Photoproduction of Mesons at CBELSA/TAPS

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Florida State University, Tallahassee, FL

Topical Workshop: Nuclear Photoproduction with GlueX

Jefferson Lab

04/29/2016

Outline

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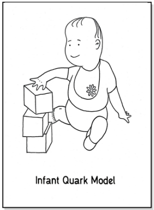
1. Introduction
   - The Spectrum of Hadrons: Baryons and Mesons
2. Spectroscopy of Baryon Resonances
   - Complete Experiments
   - Polarization Observables in $\gamma p \to N\pi$
   - Polarization Observables in $\gamma p \to p\omega$
3. Decay Cascades of Excited Baryons
4. (Very) Strange Ξ & Ω Resonances
   - Spectroscopy at JLab
5. Summary and Outlook
   - Are we there yet?

Hadrons: Baryons & Mesons

The strong coupling confines quarks and breaks chiral symmetry, and so defines the world of light hadrons.

Baryons are special because

- Their structure is most obviously related to the color degree of freedom, e. g. $|\Delta^{++}\rangle = |u^{\uparrow}u^{\uparrow}u^{\uparrow}\rangle$.
- They are the stuff of which our world is made.



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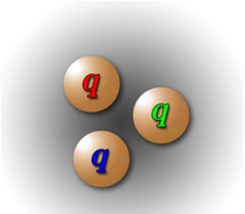
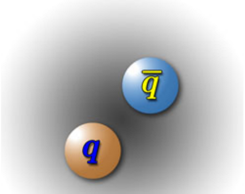
Strong Coupling QCD



Baryons



Mesons

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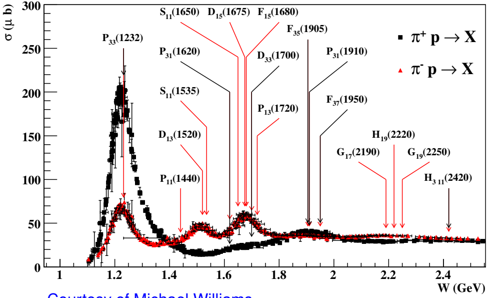
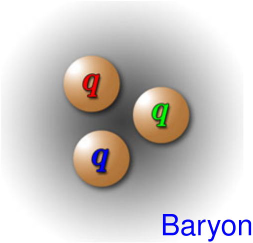


Courtesy of Michael Williams



Baryons

➜ PDG 2010, J. Phys. GG 37.

Great progress in recent years:

➜ γN & πN data

Hadrons: Baryons & Mesons

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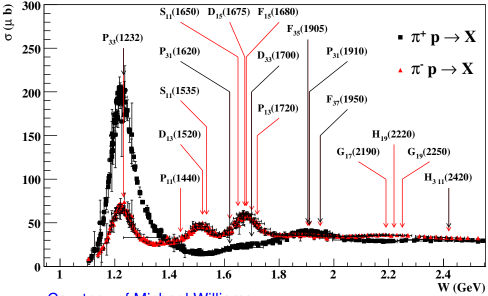

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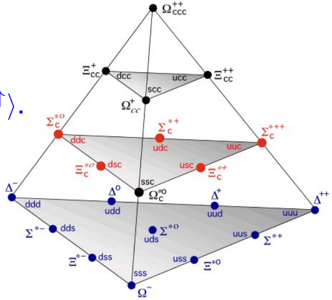
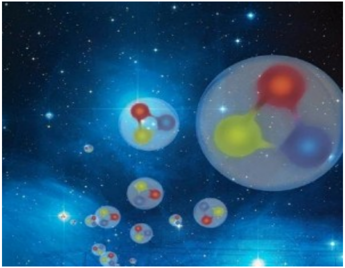


Many Y^* QN not measured:
(Quark model assignments)
➜ many Ξ^* and Ω^*, etc.

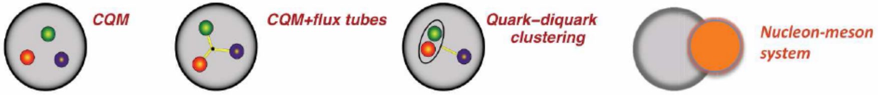
Non-Perturbative QCD



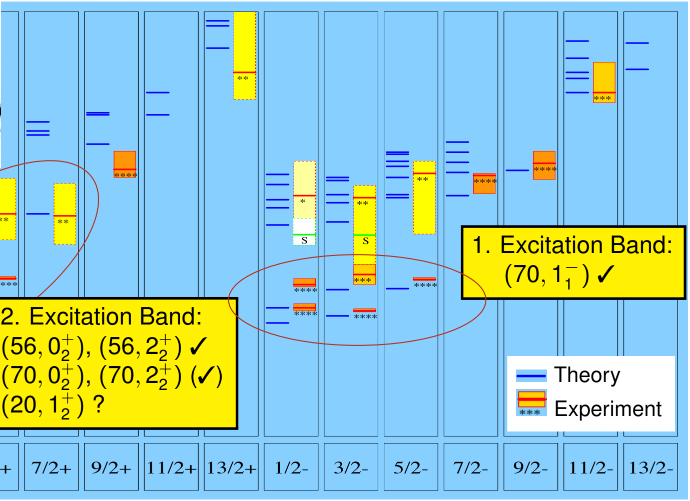
How does QCD give rise to excited hadrons?

1. What is the origin of confinement?
2. How are confinement and chiral symmetry breaking connected?
3. What role do gluonic excitations play in the spectroscopy of light hadrons, and can they help explain quark confinement?

Baryons: What are the fundamental degrees of freedom inside a nucleon? Constituent quarks? How do the degrees change with varying quark masses?

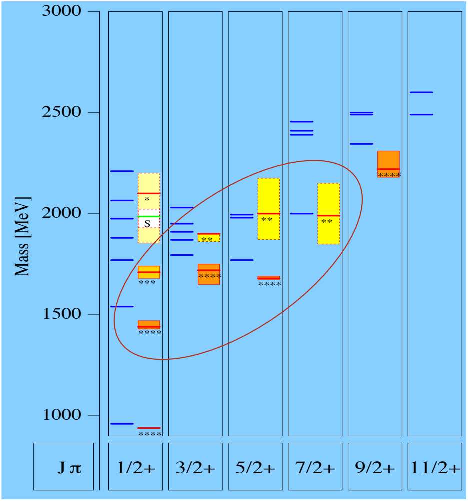


Spectrum of N^* Resonances (PDG < 2012)



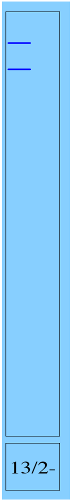
S. Capstick and N. Isgur, Phys. Rev. **D34** (1986) 2809

Spectrum of N^* Resonances



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

N^*	J^P $(L_{2I,2J})$	2010	2014
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}	**	



