Baryon Spectroscopy: An Experimental Overview

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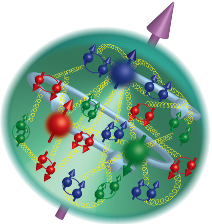

Hadron Spectroscopy: The Next Big Steps

Mainz, Germany

03/23/2022

Outline

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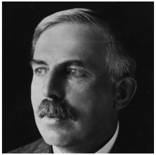
1. Introduction and Motivation
   - Some very brief history ...
   - Strong-Coupling QCD
2. Spectroscopy of Baryon Resonances
   - The Nucleon Spectrum
   - Complete Experiments
3. Experimental Approach and Results
   - Structure of Nucleon Resonances
   - N^* Spectroscopy: Polarization Measurements
   - Spectroscopy of Ξ Resonances
   - Heavy-Flavor Resonances
4. Summary and Conclusions

Particle Zoo



Name “proton” given to H nucleus by Rutherford in 1920

He had discovered earlier that proton was a candidate to be a fundamental particle & building block of nitrogen, and all other heavier atomic nuclei.

1932 Neutron

1947 First Mesons: π^+, π^-, K^+, K^-

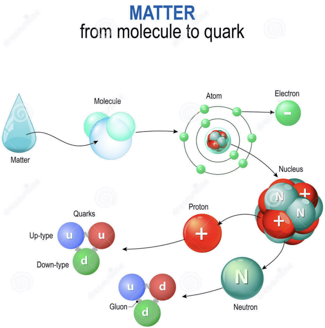
1951 Strange baryons: Λ with $|uds\rangle$

1964 Ω^- with $|sss\rangle$

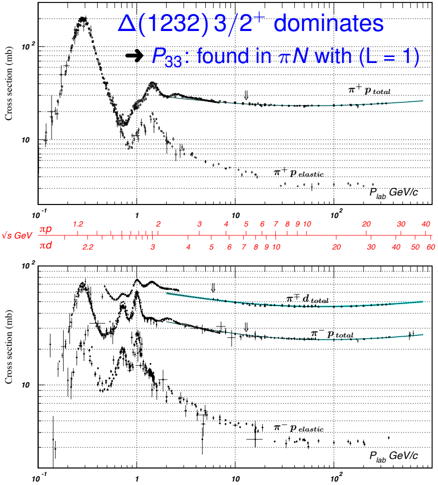
1964 Quark model

1968 Discovery of “partons” at SLAC

after 1970:
Quantum Chromodynamics



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.

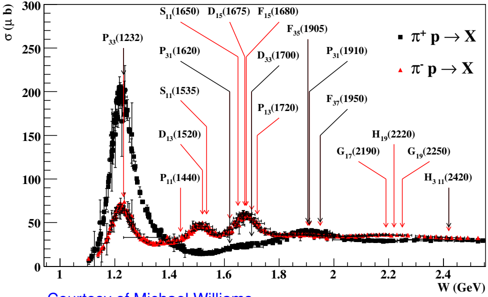
In 1952, first cross-section measurement of $\pi^+ p \to \pi^+ p$ (H. L. Anderson, E. Fermi, E. A. Long, D. E. Nagle, Phys. Rev. 85 (1952) 936).

Baryon Spectroscopy: The Light Flavors

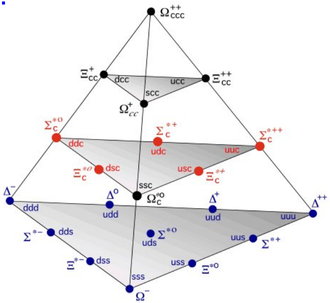
The strong coupling confines quarks and breaks chiral symmetry, and so defines the world of light hadrons.

Baryons are special because

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



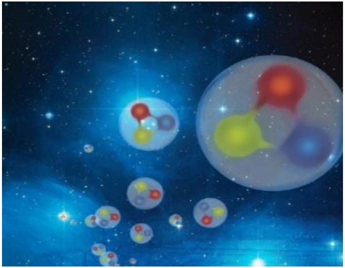
Courtesy of Michael Williams



Many Y^* QN not measured:
(Quark model assignments)

➜ Most Ξ^* and Ω^*, etc.

Non-Perturbative QCD



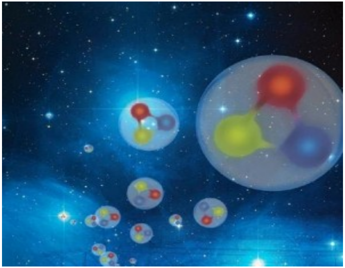
How does QCD give rise to excited hadrons?

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 mesons, and can they help explain quark confinement?

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

Non-Perturbative QCD



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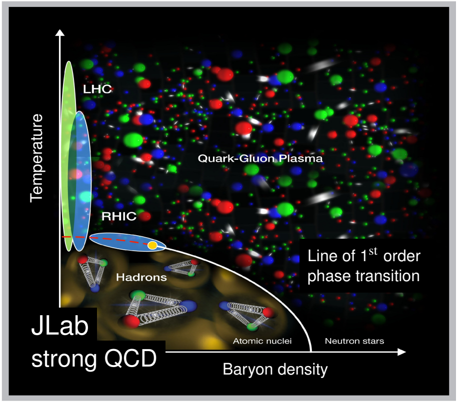
QCD Phases and the Study of Baryon Resonances

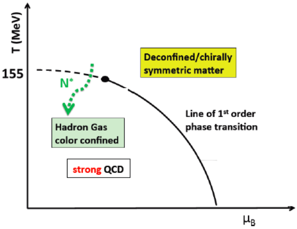


QGP

↓

hadron phase

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

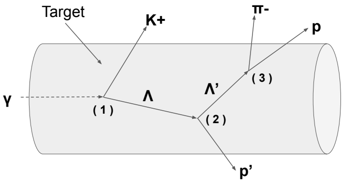


RPP (u, d, s, c) baryons not sufficient to describe freeze-out behavior.
(e. g. A. Bazavov *et al.*, PRL **113** (2014) 7, 072001)

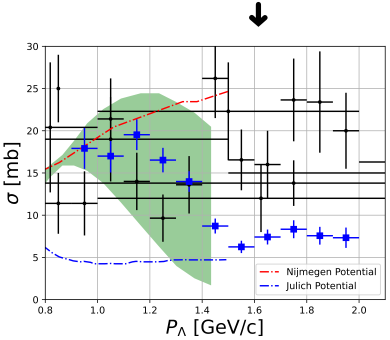
Connections to the Neutron Star Equation of State

Measurement of the $\Lambda p \to \Lambda p$ Elastic Scattering Cross Sections

(J. Rowley *et al.* [CLAS Collaboration], Phys. Rev. Lett. **127**, 272303 (2021))



likely: $\Lambda p \to \Lambda(1520) p$



Major challenges

- Preparation of a secondary beam of Λ baryons
- Estimate of Λ beam luminosity

➜ Measurements possible at GlueX for Λp and Ξp.

