Meson Spectroscopy at CLAS

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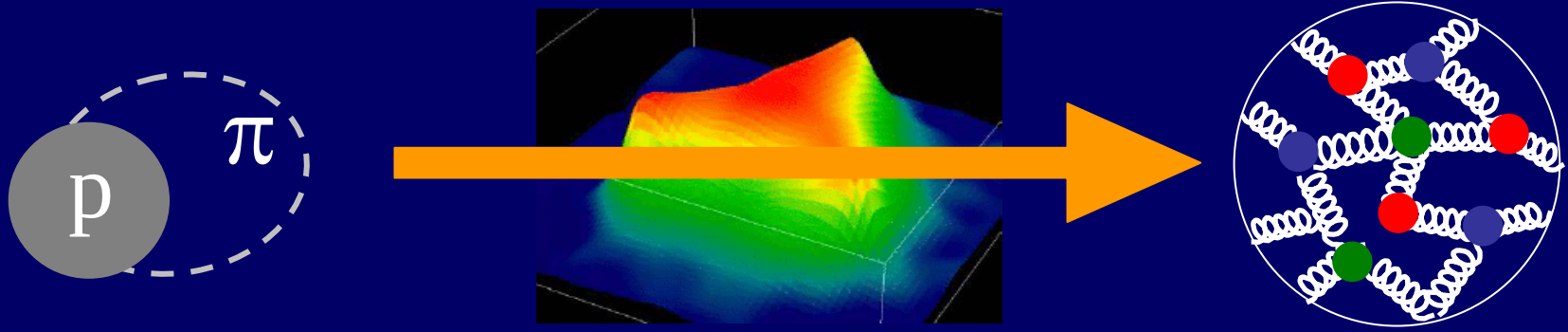
EINN09
Milos, Greece
2 October 2009

Why hadron spectroscopy?

- QCD is responsible for most of the observed mass in the universe
- Precise determination of the spectrum and internal structure of hadrons is necessary to reach a deep understanding of QCD
  - Revealing the nature of the mass of the hadrons
  - Identify the relevant degrees of freedom
  - Understand the origin of confinement
  - Validate LQCD predictions
- Meson production is a key tool to investigate these issues

> 1 fm | **0.1 – 1 fm** | **<< 0.1 fm**



Mesons & Baryons | Effective Degrees of Freedom | Quarks and Gluons

Meson Production at CLAS

Dynamic properties of constituent partons

- Vector meson photoproduction at large $-t$
- Vector meson electroproduction at large Q^2

→ Exclusive electro- and photo- scattering in a wide kinematic range

Beyond the standard quark model

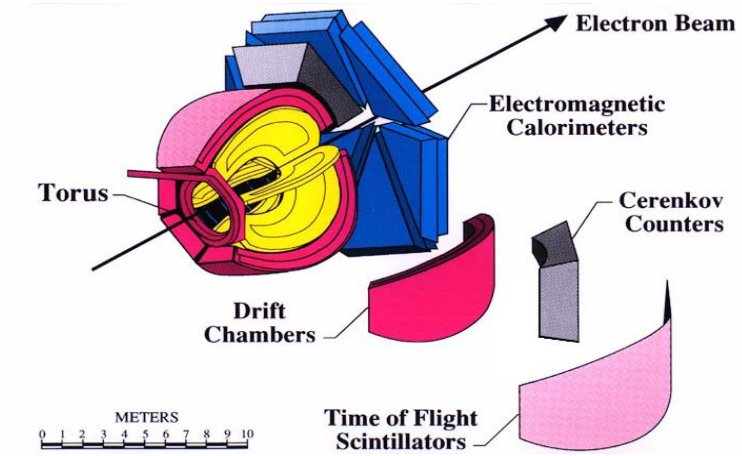
- Light meson spectroscopy and PWA with CLAS

→ High statistics, high resolution, measurement of multi-particle exclusive final states

Recent Results from Photoproduction of $\pi^+\pi^-$ Pairs on the Proton:

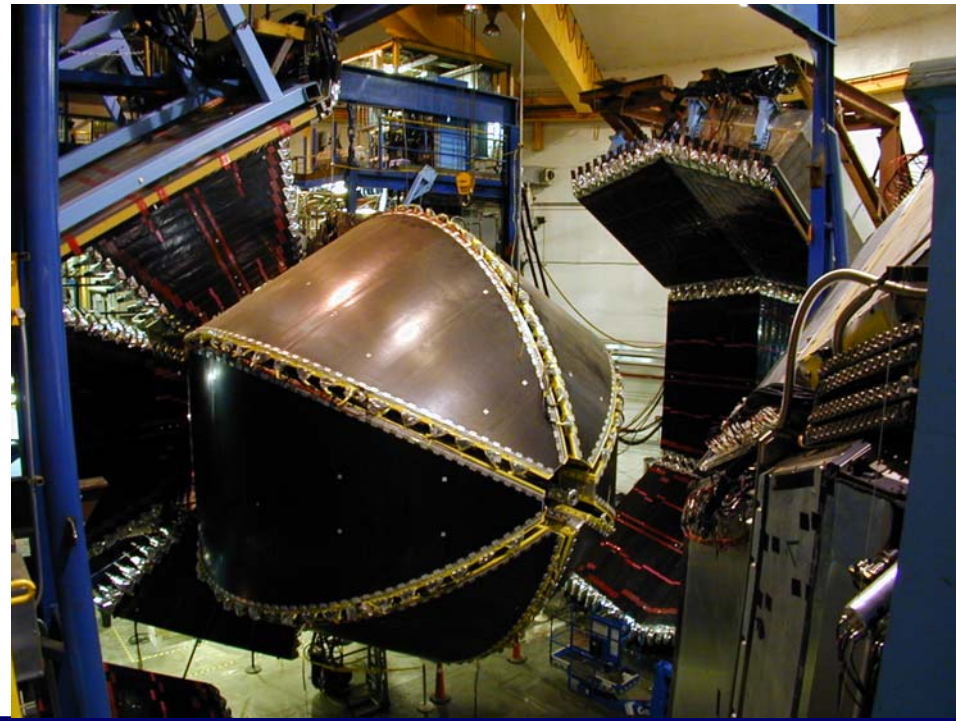
Photoproduction of the $f_0(980)$

The CLAS Spectrometer



CEBAF
Large
Acceptance
Spectrometer

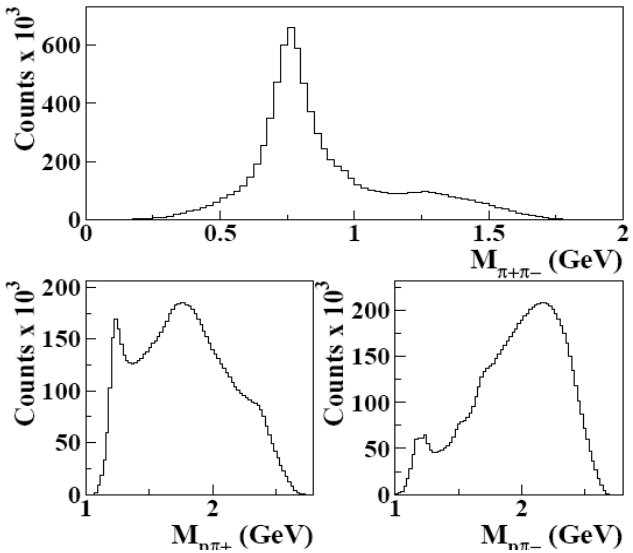
- magnetic spectrometer based on six-coil toroidal field
- large kinematical coverage
- high luminosity: $10^{34}cm^{-2}s^{-1}$
- simultaneous measurement of exclusive and inclusive reactions
- central field-free region well suited for the insertion of a polarized target
- Bremsstrahlung photon tagger

