Disentangling the Entanglement: Exploring the Excited States of the Nucleon

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Tallahassee, FL

Physics Department Colloquium

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Outline

1. Introduction
   - QCD and Hadron Spectroscopy
2. Experimental Methods in Baryon Spectroscopy
   - Photoproduction
3. Experimental Efforts
   - CLAS and the Crystal Barrel Detector
4. Photoproduction of Mesons (off Protons)
   - Single-Meson Reactions: $\gamma N \rightarrow N\eta$
   - Double-Pion Photoproduction
5. Summary and Outlook

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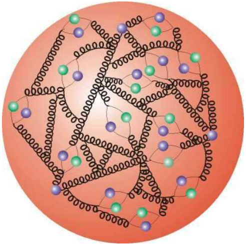
Quantum Chromodynamics (QCD)

... is the theory of strong interactions; the strong force describes the interactions of quarks and gluons making up hadrons.

QCD enjoys two important properties:

1. Asymptotic Freedom
   In high-energy reactions, quarks and gluons interact very weakly.



The inside of the proton at high energies – a “dense soup” of quarks and gluons.

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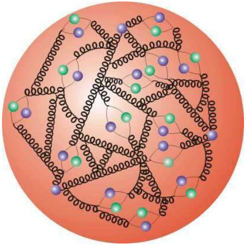

Good quantitative tests of perturbative QCD are:

- Running QCD coupling
- Scaling violation in (un)polarized DIS
- Jet cross sections in colliders
- Heavy-quark production in colliders

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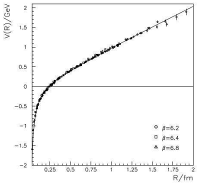
1. Asymptotic Freedom
   In high-energy reactions, quarks and gluons interact very weakly.
2. Confinement
   Force between quarks does not diminish as they are separated.



→

No free quarks!

Quantum Chromodynamics (QCD)

... is the theory of strong interactions; the strong force describes the interactions of quarks and gluons making up hadrons.

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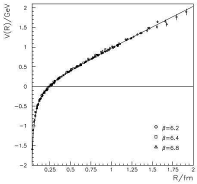

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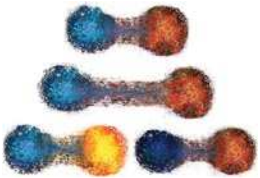
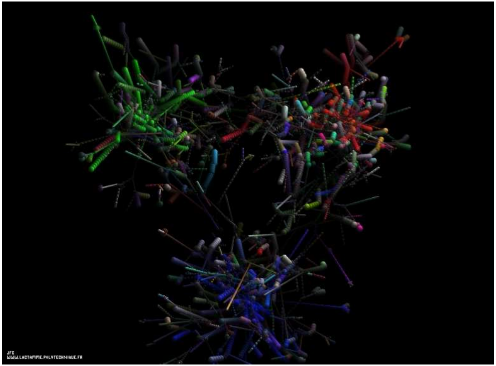


Non-Perturbative QCD

Strong interaction processes at larger distances and at small (soft) momentum transfers belong to the realm of non-perturbative QCD:



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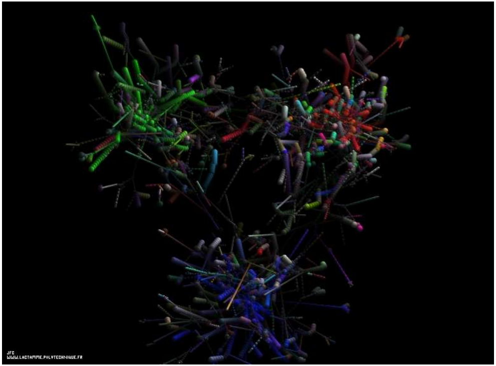

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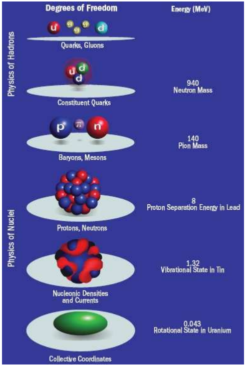

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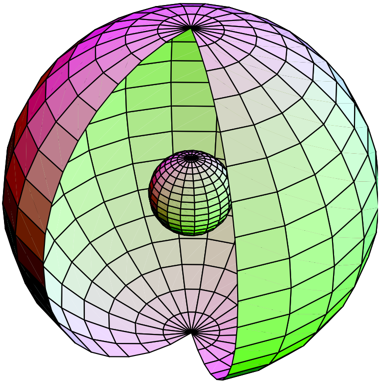
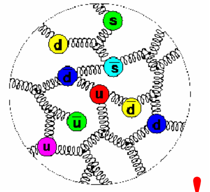
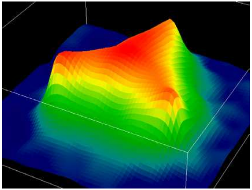
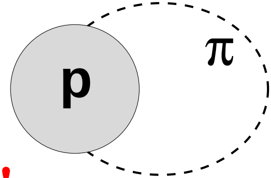


Courtesy of Craig Roberts, Argonne

How does QCD give rise to hadrons?

Interaction between quarks unknown throughout > 98 % of a hadron's volume

→

$\ll 0.1$fm		0.1 – 1.0 fm		> 1.0 fm
				
pQCD	! ? $\longleftrightarrow$? !	Models	? ! $\longleftrightarrow$! ?	ChPT
q, g, $q\bar{q}$		Quarks and Gluons as Quasiparticles		Nucleon and Mesons

1. What are the relevant degrees of freedom?
2. What are the corresponding effective interactions responsible for hadronic phenomena?

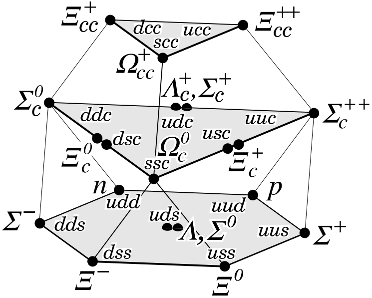
Why N^*'s (= Excited Nucleons)?

Why should we study excited baryons?

(Nathan Isgur, Workshop on Excited Nucleons (2000))

1. Nucleons are the stuff our world is made of.
2. Simplest system in which the nonabelian character of QCD is manifest.
3. Baryons are sufficiently complex to reveal physics hidden from us in the mesons.

➜ In fact, baryons were at the roots of the development of the quark model.



The quark model for baryons (qqq):

- Fermions with baryon number $\mathcal{B} = 1$
- All established baryons are consistent with qqq configuration

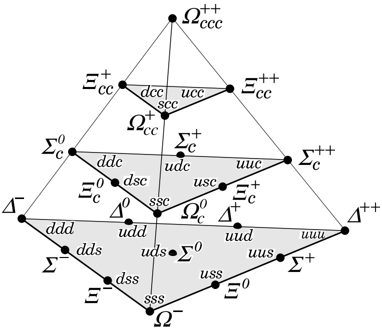
SU(6) Symmetry ($^{2S+1}$multiplets; u, d, s, spin)

$6 \otimes 6 \otimes 6 = 56_S \oplus 70_M \oplus 70_M \oplus 20_A$

$\Rightarrow \quad 56 = {}^4 10 \oplus {}^2 8$ "ground states"

$70 = {}^2 10 \oplus {}^4 8 \oplus {}^2 8 \oplus {}^2 1$

$20 = {}^2 8 \oplus {}^4 1$



One of the Goals of the N^* Program ...

Search for *missing* or yet unobserved resonances

Quark models predict many more baryons than have been observed

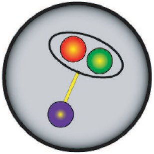
	****	***	**	*
N Spectrum	11	3	6	2
Δ Spectrum	7	3	6	6

$\Rightarrow$ according to PDG
(Phys. Lett. B **667**, 1 (2008))

$\Rightarrow$ little known
(many open questions left)

Possible solutions:

1. Quark-diquark structure



one of the internal degrees of freedom is frozen

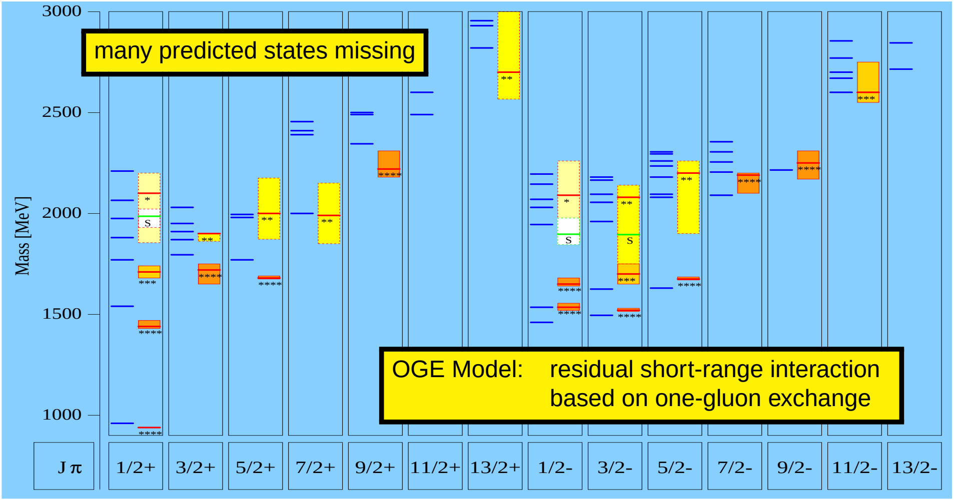
2. Have not been observed, yet

Nearly all existing data result from πN scattering experiments

➜ If the missing resonances did not couple to Nπ, they would not have been discovered!!