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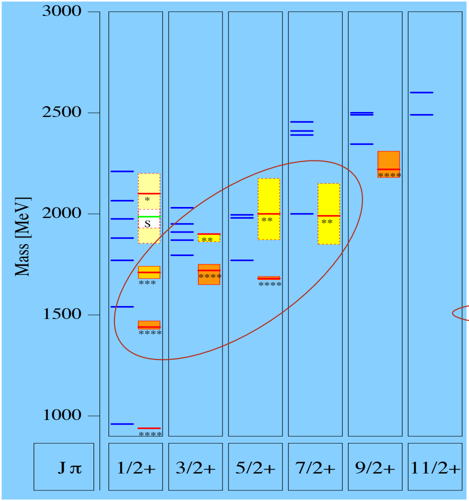
Spectrum of N^* Resonances



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$N(1680)$	$5/2^+$ (F_{15})	$****$	$****$
$N(1685)$			$*$
$N(1700)$	$3/2^-$ (D_{13})	$***$	$***$
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$N(1880)$	$1/2^+$		$**$
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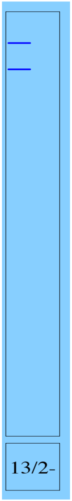
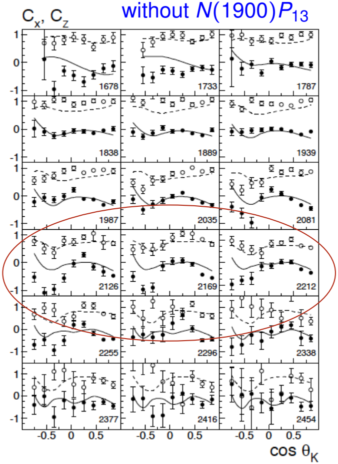
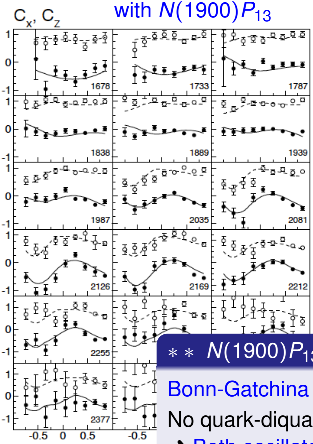
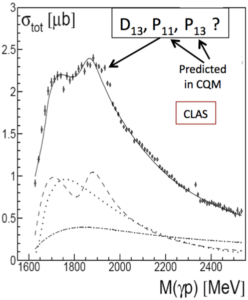
$N(1900)$	$3/2^+$ (P_{13})	$**$	$***$
$N(1990)$	$7/2^+$ (F_{17})	$**$	$**$
$N(2000)$	$5/2^+$ (F_{15})	$**$	$**$
~~$N(2080)$~~	D_{13}	$**$	
~~$N(2090)$~~	S_{11}	$*$	
$N(2040)$	$3/2^+$		$*$
$N(2060)$	$5/2^-$		$**$
$N(2100)$	$1/2^+$ (P_{11})	$*$	$*$
$N(2120)$	$3/2^-$		$**$
$N(2190)$	$7/2^-$ (G_{17})	$****$	$****$
~~$N(2200)$~~	D_{15}	$**$	



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







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

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

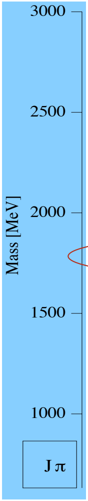
No quark-diquark oscillations!

➜ Both oscillators need to be excited.

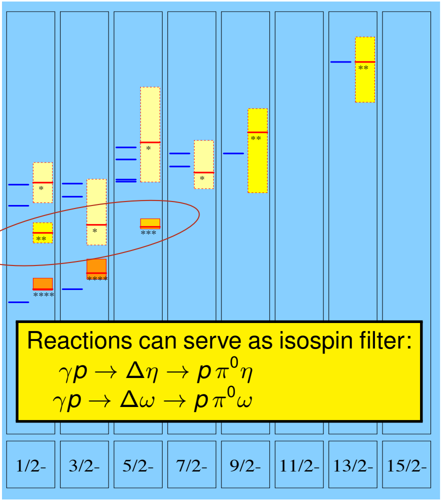
R. Bradford *et al.* [CLAS Collaboration], PRC **75**, 035205 (2007)

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

Spectrum of Δ^* Resonances



Δ^*	J^P $(L_{2I,2J})$	2010	2014
$\Delta(1232)$	$3/2^+$ (P_{33})	∗∗∗∗	∗∗∗∗
$\Delta(1600)$	$3/2^+$ (P_{33})	∗∗∗	∗∗∗
$\Delta(1620)$	$1/2^-$ (S_{31})	∗∗∗∗	∗∗∗∗
$\Delta(1700)$	$3/2^-$ (D_{33})	∗∗∗∗	∗∗∗∗
$\Delta(1750)$	$1/2^+$ (P_{31})	∗	∗
$\Delta(1900)$	$1/2^-$ (S_{31})	∗∗	∗∗
$\Delta(1905)$	$5/2^+$ (F_{35})	∗∗∗∗	∗∗∗∗
$\Delta(1910)$	$1/2^+$ (P_{31})	∗∗∗∗	∗∗∗∗
$\Delta(1920)$	$3/2^+$ (P_{33})	∗∗∗	∗∗∗
$\Delta(1930)$	$5/2^-$ (D_{35})	∗∗∗	∗∗∗
$\Delta(1940)$	$3/2^-$ (D_{33})	∗	∗∗
$\Delta(1950)$	$7/2^+$ (F_{37})	∗∗∗∗	∗∗∗∗
$\Delta(2000)$	$5/2^+$ (F_{35})	∗∗	∗∗
$\Delta(2150)$	$1/2^-$ (S_{31})	∗	∗
$\Delta(2200)$	$7/2^-$ (G_{37})	∗	∗
$\Delta(2300)$	$9/2^+$ (H_{39})	∗∗	∗∗
$\Delta(2350)$	$5/2^-$ (D_{35})	∗	∗
$\Delta(2390)$	$7/2^+$ (F_{37})	∗	∗
$\Delta(2400)$	$9/2^-$ (G_{39})	∗∗	∗∗
$\Delta(2420)$	$11/2^+$ $(H_{3,11})$	∗∗∗∗	∗∗∗∗
$\Delta(2750)$	$13/2^-$ $(I_{3,13})$	∗∗	∗∗
$\Delta(2950)$	$15/2^+$ $(K_{3,15})$	∗∗	∗∗

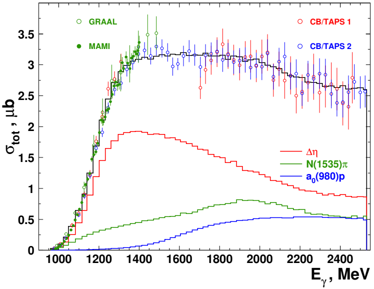


Reactions can serve as isospin filter:

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

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

$\Delta(1700)\,\frac{3}{2}^-$

$\Delta(1600)\,\frac{3}{2}^+$

$\Delta(1920)\,\frac{3}{2}^+$

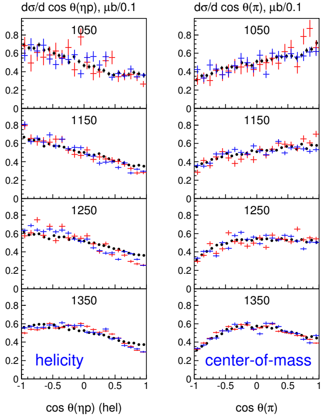
$\Delta(1940)\,\frac{3}{2}^-$

$\Delta(1905)\,\frac{5}{2}^+$

$\Delta(2360)\,\frac{3}{2}^-$

$N(1880)\,\frac{1}{2}^+$

$N(2200)\,\frac{3}{2}^+$



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

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

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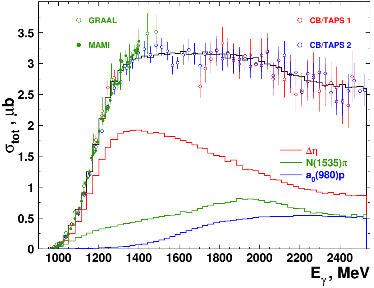
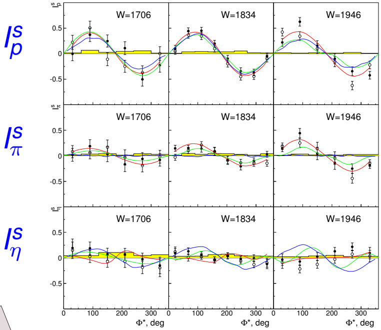
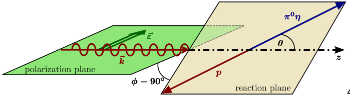
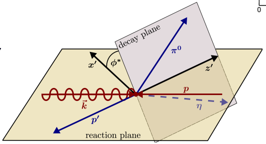




Linear Beam Polarization

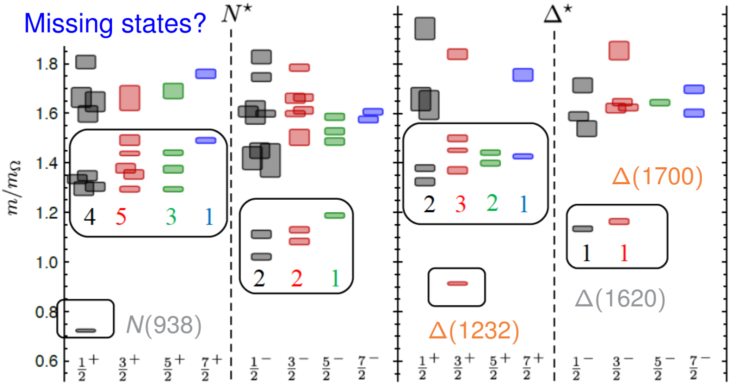




Bonn-Gatchina
A. Fix *et al.*
M. Döring *et al.*

Baryon Spectroscopy from Lattice QCD

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



$m_\pi = 396$ MeV

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

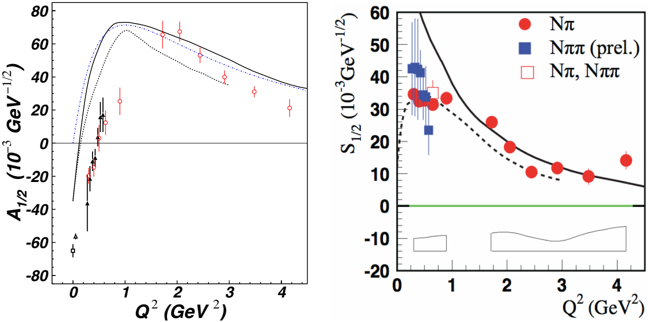
➜ Counting of levels consistent with non-rel. quark model, no parity doubling.

Components of the Experimental N^* Program

The excited baryon program has two main components:

- Probe resonance transitions at different distance scales
  Electron beams are ideal to measure resonance form factors and their corresponding Q^2 dependence.
  ➜ Provides information on the structure of excited nucleons and on the confining (effective) forces of the 3-quark system.
- 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 previously unobserved or so-called *missing resonances.*

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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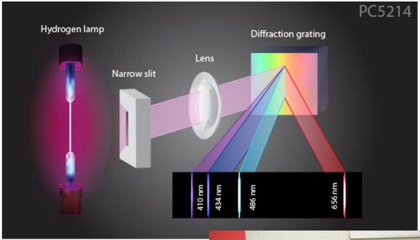
Why are Polarization Observables Important?

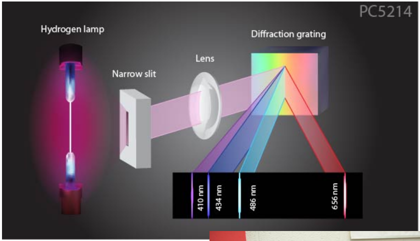
Atomic Spectrum of Hydrogen



Why are Polarization Observables Important?

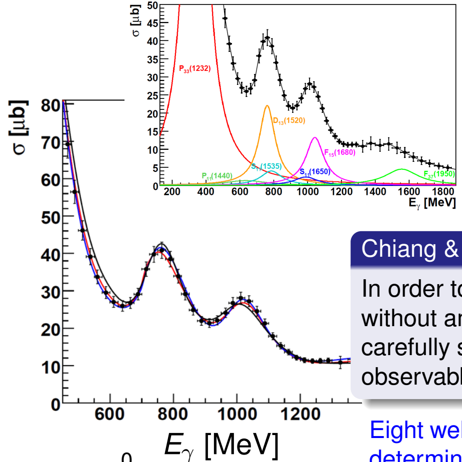

without polarizer ... but there is more.

Atomic Spectrum of Hydrogen



Baryon are broad and overlapping ...

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)

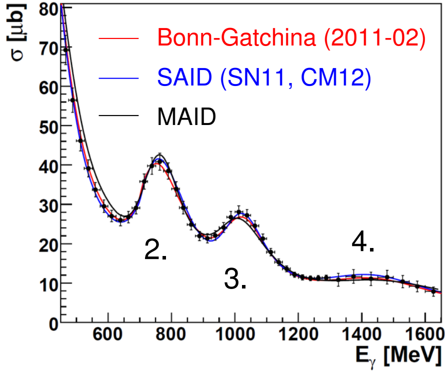
In order to determine the full scattering amplitude without ambiguities, one has to carry out eight carefully selected measurements: four double-spin observables along with four single-spin observables.

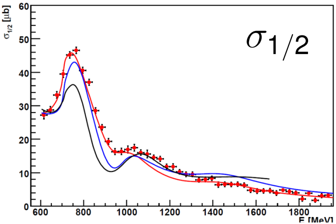
Eight well-chosen measurements are needed to fully determine production amplitudes F_1, F_2, F_3, and F_4.

