Recent Results in Baryon Spectroscopy

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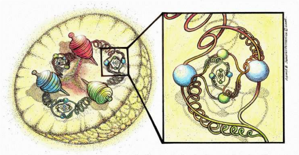
The Structure and Dynamics of Hadrons

Workshop on Gross Properties of Nuclei and Nuclear Excitations

Hirschegg, Kleinwalsertal, Austria

January 18, 2011

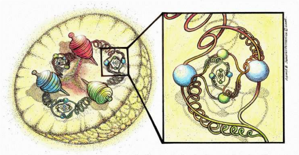
Outline



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

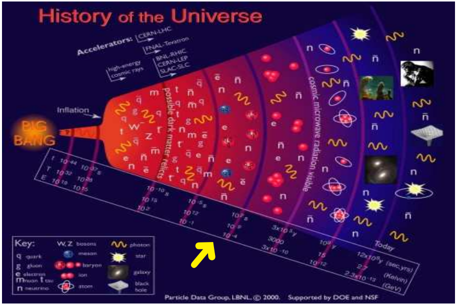
1. Introduction
   - Quarks, QCD, and Confinement
   - Why do we study excited baryons?
2. The Search for Undiscovered States
   - Meson Photo-Production Data
   - Complete Experiments
   - Experimental Status of (Polarization) Program
3. Summary and Outlook

Outline

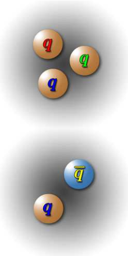


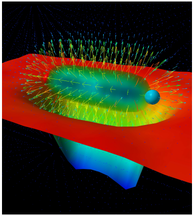
The QCD picture of the Proton Color Pencil and pen Drawing by Sebastien Parmentier and Astrid Morreale

Confinement and the Big Questions



From about 10^{-6} s on, all quark and anti-quarks became confined inside of hadronic matter. Only protons and neutrons remained after about 1 s.

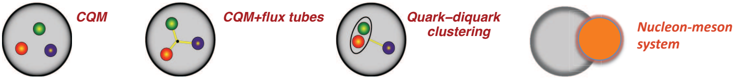




1. What is the origin of confinement?
2. How are confinement and chiral symmetry breaking connected?
3. If we knew, would this explain the origin of $\sim 99\,\%$ of observed matter?

The Issues with Hadrons

1. **The Baryons**
   What are the fundamental degrees of freedom inside of a proton and a neutron? How do they change with varying quark masses?



2. **Mesons**
   What is the role of glue in a quark-antiquark system and how is this related to the confinement of QCD?

   What are the properties of predicted states beyond simple quark-antiquark systems (hybrid mesons, glueballs, ...)?

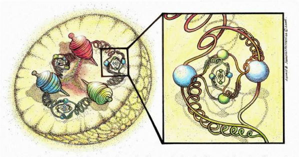
   ➜ Need to map out new states: BES III, COMPASS, Panda@GSI, GlueX@JLab, ...

Two Components of the Experimental N^* Program

The excited baryon program has two main components:

- Establish the systematics of the spectrum
  Current medium-energy experiments use photon beams to map out the baryon spectrum (JLab, ELSA, MAMI, SPring-8, etc.).
  - ➜ Provides information on the nature of the effective degrees of freedom in strong QCD and also addresses the issue of hitherto unobserved or so-called *missing resonances.*
- Probe resonance transitions at different distance scales
  Electron beams are ideal to measure transition form factors and their corresponding Q^2 dependence.
  - ➜ Provides information on the confining (effective) forces of the 3-quark system.

Outline



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

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

➜ according to PDG
(J. Phys. G **37**, 075021 (2010))

➜ little known
(many open questions left)

Are the states missing because our pictures do not capture the correct degrees of freedom?

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

Search for *missing* or yet unobserved resonances

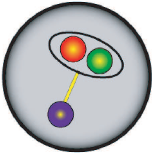
Quark models predict many more baryons than have been observed

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

→ according to PDG
(J. Phys. G **37**, 075021 (2010))
→ 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

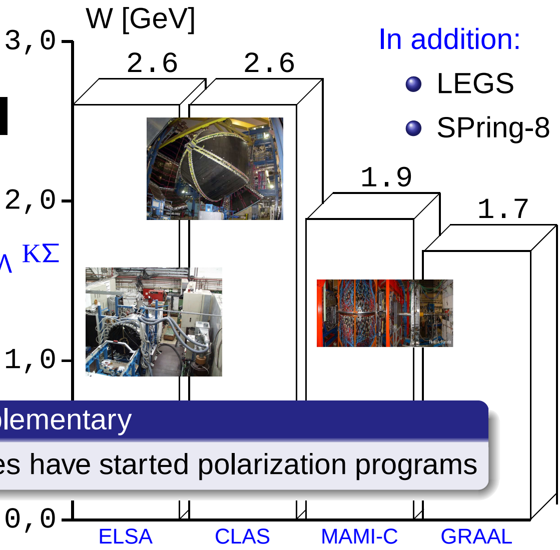
→ If the missing resonances did not couple to Nπ, they would not have been discovered!!

