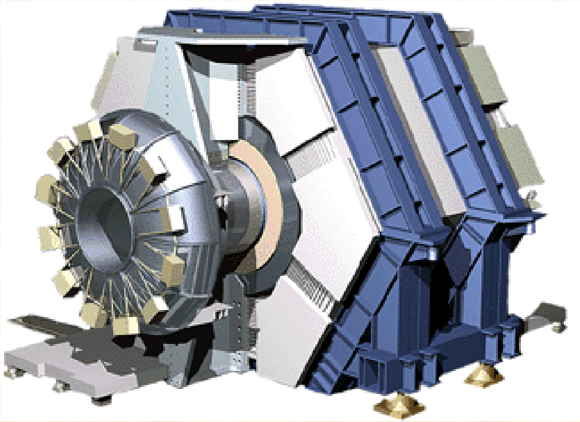
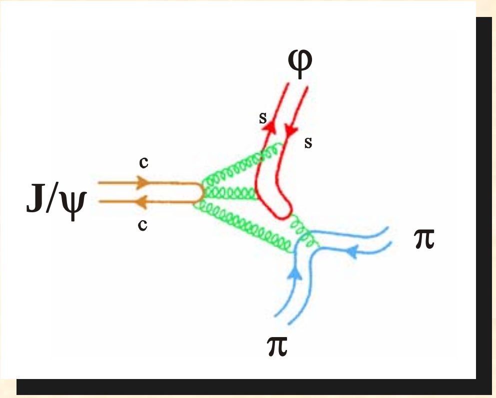
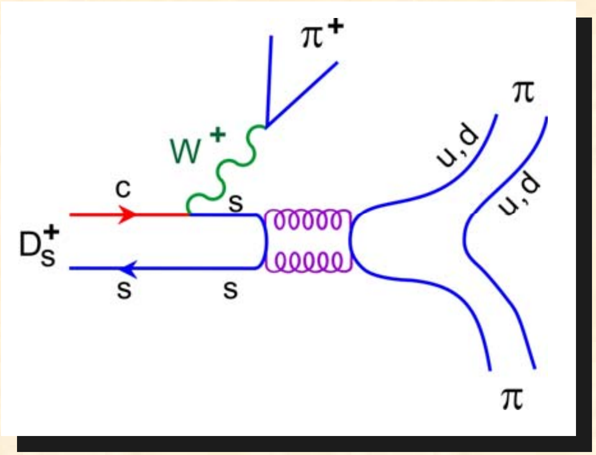
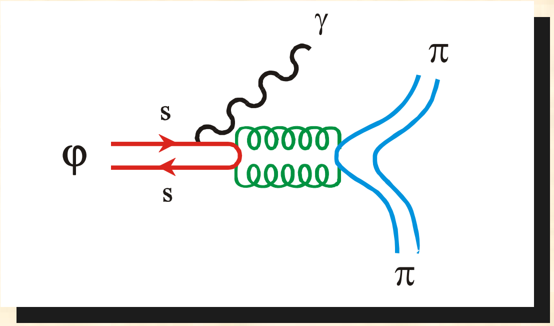


What heavy flavour decays can teach us about light meson physics and what you need to know about light quark dynamics to extract useful information from heavy flavour decays



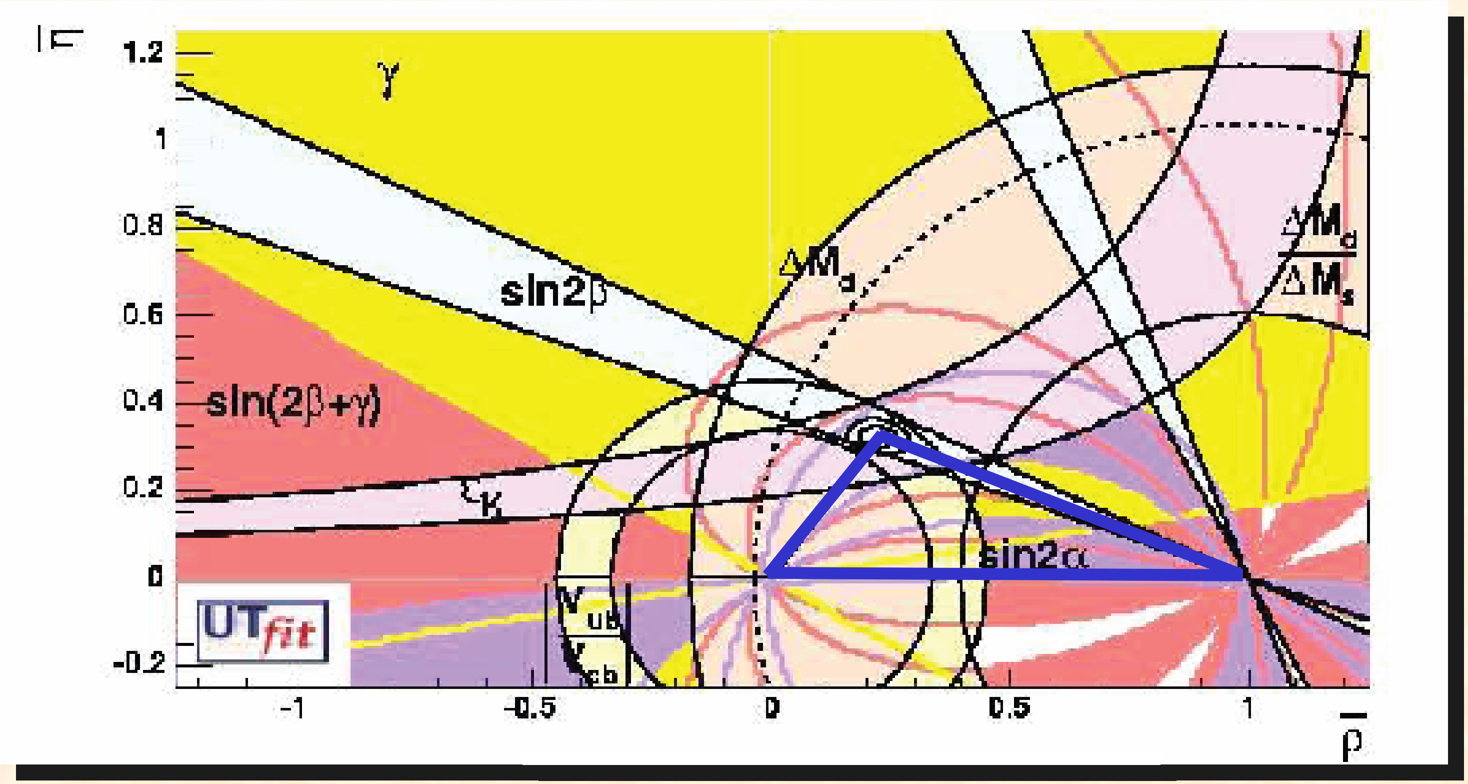


BES



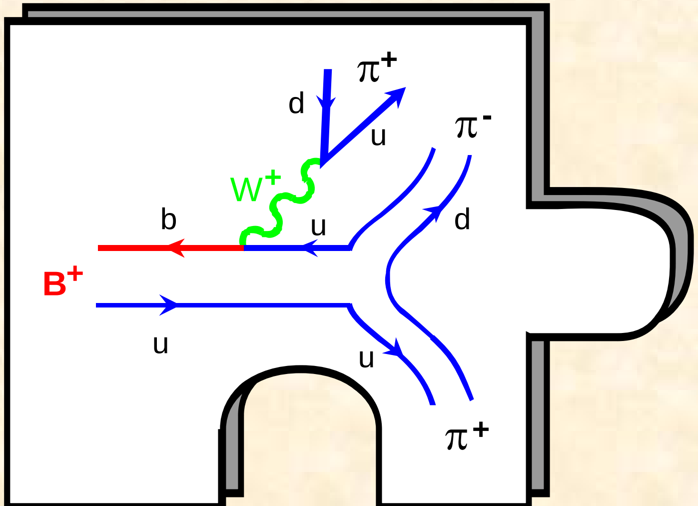
What heavy flavour decays can teach us
about light meson physics and
what you need to know about light quark dynamics
to extract useful information from heavy flavour decays

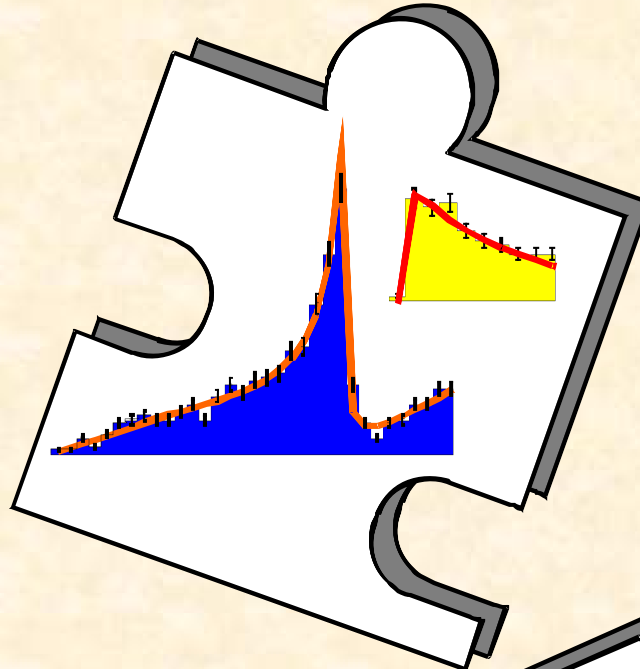
Determining the unitarity triangle



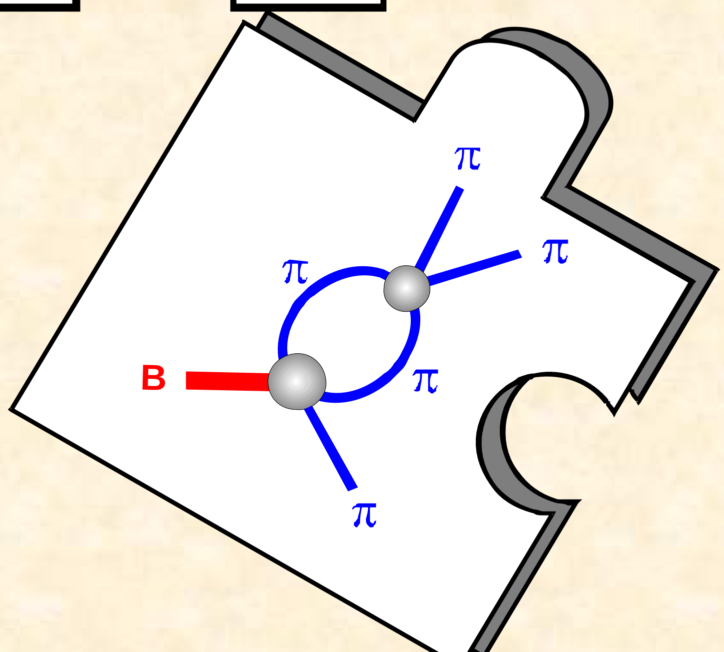
Removing constraint from Δm_s: $\gamma = (65 \pm 7)^o \longrightarrow \gamma = (60 \pm 9)^o$

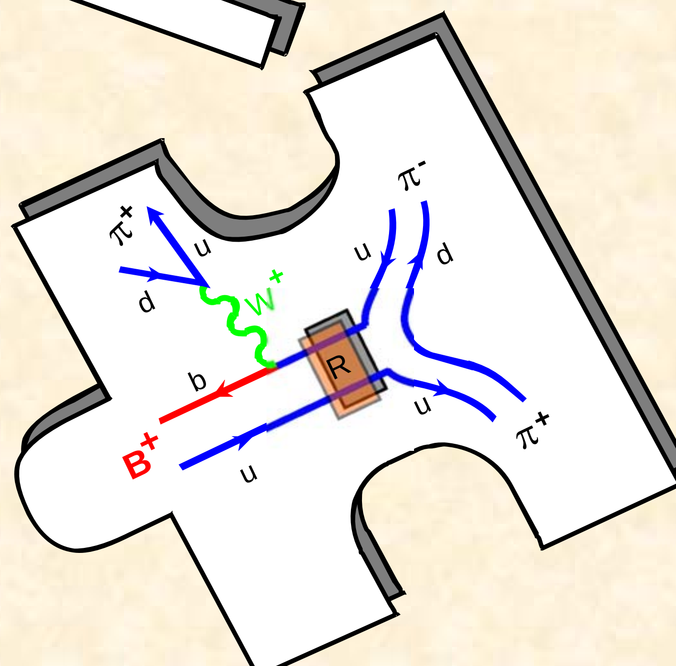
Physics Puzzle





~~CP~~

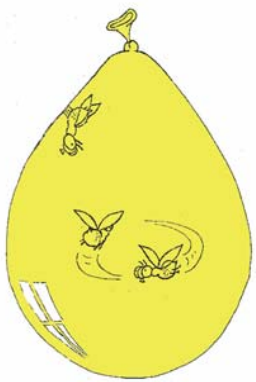




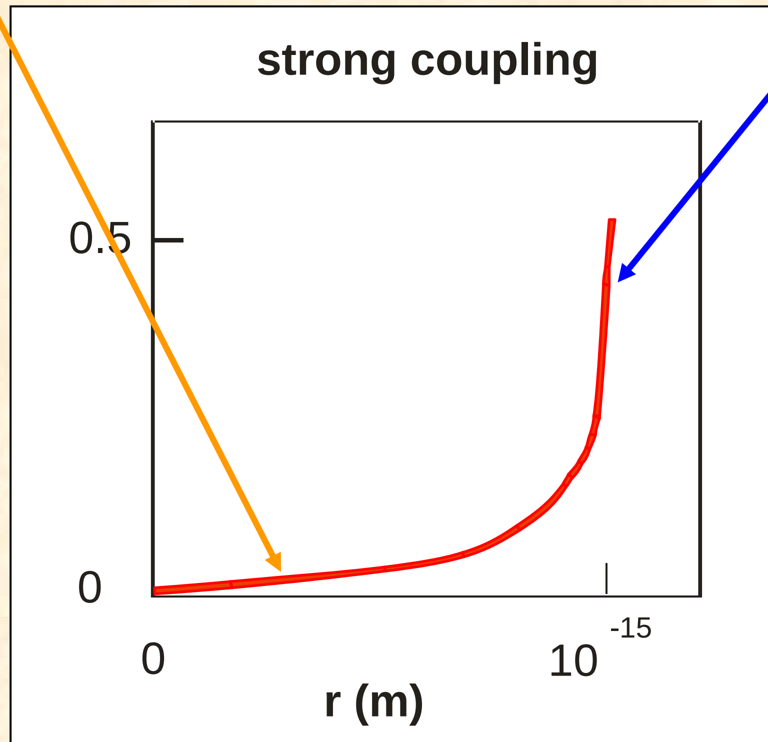
QCD

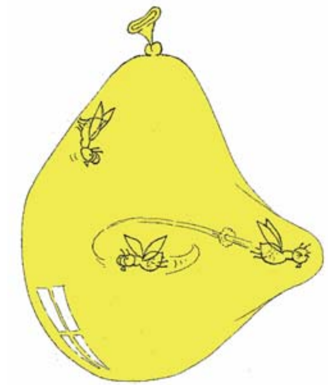
asymptotic freedom

confinement

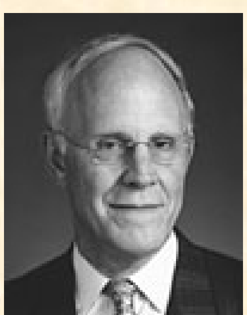


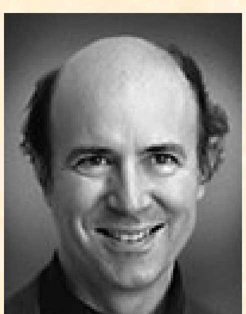
pQCD



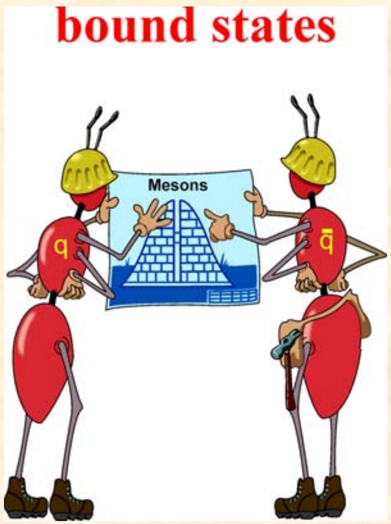


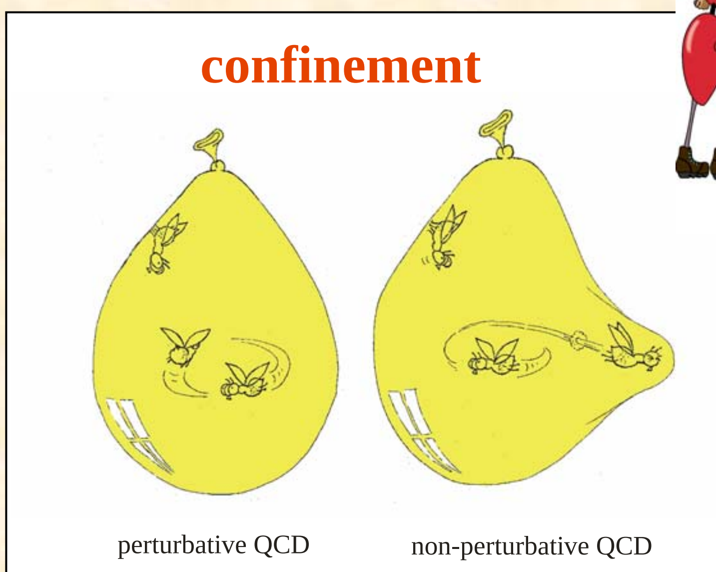
strong QCD

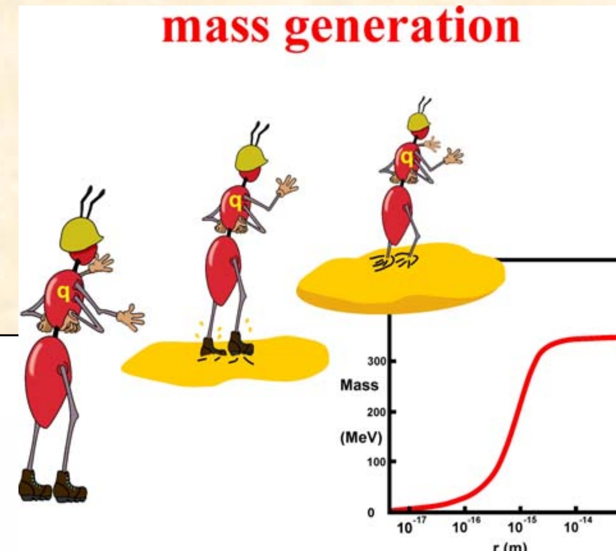




Strong physics problems

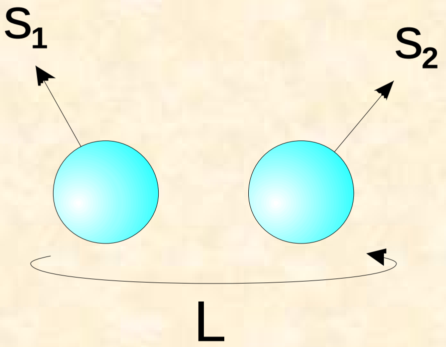




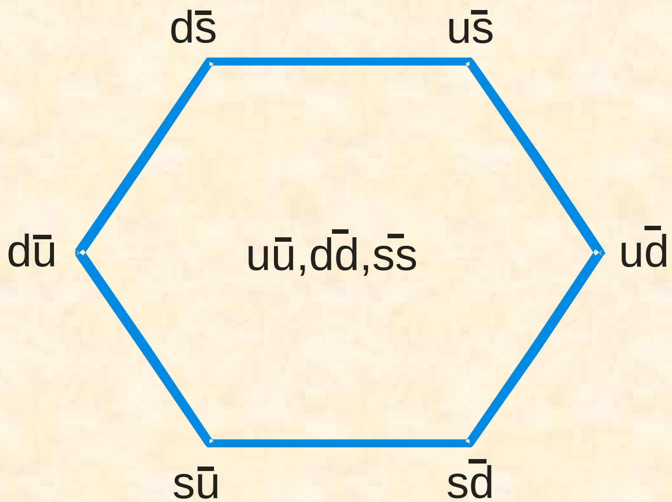


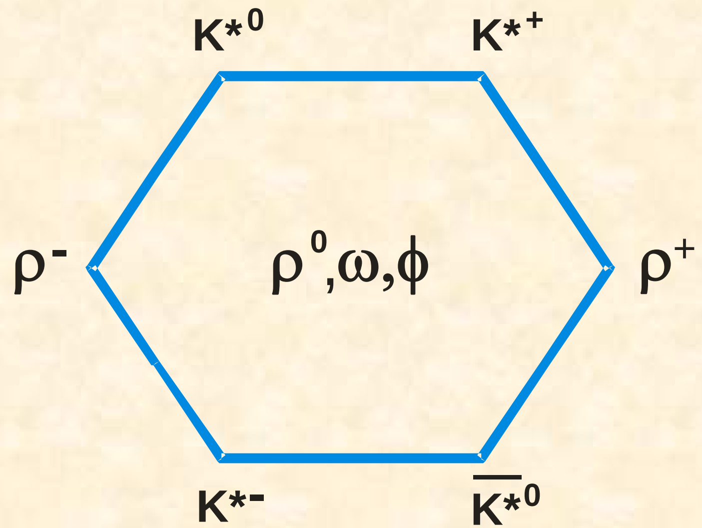
Vector meson multiplet

$J^{PC} = 1^{--}$



S = 1, L = 0

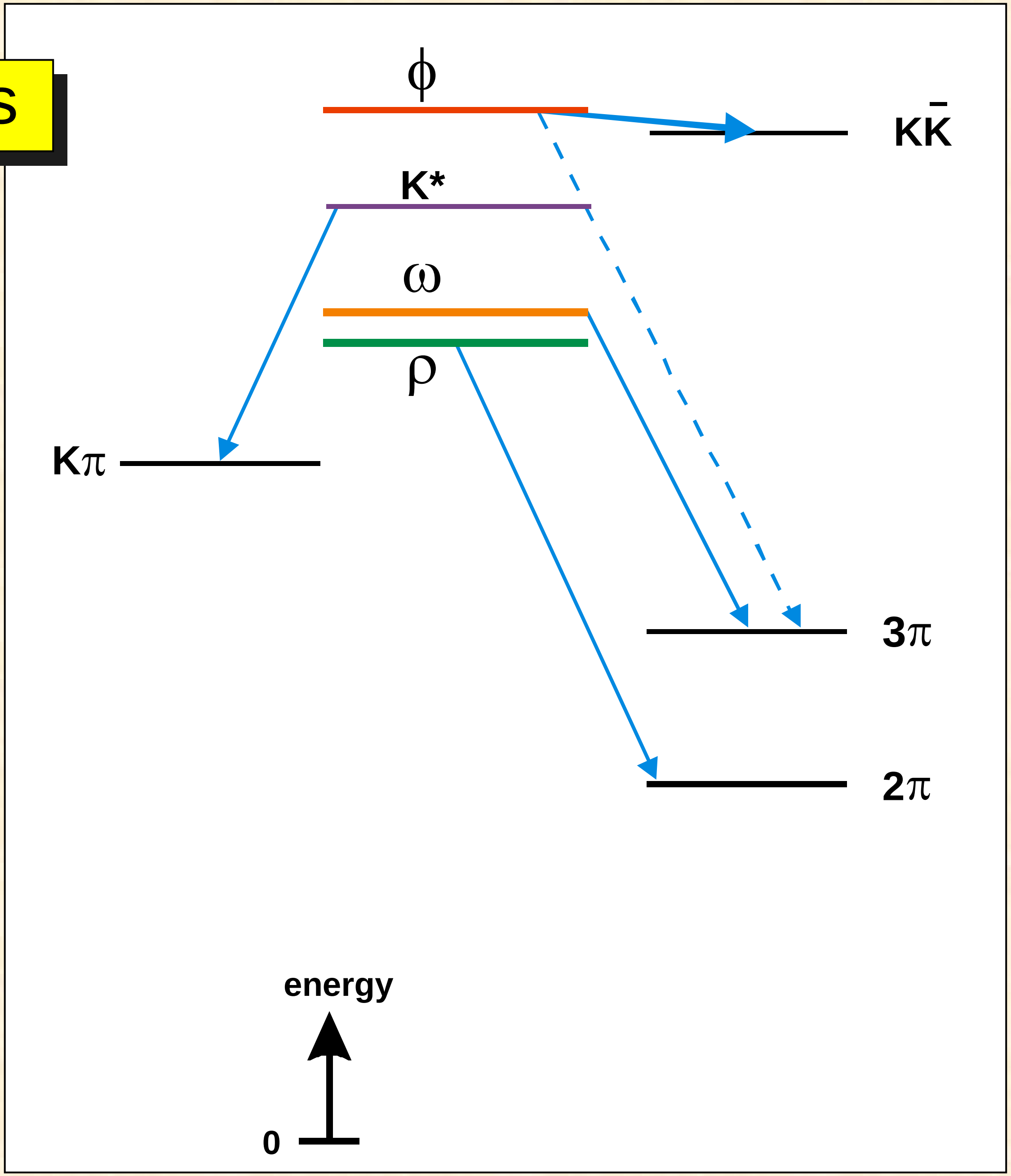




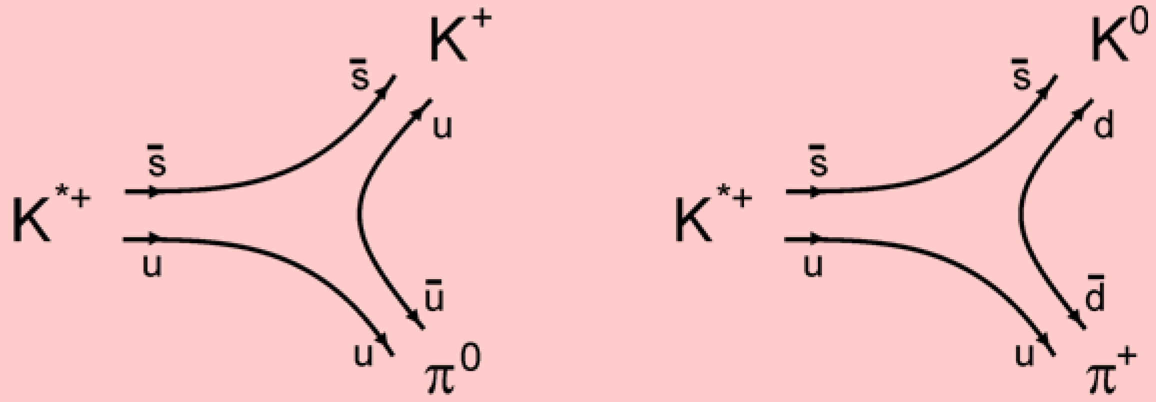
$$\frac{1}{\sqrt{2}}[u\bar{u} \pm d\bar{d}]$$

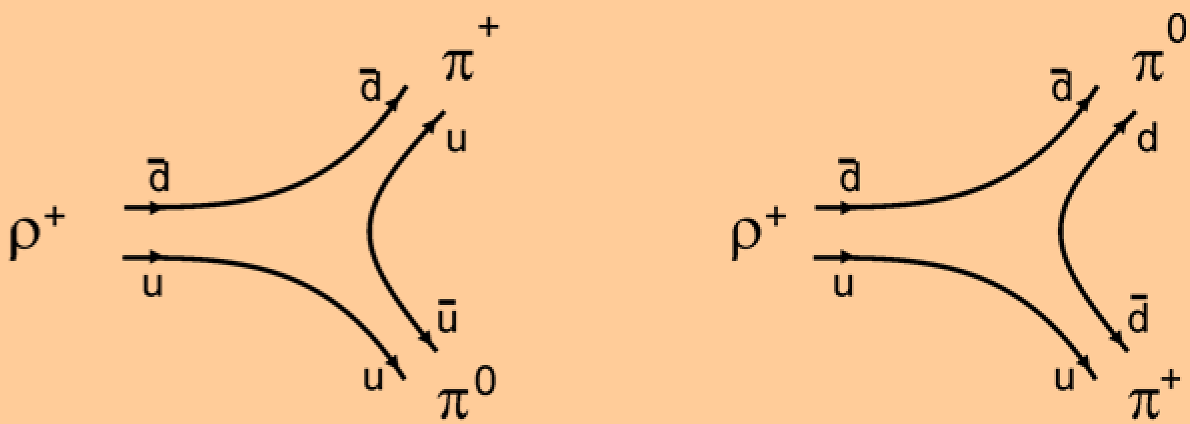
$$s\bar{s}$$

vector decays



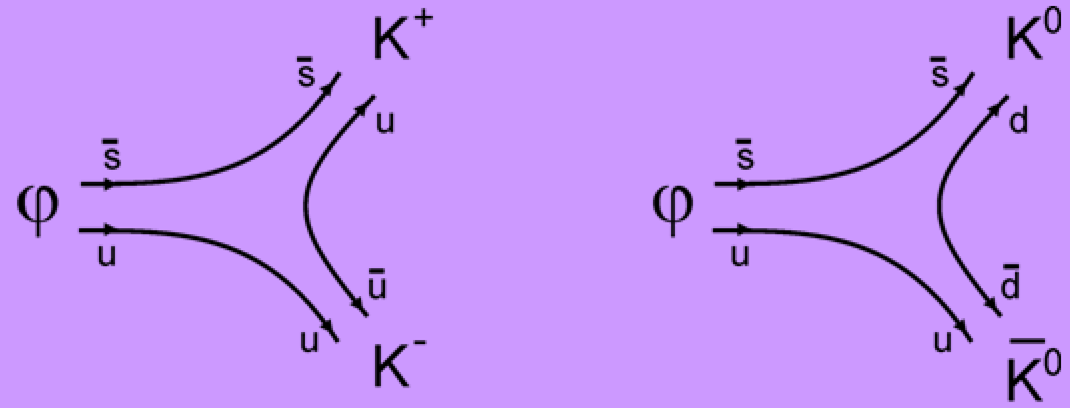
$$K^{*+} \longrightarrow K^+\pi^0,\ K^0\pi^+$$

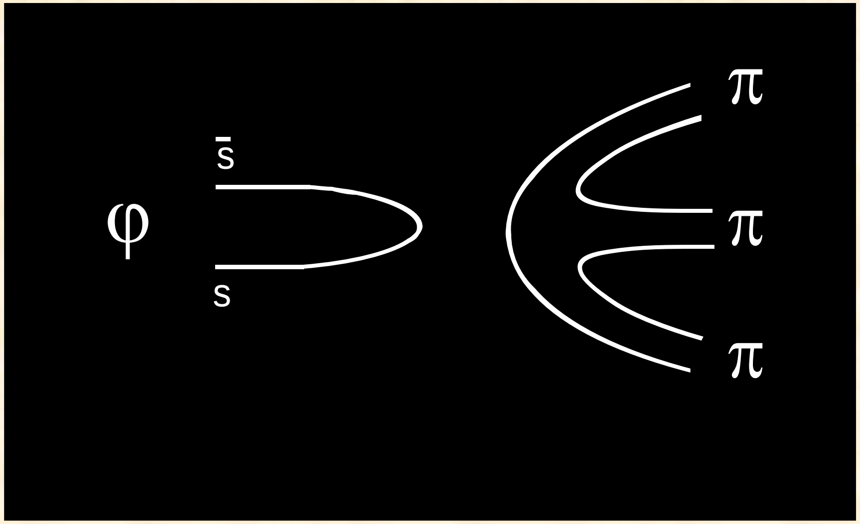




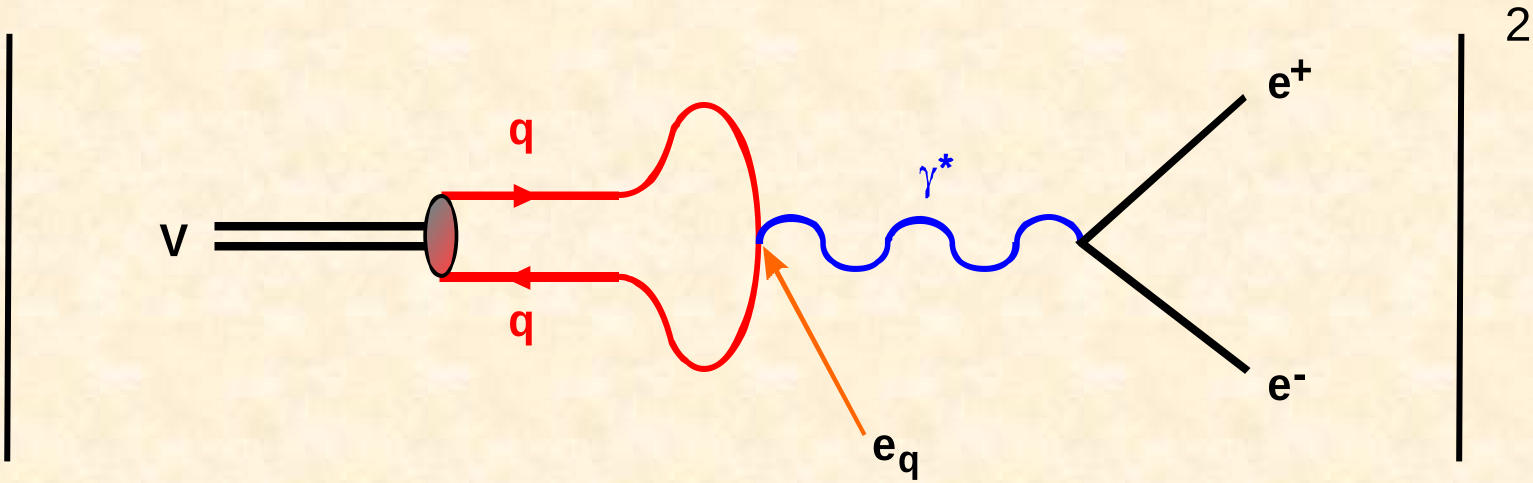
$$\rho^+ \longrightarrow \pi^+\pi^0$$

$$\varphi \longrightarrow K^+K^-,\ K^0\overline{K}^0$$





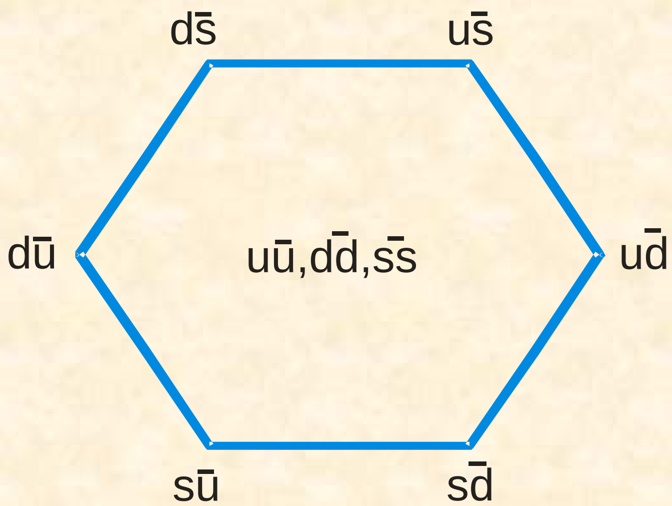
$\Gamma\,(V \longrightarrow e^+e^-)$

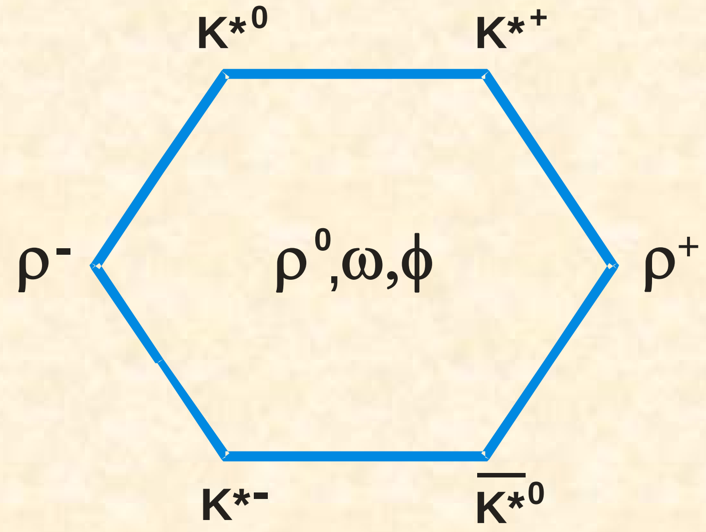


ρ	:	φ	:	ω
9	:	2	:	1

Vector meson multiplet

$J^{PC} = 1^{--}$

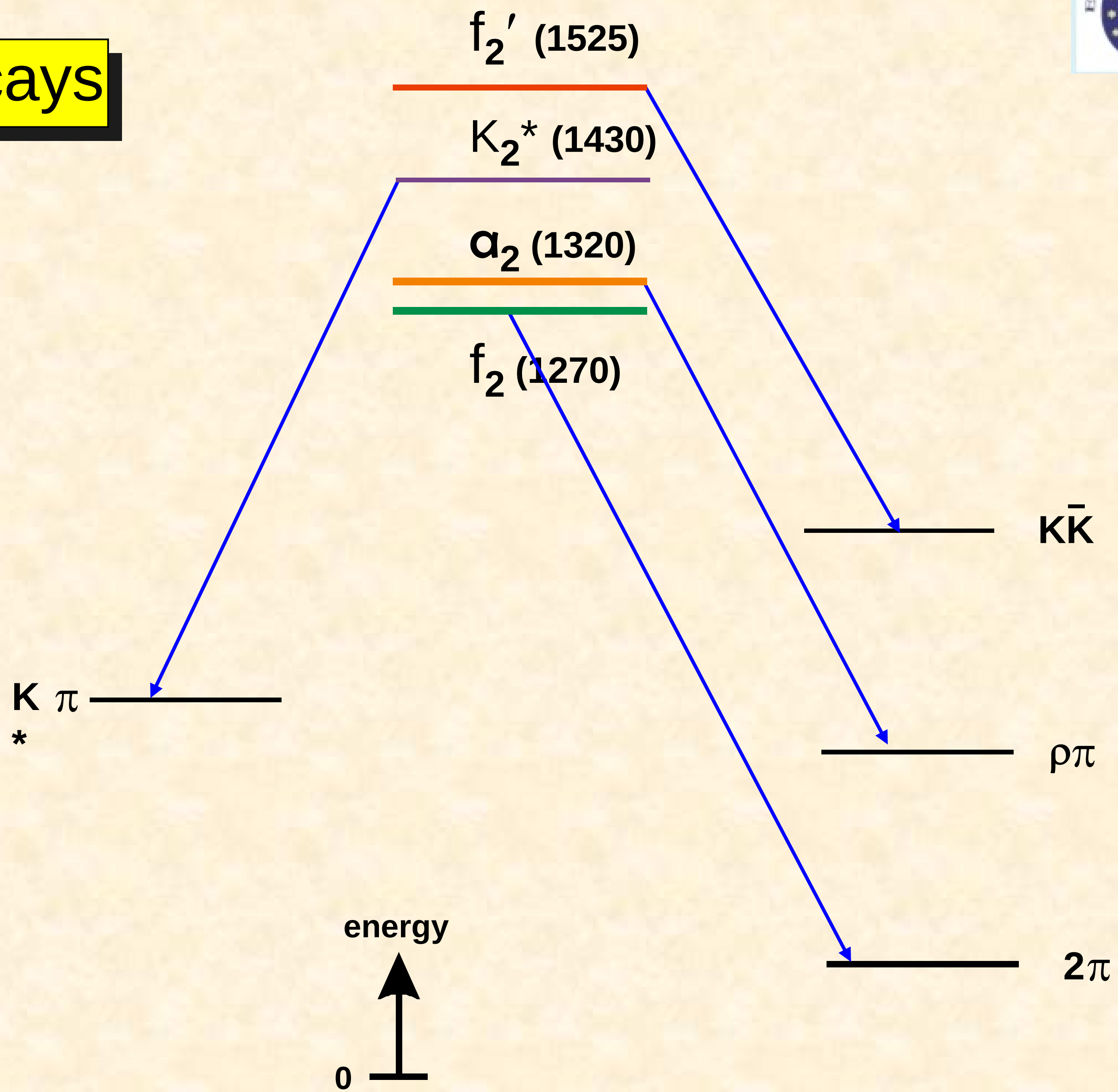




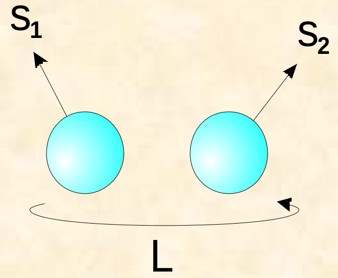
$$\frac{1}{\sqrt{2}} [\, u\bar{u} \pm d\bar{d} \,]$$

