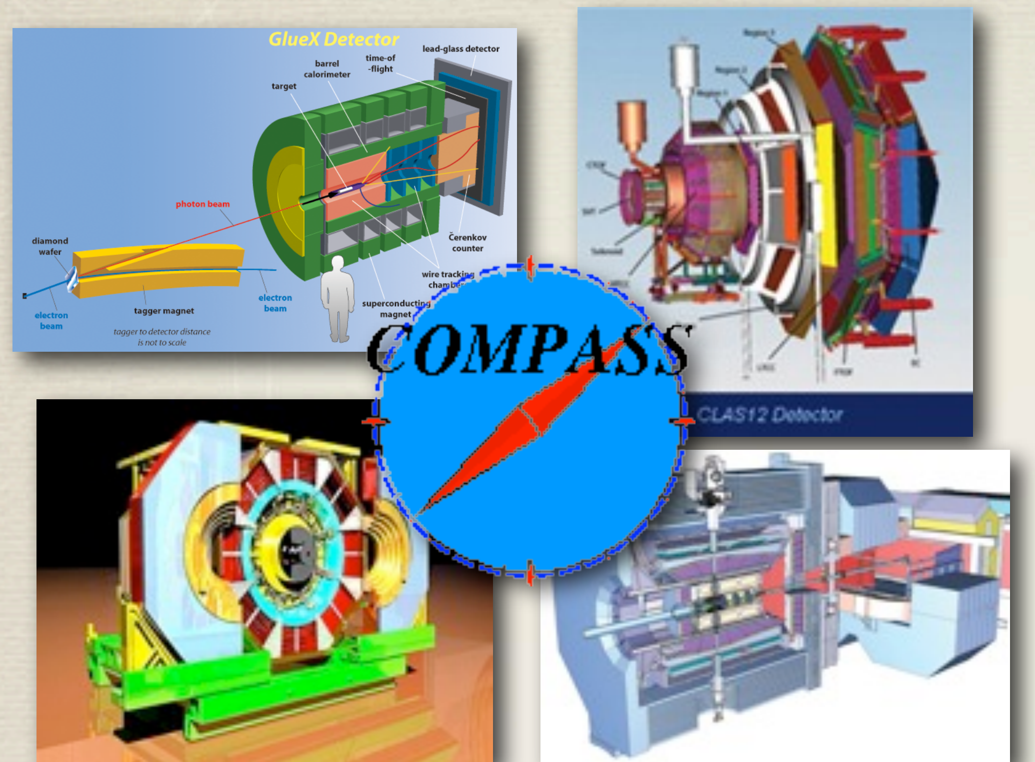
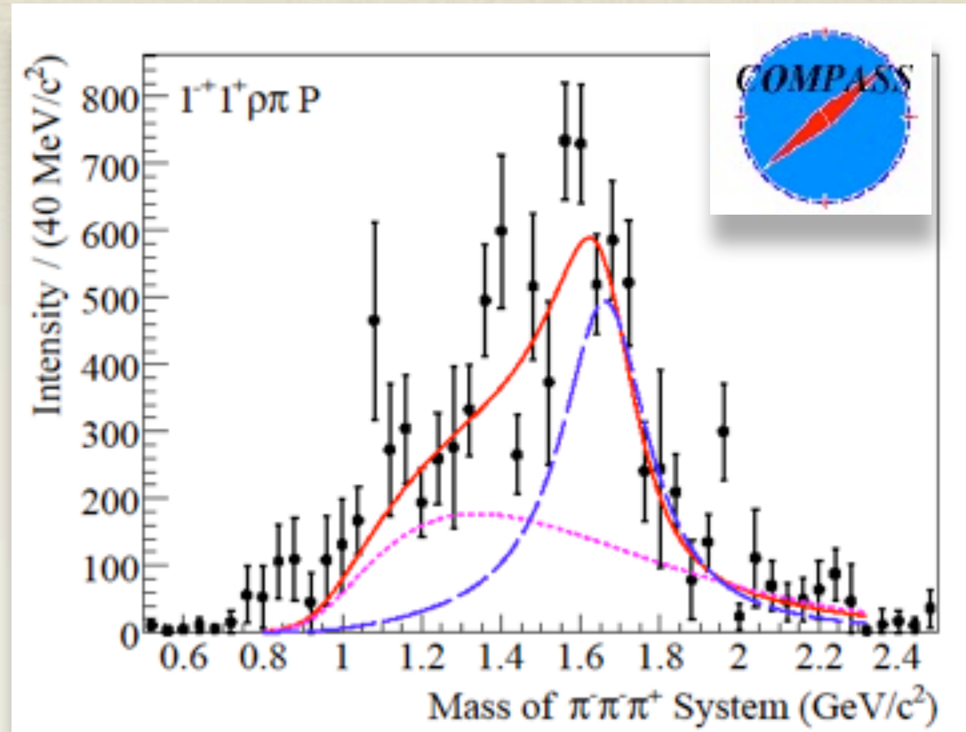
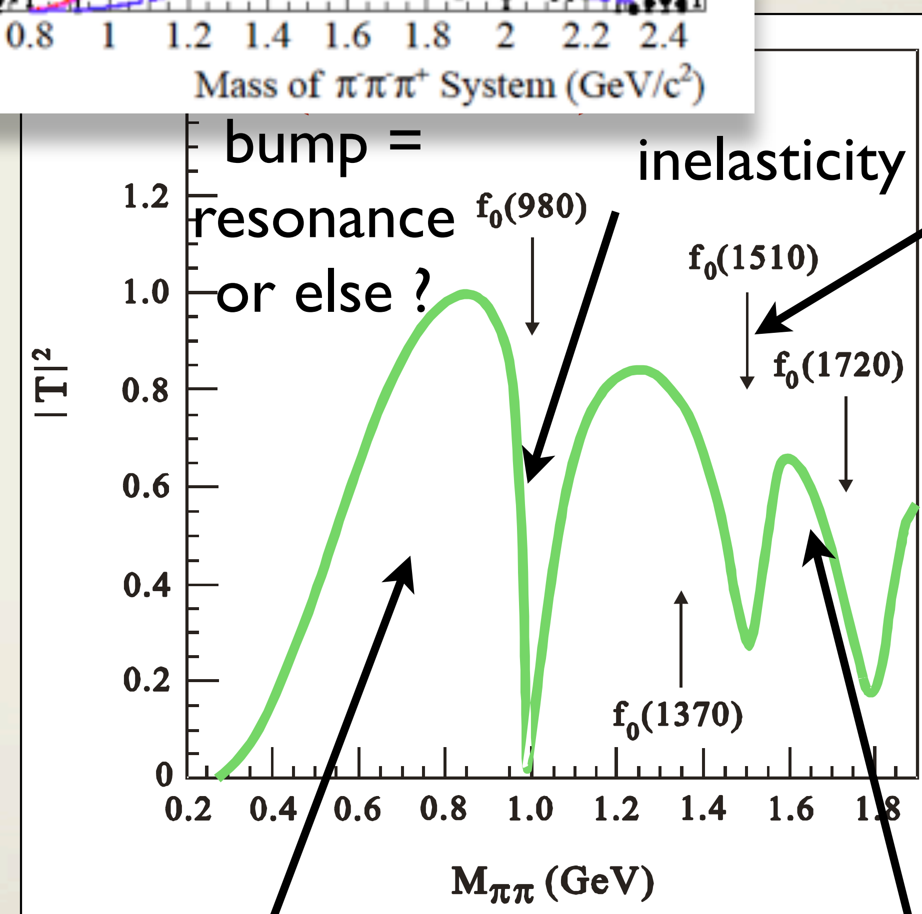
Key issues:

I What is the connection between data and physical amplitudes ?







2. What is the connection amplitudes (real world) and resonances (“unphysical sheets”) between resonances and QCD ?

3. What is the connection between resonances and QCD ?

>> amplitude analysis <<
(analytic properties,dispersion relations, QCD and model input)

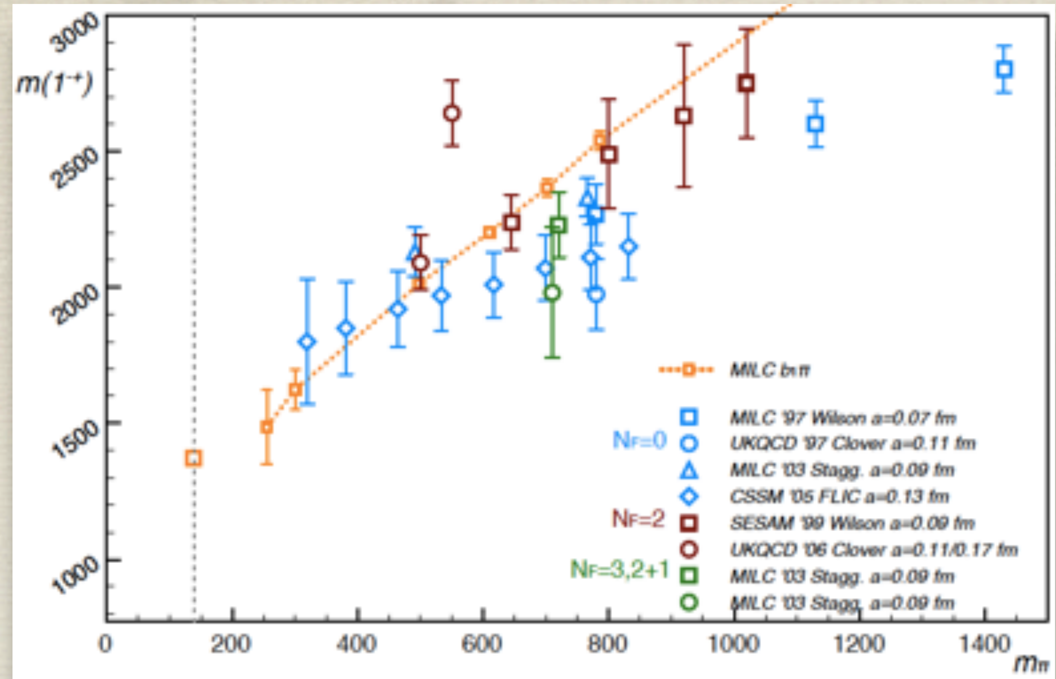
Phenomenology overview of exotics and spectroscopy

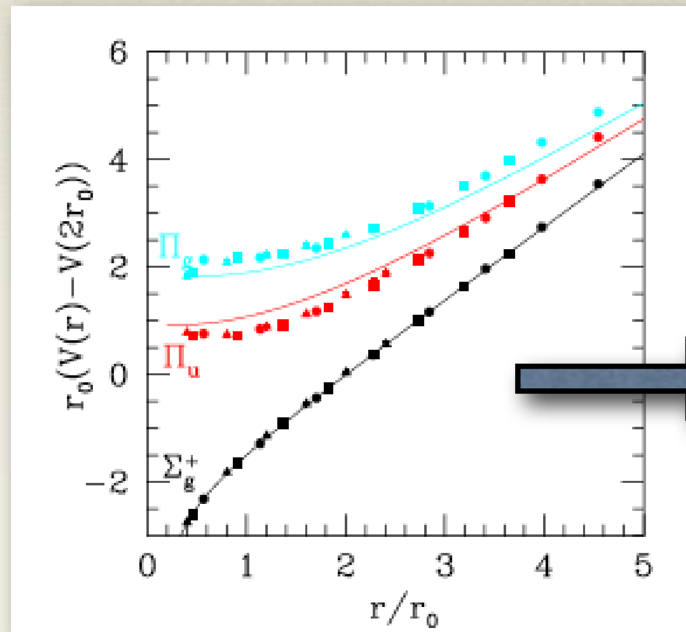
Adam Szczepaniak
Indiana University

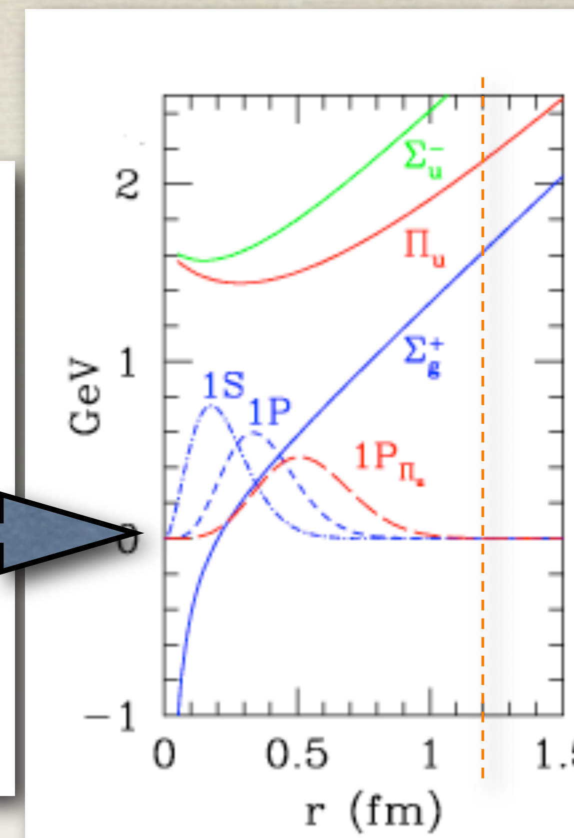
Outline:

* (Selected) aspects on theory and phenomenology of gluonic excitations
* Experimental status
* (Selected) aspects of PWA

* $1^{-+}_{S_{Q\bar{Q}}=1} = \frac{0^{++}}{2} + \rho \;\sim 0.8\ \mathrm{GeV} + 0.77\ \mathrm{MeV} \sim 1.6\ \mathrm{GeV}$



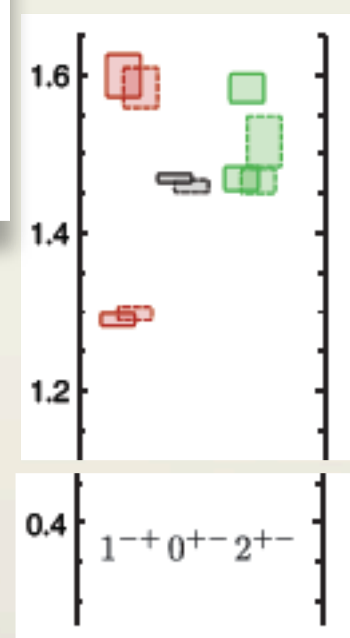




Charmonium 1^{-+}

Ref.	Method	ΔM (GeV)
MILC 97	W	1.34(8)(20)
MILC 99	SW	1.22(15)
CP-PACS 99	NR	1.323(13)
JKM 99	LBO	1.19

Excitations in excess of 1GeV



1^{-+} (1.8 GeV)	$b_1\pi$	$f_1\pi$	$\rho\pi$	
PSS	S 73 D 1	S 9 D 0.04	P 13	Γ MeV
IKP	S 51 D 11	S 14 D 7	P 12	

Isgur, Kokosky, Paton (85)
Close, Page (95)
Page, Swanson, Szczepaniak (99)
Close, Dudek (04)

*

$J^{PC} = 1^{-+}$ lowest state

Higher masses have also been resolved

Chiral extrapolations 100-200 MeV (Thomas,APS)

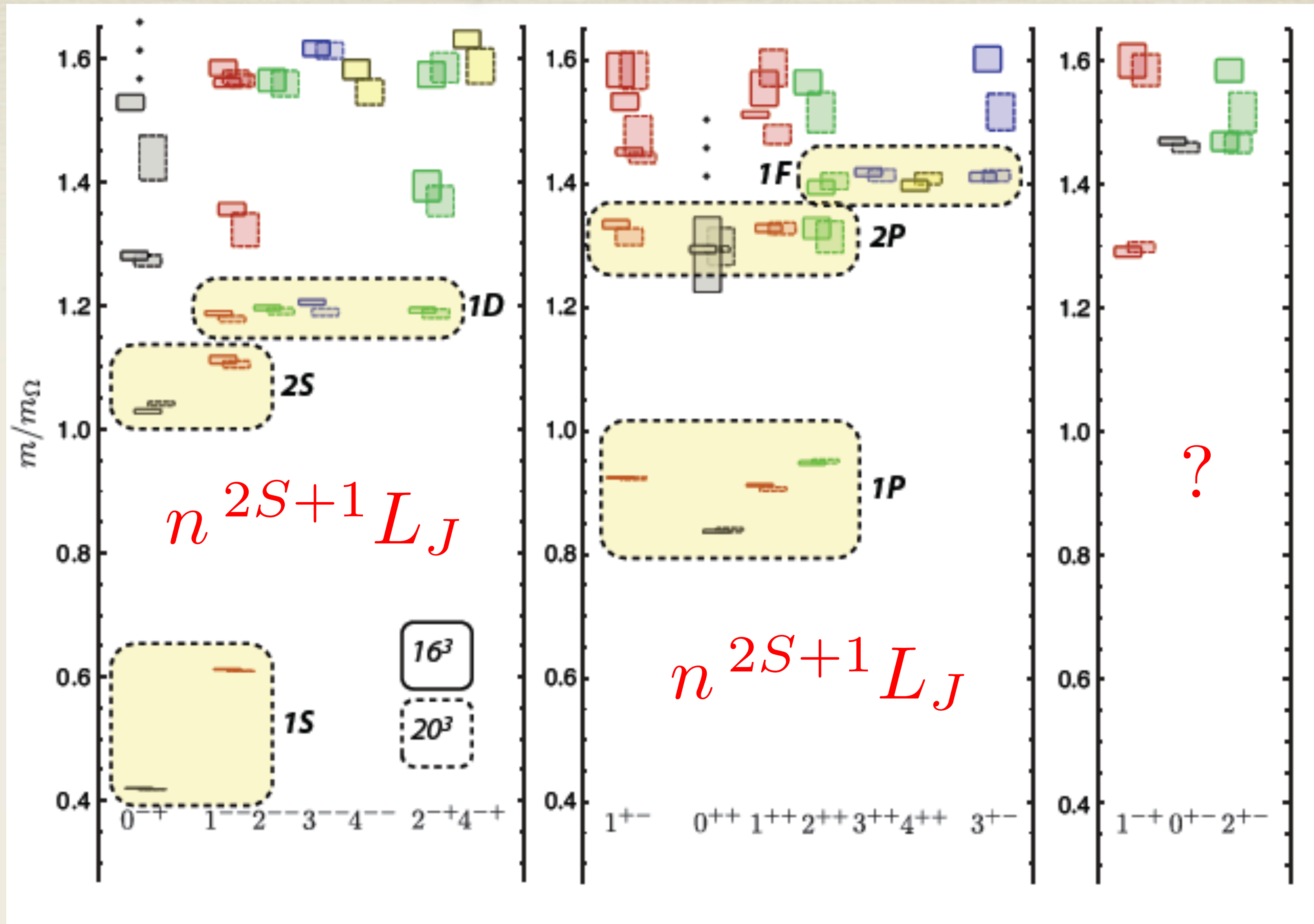
In large-Nc same as for ordinary mesons O(1/Nc) (Cohen)

Preliminary (toy) lattice computation of widths agrees with models (Michael,McNeile) (Burns,Close)

Structure

✱ normal meson spectrum seems to be very quark model-like !

(J.Dudek at al. (2010))