E_γ [GeV]

Reaction Thresholds

- 1.66
- 0.06
- 0.00

$\gamma p \to p\eta\eta$
$\gamma p \to p\pi^0\omega$
$\gamma p \to p\pi^0\eta$ $\gamma p \to K\Lambda$ $K\Sigma$
$\gamma p \to p\eta$
$\gamma p \to p\pi\pi\pi$
$\gamma p \to p\pi\pi$
$\gamma p \to p\pi$



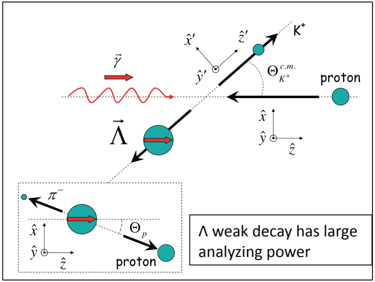
In addition:

- LEGS
- SPring-8

Partially complementary

- All facilities have started polarization programs

Complete Experiments in $K\Lambda$ Photoproduction



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 four single-spin observables.

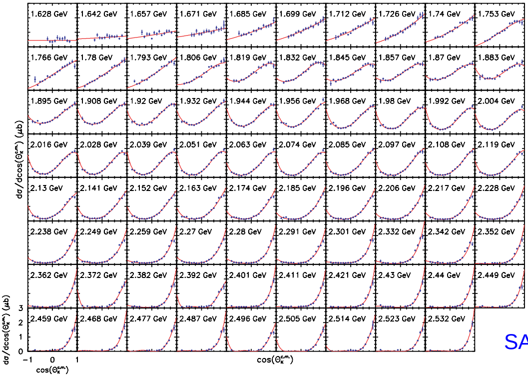
Eight well-chosen measurements are needed to fully determine the amplitude

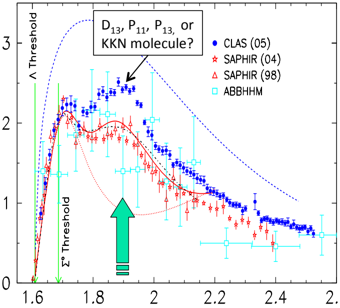
- 16 observables will be measured with CLAS
  ➜ Allows many cross checks

Photon beam		*Target*			*Recoil*			*Target - Recoil*								
					x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
		x	y	z				x	y	z	x	y	z	x	y	z
unpolarized	σ_0		T			P		$T_{x'}$		$L_{x'}$		Σ		$T_{z'}$		$L_{z'}$
linearly P_γ	Σ	H	P	G	$O_{x'}$	T	$O_{z'}$	$L_{z'}$	$C_{z'}$	$T_{z'}$	E		F	$L_{x'}$	$C_{x'}$	$T_{x'}$
circular P_γ		F		E	$C_{x'}$		$C_{z'}$		$O_{z'}$		G		H		$O_{x'}$	

✓ published
✓ to be published
✓ data taken
✓ data taken, being analyzed

Differential & Total Cross Section of $\gamma p \to K^+\Lambda$





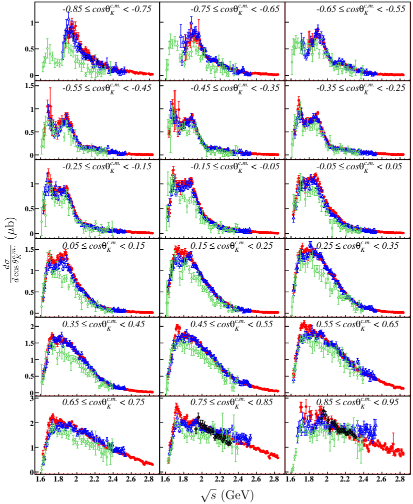
R. Bradford *et al.* [CLAS Collaboration], Phys. Rev. C **73**, 035202 (2006)

—- Fit using Legendre Polynomials

SAPHIR triggered discussion on $N(1950)D_{13}$:

- Evidence for $N(1890)D_{13}$ (Mart-Bennhold)
- Bump due to *u*-channel and off-shell effects (Saghai)
- no need for state, interference effect, strong evidence, etc.