$$s\bar{s}$$

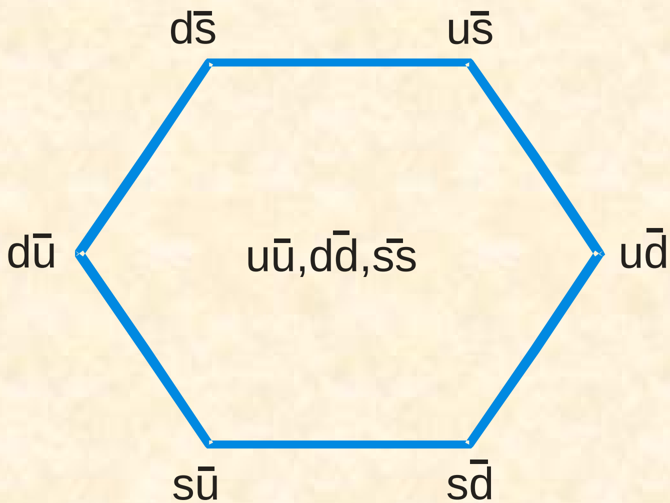
tensor decays

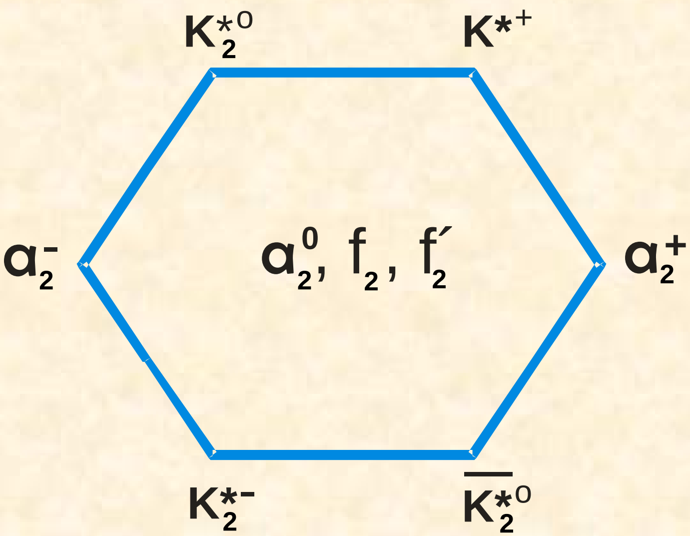


Tensor meson multiplet



$S = 1, L = 1$



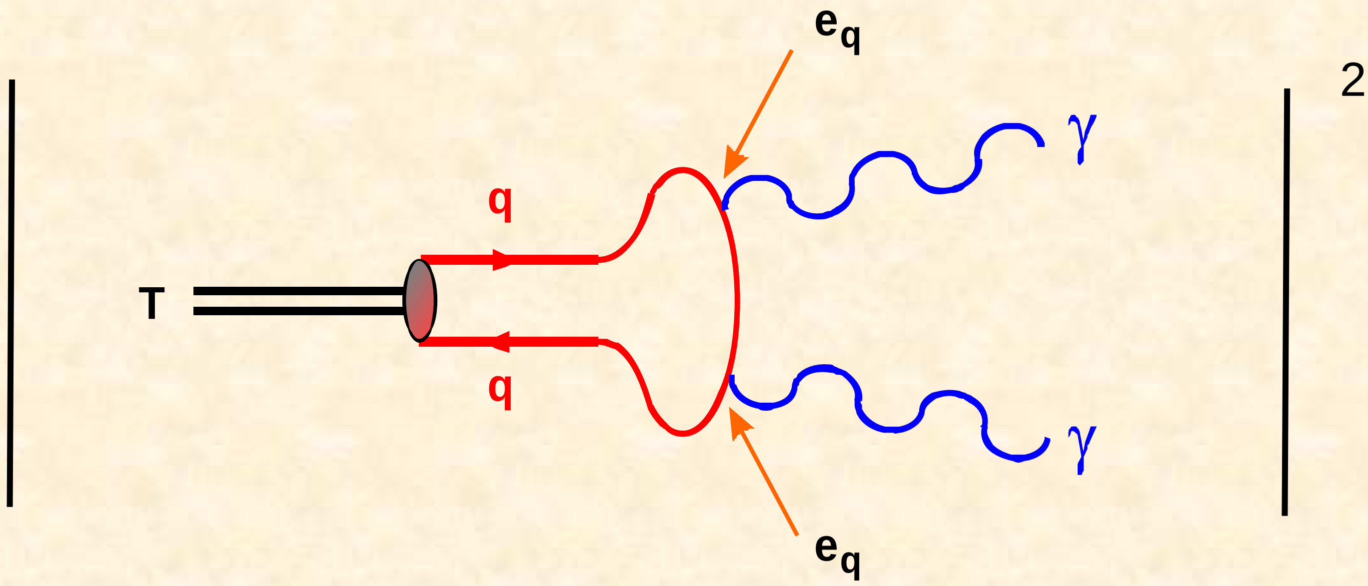


$$\frac{1}{\sqrt{2}}[u\bar{u} \pm d\bar{d}]$$

$$s\bar{s}$$

$$J^{PC} = 2^{++}$$

$\Gamma\,(\,T \longrightarrow \gamma\gamma\,)$



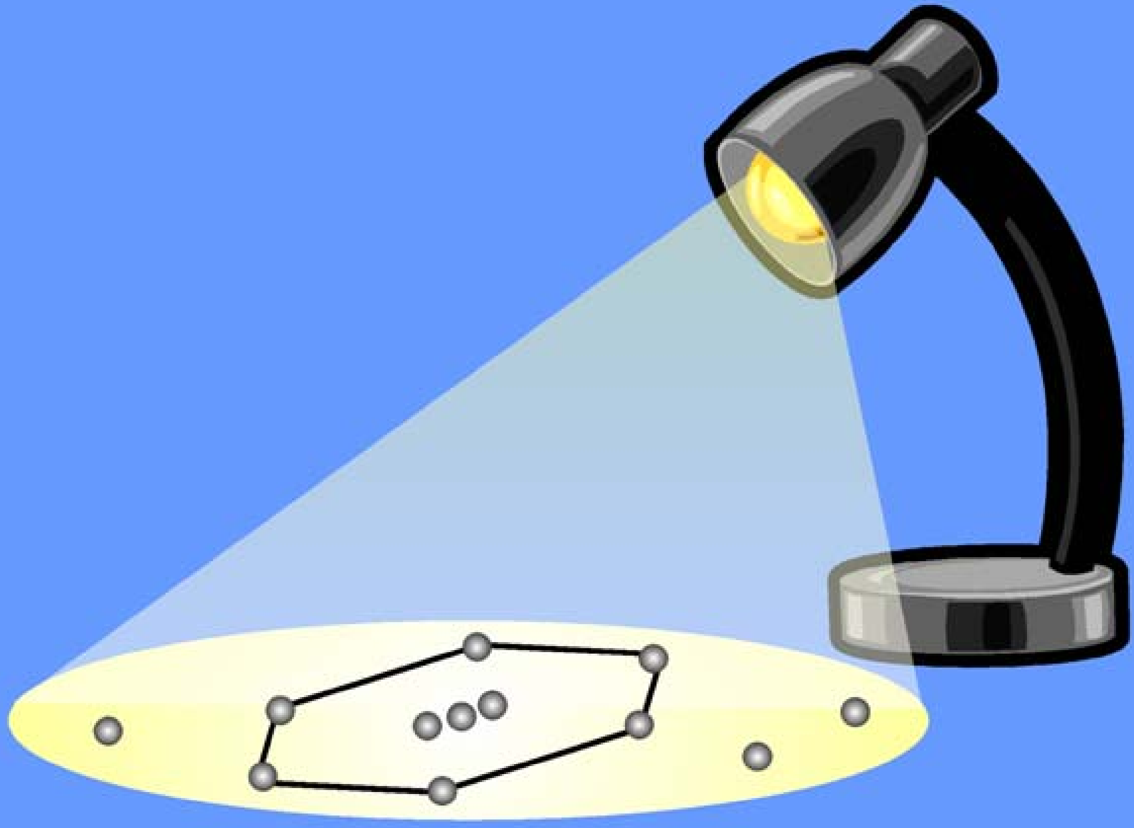
$$\Gamma\,(\,T \rightarrow \gamma\gamma\,) \;=\; \alpha^2 < e_q^{\,2} >^2 \Pi_R$$

$|\,\psi(0)\,|^2$

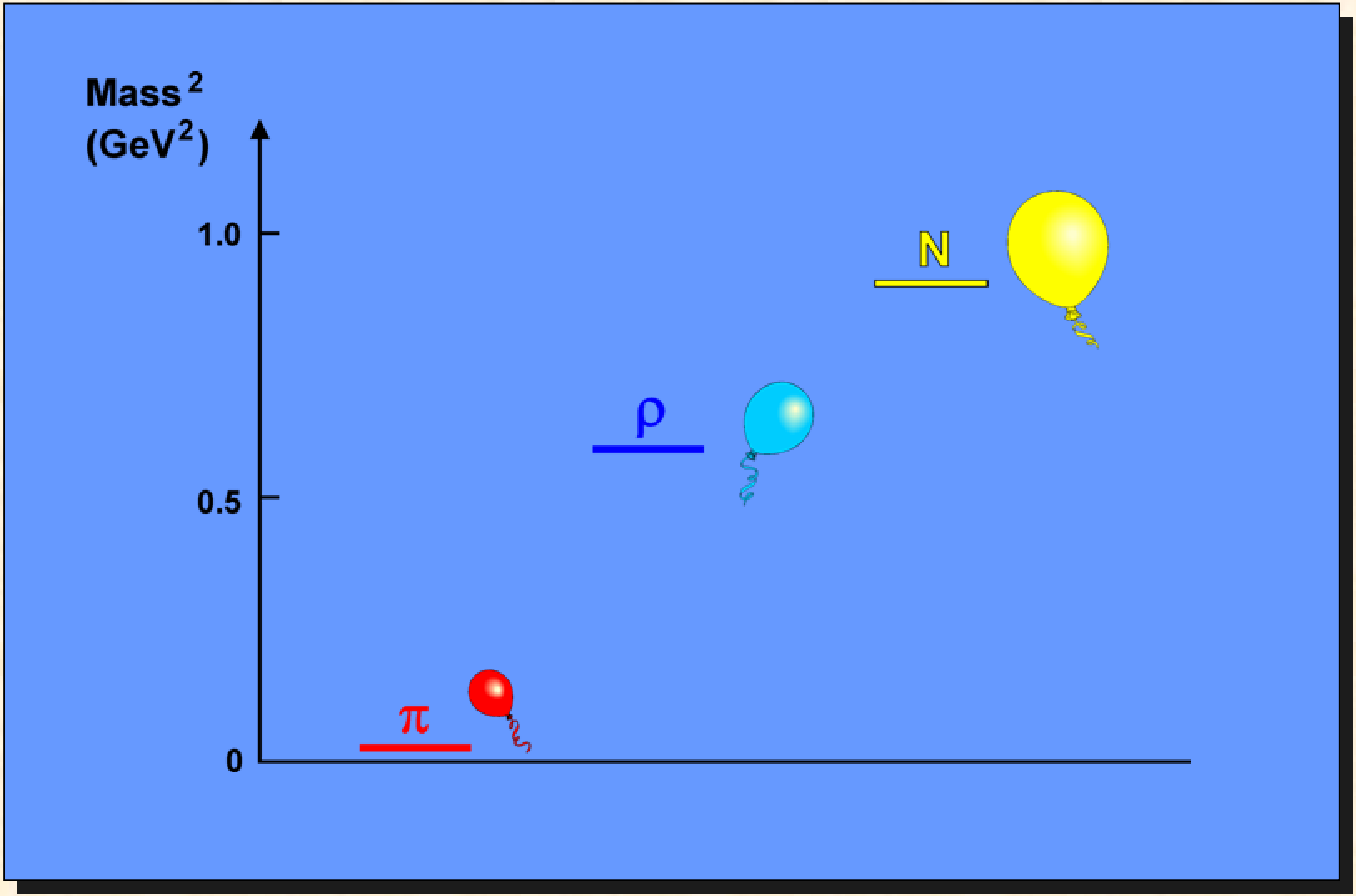
	f_2	:	a_2	:	f_2'
ideal mixing	25	:	9	:	2
experiment	25	:	10±2	:	1±0.2

J/ψ/B/D decays

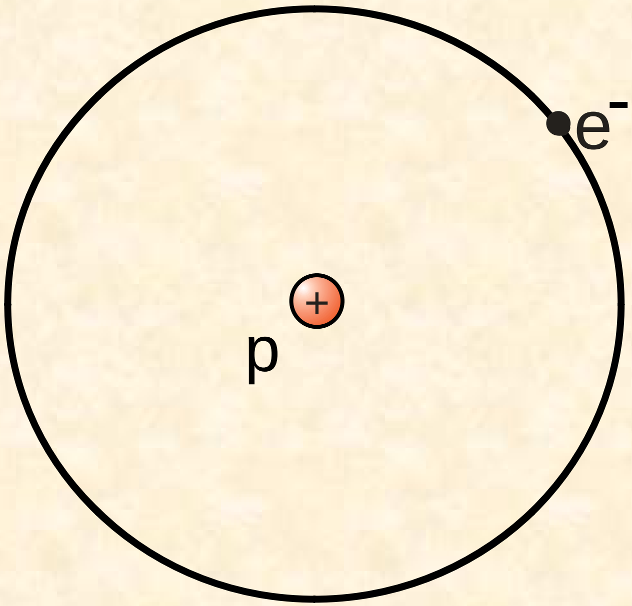
Shedding light on scalar mesons

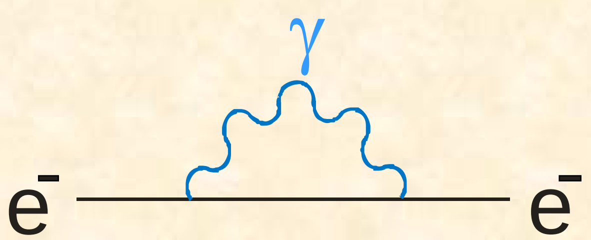


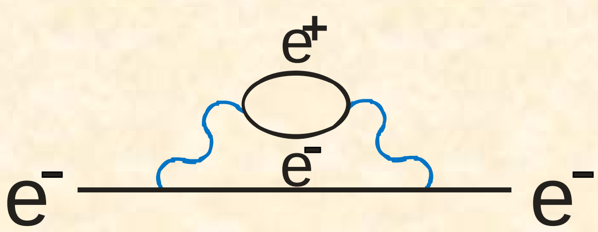
Hadron masses ^{2}

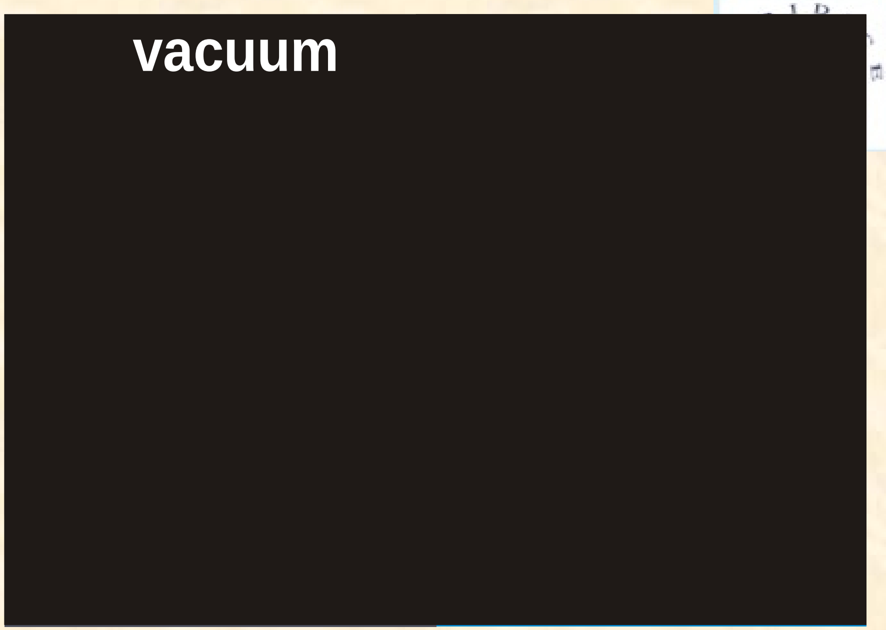


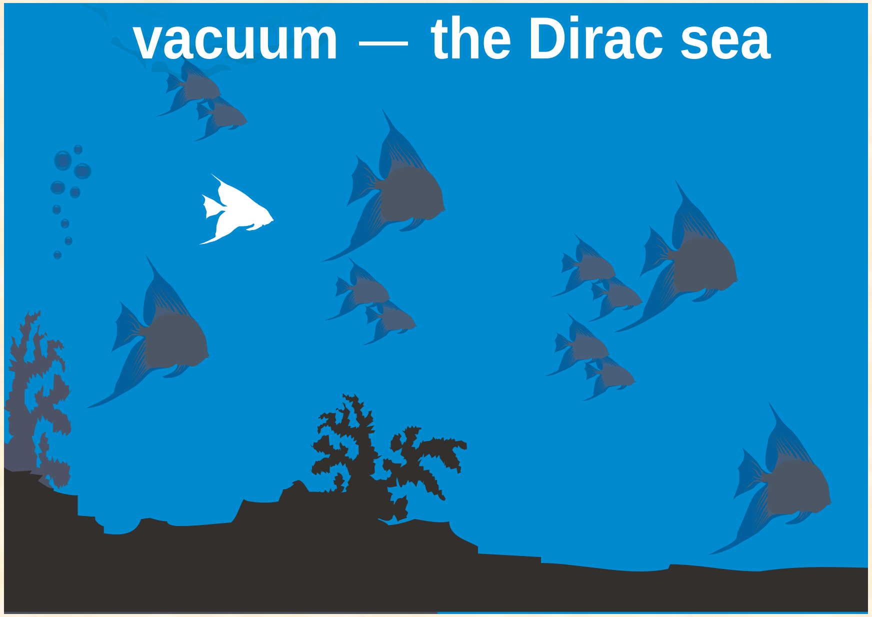
Hydrogen Atom

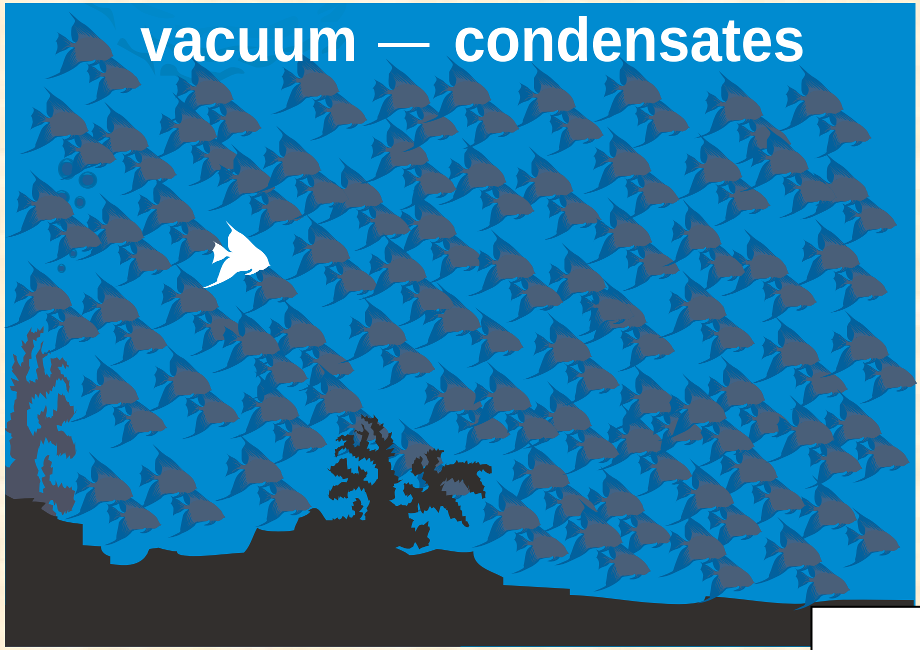


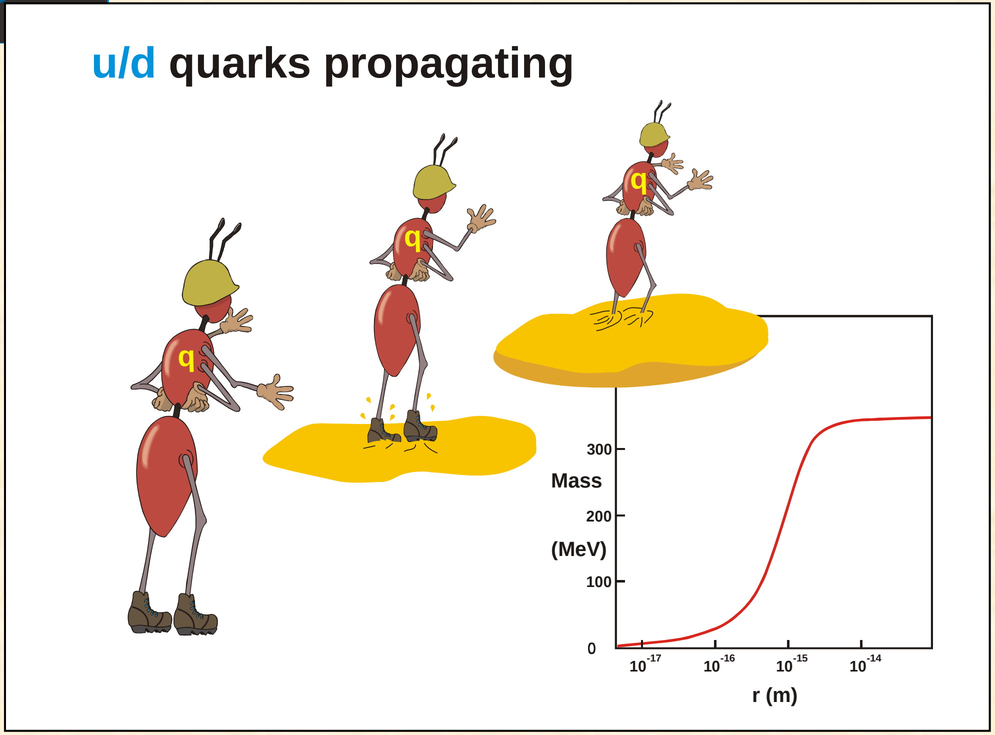


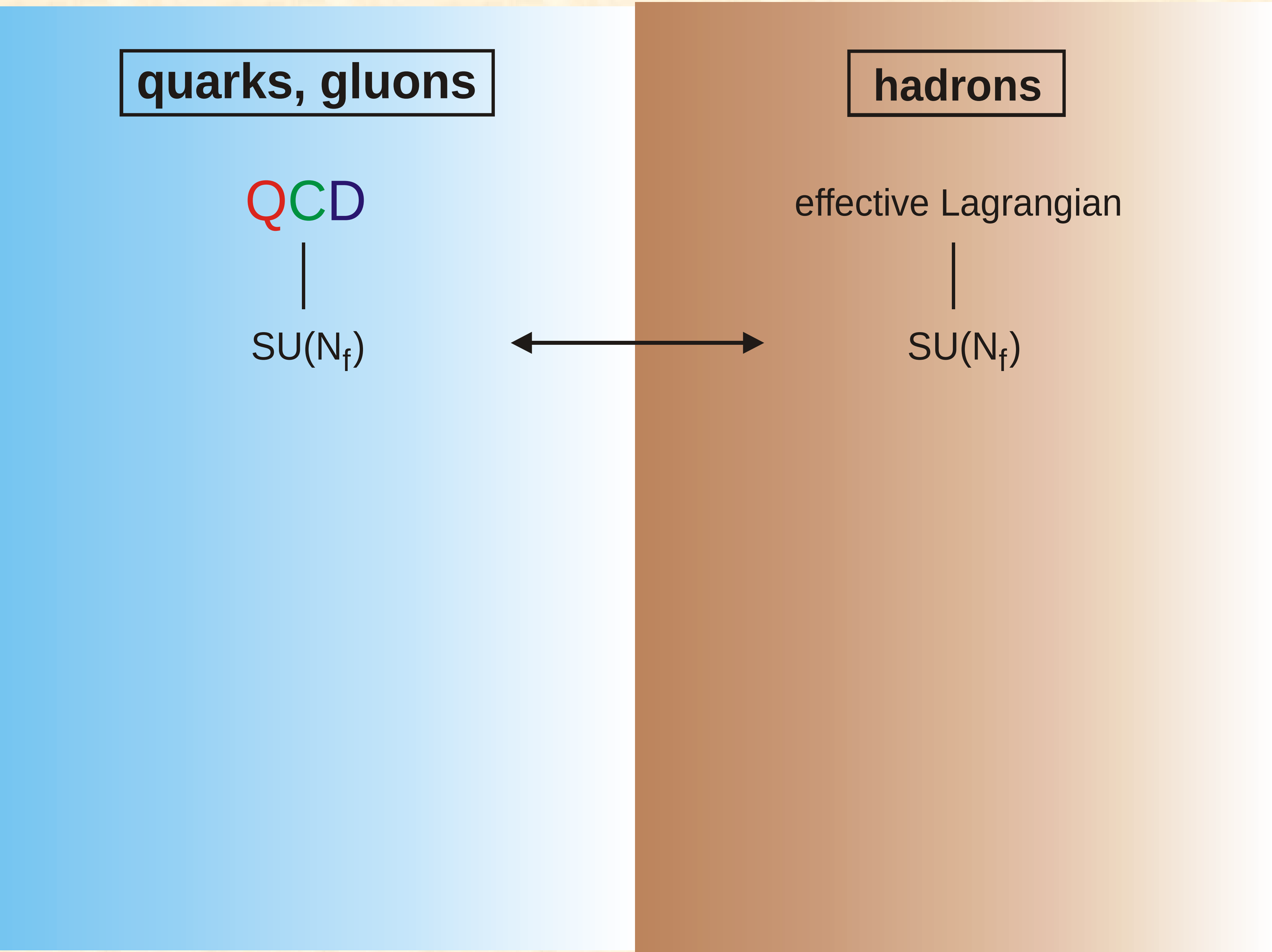


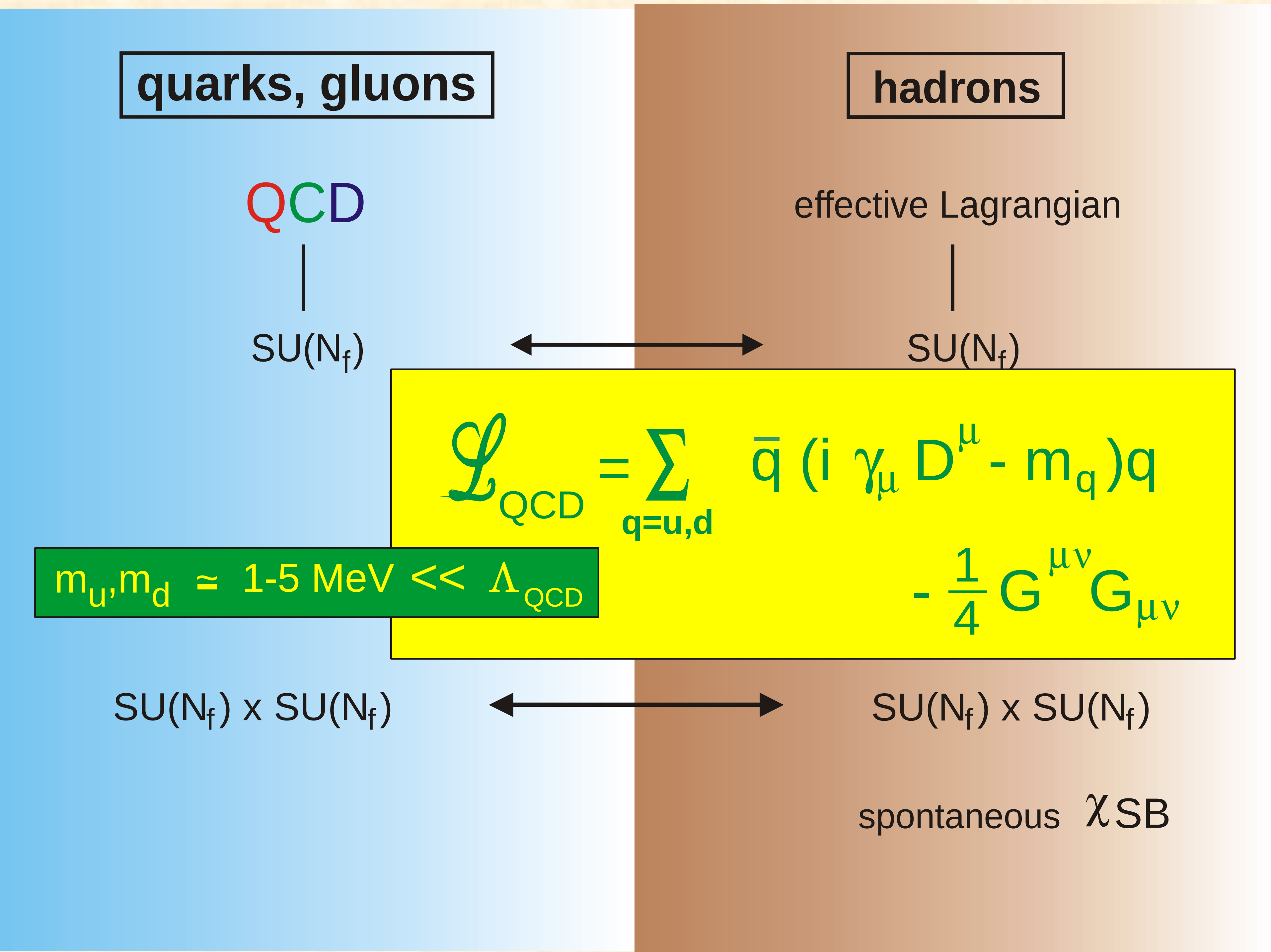





vacuum — condensates

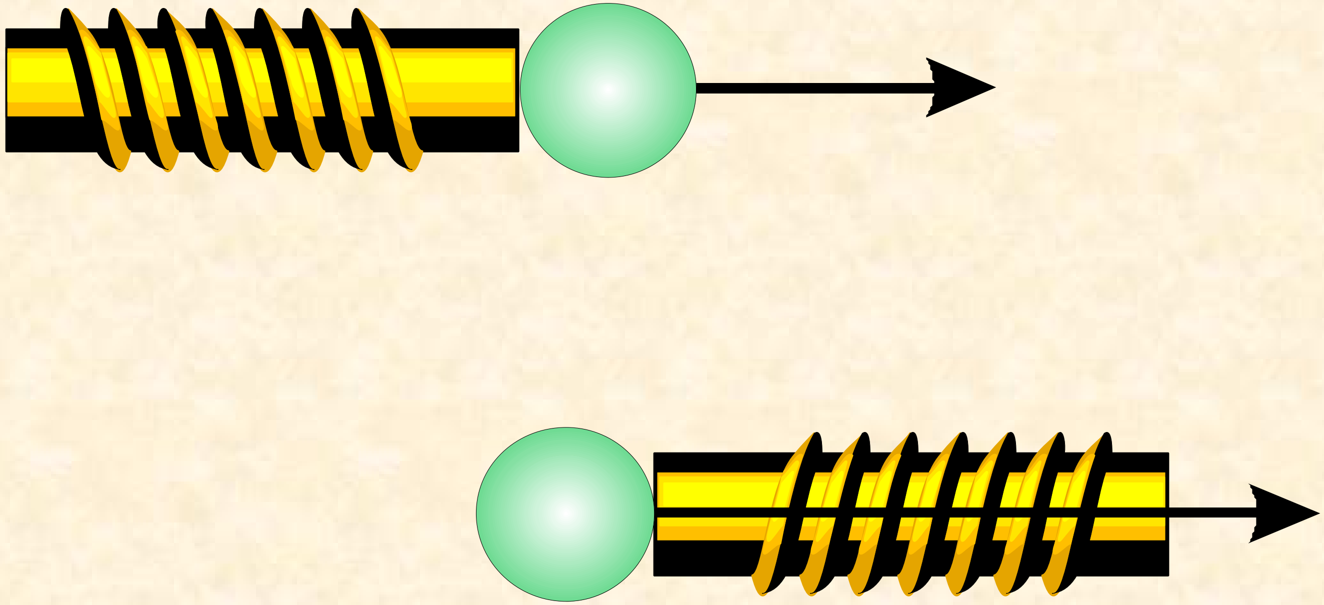

u/d quarks propagating
q
q
q
300
Mass
200
(MeV)
100
0
10-17
10-16
10-15
10-14
r (m)


quarks, gluons
hadrons
QCD
effective Lagrangian
SU(N$_f$)
SU(N$_f$)

