Physics at GlueX

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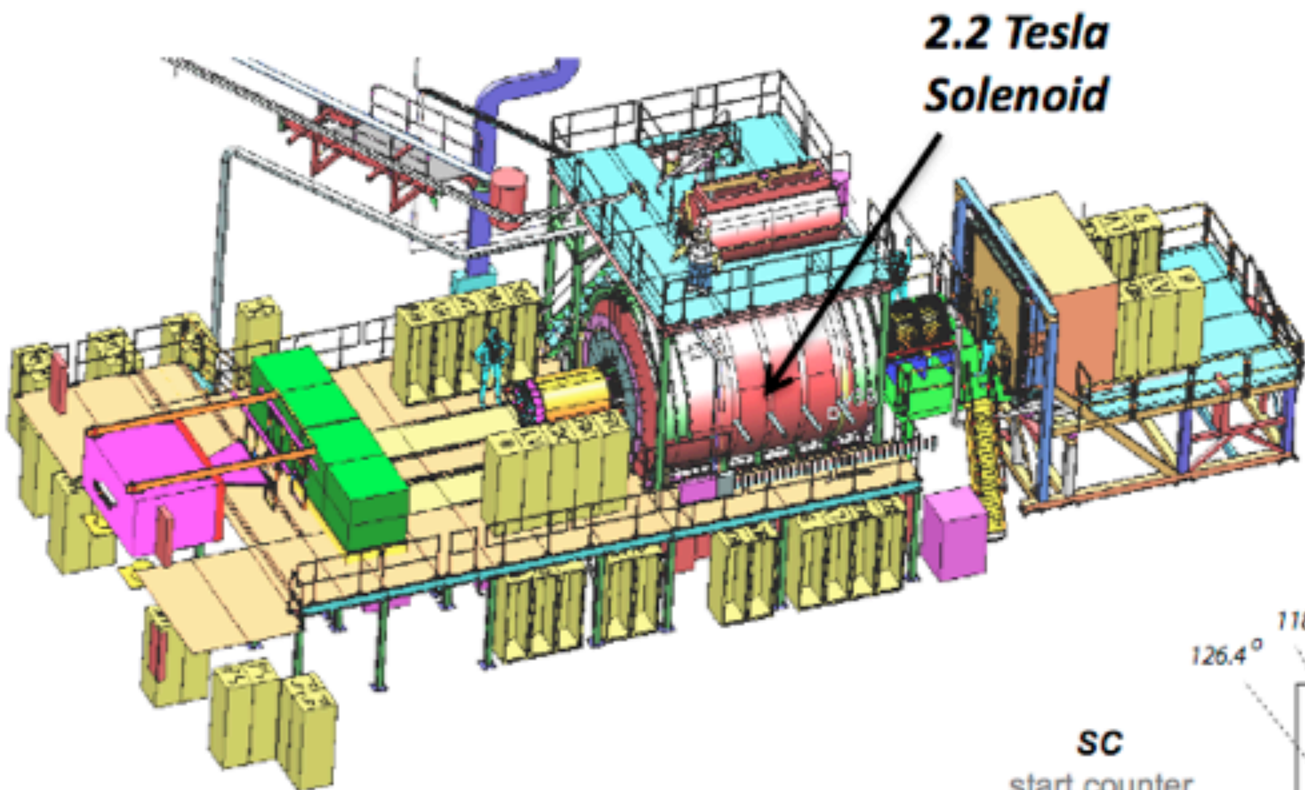
GlueX

12 GeV electron beam → 9 GeV linearly polarised photon beam (or higher ***E*** with lower polarisation)



- 2.2T superconducting solenoidal magnet
- Fixed target (LH_2)
- 10^8 tagged γ/s (8.4-9.0GeV)
- hermetic

Charged particle tracking

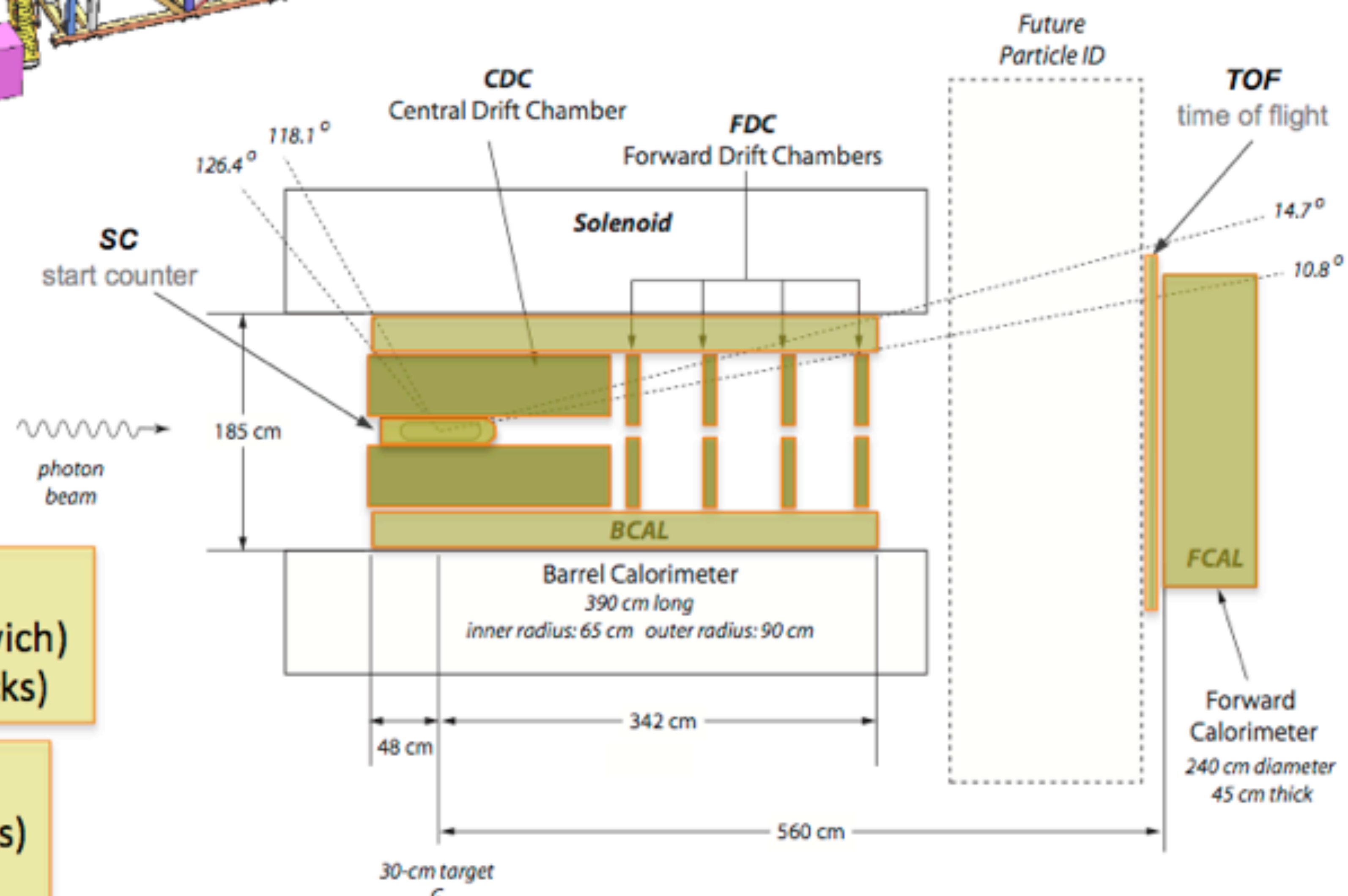
- Central drift chamber (straw tube)
- Forward drift chamber (cathode strip)

Calorimetry

- Barrel Calorimeter (lead, fiber sandwich)
- Forward Calorimeter (lead-glass blocks)

PID

- Time of Flight wall (scintillators)
- Start counter
- Barrel Calorimeter



GlueX Detector

meson spectroscopy

first dedicated photoproduction meson spectroscopy experiment

one motivation is the search for ***exotic quantum numbered*** mesons

experimentally see no mesons with ***isospin > 1*** or ***|strangeness| > 1***

motivates constituent quark model - mesons as $q\bar{q}$ bound states

chiral symmetry breaking in various QCD-like models suggests such quasi-particles

$S_{q\bar{q}} = \frac{1}{2} \otimes \frac{1}{2}$ $\quad S_{q\bar{q}} = 0, 1$

singlet, triplet

orbital ang. mom. $L = 0, 1, 2 \ldots$

bound states $^{2S+1}L_J$

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

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

$L = 0$ $\quad {}^1S_0 \to 0^{-+}$, $\quad {}^3S_1 \to 1^{--}$

$L = 1$ $\quad {}^1P_1 \to 1^{+-}$, $\quad {}^3P_{0,1,2} \to (0, 1, 2)^{++}$

exotic ***J^{PC}*** are those not accessible this way :

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

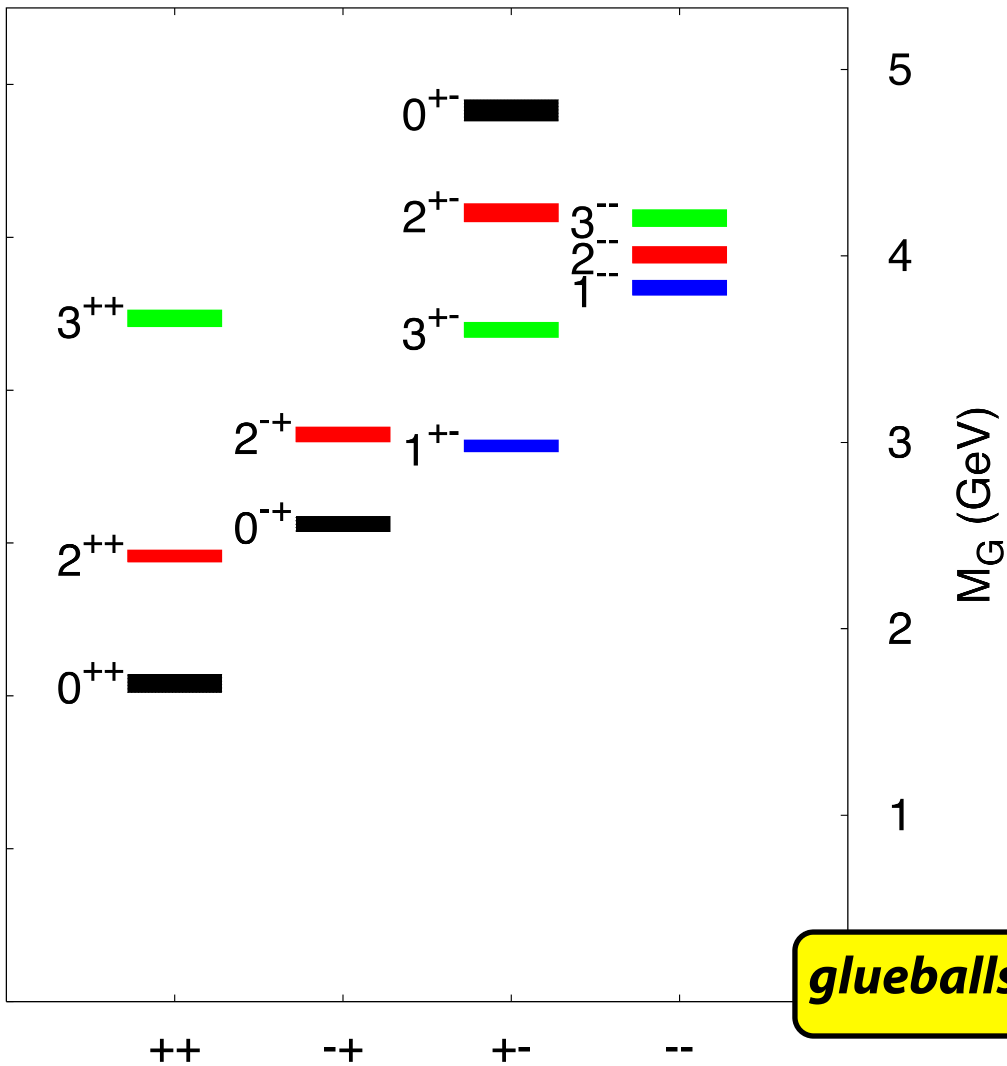
hybrids

one simple way to get exotic quantum numbers is by adding a gluonic degree-of-freedom

we know that strongly coupled glue can behave non-trivially :