Comparison of Different Data for $\gamma p \to K^+\Lambda$



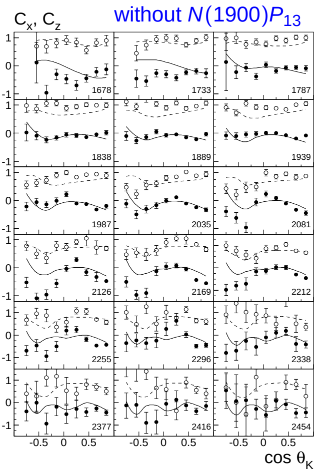
Significant improvement of the data quality in recent years

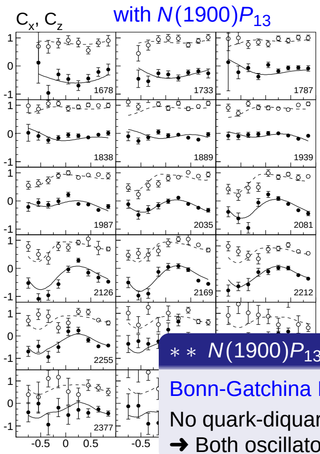
- Much more precise data with larger kinematic coverage
- High-statistics data samples allow for many different topologies to be analyzed

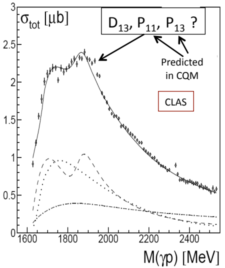
➜ Confirmation of CLAS '05 results

- CLAS 2010
  CLAS Collaboration, Phys. Rev. C **81**, 025201 (2010)
- CLAS 2006
  CLAS Collaboration, Phys. Rev. C **73**, 035202 (2006)
- SAPHIR 2004
  SAPHIR Collaboration, Eur. Phys. J. A **19**, 251 (2004)

Polarization Transfer in $\vec{\gamma} p \to K^+ \vec{\Lambda}$







$**$ $N(1900)P_{13}$, $N(2000)F_{15}$, $N(1990)F_{17}$

Bonn-Gatchina PWA requires $N(1900)P_{13}$.

No quark-diquark oscillations!

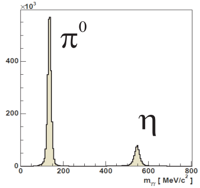
➜ Both oscillators need to be excited.

R. Bradford *et al.* [CLAS Collaboration], Phys. Rev. C **75**, 035205 (2007)

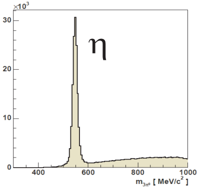
Fits: BoGa-Model, V. A. Nikonov *et al.*, Phys. Lett. B **662**, 245 (2008)

