Spectroscopy of Excited Baryon Resonances at CLAS: A Review of the 6-GeV Program

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Outline

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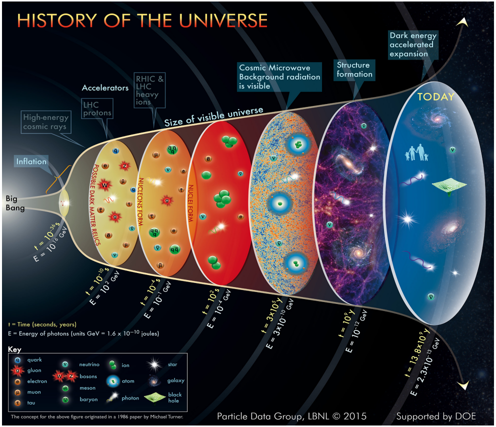
1. Introduction
   - Spectroscopy of Baryon Resonances
   - Experimental Approach at CLAS
2. Experimental Results
   - Polarization Measurements
   - Observables in Reactions off Neutrons
   - What have we learned?
3. Structure of Excited Baryons
   - Transition (Helicity) Amplitudes
4. Summary and Outlook
   - Open Issues in (Light) Baryon Spectroscopy
   - Summary and Outlook

The Evolution of the Universe



$t \sim 10^{-9}$ s Quark-Gluon Plasma

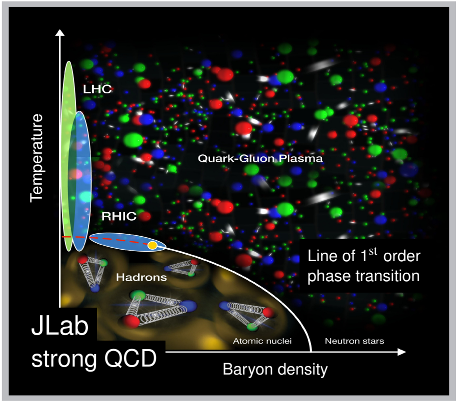
$t \sim 10^{-4}$ s Nucleons

$t \sim 10^{2}$ s Nuclei

$t \sim 3 \times 10^{5}$ s Atoms

At $t \sim 10^{-6}$ s: Transition from QGP to Nucleons

The Evolution of the Universe

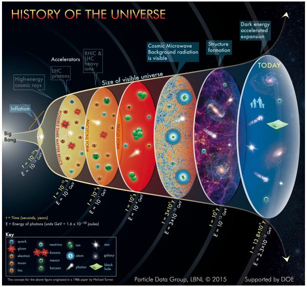


QGP

↓

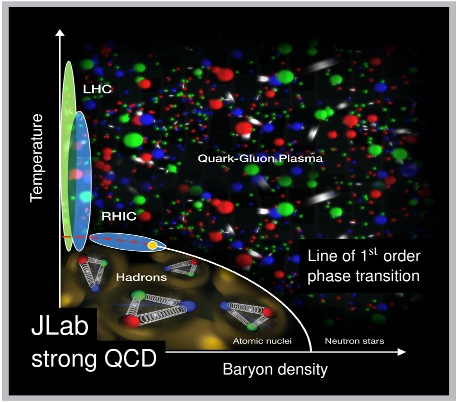
hadron phase

- Chiral symmetry is broken
- Quarks acquire mass
- Baryon resonances occur
- Color confinement emerges



Many of these events can be studied in the lab.

QCD Phases and the Study of Baryon Resonances



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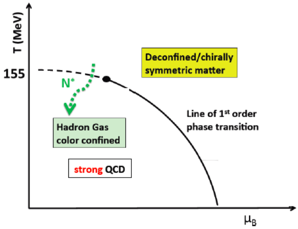
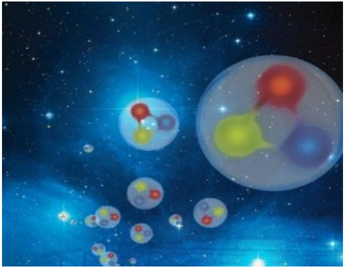


RPP (u, d, s, c) baryons not sufficient to describe freeze-out behavior.

(e. g. A. Bazavov *et al.*, PRL **113** (2014) 7, 072001)

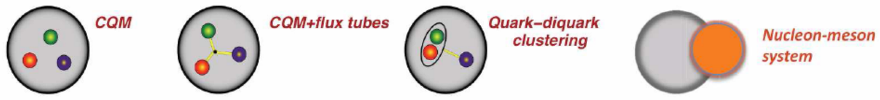
Non-Perturbative QCD



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 mesons, 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?



From the Atomic Spectrum of Hydrogen ...

Development of the theory of atomic structure required

- Hydrogen Atom (ground state)
- Together with the emission (absorption) spectrum.

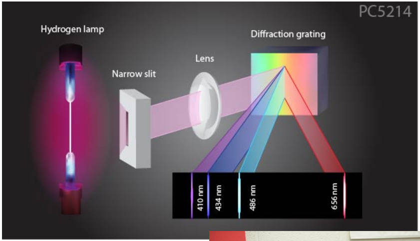
Bohr model ➜ QED

Understanding the nucleon requires

- proton (ground state)
- Together with its excitation spectrum.

