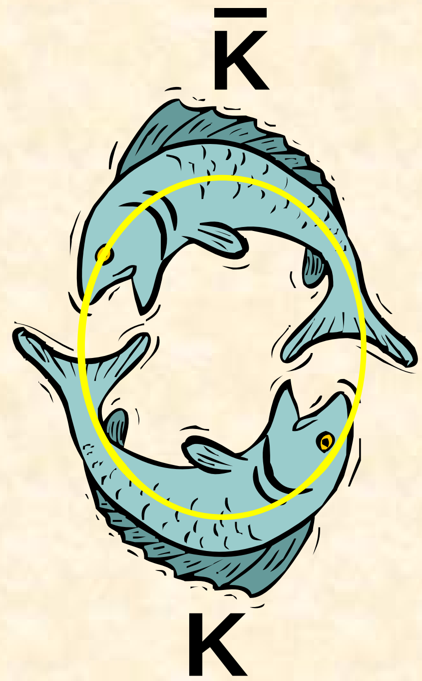




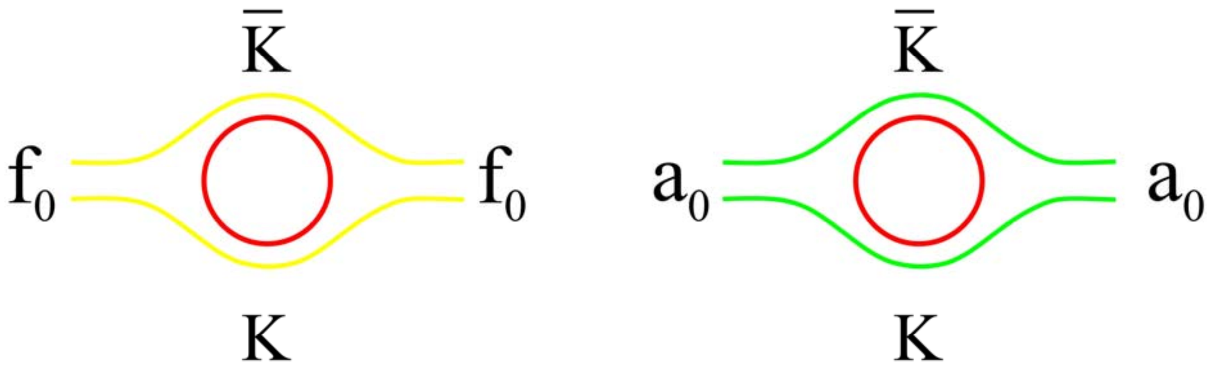
unquenching unimportant

f_0

+



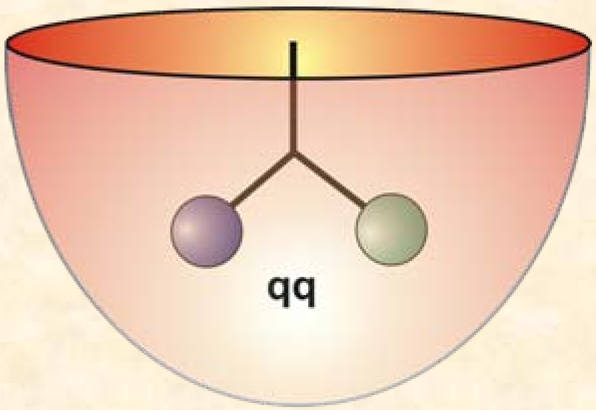
40%

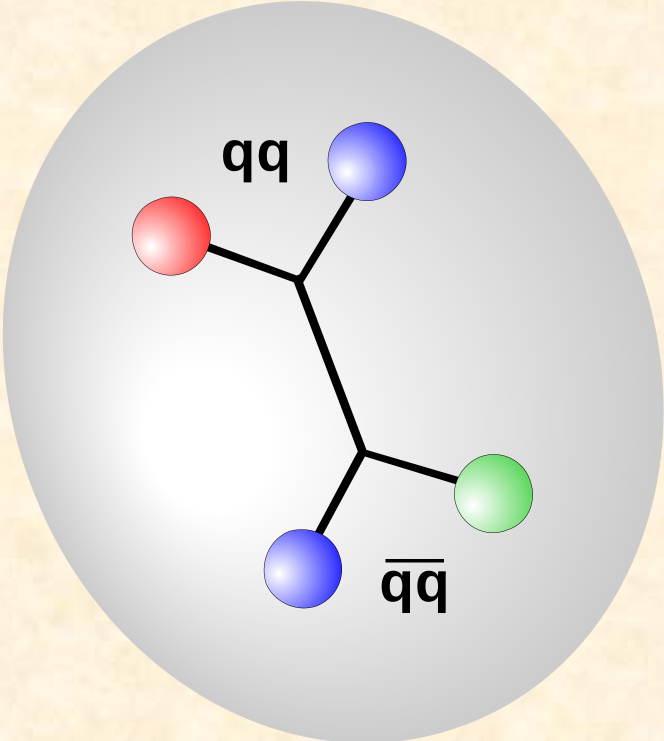


unquenching important

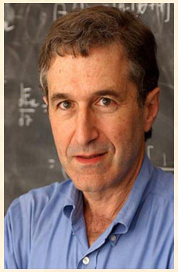
diquarks: colour

tetraquark





