Photoproduction of Light Exotic & Strange Mesons

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Excited QCD 2017
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Overview

- **Motivation & QCD Exotics**
- **Recent Results from Photoproduction**
  - **Exotic Hybrid Search in 3π**
  - **Strange Hybrids in $K\pi\pi$**
- **Upcoming Experimental Programs**

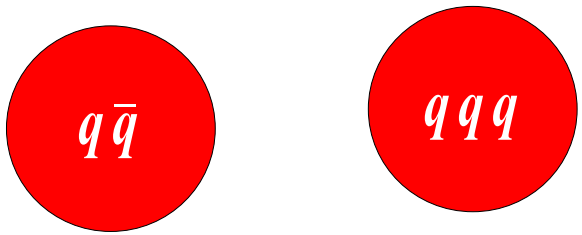
Hadronic Matter

The Quark Model of hadrons works surprisingly well, yet the Quark Model is an approximation to QCD

We can use it to build "hadrons", particles of matter with sizes ~1fm

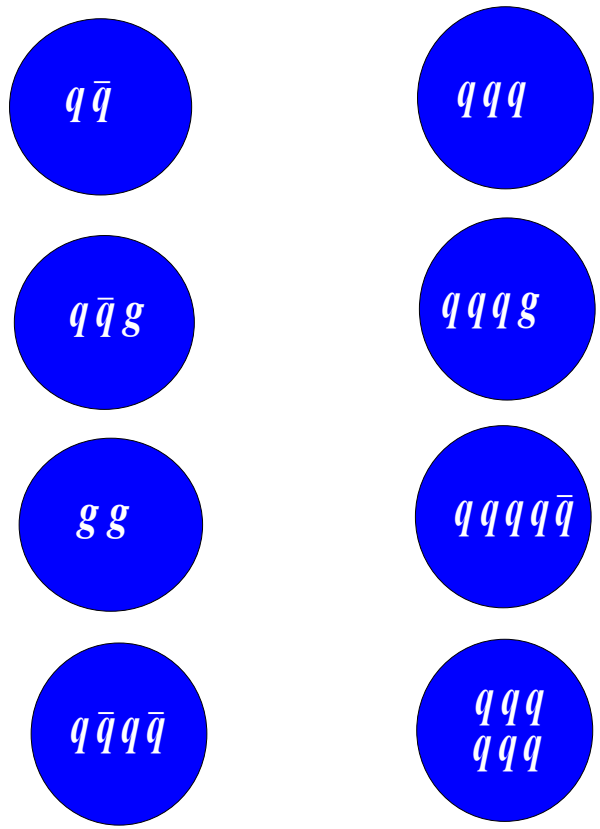
Quark Model Hadrons

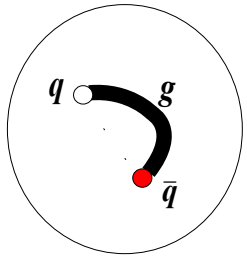
mesons baryons



However, QCD allows for a much richer spectrum of hadronic matter

mesons baryons

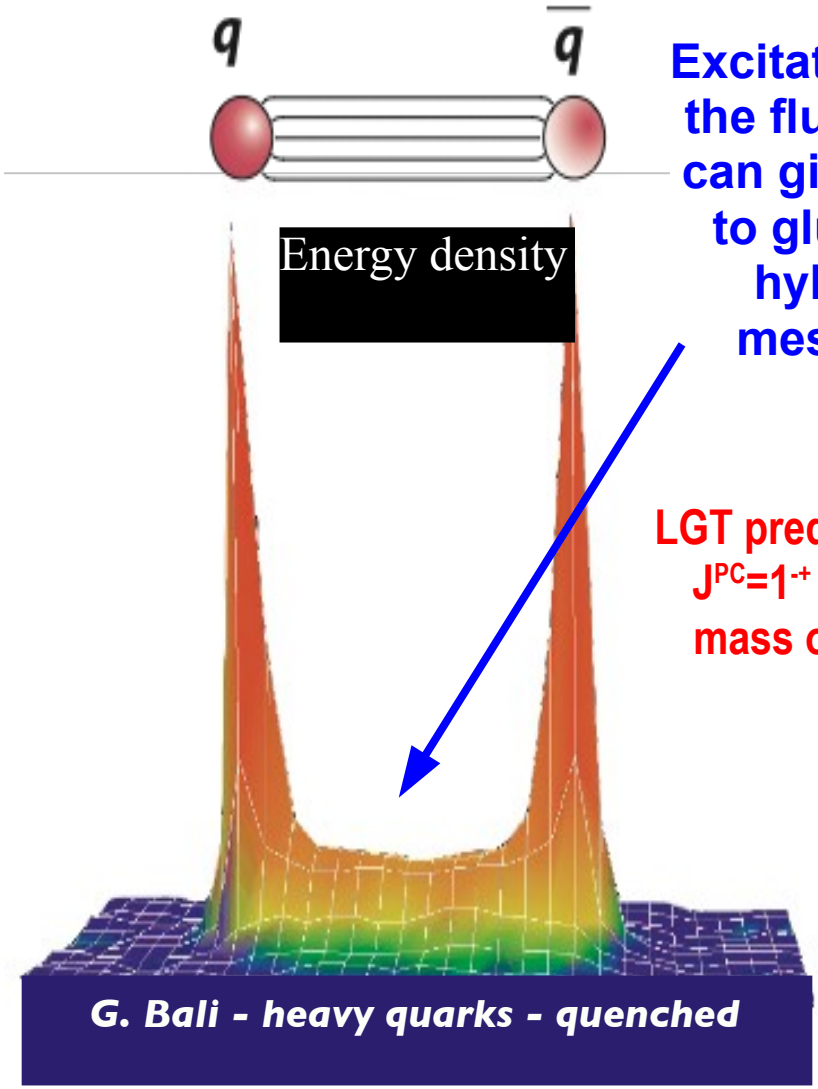




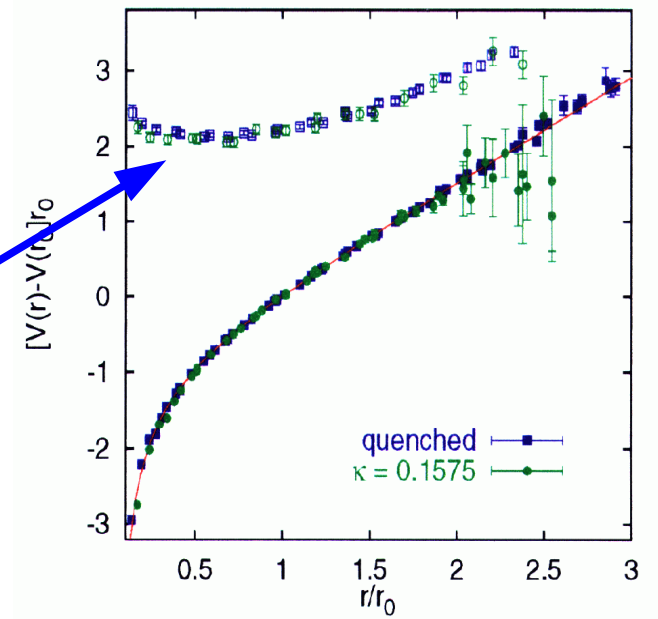
tube-like hybrid

Gluonic Hybrids

$$J^{PC}_{flux-tube} = 1^{+-}, 1^{-+}$$



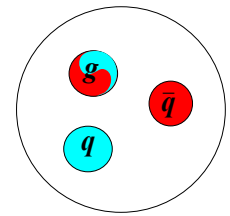
Excitations of the flux tube can give rise to gluonic hybrid mesons



LGT predicts lightest $J^{PC}=1^{-+}$ exotics w/ mass of ~2 GeV

Recent Lattice QCD calculations* exhibit spectrum patterns consistent with a bag-like constituent gluon model

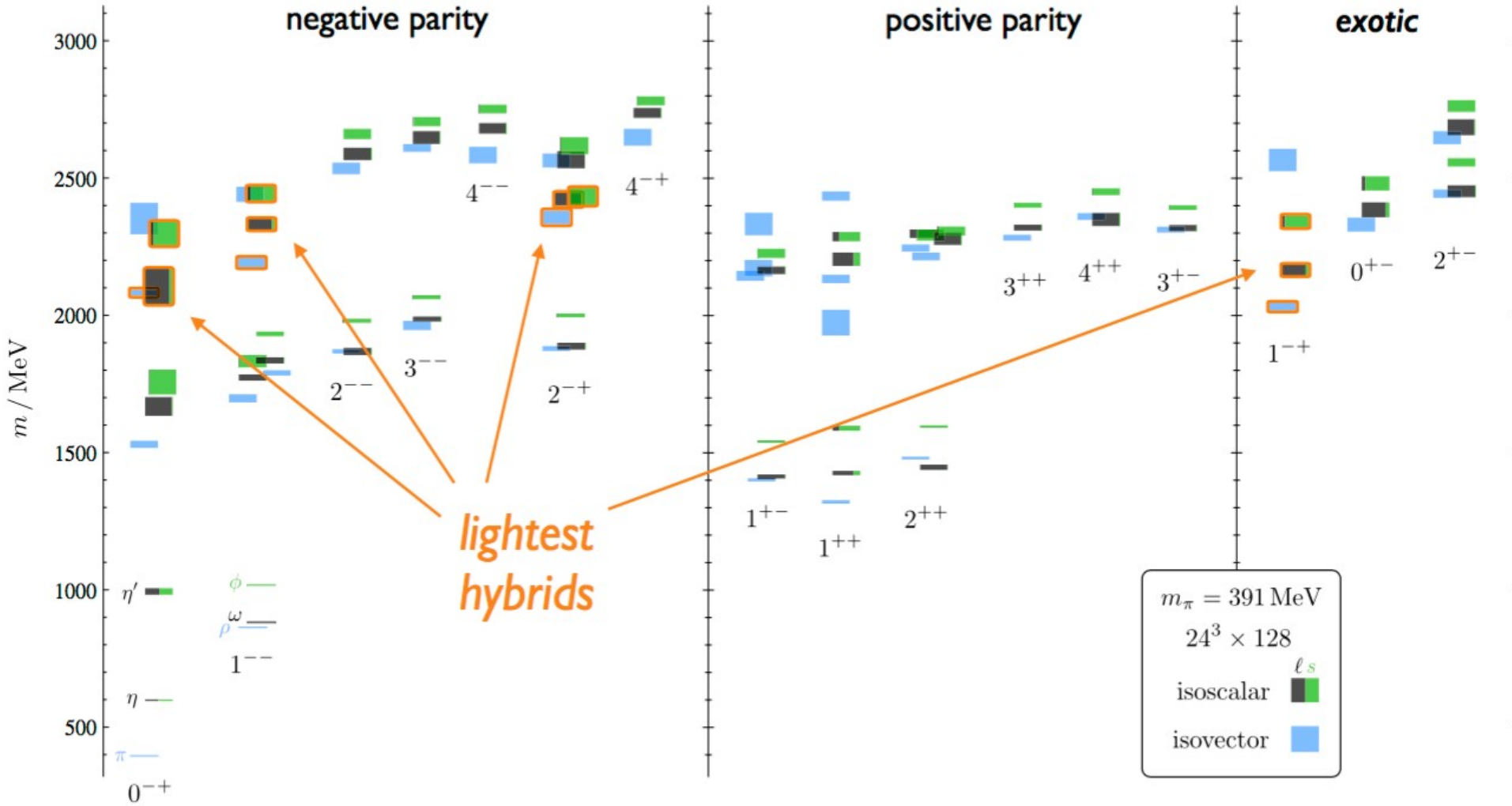
$$J^{PC}_{const.\ gluon} = 1^{+-}$$



bag-like hybrid

*Phys.Rev. D82 (2010) 034508

Lattice QCD Predictions

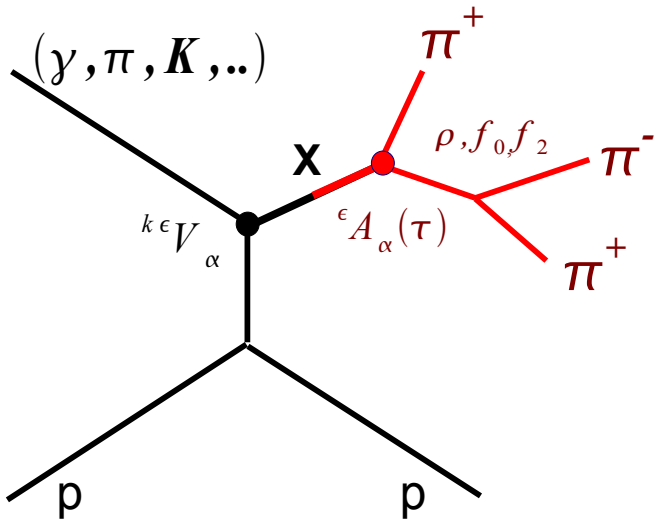


GPUs for Lattice QCD

Jefferson Lab

Dudek, Edwards, Guo, & Thomas
PRD 88, 094505 (2013)

Using PWA to Identify J^{PC} States



$$I(\tau)=\sum_{k\epsilon\epsilon'}\epsilon\epsilon'\rho_{\epsilon\epsilon'}(\tau)\sum_{\alpha\alpha'}{}^{k\epsilon'}V^*_{\alpha'}{}^{\epsilon'}A^*_{\alpha'}(\tau)\,{}^{k\epsilon}V_\alpha\,{}^{\epsilon}A_\alpha(\tau)$$

For unpolarized beam & target:

$$I(\tau)=\frac{1}{2}\sum_{k\epsilon}\left|\sum_\alpha {}^{k\epsilon}V_\alpha\,{}^{\epsilon}A_\alpha(\tau)\right|^2$$

unknown

Complex parameters varied in the PWA to fit the data

Helicity Decay Amplitudes

$$A_{\alpha,M}(\tau)=A_X^{\lambda_1\lambda_2;M}*A_{iso}^{\nu_1\nu_2;\lambda_1}\ldots$$

$$A_X^{\lambda_1\lambda_2;M}=D^J_{\lambda M}(\theta,\phi)\frac{\tilde{L}}{\tilde{J}}(L\,0;S\,\lambda|J\,\lambda)(S_1\lambda_1;S_2-\lambda_2|S\,\lambda)K$$