Quark model ➜ strong QCD

Atomic Spectrum of Hydrogen



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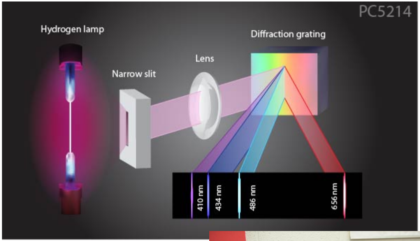
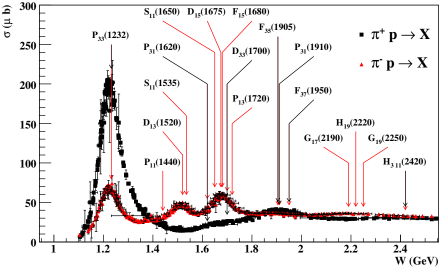


... to Understanding the N^* Spectrum

CLAS (6 GeV) at JLab 1998 - 2012

Photo-/electroproduction experiments in search for N^* states and measurement of the transition amplitudes.



Baryons are broad and overlapping ...

Courtesy of Michael Williams

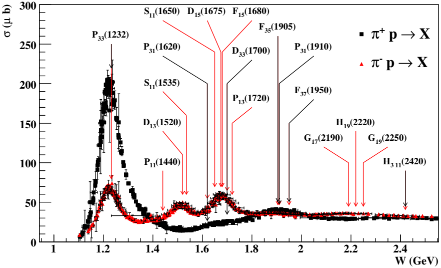
... to Understanding the N^* Spectrum

without polarizer ...

but there is more.

CLAS (6 GeV) at JLab 1998 - 2012

Photo-/electroproduction experiments in search for N^* states and measurement of the transition amplitudes.



Baryons are broad and overlapping ...

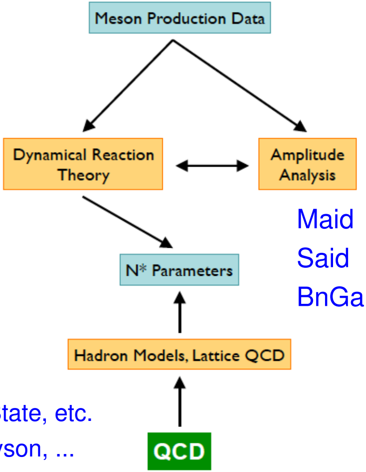
Courtesy of Michael Williams

Extraction of Resonance Parameters in N^* Physics

- Double-polarization measurements
- 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 reaction channels) needed to extract full scattering amplitude.

Coupled Channels

Jülich - GW, Gießen, Kent State, etc.
ANL - Osaka, Schwinger-Dyson, ...



Maid
Said
BnGa

Table representing CLAS@JLab measurements

	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)	✓ (red)	✓	(✓)	✓	✓	✓	✓								
$n\,\pi^+$	✓ (red)	✓ (red)	✓	(✓)	✓ (red)	✓	✓	✓								
$p\,\eta$	✓ (red)	✓ (red)	✓	(✓)	✓ (red)	✓	✓	✓								
$p\,\eta'$	✓ (red)	✓ (red)	✓	(✓)	✓	✓	✓	✓								
$p\,\omega/\phi$	✓ (red)	✓ (red)	✓ (red)	(✓)	✓ (red)	✓	✓	✓								
$K^+\,\Lambda$	✓ (red)	✓ (red)	✓ (red)	✓ (red)	✓	✓	✓	✓	✓	✓	✓	✓	✓ (red)	✓ (red)	✓ (red)	✓ (red)
$K^+\,\Sigma^0$	✓ (red)	✓ (red)	✓ (red)	✓ (red)	✓	✓	✓	✓	✓	✓	✓	✓	✓ (red)	✓ (red)	✓ (red)	✓ (red)
$K^0\,\Sigma^+$	✓	✓	✓	✓ (red)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Neutron (deuteron) targets														
$p\,\pi^-$	✓ (red)	✓			✓ (red)		✓									
$K^-\,\Sigma^+$	✓	✓	✓	✓	✓	✓	✓									
$K^0\,\Lambda$	✓ (red)	✓	✓	✓	✓ (red) *	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\,\Sigma^0$	✓	✓	✓	✓	✓ (red) *	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

✓ (red) published
✓ (blue) acquired or under analysis

Tensor polarization, SDMEs

* submitted

Complete Experiments?

"Uncertainty is an uncomfortable position. But Certainty is an absurd one."