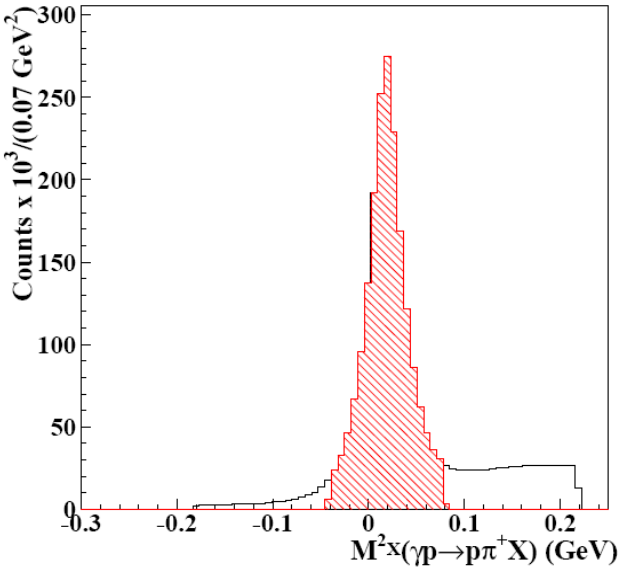


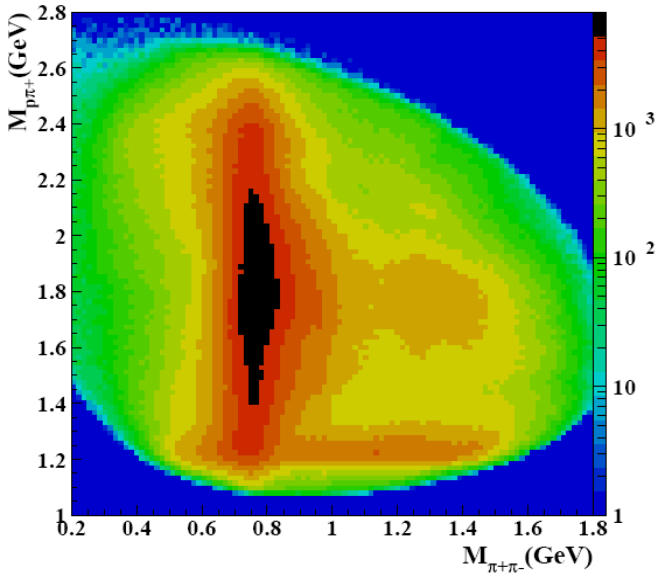
$\pi^+\pi^-$ Photoproduction

G11 Experiment:

- Bremsstrahlung photon beam: 1.6-3.8 GeV
- 40 cm long liquid hydrogen target
- ~$7 \cdot 10^9$ triggers
- Integrated Luminosity ~ 80 pb^{-1}
- Proton and π^+ detected in CLAS
- Reaction $\gamma p \rightarrow p\pi^+\pi^-$ isolated via missing mass
- Analysis focused on high energy (3.0-3.8 GeV) and low $-t$ (0.4-1.0 GeV^2) region







Partial Wave Analysis

1) Extraction of Moments of the Di-Pion Angular Distribution

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

- Moments are expanded on a set of basis function and weighted with Monte Carlo events to account for detector acceptance and efficiency
- Moments are then fitted to the data using an unbinned likelihood procedure

2) Evaluation of Partial Waves from Experimental Moments

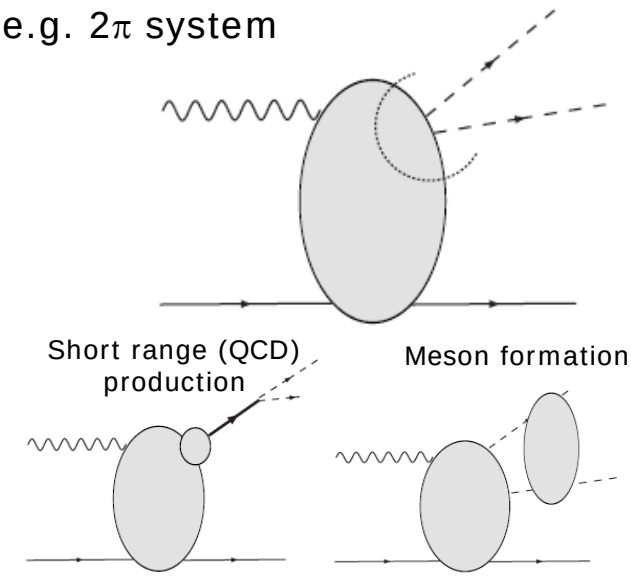
- Moments can be expressed as bilinear combination of partial wave amplitudes

$$\langle Y_{00}\rangle = N\left[|S|^2 + |P_-|^2 + |P_0|^2 + |P_+|^2 + |D_-|^2 + |D_0|^2 + |D_+|^2 + |F_-|^2 + |F_0|^2 + |F_+|^2\right]$$

- Partial Waves are parameterized using Dispersion Relations in term of known $\pi\pi$ phase shifts and unknown coefficients and fitted to the experimental moments

