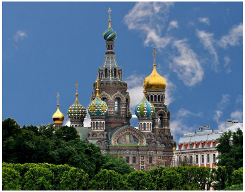
Open Issues in Light Baryon Spectroscopy

Volker Credé

Florida State University, Tallahassee, FL

XIth Quark Confinement and the Hadron Spectrum



St. Petersburg, Russia

09/08/2014

Outline

1. Introduction
   - Quarks, QCD, and Confinement
   - The Spectrum of Nucleon Resonances
2. Results from Photoproduction Experiments
   - Electromagnetic Probes
   - Mission Goal: Complete Experiments
   - Photoproduction of π^0 and π^+ Mesons off the Proton
3. Are we there yet?
   - Observables in the Photoproduction of Two Pions
   - Open Issues in Light Baryon Spectrosocpy
4. Summary and Outlook

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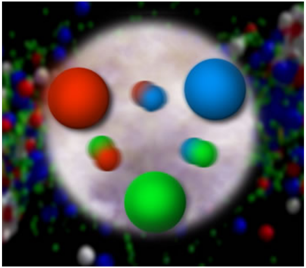
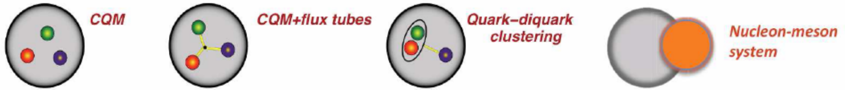
Non-Perturbative QCD



How does QCD give rise to excited hadrons?

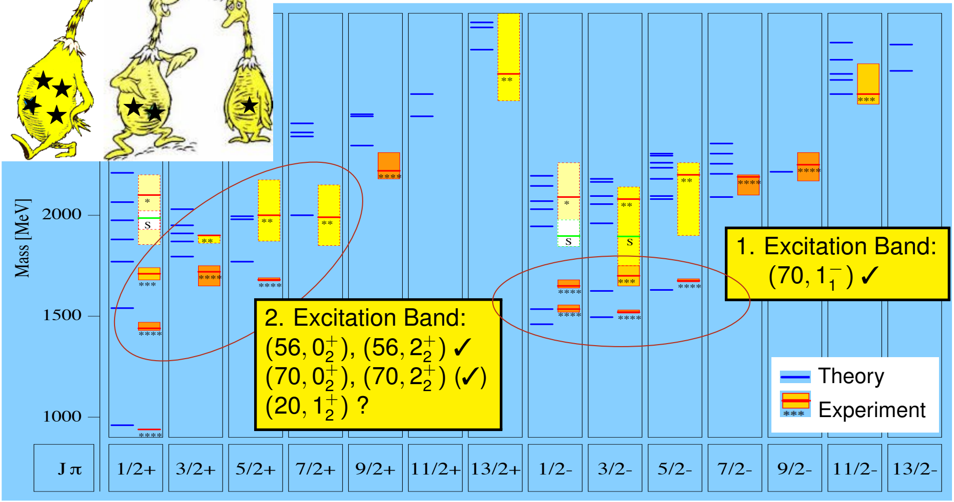
1. What is the origin of confinement?
2. How are confinement and chiral symmetry breaking connected?
3. Would the answers to these questions explain the origin of $\sim 98\,\%$ of observed matter in the universe?

Excited Baryons: What are the fundamental degrees of freedom inside a proton or a neutron? How do they change with varying quark masses?

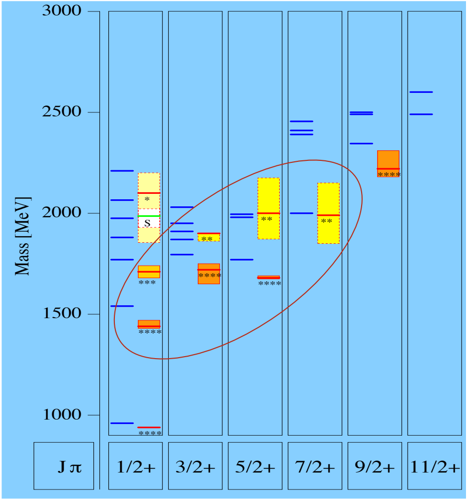


Spectrum of N^* Resonances (PDG < 2012)

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

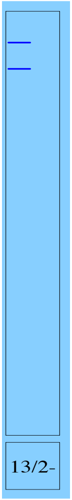


Spectrum of N^* Resonances

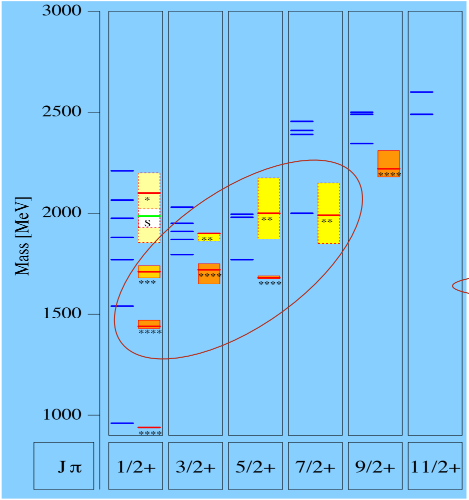


V. C. & W. Roberts, Rep. Prog. Phys. **76** (2013)

N^*	J^P $(L_{2I,2J})$	2010	2012
$N(1440)$	$1/2^+$ (P_{11})	****	****
$N(1520)$	$3/2^-$ (D_{13})	****	****
$N(1535)$	$1/2^-$ (S_{11})	****	****
$N(1650)$	$1/2^-$ (S_{11})	****	****
$N(1675)$	$5/2^-$ (D_{15})	****	****
$N(1680)$	$5/2^+$ (F_{15})	****	****
$N(1685)$			*
$N(1700)$	$3/2^-$ (D_{13})	***	***
$N(1710)$	$1/2^+$ (P_{11})	***	***
$N(1720)$	$3/2^+$ (P_{13})	****	****
$N(1860)$	$5/2^+$		**
$N(1875)$	$3/2^-$		***
$N(1880)$	$1/2^+$		**
$N(1895)$	$1/2^-$		**
$N(1900)$	$3/2^+$ (P_{13})	**	***
$N(1990)$	$7/2^+$ (F_{17})	**	**
$N(2000)$	$5/2^+$ (F_{15})	**	**
~~$N(2080)$~~	D_{13}	**	
~~$N(2090)$~~	S_{11}	*	
$N(2040)$	$3/2^+$		*
$N(2060)$	$5/2^-$		**
$N(2100)$	$1/2^+$ (P_{11})	*	*
$N(2120)$	$3/2^-$		**
$N(2190)$	$7/2^-$ (G_{17})	****	****
~~$N(2200)$~~	D_{15}	**	
$N(2220)$	$9/2^+$ (H_{19})	****	****



