(Highlights in) Light-Baryon Spectroscopy

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Outline

1. Introduction
   - The Spectrum of Hadrons: Baryons and Mesons
2. Spectroscopy of Baryon Resonances
   - Complete Experiments
   - Polarization Observables in $\gamma p \to N\pi$
   - Polarization Observables in $\gamma p \to p\omega$
3. Decay Cascades of Excited Baryons
4. Summary and Outlook
   - Are we there yet?
   - Open Issues in Light Baryon Spectrosocpy
   - Summary and Outlook

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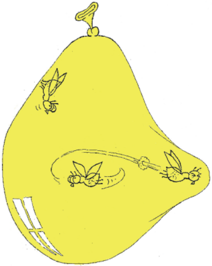
Strong-Coupling Quantum Chromodynamics (QCD)

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \bar{q}\,(i\gamma_\mu D^\mu - m_q)\,q - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

QCD is the theory of the strong nuclear force which describes the interactions of quarks and gluons making up hadrons.

Strong processes at larger distances and at small (soft) momentum transfers belong to the realm of non-perturbative QCD.



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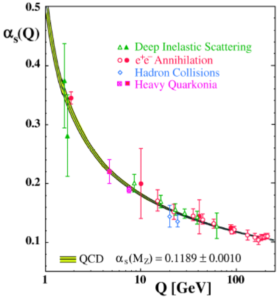
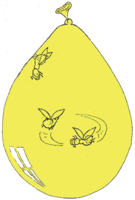
Confinement

"Strong QCD"



"pQCD"



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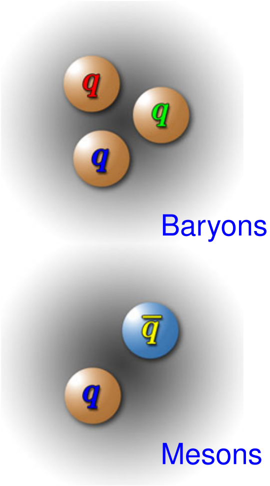
Asymptotic Freedom

Hadrons: Baryons & Mesons

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

Baryons are special because

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



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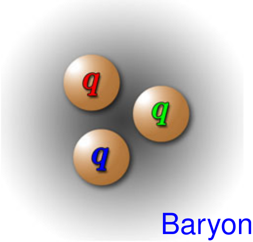
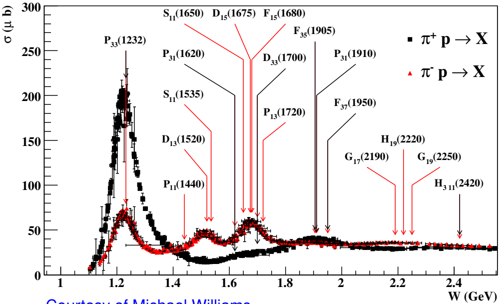


Baryons



Courtesy of Michael Williams

➜ PDG 2010, J. Phys. GG 37.

Great progress in recent years:

➜ γN & πN data

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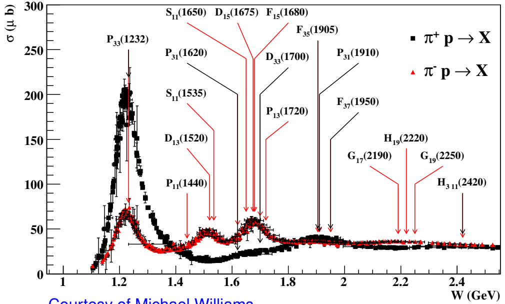
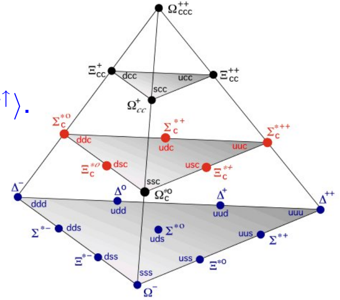


Courtesy of Michael Williams



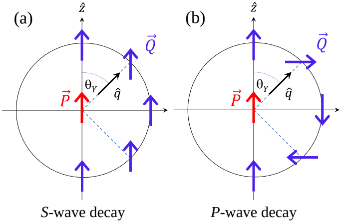
Many Y^* QN not measured:
(Quark model assignments)
➜ many Ξ^* and Ω^*, etc.

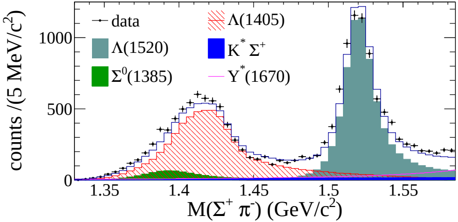
Spin and Parity Measurement of the $\Lambda(1405)$ Baryon

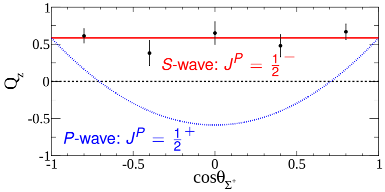
K. Moriya *et al.* [CLAS Collaboration], Phys. Rev. Lett. **112**, 082004 (2014)