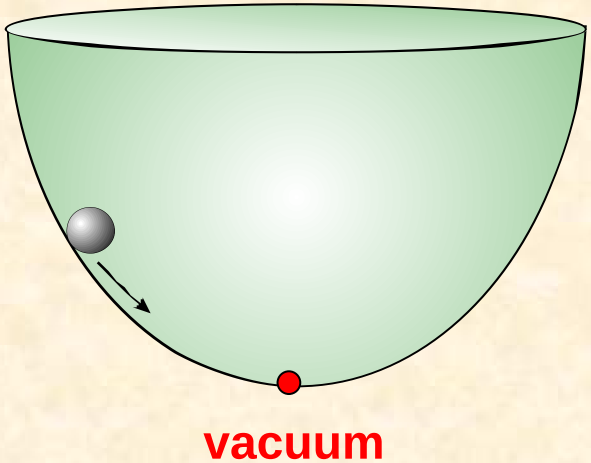


quarks, gluons
hadrons
QCD
effective Lagrangian
$SU(N_f)$
$SU(N_f)$
$\mathcal{L}_{QCD} = \sum_{q=u,d} \bar{q}\,(i\,\gamma_\mu D^\mu - m_q)q - \frac{1}{4} G^{\mu\nu} G_{\mu\nu}$
$m_u, m_d \simeq$ 1-5 MeV $\ll \Lambda_{QCD}$
$SU(N_f) \times SU(N_f)$
$SU(N_f) \times SU(N_f)$
spontaneous χSB

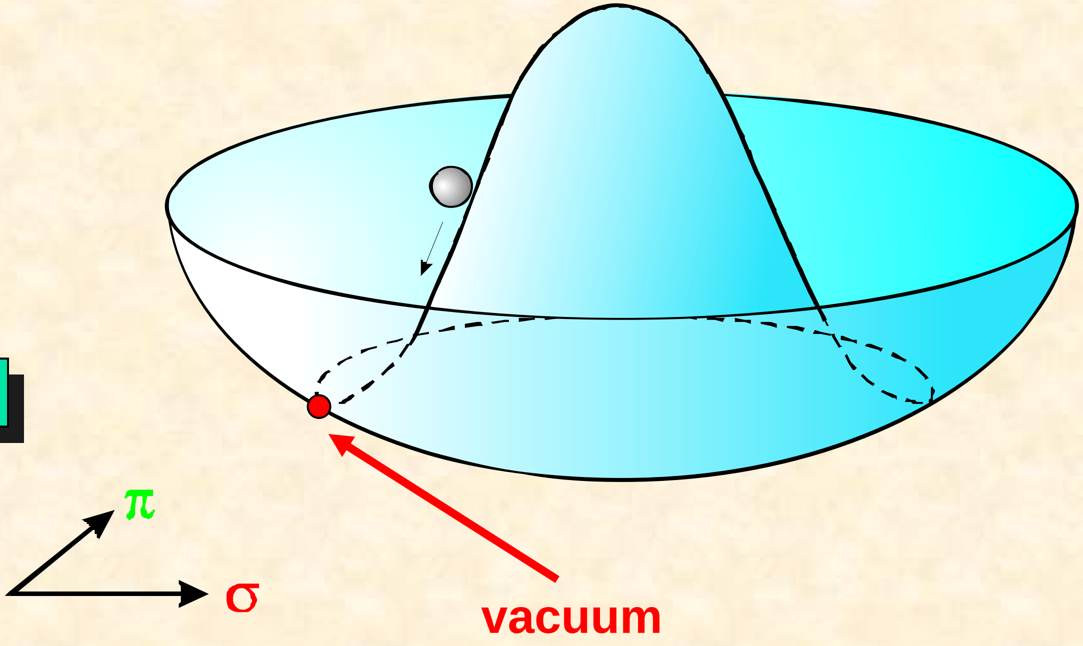
left-right symmetry

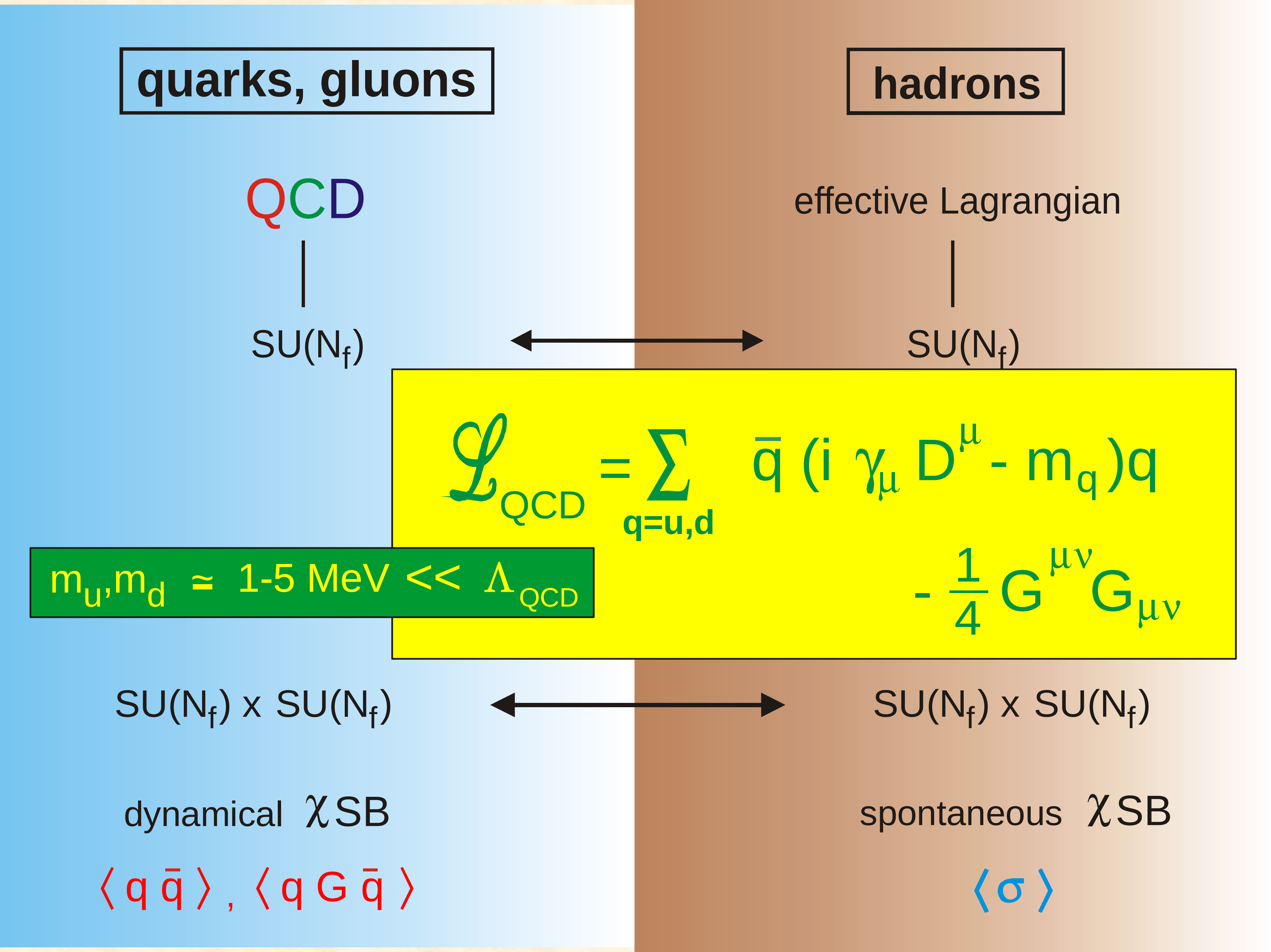


Ground State – Vacuum



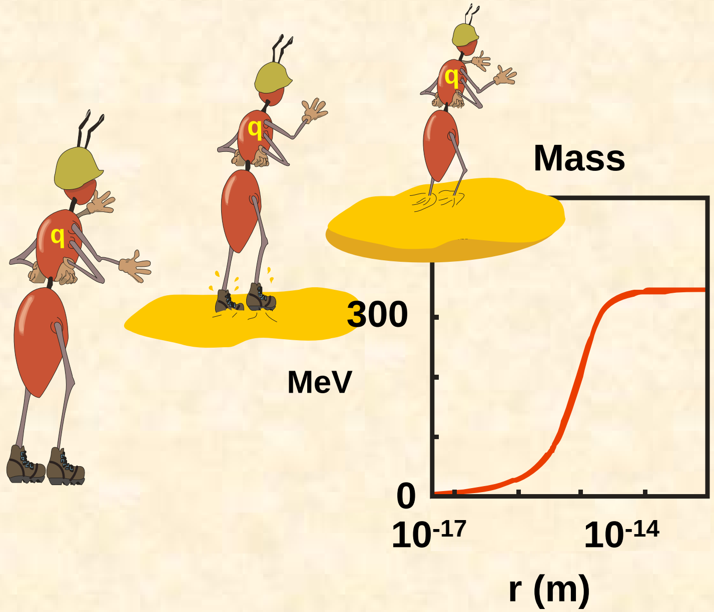
Chiral symmetry breaking

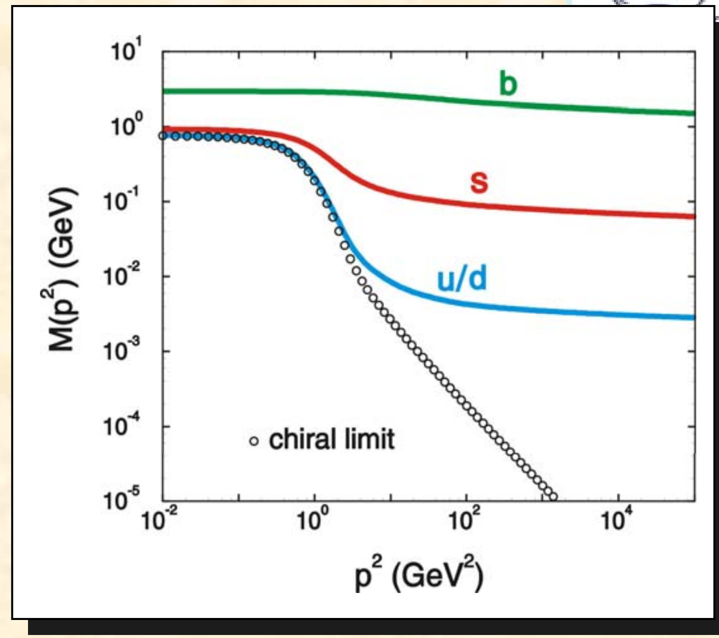




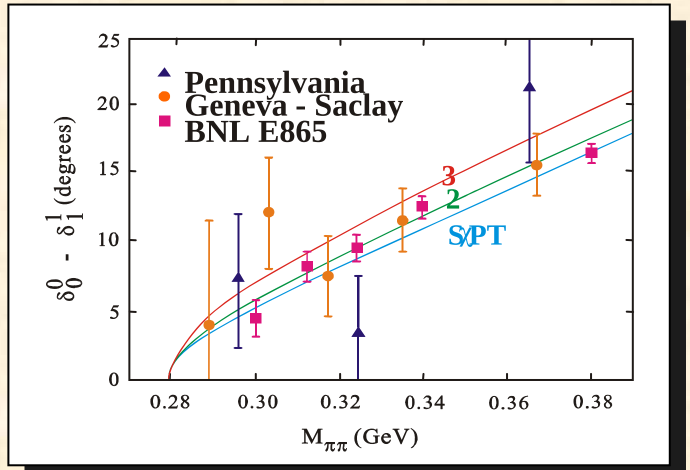
quarks, gluons
hadrons
QCD
effective Lagrangian
$SU(N_f)$
$SU(N_f)$
$\mathcal{L}_{QCD} = \sum_{q=u,d} \bar{q}\,(i\,\gamma_\mu D^\mu - m_q)q - \frac{1}{4} G^{\mu\nu} G_{\mu\nu}$
$m_u, m_d \simeq$ 1-5 MeV $<< \Lambda_{QCD}$
$SU(N_f) \times SU(N_f)$
$SU(N_f) \times SU(N_f)$
dynamical χSB
spontaneous χSB
$\langle q\,\bar{q} \rangle , \langle q\,G\,\bar{q} \rangle$
$\langle \sigma \rangle$

Mass generation



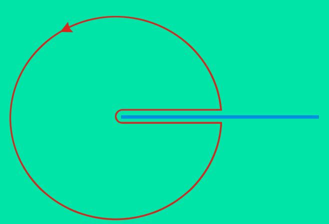


$< \bar{q}q >_0 \;\sim\; -\,(240\ \mathrm{MeV})^3$

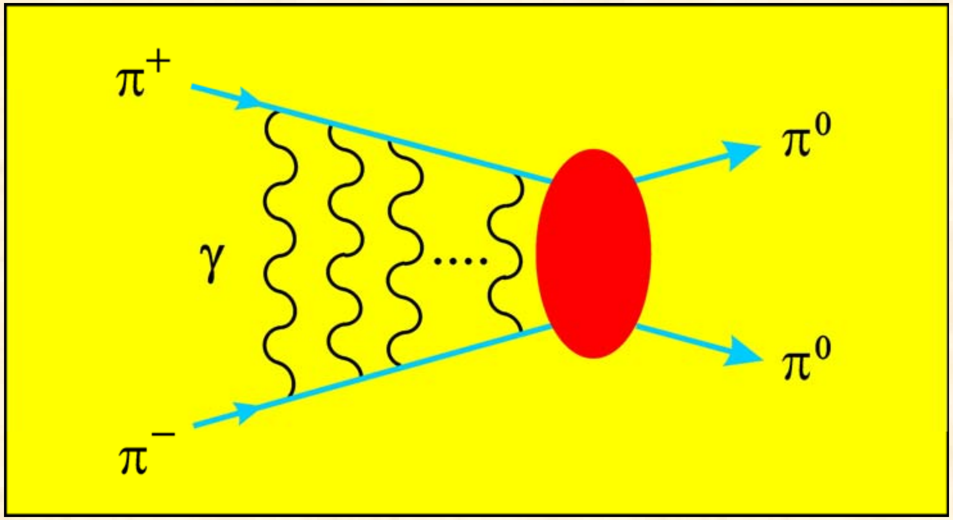


QCD sum rules

current correlator



DIRAC experiment

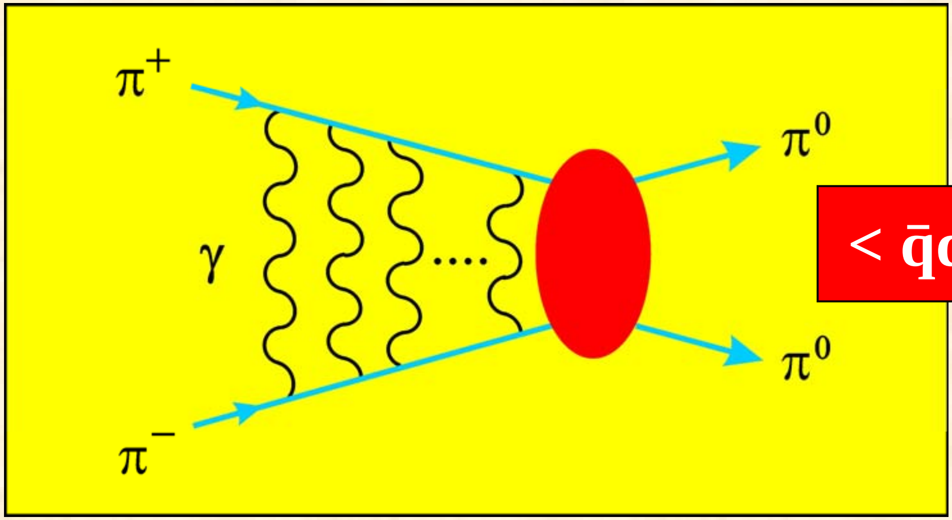


2005 results

$$\tau_{1S} = \left[\, 2.91^{+0.49}_{-0.62} \,\right] 10^{-15}\ \text{s}$$

$$\rightarrow \quad a_0 - a_2 = 0.264^{+0.033}_{-0.020}$$

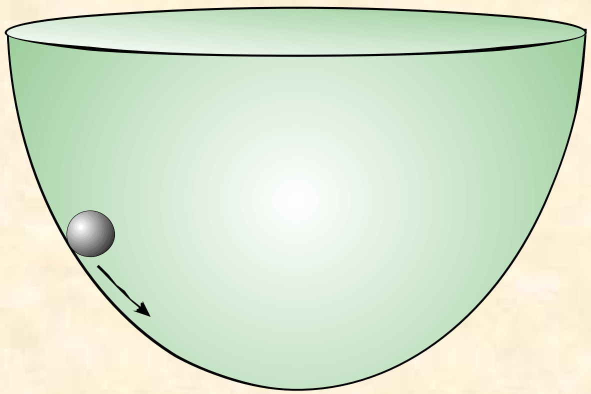
DIRAC experiment



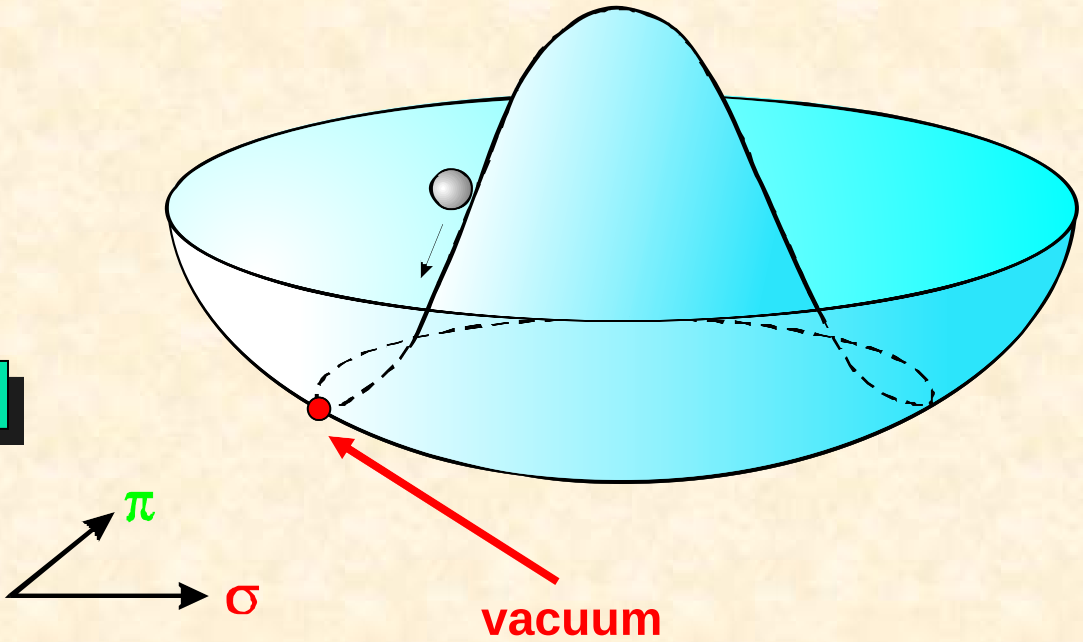
$< \bar{q}q >_0 \sim -(240\ \text{MeV})^3$

GMOR $m_\pi^2\ F_\pi^2 = -\ (m_u + m_d)\ \langle q\bar{q} \rangle\ +$ 90%

Ground State – Vacuum

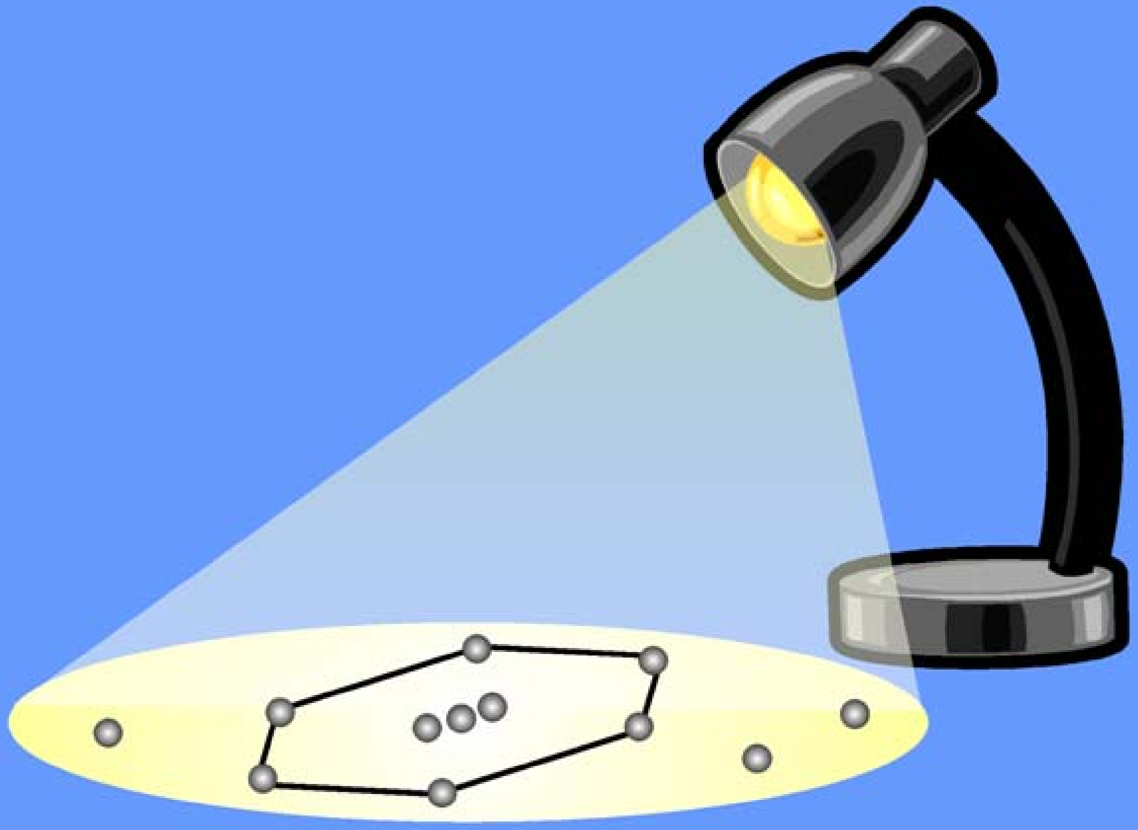


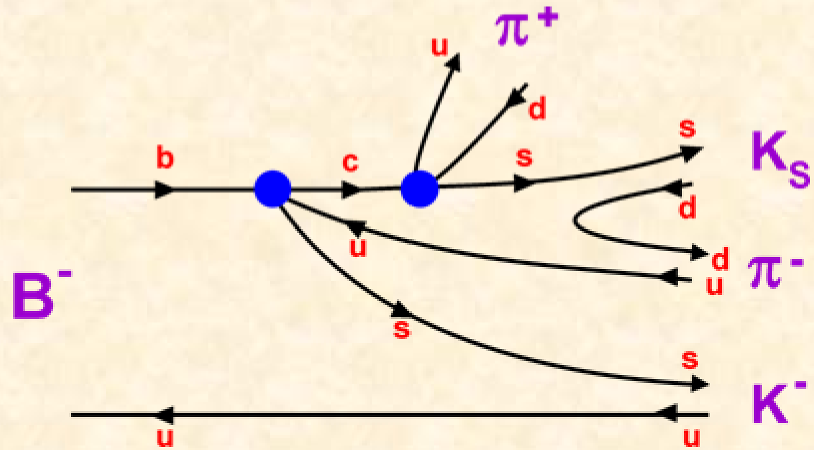
Chiral symmetry breaking



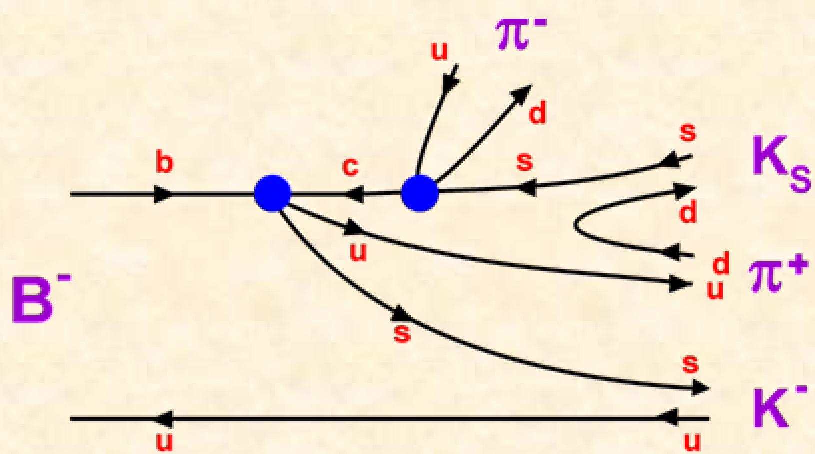
J/ψ/B/D decays

Shedding light on scalar mesons



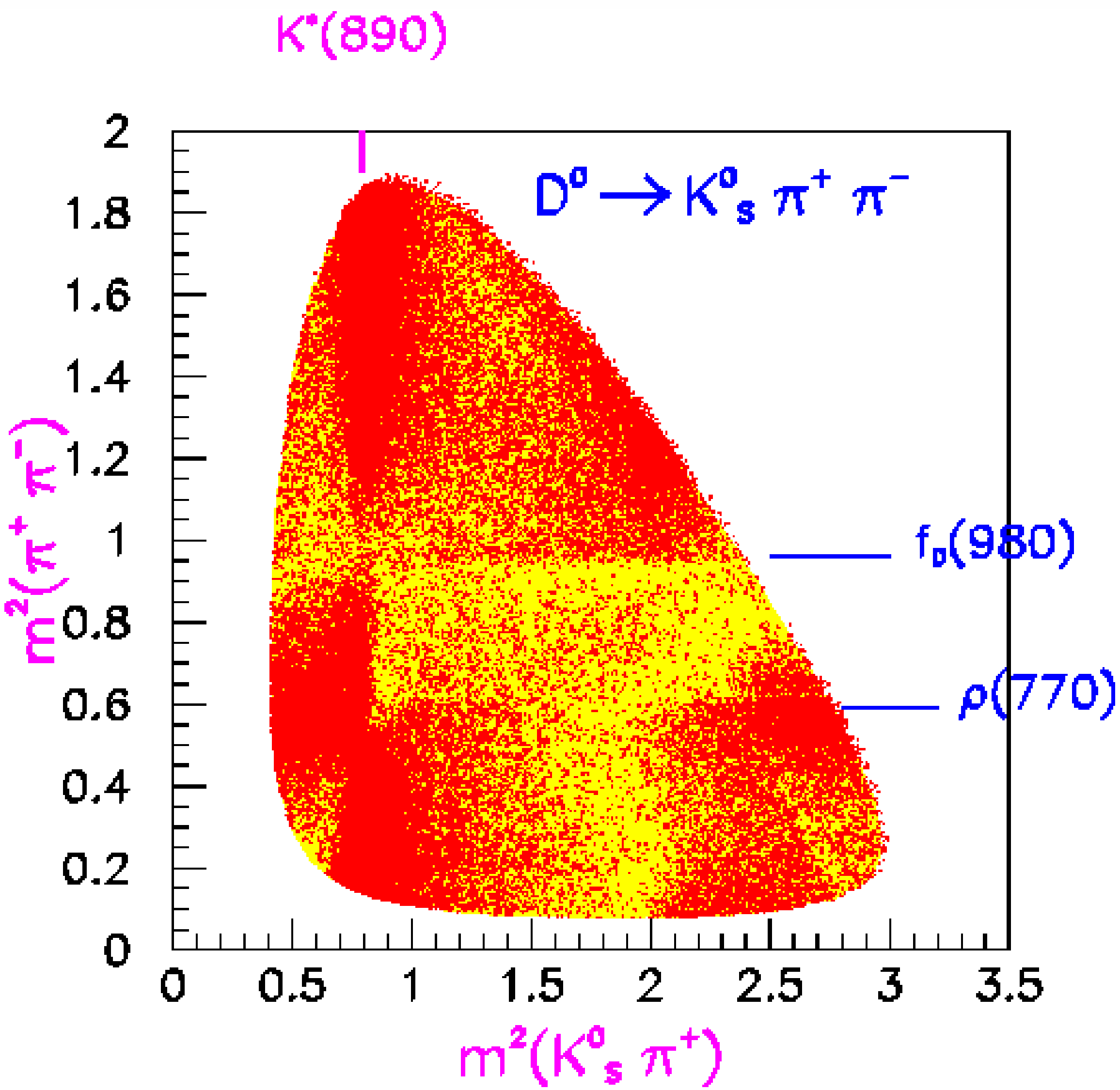


π+
u
d
s
KS
b
c
s
d
u
d
π-
u
B-
s
s
K-
u
u



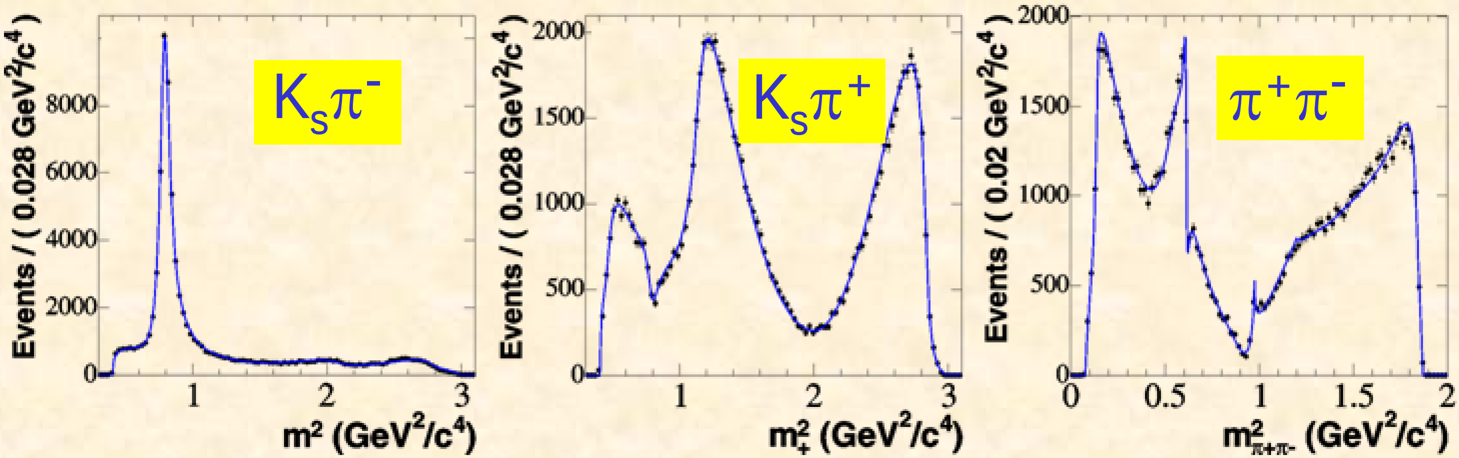
π-
u
d
s
KS
b
c
s
d
u
d
π+
u
B-
s
s
K-
u
u

Dalitz plot of $D^0 \to \bar{K}^0\pi^+\pi^-$.

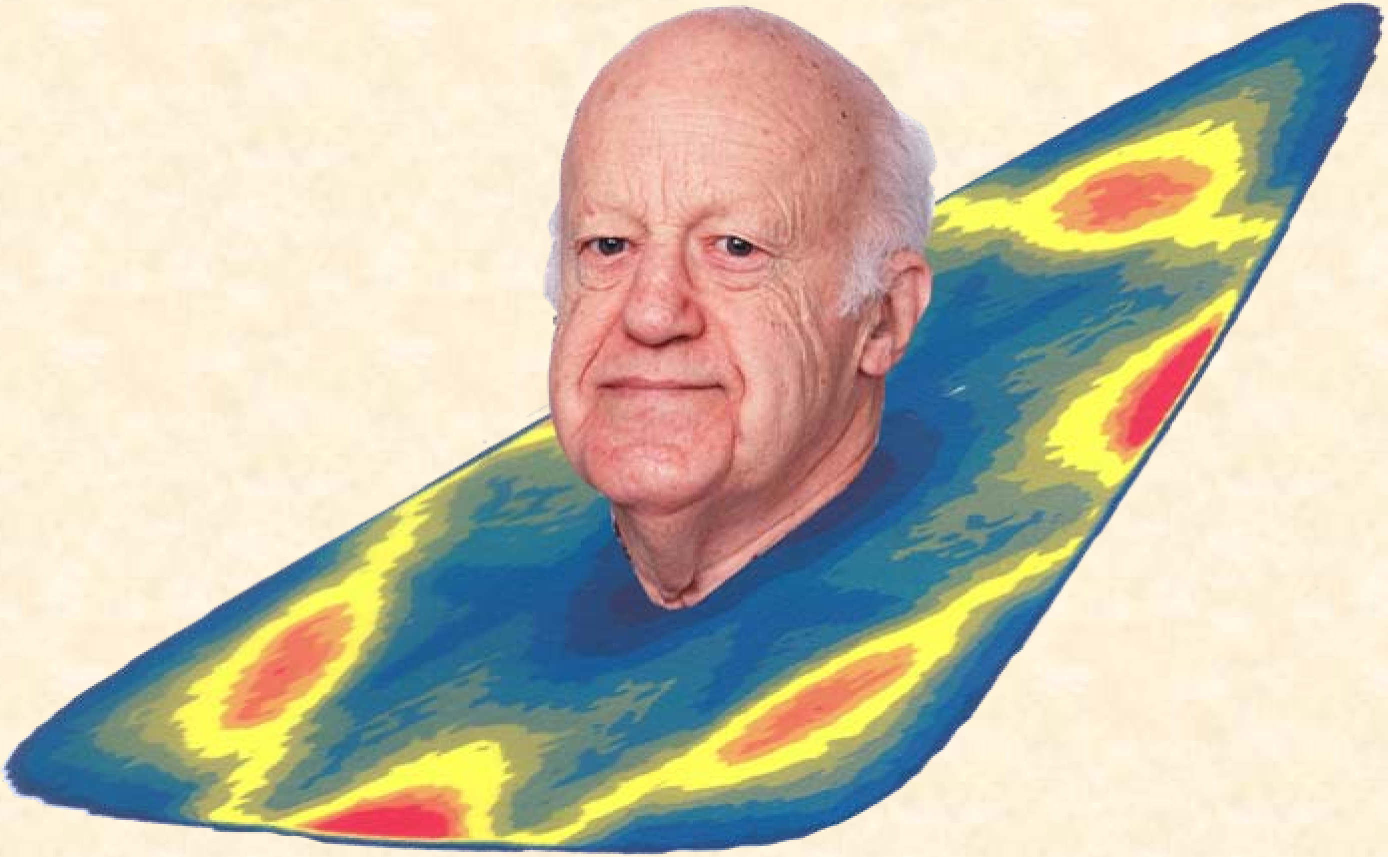


Dalitz plot of $D^0 \to \bar{K}^0\pi^+\pi^-$.