Outline

Spectrum of N^* Resonances

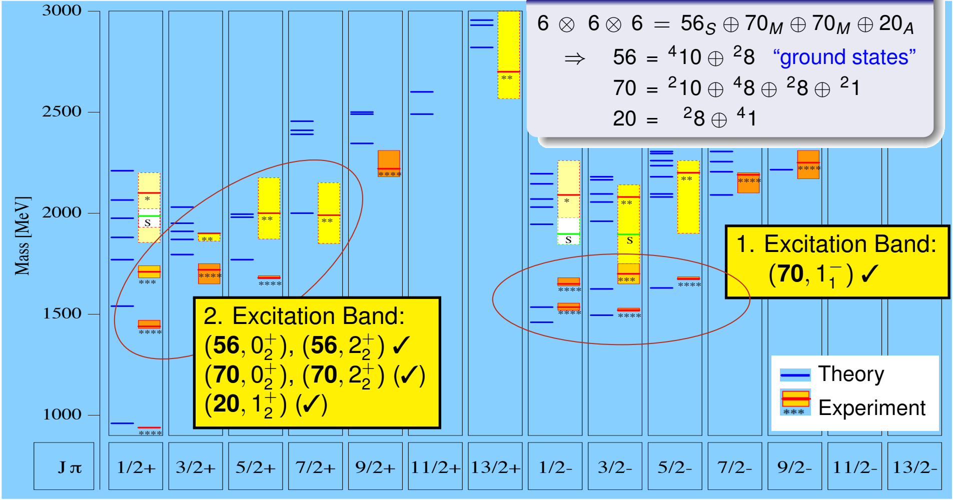
SU(6) ($^{2S+1}$multiplets; u, d, s, spin)

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

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

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

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



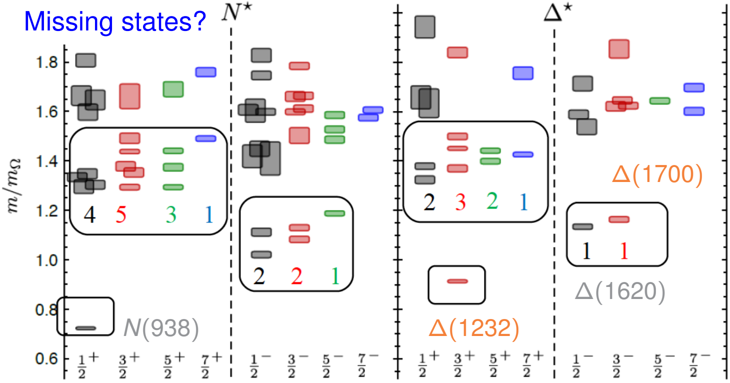
1. Excitation Band: $(\mathbf{70}, 1_1^-)$ ✓

2. Excitation Band:
$(\mathbf{56}, 0_2^+)$, $(\mathbf{56}, 2_2^+)$ ✓
$(\mathbf{70}, 0_2^+)$, $(\mathbf{70}, 2_2^+)$ (✓)
$(\mathbf{20}, 1_2^+)$ (✓)

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

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.

From the Atomic Spectrum of Hydrogen ...

Development of the theory of atomic structure required

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

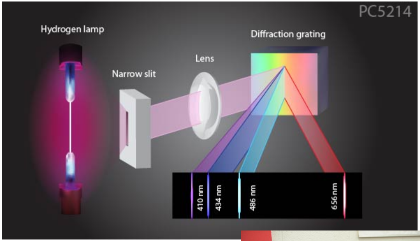
Bohr model ➜ QED

Understanding the nucleon requires

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

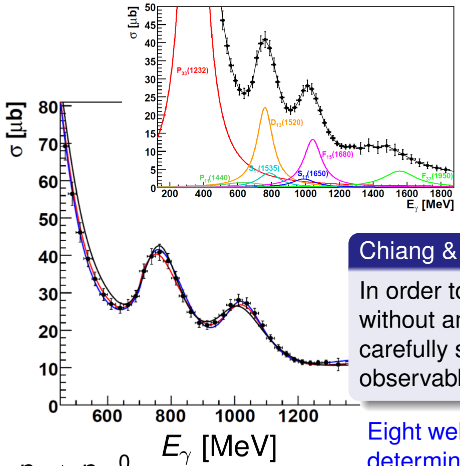
Quark model ➜ strong QCD

Atomic Spectrum of Hydrogen



Baryons are broad and overlapping ...

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.