Voltaire

Table representing CLAS@JLab measurements

	σ	Σ	T	P	E	F	G	H	$T_{x'}$	$T_{z'}$	$L_{x'}$	$L_{z'}$	$O_{x'}$	$O_{z'}$	$C_{x'}$	$C_{z'}$
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$p\,\eta$	✓ (red)	✓ (red)	✓	(✓)	✓ (red)	✓	✓	✓								
$p\,\eta'$	✓ (red)	✓ (red)	✓	(✓)	✓	✓	✓	✓								
$p\,\omega/\phi$	✓ (red)	✓ (red)	✓ (red)	(✓)	✓ (red)	✓	✓	✓								
$K^+\,\Lambda$	✓ (red)	✓ (red)	✓ (red)	✓ (red)	✓	✓	✓	✓	✓	✓	✓	✓	✓ (red)	✓ (red)	✓ (red)	✓ (red)
$K^+\,\Sigma^0$	✓ (red)	✓ (red)	✓ (red)	✓ (red)	✓	✓	✓	✓	✓	✓	✓	✓	✓ (red)	✓ (red)	✓ (red)	✓ (red)
$K^0\,\Sigma^+$	✓	✓	✓	✓ (red)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
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$p\,\pi^-$	✓ (red)	✓			✓ (red)		✓									
$K^-\,\Sigma^+$	✓	✓	✓	✓	✓	✓	✓									
$K^0\,\Lambda$	✓ (red)	✓	✓	✓	✓ (red) *	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\,\Sigma^0$	✓	✓	✓	✓	✓ (red) *	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

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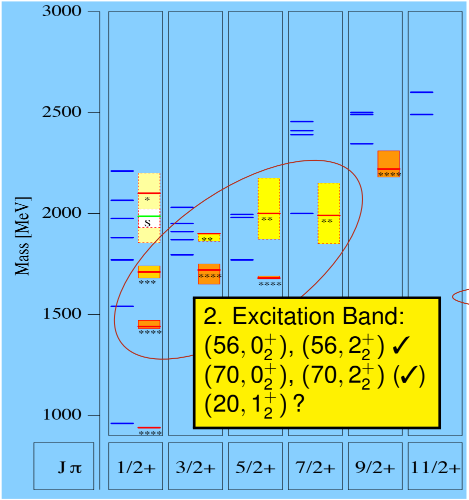
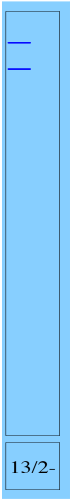
Outline

Spectrum of N^* Resonances

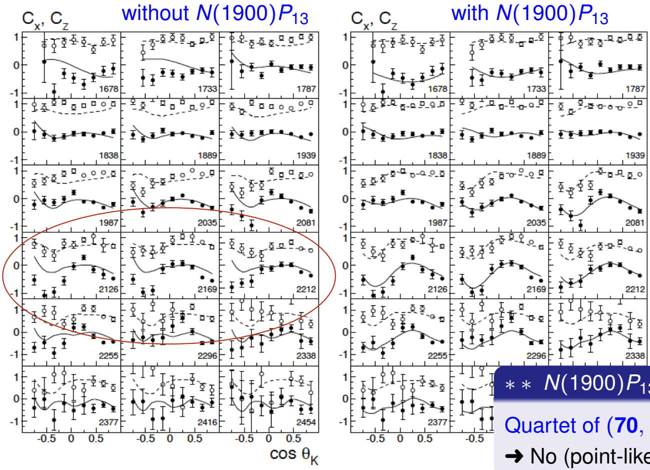


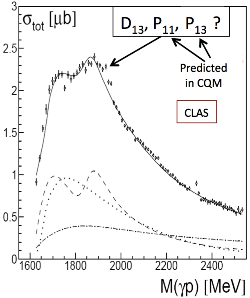
N^*	J^P $(L_{2I,2J})$	2010	2016
$N(1440)$	$1/2^+$ (P_{11})	∗∗∗∗	∗∗∗∗
$N(1520)$	$3/2^-$ (D_{13})	∗∗∗∗	∗∗∗∗
$N(1535)$	$1/2^-$ (S_{11})	∗∗∗∗	∗∗∗∗
$N(1650)$	$1/2^-$ (S_{11})	∗∗∗∗	∗∗∗∗
$N(1675)$	$5/2^-$ (D_{15})	∗∗∗∗	∗∗∗∗
$N(1680)$	$5/2^+$ (F_{15})	∗∗∗∗	∗∗∗∗
$N(1685)$			∗
$N(1700)$	$3/2^-$ (D_{13})	∗∗∗	∗∗∗
$N(1710)$	$1/2^+$ (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}	∗∗	



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

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





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

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

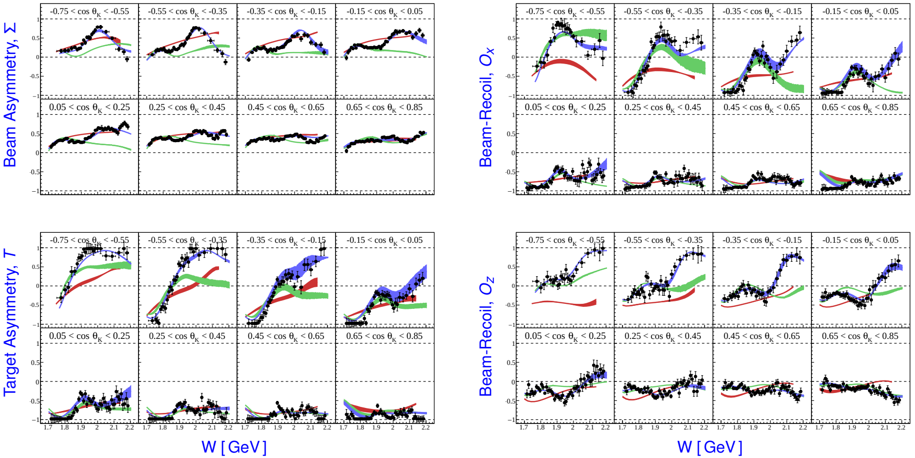
➜ No (point-like) quark-diquark oscillations!

