Understanding Excited Baryon Resonances: Results from CLAS and CBELSA/TAPS

Volker Credé

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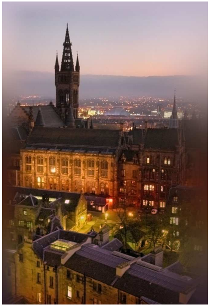


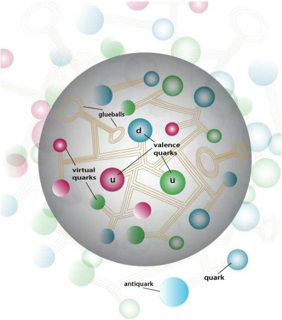
Baryons 2013

Glasgow, 06/24/2013

Outline

Outline

Non-Perturbative Quantum Chromodynamics (QCD)

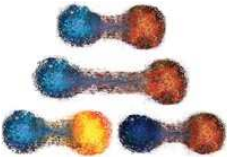


QCD is the theory of the strong nuclear force which describes the interactions of quarks and gluons making up hadrons.

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

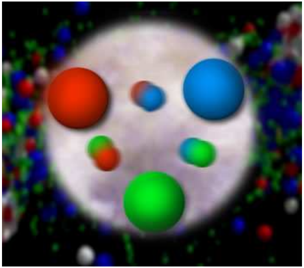
Quarks are confined within hadrons.

Confinement of quarks and gluons within nucleons is a non-perturbative phenomenon, and QCD is extremely hard to solve in non-perturbative regimes: Knowledge of internal structure of nucleons is still limited.



This is particularly true for excited nucleons.

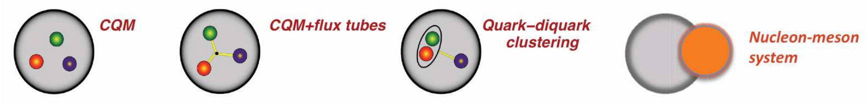
Non-Perturbative QCD



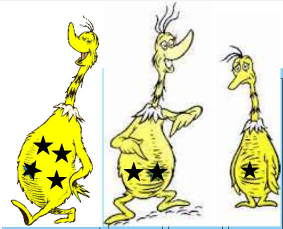
How does QCD give rise to excited hadrons?

1. What is the origin of confinement?
2. How are confinement and chiral symmetry breaking connected?
3. Would the answers to these questions explain the origin of $\sim 98\,\%$ of observed matter in the universe?

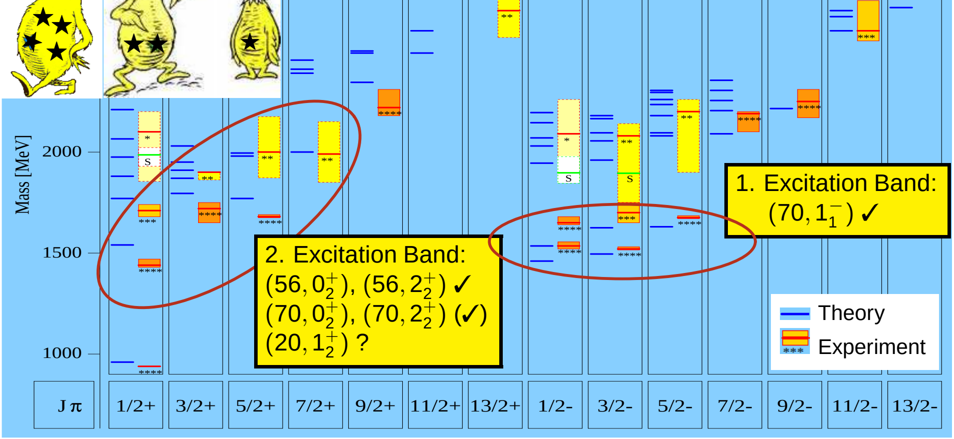
Excited Baryons: What are the fundamental degrees of freedom inside a proton or a neutron? How do they change with varying quark masses?