- Partial Wave cross sections are derived and can be compared with models

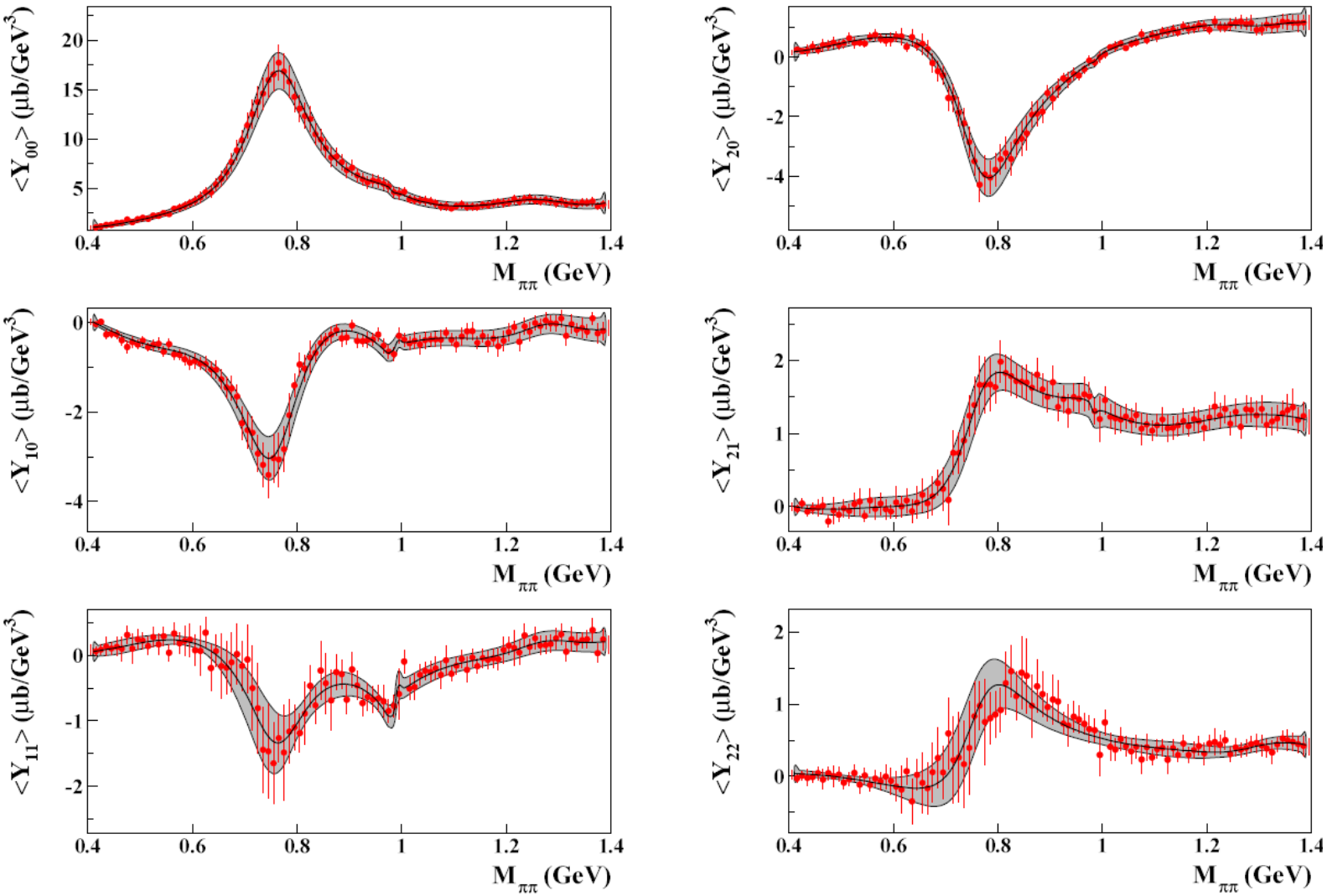
e.g. 2π system



Moments of the Di-Pion Angular Distribution

3.2 GeV < E_γ < 3.4 GeV

0.5 GeV^2 < -t < 0.6 GeV^2

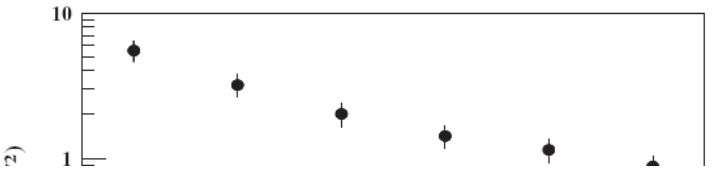


Partial Wave Amplitudes

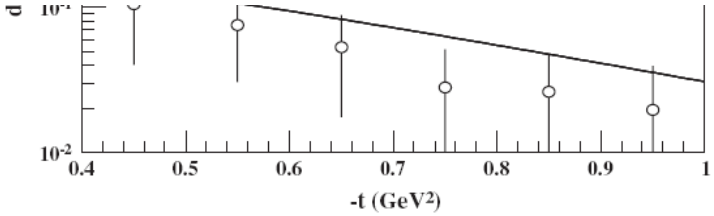
$\gamma p \rightarrow p\pi^+\pi^-$

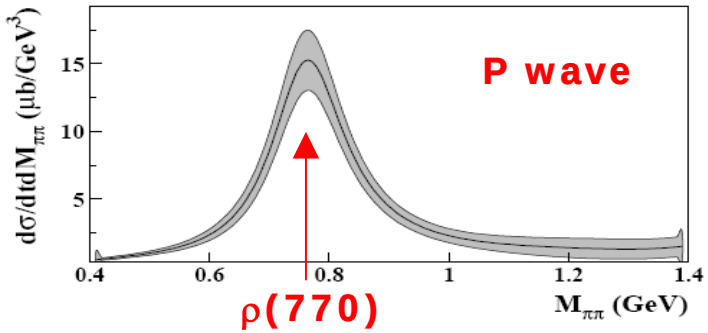
3.4 GeV < E_γ < 3.6 GeV
0.5 GeV^2 < -t < 0.6 GeV^2

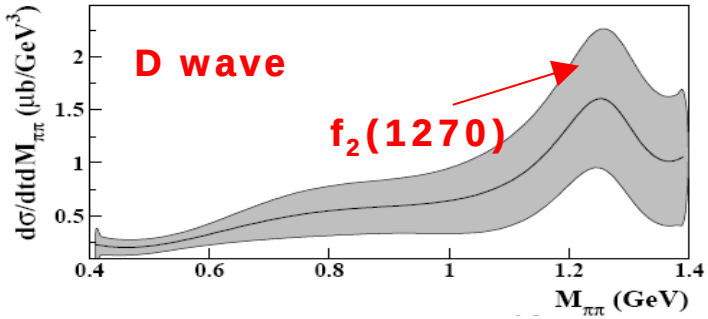
- M($\pi^+\pi^-$) spectrum below 1.5 GeV:
  - P-wave: ρ meson
  - D-wave: $f_2(1270)$
  - S-wave: σ, $f_0(980)$ and $f_0(1320)$
- Moments of the 2-pion angular distribution extracted via likelihood fit of data
- Partial Wave fitted to experimental moments
- **Known states well reproduced, e.g. $\rho(770)$**

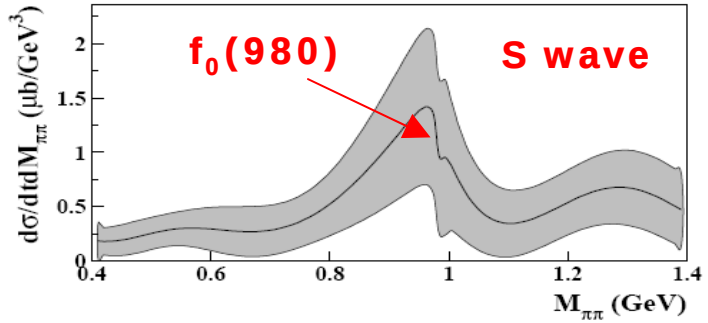


First observation of $f_0(980)$ in photoproduction









Ongoing Program

G12: Search for new forms of hadronic matter in photoproduction on the proton

- Data taking completed in 2008
- Photon Energy up to 5.4 GeV
- More than 26 billion triggers (2-prong + 3-prong)
- Total Luminosity: 68 pb^{-1}
- Several exclusive channels are being analyzed

EG6: Meson spectroscopy in coherent production on 4He

- 6 GeV electron beam on high pressure gas target
- Scattered electron at very small angles → quasi-real photo-production
- Search for exotics in $\pi\eta$, $\pi\eta'$ final states
- Recoiling nucleus detected in Radial TPC
- Hadronic final state detected in CLAS
- Data taking in progress