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

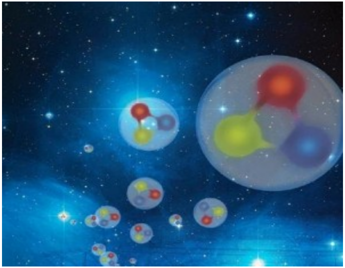
- Decay distribution of $\Lambda(1405) \to \Sigma^+\pi^-$ consistent with $J = 1/2$.
- Polarization transfer, $\vec{Q}$, in $Y^* \to Y\pi$:
  - S-wave decay: $\vec{Q}$ independent of θ_Y







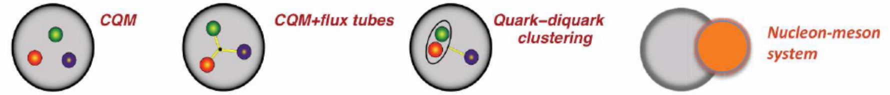
Non-Perturbative QCD



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?



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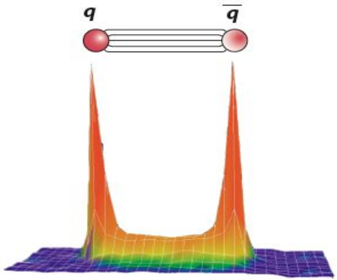

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Mesons: What are the properties of the predicted states beyond simple quark-antiquark systems (hybrid mesons, glueballs, ...)?

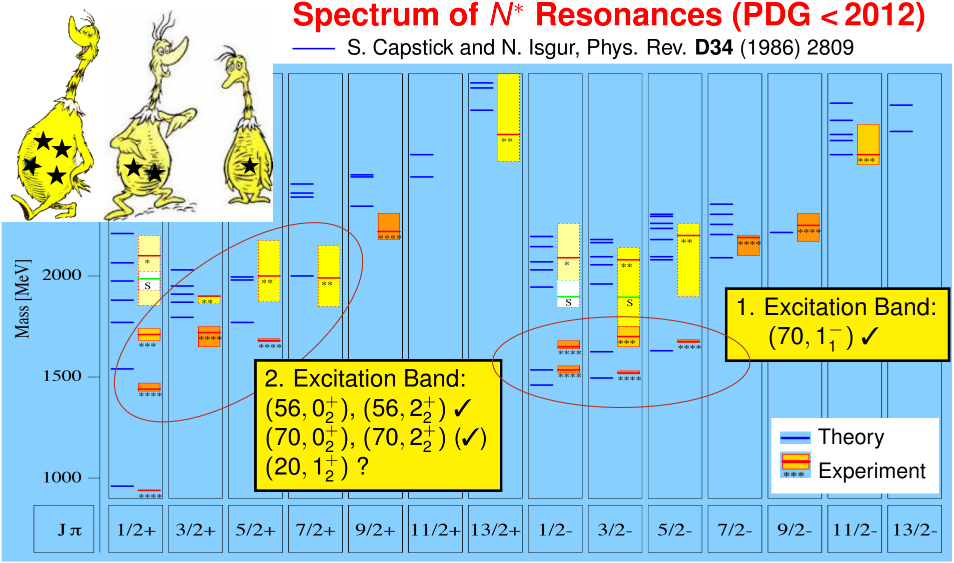
➜ Gluonic Excitations provide a measurement of the excited QCD potential.

Hybrid baryons are possible but do not carry “exotic” quantum numbers.

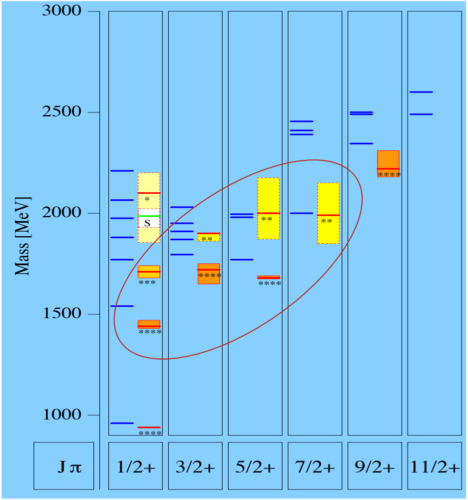
➜ Boris Grube: *Light Meson Spectroscopy* (Tuesday)

Spectrum of N^* Resonances (PDG < 2012)

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

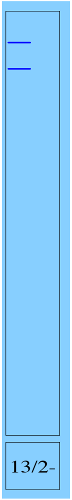


Spectrum of N^* Resonances



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

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



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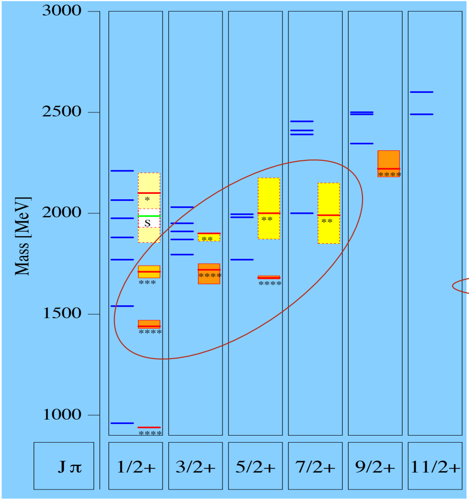
Spectrum of N^* Resonances