$$\bar{q}(x)\Gamma^i q(x) \sim b^\dagger(k)\sigma^i d(-k)$$

$$\bar{q}(x)F_{ij}(x)q(x) \sim b^\dagger(k)\vec{k}\times\vec{a}(q)d(-q-k)$$

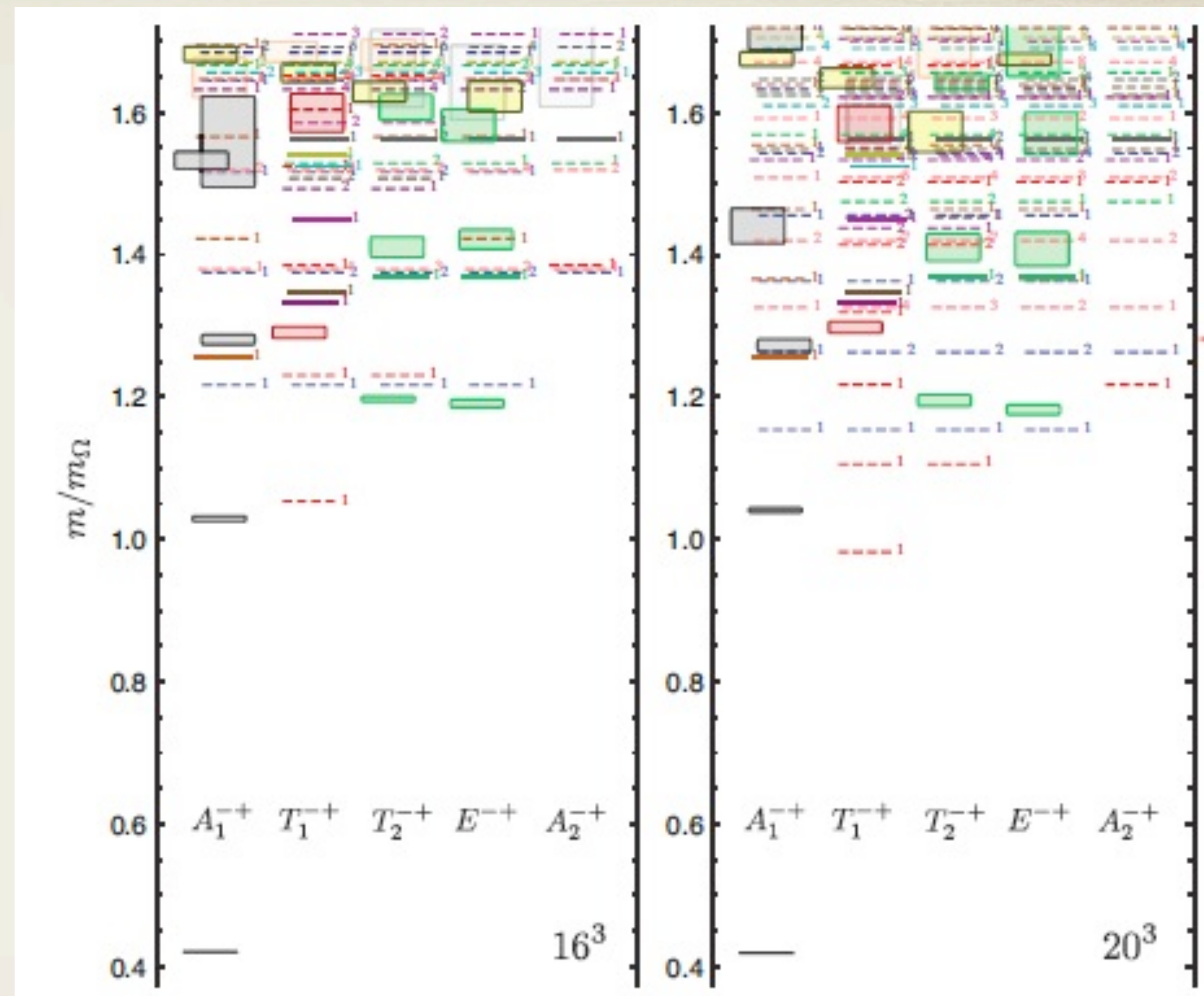
to determine structure study

$\langle \text{Vacuum}|O[q,g]|\ \text{Meson}\rangle$

if single hadron states exist: lattice is the place to find them

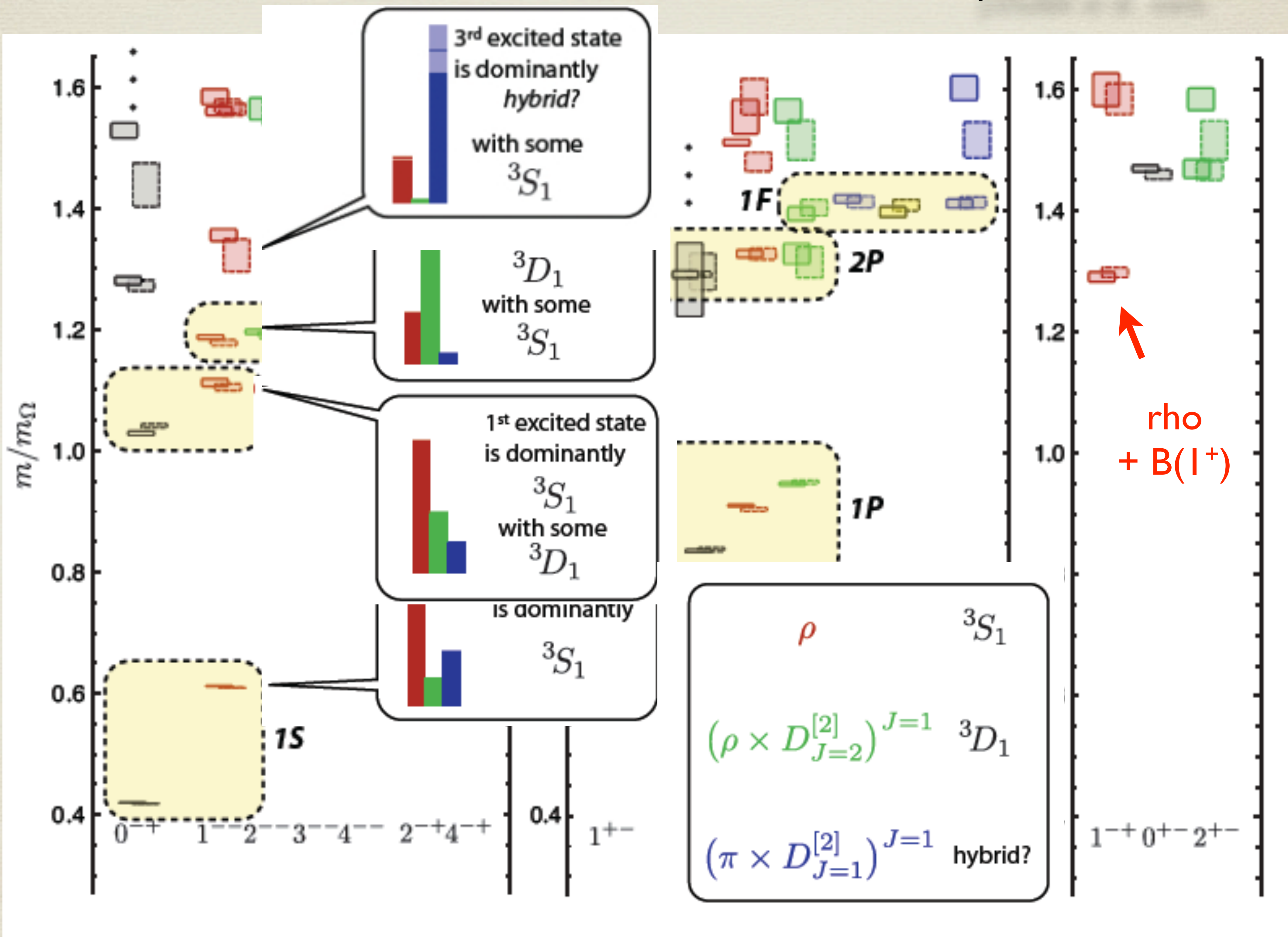
J.Dudek at al. cont.

- On finite volume multi-meson state and single hadron states are discrete.
- If there are single hadron states, use volume dependence to disentangle
- Continuum states can have any J,P,C but not single hadron states
- The choice of operators minimizes overlap with multi-meson states
- In the continuum these these states should disappear through cuts onto unphysical sheets (as CDD poles)



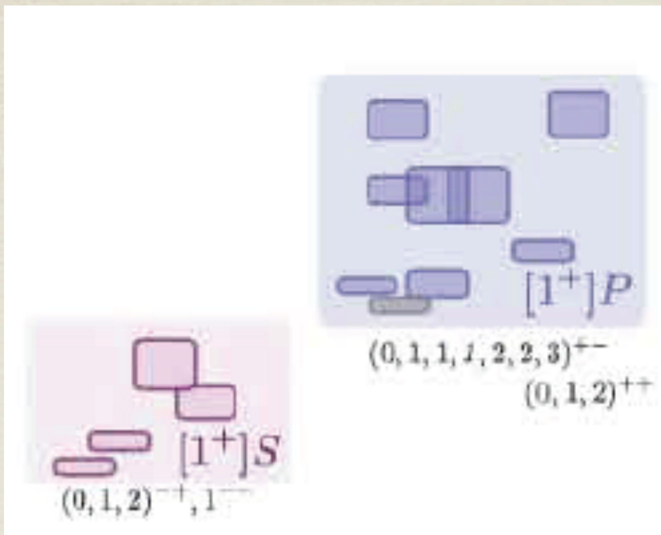
>> there is evidence for single hadron states <<
(no surprising, quark model, CDD poles, etc.)

J.Dudek at al. cont.

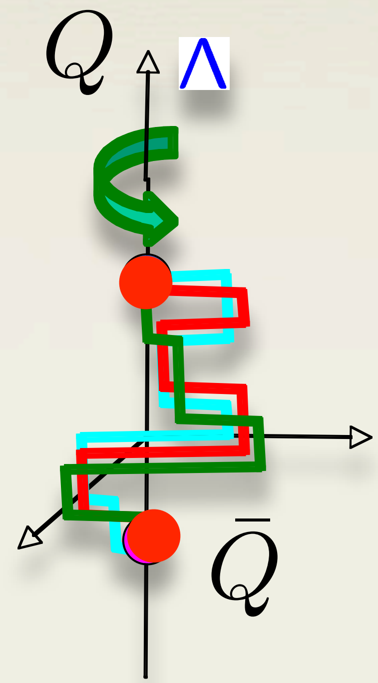


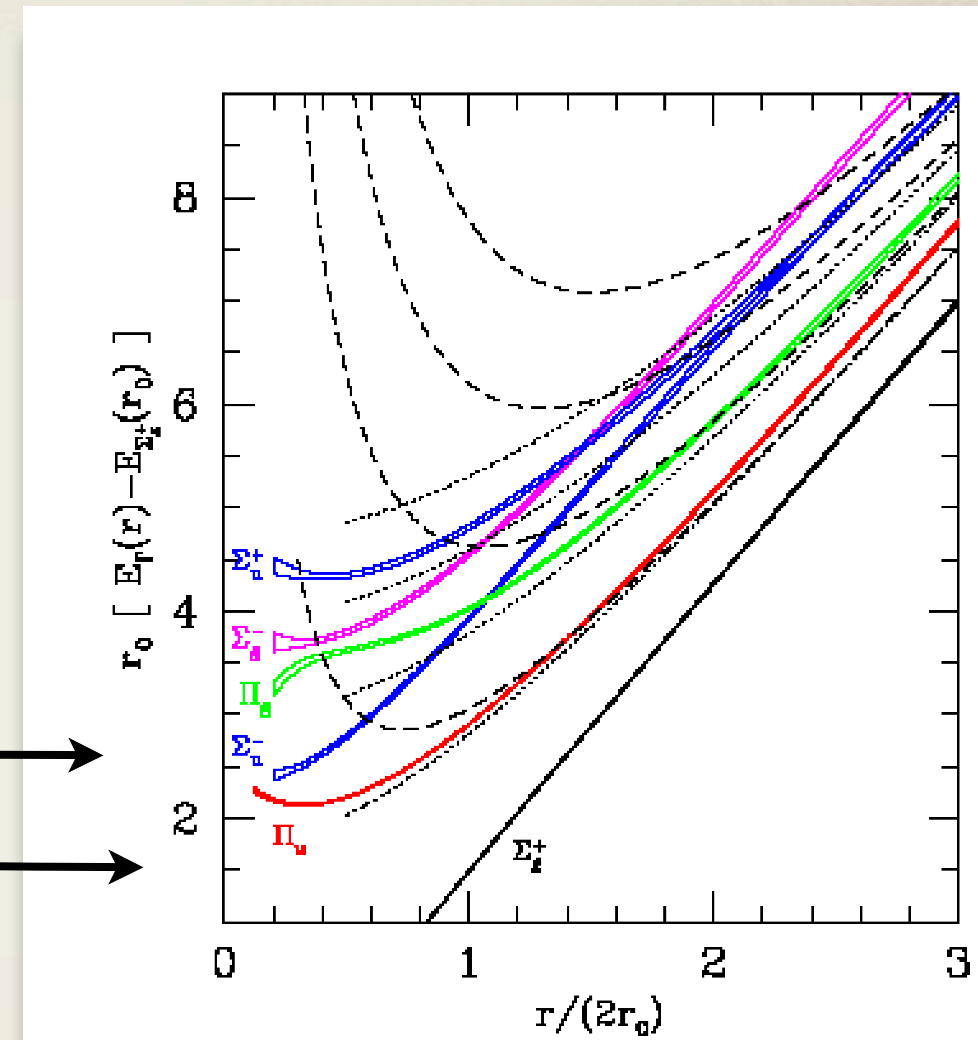
A "good" gluon structure model should describe all these :

* exotic and crypto-exotic mesons



* adiabatic potentials (axial symmetry)

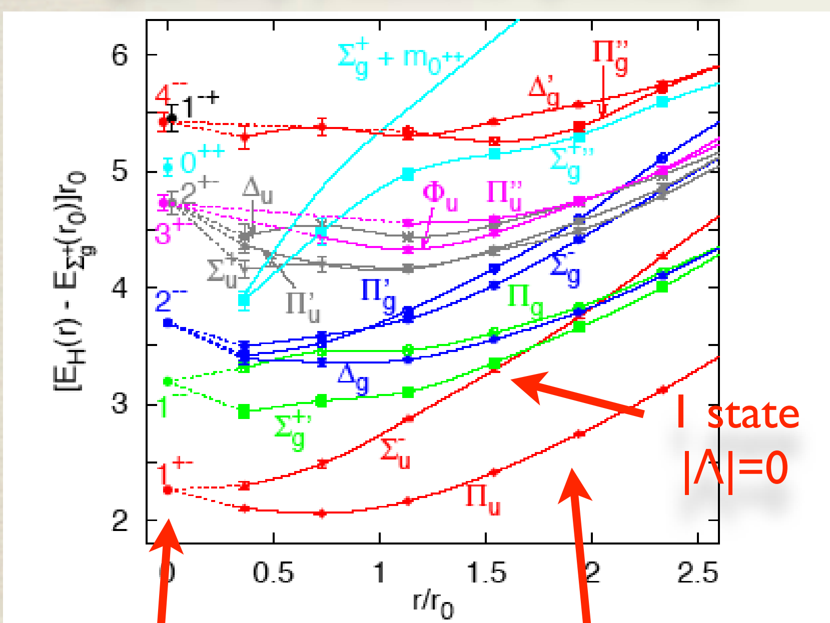




$PC = +1$ →

$PC = -1$ →

* glue lump (rotational symmetry)



1 state
|Λ|=0

3 states
M=±1,0 !

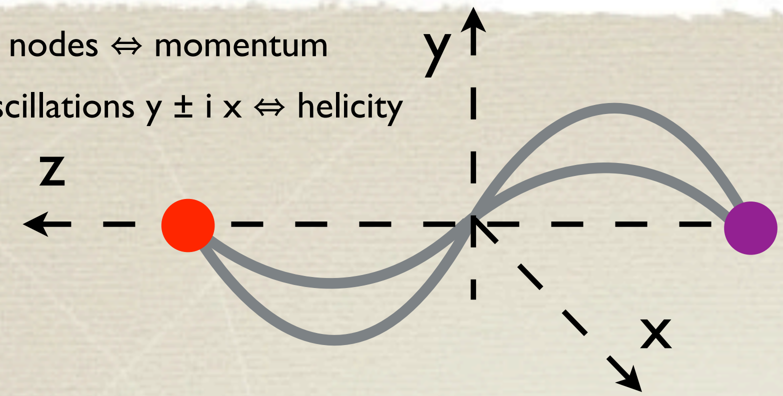
2 states
|Λ|=±1

G.Bali,A.Pineda (2003)

$$\Lambda^Y_{PC} = (\Sigma, \Pi, \Delta, \cdots)^{\pm}_{u,g}$$

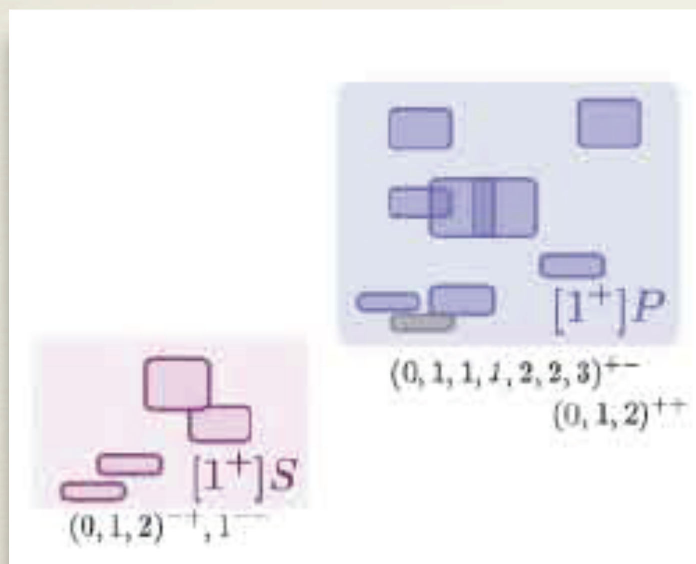
C.Morningstar et al. (1999)

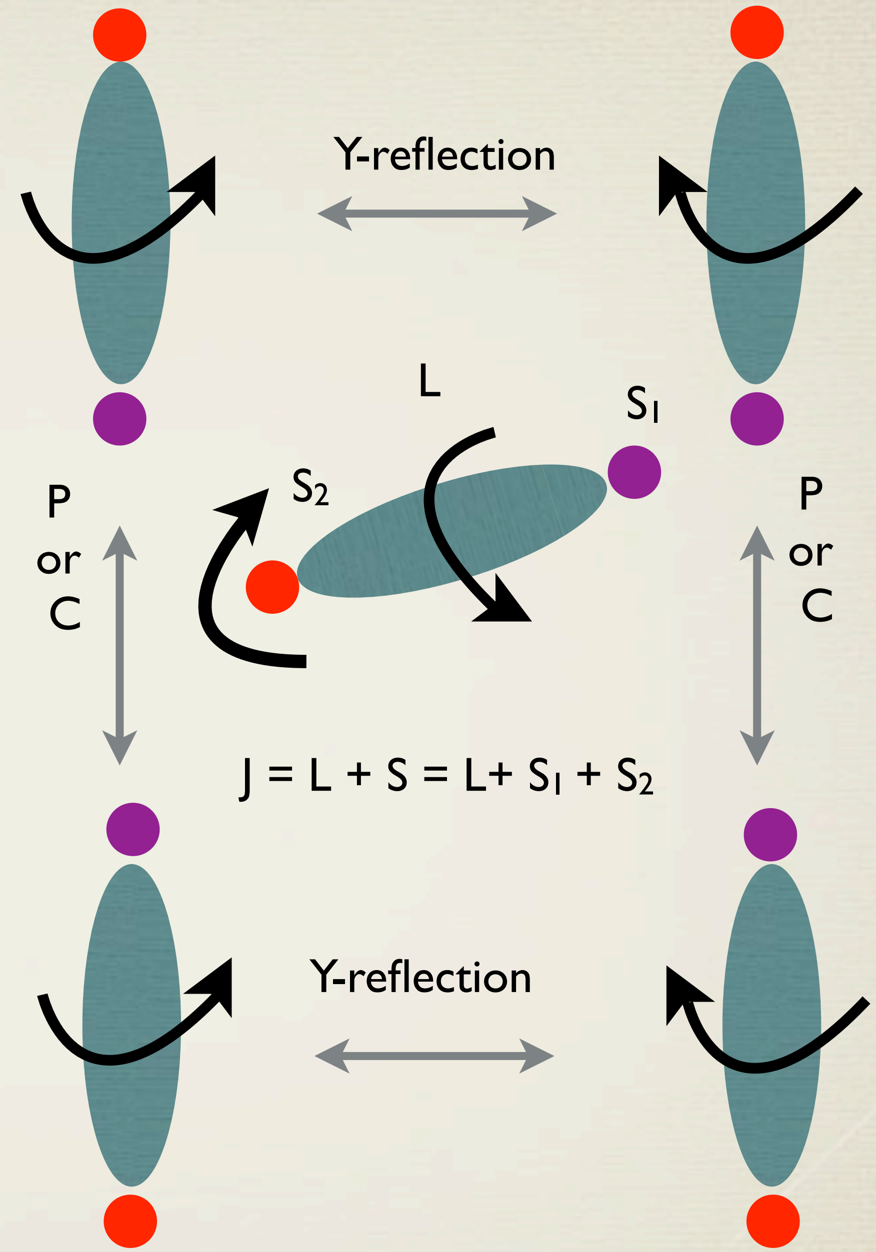
Strong coupling Hamiltonian: product of links (non-relativistic beads)
>> chain of coupled harmonic oscillators



$$
\begin{array}{lcccc}
S = 0 & & 1^{--} & 1^{++} \\
S = 1 & J^{PC} = & (0,1,2)^{-+} & (0,1,2)^{+-}
\end{array}
$$

degenerate in FT





Flux tube does not agree with lattice !

problem with the rigid rotor

non-relativistic hybrids

$$H = H_D + H_{YM} + H_C$$

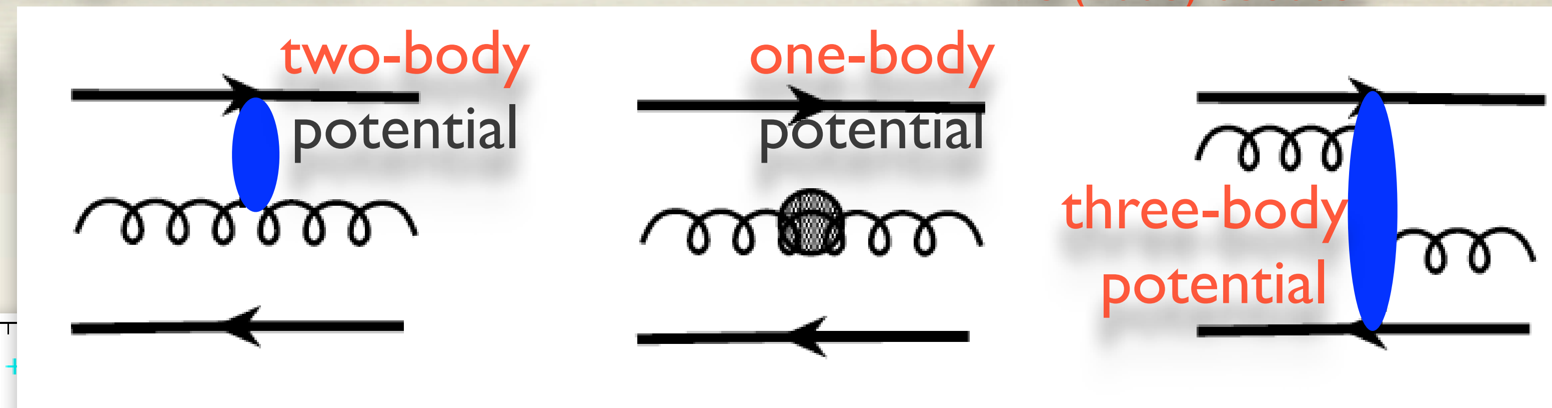
Coulomb Gauge (variational)