Wigner D-functions

Clebsch-Gordan Coefficients

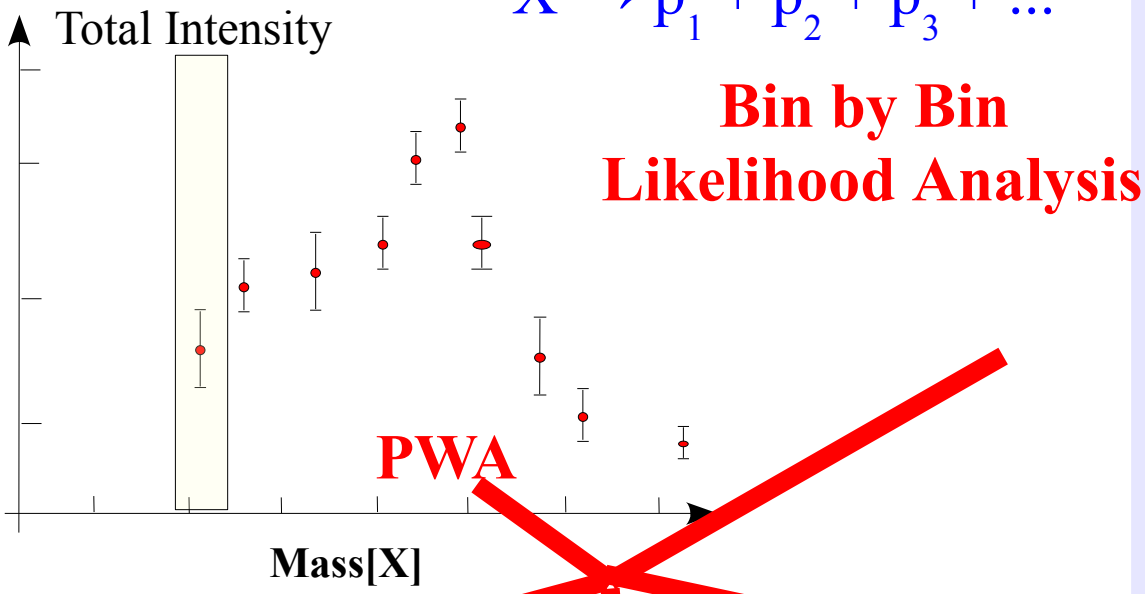
Mass Dynamic Factor (like Breit-Wigner, K-matrix, ...)

$$^{\epsilon}A_\alpha(\tau)=a[A_{\alpha,M}(\tau)\ \pm\ bA_{\alpha,-M}(\tau)]$$

$$\tilde{J}=\sqrt{J(J+1)}$$

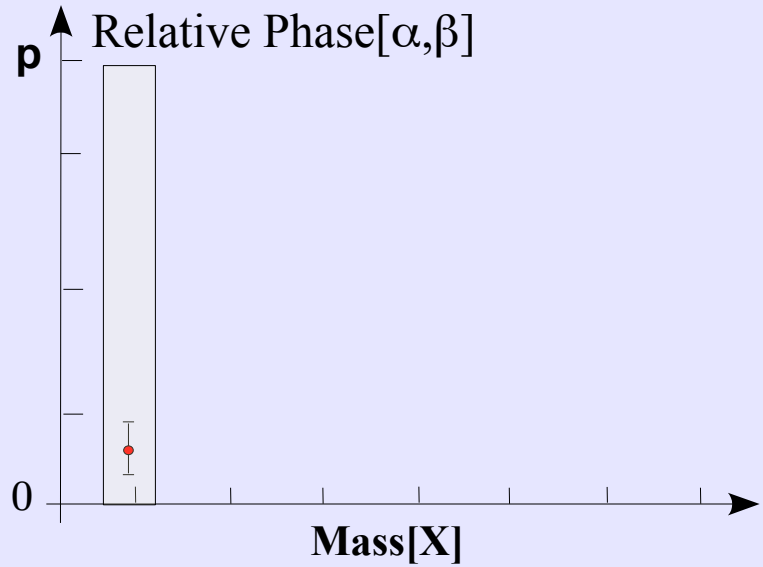
Partial Wave Analysis
Step 1: Decompose to Partial Waves

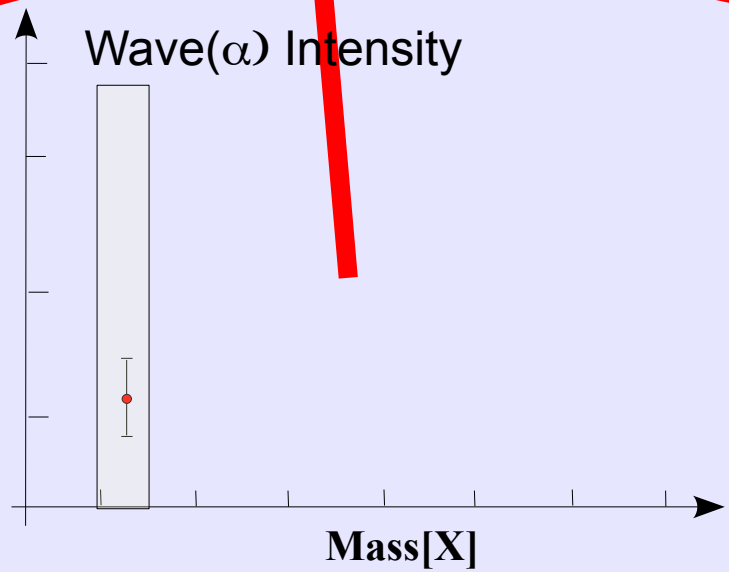
$X \rightarrow p_1 + p_2 + p_3 + \ldots$

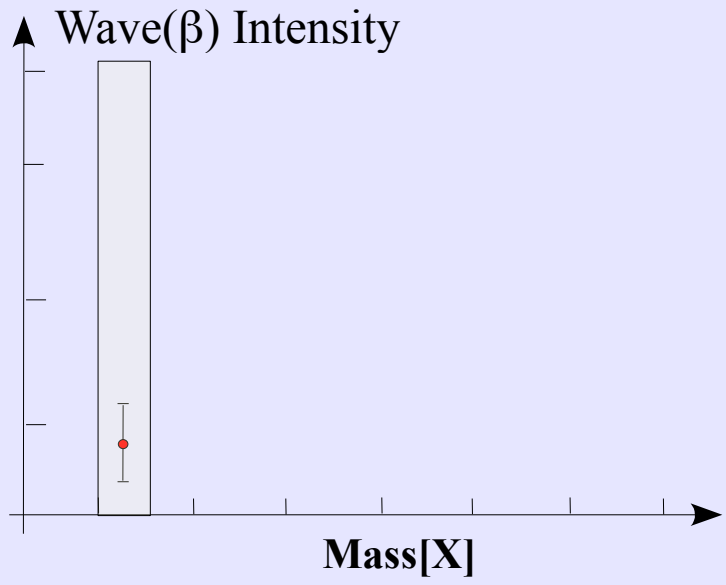


Bin by Bin Likelihood Analysis

PWA







Partial Wave Analysis
Step 1: Decompose to Partial Waves

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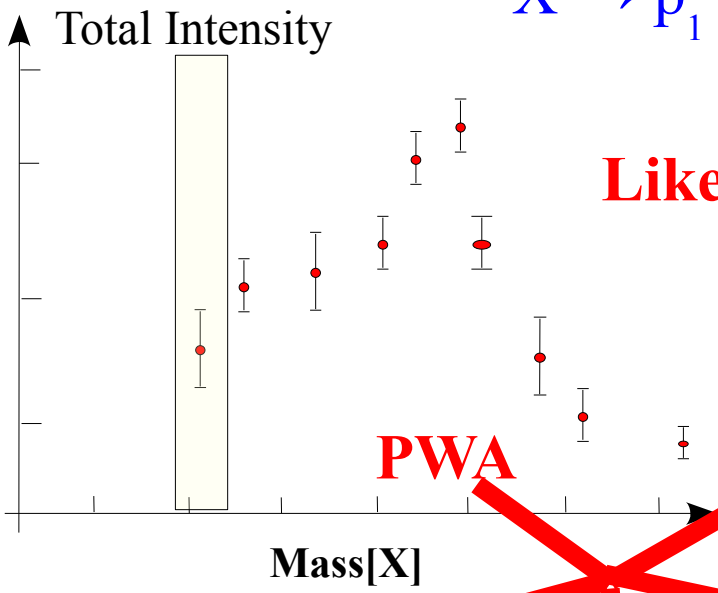
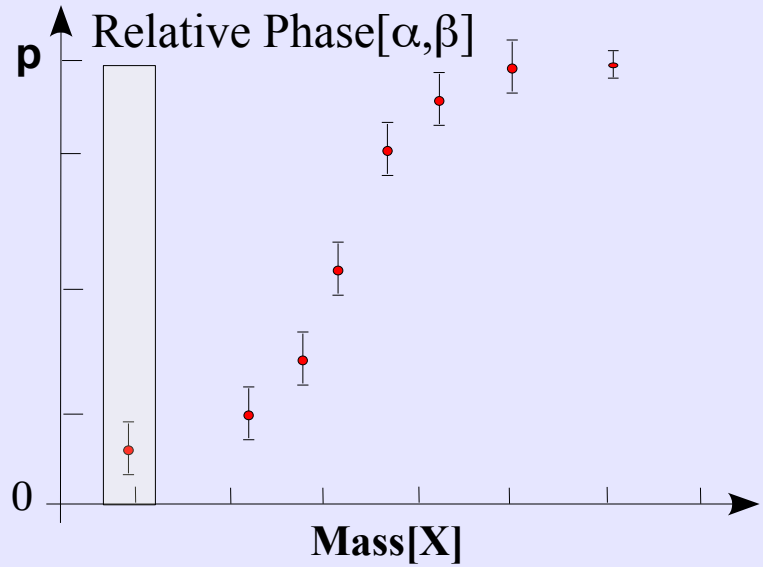
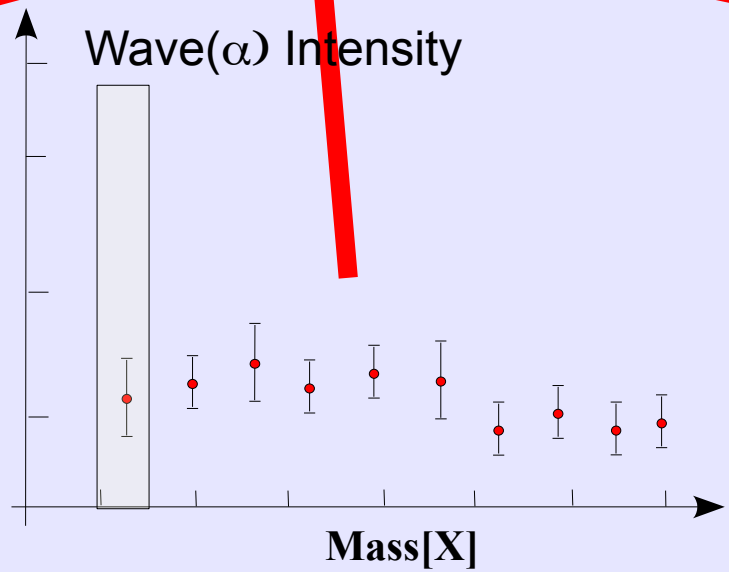
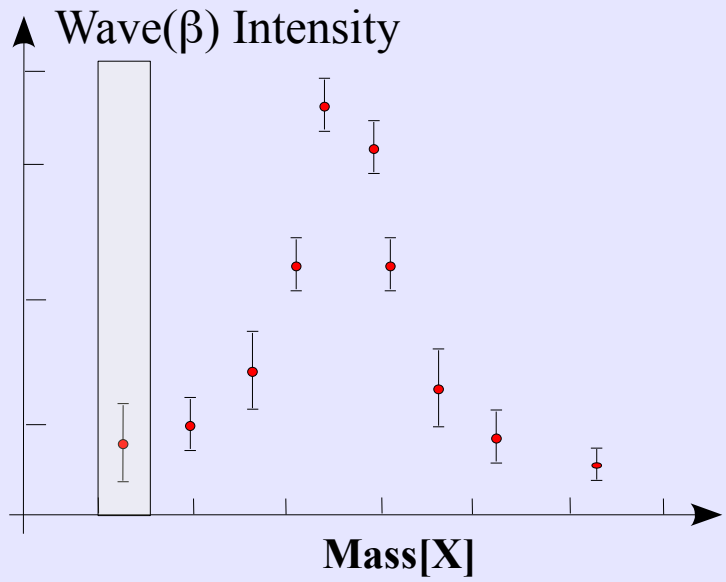


