Meson Spectroscopy at CLAS/CLAS12

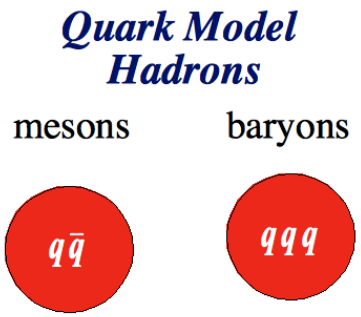
Lei Guo

Florida International University

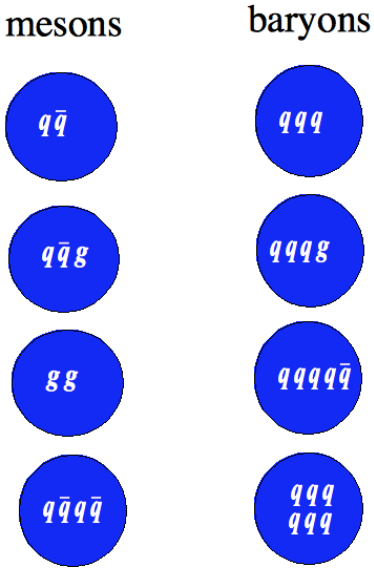
Why study meson?

- Meson, 介子 (the particle "between" lepton and baryon) is the simplest system to study strong interaction
- Quark Models have been extremely successful
- But it can't be this simple!

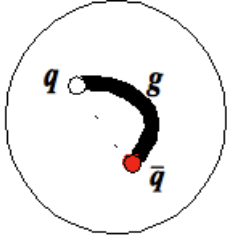
We can use it to build "hadrons", particles of matter with sizes ~1fm



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

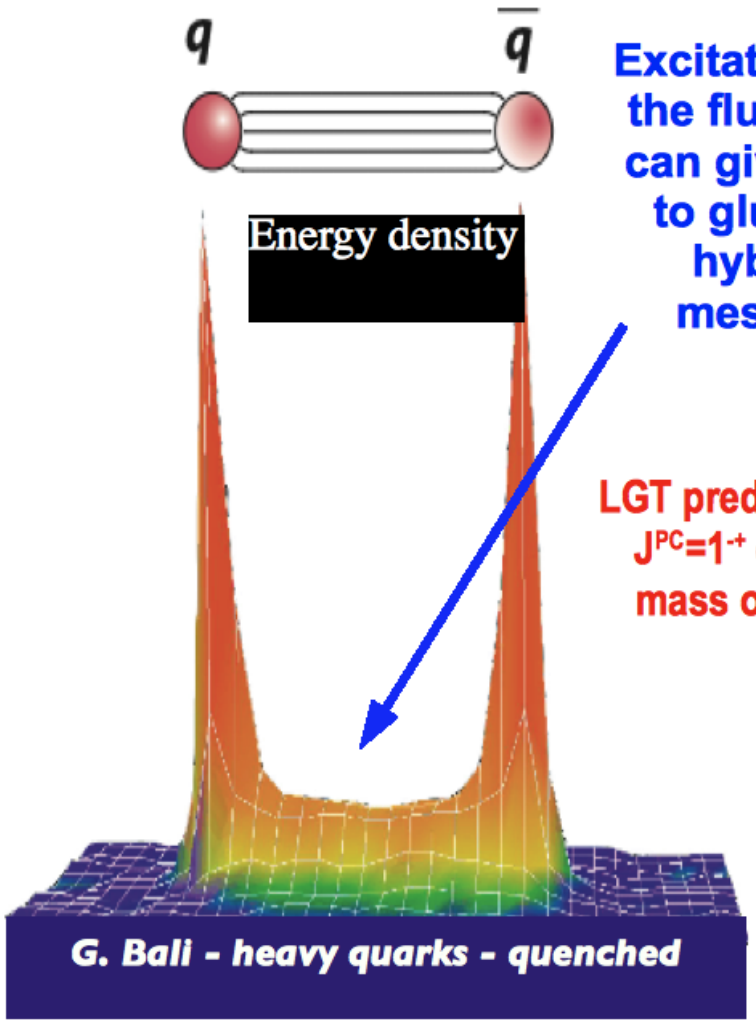


Gluonic Hybrids

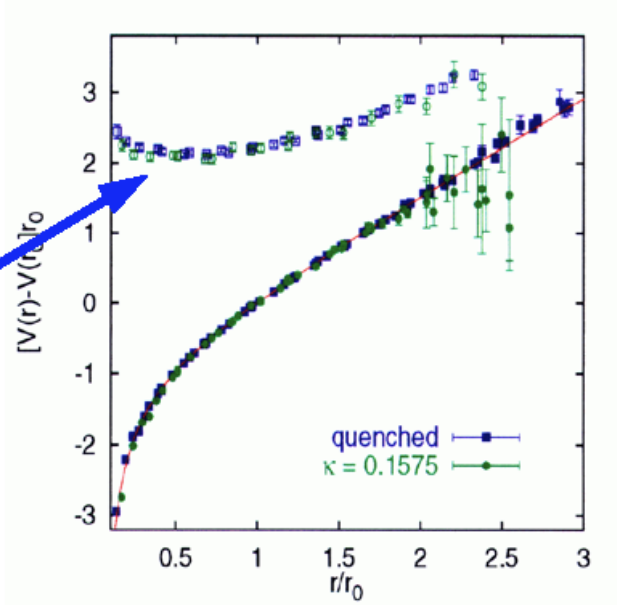


tube-like hybrid

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



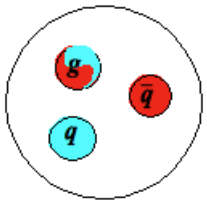
Excitations of the flux tube can give rise to gluonic hybrid mesons



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

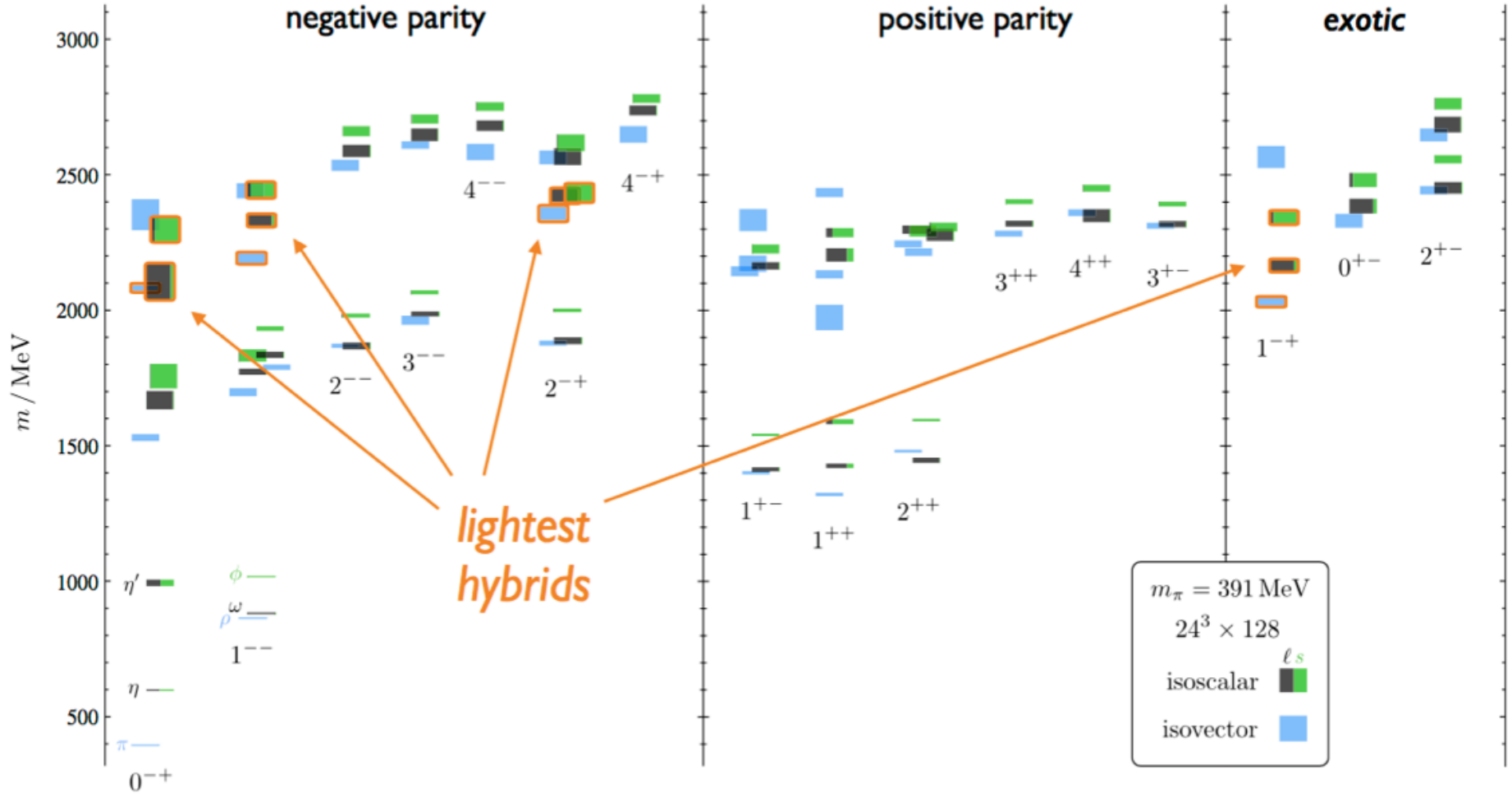
$J^{PC}_{const.\ gluon} = 1^{+-}$



bag-like hybrid

*Phys.Rev. D82 (2010) 034508

LQCD Calculations: Exotic Meson Should Exist?