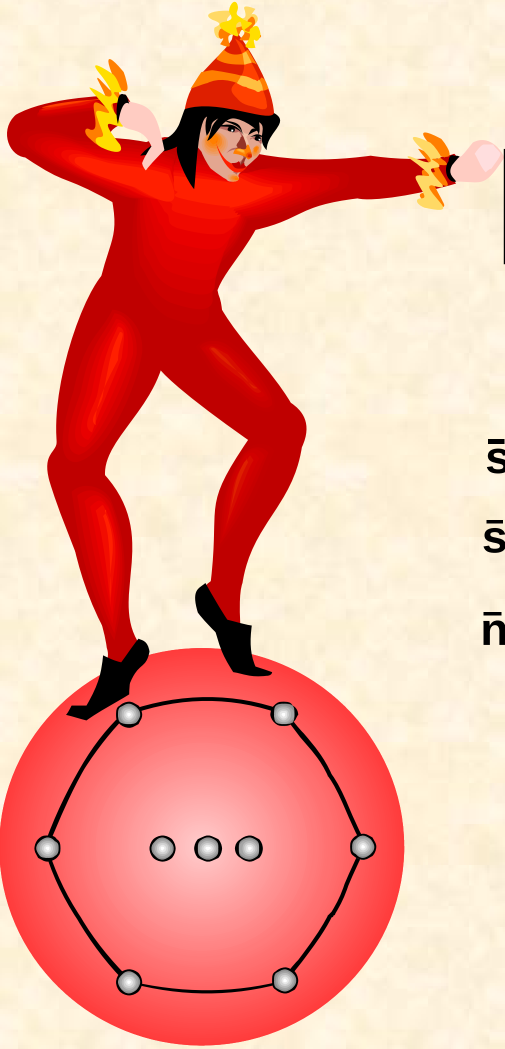
Jaffe & Wilczek



Scalar diquarks

[ud]	[us]	[ds]
[cd]	[cu]	[cs]

Scalar meson multiplets

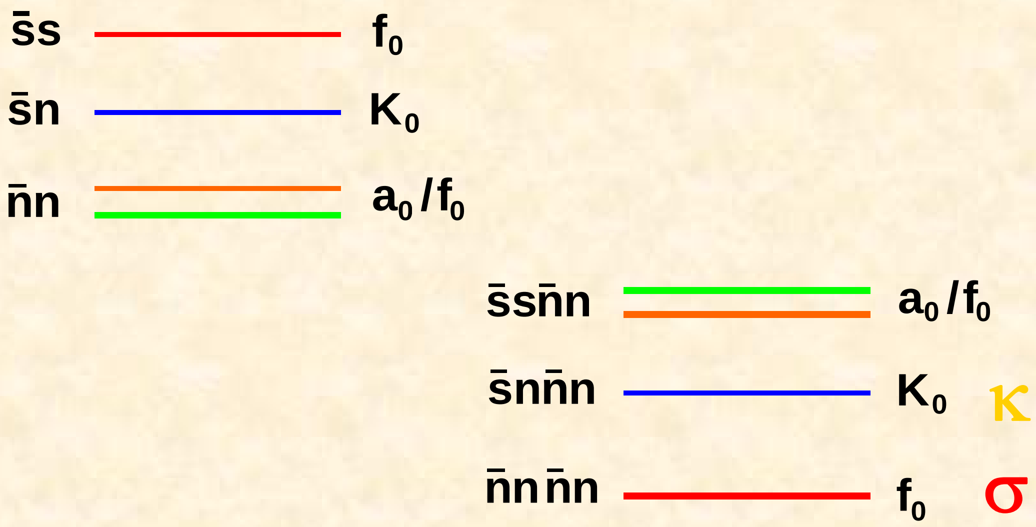


$q\bar{q}$	
$\bar{s}s$	f_0
$\bar{s}n$	K_0
$\bar{n}n$	a_0/f_0

$q\bar{q}q\bar{q}$		
$\bar{s}s\bar{n}n$	a_0/f_0	
$\bar{s}n\bar{n}n$	K_0	κ
$\bar{n}n\bar{n}n$	f_0	σ