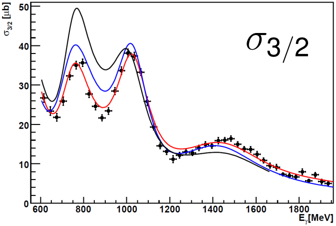
Example: Ambiguities in $\gamma p \to p\pi^0$

Helicity Difference:

$$E = -\frac{1}{2\,\Lambda_z\,\delta_\odot}\,\frac{N^{\to\Rightarrow} - N^{\to\Leftarrow}}{N^{\to\Rightarrow} + N^{\to\Leftarrow}}$$







E_γ [GeV]

Reaction Thresholds

1.66 — $\gamma p \to p\eta\eta$

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

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

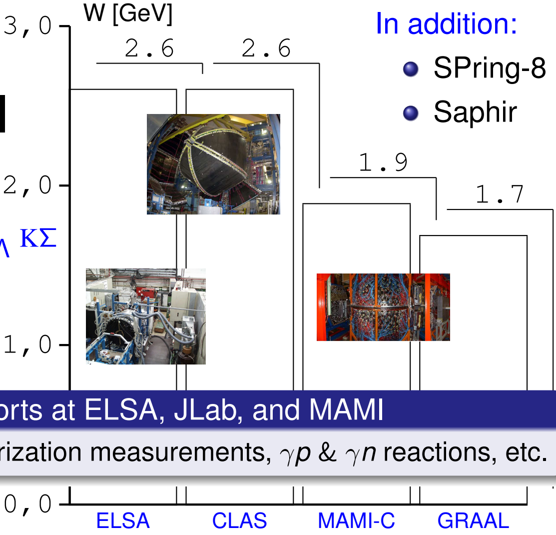
$\gamma p \to p\eta$

$\gamma p \to p\pi\pi\pi$

$\gamma p \to p\pi\pi$

0.06 — $\gamma p \to p\pi$

0.00



In addition:

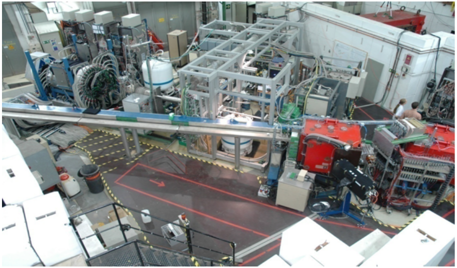
- SPring-8
- Saphir

Common efforts at ELSA, JLab, and MAMI

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

Experimental Facilities

CBELSA/TAPS at ELSA



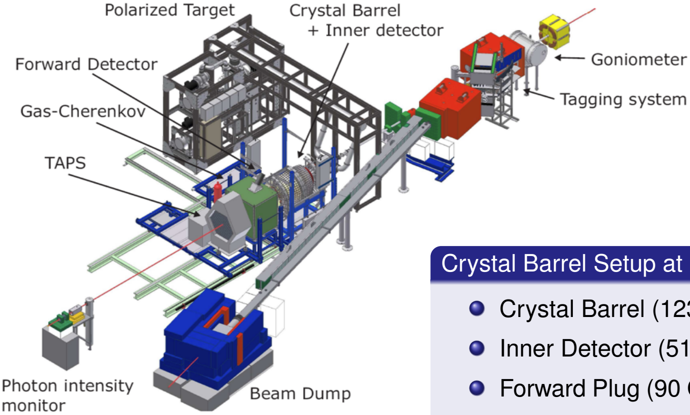
Jefferson Laboratory

Meson photoproduction:

- $\gamma p \to p\pi^0 \to p\gamma\gamma$
- $\gamma p \to p\eta \to p\gamma\gamma,\ p3\pi^0,\ p\pi^+\pi^-\pi^0$
- $\gamma p \to p\omega \to p\pi^0\gamma,\ \pi^+\pi^-\pi^0$

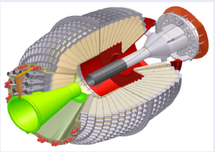
Double-Polarization: Toward Complete Experiments

Calorimeter system at ELSA is optimized for neutral particles.



Frozen-Spin Target: Butanol (C_4H_9OH)

Crystal Barrel



Close to 4π coverage

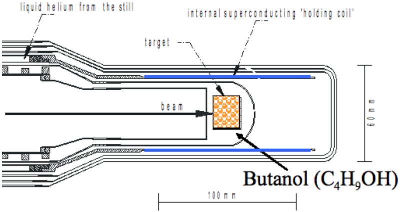
Crystal Barrel Setup at ELSA

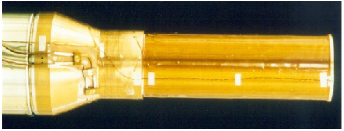
- Crystal Barrel (1230 CsI crystals)
- Inner Detector (513 scintillating fibers)
- Forward Plug (90 CsI crystals with PM's)
- MiniTAPS (216 BaF_2, 1° - 12°)

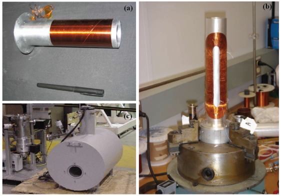
Double-Polarization: Frozen Spin Targets

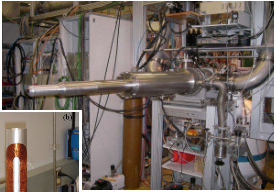
Horizontal cryostat with integrated solenoid to freeze the proton spin.

- DNP at high B-field (2.5 T), holding mode at 0.4 T
- Relaxation time at ELSA $\sim$ 500 h









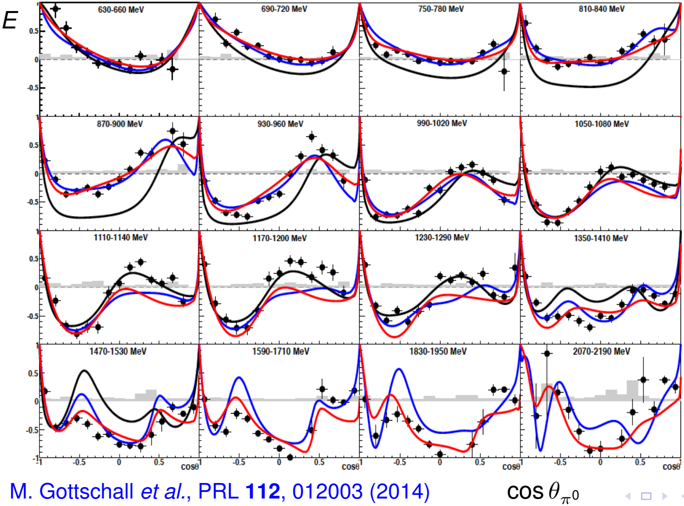
"ELSA"

"CLAS"

Transverse Target Polarization
(race-track coil - Dipole Magnet)

Longitudinally-Polarized Target ($P_z \approx 80$ %)

Helicity Asymmetry E in $\vec{\gamma}\vec{p} \to p\pi^0$ @ ELSA



$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

$E_\gamma \in [0.6, 2.2]$ GeV

- CBELSA/TAPS
- — Maid
- — Said (CM12)
- — BoGa (2011_2)

Angular distributions sensitive to interference between resonances.