Nucleon Resonances: Status of 2001

—— S. Capstick and N. Isgur, Phys. Rev. **D34** (1986) 2809



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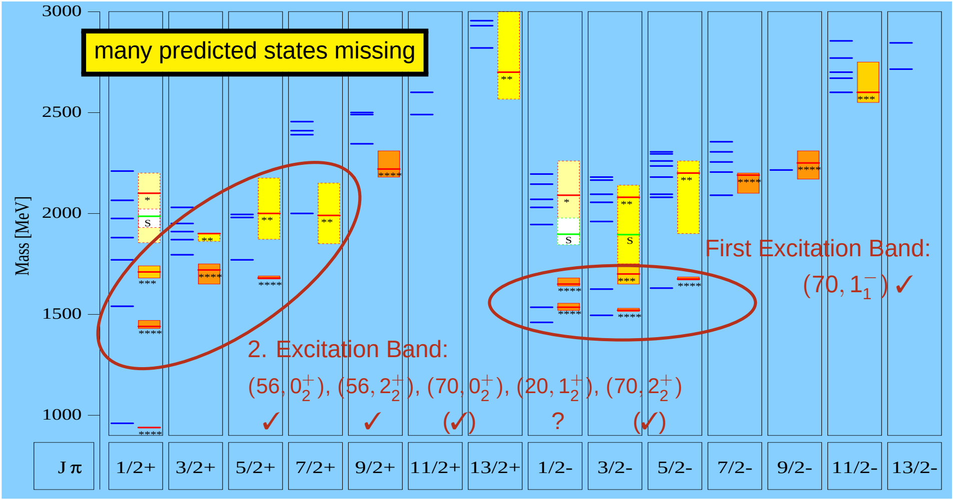
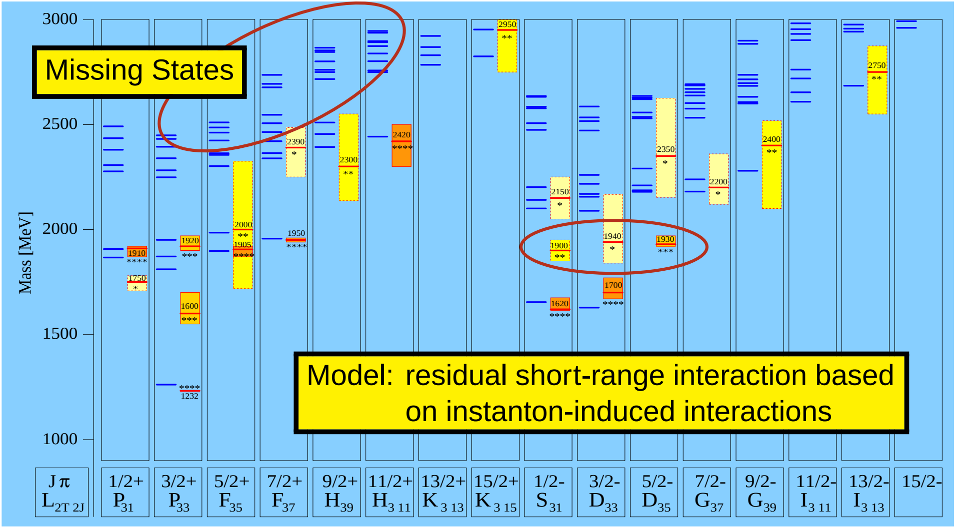
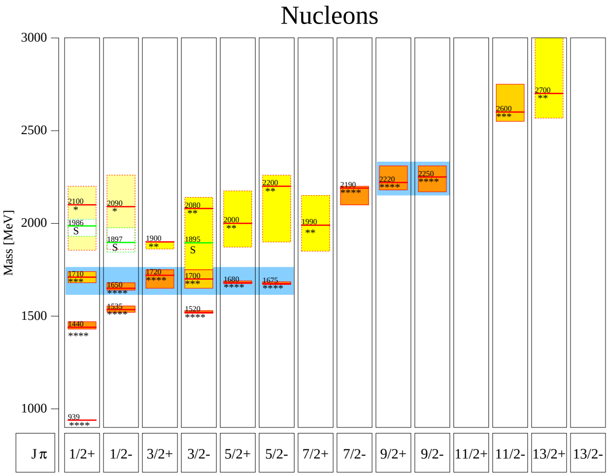


Δ Resonances

—— U. Löhring, B.Ch. Metsch, H.R. Petry, EPJ A**10** (2001) 395



Parity Doublets



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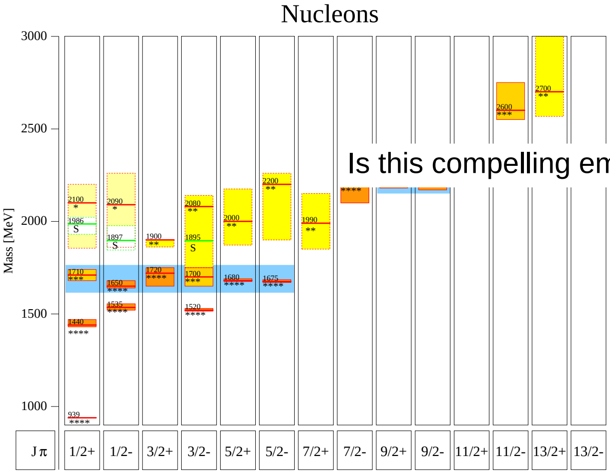
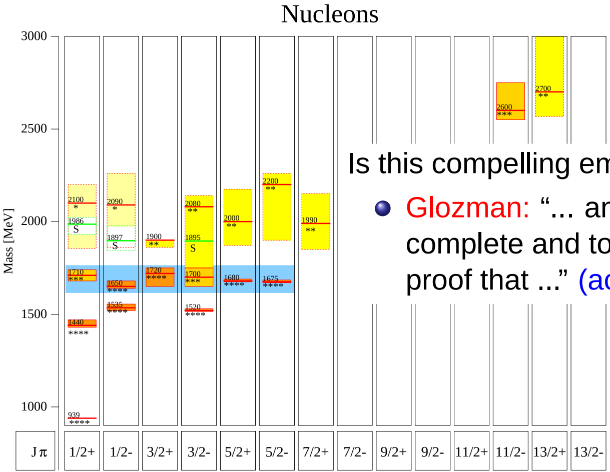


Is this compelling empirical data?

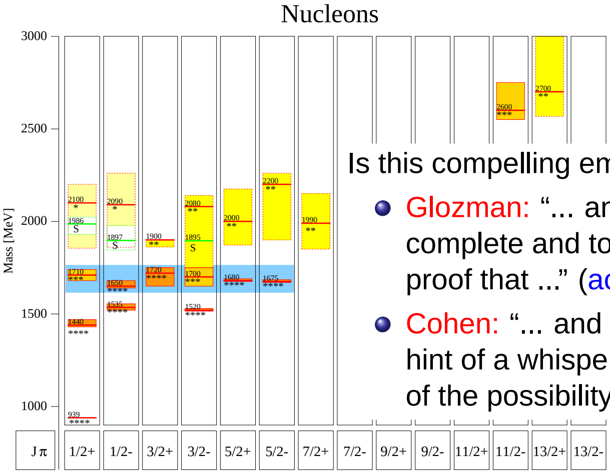
Parity Doublets



Is this compelling empirical data?

- Glozman: "... and thus we have a complete and total, 100 % ironclad proof that ..." (according to T. Cohen)

Parity Doublets



Is this compelling empirical data?

- Glozman: "... and thus we have a complete and total, 100 % ironclad proof that ..." (according to T. Cohen)
- Cohen: "... and thus we have a faint hint of a whisper of the suggestion of the possibility that perhaps ..."

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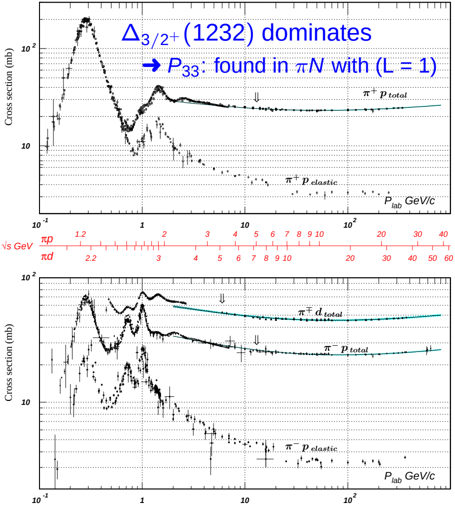
Hadron Beams: Pion- (Kaon-) Nucleon Scattering



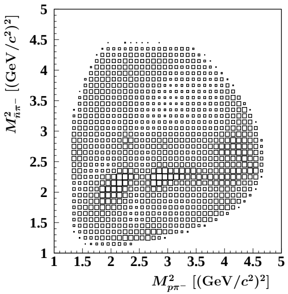
First insight into experimental difficulties:

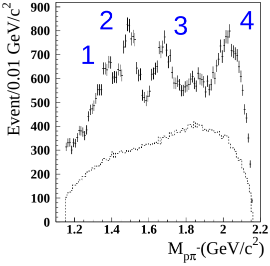
- The elastic cross section drops fast.
  ➜ The resonances decouple from elastic scattering amplitude.
- Gradual disappearance of resonant structures in the πp cross sections
  ➜ For $\sqrt{s} > 1.7$ GeV, more and more inelastic channels open.

Knowledge on N^*/Δ^* in the PDG

Mostly 5 (reference) analyses based on (mainly) $\pi N \to \pi N$ and $\pi N \to N\pi\pi$ (Kent, Karlsruhe-Helsinki, Carnegie-Mellon, SAID, ...)

Baryon Spectroscopy at BES: $J/\psi \rightarrow \mathrm{p}\pi^- \bar{\mathrm{n}}\ \ (\bar{\mathrm{p}}\pi^+ \mathrm{n})$





→ PWA favors P_{13}

$N(2080)$ D_{13} $\quad I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

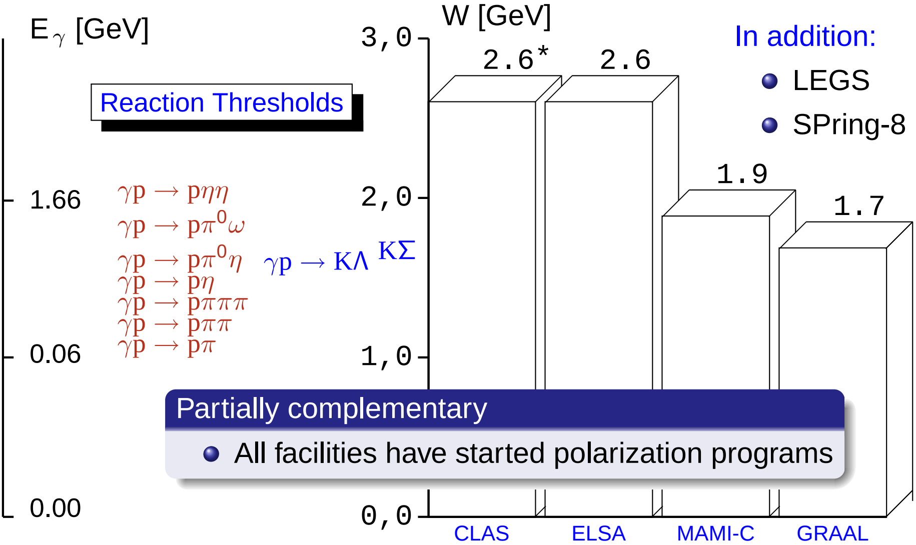
There is some evidence for two resonances in this wave between 1800 and 2200 MeV (see CUTKOSKY 80). However, the solution of HOEHLER 79 is quite different.

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** 1 (1982). Some further obsolete results published before 1984 were last included in our 2006 edition, Journal of Physics, G **33** 1 (2006).

The latest GWU analysis (ARNDT 06) finds no evidence for this resonance.

Analysis identifies four peaks: (Li *et al.*, 2009)

1. $N(1440)P_{11}$
2. Well-known 2nd resonance region around 1500 MeV
3. Well-known 3rd resonance region around 1700 MeV
4. Possible new state: $M = 2040^{+3}_{-4} \pm 25$ MeV/c^2
   $\Gamma = 230 \pm 8 \pm 52$ MeV/c^2



In addition:

- LEGS
- SPring-8

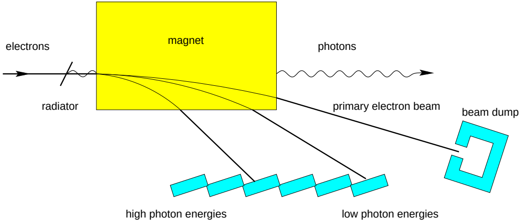
Partially complementary

- All facilities have started polarization programs

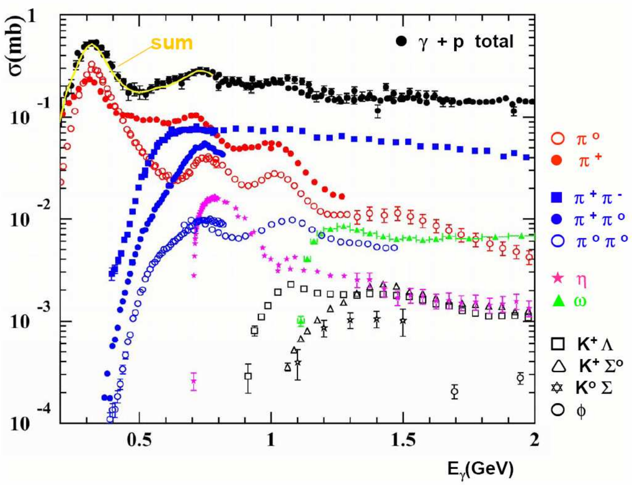
Photoproduction Experiments

Components and goals of the N^* program:

- How many baryon resonances are known?
  ➜ The PDG gives a large number of 1-star to 4-star resonances.
- How many baryon resonances are expected?
  ➜ What about quark-model (lattice) predictions?
- What is the structure of baryons?
  ➜ Electroproduction

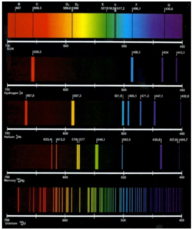


Total Photoproduction Cross Sections



No peak hunting

- Decays into neutral and charged particles
- Broad resonances



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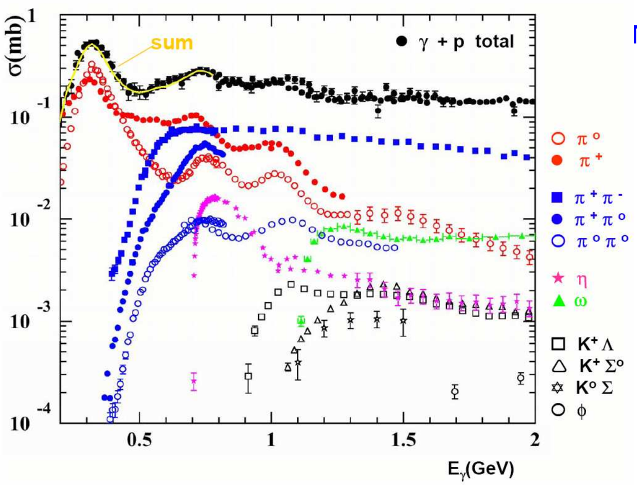

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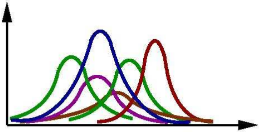

Ingredients in the Study of Excited Baryons

- Measurements off neutron and proton to resolve isospin contributions
  1. $\mathcal{A}(\gamma N \to \pi,\ \eta,\ K)^{I=3/2} \quad \Longleftrightarrow \quad \Delta^*$
  2. $\mathcal{A}(\gamma N \to \pi,\ \eta,\ K)^{I=1/2} \quad \Longleftrightarrow \quad N^*$
- Re-scattering effects: Large number of measurements (and also final states) needed to define the full scattering amplitude
- Double-polarization measurements

Chiang & Tabakin, Phys. Rev. C55, 2054 (1997)

In order to determine the full scattering amplitude without ambiguities, one has to carry out eight carefully selected measurements: four double-spin observables along with the four single-spin observables.

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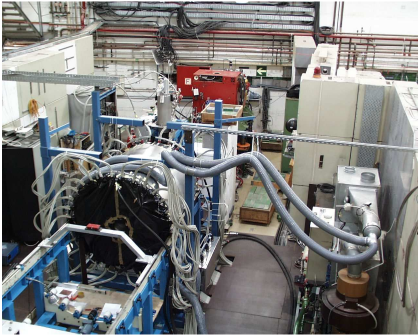
CLAS/Crystal Barrel – Complementary Detectors



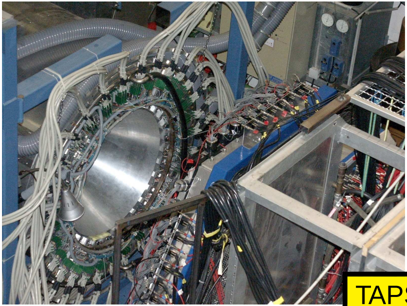
Photoproduction at ELSA with the Crystal-Barrel Detector

← Great to measure neutral particles: π^0, $\eta \to \gamma\gamma$, $\eta \to \pi^0\pi^0\pi^0$, etc.

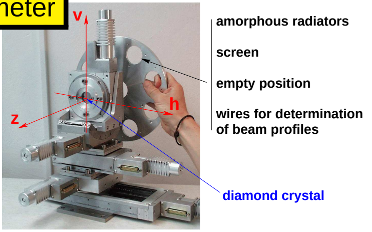
Photo/Electroproduction at CLAS

Great for charged particles: $\pi^\pm$, etc. →

The CBELSA/TAPS Experiment



Goniometer



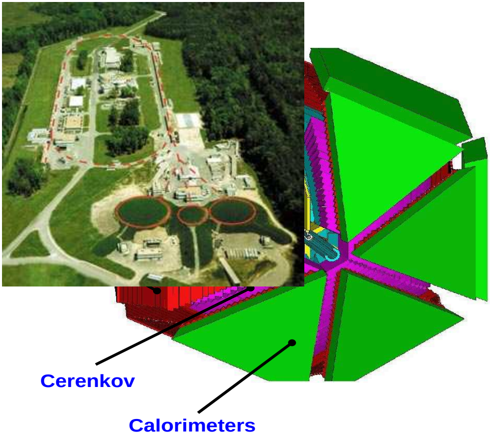
Sep. 2002 – Dec. 2003

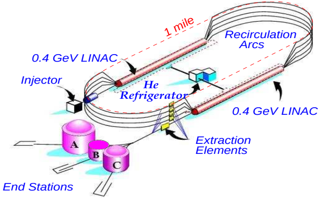
- (un)polarized beam
- liquid H_2, deuterium
- solid targets

TAPS

- 512 BaF Crystals
- Forward detector
  - High Granularity
  - Fast Trigger

CLAS Spectrometer





CHARACTERISTICS:

Electron Coverage: $\theta : 15\text{–}50^o$

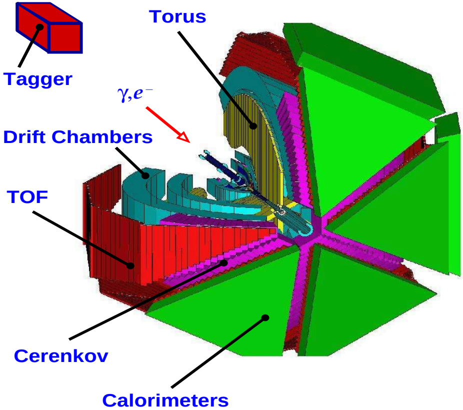
Hadron Coverage:

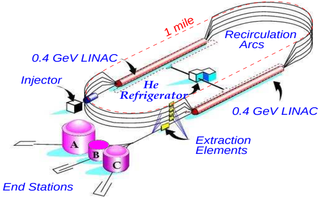
$\theta : 15\text{–}140^o,\ \phi : 80\%\ \ 2\pi$

Resolution : $\Delta p/p \sim 1\text{–}2\%$
$\Delta\theta, \Delta\phi \sim 2\ mrad$

$$\mathcal{L} = 1 \times 10^{34}\ cm^{-2} sec^{-1}$$
$$\mathcal{F}_\gamma = 1 \times 10^7/s$$

CLAS Spectrometer





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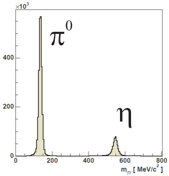
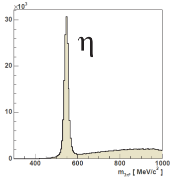
Isospin Filter: $\gamma p \longrightarrow N^* \; (I = 1/2) \; \longrightarrow p\,\eta$

$\eta \longrightarrow \gamma\gamma$

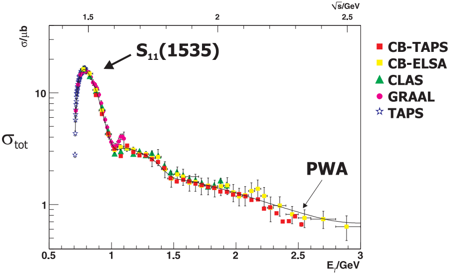


$\eta \longrightarrow 3\pi^0$



$d\sigma / d\Omega$

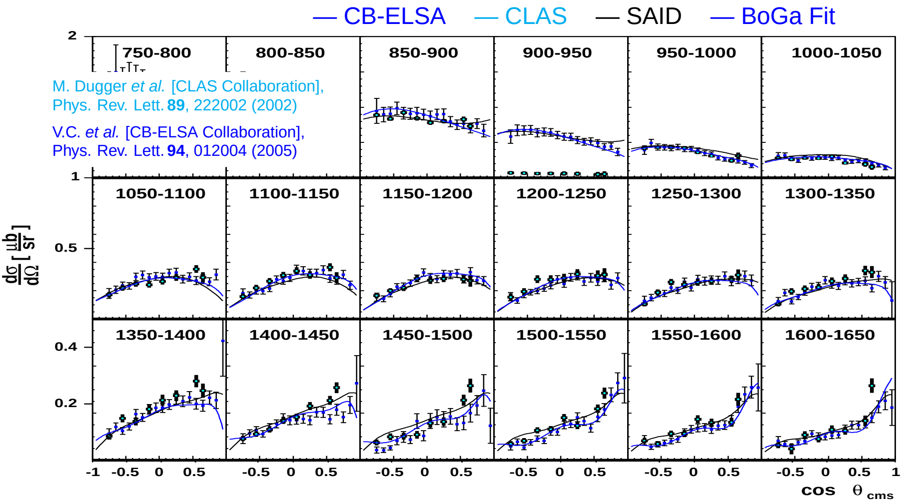
PWA



Only nucleon resonances can contribute

- $N(1535)S_{11}$, $N(1520)D_{13}$, $N(1650)S_{11}$, $N(1680)F_{15}$, $N(1720)P_{13}$, ... , ρ- and ω-t-channel exchange
- New resonance $N(2070)D_{15}$: $m = (2068 \pm 22)$ MeV/c^2
  $\Gamma = (295 \pm 40)$ MeV/c^2
  (needs confirmation in polarization experiments)

Photoproduction of η Mesons off the Proton



M. Dugger *et al.* [CLAS Collaboration], Phys. Rev. Lett. **89**, 222002 (2002)

V.C. *et al.* [CB-ELSA Collaboration], Phys. Rev. Lett. **94**, 012004 (2005)

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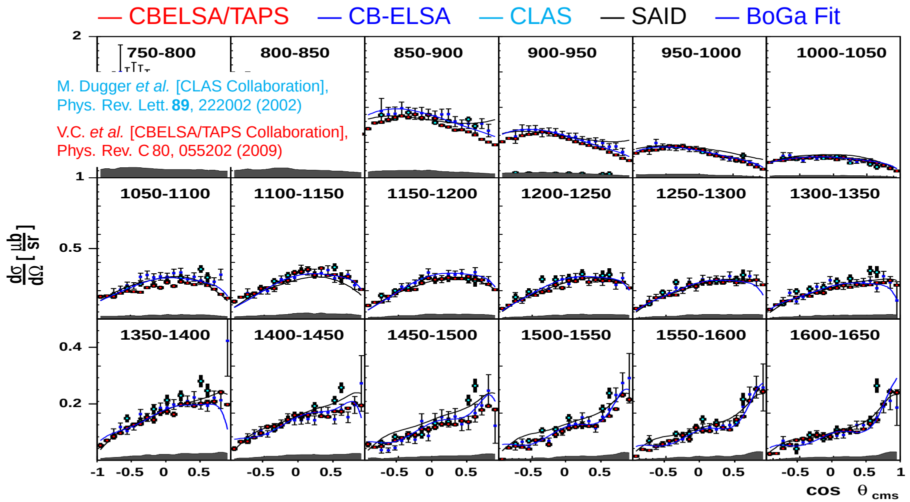
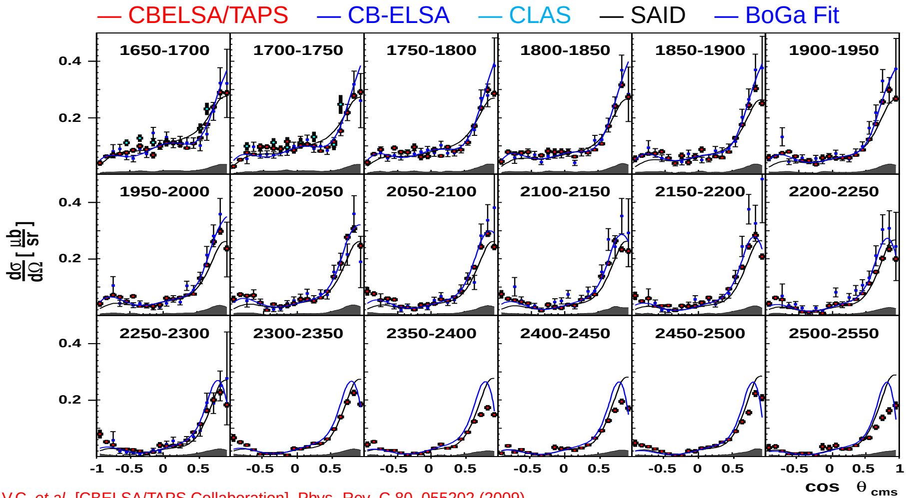