Bin by Bin Likelihood Analysis

PWA

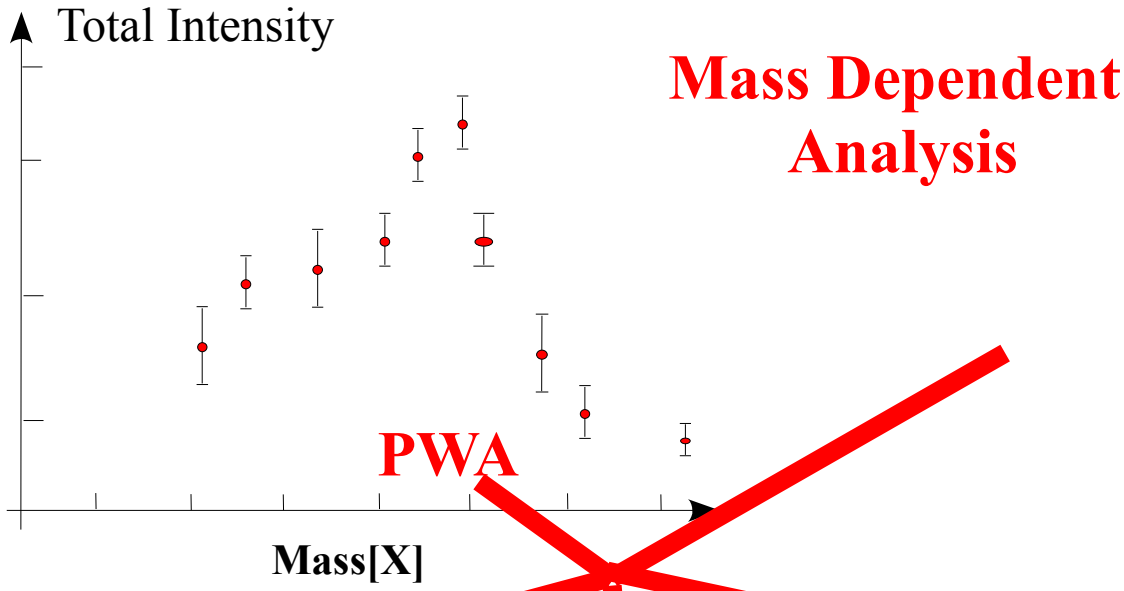






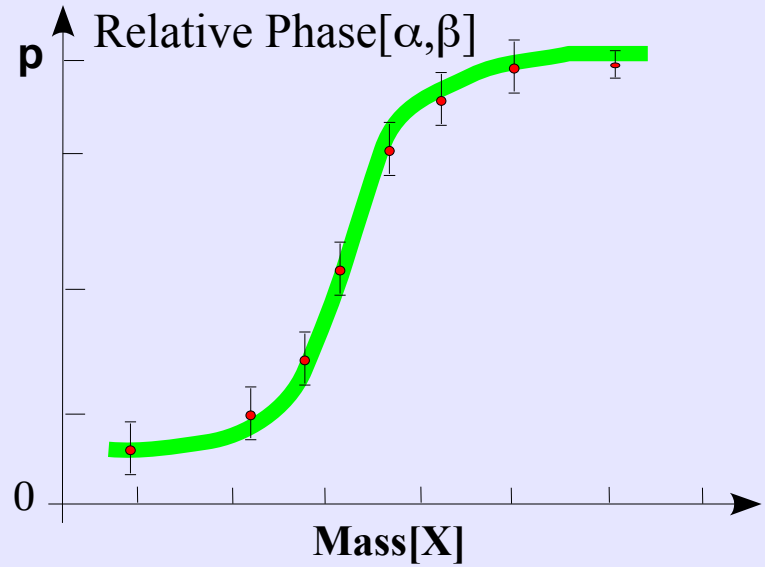
Partial Wave Analysis

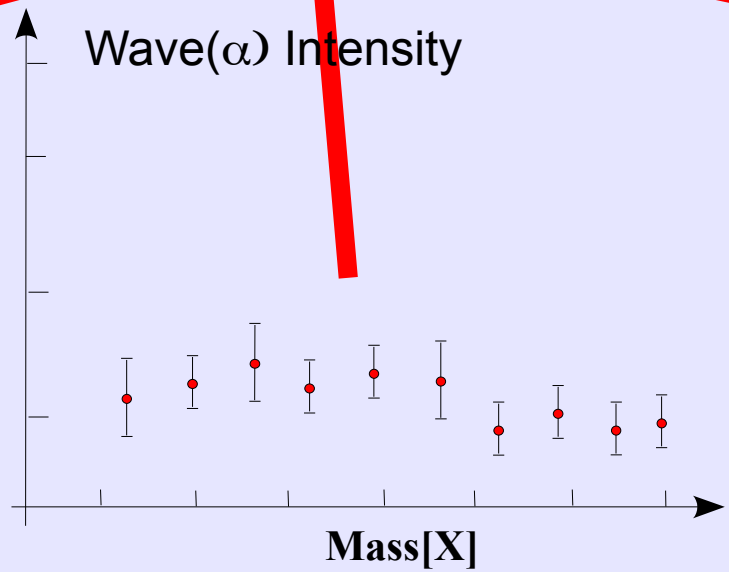
Step 2: Extract Resonance Parameters

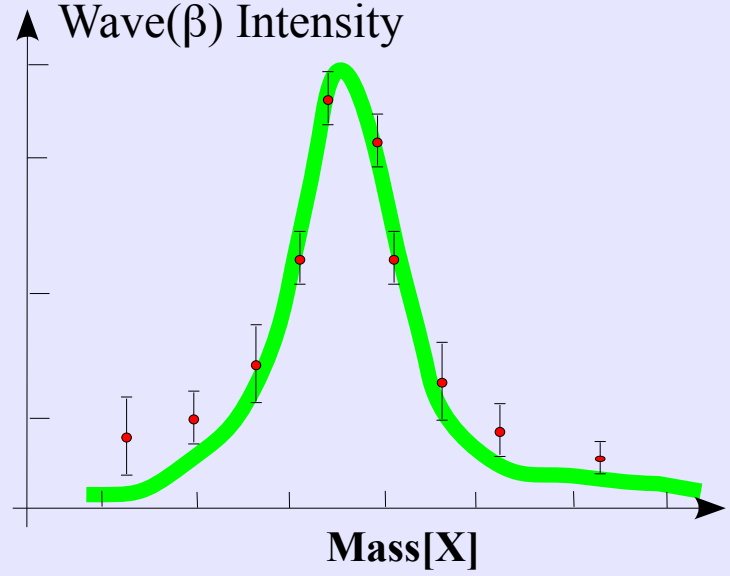


Mass Dependent Analysis

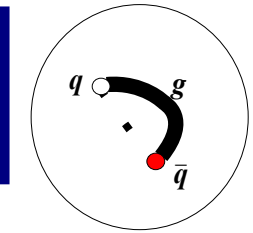
PWA

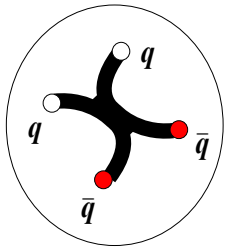






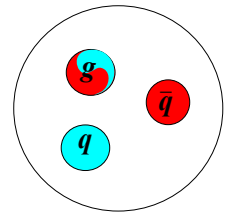
1^{-+} Exotic Hybrid Candidates



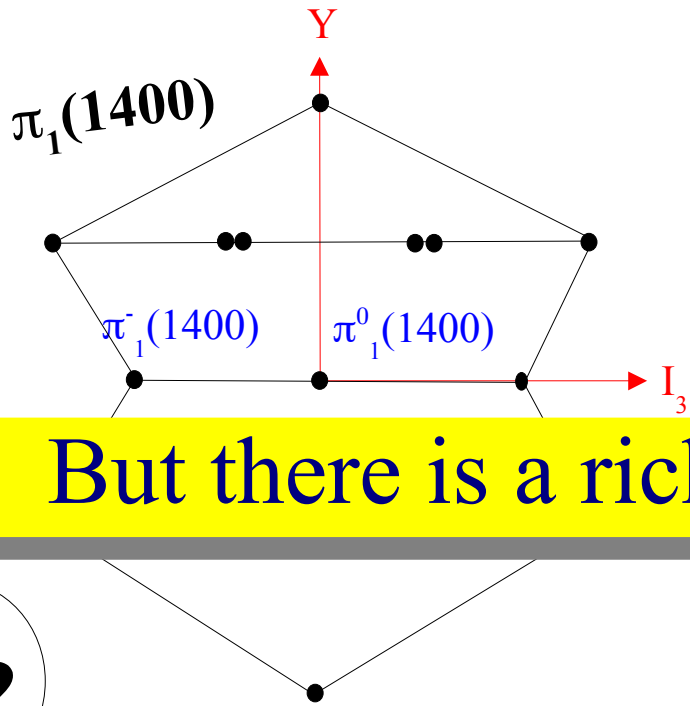


Exotic hybrids will not mix with nearby $q\bar{q}$ states

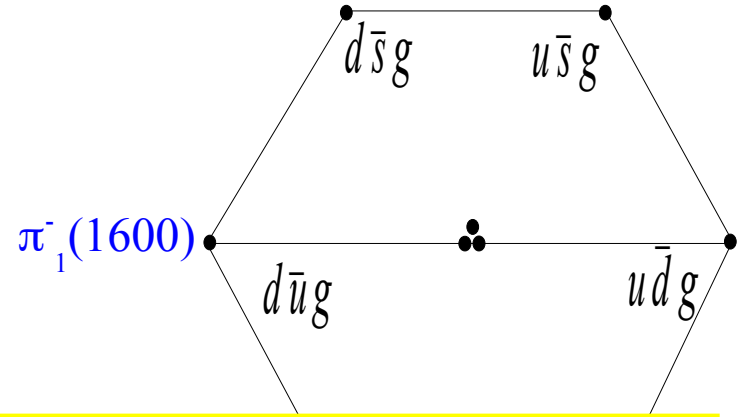
several candidates exits!



$\pi_1(1600)$ ← **most convincing!**

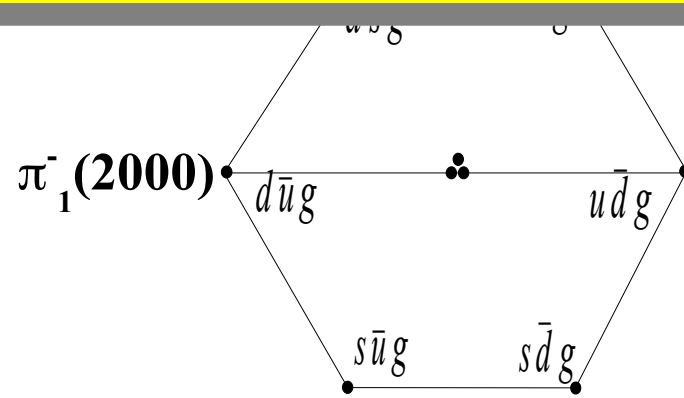


$J^{PC} = 1^{-+}$



But there is a rich history of controversy

Multiplet 17



$\pi_1(1900)$

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

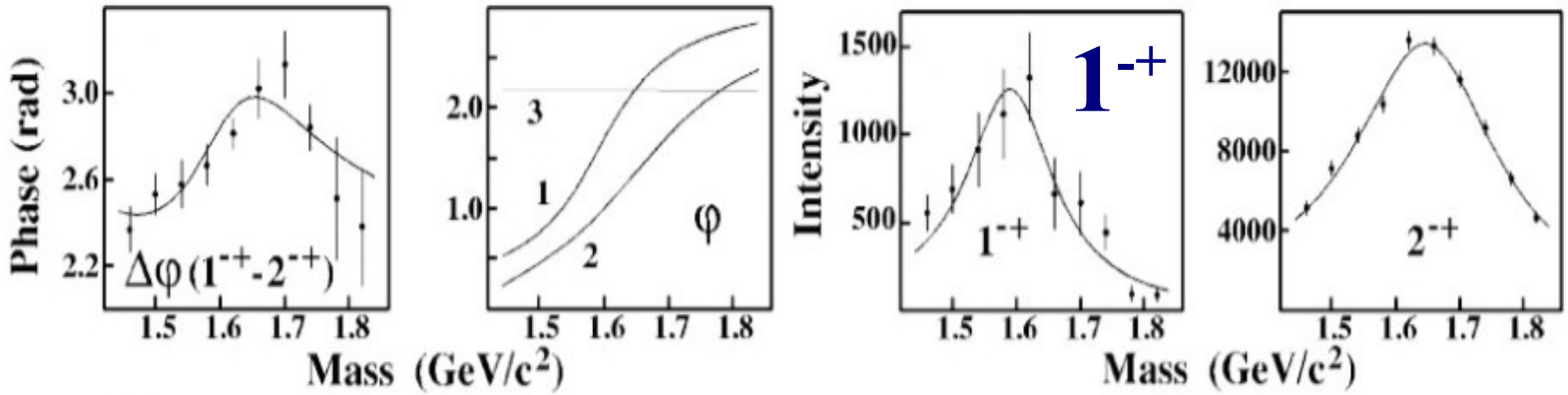


Figure: S.U. Chung *et al* [E852], Phys. Rev. **D65** 072001

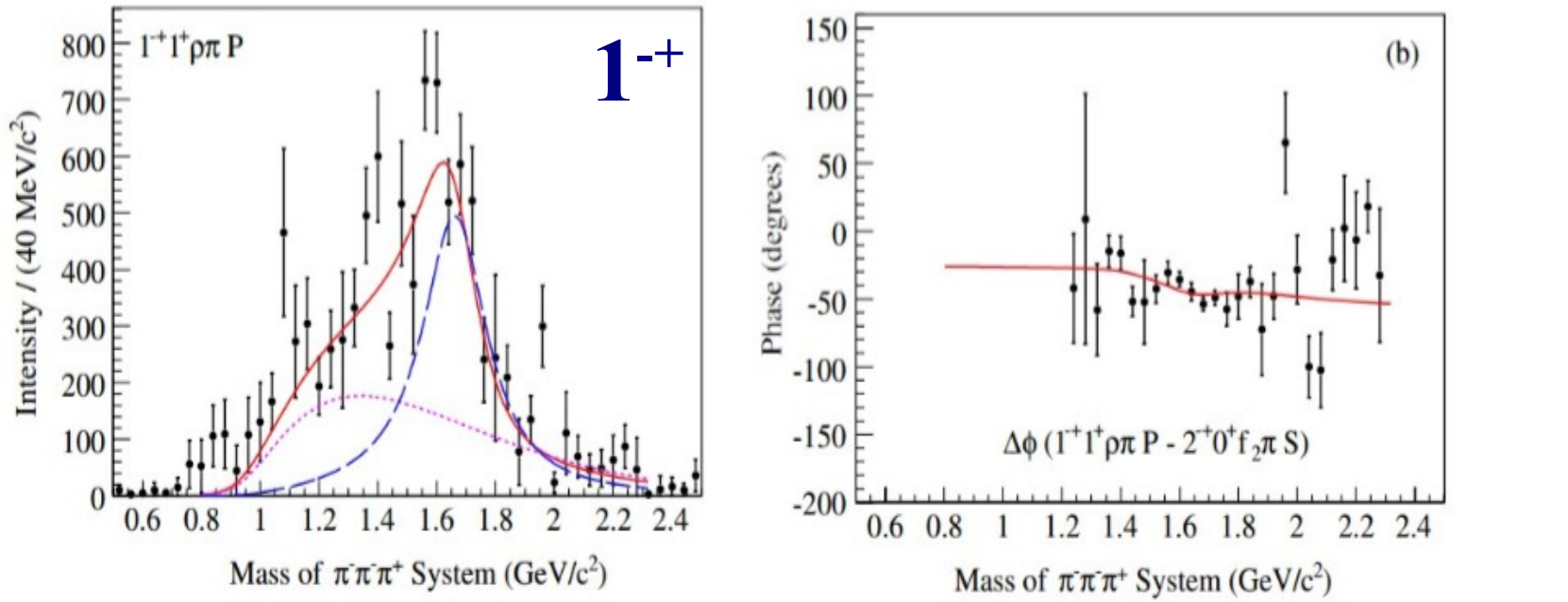


Figure: M. Alekseev *et al.* [COMPASS] Phys. Rev. Lett. **104**, 241803 (2010)

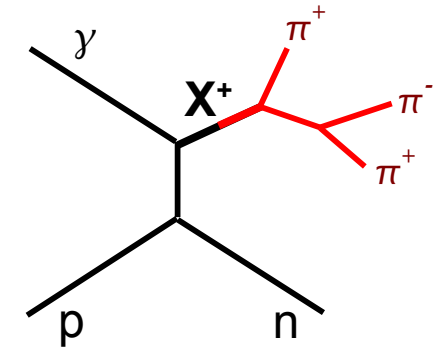
Recent Results from Jefferson Lab CLAS

CLAS g12 Experiment

Photoproduction of meson via unpolarized photons

E_{e-} 5.715 GeV

photo-production



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

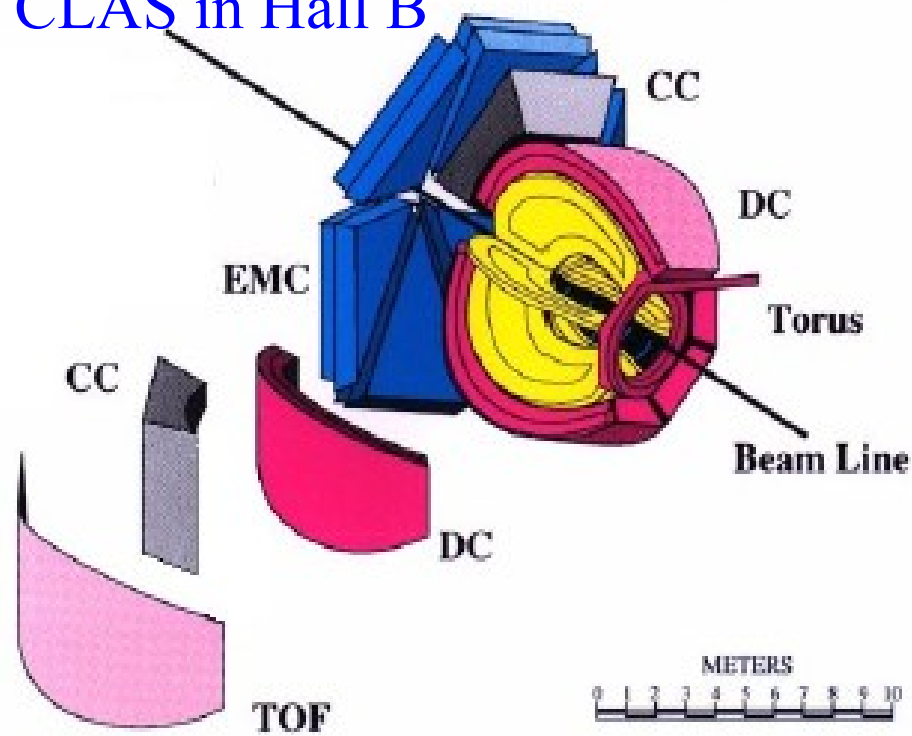
Production Data

I = 60-65 nA
E_γ = 3.584 - 5.453 GeV
26.2 Billion events
mixed triggers
68 pb^{-1}