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$N(1680)$	$5/2^+$ (F_{15})	∗∗∗∗	∗∗∗∗
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$N(1875)$	$3/2^-$		∗∗∗
$N(1880)$	$1/2^+$		∗∗
$N(1895)$	$1/2^-$		∗∗
$N(1900)$	$3/2^+$ (P_{13})	∗∗	∗∗∗
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~~$N(2080)$~~	D_{13}	∗∗	
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$N(2120)$	$3/2^-$		∗∗
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~~$N(2200)$~~	D_{15}	∗∗	
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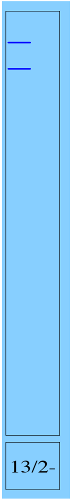
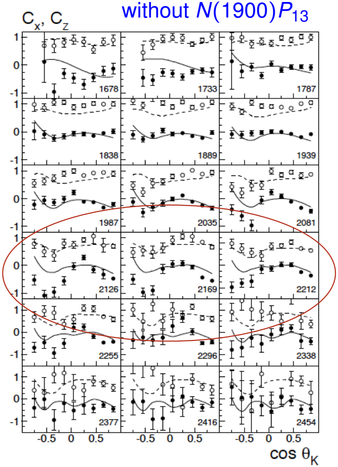
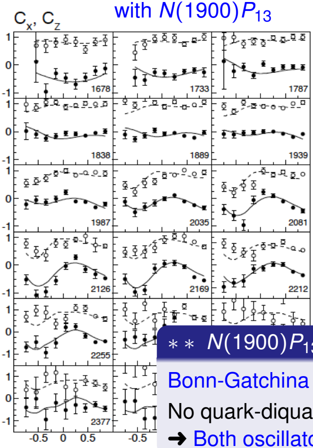


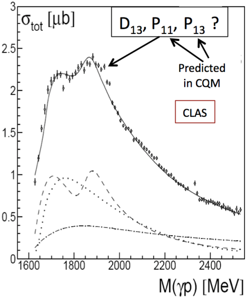
Polarization Transfer in $\vec{\gamma} p \to K^+ \vec{\Lambda}$: C_x, C_z

without $N(1900)P_{13}$



with $N(1900)P_{13}$





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

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

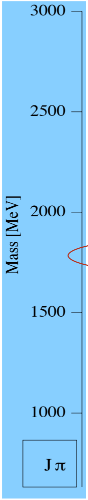
No quark-diquark oscillations!

➜ Both oscillators need to be excited.

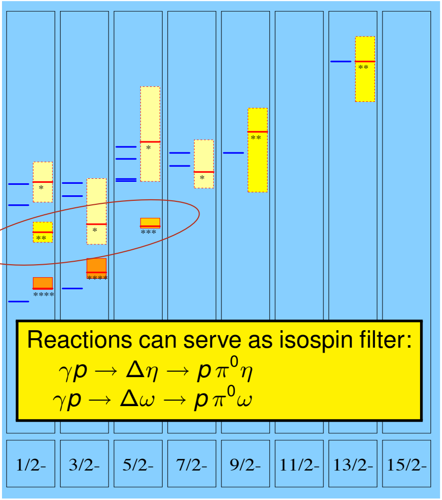
R. Bradford *et al.* [CLAS Collab.], PRC **75**, 035205 (2007)

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



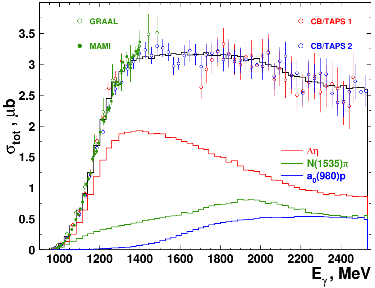
Reactions can serve as isospin filter:

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

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

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

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



Dominant Isobars

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

Observation of some

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

Bonn-Gatchina

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

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

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

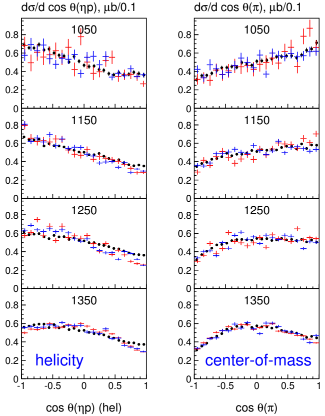
$\Delta(1940)\,\frac{3}{2}^-$

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

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

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

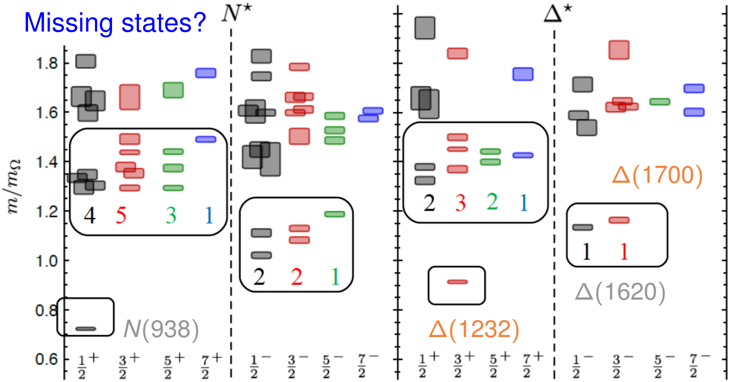
$N(2200)\,\frac{3}{2}^+$



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

Baryon Spectroscopy from Lattice QCD

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



$m_\pi = 396$ MeV

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

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

Quark-Model Classification: Ordinary & Exotic Mesons

Quantum Numbers $[q\bar{q}]$ ($J^{PC} \equiv {}^{2S+1}L_J$)