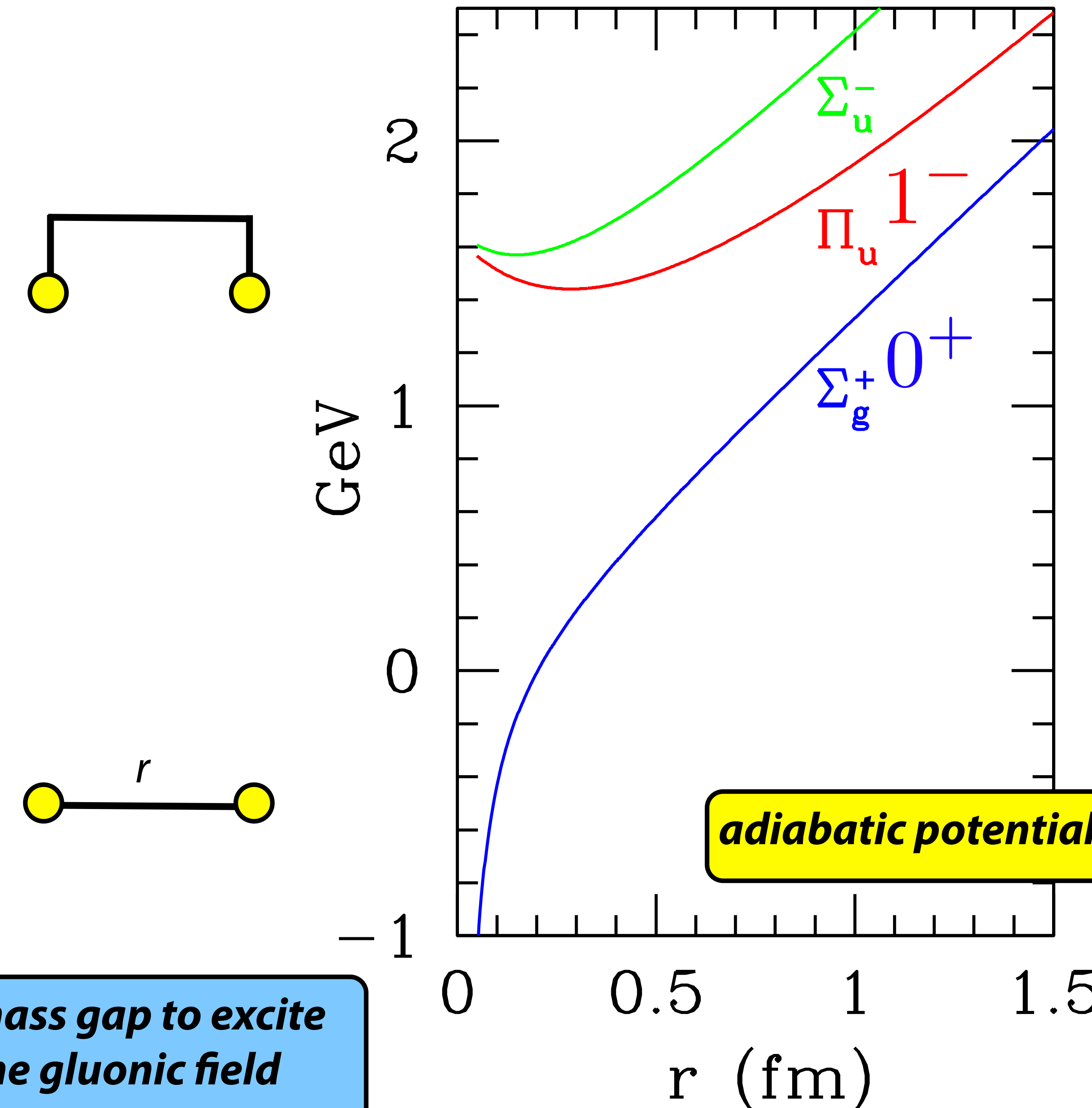
pure glue theory (Yang-Mills)

$$\mathcal{L} = \frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a$$



glueballs

infinitely heavy color sources



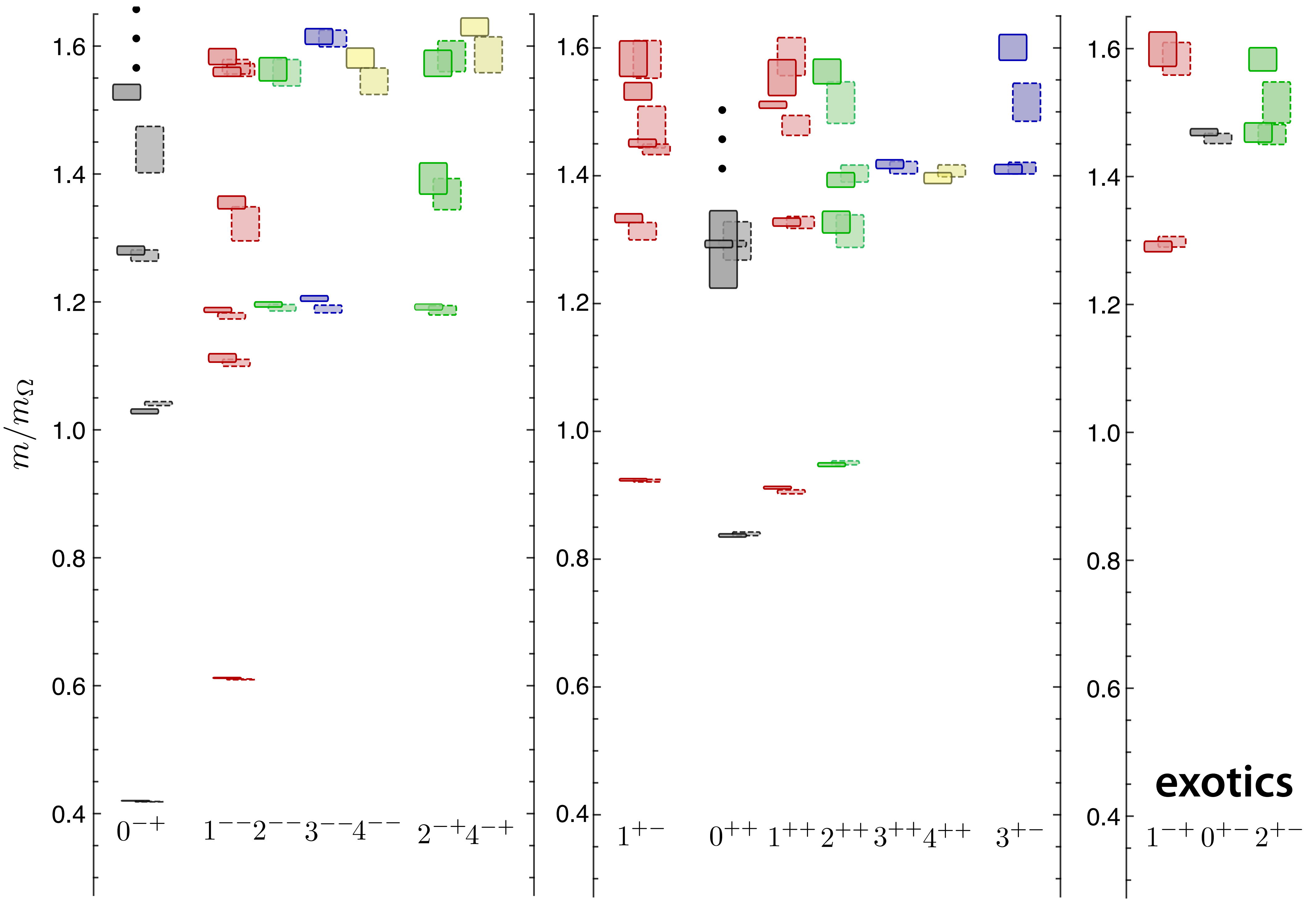
adiabatic potentials

mass gap to excite the gluonic field

hybrids

excited gluonic field in presence of quarks called a hybrid meson

lattice QCD calculations seem to indicate their presence in the spectrum



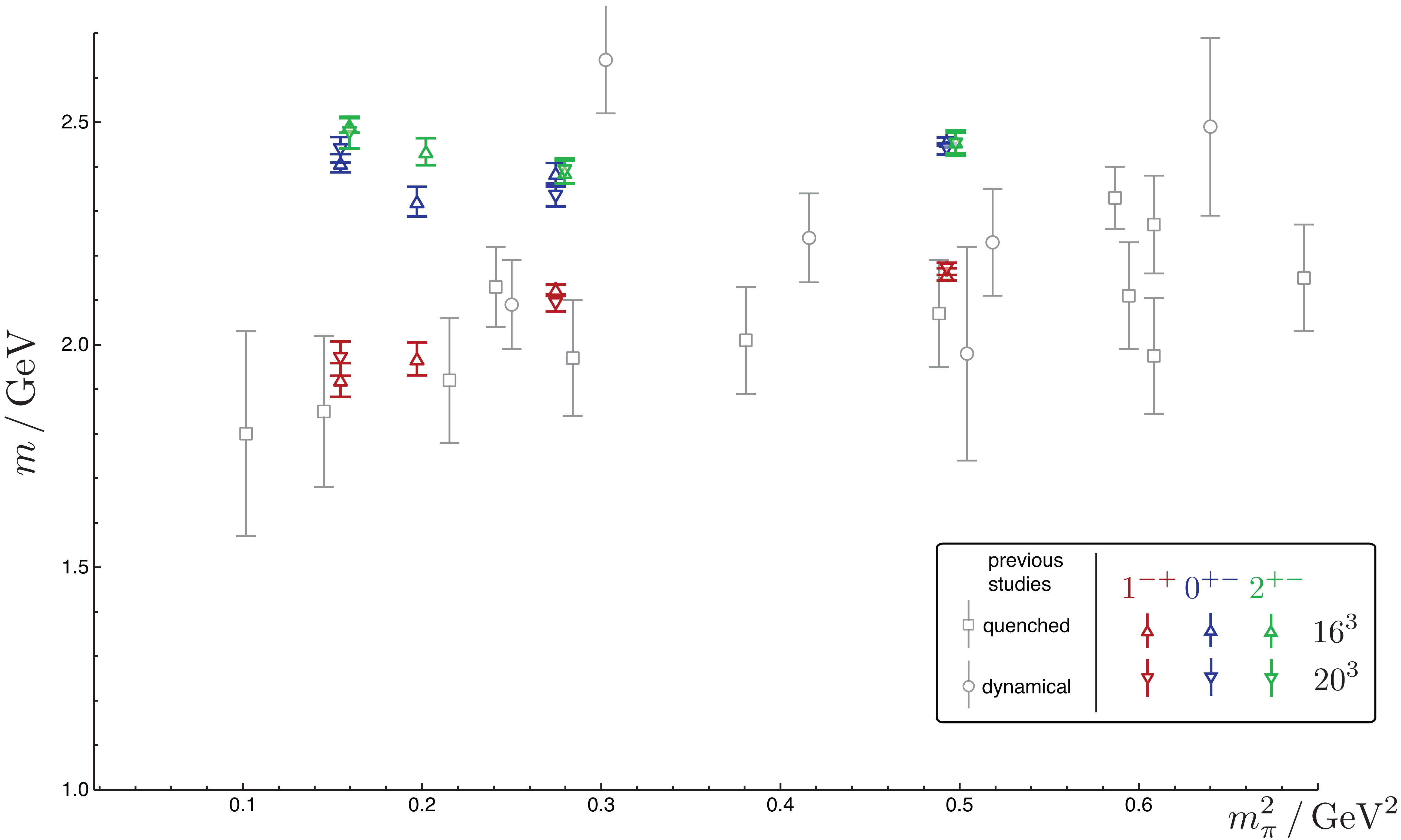
dynamical, N_F=3
(s,s,s), m_π~700 MeV

2.0^3 fm^3

2.4^3 fm^3

hybrids

excited gluonic field in presence of quarks called a hybrid meson



hybrid decays

obviously we'll seek hybrids as resonances in multi-meson final states

some 'easy' final states: $\pi_1 \to \pi\eta,\ \pi\eta',\ \pi\rho$ ...

some more complex: $b_{0,2} \to \pi\ a_1$ ...

hadronic decay models tend to suggest that high multiplicity final states are preferred ...

e.g. $\pi_1{}^0 \to \pi^+ b_1{}^0 \to \pi^+ \pi^0 \omega \to \pi^+ \pi^0\ \pi^+ \pi^- \pi^0 \to \pi^+ \pi^+ \pi^- \gamma\ \gamma\ \gamma\ \gamma$

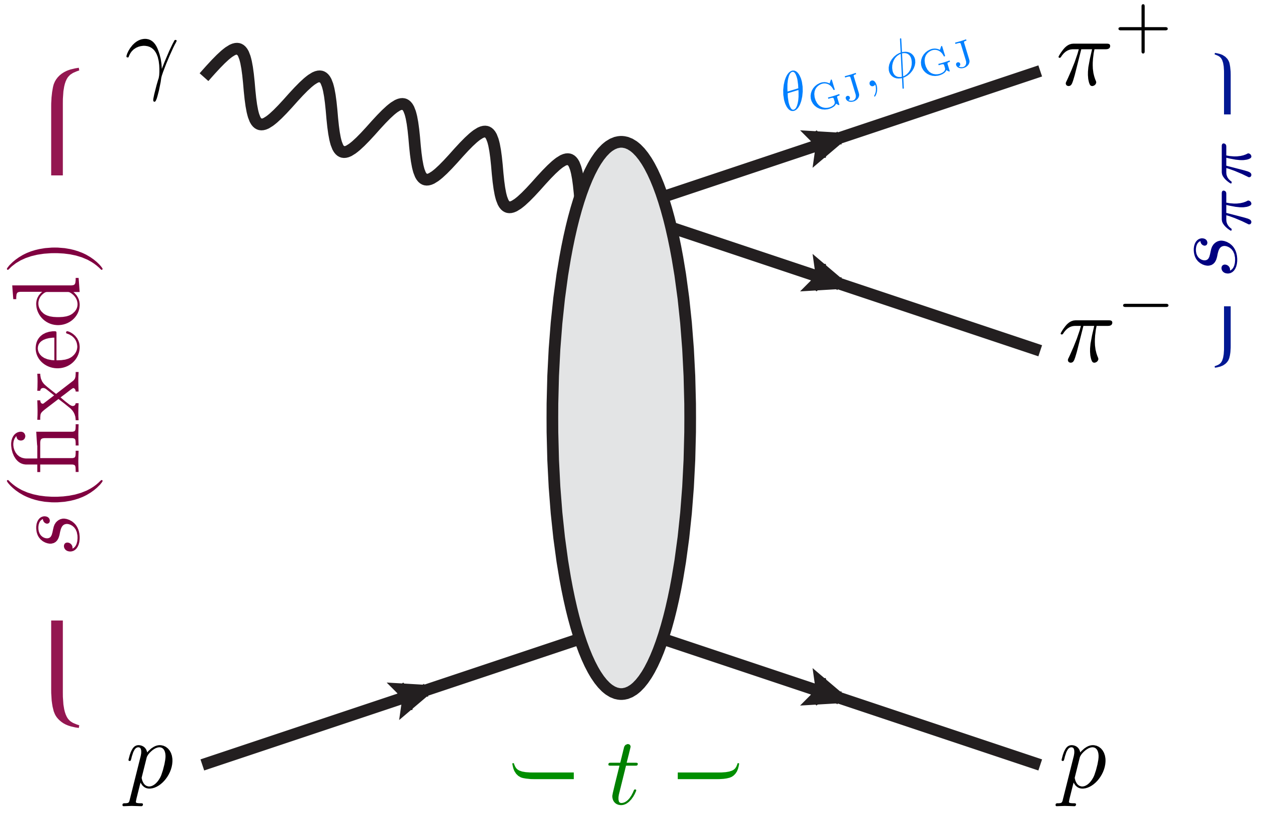
three charged and four uncharged particles !

