Hadron Spectroscopy: Progress toward understanding baryons

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Jefferson Lab, Newport News

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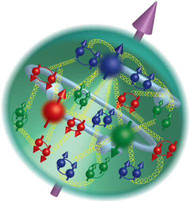
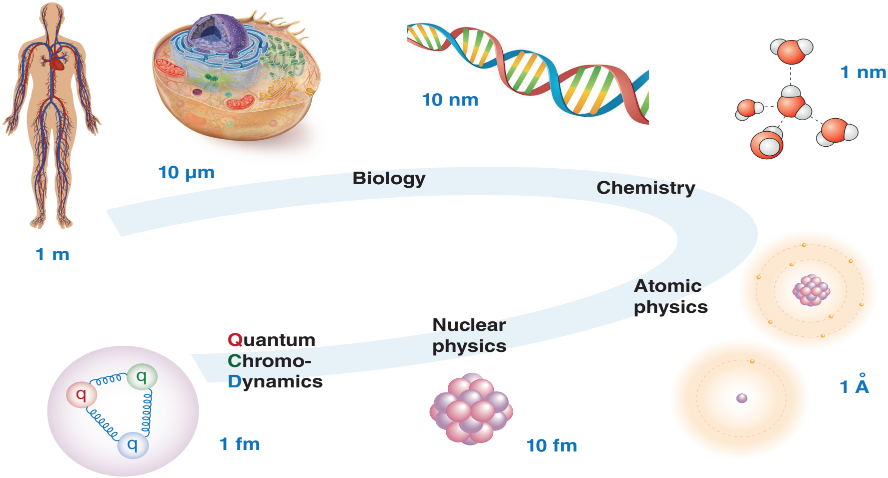


Outline

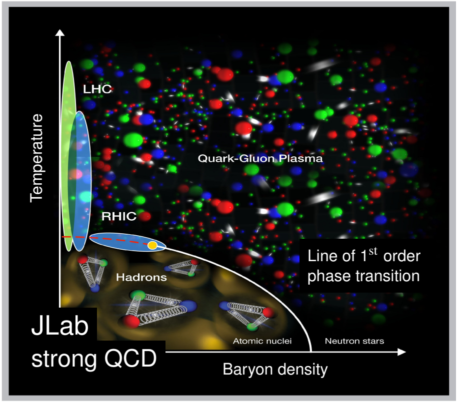
1. Introduction
   - Spectroscopy of Nucleon Resonances
   - $N^{\star}$ Spectroscopy: Polarization Measurements
   - Experimental Approach
2. Experimental Results
   - Polarization Measurements
   - Observables in Reactions off Neutrons
   - What have we learned?
3. Structure of Excited Baryons
   - Transition (Helicity) Amplitudes
4. Summary and Outlook

Outline

Quantum Chromodynamics



QCD Phases and the Study of Baryon Resonances

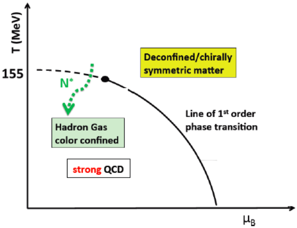


QGP

↓

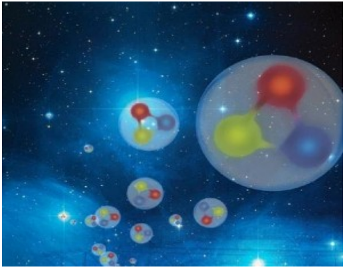
hadron phase

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



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?

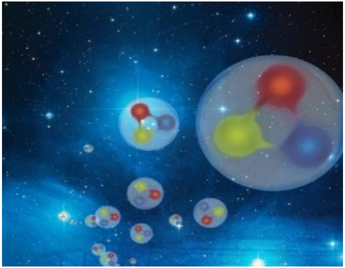
Baryons: What are the fundamental degrees of freedom inside a nucleon? Constituent quarks? How do the degrees change with varying quark masses?

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

➜ Gluonic Excitations provide a measurement of the excited QCD potential.

Hybrid baryons are also possible ...

Non-Perturbative QCD



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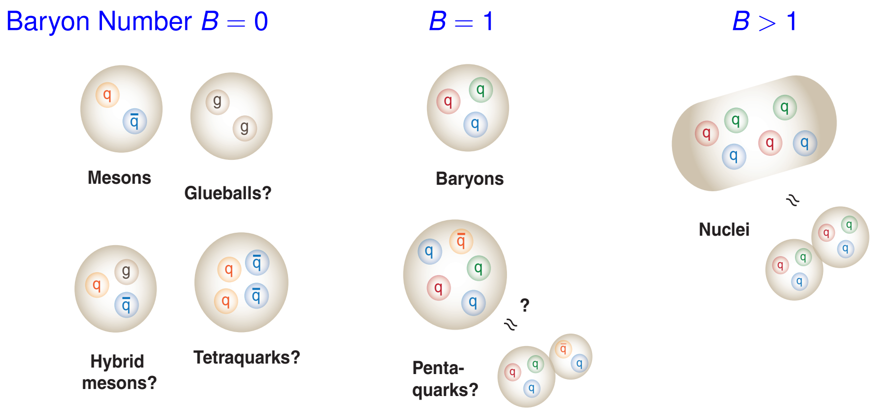
Answers to these questions will not be the direct result of some experiments.

- Models need to link observables to these fundamental questions.
- Significant observables:
  - Excitation spectra and electromagnetic couplings
  - Response of hadronic properties to a dense nuclear environment

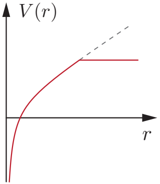
Quantum Chromodynamics



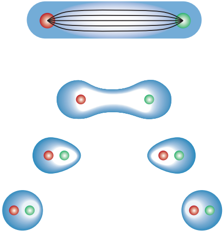
➜ Multiquark admixtures, “meson clouds” ?

Confinement

Quarks and gluons are confined in hadrons, cannot be observed in isolation.

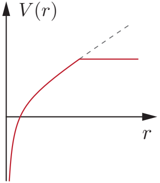


Microscopic origin still unclear – $1M prize



Confinement and Mass Generation

Quarks and gluons are confined in hadrons, cannot be observed in isolation.



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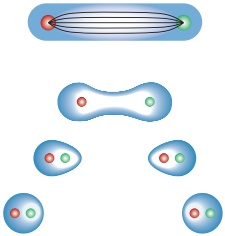
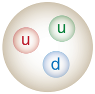


Three current quarks
do **not** make a proton:

$2m_u + m_d$ ~ 10 MeV << 1 GeV !?