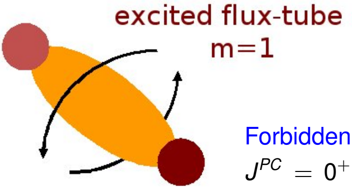
- Parity: $P = (-1)^{L+1}$
- Charge Conjugation: $C = (-1)^{L+S}$ (defined for neutral mesons)
- G parity: $G = C\,(-1)^I$

$L = 0,\ S = 0$:

e.g. π, η ($J^{PC} = 0^{-+}$)

$L = 0,\ S = 1$:

e.g. ρ, ω, ϕ ($J^{PC} = 1^{--}$)



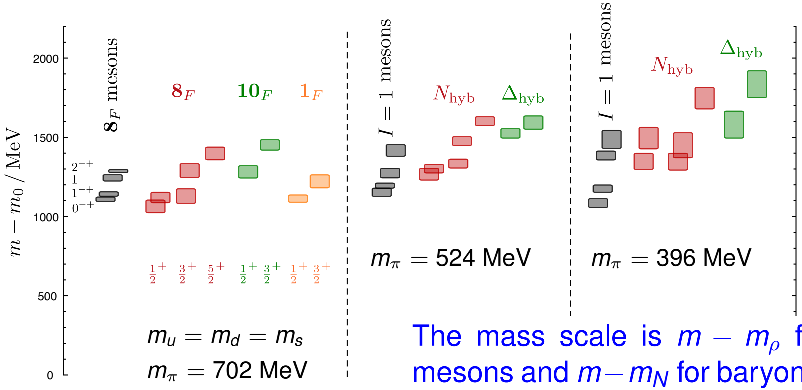
12 GeV CEBAF upgrade has high priority (DOE Office of Science, Long Range Plan) “[key area] is experimental verification of the powerful force fields *(flux tubes)* believed to be responsible for quark confinement.”

Forbidden States (Exotics):

$J^{PC} = 0^{+-}, 0^{--}, 1^{-+}, 2^{+-} \cdots$

Gluonic Excitations on the Lattice

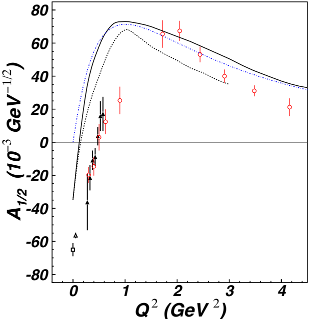
J. J. Dudek and R. G. Edwards, Phys. Rev. D **85**, 054016 (2012)

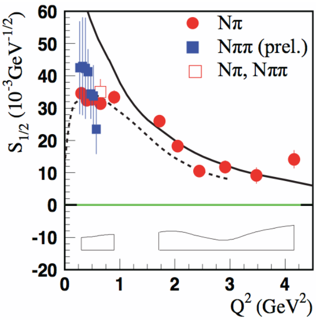


The mass scale is $m - m_\rho$ for mesons and $m - m_N$ for baryons.

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

Helicity Amplitudes for the "Roper" Resonance





Data from CLAS

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

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

Quark-model calculations:

— - - q^3 radial excitation

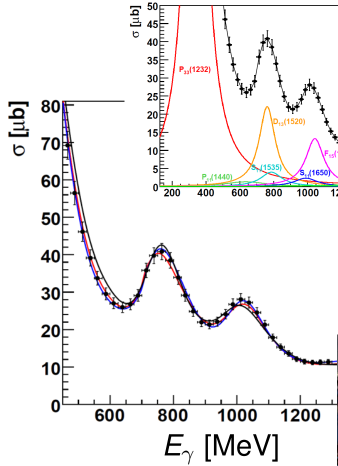
— q^3G hybrid state

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

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

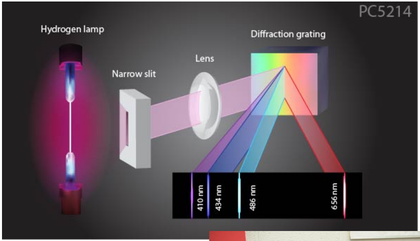
➜ Gluonic excitation likely ruled out!

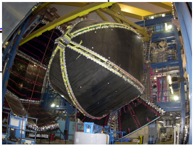
Why are Polarization Observables Important?



$\gamma p \longrightarrow p\pi^0$

Atomic Spectrum of Hydrogen

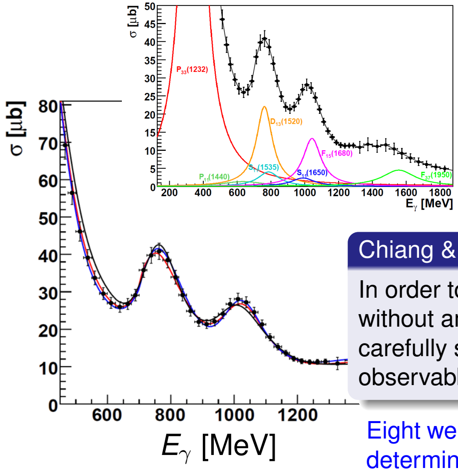




CLAS@JLab

ELSA
MAMI
GRAAL
SPring-8
...