Spectrum of N^* Resonances



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$N(1675)$	$5/2^-$ (D_{15})	****	****
$N(1680)$	$5/2^+$ (F_{15})	****	****
$N(1685)$			*
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$N(1710)$	$1/2^+$ (P_{11})	***	***
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$N(1860)$	$5/2^+$		**
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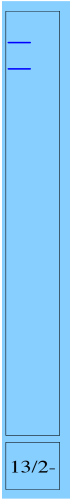
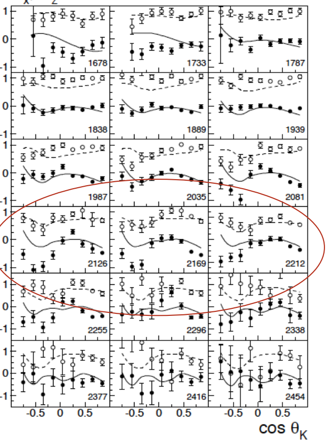
$N(2040)$	$3/2^+$		*
$N(2060)$	$5/2^-$		**
$N(2100)$	$1/2^+$ (P_{11})	*	*
$N(2120)$	$3/2^-$		**
$N(2190)$	$7/2^-$ (G_{17})	****	****
~~$N(2200)$~~	D_{15}	**	
$N(2220)$	$9/2^+$ (H_{19})	****	****



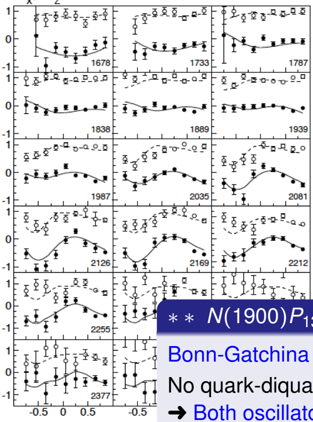
V. C. & W. Roberts, Rep. Prog. Phys. **76** (2013)

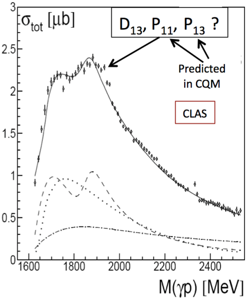
Polarization Transfer in $\vec{\gamma} p \to K^+ \vec{\Lambda}$: C_x, C_z

without $N(1900)P_{13}$



with $N(1900)P_{13}$





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

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

No quark-diquark oscillations!

➜ Both oscillators need to be excited.

R. Bradford *et al.* [CLAS Collab.], PRC **75**, 035205 (2007) [➜ R. Schumacher, Parallel II:B5]

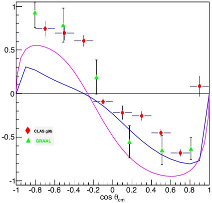
Fits: BoGa-Model, V. A. Nikonov *et al.*, Phys. Lett. B **662**, 245 (2008)

“Complete” Experiment for $K^+ Y$: $1.65 < W < 2.2$ GeV

$\gamma p \rightarrow \quad K^+\Lambda \quad | \quad K^+\Sigma^0$

$K^+\Lambda$:

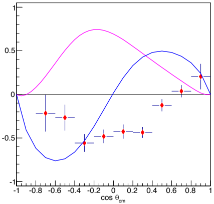
$W \in [1.90, 1.95]$ GeV



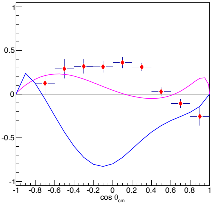
T

T_x $\quad$ T_z

$W \in [1.85, 1.90]$ GeV



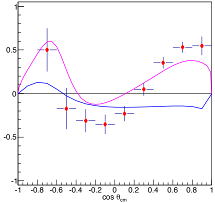
$W \in [1.90, 1.95]$ GeV



$K^+\Sigma^0$:

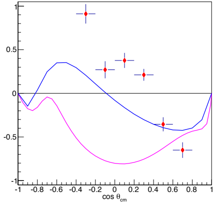
T

$W \in [2.10, 2.15]$ GeV



T_x

$W \in [1.95, 2.00]$ GeV

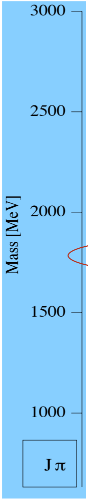


BoGa

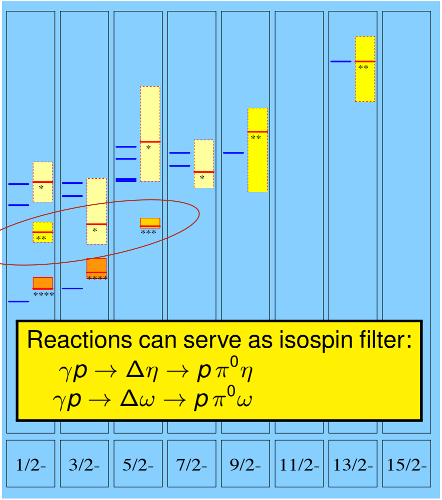
MAID

N. Walford *et al.* [CLAS Collaboration], FROST run group

Spectrum of Δ^* Resonances



Δ^*	J^P $(L_{2I,2J})$	2010	2012
Δ(1232)	$3/2^+$ (P_{33})	∗∗∗∗	∗∗∗∗
Δ(1600)	$3/2^+$ (P_{33})	∗∗∗	∗∗∗
Δ(1620)	$1/2^-$ (S_{31})	∗∗∗∗	∗∗∗∗
Δ(1700)	$3/2^-$ (D_{33})	∗∗∗∗	∗∗∗∗
Δ(1750)	$1/2^+$ (P_{31})	∗	∗
Δ(1900)	$1/2^-$ (S_{31})	∗∗	∗∗
Δ(1905)	$5/2^+$ (F_{35})	∗∗∗∗	∗∗∗∗
Δ(1910)	$1/2^+$ (P_{31})	∗∗∗∗	∗∗∗∗
Δ(1920)	$3/2^+$ (P_{33})	∗∗∗	∗∗∗
Δ(1930)	$5/2^-$ (D_{35})	∗∗∗	∗∗∗
Δ(1940)	$3/2^-$ (D_{33})	∗	∗∗
Δ(1950)	$7/2^+$ (F_{37})	∗∗∗∗	∗∗∗∗
Δ(2000)	$5/2^+$ (F_{35})	∗∗	∗∗
Δ(2150)	$1/2^-$ (S_{31})	∗	∗
Δ(2200)	$7/2^-$ (G_{37})	∗	∗
Δ(2300)	$9/2^+$ (H_{39})	∗∗	∗∗
Δ(2350)	$5/2^-$ (D_{35})	∗	∗
Δ(2390)	$7/2^+$ (F_{37})	∗	∗
Δ(2400)	$9/2^-$ (G_{39})	∗∗	∗∗
Δ(2420)	$11/2^+$ $(H_{3,11})$	∗∗∗∗	∗∗∗∗
Δ(2750)	$13/2^-$ $(I_{3,13})$	∗∗	∗∗
Δ(2950)	$15/2^+$ $(K_{3,15})$	∗∗	∗∗

