

Partial Wave Analysis of two pion final states at CLAS

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7TH INTERNATIONAL WORKSHOP ON PION-NUCLEON PARTIAL WAVE
ANALYSIS AND THE INTERPRETATION OF BARYON RESONANCES

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Meson Spectroscopy in $\pi^+\pi^-$

The two pion channel is a rich final state for meson spectroscopy studies in the light quark sector

- Dominant contribution from $\rho(770)$ meson in the P wave
- Significant contribution of :
 - scalar meson in the S wave
 - of the $f_2(1270)$ in the D wave
- Two-body final state:
 - relatively easy to be accessed experimentally (large statistics)
 - “relatively” simple PWA

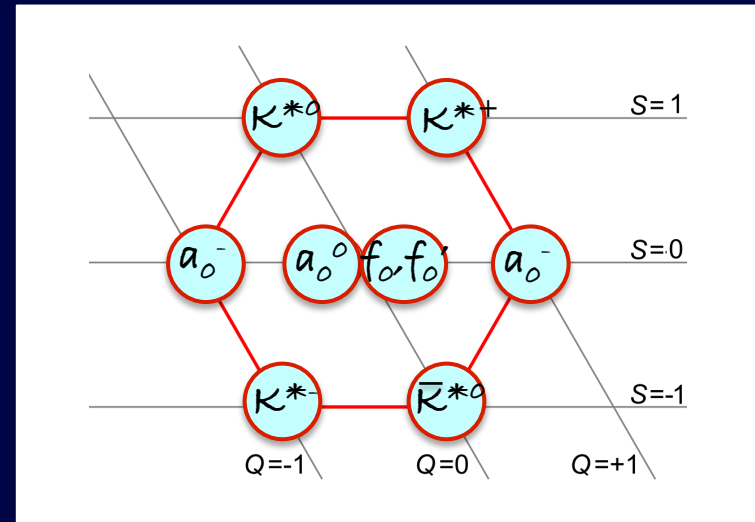
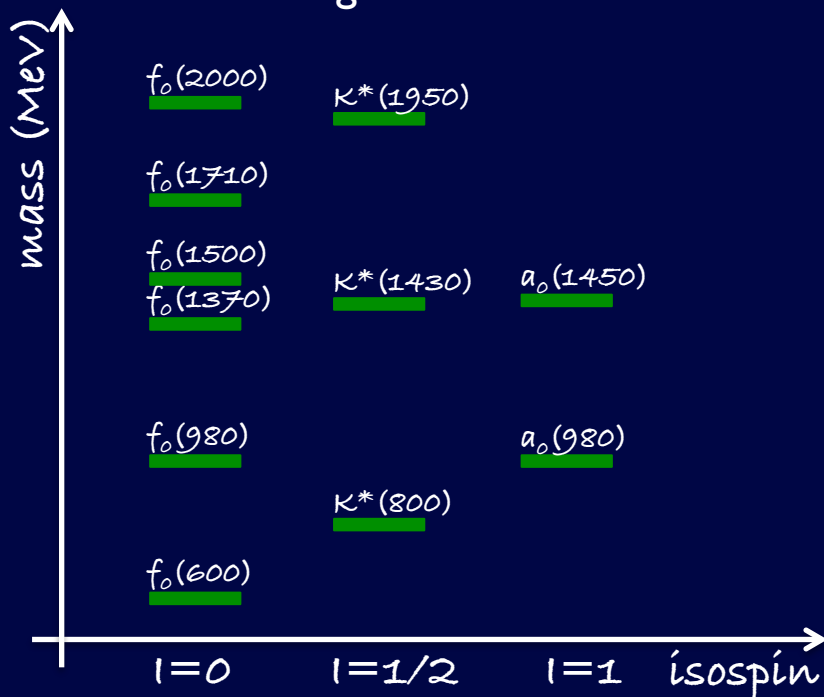
Main Focus of present analysis:

- Study of scalar mesons photoproduction
- Use of $\rho(770)$ as a benchmark

Scalar Mesons

Scalars are fundamental states because they represent the Higgs sector of strong interaction:

- same quantum numbers of the QCD vacuum
- responsible for chiral symmetry breaking

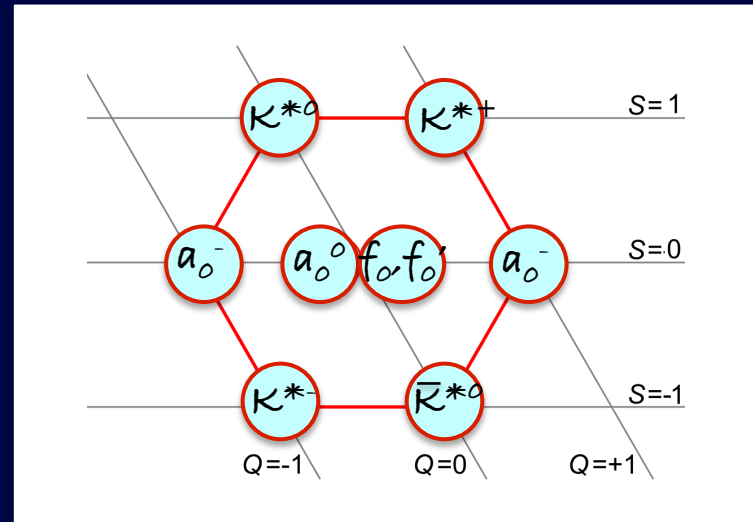
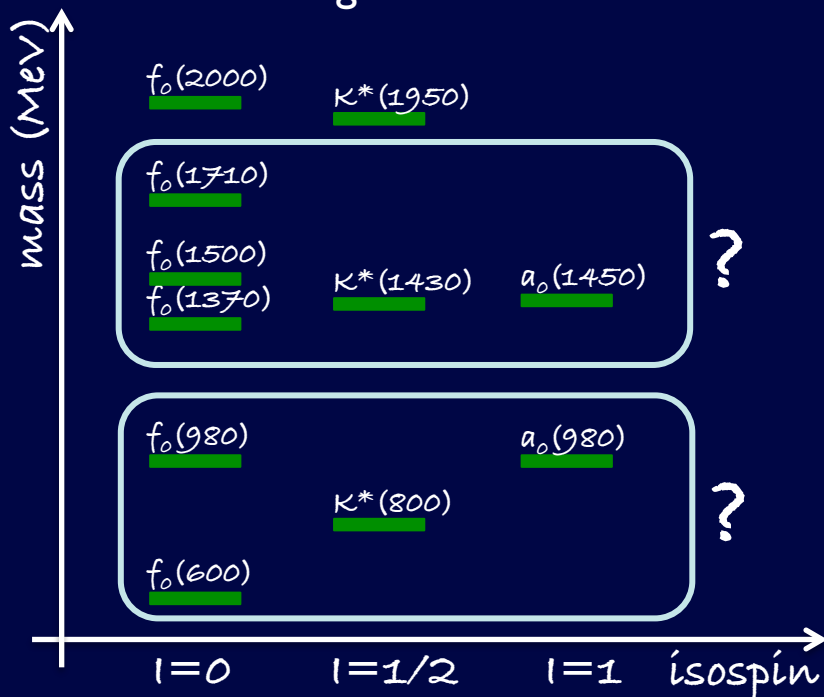