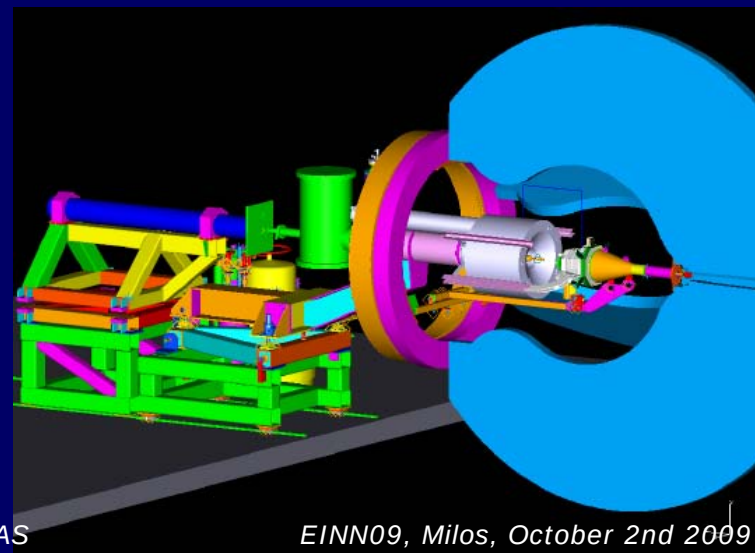
$$\gamma p \to \pi^+\pi^+\pi^-(n)$$

$$\gamma p \to K^+K^+\Xi^-(1530)$$

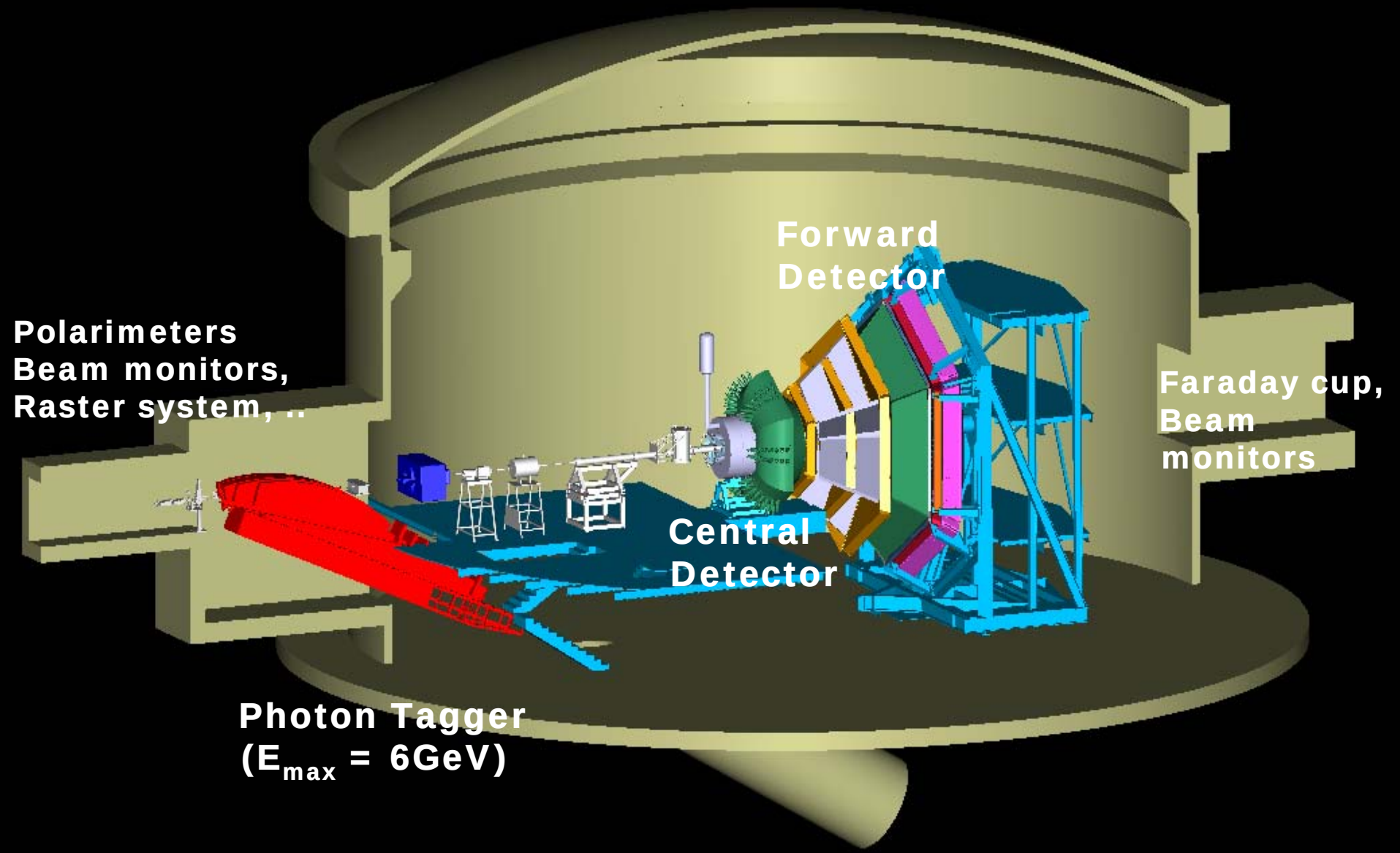
$$\gamma p \to pK^+K^-(n/\pi)$$

$$\gamma p \to p\pi^+\pi^-(n)$$

$$\gamma p \to \pi^+K^+K^-(n)$$



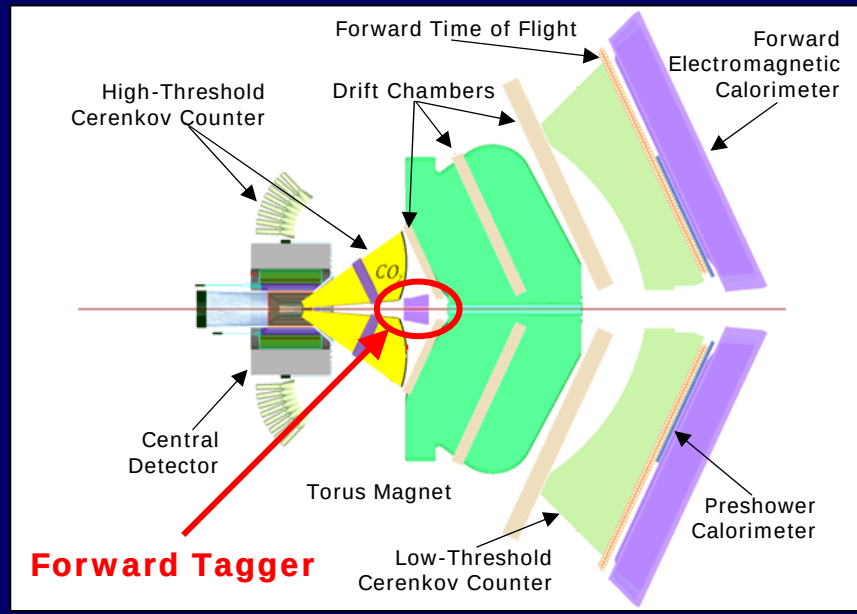
CLAS12


Forward
Detector
Polarimeters
Beam monitors,
Raster system, ..
Faraday cup,
Beam
monitors
Central
Detector
Photon Tagger
(E_{max} = 6GeV)

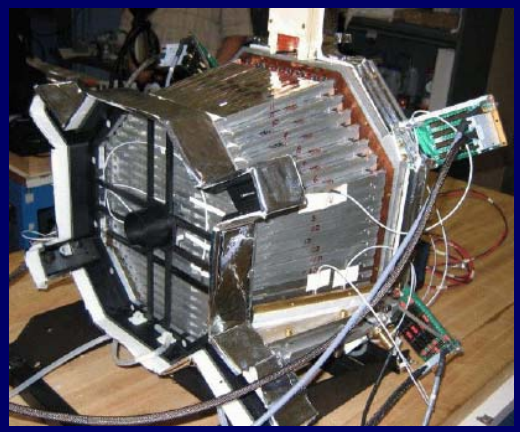
A Forward Photon Tagger for CLAS12

Use quasi-real photo-production with detection of scattered electrons at “0” degrees (LowQ, post-target tagging):