Hadron Spectroscopy Analyses

$\gamma\, p \rightarrow n\, \pi^+\, \pi^+\, \pi^-$
$\gamma\, p \rightarrow \Delta^{++}\, \pi^-\, \pi^-\, \pi^+$
$\gamma\, p \rightarrow \Lambda\, K^+ \pi^-\, \pi^+$
$\gamma\, p \rightarrow p\, \pi^-\, \pi^{-+}\, \pi^0$
$\gamma\, p \rightarrow p\, K^+\, K^-\, \eta$
$\gamma\, p \rightarrow \Delta^{++}\, \pi^-\, \eta$
$\gamma\, p \rightarrow \Xi^{-*}\, K^+\, K^+$
$\gamma\, p \rightarrow p\, p$ anti-p
+ ...

CLAS in Hall B

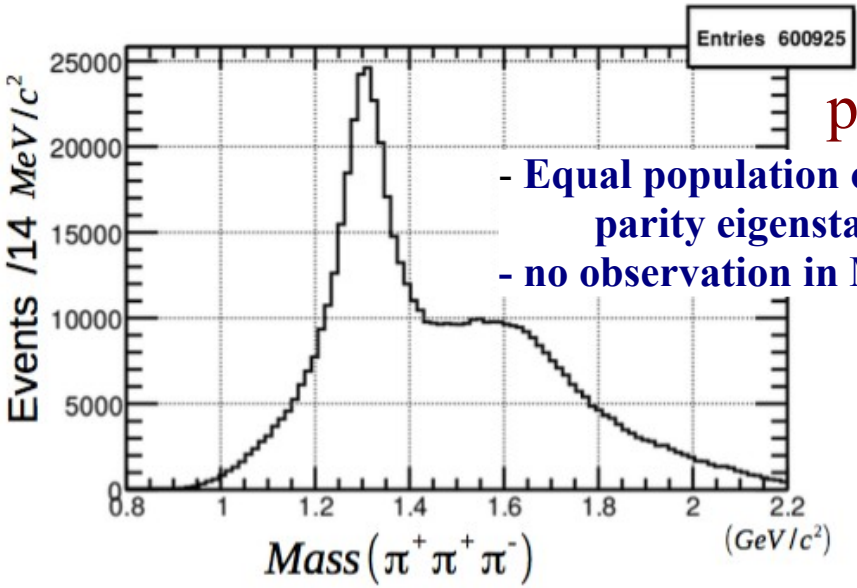


CLAS geometry optimized for peripheral production acceptance

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

CLAS g12

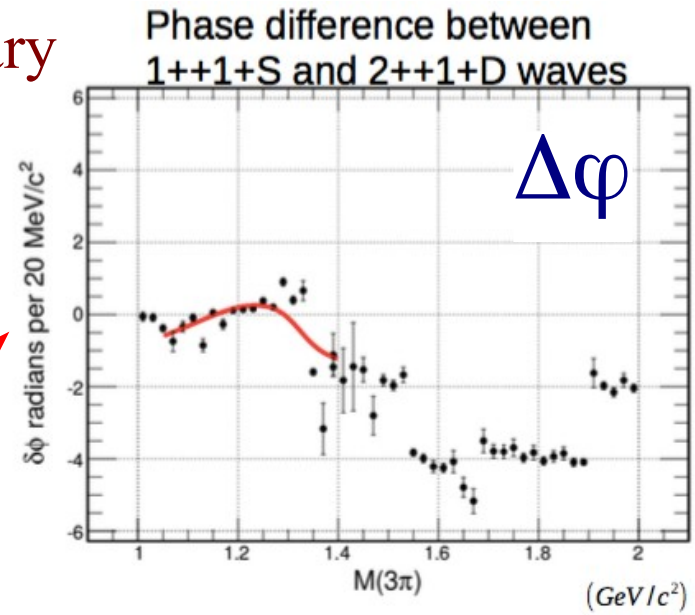
First observation of the $a_1(1260)$ in photoproduction

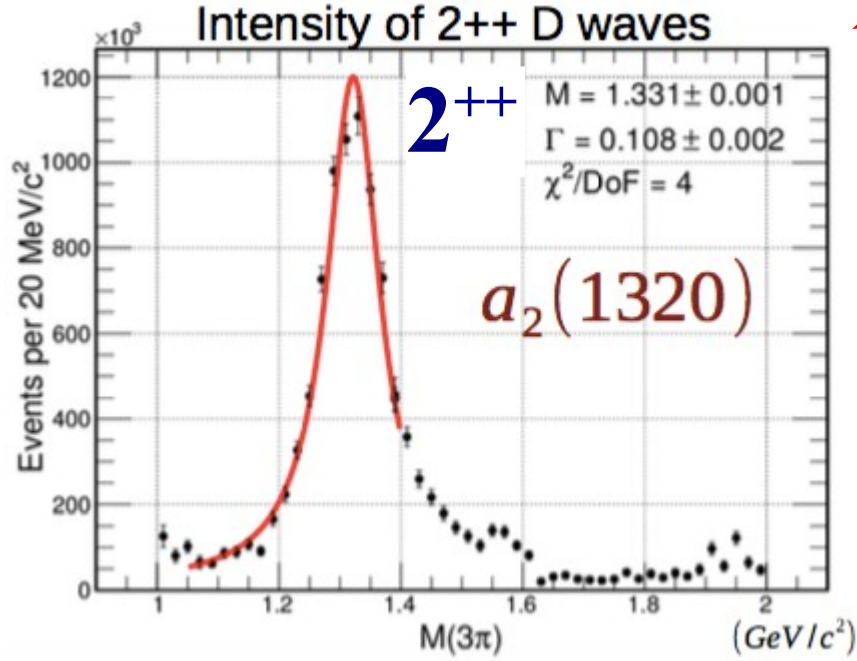


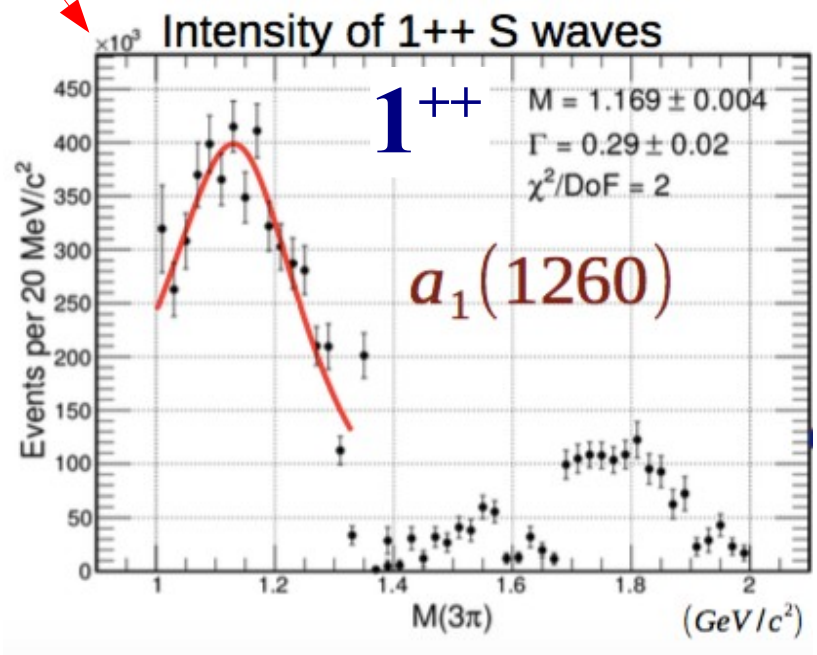
preliminary

- Equal population of both parity eigenstates
- no observation in M=0 wave

PWA





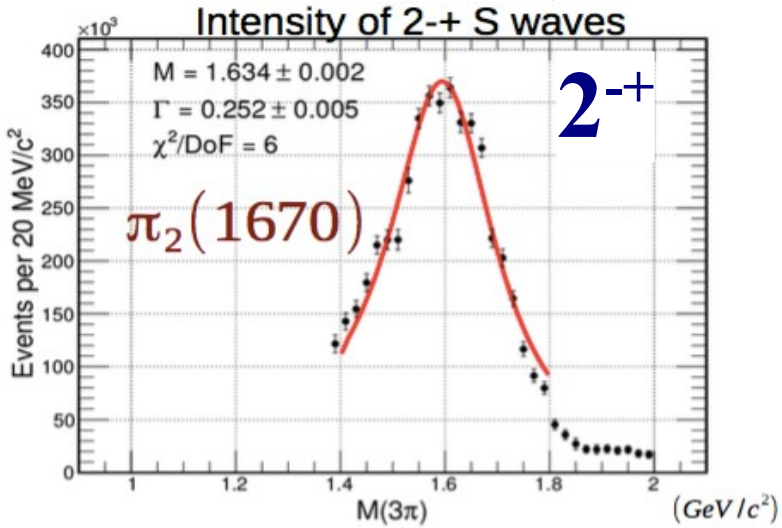


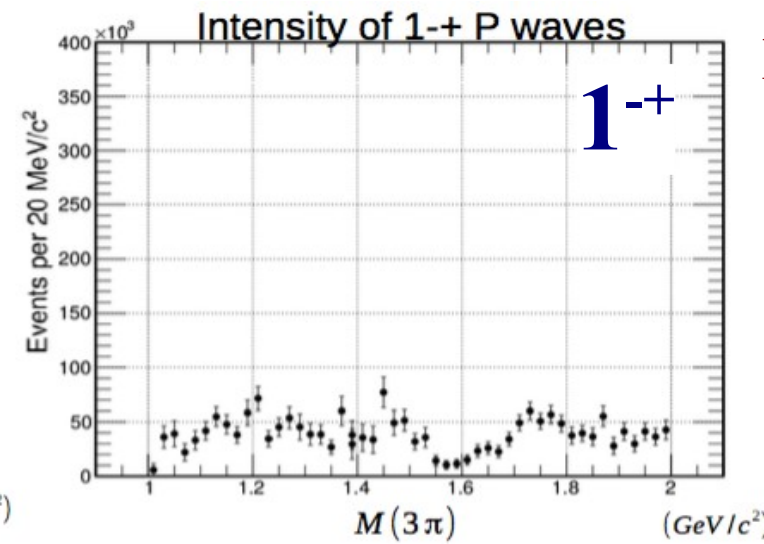
A. Tsaris (2016 FSU Dissertation)

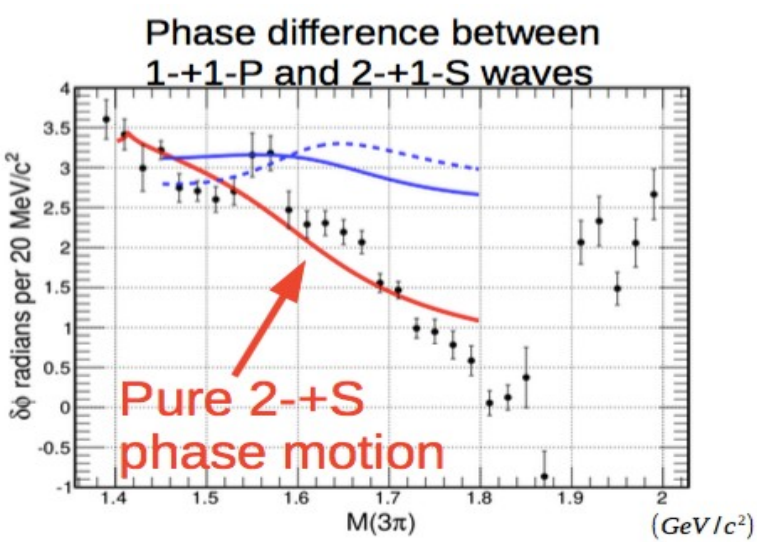
Non-resonant 1^{-+} exotic wave

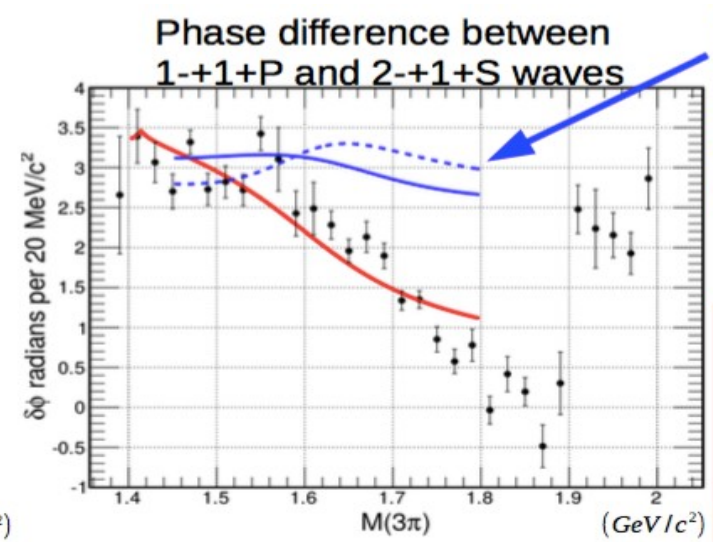
$$\gamma\, p \rightarrow n\ \pi^+\pi^+\pi^-$$