M. Dugger *et al.* [CLAS Collaboration], Phys. Rev. Lett. **89**, 222002 (2002)

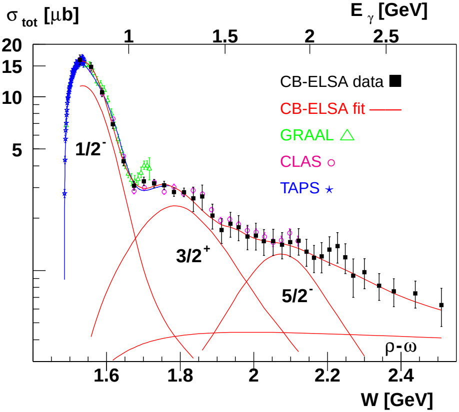
V.C. *et al.* [CBELSA/TAPS Collaboration], Phys. Rev. C 80, 055202 (2009)

Photoproduction of η Mesons off the Proton



V.C. *et al.* [CBELSA/TAPS Collaboration], Phys. Rev. C 80, 055202 (2009)

Analysis of $\gamma p \longrightarrow p\,\eta$: Total Cross Section



Isopsin Filter

➜ Only N^* resonances can contribute!

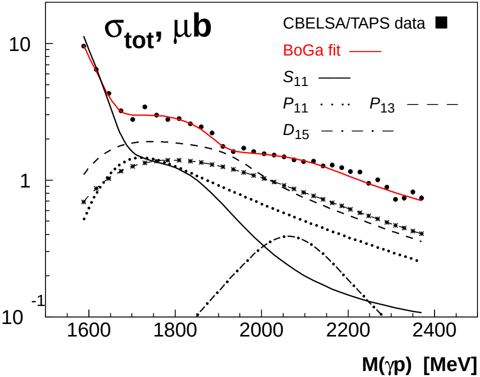
Bonn-Gatchina (PWA) group: Hints for N* resonance $N(2070)D_{15}$

(Phys. Rev. Lett. **94**, 012004 (2005))

Three resonances are dominantly contributing:

$N(1535)S_{11}$, $N(1720)P_{13}$, $N(2070)D_{15}$

Analysis of $\gamma p \to p\,\eta$: Total Cross Section



Isospin Filter

➜ Only N^* resonances can contribute!

Bonn-Gatchina (PWA) group: Hint for N* resonance (2070)D_{15}

(Phys. Rev. Lett. **94**, 012004 (2005))

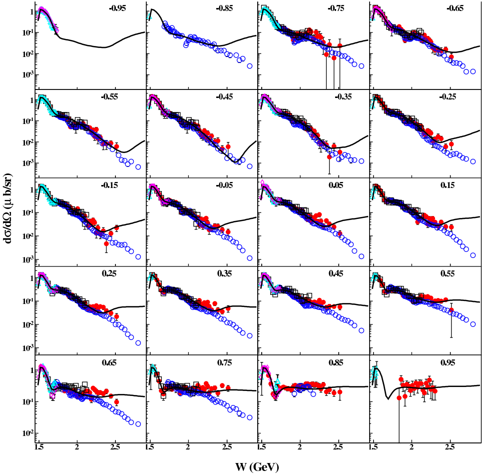
1. Confirmed in 2009 analysis!
2. $N(1720)P_{13} \to p\,\eta$?
   ➜ η-MAID:
   $N(1710)P_{11} \to p\,\eta$ significant!

Resonances dominantly contributing:

$N(1535)S_{11}$, $(N(1720)P_{13})^?$, $N(2070)D_{15}$

Photoproduction of η Mesons at CLAS (Jefferson Lab)

○ g11a ● CB-ELSA ('05) □ CLAS ('02) △ GRAAL ('02) ◇ LNS ('06) — SAID



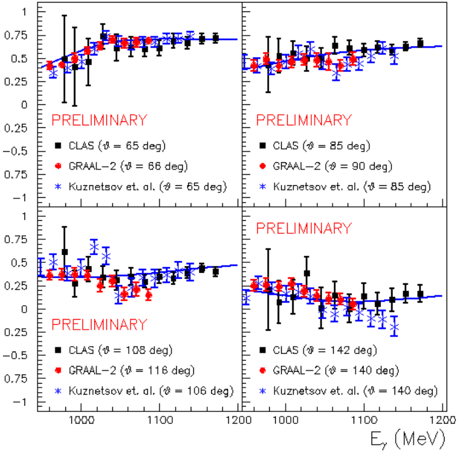
Big discrepancies at high energies and in the forward direction
➜ CLAS PWA in the works

V.C. *et al.* [CB-ELSA Collaboration], Phys. Rev. Lett. **94**, 012004 (2005)

M. Williams *et al.* [CLAS Collaboration], Phys. Rev. C 80, 045213 (2009)

Beam Asymmetry Σ in the Reaction $\vec{\gamma} p \rightarrow p\,\eta$

Higher sensitivity due to interference effects: $\Sigma \sim A_{1/2}(S_{11}) * A_{1/2}(P_{13}) + \ldots$



$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \, \Sigma \cos 2\phi$$
$$+ \Lambda_x (-\delta_l \, \mathbf{H} \sin 2\phi + \delta_\odot \, \mathbf{F})$$
$$- \Lambda_y (-\mathbf{T} + \delta_l \, \mathbf{P} \cos 2\phi)$$
$$- \Lambda_z (-\delta_l \, \mathbf{G} \sin 2\phi + \delta_\odot \, \mathbf{E}) \}$$

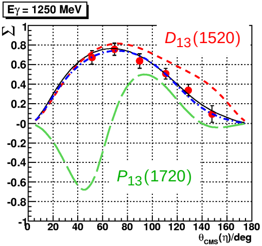
Further spin observables available

E and G from FROST run with longitudinal target polarization (2007/2008)

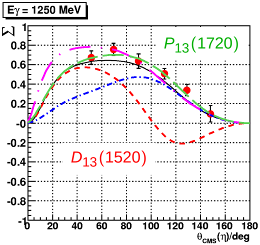
T, F, H, and P from FROST with transverse target polarization (Spring 2010)

P. Collins, CLAS g8b run group, to be published

Beam Asymmetry Σ in the Reaction $\vec{\gamma} p \longrightarrow p\,\eta$



BoGa-PWA



η-MAID

$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l\, \Sigma \cos 2\phi$$
$$+ \Lambda_x \left(-\delta_l\, \mathbf{H} \sin 2\phi + \delta_\odot\, \mathbf{F} \right)$$
$$- \Lambda_y \left(-\mathbf{T} + \delta_l\, \mathbf{P} \cos 2\phi \right)$$
$$- \Lambda_z \left(-\delta_l\, \mathbf{G} \sin 2\phi + \delta_\odot\, \mathbf{E} \right) \}$$

Further spin observables available

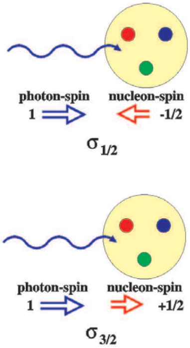
E and G from FROST run with longitudinal target polarization (2007/2008)

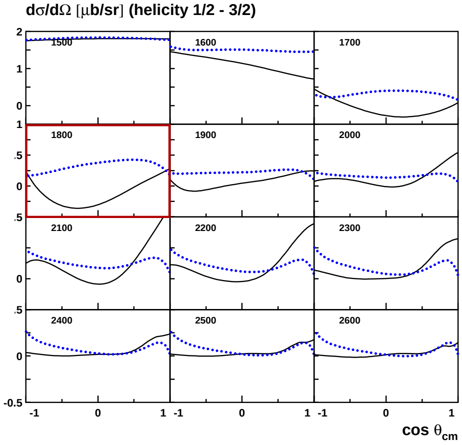
T, F, H, and P from FROST with transverse target polarization (Spring 2010)

Predictions for E “Helicity Difference”

η-MAID / BoGa-PWA

$$\frac{d\sigma_{(3/2-1/2)}}{d\Omega} = \frac{d\sigma_{3/2}}{d\Omega} - \frac{d\sigma_{1/2}}{d\Omega}$$

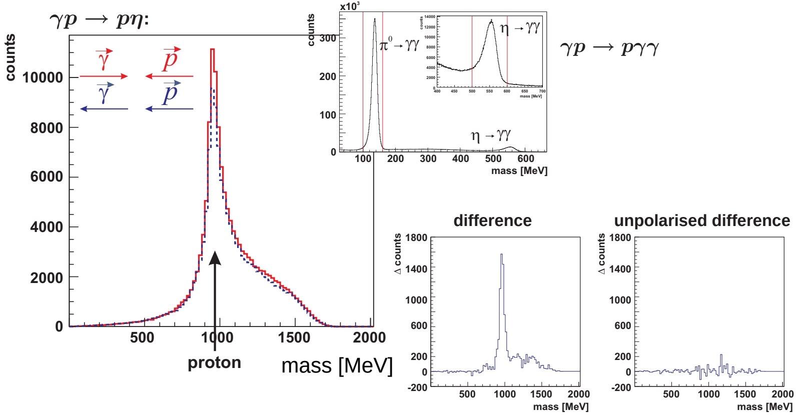




First Asymmetries Observed at ELSA

Online spectra: circularly polarised beam, longitudinally polarised target

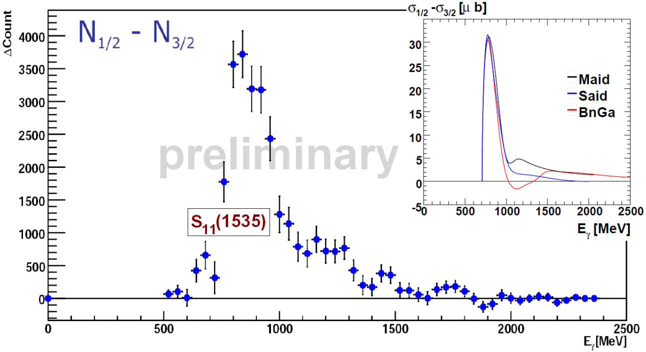
$\gamma p \longrightarrow p\eta$:



$\gamma p \longrightarrow p\gamma\gamma$

Count rate differences plotted:

M. Gottschall, Bonn



Clear asymmetries observed !