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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, J-PARC

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

2. Collider Experiments

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

   e.g. $\Xi_c^+ \to (\Xi^-\pi^+)_{\Xi^*}\pi^+$ (Belle) or $e^+e^- \to J/\psi \to N^*\bar{N}$ (BES III)

   at pp machines, e.g. LHC

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

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   $\pi\,/\,K$-induced production, e.g. HADES@GSI, J-PARC

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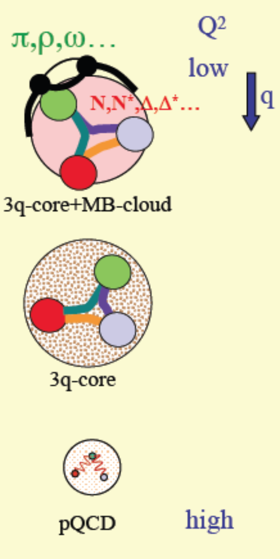


The N^* program has two main components:

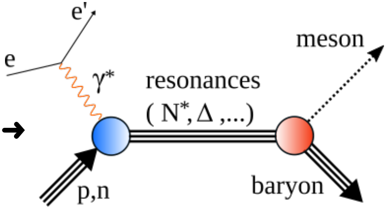
- Establish the systematics of the spectrum

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

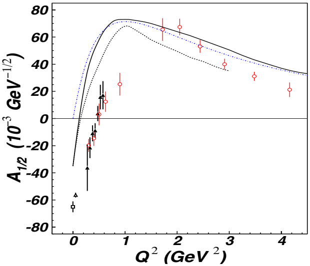
- Probe resonance transitions at different distance scales (Q^2 dependence)

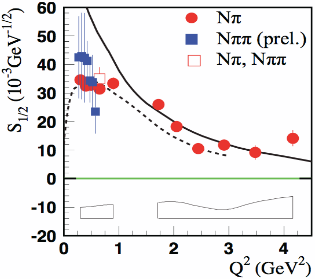
  Reveals the structure of N^* states.

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



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

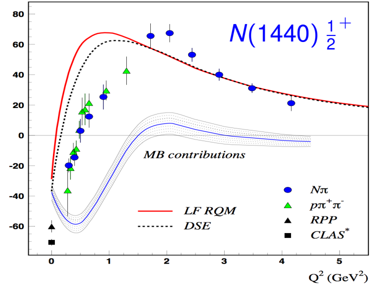
Consistency between both channels ($N\pi\pi$, $N\pi$): sign change, magnitude, ...

- 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

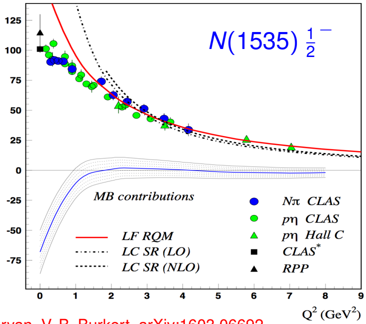


Non-quark contributions are significant at $Q^2 < 2.0$ GeV^2

➜ 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

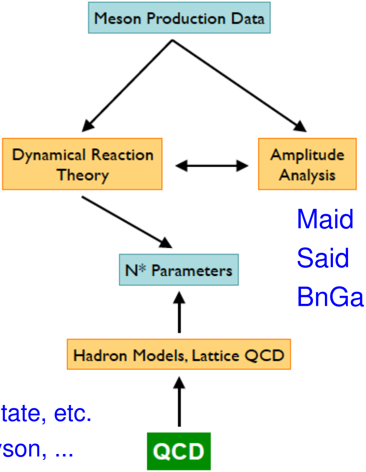
➜ State consistent with the 1st orbital excitation of the nucleon.



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

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.



Maid
Said
BnGa

Coupled Channels

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

Table representing CLAS@JLab measurements

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

	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)

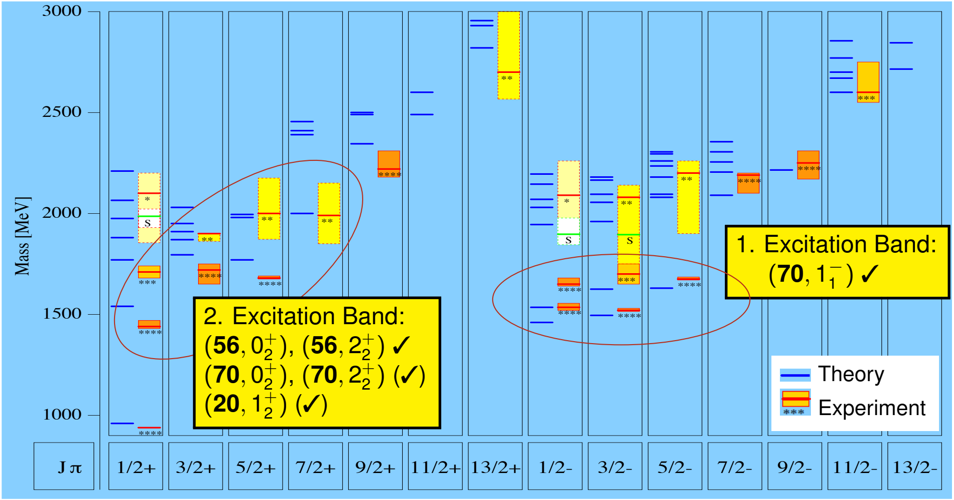
Tensor polarization, SDMEs

* published

In addition, two-meson reactions are being analyzed:

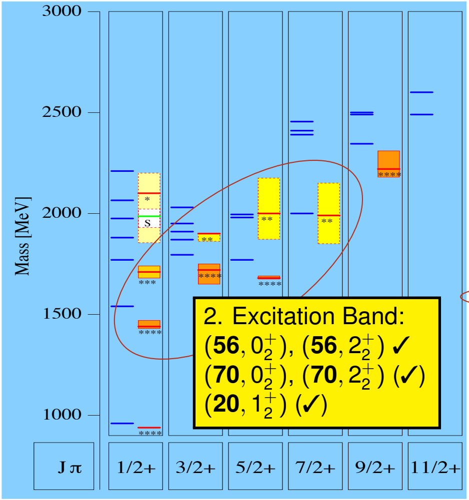
$$\gamma p \to (p\,\rho) \to p\,\pi^+\pi^- \text{ (CLAS)}, \quad \gamma p \to p\,\pi^0\pi^0, \quad p\,\pi^0\eta, \quad p\,\pi^0\omega \text{ (ELSA, MAMI, etc.)}$$

Spectrum of N^* Resonances



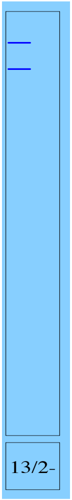
S. Capstick & N. Isgur, Phys. Rev. **D34** (1986) 2809