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

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

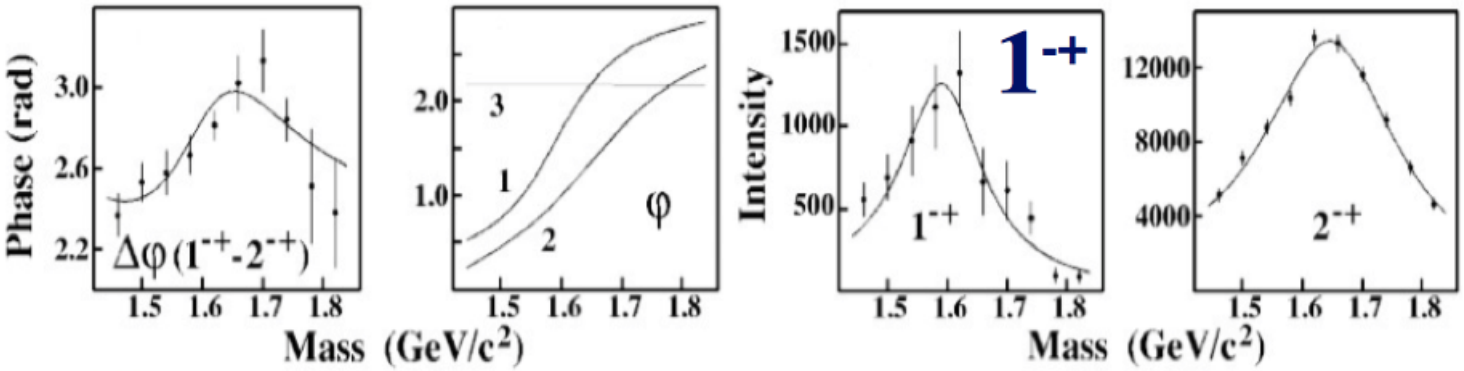


Figure: S.U. Chung *et al* [E852], Phys. Rev. **D65** 072001

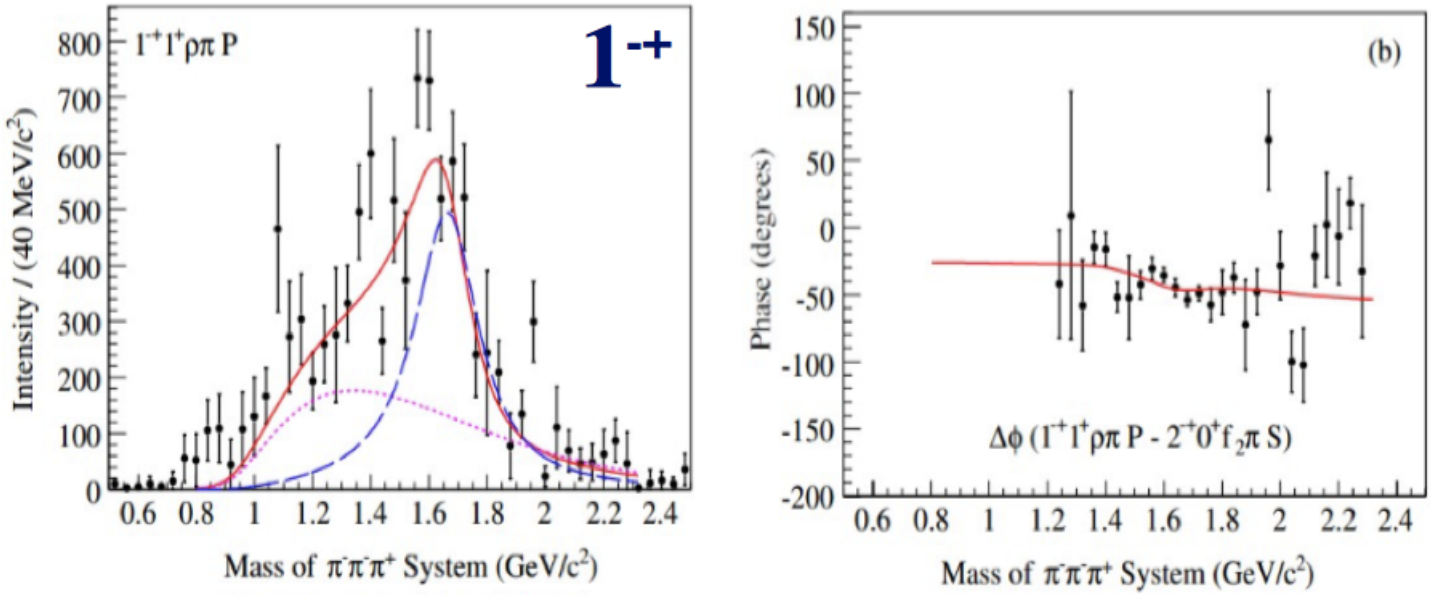
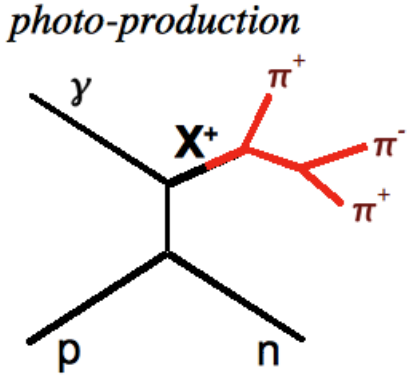


Figure: M. Alekseev *et al.* [COMPASS] Phys. Rev. Lett. **104**, 241803 (2010)

Recent CLAS results: g12



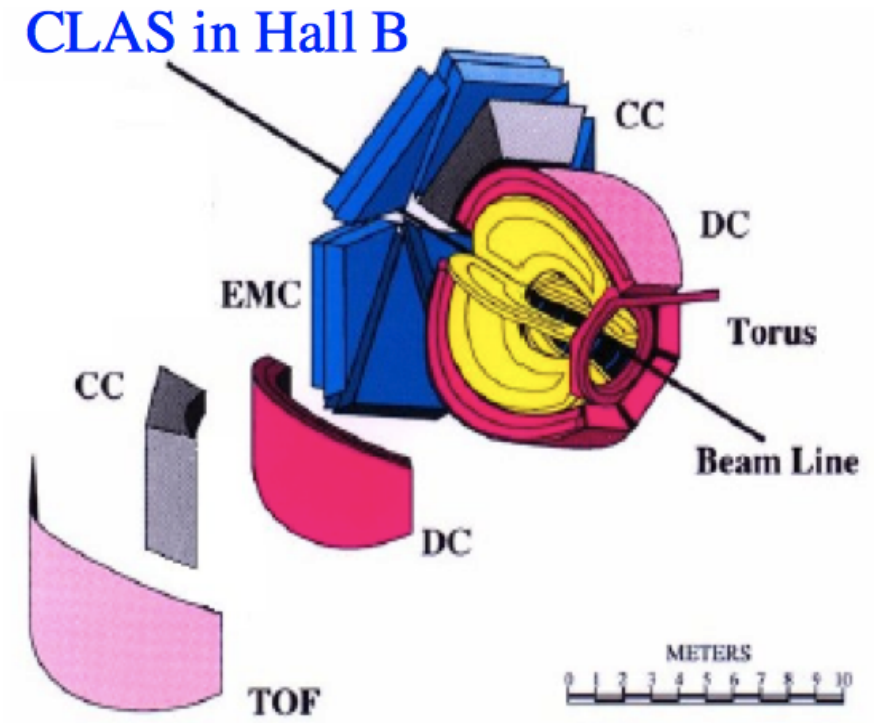
$\gamma\, p \rightarrow n\, \pi^+\, \pi^+\, \pi^-$

Production Data

I = 60-65 nA
E_g = 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
+ ...

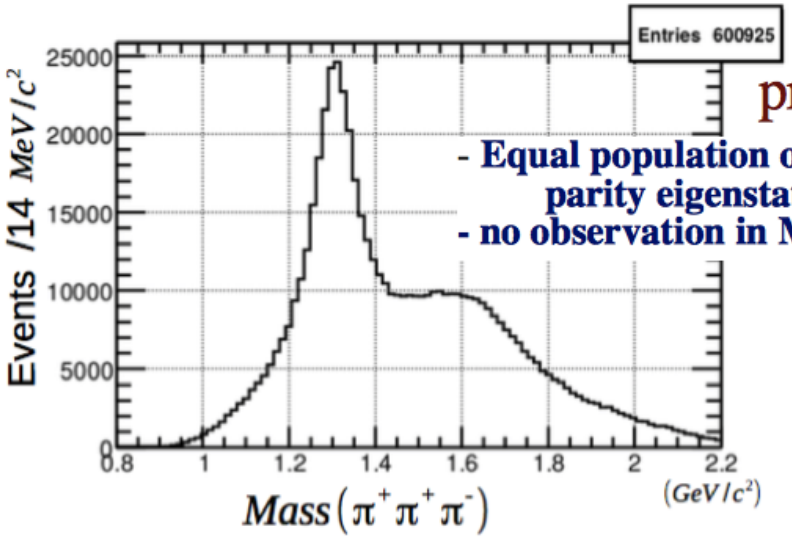


CLAS geometry optimized for peripheral production acceptance

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

CLAS g12

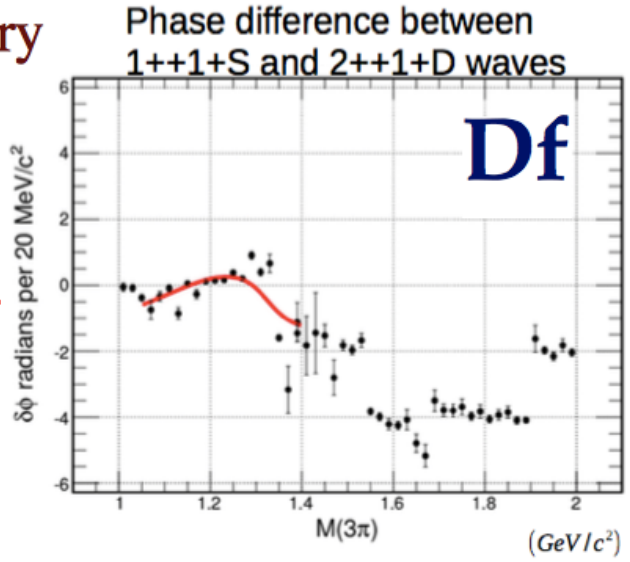
First observation of the $a_1(1260)$ in photoproduction