Higgs: Current-quark masses

QCD: Mass generation from spontaneous breaking of **chiral symmetry:**
“constituent-quark masses”

u	d	s	c	b	t
3	5	100	1000	4000	175000
350	350	350	350	350	350

[MeV]

How do we study baryons experimentally?

Light-flavor baryons are typically studied in fixed-target experiments (nuclear physics), heavy-flavor baryons are studied at colliders (high-energy physics).

1. Fixed-Target Experiments

   Photo-/electroproduction, e. g. Jefferson Lab, ELSA, MAMI, etc.

   e. g. $\gamma N\,(\mathrm{e}^- N) \to (\mathrm{e}^-)\, N^*/\Delta^*$

   $\gamma N\,(\mathrm{e}^- N) \to (\mathrm{e}^-)\, K\, Y^*\; (Y^{ast} = \Lambda^*, \Sigma^*)$

   π / K-induced production, e. g. HADES@GSI, (future J-PARC, JLab)

   e. g. $\pi N \to N^*/\Delta^*$

2. Collider Experiments

   at e^+e^- machines, e. g. BES III, Belle, BaBar, etc.

   e. g. $\Xi_c^+\,(\Lambda_c^+) \to [\Xi^-\pi^+]_{\Xi^*}\,\pi^+\,(K^+)$ or $e^+e^- \to J/\psi \to N^*\bar{N}$

   at pp machines, e. g. LHC

   e. g. $\Xi_b^{*\,-} \to \Xi_b^-\,\pi^+\pi^-$ (LHCb, CMS)

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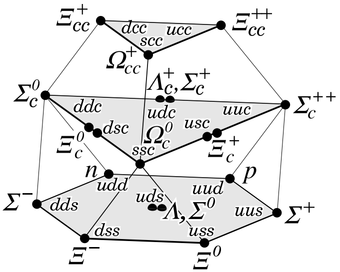


The quark model for baryons (qqq):

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

(other explanations possible)

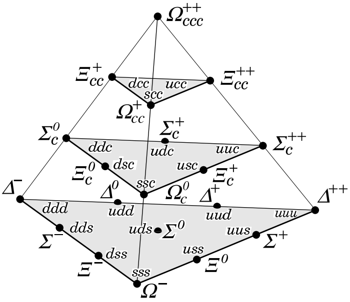
SU(6) Symmetry ($^{2S+1}$multiplets; $u, d, s,$ spin)

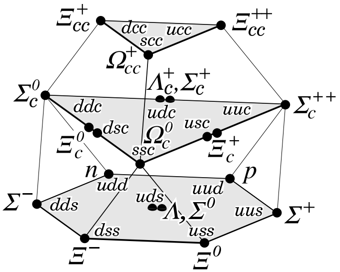
$$6 \otimes 6 \otimes 6 = 56_S \oplus 70_M \oplus 70_M \oplus 20_A$$

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

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

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





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Nomenclature

- Non-strange baryons
  $N^\star\ (I = 1/2)$, $\Delta\ (I = 3/2)$
- Strange baryons (hyperons)
  $\Lambda\ (I = 0)$, $\Sigma\ (I = 1)$,
  $\Xi\ (I = 1/2)$, $\Omega\ (I = 0)$

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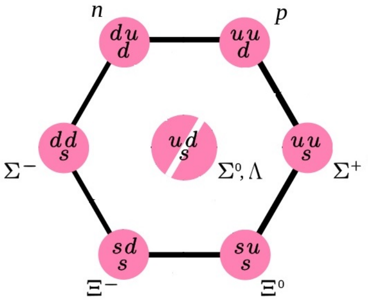
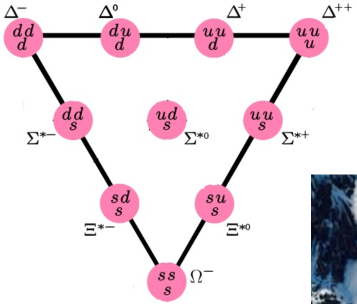
Baryon Multiplets and N* / Hyperon Spectroscopy





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

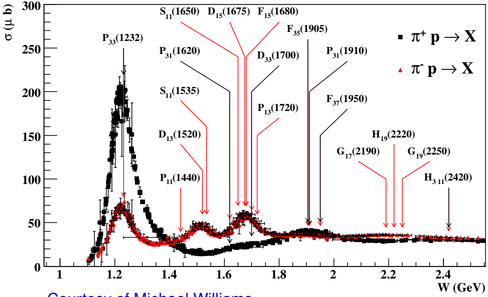
➜ We expect as many Ξ's as N^* & Δ^* states together. Moreover, their properties should be related.

Hadron Spectroscopy: The Light Flavors

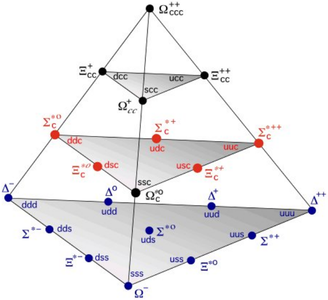
The strong coupling confines quarks and breaks chiral symmetry, and so defines the world of light hadrons.

Baryons are special because

Their structure is most obviously related to the color degree of freedom, e. g. $|\Delta^{++}\rangle = |u^{\uparrow}u^{\uparrow}u^{\uparrow}\rangle$.



Courtesy of Michael Williams

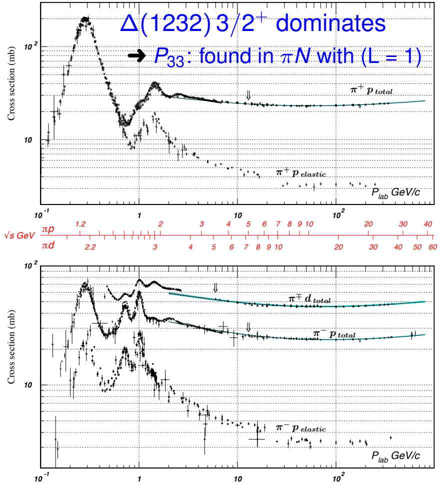


Many Y^* QN not measured:

(Quark model assignments)

➜ many Ξ^* and Ω^*, etc.

Hadron Beams: Pion- (Kaon-) Nucleon Scattering



First insight into experimental difficulties:

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

In 1952, first cross-section measurement of $\pi^+ p \to \pi^+ p$ (H. L. Anderson, E. Fermi, E. A. Long, D. E. Nagle, Phys. Rev. 85 (1952) 936).

From the Atomic Spectrum of Hydrogen ...