Spectrum of N^* Resonances

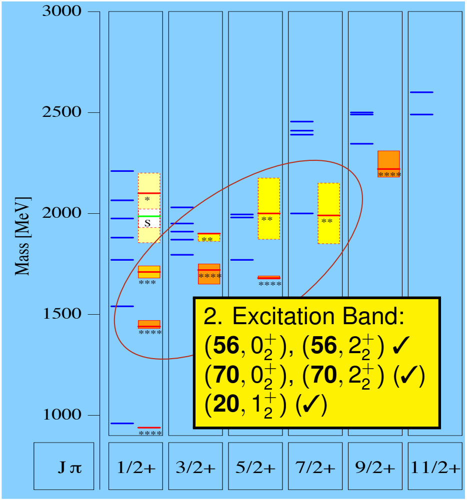


V. C. & W. Roberts, Rep. Prog. Phys. **76** (2013)

N^*	J^P $(L_{2I,2J})$	2010	2019
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}	**	



Spectrum of N^* Resonances

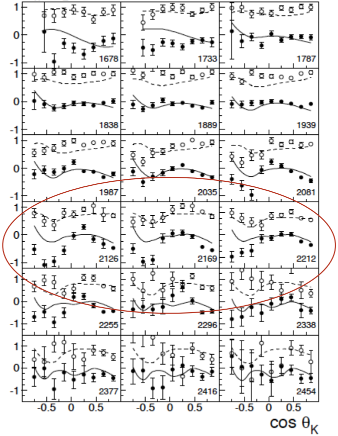


N	(D, L_N^P)	S	J^P	Octet Members				Singlets
0	$(56, 0_0^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	–
1	$(70, 1_1^-)$	$\frac{1}{2}$	$\frac{1}{2}^-$	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(1690)$	$\Lambda(1405)$
			$\frac{3}{2}^-$	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
		$\frac{3}{2}$	$\frac{1}{2}^-$	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$		–
			$\frac{3}{2}^-$	$N(1700)$				–
			$\frac{5}{2}^-$	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$		–
2	$(56, 0_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$		–
	$(70, 0_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(1710)$	$\Lambda(1810)^\dagger$	$\Sigma(1770)^\dagger$		
		$\frac{3}{2}$	$\frac{3}{2}^+$					–
	$(56, 2_2^+)$	$\frac{1}{2}$	$\frac{3}{2}^+$	$N(1720)^\dagger$	$\Lambda(1890)^\dagger$	$\Sigma(1840)^\dagger$		–
			$\frac{5}{2}^+$	$N(1680)$	$\Lambda(1820)^\dagger$	$\Sigma(1915)^\dagger$		–
	$(70, 2_2^+)$	$\frac{1}{2}$	$\frac{3}{2}^+$					
			$\frac{5}{2}^+$	$N(1860)$				
		$\frac{3}{2}$	$\frac{1}{2}^+$	$N(1880)$				–
			$\frac{3}{2}^+$	$N(1900)^\dagger$		$\Sigma(2080)^\dagger$		–
			$\frac{5}{2}^+$	$N(2000)$	$\Lambda(2110)^\dagger$	$\Sigma(2070)^\dagger$		–
			$\frac{7}{2}^+$	$N(1990)$	$\Lambda(2020)$	$\Sigma(2030)^\dagger$		–
	$(20, 1_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(2100)^\dagger$				
			$\frac{3}{2}^+$	$N(2040)^\dagger$				
			$\frac{5}{2}^+$	–	–	–	–	

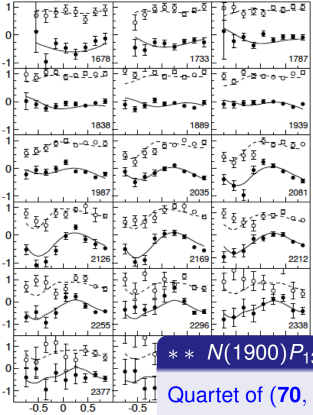
V. C. & W. Roberts, Rep. Prog. Phys. **76** (2013)

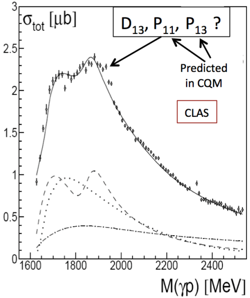
Polarization Transfer in $\vec{\gamma} p \to K^+ \vec{\Lambda}$: C_x & C_z

without $N(1900)P_{13}$



with $N(1900)P_{13}$





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

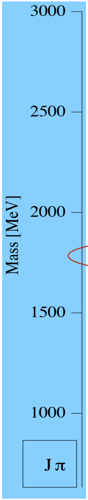
Quartet of $(\mathbf{70}, 2_2^+)$ with $S = \frac{3}{2}$

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

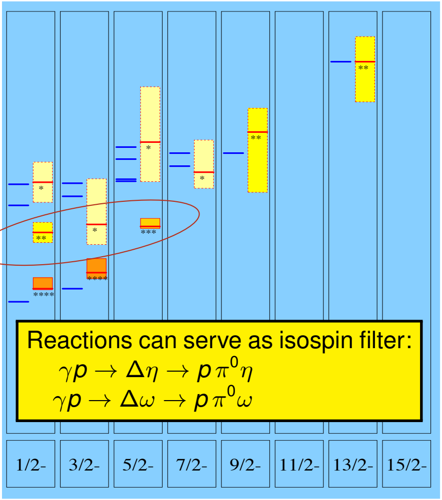
R. Bradford *et al.* [CLAS Collaboration], PRC **75**, 035205 (2007)

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

Spectrum of Δ^* Resonances

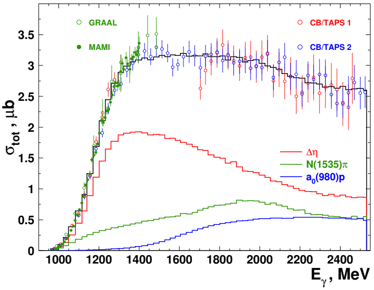


Δ^*	J^P $(L_{2I,2J})$	2010	2014
$\Delta(1232)$	$3/2^+$ (P_{33})	$****$	$****$
$\Delta(1600)$	$3/2^+$ (P_{33})	$***$	$***$
$\Delta(1620)$	$1/2^-$ (S_{31})	$****$	$****$
$\Delta(1700)$	$3/2^-$ (D_{33})	$****$	$****$
$\Delta(1750)$	$1/2^+$ (P_{31})	$*$	$*$
$\Delta(1900)$	$1/2^-$ (S_{31})	$**$	$**$
$\Delta(1905)$	$5/2^+$ (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