Spectrum of Nucleon Resonances

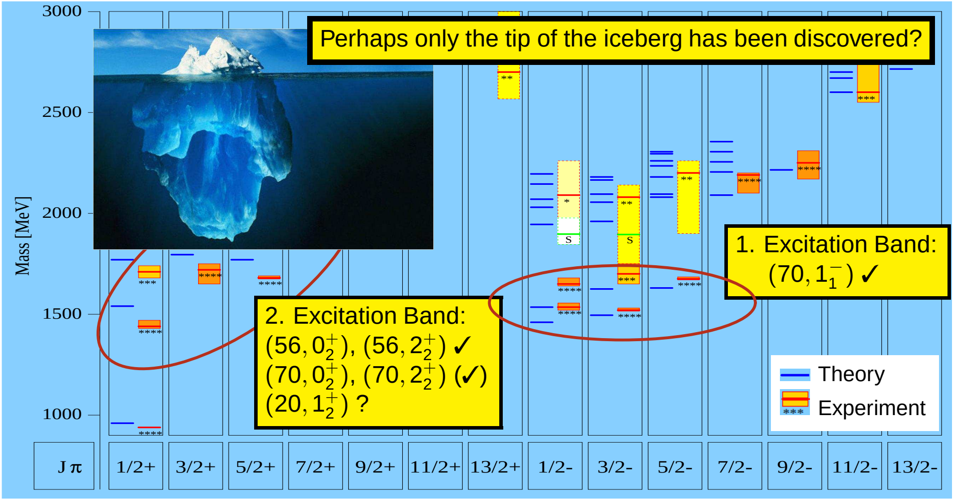


—— S. Capstick and N. Isgur, Phys. Rev. **D34** (1986) 2809



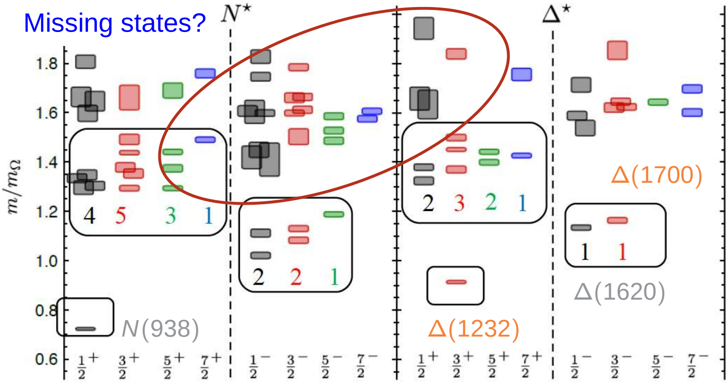
Spectrum of Nucleon Resonances

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



Excited-State Baryon Spectroscopy from Lattice QCD

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



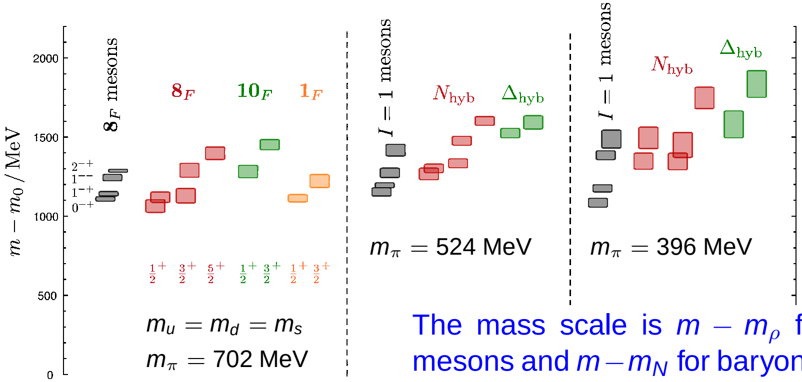
$m_\pi = 396$ MeV

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

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

Gluonic Excitations on the Lattice

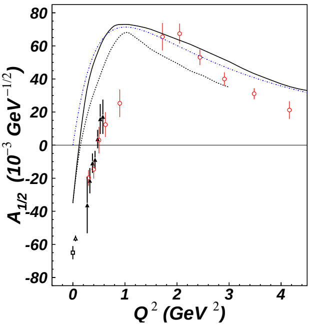
J. J. Dudek and R. G. Edwards, Phys. Rev. D **85**, 054016 (2012)

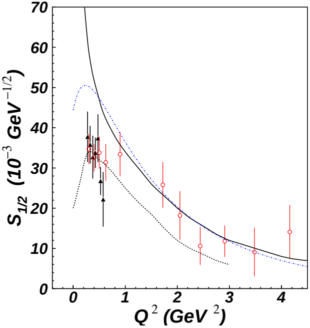


The mass scale is $m - m_\rho$ for mesons and $m - m_N$ for baryons.

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!

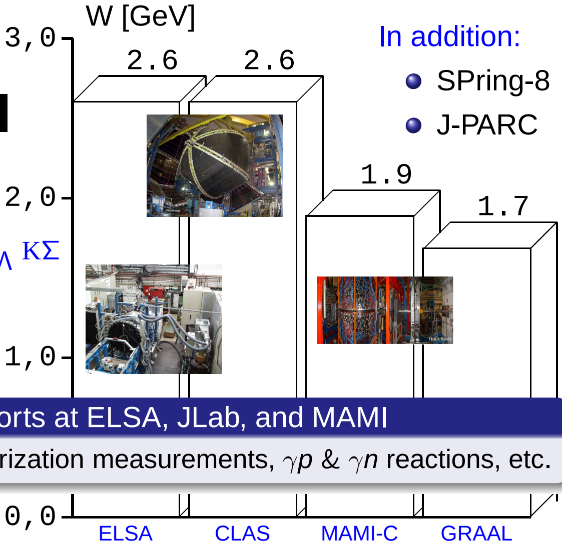
Outline

E_γ [GeV]