P.Guo et al., Phys.Rev. D78 (2008) 056003

- $Q\bar{Q}$ in L=0,S=0,1

expected degeneracies

- coupled to 1^{--} glue in the relative L=1 state => $J_g^{PC} = 1^{+-}$



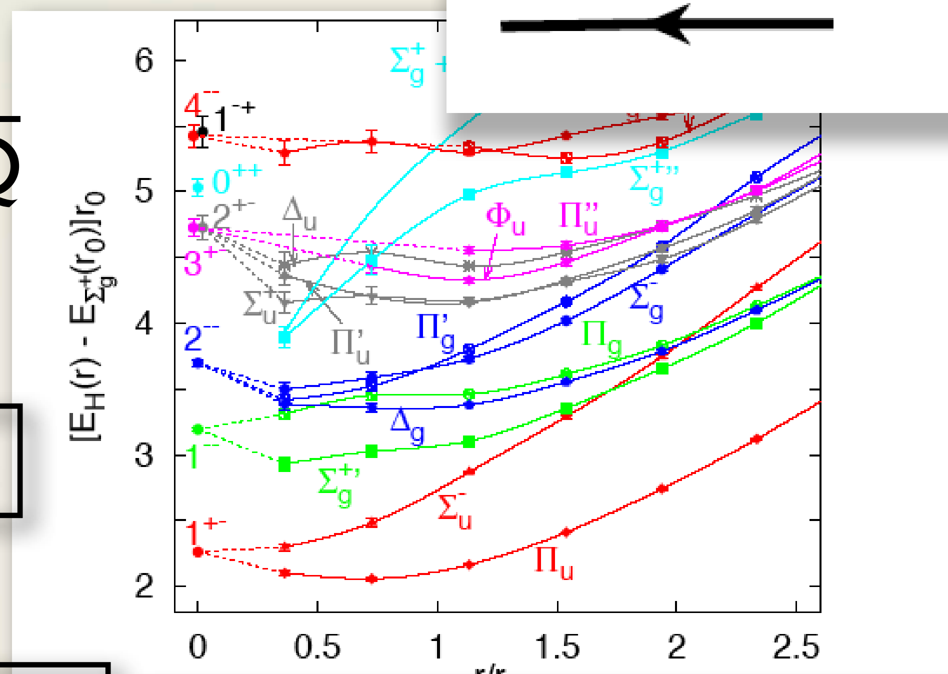
J^{PC} glue

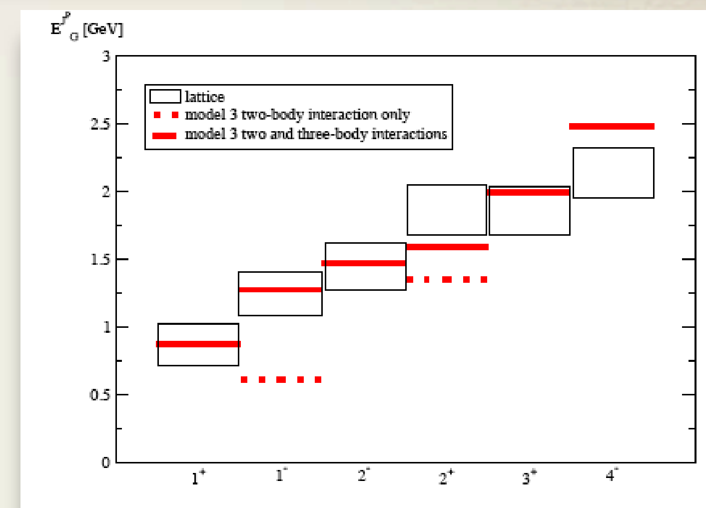
J^{PC} $Q\bar{Q}$

$$1^{+-} \times 0^{-+}_{S_{Q\bar{Q}}} = \boxed{1^{--}}$$

$$1^{+-} \times 1^{--}_{S_{Q\bar{Q}}=1} =$$

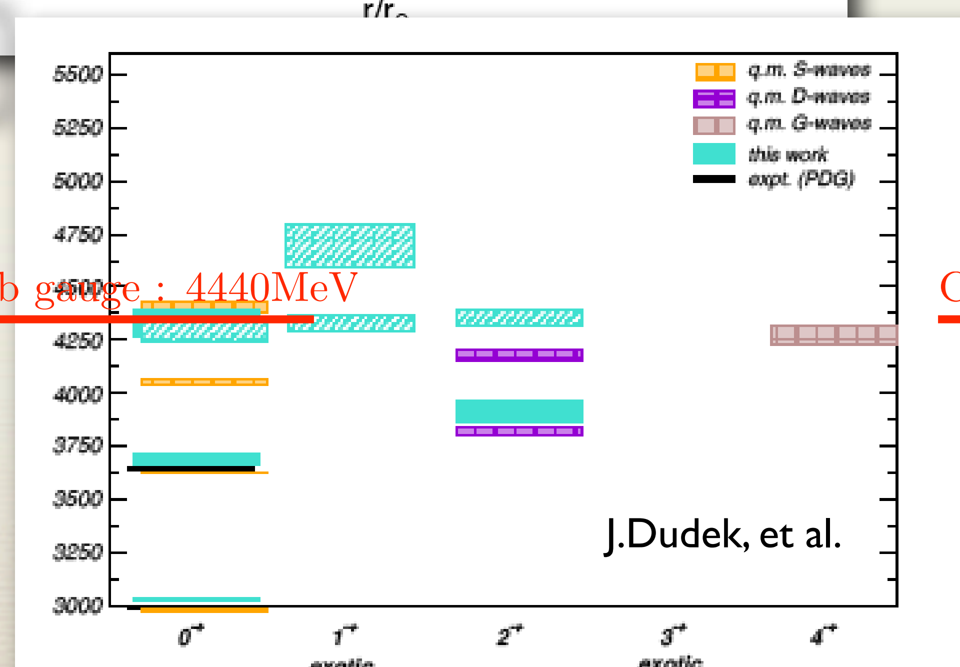
$$\boxed{0^{-+},\ 1^{-+}, 2^{-+}}$$

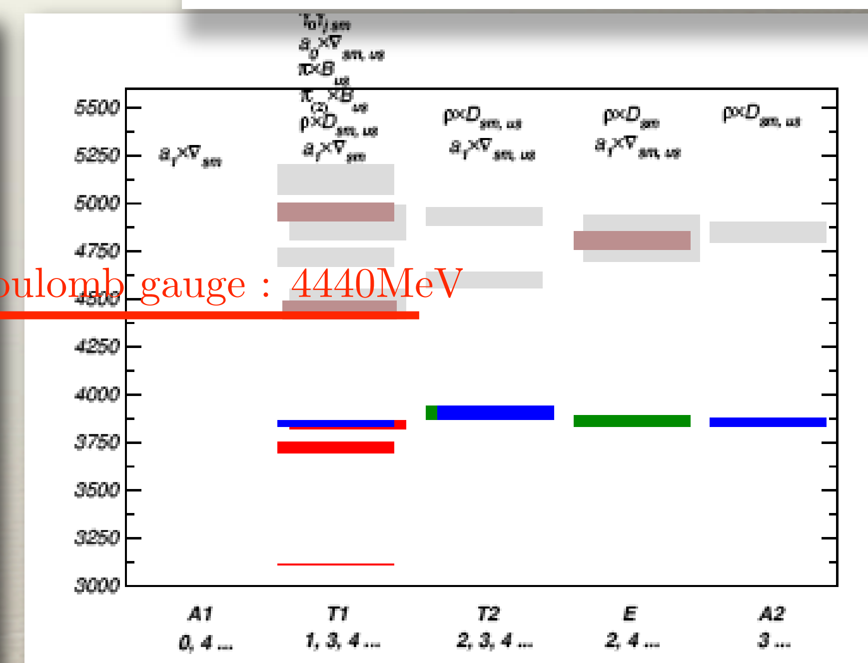




- experiment

Y(4260) (Belle,BaBar)

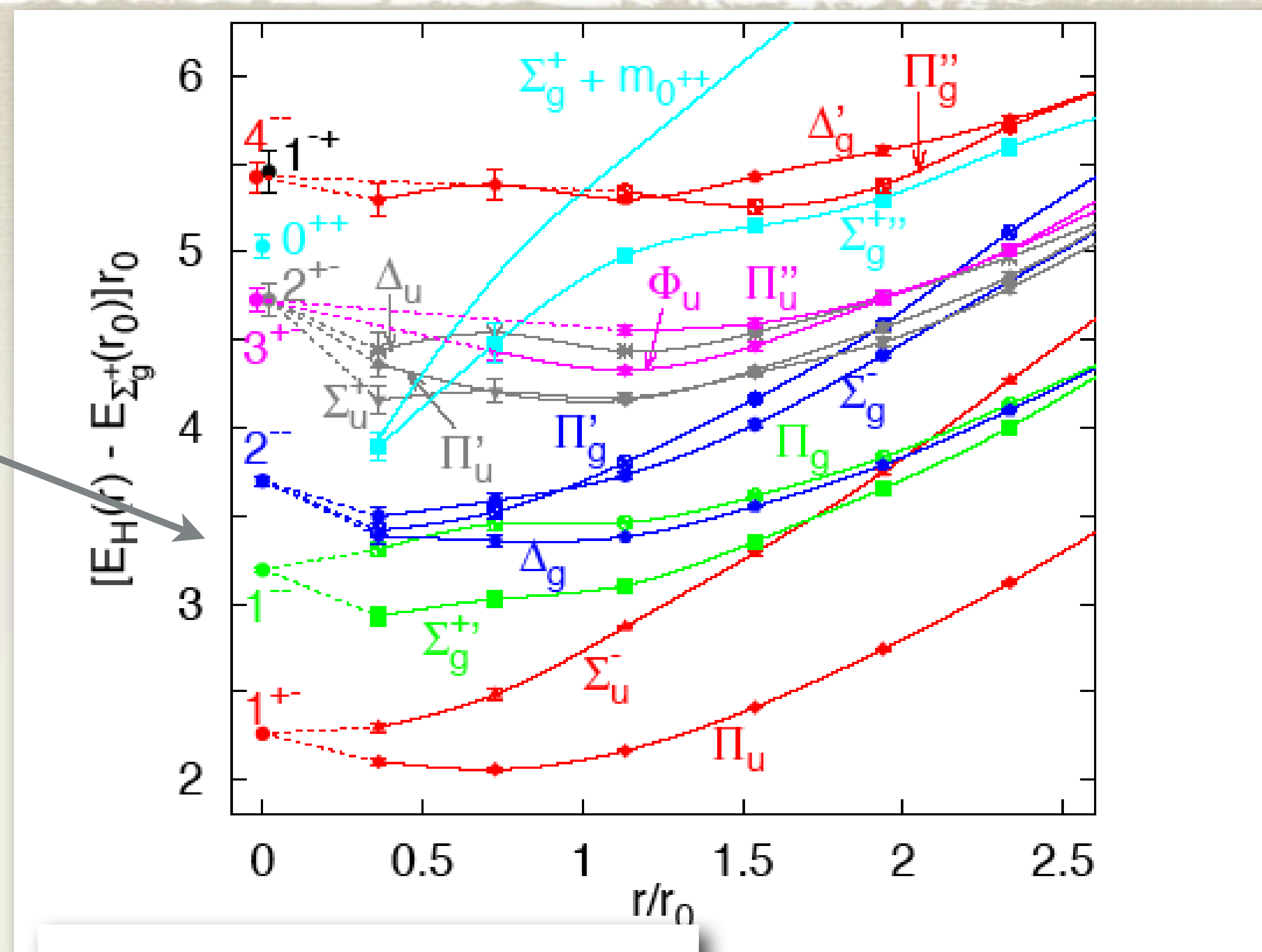




$$|hybrid\rangle = |J J_g L_{Q\bar{Q}} S\rangle$$

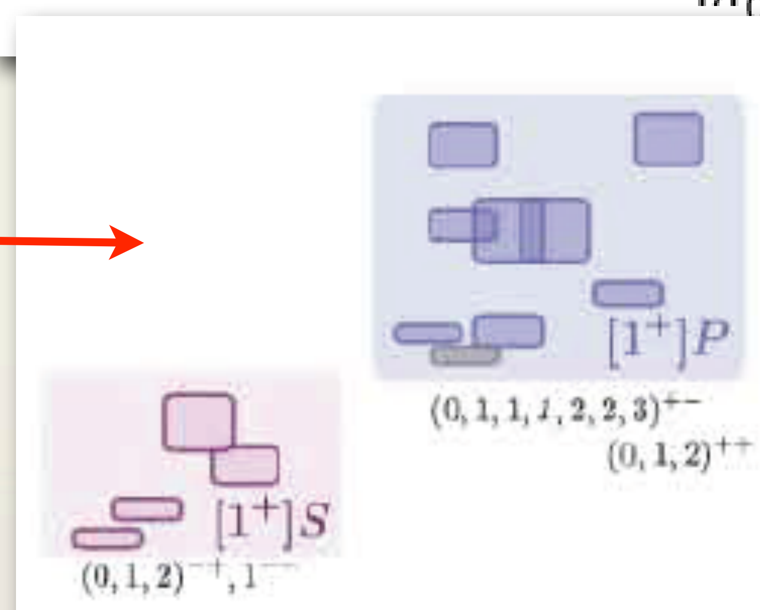
$J_g^{PC} = 1^{--}$

	$S=0$	$S=1$
$L=0$	1^{+-}	$(0,1,2)^{++}$
$L=1$	$(0,1,2)^{-+}$	$(0,1^3,2^2,3)^{--}$



$J_g^{PC} = 1^{+-}$

	$S=0$	$S=1$
$L=0$	1^{--}	$(0,1,2)^{-+}$
$L=1$	$(0,1,2)^{++}$	$(0,1^3,2^2,3)^{+-}$



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

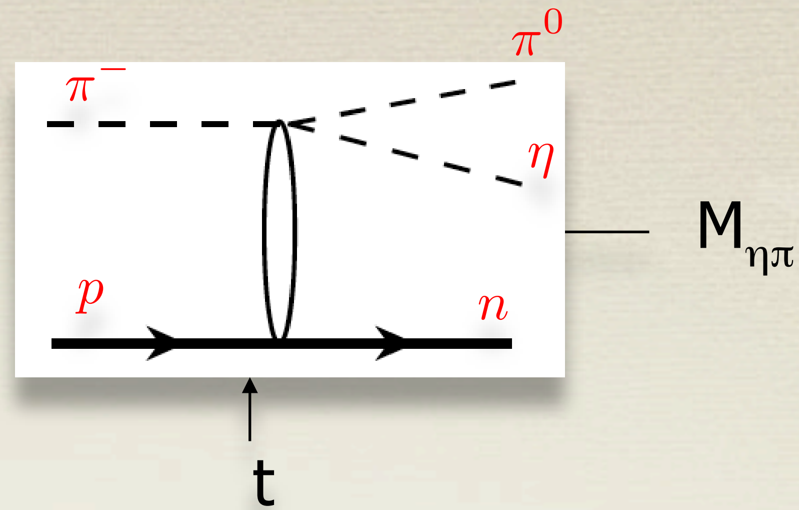
$\pi^- p \to \eta\pi^- p$	$M = 1370 \pm 16^{+50}_{-30}$ MeV / c^2 $\Gamma = 385 \pm 40^{+65}_{-105}$ MeV / c^2
$\pi^- p \to \eta\pi^0 n$	New results: No consistent B-W interpretation possible but a weak ηπ interaction exists and can reproduce the exotic wave
$\pi^- p \to \eta'\pi^- p$	$M = 1597 \pm 10^{+45}_{-10}$ MeV / c^2 $\Gamma = 340 \pm 40^{+50}_{-50}$ MeV / c^2
$\pi^- p \to \rho^0\pi^- p$	$M = 1593 \pm 8^{+29}_{-47}$ MeV / c^2 $\Gamma = 168 \pm 20^{+150}_{-12}$ MeV / c^2

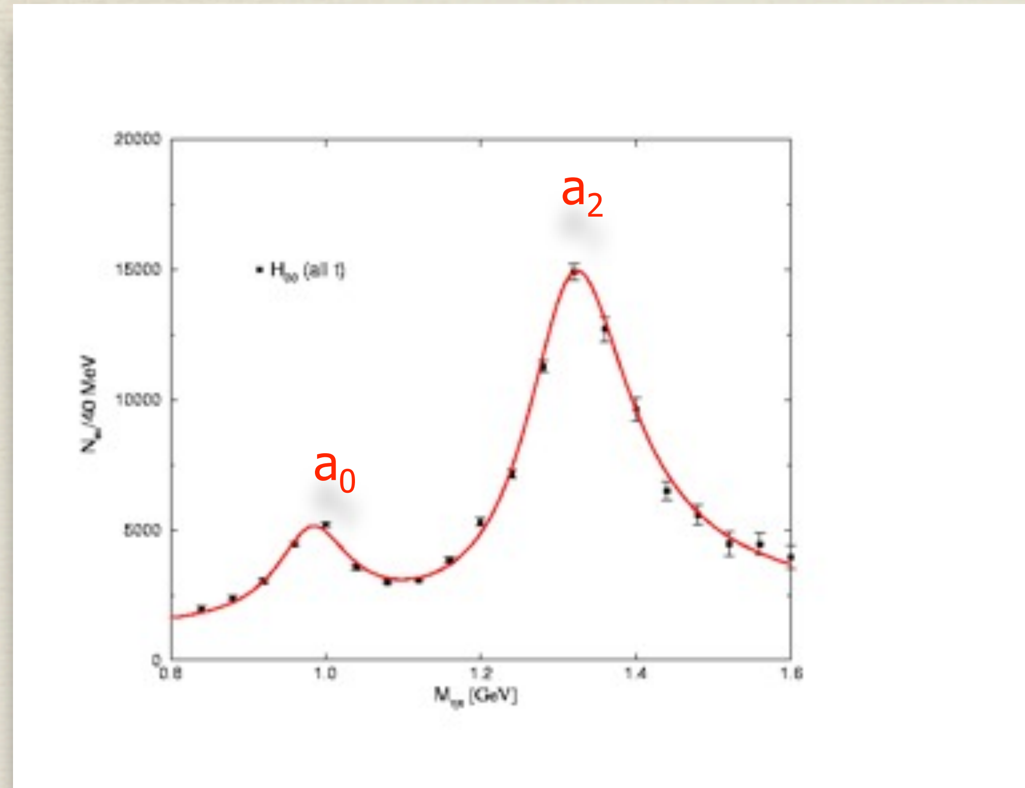
$\pi^- p \to b_1 \pi p$
$\pi^- p \to f_1 \pi p$

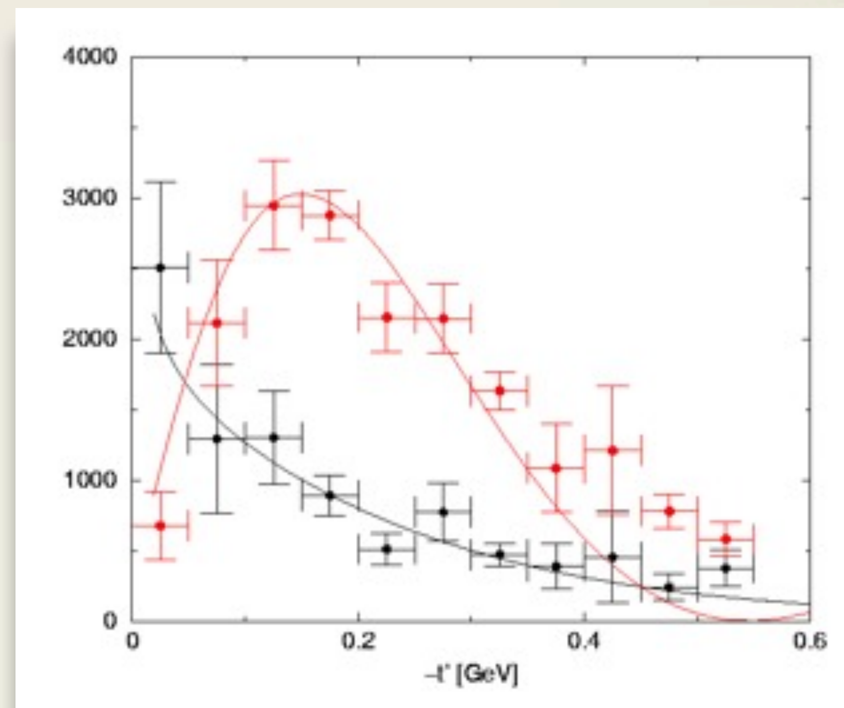
BNL (E852)
new analysis reduces the strength but COMPASS find the signal again, JLab large uncertainties

Example $\pi^- p \rightarrow \pi^0 \eta n$ (from E852)

(Dzierba, et al.)





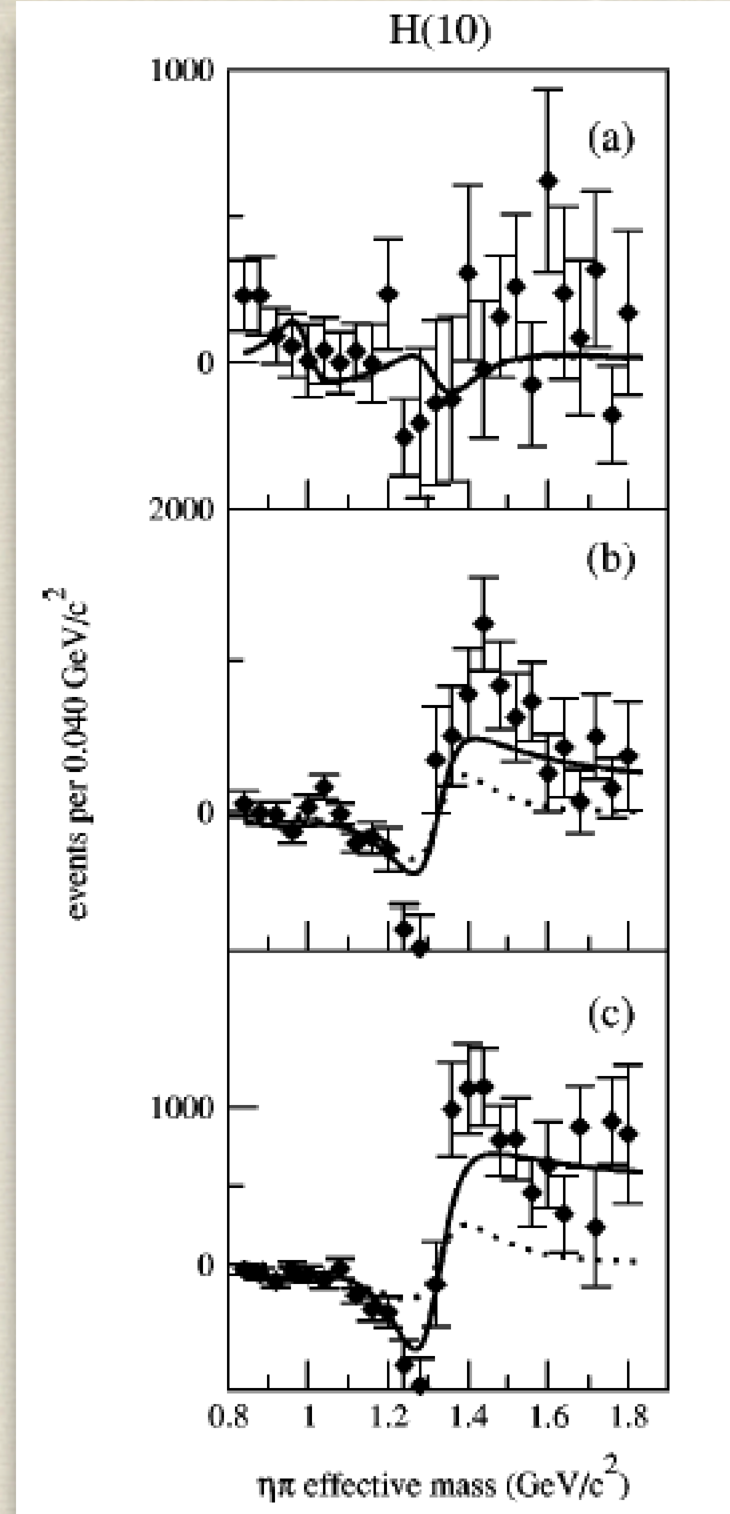


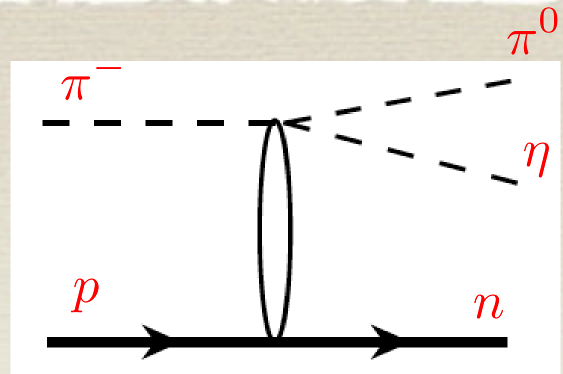
Relevant partial waves :

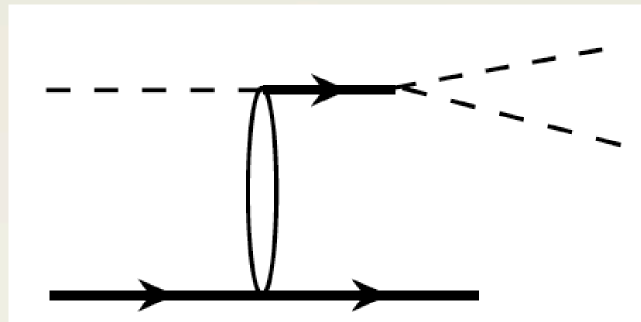
$\eta\pi$ in S : a_0

$\eta\pi$ in D : a_2

Is there an $\eta\pi$ P-wave : exotic 1^{-+} quantum numbers ?