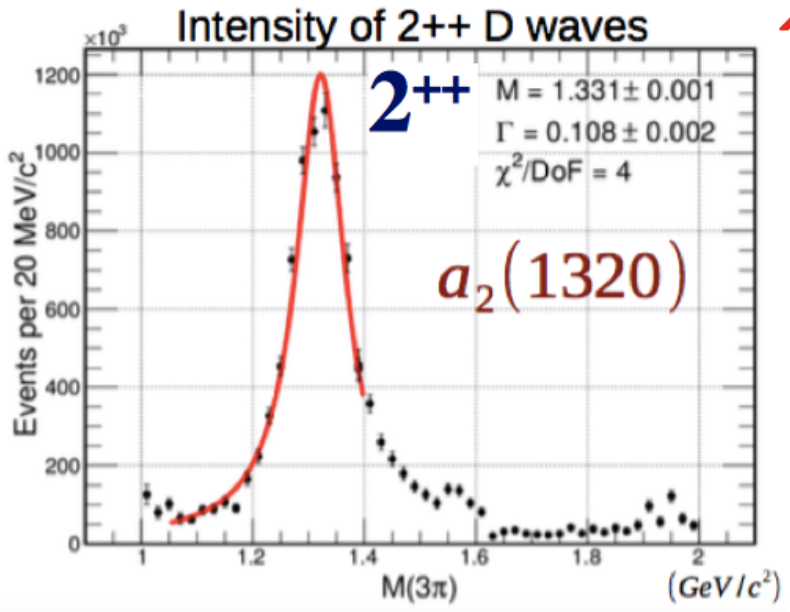


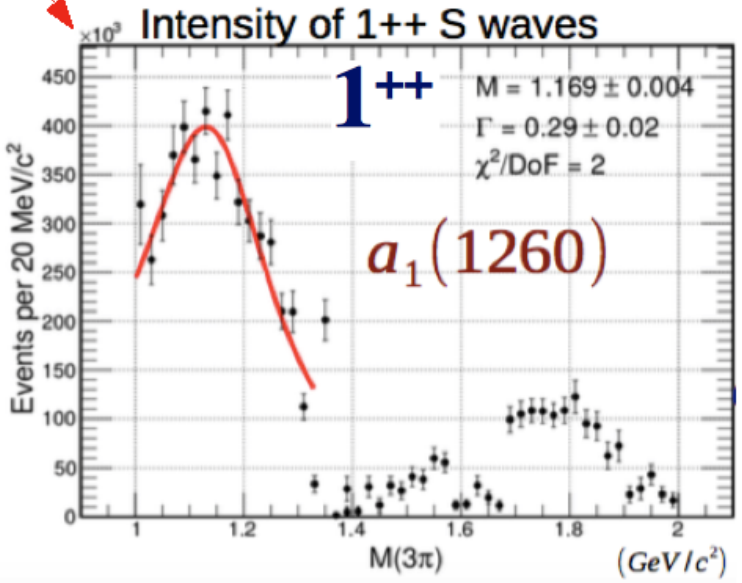
preliminary

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

PWA



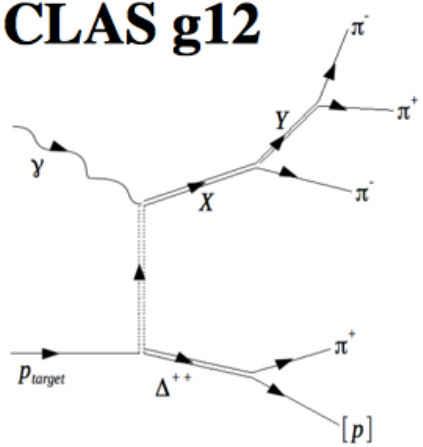


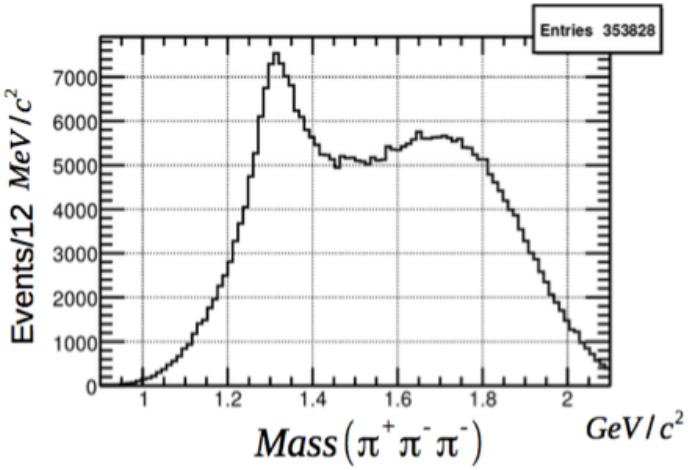


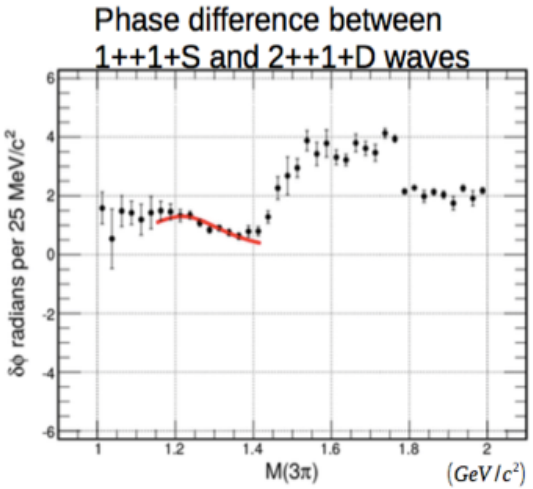
A. Tsaris (2016 FSU Dissertation)

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

CLAS g12

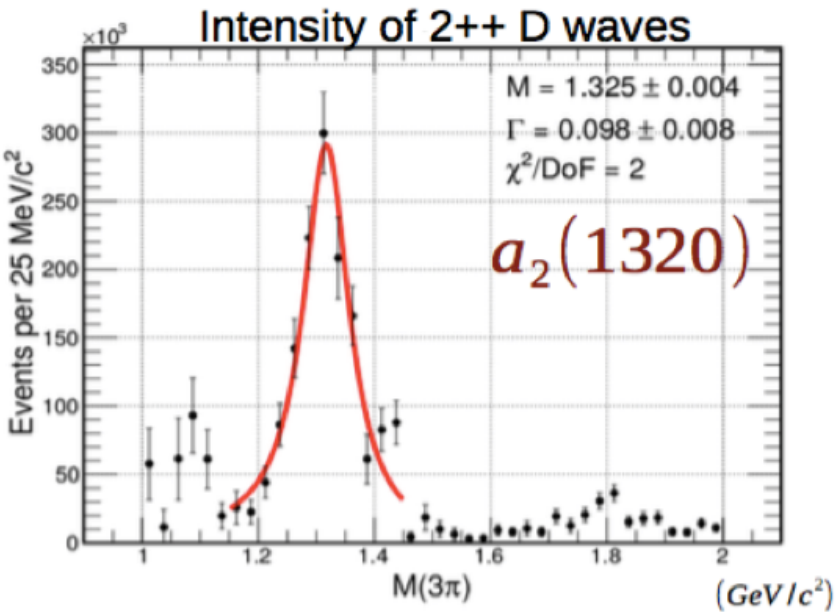


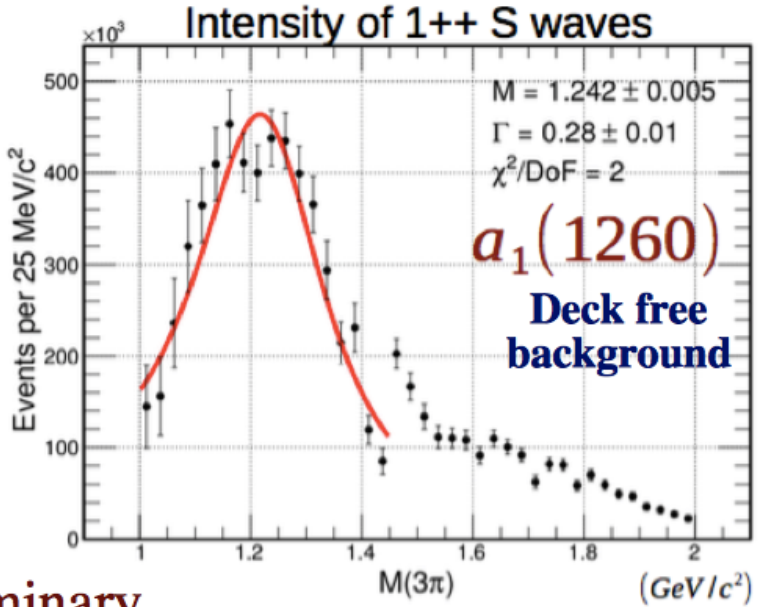




Confirmation of the $a_1(1260)$ in photoproduction

1^{-+} exotic wave was not required



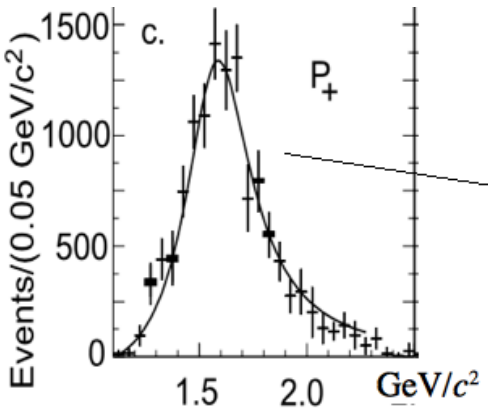


A. Tsaris (2016 FSU Dissertation)

preliminary

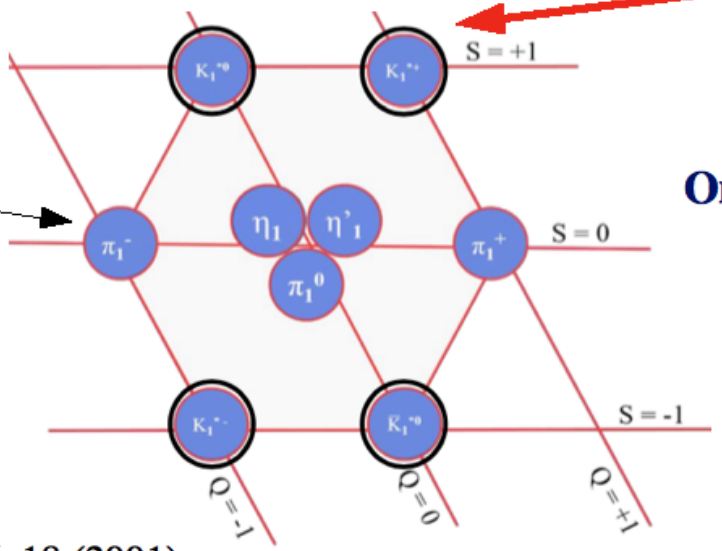
Strange Hybrids?