CLAS g12
preliminary









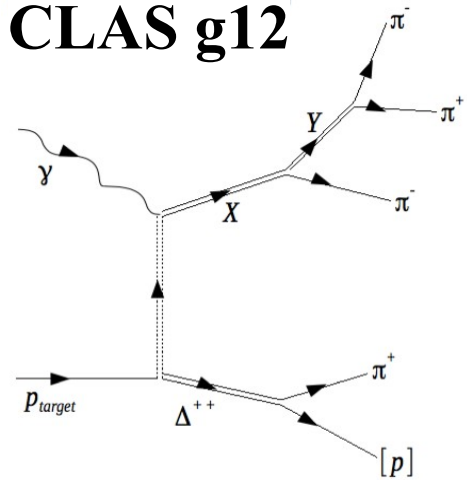
phase difference between 2-+S and a resonating 1-+P

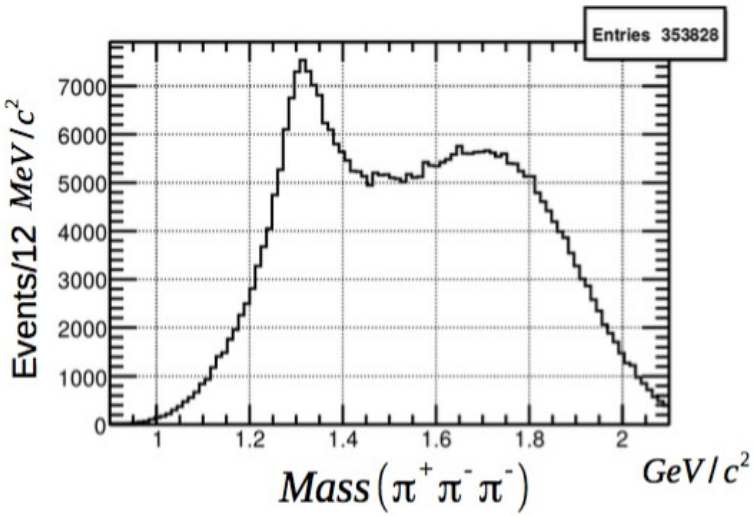
The exotic 1-+ partial wave does not show resonant behavior

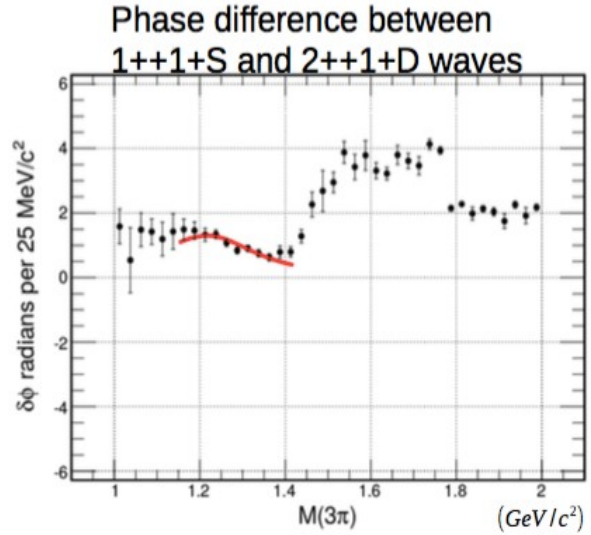
A. Tsaris (2016 FSU Dissertation)

$\gamma p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^-$

CLAS g12

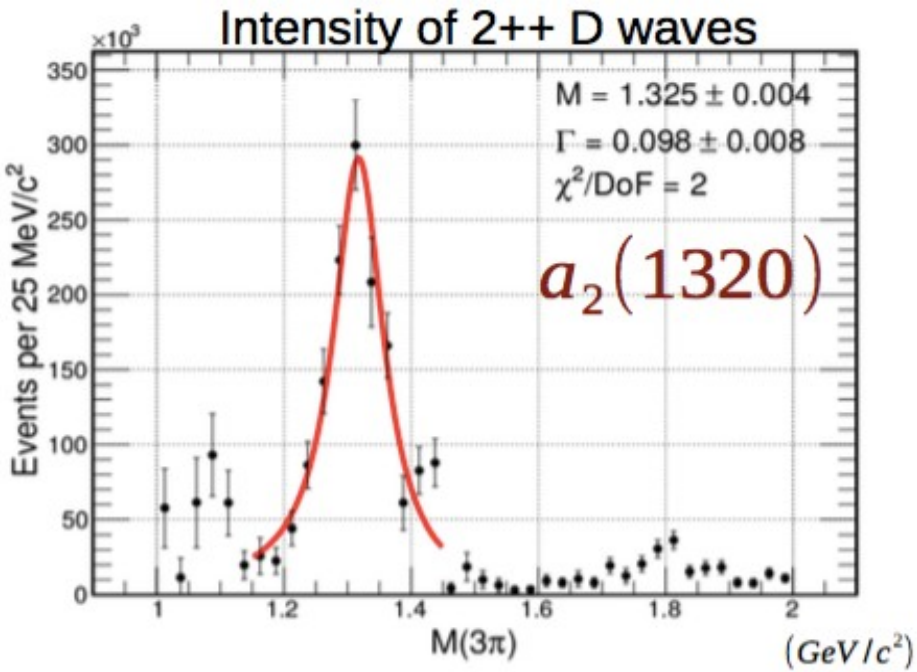


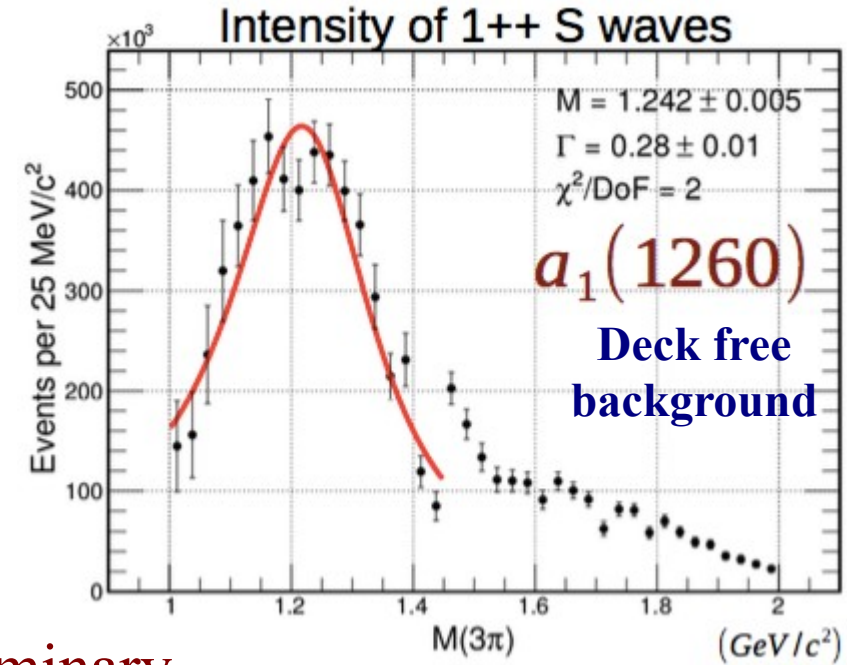




Confirmation of the $a_1(1260)$ in photoproduction

1^{-+} exotic wave was not required



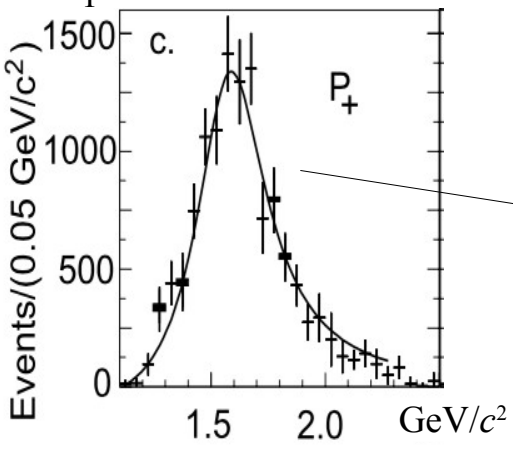


A. Tsaris (2016 FSU Dissertation)

preliminary

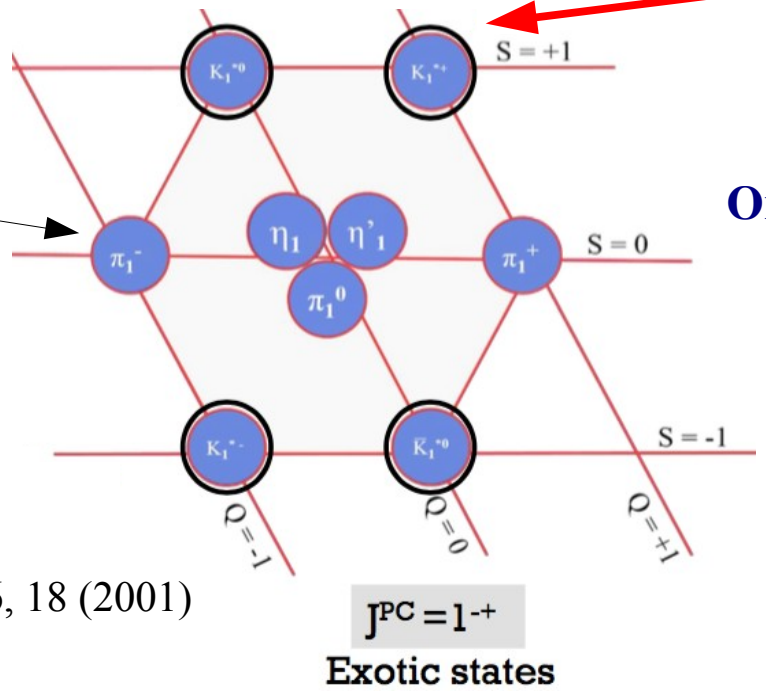
Strange Hybrids

$\pi_1(1600) \rightarrow \eta'\pi^-$



Mass($\eta'\pi$)

Ivanov *et al.*, Phys. Rev. Lett. 86, 18 (2001)

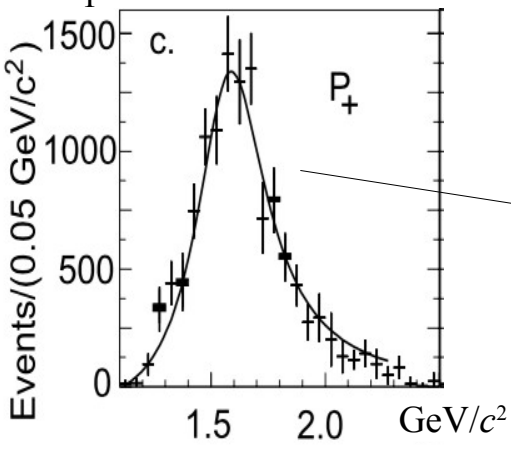


Excited strange companions to exotic states with $J^P = 1^-$

Only 3 Known 1^- Strange states: K*(892), K*(1410), K*(1680)

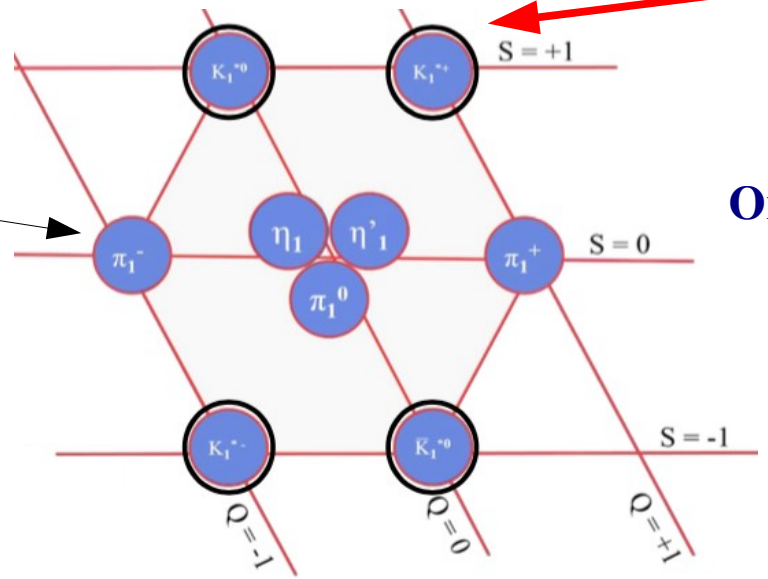
Strange Hybrids

$\pi_1(1600) \rightarrow \eta'\pi^-$



Mass($\eta'\pi$)

Ivanov *et al.*, Phys. Rev. Lett. 86, 18 (2001)



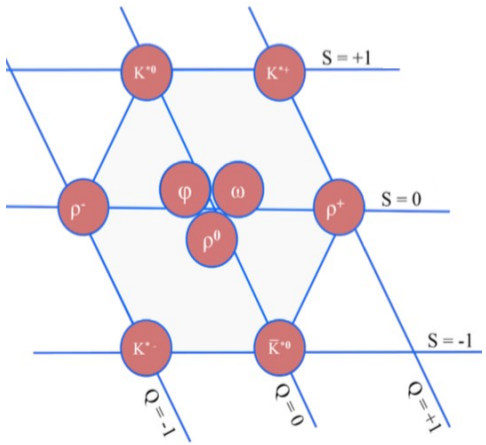
$J^{PC} = 1^{-+}$

Exotic states

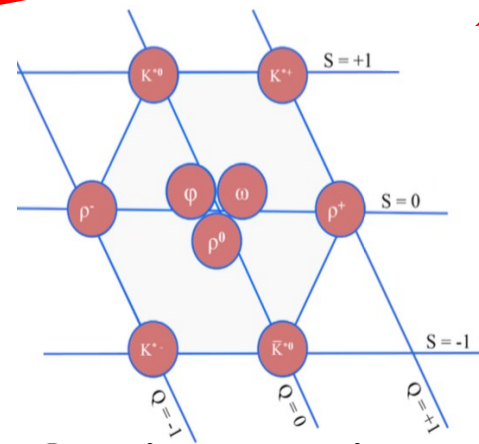
Excited strange companions to exotic states with $J^P = 1^-$

Only 3 Known 1^- Strange states: K*(892), K*(1410), K*(1680)

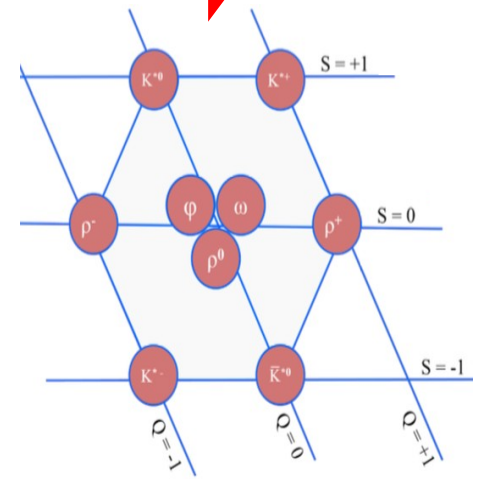
Will be difficult to separate from other strange states with $J^P = 1^-$