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

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

Polarization in $\vec{\gamma} p \to K^+ \vec{\Lambda}$: O_x & O_z + T & Σ

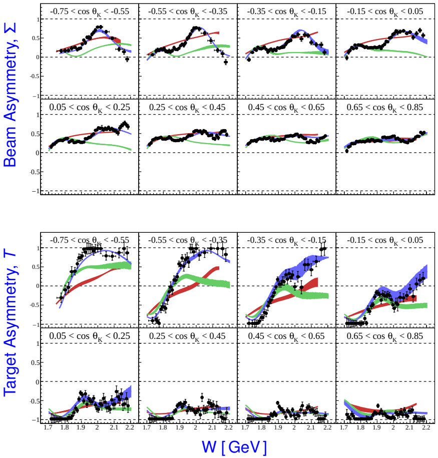
C. A. Paterson *et al.* [CLAS Collaboration], Phys. Rev. C **93**, 065201 (2016)



— ANL-Osaka — BnGa '14 — BnGa '14 refit

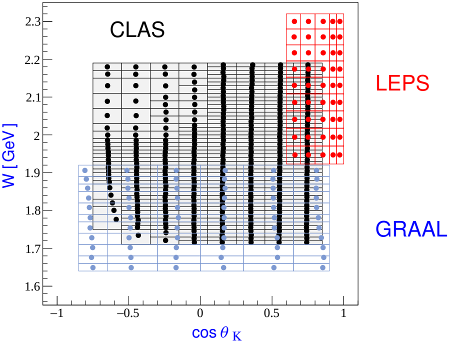
Polarization Observables in $\vec{\gamma} p \to K^+ \Lambda$

C. A. Paterson *et al.*, Phys. Rev. C **93**, 065201 (2016)



➜ Additional $N^* \frac{3}{2}^+$, $N^* \frac{5}{2}^+$ needed in BnGa refit.

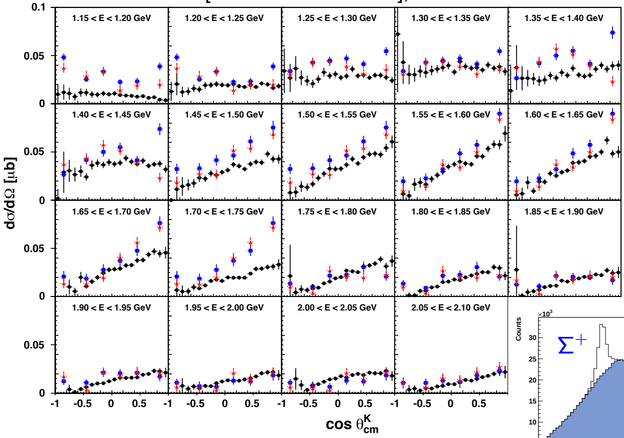
comparison of kinematic coverage



— ANL-Osaka — BnGa '14 — BnGa '14 refit

Cross Sections for $\gamma p \to K^0\,\Sigma^+ \to p\,\pi^+\pi^-\pi^0$

Z. Akbar *et al.* [CLAS Collaboration], under review.

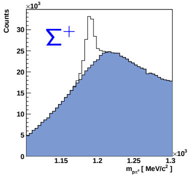


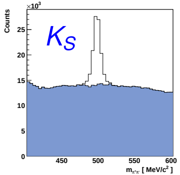
CLAS-g12 • CB-ELSA • CBELSA/TAPS •

New cross section results in 50-MeV-wide E_γ bins for

$1.15 < E_\gamma < 3.0$ GeV

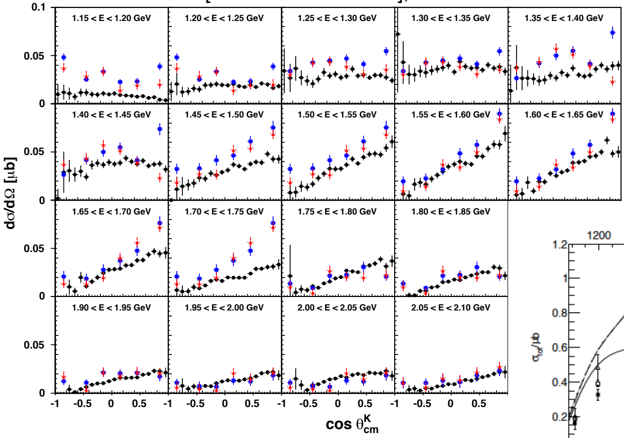
➜ Need theory support to understand physics!!





