

Meson Spectroscopy

Adam Szczepaniak
Indiana University

CLAS12 European Workshop
Genova, Feb. 25-28

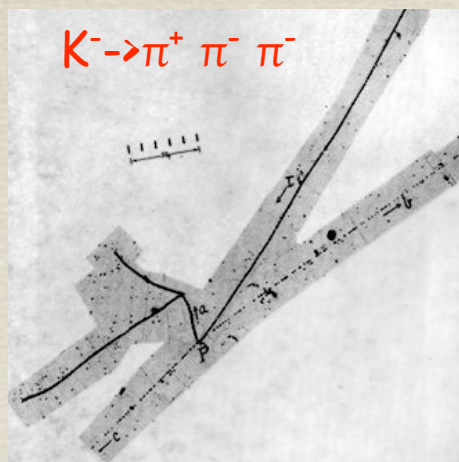


INDIANA UNIVERSITY

NUCLEAR THEORY CENTER
BLOOMINGTON

Outline

- Historical prelude
- Facts and myths: quark model or else?
- Exotics
- Amplitude analysis

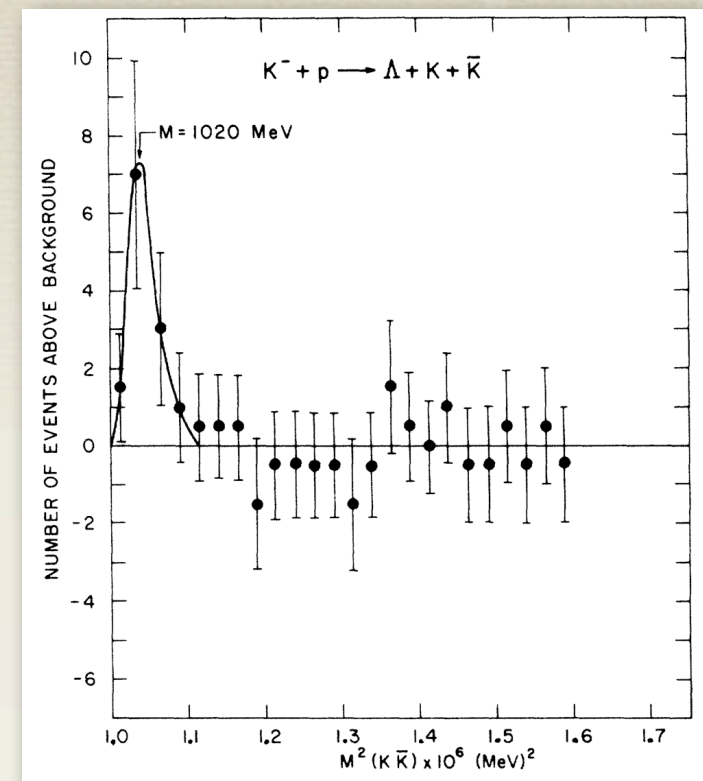
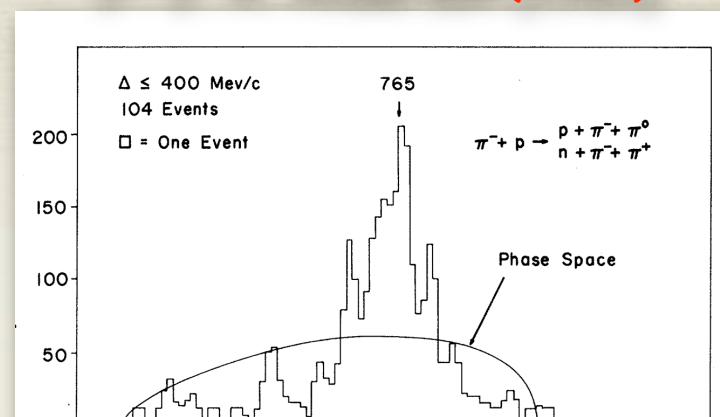


$K^- \rightarrow \pi^+ \pi^- \pi^-$

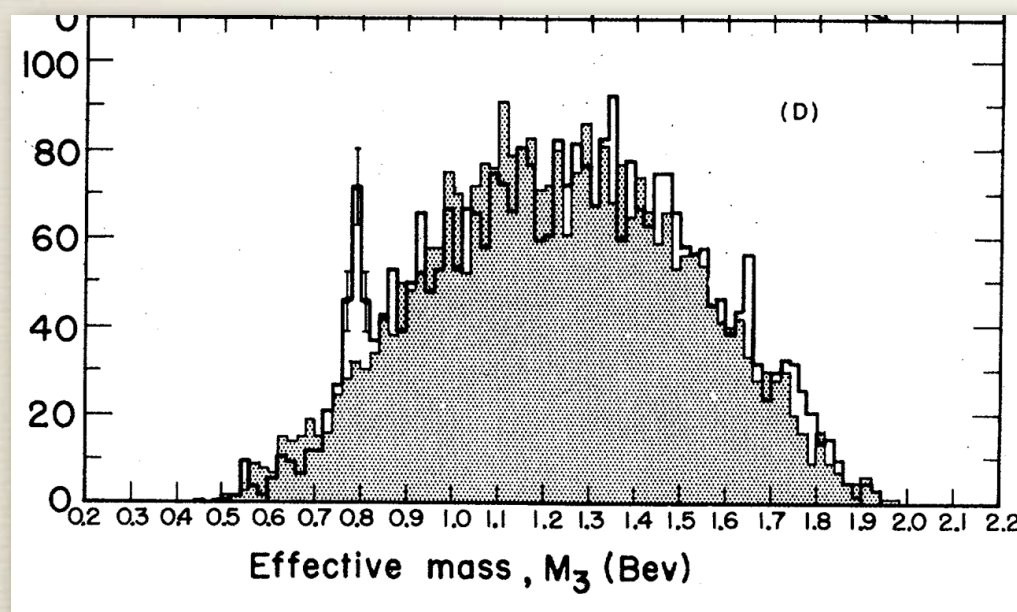
π : C.F. Powell (1947)

ρ : A.R. Erwin (1961)

ρ : J. A. Anderson (1960)



ϕ : P.L. Connolly, Pevsner (1962)



ω : L. Alvarez (1961)

η : A. Pevsner (1961)

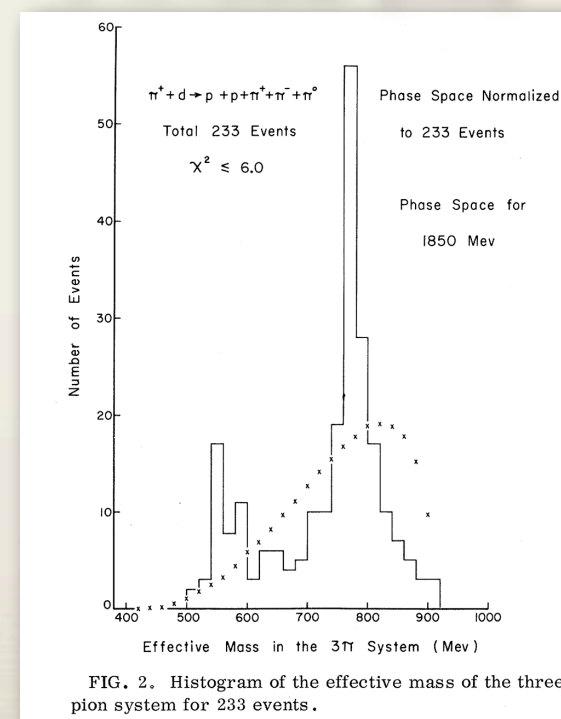
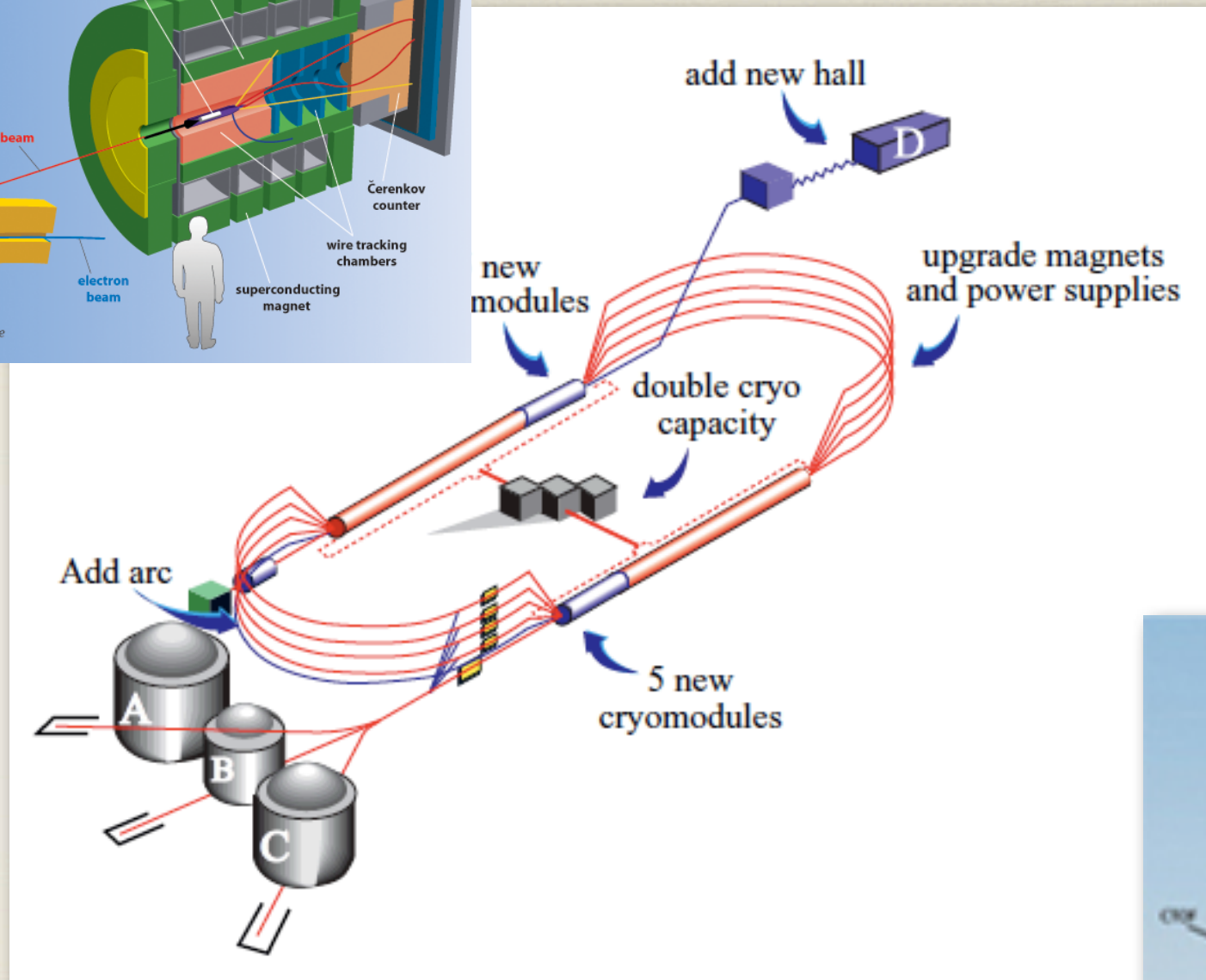
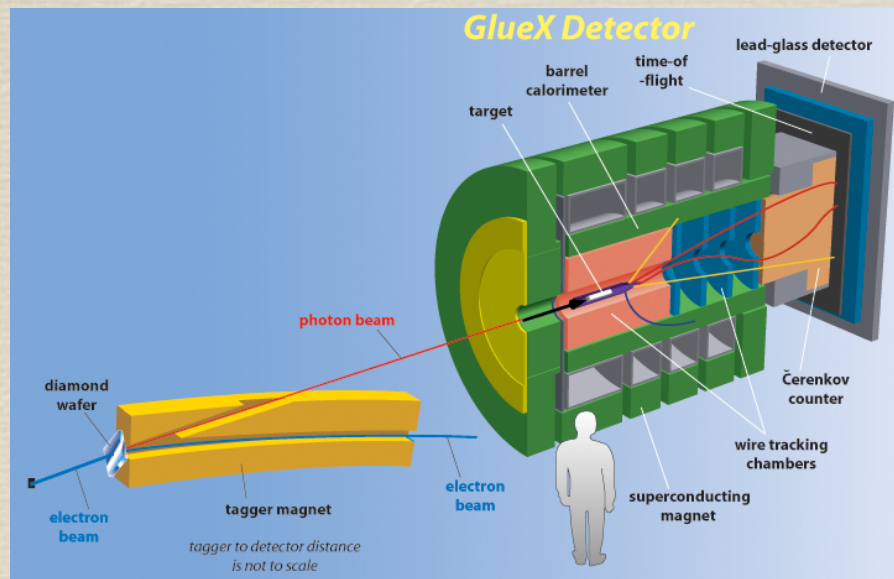
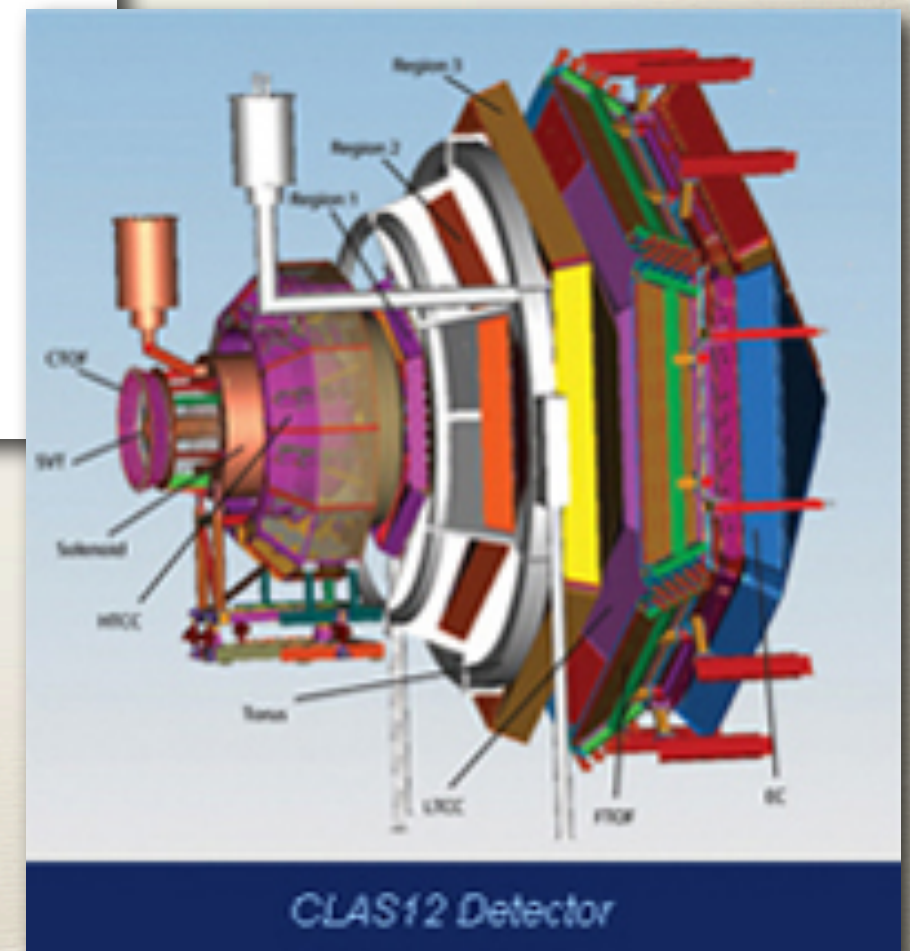


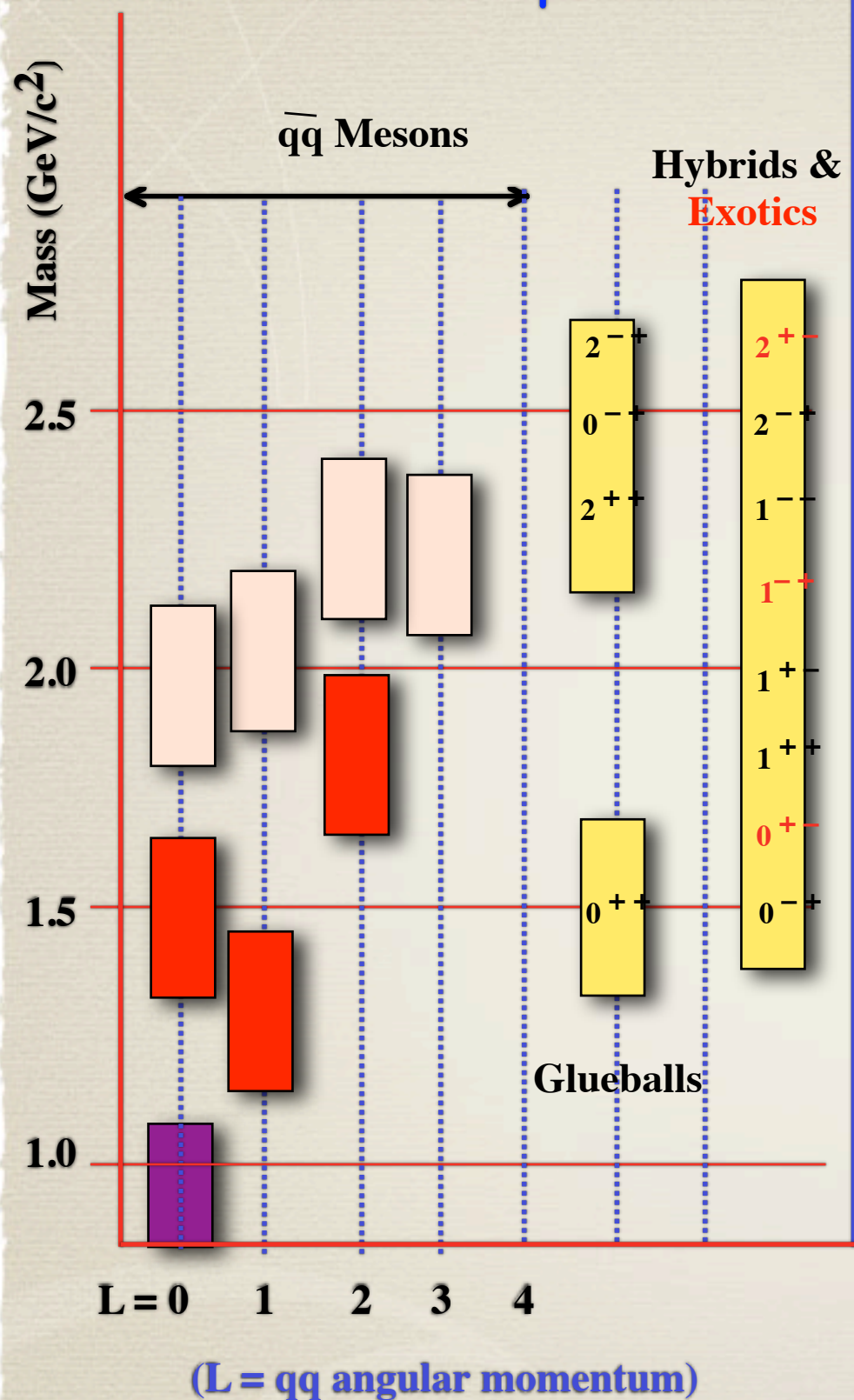
FIG. 2. Histogram of the effective mass of the three-pion system for 233 events.



New golden (platinum?)
era to come ...



Meson Map



well known states

$\pi, K, \eta, \eta', \rho, K^*, \omega, \phi$

radial and orbital excitations

$\pi', \rho', a_2, b_1, \rho_3$

higher excitations

$X(1600), X(1650), X(1750)$

Volume 8, number 3

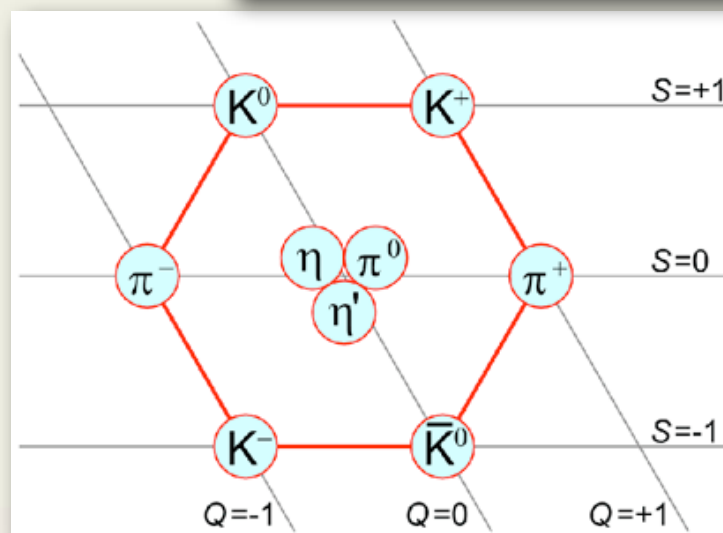
PHYSICS LETTERS

1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN

California Institute of Technology, Pasadena, California



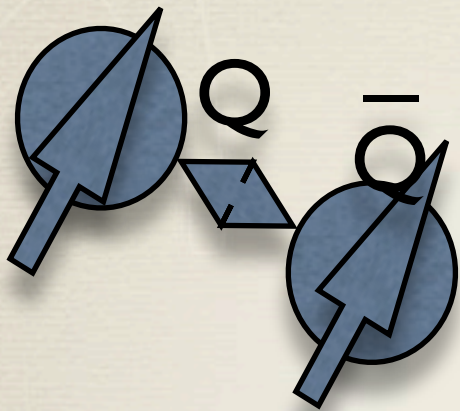
$\pi(1370)$	$K(1460)$	$\eta(????)$	$\eta(????)$	0^{-+}
$\rho(1450)$	$K^*(1410)$	$\phi(1680)$	$\omega(1420)$	1^{--}
$b_1(1235)$	K_{1B}	$h_1(1380)$	$h_1(1170)$	1^{+-}
$a_0(????)$	$K_0^*(1430)$	$f_0(????)$	$f_0(????)$	0^{++}
$a_1(1260)$	K_{1A}	$f_1(1510)$	$f_1(1285)$	1^{++}
$a_2(1320)$	$K_2^*(1430)$	$f_2(1525)$	$f_2(1270)$	2^{++}
$\pi_2(1670)$	$K_2(1770)$	$\eta_2(1870)$	$\eta_2(1645)$	2^{-+}
$\rho(1700)$	$K^*(1680)$	$\phi(???x)$	$\omega(1650)$	1^{--}
$\rho_2(???x)$	$K_2(1820)$	$\phi_2(???x)$	$\omega_2(???x)$	2^{--}
$\rho_3(1690)$	$K_3^*(1780)$	$\phi_3(1850)$	$\omega_3(1670)$	3^{--}

1. quark model extreme point of view:
Breit-Wigner resonances = QQ states

2. effective theory extreme point of
view: GB+complicated dynamical effects

Reality (QCD) is probably somewhere in between ...

Quark model: facts and myths



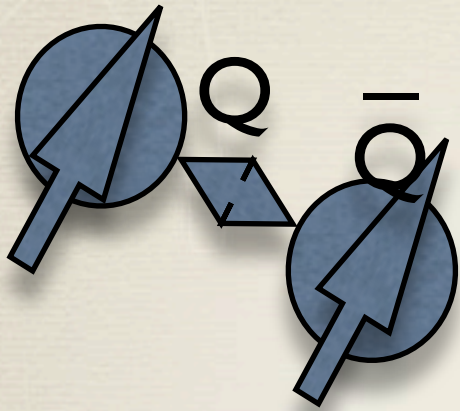
$$P = (-1)^{L+1}$$

$$C = (-1)^{L+S}$$

$$J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \dots$$

Constituent quarks and (L, S)
classification are consistent with
symmetries and dynamics of QCD

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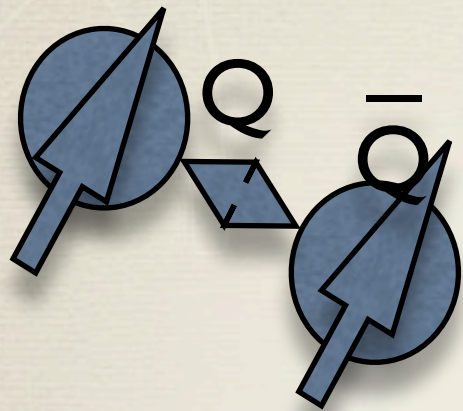
$$|h\rangle = |QQ\rangle\Psi_{q\bar{q}} + |QQg\rangle\Psi_{q\bar{q}g}$$

$$+ |Q\bar{Q}Q\bar{Q}\rangle\Psi_{q\bar{q}q\bar{q}} + \dots$$

bound vs molecular states?

$$\Psi_{q\bar{q}q\bar{q}} = \frac{\Psi_{q\bar{q}} \times \Psi_{q\bar{q}}}{\Psi_{qq\bar{q}\bar{q}}} \text{ or ?}$$

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Non-relativistic, few body problem

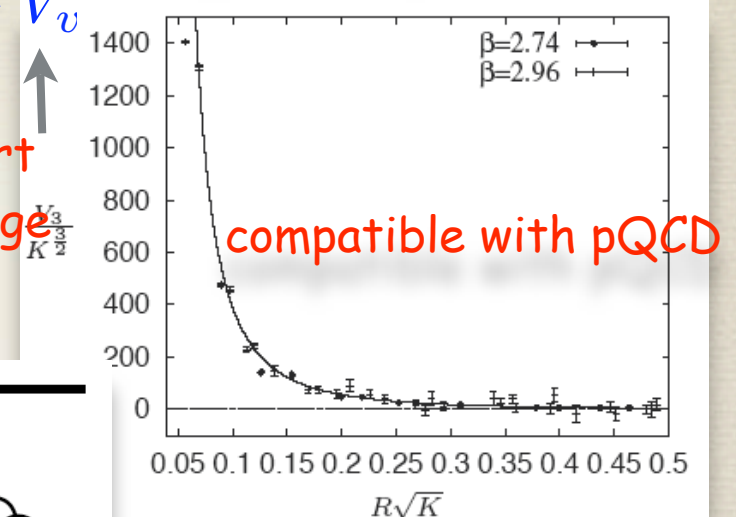
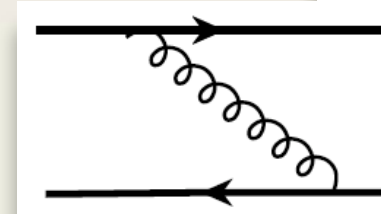
Light (constituent quarks) ~ heavy quarks originates from gluons \rightarrow potential

$$H = K_q + V_C + V_{LS} + V_{SS} + V_v$$

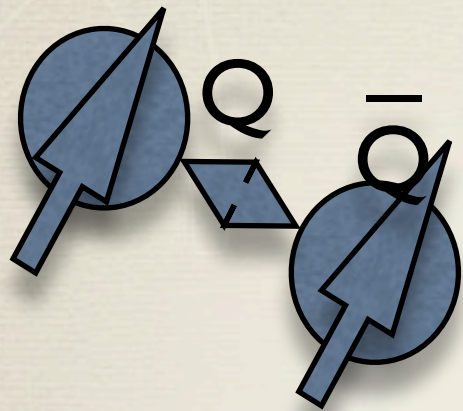
$$C_F (b_F - \alpha/r)$$

long
range

short
range



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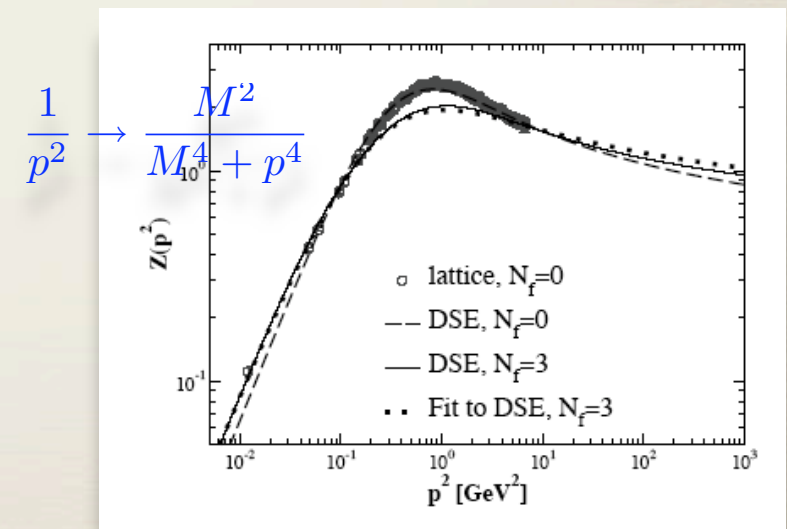
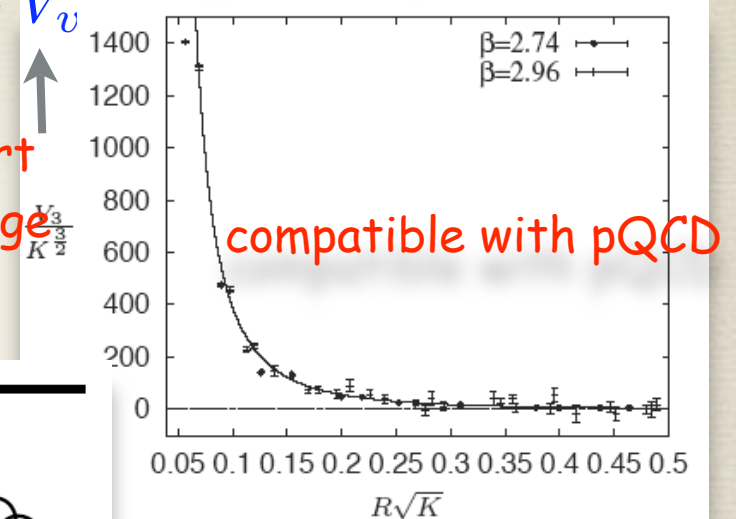
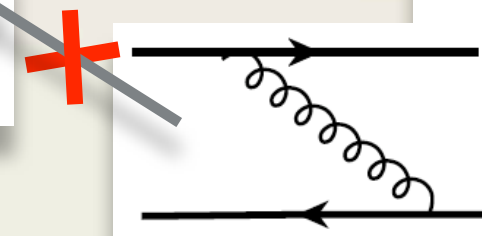
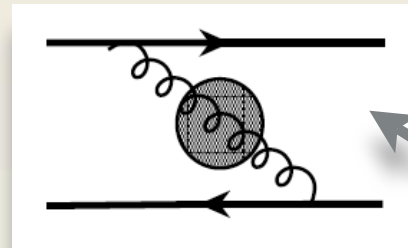
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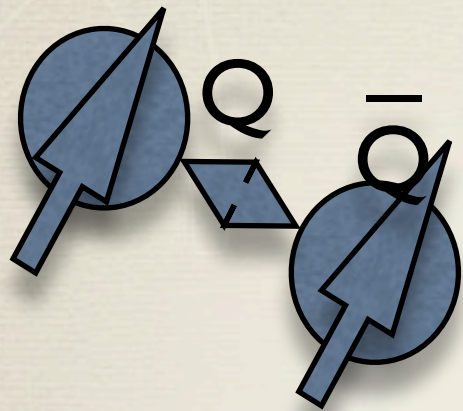
long
range

short
range



gluon propagator is IR suppressed
(Debye screening of magnetic charges)