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

$\eta \to \gamma\gamma$

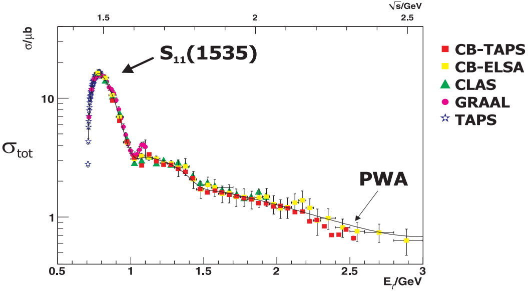


$\eta \to 3\pi^0$



$d\sigma / d\Omega$

PWA

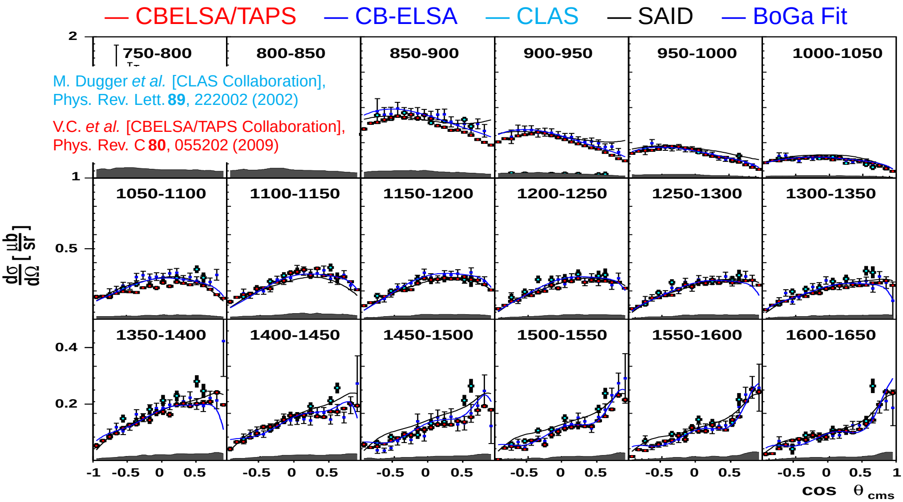


Only nucleon resonances can contribute

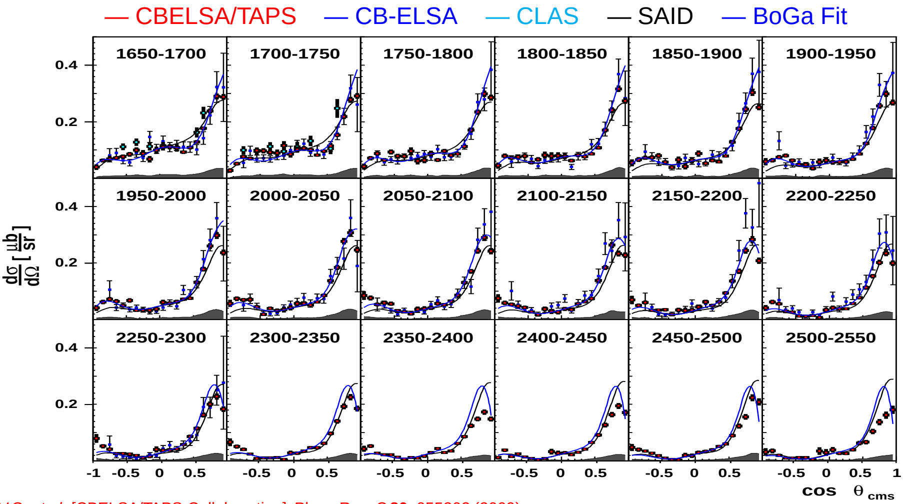
- $N(1535)S_{11}$, $N(1520)D_{13}$, $N(1650)S_{11}$, $N(1680)F_{15}$, $N(1720)P_{13}$, ..., ρ- and ω-t-channel exchange
- New resonance $N(2070)D_{15}$: $m = (2068 \pm 22)$ MeV/c^2
  $\Gamma = (295 \pm 40)$ MeV/c^2

  (needs confirmation in polarization experiments)

Photoproduction of η Mesons off the Proton

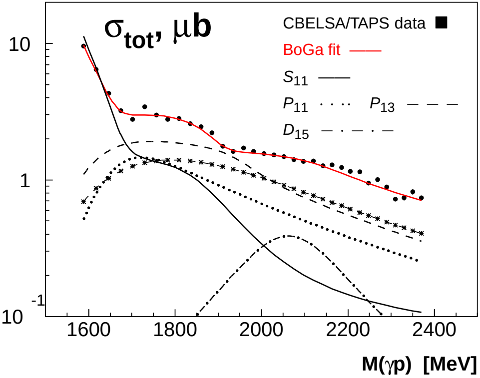


Photoproduction of η Mesons off the Proton



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

Analysis of $\gamma p \rightarrow p\,\eta$: 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. $N(1720)P_{13} \rightarrow p\,\eta$?

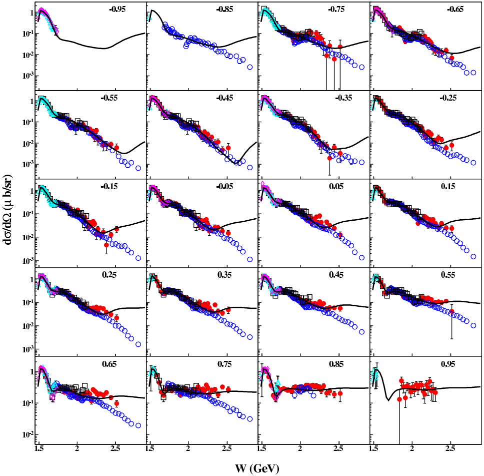
   ➜ η-MAID:
   $N(1710)P_{11} \rightarrow p\,\eta$ significant!

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

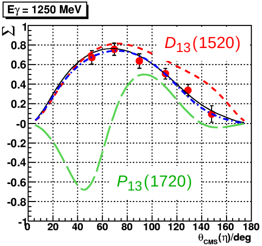
➜ CLAS PWA in the works

➜ Discrepancies need to be better understood! (studies at FSU)

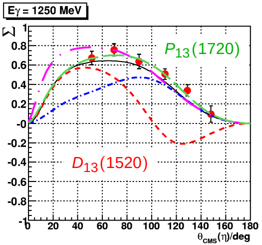
V.C. *et al.* [CB-ELSA Collaboration], Phys. Rev. Lett. **94**, 012004 (2005)

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

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



BoGa-PWA



η-MAID

[CBELSA/TAPS Collaboration], EPJ A **80**, 055202 (2009)