3 mass projections

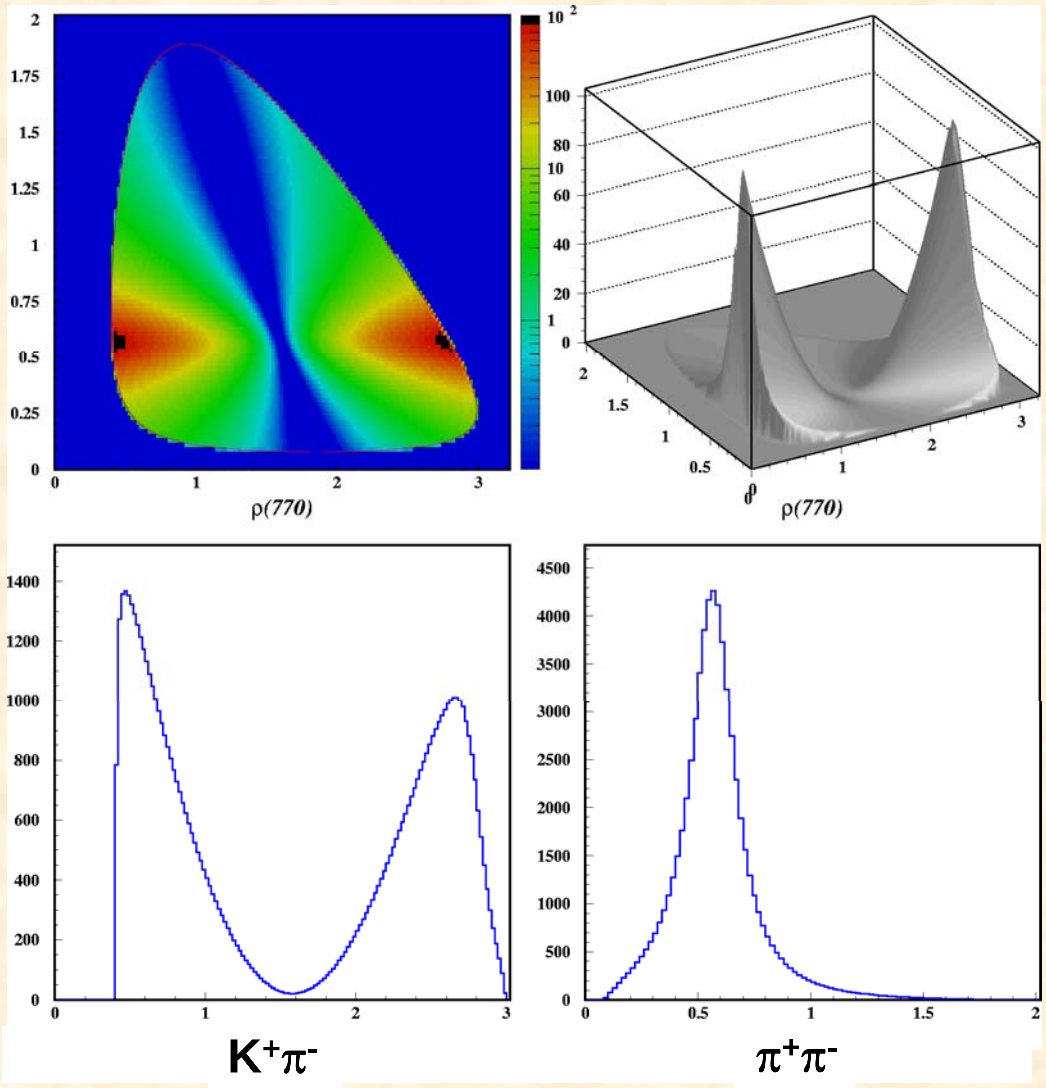


Dalitz Analysis



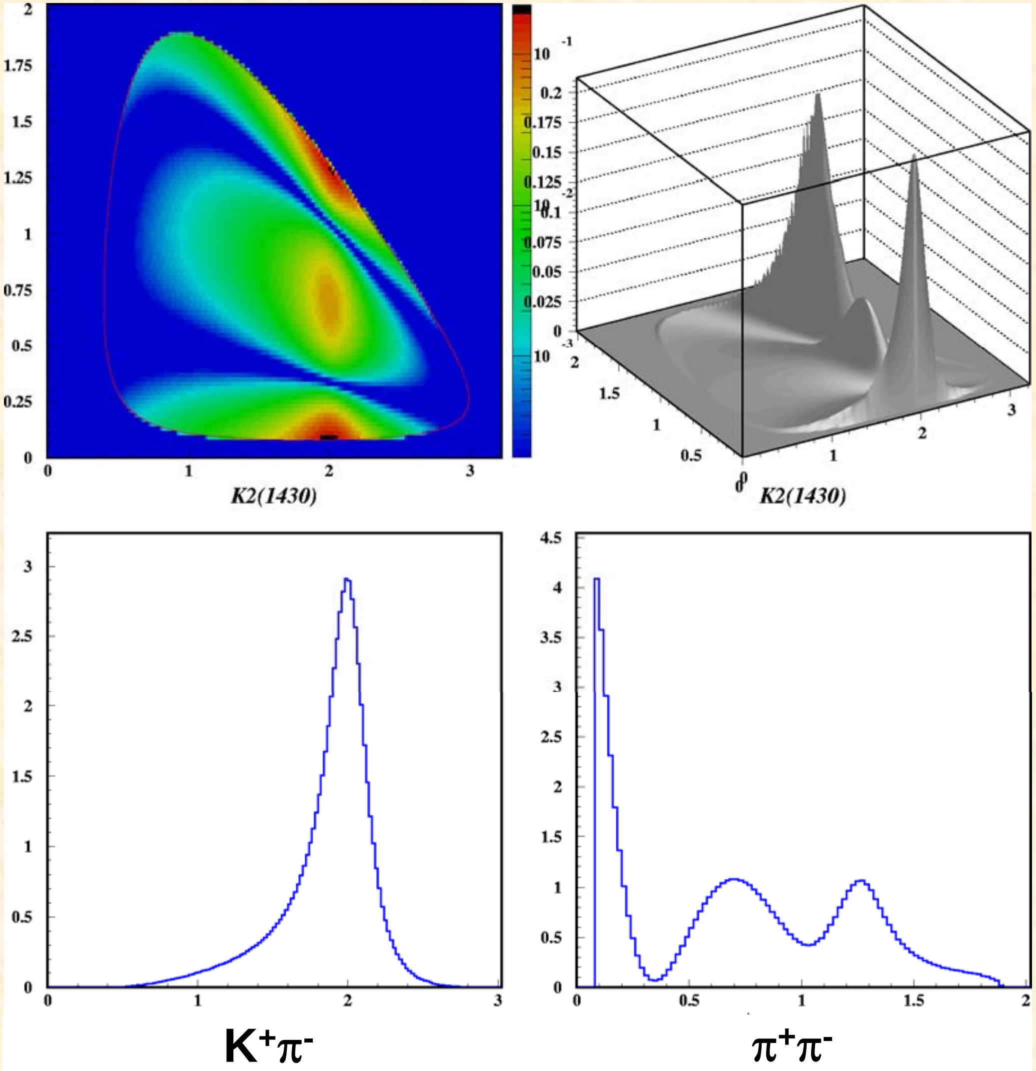
$D^+ \longrightarrow K^+\pi^+\pi^-$

$\rho(770)$

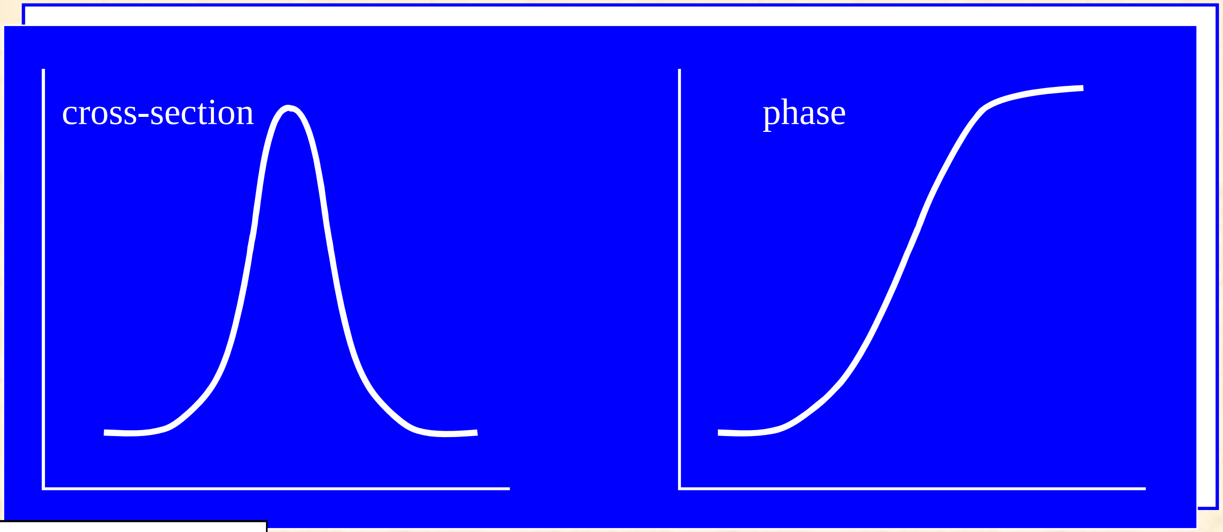


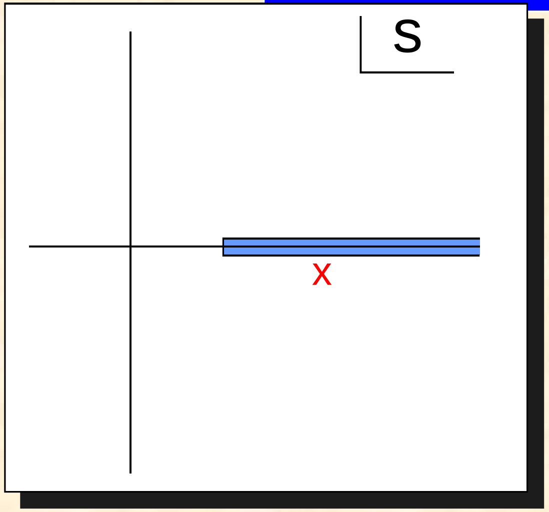
$D^+ \longrightarrow K^+\pi^+\pi^-$

$K_2^*(1430)$



Hadron states

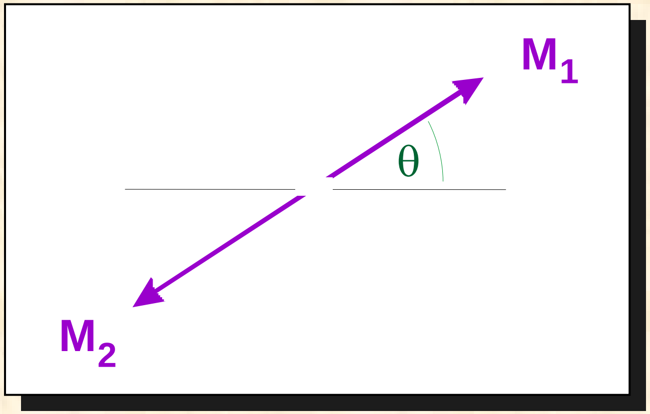


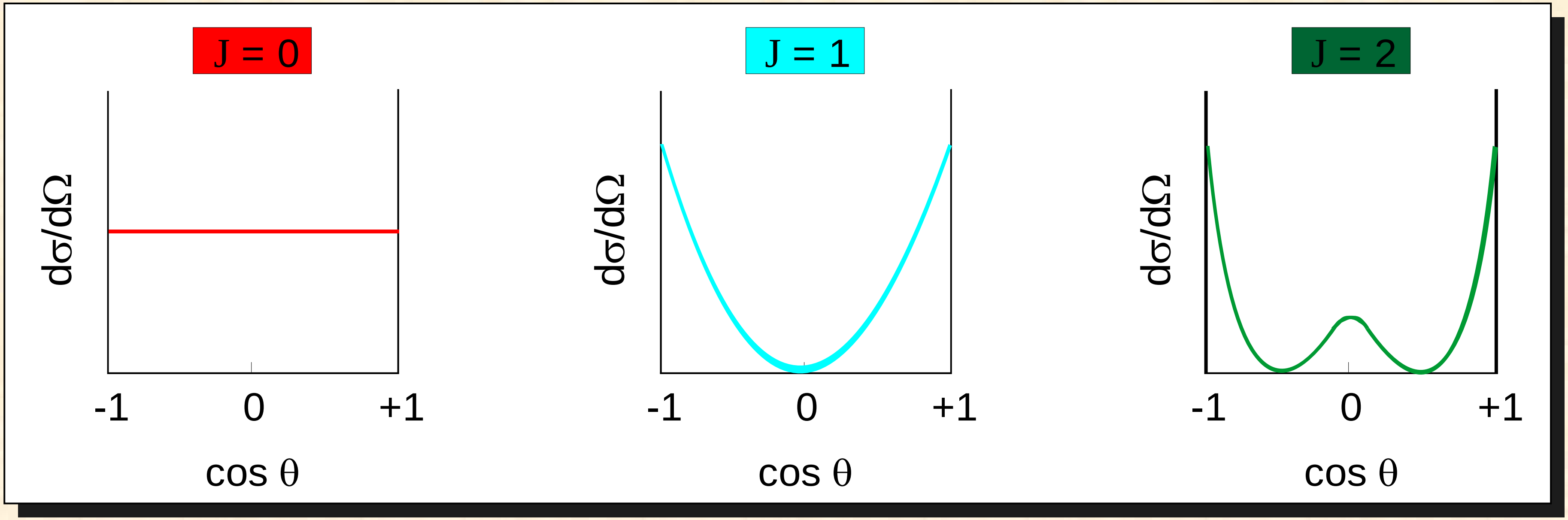


BW

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

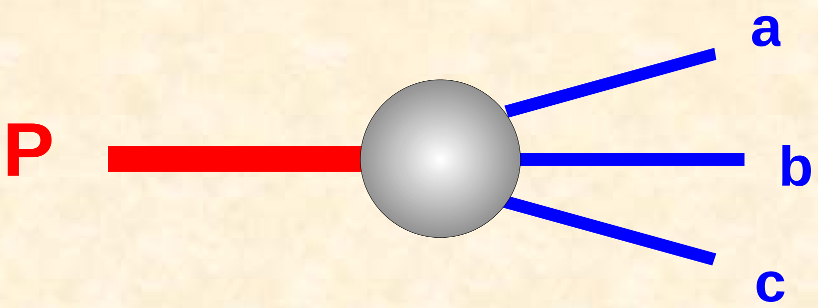
SPIN ANALYSIS



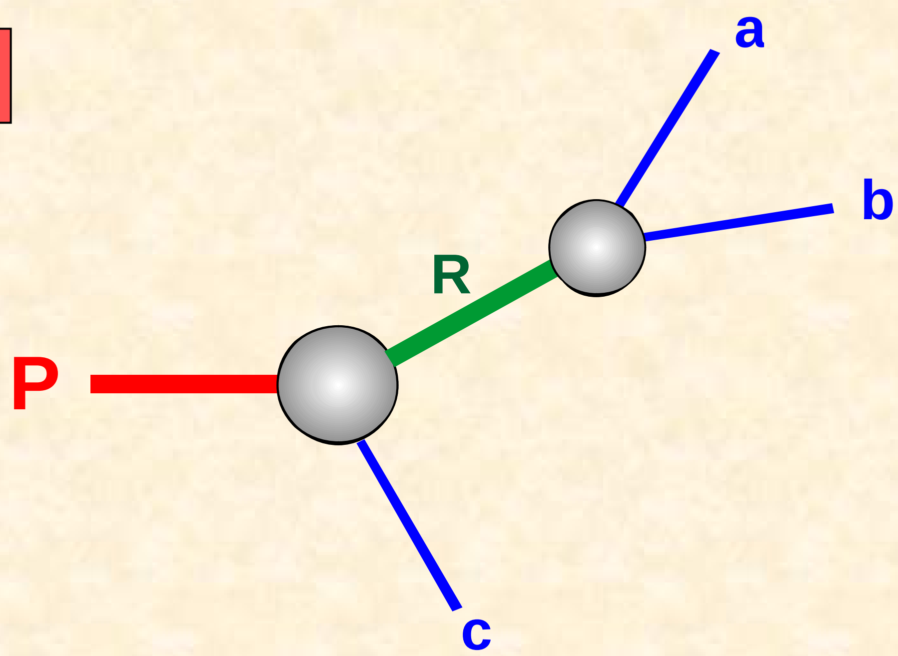


Spectroscopy: interplay of poles & zeros

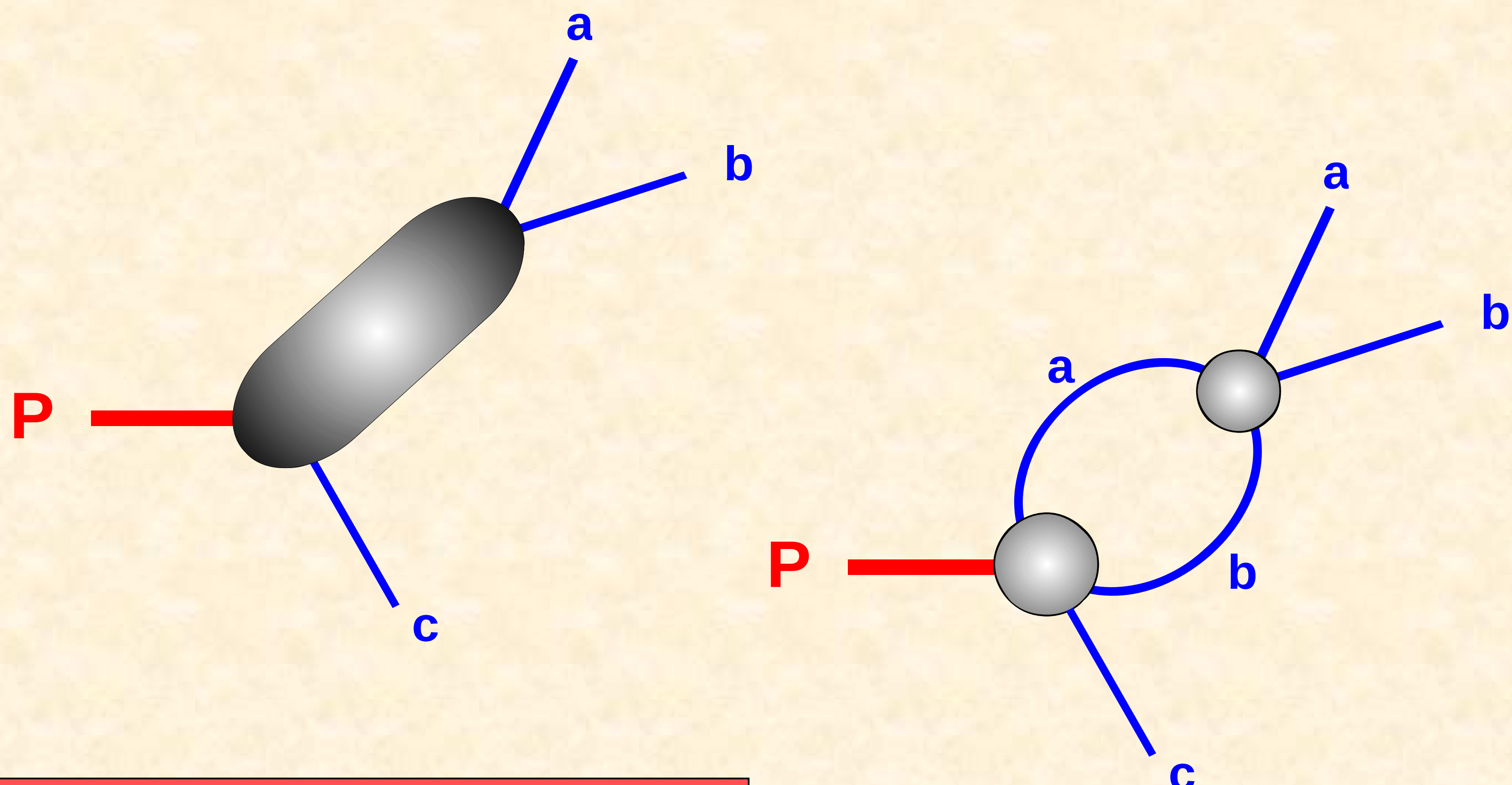
$P \longrightarrow a\ b\ c$



isobar picture

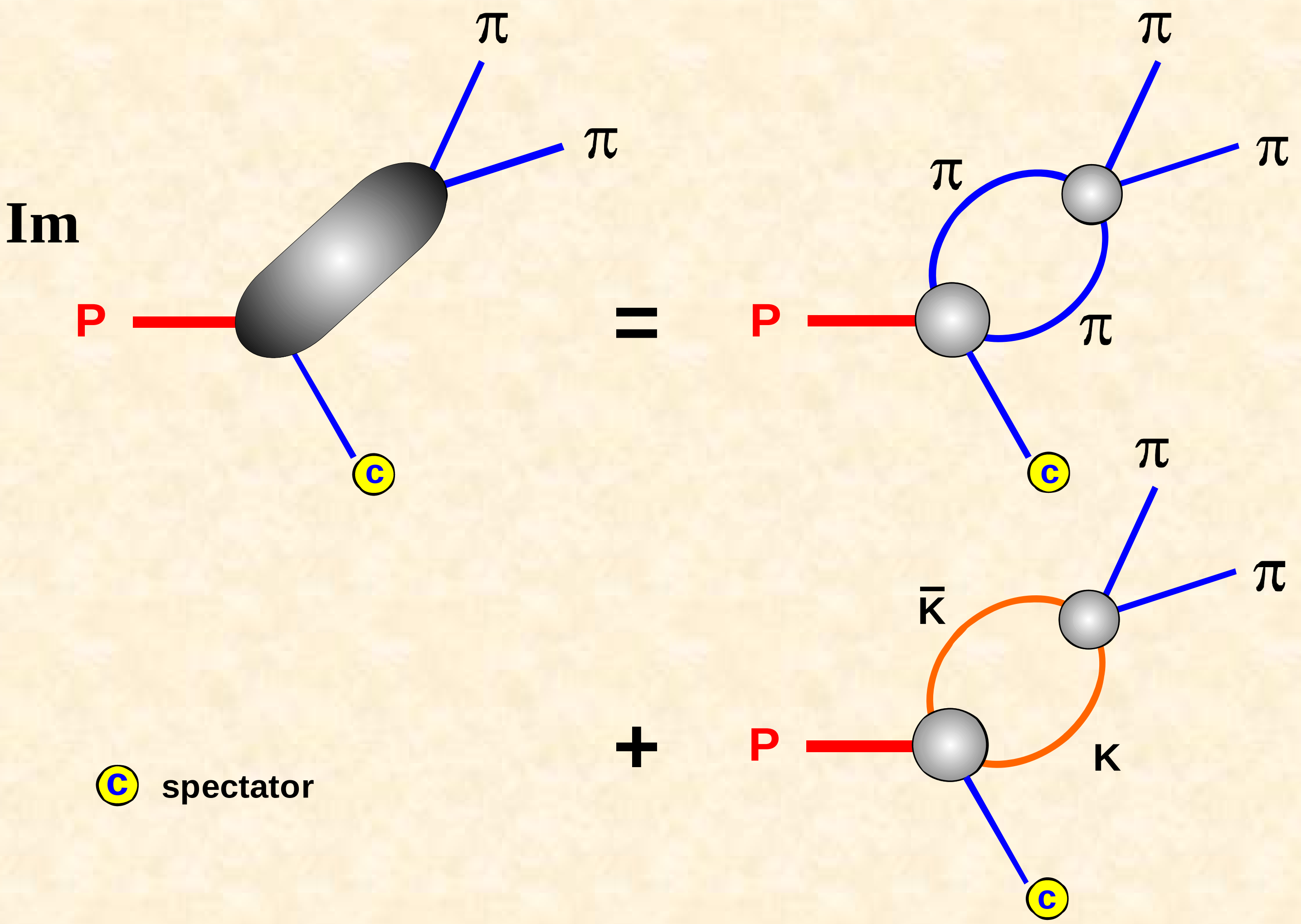


P $\longrightarrow$ a b c



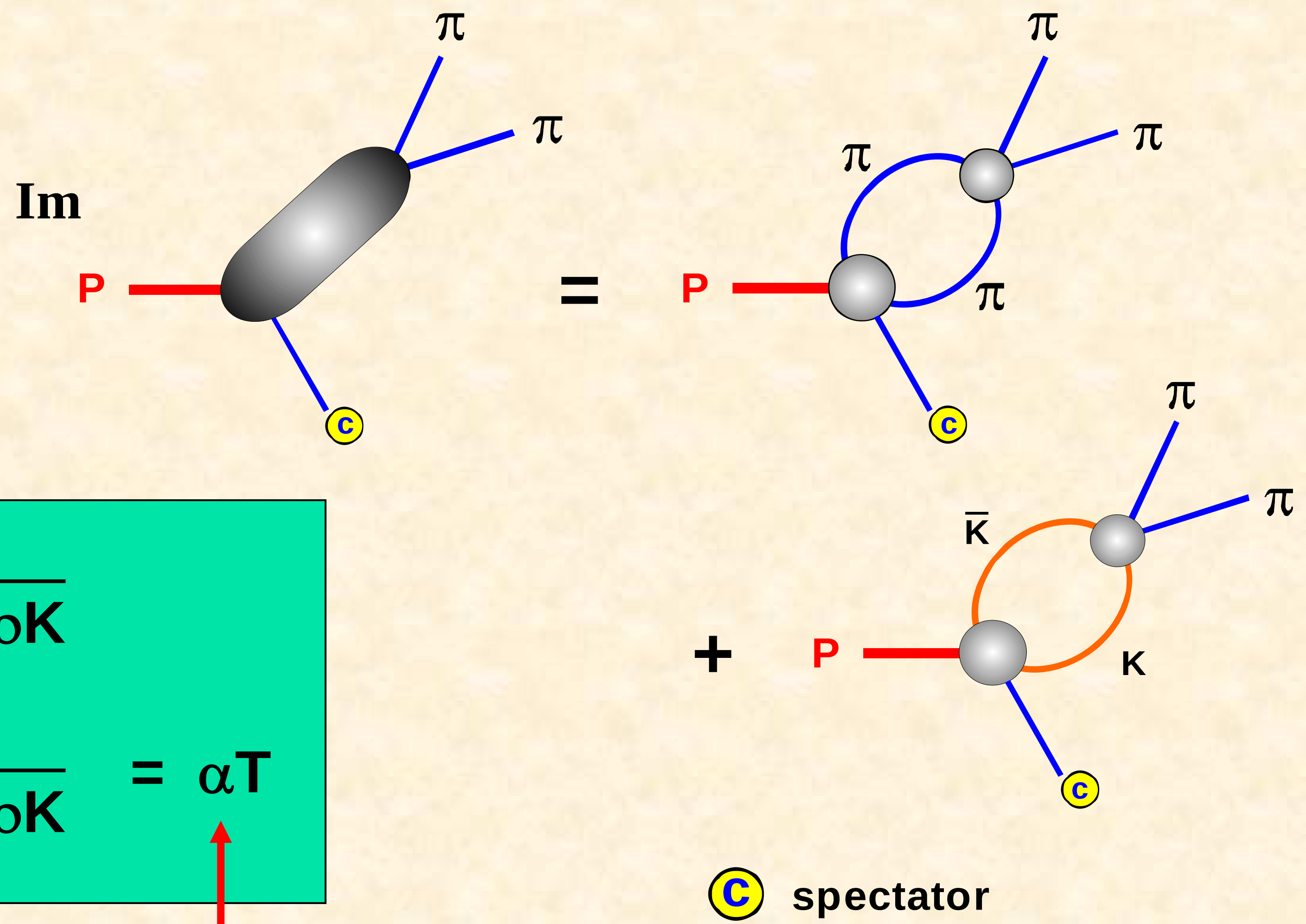
unitarity connects to hadronic scattering

Unitarity for P $\longrightarrow$ $\pi\pi$ (c)



c spectator

UNITARITY : decays in spectator picture



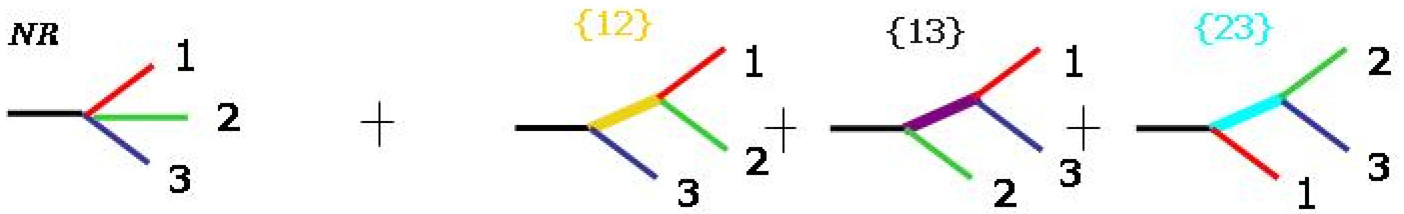
$$T = \frac{K}{1 - i\rho K}$$

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

coupling function

"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

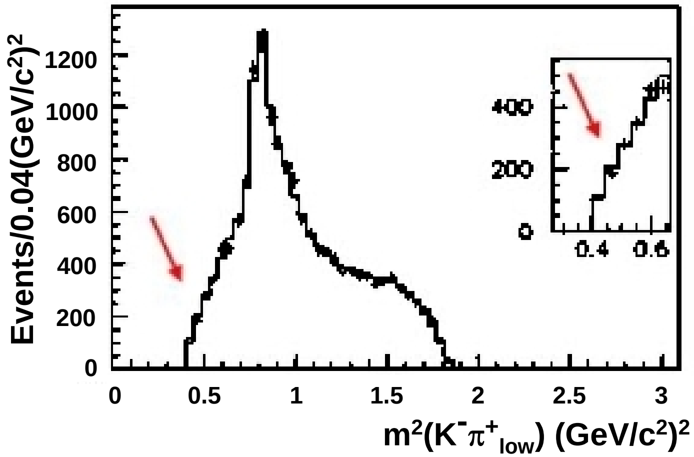
- Each resonance "**R**" (mass M_R, width Γ_R) assumed to have form

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

p, q are momenta in ij rest frame
r_D, r_R meson radii

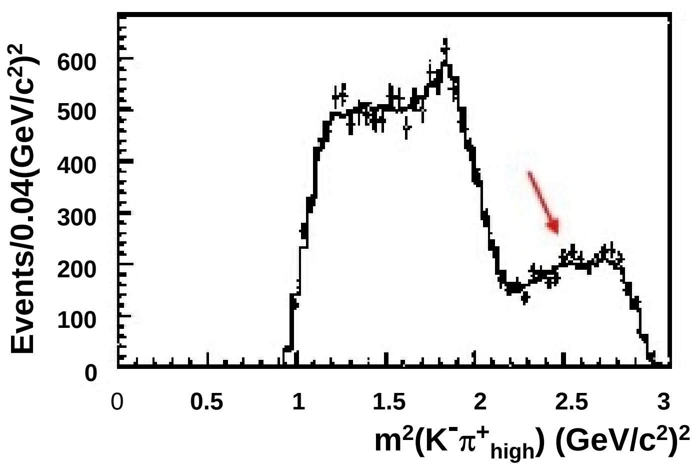
Brian Meadows

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



$\boxed{D^+}$ →

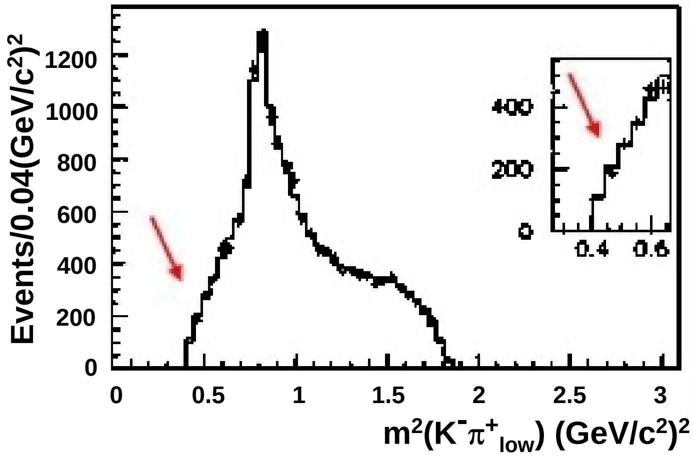
non resonant	90.0 ± 2.6%	0° (fixed)
$K^*(890)\pi^+$	13.8 ± 0.5%	54 ± 2°
$K_0^*(1430)\pi^+$	30.6 ± 1.6%	109 ± 2°
$K_2^*(1430)\pi^+$	0.4 ± 0.1%	33 ± 8°
$K_1^*(1680)\pi^+$	3.2 ± 0.3%	66 ± 3°
	~138 %	



χ^2/d.o.f. = 2.7

Brian Meadows

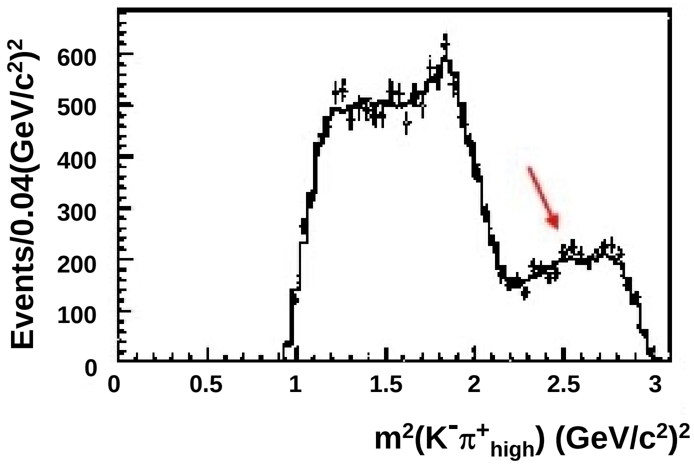
E791 $D^+ \to K^-\pi^+\pi^+$



$D^+ \to$

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

~89 %



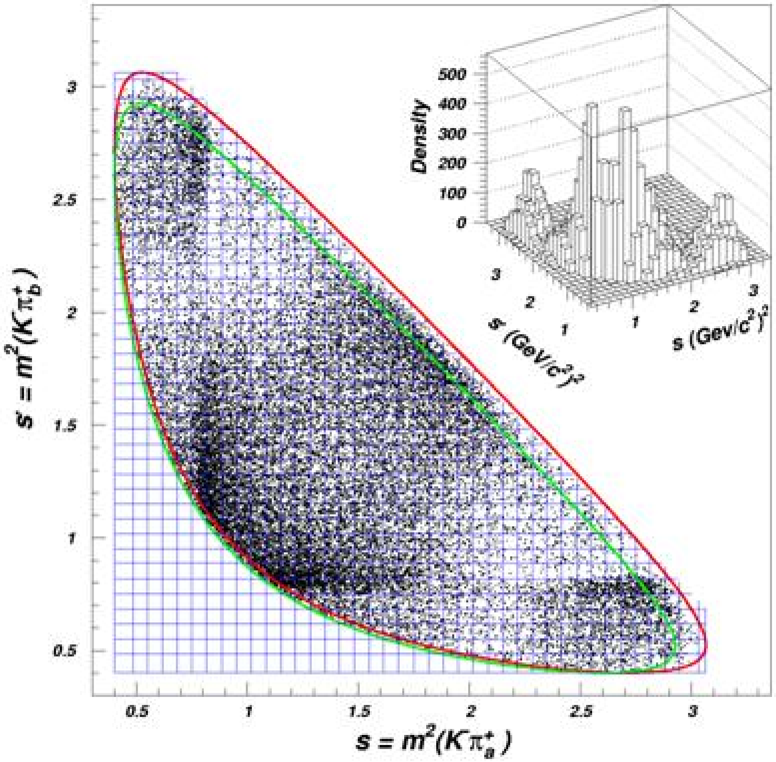
χ^2/d.o.f. = 0.73
(95 %)

Probability

M_κ = $797 \pm 19 \pm 42$ MeV/c^2
Γ_κ = $410 \pm 43 \pm 85$ MeV/c^2

Brian Meadows

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



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

  $\rightarrow$ Interference with large s–wave component

- Also:
  - Structure at $\sim$ 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.

Brian Meadows

s–wave from $D^+ \rightarrow K^-\pi^+\pi^+$ 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

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

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

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

- Model P and D

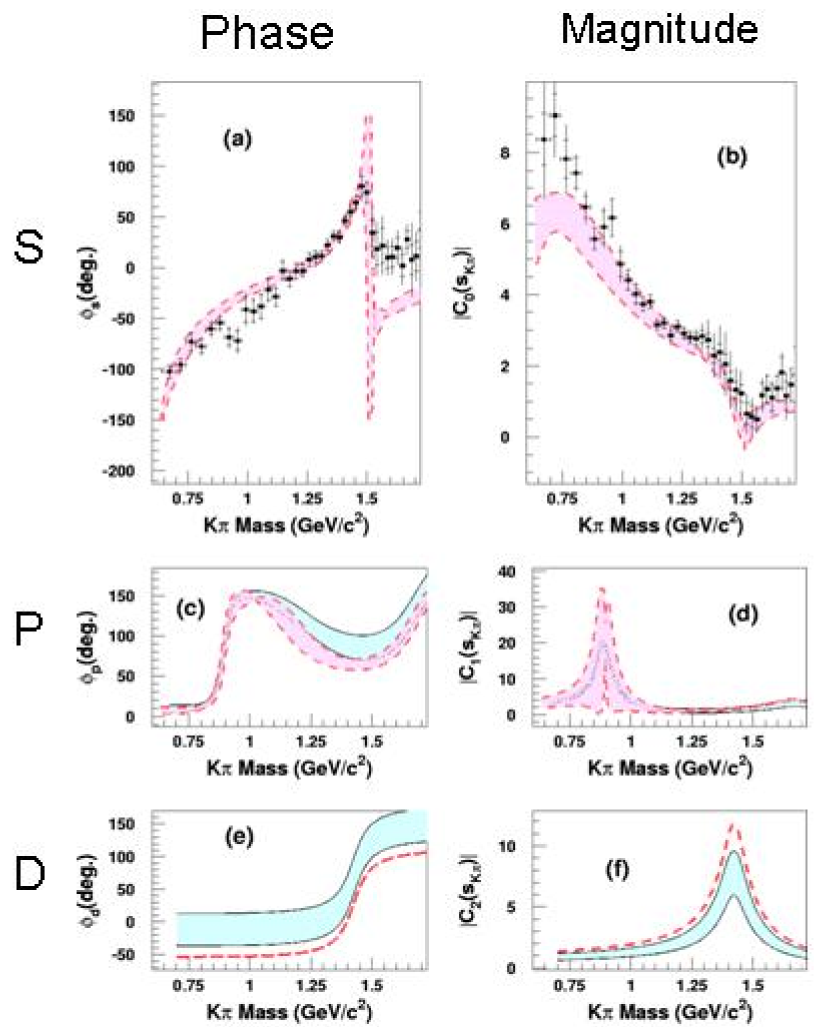
S (“partial wave”)

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 $K^*(1680)$.