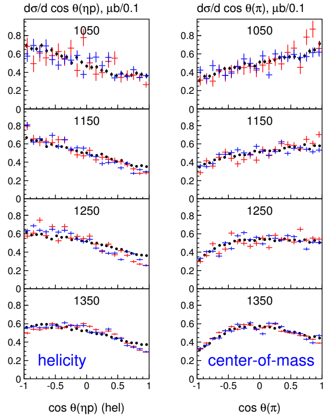
$\Delta(1232)\eta$, $N(1535)\,\frac{1}{2}^-\pi$, $pa_0(980)$

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

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

Decays observed in BnGa PWA into, e. g.

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

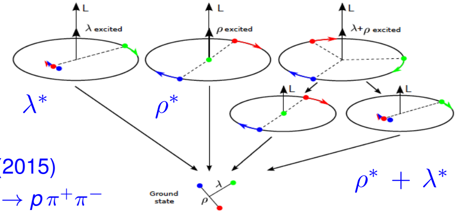
➜ Quartet of $(\mathbf{70}, 2_2^+)$ with $S = \frac{3}{2}$.

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.



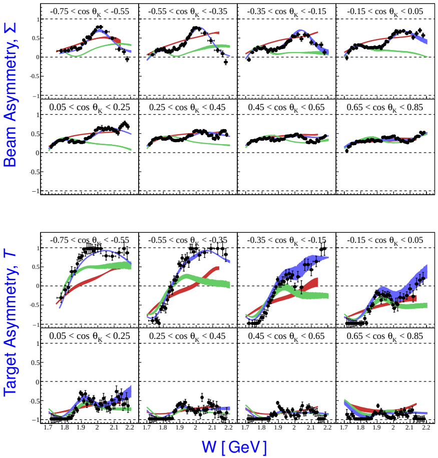
Sokhoyan, Gutz, V. C. *et al.*, EPJ A **51**, no. 8, 95 (2015)

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

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

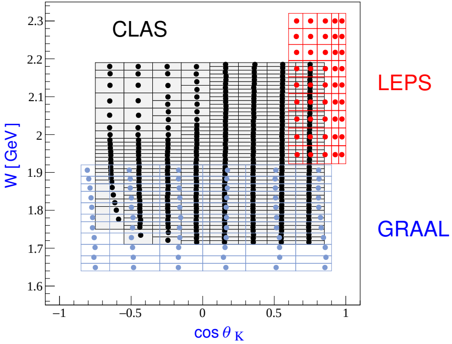
Polarization Observables in $\vec{\gamma} p \to K^+ \Lambda$ (CLAS g8b)

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



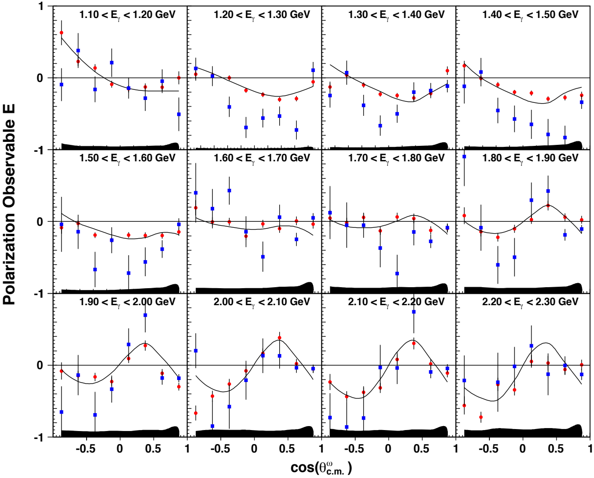
➜ Additional $N^* \frac{3}{2}^+$, $N^* \frac{5}{2}^+$ needed in BnGa refit.

comparison of kinematic coverage



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

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)

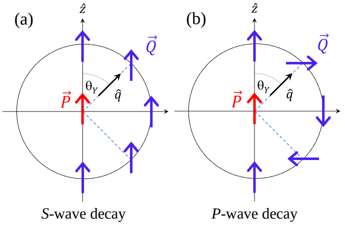
Z. Akbar *et al.* [CLAS Collaboration], PR C **96**, 065209 (2017)

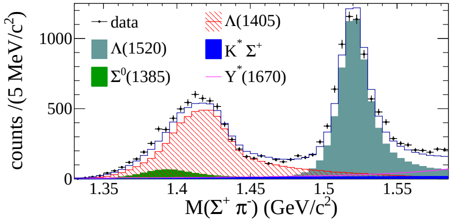
Spin and Parity Measurement of the $\Lambda(1405)$ Baryon

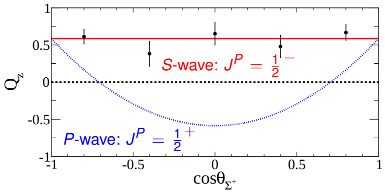
K. Moriya *et al.* [CLAS Collaboration], Phys. Rev. Lett. **112**, 082004 (2014)

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







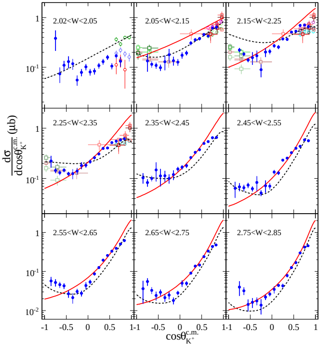
The $\Lambda(1405)/\Lambda(1520)$ Baryons at GlueX