- The scalar meson nonet should be composed by a_0 (I=1), K^* (I=1/2), f_0 and f_0' (I=0), with the a_0 as lightest state and the f_0' showing a large strange content
- At present, given the I=1 and I=1/2 states that have been identified, there is an excess of I=0 states

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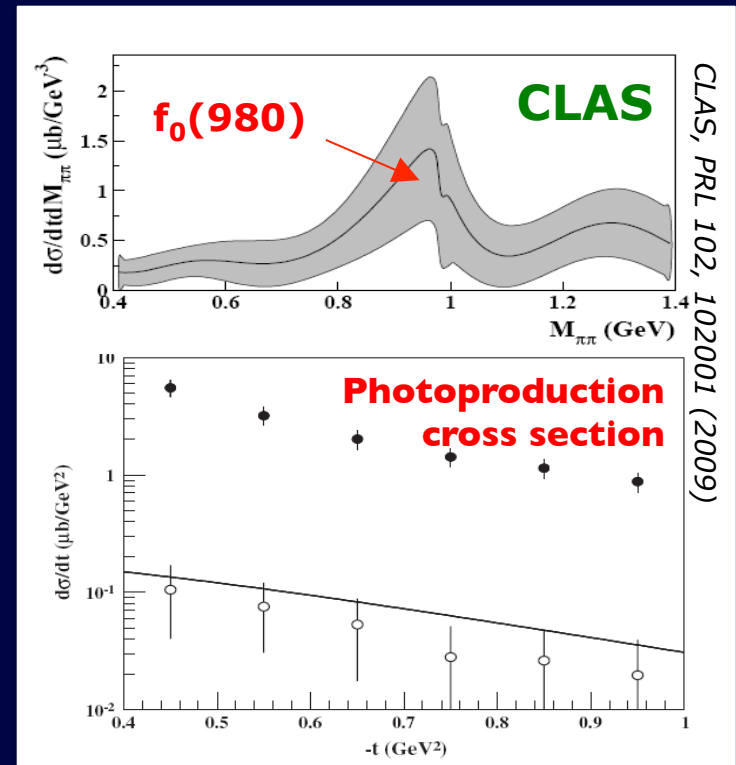
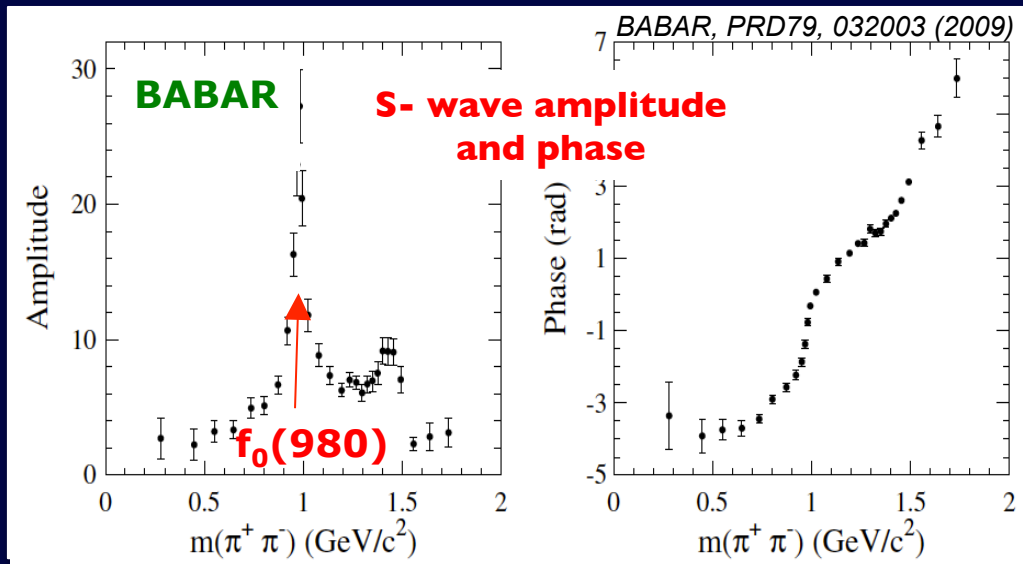
- The scalar meson nonet should be composed by $a_0(I=1)$, $K^*(I=1/2)$, f_0 and $f_0'(I=0)$, with the a_0 as lightest state and the f_0' showing a large strange content
- At present, given the $I=1$ and $I=1/2$ states that have been identified, there is an excess of $I=0$ states

The $f_0(980)$ meson

The $f_0(980)$ is one of the lowest mass scalar and isosinglet candidate of the first nonet:

→ Unusual mass hierarchy of the multiplet ($f_0(980)$ almost degenerate with $a_0(980)$) and decays led to propose these states as TETRAQUARKs

Detailed measurement of the **S wave** around the resonance mass needed to determine the nature of this state



High precision data from BES, KLOE, BABAR, CLAS and others now available can shed light on this puzzle