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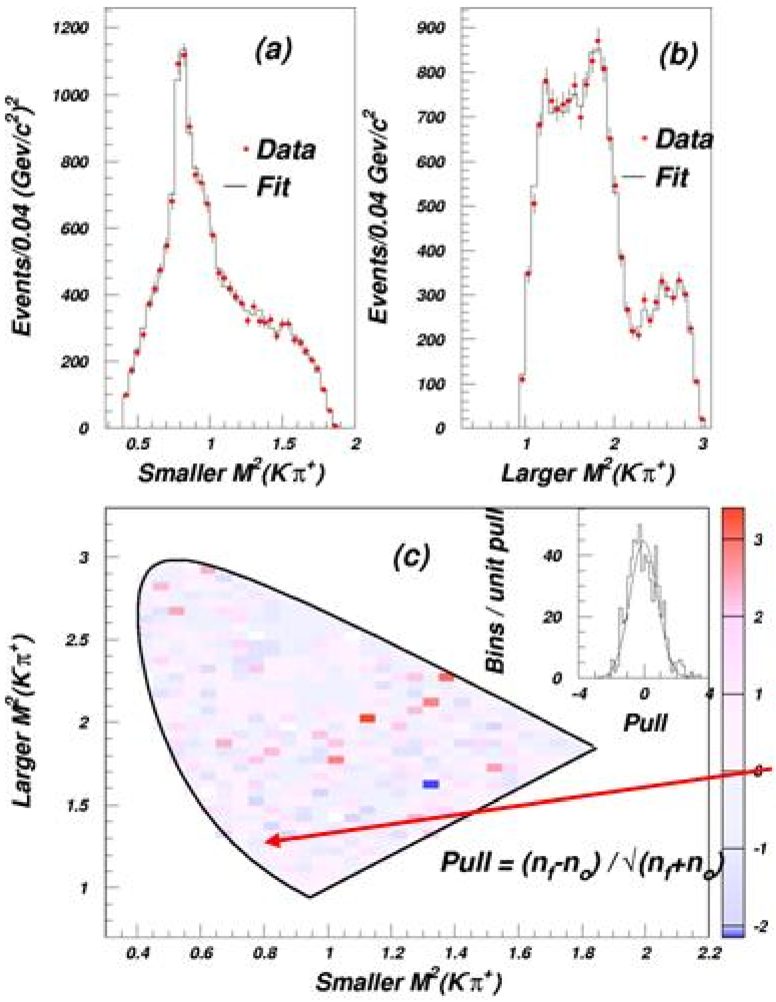
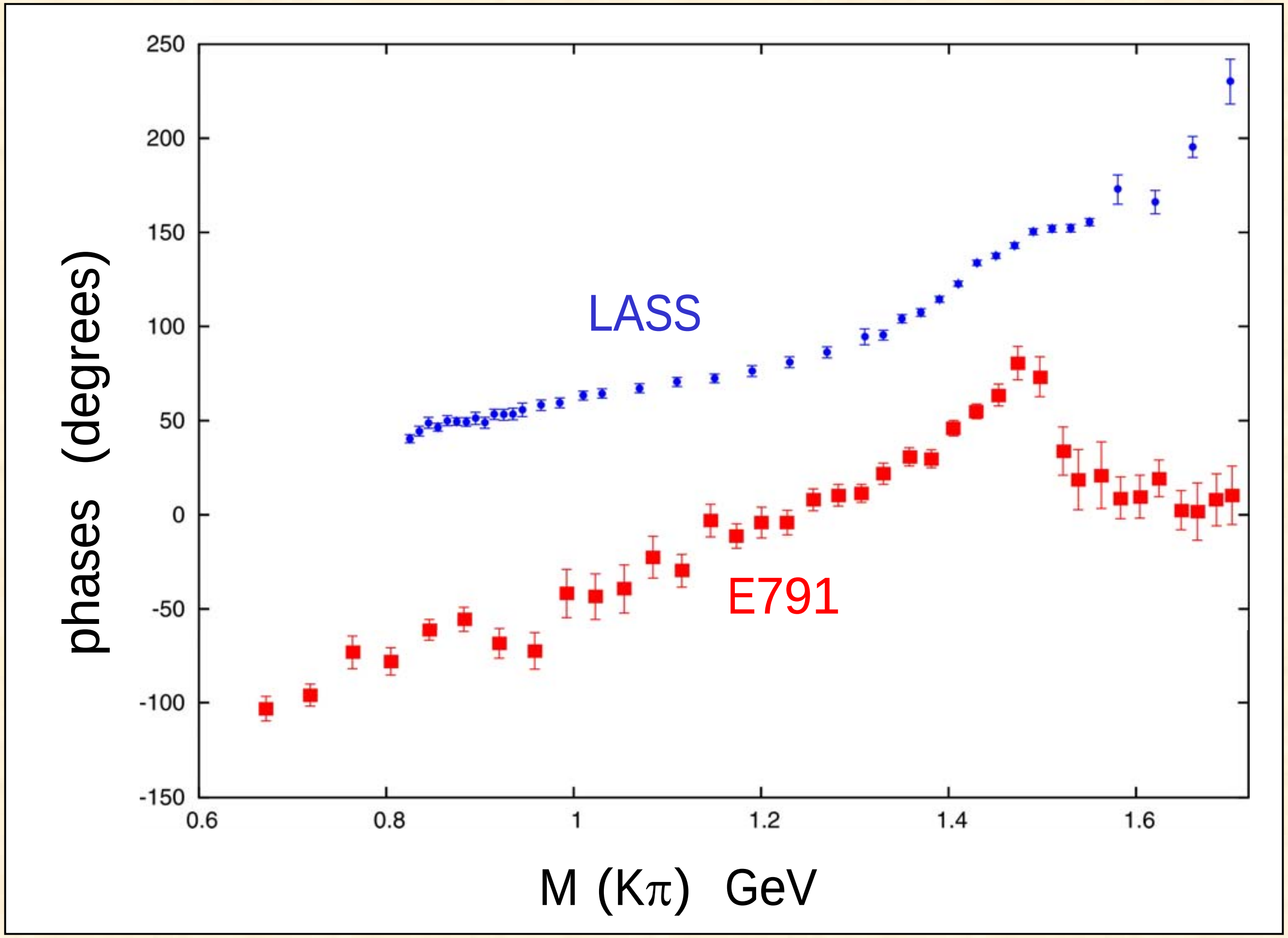
Comparison with Data



χ^2/NDF = 272/277 (48%)

Brian Meadows

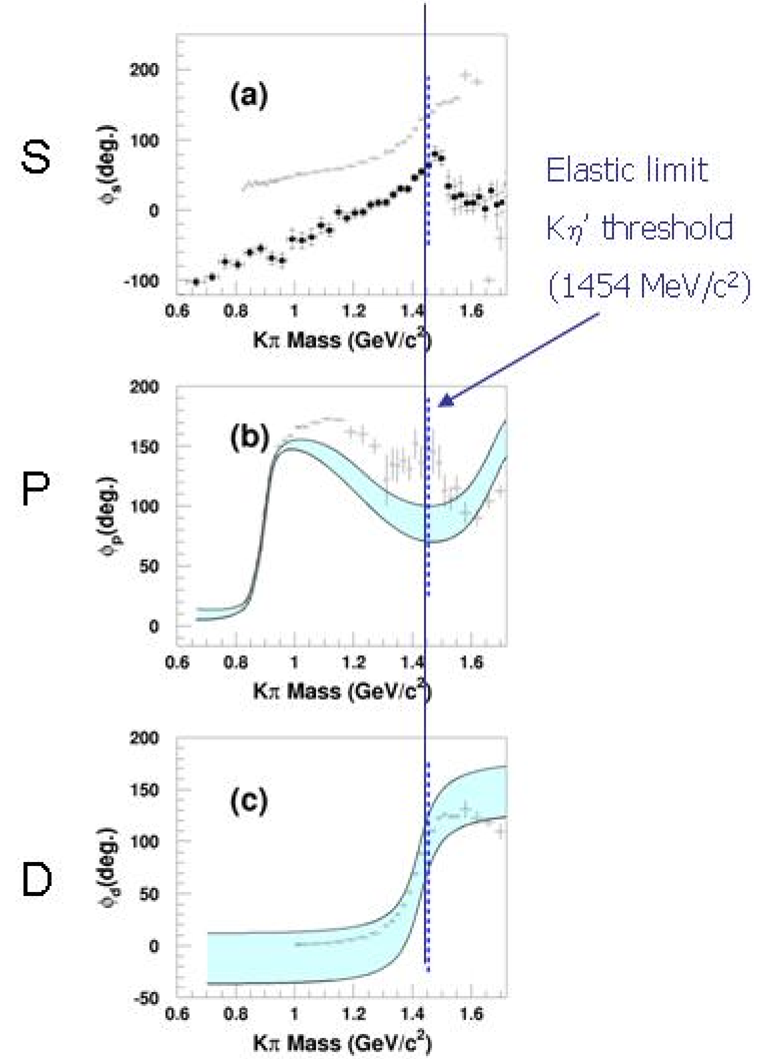
E791 v elastic scattering (LASS)



Watson Theorem - a direct test

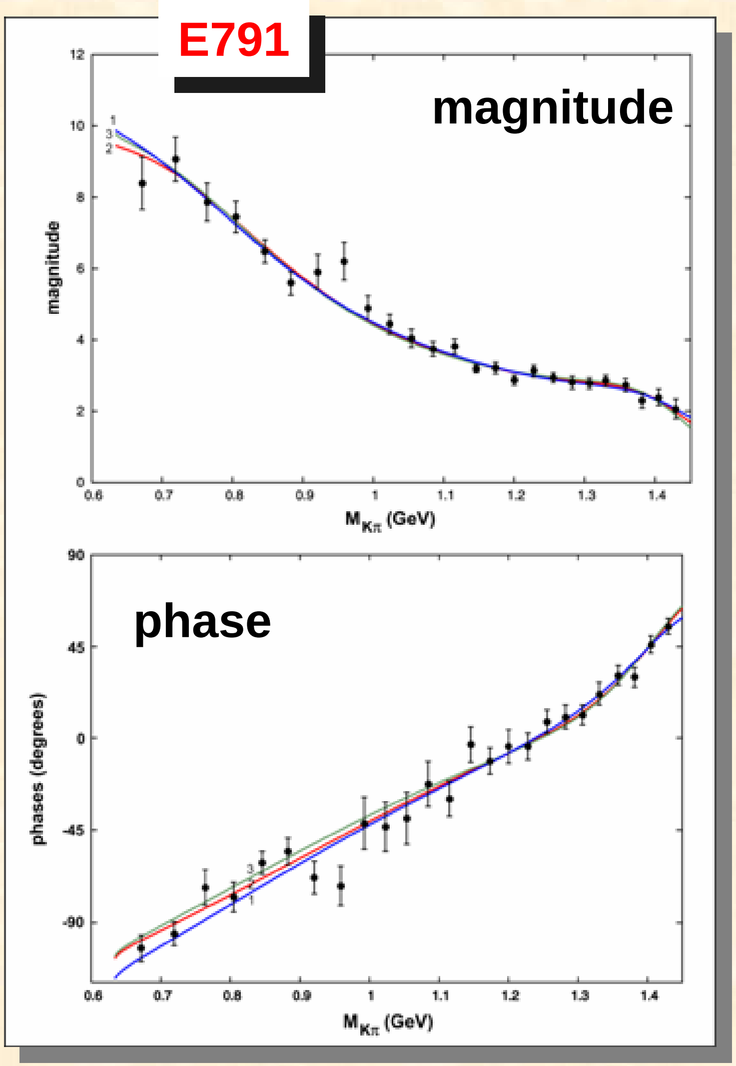
Phases for S, P and D waves are compared with those from LASS.

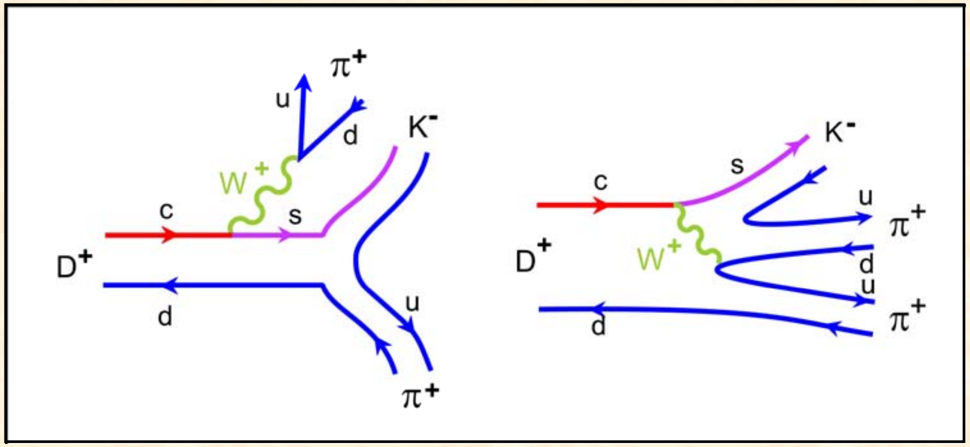
- s-wave phase ϕ_s for E791 is shifted by -75^0 wrt LASS.
  - ϕ_s energy dependence differs below 1100 MeV/c^2.
- ϕ_p does not match well between $K^*(892)$ and $K^*(1680)$ resonances
- ϕ_d match is excellent up to elastic limit.



Brian Meadows

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





$K\pi$ sector

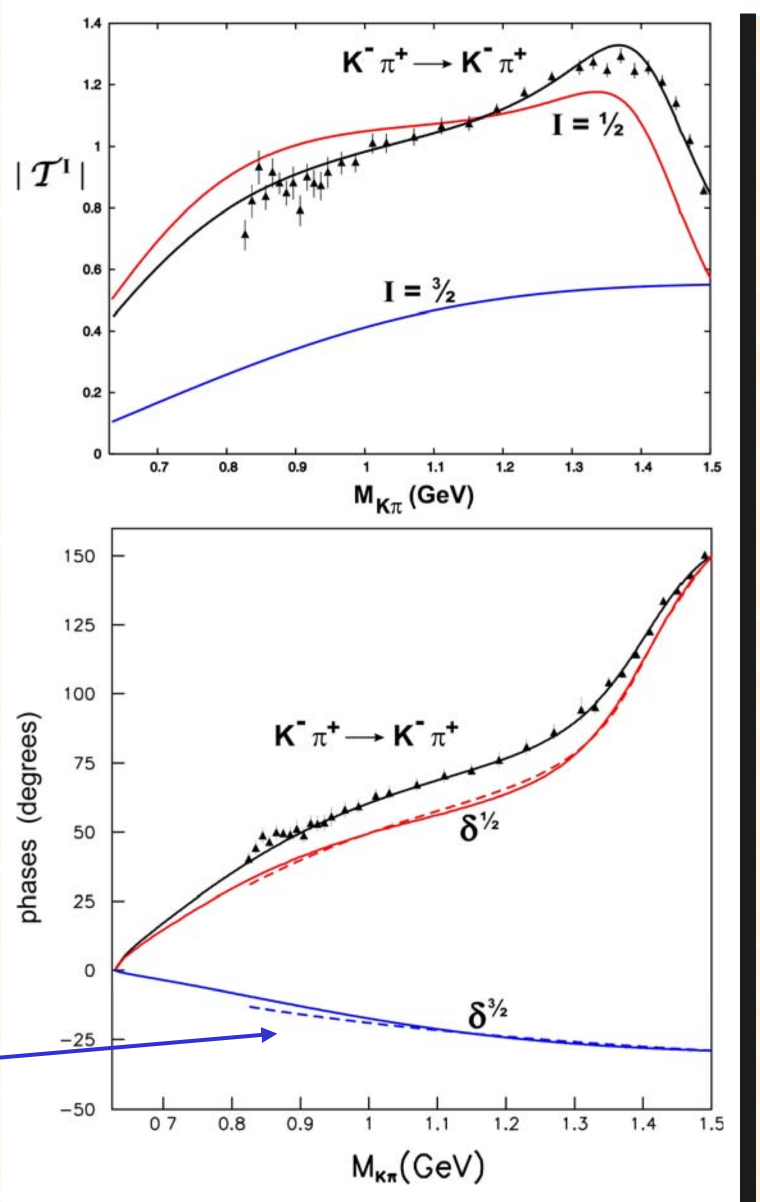
$K^-\pi^+ \longrightarrow K^-\pi^+$

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

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

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

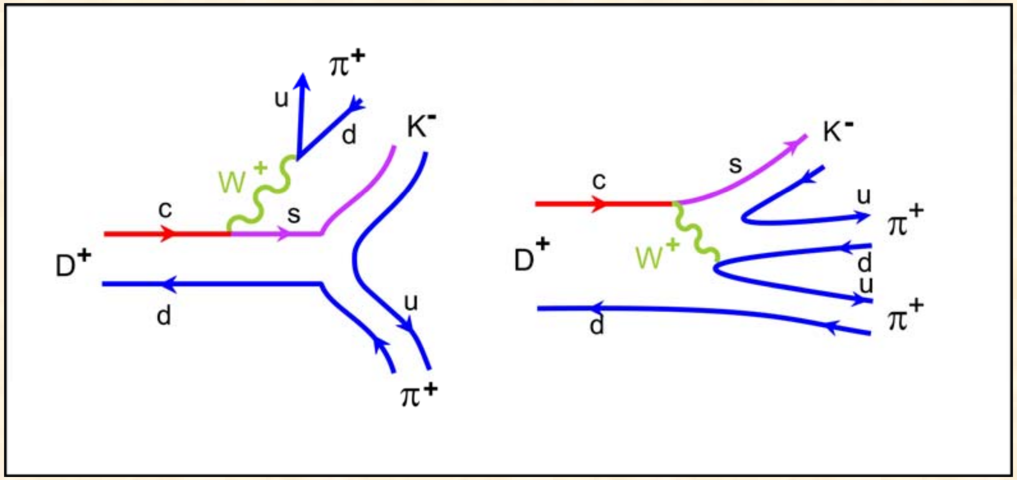
$$\frac{2}{3\rho}\left[\sin\delta^{1/2}\exp(i\delta^{1/2}) + \frac{1}{2}\sin\delta^{3/2}\exp(i\delta^{3/2})\right]$$



Descotes-Genon et al.

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

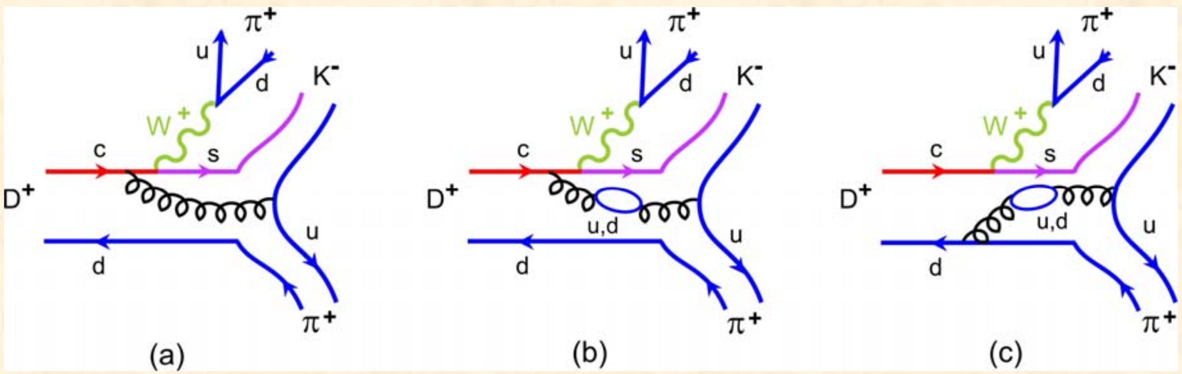
$$\mathcal{A} = \mathcal{F}^{1/2} + \mathcal{F}^{3/2}$$

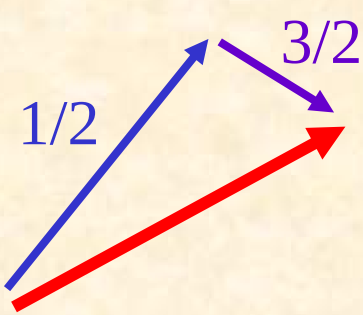


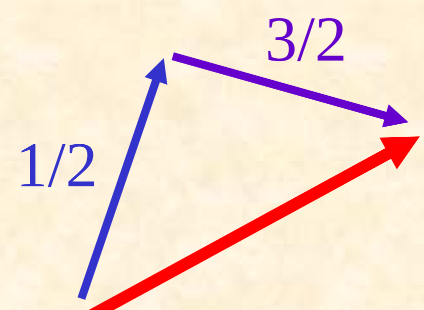
$$\mathcal{F}^I(s)_{had} = |\ \mathcal{F}^I_{had}(s)\ |\ \exp\left[i\delta^I(s) + i\beta_I\right]$$

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

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

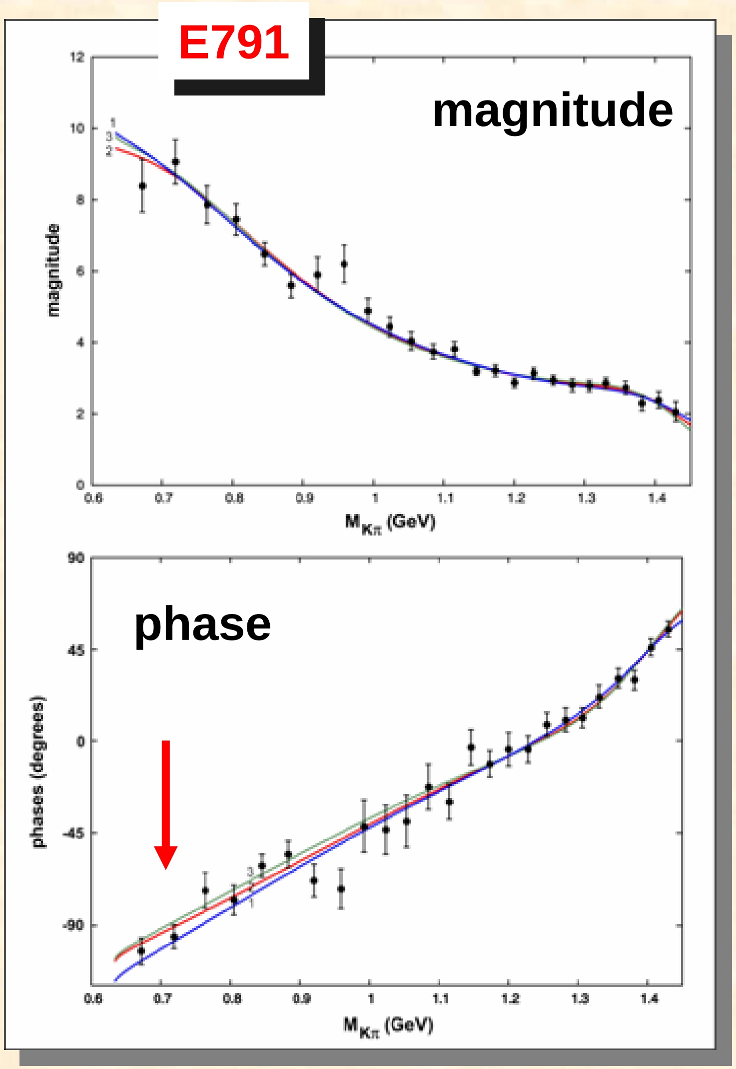


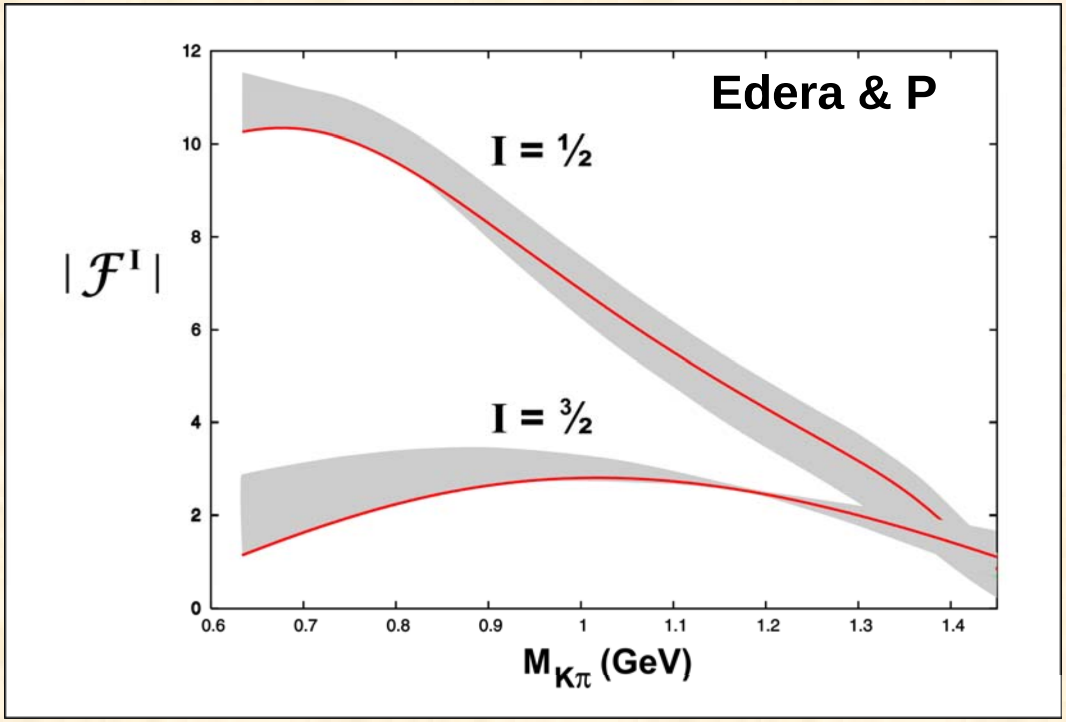




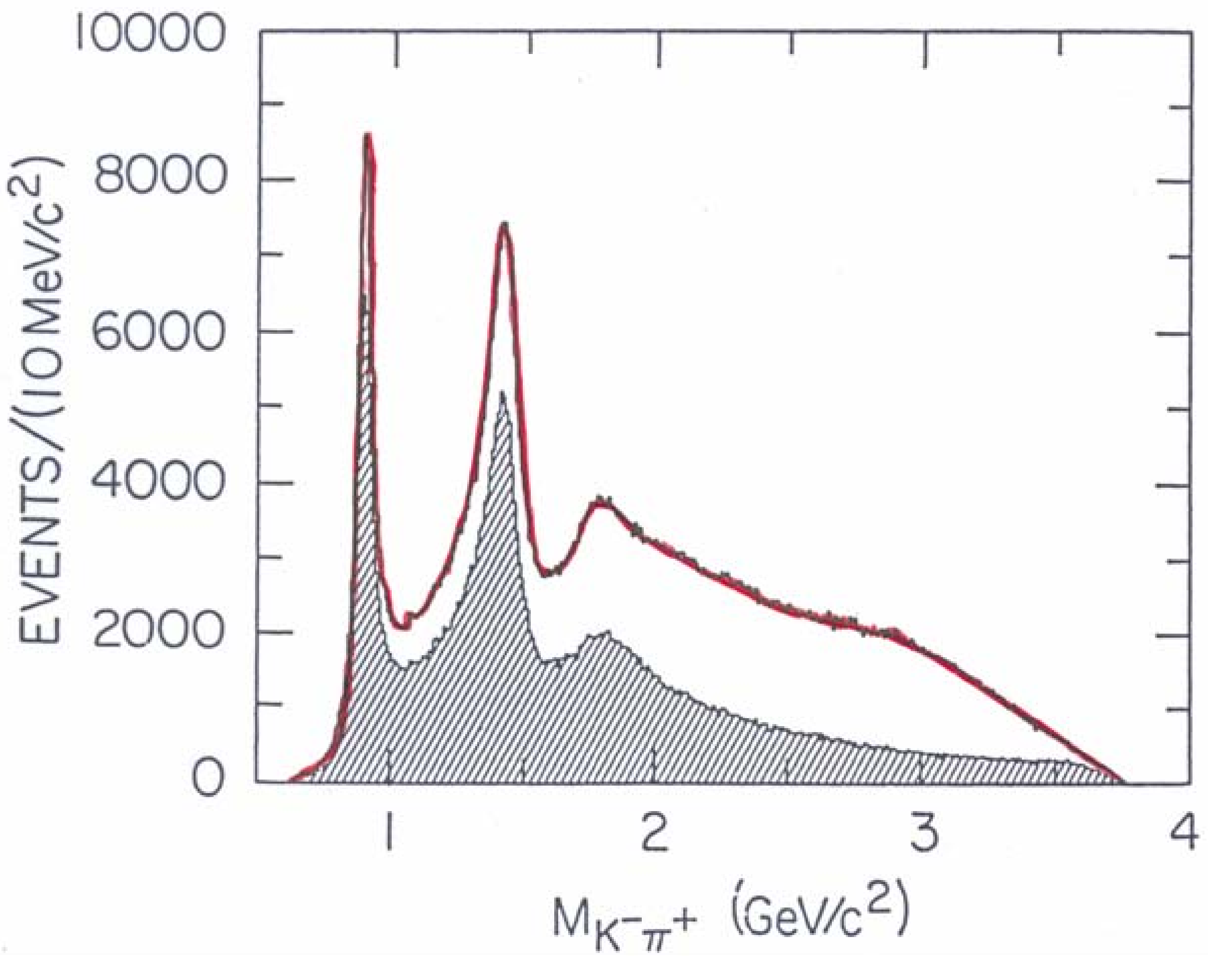
$$\mathcal{F}^I(s)_{had} = |\,\mathcal{F}^I_{had}(s)\,|\ \exp\left[i\delta^I(s) + i\beta_I\right]$$

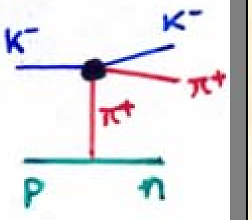
$D^+ \longrightarrow K^-\pi^+\pi^+$



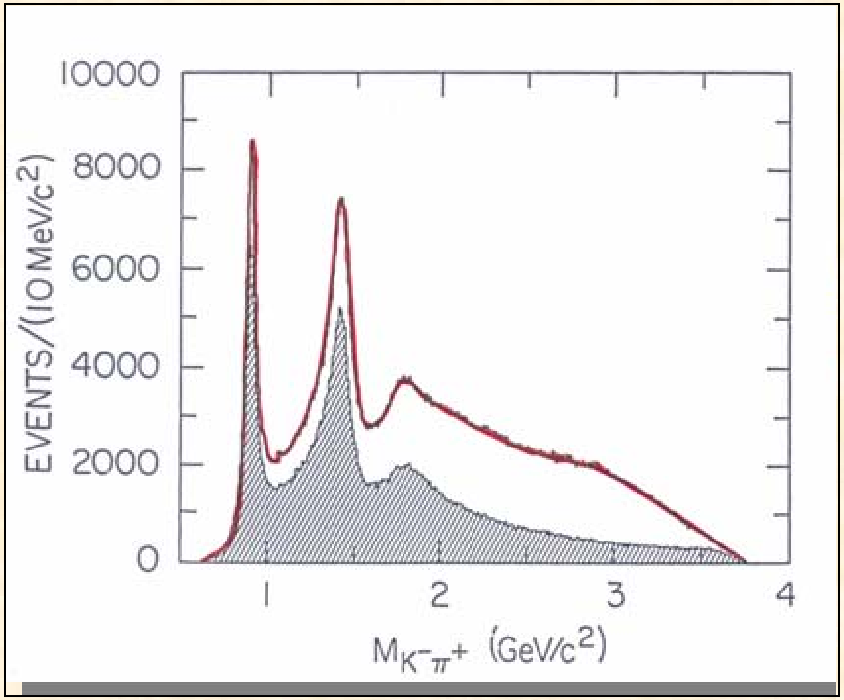


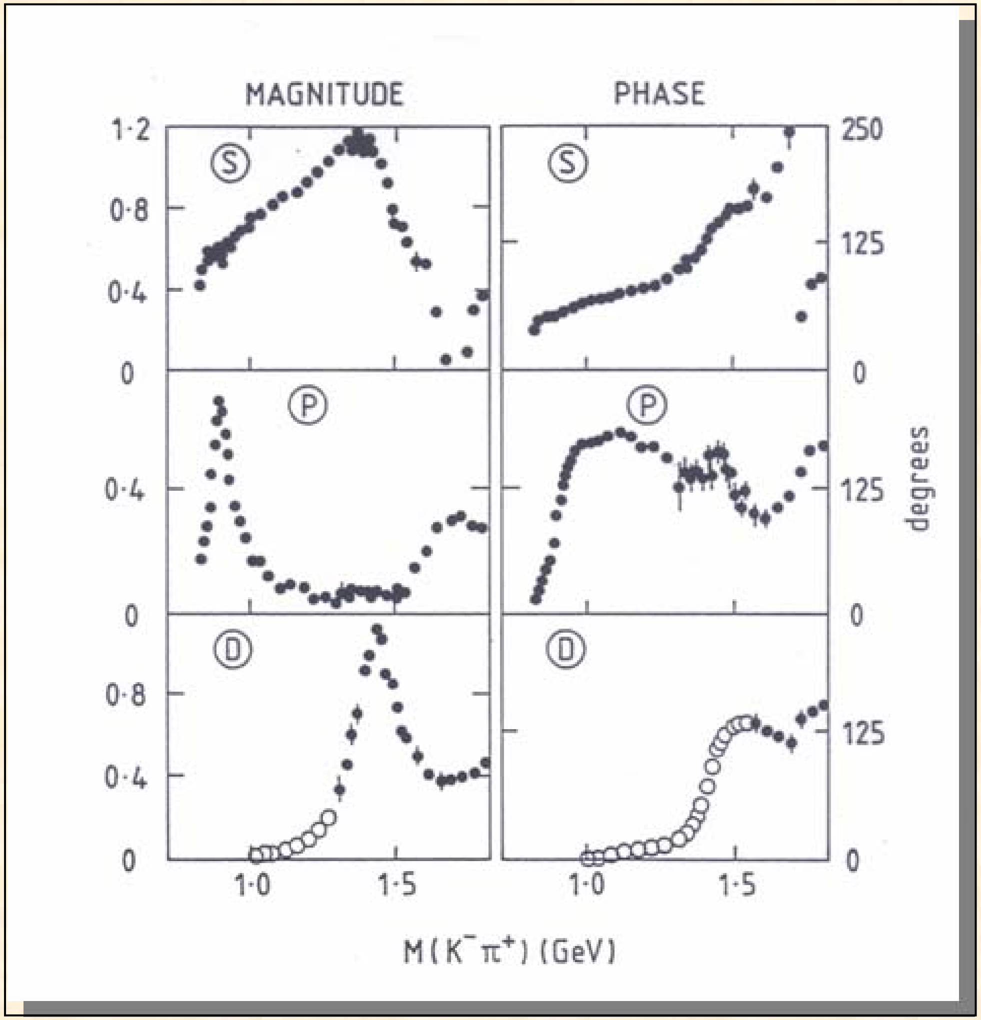
LASS: $K^- p \longrightarrow K^- \pi^+ n$