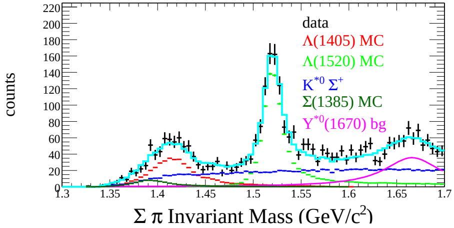
1. Measurement of the $\Sigma\pi$ photoproduction line shapes near the $\Lambda(1405)$
   K. Moriya *et al.* [CLAS Collaboration] Phys. Rev. C **87**, no. 3, 035206 (2013)

   More coming from GlueX on $\Lambda(1405) \to \Sigma^0\pi^0$

The $\Lambda(1405)/\Lambda(1520)$ Baryons at GlueX

1. **Measurement of the $\Sigma\pi$ photoproduction line shapes near the $\Lambda(1405)$**
   K. Moriya *et al.* [CLAS Collaboration] Phys. Rev. C **87**, no. 3, 035206 (2013)
2. **Differential Cross Sections for $\gamma p \to \Sigma^0(1385)$, $\Lambda(1405)$, and $\Lambda(1520)$**
   K. Moriya *et al.* [CLAS Collaboration] Phys. Rev. C **88**, 045201 (2013)

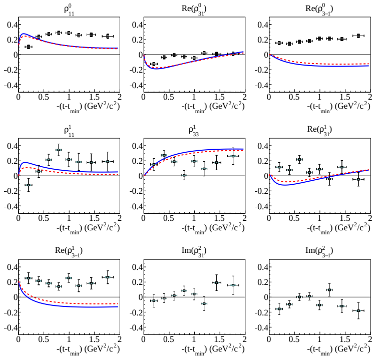


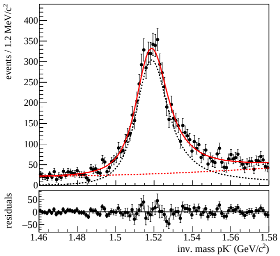


$\gamma p \to \Lambda(1520)$

The $\Lambda(1405)/\Lambda(1520)$ Baryons at GlueX

- Measurement of the $\Sigma\pi$ photoproduction line shapes near the $\Lambda(1405)$
  K. Moriya *et al.* [CLAS Collaboration] Phys. Rev. C **87**, no. 3, 035206 (2013)
- Measurement of SDMEs in $\Lambda(1520)$ photoproduction at 8.2–8.8 GeV
  S. Adhikari *et al.* [GlueX Collaboration] Phys. Rev. C **105**, no. 3, 035201 (2022)



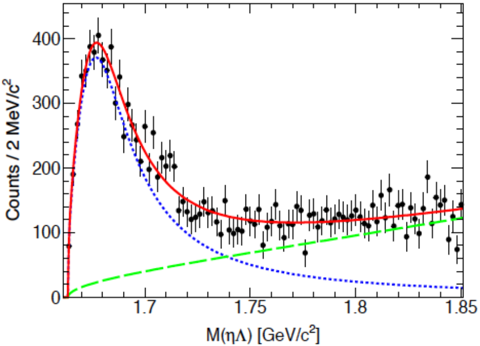


$-(t - t_0) \in [\,0.3, 0.5\,]$ GeV^2

Spectroscopy of Excited Λ^* Baryons

First direct mass and width determination for the Λ(1670)

[Belle Collaboration] Phys. Rev. D **103**, no. 5, 052005 (2021)



Resonances	Mass [MeV/c^2]	Width [MeV]
Λ(1670)	$1674.3 \pm 0.8 \pm 4.9$	$36.1 \pm 2.4 \pm 4.8$
$\Sigma(1385)^+$	$1384.8 \pm 0.3 \pm 1.4$	$38.1 \pm 1.5 \pm 2.1$

all PDG listings based on PWA

Spectroscopy of Excited Λ^* Baryons

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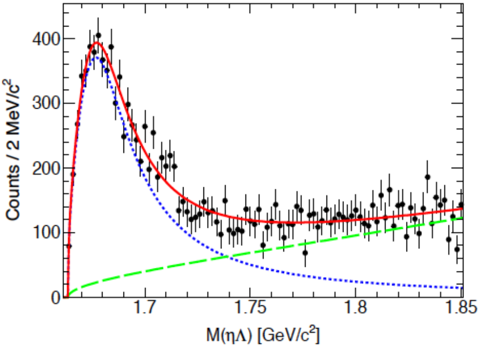
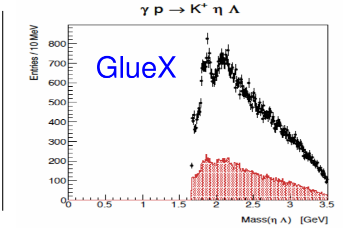
[Belle Collaboration] Phys. Rev. D **103**, no. 5, 052005 (2021)





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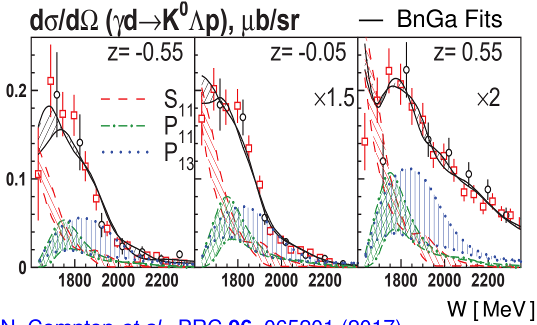
all PDG listings based on PWA

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

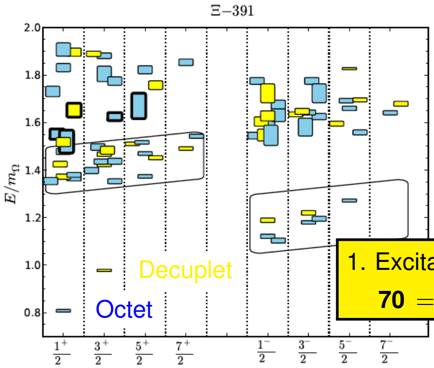
The impact of photoproduction on baryon resonances		Decay modes of nucleon resonances		
	black:	PDG 2004	****	Existence is certain.
	red:	PDG 2018	***	Existence is very likely.
	blue:	BESIII resonances	**	Evidence of existence is fair.
			*	Evidence of existence is poor.

		overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta\prime$	$N_{1440}\pi$	$N_{1520}\pi$	$N_{1535}\pi$	$N_{1680}\pi$
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, ...