Development of the theory of atomic structure required

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

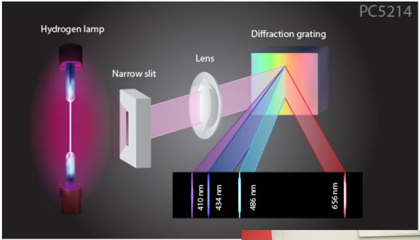
Bohr model ➜ QED

Understanding the nucleon requires

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

Quark model ➜ strong QCD

Atomic Spectrum of Hydrogen

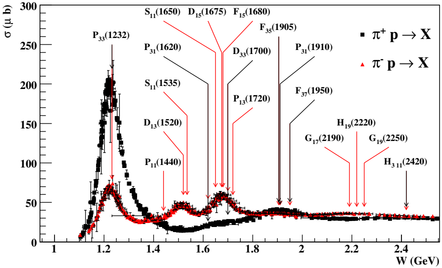


Baryons are broad and overlapping ...

... 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 ...

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... to Understanding the N^* Spectrum

without polarizer ... but there is more.

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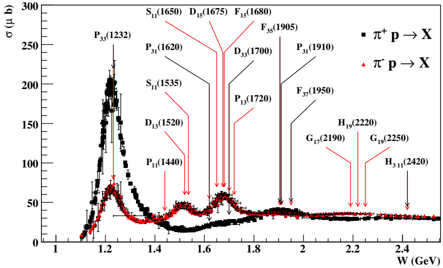

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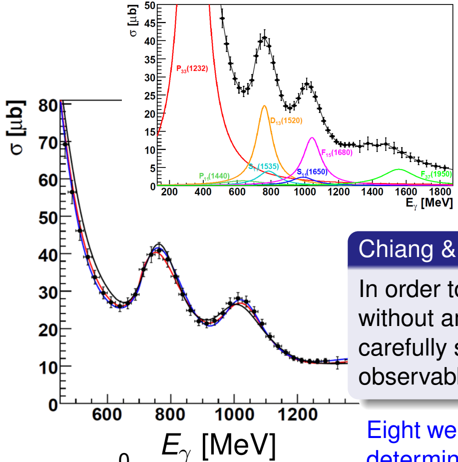
Why are Polarization Observables Important?



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

Single-(pseudoscalar) 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)

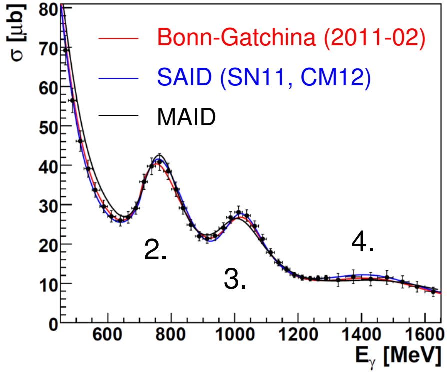
In order to determine the full scattering amplitude without ambiguities, one has to carry out eight carefully selected measurements: four double-spin observables along with four single-spin observables.

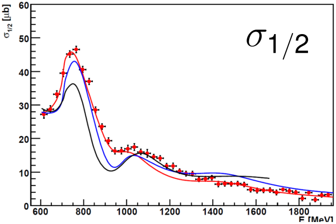
Eight well-chosen measurements are needed to fully determine production amplitudes F_1, F_2, F_3, and F_4.

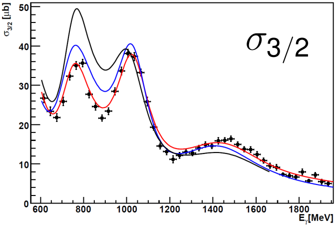
Example: Ambiguities in $\gamma p \to p \pi^0$

Helicity Difference:

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





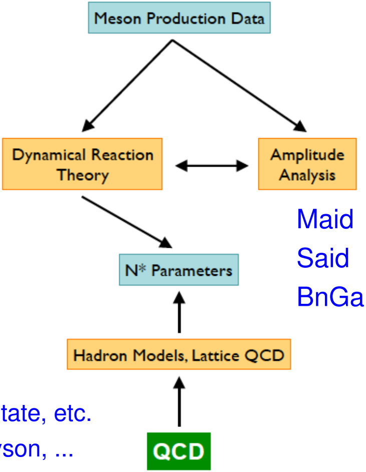


Extraction of Resonance Parameters in N^* Physics

- 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, ...

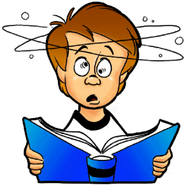


Maid
Said
BnGa

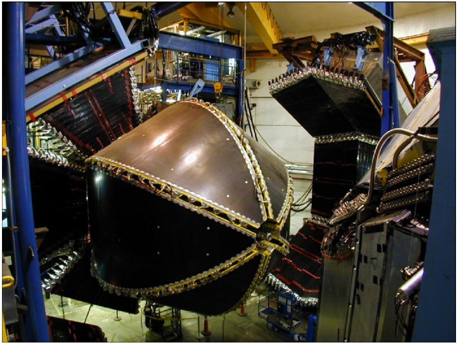
Extraction of Resonance Parameters in N^* Physics

Different modern analysis frameworks

- Unitary Isobar Models: unitary amplitudes + Breit-Wigner resonances
  MAID, Yerevan / JLab, KSU, JM model (πN & $\pi\pi N$)
- (Multi-channel) K-matrix approaches:
  GWU / SAID, BnGa (phenomenological), Gießen model
- Dynamical-coupled channel (DCC) models:
  3D scattering eq. & off-shell intermediate states
  ANL-Osaka (EBAC), Dubna-Mainz-Taipeh, Jülich-Bonn
- Other groups: JPAC (high energies),
  Mainz-Tuzla-Zagreb PWA (MAID + fixed-t dispersion relations),
  Gent model, truncated PWA, ...



CLAS (6 GeV) at JLab 1998 - 2012



Double-Polarization Experiments

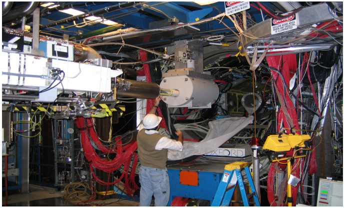


Photo-/electroproduction experiments in search for N^* states and measurement of the transition amplitudes.