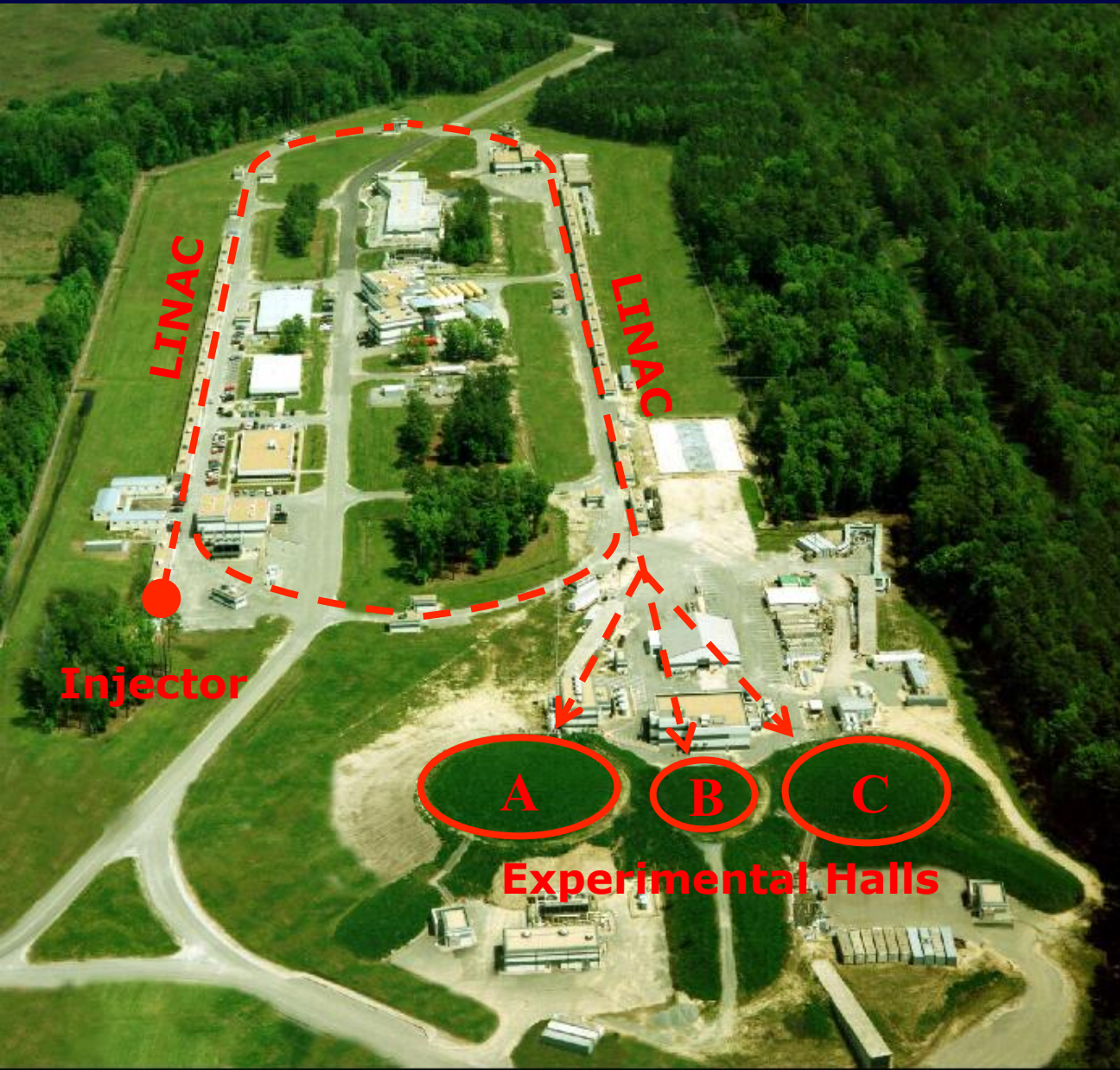
Jefferson Lab



Continuous Electron Beam Accelerator Facility

- E: 0.75 – 6 GeV
- I_{\max} : 200 μ A
- RF: 1499 MHz
- Duty Cycle: \sim 100%
- $\sigma(E)/E$: 2.5×10^{-5}
- Polarization: 80%
- Simultaneous distribution to 3 experimental Halls

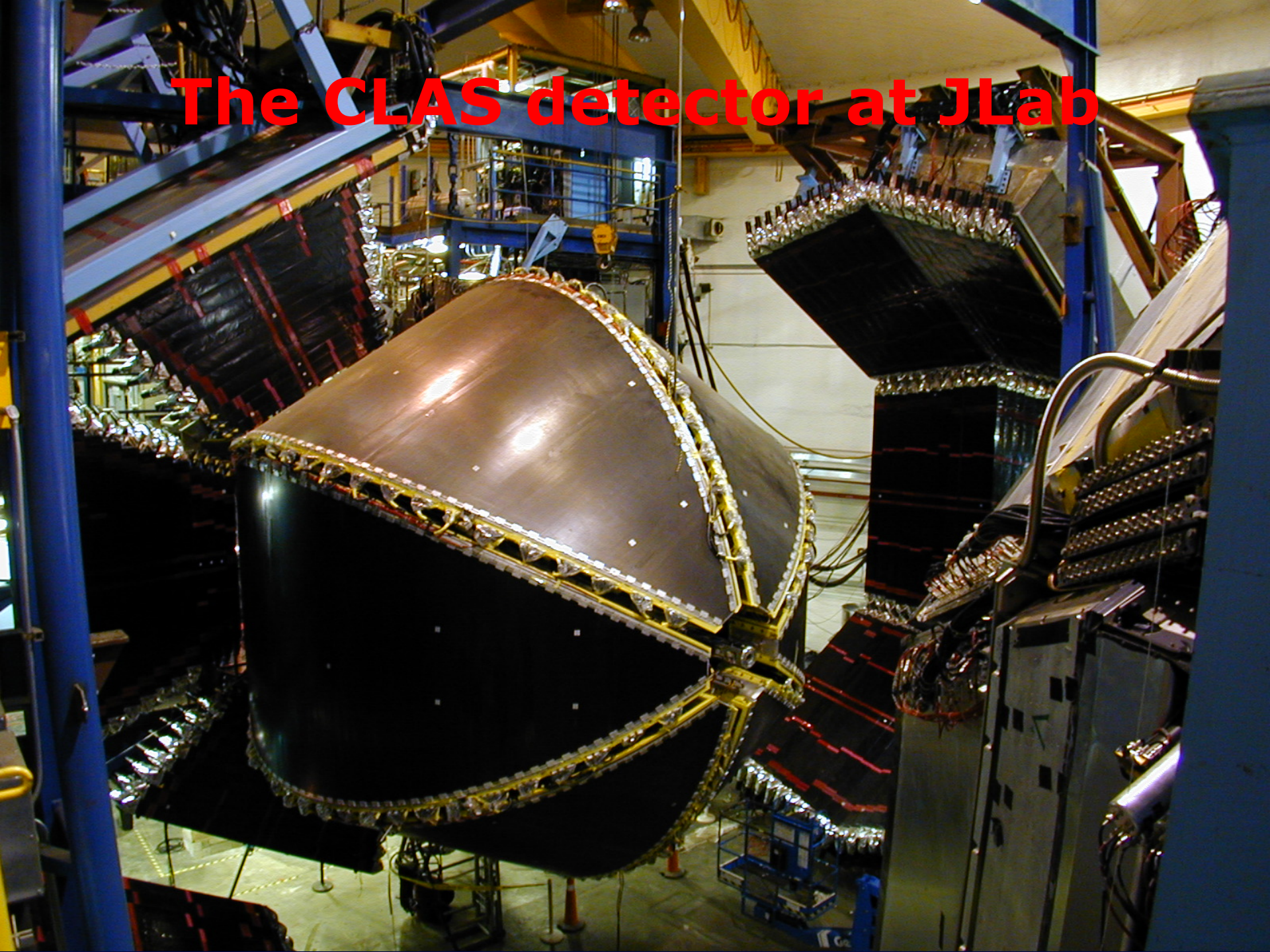
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The CLAS detector at JLab