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



$M(\eta' \pi^-)$

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

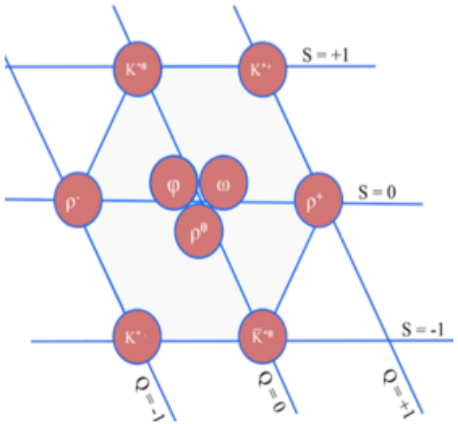


Excited strange companions to exotic states with $J^P = 1^-$

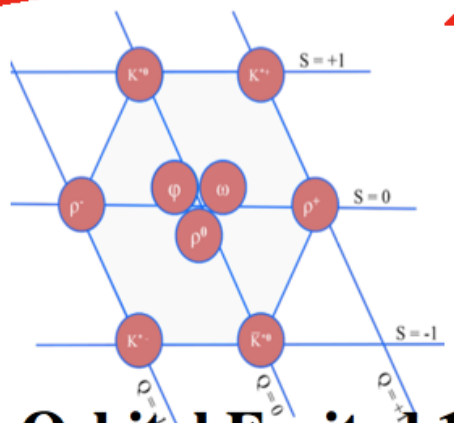
Only 3 Known 1^- Strange states: K*(892), K*(1410), K*(1680)

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

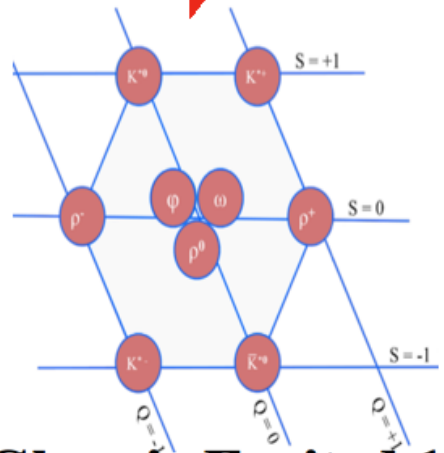
$J^{PC} = 1^{-+}$ Exotic states



Radial Excited 1^{--}

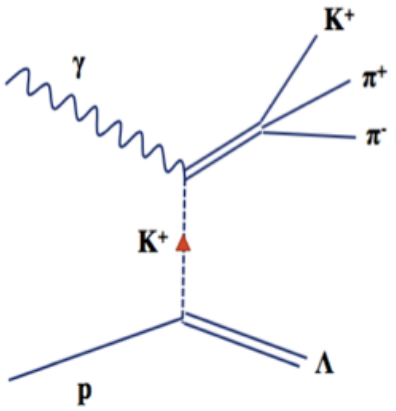


Orbital Excited 1^{--}

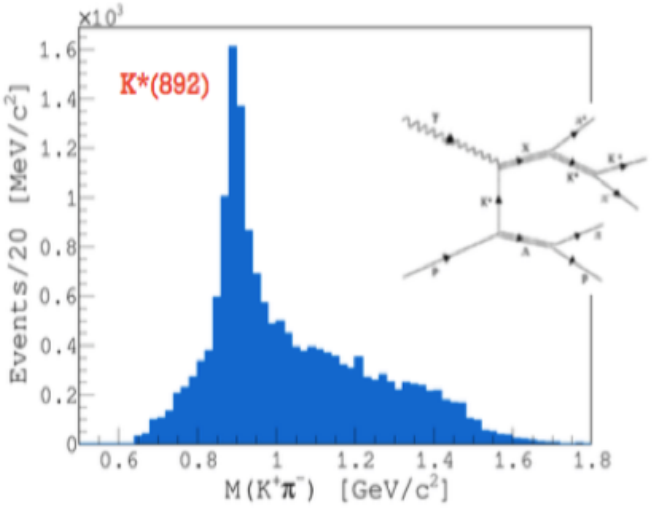


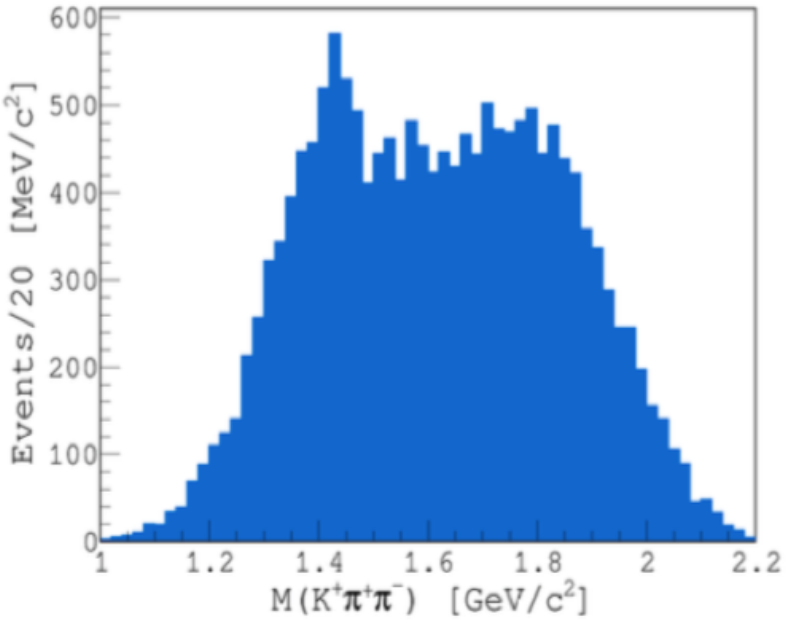
Gluonic Excited 1^{--}

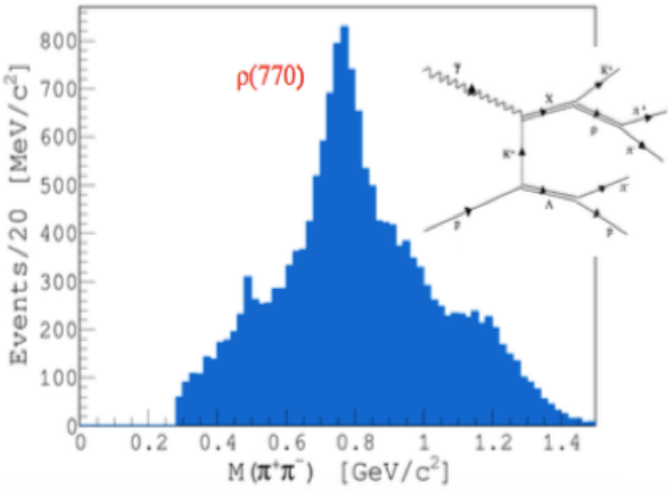
$\gamma p \rightarrow \Lambda K^+ \pi^+\pi^-$



Search for Excited Strange Mesons







The final dataset consisted of 16,618 Events !!

First ever analysis of Kpp photoproduction

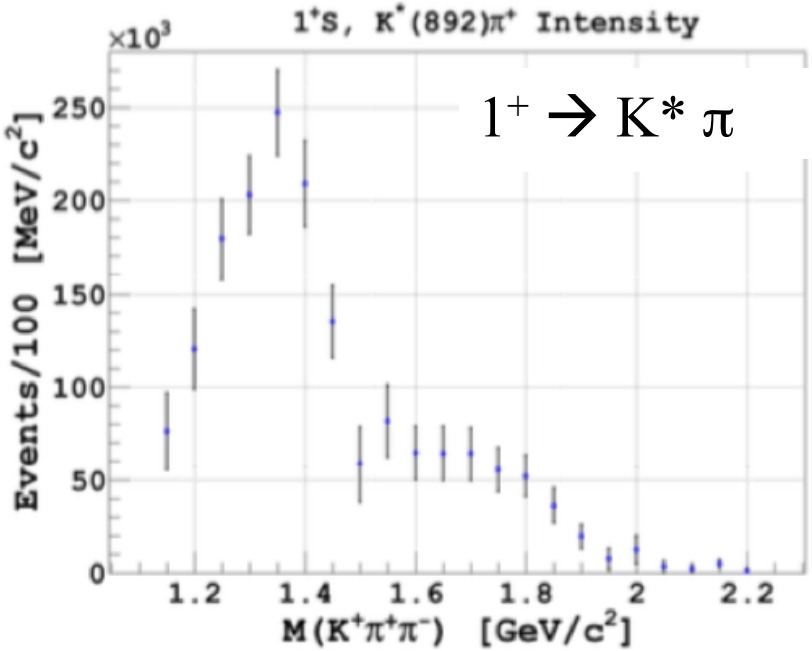
H. Al Ghoul
(2016 FSU Dissertation)