Radial Excited 1^{--}



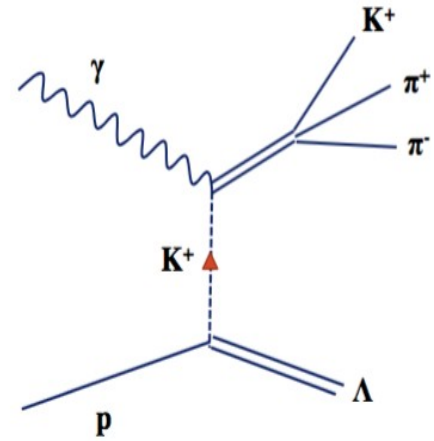
Orbital Excited 1^{--}



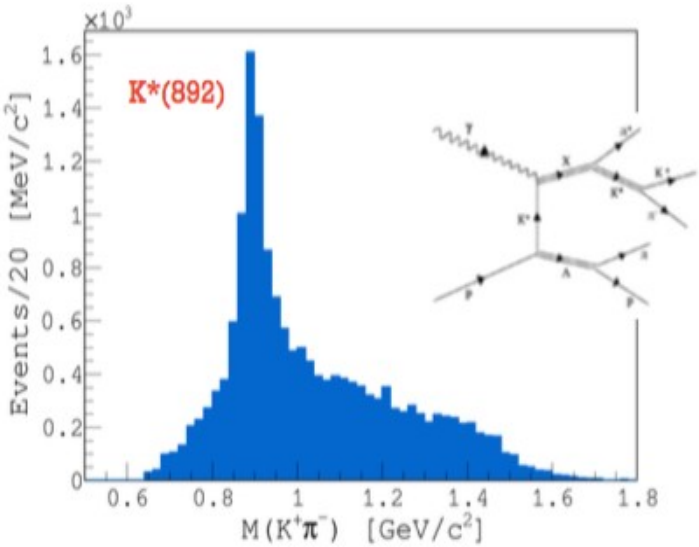
Gluonic Excited 1^{--}

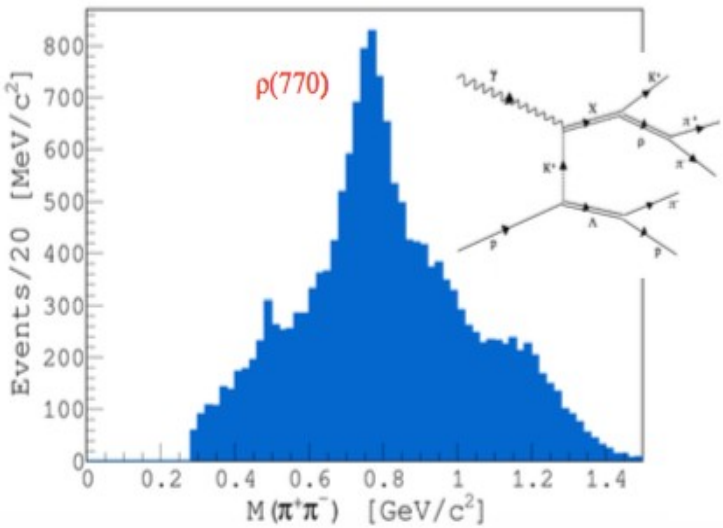
$\gamma\, p \rightarrow \Lambda\ K^+ \pi^+ \pi^-$

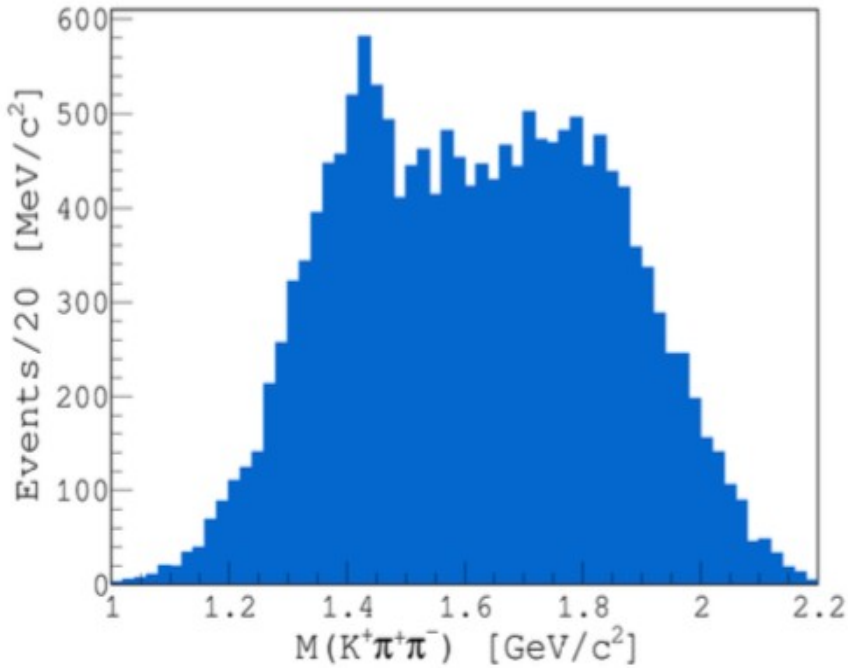
CLAS g12



Search for Excited Strange Mesons







The final dataset consisted of 16,618 Events !!

First ever analysis of Kππ photoproduction

H. Al Ghoul

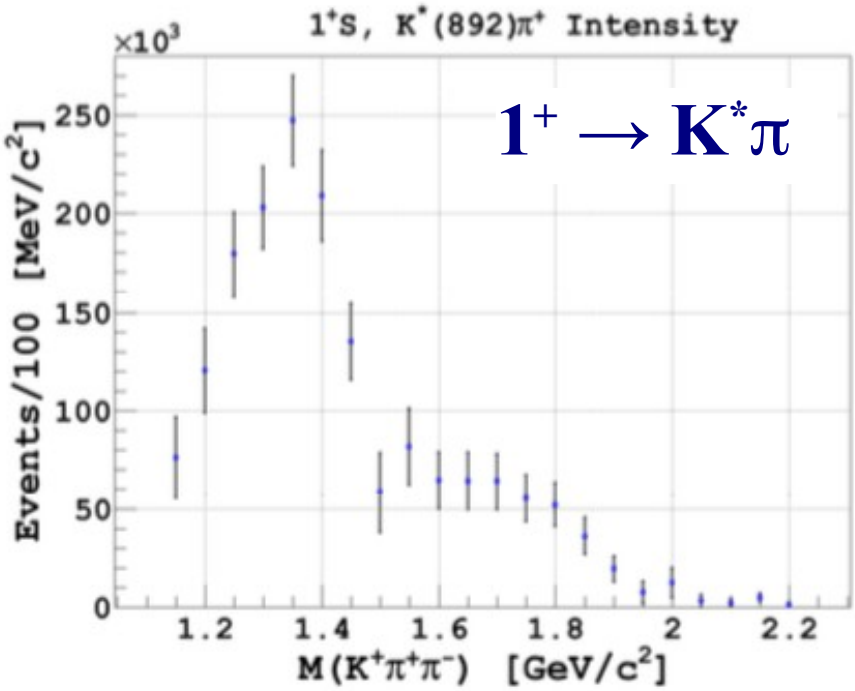
(2016 FSU Dissertation)

$K^+\pi^+\pi^-$ PWA Results for $J^P = 1^+$

preliminary

CLAS g12

PWA Results of 1^+ S



$K_1(1400) \rightarrow K^*\pi$

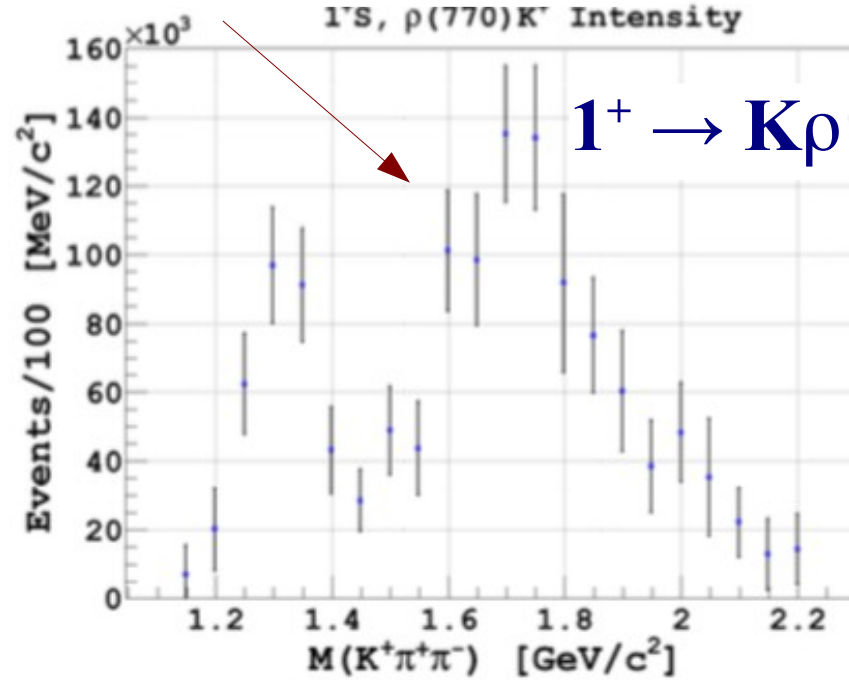
$K_1(1400)$ $I(J^P) = \frac{1}{2}(1^+)$

Mass $m = 1403 \pm 7$ MeV
Full width $\Gamma = 174 \pm 13$ MeV (S = 1.6)

$K_1(1650)$ $I(J^P) = \frac{1}{2}(1^+)$

OMITTED FROM SUMMARY TABLE

Reported but not confirmed
Mass: 1600 – 1900 MeV
Width: 150 – 250 MeV



$K_1(1270) \rightarrow K^*\pi,\ K\rho$

$K_1(1270)$ $I(J^P) = \frac{1}{2}(1^+)$

Mass $m = 1272 \pm 7$ MeV [u]
Full width $\Gamma = 90 \pm 20$ MeV [u]

H. Al Ghoul (2016 FSU Dissertation)

$K^+\pi^+\pi^-$ PWA Results for $J^P = 1^-$

preliminary

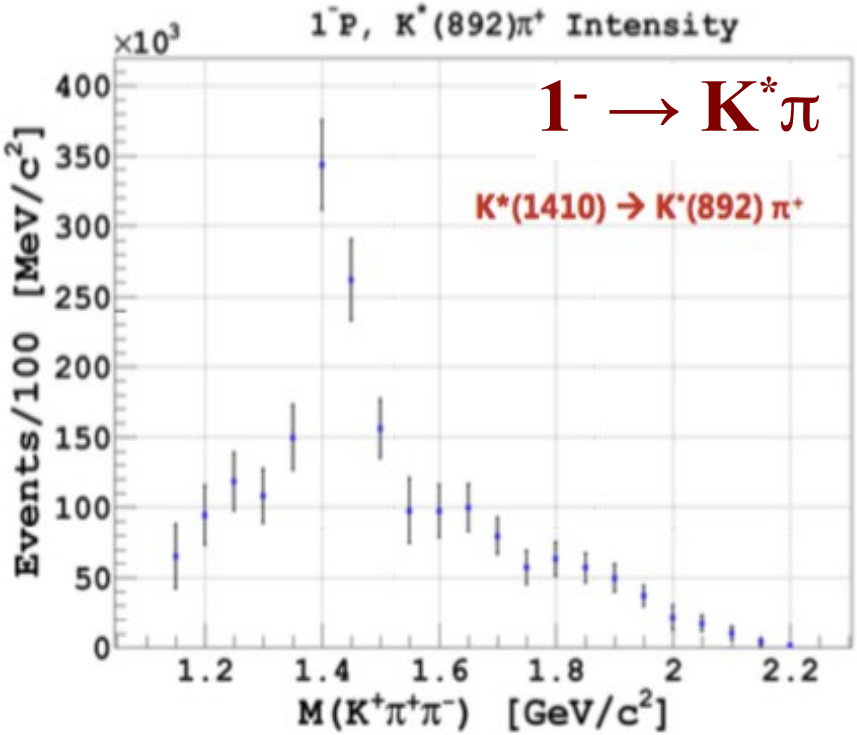
CLAS g12

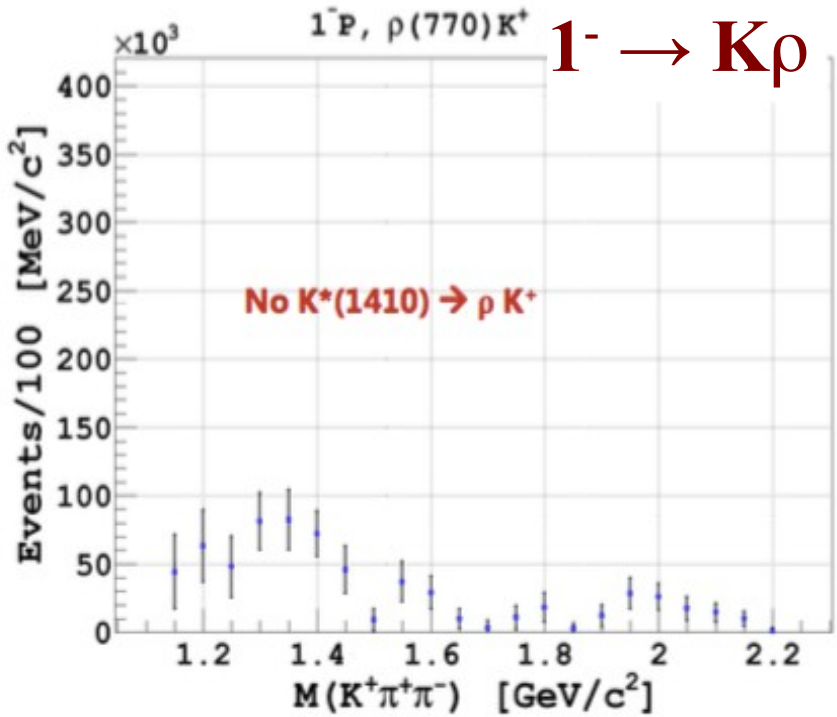
PWA Results of 1^- P

$K^*(1410)$ $I(J^P) = \frac{1}{2}(1^-)$

Mass $m = 1414 \pm 15$ MeV (S = 1.3)
Full width $\Gamma = 232 \pm 21$ MeV (S = 1.1)

$K^*(1410)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$K^*(892)\pi$	> 40 %	95%	410
$K\pi$	(6.6±1.3) %		612
$K\rho$	< 7 %	95%	305
γK^0	seen		619



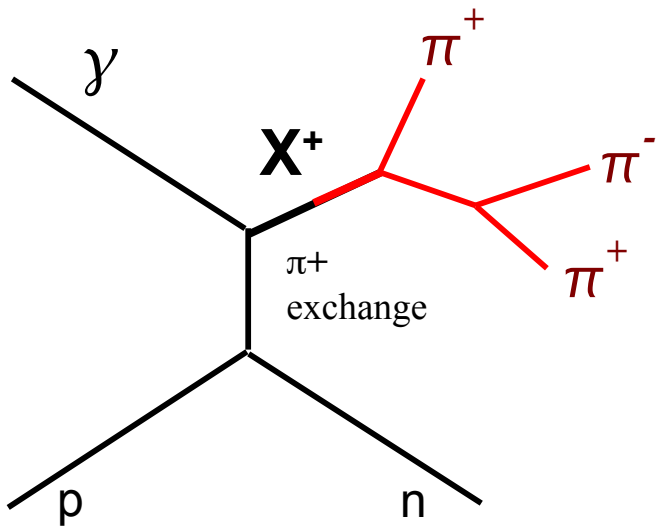


No clear K*(1680) structure even though the branching factions to K*π and Kρ are large

H. Al Ghoul (2016 FSU Dissertation)

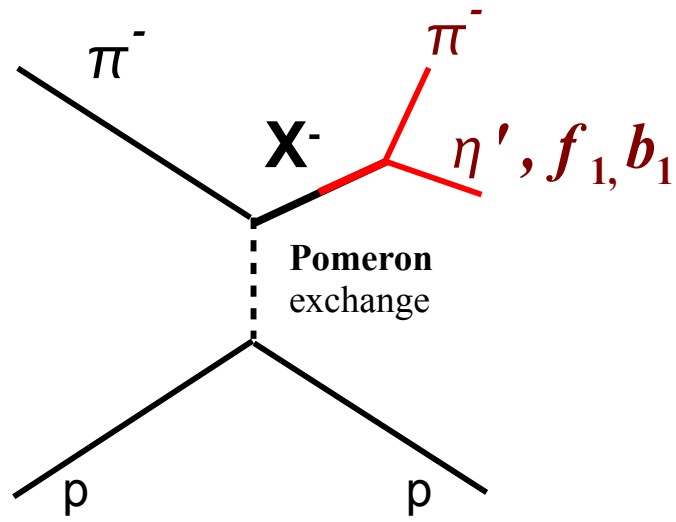
Are Hybrids Produced by Glue-rich Processes?