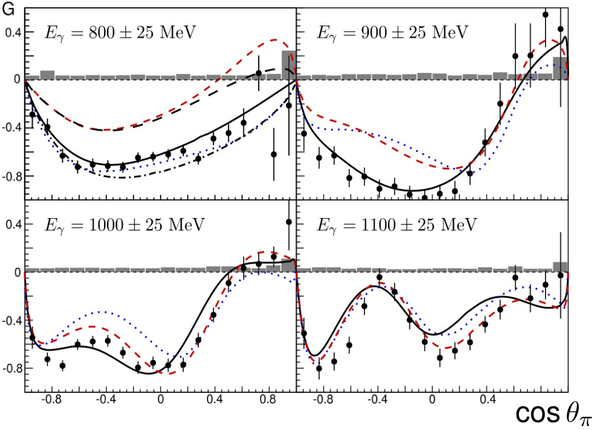
M. Gottschall *et al.*, PRL **112**, 012003 (2014)

Asymmetry G in $\vec{\gamma}\,\vec{p} \to p\,\pi^0$ @ ELSA

A. Thiel *et al.*, PRL **109**, 102001 (2012)

Full data set: arXiv:1604.02922 [nucl-ex]

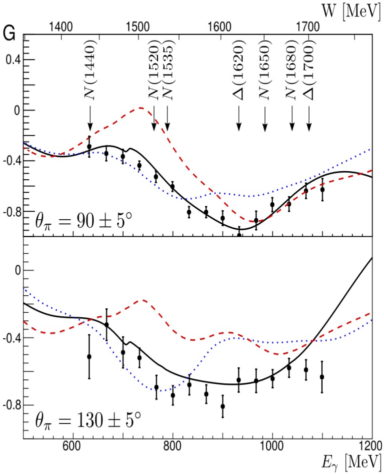
$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \Sigma \cos 2\phi + \Lambda_x (-\delta_l H \sin 2\phi + \delta_\odot F) - \Lambda_y (-T + \delta_l P \cos 2\phi) - \Lambda_z (-\delta_l G \sin 2\phi + \delta_\odot E) \}$$



Surprisingly, π production also not well understood at lower energies:

— BoGa
- - SAID
···· MAID

Asymmetry G in $\vec{\gamma}\,\vec{p} \to p\,\pi^0$ @ ELSA



A. Thiel *et al.*, PRL **109**, 102001 (2012)

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

$\theta_\pi = 90 \pm 5°$

$\theta_\pi = 130 \pm 5°$

Surprisingly, π production also not well understood at lower energies.

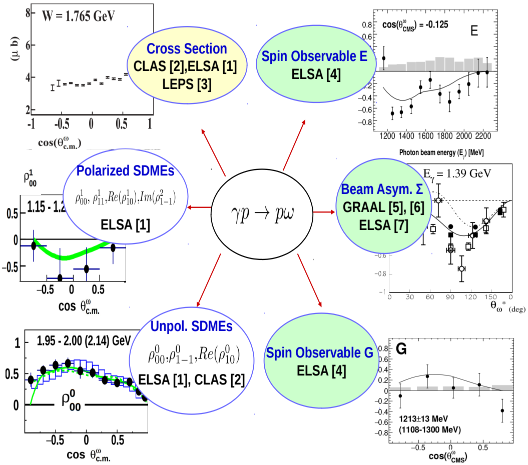
Below 1 GeV, discrepancies can be traced to the E_{0+} and E_{2-} multipoles, which are related to certain resonances:

E_{0+}: $N(1535)\,\frac{1}{2}^-$, $N(1650)\,\frac{1}{2}^-$, $\Delta(1620)\,\frac{1}{2}^-$

E_{2-}: $N(1520)\,\frac{3}{2}^-$, $\Delta(1700)\,\frac{3}{2}^-$

Baryon Resonances in the Reaction $\gamma p \to p\omega$

➜ Vector-meson photoproduction (ω, ρ, ϕ) is still underexplored.



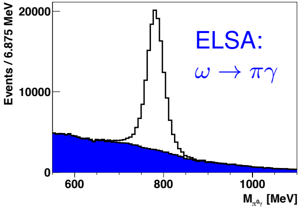
Particle J^P	Status overall	Status πN	Status γN	Status as seen in — $N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
$N(1700)\,3/2^-$	***	***	**	*			*	*	*	***
$N(1710)\,1/2^+$	***	***	***	***		**	***	**	*	**
$N(1720)\,3/2^+$	****	****	***	***			**	**	**	*
$N(1860)\,5/2^+$	**	**							*	*
$N(1875)\,3/2^-$	***	*	***			**	***	**		***
$N(1880)\,1/2^+$	**	*	*		**		*			
$N(1895)\,1/2^-$	**	*	**	**			**	*		
$N(1900)\,3/2^+$	***	**	***	**		**	***	**	*	**
$N(1990)\,7/2^+$	**	**	**					*		
$N(2000)\,5/2^+$	**	*	**	**			**	*	**	
$N(2040)\,3/2^+$	*									
$N(2060)\,5/2^-$	**	**	**	*				**		
$N(2100)\,1/2^+$	*									
$N(2150)\,3/2^-$	**	**	**				**			**
$N(2190)\,7/2^-$	****	****	***			*	**		*	
$N(2220)\,9/2^+$	****	****								
$N(2250)\,9/2^-$	****	****								
$N(2600)\,11/2^-$	***	***								
$N(2700)\,13/2^+$	**	**								

Complete Experiments in $\gamma p \to p\omega$ (& $\gamma p \to p\pi^+\pi^-$)

Bonn-Gatchina & CLAS PWA

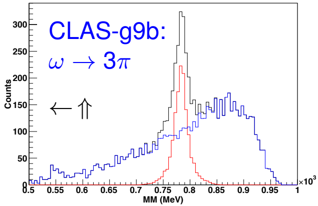
- At least two $\frac{3}{2}^+$ states contributing
- Strong contribution of $N(2000)\,\frac{5}{2}^+$ (**)
- Possibly new resonance above 2.1 GeV

full energy range



- Event-based background subtraction
  ➜ $p\pi^+(\pi^-)$, $p(\pi^+)\pi^-$, $p\pi^+\pi^-$ ✓
  $p\pi^+\pi^-(\pi^0)$ ✓ $p\pi^+\pi^-(\eta)$?

$E_\gamma \in [1.4, 1.5]$ GeV



- Physics:

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

published (+ SDME's)

in progress

Complete Experiments in $\gamma p \to p\omega$ (& $\gamma p \to p\pi^+\pi^-$)

Bonn-Gatchina & CLAS PWA

- At least two $\frac{3}{2}^+$ states contributing
- Strong contribution of $N(2000)\,\frac{5}{2}^+$ (∗∗)
- Possibly new resonance above 2.1 GeV

- Event-based background subtraction

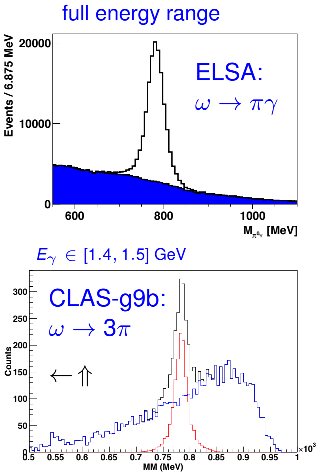
  ➜ $p\pi^+(\pi^-)$, $p(\pi^+)\pi^-$, $p\pi^+\pi^-$ ✓

  $p\pi^+\pi^-(\pi^0)$ ✓ $p\pi^+\pi^-(\eta)$?