← CLAS FROST

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

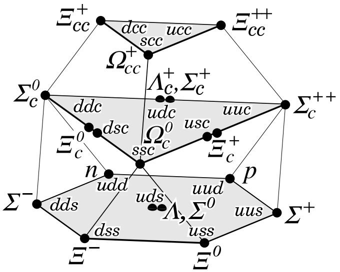
✓ (red) published
✓ (blue) acquired or under analysis

Tensor polarization, SDMEs

In addition, two-meson reactions are being analyzed:

* published

$$\gamma p \to (p\,\rho) \to p\,\pi^+\pi^- \text{ (CLAS)}, \quad \gamma p \to p\,\pi^0\pi^0, \quad p\,\pi^0\eta, \quad p\,\pi^0\omega \text{ (ELSA, MAMI, etc.)}$$



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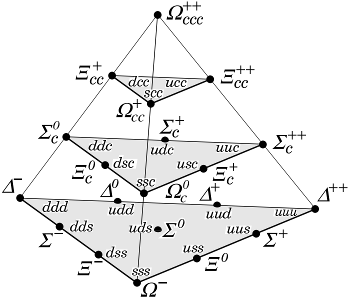
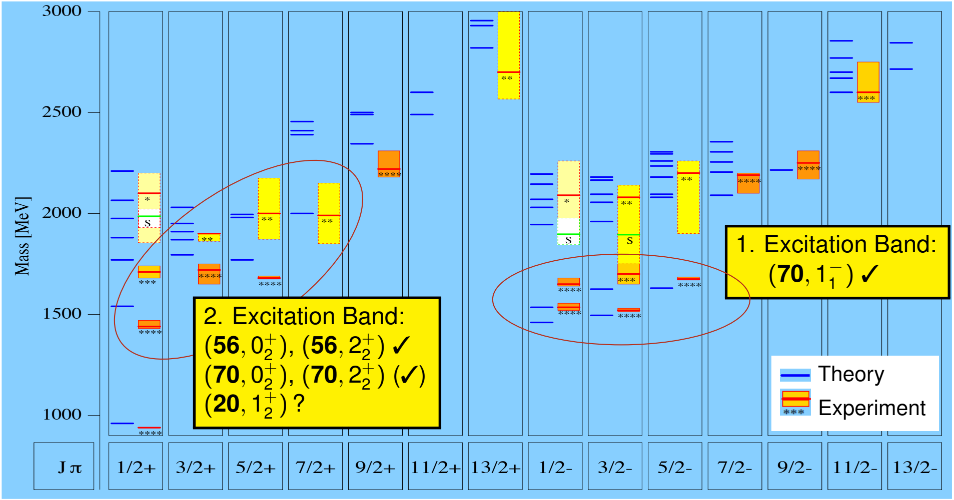
$$\Rightarrow \quad 56 = {}^4 10 \oplus {}^2 8 \quad \text{“ground states”}$$

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

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

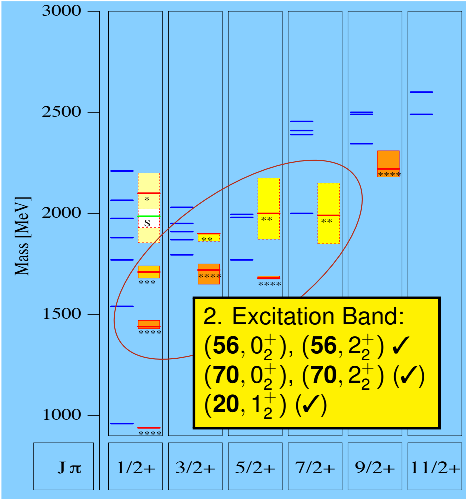


Spectrum of N^* Resonances



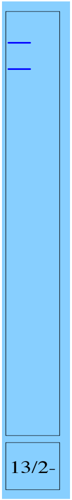
V. C. & W. Roberts, Rep. Prog. Phys. **76** (2013)

Spectrum of N^* Resonances



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

N^*	J^P $(L_{2I,2J})$	2010	2022
$N(1440)$	$1/2^+$ (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}	* *	



Particle Data Group: Unstable (Light-Flavor) Baryons





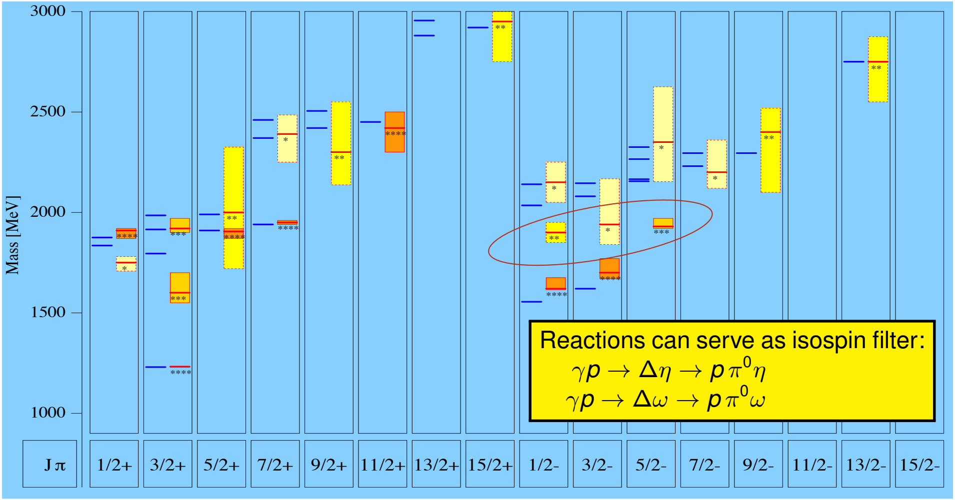
Philosophy: descriptive vs. prescriptive (generally descriptive)

descriptive: maintain listings and reviews

prescriptive: collect standards (e.g. naming scheme) and best practices (e.g. moving beyond BW parameters)

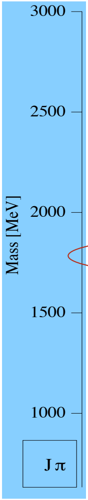
$S_{11}(1535) \longleftrightarrow N(1535)\,\frac{1}{2}^-$