∼ complete angular coverage

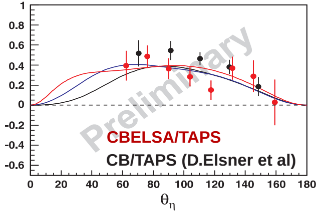
⇒ New and important information for the PWA

$\vec{\gamma}\vec{p} \longrightarrow p\eta$:

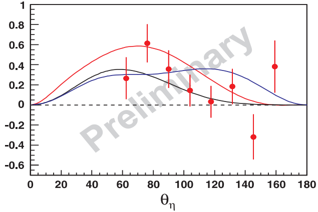
E_γ=950±50 MeV

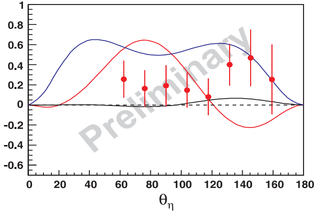
$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \, \boldsymbol{\Sigma} \cos 2\phi + \Lambda_x \left(-\delta_l \, \mathbf{H} \sin 2\phi + \delta_\odot \, \mathbf{F} \right) - \Lambda_y \left(-\mathbf{T} + \delta_l \, \mathbf{P} \cos 2\phi \right) - \Lambda_z \left(-\delta_l \, \mathbf{G} \sin 2\phi + \delta_\odot \, \mathbf{E} \right) \}$$

Σ:



G:

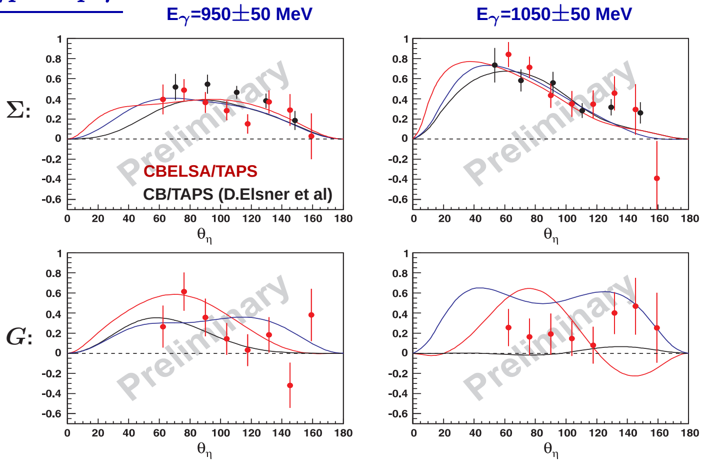




– MAID **– BnGa** **– SAID**

↔ **preliminary dilution factor included**

$\vec{\gamma}\vec{p} \longrightarrow p\eta$:

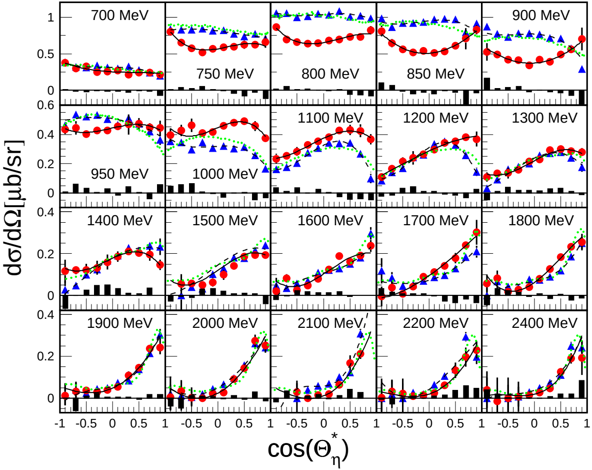


– **MAID** – **BnGa** – **SAID**

$\longleftrightarrow$ **preliminary dilution factor included**

Study of $\gamma n \rightarrow n\,\eta$

I. Jaegle et al. [CBELSA/TAPS Collaboration], Phys. Rev. Lett. **100**, 252002 (2008)



▲ quasi-free proton

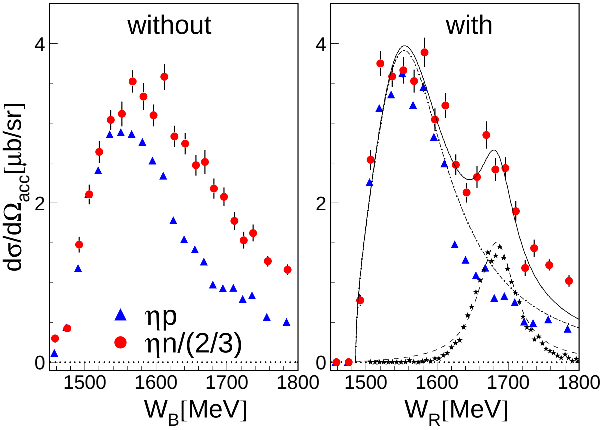
● quasi-free neutron

—— (– · –·) BoGa fits

Study of $\gamma n \longrightarrow n\,\eta$

I. Jaegle et al. [CBELSA/TAPS Collaboration], Phys. Rev. Lett. **100**, 252002 (2008)

Event-by-event correction of Fermi motion



▲ quasi-free proton

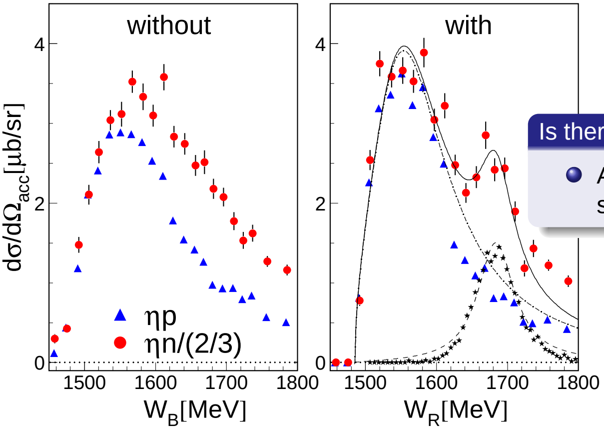
● quasi-free neutron

Excitation functions for $\cos\theta_\eta < -0.1$

Study of $\gamma n \longrightarrow n\,\eta$

I. Jaegle et al. [CBELSA/TAPS Collaboration], Phys. Rev. Lett. **100**, 252002 (2008)

Event-by-event correction of Fermi motion



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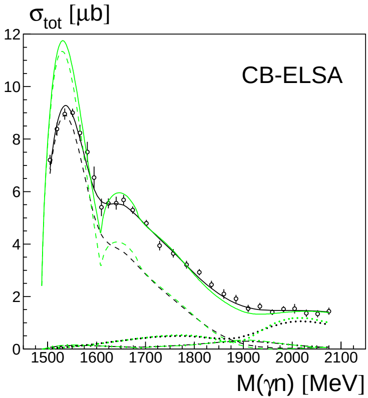
● quasi-free neutron

Is there a narrow P_{11} state?

- Absolutely no evidence for such a peak off the proton

Study of $\gamma n \longrightarrow n\,\eta$

I. Jaegle et al. [CBELSA/TAPS Collaboration], Phys. Rev. Lett. **100**, 252002 (2008)



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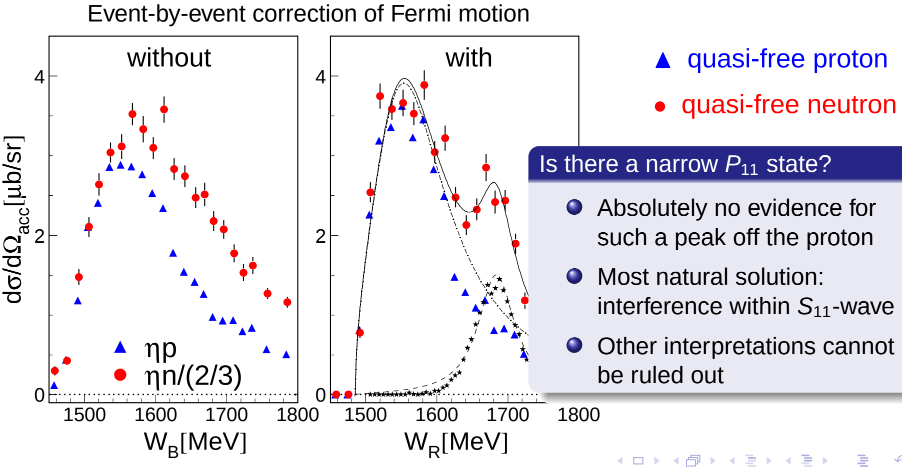
Is there a narrow P_{11} state?

- Absolutely no evidence for such a peak off the proton
- Most natural solution: interference within S_{11}-wave

Study of $\gamma n \longrightarrow n\,\eta$

I. Jaegle et al. [CBELSA/TAPS Collaboration], Phys. Rev. Lett. **100**, 252002 (2008)

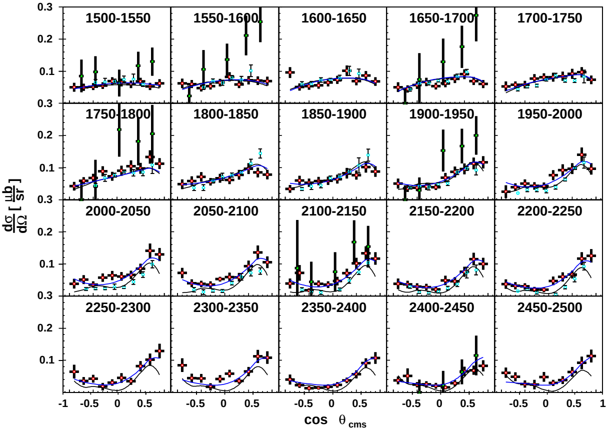


Is there a narrow P_{11} state?

- Absolutely no evidence for such a peak off the proton
- Most natural solution: interference within S_{11}-wave
- Other interpretations cannot be ruled out

Brief Summary of Further Experimental Efforts

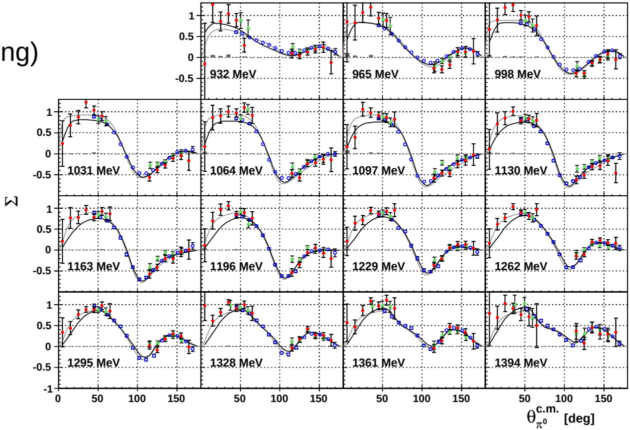
- $\gamma p \longrightarrow p\,\eta'$
  ($d\sigma/d\Omega$, Σ from CLAS)



V.C., A. McVeigh *et al.*, Phys. Rev. C 80, 055202 (2009)

Brief Summary of Further Experimental Efforts

- $\gamma p \longrightarrow p\,\eta'$
- $\gamma p \longrightarrow p\,\pi^0$ (in full swing) ($d\sigma/d\Omega$, Σ, etc.)