- electron beam on target, scattered electrons at small angles are detected
- hadronic final state is detected in CLAS12
- photon linear polarization ~ 65% - 20%
- luminosity will be limited by the forward tagger
- electromagnetic background



Electron detection via Tracker+Calorimeter for determination of angles and energy



PbWO4 Calorimeter
424 Crystals

Electron Detector	
E’	0.5-4GeV
ν	7-10.5 GeV
θ	1.9-7 deg
Q^2	0.006 – 0.6 GeV^2
Photon Flux	5 x 10^7 γ/s @ $L_e=10^{35}$
Rate	70 MHz @ $L_e=10^{35}$

Photoproduction with CLAS12

Availability of tagged photon beam in CLAS12 will open new possibilities for high quality physics beyond the already approved program:

- Meson spectroscopy
  - Partial Wave Analysis on H target
  - Spectroscopy on He4 and other gas targets
- Hadron spectroscopy
  - Heavy mass baryon resonances (Cascades)
- Compton scattering
- Meson polarizabilities
- Large $-t$ physics

Feasibility of forward tagger is presently being studied and conceptual design of electron detector is being developed

Summary

Rich physics program in meson spectroscopy with CLAS:

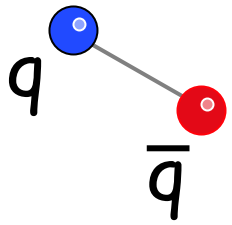
- Meson spectrum investigated in photoproduction
- PWA (Moments + Dispersion relations) feasible in CLAS
- First results published, experimental program continues...
- Present program will be extended with CLAS12 using quasi-real photoproduction

✱ Better understanding of hadrons structure
✱ Progress in understanding confinement in QCD and the role of constituent quarks and gluons in the description of the non-perturbative regime

Hybrid Mesons

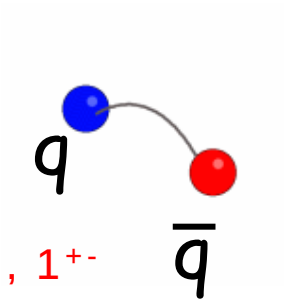
How can we find hints of the gluons that bind the quarks??

Normal meson:
flux tube in ground state



Hybrid meson:
flux tube in excited state

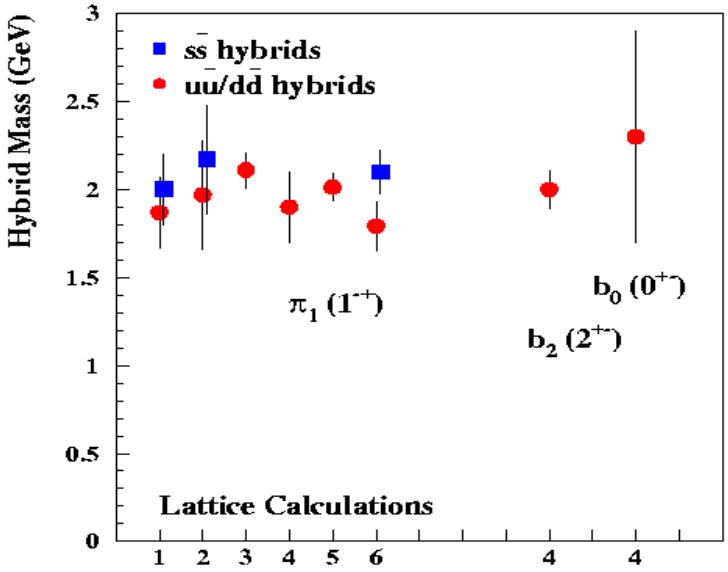
Flux tube $J^{PC}=1^{-+}$, 1^{+-}



Excitation of the flux tube leads to a **new spectrum of hadrons** that can have **exotic quantum numbers**

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

Lattice QCD calculations predict masses around 2 GeV, a range that can be explored at JLab



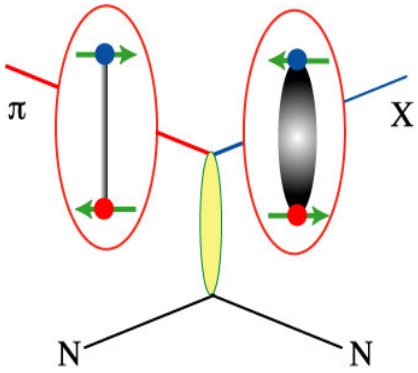
Search for Exotics in Photoproduction

- Photoproduction: exotic J^{PC} are more likely produced by S=1 probe

Pion Beam

Quark spins anti-aligned

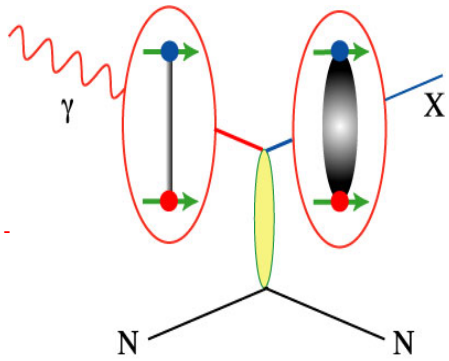
$J^{PC} = 1^{--}, 1^{++}$



Photon Beam

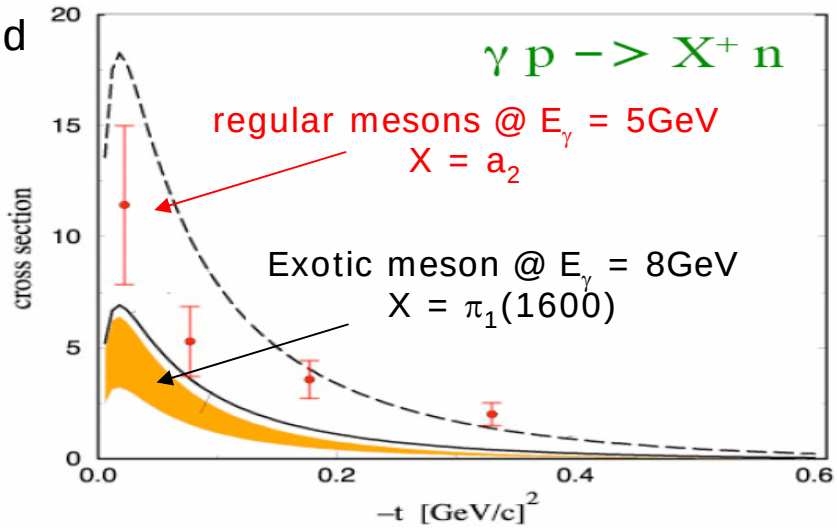
Quark spins already aligned

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



- Production rate for exotics is expected to be comparable to regular mesons

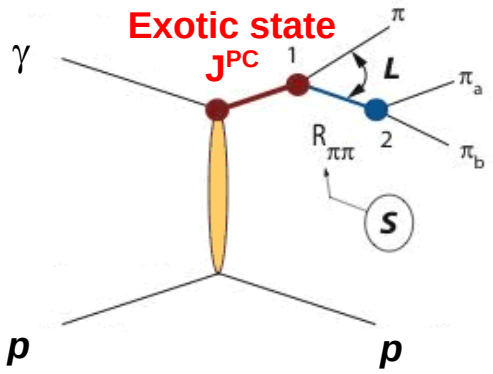
Few data (so far) but expected similar production rate as regular mesons