event-based analysis

data description on an event-by-event basis

the exp[tal] data is not corrected for the detector acceptance, the theory is

very simple example :



just one possible handy (complete) set of kinematic variables

amplitude =

$$\sum_i V_i(\,s\,,\,t\,,s_{\pi\pi}\,) \times A_i(\theta_{\rm GJ}, \phi_{\rm GJ})$$

$$\Big(A_i(\theta_{\rm GJ}, \phi_{\rm GJ}) = \mathcal{D}^{(J_i)}_{m_i,0}(\phi_{\rm GJ}, \theta_{\rm GJ}, 0)\Big)$$

each event is a set of particle 4-vectors determining s, t, $s_{\pi\pi}$, $\theta_{\rm GJ}$, $\phi_{\rm GJ}$

fit variables are the V_i

intensity $I = \left|\sum_i V_i A_i\right|^2 = \sum_{i,j} V_i V_j^* \; A_i A_j^*$

bin events in small regions of (s, t, $s_{\pi\pi}$)

maximum likelihood

in a given bin of (s, t, $s_{\pi\pi}$), define a likelihood via a product over all events (r) in that bin

$$\mathcal{L} = \frac{e^{-\mu}\mu^N}{N!} \prod_{r=1}^{N} \frac{\eta(\vec{\kappa}_r) I(\vec{\kappa}_r, \vec{V})}{\int d\vec{\kappa}\, \eta(\vec{\kappa}) I(\vec{\kappa}, \vec{V})}$$

– Poisson – stats.

taken account of the detection efficiency for each event kinematics : $\eta(\vec{\kappa}_r)$

$$\mu = \int d\vec{\kappa}\, \eta(\vec{\kappa}) I(\vec{\kappa}, \vec{V})$$

$$\ln \mathcal{L} = \sum_{r=1}^{N} \ln \left(\sum_{i,j} V_i V_j^* A_i(\vec{\kappa}_r) A_j^*(\vec{\kappa}_r) \right)$$

varies event-by-event - **no η !**

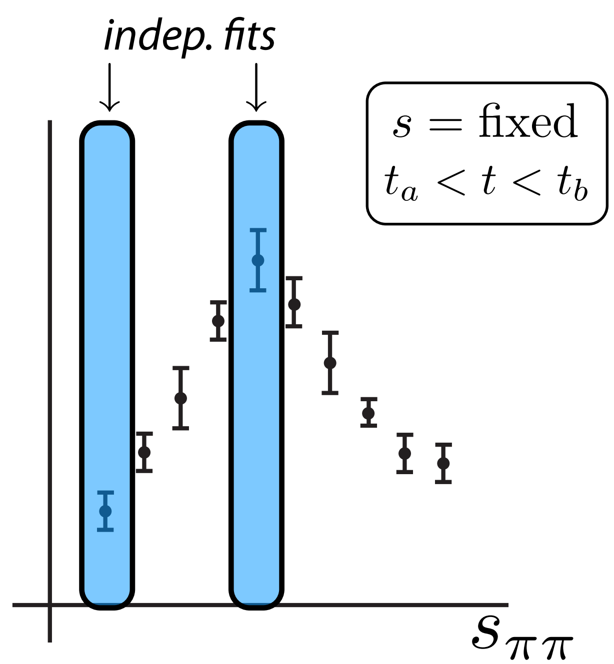
$$- \sum_{i,j} V_i V_j^* \int d\vec{\kappa}\, \eta(\vec{\kappa}) A_i(\vec{\kappa}) A_j^*(\vec{\kappa})$$

η corrects the 'theory'

no 'division by small numbers'

feed 'theory' Monte-Carlo events through detailed model of the detector

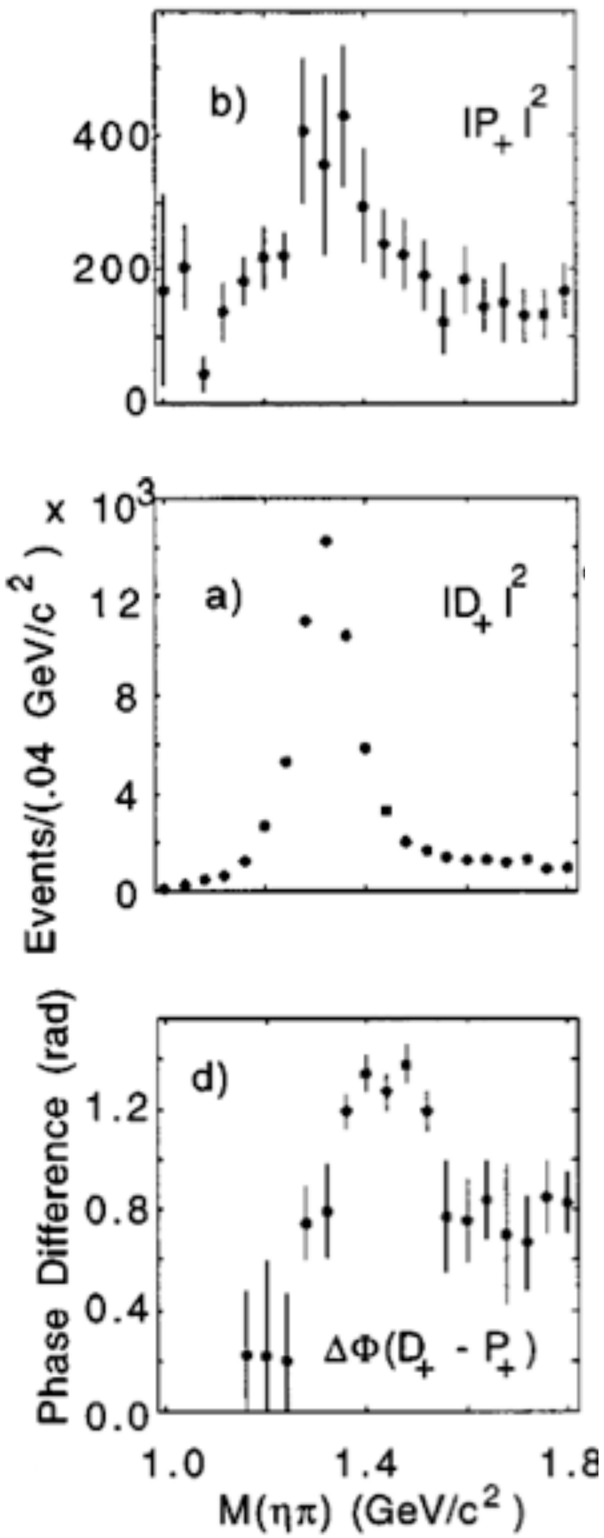
vary V_i until the log-likelihood is maximised - variation gives error estimates



pion beams

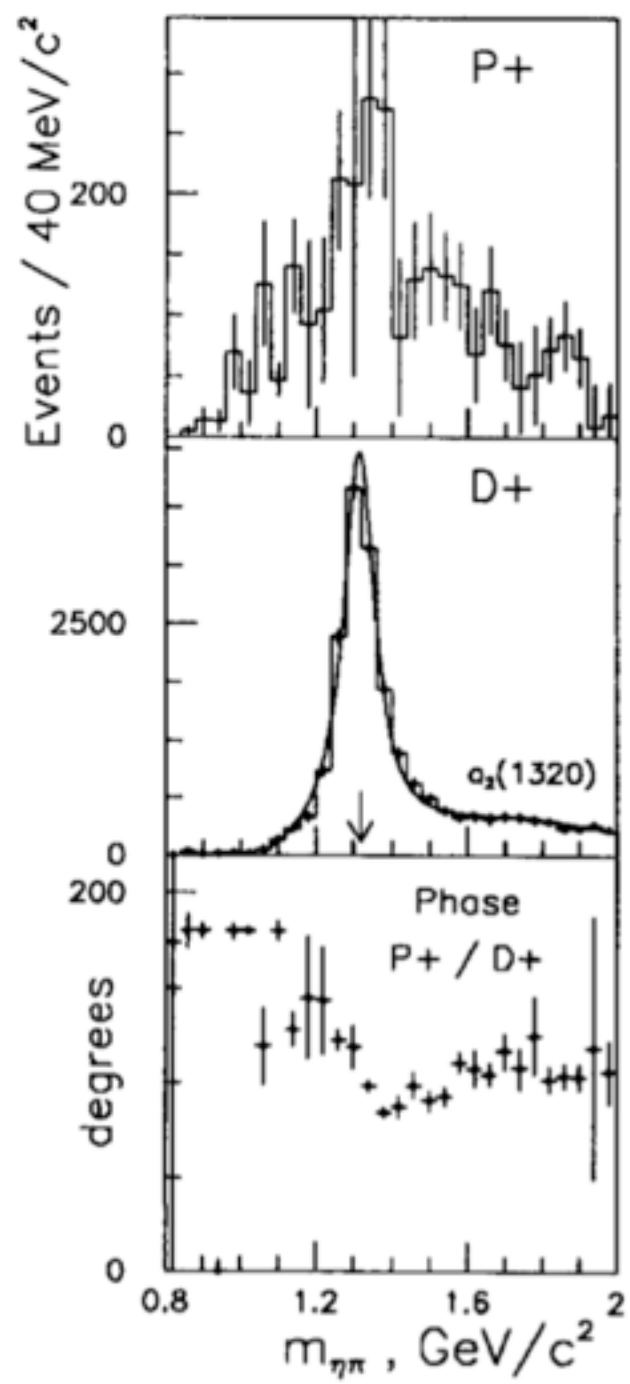
$\pi^- p \rightarrow \pi^- \eta\, p$ (E852)

18 GeV



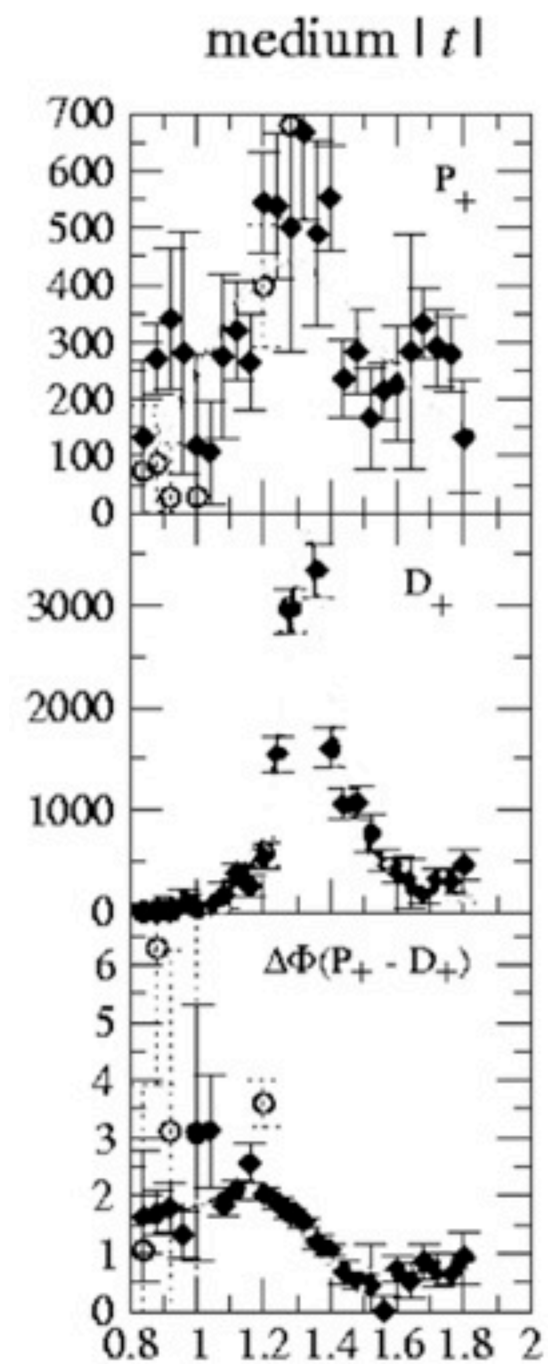
$\pi^- p \rightarrow \pi^- \eta\, p$ (VES)

37 GeV



$\pi^- p \rightarrow \pi^0 \eta\, n$ (E852 IU)

18 GeV



$\pi_1(1400)$?