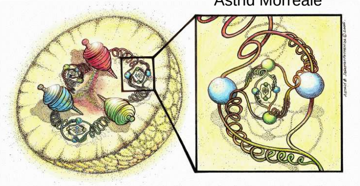


N. Sparks *et al.*, to be submitted to Phys. Rev. C

Brief Summary of Further Experimental Efforts

- $\gamma p \longrightarrow p\,\eta'$
- $\gamma p \longrightarrow p\,\pi^0$
- $\vec{\gamma}\vec{p} \longrightarrow n\,\pi^+$ (Evan McClellan, "Honors Thesis")
- $\gamma p \longrightarrow p\,\omega$
- $\vec{\gamma}\vec{p} \longrightarrow p\,\pi^0\pi^0$, $p\,\pi^0\omega$, $p\,\pi^0\eta$ (Crystal Barrel)
  Proposal ELSA/7-2005, Approval Rating "$A-$" ➜ A. Wilson, M. Szmaida (A. Woodard, "Honors Thesis")
- $\vec{\gamma}\vec{p} \longrightarrow p\,\pi^+\pi^-$ (CLAS)
  JLab Proposal (2006), E06-013, Approval Rating "$A-$" ➜ S. Park, C. Hanretty
- Whole industry on strangeness channels: $\gamma p \rightarrow \Sigma K$ and $\gamma p \rightarrow \Lambda K$
  ➜ Possibility of a complete experiment!
- Measurements off the neutron ($\vec{\gamma}\vec{n} \rightarrow$) planned for this year at CLAS

Astrid Morreale



The QCD picture of the Proton Color Pencil and pen Drawing by Sebastien Parmentier and Astrid Morreale

Proposed (New) Baryon Resonances

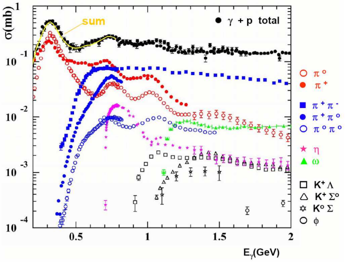
Reaction	Resonances			
$\gamma p \to N\,\pi$	$\Delta(1232)P_{33}$	$N(1520)D_{13}$	$N(1680)F_{15}$	$N(1535)S_{11}$
$\gamma p \to p\,\eta$	$N(1535)S_{11}$	$N(1720)P_{13}$	$N(2070)D_{15}$	$N(1650)S_{11}$
$\gamma p \to p\,\pi^0\pi^0$	$\Delta(1700)D_{33}$	$N(1520)D_{13}$	$N(1680)F_{15}$	
$\gamma p \to p\,\pi^0\eta$	$\Delta(1940)D_{33}$	$\Delta(1920)P_{33}$	$N(2200)P_{13}$	$\Delta(1700)D_{33}$
$\gamma p \to \Lambda K^+$	$S_{11} - wave$	$N(1720)P_{13}$	$N(1900)P_{13}$	$N(1840)P_{11}$
$\gamma p \to \Sigma K$	$S_{11} - wave$	$N(1900)P_{13}$	$N(1840)P_{11}$	
$\pi^- p \to n\,\pi^0\pi^0$	$N(1440)P_{11}$	$N(1520)D_{13}$	$S_{11} - wave$	

The available data sets comprising various high-statistics differential cross sections, beam, target, recoil asymmetries, double polarization observables, and also data resolving isospin contributions are not yet sufficient to converge into a unique solution.

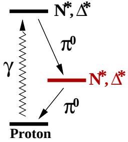
Beam-Target Polarization Observables

$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \, \Sigma \cos 2\phi + \Lambda_x (-\delta_l \, \mathbf{H} \sin 2\phi + \delta_\odot \, \mathbf{F}) - \Lambda_y (-\mathbf{T} + \delta_l \, \mathbf{P} \cos 2\phi) - \Lambda_z (-\delta_l \, \mathbf{G} \sin 2\phi + \delta_\odot \, \mathbf{E}) \}$$

$\Leftarrow$ Single-Meson Final States (7 Observables)



At higher excitation energies:
Multi-meson final states play an increasingly important role



➜ Search for states in cascades!

Beam-Target Polarization Observables

$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \, \Sigma \cos 2\phi + \Lambda_x (-\delta_l \, \mathbf{H} \sin 2\phi + \delta_\odot \, \mathbf{F}) - \Lambda_y (-\mathbf{T} + \delta_l \, \mathbf{P} \cos 2\phi) - \Lambda_z (-\delta_l \, \mathbf{G} \sin 2\phi + \delta_\odot \, \mathbf{E}) \}$$

$\Leftarrow$ Single-Meson Final States (7 Observables)

$$I = I_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}) + \delta_\odot (\mathbf{I}^\odot + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^\odot) + \delta_l [\sin 2\beta (\mathbf{I}^\mathbf{s} + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^\mathbf{s}) \cos 2\beta (\mathbf{I}^\mathbf{c} + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^\mathbf{c})] \}$$

Two-Meson Final States $\Rightarrow$ (15 Observables)

Photoproduction of $\pi^+\pi^-$ off the Proton: Kinematics

Two mesons in the final state require 5 independent variables!

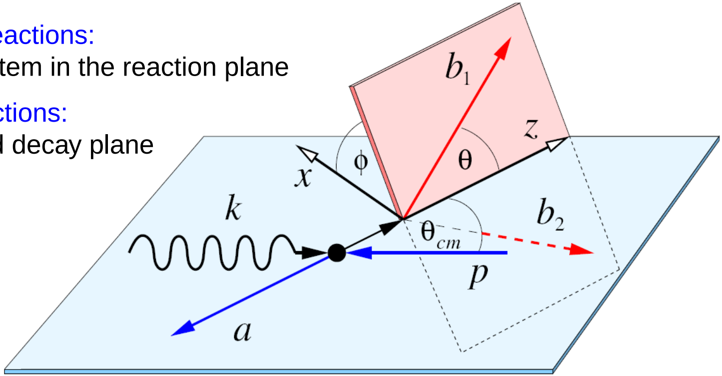
For example: E_γ, $\Theta_{\rm c.m.}$, ϕ^*, θ^*, $M_{p\,+\,meson_1}$

Single-meson reactions:

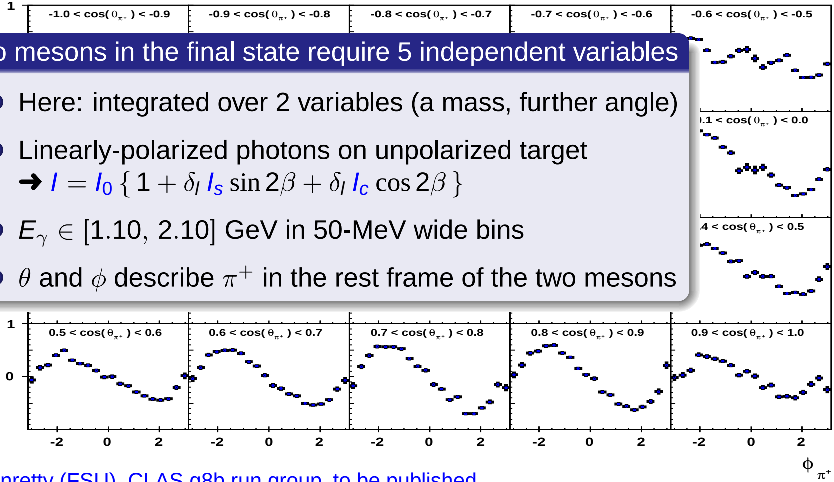
➜ p-meson system in the reaction plane

Two-meson reactions:

➜ Reaction and decay plane form angle ϕ



Photoproduction of $\pi^+\pi^-$: Beam Asymmetry I_s (new)

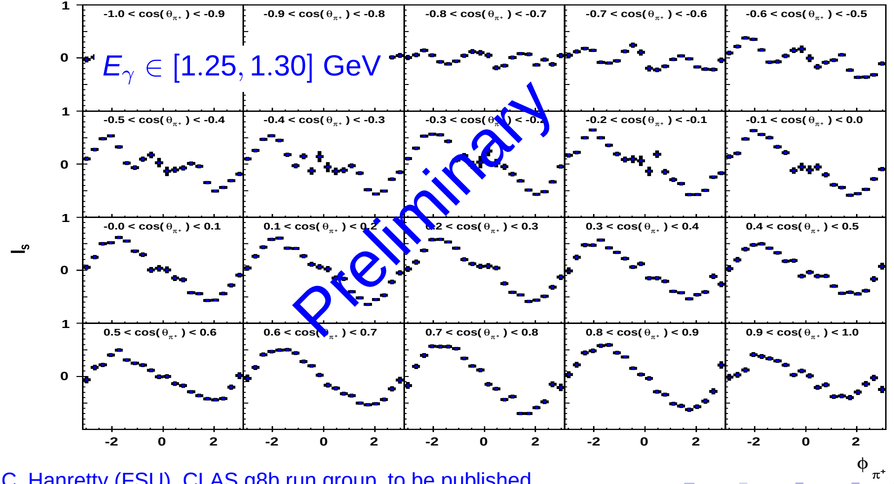


Two mesons in the final state require 5 independent variables

- Here: integrated over 2 variables (a mass, further angle)
- Linearly-polarized photons on unpolarized target
  ➜ $I = I_0 \{ 1 + \delta_l \, I_s \sin 2\beta + \delta_l \, I_c \cos 2\beta \}$
- $E_\gamma \in [1.10,\ 2.10]$ GeV in 50-MeV wide bins
- θ and ϕ describe π^+ in the rest frame of the two mesons

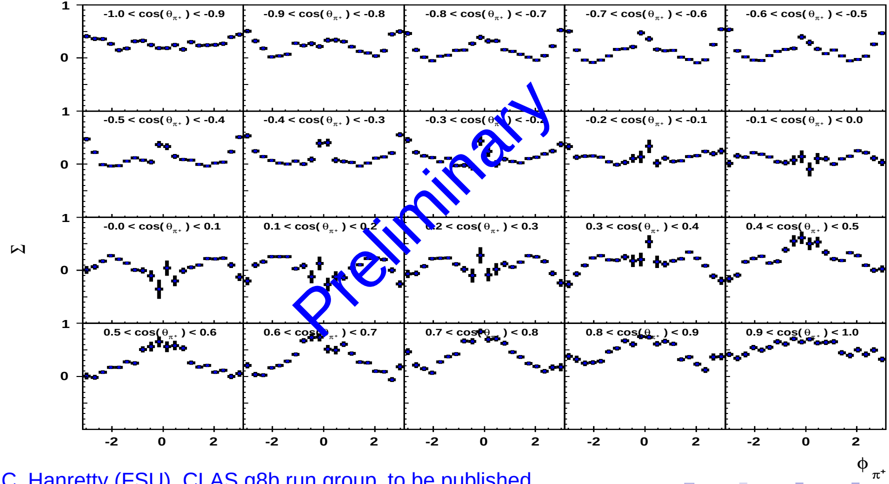
C. Hanretty (FSU), CLAS g8b run group, to be published

Photoproduction of $\pi^+\pi^-$: Beam Asymmetry I_s (new)



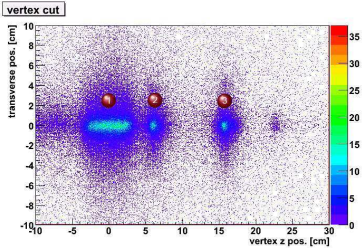
C. Hanretty (FSU), CLAS g8b run group, to be published

Photoproduction of $\pi^+\pi^-$: Beam Asymmetry I_c $(= \Sigma)$

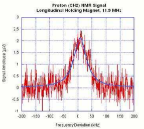


C. Hanretty (FSU), CLAS g8b run group, to be published

The Frozen-Spin (FROST) Target



$\Delta B/B \approx 3 \cdot 10^{-3}$ at 0.5 T



$B \approx 0.5$ T

$T \approx 0.05$ K

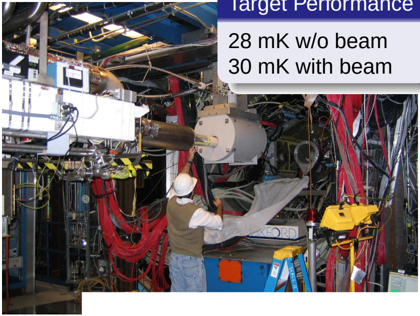
Production Data

- Target (Butanol)

  Longitudinally-polarized target
  Average polarization $\sim 80\,\%$
  Additional targets: ^{12}C, CH_2