Quark model: facts and myths



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Non-relativistic, few body problem

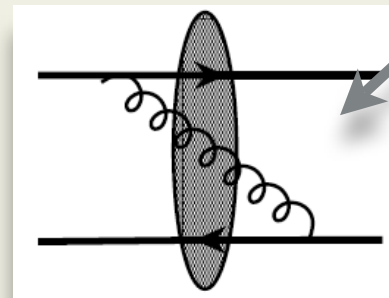
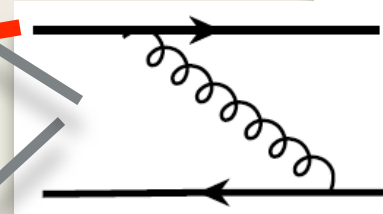
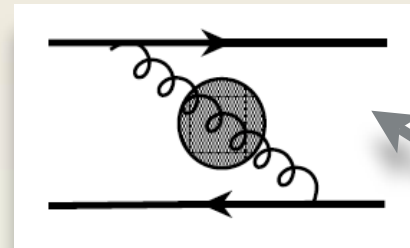
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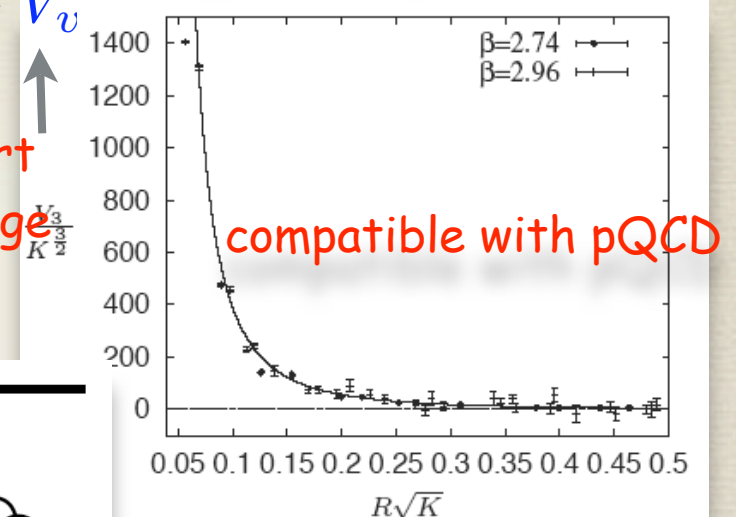
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long
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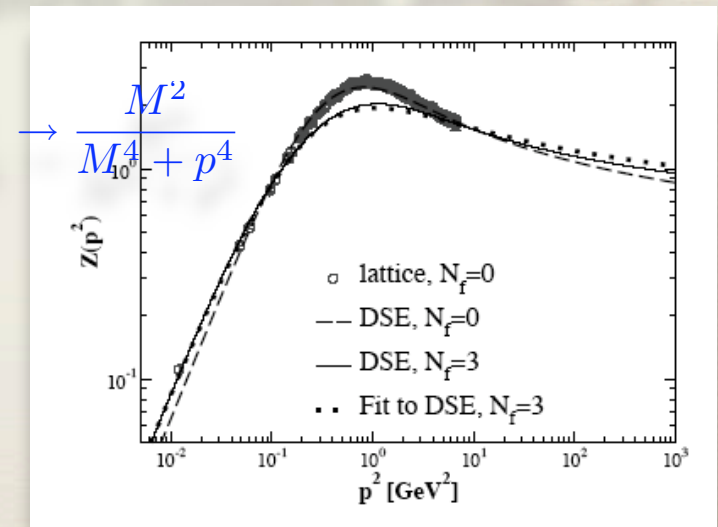


long range interactions reflect many-body features (monopoles, strings, ...)



No evidence for One Gluon exchange effects beyond hyperfine-splitting in quarkonia !

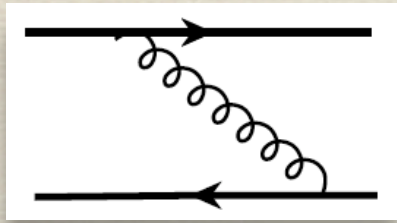
$$\frac{1}{p^2} \rightarrow \frac{M^2}{M_{10}^4 + p^4}$$



gluon propagator is IR suppressed (Debye screening of magnetic charges)

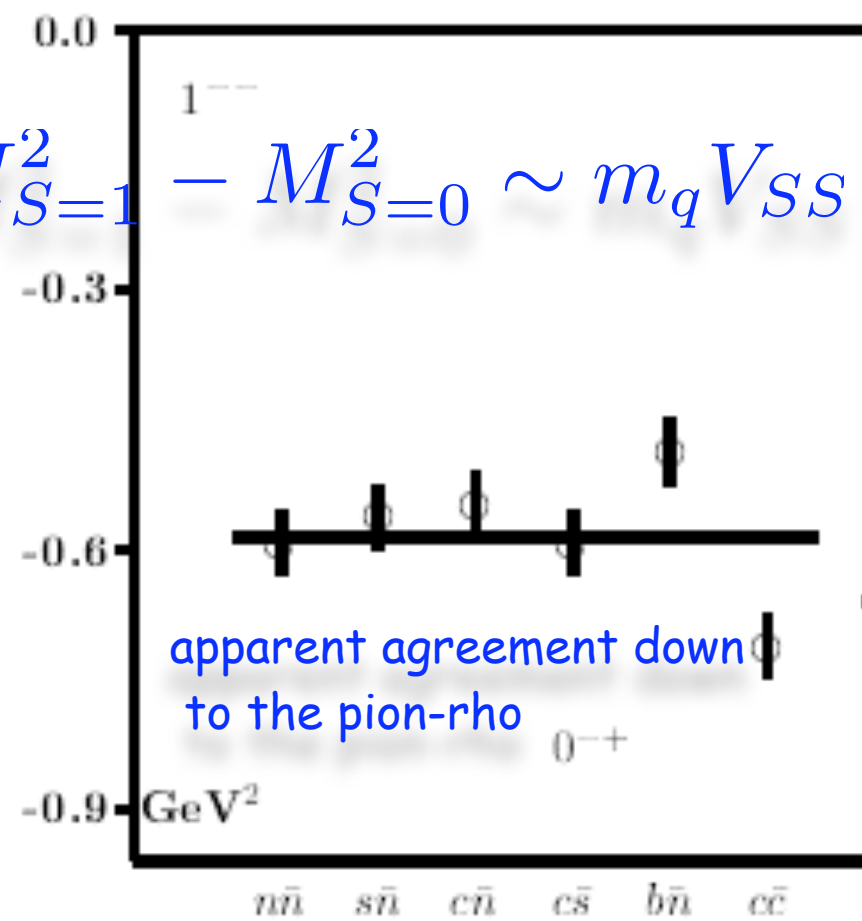
hyperfine-splitting from OGE

$$M_{S=1} - M_{S=0} \sim V_{SS}$$



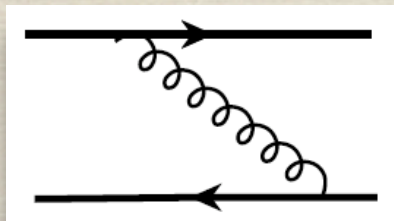
$$V_{SS} \sim \frac{\alpha}{m_q^2} \mathbf{S}_q \cdot \mathbf{S}_{\bar{q}} \delta^3(r_{q\bar{q}})$$

$$M_{S=1}^2 - M_{S=0}^2 \sim m_q V_{SS}$$



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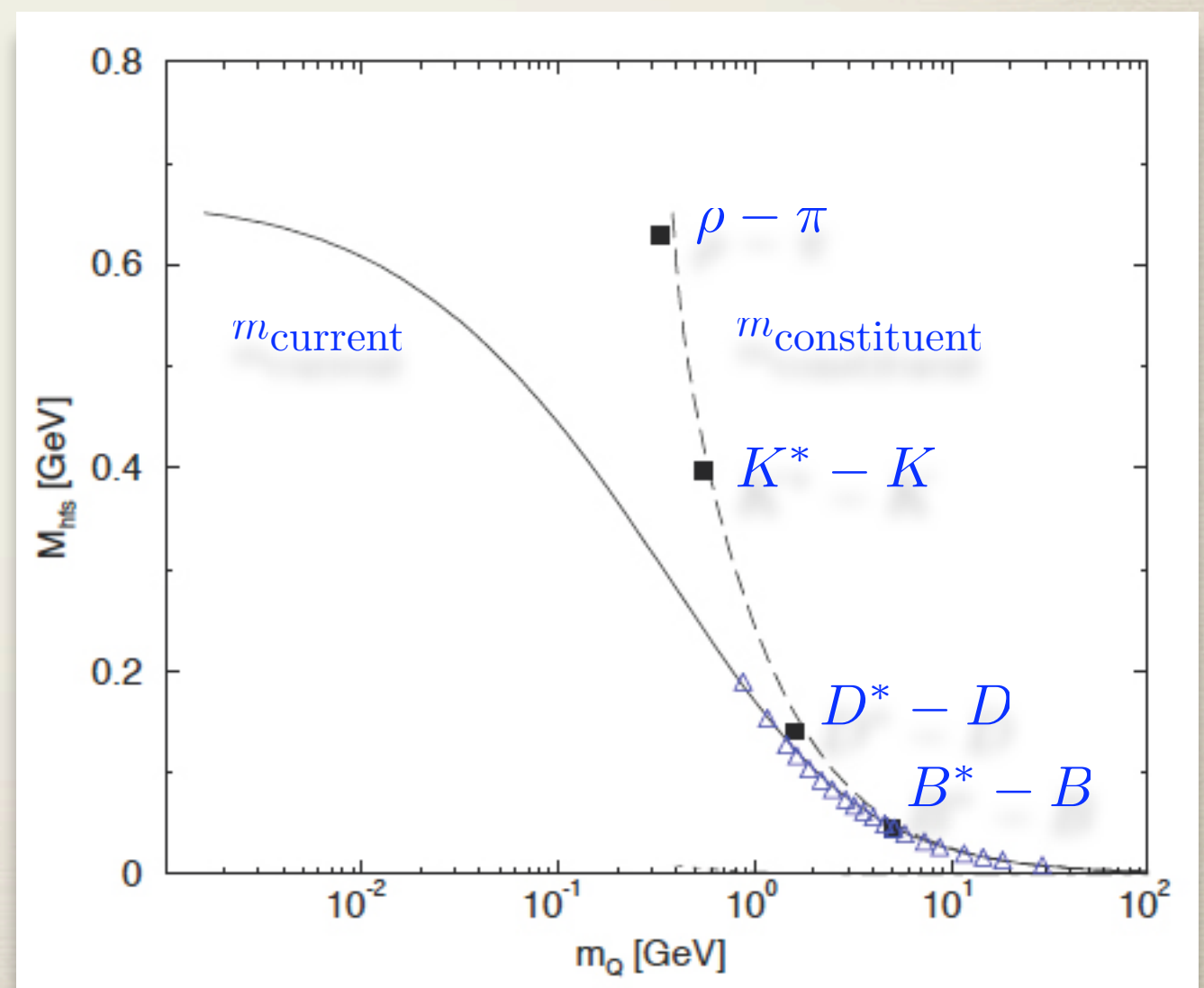
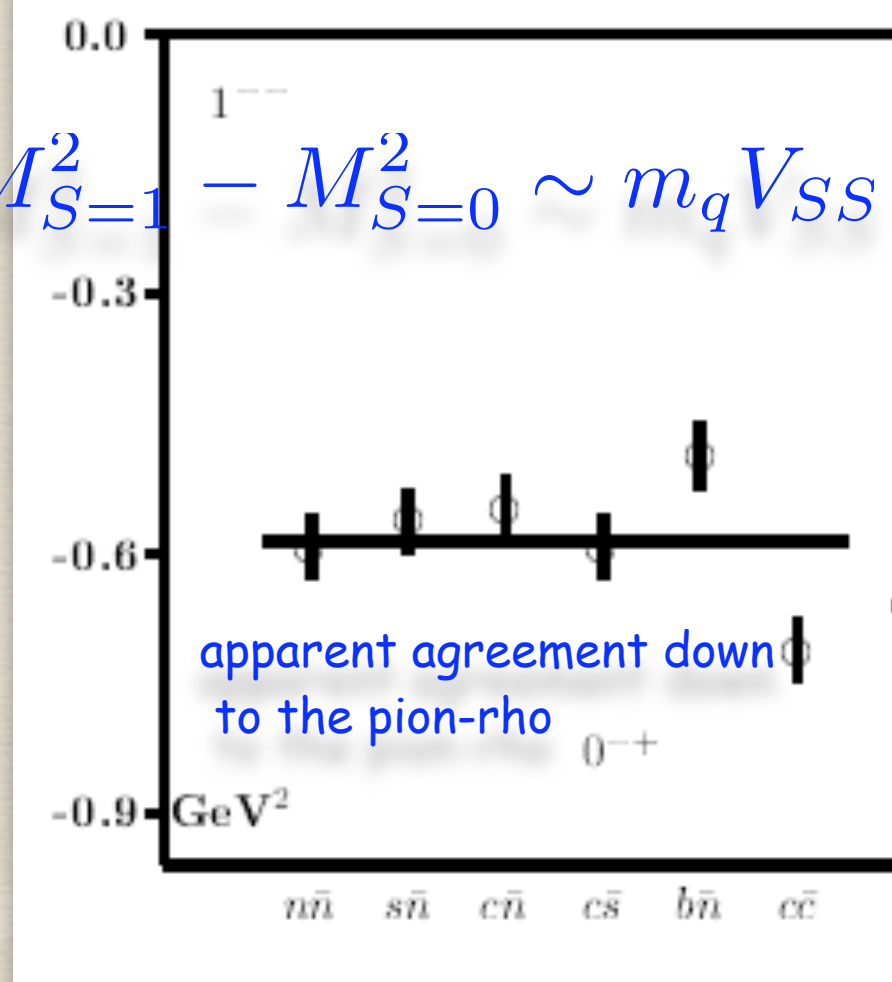
$$V_{SS} \sim \frac{\alpha}{m_q^2} \mathbf{S}_q \cdot \mathbf{S}_{\bar{q}} \delta^3(r_{q\bar{q}})$$

pion is not a qq pair -> it is a coherent state of constituent qq pairs.

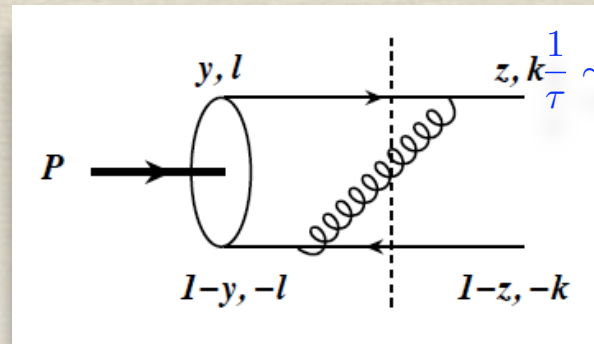
$$|\pi\rangle = |Q\bar{Q}\rangle + |Q\bar{Q}^2\rangle + |(Q\bar{Q})^3\rangle$$

The apparent $1/m_q$ ρ - π mass splitting is accidental ! Even happens in absence of spin-dependent interactions !

$$M_{S=1}^2 - M_{S=0}^2 \sim m_q V_{SS}$$



more on one-gluon
exchange and light
quarks



$$\sum_i E_i - E \sim \sum_i \frac{k_{\perp,i}^2 + m_i^2}{zP^+} - \frac{M^2}{P^+}$$

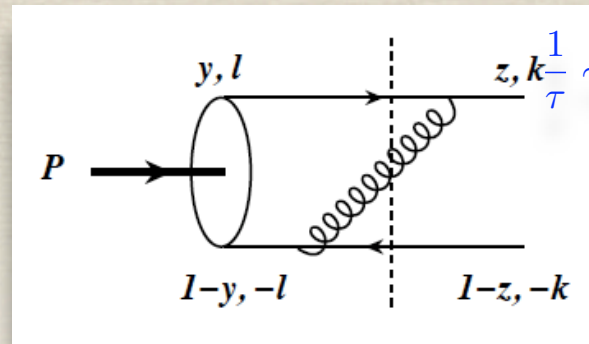
$$zP^+ \gg (k_{\perp,i}, m_i)$$

$$\Psi_{LC}(zp^+, k_{\perp}) \sim \frac{1}{\Delta E_{LC}} \sim \frac{z(1-z)}{k_{\perp}^2}$$

expansion not valid at end points $z \rightarrow 0, 1$!
w.f may be less suppressed at end points



more on one-gluon exchange and light quarks

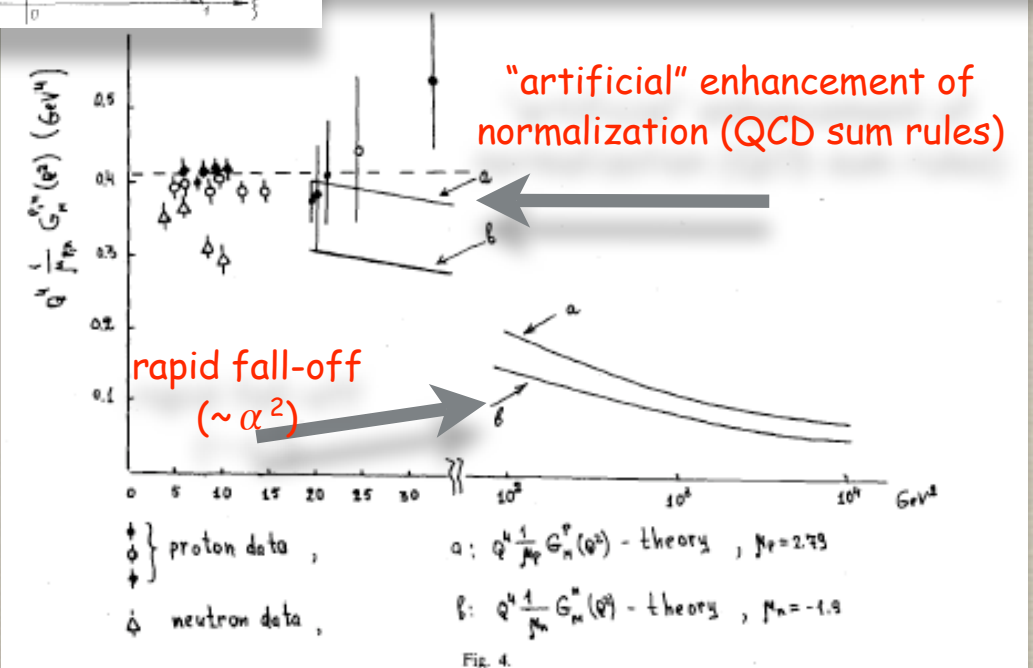
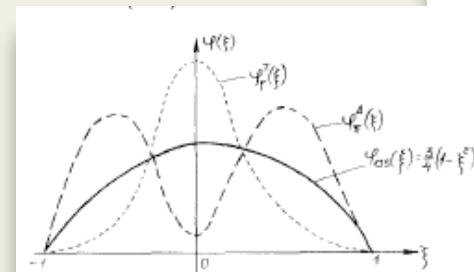
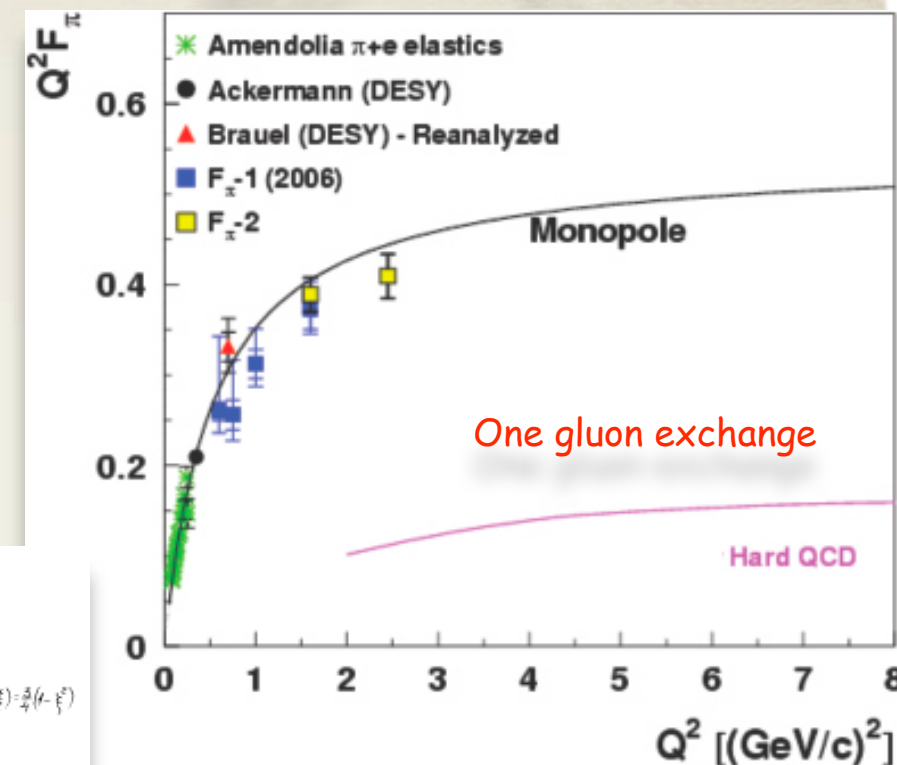


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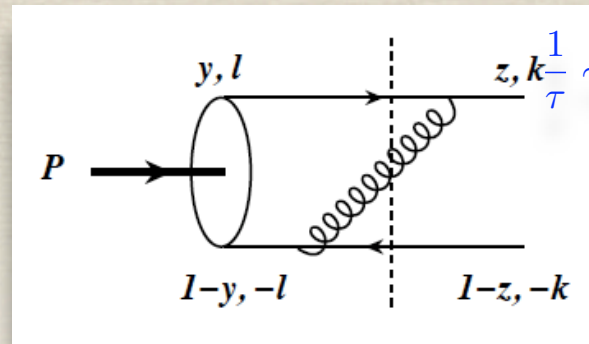
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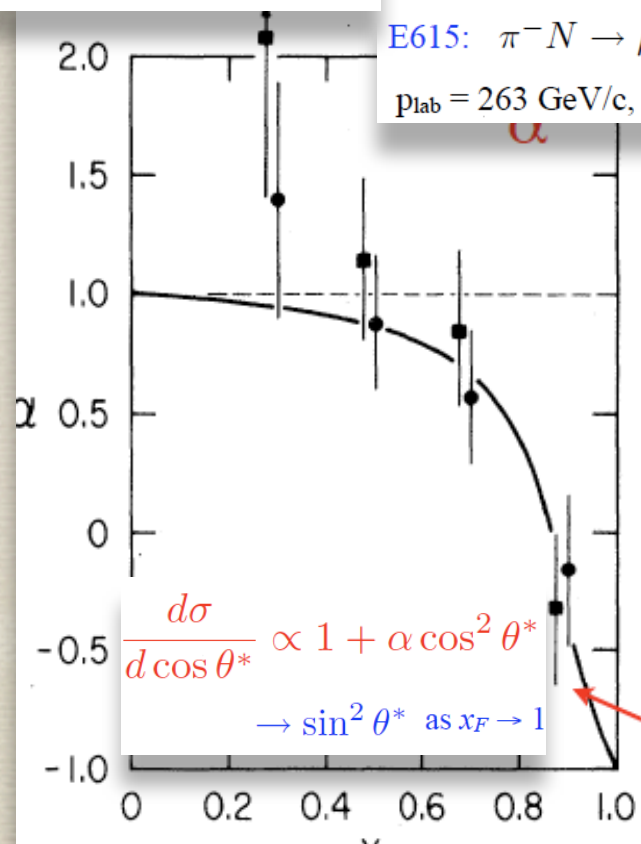
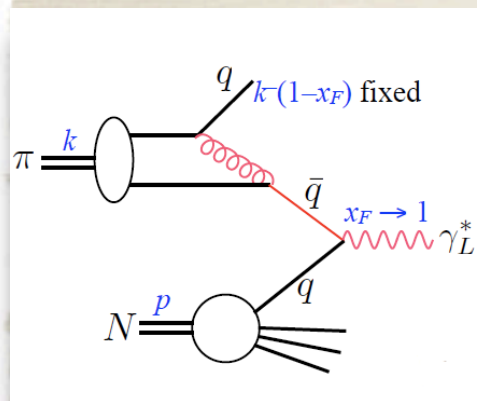


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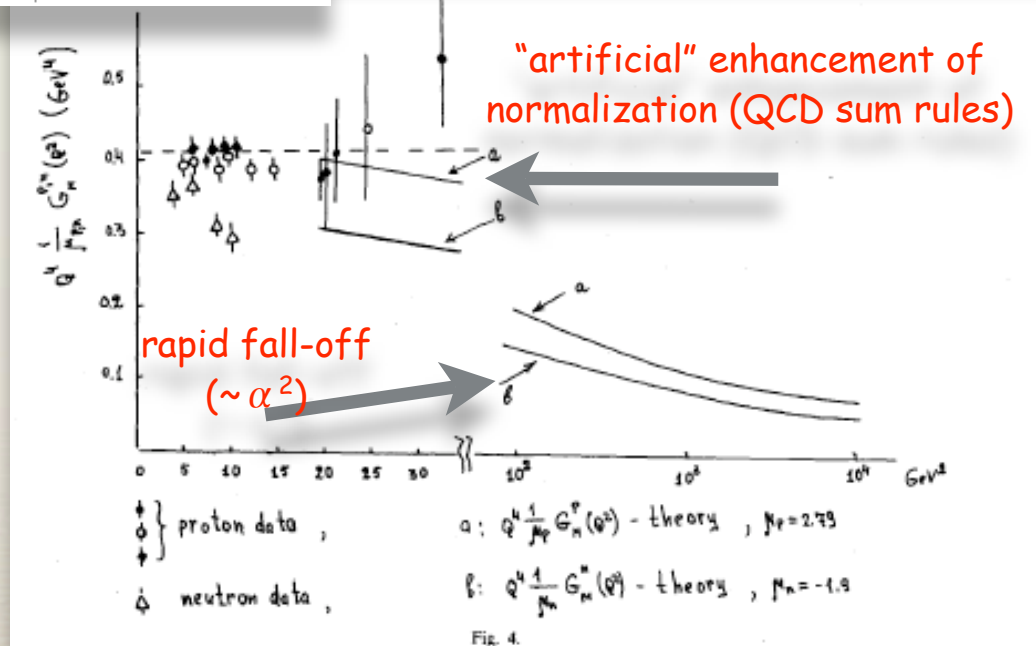
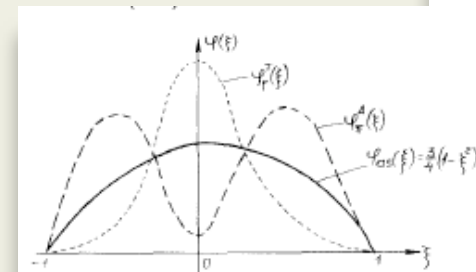
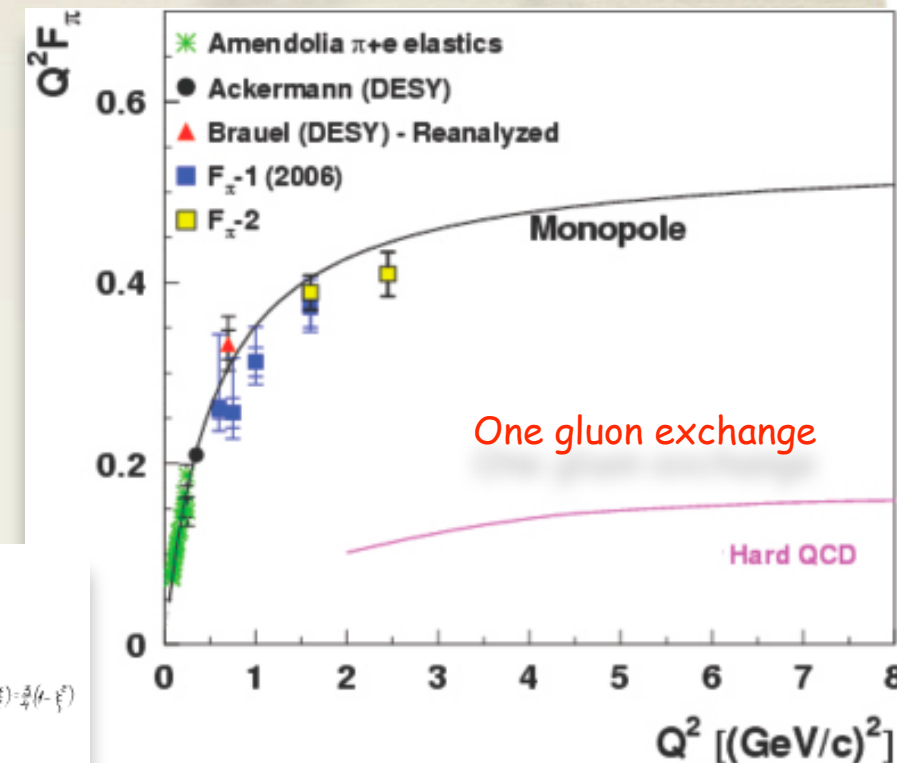