0-10%

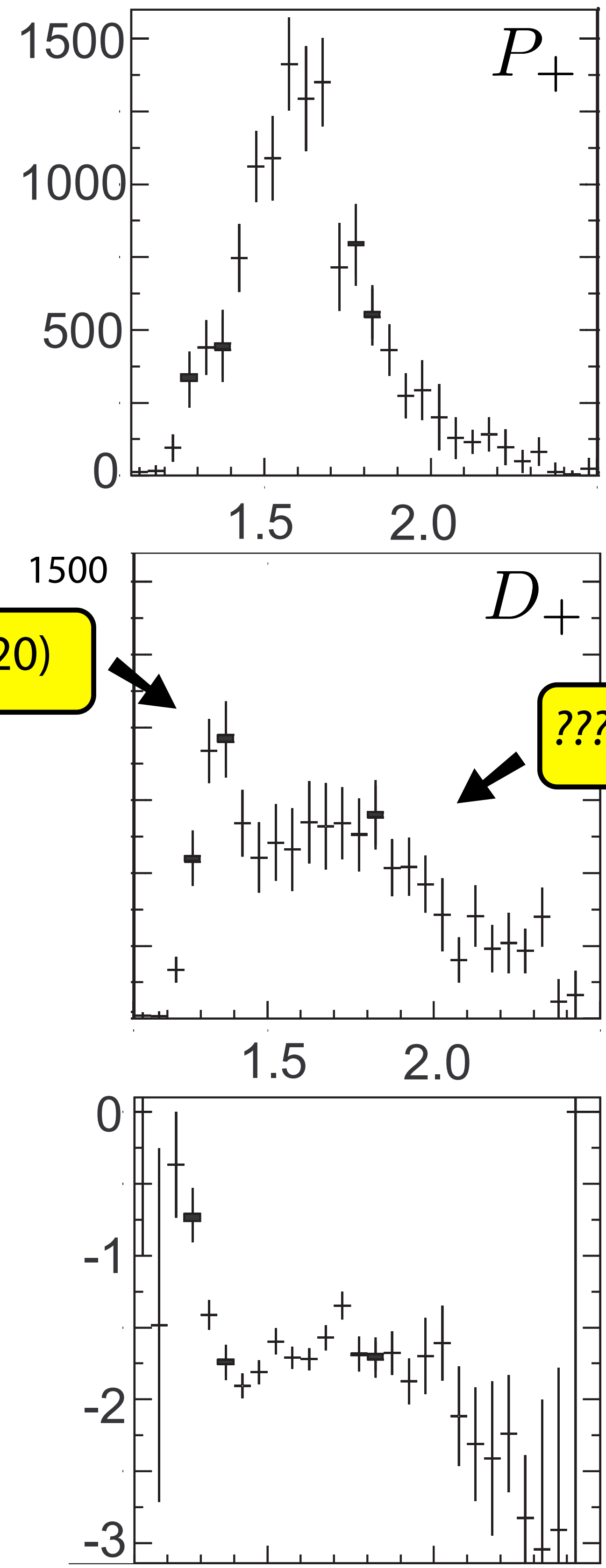
$a_2(1320)$

in my opinion far from clear there's a *P*-wave resonance

pion beams

$\pi^- p \to \pi^- \eta' p$ (E852)

18 GeV



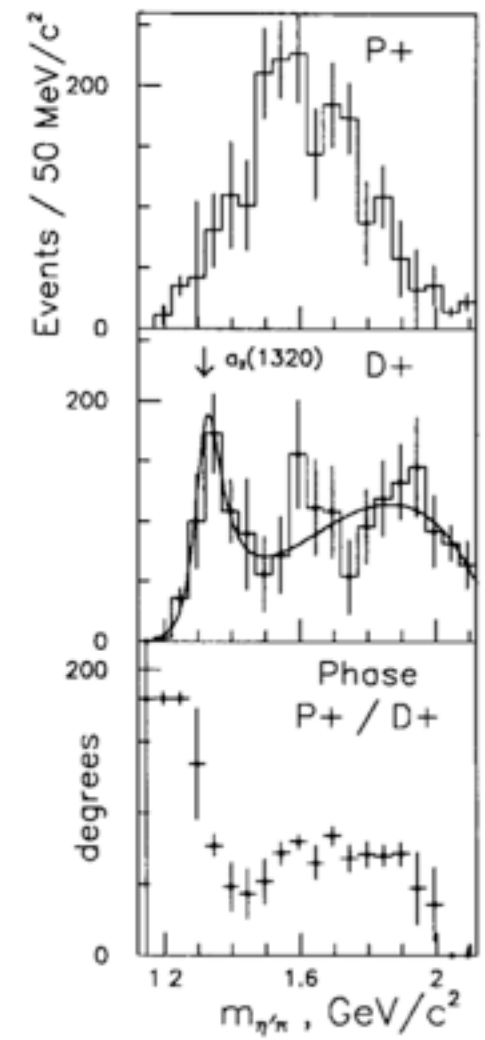
a$_2$(1320)

?????

π$_1$(1600) ?

as strong

$\pi^- p \to \pi^- \eta' p$ (VES)



something strong in the *P*-wave - good candidate for further study

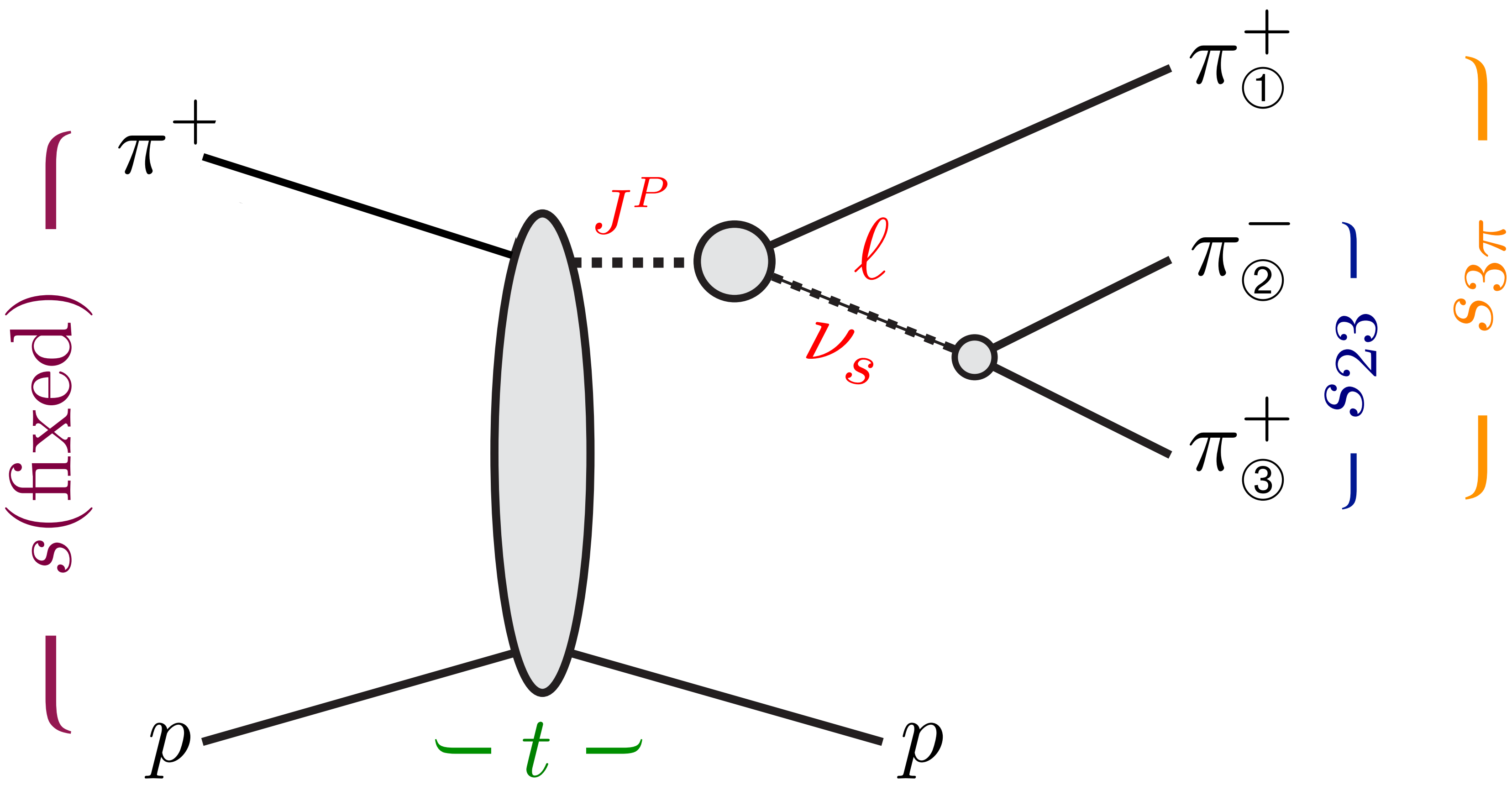
higher multiplicity analysis

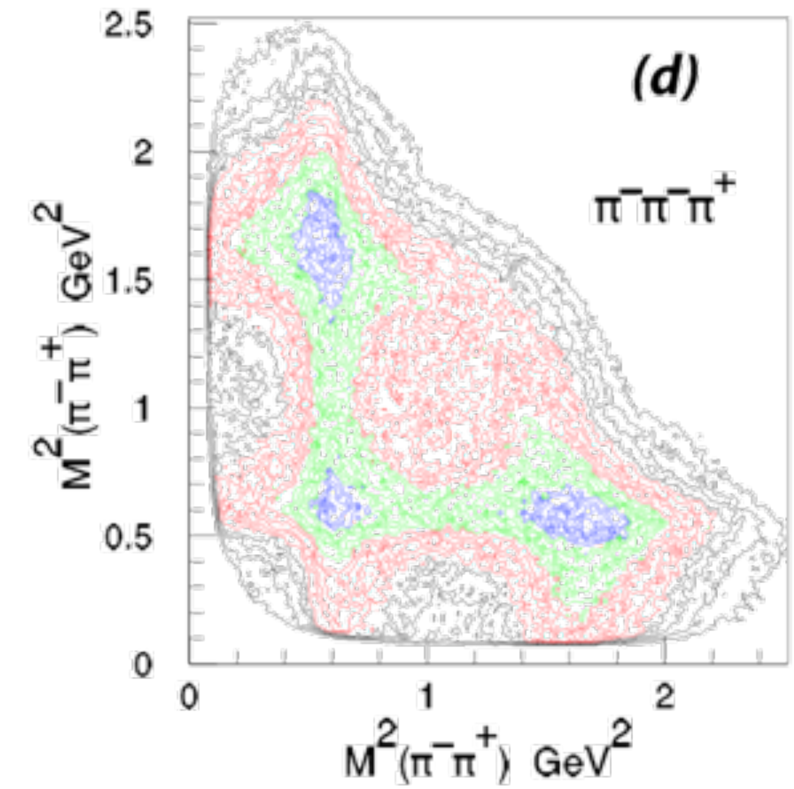
starts getting increasingly model dependent - common approach is the ***isobar model***

parameterising the decay amplitude

e.g. π p→π π π p

'isobars' $\nu_s = (f_0, \rho_1, f_2 \ldots)$





$$\mathcal{A} = \sum_{J^P, \nu_s, \ell} C^{J^P}_{\nu_s, \ell}(s, t, s_{3\pi}) \; \frac{1}{\mathbb{D}_{\nu_s}(s_{23})} \; \mathcal{D}^{J*}_{M,\lambda}(\phi_1, \theta_1, 0) \; \mathcal{D}^{s*}_{\lambda,0}(\phi_3, \theta_3, 0)$$

amplitudes to be fitted

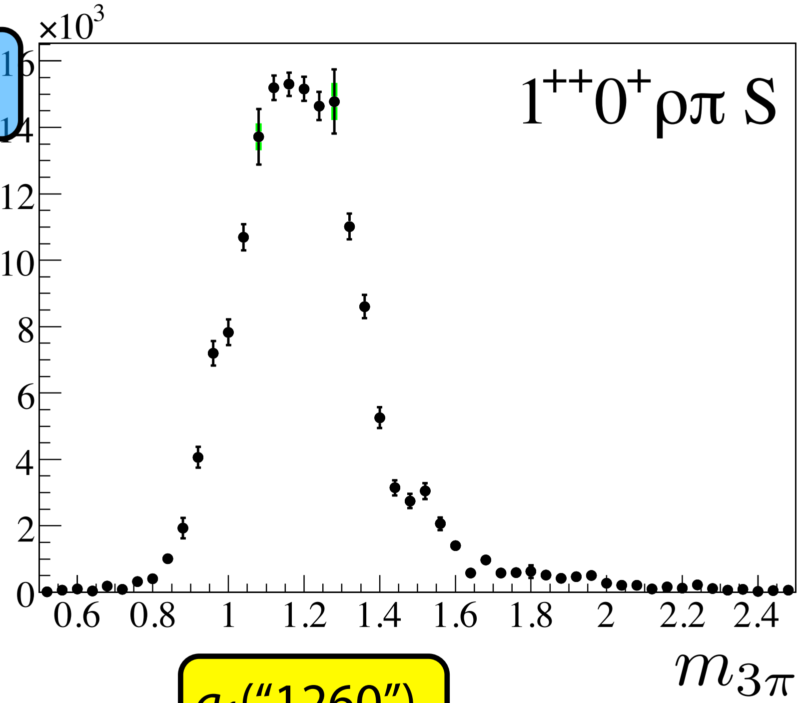
isobar propagator (supplied)

(simplified notation)

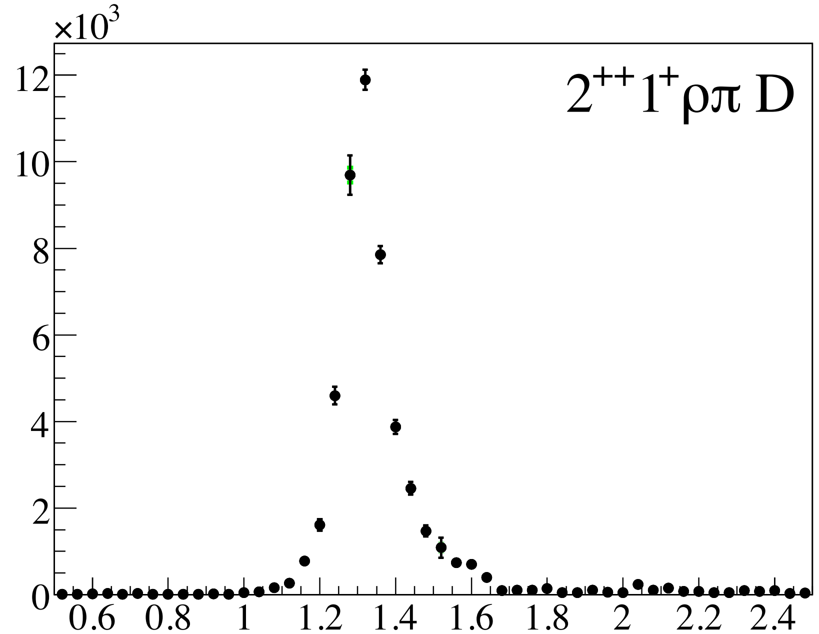
isobar model application

Compass $\pi^- Pb \rightarrow \pi^- \pi^- \pi^+ Pb$

16K



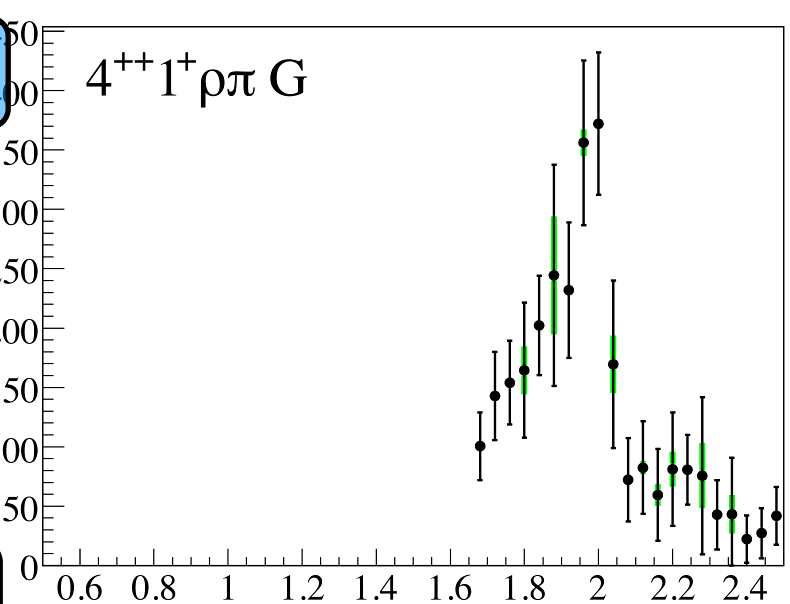
a_1("1260")