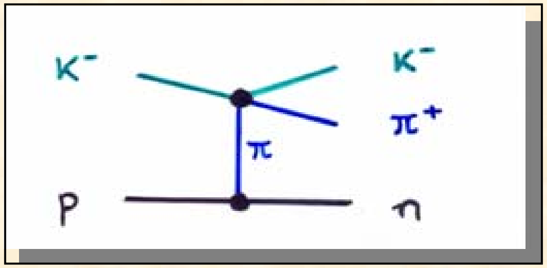


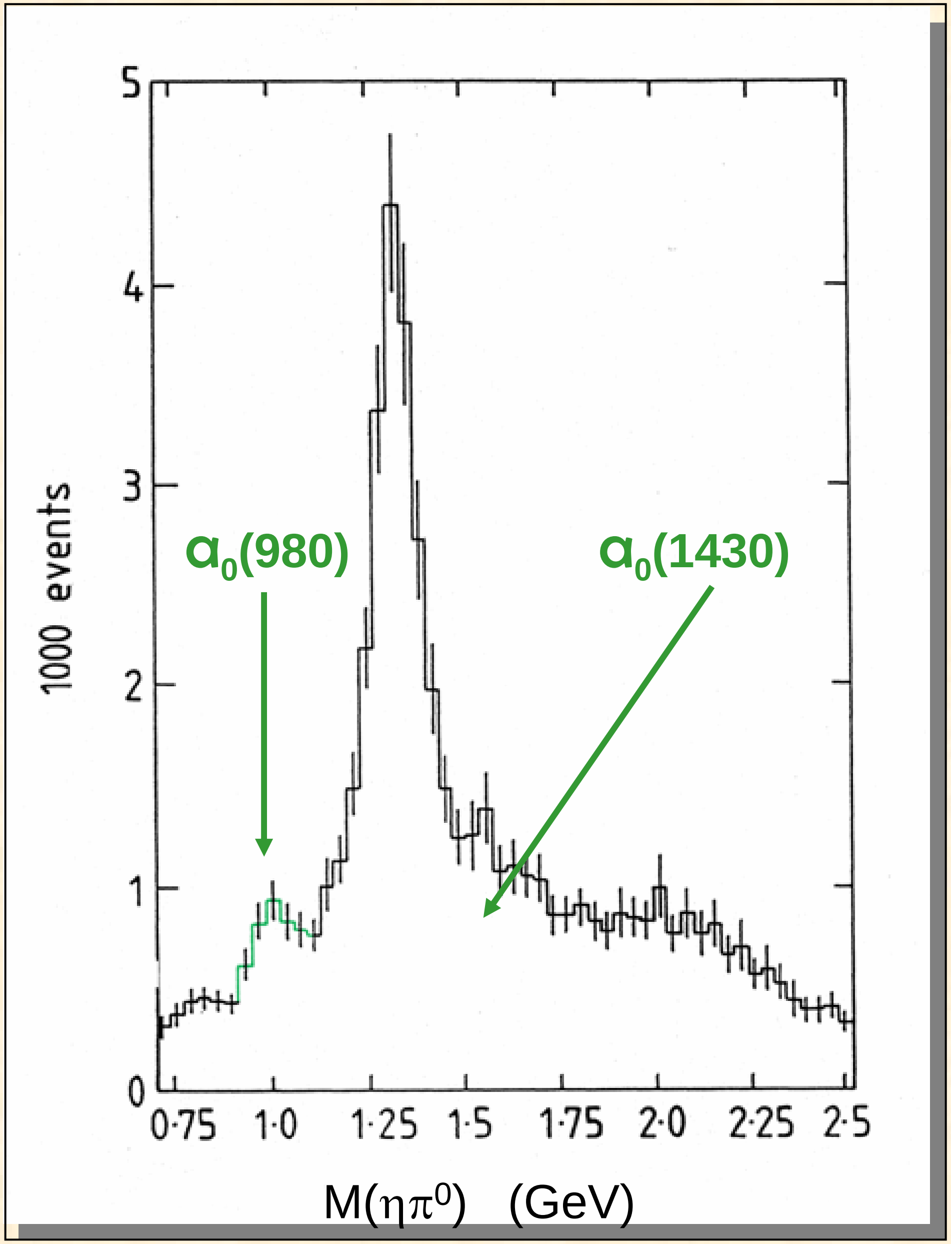


LASS: $K^- p \longrightarrow K^- \pi^+ n$







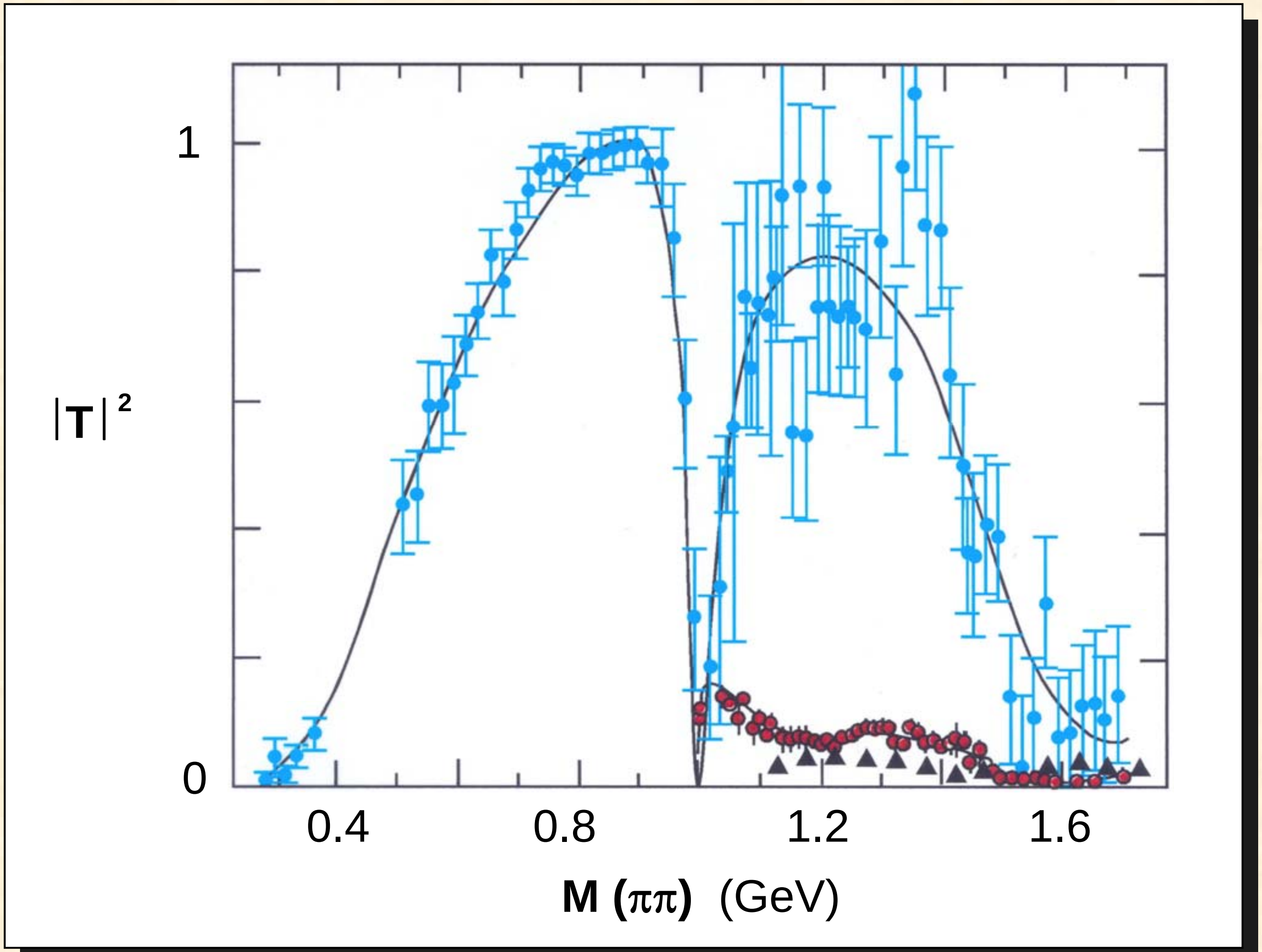


GAMS

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

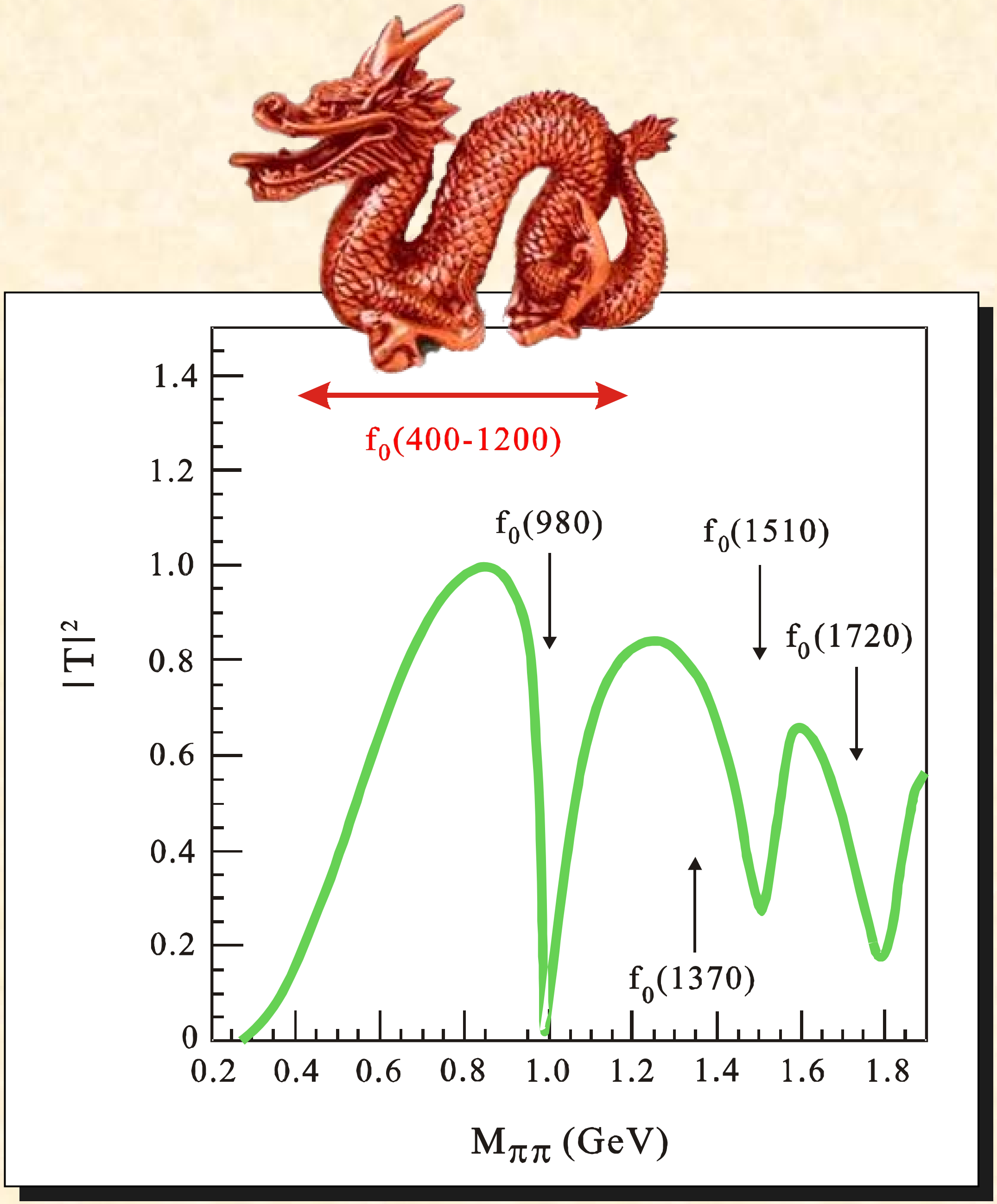
$\eta \to \gamma\gamma$, $\pi^0 \to \gamma\gamma$

I = J = 0



● ππ → ππ ● ππ → $K\bar{K}$ ▲ ππ → ηη

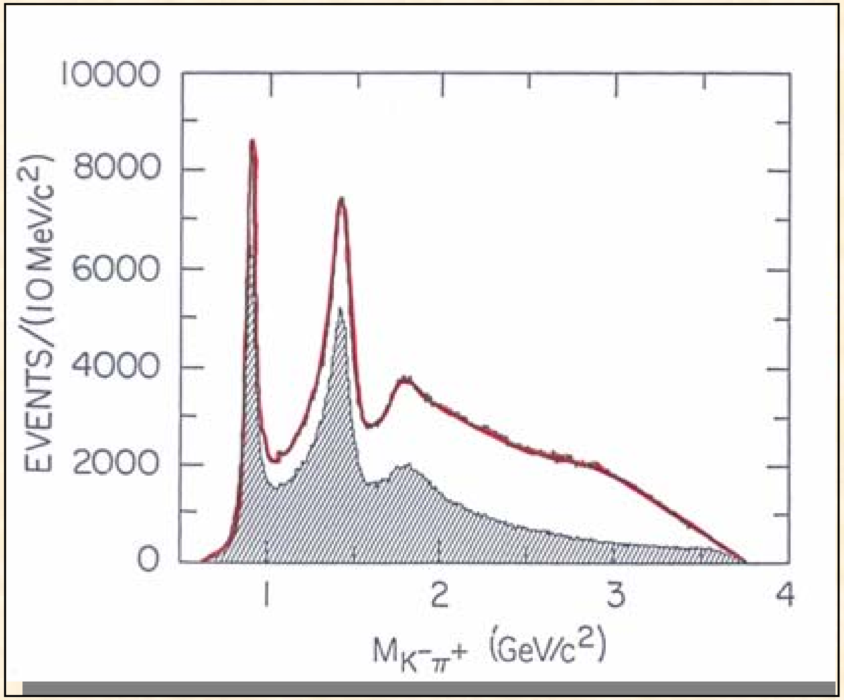
I = J = 0

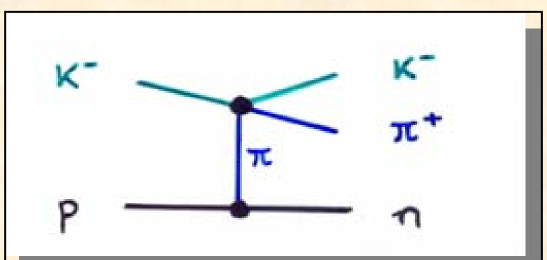


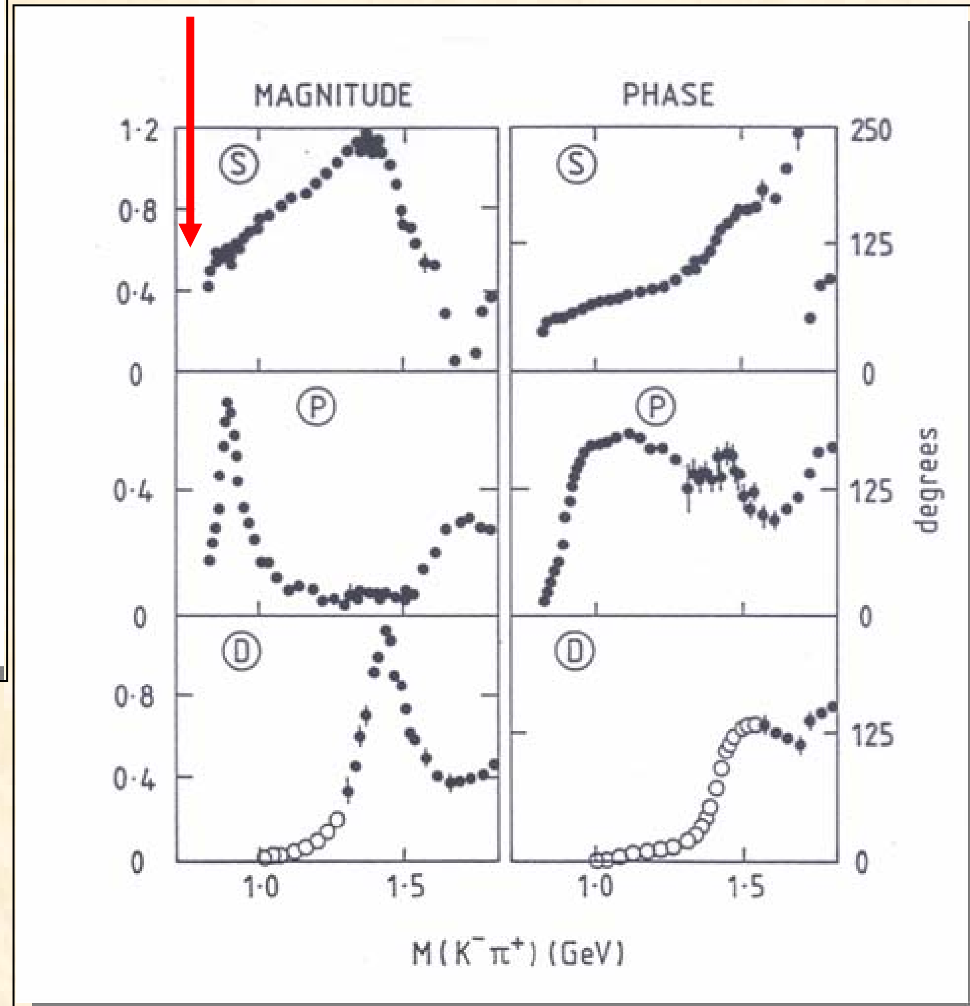
Minkowski
& Ochs

Zou

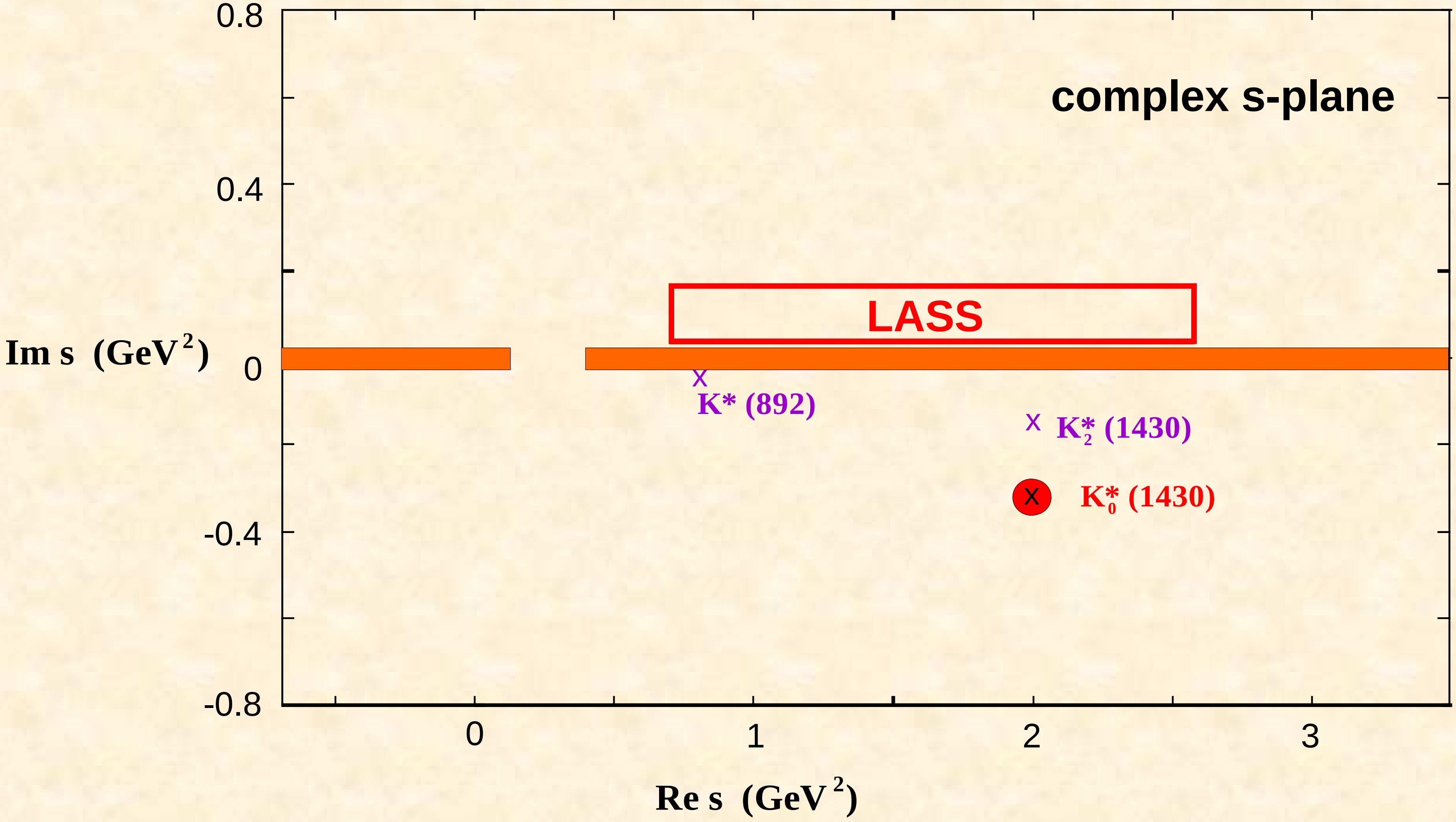
LASS: $K^- p \longrightarrow K^- \pi^+ n$





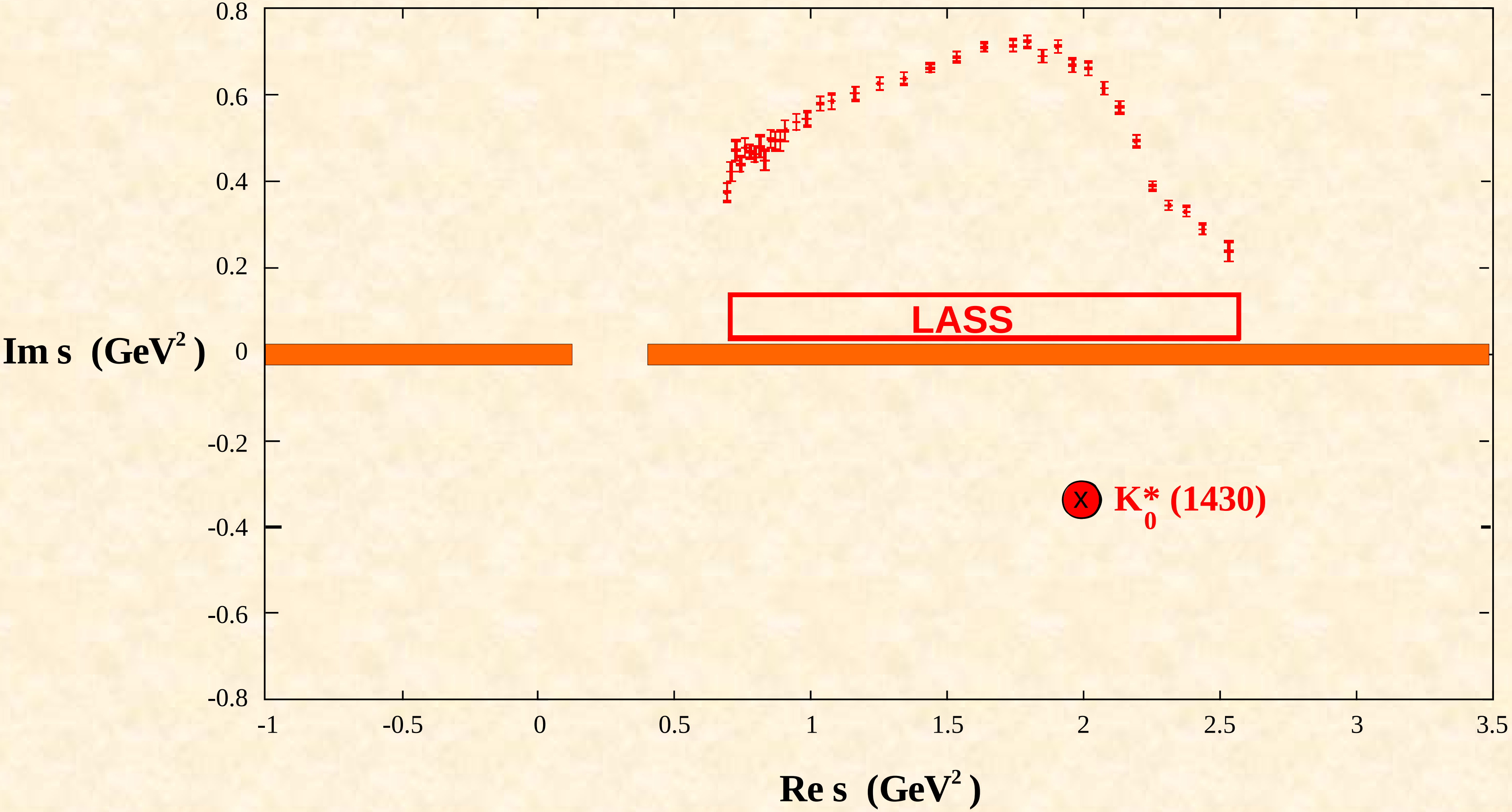


πK : I = ½ , J



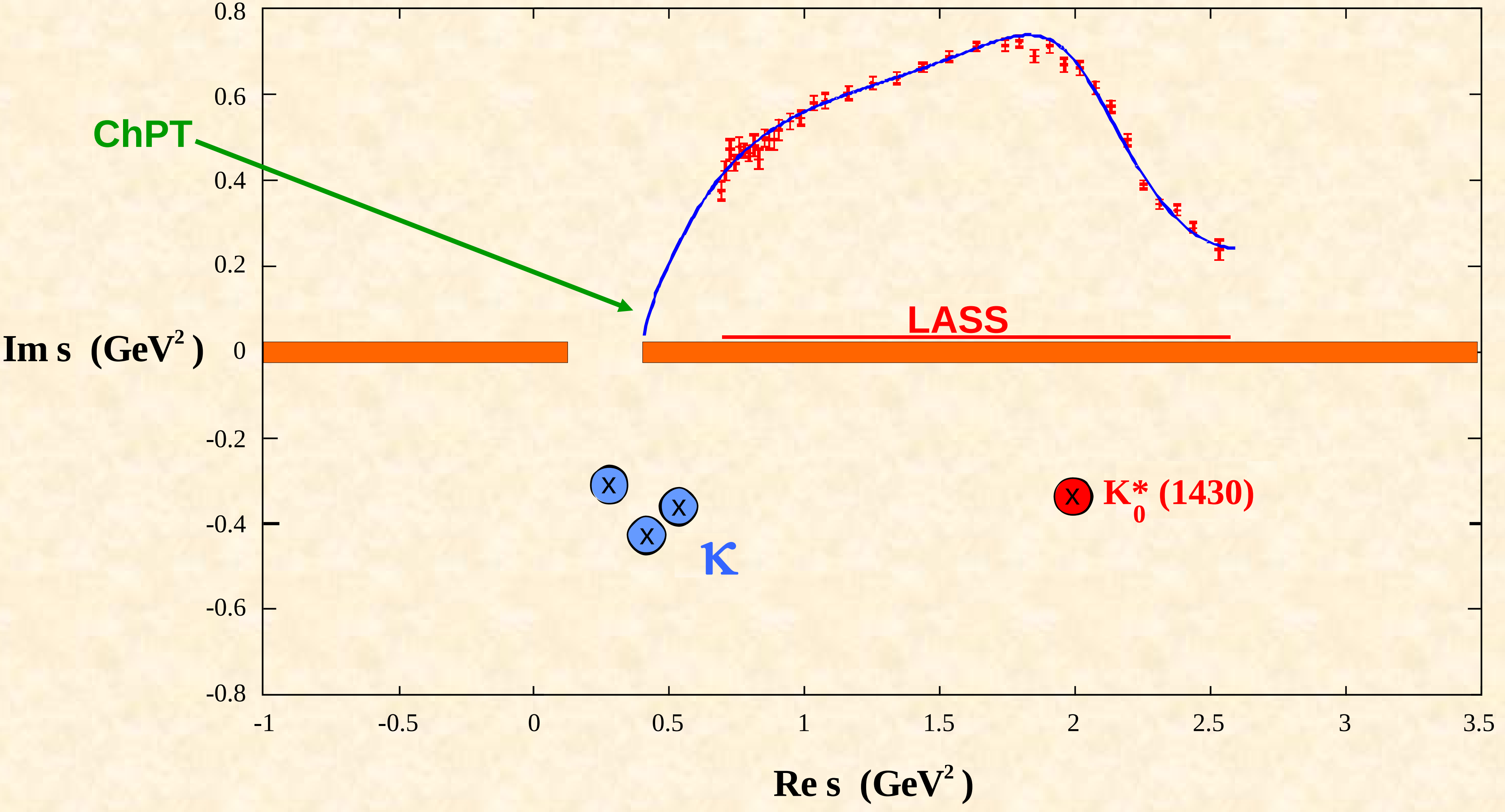
complex s-plane
LASS
K* (892)
K_2^* (1430)
K_0^* (1430)
Im s (GeV^2)
Re s (GeV^2)
0.8
0.4
0
-0.4
-0.8
0
1
2
3

πK : I = ½, J = 0

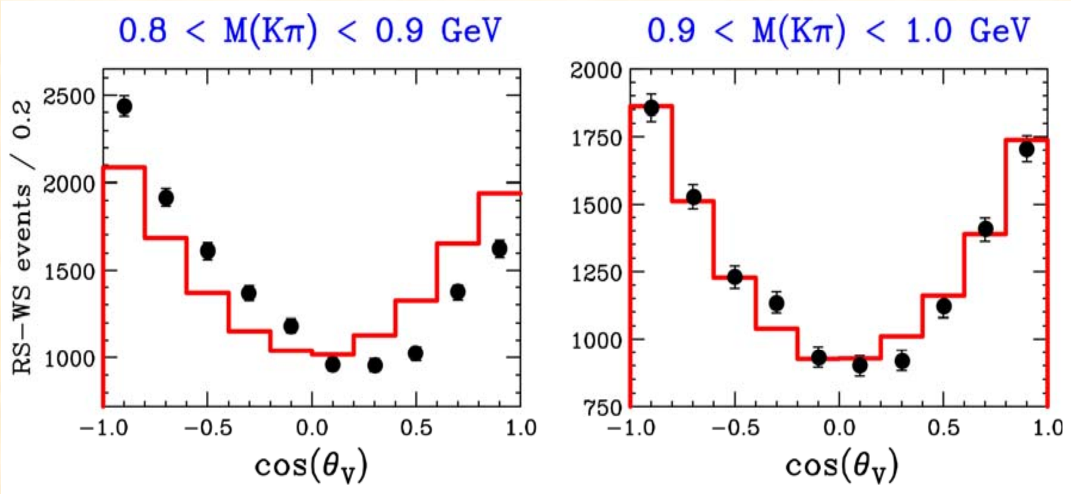


0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
Im s (GeV^2)
-1
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
Re s (GeV^2)
LASS
X
K_0^* (1430)

πK : I = ½, J = 0

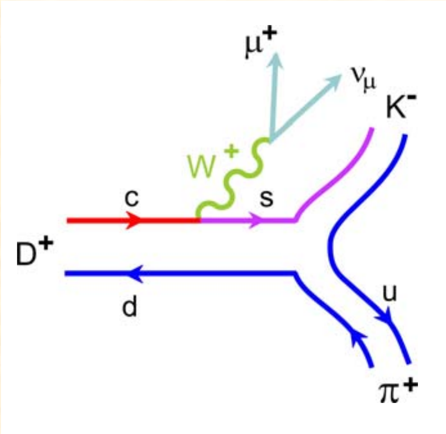

ChPT
LASS
Im s (GeV²)
Re s (GeV²)
κ
K*0 (1430)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-0.5
0
0.5
1
1.5
2
2.5
3
3.5

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

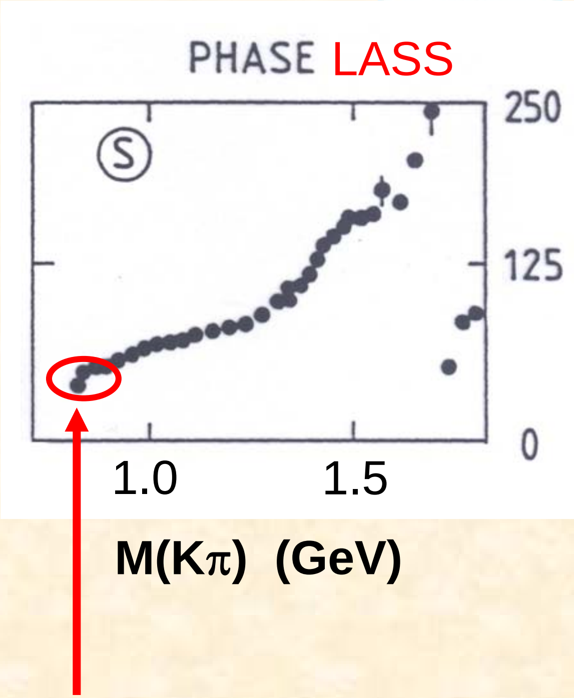


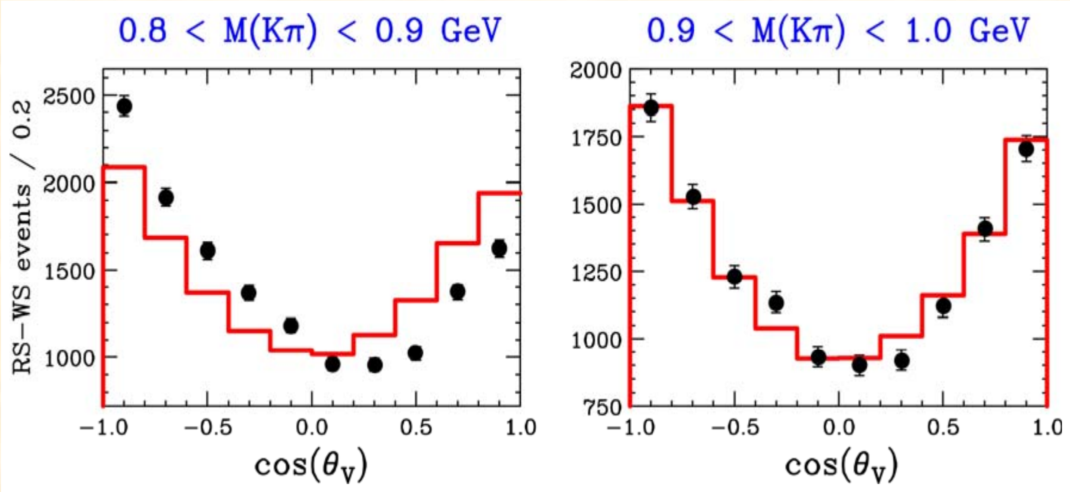
$$\mathcal{F}(D \to (K\pi)\mu\nu; s) \;=\; \mathcal{F}_{sl}^{1/2}(s) \;+\; \mathcal{F}_{sl}^{3/2}(s)$$

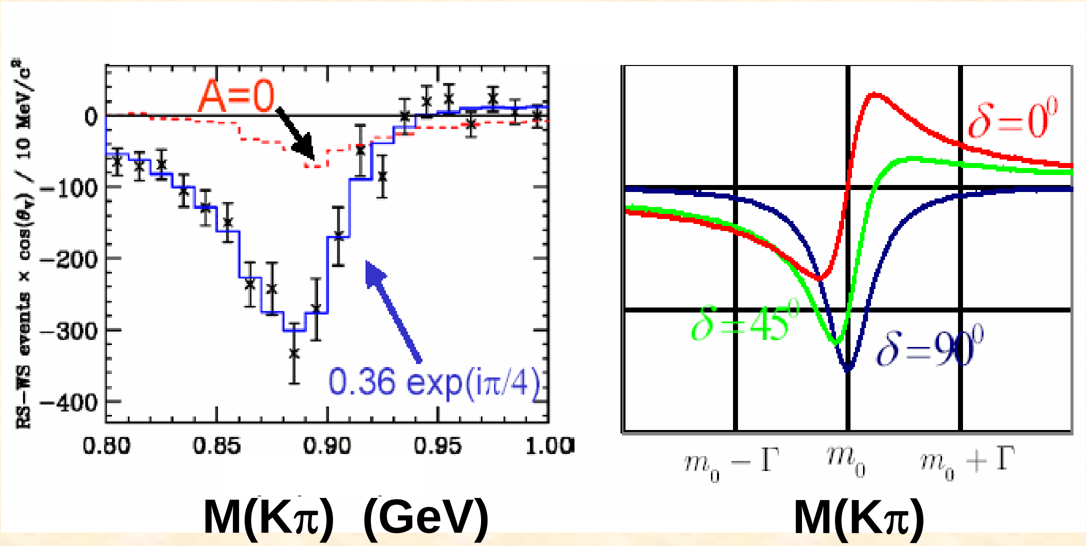
$$\mathcal{F}_{sl}^{I}(s) \;= \mid \mathcal{F}_{sl}^{I}(s) \mid \, \exp\left[i\delta^{I}(s)\right]$$