E615: $\pi^- N \rightarrow \mu^+ \mu^- + X$
 $p_{\text{lab}} = 263 \text{ GeV/c}$, $Q > 4 \text{ GeV}$

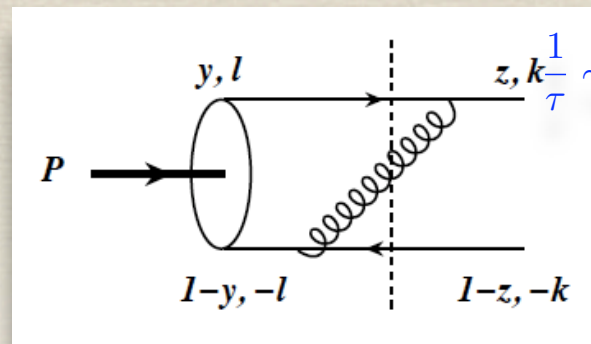
$$\frac{d\sigma}{d\cos\theta^*} \propto 1 + \alpha \cos^2\theta^*$$

$$\rightarrow \sin^2\theta^* \text{ as } x_F \rightarrow 1$$

... low-x partons are soft and coherent with the hard scattering sub-process



more on one-gluon exchange and light quarks

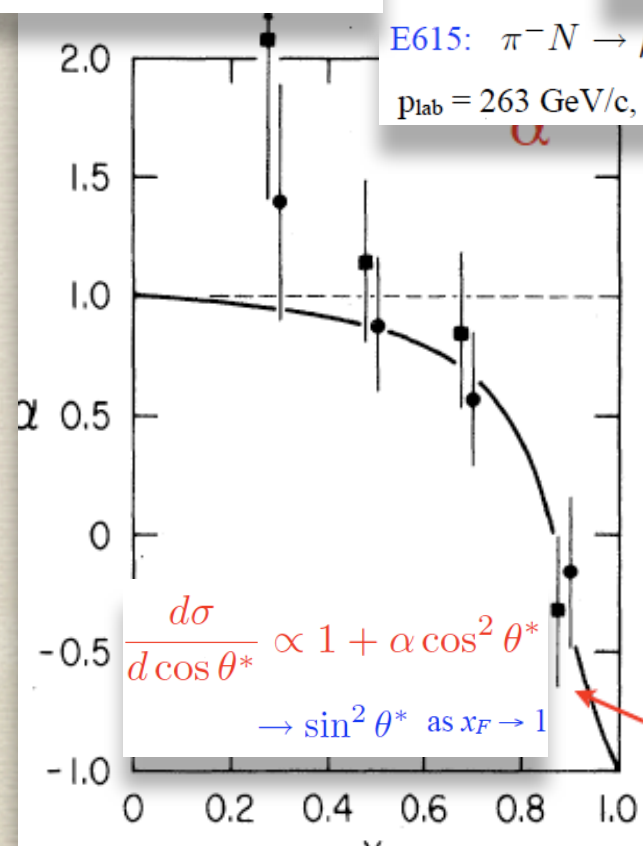
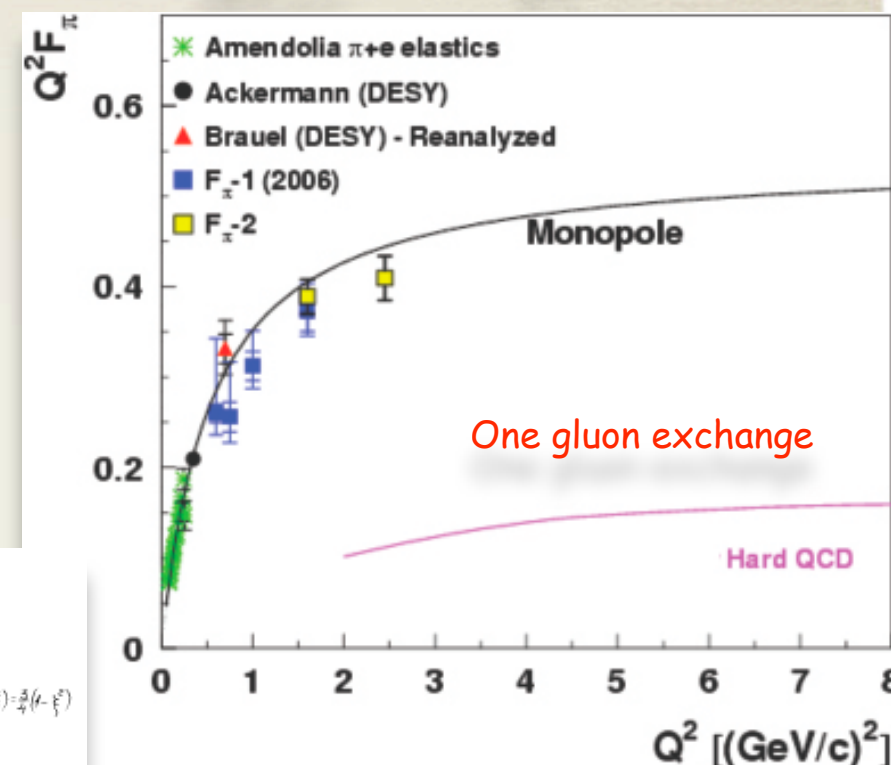
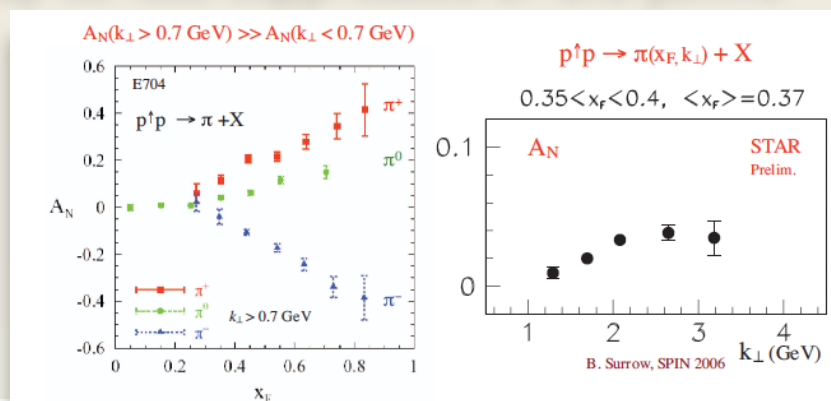
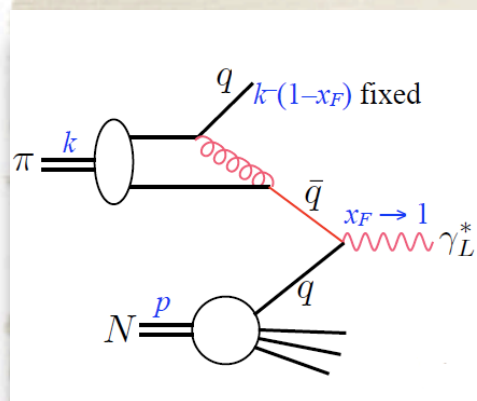


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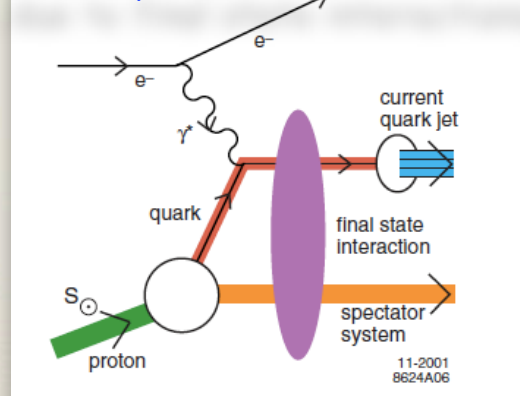
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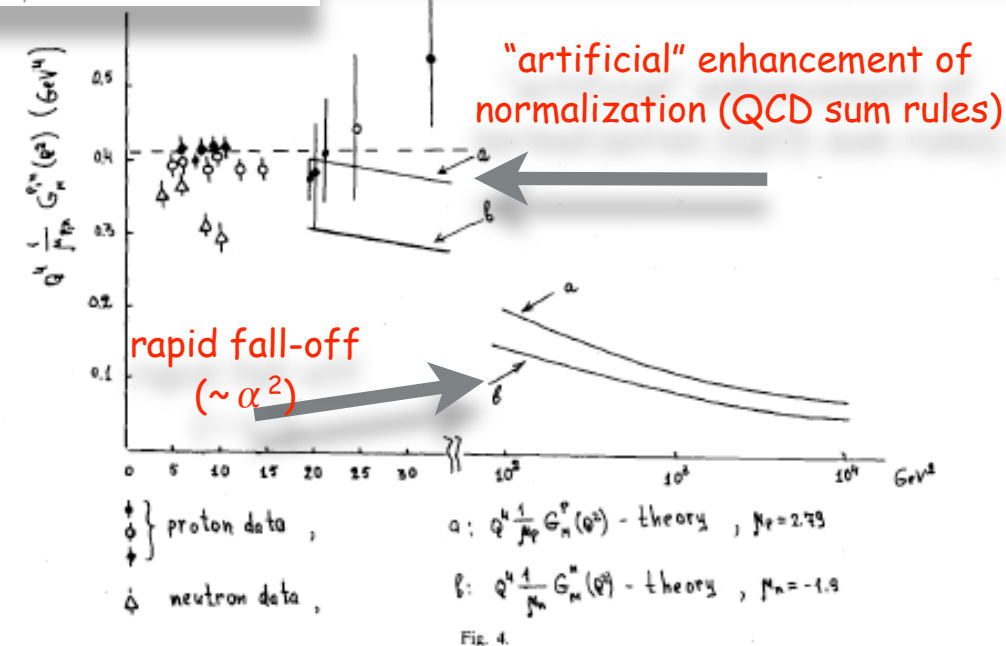
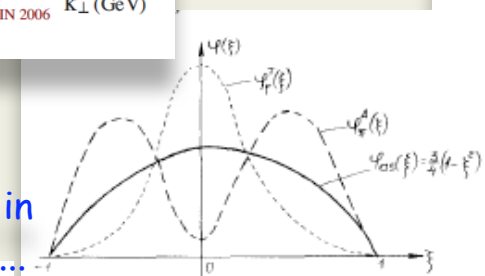


E615: $\pi^- N \rightarrow \mu^+ \mu^- + X$
 $p_{\text{lab}} = 263 \text{ GeV/c}$, $Q > 4 \text{ GeV}$

Asymmetry strongly suppressed in pQCD analysis (quark mass, α) ...
... due to final state interactions



... low-x partons are soft and coherent with the hard scattering sub-process



Meson resonances
from Goldstone
boson dynamics

GB : collective excitations
of the $q\bar{q}$ sea



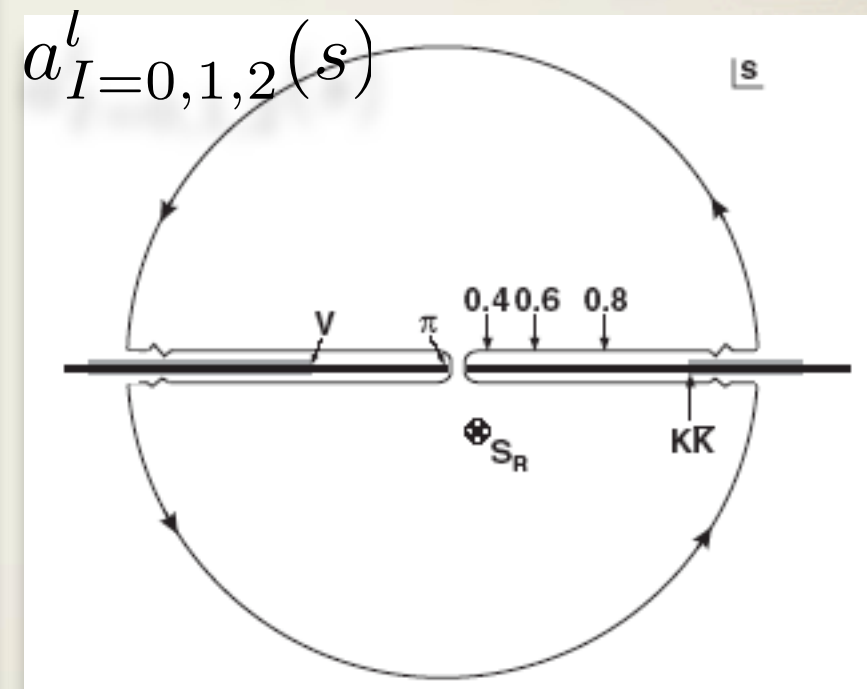
Meson resonances from Goldstone boson dynamics

GB : collective excitations of the $q\bar{q}$ sea

low energy ($E \sim m_\pi$) constrained by chiral symmetry.
Corrections appear at $E \sim 1\text{GeV}$ and probe internal quark dynamics

$$A(s, t) = \sum_{I, L} a_L^I(s) P_L(\cos(\theta))$$

$\pi\pi \rightarrow \pi\pi$ is crossed symmetric : Cauchy representation : closed system of equations (Roy eq.)



solution outside the physical region (resonances) completely determined by data

f ₀ (600) T-MATRIX POLE \sqrt{s}		References		History since 1996
VALUE (MeV)	DOCUMENT ID	TECH	COMMENT	
f ₀ (600) T-MATRIX POLE \sqrt{s}				
Note that $\Gamma \approx 2 \text{Im}(\sqrt{s_{\text{pole}}})$.				
OUR ESTIMATE				
*** We do not use the following data for averages, fits, limits, etc. ***				
(400 - 1200) - i(250 - 500)				
(441 ± 16 - 8) - i(272 ± 9 - 12.5)	1 CAPRINI	06	RVUE	
(470 ± 50) - i(285 ± 25)	2 ZHOU	05	RVUE	
(541 ± 39) - i(252 ± 42)	3 ABLIKIM	04A	BES2	
(528 ± 32) - i(207 ± 23)	4 GALLEGOS	04	RVUE	
(440 ± 8) - i(212 ± 15)	5 PELAEZ	04A	RVUE	
(533 ± 25) - i(247 ± 25)	6 BUGG	03	RVUE	
532 - i272	BLACK	01	RVUE	
(470 ± 30) - i(295 ± 20)	1 COLANGELO	01	RVUE	
(535 ± 48 - 36) - i(155 ± 76 - 53)	7 ISHIDA	01		
610 ± 14 - i620 ± 26	8 SUROVTSEV	01	RVUE	
(558 ± 34 - 27) - i(196 ± 32 - 41)	ISHIDA	00B		
445 - i235	HANNAH	99	RVUE	
(523 ± 12) - i(259 ± 7)	KAMINSKI	99	RVUE	
469 - i203	OLLER	99B	RVUE	
445 - i221	OLLER	99C	RVUE	
442 - i 227	OLLER	99	RVUE	
(1530 ± 90 - 250) - i(560 ± 40)	ANISOVICH	98B	RVUE	
420 - i 212	LOCHER	98	RVUE	
(602 ± 26) - i(196 ± 27)	9 ISHIDA	97		
(537 ± 20) - i(250 ± 17)	10 KAMINSKI	97B	RVUE	
470 - i250	11, 12 TORNQVIST	96	RVUE	
~(1100 - i300)	AMSLER	95B	CBAR	
1100 - i137	12, 13 AMSLER	95D	CBAR	
400 - i500	12, 14 AMSLER	95D	CBAR	
387 - i305	15, 12 JANSSEN	95	RVUE	
525 - i269	16 ACHASOV	94	RVUE	
(506 ± 10) - i(247 ± 3)	KAMINSKI	94	RVUE	
370 - i356	17 ZOU	94B	RVUE	
406 - i342	17, 12 ZOU	93	RVUE	
870 - i370	12, 18 AU	87	RVUE	
470 - i208	19 BEVEREN	86	RVUE	
(750 ± 50) - i(450 ± 50)	20 ESTABROOKS	79	RVUE	
(660 ± 100) - i(320 ± 70)	PROTOPODESC...	73	HBC	
650 - i370	21 BASDEVANT	72	RVUE	

QCD content ? $N_c \rightarrow \infty$



FIG. 3: Representative diagrams contributing to meson-meson scattering and their N_c scaling.

$$|T| \sim O(1)$$

resonance pole moves
towards the real axis

$$|T| \rightarrow 0$$

resonance pole moves
deep into the complex
plane

QCD content ? $N_c \rightarrow \infty$



FIG. 3: Representative diagrams contributing to meson-meson scattering and their N_c scaling.

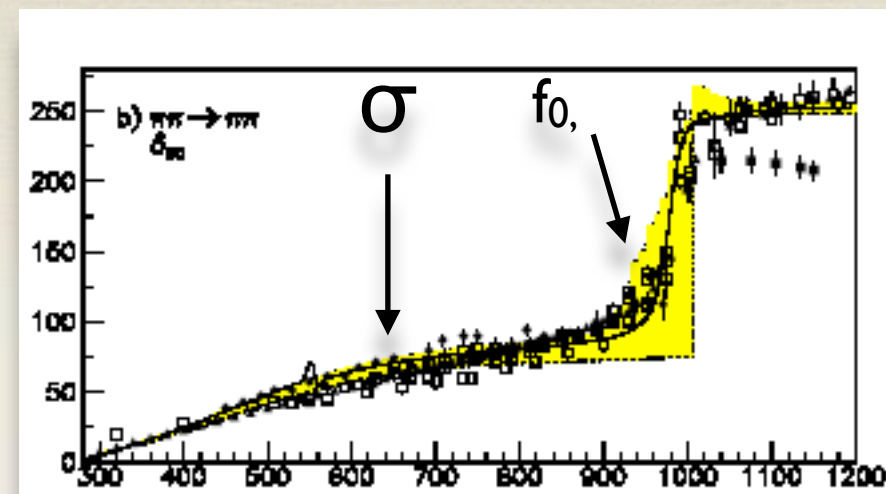
$$|T| \sim O(1)$$

resonance pole moves
towards the real axis

$$|T| \rightarrow 0$$

resonance pole moves
deep into the complex
plane

Fit low energy constants in
the physical region $N_c = 3 \dots$



... and extrapolate to $N_c = \infty$

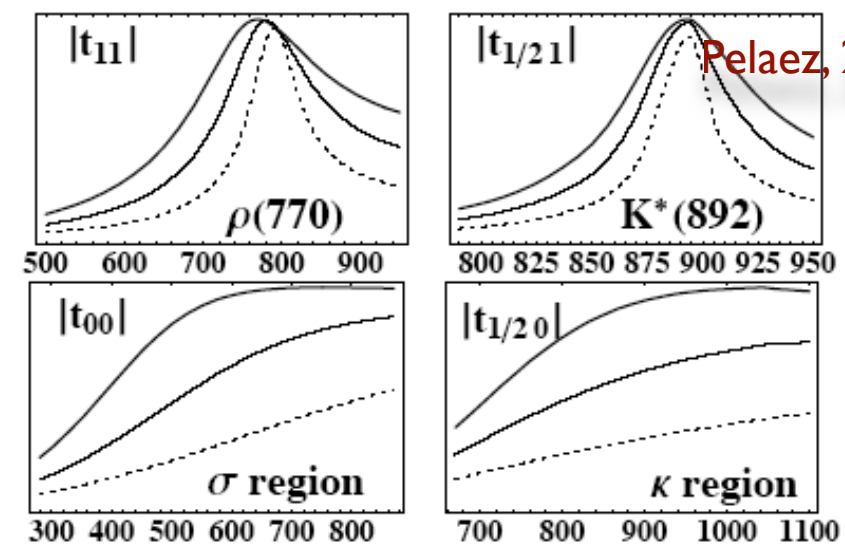
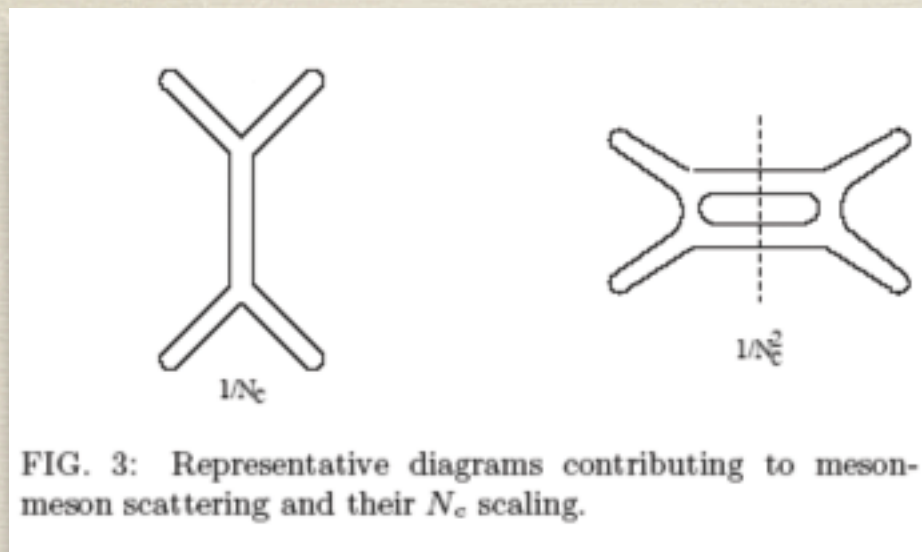


FIG. 1: Modulus of amplitudes in different meson-meson channels for $N_c = 3$ (thick line) $N_c = 5$ (thin continuous line) and $N_c = 10$ (thin dotted line), scaled at $\mu = 770$ MeV.

Pelaez, 2004

QCD content ? $N_c \rightarrow \infty$



$$|T| \sim O(1)$$

resonance pole moves
towards the real axis

$$|T| \rightarrow 0$$

resonance pole moves
deep into the complex
plane

Crouching Sigma, Hidden Scalar
in $\gamma\gamma \rightarrow \pi^0\pi^0$

M.R. Pennington

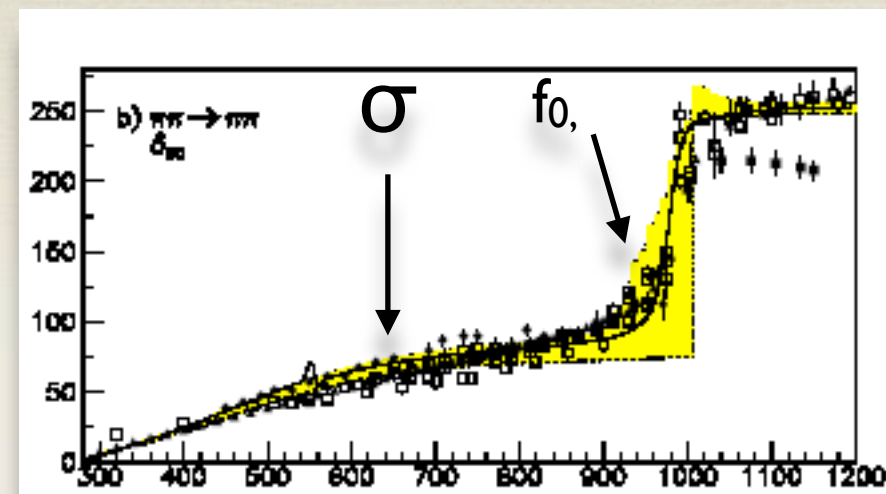
There has long been speculation about the nature of the σ -resonance. For three decades Jaffe has argued for a tetraquark composition, while others have claimed it is largely a glueball. A key pointer to its nature is its coupling to two photons. Consequently, there have been recent proposals to observe this important scalar hiding in $\gamma\gamma \rightarrow \pi^0\pi^0$. We show here that the σ is already crouching in this cross-section exactly as measured twenty years ago. What is new is that precise knowledge of the position of the σ -pole, provided by the analysis of the Roy equations, now allows its two photon coupling to be accurately fixed. Its two photon width is found to be (4.1 ± 0.3) keV, a value far too large for a gluonic, or even a tetraquark, state.

Quark Model : resonance have small sizes

GB dynamics: resonances have large spacial extent

So : crucial to measure size

Fit low energy constants in
the physical region $N_c = 3 \dots$



... and extrapolate to $N_c = \infty$

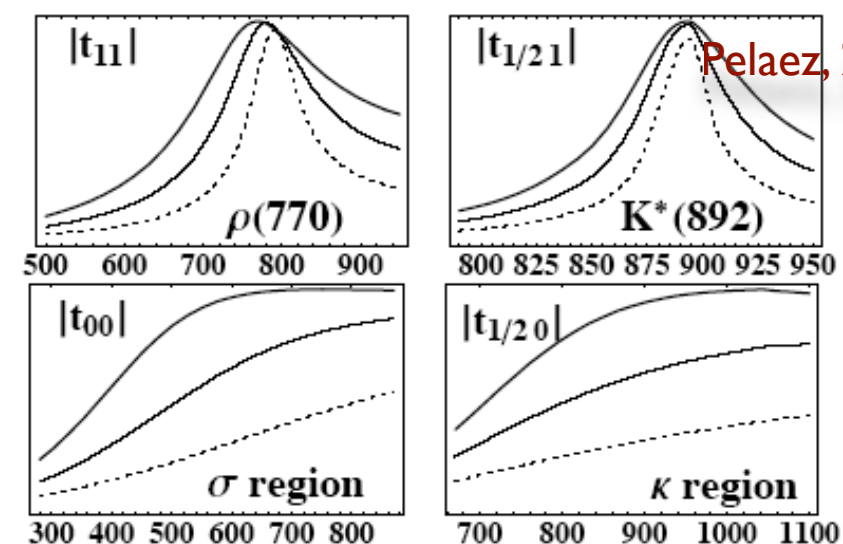
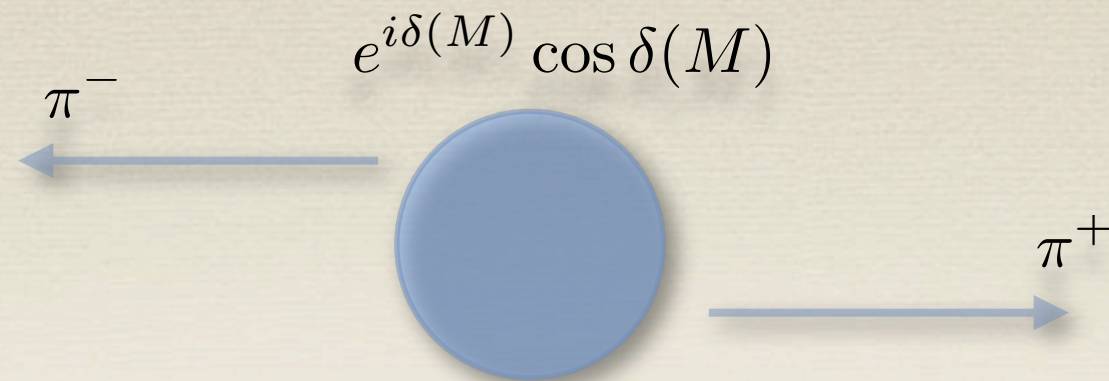


FIG. 1: Modulus of amplitudes in different meson-meson channels for $N_c = 3$ (thick line) $N_c = 5$ (thin continuous line) and $N_c = 10$ (thin dotted line), scaled at $\mu = 770$ MeV.