Cross Sections for $\gamma p \to K^0 \Sigma^+ \to p \pi^+ \pi^- \pi^0$

Z. Akbar *et al.* [CLAS Collaboration], under review.

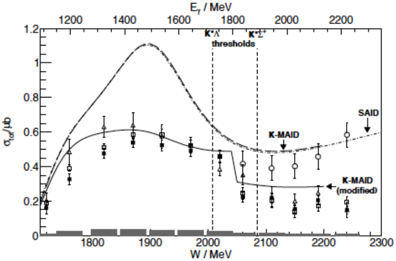


CLAS-g12 • CB-ELSA • CBELSA/TAPS •

New cross section results in 50-MeV-wide E_γ bins for

$1.15 < E_\gamma < 3.0$ GeV

Phys. Lett. B **713**, 180 (2012)



➜ In preparation for $K^0 \Sigma^+$: $E, \Sigma, T, C_x, C_z, O_x, O_z$.

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

- Event-based background subtraction (event-based dilution factors)

  ➜ $\gamma p \to p\pi^+\pi^-$ ✓ $\gamma p \to p\pi^+\pi^-(\pi^0)$ ✓

- In analogy to pseudoscalar mesons:

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

published (+ SDME's) $\quad - \Lambda_y(-T + \delta_l P \cos 2\phi)$

in progress $\quad - \Lambda_z(-\delta_l G \sin 2\phi + \delta_\odot E)\}$

$\phi = \Psi \equiv$ Angle between $p\omega$ production plane and the photon polarization plane in the overall CM frame.

$\Phi \equiv$ Azimuthal angle of normal to the ω decay plane in helicity frame - quantization axis in the direction opposite the recoiling proton in the ω rest frame.

The ω is a vector meson (A. I. Titov and B. Kampfer, Phys. Rev. C 78, 038201 (2008))

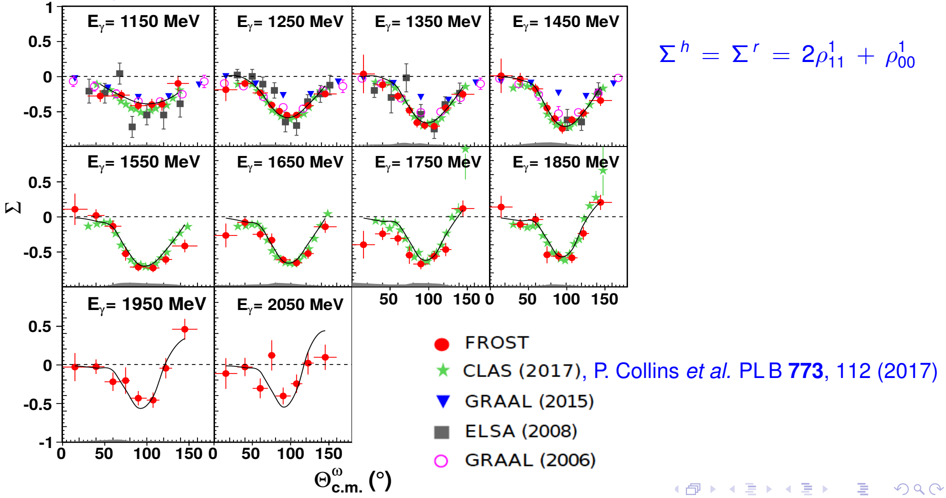
$$2\pi\, W^f(\Phi,\Psi) = 1 - \Sigma^f_\Phi \cos 2\Phi - P_\gamma \Sigma^f_b \cos 2\Psi + P_\gamma \Sigma^f_d \cos 2(\Phi - \Psi)$$

$$\boxed{\Sigma^h_b = \Sigma^r_b = 2\rho^1_{11} + \rho^1_{00}} \qquad -\frac{1}{2}\Sigma^h_d = \Sigma^r_d = \rho^1_{1\,-1} \qquad -\frac{1}{2}\Sigma^h_\Phi = \Sigma^r_\Phi = -\rho^0_{1\,-1}$$

Pol. SDMEs: B. Vernarsky (CMU), PhD dissertation

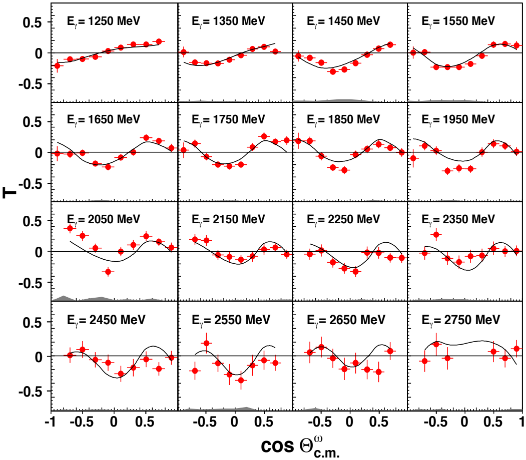
The Beam Asymmetry in $\vec{\gamma}\, p \to p\,\omega$ (CLAS-g9b)

P. Roy *et al.* [CLAS Collaboration], PR C **97**, 055202 (2018)



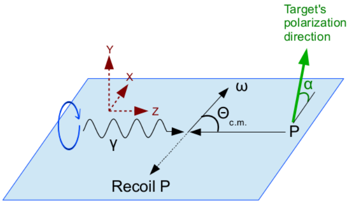
$$\Sigma^h = \Sigma^r = 2\rho^1_{11} + \rho^1_{00}$$