- PhotonBeam

  Circular and linear Polarization
  Excellent degrees of polarization



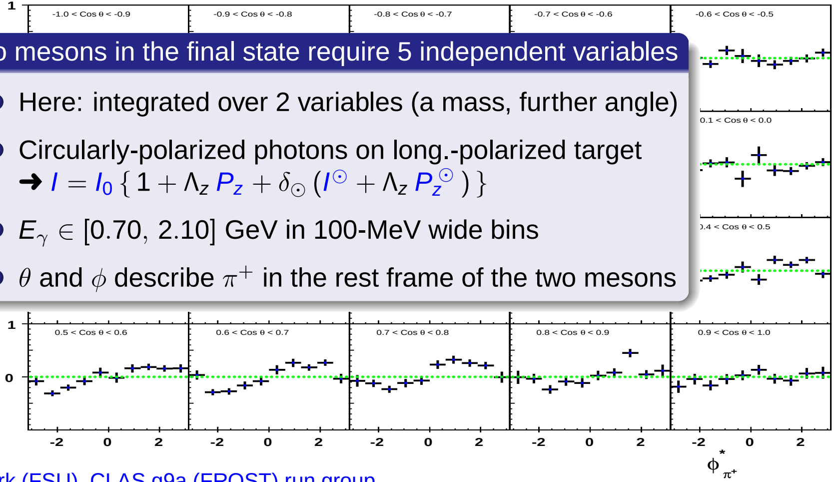
Target Performance

28 mK w/o beam
30 mK with beam

Photoproduction of $\pi^+\pi^-$: Helicity Difference $P_z^{\odot}$ $(= E)$

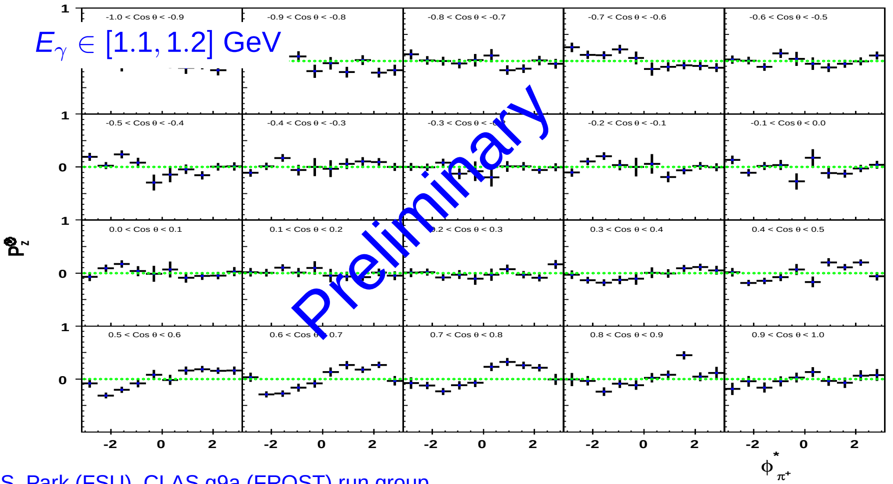
Two mesons in the final state require 5 independent variables

- Here: integrated over 2 variables (a mass, further angle)
- Circularly-polarized photons on long.-polarized target
  ➜ $I = I_0\,\{\,1 + \Lambda_z\, P_z + \delta_{\odot}\,(I^{\odot} + \Lambda_z\, P_z^{\odot}\,)\,\}$
- $E_\gamma \in [0.70,\, 2.10]$ GeV in 100-MeV wide bins
- θ and ϕ describe π^+ in the rest frame of the two mesons



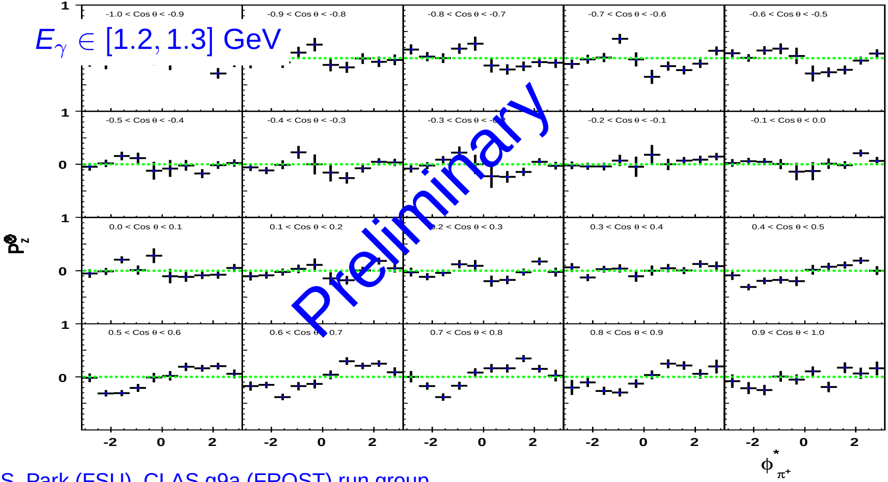
S. Park (FSU), CLAS g9a (FROST) run group

Photoproduction of $\pi^+\pi^-$: Helicity Difference $P_z^{\odot}$ $(= E)$



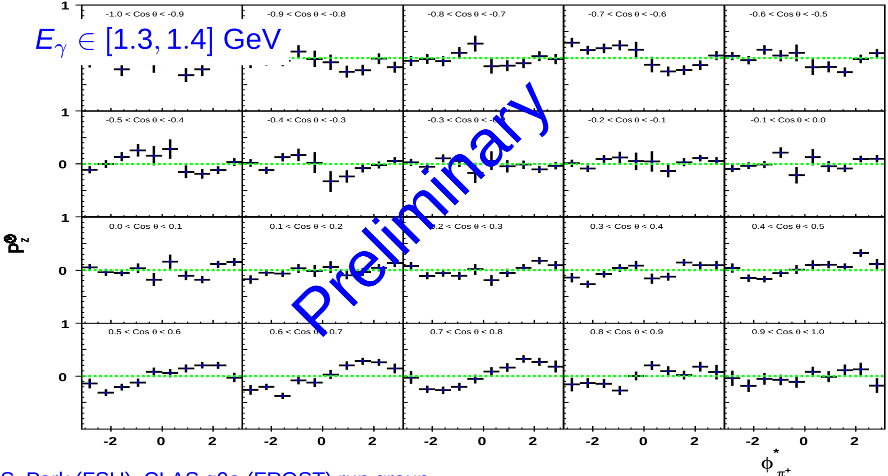
S. Park (FSU), CLAS g9a (FROST) run group

Photoproduction of $\pi^+\pi^-$: Helicity Difference $P_z^{\odot}$ $(= E)$



S. Park (FSU), CLAS g9a (FROST) run group

Photoproduction of $\pi^+\pi^-$: Helicity Difference $P_z^{\odot}$ $(= E)$



S. Park (FSU), CLAS g9a (FROST) run group

Outline

1. Introduction
   - QCD and Hadron Spectroscopy
2. Experimental Methods in Baryon Spectroscopy
   - Photoproduction
3. Experimental Efforts
   - CLAS and the Crystal Barrel Detector
4. Photoproduction of Mesons (off Protons)
   - Single-Meson Reactions: $\gamma N \to N\eta$
   - Double-Pion Photoproduction
5. Summary and Outlook

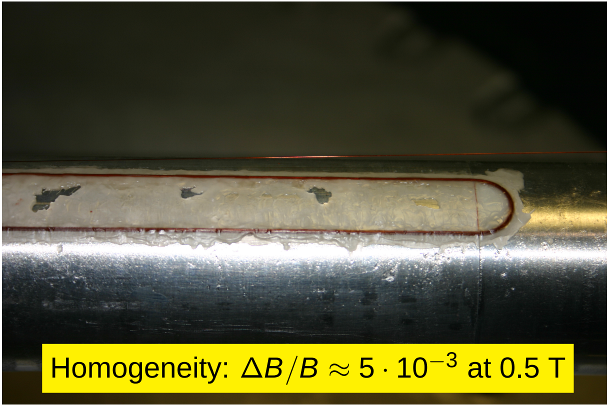
Summary

Many high-statistics (photoproduction) data samples available with excellent energy and angular coverage:

- Several analyses provide good description of π, η, $\pi\pi$, and hyperon data
  - (New) baryon resonances have been confirmed (proposed)

    ➜ Studies do not always agree, ambiguities!
- Polarization measurements have started at all facilities
  - First asymmetries in double-polarization have been observed
  - Complete experiment in hyperon photoproduction possible
- New FROST run starting next month using CLAS at JLab with transverse target polarization

Transverse Holding Magnet: Dipole *(Race-Track Coils)*



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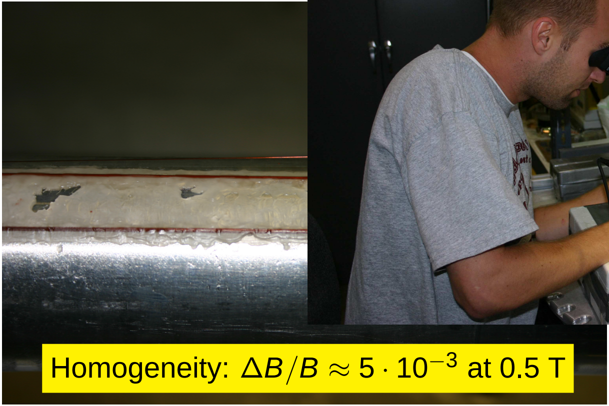
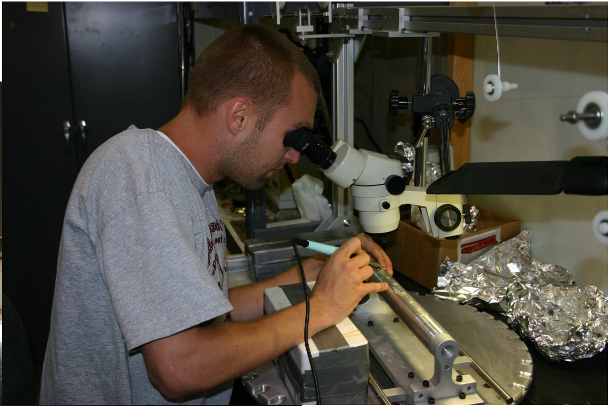
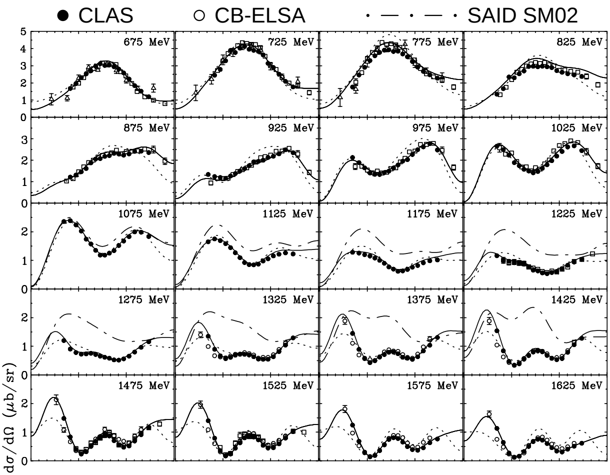