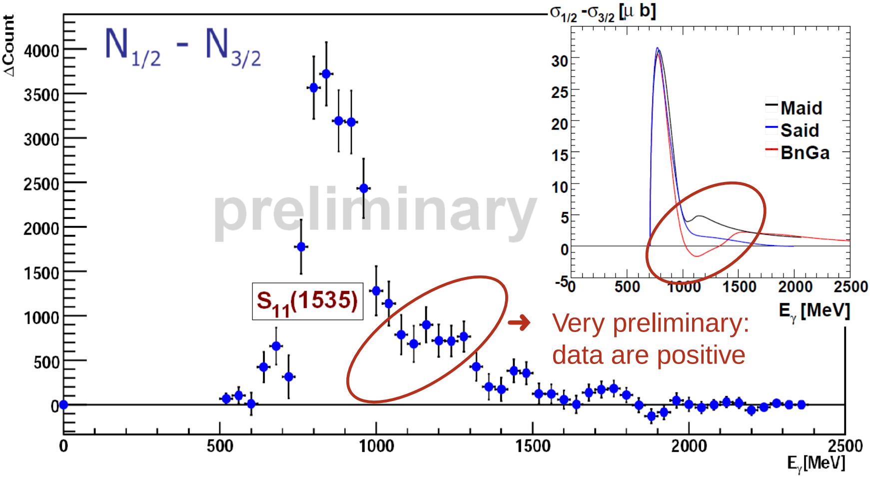
$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l\, \Sigma \cos 2\phi + \Lambda_x (-\delta_l\, \mathbf{H} \sin 2\phi + \delta_\odot\, \mathbf{F}) - \Lambda_y (-\mathbf{T} + \delta_l\, \mathbf{P} \cos 2\phi) - \Lambda_z (-\delta_l\, \mathbf{G} \sin 2\phi + \delta_\odot\, \mathbf{E}) \}$$

Further spin observables available

G and E from 2007-2009 experiments with longitudinal target polarization at MAMI-C, ELSA, CLAS ➜ data being analyzed.

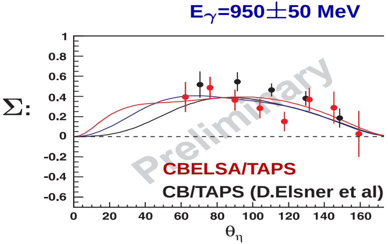
H, F, T, P from experiments with transverse target polarization (program completed at CLAS@JLab, soon at ELSA and MAMI)

Clear Asymmetries Observed in $\gamma p \rightarrow p\,\eta$ (ELSA)

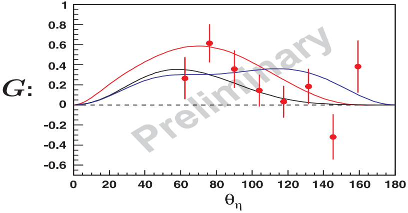


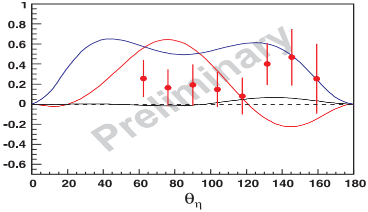
➜ Very preliminary: data are positive

U. Thoma, HADRON 2009



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





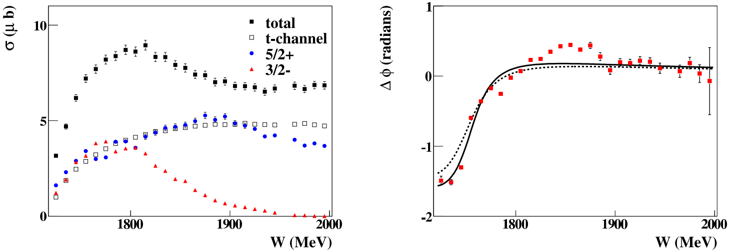
– MAID – BoGa – SAID

↔ **preliminary dilution factor included**

A. Thiel, Bonn

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

M. Williams *et al.* [CLAS Collaboration], Phys. Rev. C **80**, 065209 (2009)



PWA fit includes resonances + t-channel amplitudes.

Strong evidence for $(W < 2$ GeV):

$(3/2)-$ N(1700) $***$

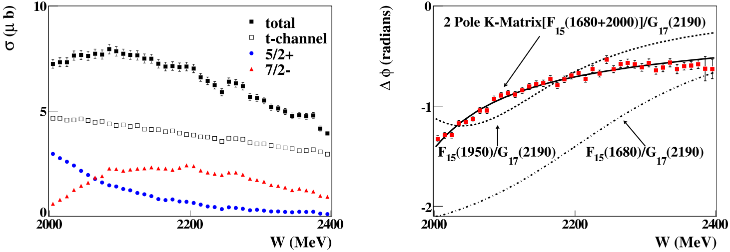
$(5/2)+$ N(1680) $****$

Only nucleon resonances can contribute (isospin filter)

- First-time PWA of ω photoproduction channel
- High statistics data sets are key to pull out signals.
  - ➜ CLAS at JLab can provide statistics, but there are also limitations in the acceptance.
- Hint for a missing state!