Why are Polarization Observables Important?



$\gamma p \longrightarrow p\pi^0$

For single-meson production:

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

Chiang & Tabakin, Phys. Rev. C55, 2054 (1997)

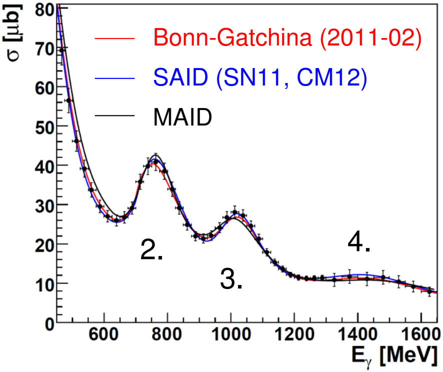
In order to determine the full scattering amplitude without ambiguities, one has to carry out eight carefully selected measurements: four double-spin observables along with four single-spin observables.

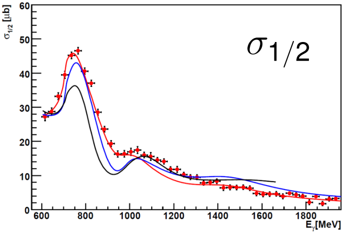
Eight well-chosen measurements are needed to fully determine production amplitudes F_1, F_2, F_3, and F_4.

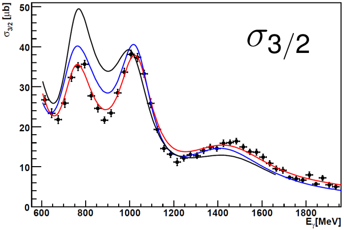
Example: Ambiguities in $\gamma\, p \to p\, \pi^0$

Helicity Difference:

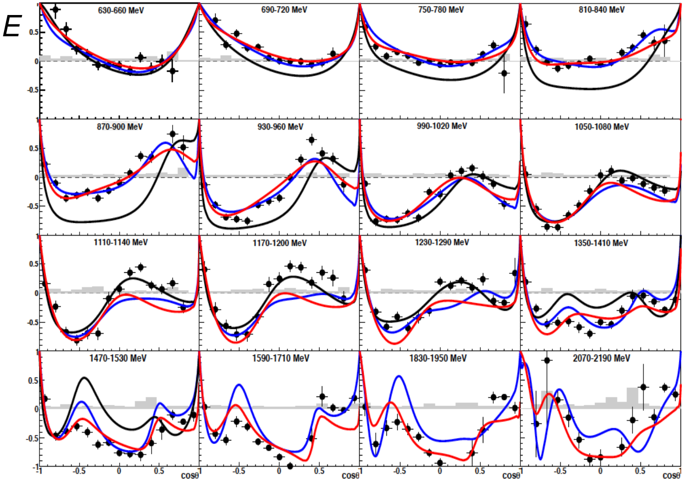
$$E = -\frac{1}{2\,\Lambda_z\,\delta_\odot}\,\frac{N^{\to\Rightarrow} - N^{\to\Leftarrow}}{N^{\to\Rightarrow} + N^{\to\Leftarrow}}$$







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



$\cos\theta_{\pi^0}$

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

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

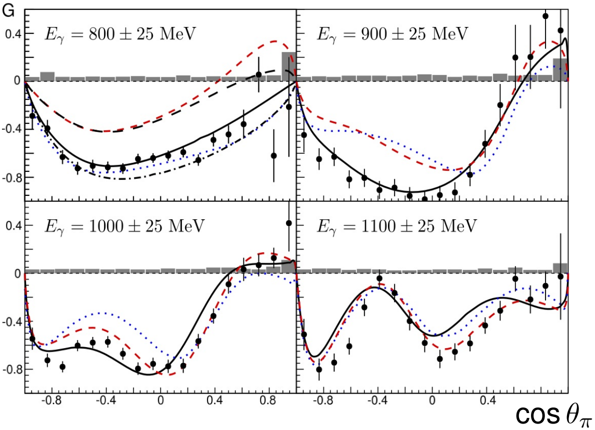
- • CBELSA/TAPS
- — Maid
- — Said (CM12)
- — BoGa (2011_2)

Angular distributions sensitive to interference between resonances.