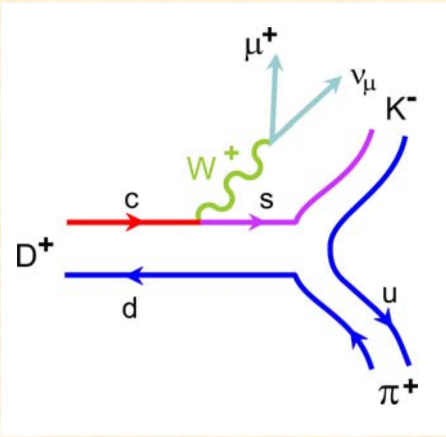


$D^+ \longrightarrow (K^-\pi^+)\mu^+\nu_\mu$



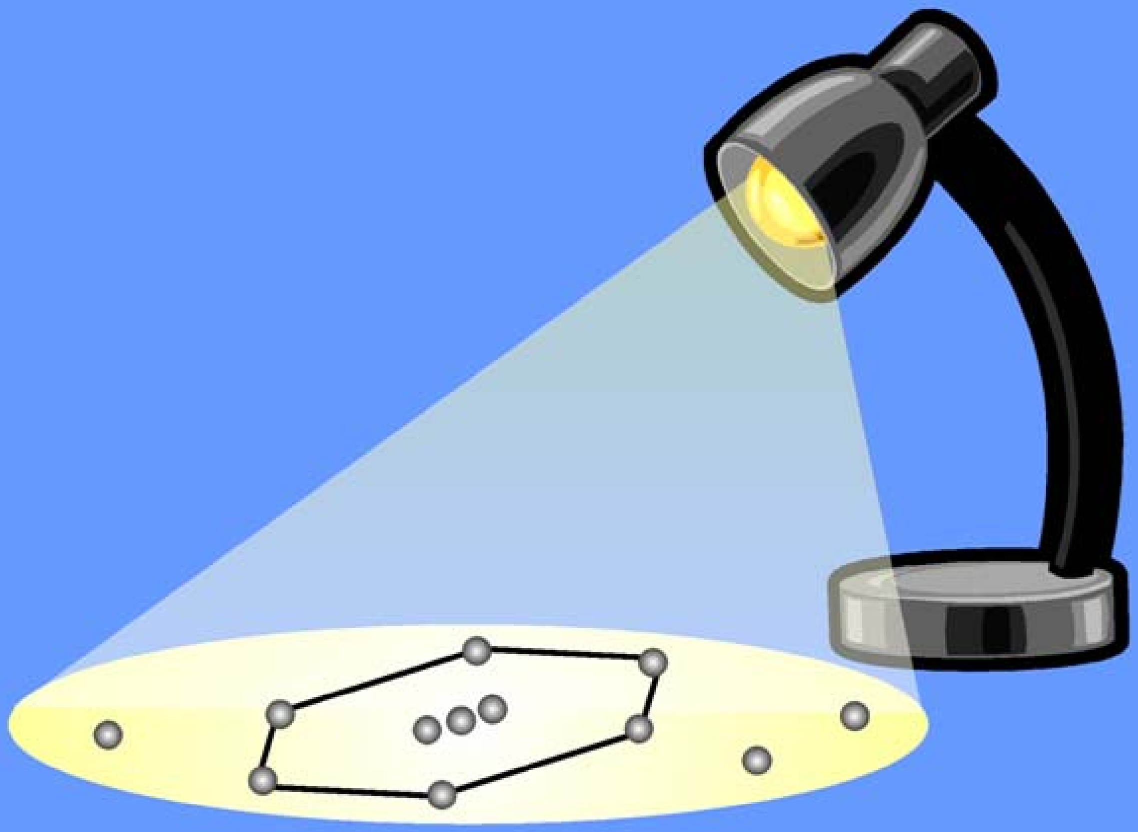






J/ψ/B/D decays

Shedding light on scalar mesons



Scalar mesons

$f_0(980)$

$f_0(1710)$

$f_0(600)$

$f_0(1500)$

$\kappa_0^*(1430)$

$f_0(1370)$

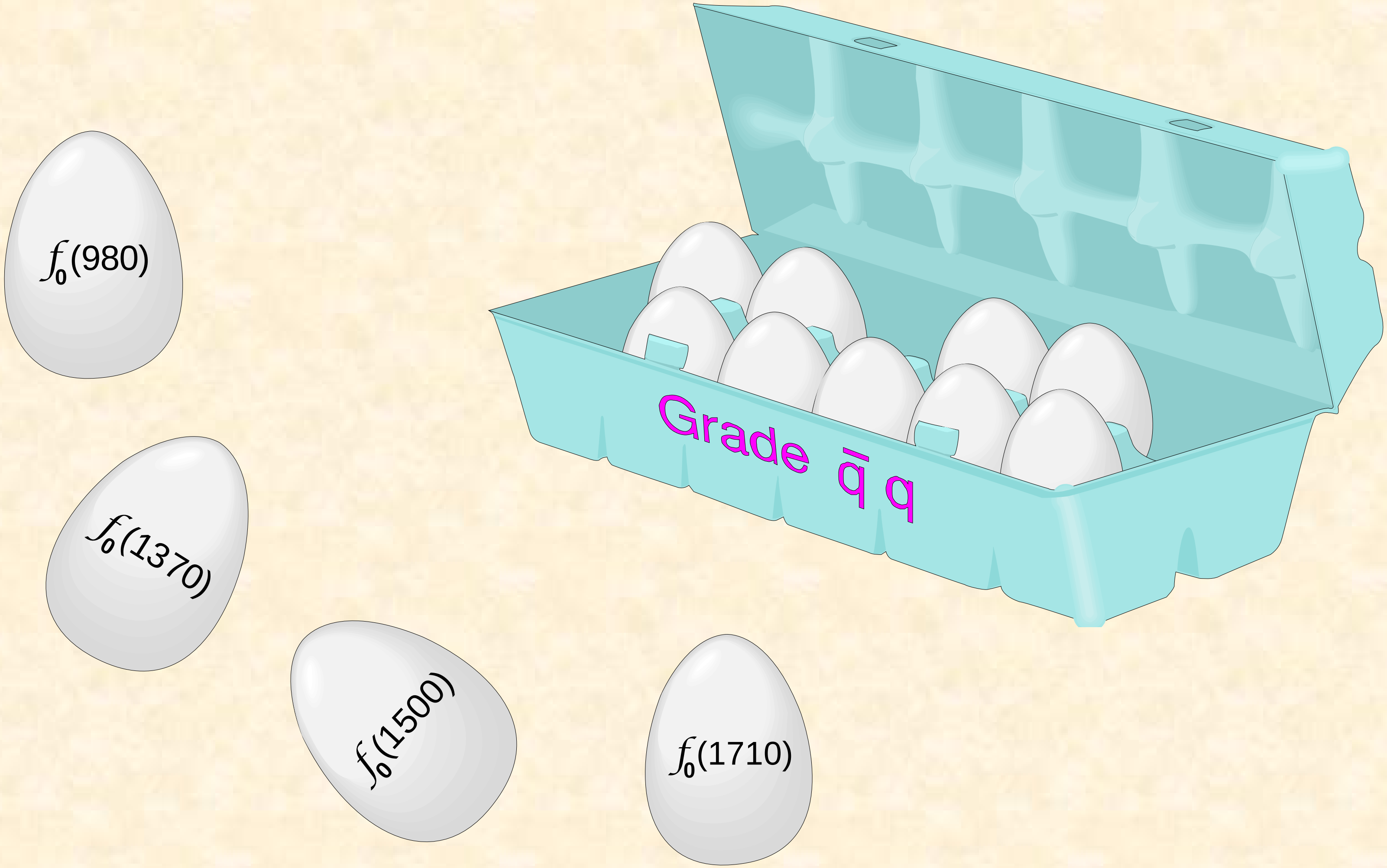
$a_0(1450)$

$a_0(980)$

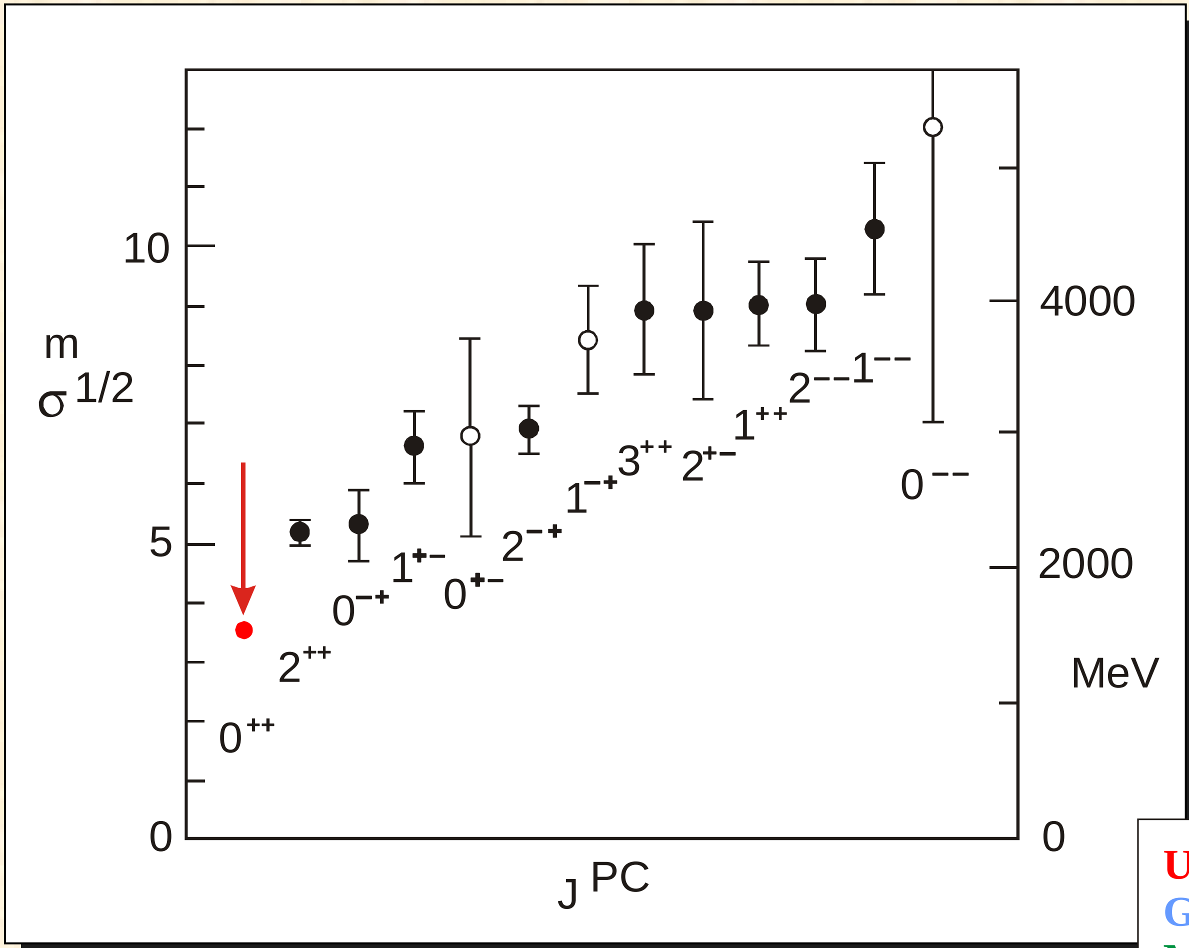
$\kappa(800)$

$\kappa_0^*(1950)$

Which f_0 is in which nonet?



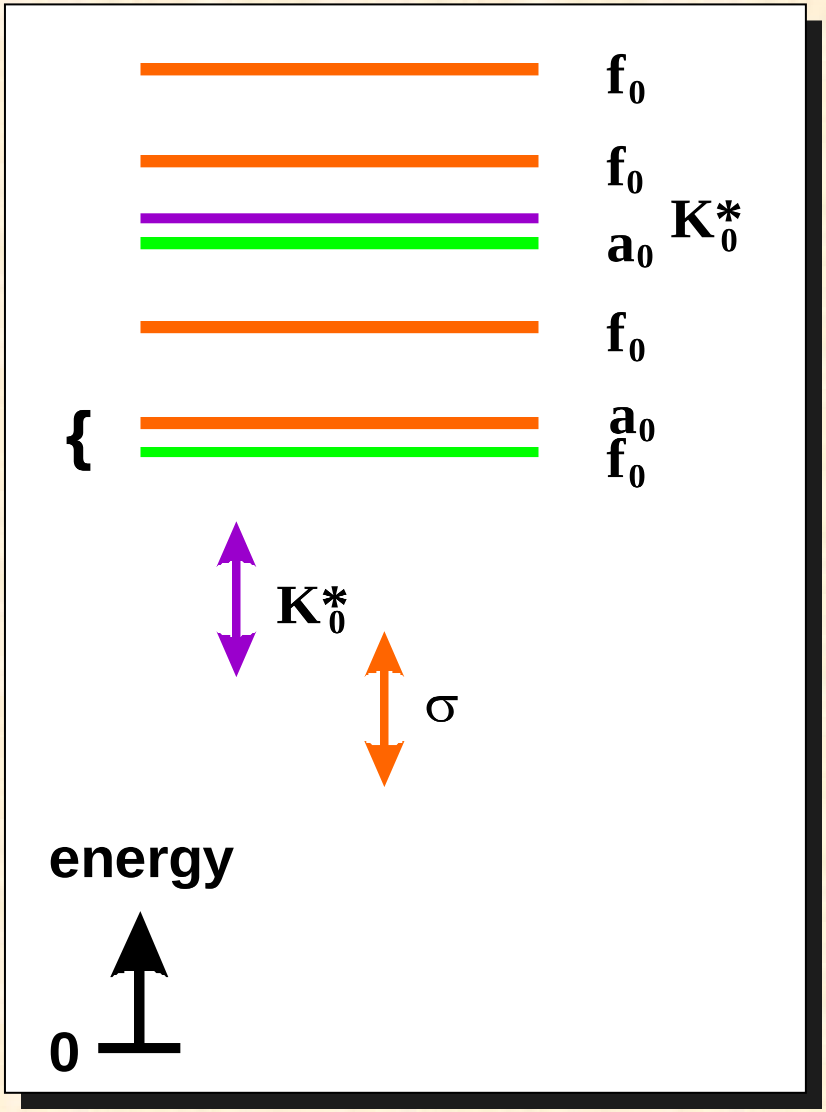
glueball spectrum in a world without quarks



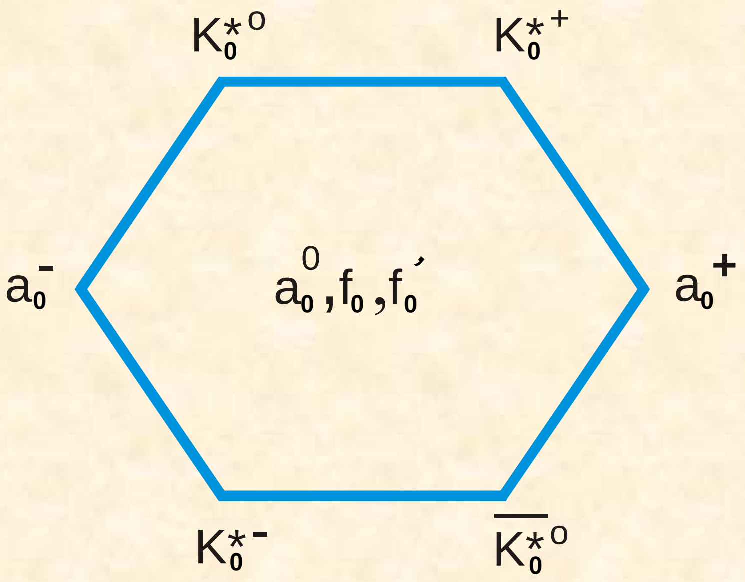
UKQCD	1568 ± 89
GF11	1740 ± 71
MP	1630 ± 100
GF11 (reanal)	1648 ± 58

m =

Scalar multiplet

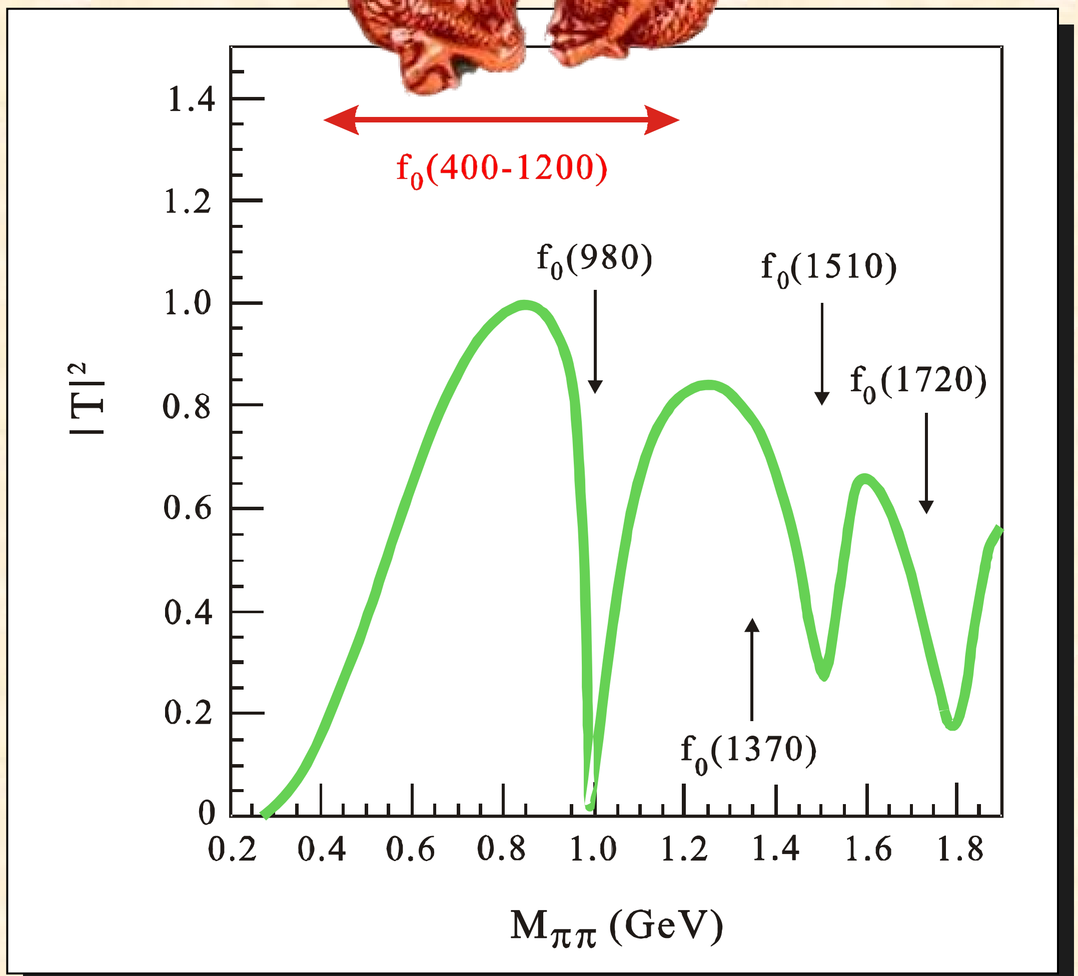


$J^{PC} = 0^{++}$



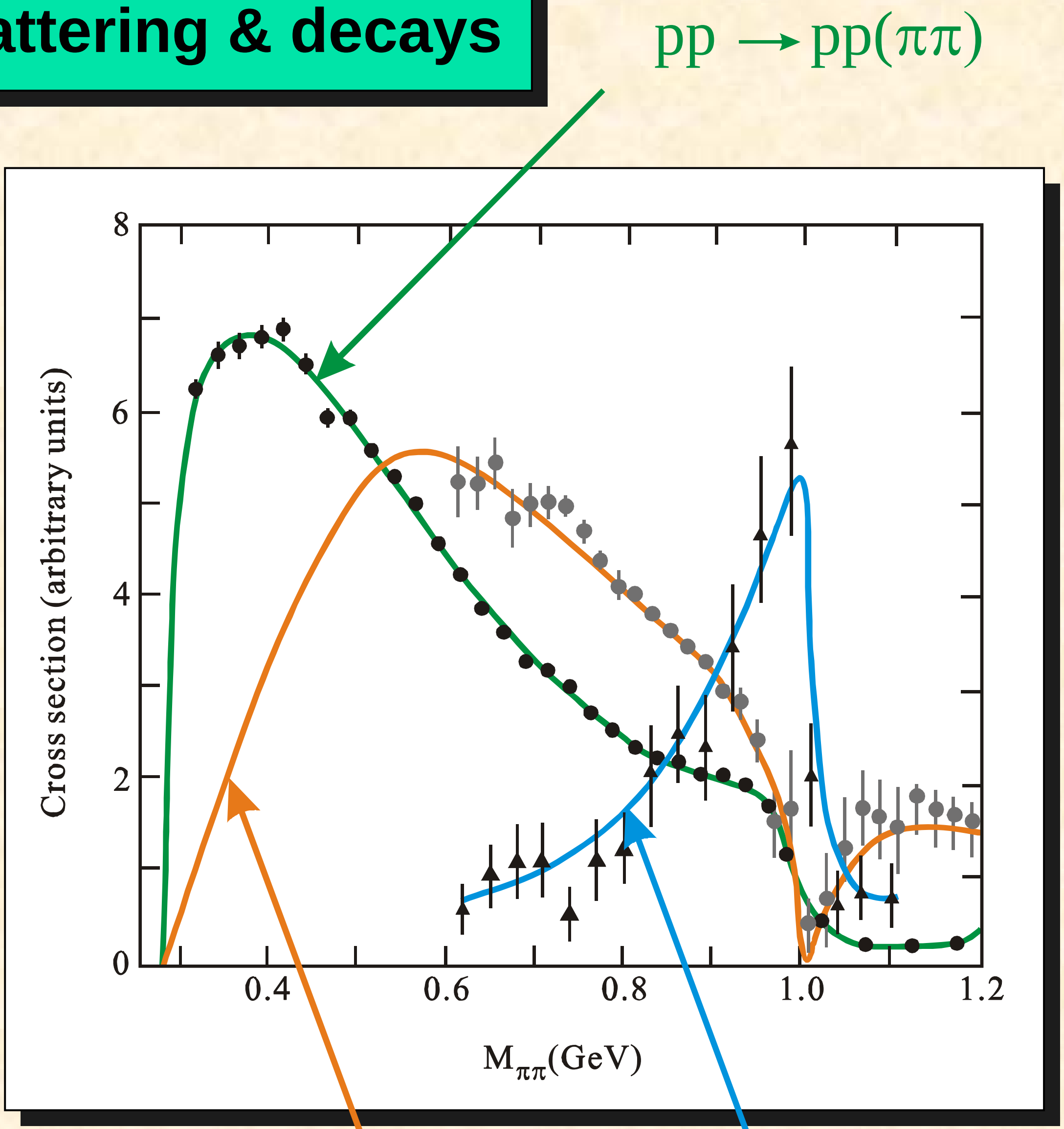
I = J = 0

Minkowski
& Ochs

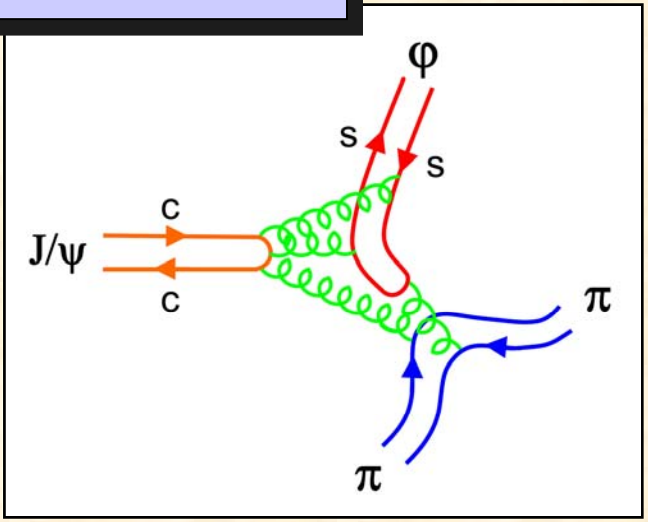


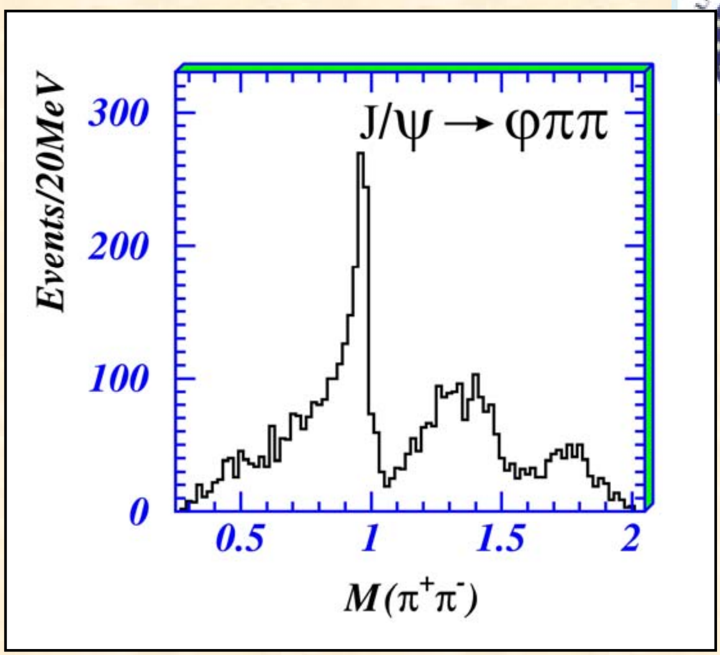
Zou

ππ sector in scattering & decays

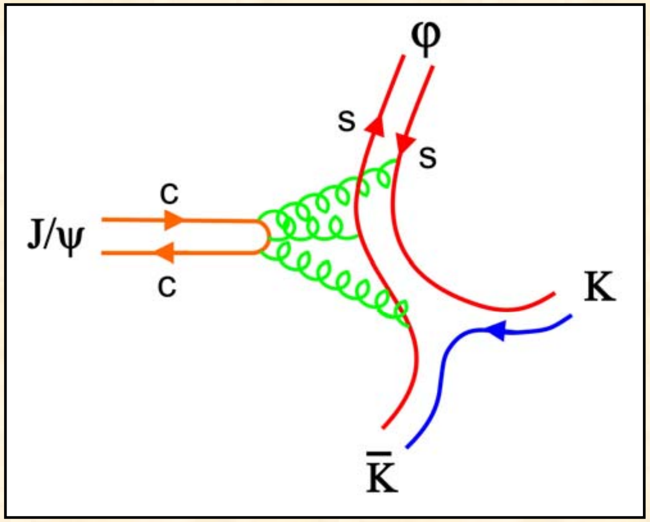


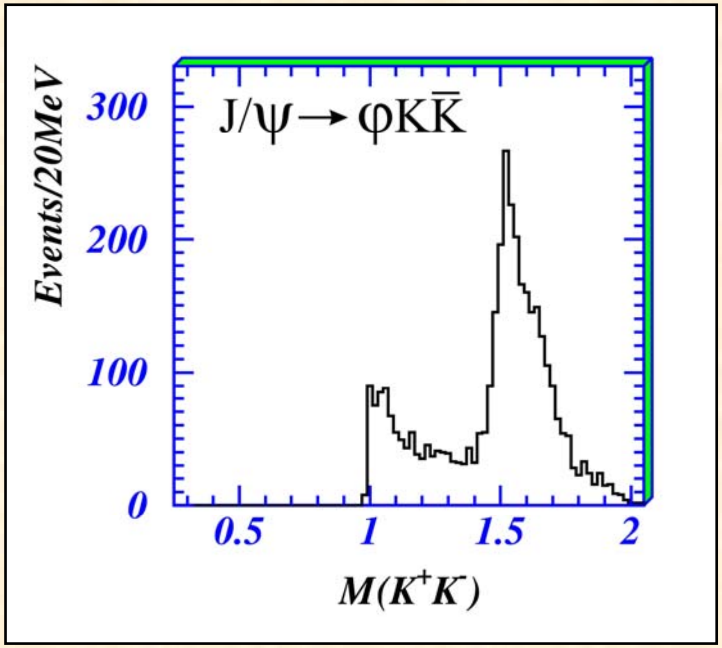
$J/\psi \longrightarrow \varphi M^+M^-$



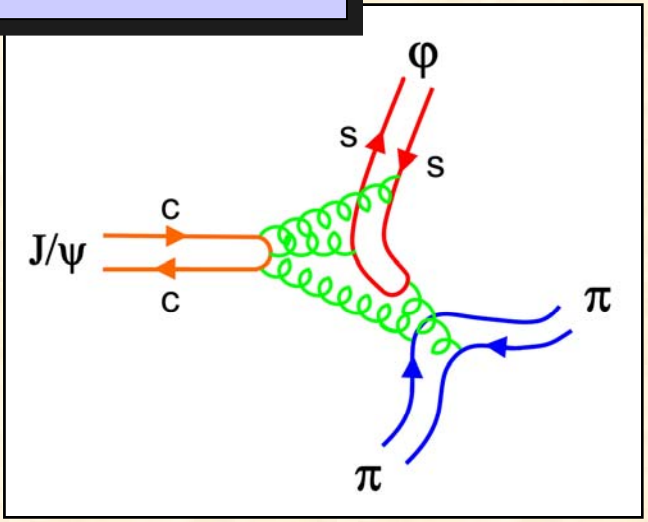


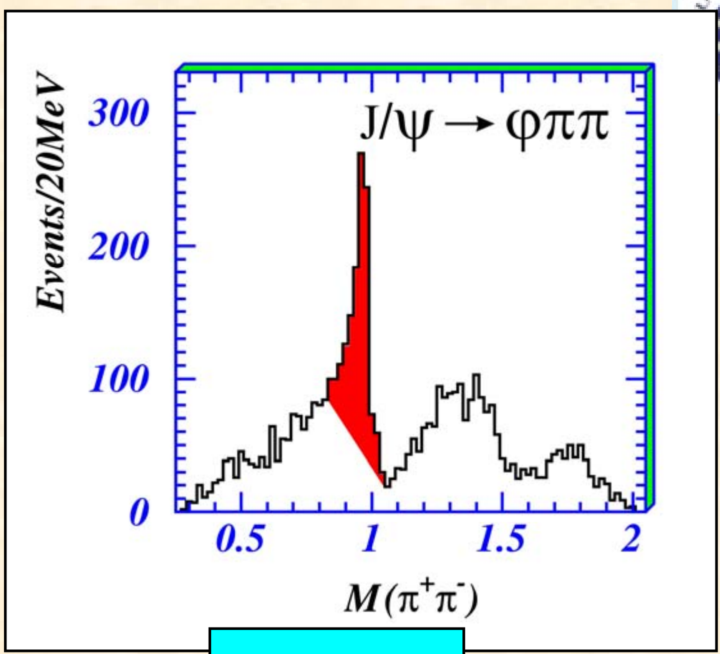
BES



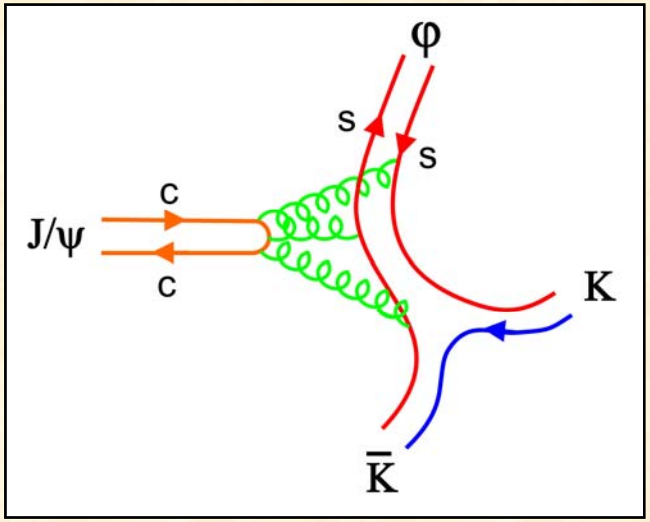


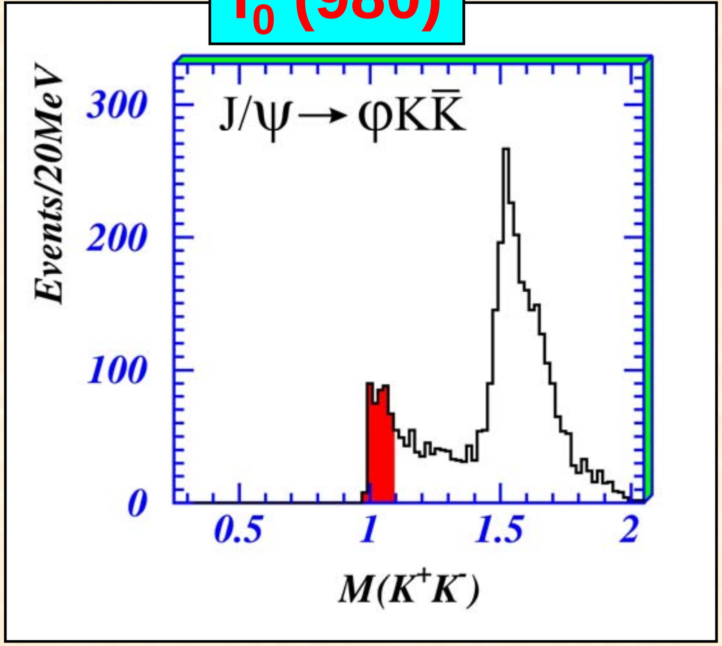
$J/\psi \longrightarrow \varphi M^+M^-$



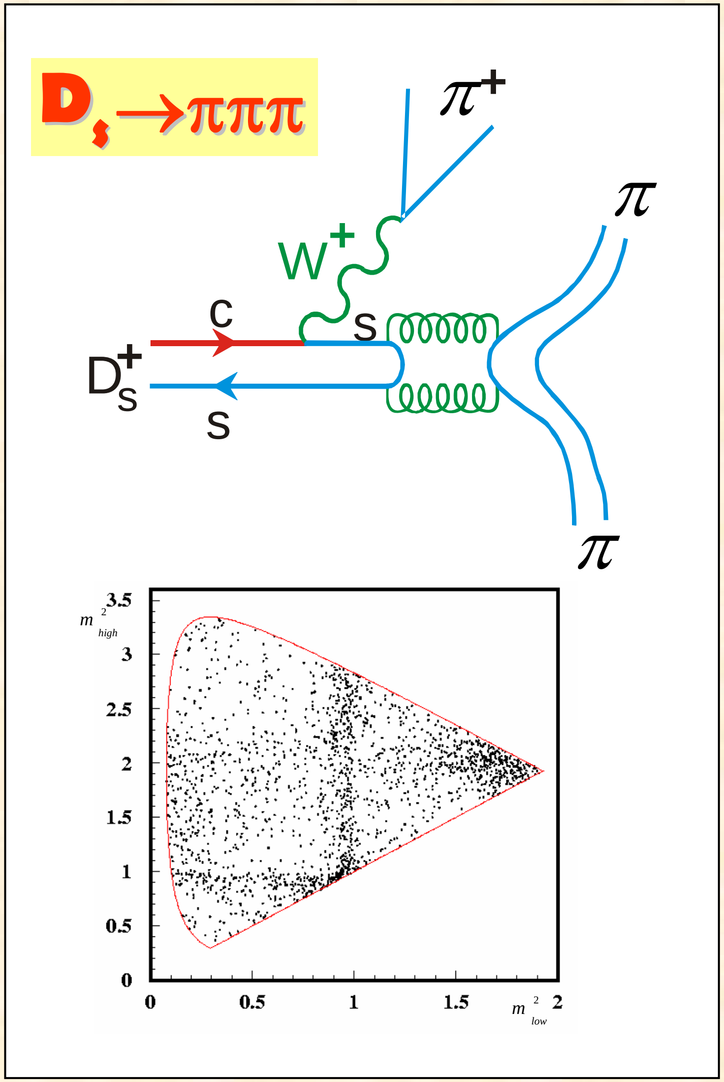


f_0 (980)

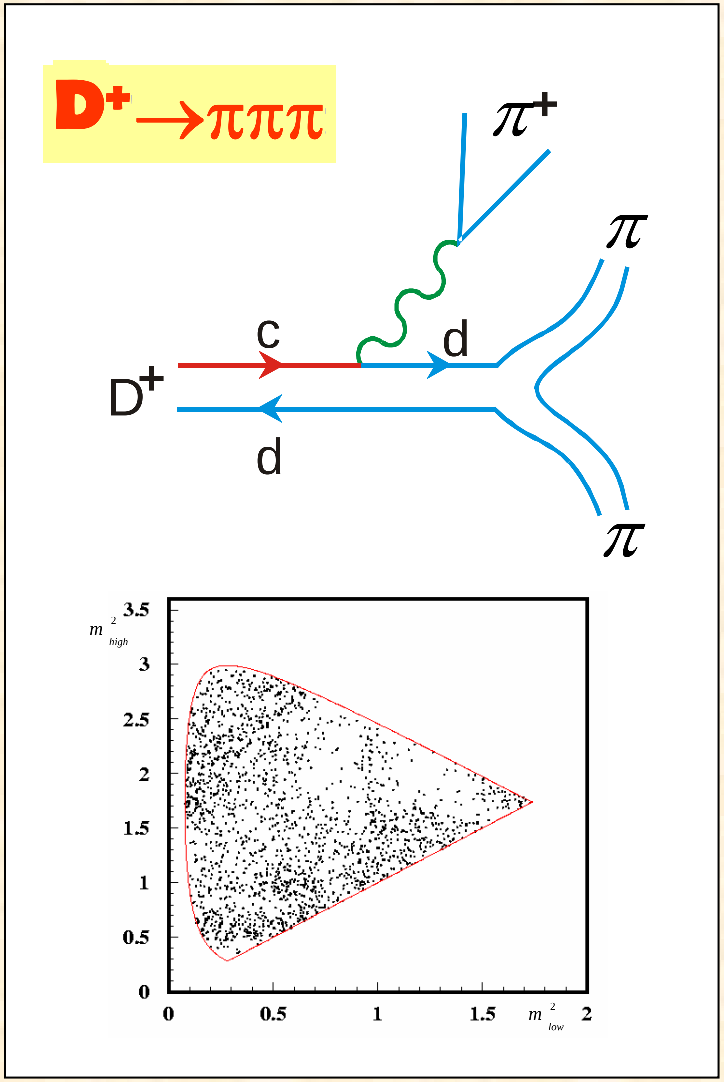




BES



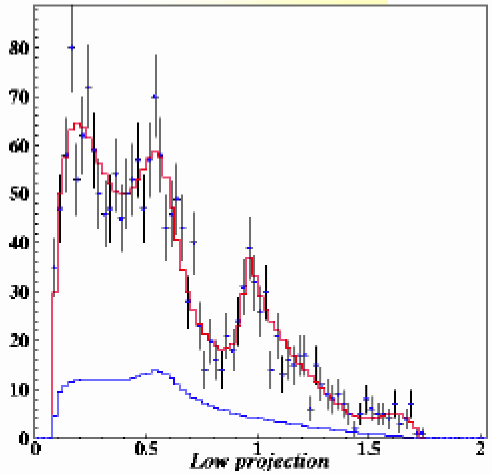
$D_s \rightarrow \pi\pi\pi$
π^+
W^+
π
c
s
D_s^+
s
π
m^2_{high}
m^2_{low}