Isospin Filter: $\gamma p \to N^* \, (I = 1/2) \, \to p\,\omega$

M. Williams *et al.* [CLAS Collaboration], Phys. Rev. C **80**, 065209 (2009)



PWA fit includes resonances + t-channel amplitudes.

Strong evidence for ($W > 2$ GeV):

$(3/2)-$ N(1700) $***$

$(5/2)+$ N(1680) $****$

$(5/2)+$ N(1680) $****$

$(5/2)+$ N(1950) $**$

$(7/2)-$ N(2190) $****$

Only nucleon resonances can contribute (isospin filter)

- First-time PWA of ω photoproduction channel
- High statistics data sets are key to pull out signals.
  - ➜ CLAS at JLab can provide statistics, but there are also limitations in the acceptance.
- Hint for a missing state!

Status of N^* Polarization Program

	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
Proton targets																
$p\pi^0$	✓ (red)	✓	✓ (blue)		✓	✓ (blue)	✓	✓ (blue)								
$n\pi^+$	✓ (red)	✓	✓ (blue)		✓	✓ (blue)	✓	✓ (blue)								
$p\eta$	✓ (red)	✓	✓ (blue)		✓	✓ (blue)	✓	✓ (blue)								
$p\eta'$	✓ (red)	✓	✓ (blue)		✓	✓ (blue)	✓	✓ (blue)								
$p\omega$	✓ (red)	✓	✓ (blue)		✓	✓ (blue)	✓	✓ (blue)								
$K^+\Lambda$	✓ (red)	✓	✓ (blue)	✓ (red)	✓	✓ (blue)	✓	✓ (blue)	✓ (blue)	✓ (blue)	✓	✓	✓	✓	✓ (red)	✓ (red)
$K^+\Sigma^0$	✓ (red)	✓	✓ (blue)	✓ (red)	✓	✓ (blue)	✓	✓ (blue)	✓ (blue)	✓ (blue)	✓	✓	✓	✓	✓ (red)	✓ (red)
$K^{0*}\Sigma^+$	✓ (red)	✓									✓	✓				
Neutron targets																
$p\pi^-$	✓ (red)	✓	✓ (green)		✓ (green)	✓ (green)	✓ (green)	✓ (green)								
$p\rho^-$	✓	✓	✓ (green)		✓ (green)	✓ (green)	✓ (green)	✓ (green)								
$K^-\Sigma^+$	✓	✓	✓ (green)		✓ (green)	✓ (green)	✓ (green)	✓ (green)								
$K^0\Lambda$	✓	✓	✓ (green)	✓	✓ (green)	✓ (green)	✓ (green)	✓ (green)	✓ (green)	✓ (green)	✓ (green)	✓ (green)	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓	✓ (green)	✓	✓ (green)	✓ (green)	✓ (green)	✓ (green)	✓ (green)	✓ (green)	✓ (green)	✓ (green)	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓														

✓ (red) published

✓ acquired (being analyzed)