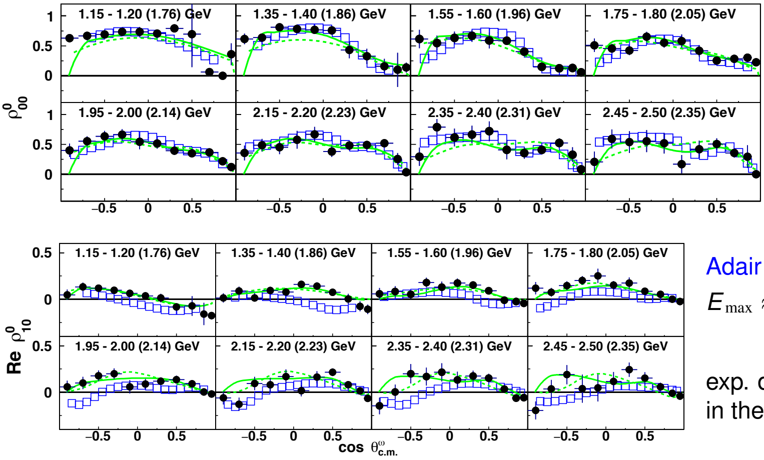
- Physics: $$\frac{d\sigma}{d\Omega} = \sigma_0\{1 - \delta_l\,\Sigma\cos 2\phi + \Lambda_x(-\delta_l\,H\sin 2\phi + \delta_\odot\,F) - \Lambda_y(-T + \delta_l\,P\cos 2\phi) - \Lambda_z(-\delta_l\,G\sin 2\phi + \delta_\odot\,E)\}$$

published (+ SDME's)

in progress



Complete Experiments in $\gamma p \to p\omega$: SDMEs



Adair Frame

$E_{\max} \approx 3.8$ GeV (CLAS)

exp. disagreement in the element Re ρ^0_{10}

A. Wilson *et al.*, PLB **749**, 407 (2015) M. Williams *et al.*, PRC **80** 045213 (2009)

Complete Experiments in $\gamma\, p \to p\omega$ (& $\gamma\, p \to p\pi^+\pi^-$)

Spin-Density Matrix Elements: $\Sigma_\omega = \rho^1_{00} + 2\rho^1_{11}$

$$
\begin{aligned}
W_1(\Omega_d, \rho) \;=\; & \sin^2\theta_d\, \rho^1_{00} \\
& + (1+\cos^2\theta_d)\, \rho^1_{11} \\
& + \sin^2\theta_d \cos 2\phi_d\, \rho^1_{1-1} \\
& + \sqrt{2}\sin 2\theta_d \cos\phi_d\, \mathrm{Re}\, \rho^1_{10}
\end{aligned}
$$

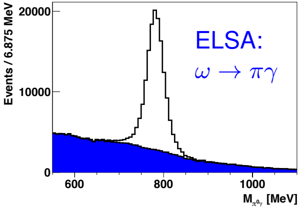
- Event-based background subtraction
  ➜ $p\pi^+(\pi^-)$, $p(\pi^+)\pi^-$, $p\pi^+\pi^-$ ✓
  $p\pi^+\pi^-(\pi^0)$ ✓ $p\pi^+\pi^-(\eta)$?
- Physics:

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

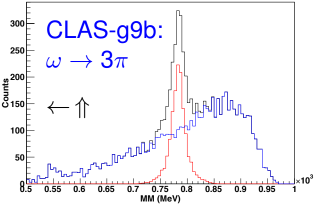
published (+ SDME's)

in progress

full energy range

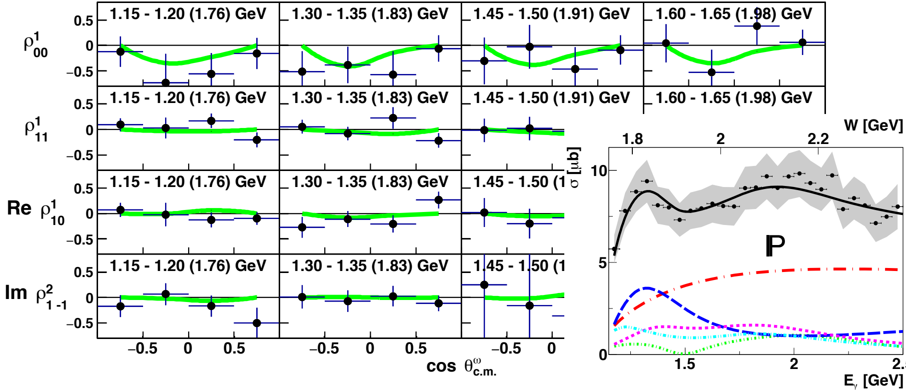


$E_\gamma \in [1.4, 1.5]$ GeV



Complete Experiments in $\gamma\, p \to p\,\omega$: SDMEs

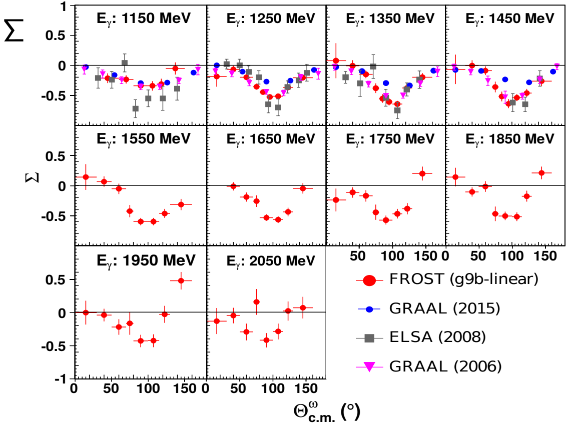
➜ Among non-resonant contributions: pomeron-exchange dominates.



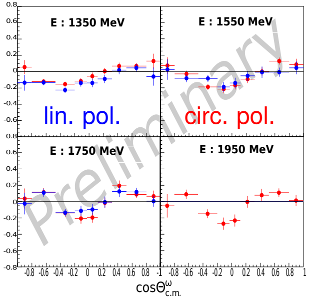
A. Wilson *et al.* [CBELSA/TAPS], Phys. Lett. B **749**, 407 (2015)

Beam- & Target-Asymmetry in $\gamma p \to p\omega$

We are close to a complete experiment in $\gamma p \to p\omega$ ...