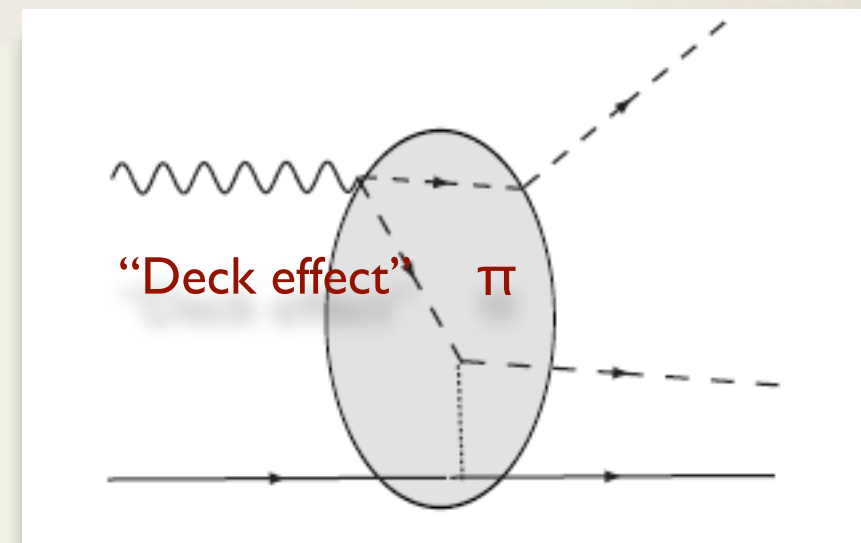
Pelaez, 2004

long range $> \pi$ exchange

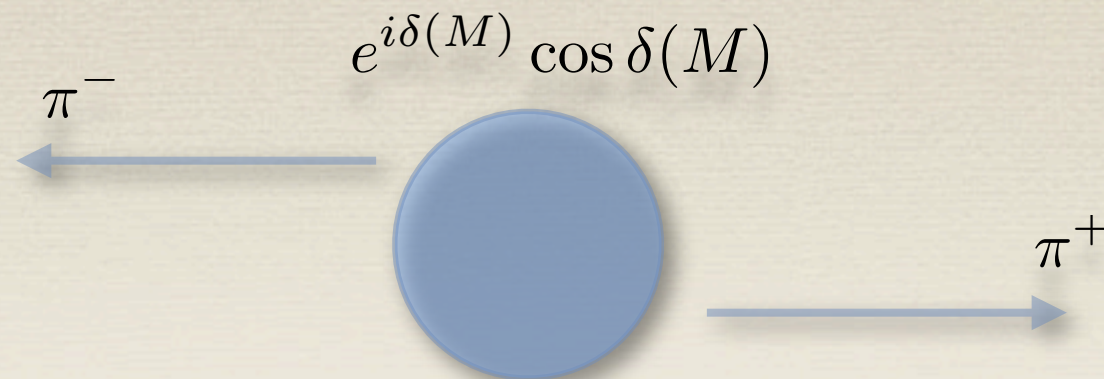


Diffuse source suppresses resonance production (Watson theorem)

e.g. a_1 via pion exchange



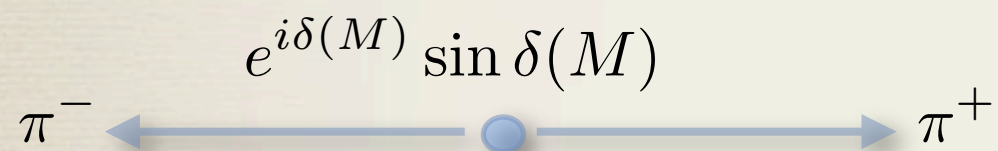
long range > π exchange



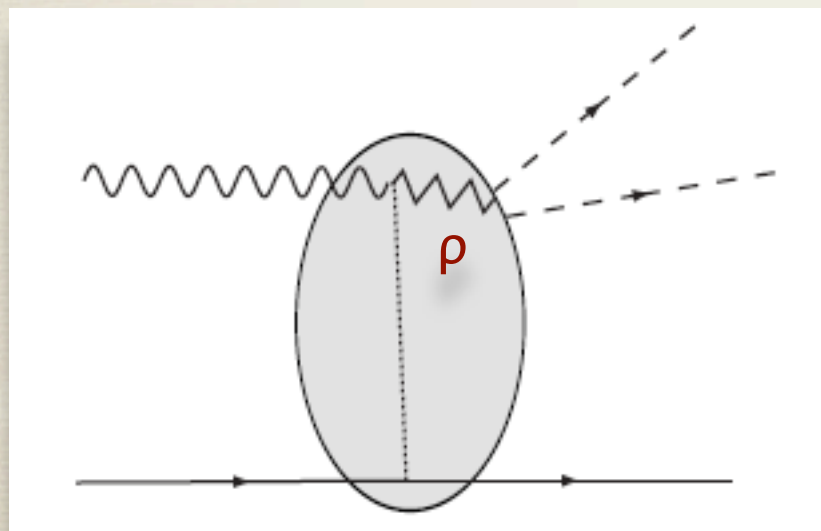
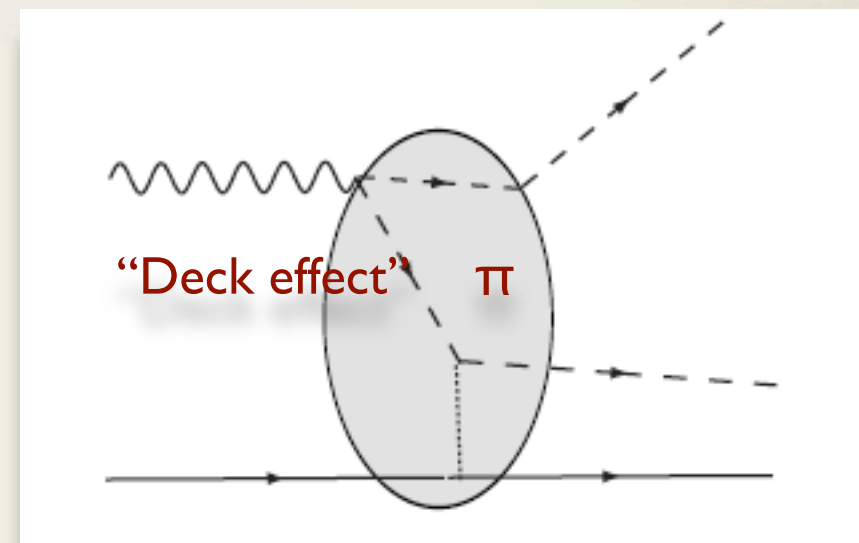
Diffuse source suppresses resonance production (Watson theorem)

e.g. a_1 via pion exchange

short range > everything else



e.g. ρ , ϕ in diffractive photo-production



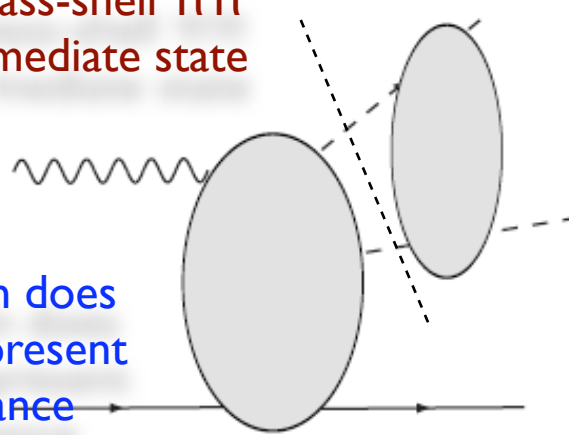
dispersive analysis of partial waves in
of $\pi^-\pi^+$ photoproduction (CLAS g11)

$$a(s) = \left[\frac{1 + S(s)}{2} \right] a_L(s) - \frac{1}{D(s)} P.V. \int_{s_{th}} \frac{ds'}{\pi} \frac{\rho(s') N(s') a_L(s')}{s' - s}$$

$\pi\pi$ phase shifts scattering

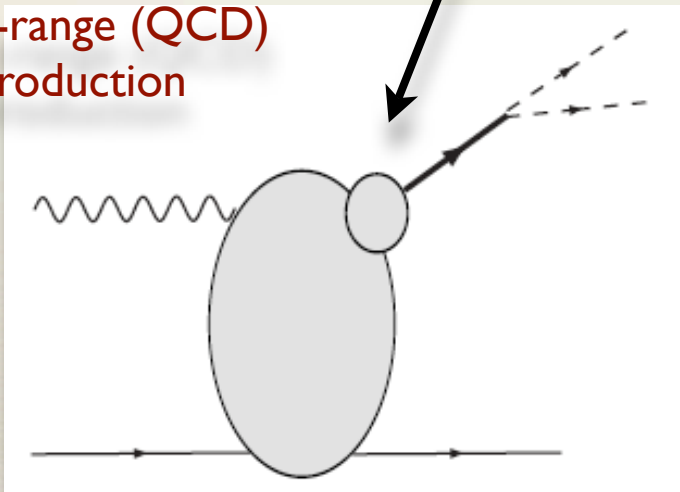
on mass-shell $\pi\pi$
intermediate state

this term does
NOT represent
resonance
photoproduction

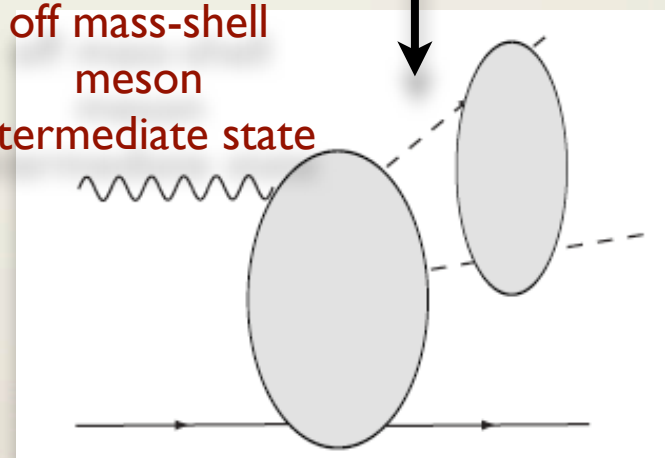


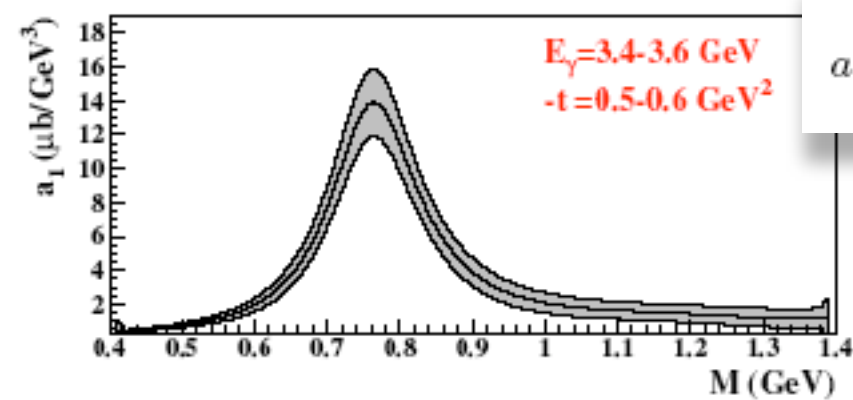
$$\frac{C}{D(s)} - \frac{(s + \mu^2)}{D(s)} P.V. \int_{s_{th}} \frac{ds'}{\pi} \frac{\rho(s') N(s') a_L(s')}{(s' - s)(s' + \mu^2)}$$

short-range (QCD)
production

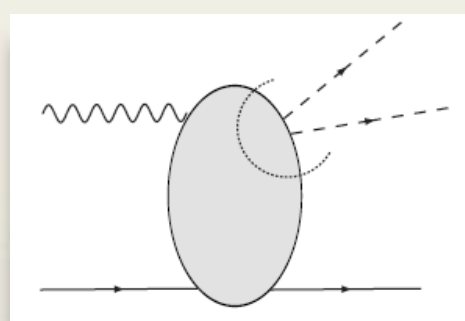
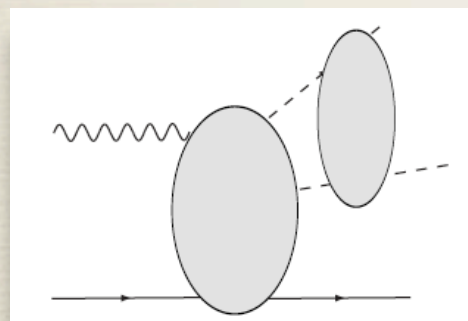
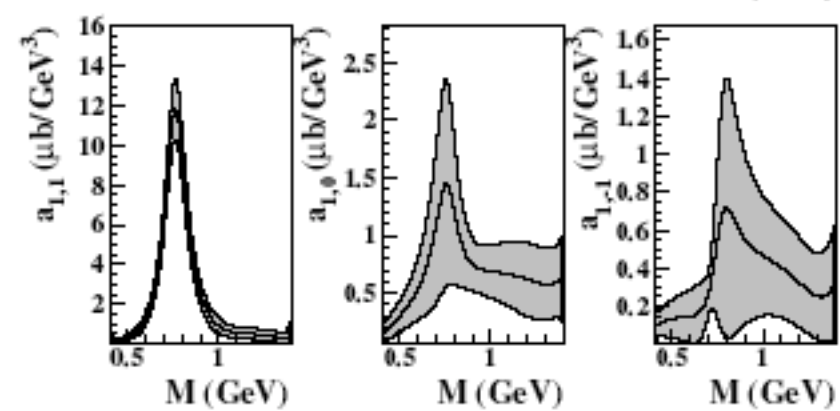


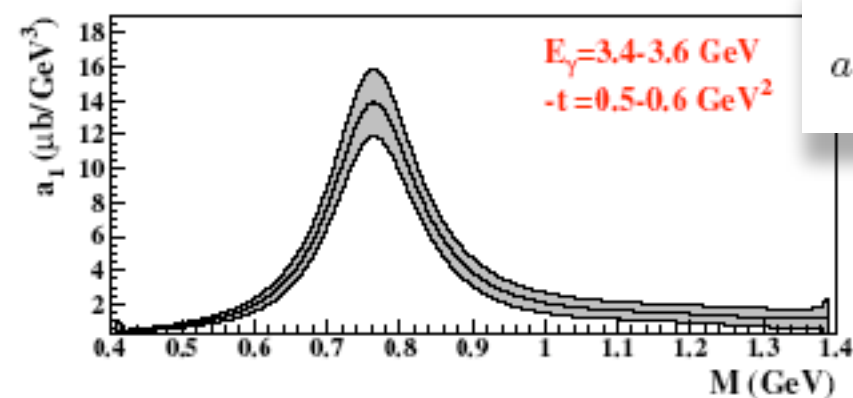
off mass-shell
meson
intermediate state



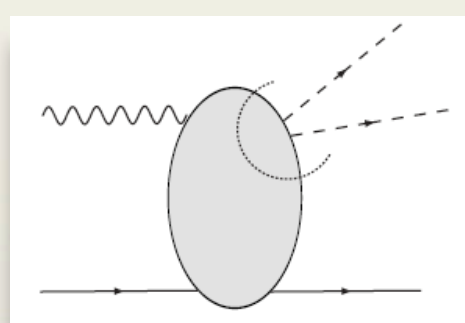
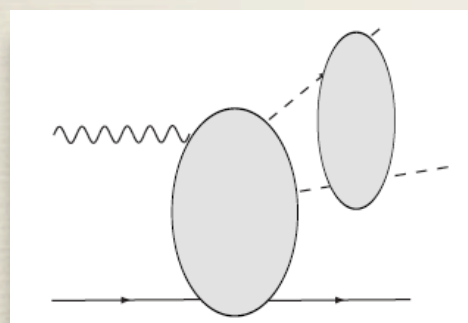
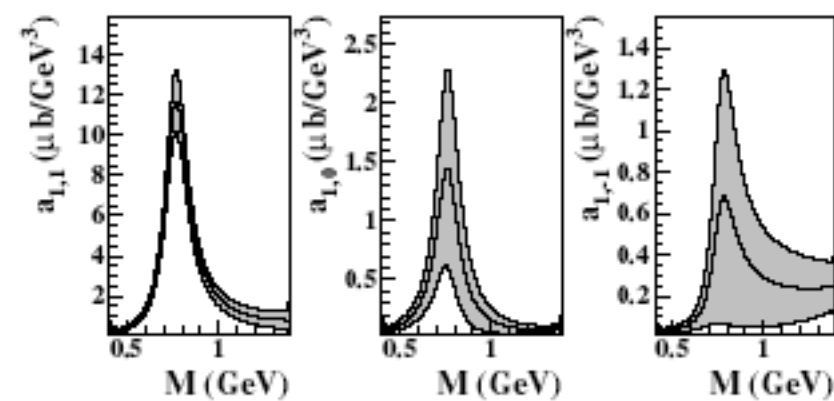
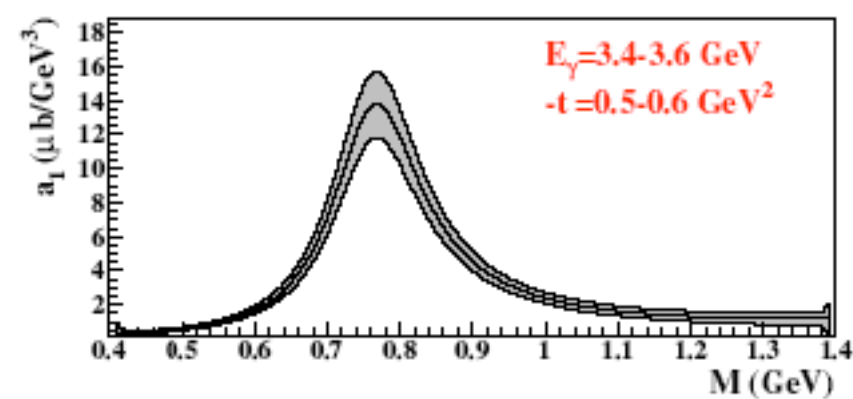
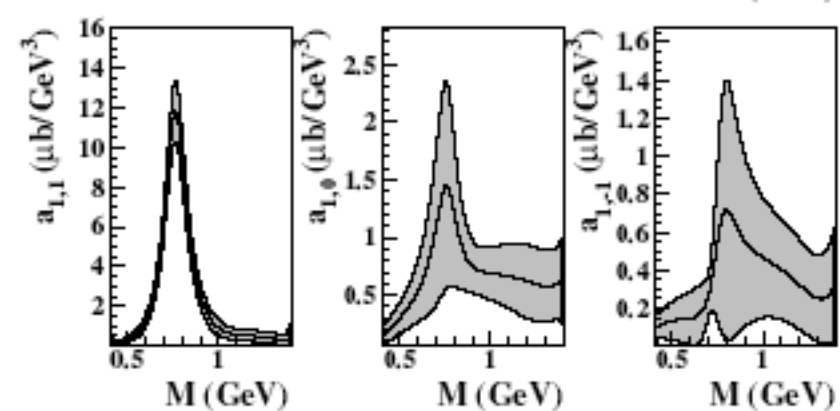
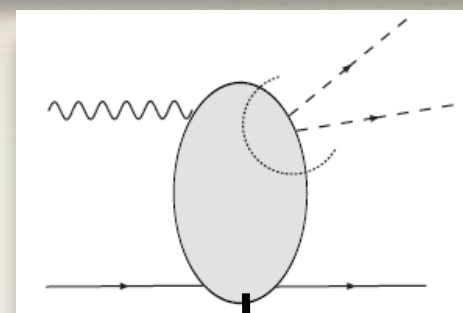


$$a(s) = \left[\frac{1 + S(s)}{2} \right] a_L(s) - \frac{1}{D(s)} P.V. \int_{s_{th}} \frac{ds'}{\pi} \frac{\rho(s') N(s') a_L(s')}{s' - s}$$

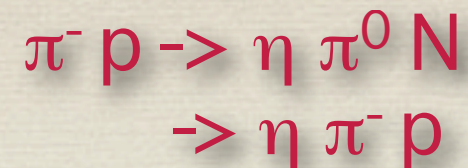




~~$$a(s) = \left[\frac{1 + S(s)}{2} \right] a_L(s) - \frac{1}{D(s)} P.V. \int_{s_{th}} \frac{ds'}{\pi} \frac{\rho(s') N(s') a_L(s')}{s' - s}$$~~



Exotic story

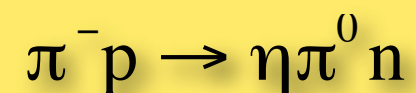


$(\eta\pi^0)$ in P-wave has $J^{PC}=1^-+$!

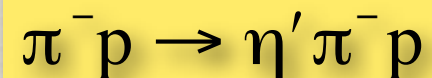


$$M = 1370 \pm 16_{-30}^{+50} \text{ MeV} / c^2$$

$$\Gamma = 385 \pm 40_{-105}^{+65} \text{ MeV} / c^2$$

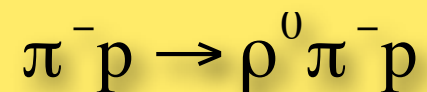


New results: No consistent B-W interpretation possible but a weak $\eta\pi\pi$ interaction exists and can reproduce the exotic wave



$$M = 1597 \pm 10_{-10}^{+45} \text{ MeV} / c^2$$

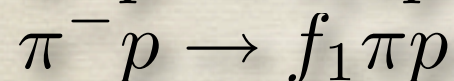
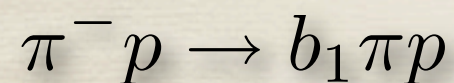
$$\Gamma = 340 \pm 40_{-50}^{+50} \text{ MeV} / c^2$$



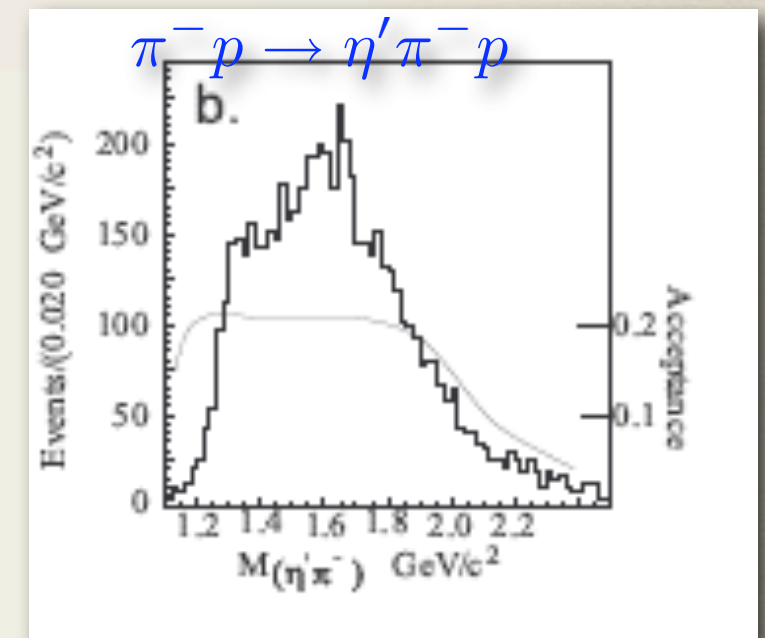
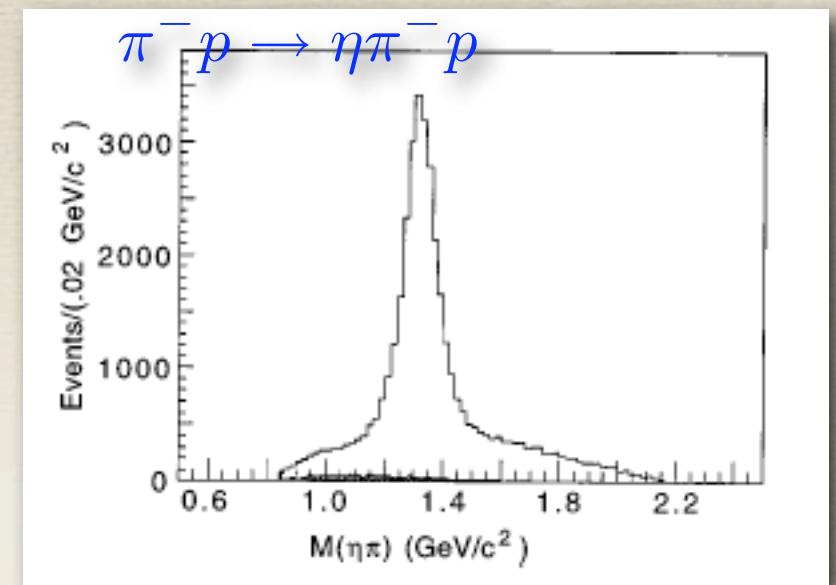
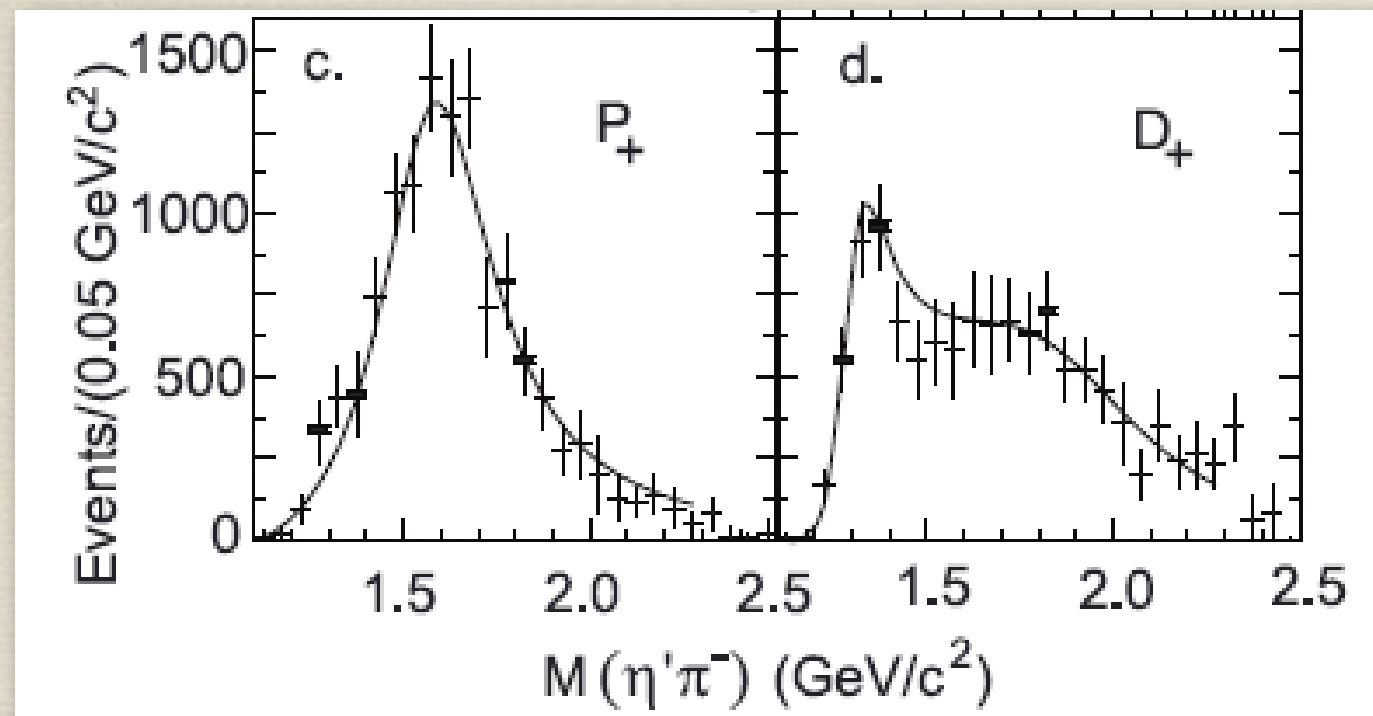
$$M = 1593 \pm 8_{-47}^{+29} \text{ MeV} / c^2$$