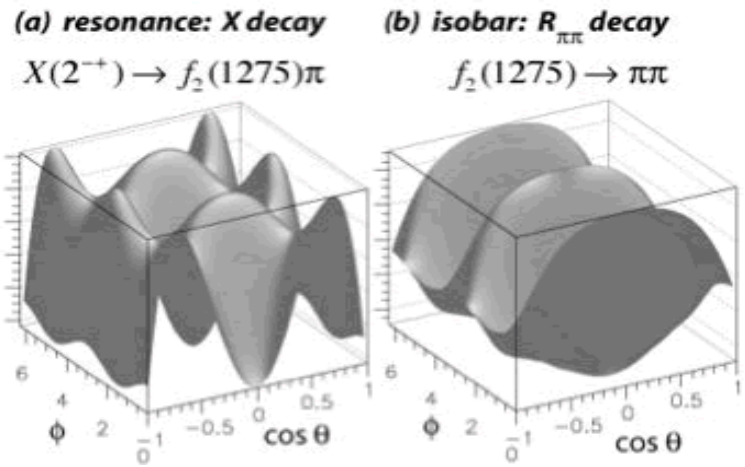


Partial Wave Analysis

1) Isobar Model

e.g. 3π system





2) Moments+Dispersion Relations

1) Moments of the angular distribution in term of partial waves

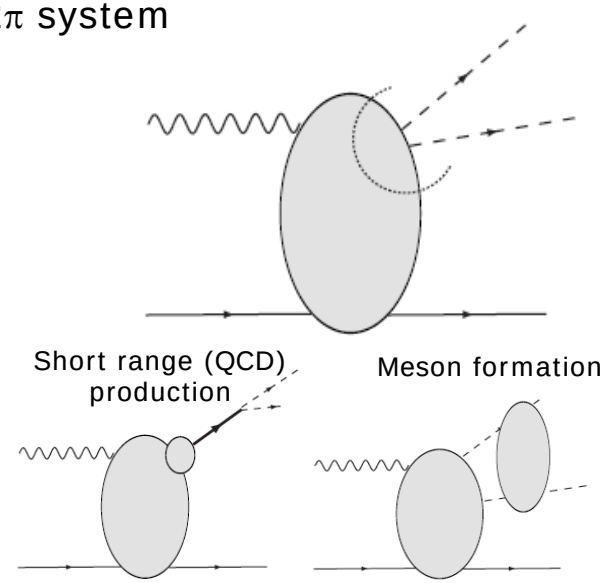
$$\langle Y_{\lambda\mu}\rangle(E_\gamma,t,M) = \frac{1}{\sqrt{4\pi}}\int d\Omega_\pi \frac{d\sigma}{dtdMd\Omega_\pi} Y_{\lambda\mu}(\Omega_\pi)$$

$$\langle Y_{00}\rangle = N\left[|S|^2+|P_-|^2+|P_0|^2+|P_+|^2+|D_-|^2 + |D_0|^2+|D_+|^2+|F_-|^2+|F_0|^2+|F_+|^2\right]$$

2) Parametrize partial waves in term of known ππ phase shift and unknown coefficients using Dispersion Relations

3) Derive partial wave cross sections to compare with models

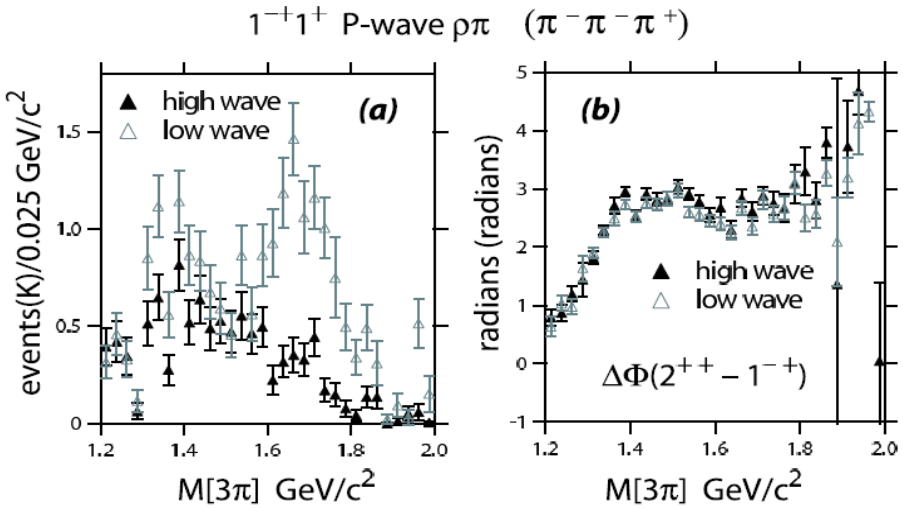
e.g. 2π system



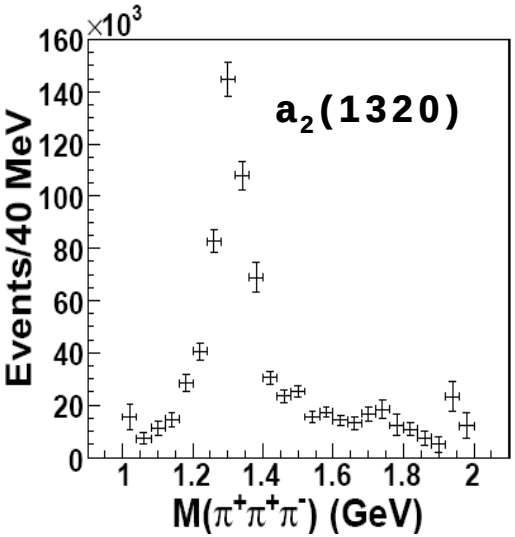
PWA with Isobar Model

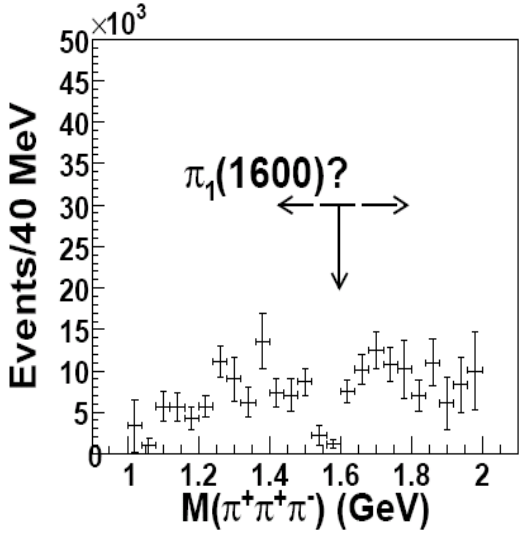
$\gamma p \rightarrow \pi^+\pi^+\pi^-(n)$

- Possible evidence of exotic meson $\pi_1(1600)$ in $\pi p \rightarrow (3\pi)^- p$ (E852-Brookhaven)
- Not confirmed in a re-analysis of a higher statistic sample