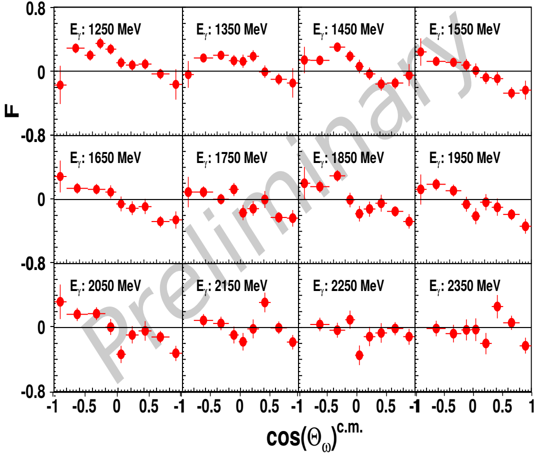


Target-Asymmetry (CLAS)
(first-time measurement)

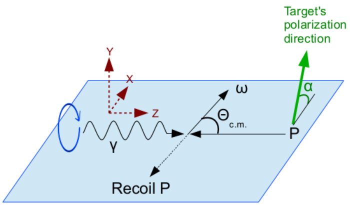


Priyashree Roy (Florida State), to be published

Beam-Target Asymmetry F in $\vec{\gamma}\vec{p} \to p\omega$ (CLAS-g9b)



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



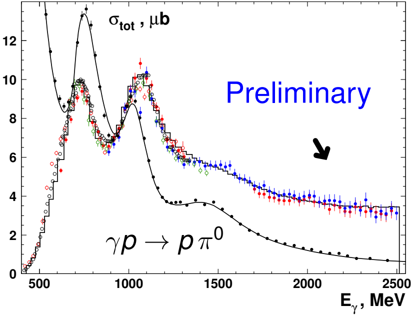
Priyashree Roy (Florida State), to be published

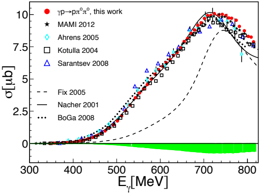
Outline

1. Introduction
   - The Spectrum of Hadrons: Baryons and Mesons
2. Spectroscopy of Baryon Resonances
   - Complete Experiments
   - Polarization Observables in $\gamma p \to N\pi$
   - Polarization Observables in $\gamma p \to p\omega$
3. Decay Cascades of Excited Baryons
4. (Very) Strange Ξ & Ω Resonances
   - Spectroscopy at JLab
5. Summary and Outlook
   - Are we there yet?

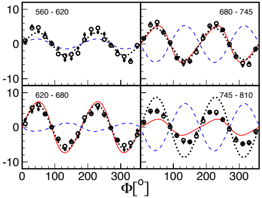
Observation of Decay Cascades in $\gamma p \to p \pi^0 \pi^0$

F. Zehr *et al.*, Eur. Phys. J. A **48**, 98 (2012) @MAMI





Cross Sections

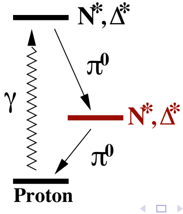


Beam Asymmetry, $I^{\odot}$

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

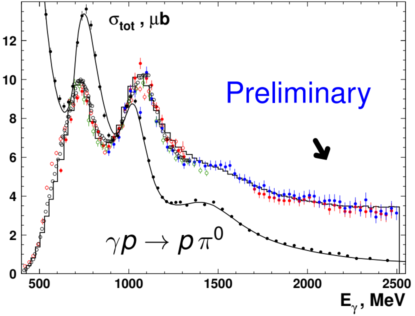
—— Bonn-Gatchina PWA

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



➜ Search for states in decay cascades!

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



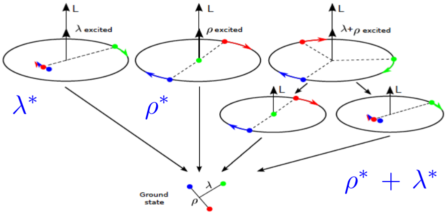
Observation of new decay modes in the decay of N^* resonances; weak at most in Δ^* decays.

—— Bonn-Gatchina PWA

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 $\mathcal{M}_\mathcal{S}$ 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.



Sokhoyan, Gutz, V. C. *et al.*, EPJ A **51**, no. 8, 95 (2015)

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

Decays observed in PWA into, e. g.

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

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

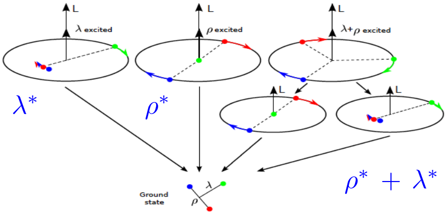
Observation of new decay modes in the decay of N^* resonances; weak at most in Δ^* decays.

—— Bonn-Gatchina PWA

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 $\mathcal{M}_\mathcal{S}$ and

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

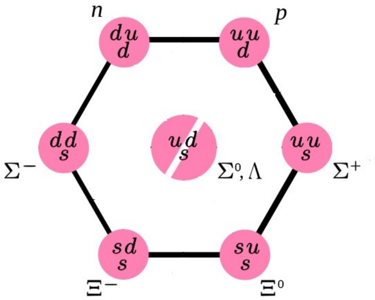
a component in which both the ρ and the λ oscillator are excited simultaneously.

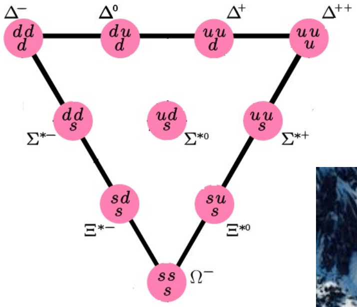


Sokhoyan, Gutz, V. C. *et al.*, EPJ A **51**, no. 8, 95 (2015)

Outline

Cascade Spectrum and Multiplets

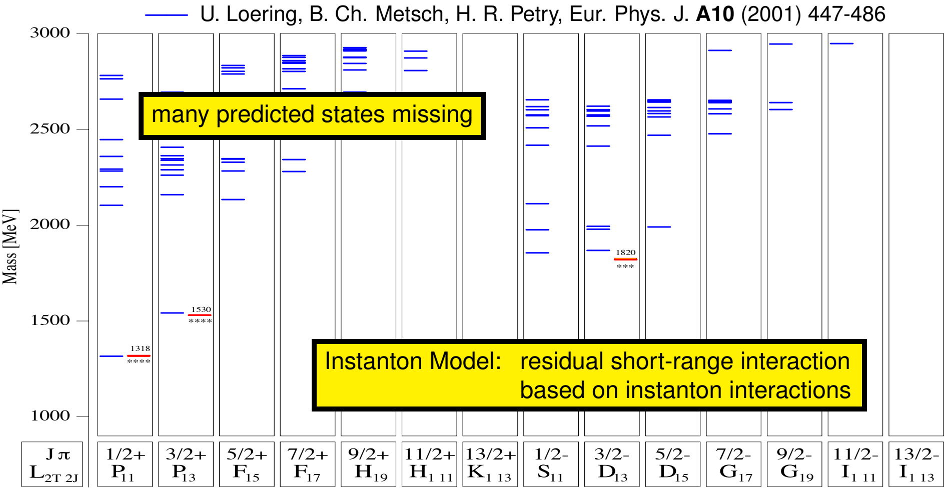




The decuplets consist of Δ^*, Σ^*, Ξ^*, and Ω^* resonances, but also the octets consist of an Ξ^* state.