γp → Λ K⁺ π⁺π⁻ PWA results

preliminary

CLAS g12

PWA Results of 1⁺ S



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

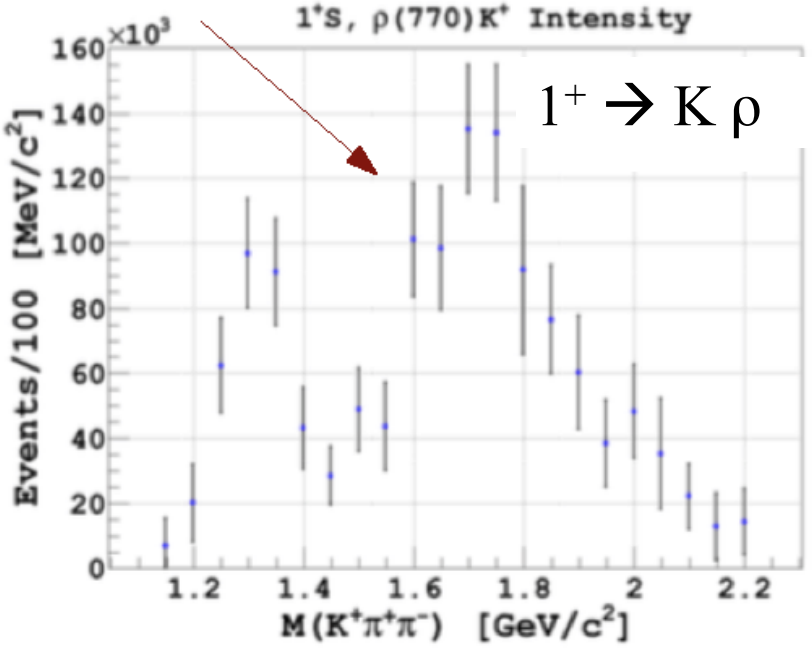
$K_1(1400)$ $I(J^P) = \frac{1}{2}(1^+)$

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



$K_1(1270) \rightarrow K^*p,\ Kr$

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

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

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γp → Λ K⁺ π⁺π⁻ PWA results

preliminary

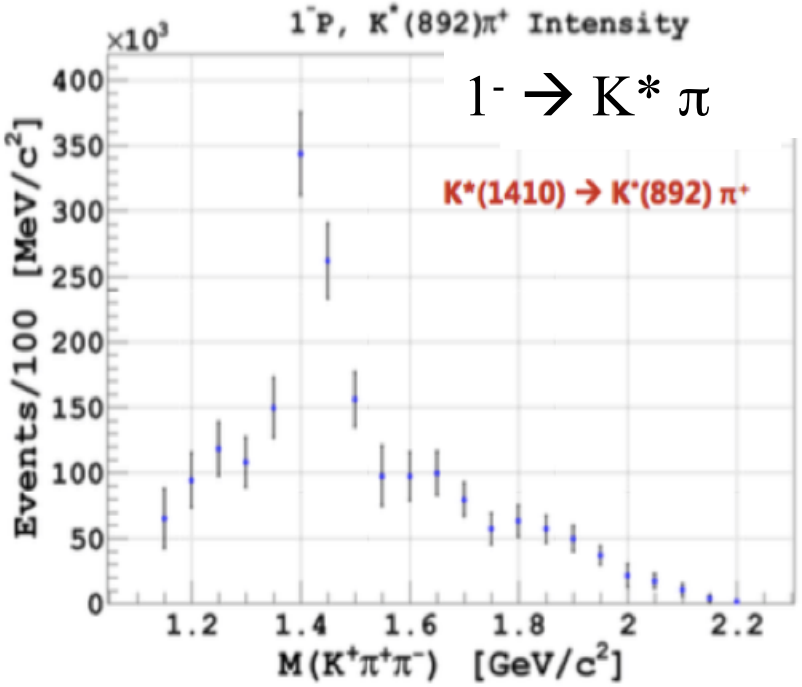
CLAS g12

PWA Results of 1⁻ P

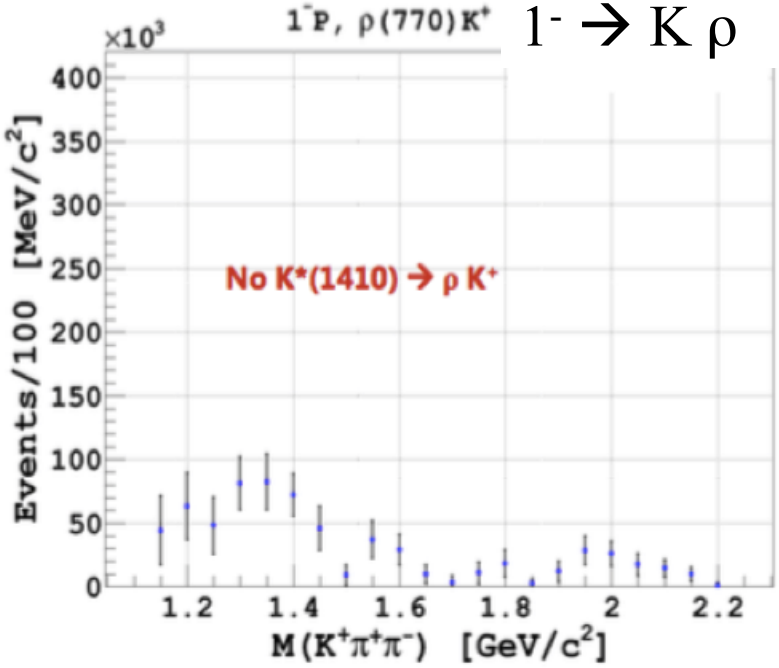
K*(1410) $I(J^P) = \frac{1}{2}(1^-)$

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



1⁻ → K* π



1⁻ → K ρ

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

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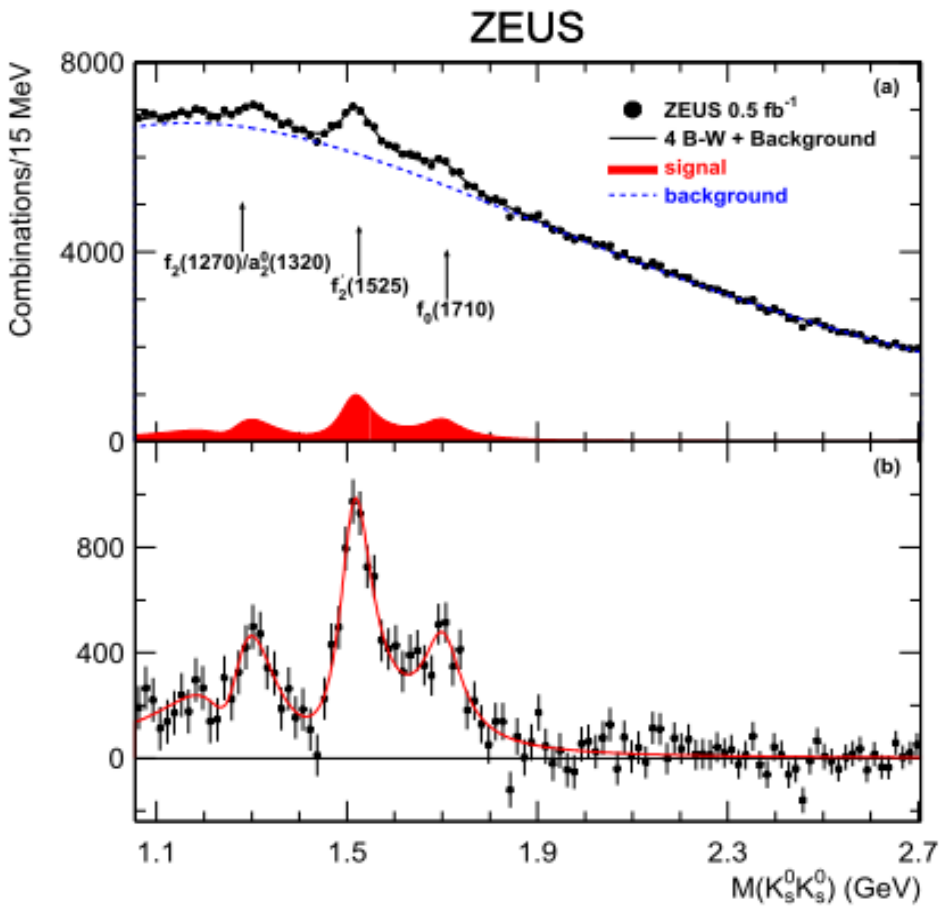
Scalar mesons and glueball candidates?

I=0

Name	Mass [MeV/c^2]
$f_0(600)$ *	$400 - 1200$
$f_0(980)$ *	980 ± 10
$f_0(1370)$ *	$1200 - 1500$
$f_0(1500)$ *	1507 ± 5
$f_0(1710)$ *	1718 ± 6

- There are 5 **isoscalar** states identified by experiment: f0 (600),f_0(980), f_0(1370), f_0 (1500) and f_0(1710)
- There are only 2 slots for the f_0 states in the quark model
- The assignments of the f_0 states is still uncertain
  - Glueball content/mixture?

Scalar mesons and glueball candidates?



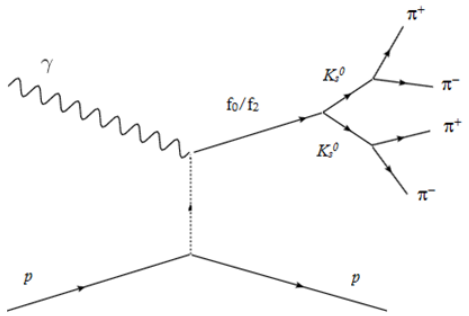
ZEUS Collaboration: S. Chekanov, et al, *Inclusive $K^0_S K^0_S$ resonance production in ep collisions at HERA, Phys.Rev.Lett. 101:112003,2008, arXiv:0806.0807v2*

Why choose strange decay?

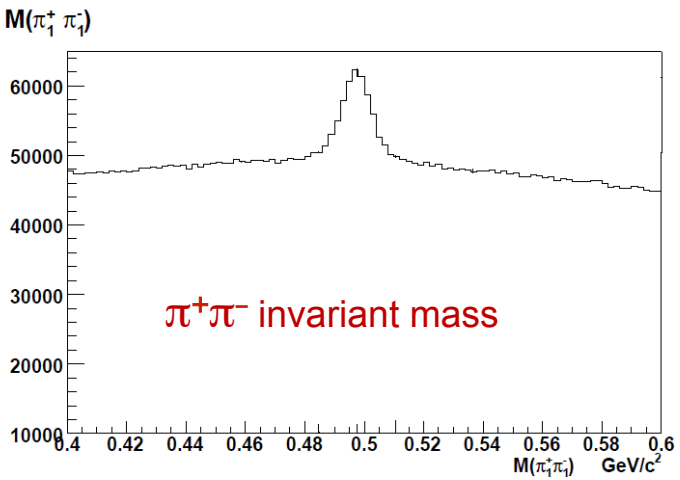
M.Chanowitz suggests in PRL 95, 172001 (2005) that glueballs are more likely to decay to strange channels

Why choose $K_s^0 K_s^0$?

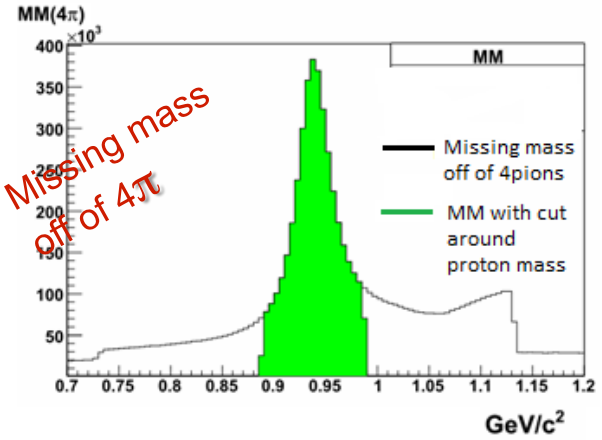
Ensure that the final state has the same PC =++ as the lightest glueball

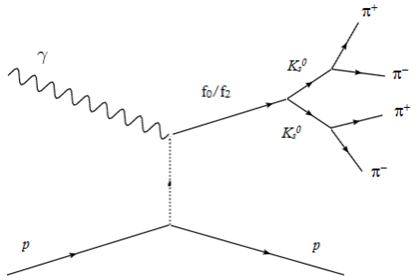


CLAS g12: Scalar mesons and glueball candidates?