CLAS-g6C



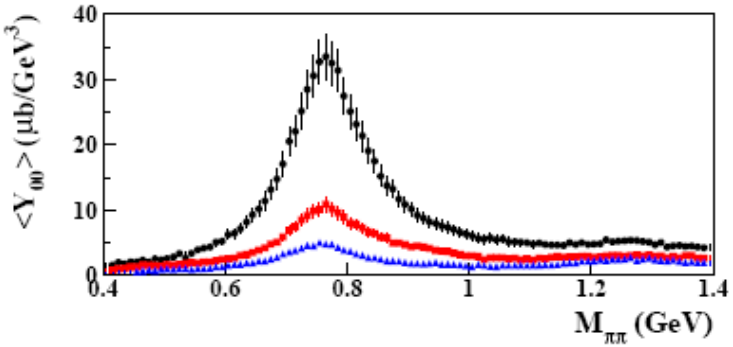


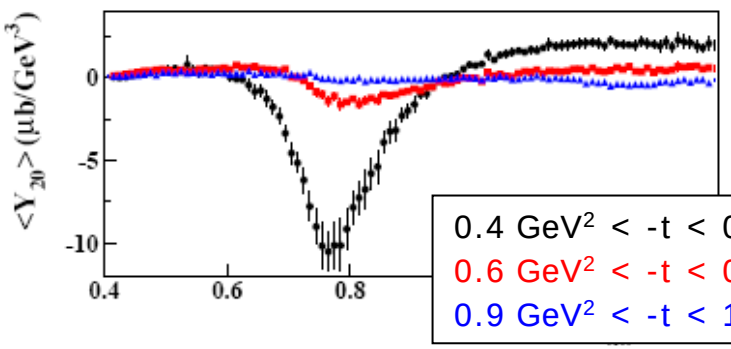
- Clear evidence of non-exotic 2^{++} state $a_2(1320)$
- No-evidence of exotic 1^{-+} state $\pi_1(1600)$
- Relevance of baryon resonance background

PWA in CLAS is feasible!

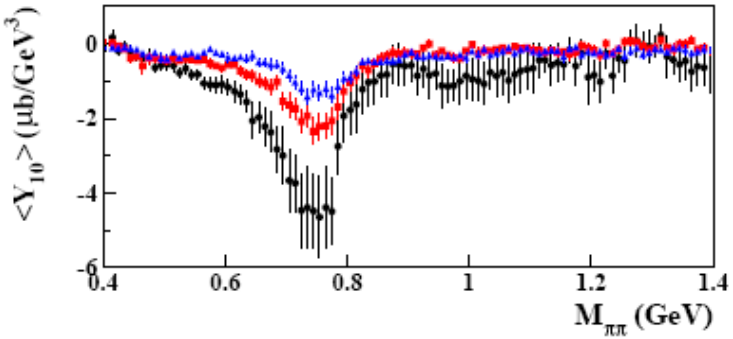
Moments of the Di-Pion Angular Distribution

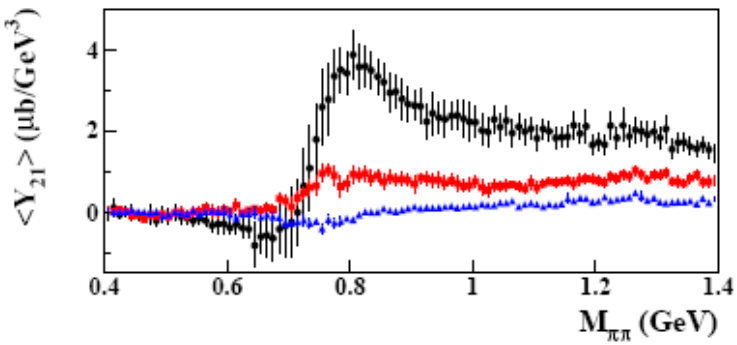
3.2 GeV < E_γ < 3.4 GeV

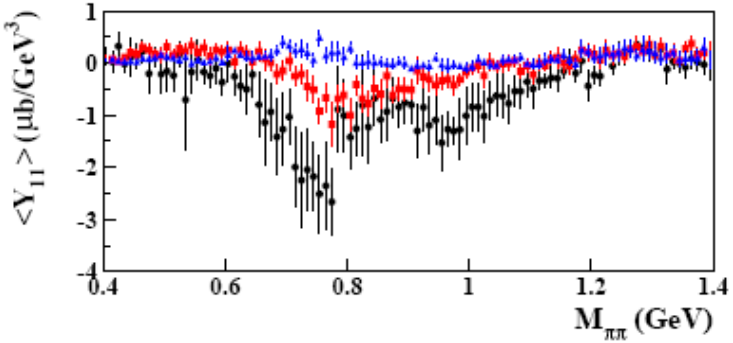


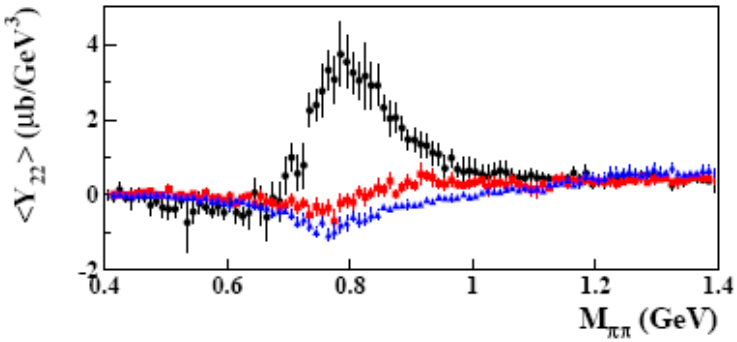


0.4 GeV^2 < -t < 0.5 GeV^2
0.6 GeV^2 < -t < 0.7 GeV^2
0.9 GeV^2 < -t < 1.0 GeV^2









New High Statistics Photon run: g12

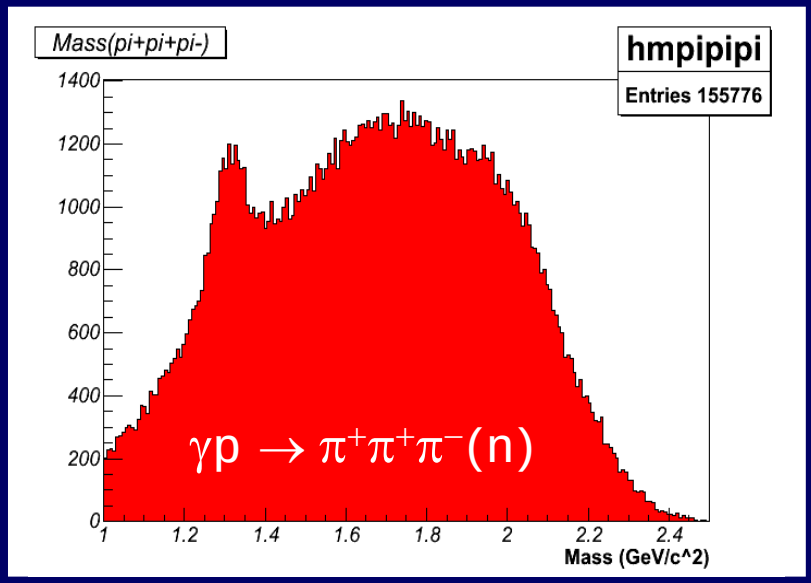
Search for new forms of hadronic matter in photoproduction on the proton