Reaction Thresholds

1.66
$\gamma p \rightarrow p\eta\eta$
$\gamma p \rightarrow p\pi^0\omega$
$\gamma p \rightarrow p\pi^0\eta$ $\gamma p \rightarrow K\Lambda\ K\Sigma$
$\gamma p \rightarrow p\eta$
$\gamma p \rightarrow p\pi\pi\pi$
$\gamma p \rightarrow p\pi\pi$
0.06
$\gamma p \rightarrow p\pi$

0.00



In addition:

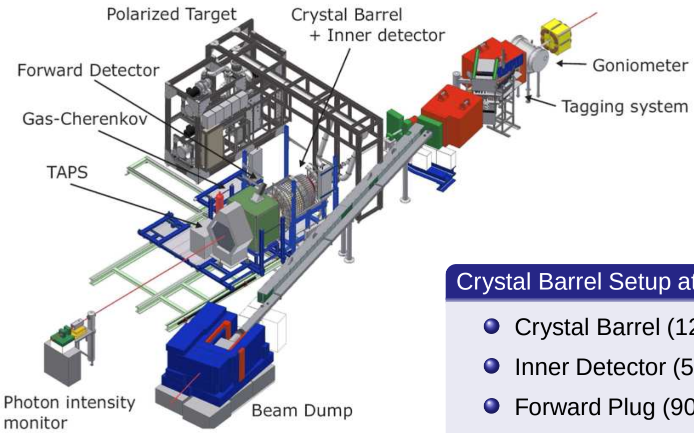
- SPring-8
- J-PARC

Common efforts at ELSA, JLab, and MAMI

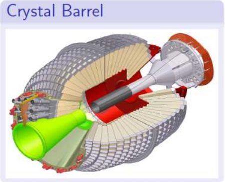
(Double-)polarization measurements, γp & γn reactions, etc.

Double-Polarization: Toward Complete Experiments

Calorimeter system at ELSA is optimized for neutral particles.



Frozen-Spin Target: Butanol (C_4H_9OH).

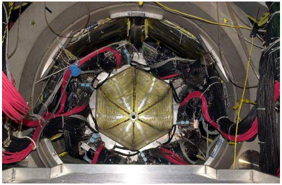


Close to 4π coverage

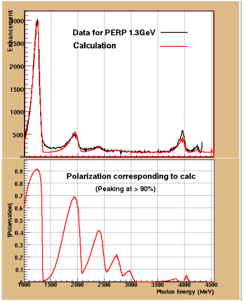
Crystal Barrel Setup at ELSA

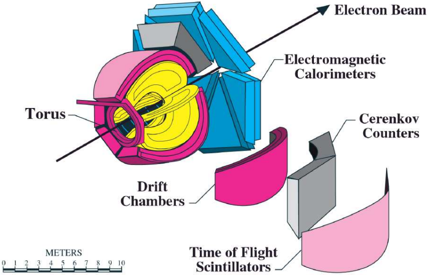
- Crystal Barrel (1230 CsI crystals)
- Inner Detector (513 scintillating fibers)
- Forward Plug (90 CsI crystals)
- MiniTAPS (216 BaF_2, 1° - 12°)

The CLAS Spectrometer at Jefferson Laboratory

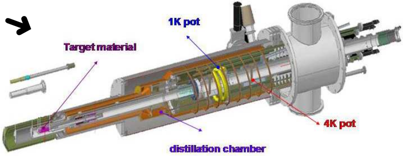


g8b
linear beam polarization





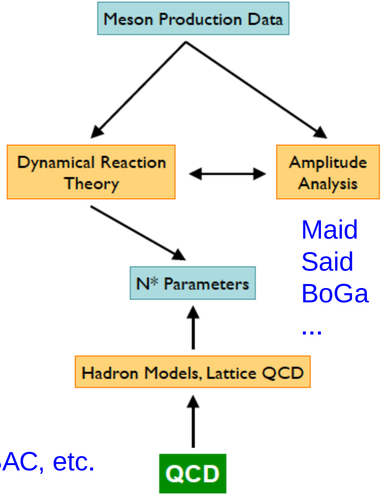
FROST
double polarization



Extraction of Resonance Parameters

- 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.