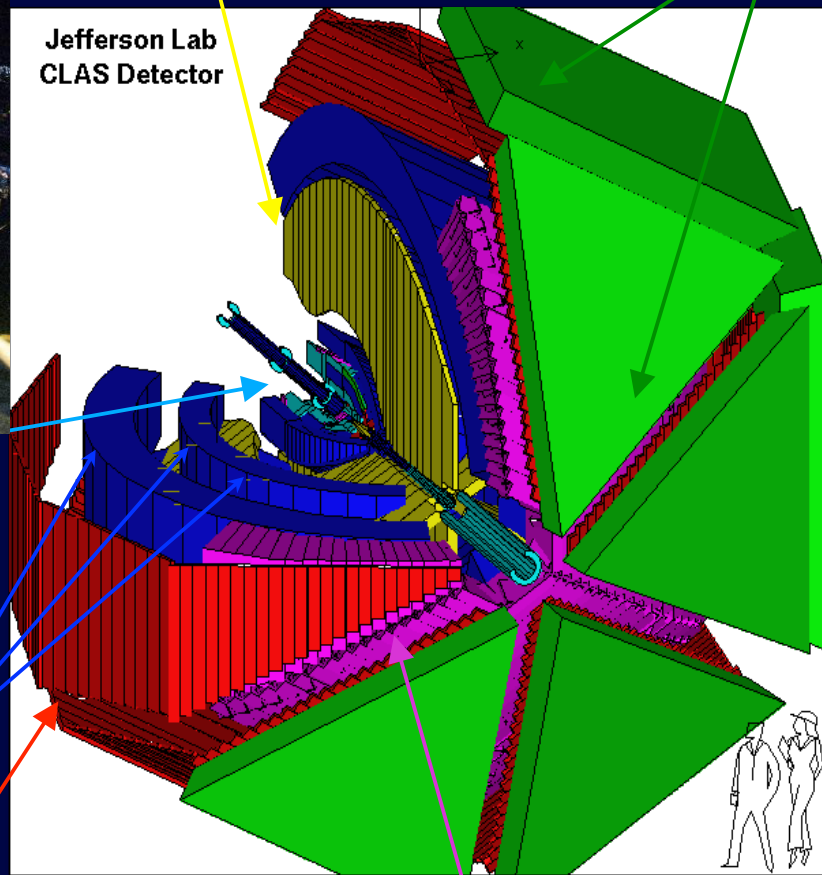


CEBAF Large Acceptance Spectrometer



Torus Magnet
6 Superconductive Coils

Electromagnetic Calorimeter
lead/plastic scintillator, 1296 PMTs

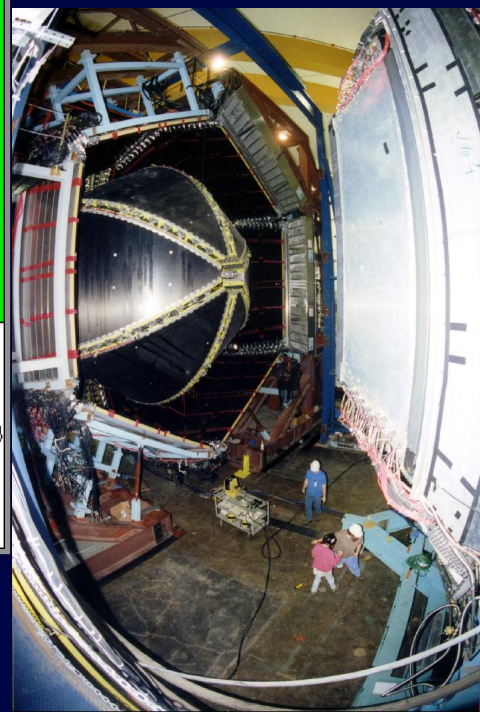


Target +
start counter
e mini-torus

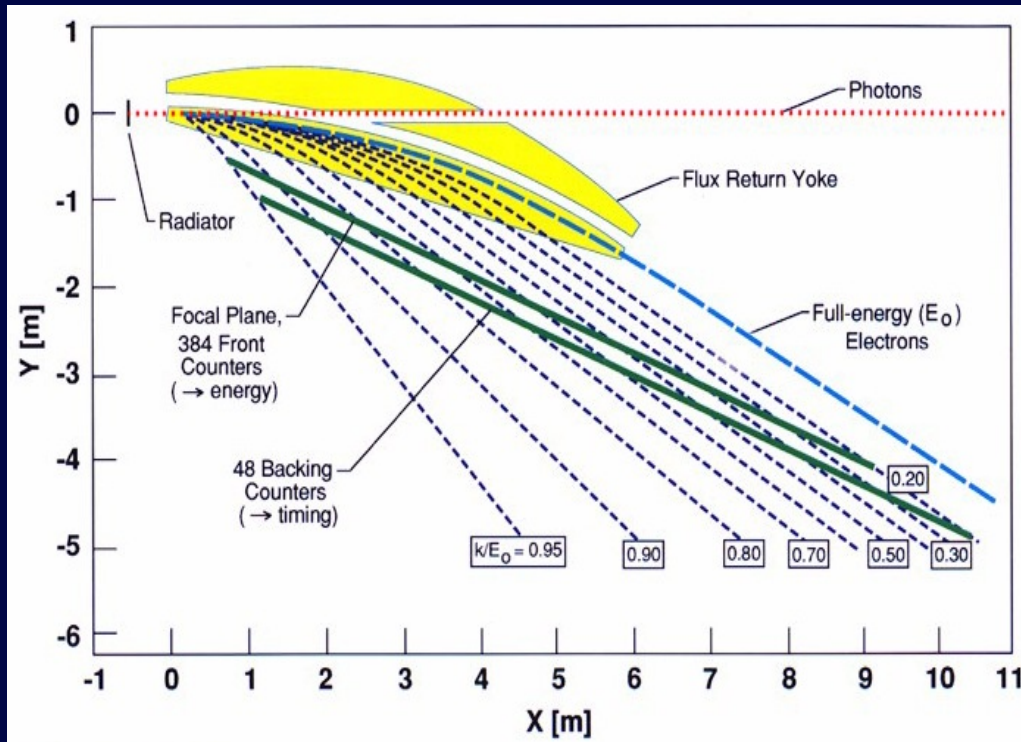
Drift Chamber
35,000 cells

Time of Flight
Plastic Scintillator,
684 PMTs

Cherenkov Counter
e/ π separation, 256 PMTs



Hall-B Photon Tagger



- Photon beam produced from the primary electron beam via Bremsstrahlung
- Gold and diamond radiator for In/Coherent Bremsstrahlung
- Energy coverage: $0.2-0.95 E_0$
- Efficiency $\sim 80\%$
- Energy Resolution $\sim 10^{-3}$
- Timing Resolution ~ 100 ps