Photoproduction



no resonant exotic signal

Pion Production



observed resonant exotic signal

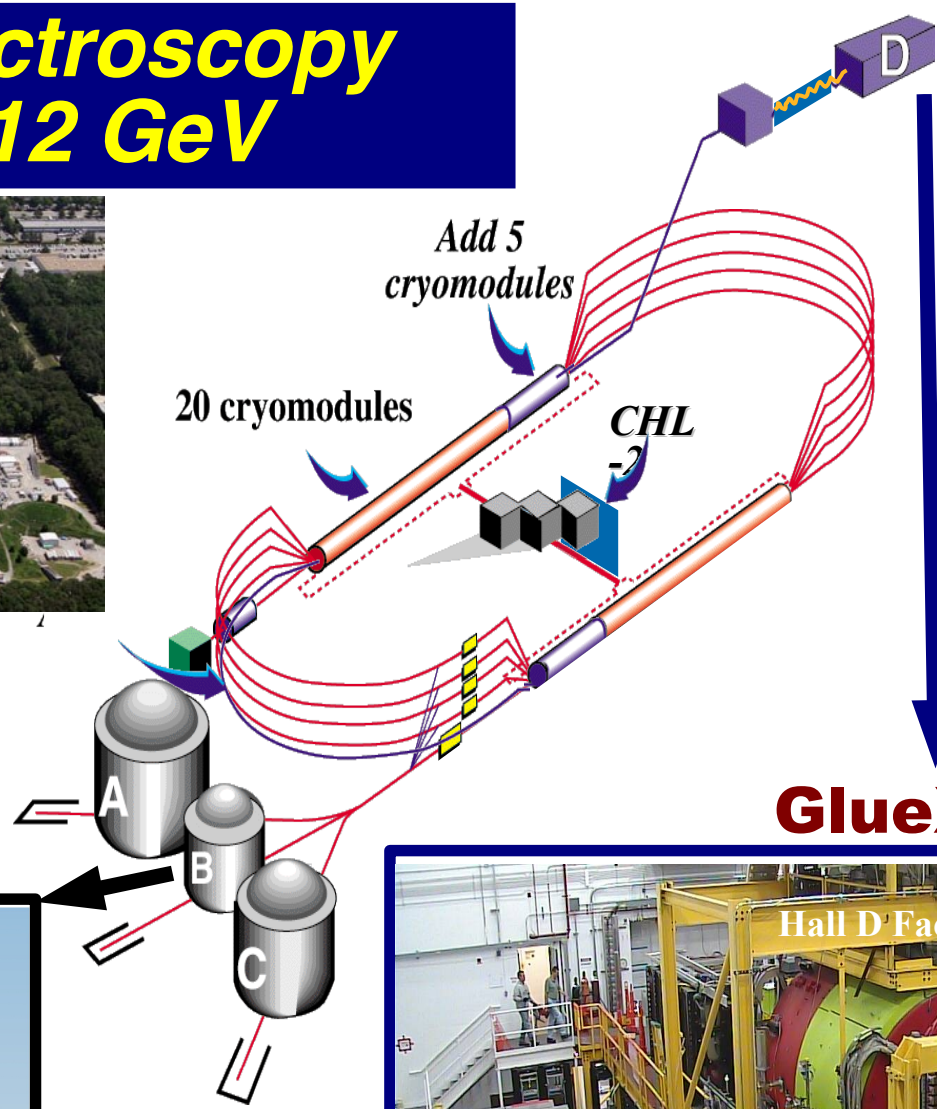
Non-observation of $\pi_1(1600)$ in charge exchange photoproduction is consistent with exotic production via Pomeron

Non-observation of the K*(1680) in charge exchange photoproduction may hint to hybrid nature

Additional Data is Needed

Meson Spectroscopy at JLab 12 GeV

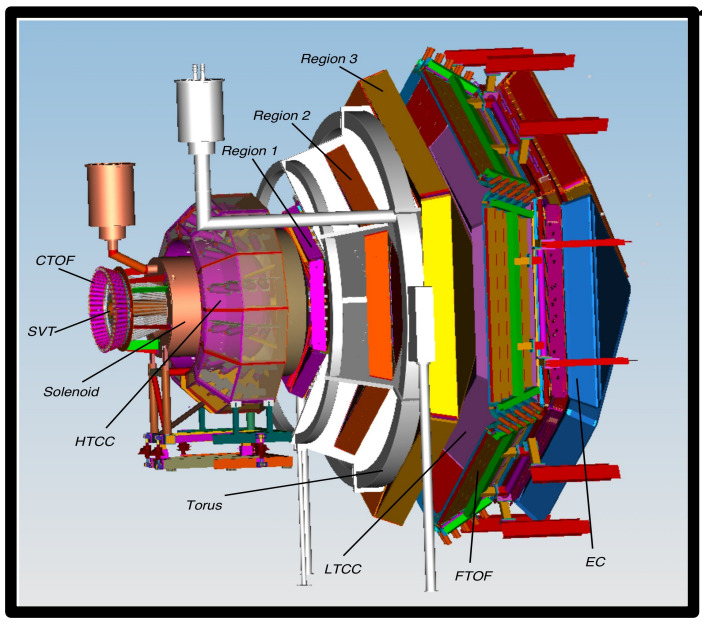
Jefferson Lab



Max Pass energy: 2.2 GeV
Max Enery Hall A-C: 10.9 GeV
Max Energy Hall D: 12 GeV

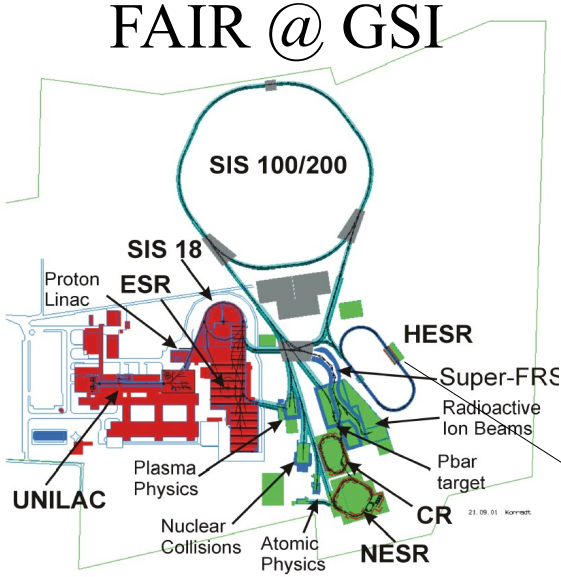
GlueX

CLAS12



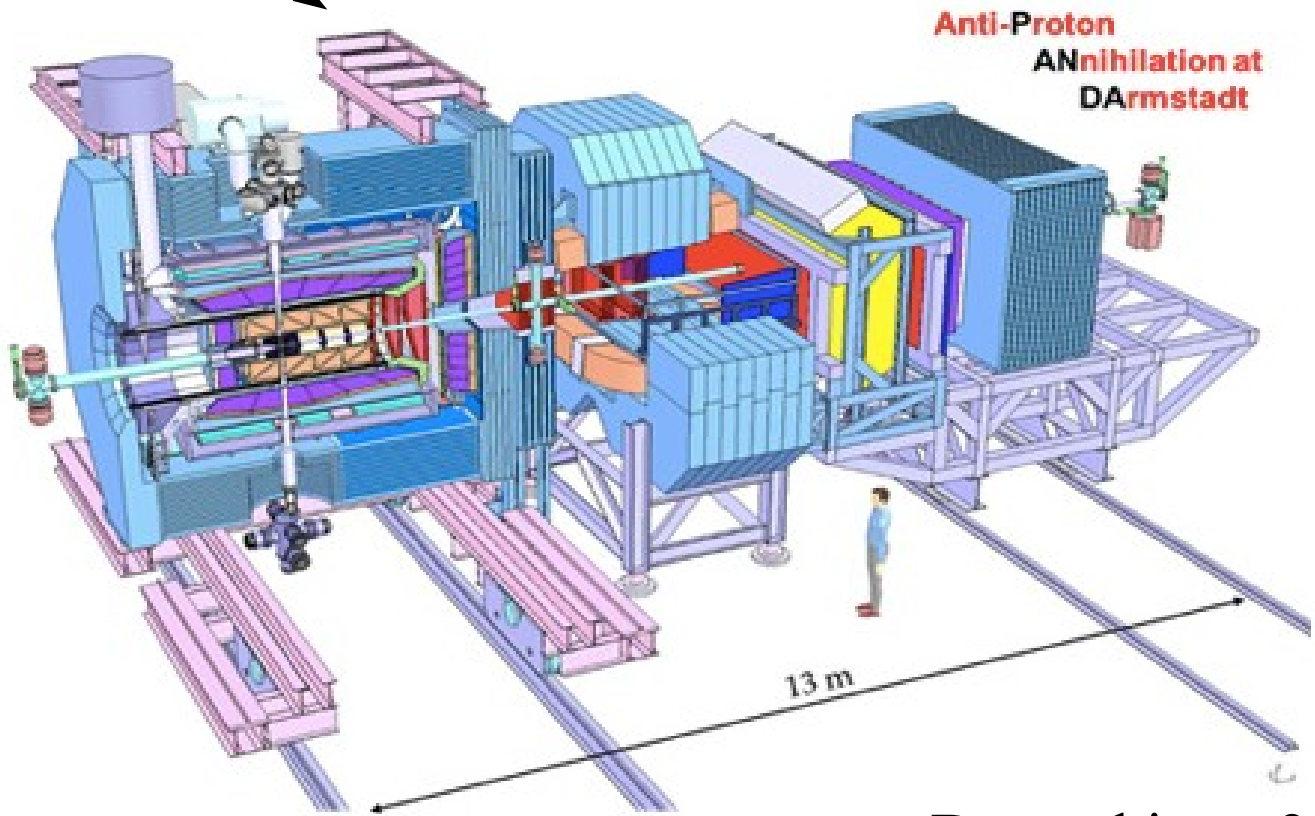
See talk by Andrea Celentano on the current status

FAIR @ GSI



The PANDA Experiment

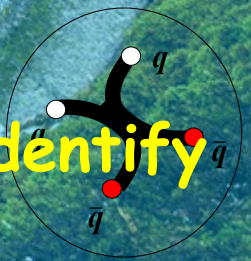
A study of antiproton annihilations on nucleons and nuclei in the energy range of strange and charmed hadrons



Data taking ~2020

Summary & Outlook

- The Quark Model of hadrons works surprisingly well, yet QCD allows for a much richer spectrum of hadronic matter
  - The excitation of the gluonic fields leads to an entirely new spectrum of mesons
  - Several promising gluonic hybrid candidates exist
    - New results from photoproduction are shedding light on understanding the hybrid spectrum
      - $\pi_1(1600)$ not observed in 3π
        - Suggests glue-rich production for hybrids
      - Search for excited strange mesons finds evidence for K*(1410) but no K*(1680)
        - Non-observation hints of a hybrid nature for K*(1680)
    - Additional Data is needed and on the horizon

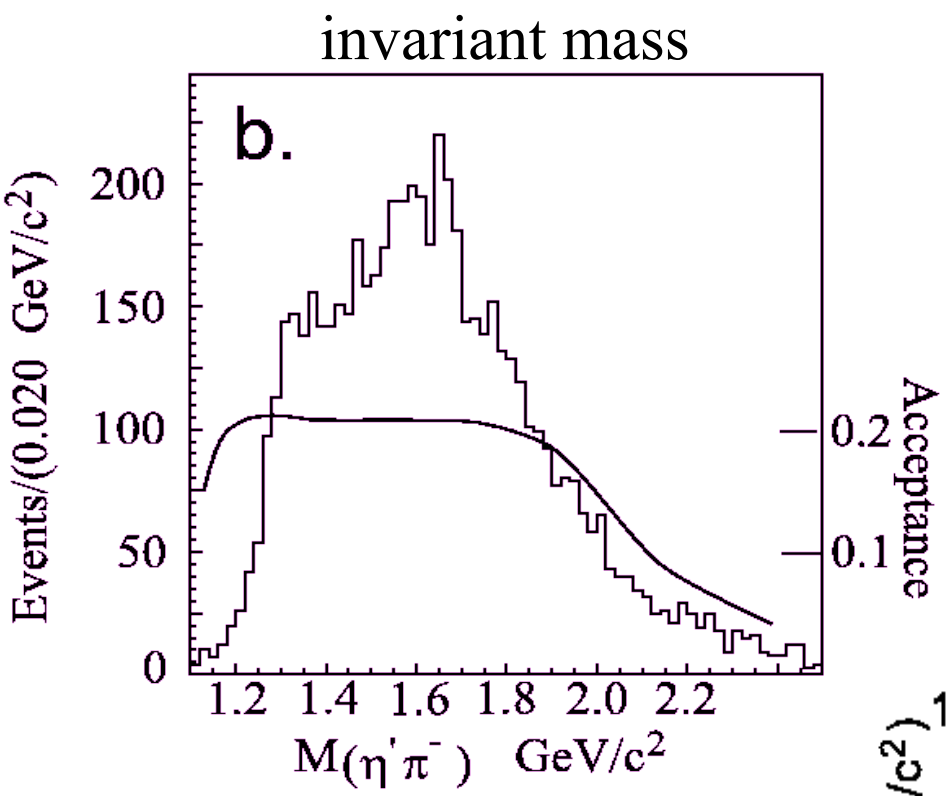


- Future experimental programs plans to firmly identify and map out the hybrid and exotic spectrum
  - A wealth of new data is coming