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



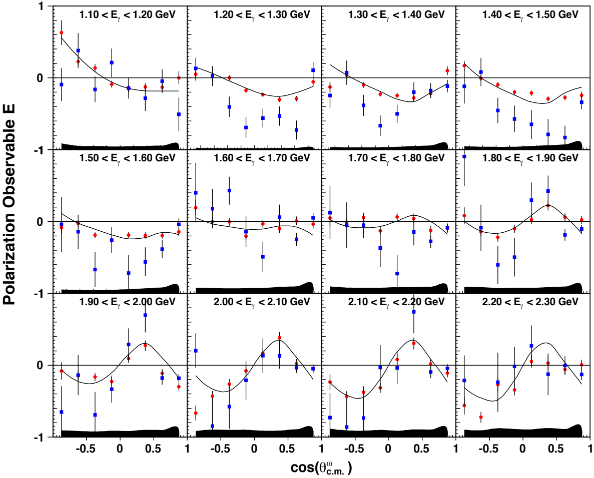
Polarized Cross Section

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



P. Roy *et al.* [CLAS Collaboration], PR C **97**, 055202 (2018)

Helicity Asymmetry in $\vec{\gamma}\,\vec{p} \to p\,\omega$ (CLAS g9a)



BnGa (coupled-channels) PWA

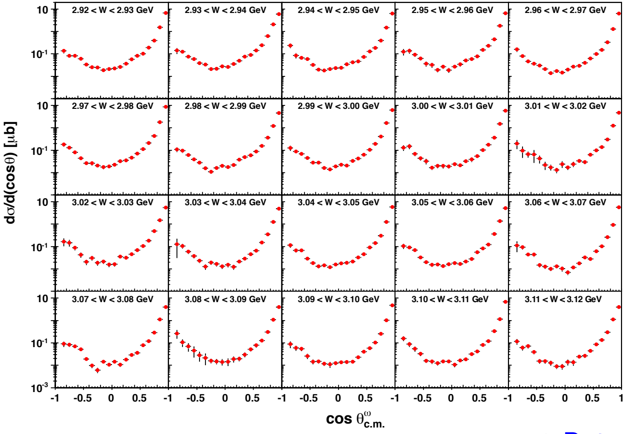
- Dominant $\mathbb{P}$ exchange
- Complex $3/2^+$ wave
    1. $N(1720)$
    2. $W \approx 1.9$ GeV
- $N(1895)\,1/2^-$ (new state)
- $N(1680), N(2000)\,5/2^+$
- 7/2 wave > 2.1 GeV

● CLAS-g9a

■ CBELSA/TAPS
Phys. Lett. B **750**, 453 (2015)

Z. Akbar *et al.* [CLAS Collaboration], PR C **96**, 065209 (2017)

Cross Sections for the Reaction $\gamma p \to p\omega \to p\pi^+\pi^-\pi^0$



New cross section results in 10-MeV-wide W bins for

$1.15 < E_\gamma < 5.40$ GeV, or

$1.75 < W < 3.32$ GeV

➜ Need theory support to understand physics at these high energies!!

Working with JPAC.

(V. Mathieu *et al.*)

(SDMEs under review)

➜ Data of unprecedented quality

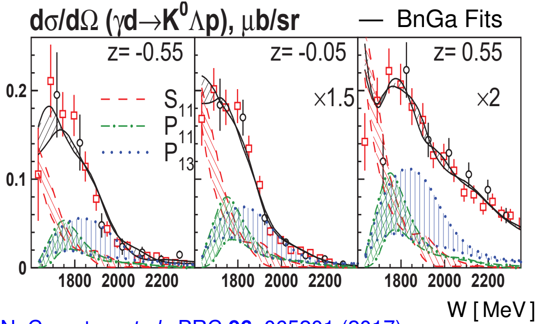
Z. Akbar *et al.* [CLAS Collaboration], under review.

Brief Summary of Measurements off the Neutron

$\gamma n \to p\,\pi^-$ σ, E observable

$\gamma n \to K^0\,\Sigma^0$ E observable (submitted)

$\gamma n \to K^0\,\Lambda$ σ, E observable (submitted)



N. Compton *et al.*, PRC **96**, 065201 (2017)

Summary of neutron results:

- No introduction of new resonances so far.
- Helicity amplitudes, $N(1900)\,\frac{3}{2}^+$, $N(1720)\,\frac{3}{2}^+$.
- Convergence of groups on $\gamma n N^*$ (A_n^h) for $N(2190)\,\frac{7}{2}^-$.