Homogeneity: $\Delta B/B \approx 5 \cdot 10^{-3}$ at 0.5 T

Backup Slides

Photoproduction of π^0 Mesons off the Proton

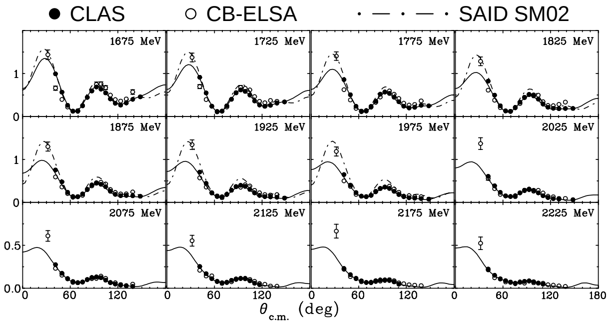


Resonance	πN SAID	$A_{1/2}$	$A_{3/2}$
$N(1535)S_{11}$	W_R=1547 MeV	91.0±2.2	
	Γ=188 MeV	90±30	
	Γ_π/Γ=0.36		
$N(1650)S_{11}$	W_R=1635 MeV	22.2±7.2	
	Γ=115 MeV	53±16	
	Γ_π/Γ=1.00		
$N(1440)P_{11}$	W_R=1485 MeV	−50.6±1.9	
	Γ=284 MeV	−65±4	
	Γ_π/Γ=0.79		
$N(1720)P_{13}$	W_R=1764 MeV	96.6±3.4	−39.0±3.2
	Γ=210 MeV	18±30	−19±20
	Γ_π/Γ=0.09		
$N(1520)D_{13}$	W_R=1515 MeV	−28.0±1.9	143.1±2.0
	Γ=104 MeV	−24±9	166±5
	Γ_π/Γ=0.63		
$N(1675)D_{15}$	W_R=1674 MeV	18.0±2.3	21.2±1.4
	Γ=147 MeV	19±8	15±9
	Γ_π/Γ=0.39		
$N(1680)F_{15}$	W_R=1680 MeV	−17.3±1.4	133.6±1.6
	Γ=128 MeV	−15±6	133±12
	Γ_π/Γ=0.70		
$\Delta(1620)S_{31}$	W_R=1615 MeV	49.6±2.2	
	Γ=147 MeV	27±11	
	Γ_π/Γ=0.32		
$\Delta(1232)P_{33}$	W_R=1233 MeV	−139.1±3.6	−257.6±4.6
	Γ=119 MeV	−135±6	−250±8
	Γ_π/Γ=1.00		
$\Delta(1700)D_{33}$	W_R=1695 MeV	125.4±3.0	105.0±3.2
	Γ=376 MeV	104±15	85±22
	Γ_π/Γ=0.16		
$\Delta(1905)F_{35}$	W_R=1858 MeV	21.3±3.6	−45.6±4.7
	Γ=321 MeV	26±11	−45±20
	Γ_π/Γ=0.12		

M. Dugger *et al.* [CLAS Collaboration], PRC **76**, 025211 (2007)

Photoproduction of π^0 Mesons off the Proton

- Strong excitation of $N(1720)P_{13}$ consistent with analysis of $\pi^+\pi^-$ electro-couplings
- No new nucleon resonances needed!



M. Dugger *et al.* [CLAS Collaboration], PRC **76**, 025211 (2007)

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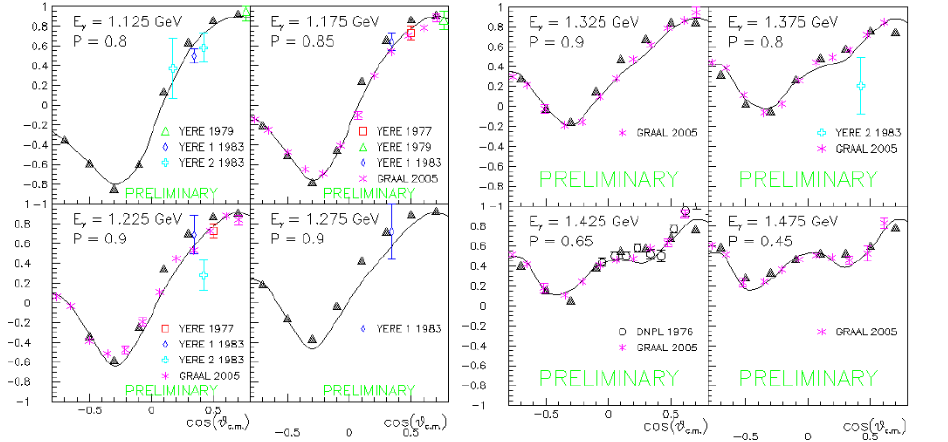
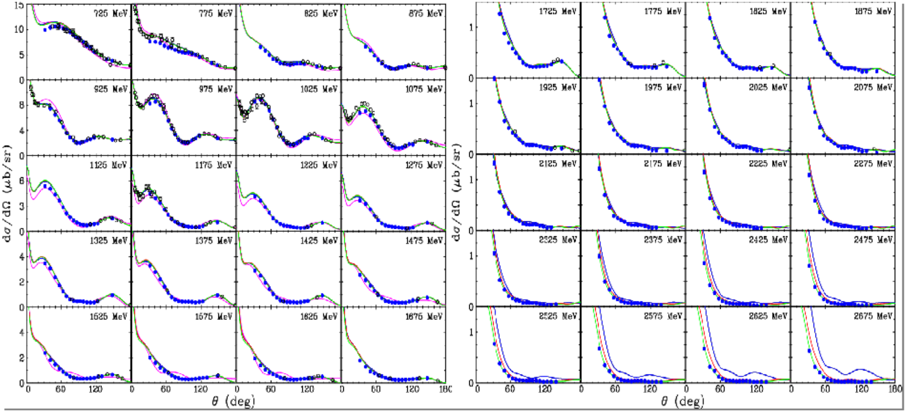
Photoproduction of π^0 Mesons: Beam Asymmetry Σ



M. Dugger, CLAS g8b run group, to be published (▲)

Photoproduction of π^+ Mesons: $\gamma p \to n\,\pi^+$

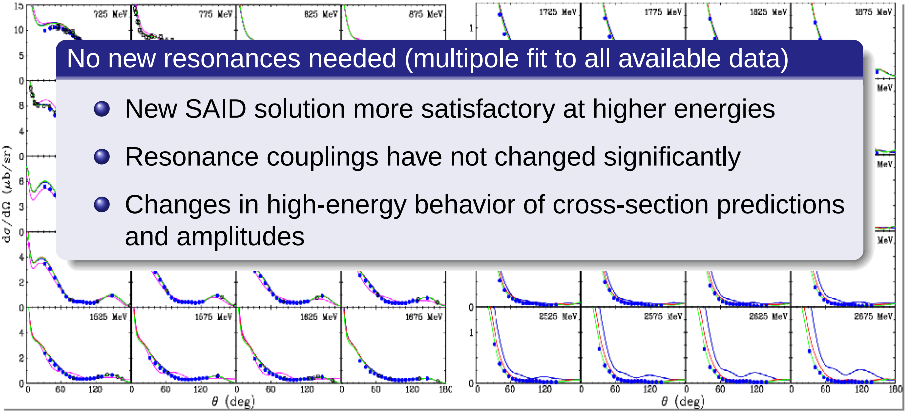
SAID FA07 MAID07 — ? SAID FA08



M. Dugger *et al.* (CLAS g1c), PRC **76**, 065206 (2009)

Photoproduction of π^+ Mesons: $\gamma p \to n\,\pi^+$

SAID FA07 MAID07 — ? SAID FA08

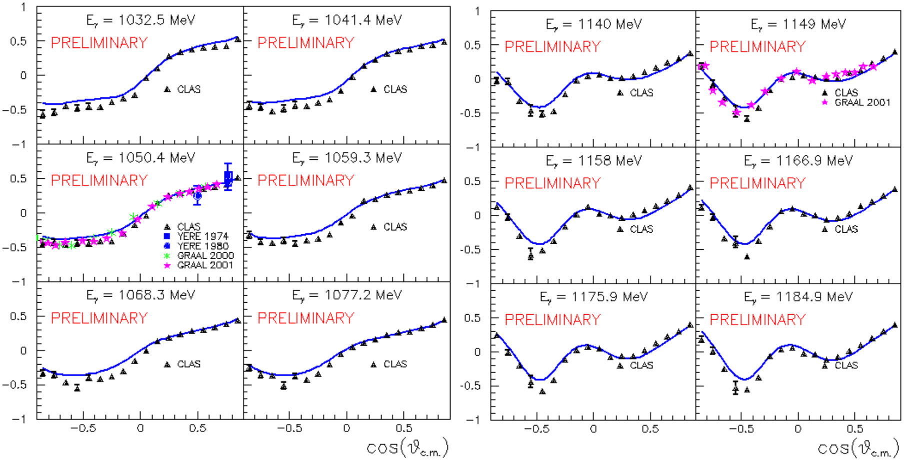


No new resonances needed (multipole fit to all available data)

- New SAID solution more satisfactory at higher energies
- Resonance couplings have not changed significantly
- Changes in high-energy behavior of cross-section predictions and amplitudes

M. Dugger *et al.* (CLAS g1c), PRC **76**, 065206 (2009)

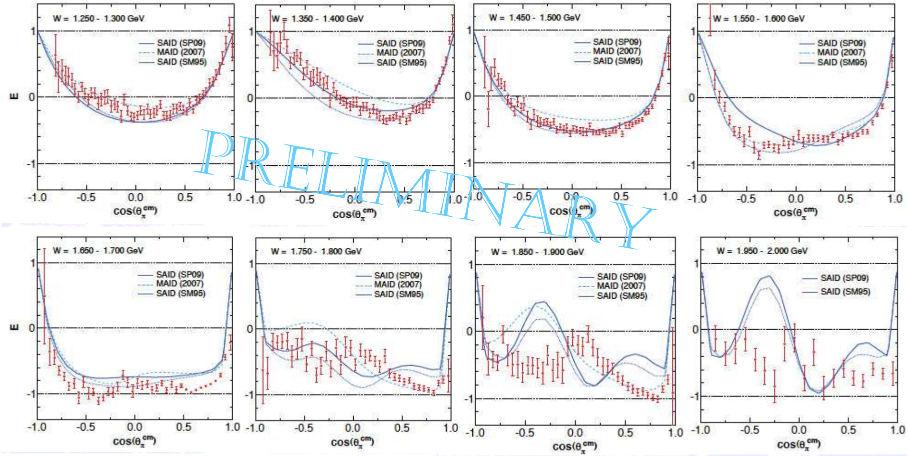
Photoproduction of π^+ Mesons: Σ in $\gamma p \rightarrow n\,\pi^+$



CLAS g8b run group, ASU analysis, to be published (▲)

Photoproduction of π^+ Mesons: Helicity Difference E

circ.-pol. beam on long.-pol. target: good agreement with SAID & MAID for $W < 1.7$ GeV



CLAS g9a (FROST) run group, USC analysis

Refrigeration below 4.2 K

1. Evaporative Cooling

   In order to evaporate 1 mole of ^{4}He, heater must supply:

   $L \approx$ 80 J/mol (L is latent heat of vaporazation)

   $\Rightarrow$ In absence of a heater, liquid will absorb heat from surroundings and temperature will drop ($T \approx$ 1.5 K)

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2. ^{3}He/^{4}He Dilution Refrigeration
   Below 0.8 K, a ^{3}He/^{4}He mixture will separate into two phases:
   1. Lighter *concentrated phase* rich in ^{3}He
   2. Heavier *dilute phase* rich in ^{4}He (concentration of ^{3}He $\geq 6\,\%$)

   $\Rightarrow$ Thus, ^{3}He will absorb energy when it dissolves *(evaporates)* into the dilute phase providing highly-effective cooling

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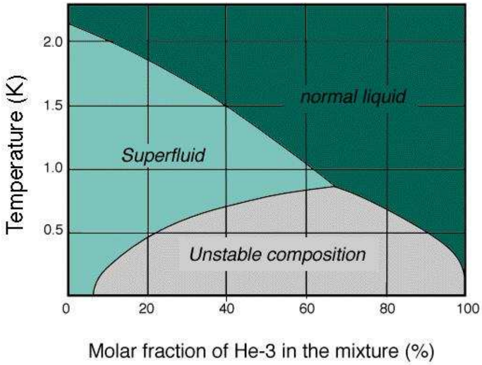

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