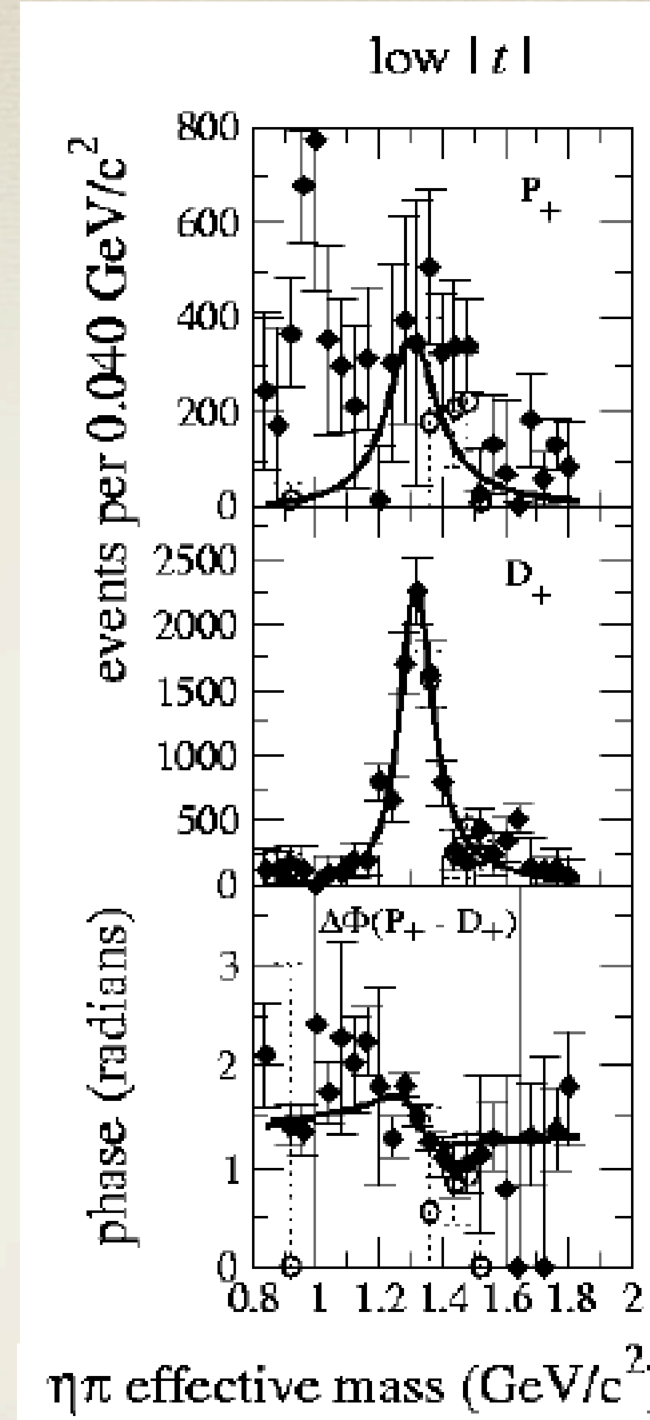






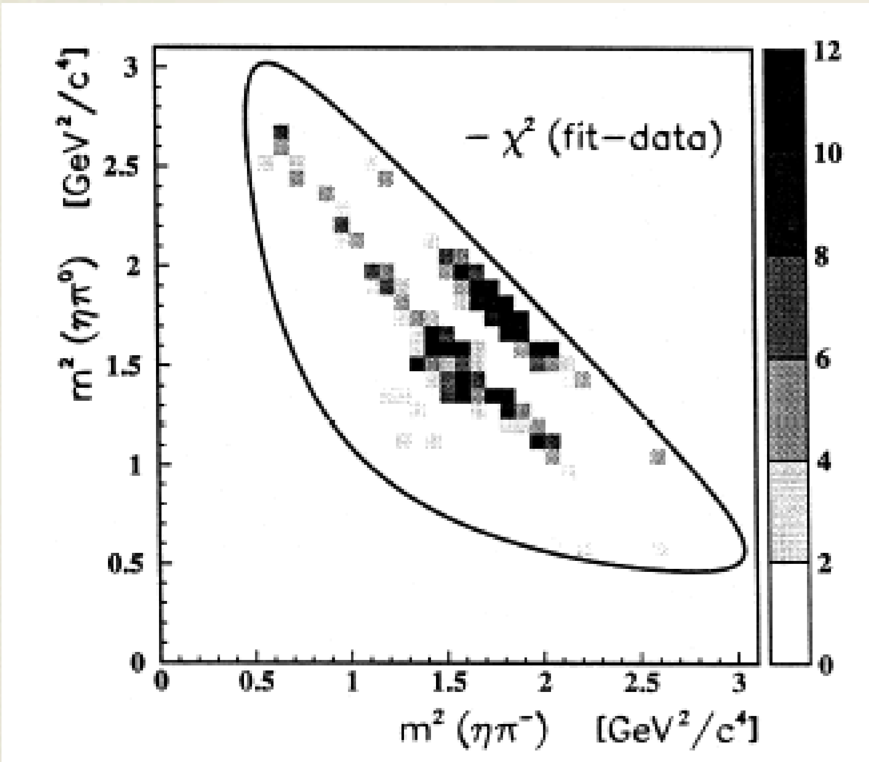
Hard to find a common set of BW parameters for all three helicity states of the resonance

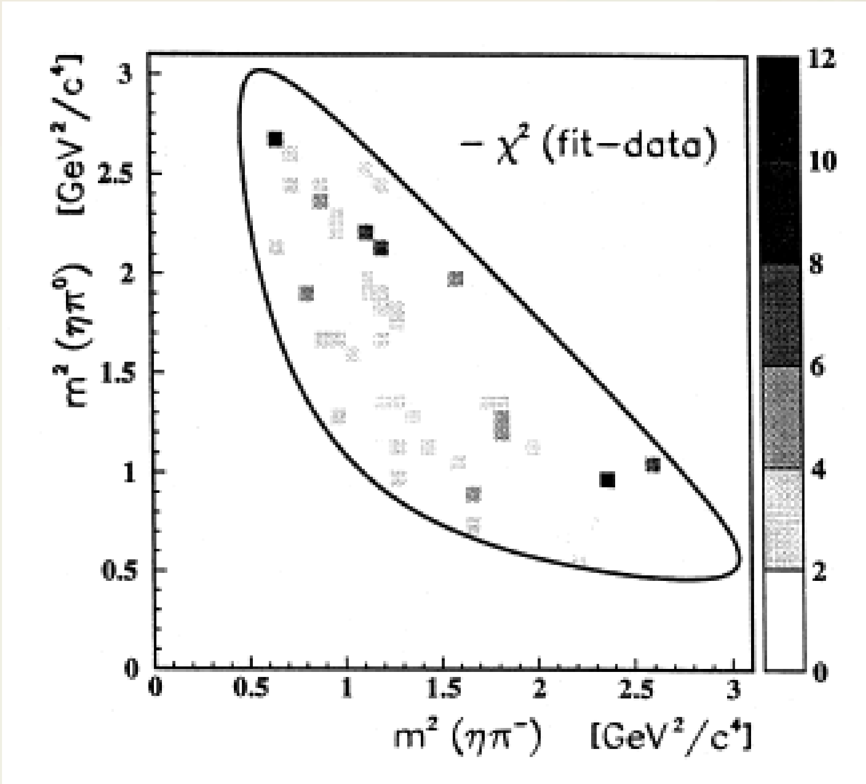
$\pi_1(1400) \to \pi_1(900 - 5000)!$



Crystal Barrel

$$\bar{p}n \rightarrow \pi^- \pi^0 \eta$$

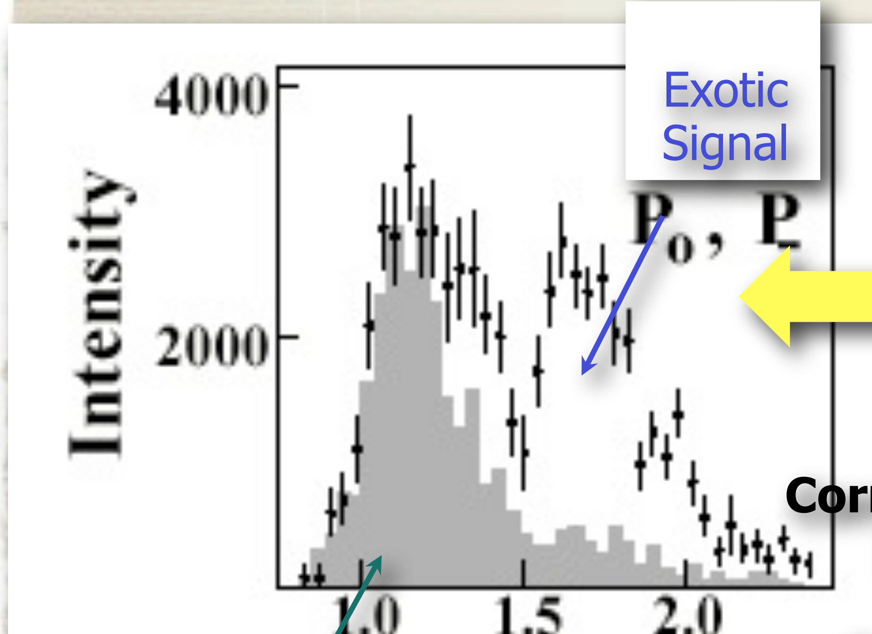




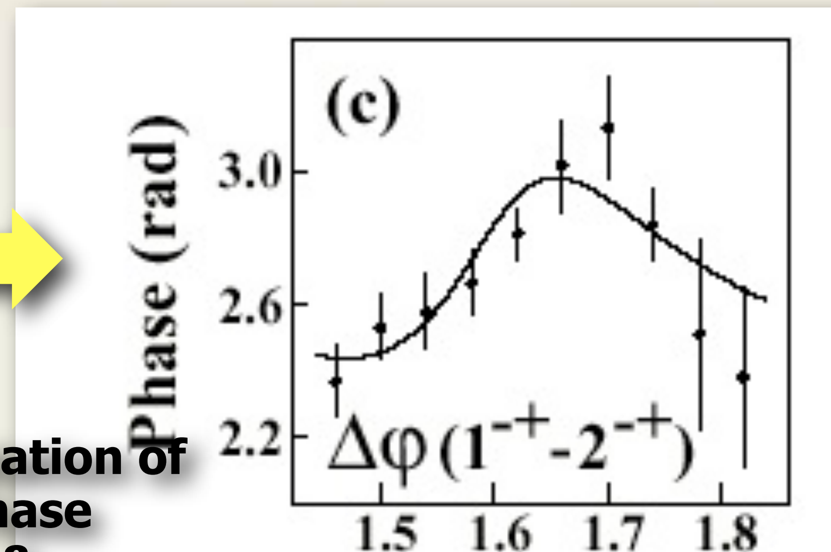
ρ, a_0, a_2

ρ, a_0, a_2, π_1

$\pi_1(1600)$ in $\pi^+\pi^-\pi^-$



Exotic Signal

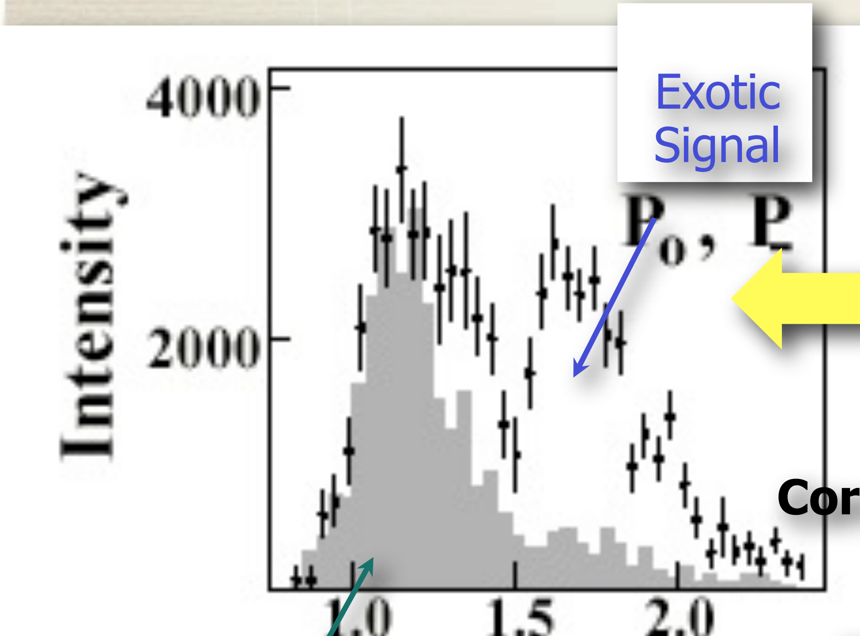


Correlation of Phase & Intensity

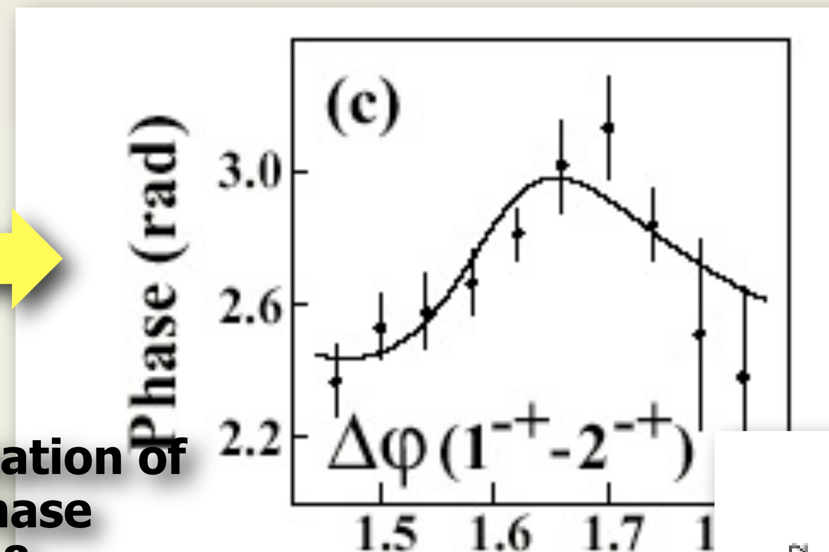
Leakage From Non-exotic Wave due to imperfectly understood acceptance

Based on 250K events

$\pi_1(1600)$ in $\pi^+\pi^-\pi^-$



Leakage
From
Non-exotic Wave
due to imperfectly
understood acceptance



Correlation of Phase & Intensity

E852 result

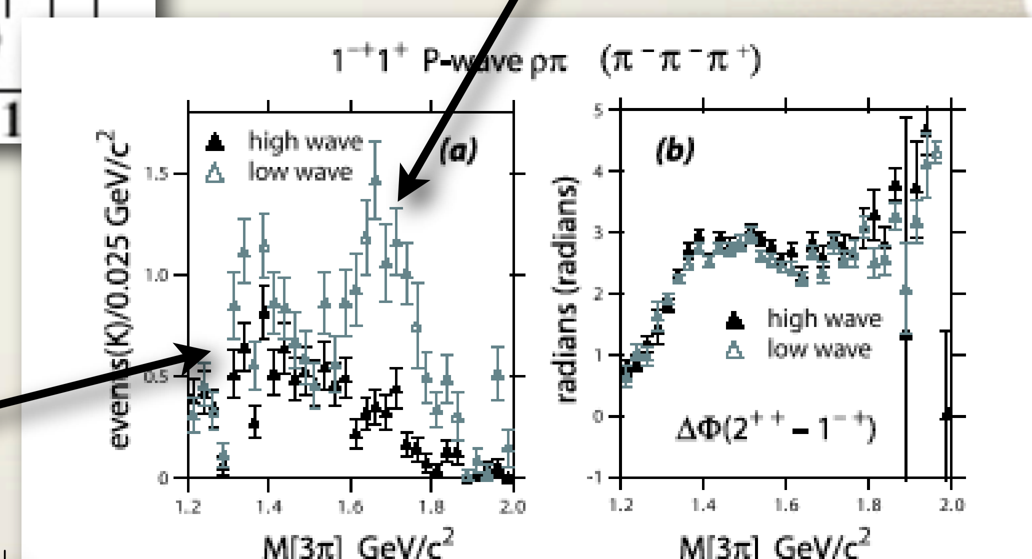


FIG. 25: (a) The $1^{-+}1^{+}$ P-wave $\rho\pi$ partial wave in the charged mode ($\pi^-\pi^-\pi^+$) for the high-wave set PWA and the low-wave set PWA and (b) the phase difference $\Delta\Phi$ between the 2^{++} and 1^{-+} for the two wave sets.

$$\pi^- p \to \pi_2^-(1600)p$$
$$\pi_2^- \to \rho^0\pi^-$$
$$\rho^0 \to \pi^-\pi^+$$

Based on 250K events

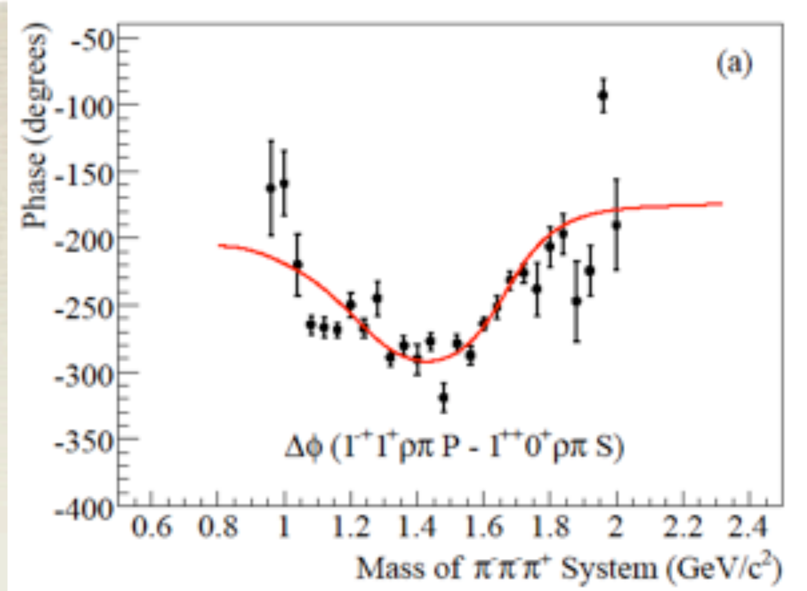
$\pi_1(1600)$ in $\pi^+\pi^-\pi^-$

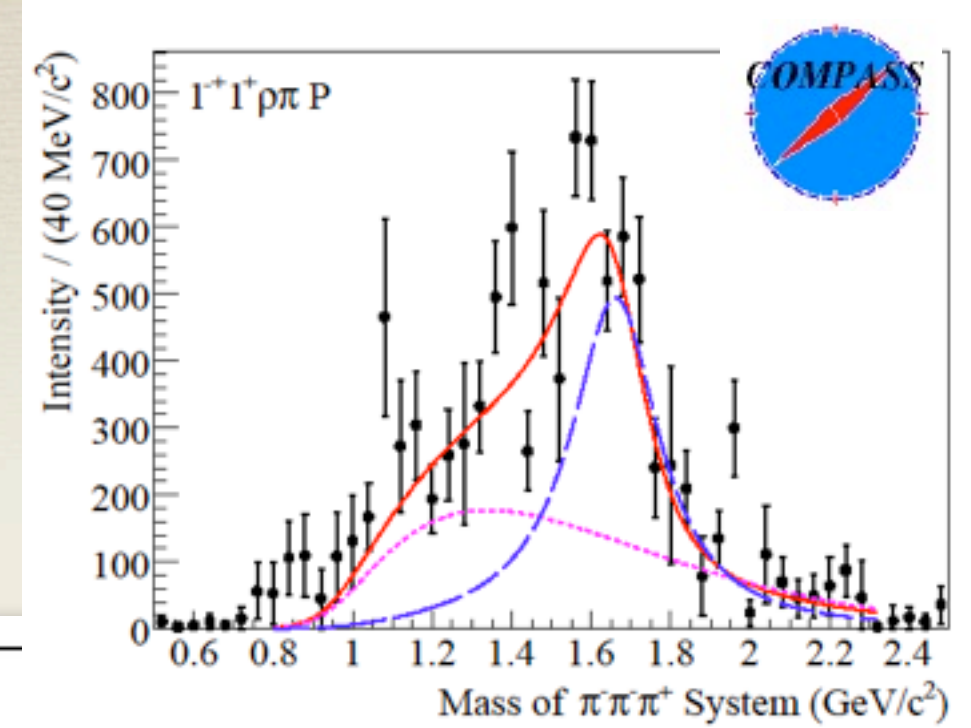
- BW parameters for $\pi_1(1600)$

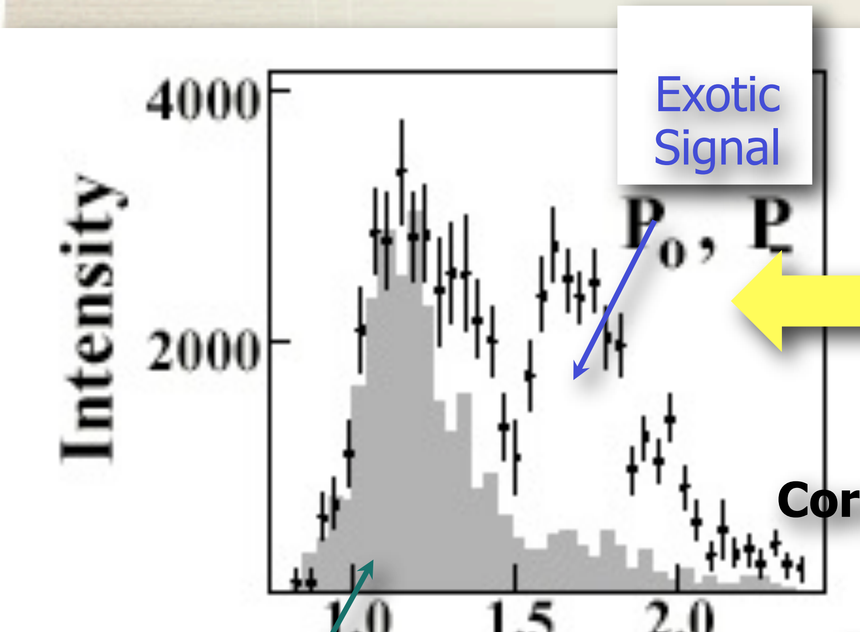
$$M = \left(1660 \pm 10 \,^{+0}_{-64}\right) \mathrm{MeV}/c^2$$

$$\Gamma = \left(269 \pm 21 \,^{+42}_{-64}\right) \mathrm{MeV}/c^2$$

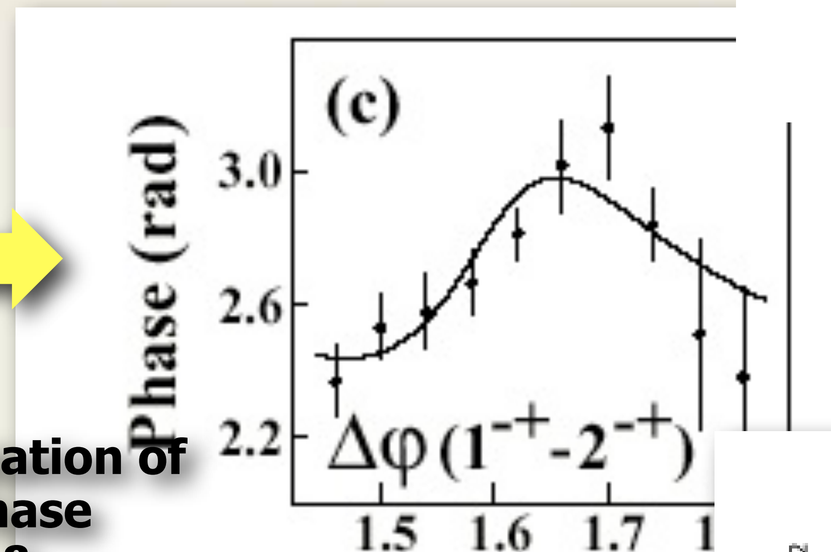
- Leakage negligible: <5%







Correlation of Phase & Intensity



E852 result

Leakage From Non-exotic Wave due to imperfectly understood acceptance

Based on 250K events

$$\pi^- p \to \pi_2^-(1600) p$$
$$\pi_2^- \to \rho^0 \pi^-$$
$$\rho^0 \to \pi^- \pi^+$$