The impact of photoproduction on baryon resonances		Decay modes of nucleon resonances		
	black:	PDG 2004	****	Existence is certain.
	red:	PDG 2018	***	Existence is very likely.
	blue:	BESIII resonances	**	Evidence of existence is fair.
			*	Evidence of existence is poor.

		overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$	$N_{1440}\pi$	$N_{1520}\pi$	$N_{1535}\pi$	$N_{1680}\pi$
N	$1/2^+$	****														
$N(1440)$	$1/2^+$	****	****	****	****	***										
$N(1520)$	$3/2^-$	****	****	****	****	**	****									
$N(1535)$	$1/2^-$	****	****	****	***	*	****									
$N(1650)$	$1/2^-$	****	****	****	***	*	****	***					*			
$N(1675)$	$5/2^-$	****	****	****	****	***	*	*	*	**				*		
$N(1680)$	$5/2^+$	****	****	****	****	***	*			****						
$N(1700)$	$3/2^-$	***	**	***	***	*	*	**	*	*						
$N(1710)$	$1/2^+$	****	****	****	**		***	**	*	*	*				*	
$N(1720)$	$3/2^+$	****	****	****	***	*	*	****	*	**	*					
$N(1860)$	$5/2^+$	**	*	**		*	*									
$N(1875)$	$3/2^-$	***	**	**	*	**	*	*	*	*	*	*	*			
$N(1880)$	$1/2^+$	***	**	*	**	*	*	**	**		**				*	
$N(1895)$	$1/2^-$	****	****	*	*	*	****	**	**	*	*	****	*			
$N(1900)$	$3/2^+$	****	****	**	**	*	*	**	**	*	*	**				
$N(1990)$	$7/2^+$	**	**	**	*	*	*	**	**							
$N(2000)$	$5/2^+$	**	**	**	**	*	*	*	*		*					
$N(2040)$	$3/2^+$	*		*												
$N(2060)$	$5/2^-$	***	***	**	*	*	*	*	*	*	*		*	*		*
$N(2100)$	$1/2^+$	***	**	***	**	**	*	*		*	*	**			***	
$N(2120)$	$3/2^-$	***	***	***	**	**		**	*		*	*	*	*	*	
$N(2190)$	$7/2^-$	****	****	****	****	**	*	**	*	*	*					
$N(2220)$	$9/2^+$	****	**	****			*	*	*							
$N(2250)$	$9/2^-$	****	**	****			*	*	*							
$N(2300)$	$1/2^+$	*		*												
$N(2570)$	$5/2^-$	*		*												
$N(2600)$	$11/2^-$	***		***												
$N(2700)$	$13/2^+$	**		**												

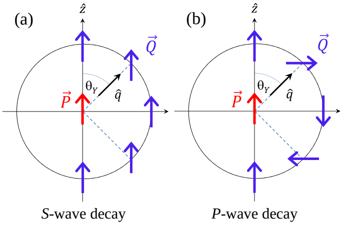
Based on results at Jefferson Lab, ELSA, MAMI, ...

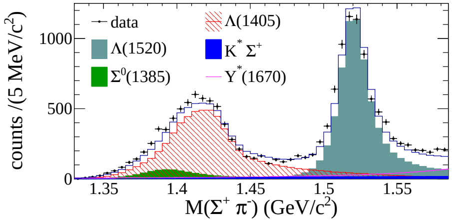
Spin and Parity Measurement of the Λ(1405) Baryon

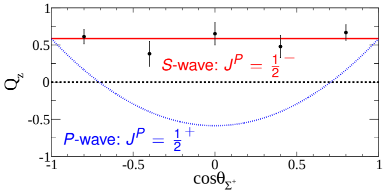
K. Moriya *et al.* [CLAS Collaboration], Phys. Rev. Lett. **112**, 082004 (2014)

Data for $\gamma p \to K^+\Lambda(1405)$ support $J^P = \frac{1}{2}^-$

- Decay distribution of $\Lambda(1405) \to \Sigma^+\pi^-$ consistent with $J = 1/2$.
- Polarization transfer, $\vec{Q}$, in $Y^* \to Y\pi$:
  - S-wave decay: $\vec{Q}$ independent of θ_Y





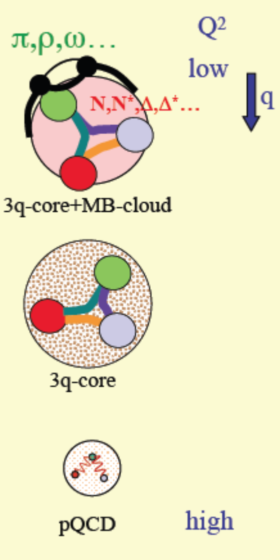


Outline

The N^* program has two main components:

- Establish the systematics of the spectrum

  Provides information on the nature of the effective degrees of freedom in strong QCD.



The N^* program has two main components:

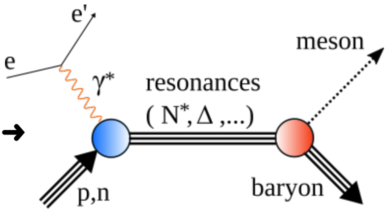
- Establish the systematics of the spectrum

  Provides information on the nature of the effective degrees of freedom in strong QCD.

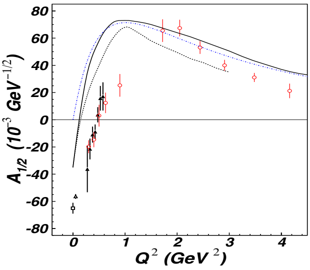
- Probe resonance transitions at different distance scales (Q^2 dependence)

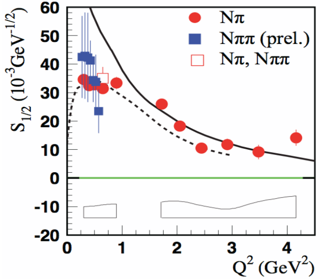
  Reveals the structure of N^* states.