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

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

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

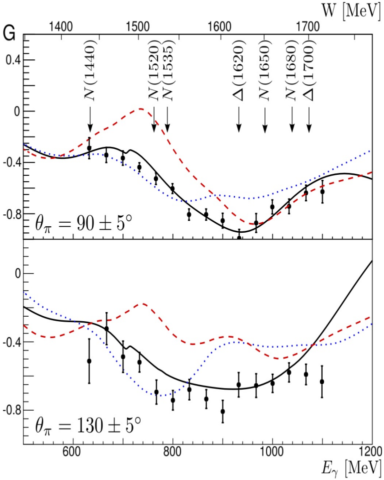


Surprisingly, π production also not well understood at lower energies:

— BoGa
- - SAID
···· MAID

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

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



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

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

$\theta_\pi = 90 \pm 5°$

$\theta_\pi = 130 \pm 5°$

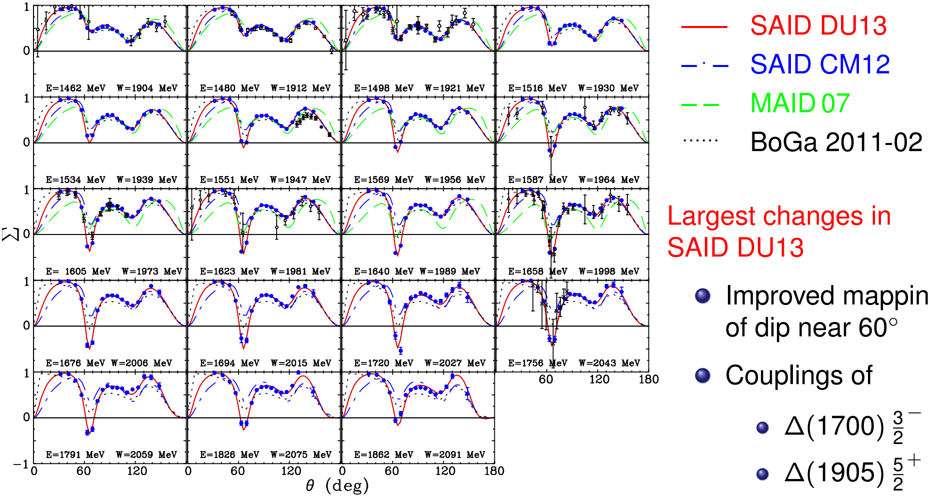
Surprisingly, π production also not well understood at lower energies.

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

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

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

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

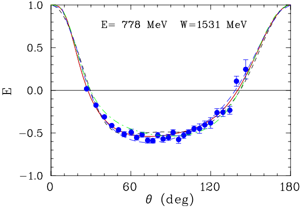


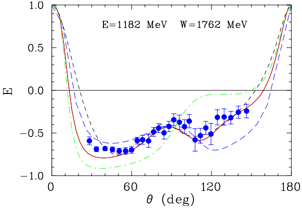
Largest changes in SAID DU13

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

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

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





SAID ST14

MAID 07

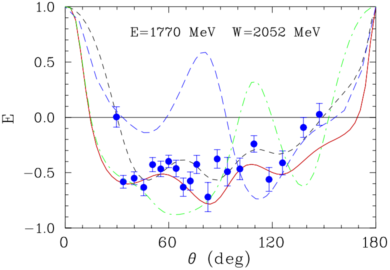
BoGa 2011-02

Jülich 14

Δ^+ $\qquad$ N^*

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

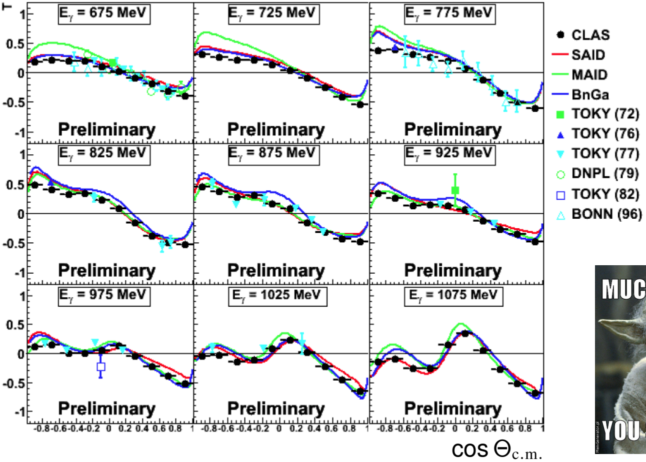
$$n\,\pi^+ : \sqrt{\frac{1}{3}}\,|I = \frac{3}{2},\, I_3 = \frac{1}{2}\rangle + \sqrt{\frac{2}{3}}\,|I = \frac{1}{2},\, I_3 = \frac{1}{2}\rangle$$



S. Strauch (SC), CLAS Collaboration, submitted to PRC

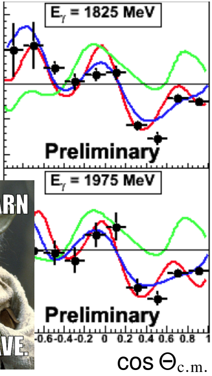
Target Asymmetry T in $\gamma\,\vec{p} \longrightarrow n\,\pi^+$ (CLAS FROST)

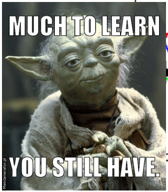
– MAID 07 – SAID – BoGA 12



Early-stage results (g9b)

- Transverse Target Polarization

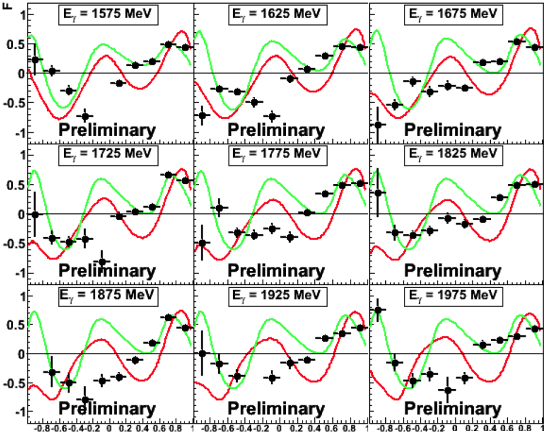




M. Dugger (ASU), CLAS g9b run group

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

– MAID 07 – SAID 12 BoGa not shown



cos $\Theta_{\text{c.m.}}$

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

Transv. target pol. & circ. beam pol.