The Ξ^* and Ω^* Spectrum from Lattice QCD

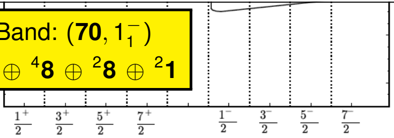
R. Edwards *et al.*, PRD **87**, 054506 (2013)



$\Xi(1320)$	****	$\to \Lambda\pi$	$I\,(J^P) = \frac{1}{2}\left(\frac{1}{2}^+\right)$
$\Xi(1530)$	****	$\to \Xi\pi$	$I\,(J^P) = \frac{1}{2}\left(\frac{3}{2}^+\right)$
$\Xi(1620)$	*	$\to \Xi\pi$?	$I\,(J^P) = \frac{1}{2}\left(\frac{1}{2}^+ \text{ or } \frac{1}{2}^+\right)$
$\Xi(1690)$	***		$I\,(J^P) = \frac{1}{2}\left(\frac{1}{2}^- ?\right)$
$\Xi(1820)$	***	$\to \Lambda\overline{K}$	$I\,(J^P) = \frac{1}{2}\left(\frac{3}{2}^-\right)$
$\Xi(1950)$	***		$I\,(J^P) = \frac{1}{2}\left(\frac{3}{2}^- ?\right)$
$\Xi(2030)$	***	$\to Y\overline{K}$	$I\,(J^P) = \frac{1}{2}\left(\geq \frac{5}{2}^?\right)$

1. Excitation Band: $(\mathbf{70}, 1_1^-)$

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



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

➜ Counting of states of each flavor and spin consistent with QM for the lowest negative- and positive-parity bands.

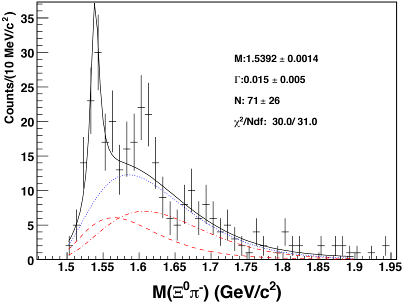
CLAS g11a: Excited States in $\gamma p \to K^+ K^+ \pi^- (X)$

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.*
Phys. Rev. C **76**, 025208 (2007)

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

➜ CLAS 12 and GlueX at Jefferson Lab



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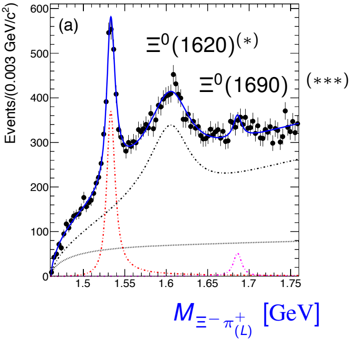
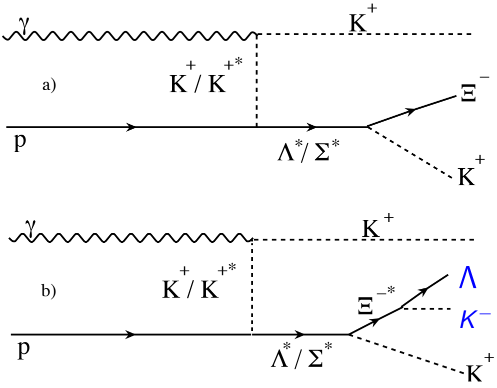
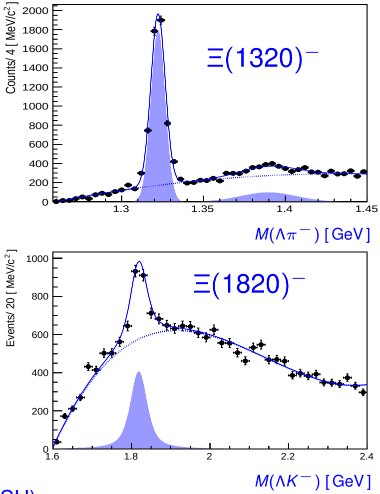
Belle: PRL **122**, 072501 (2019)



Possible Production Mechanisms

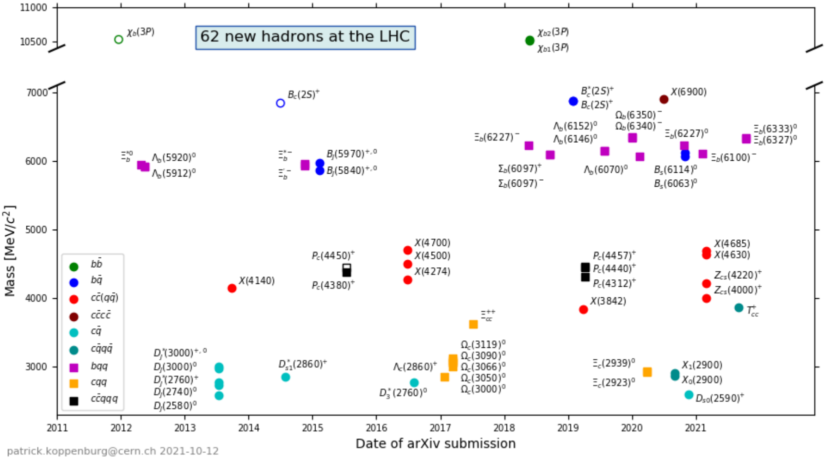


$$\gamma p \to K^+ (K^+ \Xi^{-*}) \to K^+ (p \pi^- K^-) K^+$$



Courtesy of Jesse Hernandez, Chandra Akondi (FSU)