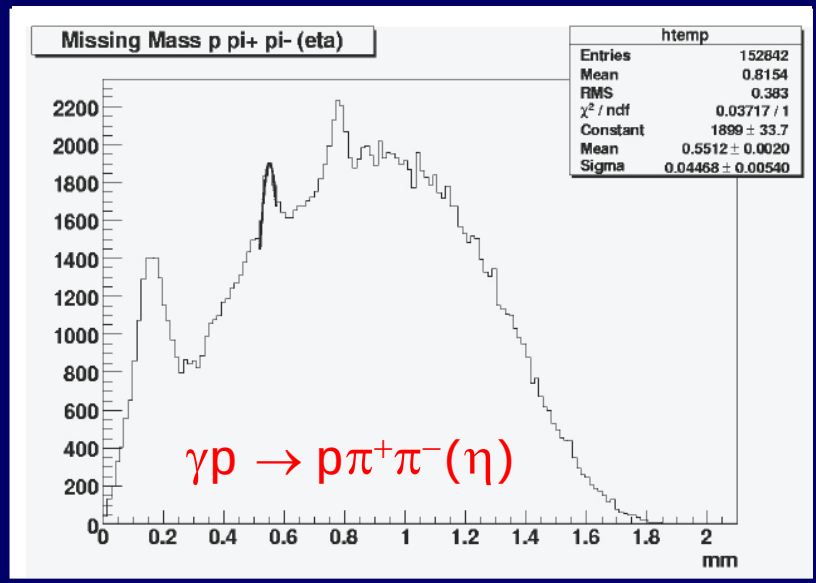
- Data taking completed in 2008
- Photon Energy up to 5.4 GeV
- More than 26 billion triggers (2-prong + 3-prong)
- Total Luminosity: 68 pb^{-1}

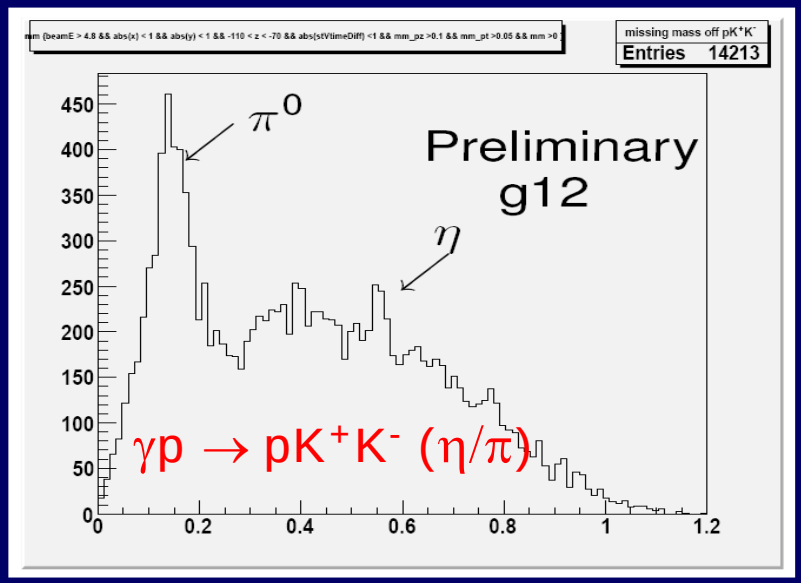
Several exclusive channels are being analyzed

Craig Bookwalter (FSU):	$\gamma p \rightarrow \pi^+\pi^+\pi^-(n)$
Johann Goetz (UCLA):	$\gamma p \rightarrow K^+K^+ \Xi^{*-}(1530)$
Mukesh Saini (FSU):	$\gamma p \rightarrow pK^+K^- (\eta/\pi)$
Diane Schott (FIU):	$\gamma p \rightarrow p\pi^+\pi^-(\eta)$
Jane Spriggs (RPI):	$\gamma p \rightarrow \pi^+K^+K^-(n)$

A hint of the new data



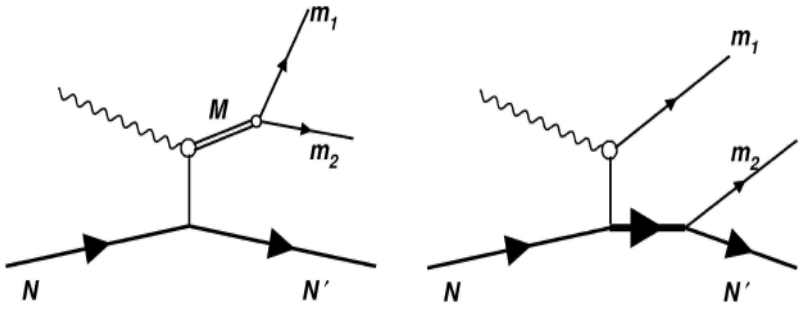


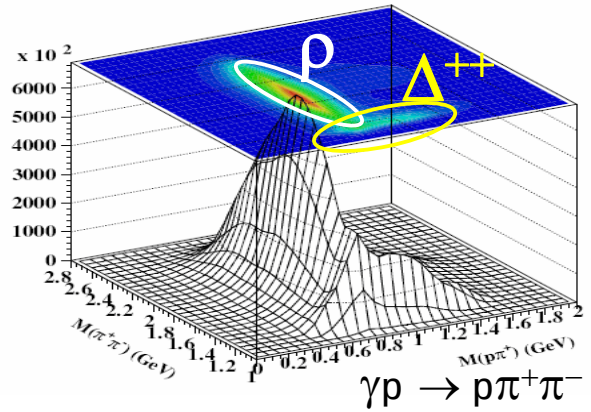


G12
5 % of Total Statistics

Coherent Meson Production on Nuclei

* **Eliminate *s-channel* resonance background**



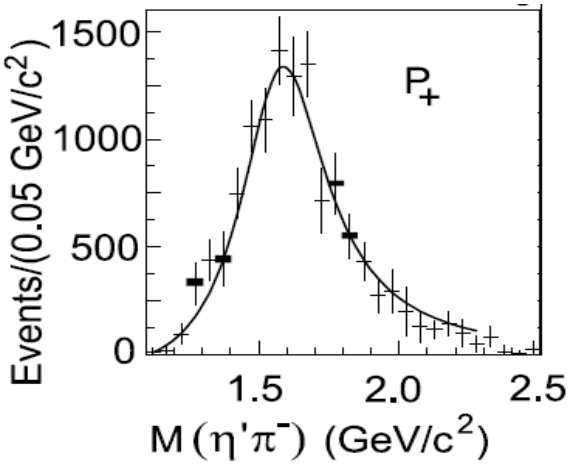


* **Simper PWA: S=I=0 target acts as spin and parity filter for final state mesons**
* **Production cross section expected ~ $e^{-bt}\,|A\,F_A(t)|^2$ → low *-t* kinematic**

Meson spectroscopy on ^{4}He

$\gamma\,^4\mathrm{He} \rightarrow {}^4\mathrm{He}\pi^0\eta$ $\qquad$ $\gamma\,^4\mathrm{He} \rightarrow {}^4\mathrm{He}\pi^0\eta'$

* Strongest evidence of $J^{PC}=1^{-+}$ $\pi_1(1400)$ exotic meson $\pi^- p \rightarrow n\eta\pi^0$ in E852-Brookhaven
* Search for a resonance in P-wave in $\pi^0\eta$ and $\pi^0\eta'$
* Known (non-exotic) resonances can be used as a benchmark (e.g. $J^{PC}=2^{++}$ $a_2(1232)$)



EG6: Meson spectroscopy in coherent production on ^{4}He

- 6 GeV electron beam on target on high pressure gas target
- scattered electron at very small angles → quasi-real photo-production
- search for exotics in $\pi\eta$, $\pi\eta'$ final states
- recoiling nucleus detected in Radial TPC
- hadronic final state detected in CLAS
- data taking in fall 2009

Analysis of existing CLAS data shows clear peaks associated to known mesons in

$ep \rightarrow (e')p\pi^0\pi^0$

$ep \rightarrow (e')p\pi^0\eta$

- Radial TPC with 7atm. He4 Target
- Solenoid for forward-focusing of Moeller electrons and bending of recoil nucleus in the TPC
- PbWO4 calorimeter for improved photon acceptance at forward angles

The Technique works!!