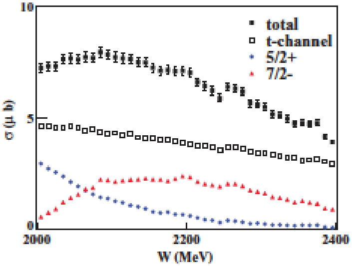
- Early-stage analysis
- Reasonable agreement among predictions for $W < 1.7$ GeV

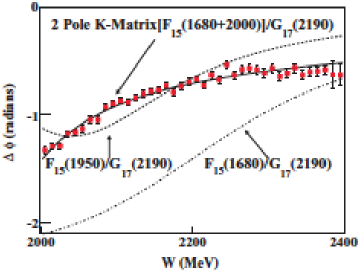
  ➜ Much to learn at the higher energies

M. Dugger (ASU), CLAS g9b run group

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

M. Williams *et al.* [CLAS Collaboration], Phys. Rev. C **80**, 065209 (2009)

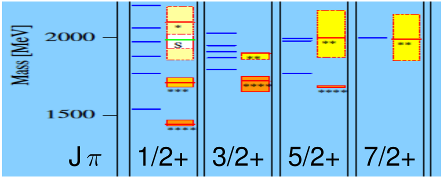




PWA fit includes resonances + *t*-channel amplitudes.

Strong evidence for $(W > 2$ GeV):

- $(5/2)^+$ N(1680) $****$
- $(5/2)^+$ N(1950) $**$
- $(7/2)^-$ N(2190) $****$



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

$\gamma p \to p\,\omega \to p\,\pi^+\pi^-\pi^0_{\text{miss}}$ ➜ same final state as $\gamma p \to p\,\pi^+\pi^-$

Analysis in basically three steps:

- Kinematics & Event Selection ($p\,\pi^+\pi^-$)

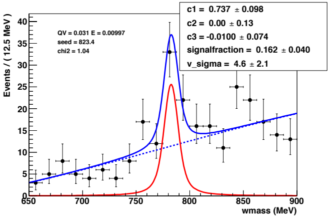
	lin. pol.	circ. pol.
g9a	USC (✓)	FSU ✓, CU (✓)
g9b	FSU ✓	USC (✓)

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

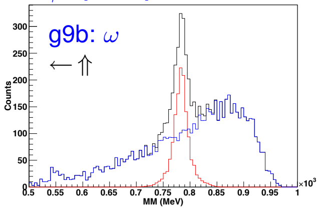
- Physics: $$\frac{d\sigma}{d\Omega} = \sigma_0\,\{1 - \delta_l\,\Sigma\cos 2\phi$$
  $$+ \Lambda_x\,(-\delta_l\,H\sin 2\phi + \delta_\odot\,F)$$

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

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



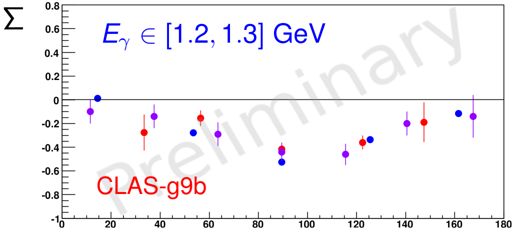
$E_\gamma \in [1.4, 1.5]$ GeV



Beam- & Target-Asymmetry in $\gamma\, p \to p\,\omega$ (CLAS-g9b)

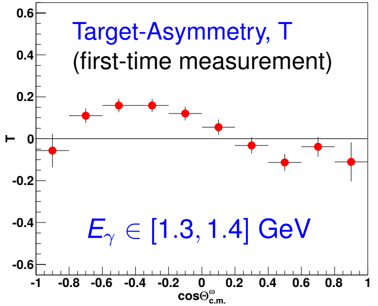
We are close to a complete experiment in $\gamma\, p \to p\,\omega$:

- Event-based dilution factors (➜ frozen-spin butanol target)
- Extraction of observables in event-based likelihood fits



Vegna *et al.* (GRAAL), arXiv:1306.5943

Ajaka *et al.* (GRAAL), PRL 96, 132003 (2006)

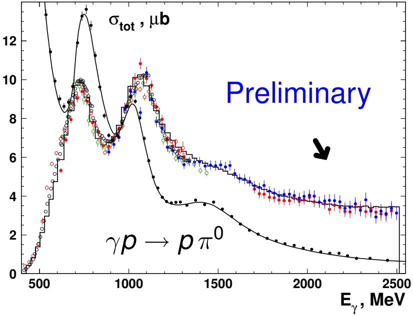


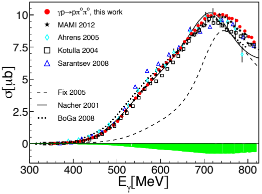
Priyashree Roy (Florida State), to be published