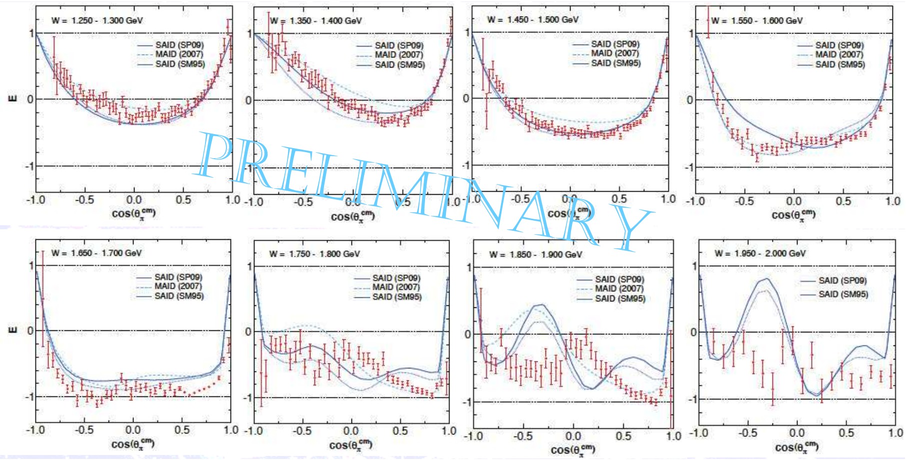
✓ (blue) acquired at Jefferson Lab

planned at ELSA, MAMI

✓ (green) planned

Double-Spin Asymmetry with FROST: $\vec{\gamma}\vec{p} \to n\,\pi^+$

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

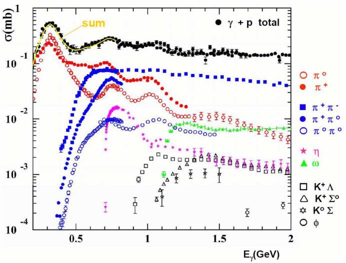


CLAS g9a (FROST) run group, USC analysis

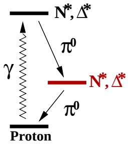
Beam-Target Polarization Observables

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

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



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

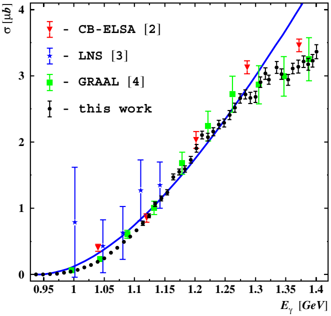


➜ Search for states in cascades!

Double-Meson Reactions: $\gamma p \to p\,\pi^0\eta$

Many two-meson results in recent years:

- Reaction $\gamma p \to p\pi^0\eta$ dominated by the excitation and sequential decay of the $\Delta(1700)D_{33}$.
- High-statistics angular distributions at MAMI allow the determination of the ratio of hadronic decay widths $\Gamma_{\eta\Delta}/\Gamma_{\pi S_{11}}$ for $E_\gamma < 1.5$ GeV.

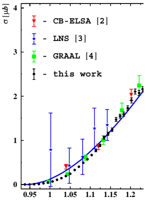


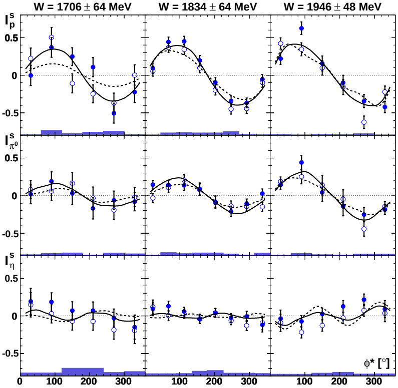
V. L. Kashevarov *et al.* [CB@MAMI Collaboration], EPJ A **42**, 141 (2009)

Double-Meson Reactions: $\vec{\gamma} p \to p\, \pi^0 \eta$

Many two-meson results in recent years:

- At ELSA, beam asymmetries have been determined for $\vec{\gamma} p \to p\, \pi^0 \eta$.
- Two negative-parity 3/2 resonances needed: $\Delta(1700)$ **** and $\Delta(1940)$ *



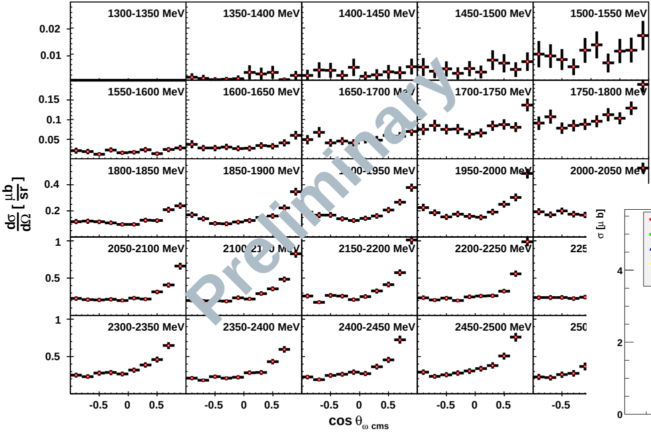


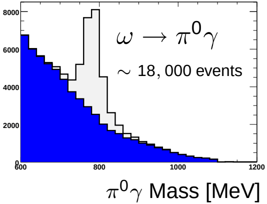
— Full BoGa PWA solution
.... Solution without $3/2^-$ wave

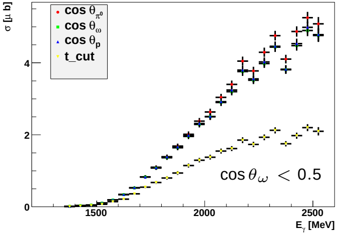
E. Gutz *et al.* [CBELSA/TAPS Collaboration], Phys. Lett. B **687**, 11 (2010)

Isospin Filter: $\gamma p \rightarrow \Delta^* \, (I = 3/2) \rightarrow \Delta\,\omega \rightarrow p\,\pi^0\omega$

Preliminary Differential Cross Sections for $\gamma p \rightarrow p\,\pi^0\omega$