$$\Gamma = 168 \pm 20_{-12}^{+150} \text{ MeV} / c^2$$

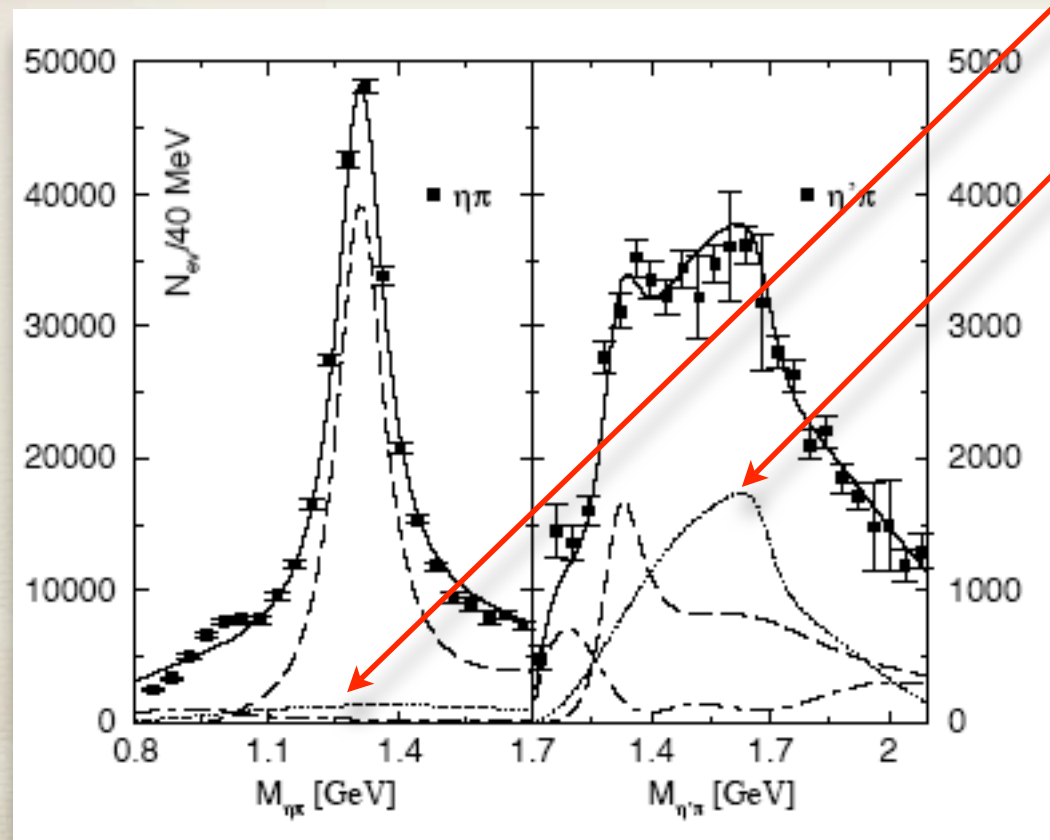
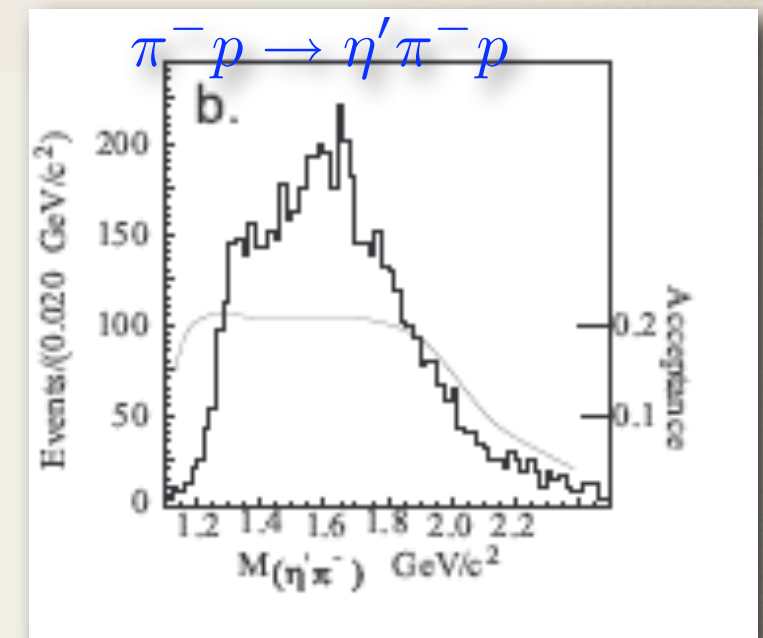
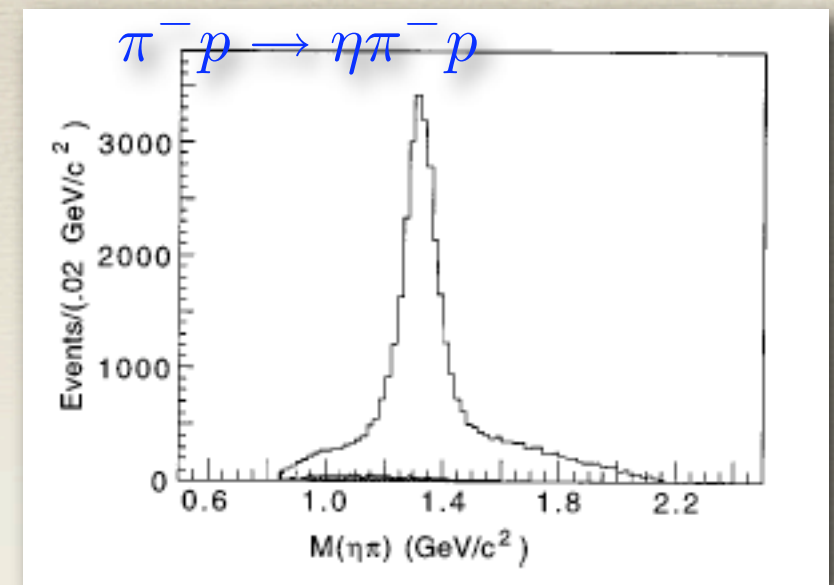
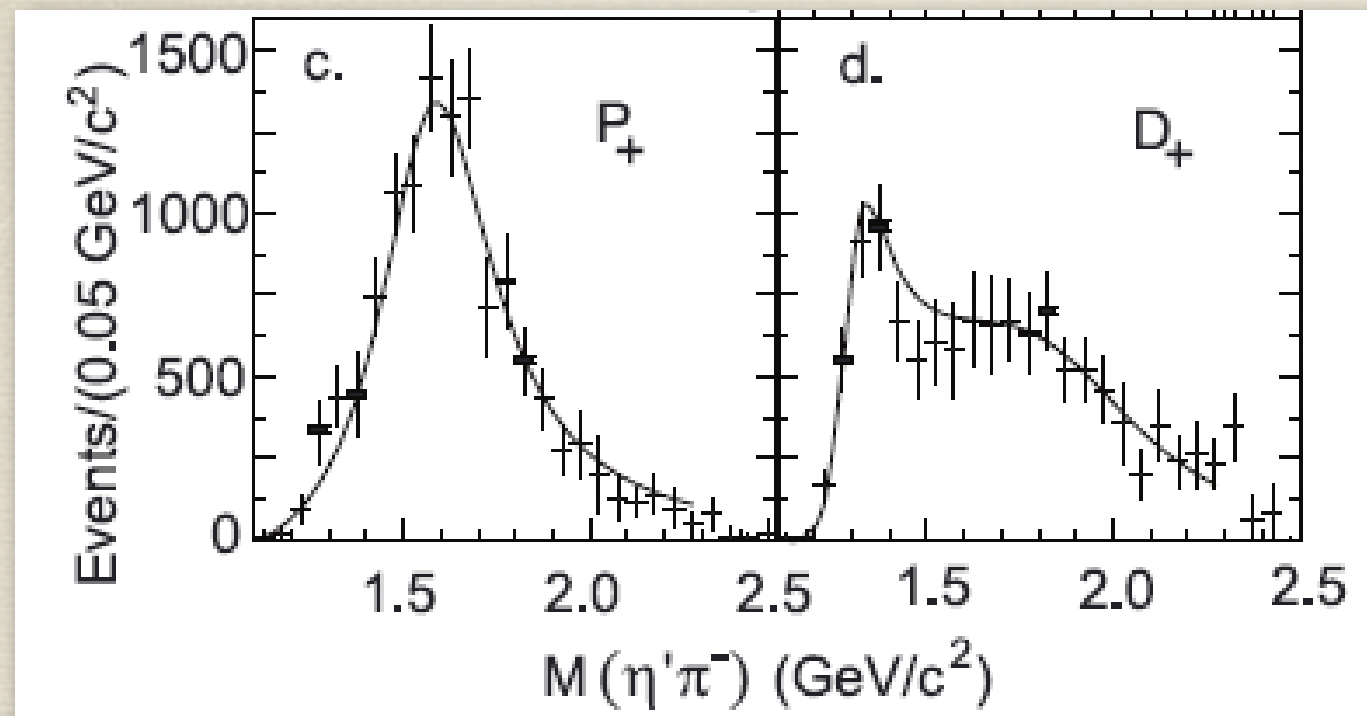
BNL (E852) and VES
new analysis reduces the strength



$J^{PC} = 1^{-+}$ exotic wave signal (E852)



$J^{PC} = 1^{-+}$ exotic wave signal (E852)

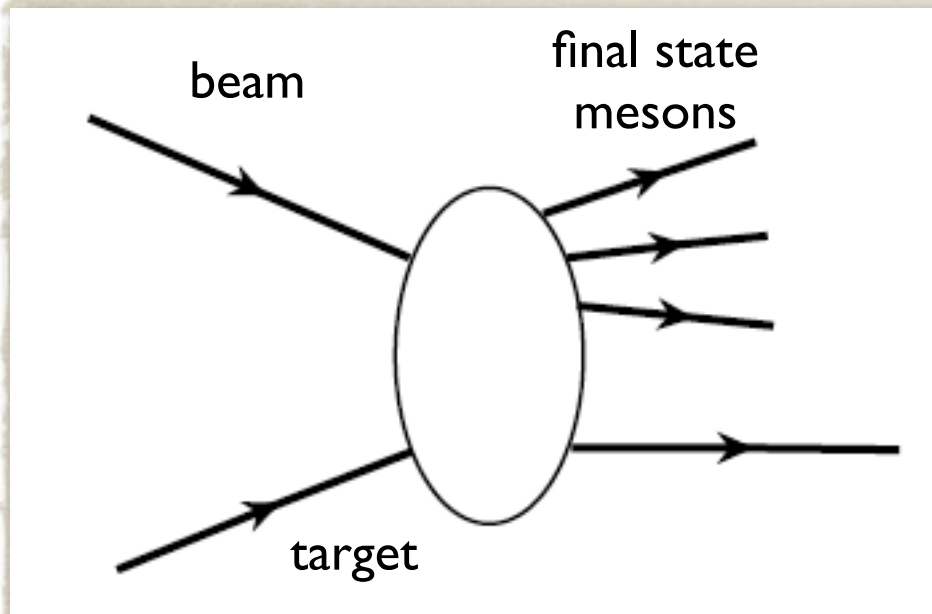


P-wave

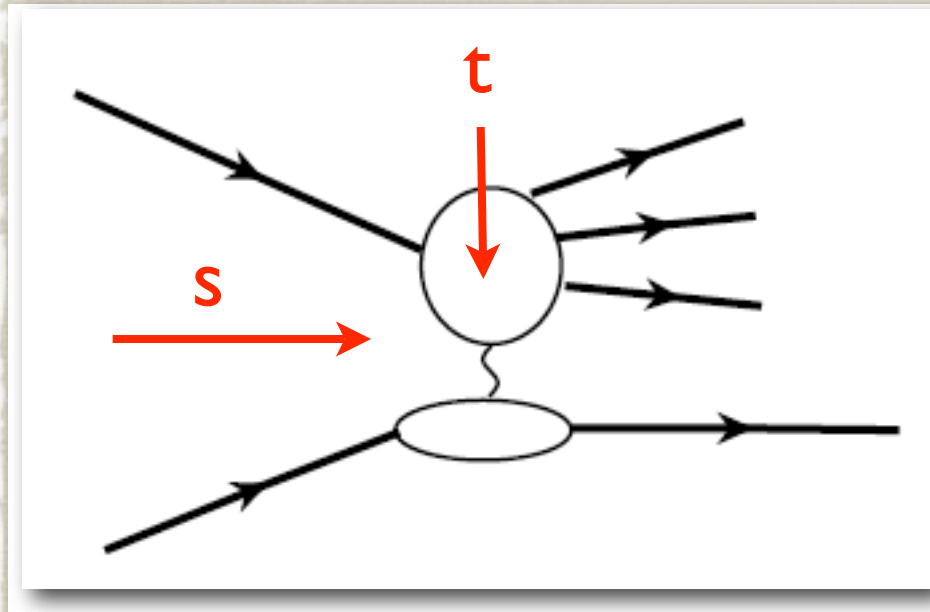
P -wave $\eta\pi$, $\eta'\pi$
2 coupled channels

S, D -wave KK , $\eta\pi$, $\eta'\pi$
3 coupled channels

Model (in)dependence in pwa



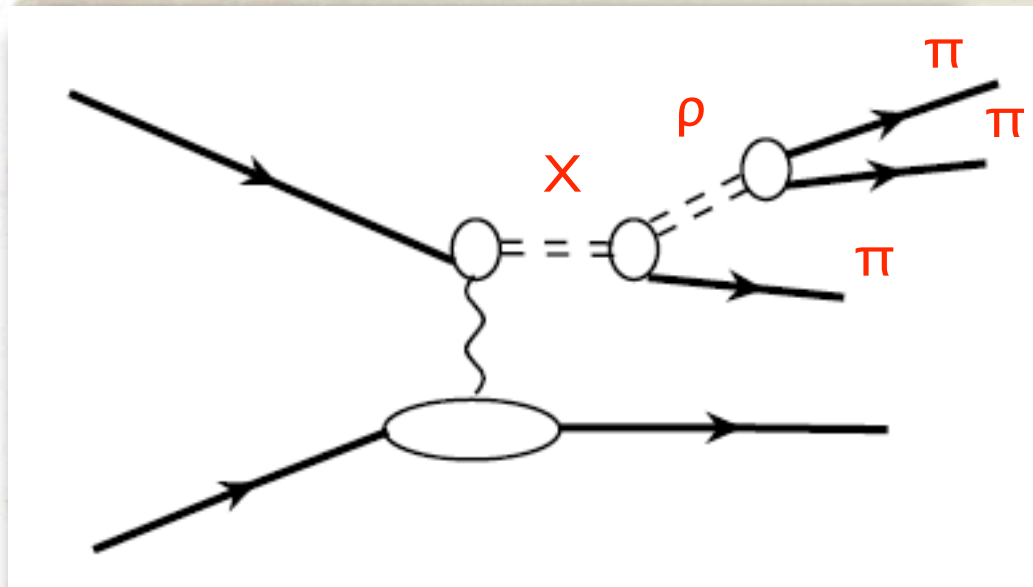
Model (in)dependence in pwa



$$t/s \ll 1$$

t-channel singularities close to the
physical region dominate (Regge sums)

Model (in)dependence in pwa

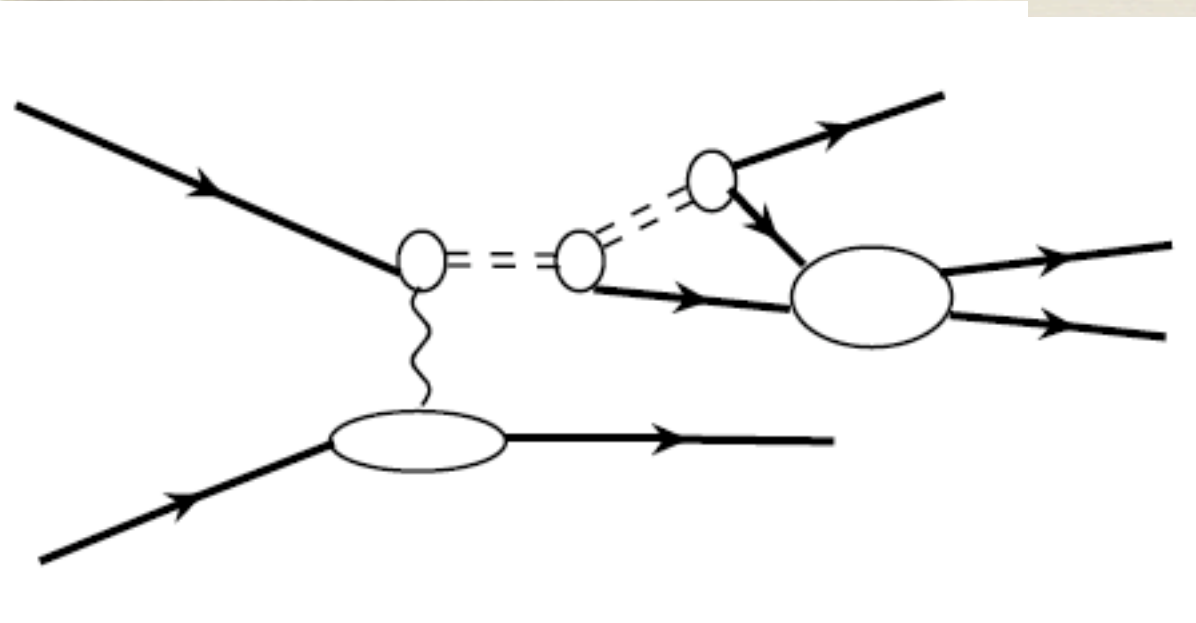


$$t/s \ll 1$$

t-channel singularities close to the
physical region dominate (Regge sums)

isobar model: quasi two-body decays

Model (in)dependence in pwa



$$t/s \ll 1$$

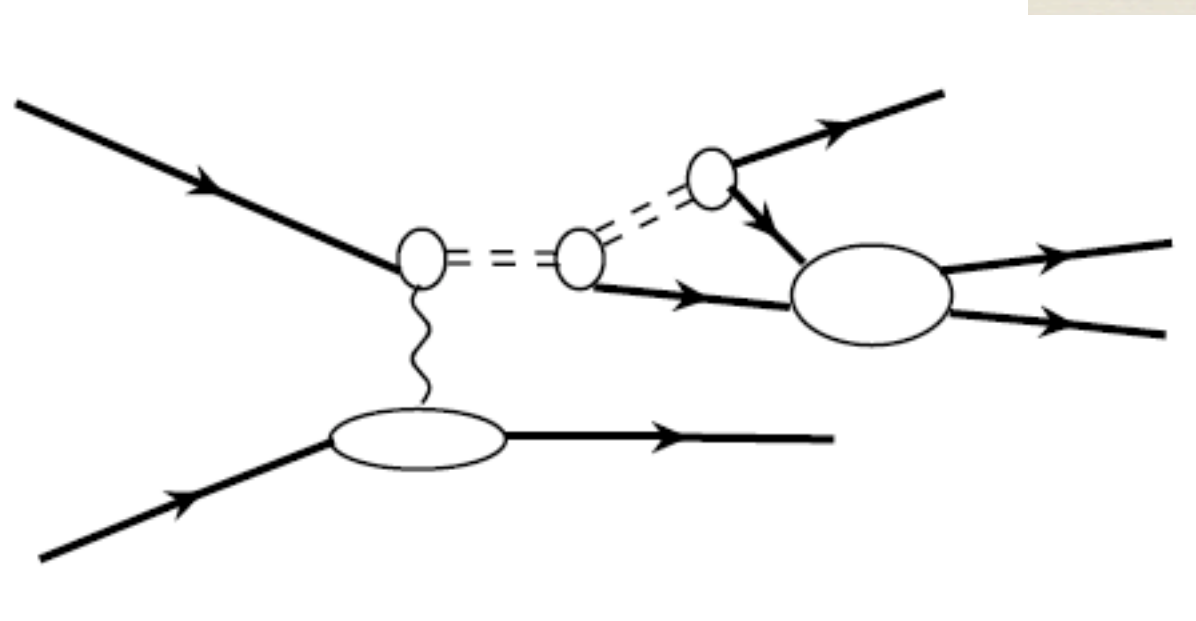
t-channel singularities close to the
physical region dominate (Regge sums)

isobar model: quasi two-body decays

corrections to isobar model:
unitarity constraints

general two-body amplitudes

Model (in)dependence in pwa



$$t/s \ll 1$$

t-channel singularities close to the physical region dominate (Regge sums)

isobar model: quasi two-body decays

corrections to isobar model:
unitarity constraints

general two-body amplitudes

formalism describing unitary and analytical 3 particle final states exist (but have seldom being used)

$$A(s_1, s_2, s)$$

1

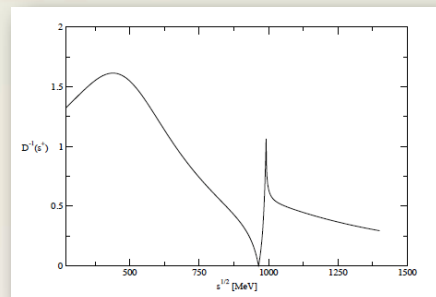
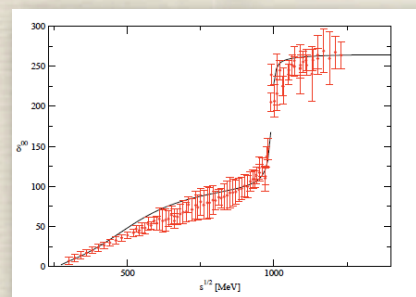
$$s_i = (p_j + p_k)^2$$

2

3

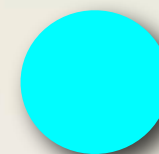
$$\sum_i s_i = s + \sum_i m_i^2$$

$$\text{Dis}_1 A(s_1, \dots) = A_1(s_1 + i\epsilon, \dots) - A(s_1 - i\epsilon, \dots) \neq 0$$



2-body scattering
amplitude, e.g.
 $(s_i - m_R^2 - i m_R \Gamma)^{-1}$

=



$$N(s_i)$$

×

=

$$D^{-1}(s_i)$$

$$A(s_1, s_2, s)$$

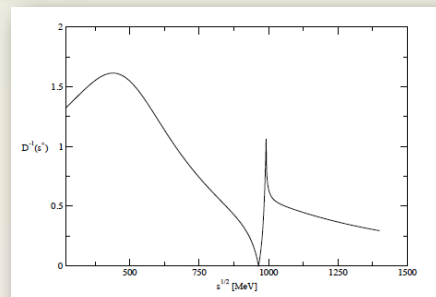
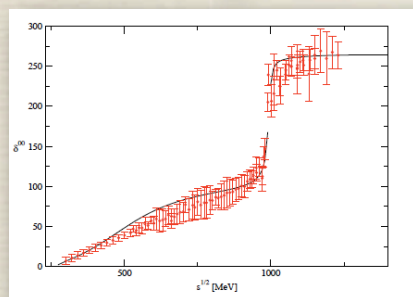
1

$$s_i = (p_j + p_k)^2$$

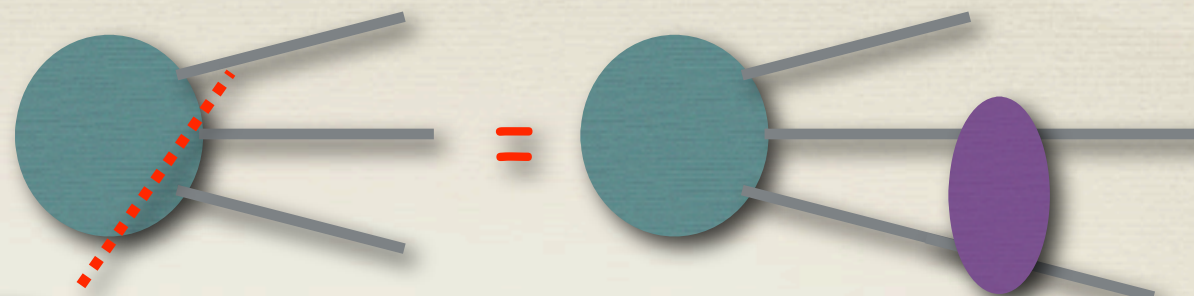
2

3

$$\sum_i s_i = s + \sum_i m_i^2$$



$$\text{Dis}_1 A(s_1, \dots) = A_1(s_1 + i\epsilon, \dots) - A(s_1 - i\epsilon, \dots) \neq 0$$

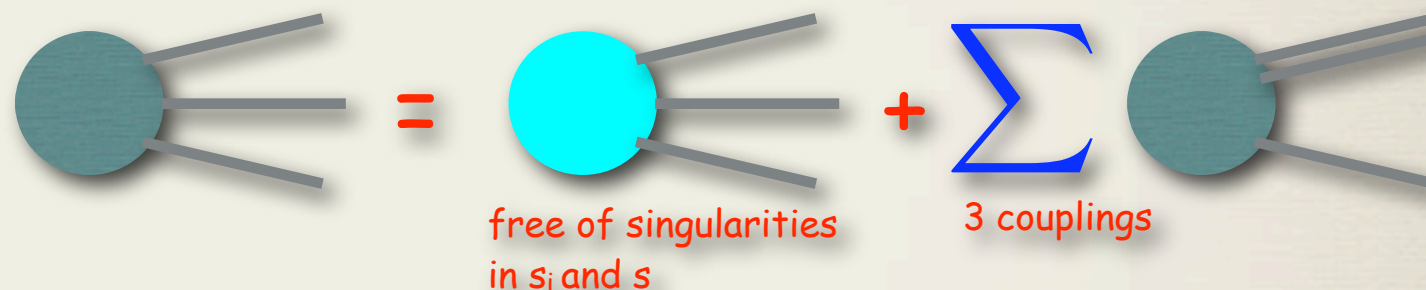


2-body scattering
amplitude, e.g.
 $(s_i - m_R^2 - i m_R \Gamma)^{-1}$

$$= \text{[Tree-level diagram]} \times \frac{N(s_i)}{D^{-1}(s_i)}$$

Dominance of 2-body interactions

$$A(s_i, s) = A_0(s_i, s) + \sum_i A_i(s_i, s)$$

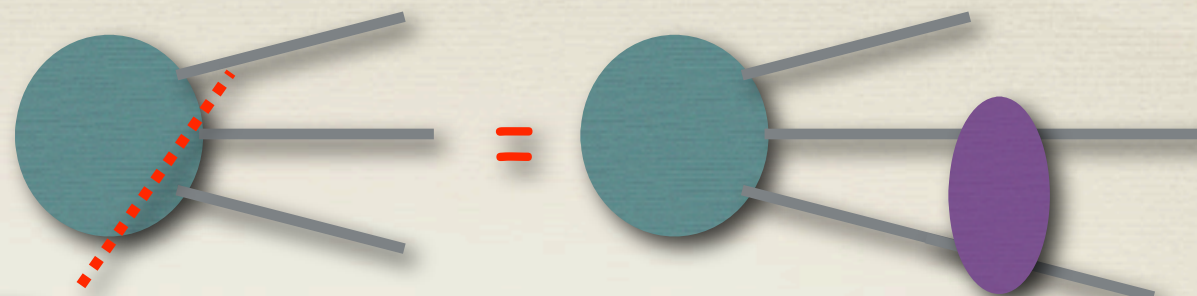
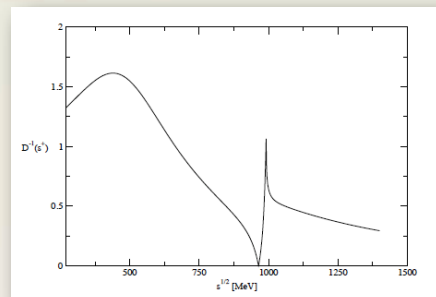
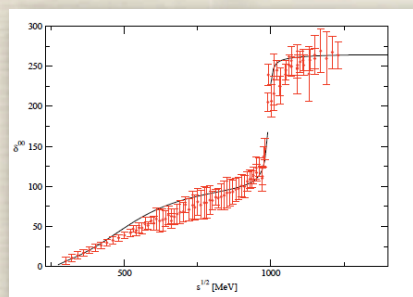


$$A(s_1, s_2, s)$$

$$s_i = (p_j + p_k)^2$$

$$\text{Dis}_1 A(s_1, \dots) = A_1(s_1 + i\epsilon, \dots) - A(s_1 - i\epsilon, \dots) \neq 0$$

$$\sum_i s_i = s + \sum_i m_i^2$$

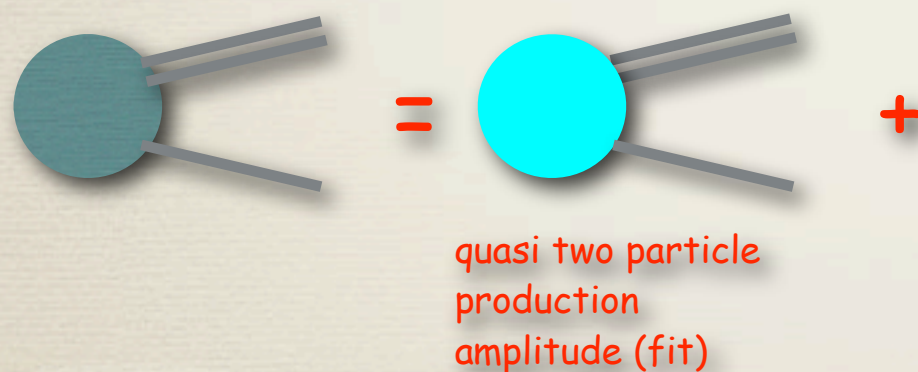
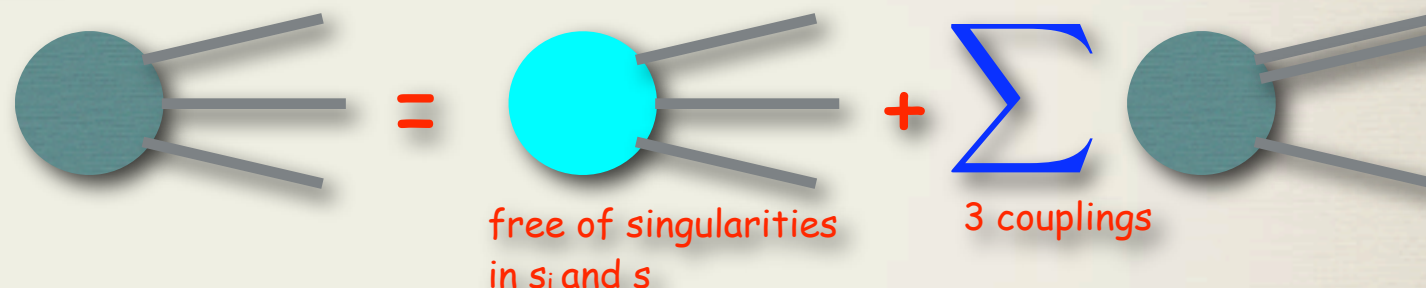


2-body scattering
amplitude, e.g.
 $(s_i - m_R^2 - i m_R \Gamma)^{-1}$

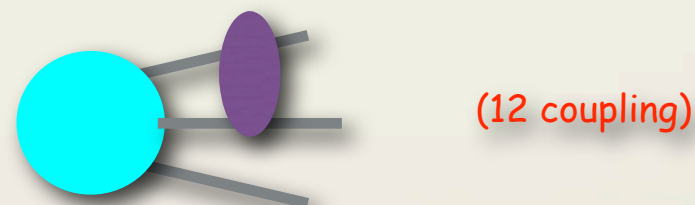
$$= N(s_i) \times D^{-1}(s_i)$$

Dominance of 2-body interactions

$$A(s_i, s) = A_0(s_i, s) + \sum_i A_i(s_i, s)$$

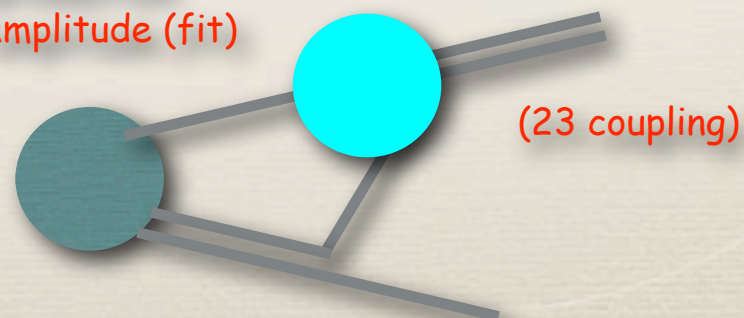


quasi two particle
production
amplitude (fit)