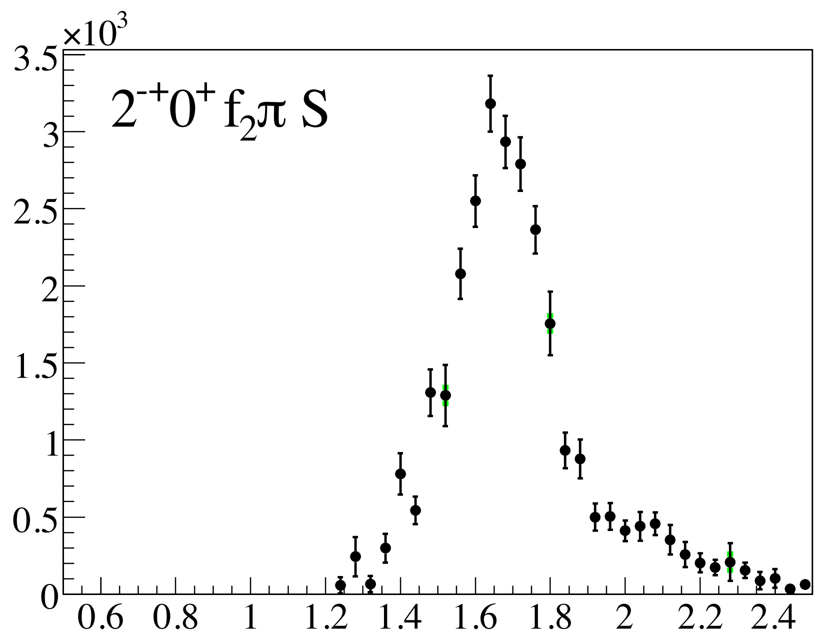
a_2(1320)

400

3%



a_4(2000)



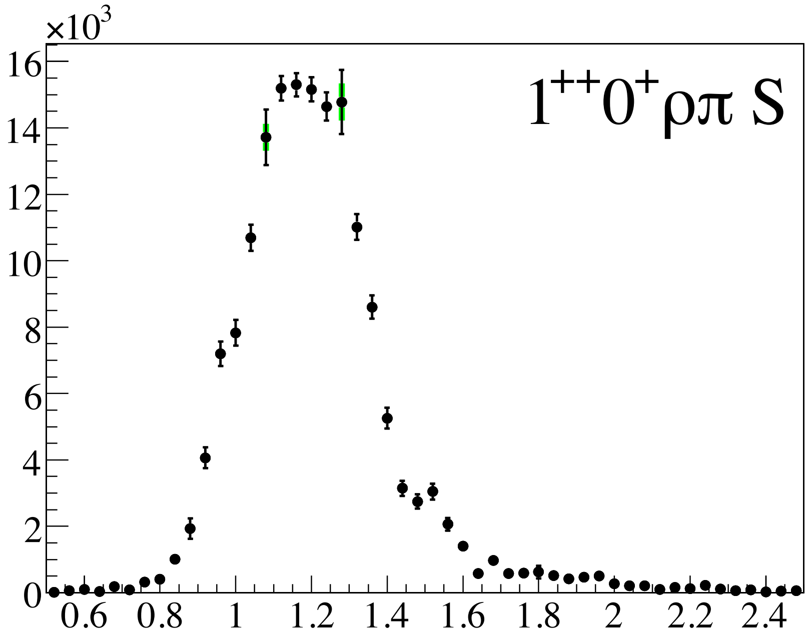
π_2(1670)

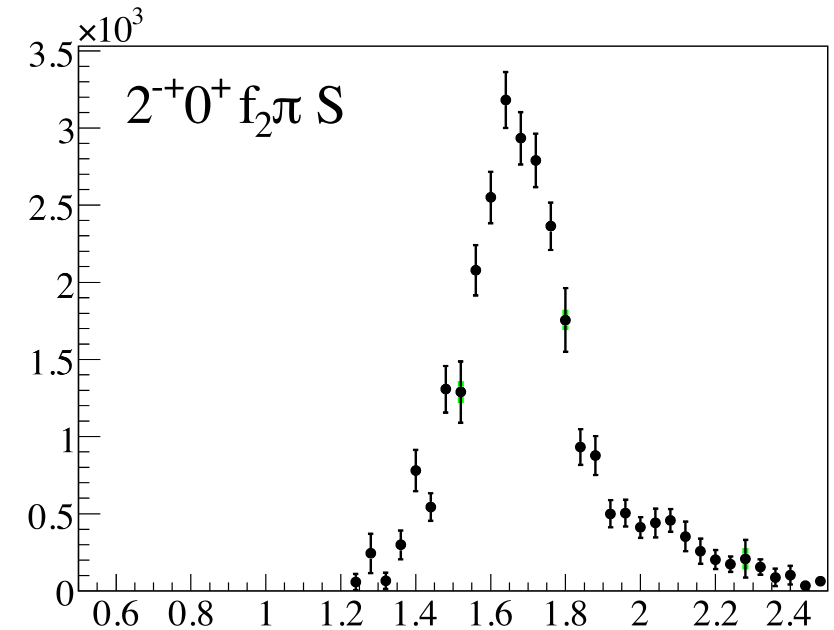
J^{PC}	M^ϵ	L	Isobar π	Threshold [GeV/c^2]
0^{-+}	0^+	S	$(\pi\pi)_S\pi$	—
0^{-+}	**0^+**	**S**	**$f_0\pi$**	**1.400**
0^{-+}	0^+	P	$\rho\pi$	—
1^{-+}	**1^+**	**P**	**$\rho\pi$**	**—**
1^{++}	**0^+**	**S**	**$\rho\pi$**	**—**
1^{++}	0^+	P	$f_2\pi$	1.200
1^{++}	0^+	P	$(\pi\pi)_S\pi$	0.840
1^{++}	0^+	D	$\rho\pi$	1.300
1^{++}	1^+	S	$\rho\pi$	—
1^{++}	1^+	P	$f_2\pi$	1.400
1^{++}	1^+	P	$(\pi\pi)_S\pi$	1.400
1^{++}	1^+	D	$\rho\pi$	1.400
2^{-+}	**0^+**	**S**	**$f_2\pi$**	**1.200**
2^{-+}	0^+	P	$\rho\pi$	0.800
2^{-+}	0^+	D	$f_2\pi$	1.500
2^{-+}	0^+	D	$(\pi\pi)_S\pi$	0.800
2^{-+}	0^+	F	$\rho\pi$	1.200
2^{-+}	1^+	S	$f_2\pi$	1.200
2^{-+}	1^+	P	$\rho\pi$	0.800
2^{-+}	1^+	D	$f_2\pi$	1.500
2^{-+}	1^+	D	$(\pi\pi)_S\pi$	1.200
2^{-+}	1^+	F	$\rho\pi$	1.200
2^{++}	1^+	P	$f_2\pi$	1.500
2^{++}	**1^+**	**D**	**$\rho\pi$**	**—**
3^{++}	0^+	S	$\rho_3\pi$	1.500
3^{++}	0^+	P	$f_2\pi$	1.200
3^{++}	0^+	D	$\rho\pi$	1.500
3^{++}	1^+	S	$\rho_3\pi$	1.500
3^{++}	1^+	P	$f_2\pi$	1.200
3^{++}	1^+	D	$\rho\pi$	1.500
4^{-+}	0^+	F	$\rho\pi$	1.200
4^{-+}	1^+	F	$\rho\pi$	1.200
4^{++}	1^+	F	$f_2\pi$	1.600
4^{++}	**1^+**	**G**	**$\rho\pi$**	**1.640**
1^{-+}	0^-	P	$\rho\pi$	—
1^{-+}	1^-	P	$\rho\pi$	—
1^{++}	1^-	S	$\rho\pi$	—
2^{-+}	1^-	S	$f_2\pi$	1.200
2^{++}	0^-	P	$f_2\pi$	1.300

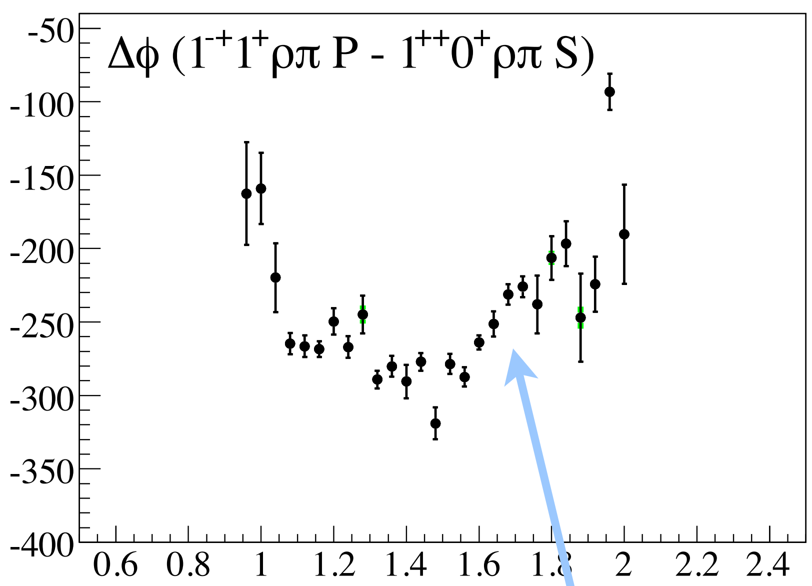
model contains sufficient angular dependence to pull out e.g. weak high-spin waves

isobar model - phases

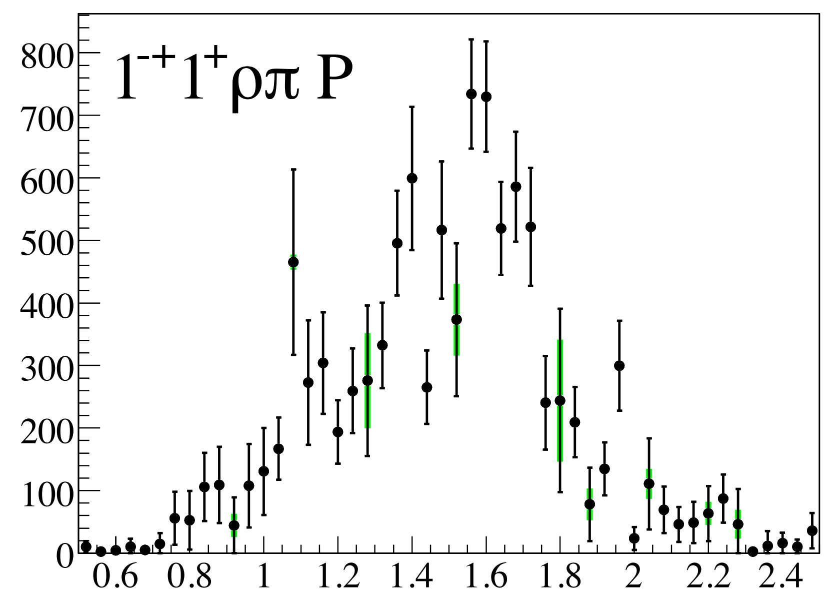
Compass $\pi^- Pb \rightarrow \pi^- \pi^- \pi^+ Pb$





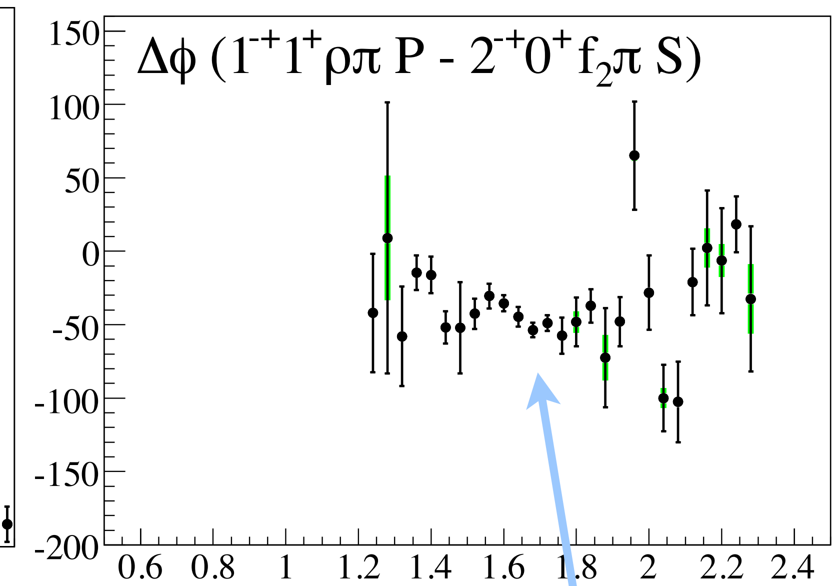


rising res. phase ?