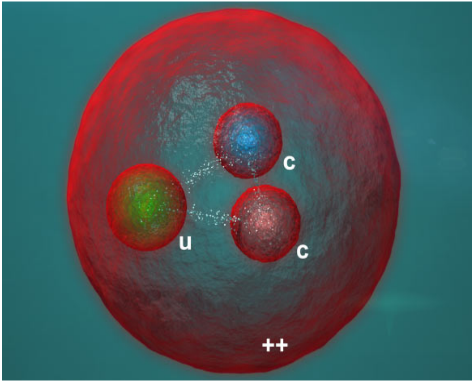
Peak Hunting for Heavy-Flavor States

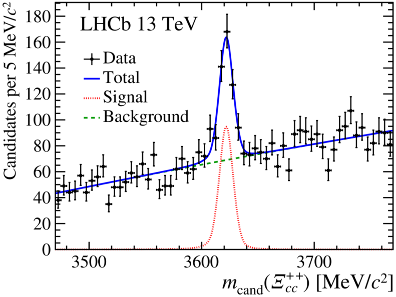


https://www.nikhef.nl/ pkoppenb/particles.html

Doubly-Heavy (Charmed) Resonances

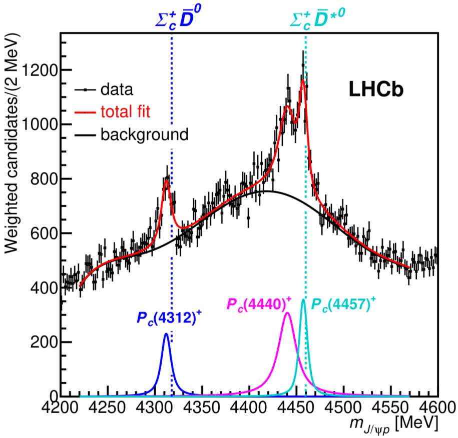
2017: The LHCb (Large Hadron Collider beauty) collaboration at CERN's Large Hadron Collider in Switzerland has reported the observation of a doubly charmed particle, $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$.





R. Aaij *et al.*, PRL **119** (2017) 112001

Observation of a Narrow Pentaquark State



A narrow pentaquark state, $P_c(4312)^+$, decaying to $J/\psi\, p$ was discovered by the LHCb Collaboration with statistical significance of 7.3σ in a data sample of $\Lambda_b^0 \to (J/\psi\, p)\, K^-$ decays.

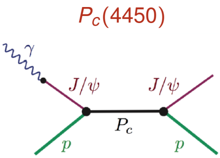
A higher-mass $P_c(4450)^+$ pentaquark structure formerly reported by LHCb confirmed and observed to consist of two narrow overlapping peaks, $P_c(4440)^+$ and $P_c(4457)^+$.

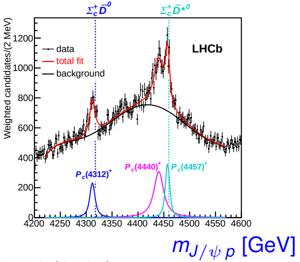
R. Aaij *et al.*, PRL **122**, 222001 (2019)

J/ψ Photoproduction Near Threshold

Photoproduction of J/ψ (near threshold) provides clean laboratory to study $c\bar{c}$:

- Probes gluon distribution in proton
- Sensitive to multi-quark correlations
- Intriguing possibility of five-quark interaction





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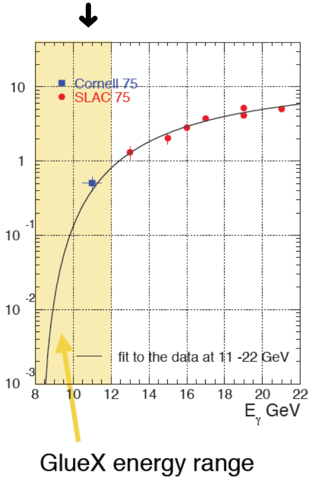
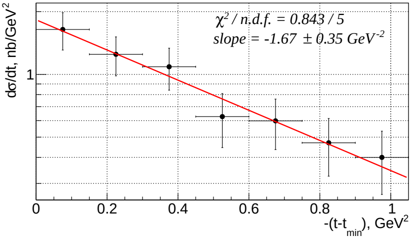
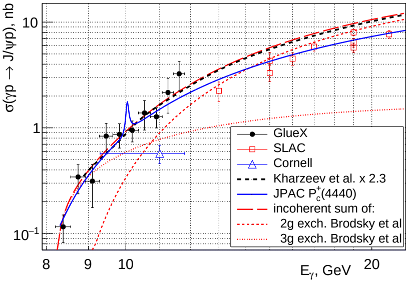


Observation of J/ψ at GlueX

A. Ali *et al.* [GlueX], Phys. Rev. Lett. **123**, no.7, 072001 (2019)





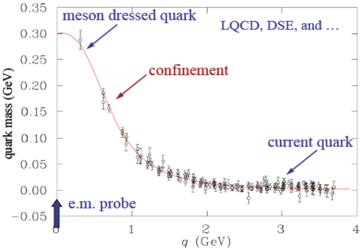
First observation of J/ψ at Jefferson Lab in $\gamma p \to p\, J/\psi \to p\, e^+ e^-$

- First detailed look at cross section near threshold
- Measurement of t slope (at 10.7 GeV avg. E_γ): (-1.67 ± 0.39) GeV^{-2}
- Limits on pentaquark production

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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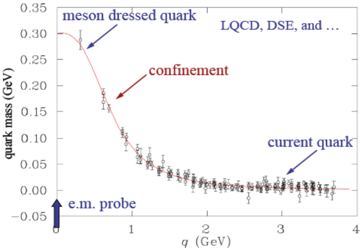

Summary and Conclusions

Quantum Chromodynamics (QCD) is (most likely) the correct theory of strong interactions. However, the theory remains still fairly untested and not very well understood at low energies (spectra and properties of hadrons).

Hadron spectroscopy is a powerful tool to scrutinize ideas on the effective degrees of freedom that govern hadron dynamics.

- QCD-inspired models have been very successful at describing the overall features of the spectrum of mesons and baryons, and also their decays, form factors, transition form factors, magnetic moments, etc.
- However, these models have also exhibited important failures:
  - Link between partonic degrees of freedom seen in deep inelastic scattering and constituent quarks remains poorly understood.
  - Experiments have yet to provide compelling evidence for gluonic excitations (glueballs, hybrids, etc.)