3 particle
production
amplitude (fit)

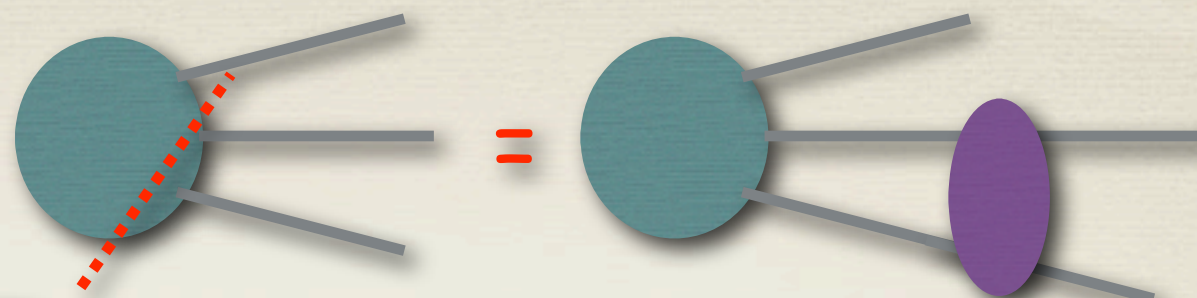
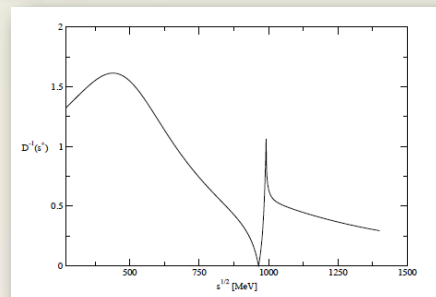
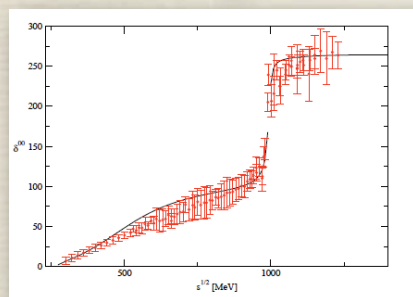
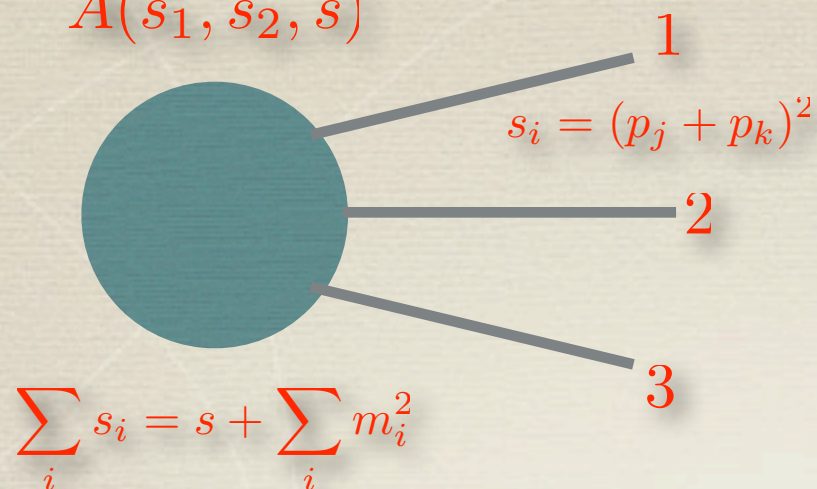
Set of 3 integral equations for
 $A_i(s_i, s)$



13 coupling

$$A(s_1, s_2, s)$$

$$\text{Dis}_1 A(s_1, \dots) = A_1(s_1 + i\epsilon, \dots) - A(s_1 - i\epsilon, \dots) \neq 0$$

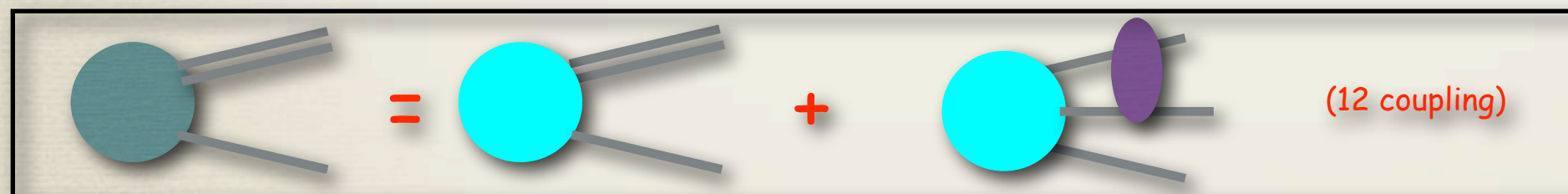
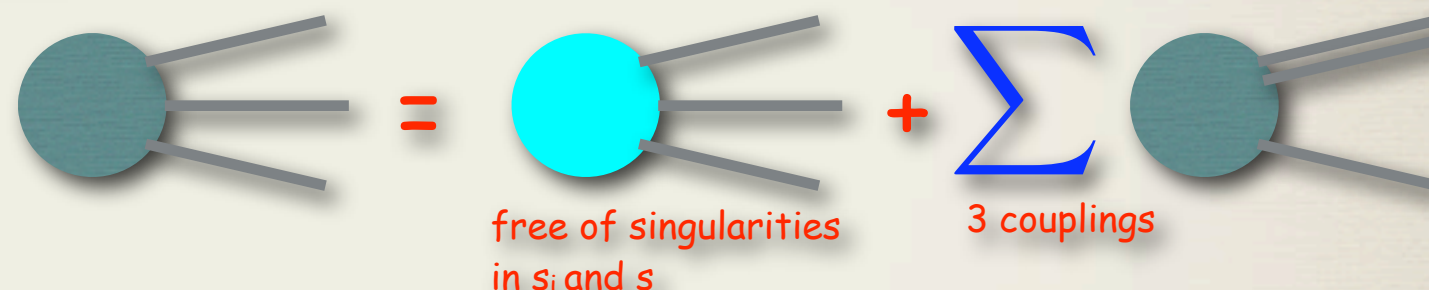


2-body scattering
amplitude, e.g.
 $(s_i - m_R^2 - i m_R \Gamma)^{-1}$

$$= N(s_i) \times D^{-1}(s_i)$$

Dominance of 2-body interactions

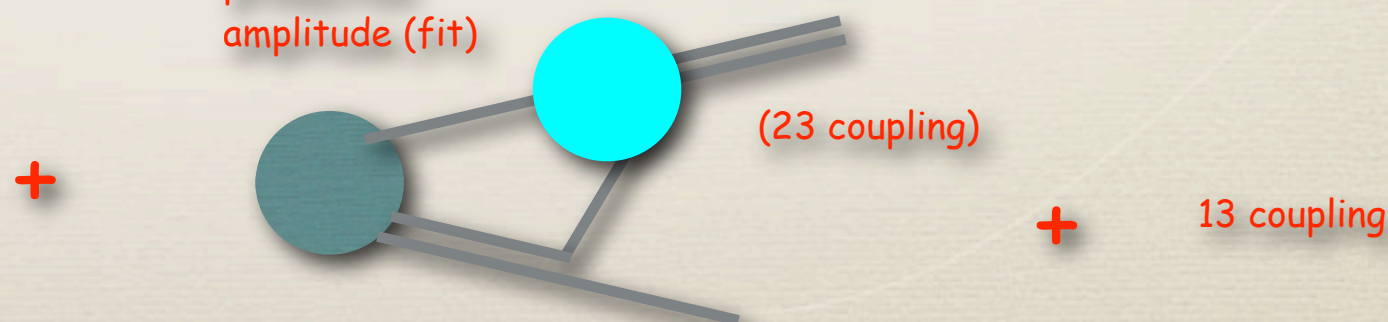
$$A(s_i, s) = A_0(s_i, s) + \sum_i A_i(s_i, s)$$



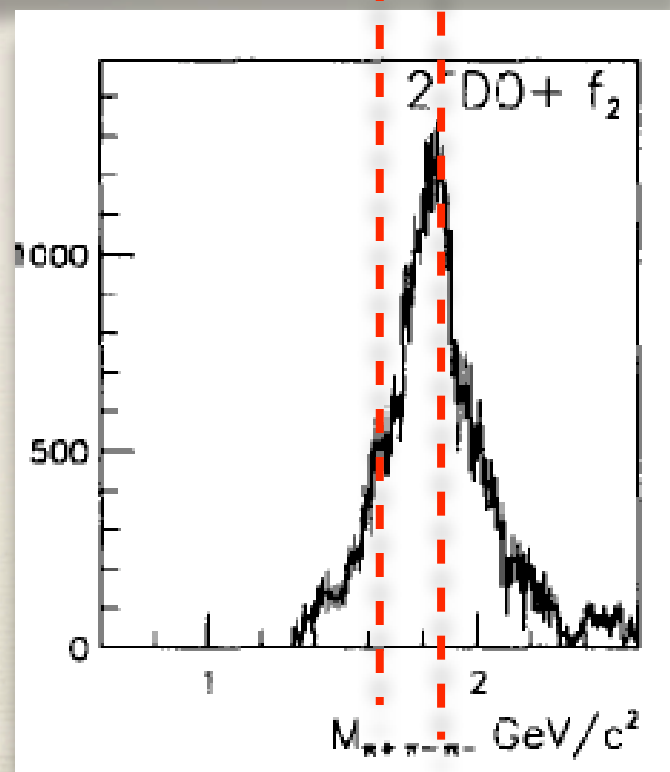
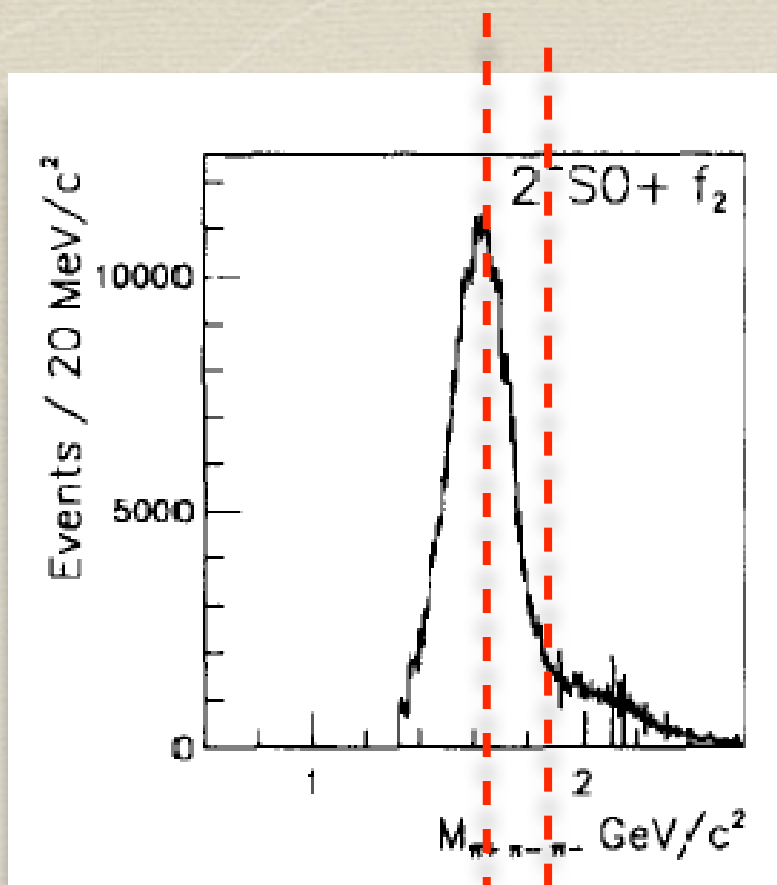
quasi two particle
production
amplitude (fit)

3 particle
production
amplitude (fit)

Set of 3 integral equations for
 $A_i(s_i, s)$



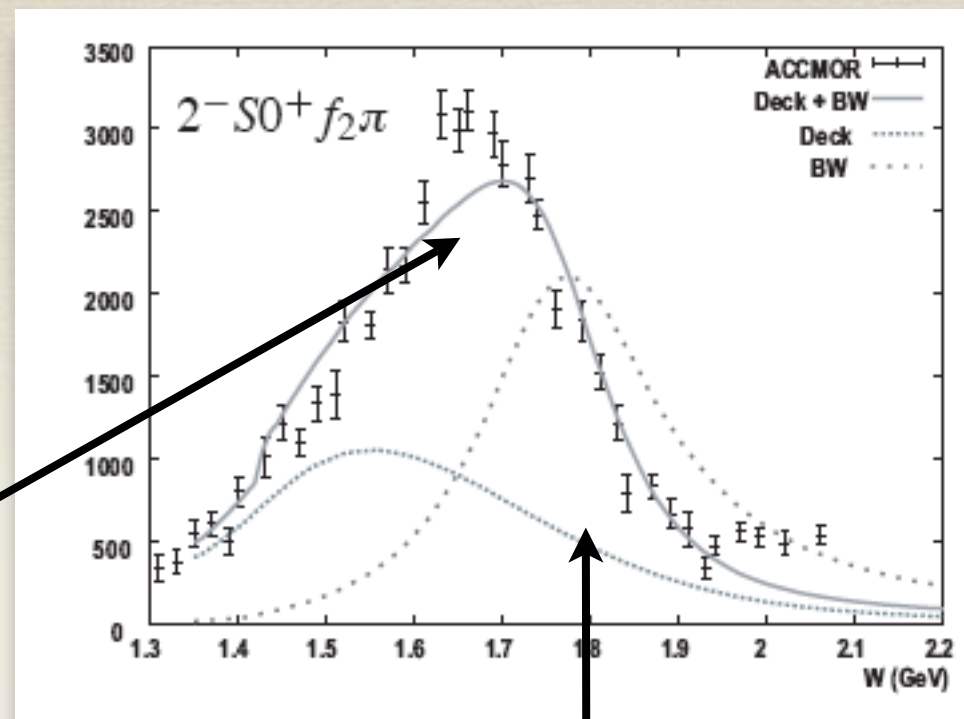
Moving $\pi_2(1670)$ peak



VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1672.4 ± 3.2 OUR AVERAGE					
Error includes scale factor of 1.4. See the ideogram below.					
1749 ± 10 ± 100	145k	LU	05	E852	18 $\pi^- p \rightarrow \omega \pi^- \pi^0 p$
1676 ± 3 ± 8		1 CHUNG	02	E852	18.3 $\pi^- p \rightarrow \pi^+ \pi^- \pi^- p$
1685 ± 10 ± 30		2 BARBERIS	01		450 $p p \rightarrow p_f 3 \pi^0 p_s$
1687 ± 9 ± 15		AMELIN	99	VES	37 $\pi^- A \rightarrow \omega \pi^- \pi^0 A^+$
1669 ± 4		BARBERIS	98B		450 $p p \rightarrow p_f p \pi p_s$
1670 ± 4		BARBERIS	98B		450 $p p \rightarrow p_f f_2(1270) \pi p_s$
1730 ± 20		3 AMELIN	95B	VES	36 $\pi^- A \rightarrow \pi^+ \pi^- \pi^- A$
1690 ± 14		4 BERDNIKOV	94	VES	37 $\pi^- A \rightarrow K^+ K^- \pi^- A$
1710 ± 20	700	ANTIPOV	87	SIGM	- 50 $\pi^- Cu \rightarrow \mu^+ \mu^- \pi^- Cu$
1676 ± 6		4 EVANGELISTA	81	OMEG	- 12 $\pi^- p \rightarrow 3 \pi p$
1657 ± 14		4,5 DAUM	80D	SPEC	- 63-94 $\pi p \rightarrow 3 \pi X$
1662 ± 10	2000	4 BALTAY	77	HBC	+ 15 $\pi^+ p \rightarrow p 3 \pi$
*** We do not use the following data for averages, fits, limits, etc. ***					
1742 ± 30 ± 49		ANTREASYAN	90	CBAL	$e^+ e^- \rightarrow e^+ e^- \pi^0 \pi^0 \pi^0$
1624 ± 21		1 BELLINI	85	SPEC	40 $\pi^- A \rightarrow \pi^- \pi^+ \pi^- A$
1622 ± 35		6 BELLINI	85	SPEC	40 $\pi^- A \rightarrow \pi^- \pi^+ \pi^- A$
1693 ± 28		7 BELLINI	85	SPEC	40 $\pi^- A \rightarrow \pi^- \pi^+ \pi^- A$
1710 ± 20		8 DAUM	81B	SPEC	- 63,94 $\pi^- p$
1660 ± 10		4 ASCOLI	73	HBC	- 5-25 $\pi^- p \rightarrow p \pi_2$

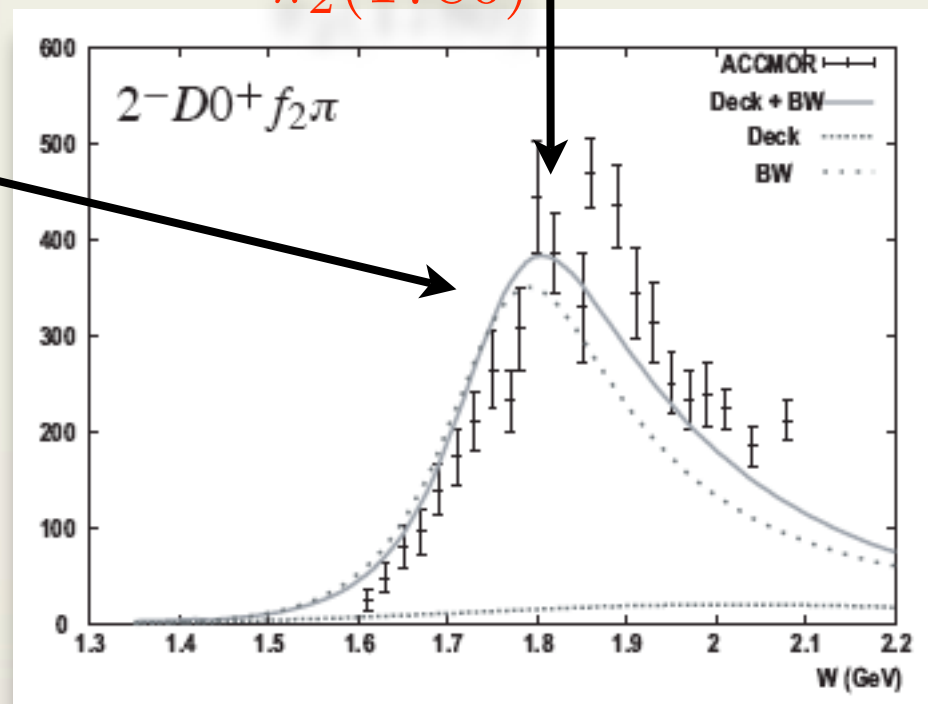
$$\gamma p \rightarrow f_2 \pi^+ n \rightarrow \pi^+ \pi^- \pi^+ n$$

$\pi_2(1670)$



$\pi_2(1780)$

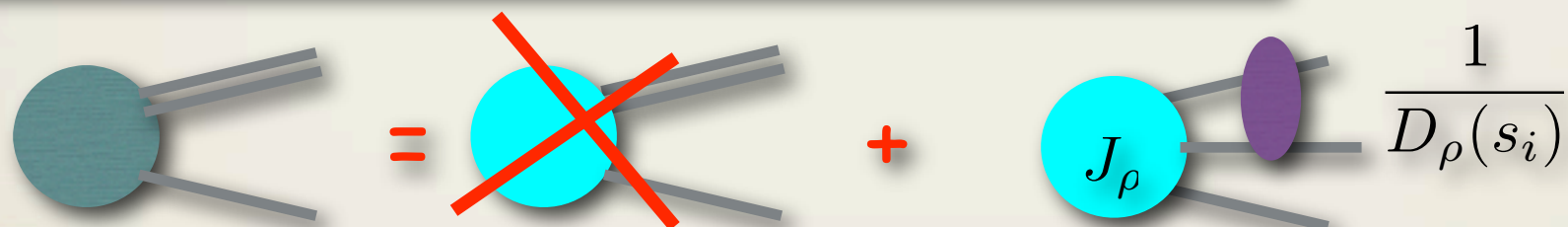
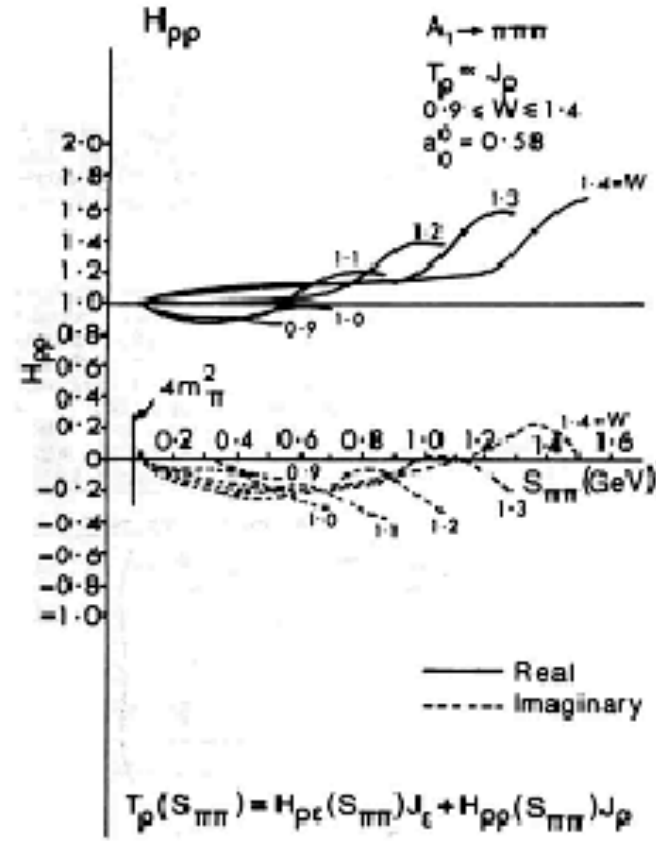
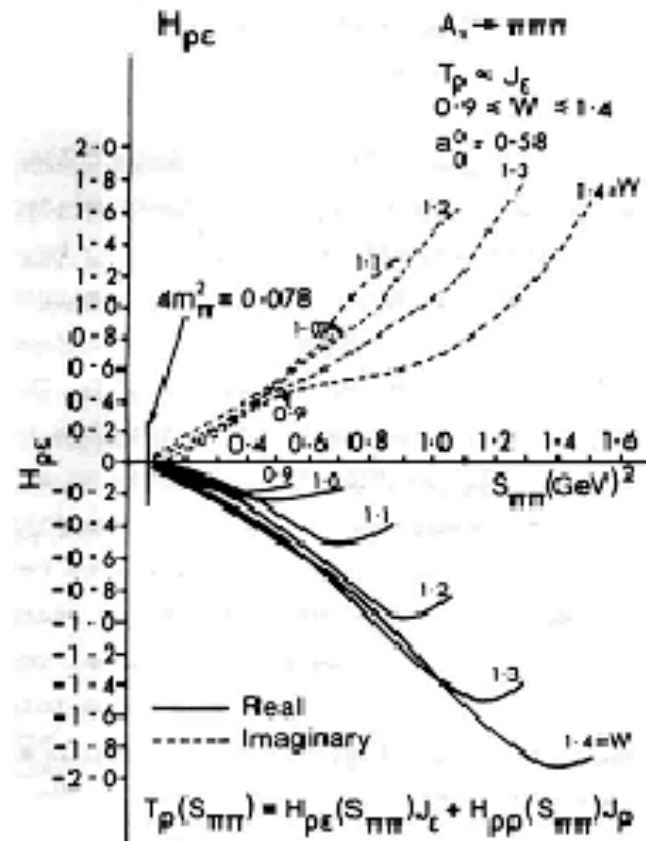
$\pi_2(1810)$



Isobar-type fits could
produce spurious
resonances

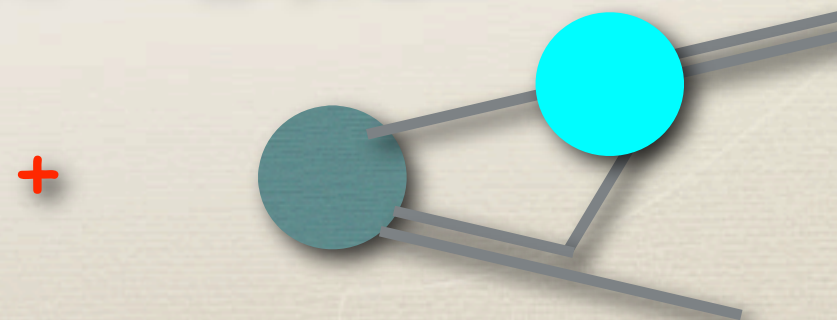
$$\gamma p \rightarrow f_2 \pi^+ n \rightarrow \pi^+ \pi^- \pi^+ n$$

Y.Goradia (ca 1975)



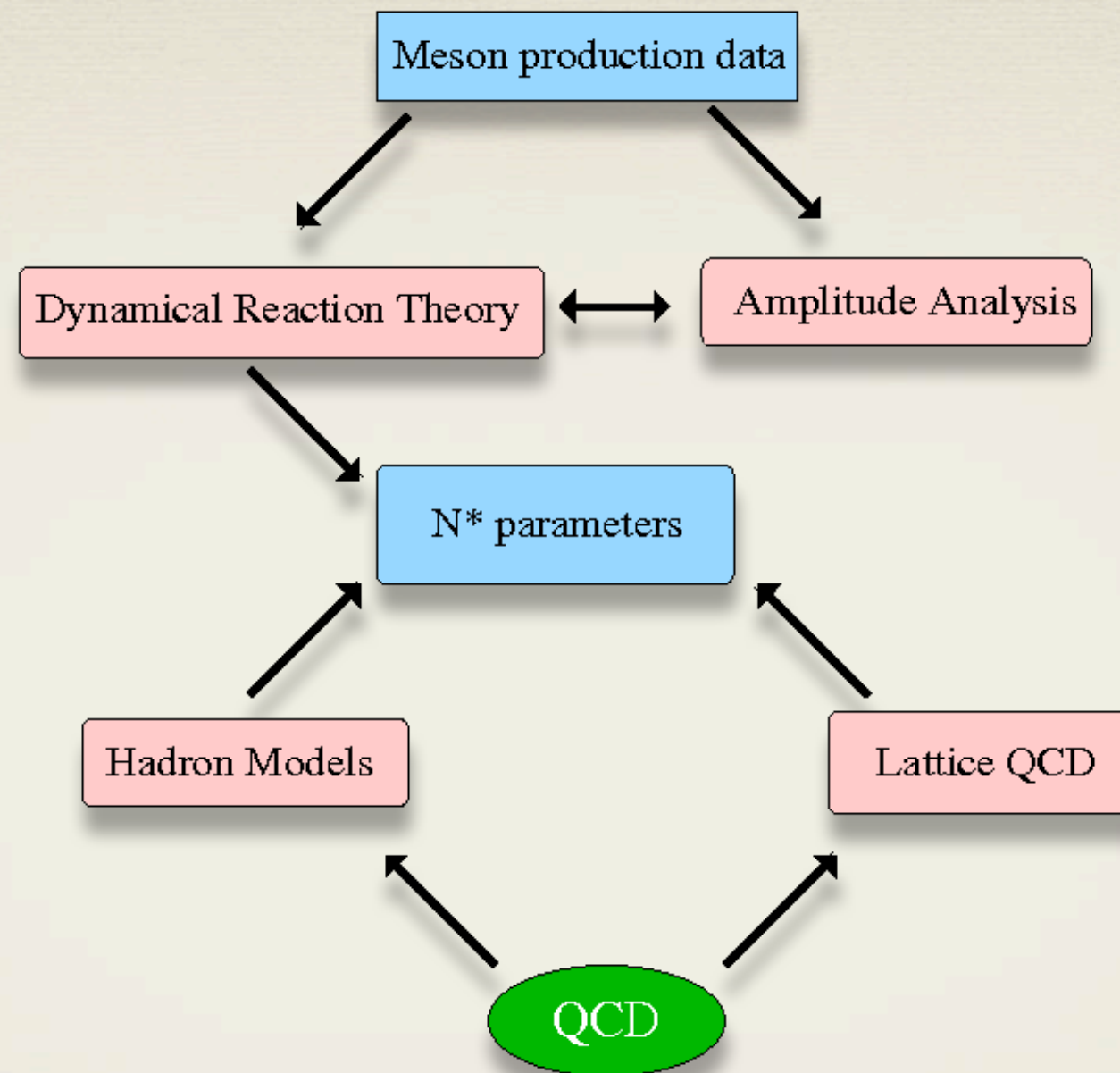
$$T_\rho = 1 \times J_\rho(s_i) \equiv H_{\rho\rho} J_\rho(s_i)$$

$$T_\rho = H_{\rho\rho} J_\rho(s_i) + H_{\rho\sigma} J_\sigma(s_i)$$



Dynamical Coupled-Channel Analysis at EBAC

Theory Center, JLAB



The **Excited Baryon Analysis Center (EBAC)** is conducting dynamical coupled-channel analyses of JLab data and other relevant data in order to extract N^* parameters and to investigate the reaction mechanisms for mapping out the quark-gluon substructure of N^* . This effort is also providing theoretical input to the data analyses by the experimental groups, especially by the CLAS collaboration at JLab.