5%

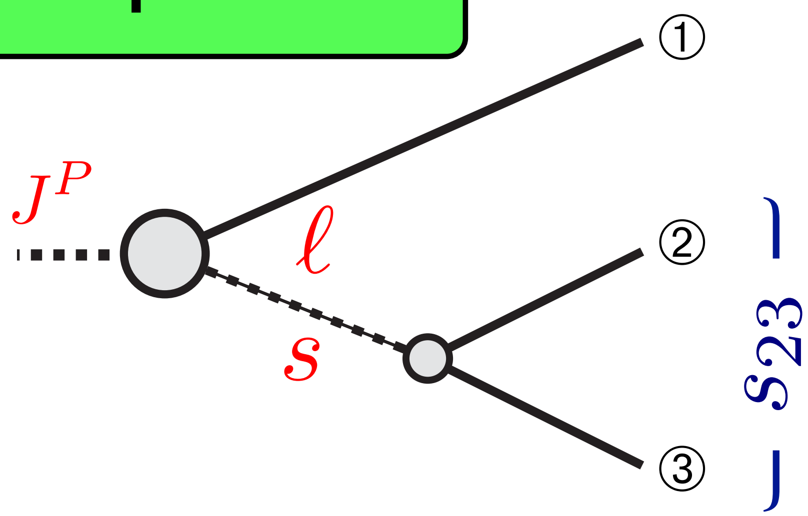
$\pi_1(1670)$?



$\pi_1(1670)$ phase cancels with $\pi_2(1670)$

isobar model problems

isobar



$$T^J_{\ell,s}(s_{3\pi}, s_{23}, s_{13}) = C^J_{\ell,s}(s_{3\pi})\frac{1}{\mathbb{D}_s(s_{23})} \times \ldots$$

suppose only (13), (23) interact strongly

& ignore multiple channels $J = \ell = s = 0$

$$F_{\text{iso.}}(s_{3\pi}, s_{13}, s_{23}) = \frac{C_{13}(s_{3\pi})}{\mathbb{D}_{13}(s_{13})} + \frac{C_{23}(s_{3\pi})}{\mathbb{D}_{23}(s_{23})}$$

but more generally we can have

$$F(s_{3\pi}, s_{13}, s_{23}) = \frac{\phi_{13}(s_{3\pi}, \boxed{s_{13}})}{\mathbb{D}_{13}(s_{13})} + \frac{\phi_{23}(s_{3\pi}, \boxed{s_{23}})}{\mathbb{D}_{23}(s_{23})}$$

isobar model problems

but more generally we can have

$$F(s_{3\pi}, s_{13}, s_{23}) = \frac{\phi_{13}(s_{3\pi}, s_{13})}{\mathbb{D}_{13}(s_{13})} + \frac{\phi_{23}(s_{3\pi}, s_{23})}{\mathbb{D}_{23}(s_{23})}$$

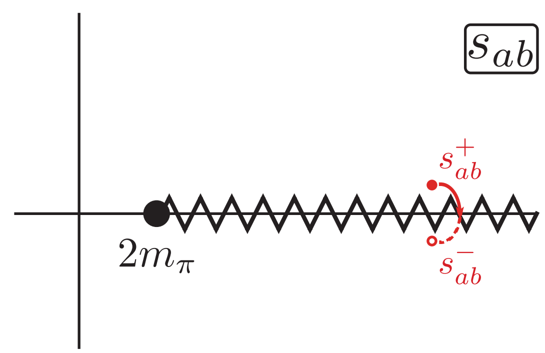
2-body unitarity in the (23) channel ⇒

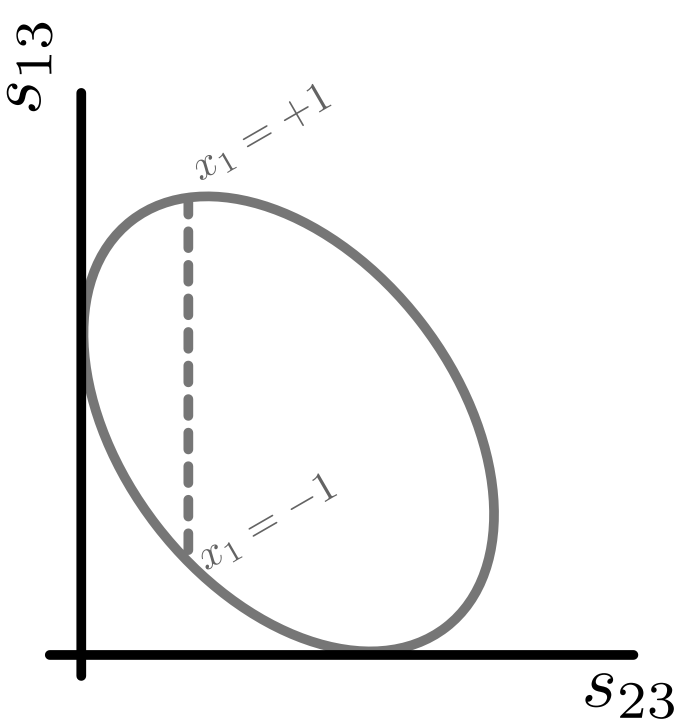
$$\phi_{23}(s_{23}^{+}, s_{3\pi}) - \phi_{23}(s_{23}^{-}, s_{3\pi})$$

$$= 2i\, \rho(s_{23}) \mathbb{N}_{23}(s_{23}) \frac{1}{2} \int_{-1}^{+1} dx_1\, \frac{\phi_{13}(s_{13}, s_{3\pi})}{\mathbb{D}_{13}(s_{13})}$$

$$\mathbb{M}(s_{ab}) \equiv \frac{\mathbb{N}(s_{ab})}{\mathbb{D}(s_{ab})}$$

$$\mathbb{M}(s_{ab}^{+}) - \mathbb{M}(s_{ab}^{-}) = 2i\, \rho(s_{ab}) \mathbb{M}(s_{ab}^{+}) \mathbb{M}(s_{ab}^{-})$$





$\phi_{23}(s_{23})$ needs a discontinuity in s_{23}!

isobar model doesn't have this - violates unitarity

"... this is one good reason why the isobar model is open to criticism, particularly if the **phase** of the ϕ functions are important ... since functions with a branch point have a habit of developing a varying phase." (*I.J.R. Aitchison, 1975*)

could 'weak' wave phases/intensities be artifacts of the isobar model ?

isobar model problems

but more generally we can have

$$F(s_{3\pi}, s_{13}, s_{23}) = \frac{\phi_{13}(s_{3\pi}, s_{13})}{\mathbb{D}_{13}(s_{13})} + \frac{\phi_{23}(s_{3\pi}, s_{23})}{\mathbb{D}_{23}(s_{23})}$$

2-body unitarity in the (23) channel ⇒

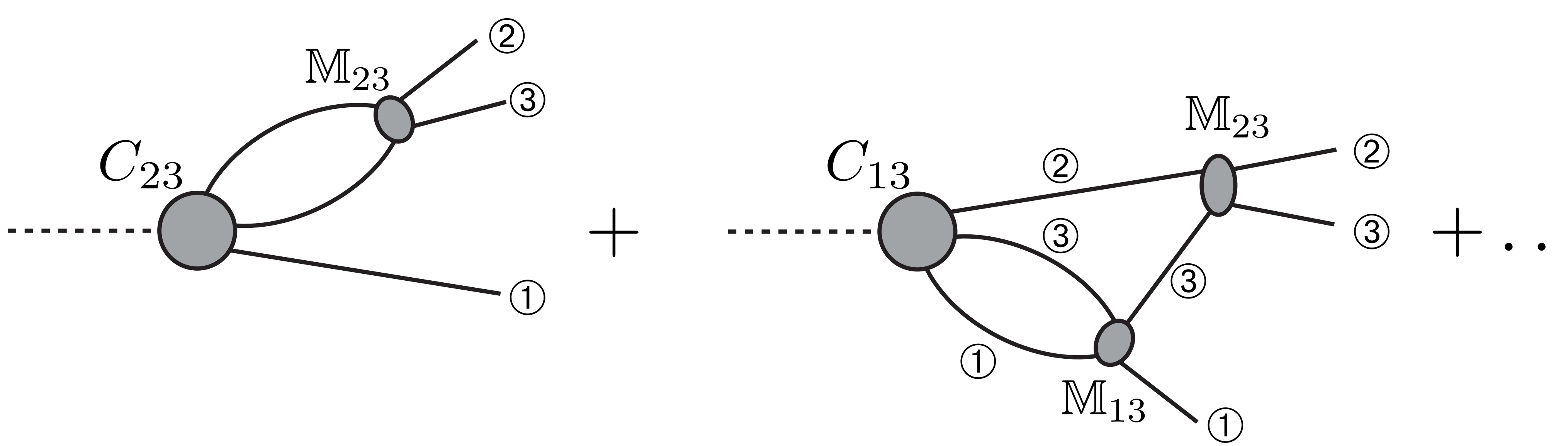
$$\phi_{23}(s_{23}^{+}, s_{3\pi}) - \phi_{23}(s_{23}^{-}, s_{3\pi})$$

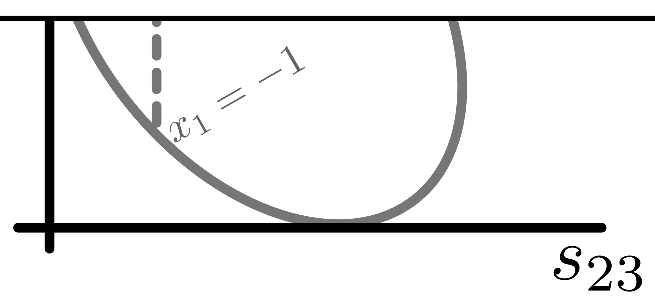
$$= 2i\, \rho(s_{23}) \mathbb{N}_{23}(s_{23}) \frac{1}{2} \int_{-1}^{+1} dx_1 \, \frac{\phi_{13}(s_{13}, s_{3\pi})}{\mathbb{D}_{13}(s_{13})}$$

$$\mathbb{M}(s_{ab}) \equiv \frac{\mathbb{N}(s_{ab})}{\mathbb{D}(s_{ab})}$$

$$\mathbb{M}(s_{ab}^{+}) - \mathbb{M}(s_{ab}^{-}) = 2i\, \rho(s_{ab}) \mathbb{M}(s_{ab}^{+}) \mathbb{M}(s_{ab}^{-})$$

e.g. 'corrections' to isobar (powers of ***M***)





1970's investigation

Wyld et al. - U.Illinois

implement the required discontinuity using a ***K***-matrix

boiled down to an on-shell Faddeev system

rather unsuccessful - fits to $\pi\pi\pi$ data worse than isobar mode

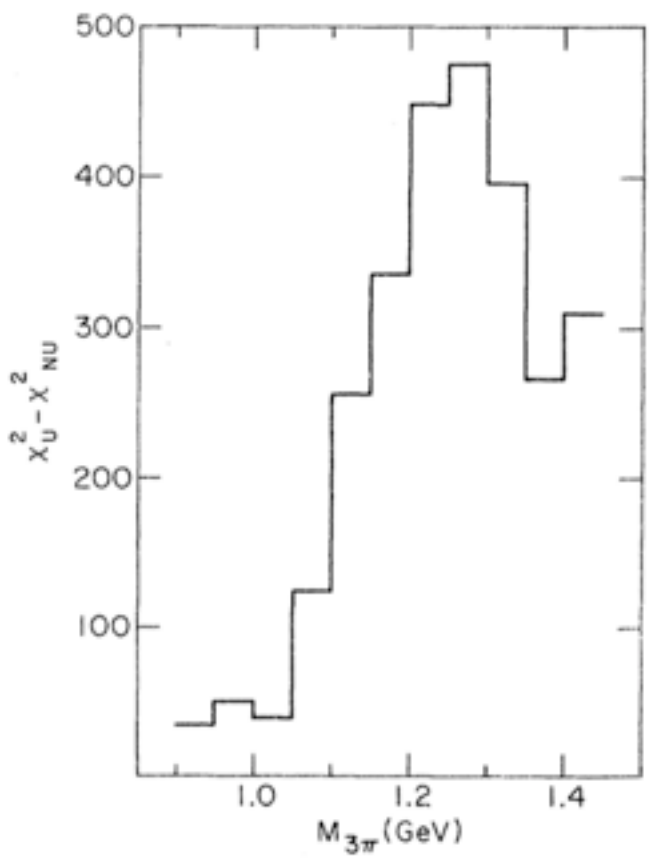
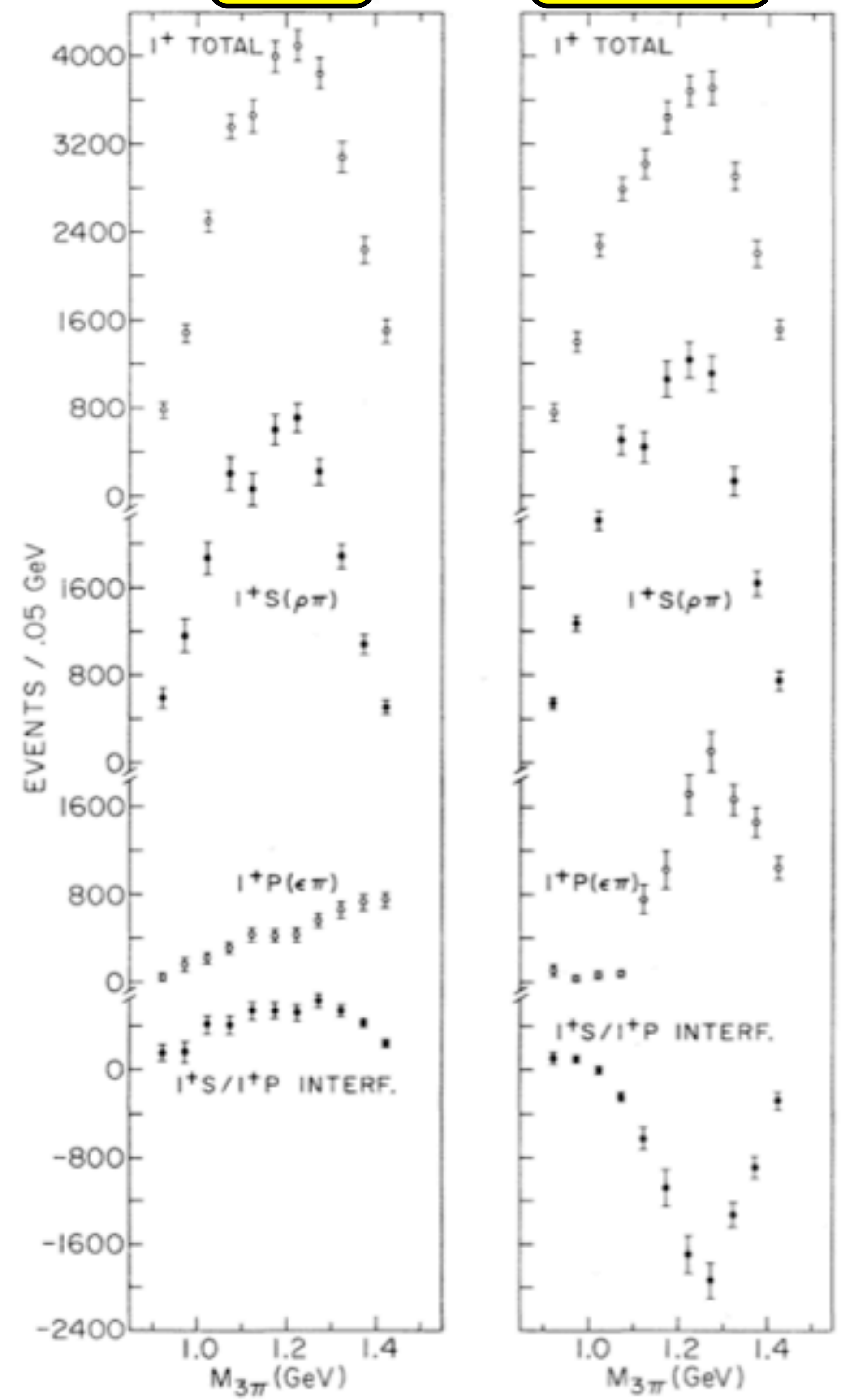