Spectrum of Δ^* Resonances

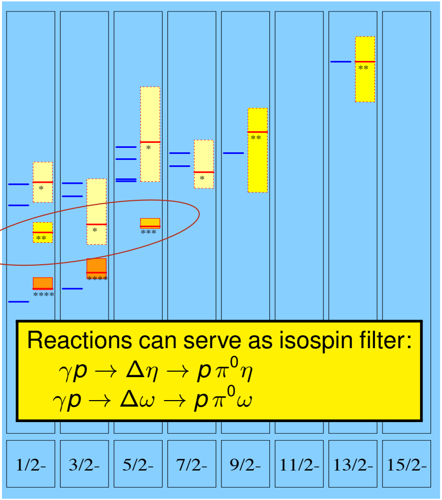


S. Capstick & N. Isgur, Phys. Rev. **D34** (1986) 2809

Spectrum of Δ^* Resonances

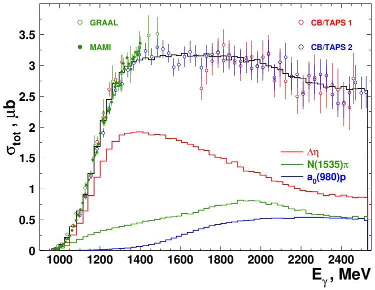


Δ^*	J^P $(L_{2I,2J})$	2010	2014
$\Delta(1232)$	$3/2^+$ (P_{33})	****	****
$\Delta(1600)$	$3/2^+$ (P_{33})	***	***
$\Delta(1620)$	$1/2^-$ (S_{31})	****	****
$\Delta(1700)$	$3/2^-$ (D_{33})	****	****
$\Delta(1750)$	$1/2^+$ (P_{31})	*	*
$\Delta(1900)$	$1/2^-$ (S_{31})	**	**
$\Delta(1905)$	$5/2^+$ (F_{35})	****	****
$\Delta(1910)$	$1/2^+$ (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})	**	**
$\Delta(2420)$	$11/2^+$ $(H_{3,11})$	****	****
$\Delta(2750)$	$13/2^-$ $(I_{3,13})$	**	**
$\Delta(2950)$	$15/2^+$ $(K_{3,15})$	**	**



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

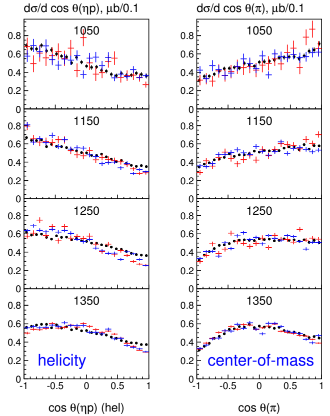
$\Delta(1232)\eta$, $N(1535)\,\frac{1}{2}^-\pi$, $pa_0(980)$

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

A Word on Partial-Wave Analysis (PWA)

Resonances are described by amplitudes! The lineshape of a single isolated resonance follows a Breit-Wigner distribution:

$$BW(E) = \frac{\Gamma/2}{(E_0 - E) - \mathrm{i}\Gamma/2} = \frac{1/2}{(E_0 - E)/\Gamma - \mathrm{i}/2}$$

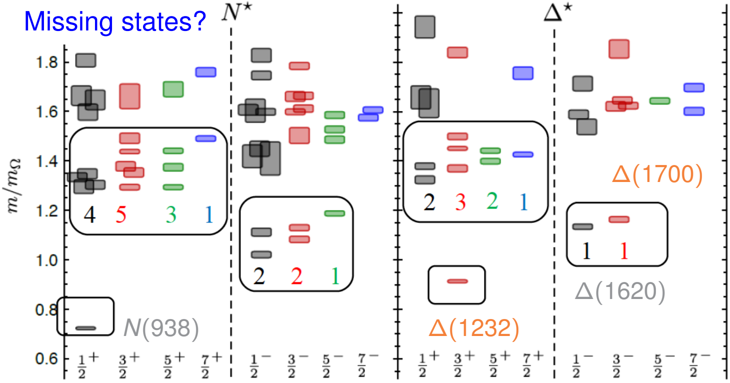
With $2(E_0 - E)/\Gamma = \cot\delta$:

$$f(E) = \frac{1}{\cot\delta - \mathrm{i}} = \mathrm{e}^{\mathrm{i}\delta}\sin\delta = \frac{\mathrm{i}}{2}(1 - \mathrm{e}^{2\mathrm{i}\delta})$$

This formula is derived from S matrix theory, where δ is called the phase shift. The amplitude is zero for $\Gamma/(E - E_0) \ll 0$ and starts to be real and positive with a small positive imaginary part. For $\Gamma/(E - E_0) \gg 0$, the amplitude is small, real and positive with a small negative imaginary part. The amplitude is purely imaginary for $E = E_0$. The phase δ goes from 0 to $\pi/2$ at resonance and to π at high energies.

The N^* and Δ^* Spectrum from Lattice QCD

R. Edwards *et al.*, Phys. Rev. D **84**, 074508 (2011); Phys. Rev. D **87**, 054506 (2013)



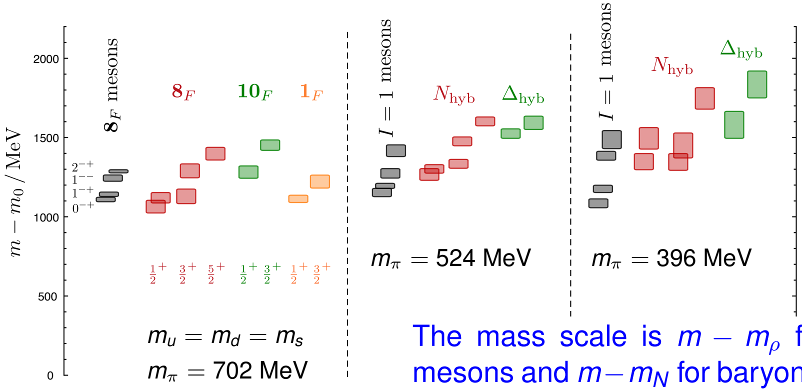
$m_\pi = 396$ MeV

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.

Outline

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

Decays observed in BnGa PWA into, e. g.

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

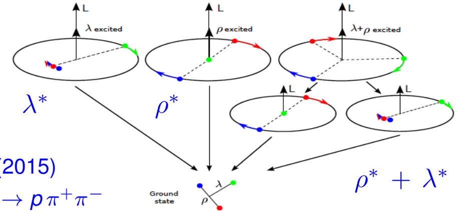
➜ Quartet of $(\mathbf{70},\, 2^+_2)$ with $S = \frac{3}{2}$.

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

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.