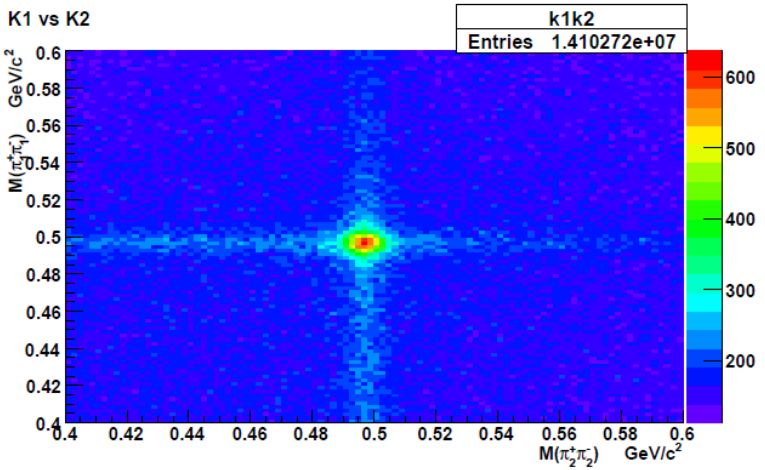
There is a clear kaon peak above the combinatorial background





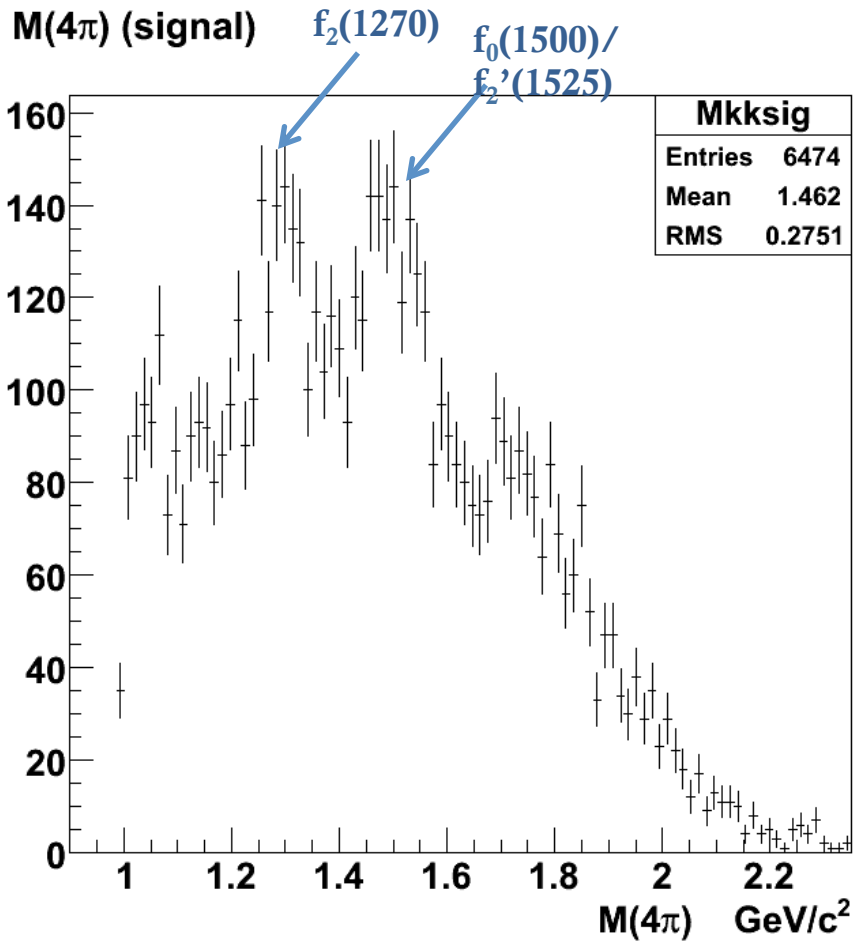
Only those events are selected which have a missing mass of the proton

The plot of the two K_s^0 plotted against each other shows the high correlation between them.



4 combinations of $\pi^+\pi^-$ are possible. We select the 2 combinations that most closely match the PDG value of the Ks mass.

CLAS g12: Scalar mesons



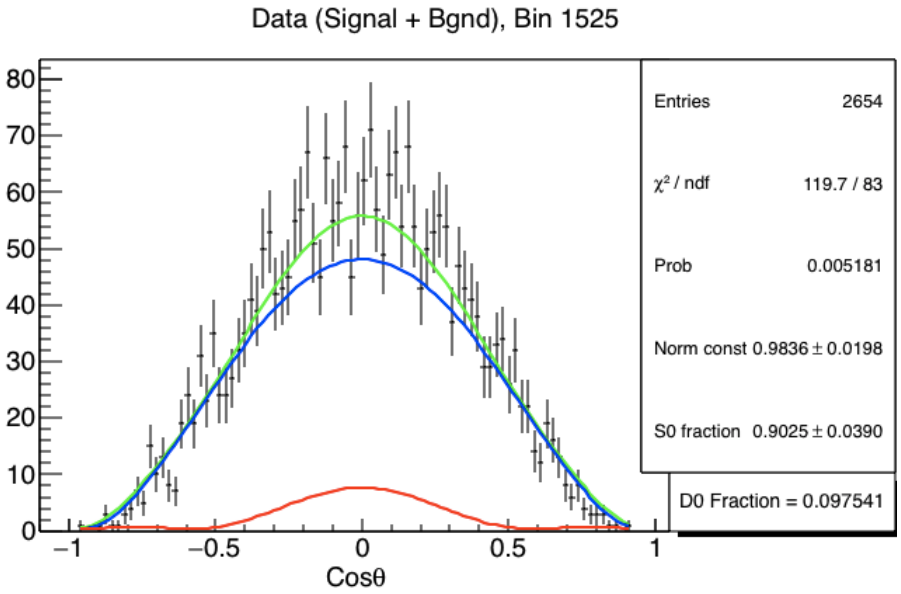
Not corrected for acceptance

The cuts:

- Timing cuts for pion identification
- Missing mass (proton)
- DOCA of each pion pair
- DOCA of kaon pair
- $E\gamma > 2.7$ GeV
- Kinematic fit confidence level > 10%

The $K_s^0 K_s^0$ invariant mass spectrum has a peak around 1270 MeV and another around 1500 MeV.

CLAS g12: Scalar mesons
S-wave domination



- PWA attempted but not successful
- Angular distributions analyzed and compared with simulaton
- S-wave dominates

Mass Bin (MeV)	S-wave fraction (S+B region)	S-wave fraction (Sidebands)
1000-1050	1.000 ± 0.045	1.000 ± 0.031
1050-1100	1.000 ± 0.031	1.000 ± 0.029
1100-1150	0.973 ± 0.025	0.982 ± 0.018
1150-1200	1.000 ± 0.023	1.000 ± 0.015
1200-1250	1.000 ± 0.022	1.000 ± 0.011
1250-1300	1.000 ± 0.013	1.000 ± 0.063
1300-1350	1.000 ± 0.020	1.000 ± 0.011
1350-1400	1.000 ± 0.028	1.000 ± 0.026
1400-1450	1.000 ± 0.025	0.922 ± 0.019
1450-1500	0.928 ± 0.037	0.890 ± 0.023
1500-1550	0.903 ± 0.039	0.879 ± 0.021
1550-1600	0.803 ± 0.044	0.897 ± 0.024
1600-1650	0.791 ± 0.056	0.883 ± 0.032
1650-1700	0.762 ± 0.052	0.910 ± 0.031
1700-1750	0.660 ± 0.053	0.902 ± 0.033
1750-1800	0.690 ± 0.071	0.941 ± 0.041
1800-1850	0.845 ± 0.086	0.994 ± 0.096

CLAS g11: First observation of $f_0(980)$ in photoproduction

MB, R.DeVita A. Szczpaniak et al Phys.Rev.Lett. 102:102001,2009
MB, R.DeVita A. Szczpaniak et al Phys.Rev. D80:072005,2009

$\gamma p \rightarrow p \pi \pi$

$M(\pi^+\pi^-)$ spectrum below 1.5 GeV:

- P-wave: ρ meson
- D-wave: $f_2(1270)$
- S-wave: σ, $f_0(980)$ and $f_0(1320)$

$$\langle Y_{\lambda\mu}\rangle(E_\gamma,t,M)=\frac{1}{\sqrt{4\pi}}\int d\Omega_\pi \frac{d\sigma}{dtdMd\Omega_\pi}Y_{\lambda\mu}(\Omega_\pi)$$

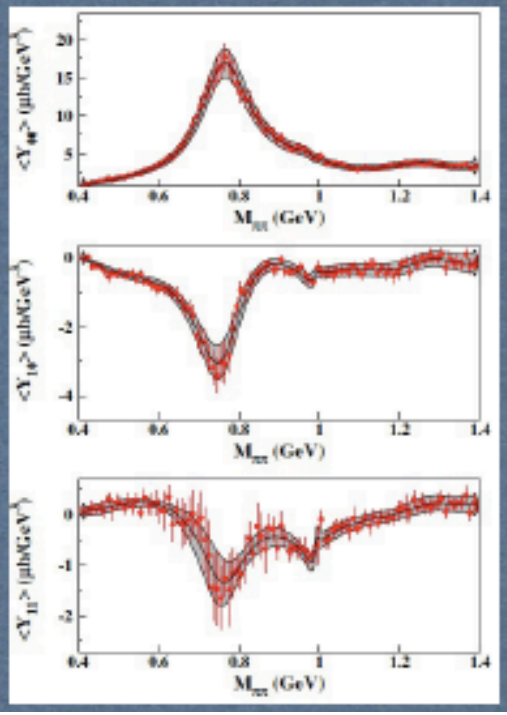
Amplitude parametrization (Dispersion relation)

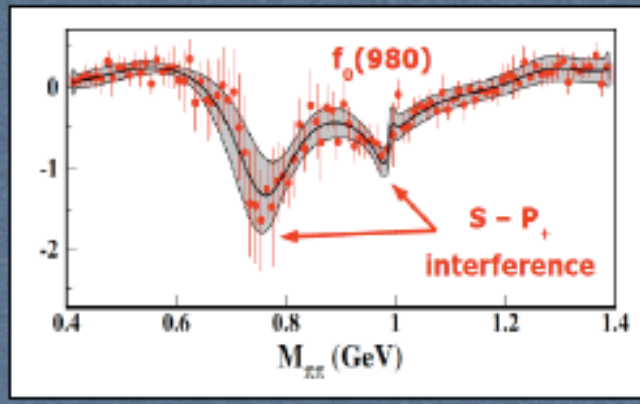
Related to ππ scattering matrix: phase-shift, inelasticity, S-P-D-F amplitude in 0.4 GeV < $M_{\pi\pi}$ < 1.4 GeV