FIG. 7. χ^2 difference between U (unitarized) and NU (nonunitarized) fits to the Serpukhov data (Refs. 8 and 9).

isobar

unitary - K



K-matrix form → ~~analyticity~~ → spurious phase motion

1970's investigation

Wyld et al. - U.Illinois

tried a particular off-shell Faddeev system

rather more successful - fits to $\pi\pi\pi$ data similar to isobar model

used a very small number of waves on low stats data

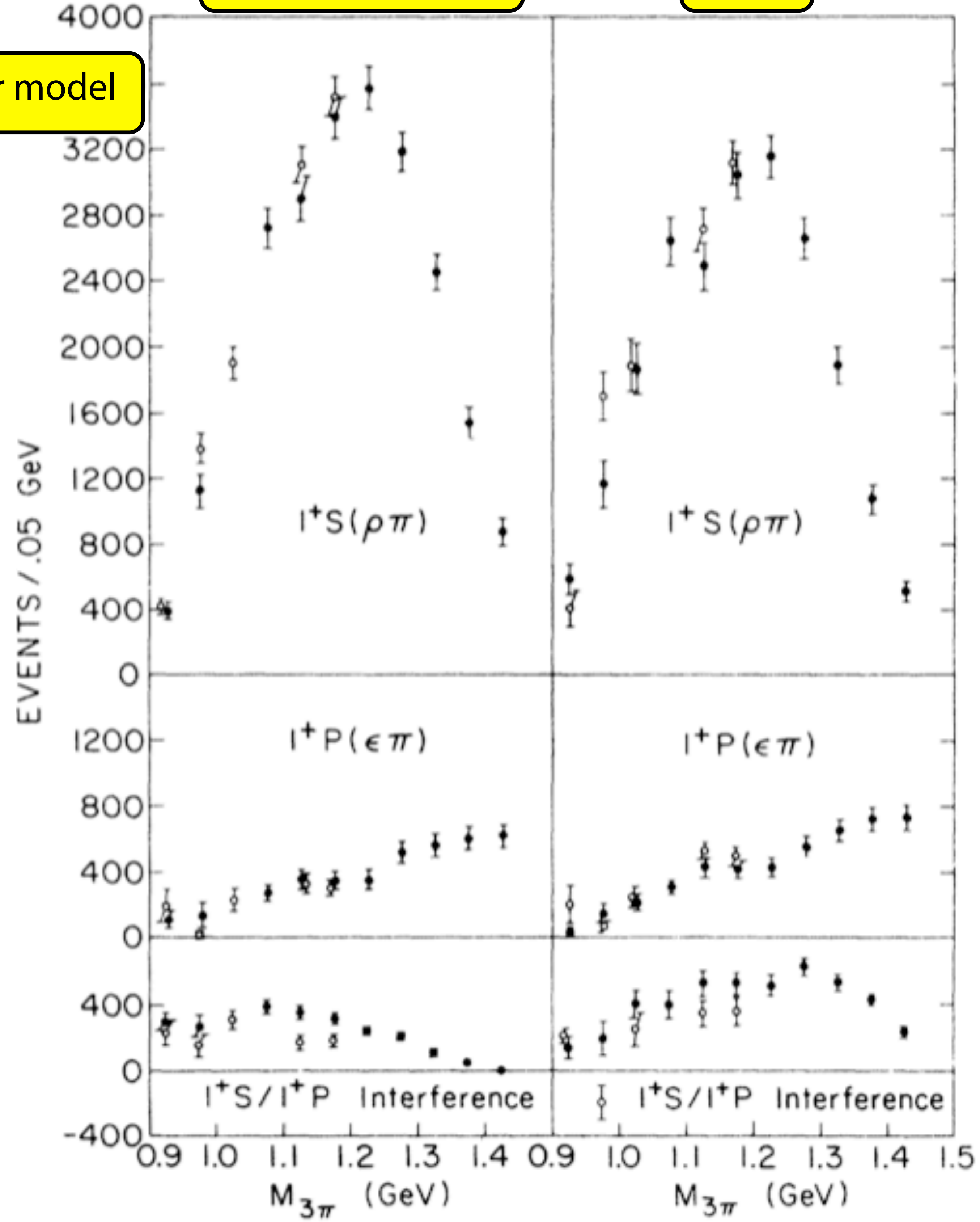
isobar model looks good for strong waves

but no test yet for small waves ~ O(1%)

would be a useful to study to do something like this using modern high-stats data

unitary - Fadeev

isobar



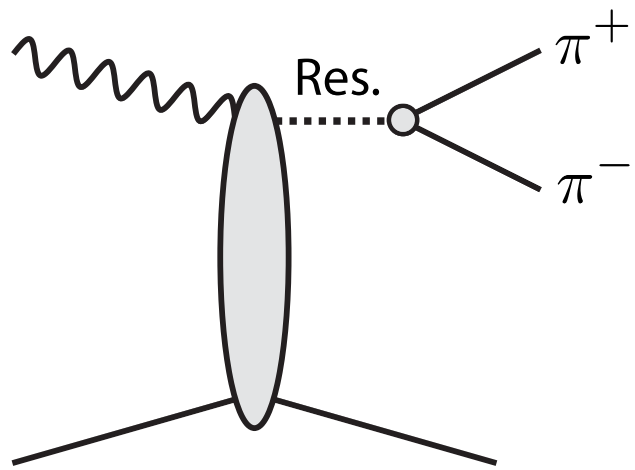
mass-dependent analysis

usually just fitting Breit-Wigners to complex amplitudes

¡ probably not as simple as that really !

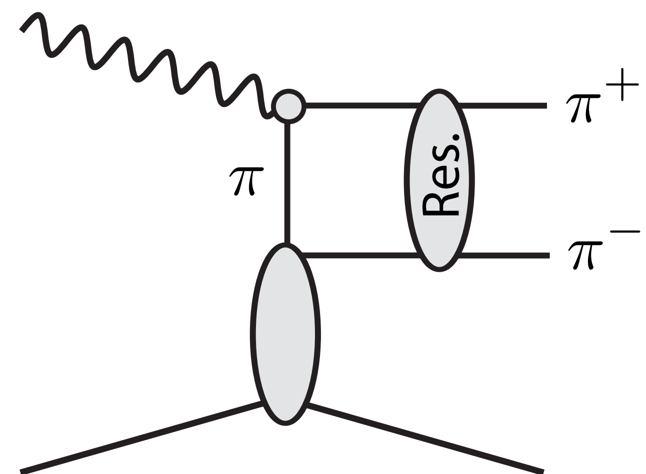
e.g. Deck and related effects

e.g. $\gamma\, p \to \pi^+\pi^-\, p$



$$\sim P\, e^{i\delta} \sin\delta$$

e.g. BW



$$\sim B\, e^{i\delta} \cos\delta$$

not BW

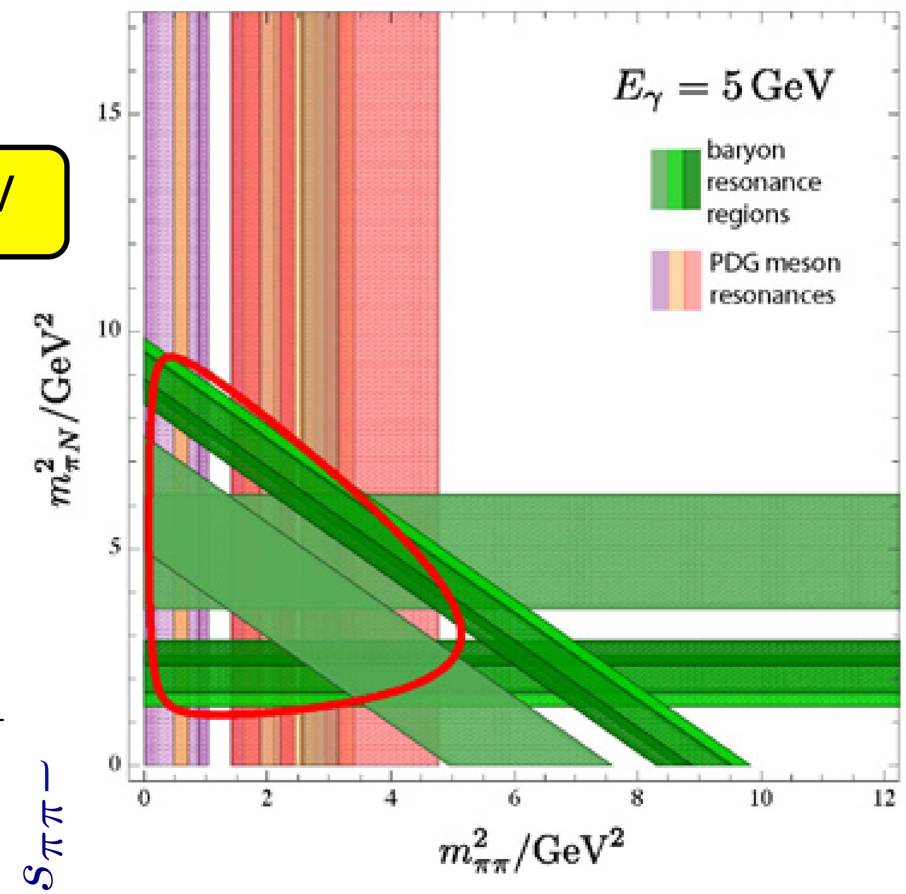
$$+\, e^{i\delta} \sin\delta\, \frac{1}{kN\pi} \mathcal{P} \int ds' \, \frac{N'k'B'}{s'-s}$$

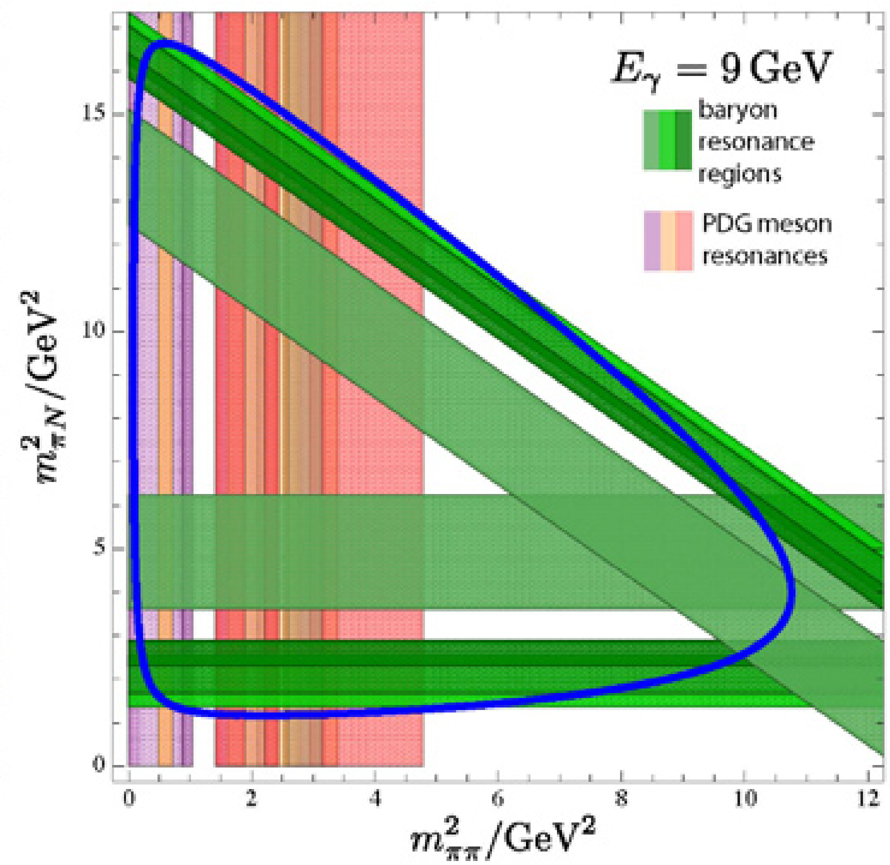
probably the origin of
* asymmetric ρ peak
* peculiar a_1 lineshape in $\pi\pi\pi$
* π_2 mass shift in $f_2\pi$ S and D-waves