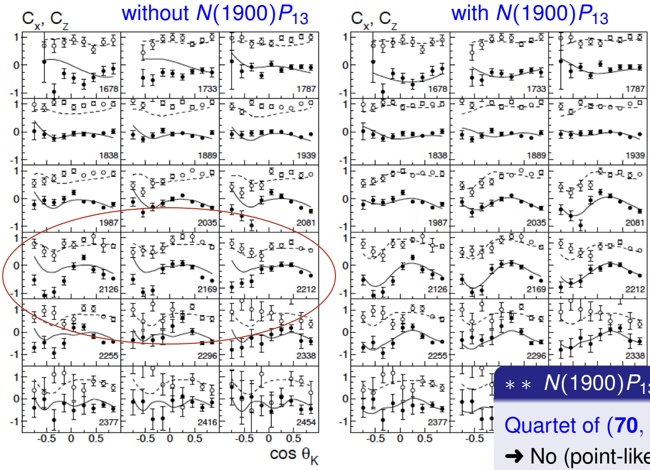


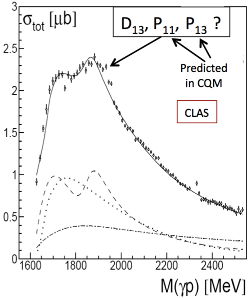
Sokhoyan, Gutz, V. C. *et al.*, EPJ A **51**, no. 8, 95 (2015)

➜ Refit includes CLAS cross-section data on $\gamma p \to p\,\pi^+\pi^-$

(E. Golovatch *et al.*, Phys. Lett. B **788**, 371 (2019))

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 $S = \frac{3}{2}$

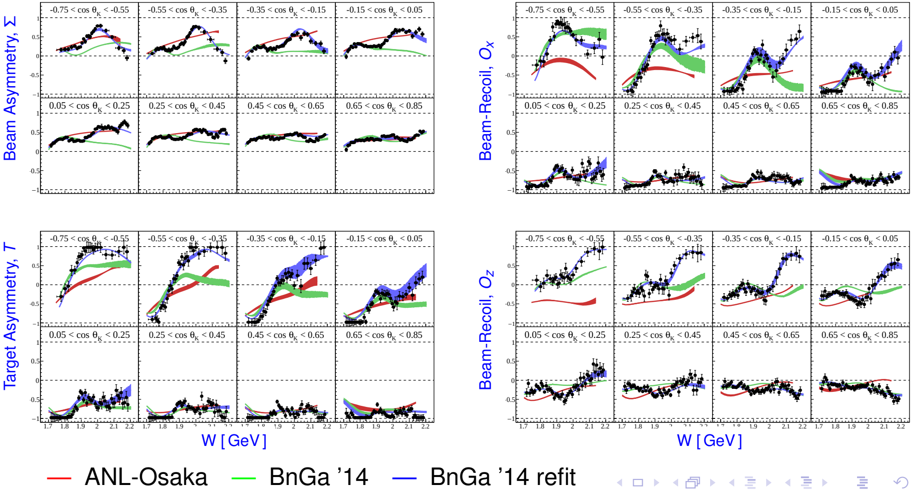
➜ No (point-like) quark-diquark oscillations!

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

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

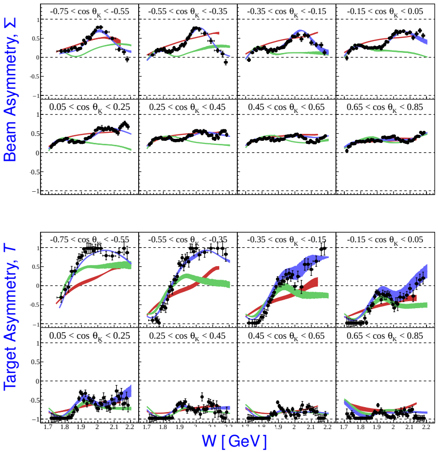
Polarization in $\vec{\gamma} p \to K^+ \vec{\Lambda}$: O_x & O_z + T & Σ

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



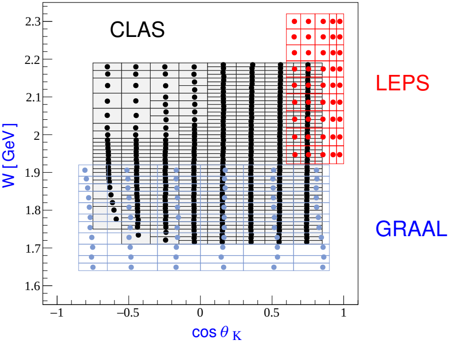
Polarization Observables in $\vec{\gamma} p \to K^+ \Lambda$

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



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

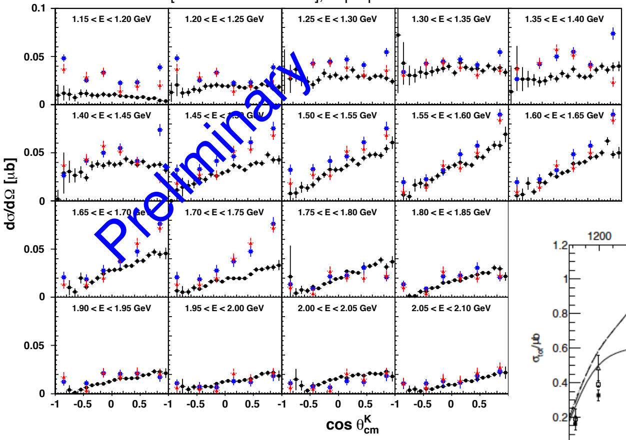
comparison of kinematic coverage



— 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], in preparation.

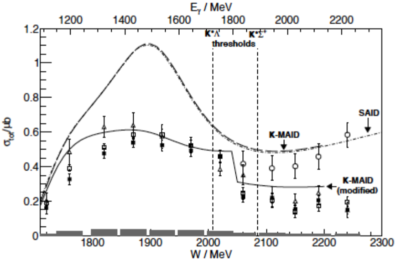


CLAS-g12 • CB-ELSA • CBELSA/TAPS •

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

$$1.15 < E_\gamma < 3.0 \text{ GeV}$$

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) $$- \Lambda_y(-T + \delta_l P \cos 2\phi)$$
in progress $$- \Lambda_z(-\delta_l G \sin 2\phi + \delta_\odot E)\}$$

$\phi = \Psi \equiv$ 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))

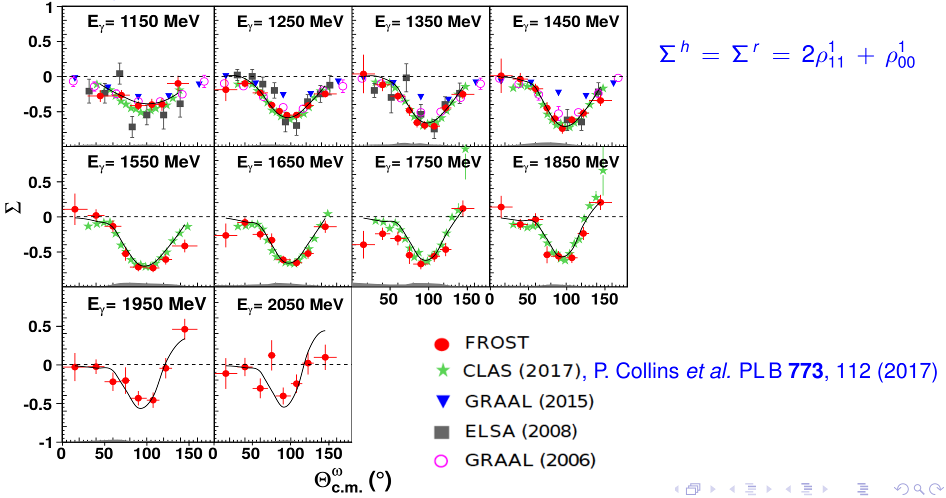
$$2\pi\, W^f(\Phi,\Psi) = 1 - \Sigma^f_\Phi \cos 2\Phi - P_\gamma \Sigma^f_b \cos 2\Psi + P_\gamma \Sigma^f_d \cos 2(\Phi - \Psi)$$