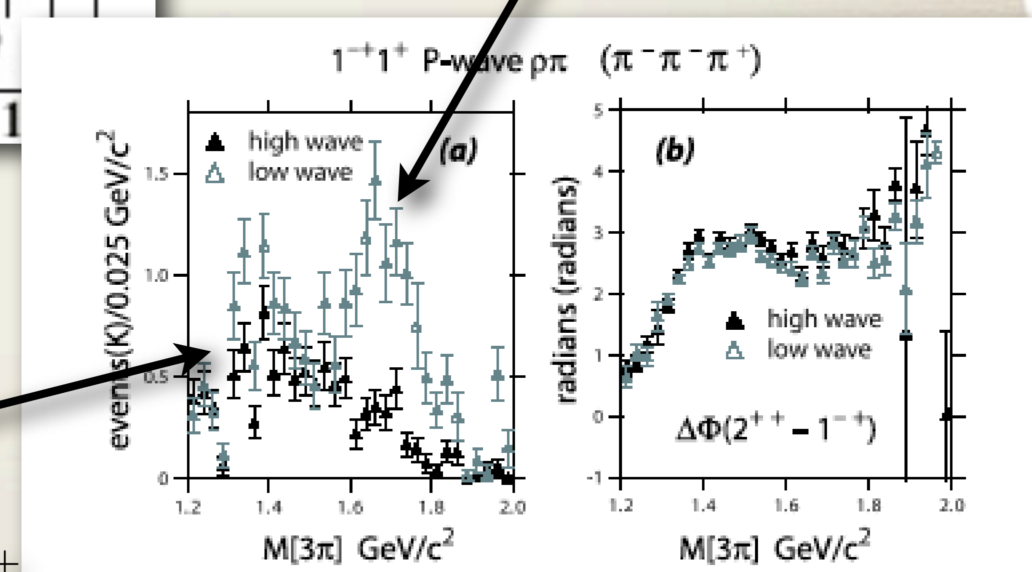
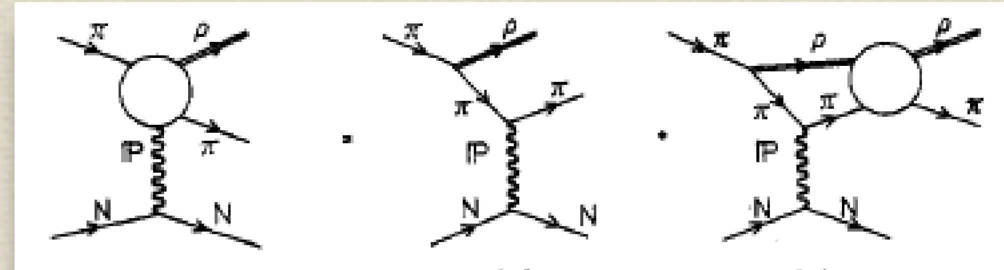


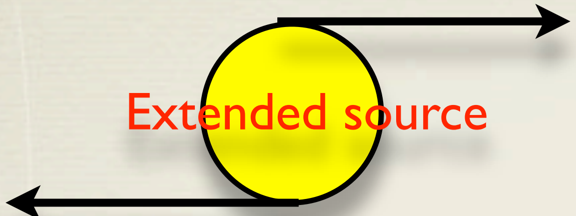
FIG. 25: (a) The $1^{-+}1^+$ P-wave $\rho\pi$ partial wave in the charged mode ($\pi^-\pi^-\pi^+$) for the high-wave set PWA and the low-wave set PWA and (b) the phase difference $\Delta\Phi$ between the 2^{++} and 1^{-+} for the two wave sets.

$$e^{i\delta(E)}\cos\delta(E)$$

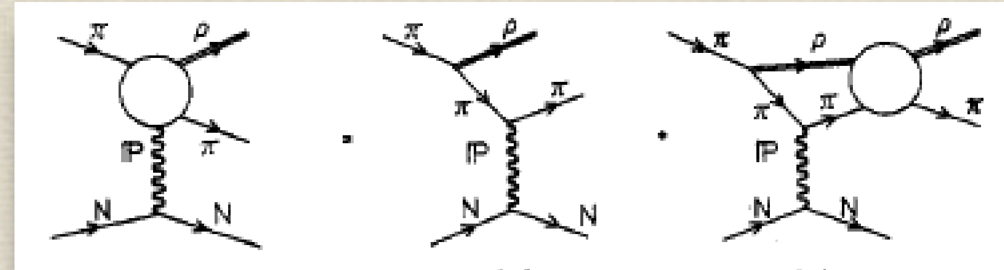


$$e^{i\delta(E)}\frac{\sin\delta(E)}{k}$$

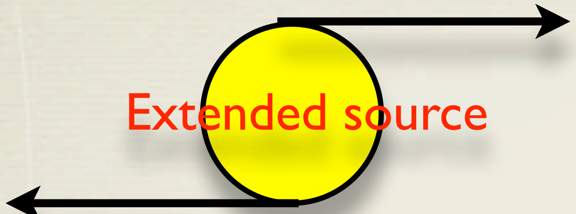
force=OPE



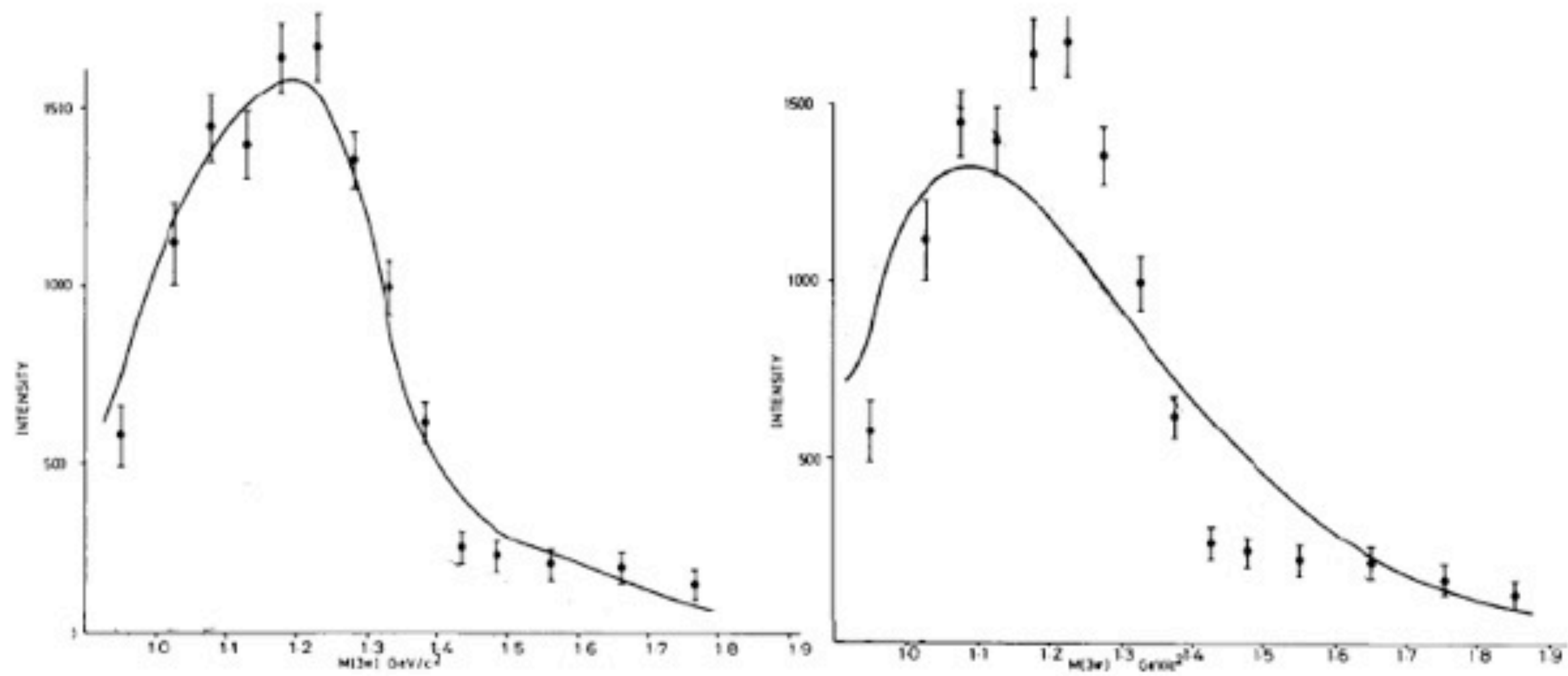
$$e^{i\delta(E)}\cos\delta(E)$$



force=OPE



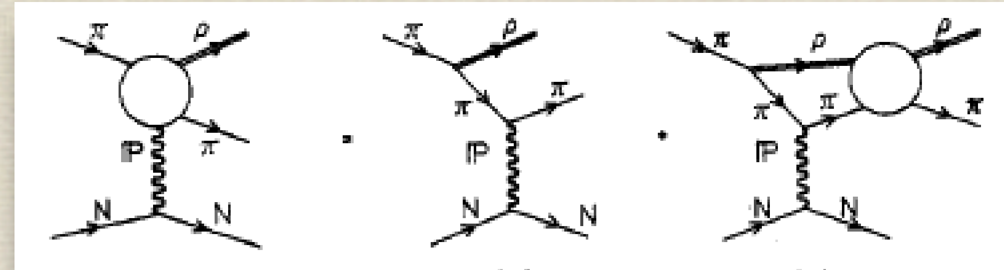
$$e^{i\delta(E)}\frac{\sin\delta(E)}{k}$$



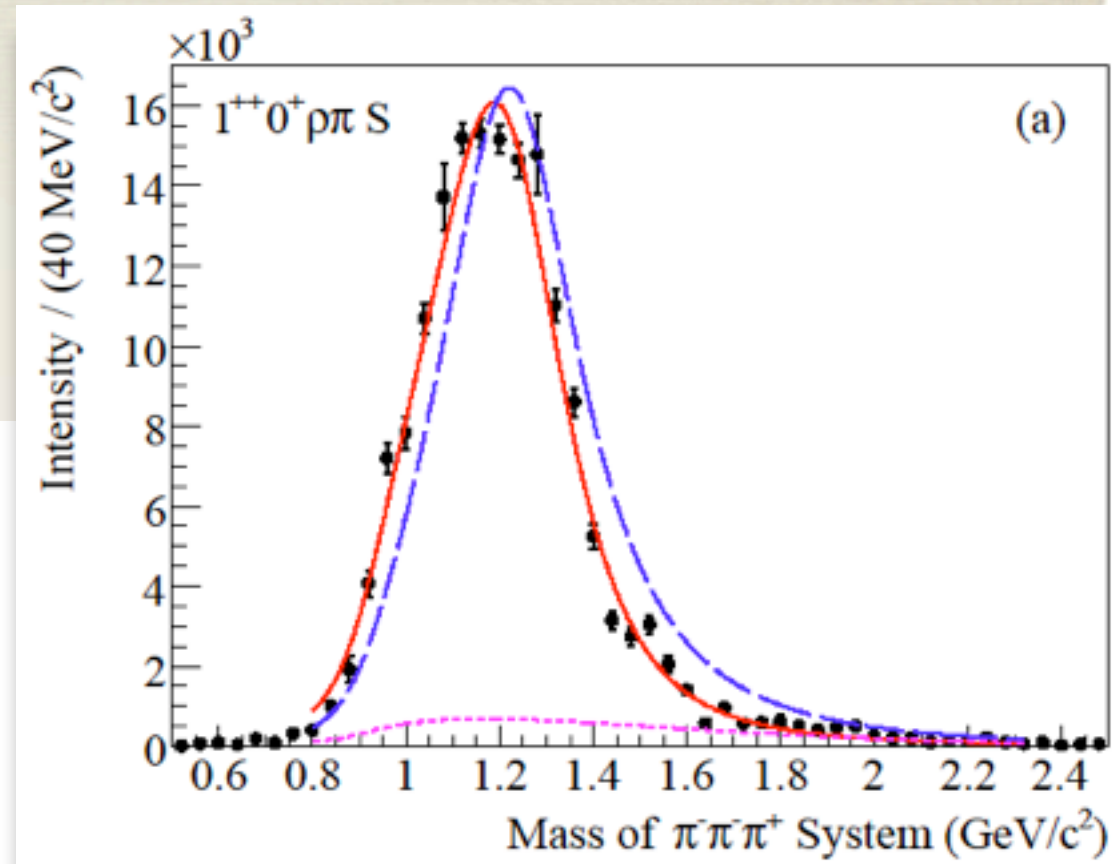
M.G.Bowler,(1975)

Figure 11: Fit to the 1^+ $\rho\pi$ intensity from $\pi^- p \to \pi^-\pi^-\pi^+ p$ at $E_\pi = 25$ and $E_\pi = 40$ GeV, CERN data [70], with (left) both long-range production from one pion exchange and short-range direct production and (right) short-range direct production only [63].

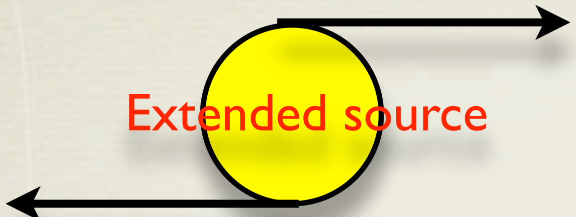
$$e^{i\delta(E)}\cos\delta(E)$$

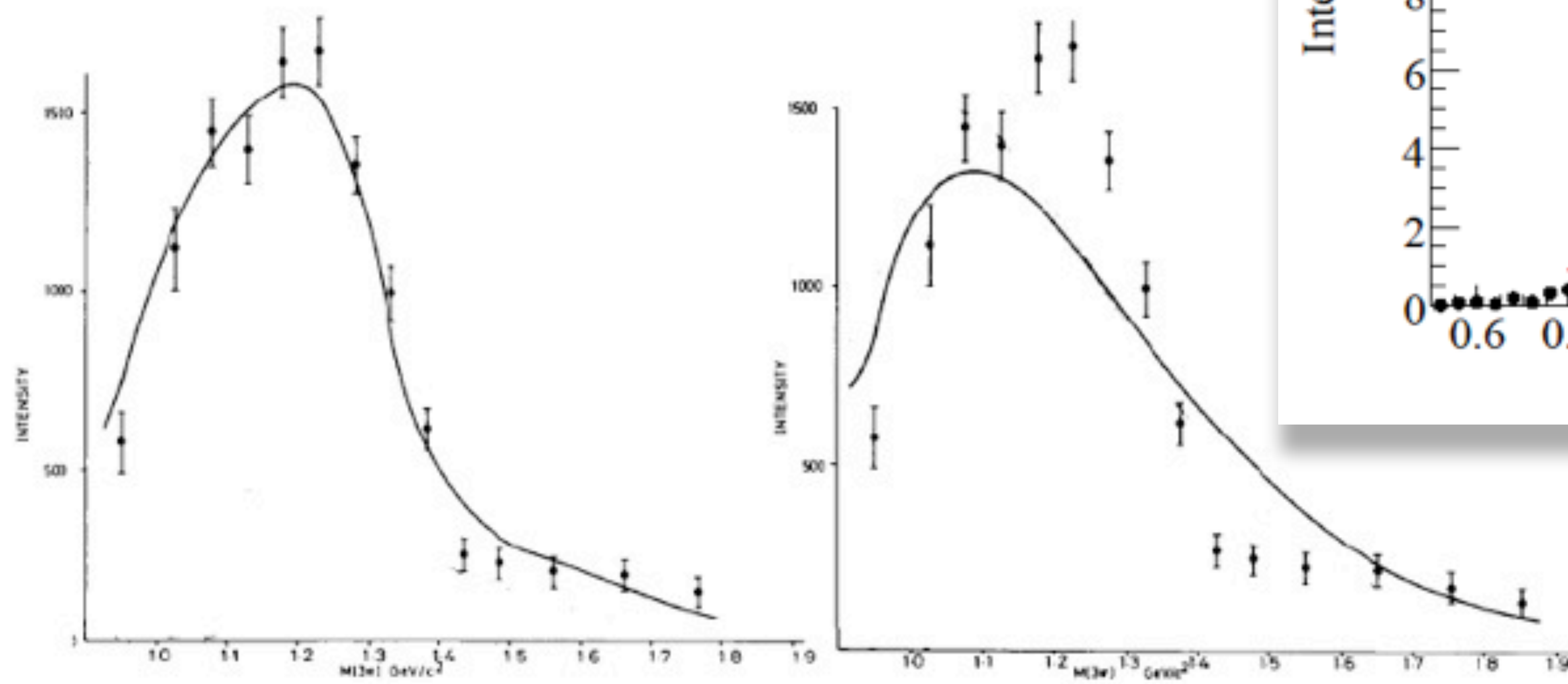


$$e^{i\delta(E)}\frac{\sin\delta(E)}{k}$$



force=OPE

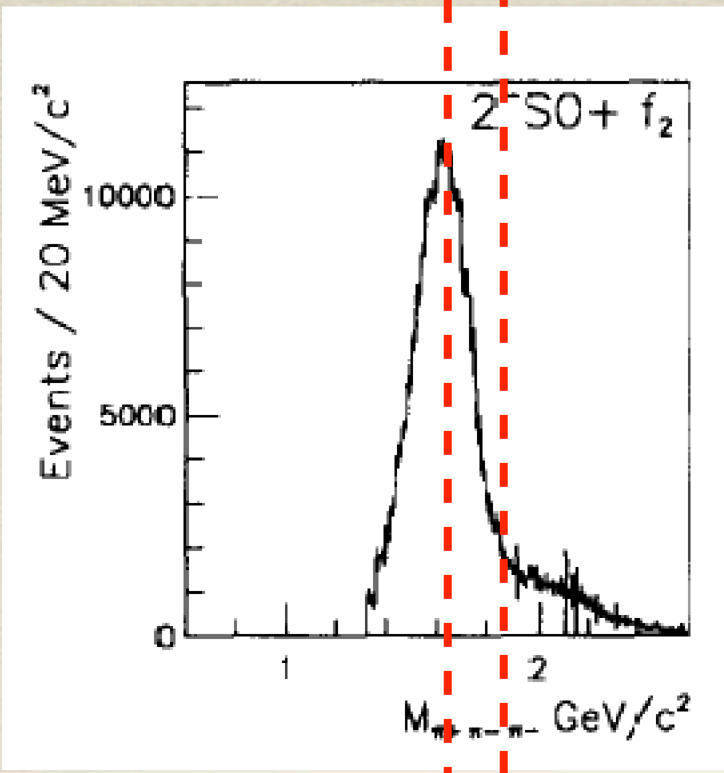


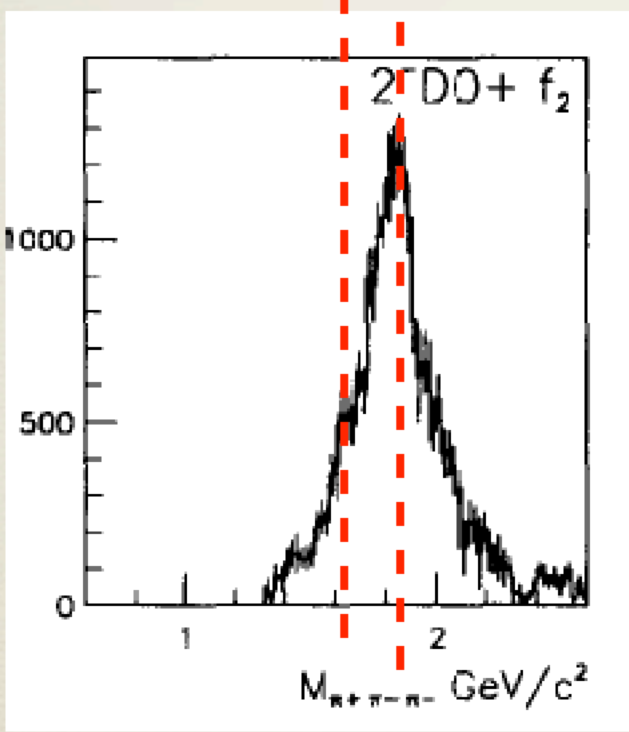


M.G.Bowler,(1975)

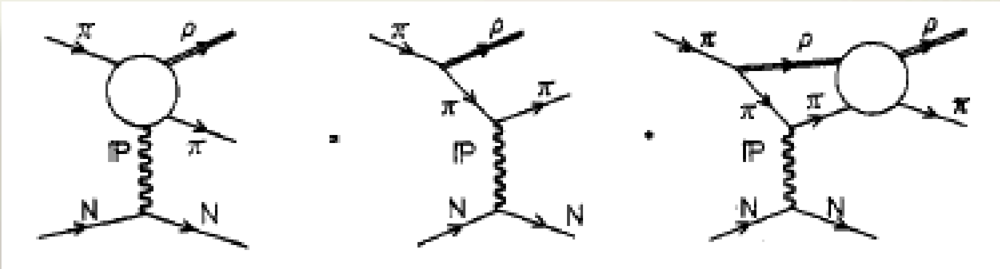
Figure 11: Fit to the 1^+ $\rho\pi$ intensity from $\pi^- p \to \pi^-\pi^-\pi^+ p$ at $E_\pi = 25$ and $E_\pi = 40$ GeV, CERN data [70], with (left) both long-range production from one pion exchange and short-range direct production and (right) short-range direct production only [63].