➜ We expect as many Ξ's as N^* & Δ^* states together. Moreover, their properties should be related.

Cascade Resonances: Status of 2015



Measurements at BNL in $K^- p \to K^+_{\rm slow} + X^-$

"Existence of Ξ Resonances above 2 GeV"
(C.M. Jenkins *et al.*, Phys. Rev. Lett. **51**, 951 (1983))

Observed Ξ States:

$\Xi(1320)$ **** $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

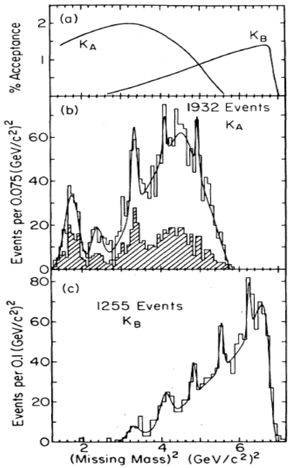
$\Xi(1530)$ **** $I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$

$\Xi(1820)$ *** $I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$

$\Xi(2030)$ *** $I(J^P) = \frac{1}{2}(\geq \frac{5}{2}^?)$

$\Xi(2370)$ *** $I(J^P) = \frac{1}{2}(?^?)$

$\Xi(2500)$ *** $I(J^P) = \frac{1}{2}(?^?)$

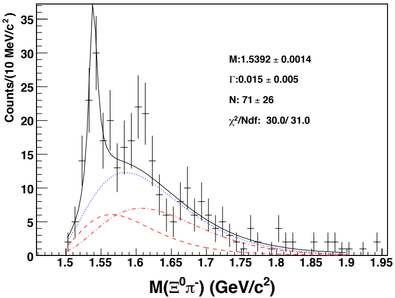


CLAS g11a: Excited States in $\gamma p \rightarrow K^+K^+\pi^-\ (X)$

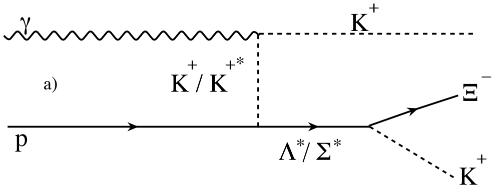
From the paper: *Although a small enhancement is observed in the $\Xi^0\pi^-$ invariant mass spectrum near the controversial 1-star $\Xi^-(1620)$ resonance, it is not possible to determine its exact nature without a full partial wave analysis.*

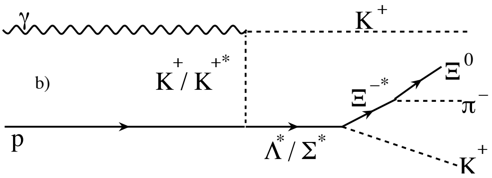
Need high-statistics, high-energy data from an experiment designed to see Ξ states:

- 3- or 4-track trigger
- Reconstruction of full decay chain
- Higher photon energy
- Improved detectors



Possible Production Mechanisms





$K^+(\Xi^- K^+)$, $K^+(\Xi^0 K^0)$, $K^0(\Xi^0 K^+)$

➜ Cross sections, beam asymmetries (similar to $p\,\pi\pi$ & $p\,KK^*$)

Production of excited states via a

1. forward-going K^0 meson
   ➜ $K^0\,(\,\Xi^-\,\pi^+\,)\,K^+$, etc.
2. forward-going K^+ meson
   ➜ $K^+\,(\,\Xi^-\,\pi^+\,)\,K^0$,
   $K^+\,(\,\Xi^0\,\pi^-\,)\,K^+$, etc.

* W. Roberts *et al.*, Phys. Rev. C **71**, 055201 (2005)

Ξ Spectroscopy with the GlueX Detector

The Ξ octet ground states (Ξ^0, Ξ^-) will be challenging to study via exclusive *t*-channel (meson exchange) production. The typical final states have kinematics for which the baseline GlueX detector has very low acceptance due to:

- the high-momentum forward-going kaon and
- the relatively low-momentum pions produced in the Ξ decay.

The production of the Ξ decuplet ground state, Ξ(1530), and other excited Ξ's decaying to $\Xi\pi$ results in a lower momentum kaon at the upper vertex, and these heavier Ξ states produce higher momentum pions in their decays.

The lightest excited Ξ states are expected to decouple from $\Xi\pi$ and can be searched for and studied also in their decays to $\Lambda\overline{K}$ and $\Sigma\overline{K}$:

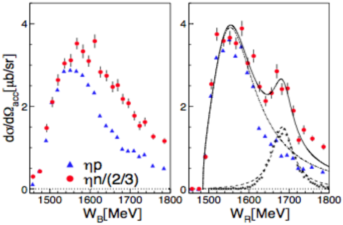
$$\gamma p \to K\,Y^* \quad\to\quad K^+\,(\overline{K}\Lambda)_{\Xi^{-*}}\,K^+,\quad K^+\,(\overline{K}\Lambda)_{\Xi^{0*}}\,K^0,\quad K^0\,(\overline{K}\Lambda)_{\Xi^{0*}}\,K^+,$$

$$\gamma p \to K\,Y^* \quad\to\quad K^+\,(\overline{K}\Sigma)_{\Xi^{-*}}\,K^+,\quad K^+\,(\overline{K}\Sigma)_{\Xi^{0*}}\,K^0,\quad K^0\,(\overline{K}\Sigma)_{\Xi^{0*}}\,K^+.$$

Outline

Open Issues 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? To what extent are diquark correlations, gluonic modes or hadronic degrees of freedom important in this physics?
2. Can we identify unconventional states in the strangeness sector, e.g. a $\Lambda(1405)$ or the $N(1440)$?
3. Can we identify the leading interactions between the constituents?
4. Do we understand the decay of high-mass baryon resonances? Is a similar dynamical mechanism applicable (hadronic d.o.f.)?
5. Do we observe states *truely* 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?



Summary and Outlook

Baryon Spectroscopy: Are we there, yet? Certainly not ...

New era in the spectroscopy of strange baryons (GlueX, LHCb, PANDA, ...)

- Mapping out the spectrum of Ξ baryons is the primary motivation (including parity measurements); some hope for peak hunting.
- Ground-state Ξ in $\gamma p \to KK\,\Xi$ will allow the spectroscopy of Σ^* / Λ^* states.

The multi-strange baryons provide a missing link between the light-flavor and the heavy-flavor baryons. Also:

1. Do the lightest excited Ξ states in certain partial waves decouple from the $\Xi\pi$ channel, confirming the flavor independence of confinement?
2. Ξ baryons as a probe of excited hadron structure?
   ➜ Measurements of the isospin splittings in spatially excited Ξ states appear possible for the first time (similar to $n - p$ or $\Delta^0 - \Delta^{++}$).