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

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

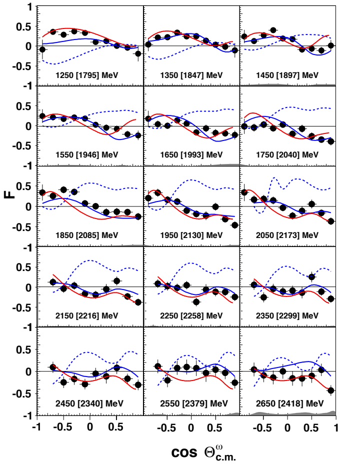
The Beam Asymmetry in $\vec{\gamma}\, p \to p\, \omega$ (CLAS-g9b)

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



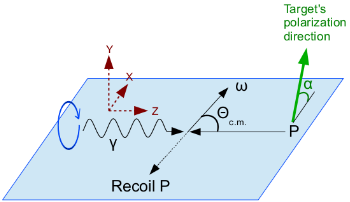
$$\Sigma^h = \Sigma^r = 2\rho^1_{11} + \rho^1_{00}$$

F Observable in $\vec{\gamma}\,\vec{p} \to p\,\omega$ (CLAS g9b)



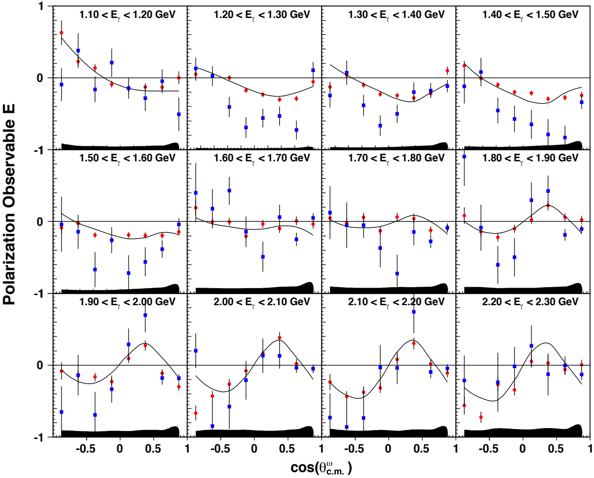
Polarized Cross Section

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



P. Roy *et al.* [CLAS Collaboration], PRL **122**, 162301 (2019)

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)

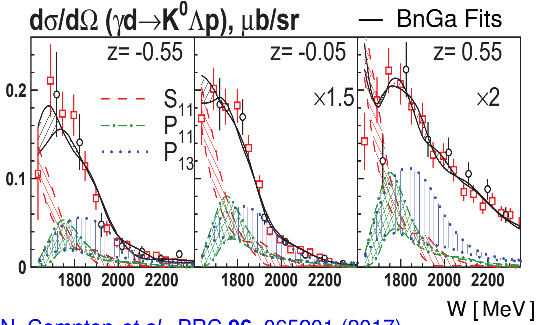
Z. Akbar *et al.* [CLAS Collaboration], PR C **96**, 065209 (2017)

Brief Summary of Measurements off Neutron (CLAS)

$\gamma n \to p\,\pi^-$ σ, E observable (P. T. Mattione *et al.*, Phys. Rev. C **96**, 035204 (2017))

$\gamma n \to K^0\,\Sigma^0$ E observable (D. H. Ho *et al.*, Phys. Rev. C **98**, 045205 (2018))

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

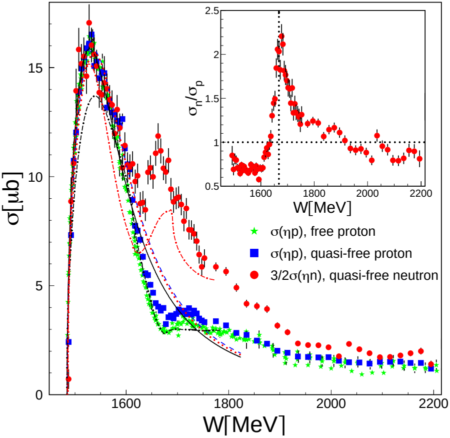


N. Compton *et al.*, PRC **96**, 065201 (2017)

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 $N(2190)\,\frac{7}{2}^-$.

Fascinating Discovery in Reactions off the Neutron



Neutron measurements important:

- Different resonance contributions
- Study of isospin composition of el.-magn. couplings

Narrow structure in $\gamma d \to n\eta + p$ with $M \approx 1670$ MeV and $\sigma = 25$ MeV:

- Interference effect of the $S_{11}(1535)$ and $S_{11}(1535)$ resonances
- Coupled channel effect of $S_{11}(1535)$ and $P_{11}(1710)$
- New narrow state?

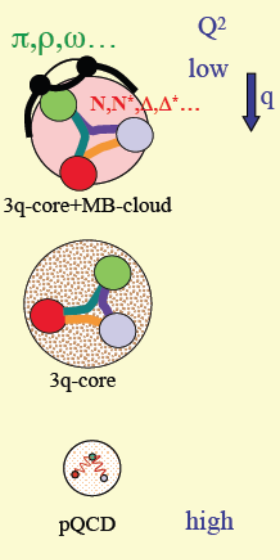
I. Jaegle *et al.* [CBELSA/TAPS], Eur. Phys. J. A **47**, 89 (2011)

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, ...

Outline



The N^* program has two main components:

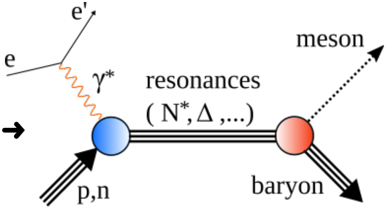
- Establish the systematics of the spectrum

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

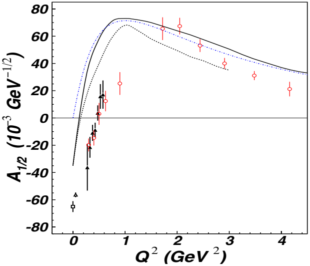
- Probe resonance transitions at different distance scales (Q^2 dependence)

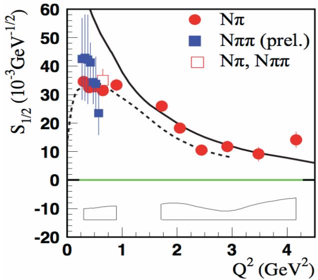
  Reveals the structure of N^* states.