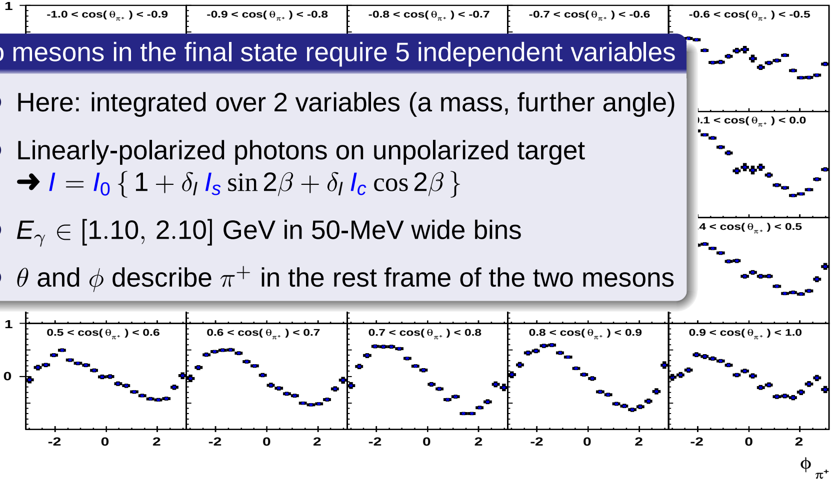






A. Wilson, Florida State University

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

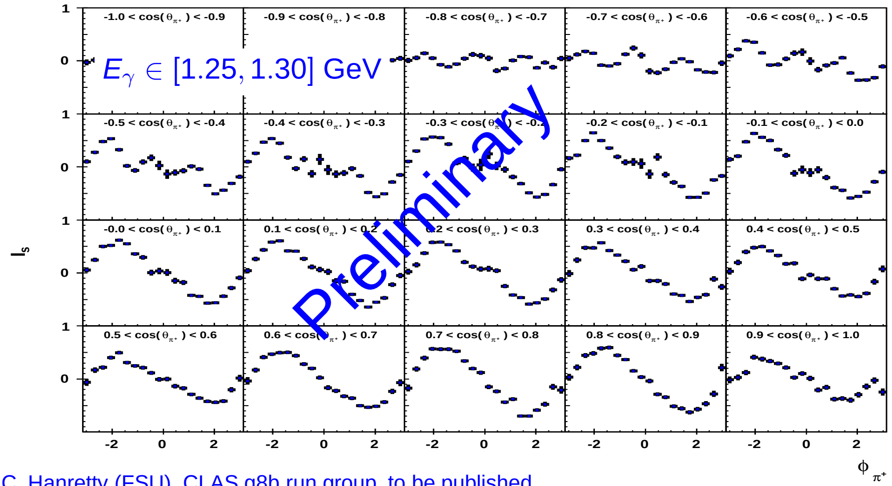


Two mesons in the final state require 5 independent variables

- 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

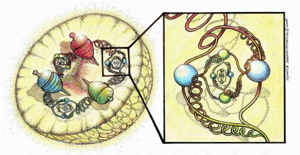
(New) Baryon Resonances in Photoproduction?

Reaction				
$\gamma p \to N\pi$	$\Delta(1232)P_{33}$	$N(1520)D_{13}$	$N(1680)F_{15}$	$N(1535)S_{11}$
$\gamma p \to p\eta$	$N(1535)S_{11}$	$N(1720)P_{13}$	$N(2070)D_{15}$	$N(1650)S_{11}$
$\gamma p \to p\omega$	$N(1700)D_{13}$	$N(1680)F_{15}$	$N(2190)G_{17}$	$N(1950)F_{15}$
$\gamma p \to p\pi^0\pi^0$	$\Delta(1700)D_{33}$	$N(1520)D_{13}$	$N(1680)F_{15}$	
$\gamma p \to p\pi^0\eta$	$\Delta(1940)D_{33}$	$\Delta(1920)P_{33}$	$N(2200)P_{13}$	$\Delta(1700)D_{33}$
$\gamma p \to \Lambda K^+$	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.

Outline

1. Introduction
   - Quarks, QCD, and Confinement
   - Why do we study excited baryons?
2. The Search for Undiscovered States
   - Meson Photo-Production Data
   - Complete Experiments
   - Experimental Status of (Polarization) Program
3. Summary and Outlook



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

Summary and Outlook

I hope our quest to understand confinement and the strong force is about to make great leaps forward:

- New results from the current polarization programs worldwide will (soon) give us new insight on the observed and *missing* baryons.
  ➜ New candidates for baryon resonances have been proposed.
- However, more support needed from theory to describe and understand the baryon spectrum.

Prospects in baryon spectroscopy:

- Program on Ξ baryons at JLab (GlueX, CLAS) in photoproduction
- Excited baryons at PANDA: $p\bar{p} \to \overline{\Xi}\Xi^*$, for instance.
  (also Ω and charmed baryons possible)

Nucleon Resonances: Status of 2001

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