similar efforts
proposed for the
meson program

dispersive analysis of partial waves in of $\pi^-\pi^+$ photoproduction

1 Highest γ energy in the gl I data set
 $E_\gamma \sim 3\text{-}4$ GeV. Low momentum
transfer ($-t < 1$ GeV²)

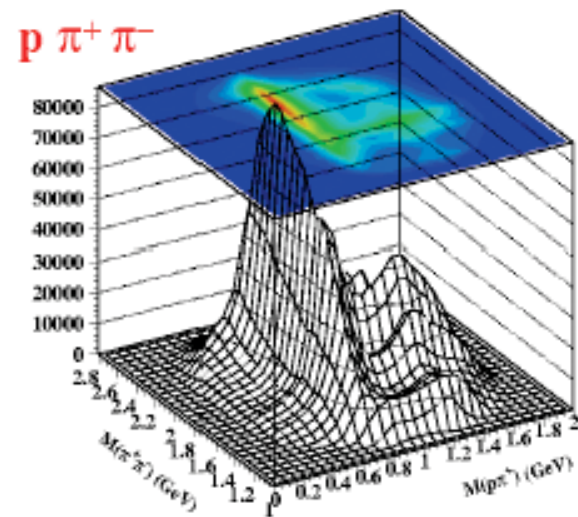
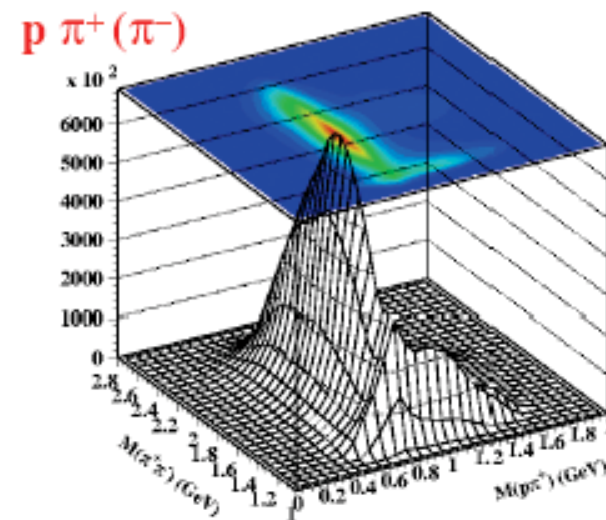
2 Extract moments of the angular
distribution (correcting for the CLAS
acceptance) by log-likelihood fit

3 Describe moments in terms of
partial waves

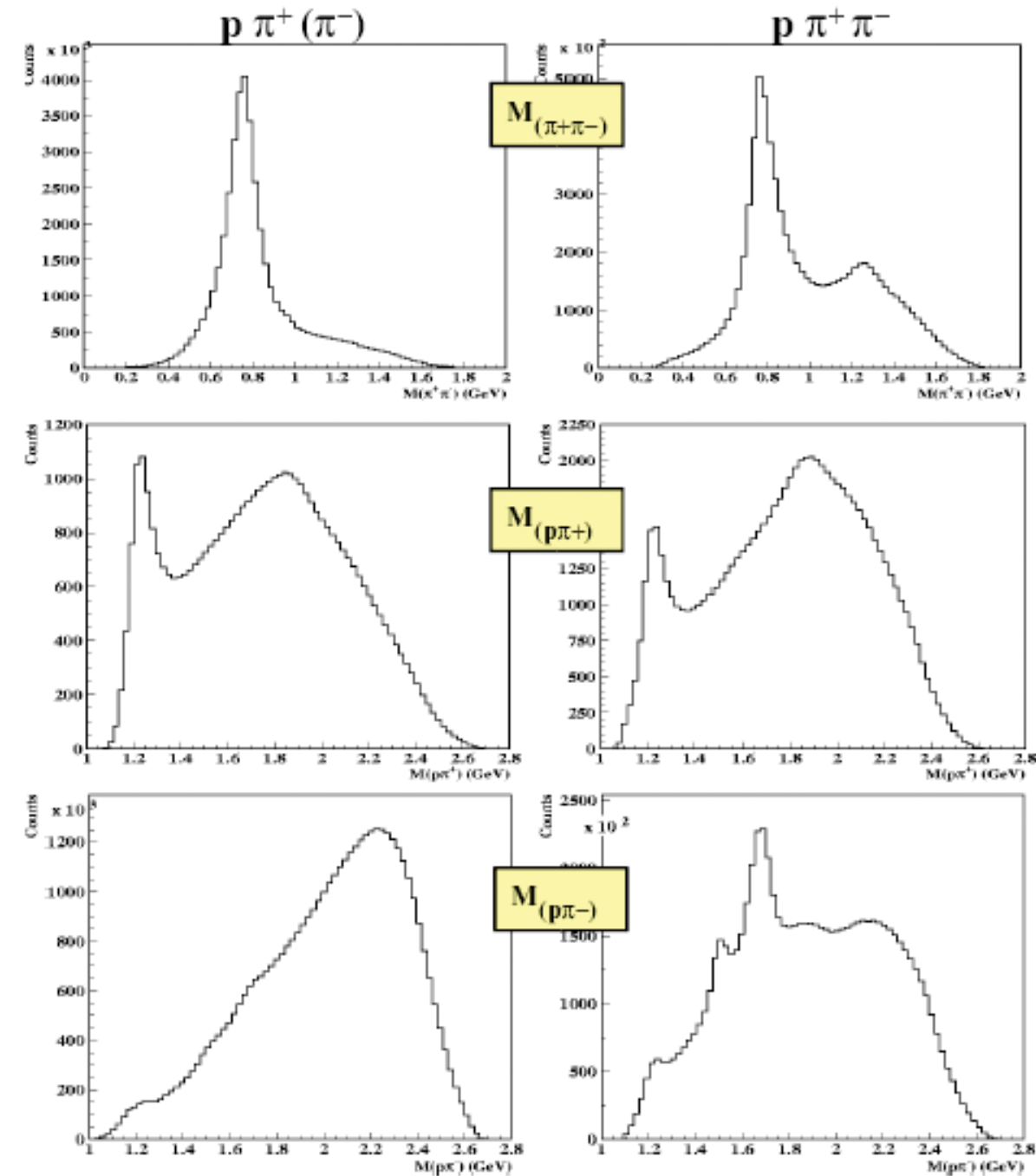
3 Parametrize partial waves
in terms of
known $\pi\pi$ phase shifts and
unknown production
amplitudes

4 Derive partial wave
cross sections
to compare with models

Mass spectra



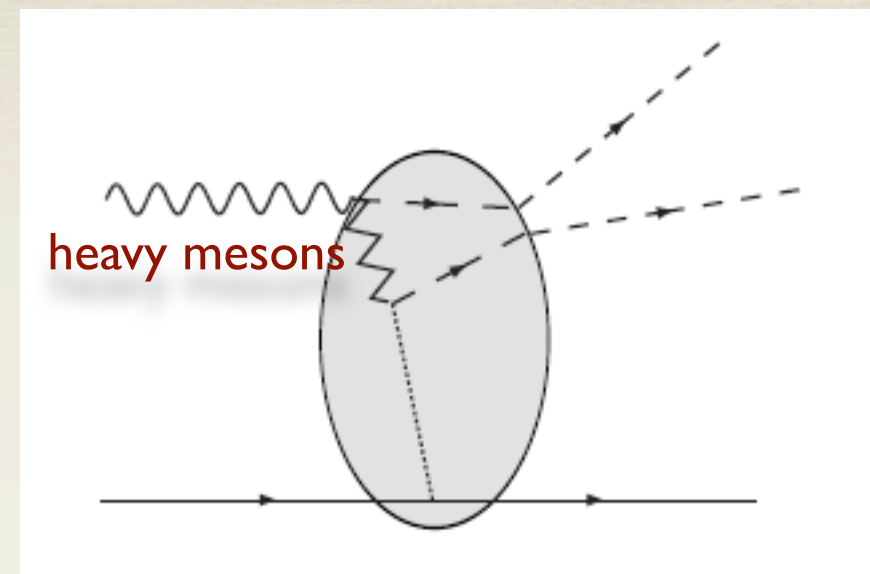
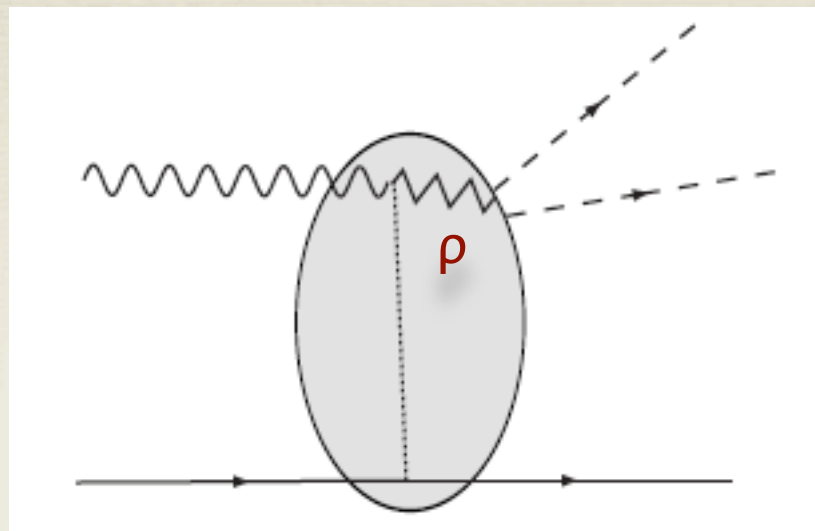
Photoproduction of $\pi\pi$ meson pairs



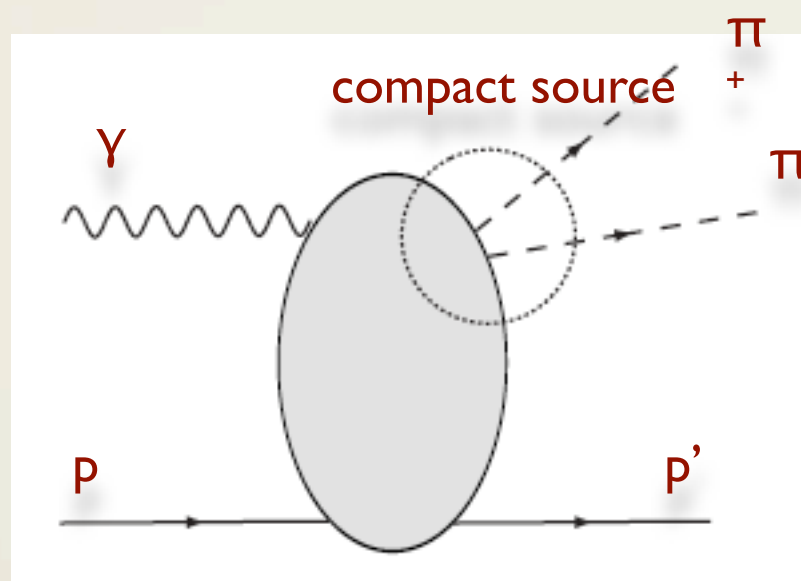
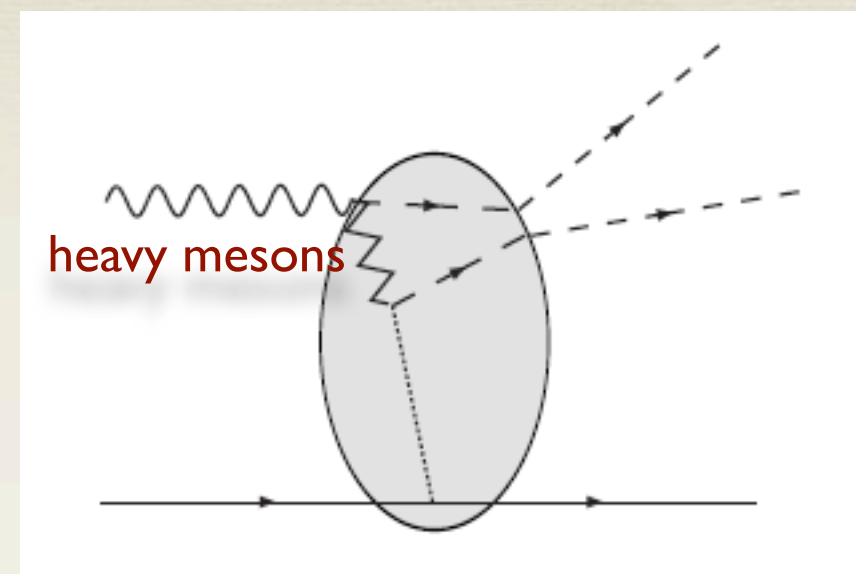
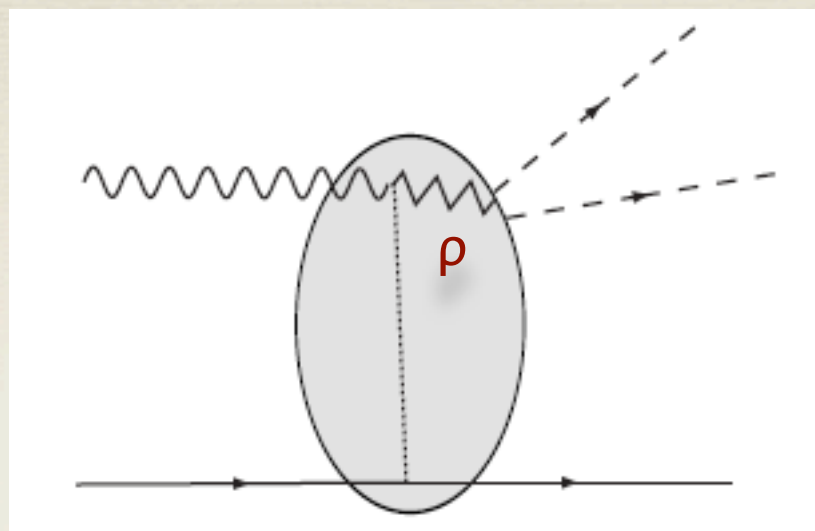
M.Battaglieri

CLAS Collaboration Meeting Nov 07

π

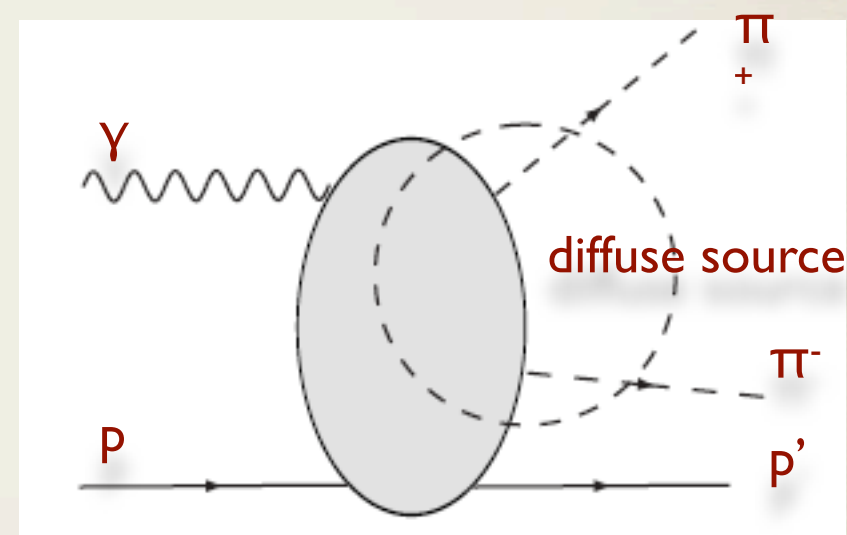
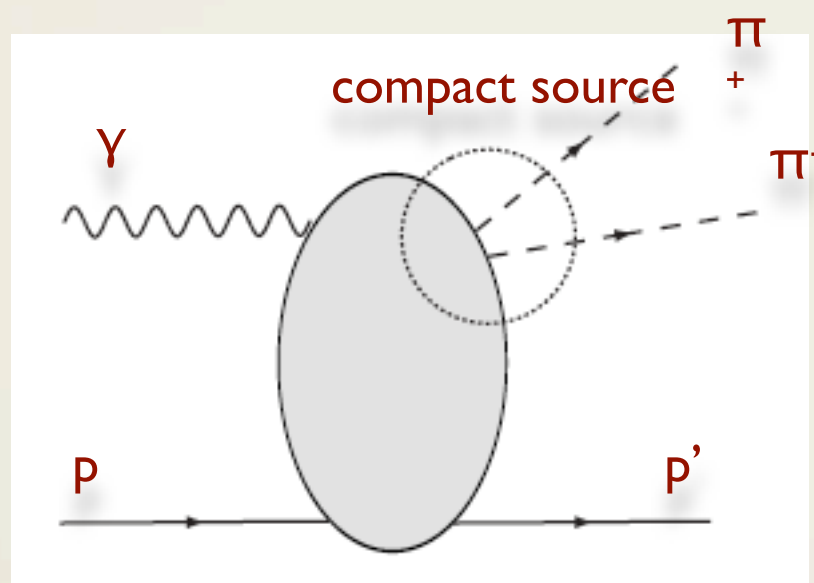
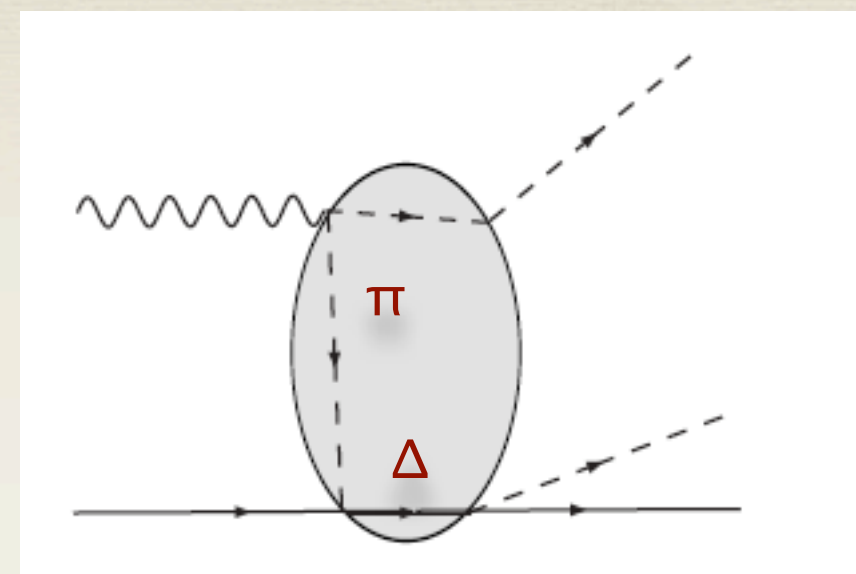
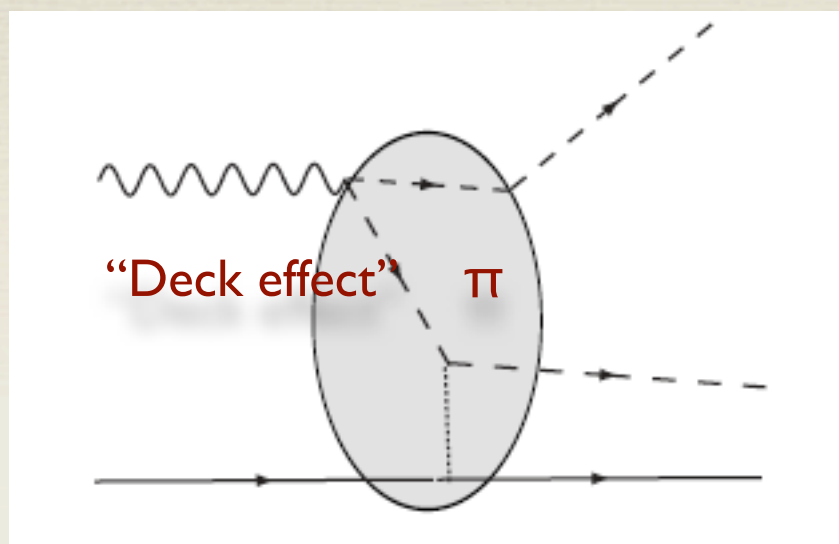


π



$$e^{i\delta_{\pi\pi}^{(l,I)}} \sin(\delta_{\pi\pi}^{(l,I)})$$

π



$$e^{i\delta_{\pi\pi}^{(l,I)}} \sin(\delta_{\pi\pi}^{(l,I)})$$

$$e^{i\delta_{\pi\pi}^{(l,I)}} \cos(\delta_{\pi\pi}^{(l,I)})$$

$$A(s_1, s_2, s)$$

1

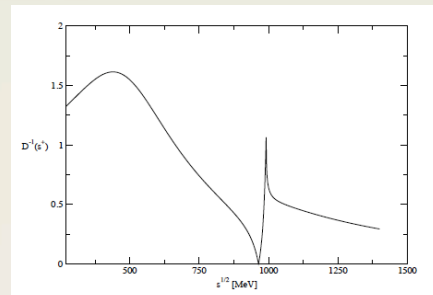
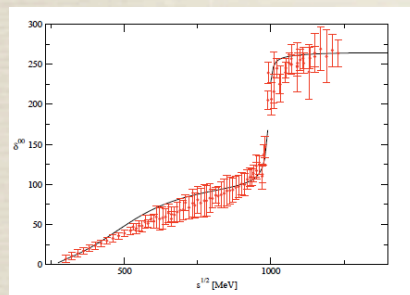
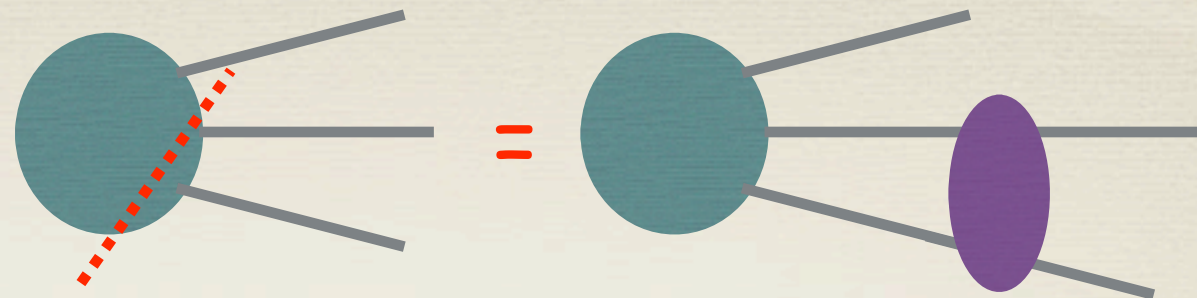
$$s_i = (p_j + p_k)^2$$

2

3

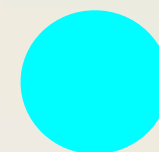
$$\sum_i s_i = s + \sum_i m_i^2$$

$$\text{Dis}_1 A(s_1, \dots) = A_1(s_1 + i\epsilon, \dots) - A(s_1 - i\epsilon, \dots) \neq 0$$



2-body scattering
amplitude, e.g.
 $(s_i - m_R^2 - i m_R \Gamma)^{-1}$

=



×

=

$$N(s_i)$$

$$D^{-1}(s_i)$$

$$A(s_1, s_2, s)$$

1

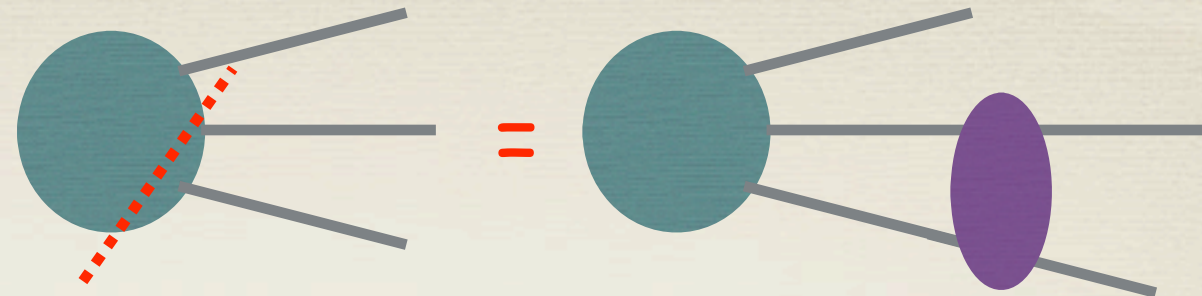
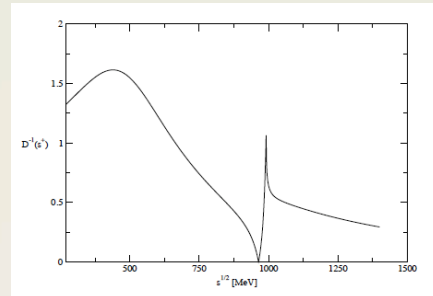
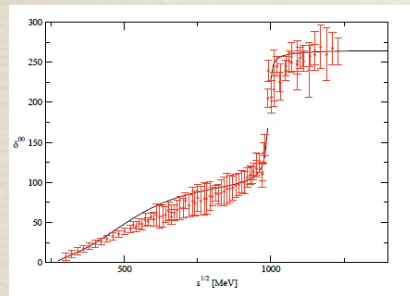
$$s_i = (p_j + p_k)^2$$

2

3

$$\sum_i s_i = s + \sum_i m_i^2$$

$$\text{Dis}_1 A(s_1, \dots) = A_1(s_1 + i\epsilon, \dots) - A(s_1 - i\epsilon, \dots) \neq 0$$

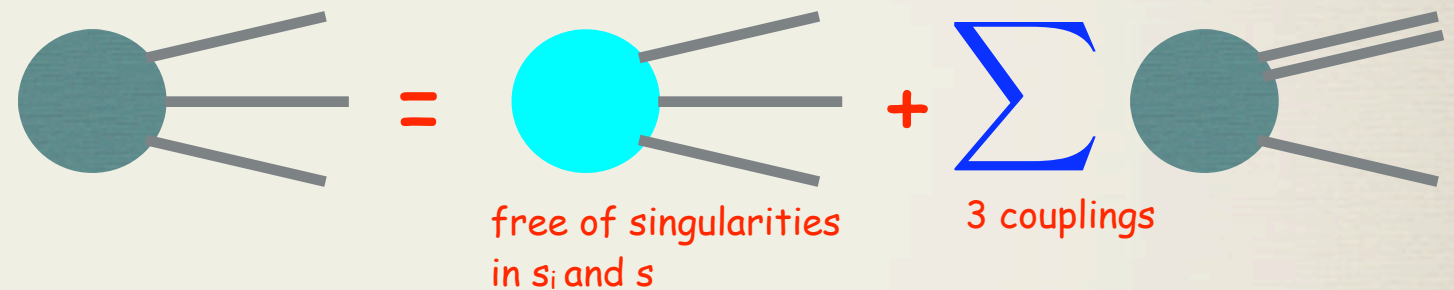


2-body scattering
amplitude, e.g.
 $(s_i - m_R^2 - i m_R \Gamma)^{-1}$

$$= N(s_i) \times D^{-1}(s_i)$$

Dominance of 2-body interactions

$$A(s_i, s) = A_0(s_i, s) + \sum_i A_i(s_i, s)$$

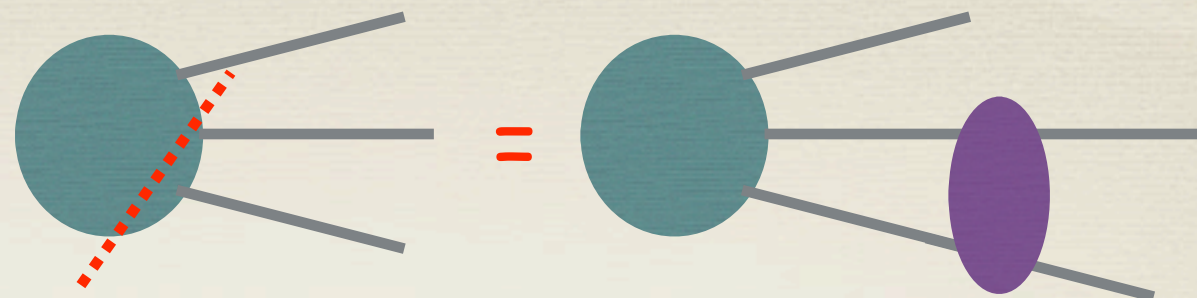
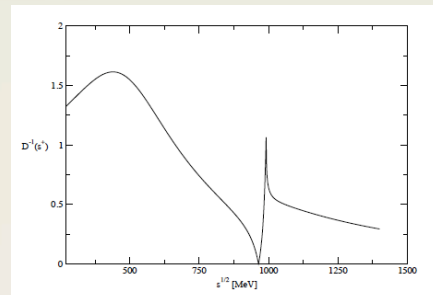
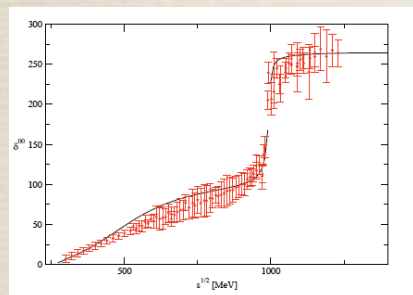


$$A(s_1, s_2, s)$$

$$s_i = (p_j + p_k)^2$$

$$\text{Dis}_1 A(s_1, \dots) = A_1(s_1 + i\epsilon, \dots) - A(s_1 - i\epsilon, \dots) \neq 0$$

$$\sum_i s_i = s + \sum_i m_i^2$$

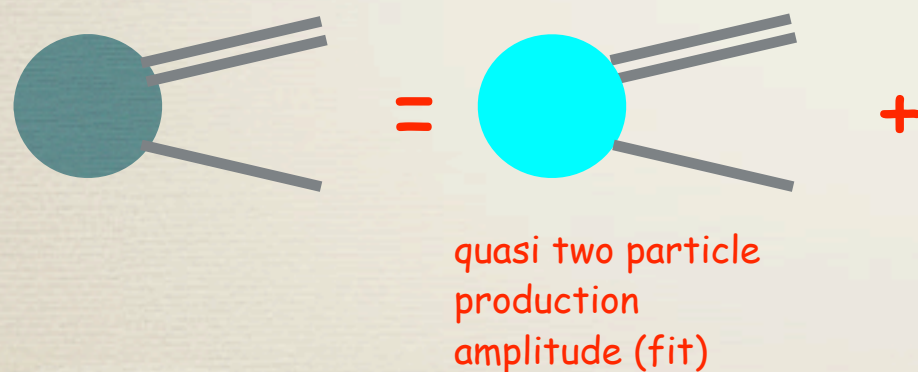
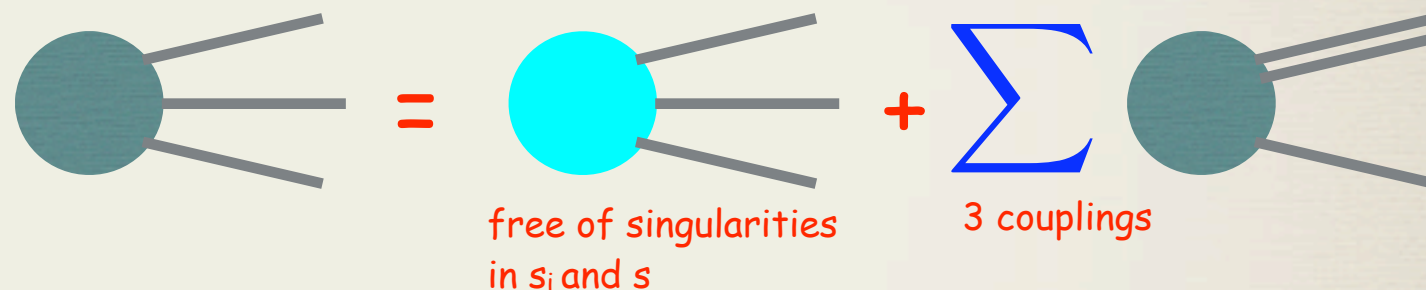