Outline

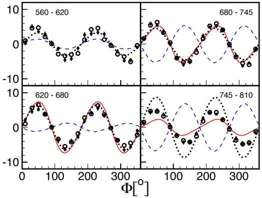
Observation of Decay Cascades in $\gamma p \to p \pi^0 \pi^0$

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





Cross Sections

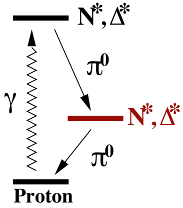


Beam Asymmetry, $I^{\odot}$

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

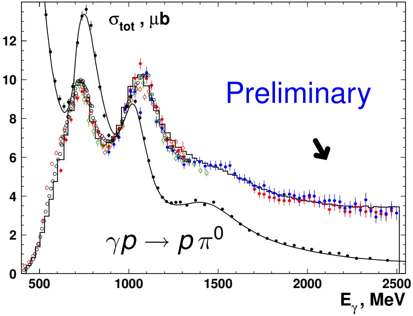
—— Bonn-Gatchina PWA

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



→ Search for states in decay cascades!

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



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

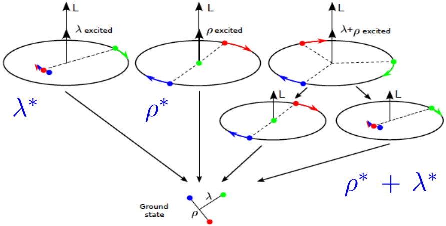
—— Bonn-Gatchina PWA

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

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

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

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



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

Decays observed in PWA into, e. g.

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

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

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

—— Bonn-Gatchina PWA

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

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

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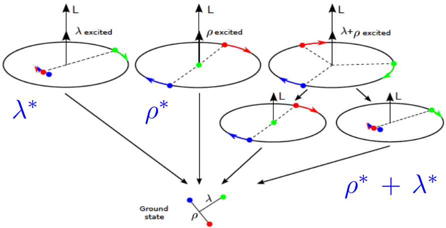
a component in which both the ρ and the λ oscillator are excited simultaneously.



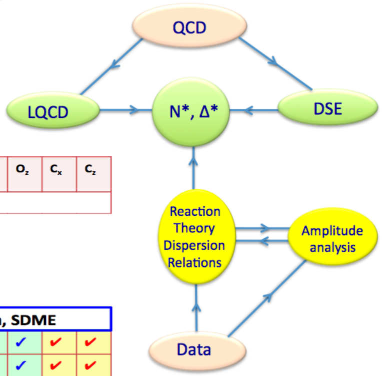
Outline

➜ M. Anderson, Session B (Tuesday):

"Measurements of Spin Observables for $\gamma p \to p\,\rho$"

V. Kashevarov, Session B:

"Baryon Spectroscopy at MAMI"



✔ published ✓ acquired or under analysis

Obser vables	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																
$p\pi^0$	✔	✔	✓	(✓)	✓	✓	✓	✓								
$n\pi^+$	✔	✔	✓	(✓)	✓	✓	✓	✓								
$p\eta$	✔	✓	✓	(✓)	✓	✓	✓	✓								
$p\eta'$	✔	✓	✓	(✓)	✓	✓	✓	✓								
$p\omega/\phi$	✔	✓	✓	(✓)	✓	✓	✓	✓	Tensor polarization, SDME							
$K^+\Lambda$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^+\Sigma^0$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^{0*}\Sigma^+$	✔	✓									✓	✓				
Neutron targets																
$p\pi^-$	✔	✓		(✓)	✓	✓	✓									
$p\rho^-$	✓	✓		(✓)	✓	✓	✓									
$K^-\Sigma^+$	✓	✓		(✓)	✓	✓	✓									
$K^0\Lambda$	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓									✓	✓				

Table representing CLAS@JLab measurements.

Need more observables on:

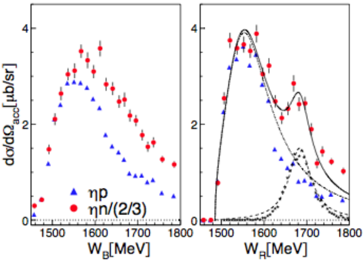
$\gamma p \to p\,\pi\pi,\ p\,\pi\eta$

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

Open Issues in Light Baryon Spectroscopy

Some questions need to be addressed in light baryon spectroscopy:

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



Summary and Outlook

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

- Goal of performing (almost) complete experiments has been (almost) achieved; significant contributions from (double-)polarization experiments.
- Still too early to nail down degrees of freedom in excited baryons?
  Well, is any of the different approaches THE correct one?
  Or, do they just represent different legitimate views?

I think we are moving toward a new exciting era in hadron spectroscopy (COMPASS@CERN, BES III, PANDA, etc.):

- GlueX in Hall-D at JLab will start to take physics data this year.

Advances in both theory and experiment will allow us to finally understand QCD and confinement.