$A_{\frac{1}{2}}, A_{\frac{3}{2}}, S_{\frac{1}{2}}$ ➜



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

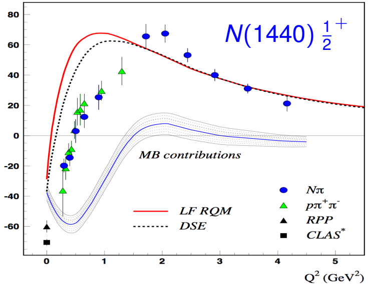
Consistency between both channels ($N\pi\pi$, $N\pi$): sign change, magnitude, ...

- At short distances (high Q^2), Roper behaves like radial excitation.
- Low-Q^2 behavior not well described by LF quark models
  ➜ ANL - Osaka achieves good description by adding meson-baryon interactions.
  DSE prediction: Mass of the quark core of the first radial excitation = 1.73 GeV.

➜ Gluonic excitation likely ruled out!

First Nucleon Excitations: Helicity Amplitude $A_{1/2}$

DSE: J. Segovia *et al.*, PR C **94** (2016) 042201

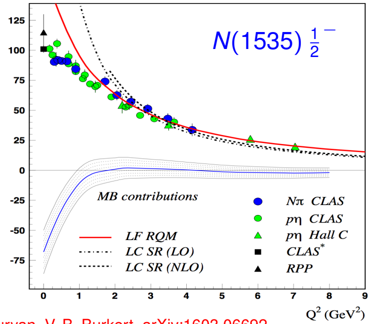


Non-quark contributions are significant at $Q^2 < 2.0$ GeV^2

➜ The 1st radial excitation of the q^3 core emerges as the probe penetrates the MB cloud.

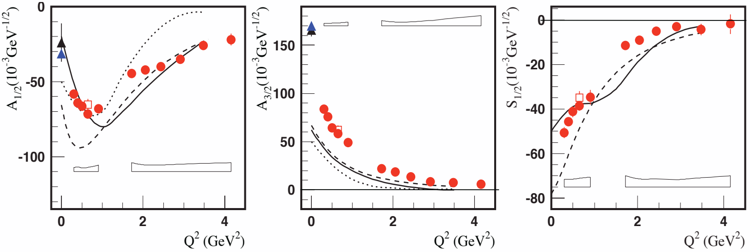
Non-quark contributions are significant at $Q^2 < 1.5$ GeV^2

➜ State consistent with the 1st orbital excitation of the nucleon.



— I. Aznauryan, V. B. Burkert, arXiv:1603.06692

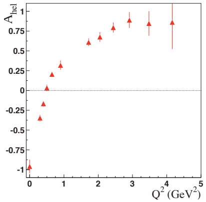
Helicity Amplitudes for $\gamma p \to N(1520)D_{13}$ Transition



There is clear evidence for helicity switch from $\lambda = 3/2$ (at photon point) to $\lambda = 1/2$ at high Q^2:

- Rapid change in helicity structure when going from photo- to electroproduction of a nucleon resonance
  ➜ Stringent prediction of CQM!

$$\mathcal{A}_{\text{hel}} = \frac{|A_{1/2}|^2 - |A_{3/2}|^2}{|A_{1/2}|^2 + |A_{3/2}|^2}$$ ➜



Outline

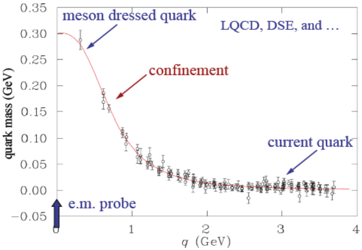
Open Issues in (Light) Baryon Spectroscopy

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 $N(1440)$? What is the situation with the $(\mathbf{20}, 1^+_2)$?

3. What is the nature of non-quark contributions, e. g. meson-baryon cloud or dynamically-generated states?
   ➜ Probe the running quark mass and determine the relevant degrees of freedom at different distance scales.

4. How do nearly massless quarks acquire mass? (as predicted in DSE and LQCD)



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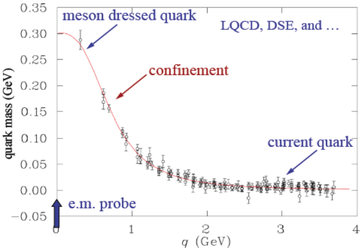

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Summary and Outlook

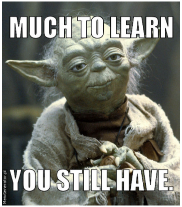
Baryon Spectroscopy: Are we there, yet?

The analysis of photoproduction data (from CLAS, ELSA, MAMI, SPring-8, etc.) continues and many new N^* resonances have been discovered.

- Polarization observables crucial in the seach for new baryon states.
- Multi-channel (PWA) approaches critical.

New era in spectroscopy of strange baryons (GlueX, CLAS12, LHCb, ...)

- 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 also allow the spectroscopy of $\Sigma^*\,/\,\Lambda^*$ states.



Acknowledgement

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