Acknowledgements

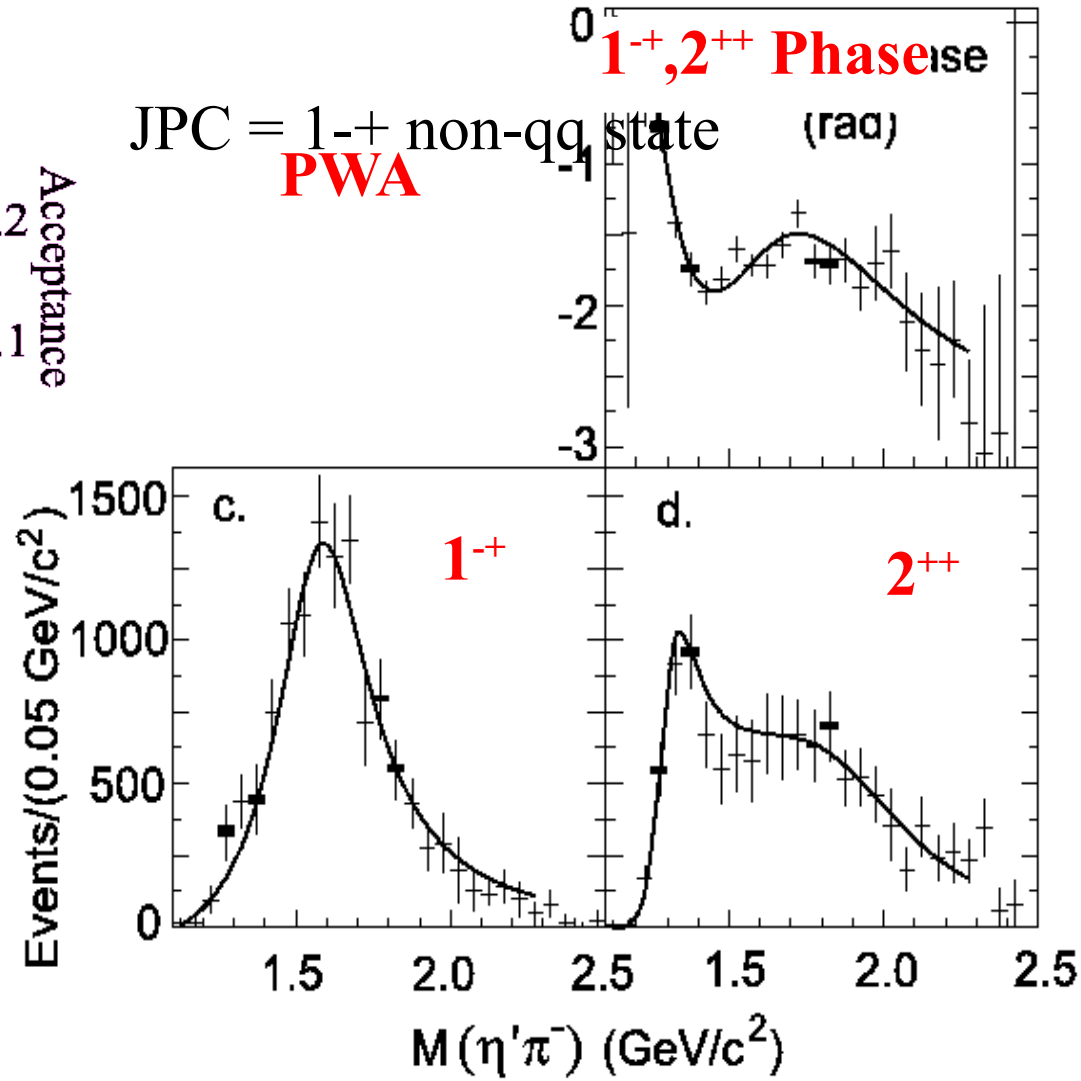
This material is based upon work supported in part by the U.S. Department of Energy , Office of Science, Office of Nuclear Physics, under Award Number DE-FG02-92ER40735.

Observation of Exotic $\pi_1(1600)$



$J^{PC} = 1^{-+}$ *non-$q\bar{q}$ state*

$\pi_1(1600) \rightarrow \eta'\pi$

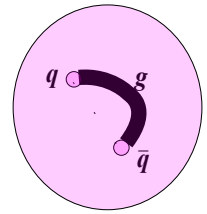


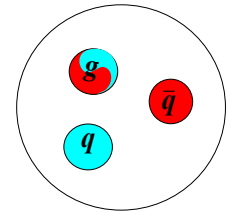
BNL-E852

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

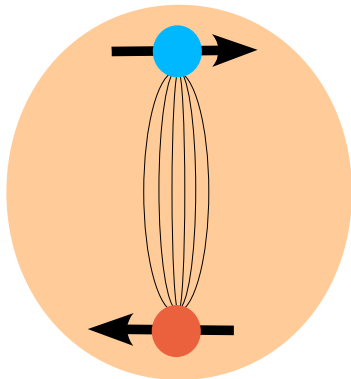
Photoproduction of Gluonic Excitations

- **It has been pointed out[1,2,3] that in the case of photoproduction exotic hybrids should be produced copiously.**
- **Recent lattice calculations show that the strength of charmonium hybrid radiative decays are similar to normal mesons[4]**



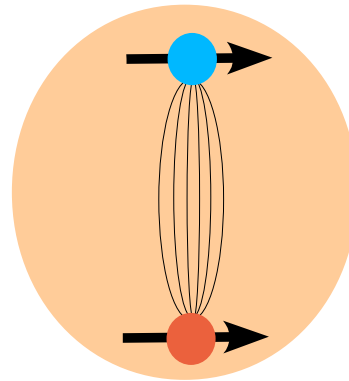


pseudoscalar probe



$$_{quarks}J^{PC} \otimes {}_{gluon}J^{PC} = 1^{--},\ \boxed{1^{++}}$$

vector probe



$$_{quarks}J^{PC} \otimes {}_{gluon}J^{PC} = 0^{-+},\ \boxed{1^{-+}}\ 2^{-+},$$

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

- **Very little photoproduction data exists!**

[1]Close *et al*. Phys. Rev. D52:1706 (1995)

[2]Afanasev *et al*. Phys. Rev. D57:6771 (1998)

[3]Szczepaniak *et al*. Phys. Lett. B516:72 (2001)

[4] Dudek *et al*. Phys. Rev. D79:094504 (2009)

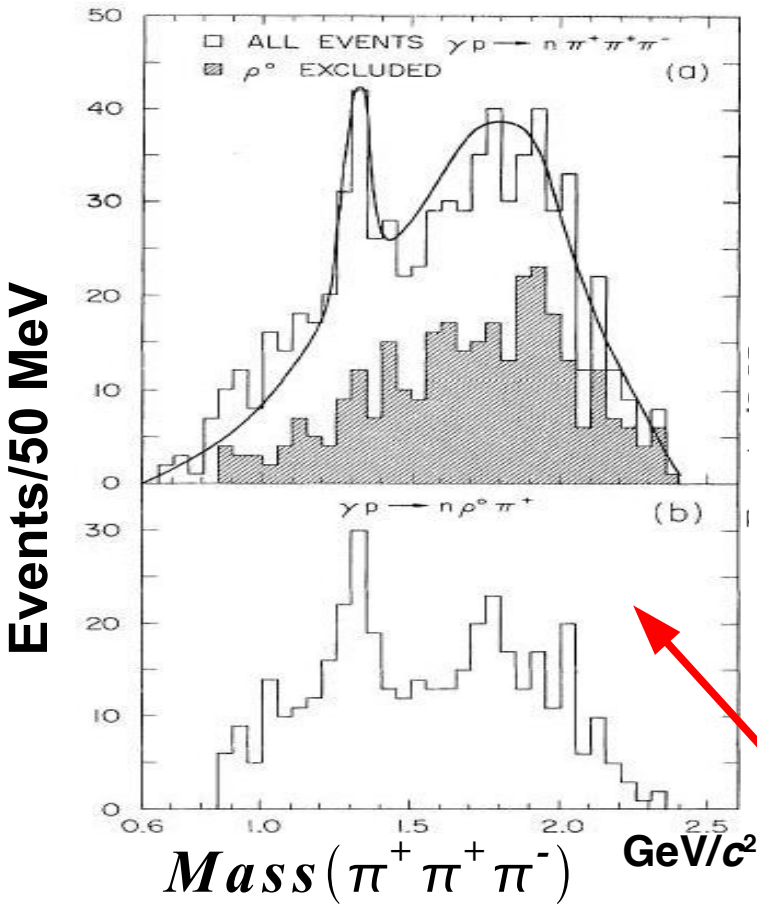
Meson Photoproduction Data*

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

Virtually unexplored production

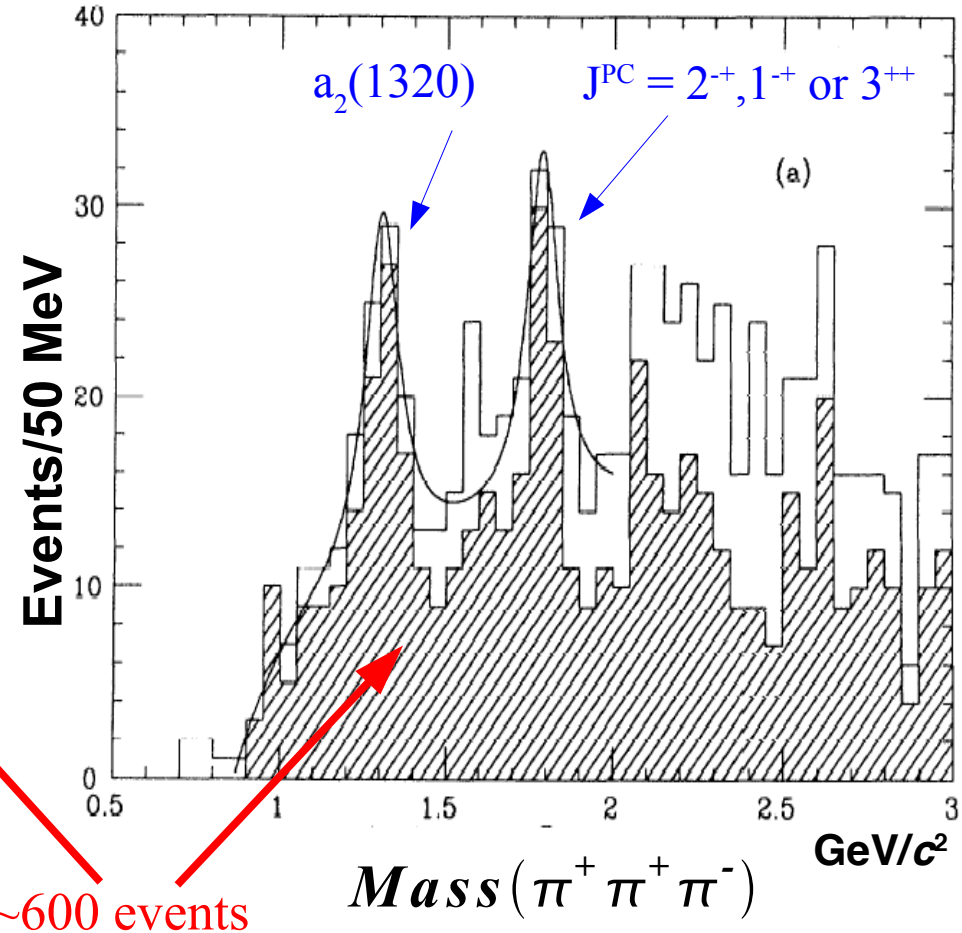
$E_\gamma = 5.4 \;\&\; 4.3\,GeV$

Ballam et al., PRL **23**, 1322 (1969)



$E_\gamma \approx 19\,GeV$

Condo et al., PRD 43 #9, 2787 (1991)

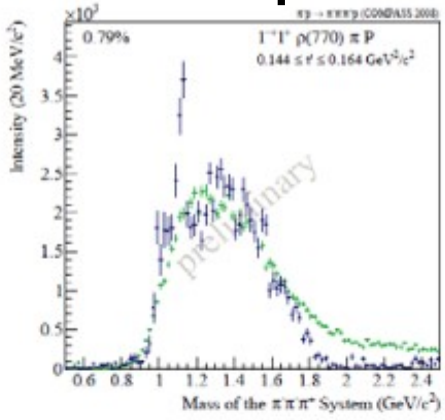


~600 events

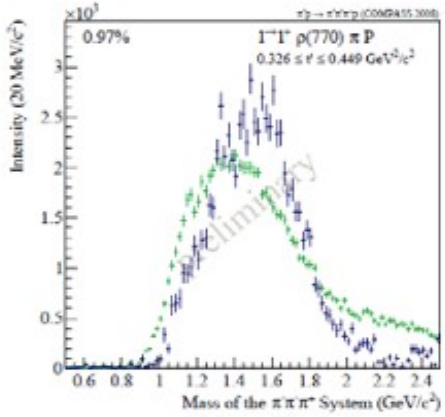
*Existing Data prior to recent JLab results

COMPASS: Update on the 1^{-+} Exotic in 3π

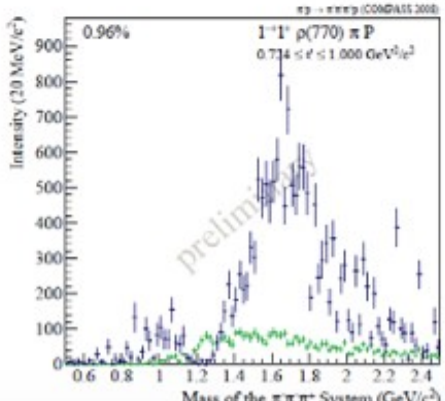
$1^{-+}1^{-}\rho\pi$



(b)

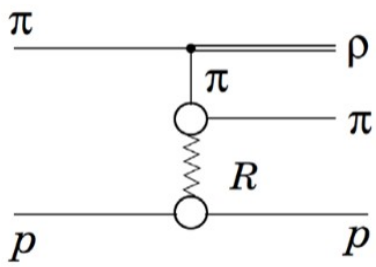


(d)



t'

Non-resonant Deck



— Data

— Deck

B. Ketzer (Hadron 2015)

The 1^{-+} is non-resonant at low t' which is in agreement with the CLAS g12 results

Low values of t':

- Mostly non-resonant production
- Good description by Deck model

High values of t':

- Deck background disappears
- Resonant component increasing
- Dominates highest t' - bin