Scalar meson multiplets

$q\bar{q}$ | $q\bar{q}q\bar{q}$



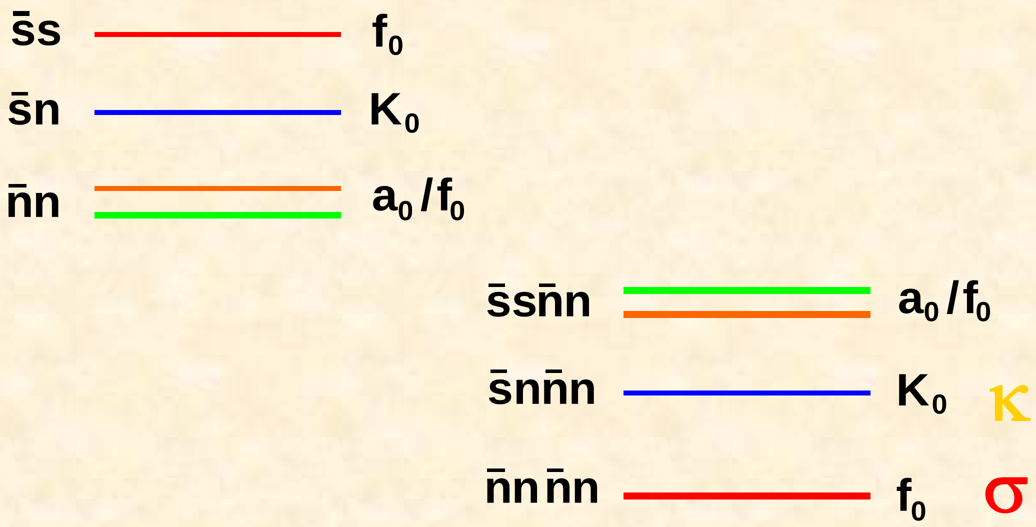
Jaffe

Maiani, Piccinini, Polosa, Riquer

Scalar meson multiplets

$q\bar{q}$

$q\bar{q}q\bar{q}$

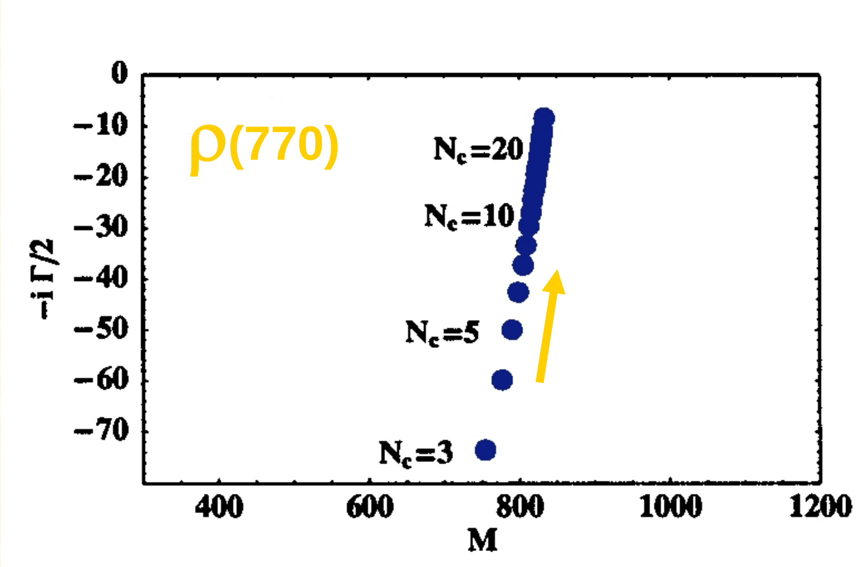