Moving $\pi_2(1670)$ peak

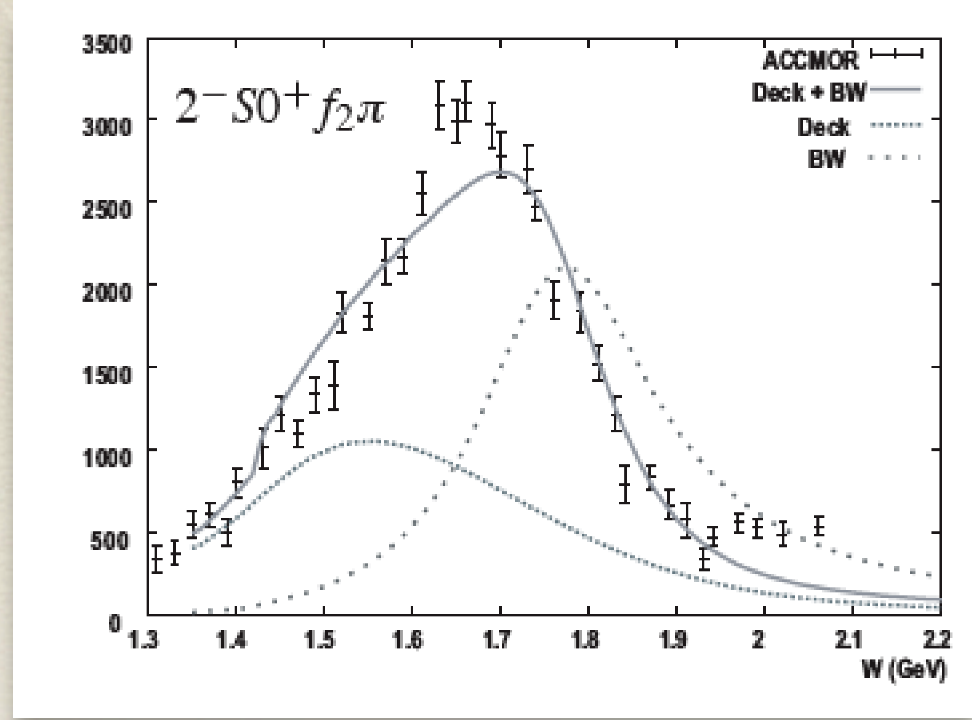


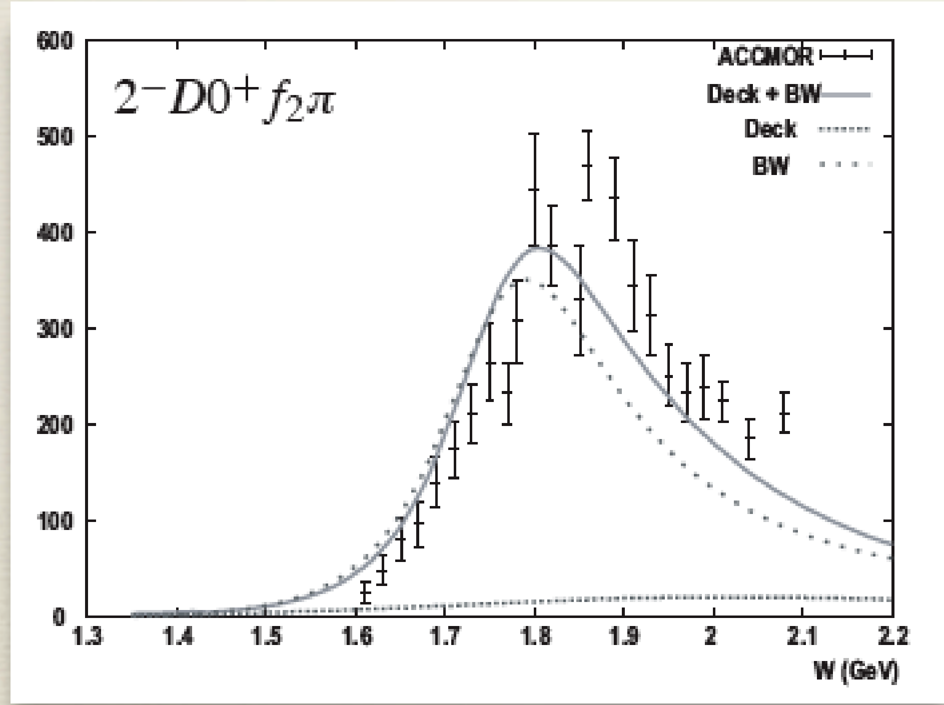


VALUE (MeV)			EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1672.4±	**3.2 OUR AVERAGE**			Error includes scale factor of 1.4. See the ideogram below.				
1749	±10	±100	145k	LU	05	E852		18 $\pi^- p \to \omega\pi^-\pi^0 p$
1676	± 3	± 8		[1] CHUNG	02	E852		18.3 $\pi^- p \to \pi^+\pi^-\pi^- p$
1685	±10	± 30		[2] BARBERIS	01			450 $p p \to p_f 3\pi^0 p_s$
1687	± 9	± 15		AMELIN	99	VES		37 $\pi^- A \to \omega\pi^-\pi^0 A^*$
1669	± 4			BARBERIS	98B			450 $p p \to p_f \rho\pi p_s$
1670	± 4			BARBERIS	98B			450 $p p \to p_f f_2(1270)\pi p_s$
1730	±20			[3] AMELIN	95B	VES		36 $\pi^- A \to \pi^+\pi^-\pi^- A$
1690	±14			[4] BERDNIKOV	94	VES		37 $\pi^- A \to K^+ K^-\pi^- A$
1710	±20		700	ANTIPOV	87	SIGM	−	50 π^- Cu $\to \mu^+\mu^-\pi^-$ Cu
1676	± 6			[4] EVANGELISTA	81	OMEG	−	12 $\pi^- p \to 3\pi p$
1657	±14			[4,5] DAUM	80D	SPEC	−	63–94 $\pi p \to 3\pi X$
1662	±10		2000	[4] BALTAY	77	HBC	+	15 $\pi^+ p \to p 3\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •								
1742	±31	± 49		ANTREASYAN	90	CBAL		$e^+ e^- \to e^+ e^- \pi^0\pi^0\pi^0$
1624	±21			[1] BELLINI	85	SPEC		40 $\pi^- A \to \pi^-\pi^+\pi^- A$
1622	±35			[6] BELLINI	85	SPEC		40 $\pi^- A \to \pi^-\pi^+\pi^- A$
1693	±28			[7] BELLINI	85	SPEC		40 $\pi^- A \to \pi^-\pi^+\pi^- A$
1710	±20			[8] DAUM	81B	SPEC	−	63,94 $\pi^- p$
1660	±10			[4] ASCOLI	73	HBC	−	5–25 $\pi^- p \to p\pi_2$

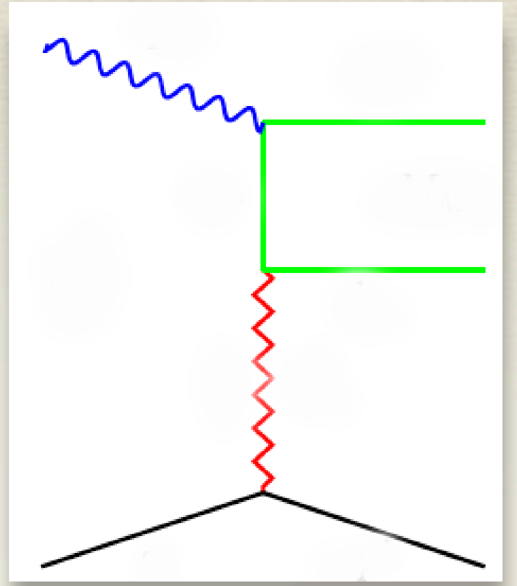


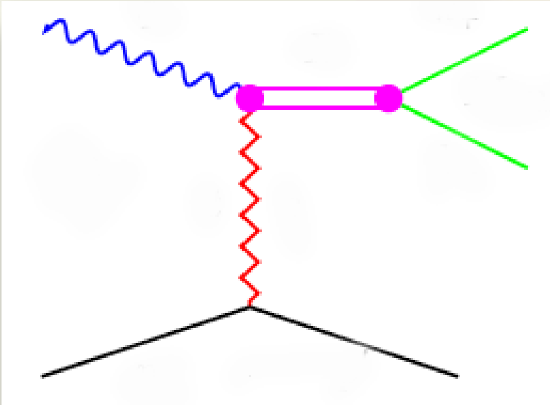
Duality @ work ?



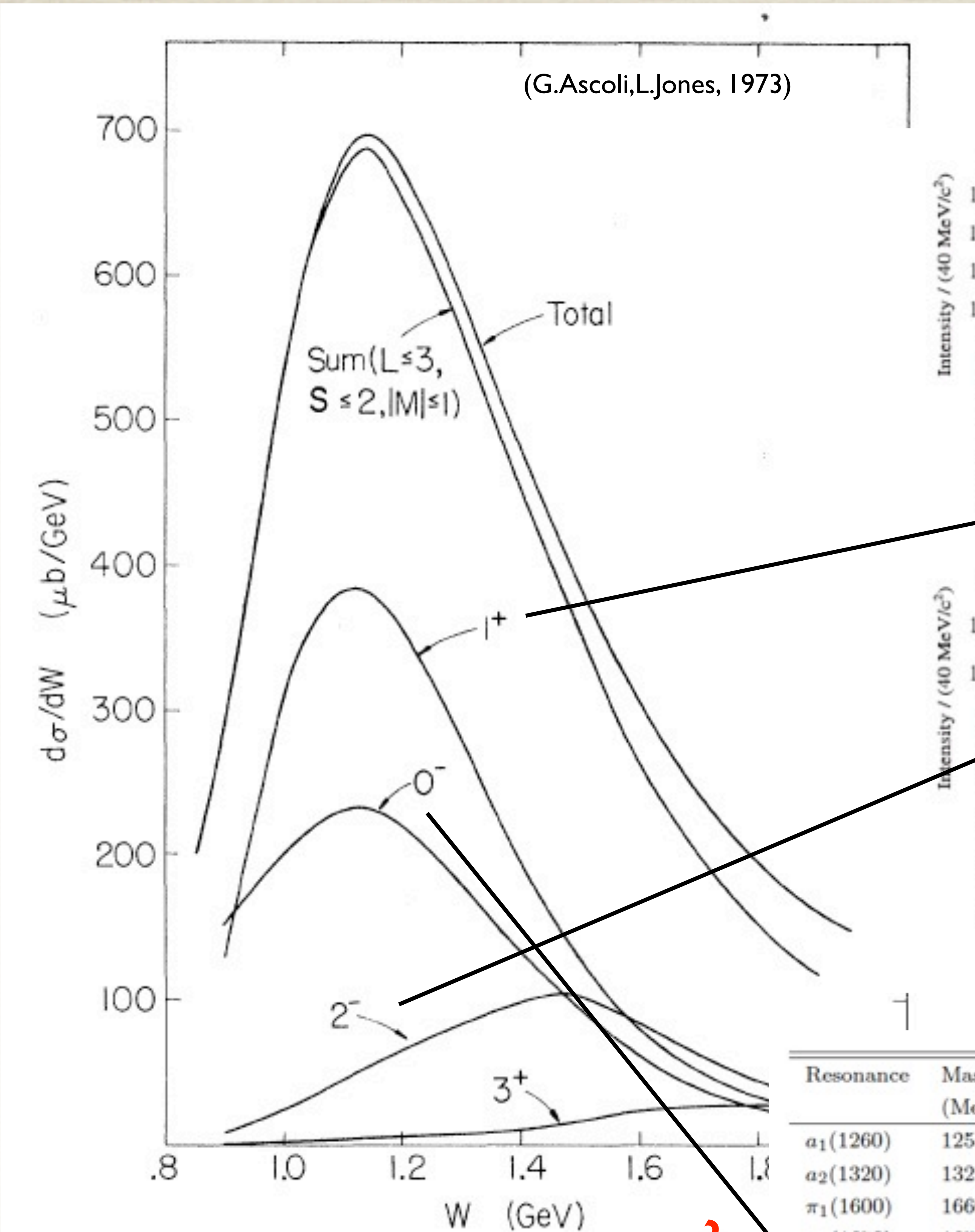


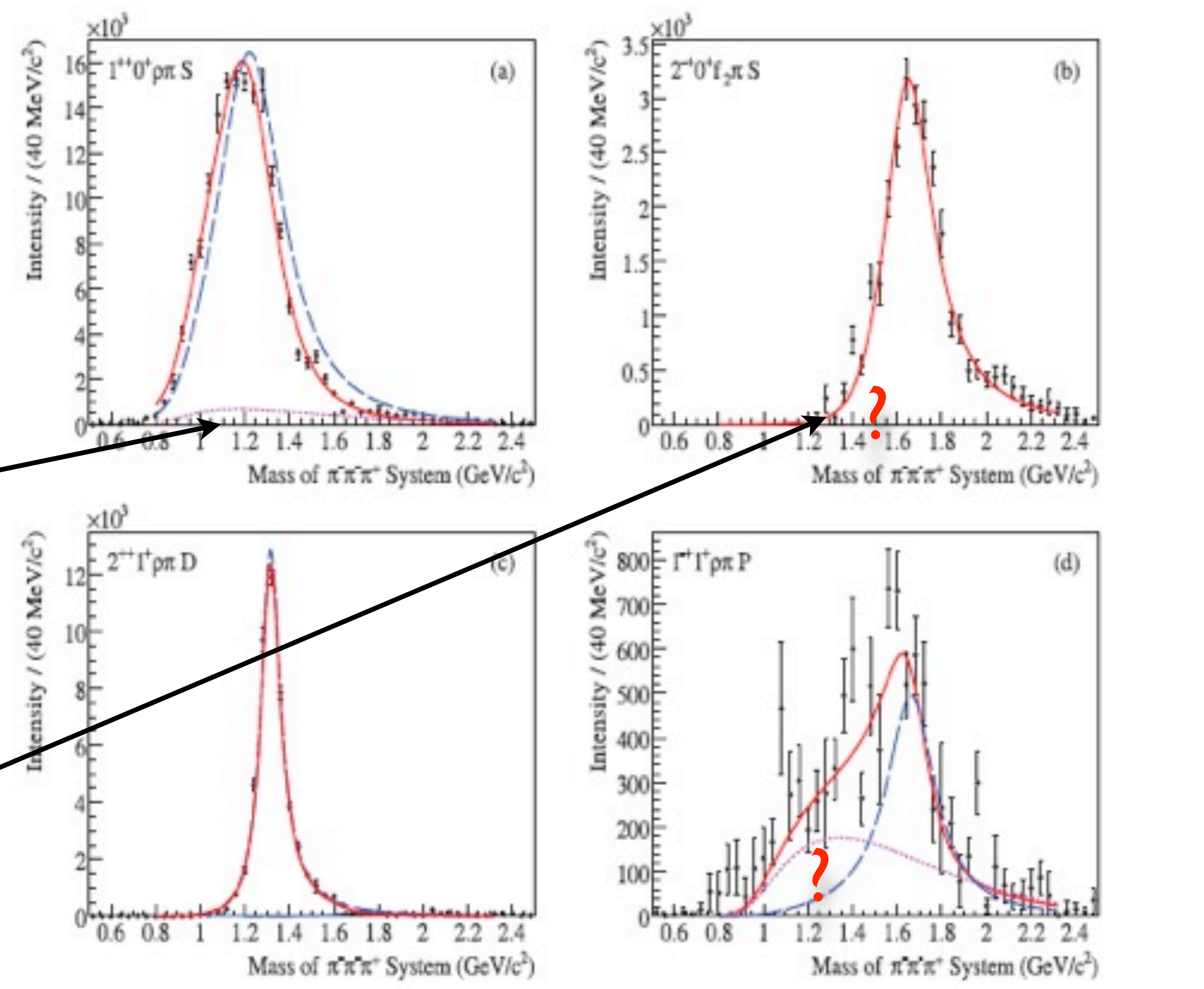
J,Dudek, AS (2006)





Isobar-type fits could involve spurious resonances





M.G.Alekseev, et al., COMPASS (2010)

Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	Intensity (%)	Channel $J^{PC}M^{\epsilon}$[isobar]L	Mass [26] (MeV/c^2)	Width [26] (MeV/c^2)
$a_1(1260)$	$1255 \pm 6^{+7}_{-17}$	$367 \pm 9^{+28}_{-25}$	$67 \pm 3^{+4}_{-20}$	$1^{++}0^{+}\ \rho\pi\ S$	1230 ± 40	$250 - 600$
$a_2(1320)$	$1321 \pm 1^{+0}_{-7}$	$110 \pm 2^{+2}_{-15}$	$19.2 \pm 0.6^{+0.3}_{-2.2}$	$2^{++}1^{+}\ \rho\pi\ D$	1318.3 ± 0.6	107 ± 5
$\pi_1(1600)$	$1660 \pm 10^{+0}_{-64}$	$269 \pm 21^{+42}_{-64}$	$1.7 \pm 0.2^{+0.9}_{-0.1}$	$1^{-+}1^{+}\ \rho\pi\ P$	1662^{+15}_{-11}	234 ± 50
$\pi_2(1670)$	$1658 \pm 3^{+24}_{-8}$	$271 \pm 9^{+22}_{-24}$	$10.0 \pm 0.4^{+0.7}_{-0.7}$	$2^{-+}0^{+}\ f_2\pi\ S$	1672.4 ± 3.2	259 ± 9
$\pi(1800)$	$1785 \pm 9^{+12}_{-6}$	$208 \pm 22^{+21}_{-37}$	$0.8 \pm 0.1^{+0.3}_{-0.1}$	$0^{-+}0^{+}\ f_0\pi\ S$	1816 ± 14	208 ± 12
$a_4(2040)$	$1885 \pm 13^{+50}_{-2}$	$294 \pm 25^{+46}_{-19}$	$1.0 \pm 0.3^{+0.1}_{-0.1}$	$4^{++}1^{+}\ \rho\pi\ G$	2001 ± 10	313 ± 31

Q: How important are multi-particle correlations
at low-energies
i.e. re-scattering in the isobar model?

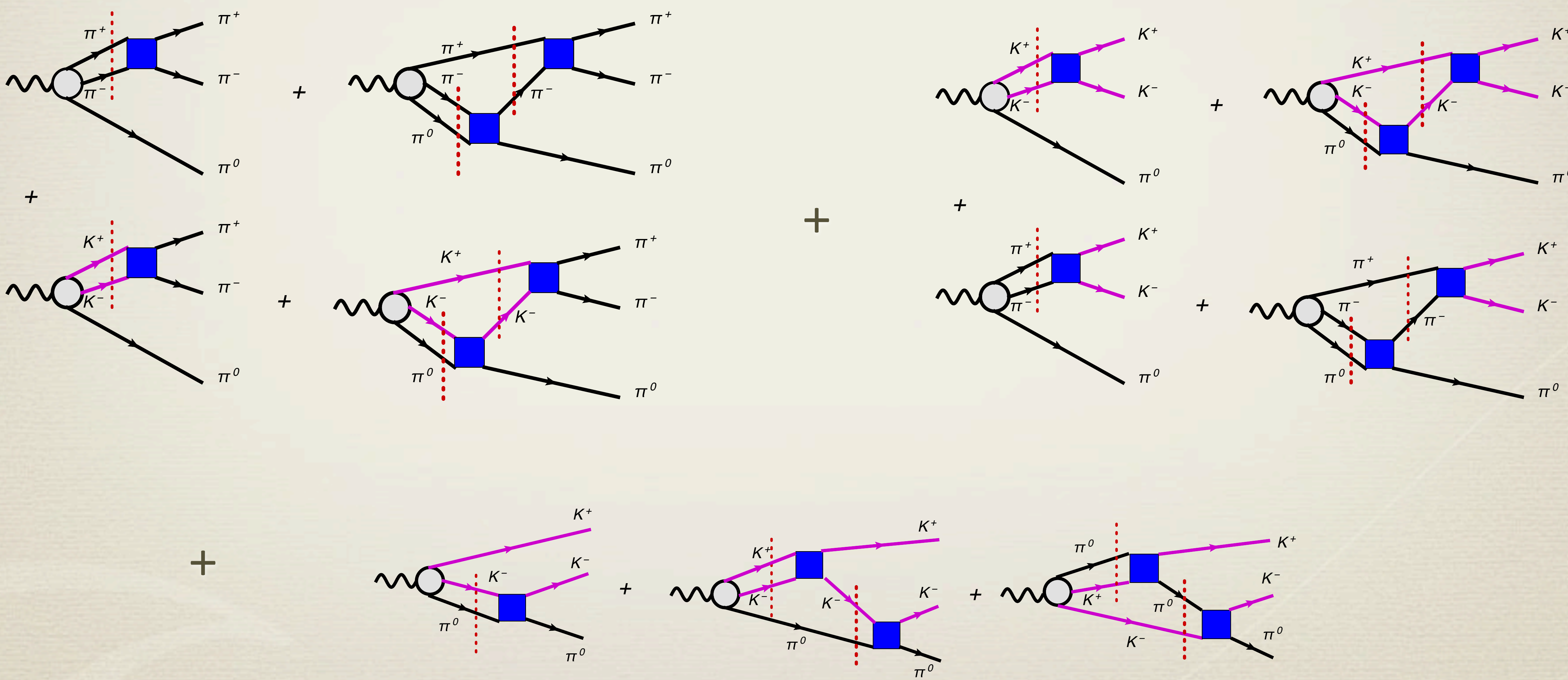
Khuri-Treiman (1960)
Pasquier-Pasquier (1968-1970)
Aitchison,Brehm (late 70's)

A: Apparently very small

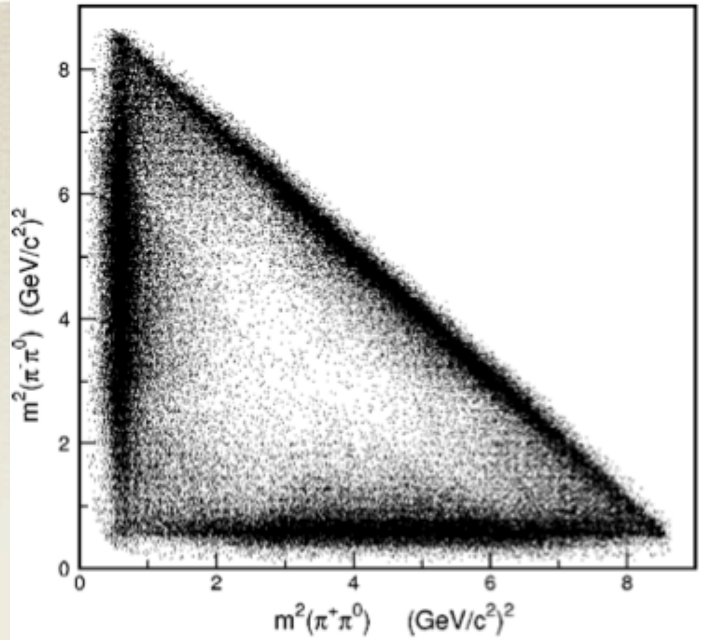
In three body final states ... one should consider ...