baryon resonances

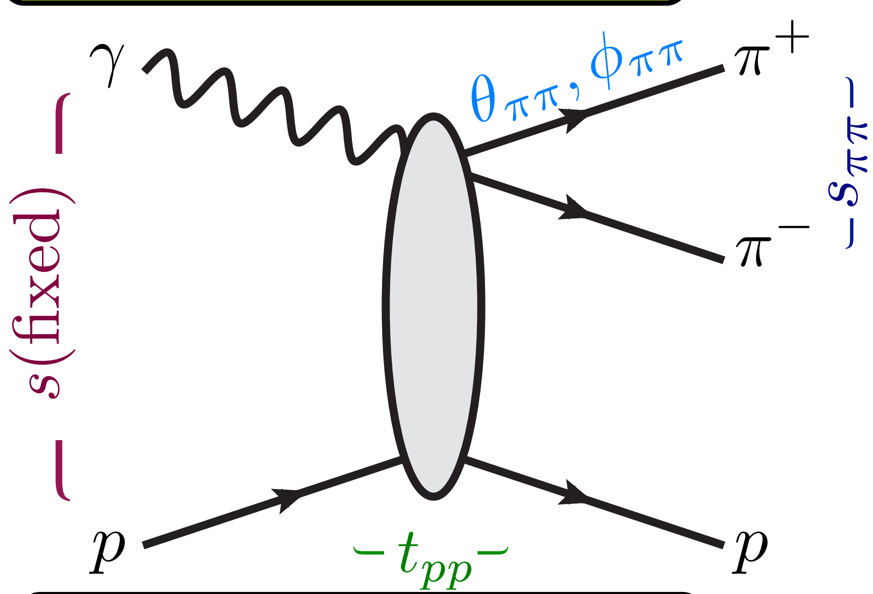
don't dominate Dalitz plots at 9 GeV

but clearly still contributing



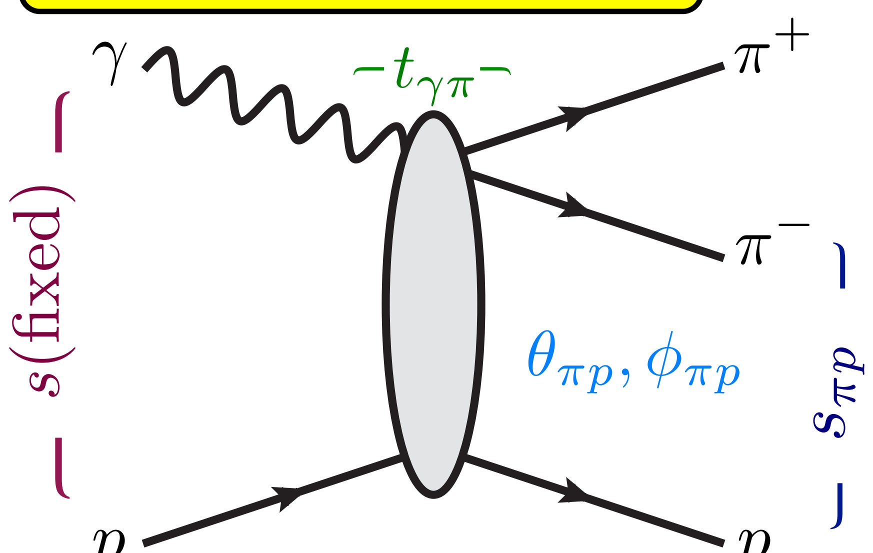


meson 'preferred' variables :



$$\sum_\ell A_\ell(s_{\pi\pi}, t_{pp}) P_\ell(\cos\theta_{\pi\pi})$$

baryon 'preferred' variables :



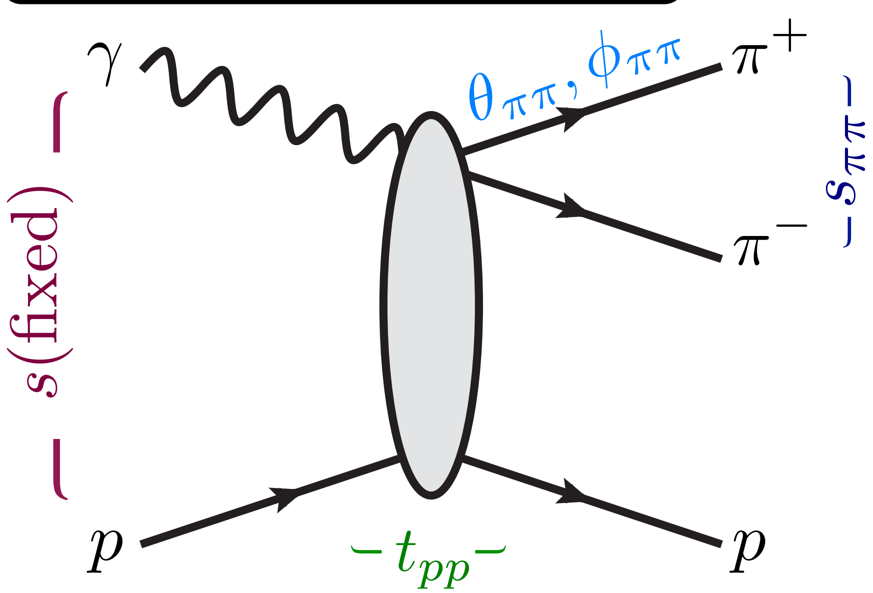
$$\sum_L B_L(s_{\pi p}, t_{\gamma\pi}) P_L(\cos\theta_{\pi p})$$

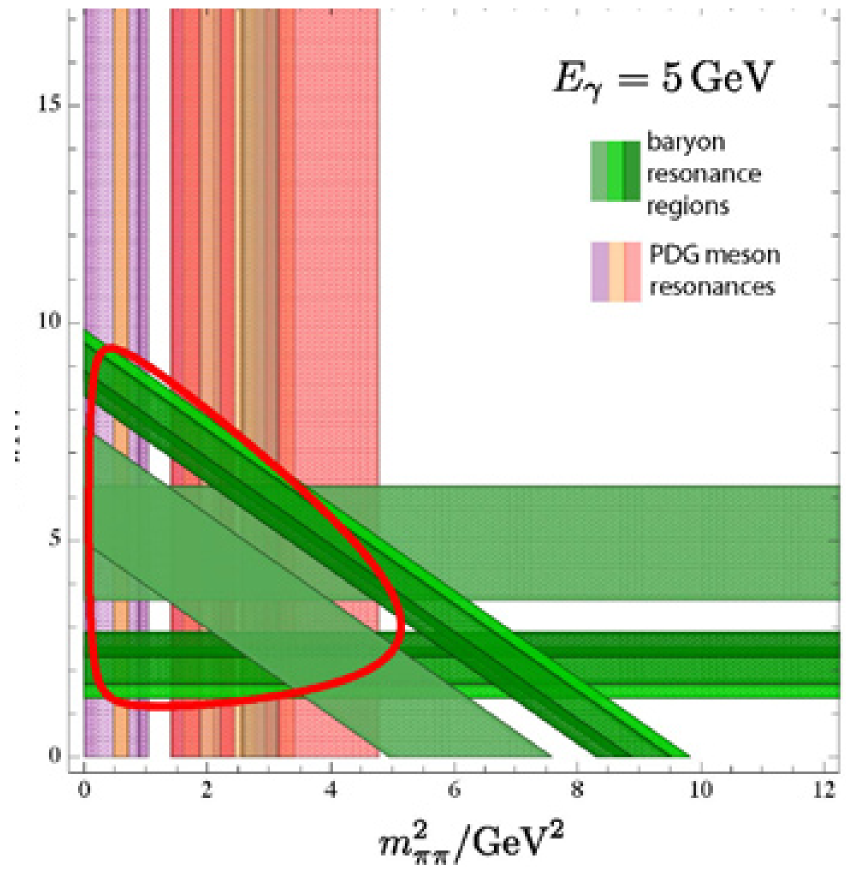
can use either for infinite sums

for truncated sums, sharp resonances in 'wrong' channels cause problems

baryon resonances

meson 'preferred' variables :

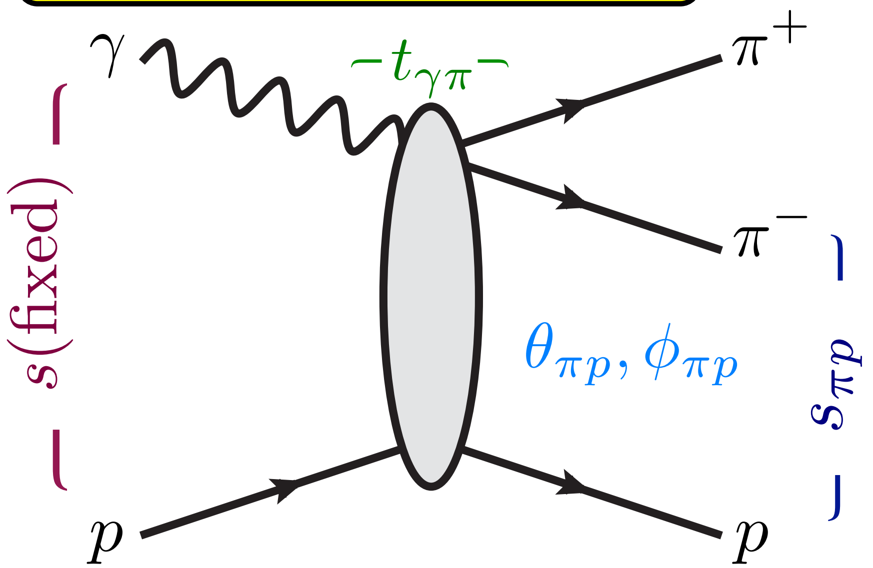


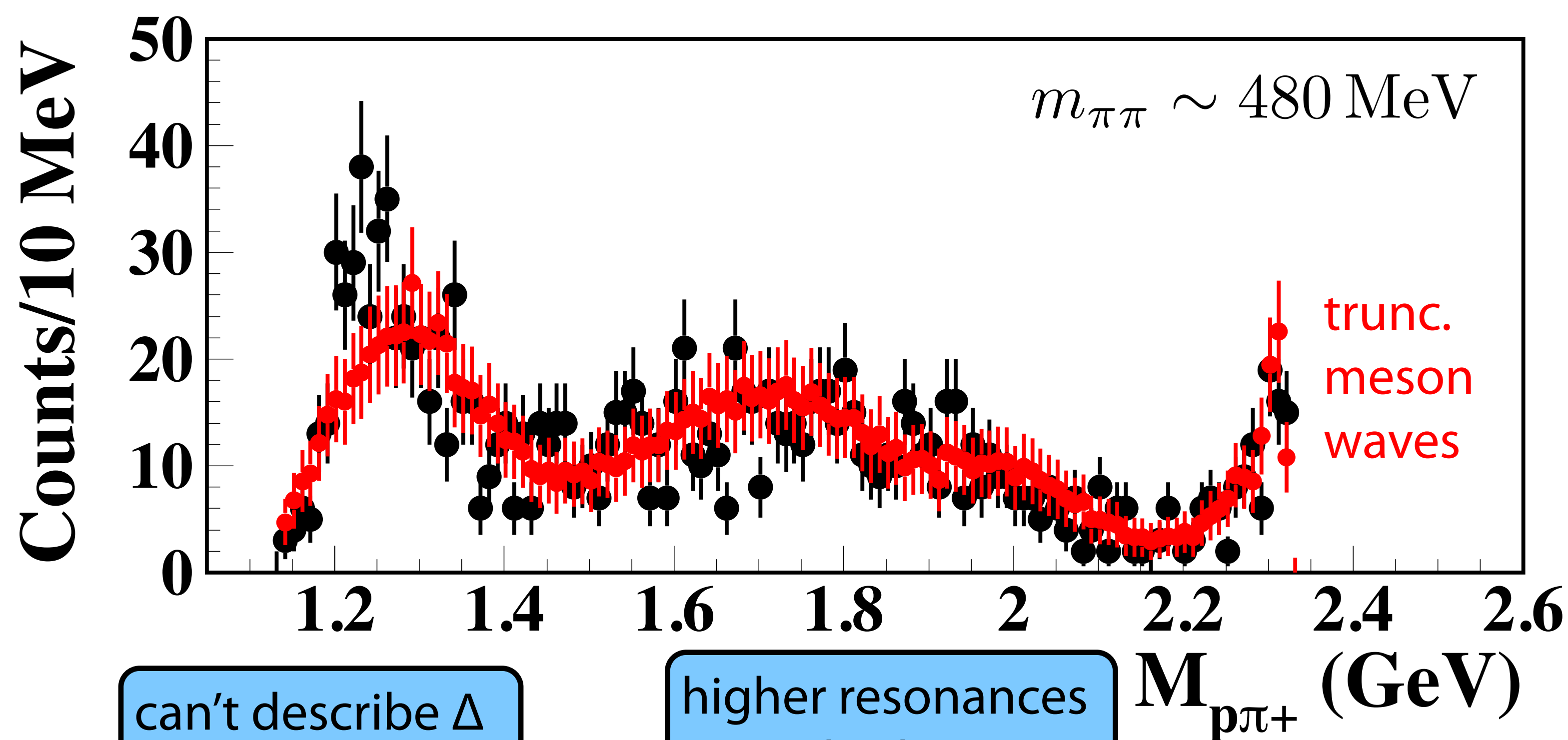


can use either for infinite sums

for truncated sums, sharp resonances in 'wrong' channels cause problems

baryon 'preferred' variables :





can't describe Δ

higher resonances smoothed out

summary

GlueX plans an ambitious program of meson photoproduction

- through efficient detection of charged and neutral particles collect data on high-multiplicity end states
- analysis plans to use event-based methods - software developed to 'plug in' any amplitudes

isobar model is state-of-the-art

- has its problems
- needs to be determined how robust are weak waves to correcting unitarity

mass-dependent analysis is unlikely to be as simple as BW (as EBAC knows well)

- more q.n.'s in meson sector - less resonance overlap - ***might*** be easier