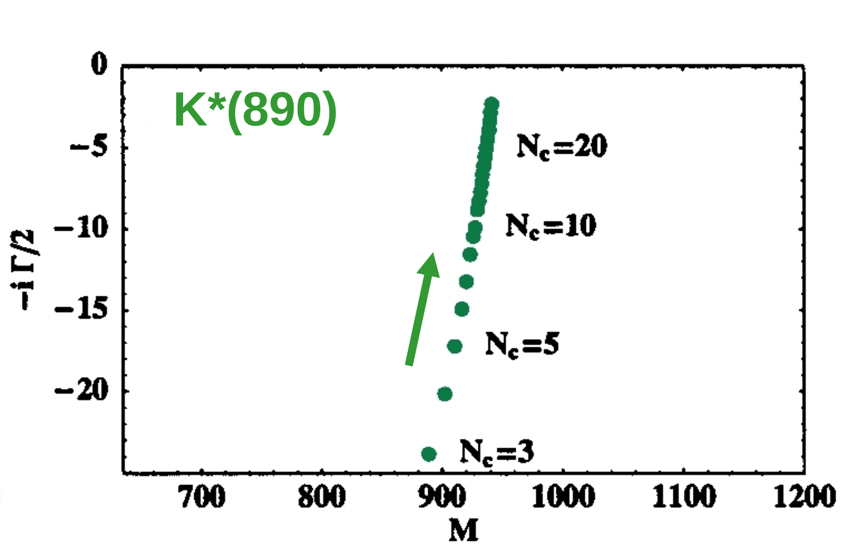
N_c large ⟶ stable

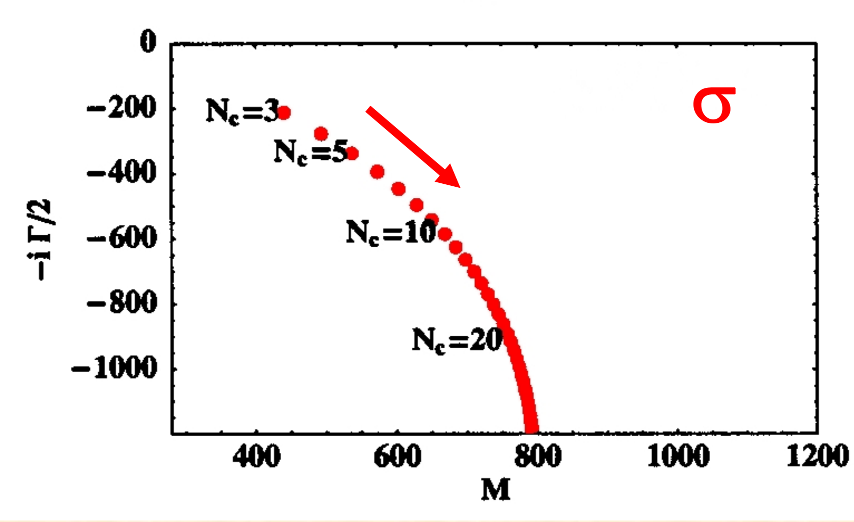
N_c large ⟶ meson continuum

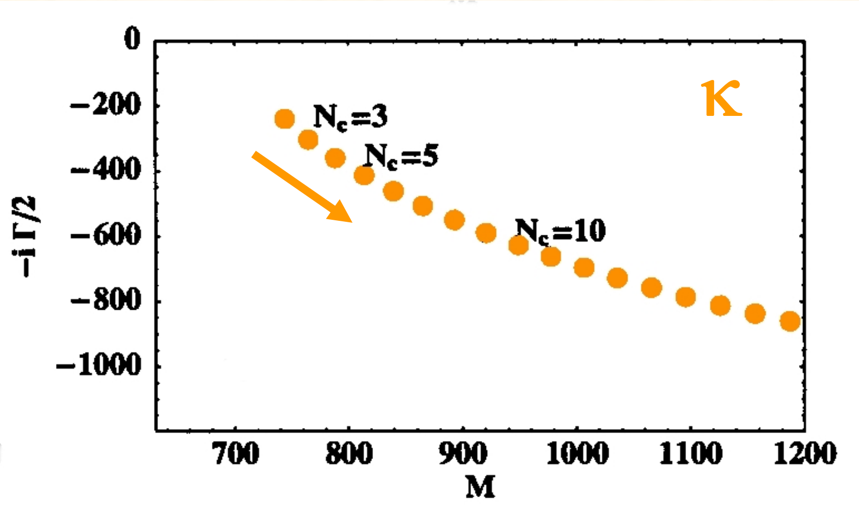
$N_c \to \infty$

Pelaez
Jaffe

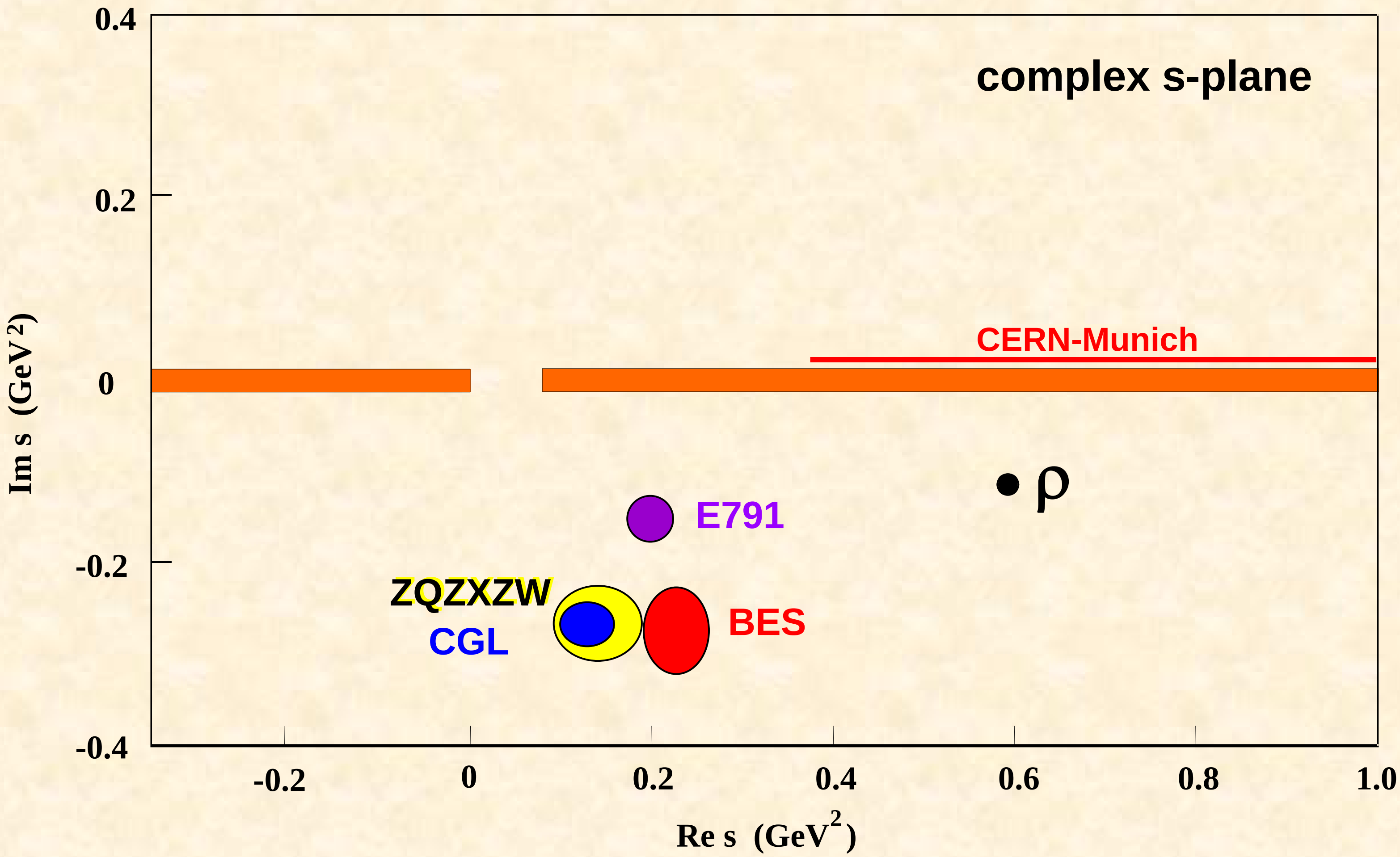








$\pi\pi$: I = 0, J = 0



Zhou, Qin, Zhang, Xiao, Zheng & Wu

Colangelo, Gasser & Leutwyler

CP

To learn about the Higgs sector of QCD

demands a global Dalitz analysis of J/ψ, B/D decays, $\gamma\gamma$,…
in Comprehensive Analyses

LNF Spring Institute
May-July 2005