Three-body interaction
+
Coupled-channels
+
Unitarity & Analyticity

$$J/\Psi \rightarrow 3\pi + K\bar{K}\pi$$

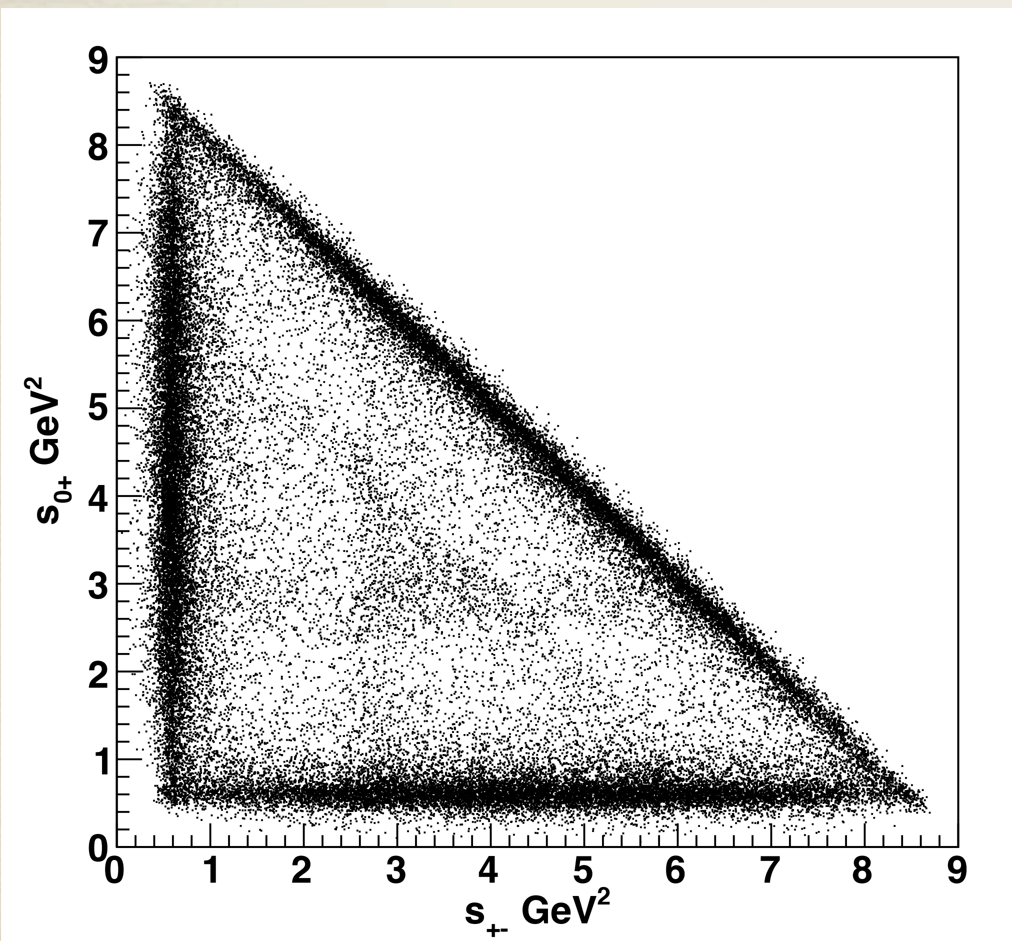


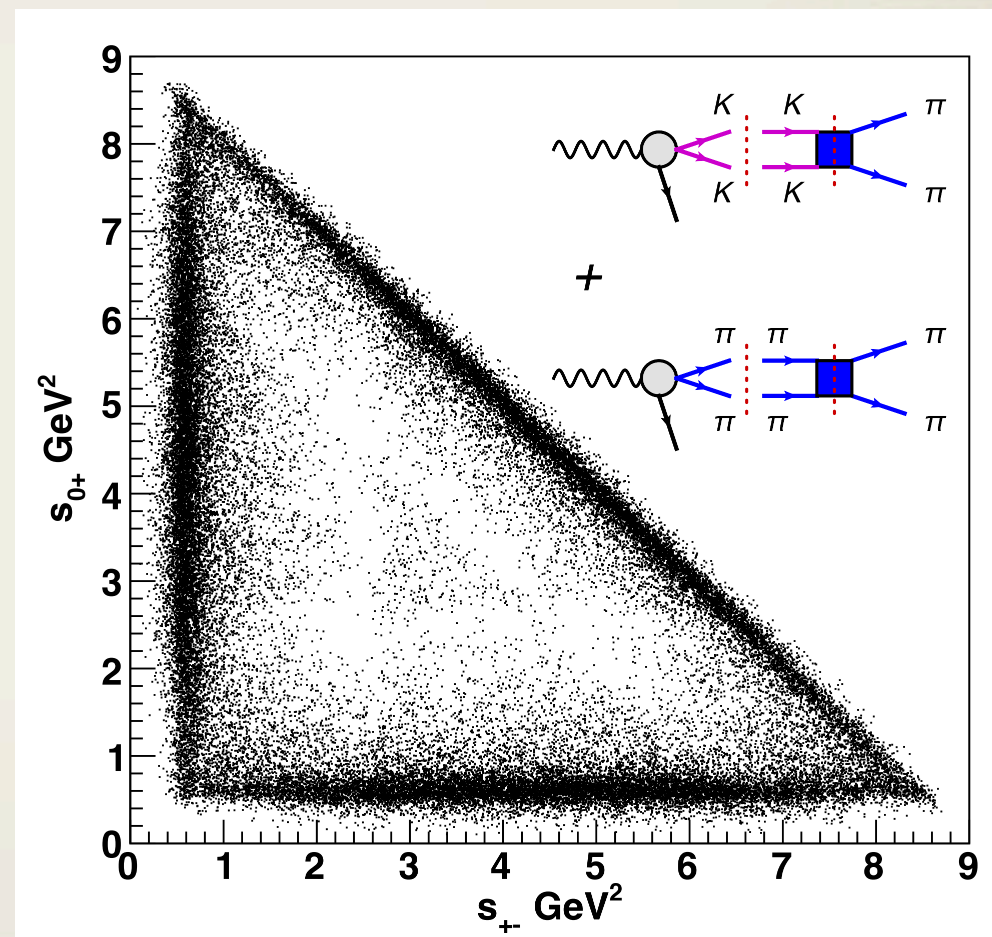
$J/\psi \to 3\pi$



BES Collaboration

Phys.Rev.D70:012005,2004

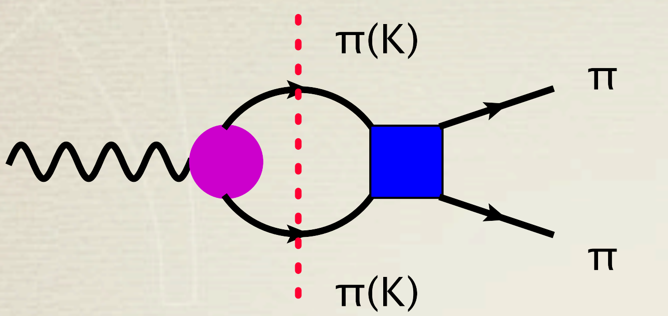




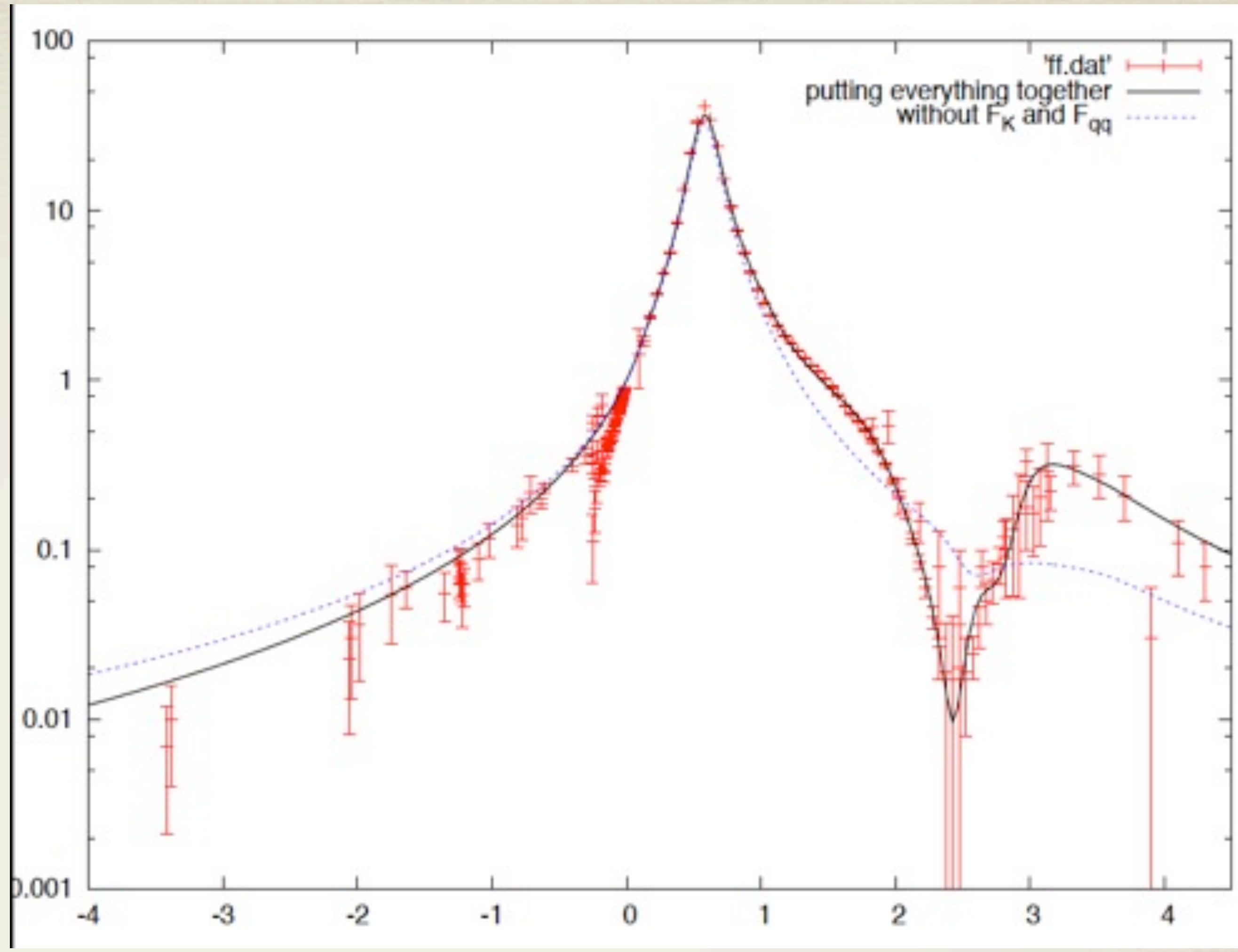
$$F(s) \sim \frac{1}{D_{\pi\pi\to\pi\pi}(s)}$$

$$F(s) \sim \frac{1 + c_1 s}{D_{\pi\pi\to\pi\pi}(s)} + \frac{c_0}{D_{K\bar{K}\to\pi\pi}(s)}$$

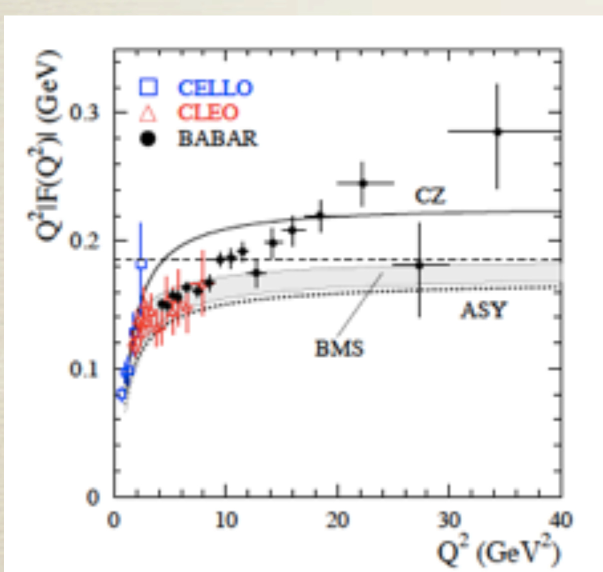
Pion formfactor: $|F_{\pi\pi}(s)|^2$

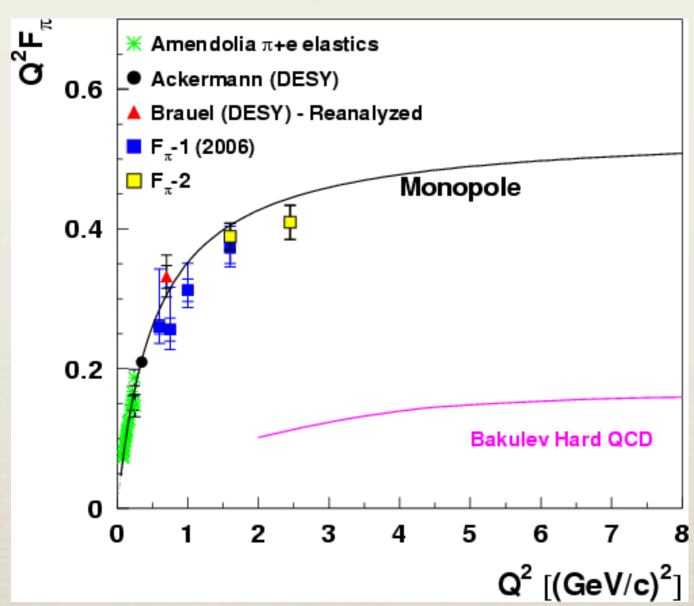


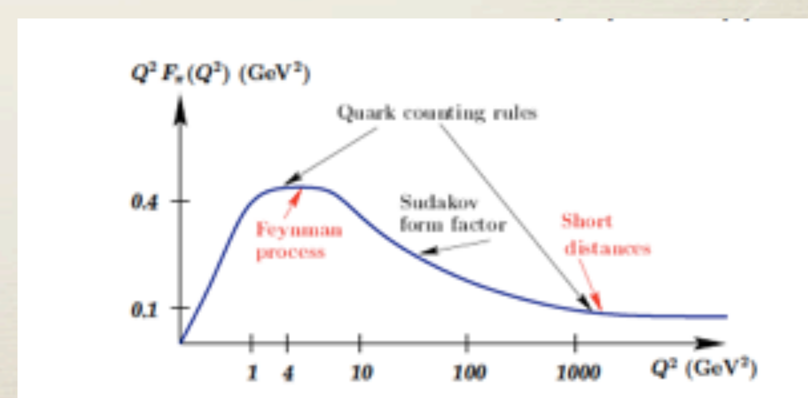
$$F(s) \sim \frac{1 + c_1 s}{D_{\pi\pi\to\pi\pi}(s)} + \frac{c_0}{D_{K\bar{K}\to\pi\pi}(s)}$$



Novel interpretation of asymptotic behavior
(M.Gorshteyn,P.Guos,AS (2011)

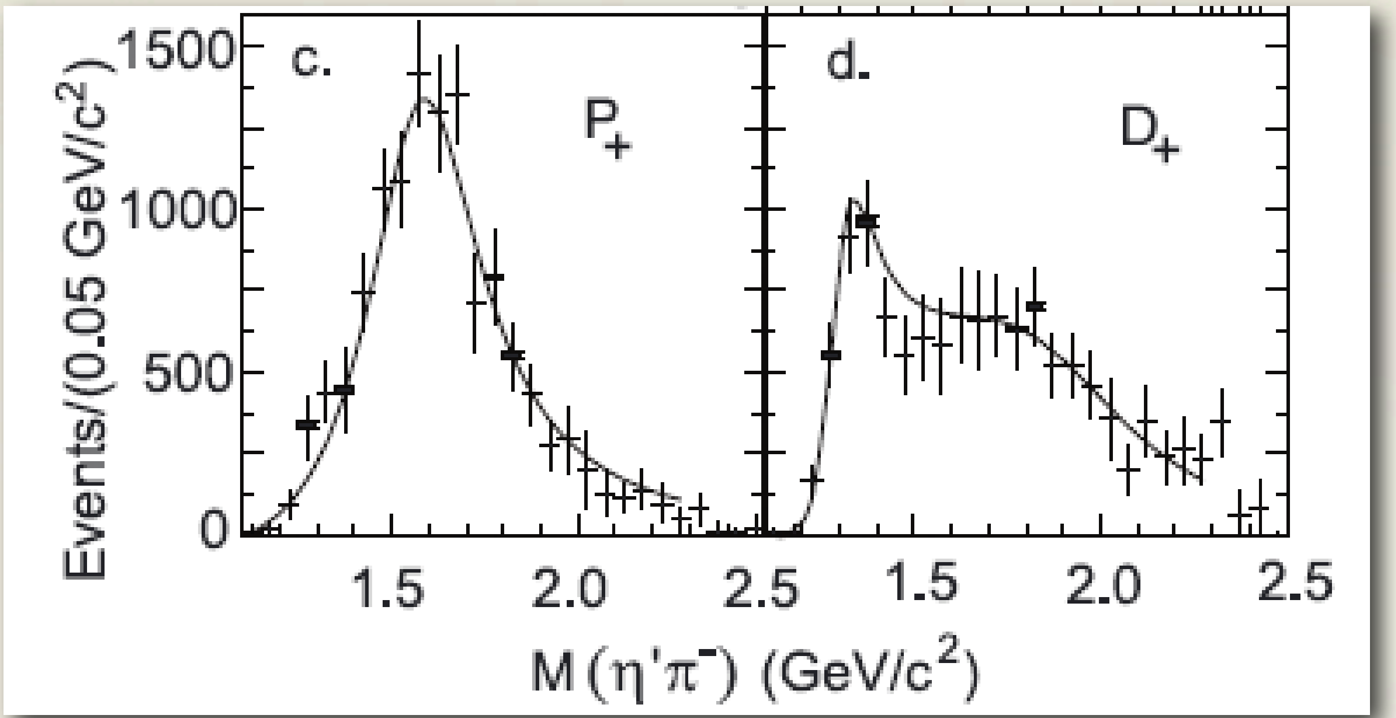






$J^{PC} = 1^{-+}$ exotic wave signals (E852 data)

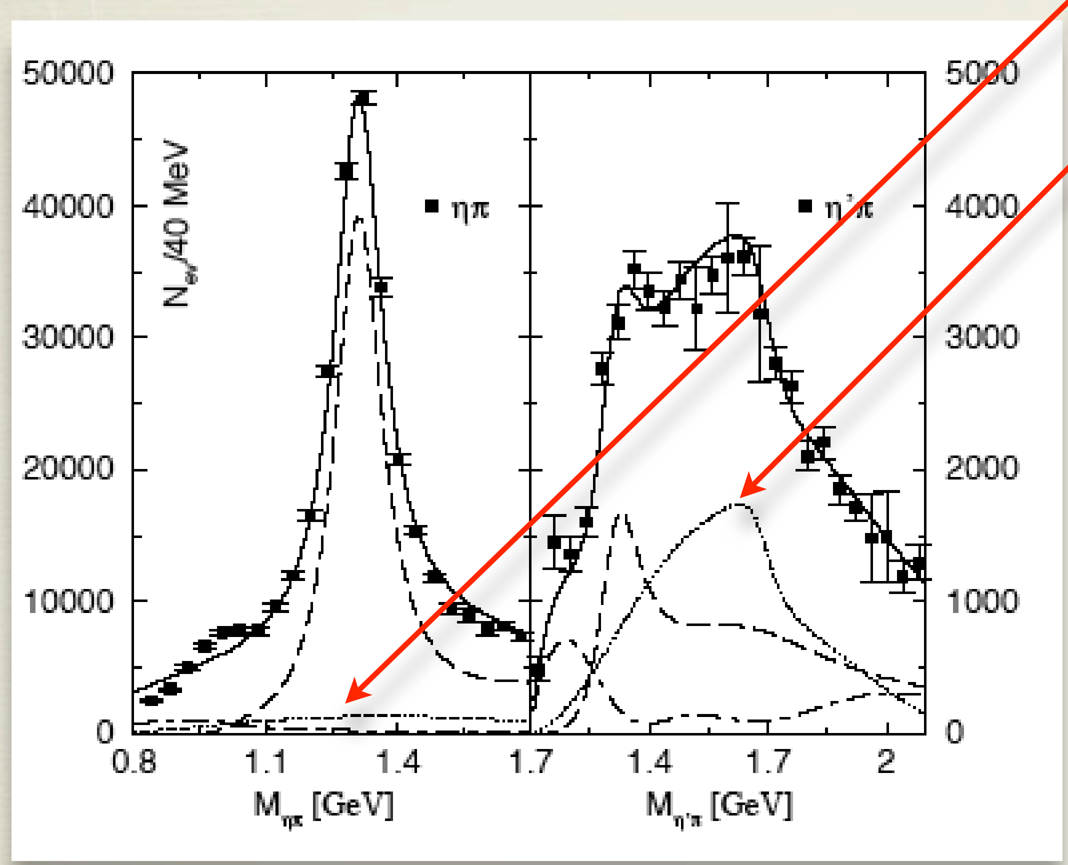
$\pi^- p \rightarrow \eta' \pi^- p$



(other signals identified by E852, CB,VES)

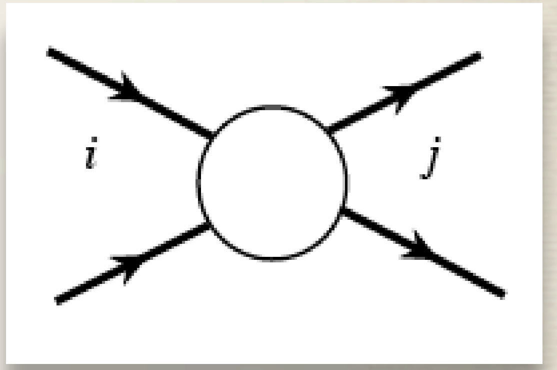
Fitting the E852 the ηπ and η' π spectra using eft give a good description of the exotic wave (APS et al.)

P-wave



P -wave ηπ, η'π
2 coupled channels

S, D -wave $K\bar{K}$, ηπ, η'π
3 coupled channels



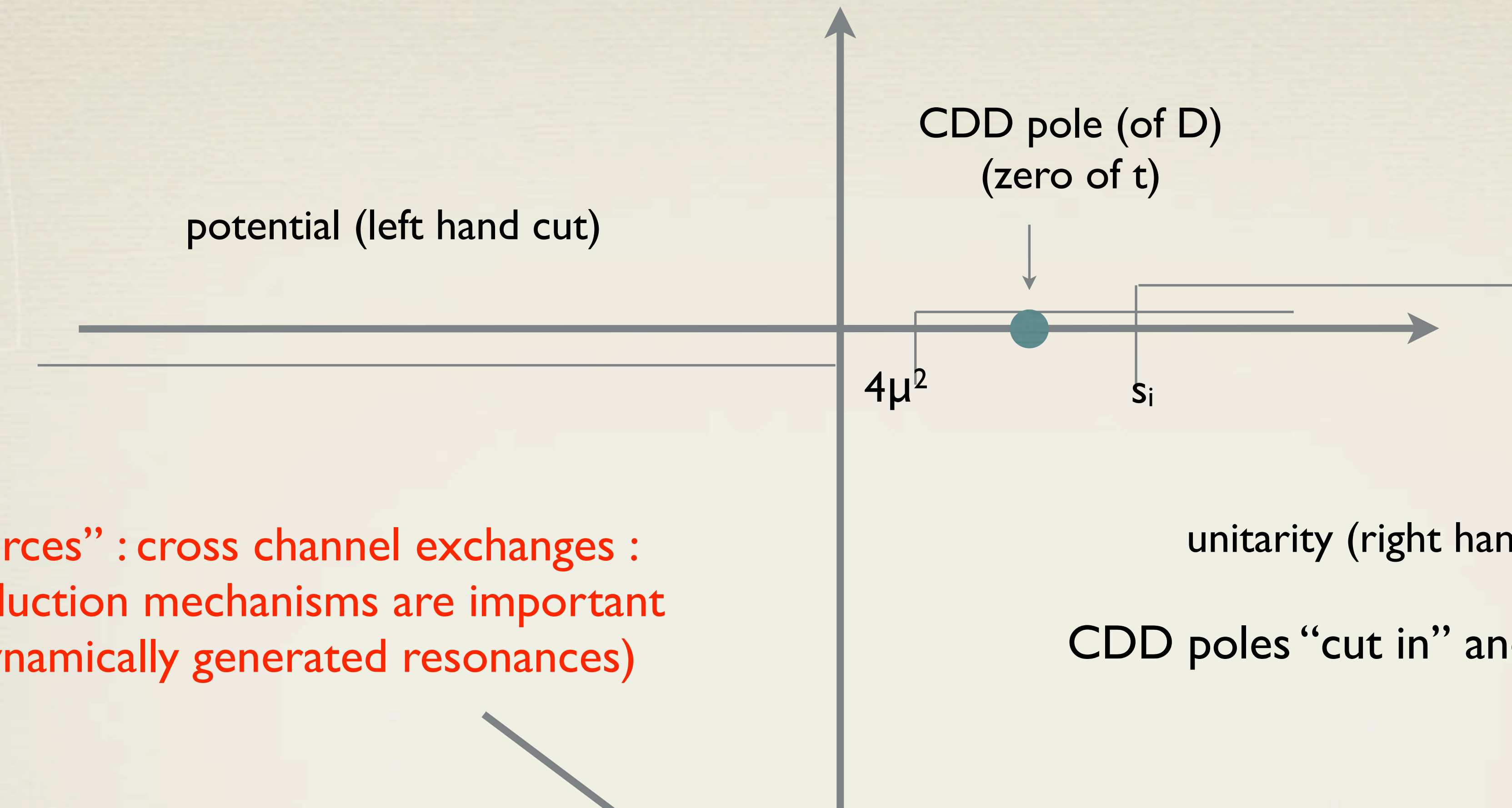
$$t(s) = \frac{1}{\mathrm{Re}\, V^{-1} - i\rho}$$

long range forces between η and π are expected to be weak

to fit the data V needs to have short range interactions

Dynamical resonance or CDD poles ?