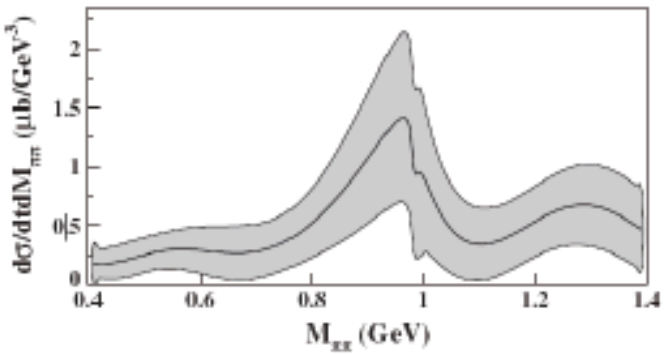
$$a_{lm,I}(s)=\frac{1}{2}[I+S_{lm,I}(s)]\tilde{a}_{lm,I}(s)-\frac{1}{\pi}D^{-1}_{lm,I}(s)PV\int_{s_0} ds'\frac{N_{lm,I}(s')\rho(s')\tilde{a}_{lm,I}(s')}{s'-s}$$

$$\tilde{a}_{lm,I}=[\mathcal{A}+\mathcal{B}s+\mathcal{C}s^2+\cdots][k]$$

Expanded in a Taylor series: coefficient fit to the experimental moment



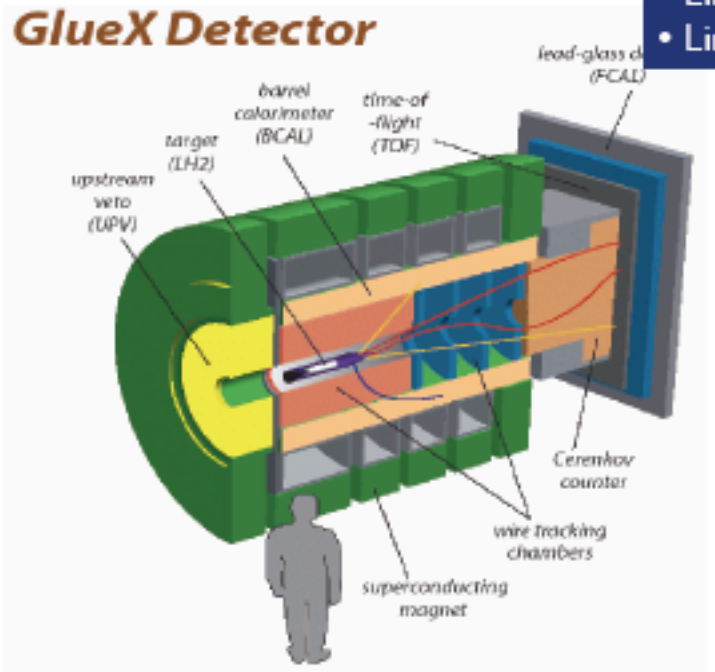




First observation of the $f_0(980)$ in a photoproduction experiment

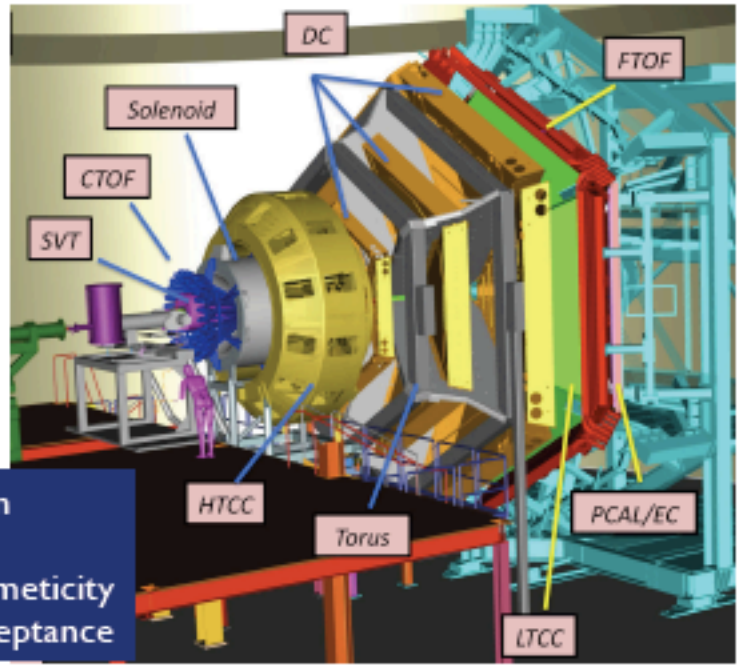
Meson Spectroscopy at JLAB 12 GeV
GlueX and CLAS12

Hall-D - GlueX Detector



- Good hermeticity
- Uniform acceptance
- Limited resolution
- Limited pID

Hall-B - CLAS12 Detector



- Good resolution
- Good pID
- Reasonable hermeticity
- Un-uniform acceptance

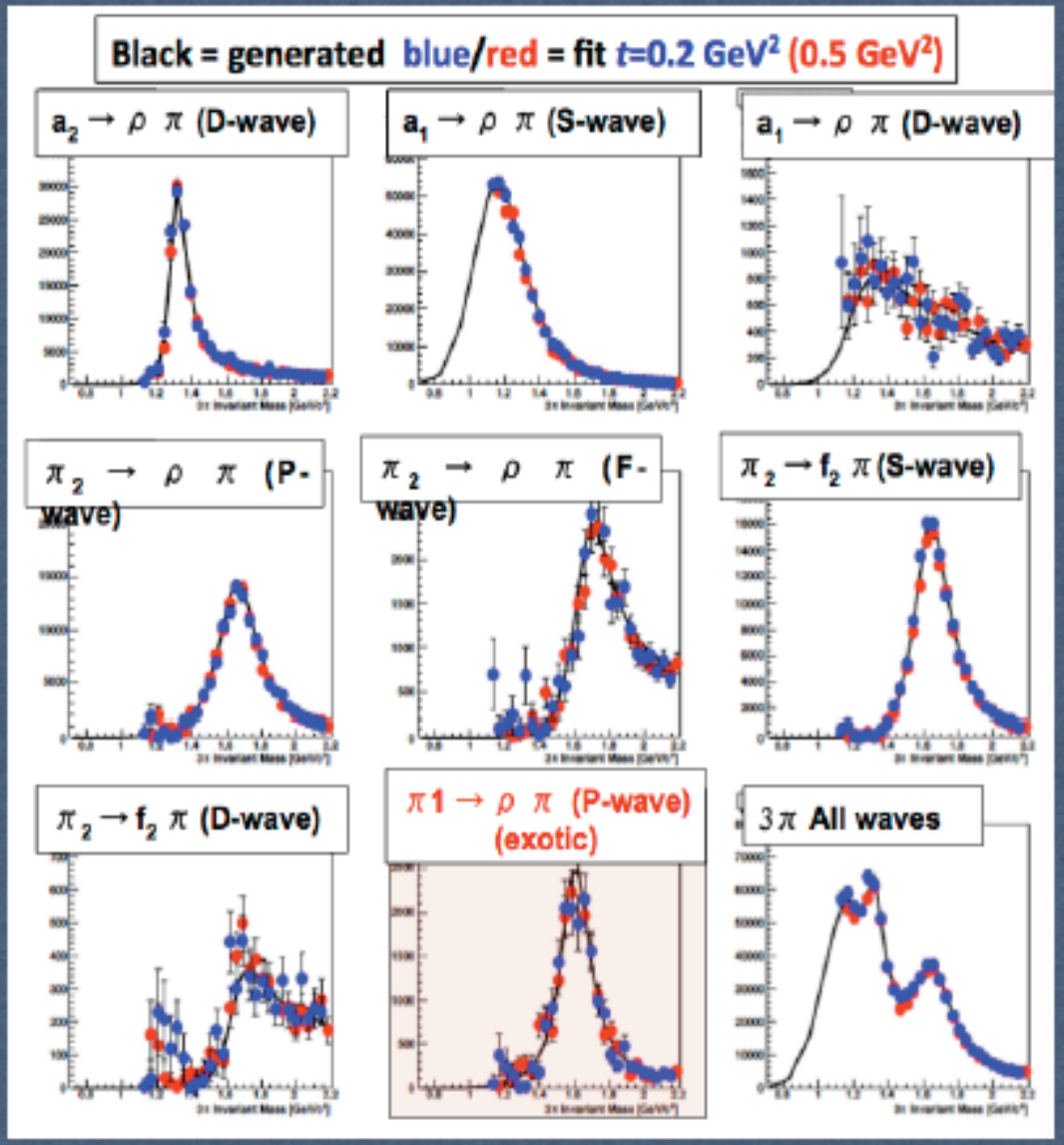
CLAS12: PWA with FAST MC

D.Glazier (U of Glasgow)

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

- The process is described as sum of 8 isobar channels:
  - $a_2 \rightarrow \rho \pi$ (D-wave)
  - $a_1 \rightarrow \rho \pi$ (S-wave)
  - $a_1 \rightarrow \rho \pi$ (D-wave)
  - $\pi_2 \rightarrow \rho \pi$ (P-wave)
  - $\pi_2 \rightarrow \rho \pi$ (F-wave)
  - $\pi_2 \rightarrow f_2 \pi$(S-wave)
  - $\pi_2 \rightarrow f_2 \pi$ (D-wave)
  - $\pi 1 \rightarrow \rho \pi$ (P-wave) (exotic)
- Amplitudes calculated by A.Szczepaniak and P.Guo
- CLAS12 acceptance projected and fitted
- PWA is stable against CLAS12 acceptance/ resolution distortion

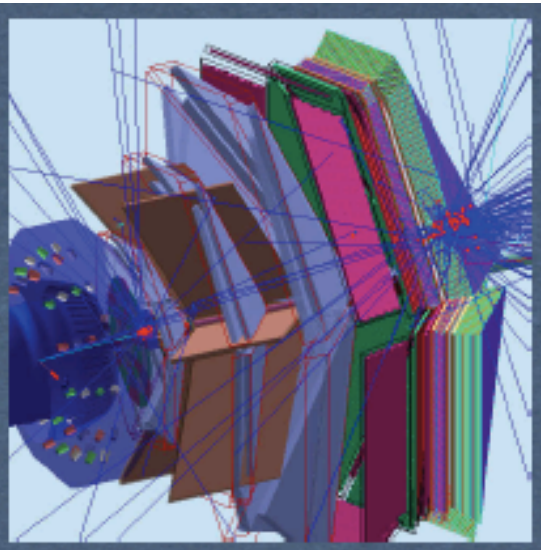
PWA in CLAS12 is feasible!