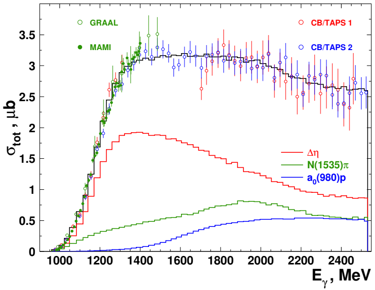


Reactions can serve as isospin filter:

$$\gamma p \to \Delta\eta \to p\pi^0\eta$$
$$\gamma p \to \Delta\omega \to p\pi^0\omega$$

High Statistics Study of the Reaction $\gamma p \to p\,\pi^0\eta$

E. Gutz, V. C. *et al.* [CBELSA/TAPS Collaboration], Eur. Phys. J. A **50**, 74 (2014)



Dominant Isobars

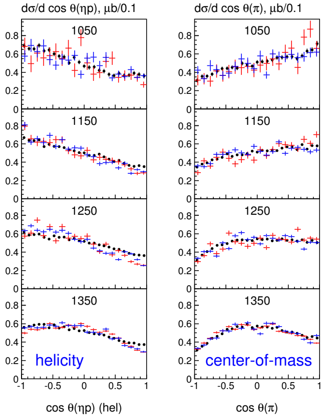
$\Delta(1232)\eta$, $N(1535)\,\frac{1}{2}^-\pi$, $pa_0(980)$

Observation of some

$\Delta^* \to N(1535)\,\frac{1}{2}^-\pi \to p\,\pi\eta$

Bonn-Gatchina

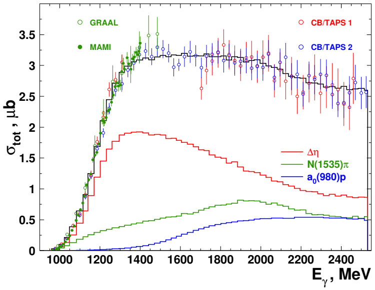
- $\Delta(1700)\,\frac{3}{2}^-$
- $\Delta(1600)\,\frac{3}{2}^+$
- $\Delta(1920)\,\frac{3}{2}^+$
- $\Delta(1940)\,\frac{3}{2}^-$
- $\Delta(1905)\,\frac{5}{2}^+$
- $\Delta(2360)\,\frac{3}{2}^-$
- $N(1880)\,\frac{1}{2}^+$
- $N(2200)\,\frac{3}{2}^+$



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

High Statistics Study of the Reaction $\vec{\gamma} p \to p\,\pi^0\eta$

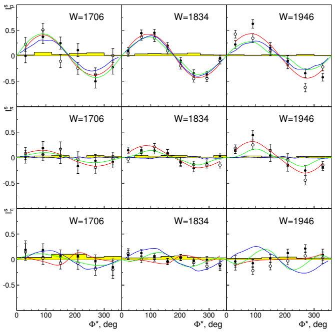
E. Gutz, V. C. *et al.* [CBELSA/TAPS Collaboration], Eur. Phys. J. A **50**, 74 (2014)



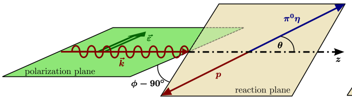
I^s_p

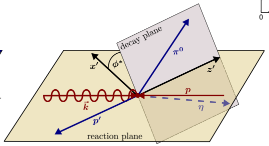
I^s_π

I^s_η



Linear Beam Polarization





Bonn-Gatchina

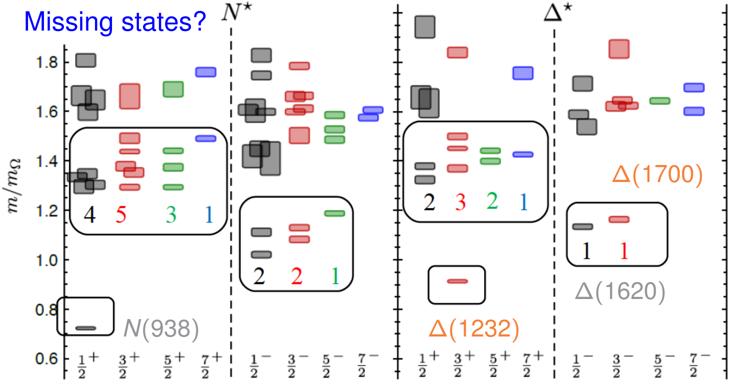
A. Fix *et al.*

M. Döring *et al.*

Baryon Spectroscopy from Lattice QCD

R. Edwards *et al.*, Phys. Rev. D **84**, 074508 (2011)

Missing states?



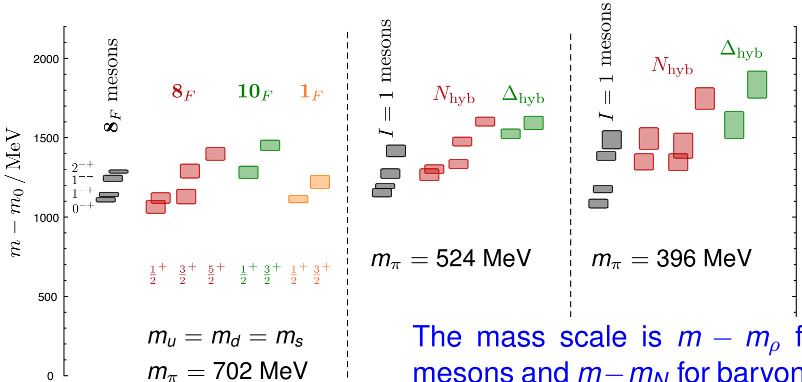
$m_\pi = 396$ MeV

Exhibits broad features expected of $SU(6) \otimes O(3)$ symmetry

➜ Counting of levels consistent with non-rel. quark model, no parity doubling

Gluonic Excitations on the Lattice

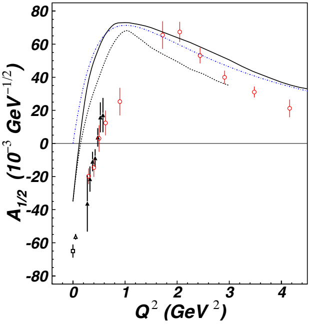
J. J. Dudek and R. G. Edwards, Phys. Rev. D **85**, 054016 (2012)

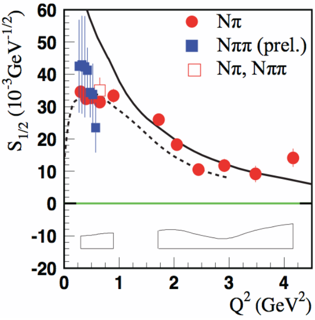


The mass scale is $m - m_\rho$ for mesons and $m - m_N$ for baryons.