2-body scattering
amplitude, e.g.
 $(s_i - m_R^2 - i m_R \Gamma)^{-1}$

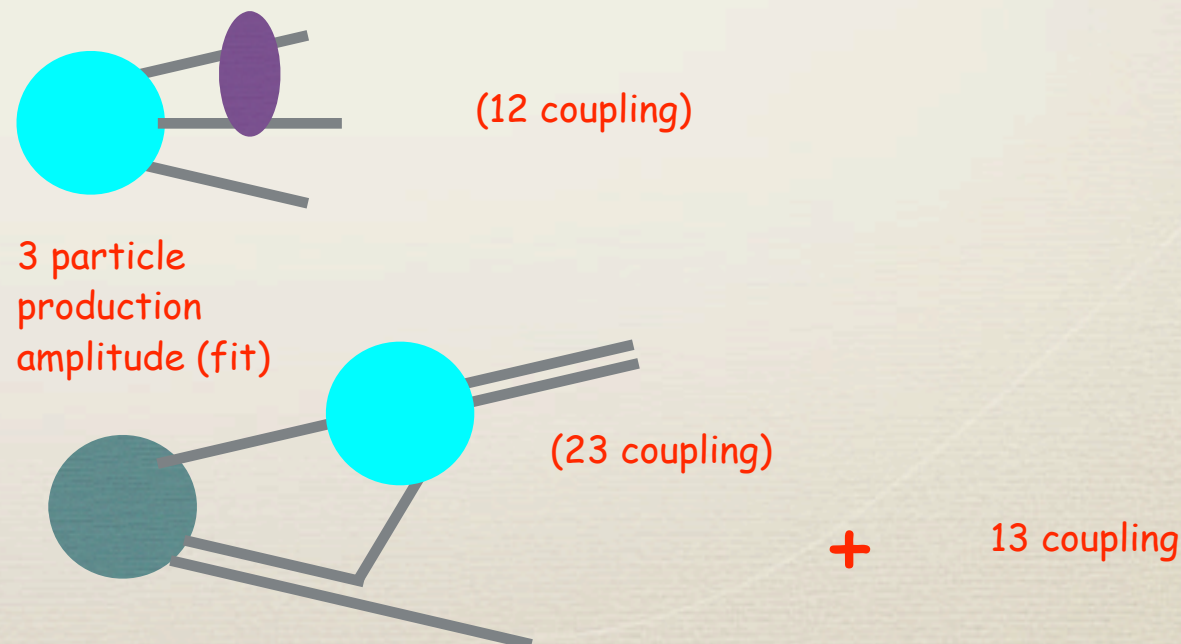
$$N(s_i) \times D^{-1}(s_i)$$

Dominance of 2-body interactions

$$A(s_i, s) = A_0(s_i, s) + \sum_i A_i(s_i, s)$$



Set of 3 integral equations for
 $A_i(s_i, s)$

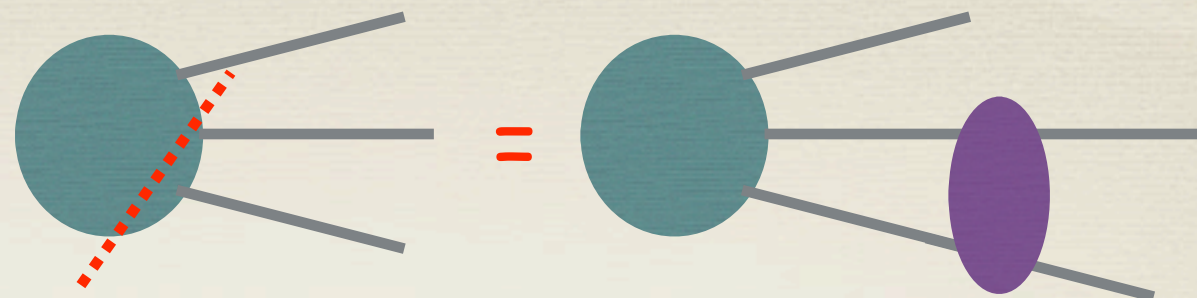
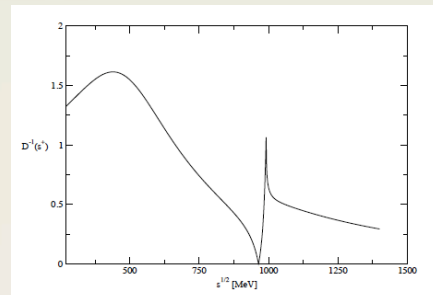
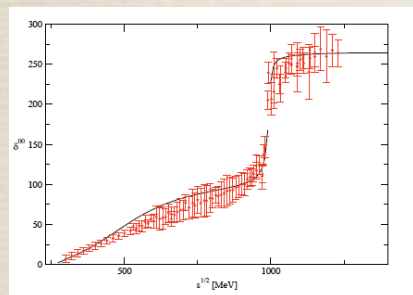


$$A(s_1, s_2, s)$$

$$s_i = (p_j + p_k)^2$$

$$\text{Dis}_1 A(s_1, \dots) = A_1(s_1 + i\epsilon, \dots) - A(s_1 - i\epsilon, \dots) \neq 0$$

$$\sum_i s_i = s + \sum_i m_i^2$$

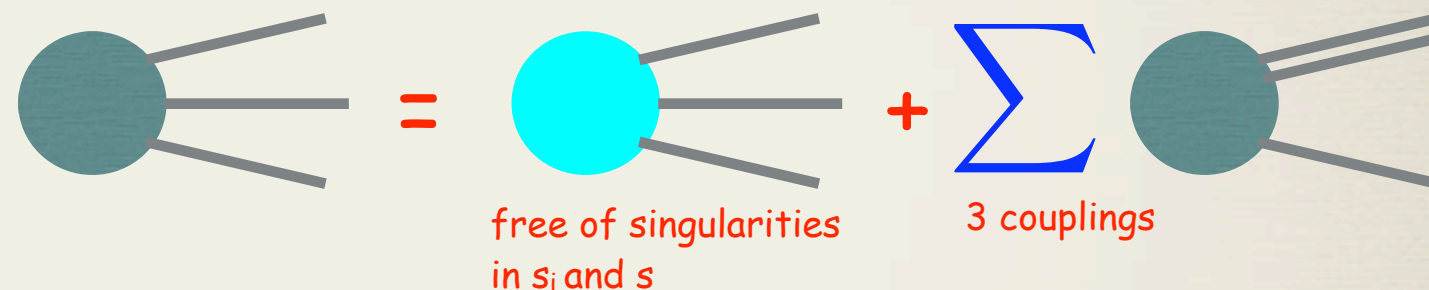


2-body scattering
amplitude, e.g.
 $(s_i - m_R^2 - i m_R \Gamma)^{-1}$

$$= N(s_i) \times D^{-1}(s_i)$$

Dominance of 2-body interactions

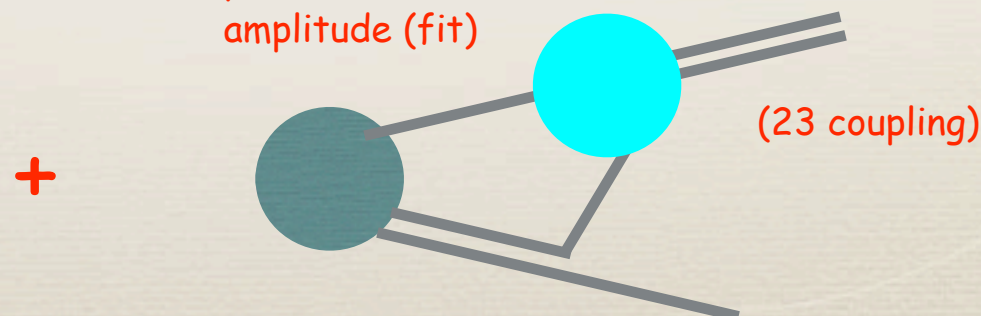
$$A(s_i, s) = A_0(s_i, s) + \sum_i A_i(s_i, s)$$



quasi two particle
production
amplitude (fit)

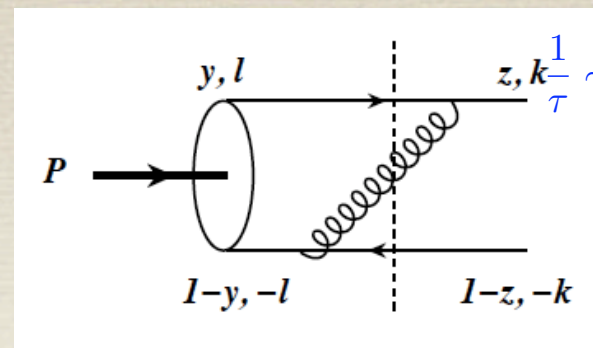
3 particle
production
amplitude (fit)

Set of 3 integral equations for
 $A_i(s_i, s)$



13 coupling

more on one-gluon exchange and light quarks

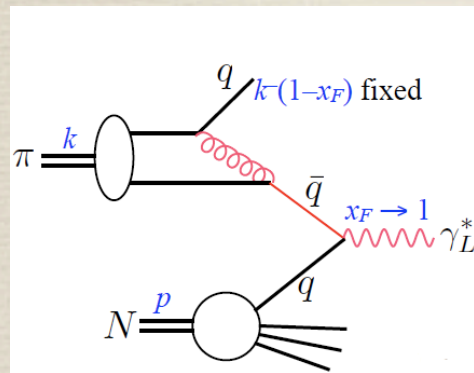


$$\sum_i E_i - E \sim \sum_i \frac{k_{\perp,i}^2 + m_i^2}{zP^+} - \frac{M^2}{P^+}$$

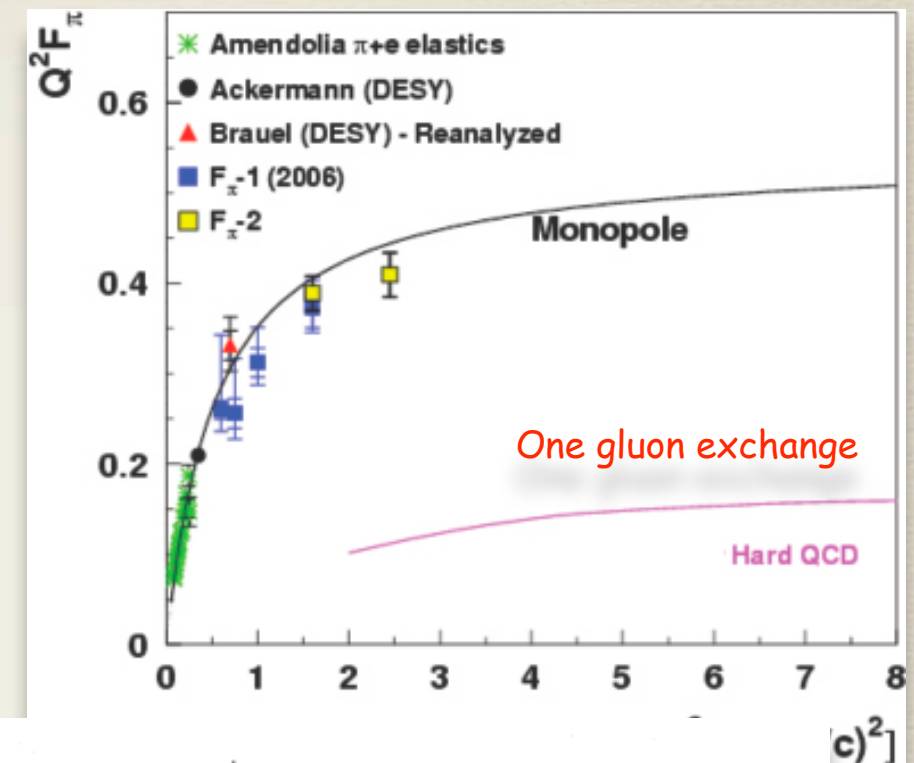
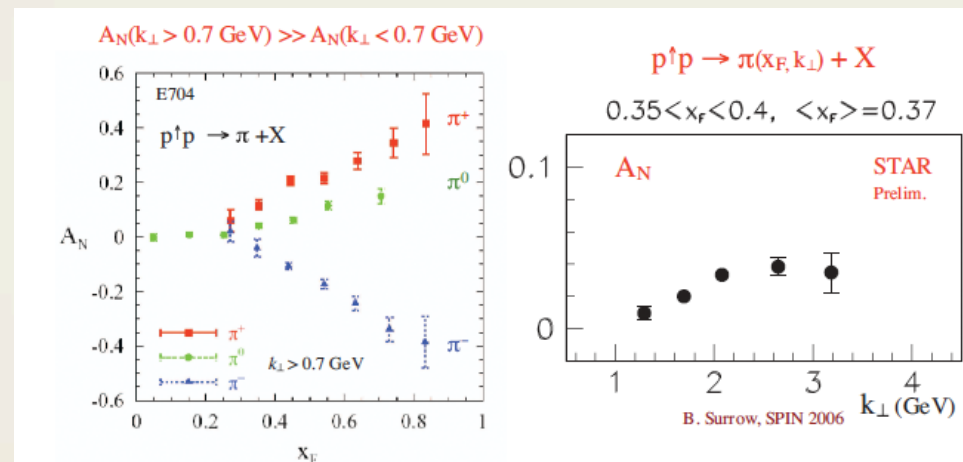
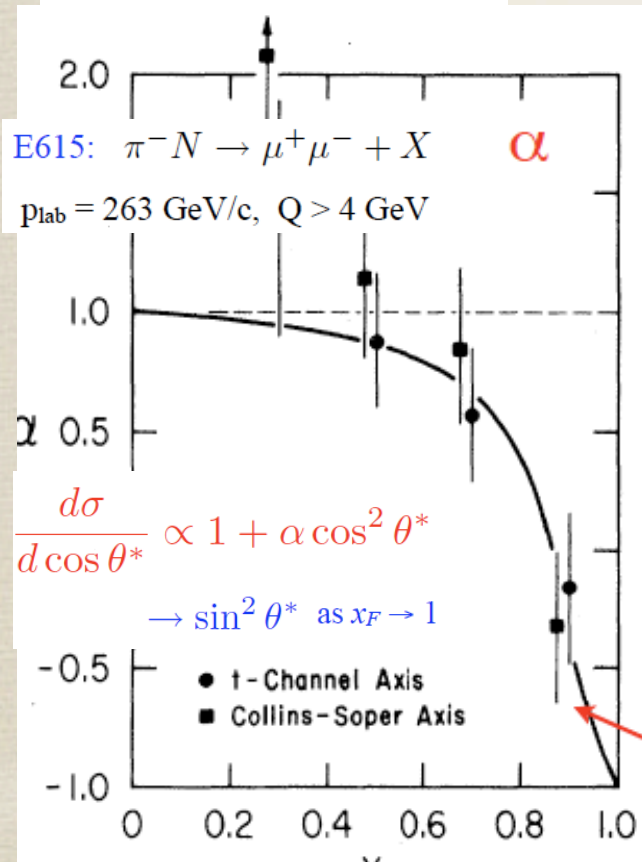
$$zP^+ \gg (k_{\perp,i}, m_i)$$

$$\Psi_{LC}(zp^+, k_{\perp}) \sim \frac{1}{\Delta E_{LC}} \sim \frac{z(1-z)}{k_{\perp}^2}$$

expansion not valid at end points $z \rightarrow 0, 1$!
w.f may be less suppressed at end points

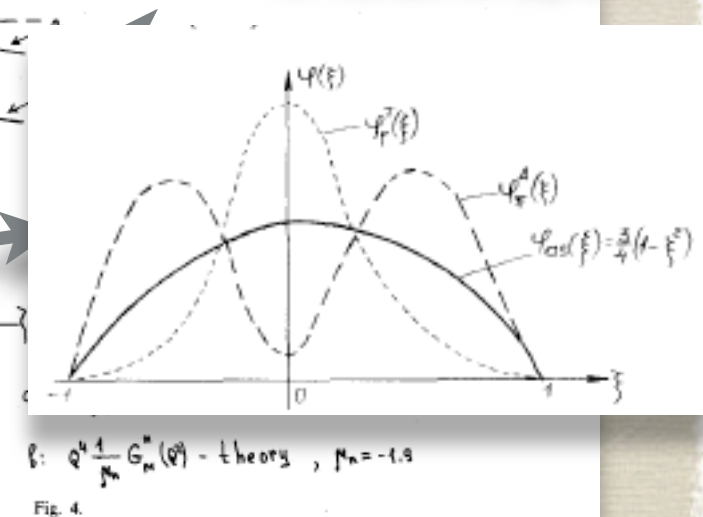
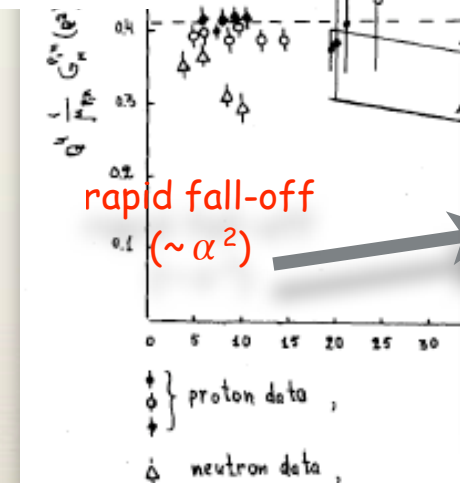
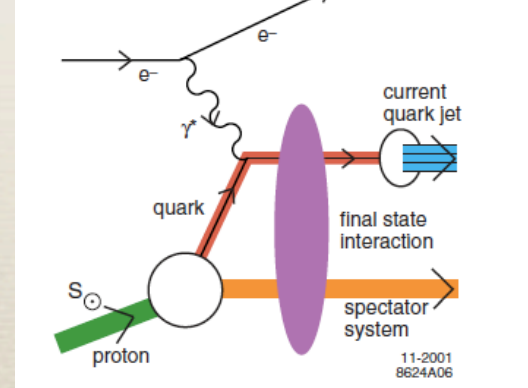


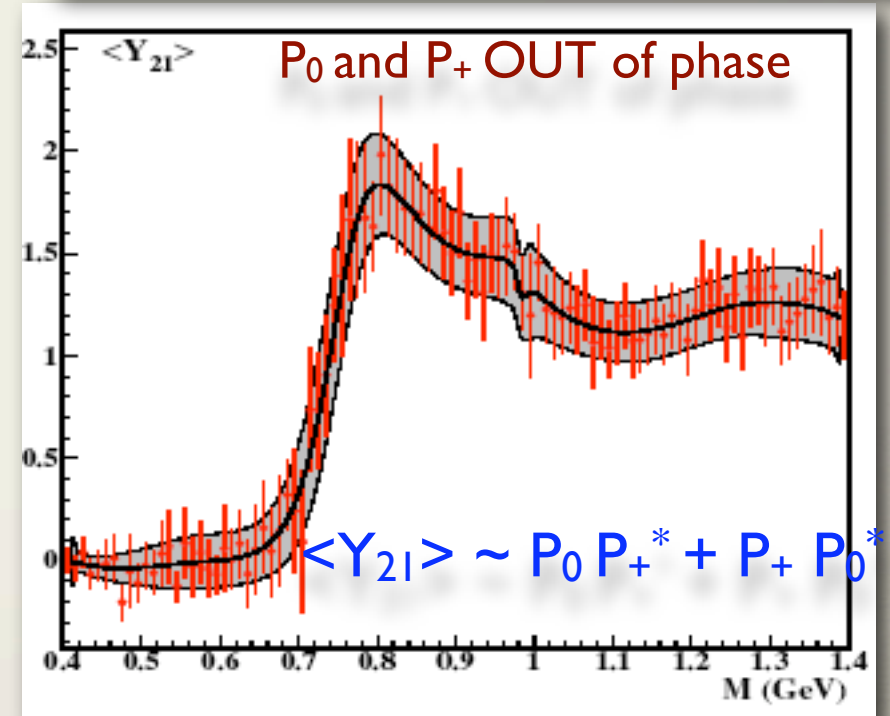
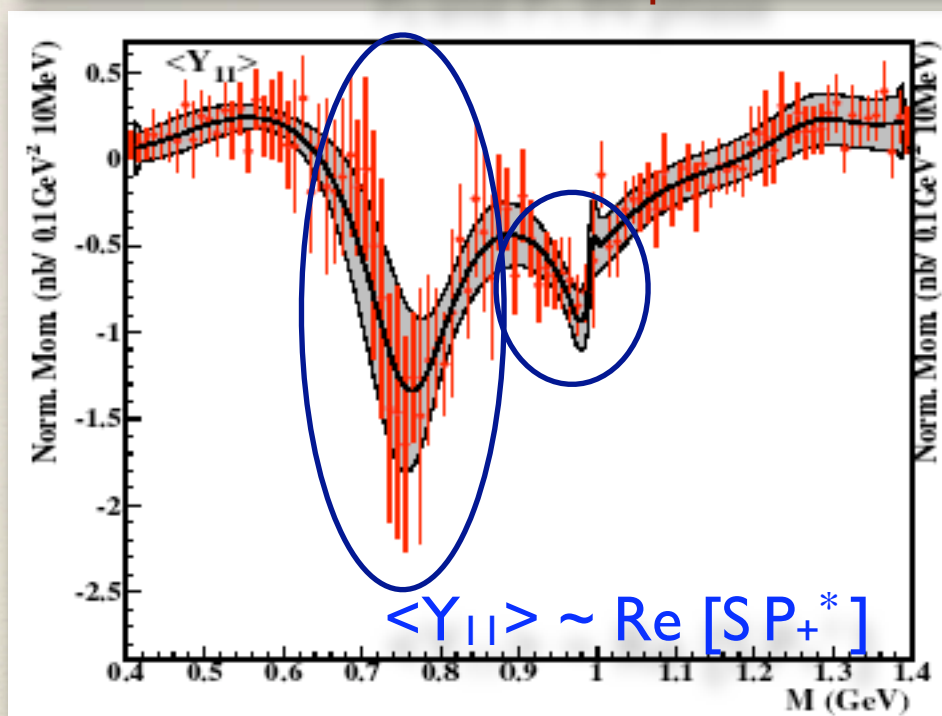
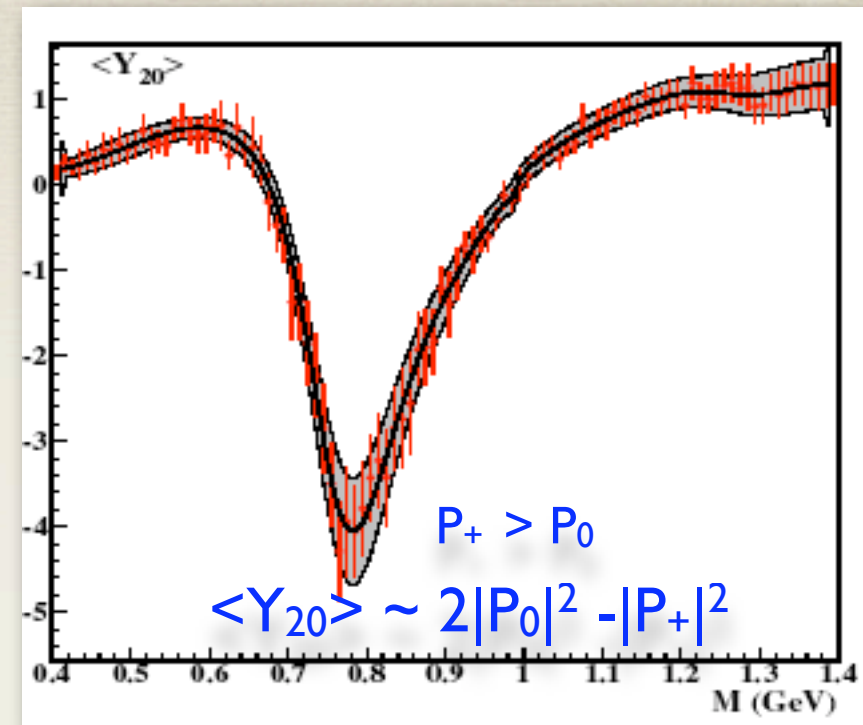
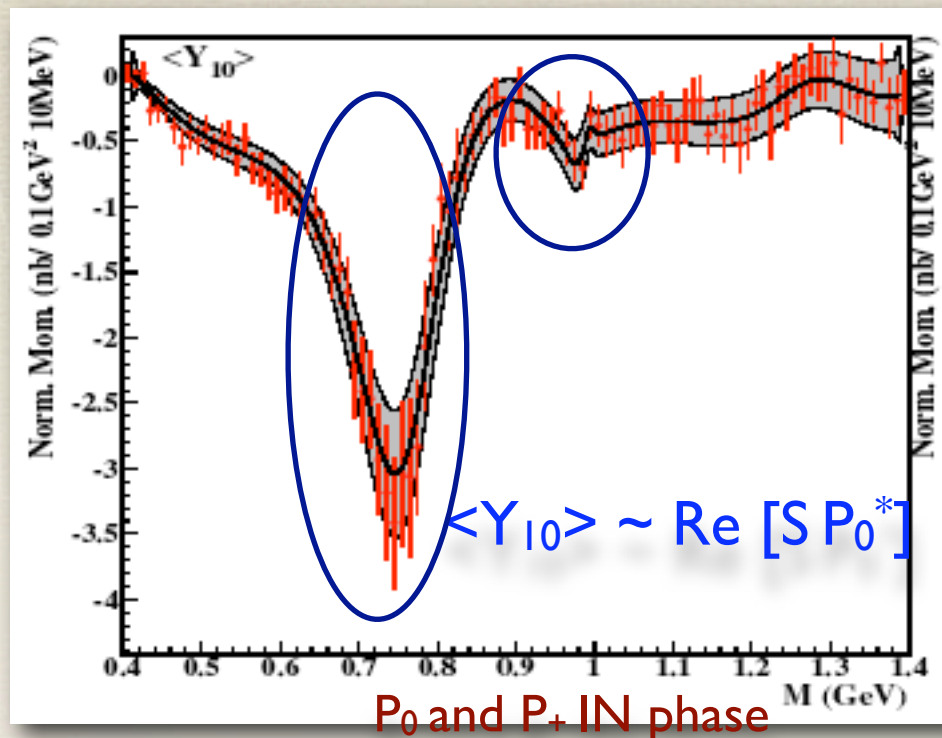
... low-x partons are soft and coherent with the hard scattering sub-process



"artificial" enhancement of normalization (QCD sum rule)

Asymmetry strongly suppressed in pQCD analysis (quark mass, α)
... due to final state interactions





CLAS efficiency

- The kinematic region of interest is $0.0 < -t < 1.0 \text{ GeV}^2$

- CLAS Efficiency for $p \pi^+ \pi^-$ show a steep dependence up to $-t < 1.0 \text{ GeV}^2$



Only the topology $p \pi^+ (\pi^-)$ is used in this analysis