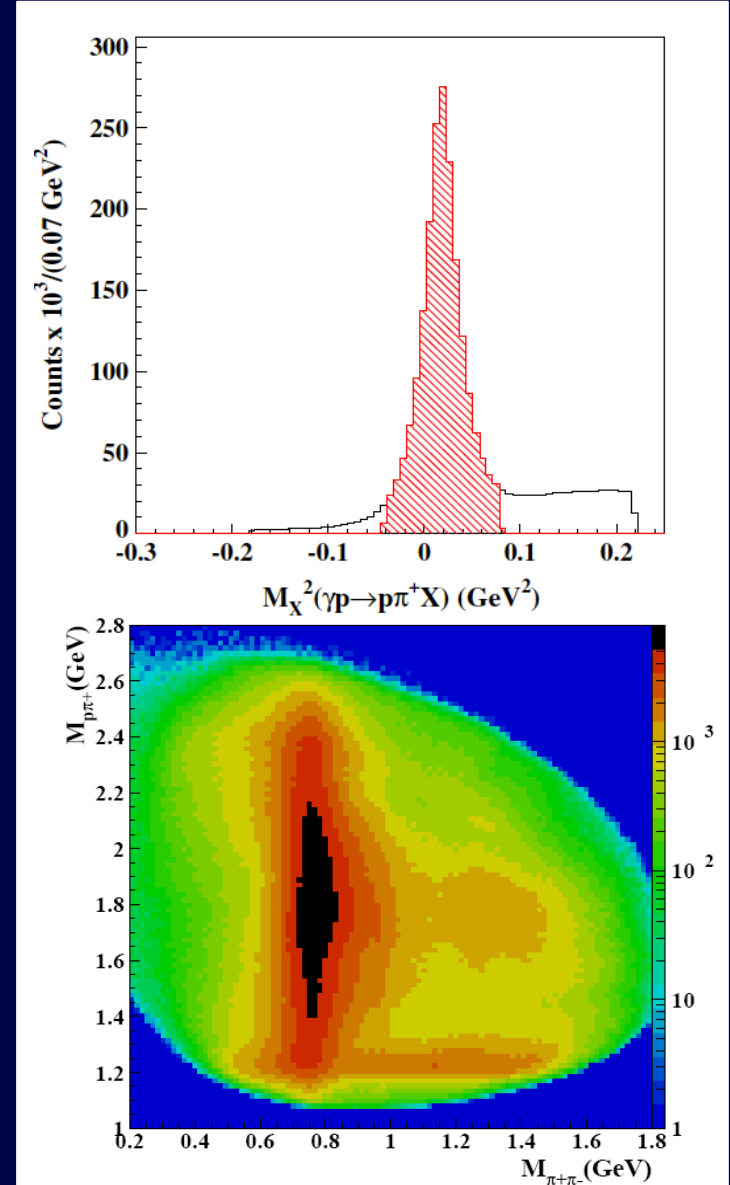
✱ Maximum photon energy of 5.7 GeV
- $W_{\max} \sim 3.4$ GeV