Common scale of $\sim$ 1.3 GeV for gluonic excitation, but hybrid baryons are difficult to identify experimentally.

Helicity Amplitudes for the “Roper” Resonance





Data from CLAS

$A_{1/2}$ and $S_{1/2}$ amplitudes:

e.g. V. Mokeev *et al.*, PRC **86**, 035203 (2012); PRC **80**, 045212 (2009).

Quark-model calculations:

— - - - q^3 radial excitation

— q^3G hybrid state

Consistency between both channels ($N\pi\pi$, $N\pi$): sign change, magnitude, ...

- At short distances (high Q^2), Roper behaves like radial excitation.
- Low Q^2 behavior not well described by LF quark models: e.g. meson-baryon interactions missing

➜ Gluonic excitation likely ruled out!

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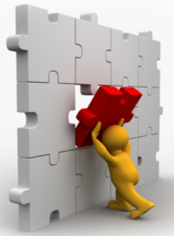
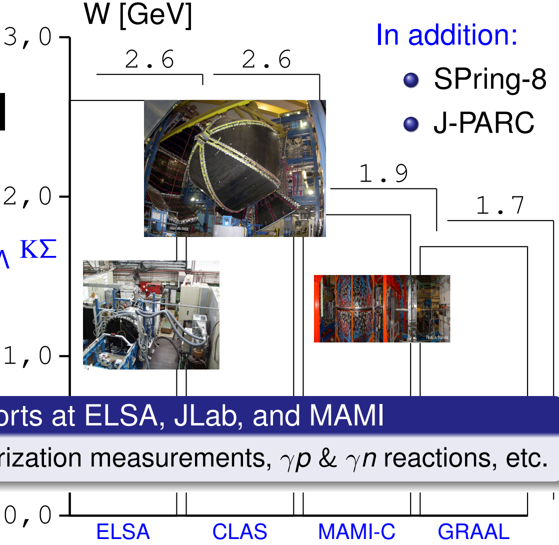


E_γ [GeV]

Reaction Thresholds

1.66
$\gamma p \to p\eta\eta$
$\gamma p \to p\pi^0\omega$
$\gamma p \to p\pi^0\eta$ $\quad \gamma p \to K\Lambda \quad K\Sigma$
$\gamma p \to p\eta$
$\gamma p \to p\pi\pi\pi$
$\gamma p \to p\pi\pi$
0.06
$\gamma p \to p\pi$
0.00



In addition:

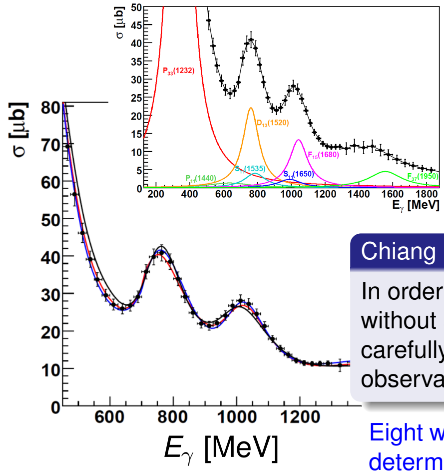
- SPring-8
- J-PARC

Common efforts at ELSA, JLab, and MAMI

(Double-)polarization measurements, γp & γn reactions, etc.

➜ J. Hartmann, Parallel III: B10 on ELSA

Why are Polarization Observables Important?



$\gamma p \to p\pi^0$

For single-meson production:

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

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.

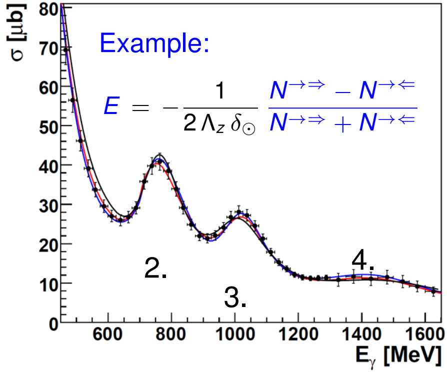
Eight well-chosen measurements are needed to fully determine production amplitudes F_1, F_2, F_3, and F_4.

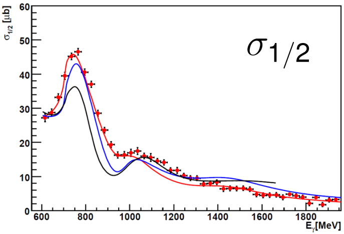
Example: Ambiguities in $\gamma\, p \rightarrow p\, \pi^0$

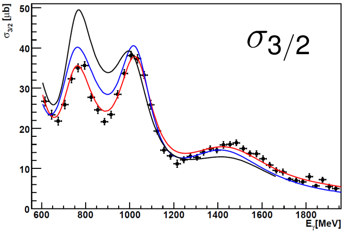
— Bonn-Gatchina (2011-02)

— SAID (SN11, CM12)

— MAID

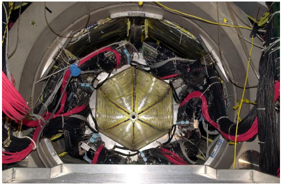


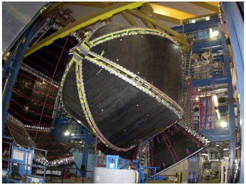




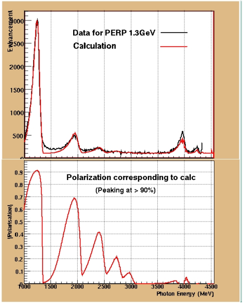
M. Gottschall *et al.*, Phys. Rev. Lett. **112**, 012003 (2014)