Towards a connection between data and resonances



unitarity (right hand cut)

CDD poles "cut in" and produce bumps

"forces" : cross channel exchanges : production mechanisms are important (dynamically generated resonances)

resonances: poles on unphysical sheets

CDD pole corresponds to an elementary particle (move out from inelastic cut when coupling is decreased)

* General idea

$$ImA(s) = R(s)\rho(s)|A(s)|^2$$

$$A(s) = \frac{1}{\pi}\int_{-\infty}^{0} ds' \frac{ImA(s')}{s'-s} + \frac{1}{\pi}\int_{s_{th}}^{\infty} ds' \frac{ImA(s')}{s'-s}$$

integral equation for the amplitude

* output : through unitarity related to measured x-section

* input ("potential") : through crossing lhc is related to other physical amplitudes

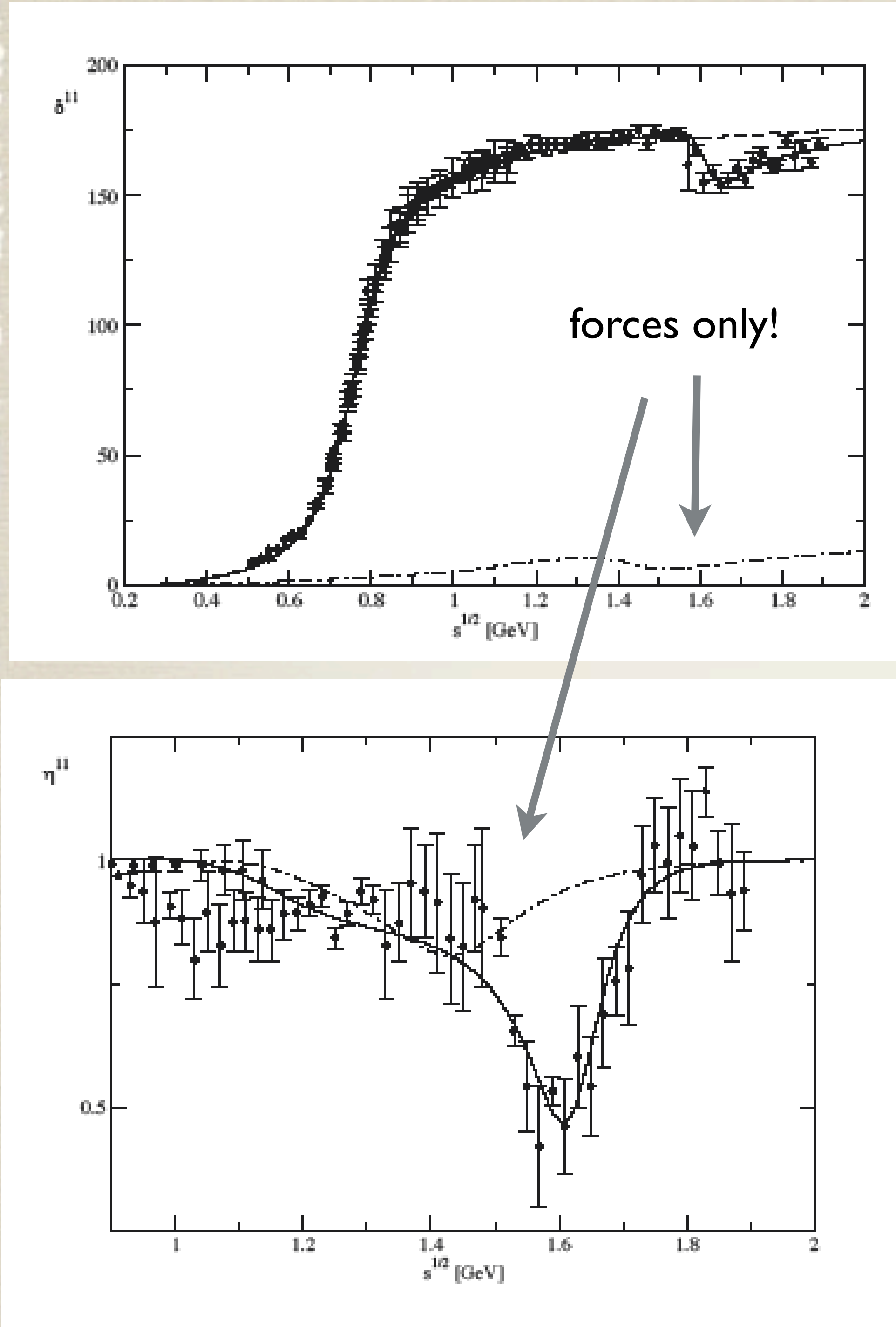
caveats

* potential not known everywhere
* in principle many (∞) channels contribute
* x-sections known over limited energy range
* solutions are not unique (CDD)

recent improvements and (1960's vs 2000)

* QCD: interpretation of the ambiguities
* chiral symmetry: low energy constraints

From dispersion relations



* CDD pole required

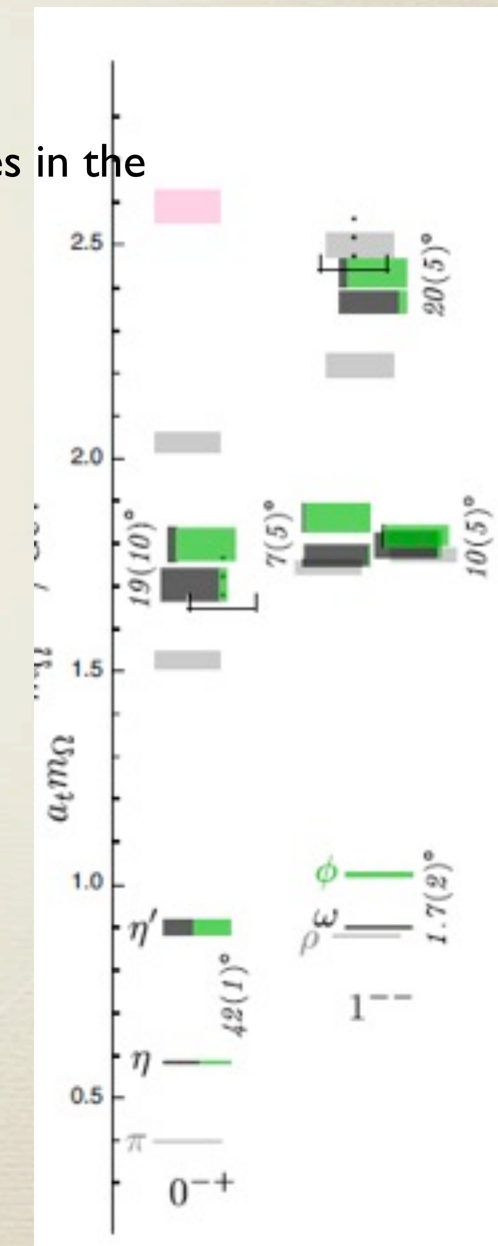
FIG. 1: *P*-wave phase shift (upper panel) and inelasticity (lower panel). Data from [34–36], dahsed-dotted (solid) line solution of dispersion relation without (with) a CDD pole. Dashed line is the fit of the quark model from Eq.(33).

M.Battaglieri,R.de Vita,P.Guo,AS

* bootstrap failed

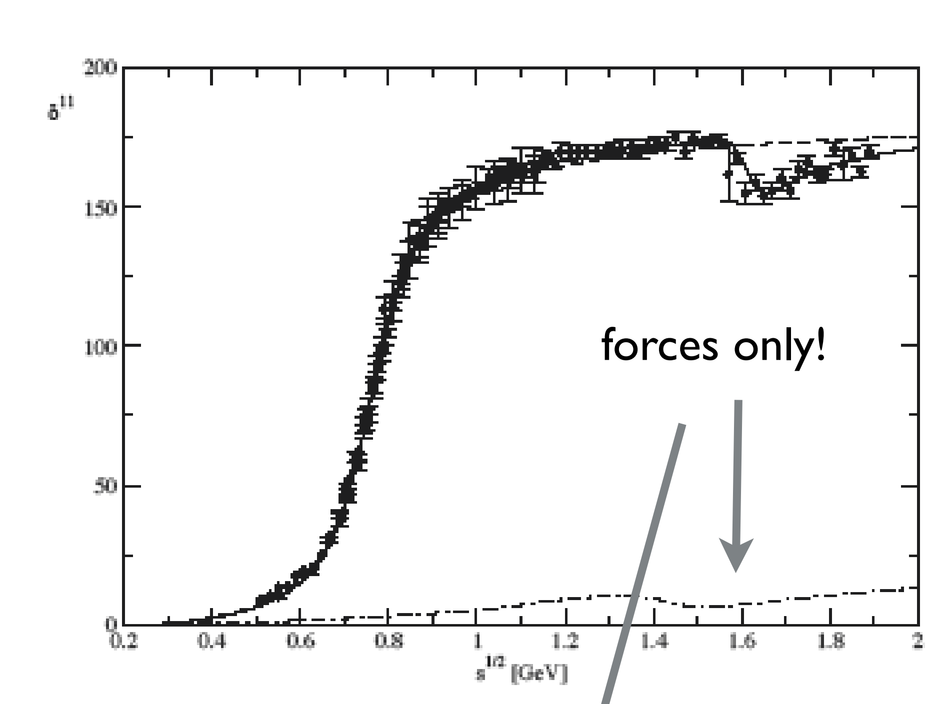
* resonances are not generated dynamically from interactions between other resonances

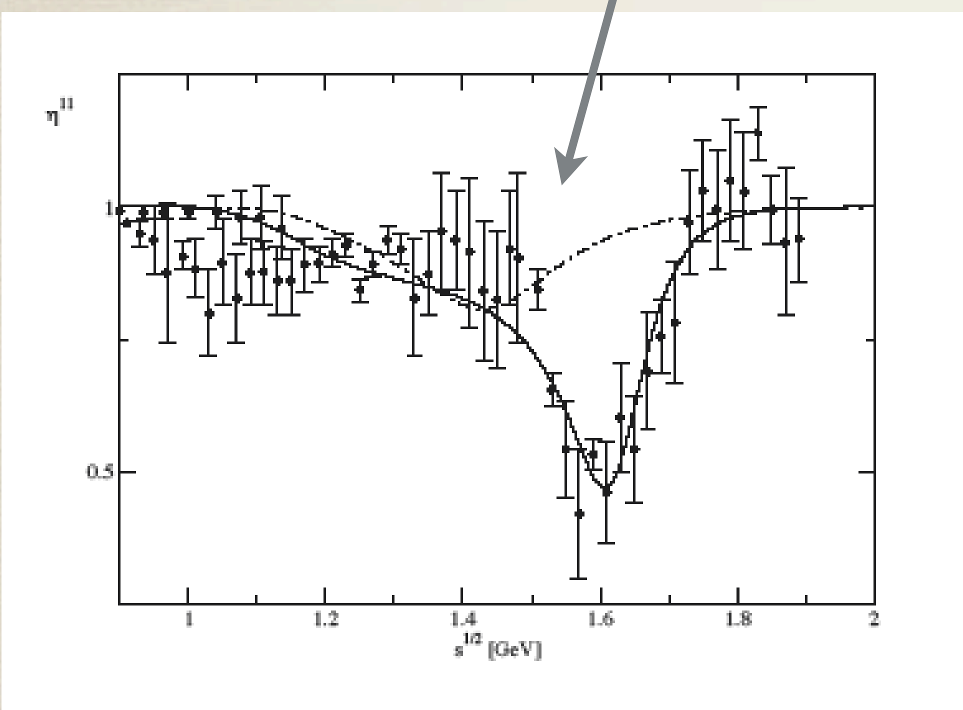
* or as lattice suggests there are single hadron states in the spectrum



J.Dudek et al. 2011

From dispersion relations





* CDD pole required

FIG. 1: *P*-wave phase shift (upper panel) and inelasticity (lower panel). Data from [34–36], dahsed-dotted (solid) line solution of dispersion relation without (with) a CDD pole. Dashed line is the fit of the quark model from Eq.(33).

M.Battaglieri, R.de Vita, P.Guo, AS

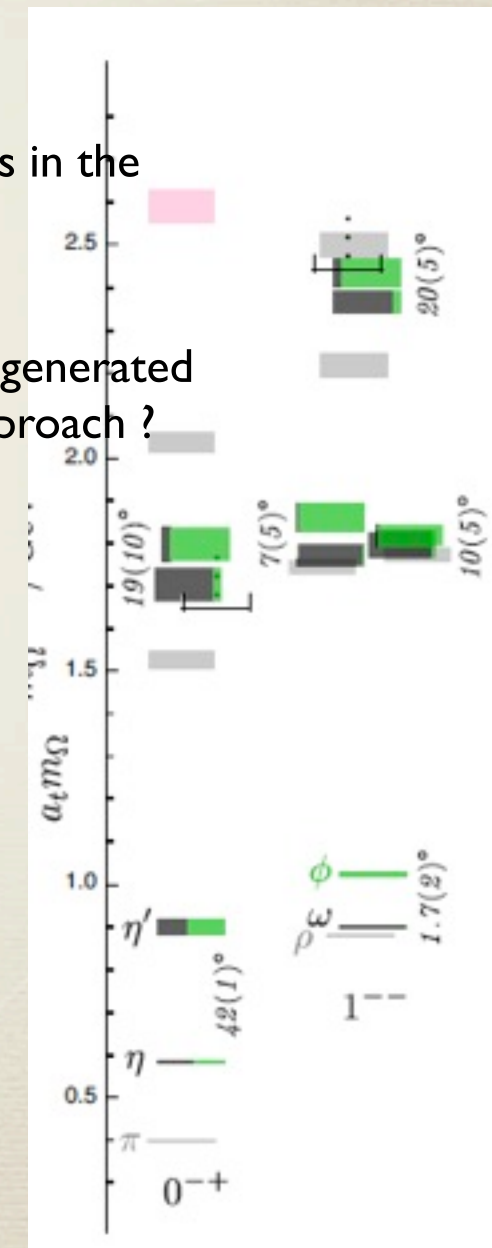
* bootstrap failed

* resonances are not generated dynamically from interactions between other resonances

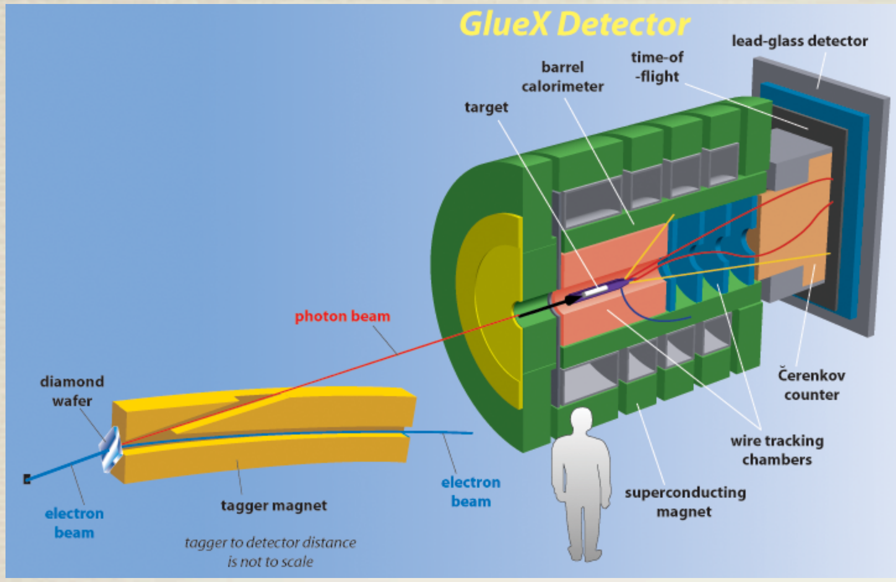
* or as lattice suggests there are single hadron states in the spectrum

* how does it fit in with the success of dynamically generated resonance program from a unitarized chi-PT approach ?

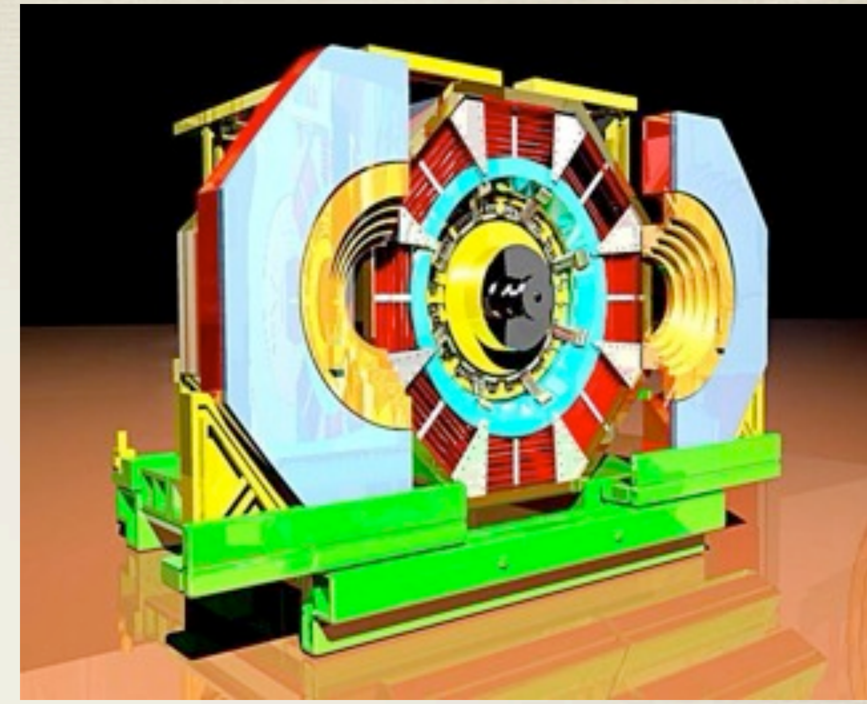
do the Uch-PT poles move?

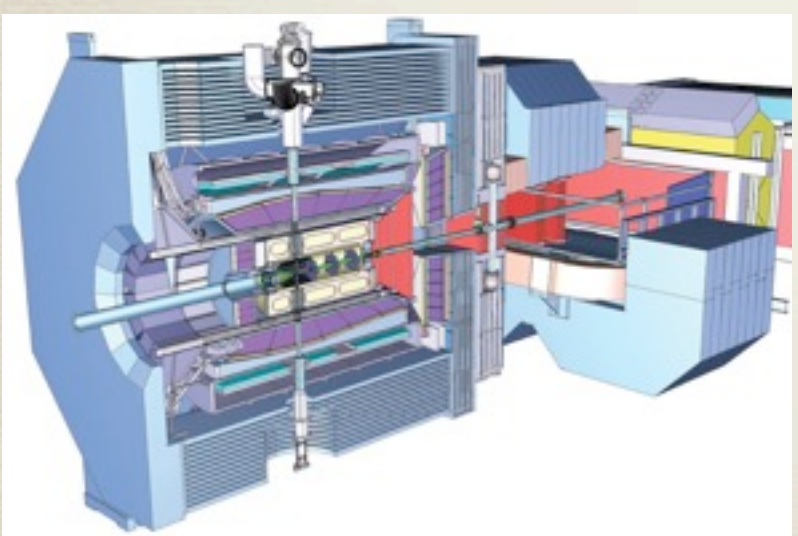


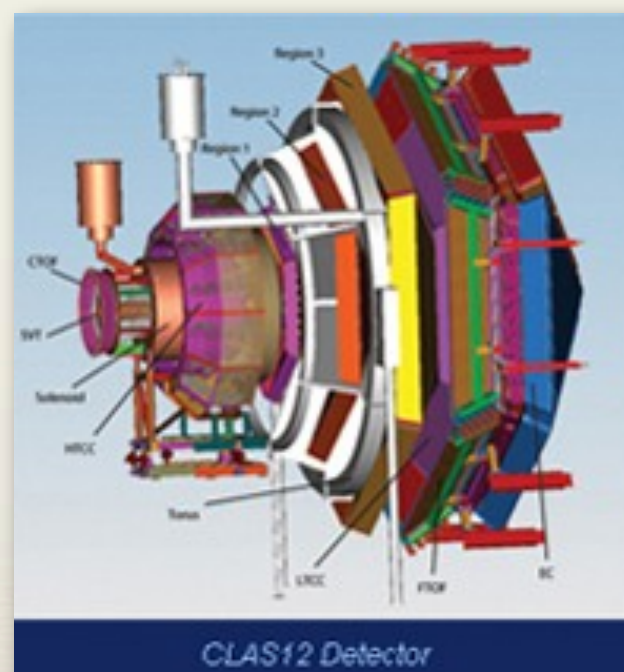
J.Dudek et al. 2011



COMPASS







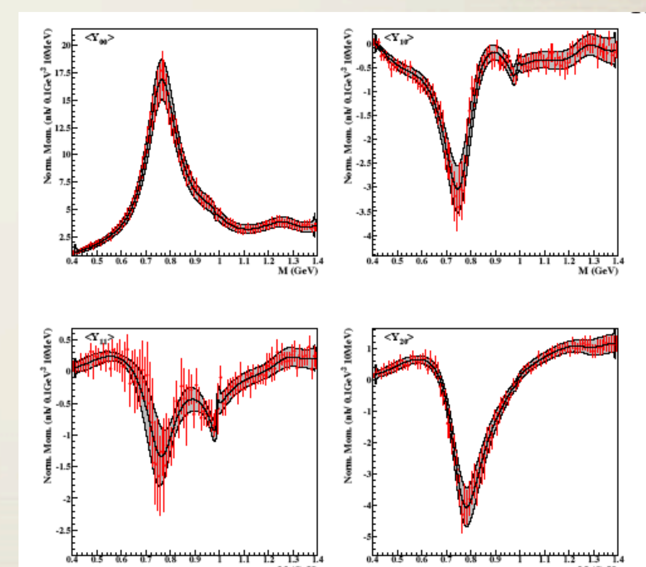


FIG. 6: Fit result (black line) of the final experimental moments (in red) in $3.2 < E < 3.4$ GeV and $0.5 < -t < 0.6$ GeV^2 bins.

CLAS PWA
M.Battaglieri et al. (2009)