✱ Beam intensity 10^7 γ/s

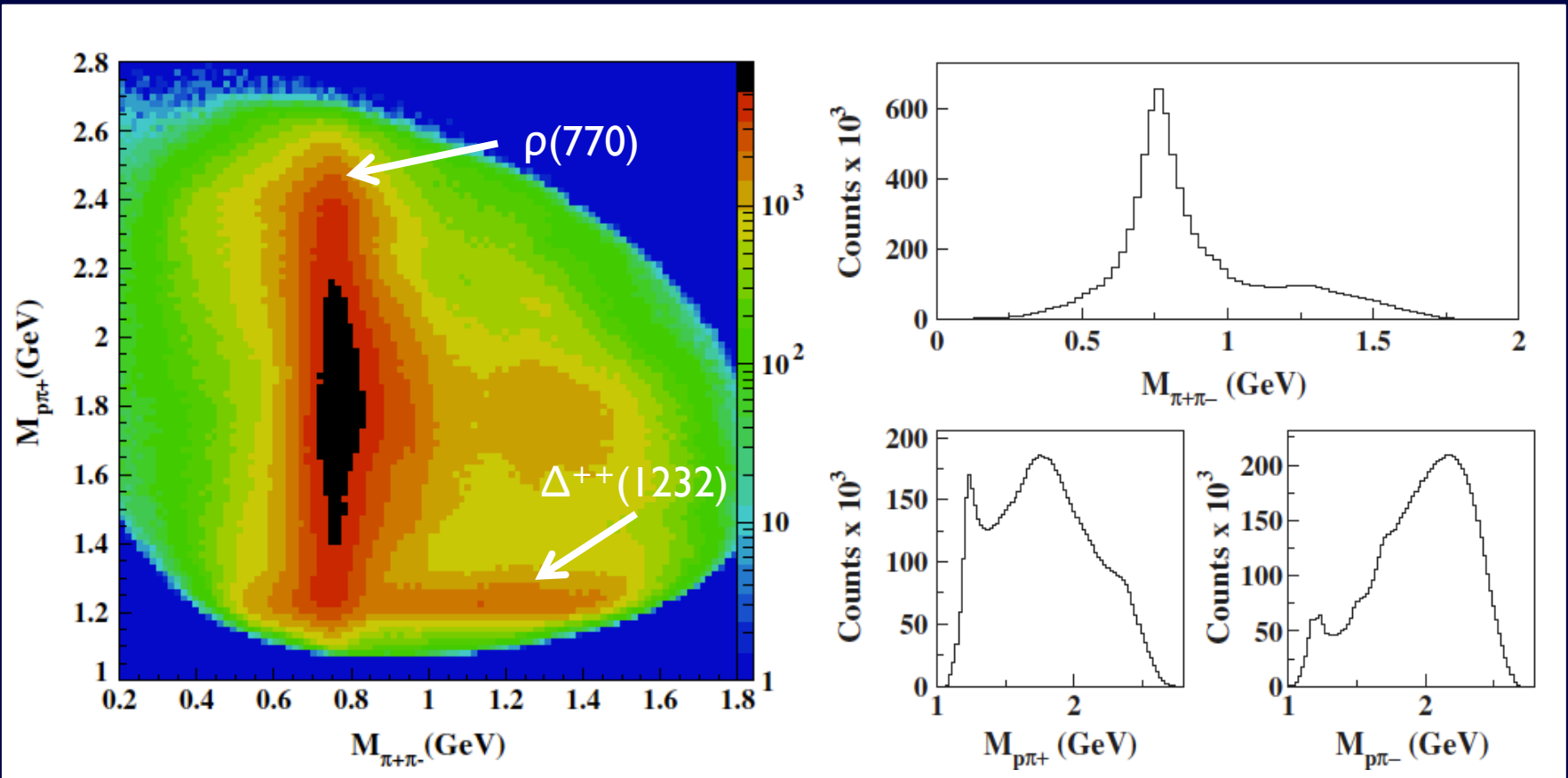
Photoproduction of Pion Pairs

Study of $\pi^+\pi^-$ production on the proton and study of scalar mesons

- Bremsstrahlung photon beam: 1.6-3.8 GeV
- 40 cm long liquid hydrogen target
- $\sim 7 \cdot 10^9$ triggers
- Integrated Luminosity $\sim 80 \text{ pb}^{-1}$
- 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
- 41 M events selected



Photoproduction of Pion Pairs



- $\pi\pi$ mass spectrum dominated by $\rho(770)$ contribution
- $\Delta(1232)$ peak visible in the $p\pi$ spectra introduces smooth background in the $\pi\pi$ mass

Photoproduction of Pion Pairs

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 fitted to the data using an unbinned likelihood procedure

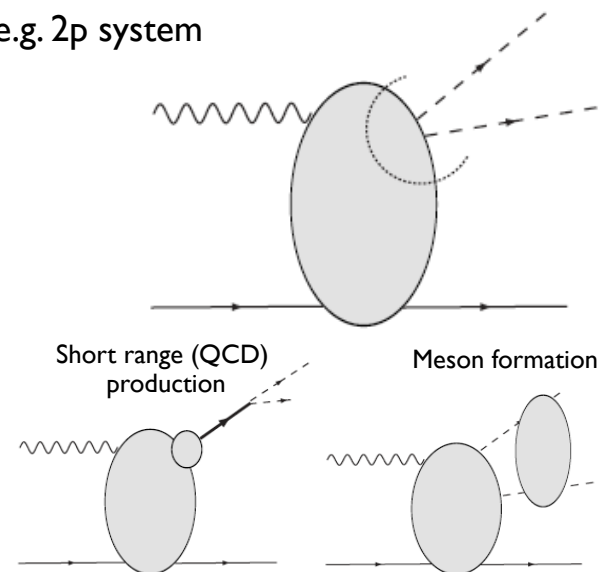
2) Evaluation of Partial Waves from Experimental Moments

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

$$\begin{aligned} \langle Y_{00} \rangle &= N [|S|^2 + |P_-|^2 + |P_0|^2 + |P_+|^2 + |D_-|^2 \\ &\quad + |D_0|^2 + |D_+|^2 + |F_-|^2 + |F_0|^2 + |F_+|^2] \\ \langle Y_{10} \rangle &= N \left[SP_0^* + P_0 S^* + \sqrt{\frac{3}{5}} (P_- D_-^* + P_- S^* + P_+ D_+^* \right. \\ &\quad \left. \dots \right] \end{aligned}$$

- Partial Waves are parameterized using Dispersion Relations in term of known pp 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. 2p system



Moments Extraction

Projection of the differential cross section onto spherical harmonics

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

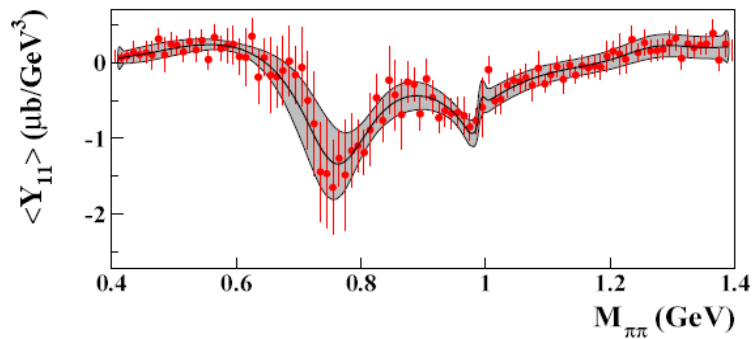
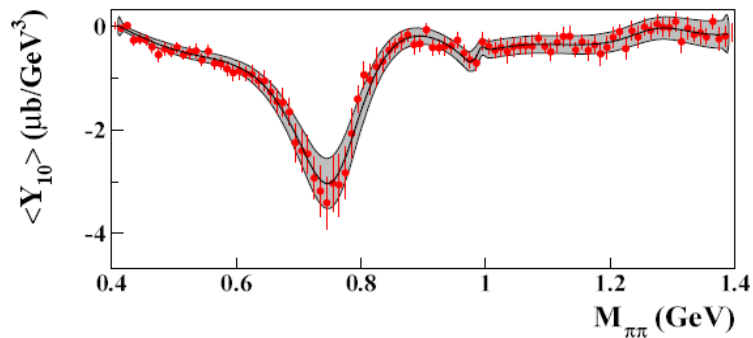
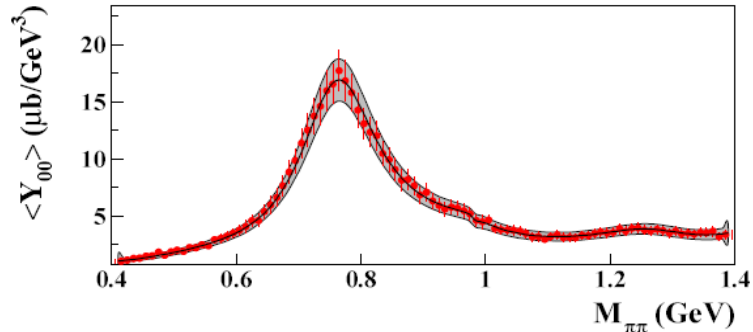
- Moments can be expressed as bi-linear in terms of partial waves
- Depending on L and M, show specific sensitivity to subset of PW
- Are physics observables that can be compared to models

Extraction technique:

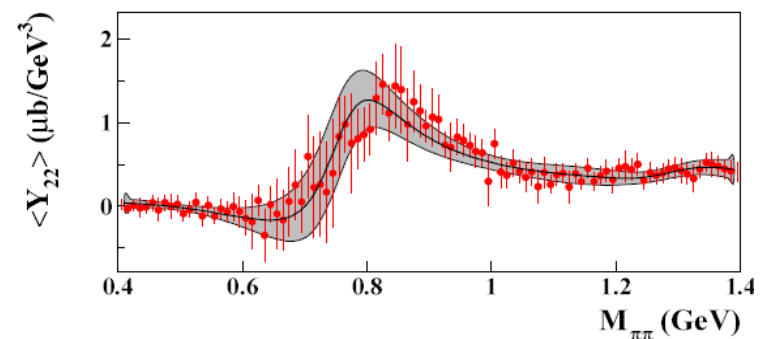
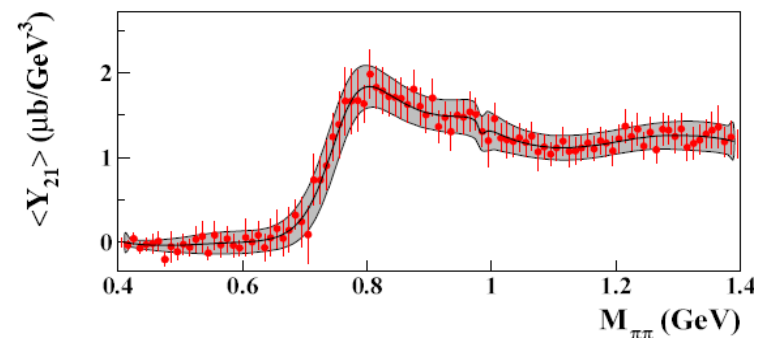
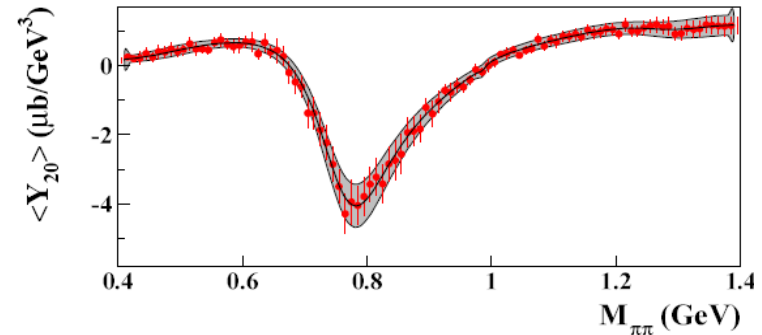
- Moments are expanded on a set of basis function and weighted with Monte Carlo events (4 B) to account for detector acceptance and efficiency
- Moments are fitted to the data using an unbinned likelihood procedure
- Parameterization based on moments or amplitudes were implemented and used for comparison and systematic studies

Moments

3.2 GeV < E_γ < 3.4 GeV



0.5 GeV² < -t < 0.6 GeV²



M. Battaglieri et al. (CLAS Collaboration), PRD 80, 072005

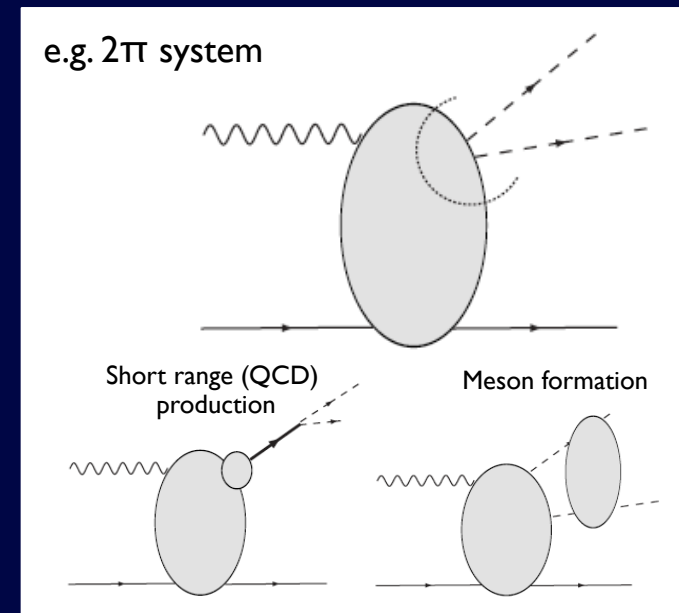
Partial Wave Extraction

- **Partial Wave Amplitudes can be evaluated from moments:**

$$\langle Y_{00} \rangle = |S|^2 + |P_-|^2 + |P_0|^2 + |P_+|^2 + |D_-|^2 + |D_0|^2 + |D_+|^2 + |F_-|^2 + |F_0|^2 + |F_+|^2$$
$$\langle Y_{10} \rangle = SP_0^* + P_0S^* + \sqrt{\frac{3}{5}}(P_-D_-^* + P_-^*D_- + P_+D_+^* + P_+^*D_+) + \sqrt{\frac{4}{5}}(P_0D_0^* + D_0P_0^*) + \dots$$

Extraction technique:

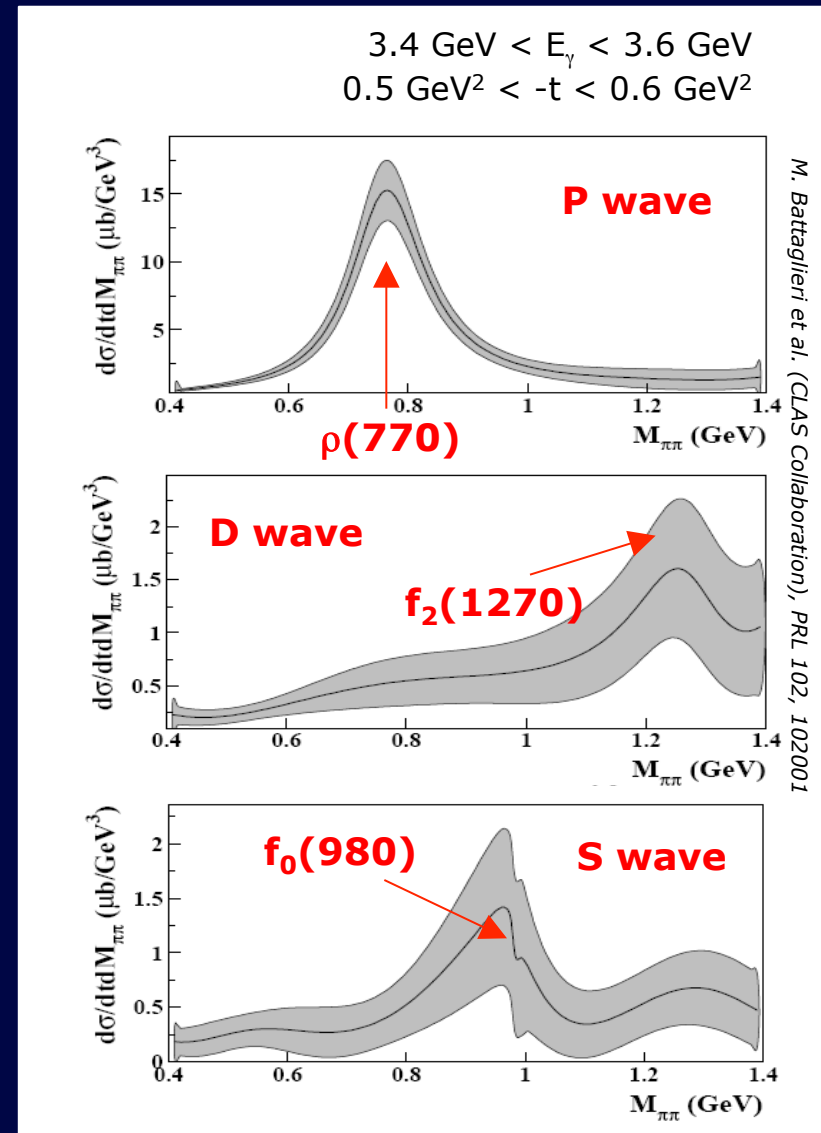
- Partial Waves are parameterized using Dispersion Relations in term of known $\pi\pi$ phase shifts and inelasticities
- Constructed amplitudes have the correct analytical (singularities, cuts, ...) properties expected for partial waves
- Unknown coefficients are fitted to the experimental moments
- Partial Wave cross sections are derived and can be compared with models



Partial Wave Amplitudes

PWA fit:

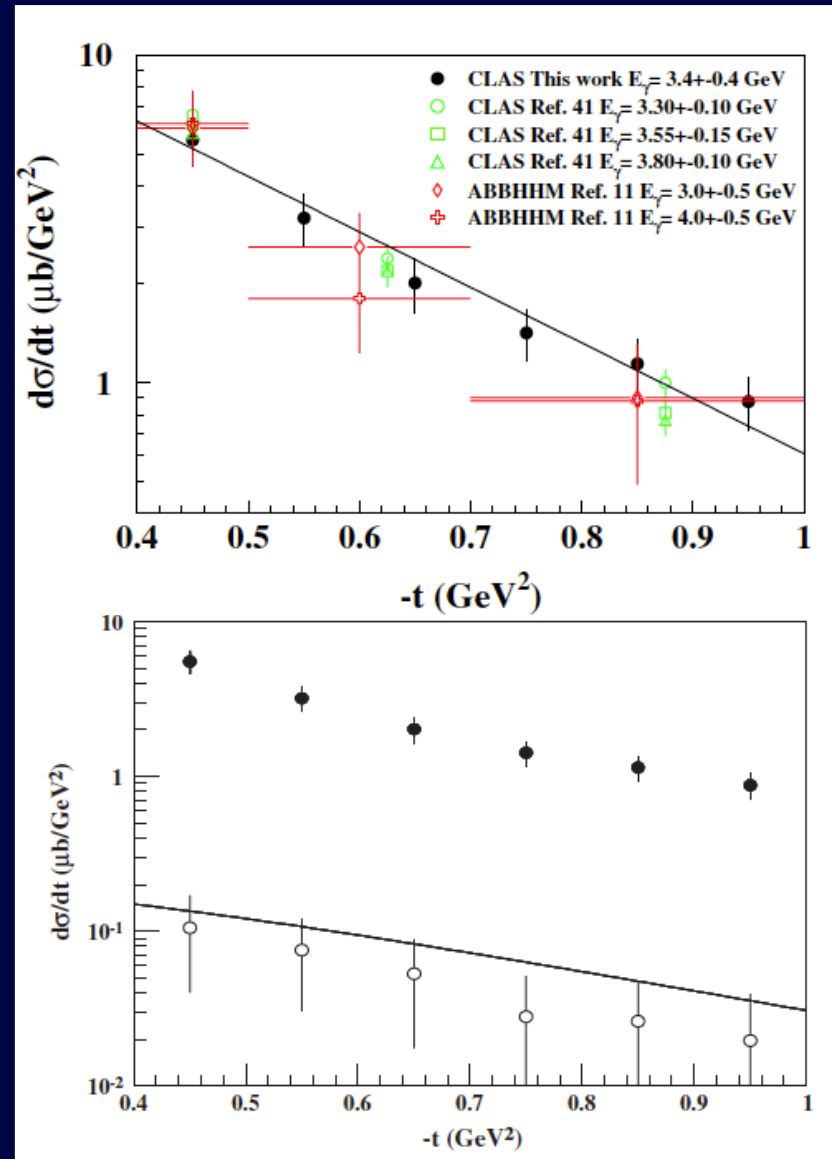
- * Partial Waves fitted to moment with $L \leq 4$ and $M \leq 3$
 - * Waves up to $l=3$ (S,P,D,F)
 - * $M(\pi^+\pi^-)$ spectrum below 1.5 GeV:
 - P-wave: ρ meson
 - D-wave: $f_2(1270)$
 - S-wave: $f_0(600)$, $f_0(980)$ and $f_0(1370)$
 - * Systematic error estimated from comparison of fits of different sets of moments
-
- * **Known states well reproduced, e.g. $\rho(770)$**
 - * **First observation of $f_0(980)$ in photoproduction**



Cross sections

Cross sections for meson resonances were evaluated from the extracted partial waves

- $\rho(770)$ differential cross section is found to be in agreement with world data
- S-wave cross section in the mass region of the $f_0(980)$ is found to be ~ 50 times smaller than the $\rho(770)$



Summary and Perspectives

- Two pion photo-production data from CLAS were analyzed to study meson spectroscopy and scalar production
- A full PWA analysis was performed, evaluating moments of the di-pion angular distribution and extracting amplitudes from the experimental moments
- The dominant $\rho(770)$ was used as a benchmark for the whole analysis procedure confirming the reliability of the extracted results
- The cross section of the S wave in the mass region of the $f_0(980)$ was found to be ~ 50 times smaller than the dominant $\rho(770)$ cross section
 - First observation of the $f_0(980)$ in photo-production
- PWA of KK final states with the same procedure is in progress