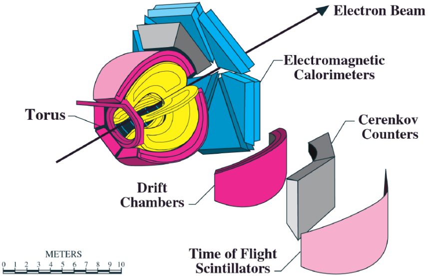
The CLAS Spectrometer at Jefferson Laboratory



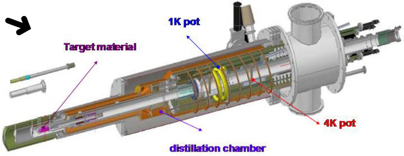


g8b
linear beam
polarization

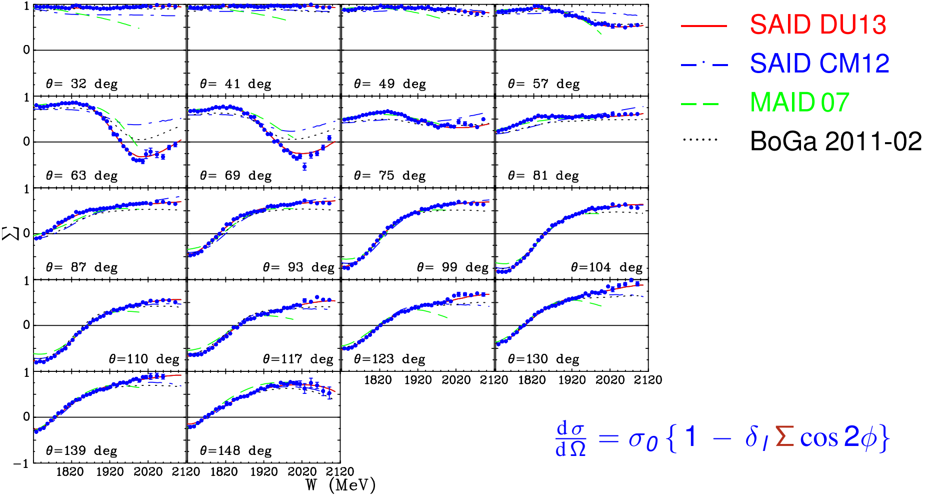




FROST
double polarization



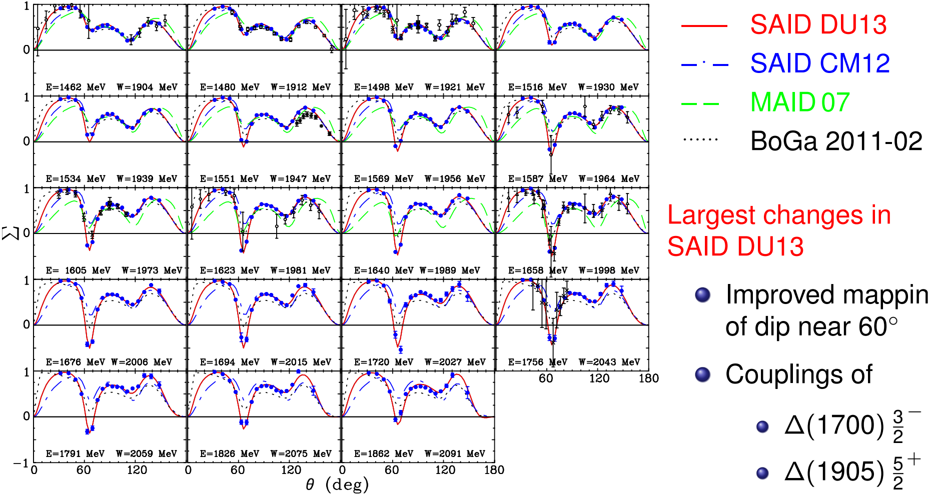
Beam Asymmetry Σ in $\vec{\gamma} p \to p \pi^0$ @ CLAS (g8b)



$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \Sigma \cos 2\phi \}$$

M. Dugger *et al.* [CLAS Collaboration], Phys. Rev. C **88**, 065203 (2013)

Beam Asymmetry Σ in $\vec{\gamma} p \to p \pi^0$ @ CLAS (g8b)

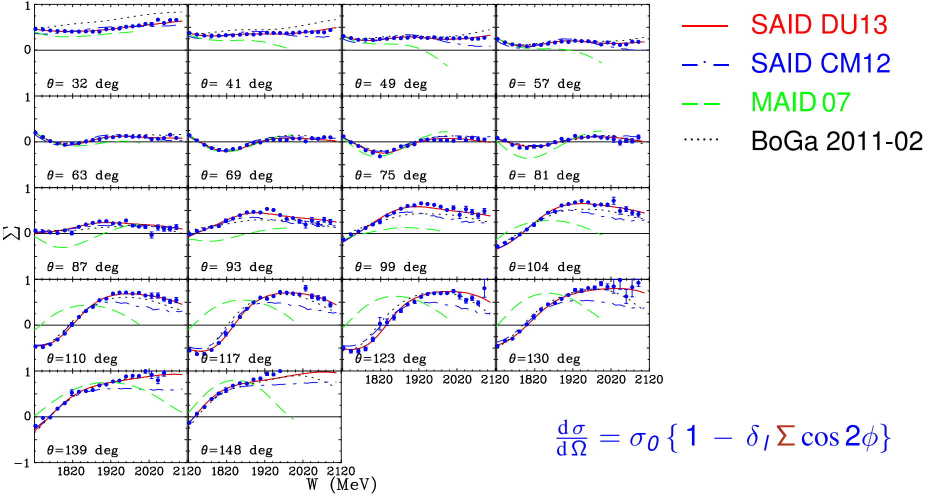


Largest changes in SAID DU13

- Improved mapping of dip near 60°
- Couplings of
  - $\Delta(1700)\,\frac{3}{2}^-$
  - $\Delta(1905)\,\frac{5}{2}^+$