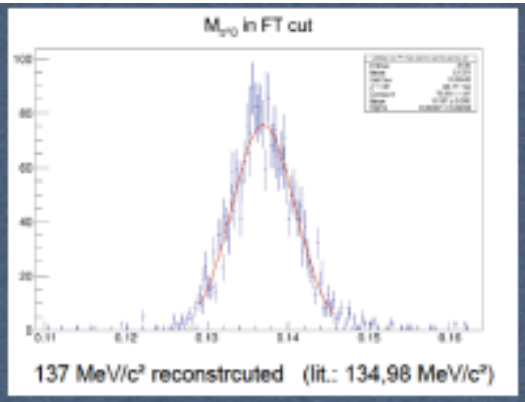


CLAS12: PWA with Realistic Simulation

e p → e' p π0 (γ p → p π0)

- S.Diehl (U Giessen)
- Full CLAS12 GEANT4 simulation
- Full reconstruction
- Electroproduction amplitudes provided by JPAC (V.Mathieu)
- AMPTOOLS
- Electron detected at small angles in the CLAS12-FT

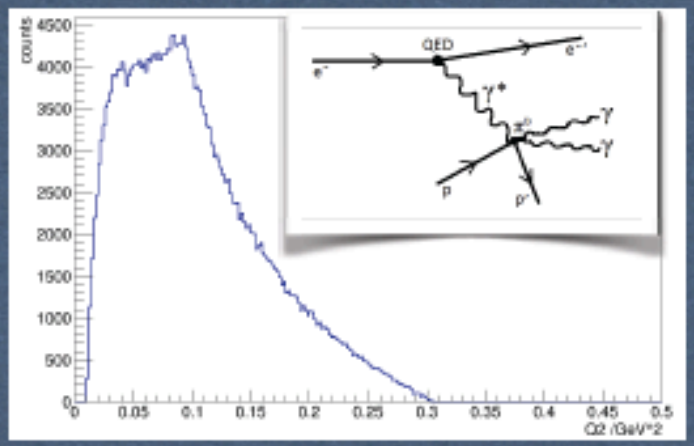


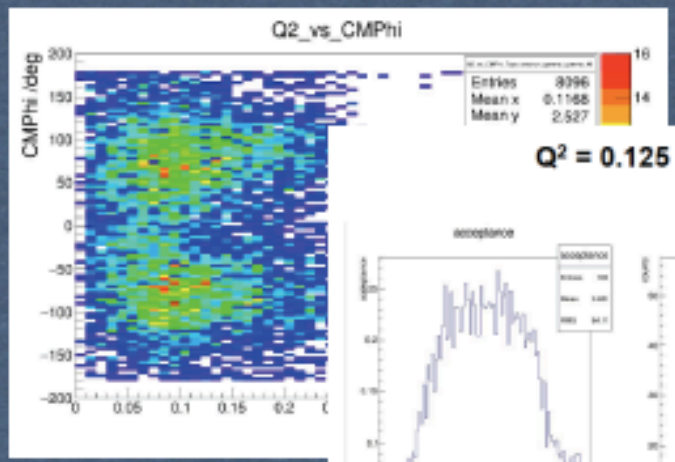


High level physics analysis

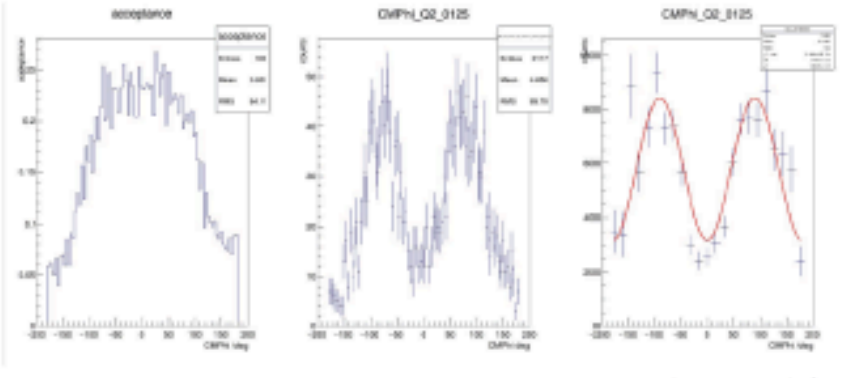
- γ_v Linear polarisation: σ'_{TT} (Σ)
- Xsection
- Large-t behaviour - $d\sigma/dt(90^o)$

- e- polarisation: σ_{TL} (not available in photoproduction!)
- Full PWA

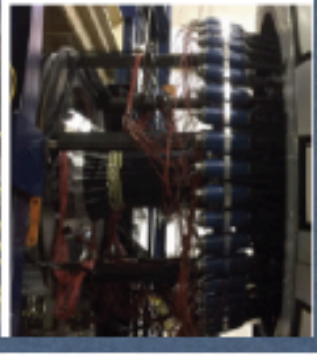




Q^2 = 0.125 GeV² (0.10 – 0.15 GeV²)

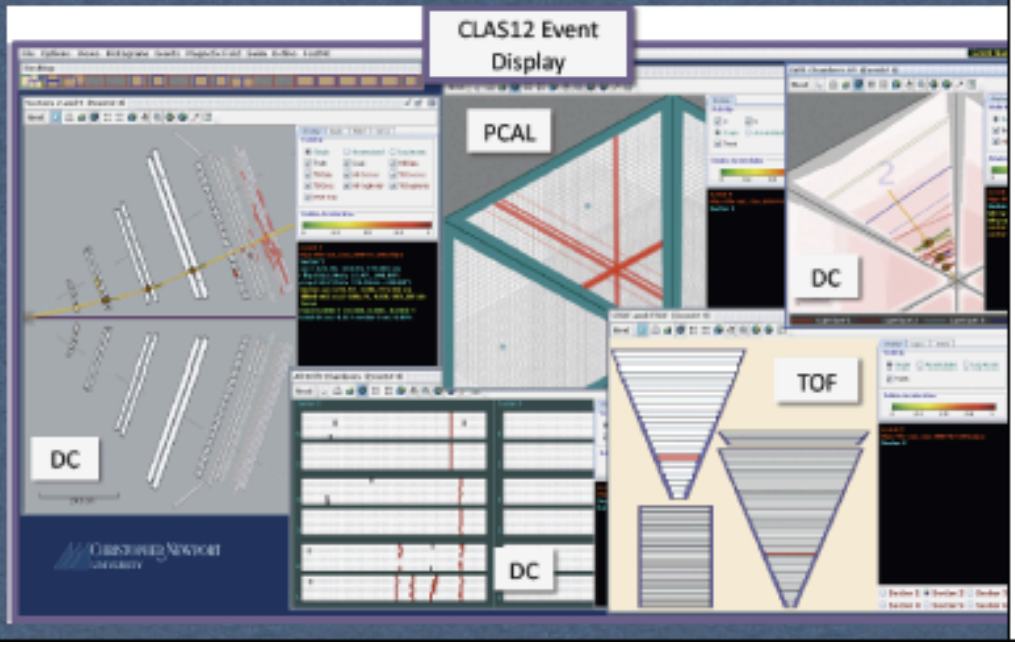


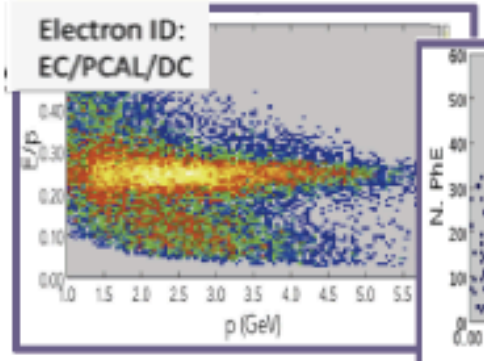
CLAS12: KPP run

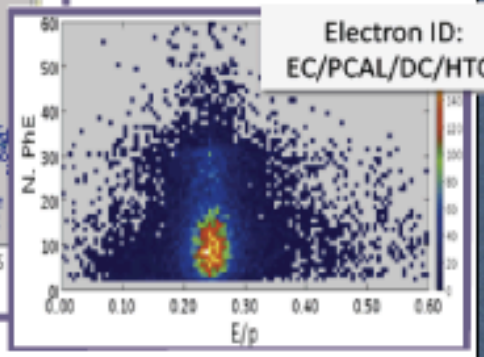


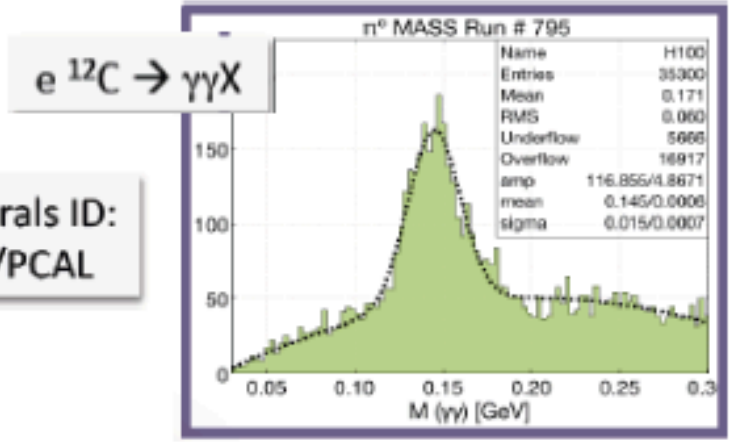
First data tacking with CLAS12

- ★ Short test run in February at E=6.5 GeV
- ★ All base equipment installed and operational (CTOF,DC, EC, FTOF, HTCC, LTCC, PCAL, SVT)
- ★ The run successfully proved the CLAS12 key performance parameters









Summary

- CLAS has been successful in various meson spectroscopy experiments/analysis
- No sighting/evidence for exotic meson/hybrids/ glueballs
- CLAS12, with higher energy and statistics, will start data collection soon (Spring 2018)

  Stay tuned!

Acknowledgement

- Organizers and Jefferson Lab
- Paul Euginio/Ken Hicks/Marco Battegleri
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