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



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

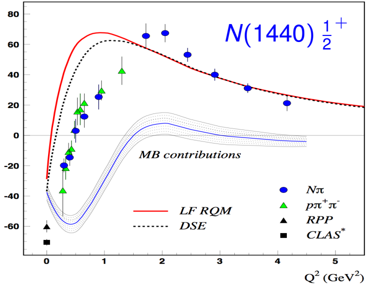
  ➜ ANL - Osaka achieves good description by adding meson-baryon interactions.

  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

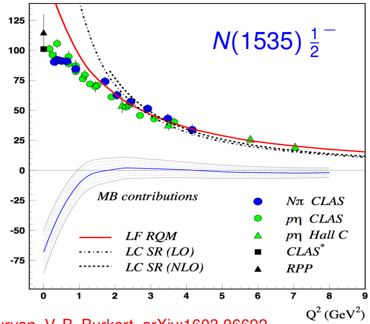


Non-quark contributions are significant at $Q^2 < 2.0$ GeV^2

➜ 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

Outline

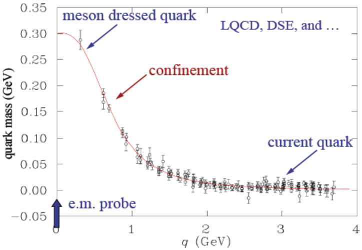
Open Issues in (Light) Baryon Spectroscopy

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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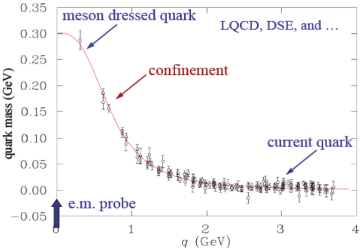
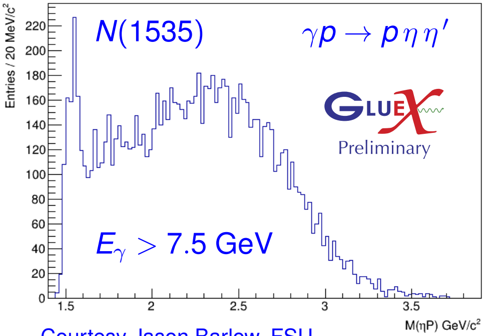


N^* Spectroscopy at GlueX

GlueX is not the ideal experiment for N^* spectroscopy without a polarized target. However,

- N^* resonances are abundantly produced at $E_\gamma > 7$ GeV.
- Interesting program on N^* physics is possible.



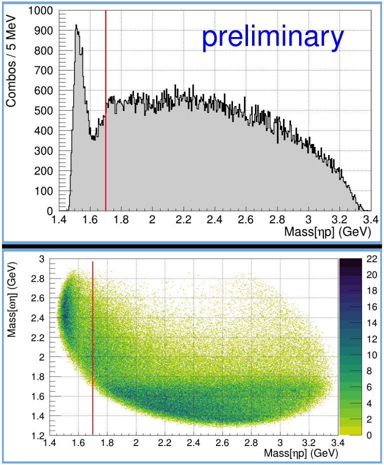
Courtesy Jason Barlow, FSU

Data selection:

- General cuts to improve overall event kinematics (CL, missing mass, etc.).
- No cuts (yet) to enhance $\gamma p \to \eta' \, N(1535)$ production.

Possibly, direct access to $N(1535)\,\frac{1}{2}^-$ due to t-channel production.

N^* Spectroscopy at GlueX



Courtesy Edmundo Barriga, FSU

Reaction: $\gamma p \to p \, \eta \, \omega$

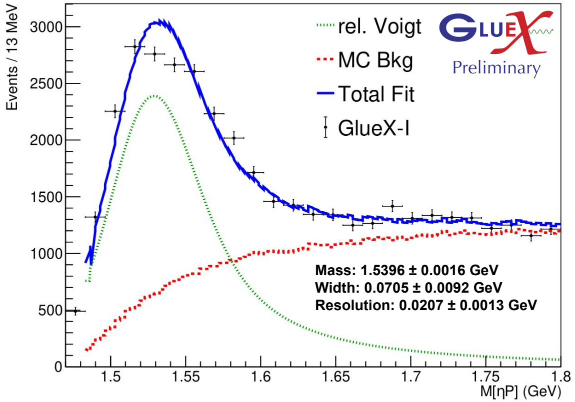
Data selection:

- General cuts to improve overall event kinematics (CL, missing mass, etc.).
- $8.2 \text{ GeV} < E_\gamma < 8.8 \text{ GeV}$
- $-t < 0.6 \text{ GeV}^2$
- No cuts (yet) to enhance $\gamma p \to \omega \, N(1535)$ production.

Possibly, direct access to $N(1535) \, \frac{1}{2}^-$ due to t-channel production.

N^* Spectroscopy at GlueX

V. C. *et al.* [GlueX], Few Body Syst. **64** (2023) 2, 32



Courtesy Edmundo Barriga, FSU

N(1535) BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
125 to 175 (≈ 150) OUR ESTIMATE				
147 ± 5	[6] HUNT	19	DPWA	Multichannel
163 ±25	KASHEVAROV	17	DPWA	$\gamma p \to \eta p, \eta' p$
120 ±10	SOKHOYAN	15A	DPWA	Multichannel
131 ±12	[6] SHKLYAR	13	DPWA	Multichannel
188.4 ± 3.8	[6] ARNDT	06	DPWA	$\pi N \to \pi N, \eta N$
240 ±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
120 ±20	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
128 ±14	ANISOVICH	12A	DPWA	Multichannel
141 ± 4	[6] SHRESTHA	12A	DPWA	Multichannel
182 ±25	BATINIC	10	DPWA	$\pi N \to N\pi, N\eta$
129 ± 8	PENNER	02C	DPWA	Multichannel
95 ±25	BAI	01B	BES	$J/\psi \to p\bar{p}\eta$
143 ±18	THOMPSON	01	CLAS	$\gamma^* p \to p\eta$

Description with rel. Voigtian

Barrier factor of $L = 1$

$\eta\omega$ MC background

$M_{\eta\omega} < 2$ GeV/c^2

➜ $\Gamma = 70.5 \pm 9.2$ MeV

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 $\Sigma^*\,/\,\Lambda^*$ 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 $\Delta^0 - \Delta^{++}$).

Acknowledgement

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