M. Dugger *et al.* [CLAS Collaboration], Phys. Rev. C **88**, 065203 (2013)

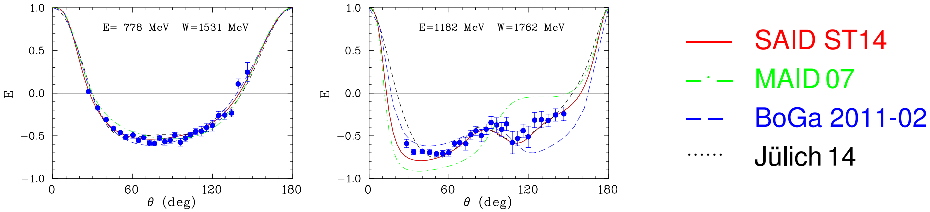
Beam Asymmetry Σ in $\vec{\gamma} p \rightarrow n \pi^+$ @ CLAS (g8b)



$$\frac{d\sigma}{d\Omega} = \sigma_0 \{1 - \delta_l \Sigma \cos 2\phi\}$$

M. Dugger *et al.* [CLAS Collaboration], Phys. Rev. C **88**, 065203 (2013)

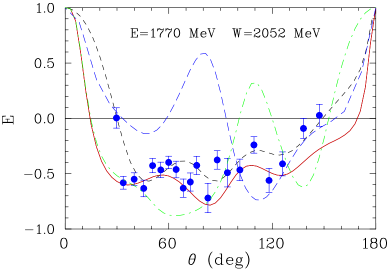
Helicity Difference E in $\vec{\gamma}\,\vec{p} \to n\,\pi^+$ @ CLAS (FROST)



Δ^+ $\qquad$ N^*

$$p\,\pi^0 : \sqrt{\frac{2}{3}}\,|I = \frac{3}{2},\, I_3 = \frac{1}{2}\rangle - \sqrt{\frac{1}{3}}\,|I = \frac{1}{2},\, I_3 = \frac{1}{2}\rangle$$

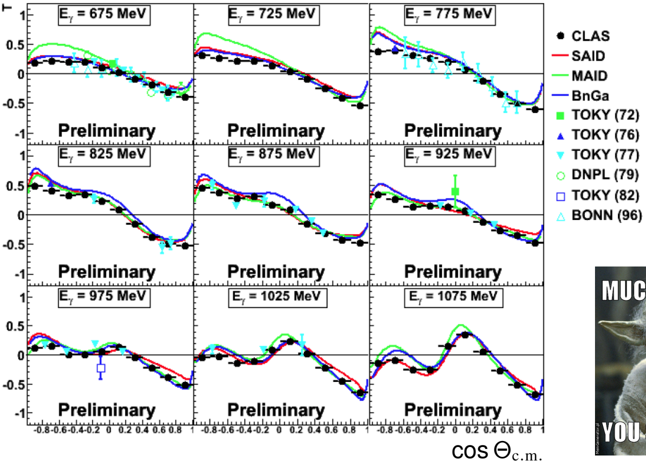
$$n\,\pi^+ : \sqrt{\frac{1}{3}}\,|I = \frac{3}{2},\, I_3 = \frac{1}{2}\rangle + \sqrt{\frac{2}{3}}\,|I = \frac{1}{2},\, I_3 = \frac{1}{2}\rangle$$



S. Strauch (SC), under CLAS collaboration review

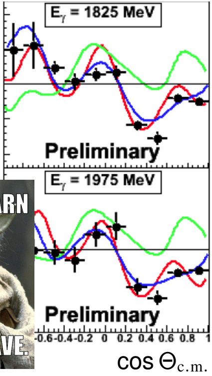
Target Asymmetry T in $\gamma\,\vec{p} \to n\,\pi^+$ (CLAS FROST)

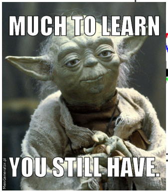
– MAID 07 – SAID – BoGA 12



Early-stage results (g9b)

- Transverse Target Polarization

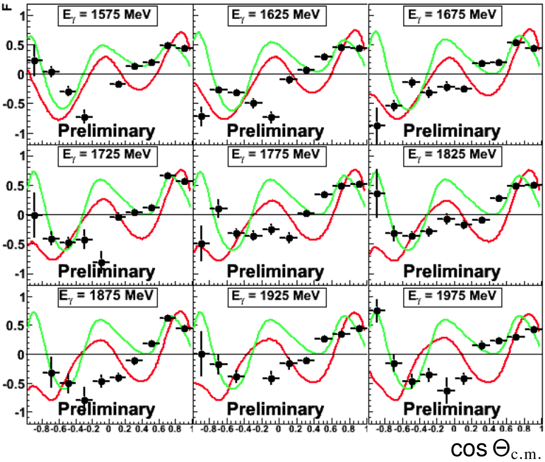




M. Dugger (ASU), CLAS g9b run group

Observable F in $\vec{\gamma}\vec{p} \to n\pi^+$ (CLAS FROST-g9b)

– MAID 07 – SAID 12 BoGa not shown



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

Transv. target pol. & circ. beam pol.

- Early-stage analysis
- Reasonable agreement among predictions for $W < 1.7$ GeV
  - ➜ Much to learn at the higher energies

M. Dugger (ASU), CLAS g9b run group

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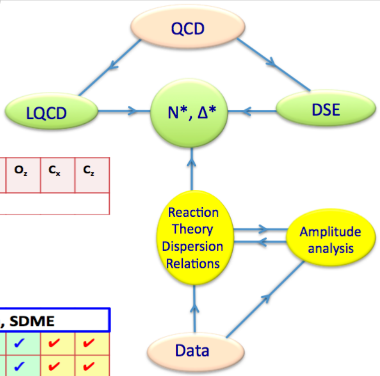
   - Observables in the Photoproduction of Two Pions
   - Open Issues in Light Baryon Spectrosocpy
4. Summary and Outlook

- ➜ M. Battaglieri, Parallel II: B5 “Light Quarks”
- ➜ R. Schumacher, Parallel II:B5
  (more results from CLAS@JLab)



Observables	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
✔ published		✓ acquired or under analysis														
$p\pi^0$	✔	✔	✓	(✓)	✓	✓	✓	✓	Proton targets							
$n\pi^+$	✔	✔	✓	(✓)	✓	✓	✓	✓								
$p\eta$	✔	✓	✓	(✓)	✓	✓	✓	✓								
$p\eta'$	✔	✓	✓	(✓)	✓	✓	✓	✓								
$p\omega/\phi$	✔	✓	✓	(✓)	✓	✓	✓	✓	Tensor polarization, SDME							
$K^+\Lambda$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^+\Sigma^0$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^{0*}\Sigma^+$	✔	✓									✓	✓				
$p\pi^-$	✔	✓		(✓)	✓	✓	✓		Neutron targets							
$p\rho^-$	✓	✓		(✓)	✓	✓	✓									
$K^-\Sigma^+$	✓	✓		(✓)	✓	✓	✓									
$K^0\Lambda$	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓									✓	✓				

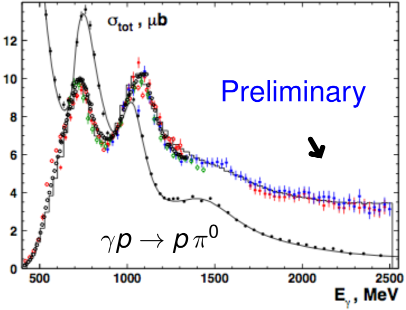
Table representing CLAS@JLab measurements.