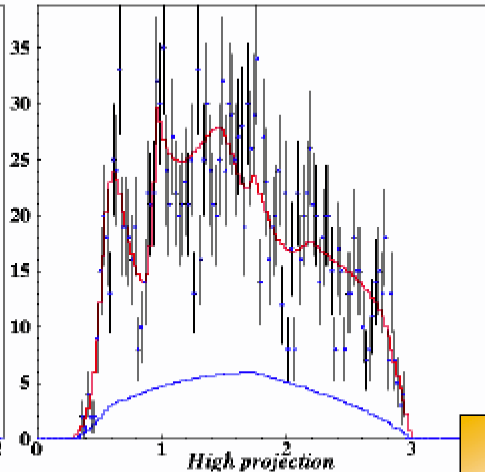


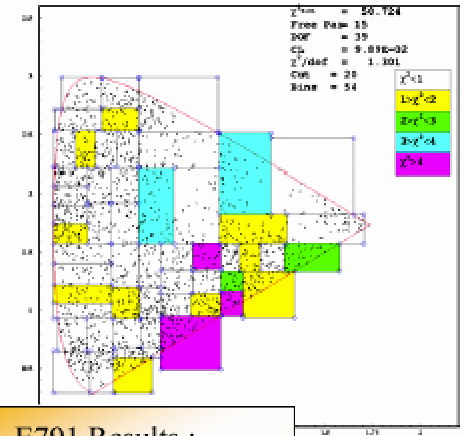
$D^+ \rightarrow \pi\pi\pi$
π^+
π
c
d
D^+
d
π
m^2_{high}
m^2_{low}

Preliminary

With $f_0(400)$







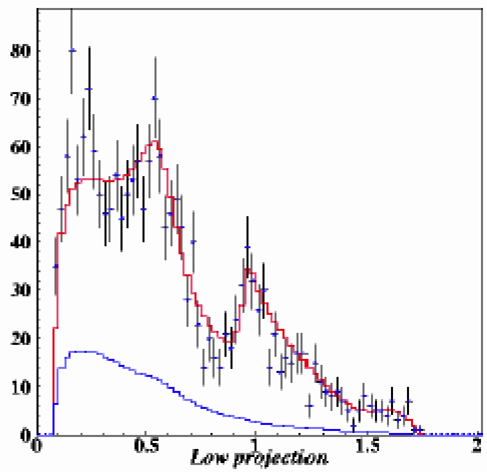
E791 Results :

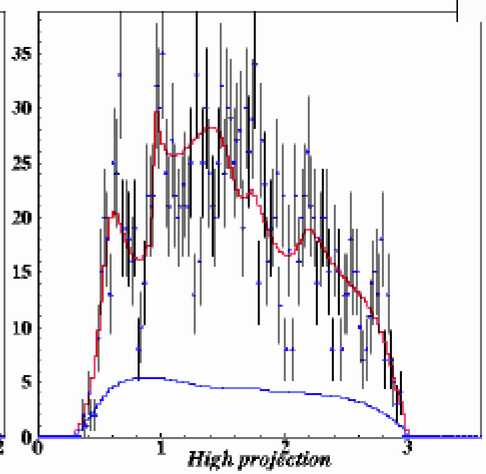
$m = 478^{+24}_{-23} \pm 17 MeV$

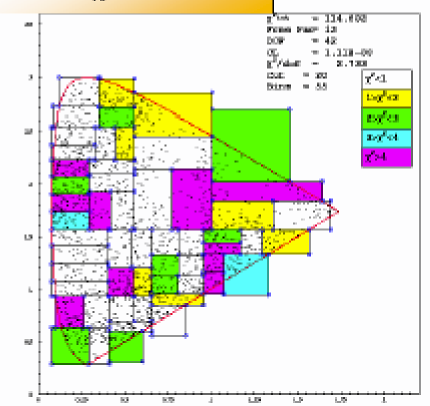
$\Gamma = 324^{+42}_{-40} \pm 21 MeV$

C.L. ~ 1 0%

Without $f_0(400)$

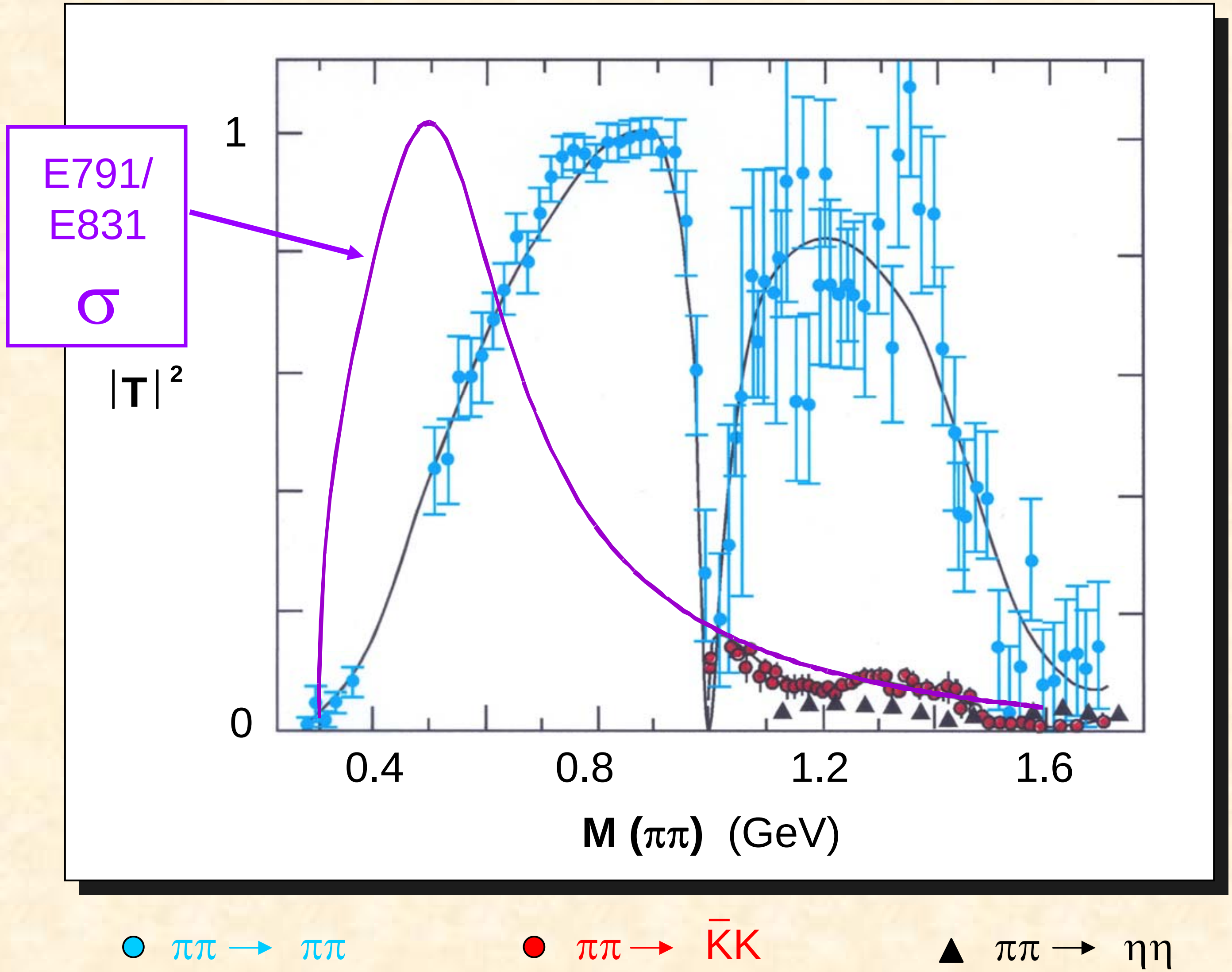






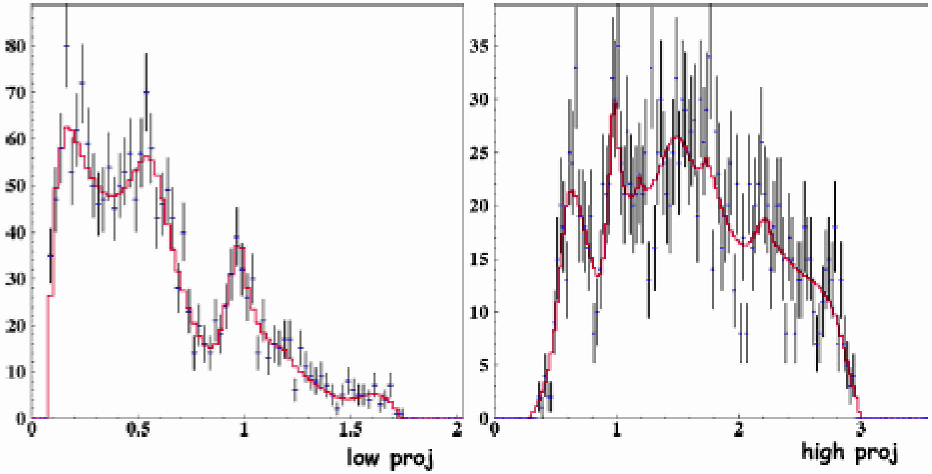
~ 10^{-8} %

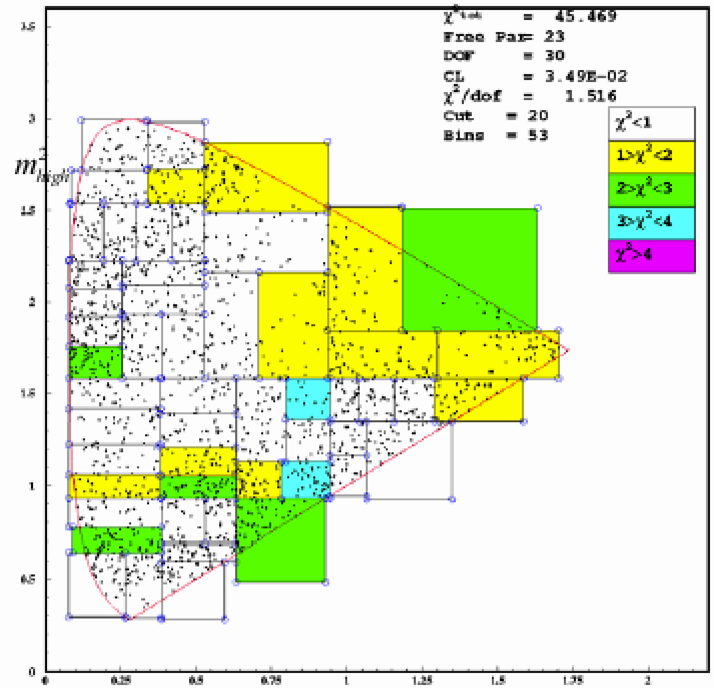
I = J = 0



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

preliminary



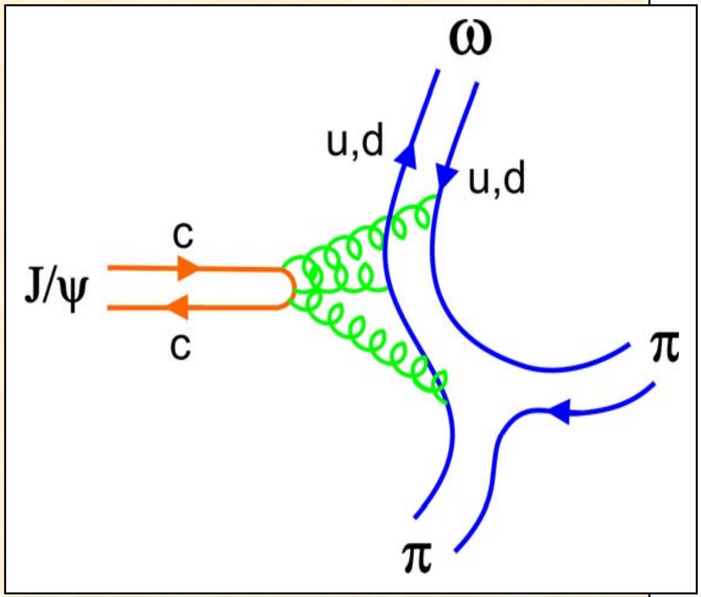


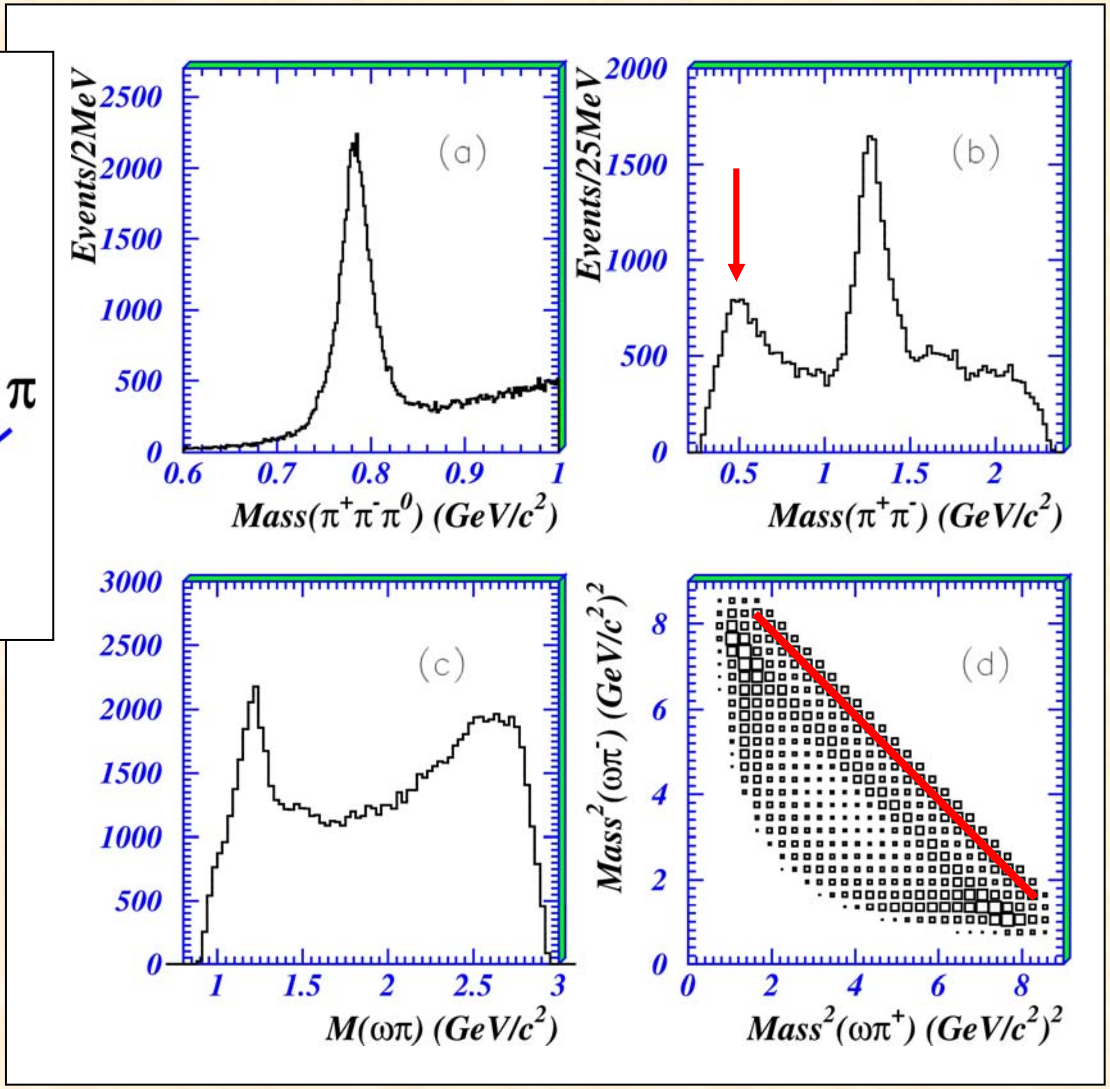
	fit fractions	phases
Γ Swave	= 0.6647 ± 0.0416	(101.8 ± 22.5)
Γ ρ(770)	= 0.2116 ± 0.0436	(0.0 ± 0.0)
Γ f_2(1275)	= 0.1143 ± 0.0142	(-113.0 ± 9.0)

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

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

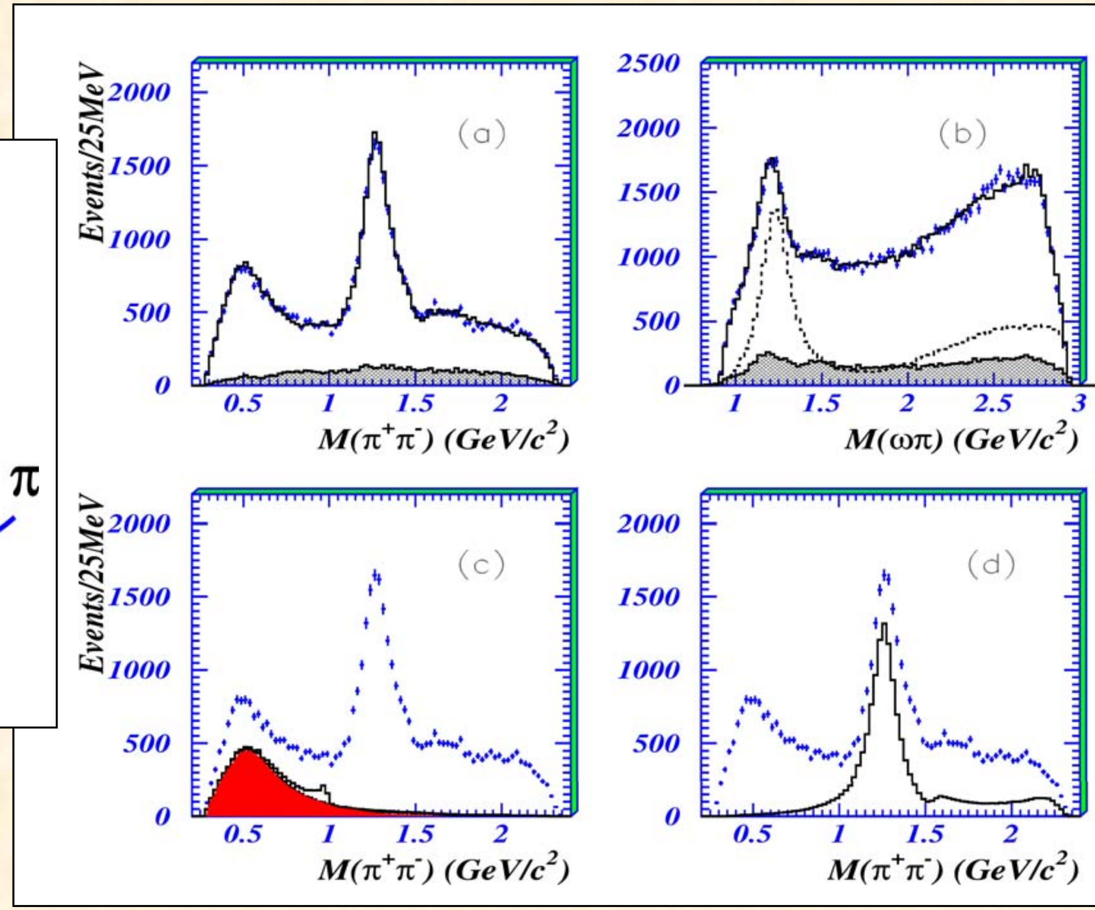
BES

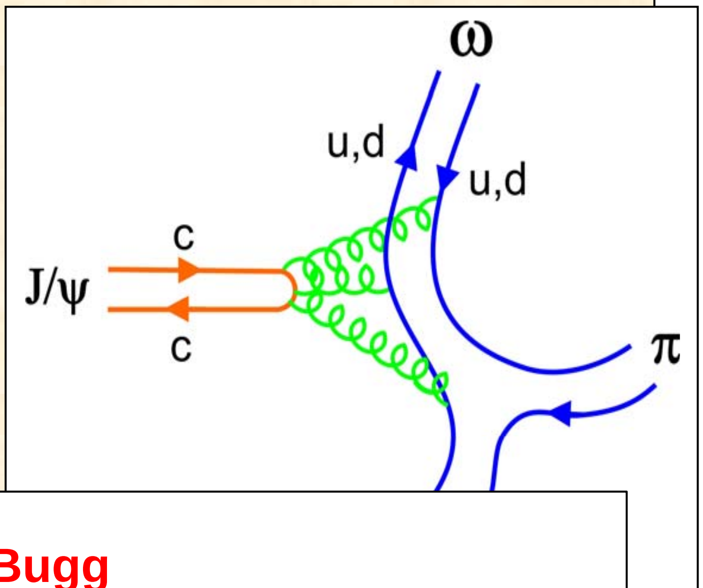


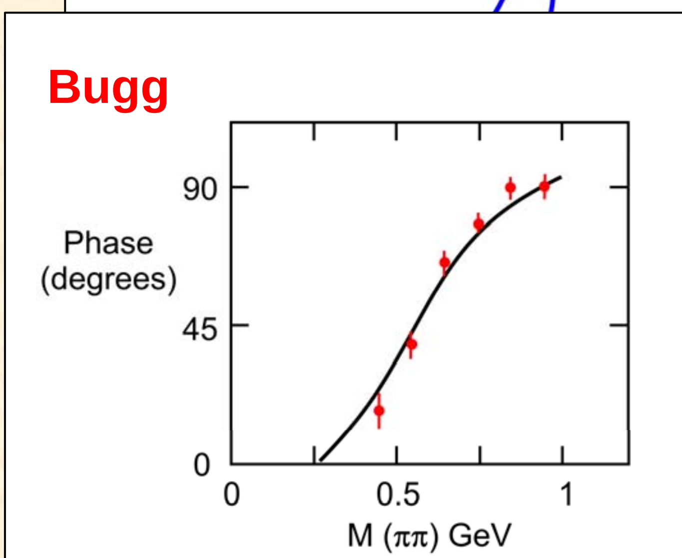


$J/\psi \longrightarrow \omega\,\pi^+\pi^-$

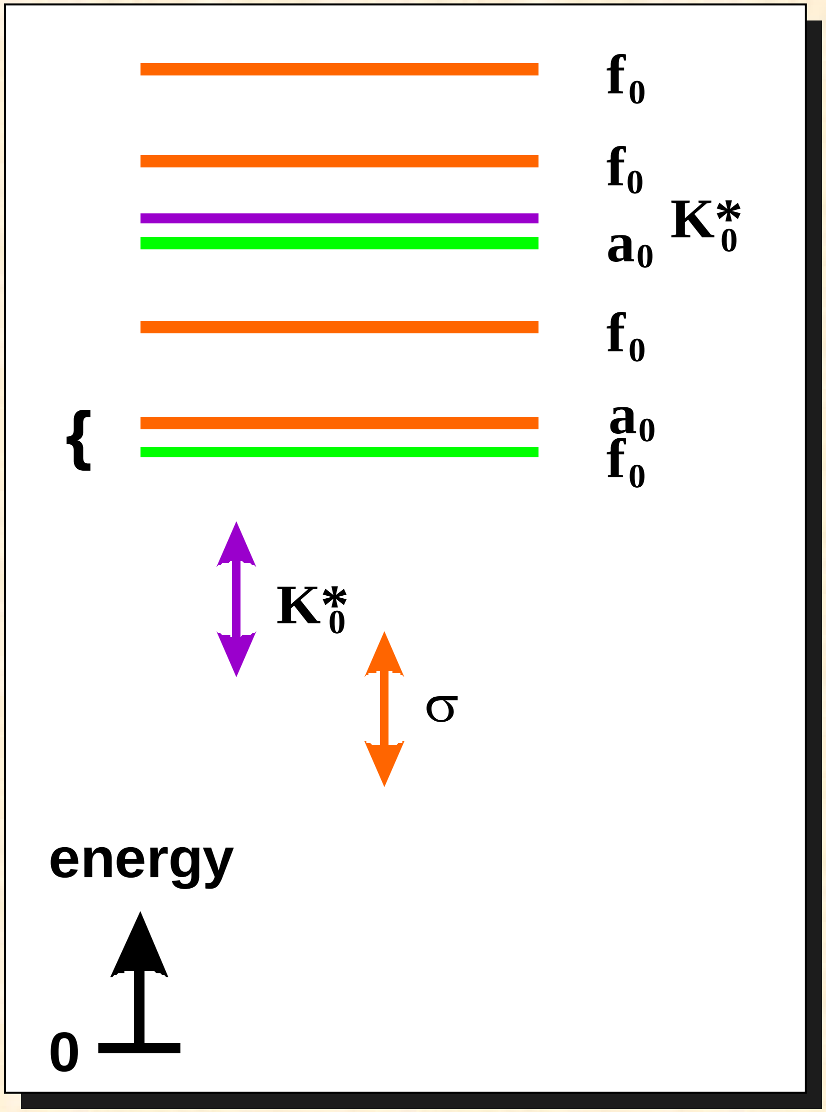
BES



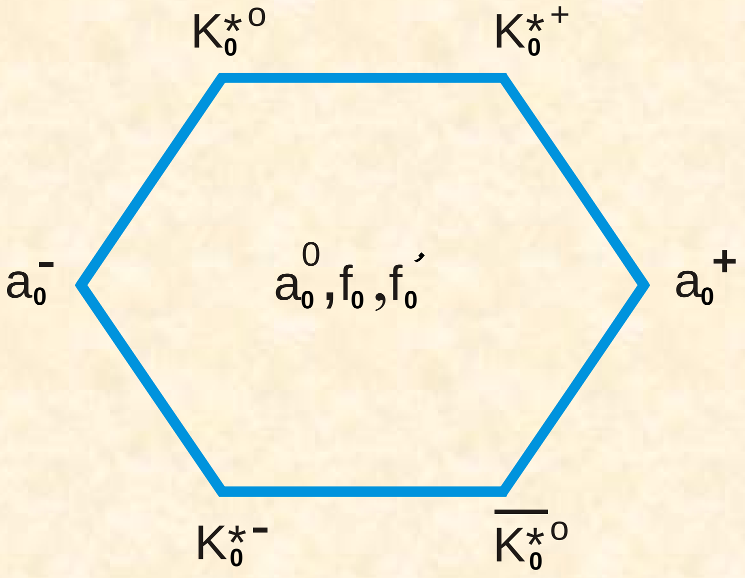




Scalar multiplet



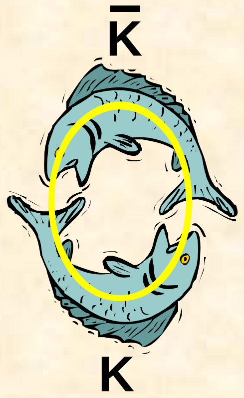
$J^{PC} = 0^{++}$



quark model = hadron world?

φ

+

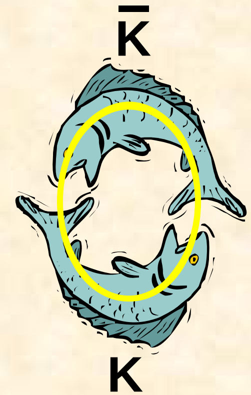


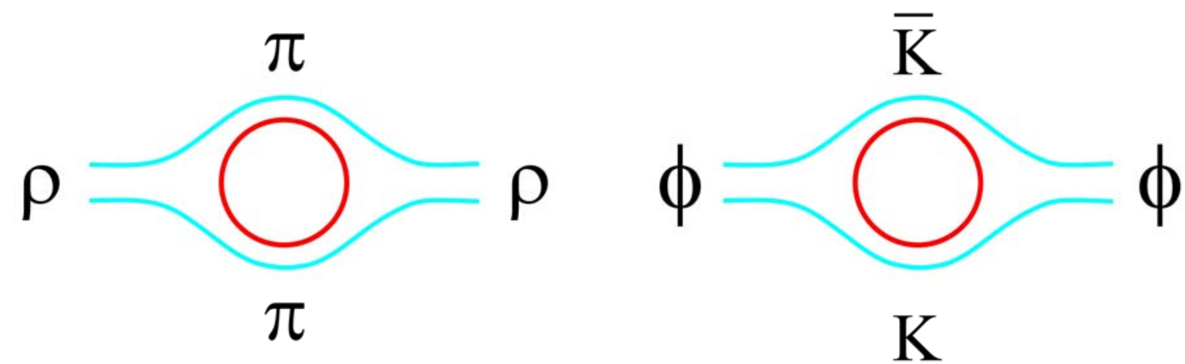
$$\frac{1}{m_0^2 - s} \longrightarrow \frac{1}{M^2 - s - iM\Gamma}$$

quark model = hadron world?

φ

$+ \quad \frac{1}{N_c}$

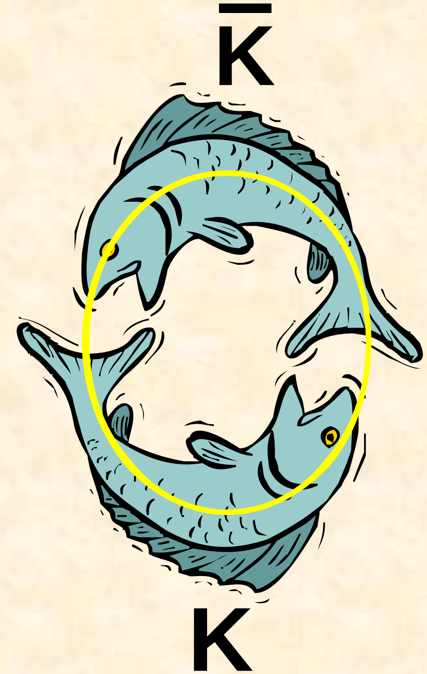




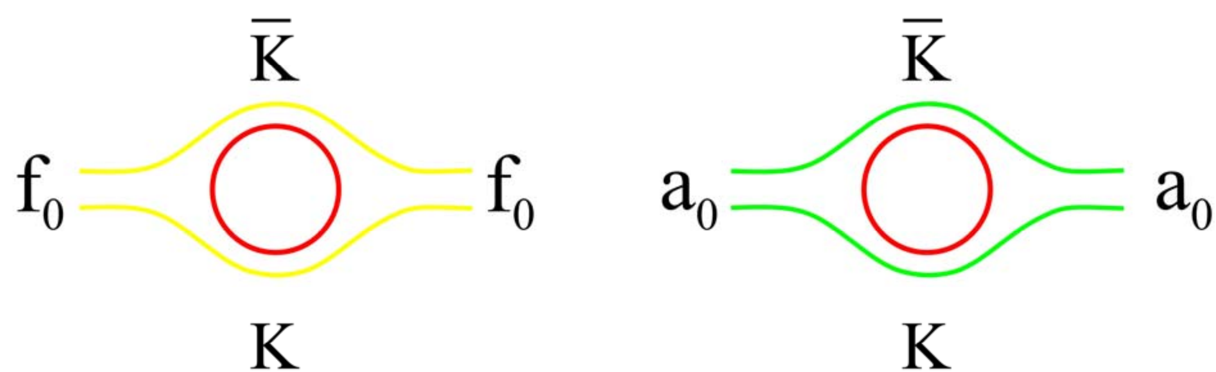
unquenching unimportant

f_0

+

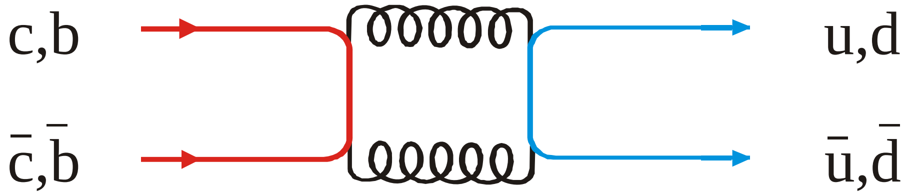


40%



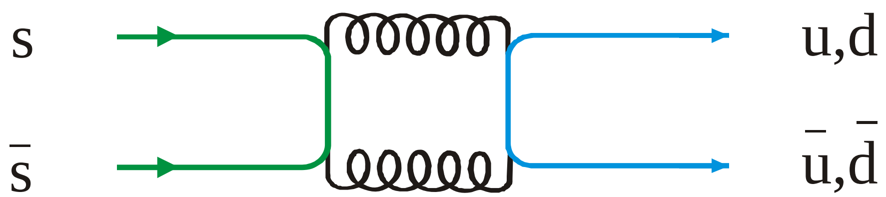
unquenching important

Flavour structure of QCD



Suppressed

$N_C = 3$, $N_C \to \infty$

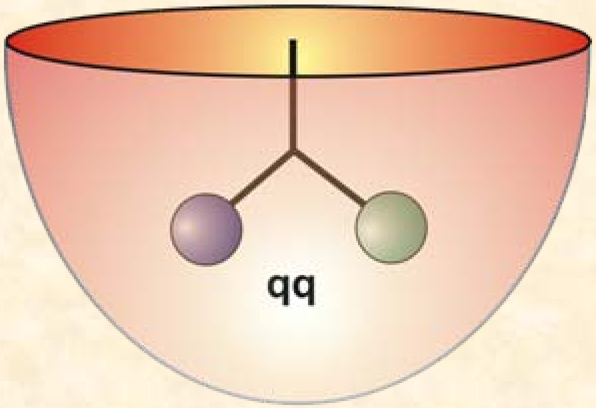


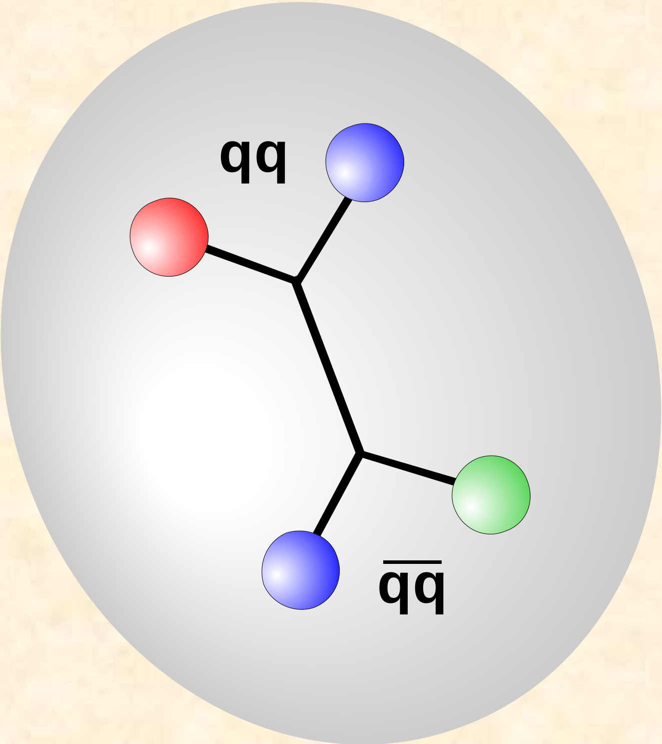
Suppression?

$N_C = 3$, $N_C \to \infty$

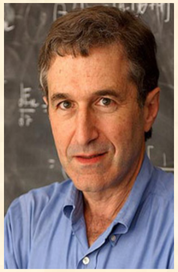
diquarks: colour

tetraquark





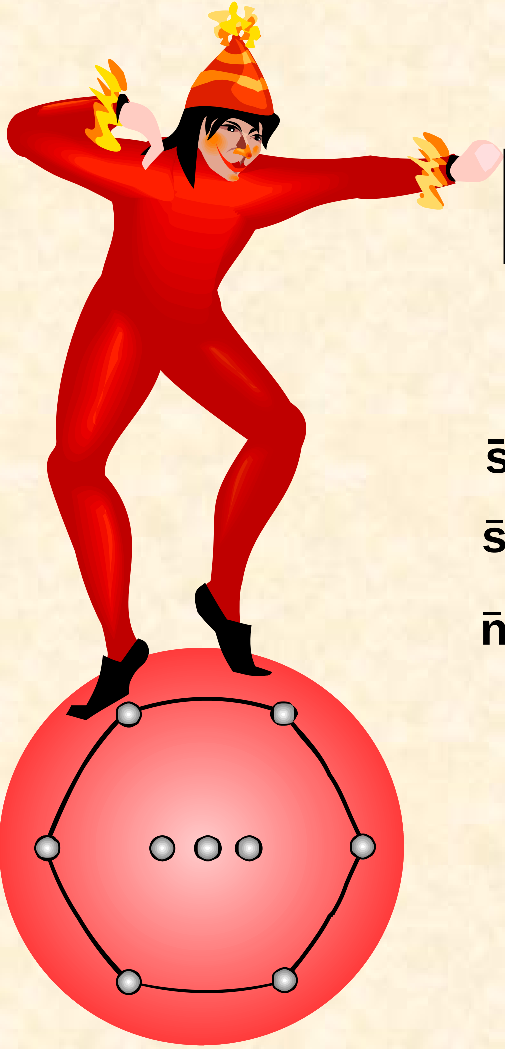
Jaffe & Wilczek



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

$q\bar{q}$

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

$\bar{s}s$ — f_0

$\bar{s}n$ — K_0

$\bar{n}n$ — a_0/f_0

$\bar{s}s\bar{n}n$ — a_0/f_0

$\bar{s}n\bar{n}n$ — K_0 κ

$\bar{n}n\bar{n}n$ — f_0 σ

Jaffe

Maiani, Piccinini, Polosa, Riquer

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

N_c large $\longrightarrow$ stable

N_c large $\longrightarrow$ meson continuum

To learn about the Higgs sector of QCD

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

~~CP~~