Need more observables on:

$$\gamma p \to p\pi\pi,\ p\pi\eta$$

$$\gamma p \to p\pi\omega,\ \ldots$$

Observation of Decay Cascades in $\gamma\, p \rightarrow p\, \pi^0 \pi^0$



Observation of new decay modes in the decay of N^* resonances; weak at most in Δ^* decays.

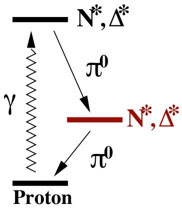
—— Bonn-Gatchina PWA

V. Sokhoyan, E. Gutz, V. C. *et al.* @ELSA

Cross Section and Polarization Observables

(W. Roberts *et al.*, PRC **71**, 055201 (2005))

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



➜ Search for states in decay cascades!

Observation of Decay Cascades in $\gamma\, p \to p\, \pi^0 \pi^0$

Decays observed in PWA into, e.g.

$$\left.\begin{array}{l} N(1880)\,1/2^+ \\ N(1900)\,3/2^+ \\ N(2000)\,5/2^+ \\ N(1990)\,7/2^+ \end{array}\right\} \begin{array}{l} N(1520)\pi \\ N(1535)\pi \\ N(1680)\pi \\ N\sigma\ (I=1) \end{array}$$

➜ Quartet of $(\mathbf{70}, 2_2^+)$ with $S = \frac{3}{2}$.

Observation of new decay modes in the decay of N^* resonances; weak at most in Δ^* decays.

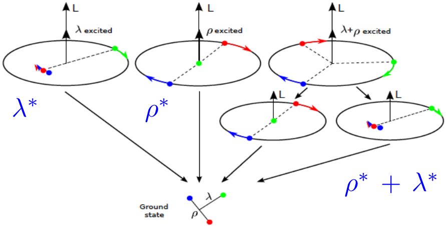
—— Bonn-Gatchina PWA

V. Sokhoyan, E. Gutz, V. C. *et al.* @ELSA

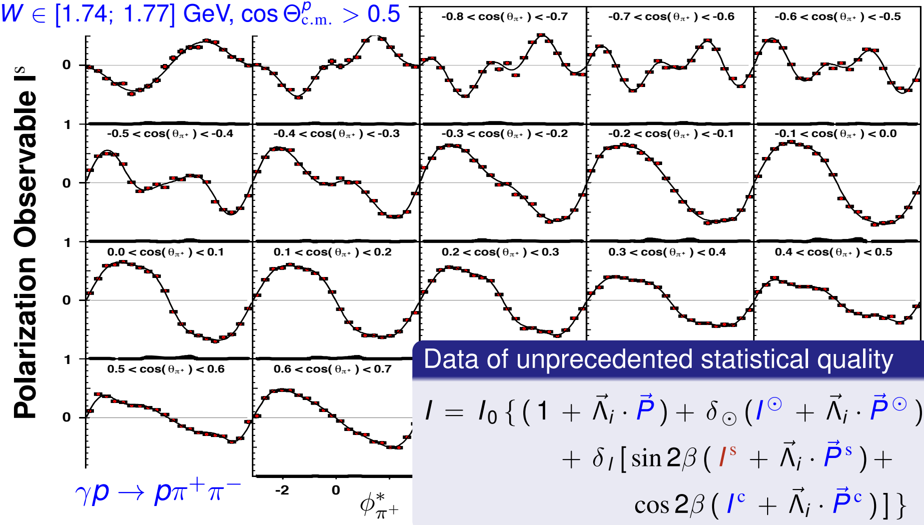
Nucleon states with $S = \frac{3}{2}$ require spatial wave functions of mixed symmetry. For $L = 2$ the wave functions do have equal admixtures of $\mathcal{M}_S$ and

$$\mathcal{M}_\mathcal{A} = [\,\phi_{0p}(\vec{\rho}) \times \phi_{0p}(\vec{\lambda}\,)\,]^{(L=2)}\,,$$

a component in which both the ρ and the λ oscillator are excited simultaneously.



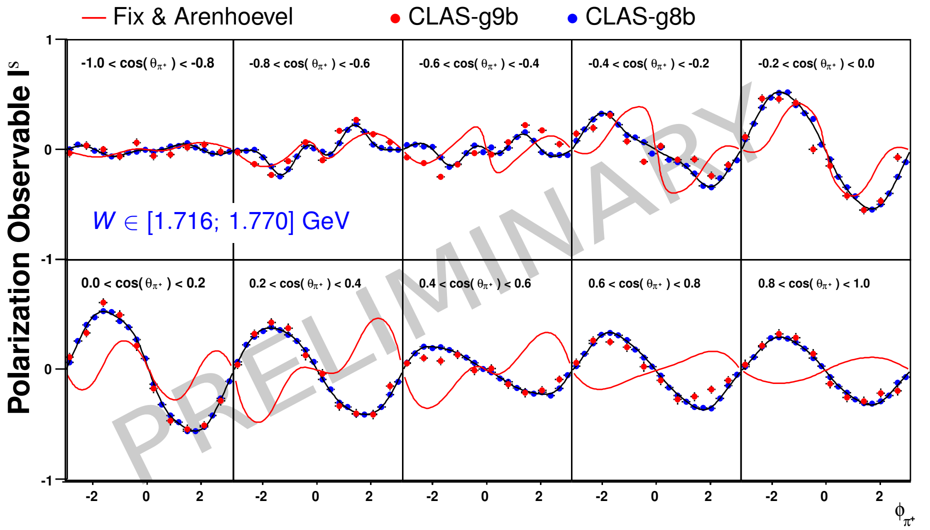
$W \in [1.74;\ 1.77]$ GeV, $\cos\Theta^{p}_{\mathrm{c.m.}} > 0.5$



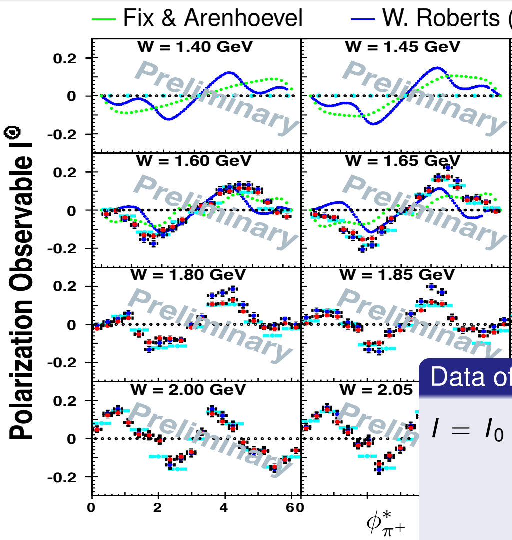
Data of unprecedented statistical quality

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

Charles Hanretty (FSU), approved by CLAS collaboration



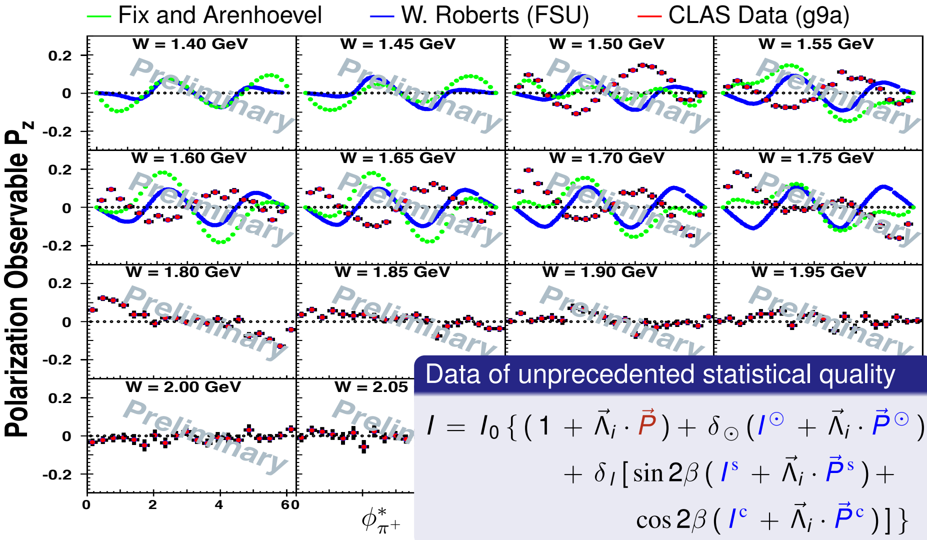
Priyashree Roy (Florida State), CLAS g9b (FROST)



Data of unprecedented statistical quality

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

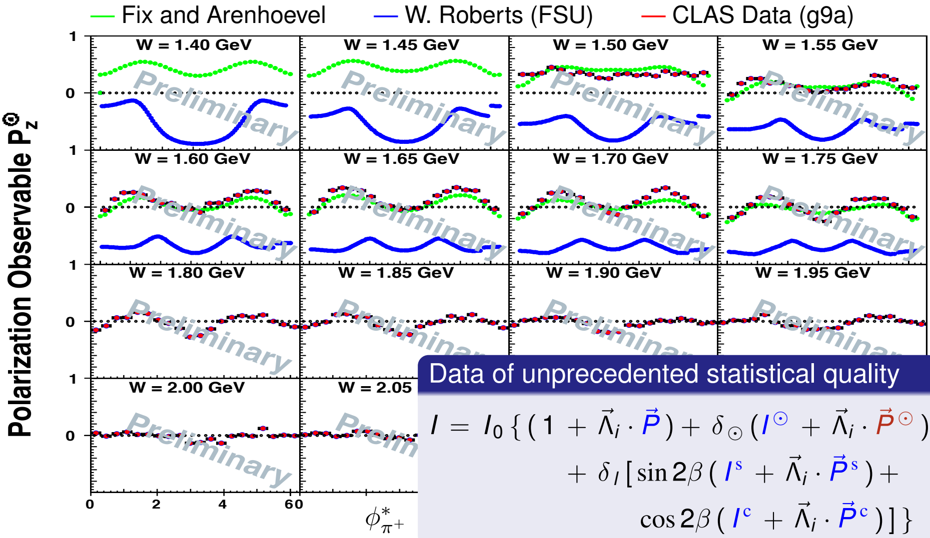
Sungkyun Park (FSU), under collaboration review



Data of unprecedented statistical quality

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

Sungkyun Park (FSU), under collaboration review



Data of unprecedented statistical quality

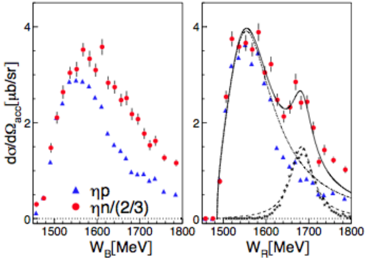
$$I = I_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_\odot (I^\odot + \vec{\Lambda}_i \cdot \vec{P}^\odot) + \delta_l [\sin 2\beta (I^s + \vec{\Lambda}_i \cdot \vec{P}^s) + \cos 2\beta (I^c + \vec{\Lambda}_i \cdot \vec{P}^c)] \}$$

Sungkyun Park (FSU), under collaboration review

Open Issues in Light Baryon Spectroscopy

Some questions need to be addressed in light baryon spectroscopy:

1. What are the relevant degrees of freedom in (excited) baryons? Can the high-mass states be described by the dynamics of three flavored quarks?
2. Can we identify the leading interactions between the constituents?
3. Do we understand the decay of high-mass baryon resonances?
4. Do hybrid baryons exist? What is the role of glue in excited baryons?
5. Do we observe states beyond the simple $|qqq\rangle$ picture, e.g. in $\gamma n \to n\,\eta$? ➜
6. What are the missing resonances and why are so many still missing?



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Summary and Outlook

Our understanding of baryon resonances has made great leaps forward. There is good evidence that most of the known states (listed in the PDG) will also be confirmed in photoproduction and that new states will be revealed:

- Goal of performing (almost) complete experiments has been (almost) achieved; significant contributions from (double-)polarization experiments.
- Still too early to nail down relevant degress of freedom in excited baryons.
  ➜ Some states might be generated dynamically ...

$N(1860)\ \frac{5}{2}^+$	$**$	πN	γN				
$N(1875)\ \frac{3}{2}^-$	$***$	πN	γN		ΛK	ΣK	
$N(1880)\ \frac{1}{2}^+$	$**$	πN	γN		ΛK	ΣK	
$N(1895)\ \frac{1}{2}^-$	$**$	πN	γN	ηN	ΛK	ΣK	
$N(1900)\ \frac{3}{2}^+$	$***$	πN	γN	ηN	ΛK	ΣK	$\Delta\pi$
$N(2060)\ \frac{5}{2}^-$	$**$	πN	γN	ηN		ΣK	
$\Delta(1940)\ \frac{3}{2}^-$	$* \to **$	πN	γN				$\Delta\eta$ (!)

New States in PDG 2012.