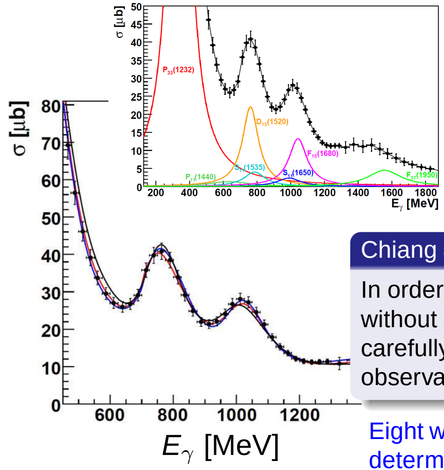
Coupled Channels



Maid
Said
BoGa
...

Jülich, Gießen, EBAC, etc.

Why are Polarization Observables Important?



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

For single-meson production:

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

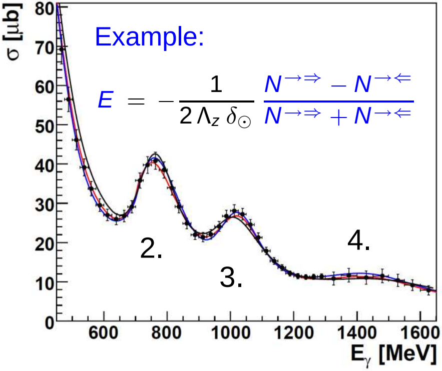
Chiang & Tabakin, Phys. Rev. C55, 2054 (1997)

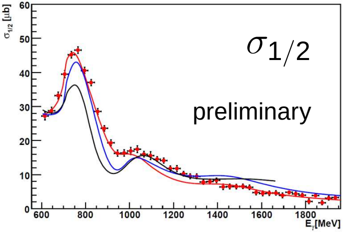
In order to determine the full scattering amplitude without ambiguities, one has to carry out eight carefully selected measurements: four double-spin observables along with four single-spin observables.

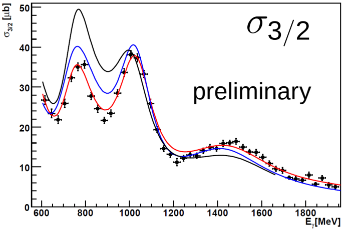
Eight well-chosen measurements are needed to fully determine production amplitudes F_1, F_2, F_3, and F_4.

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

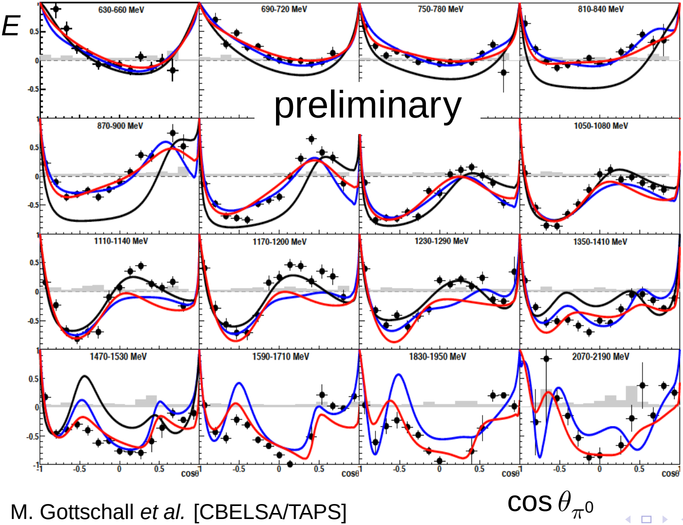
- Bonn-Gatchina (2011_2)
- SAID (SN11, CM12)
- MAID







Helicity Asymmetry E in $\vec{\gamma}\vec{p} \to p\,\pi^0$ (CBELSA/TAPS)



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

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

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

Angular distributions sensitive to interference between resonances.

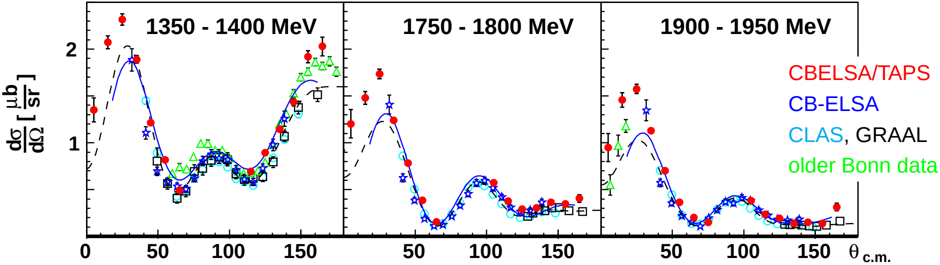
M. Gottschall *et al.* [CBELSA/TAPS]

Outline

Photoproduction of π^0 Mesons from the Proton

Reaction $\gamma p \to p\,\pi^0$ remains important for our understanding of baryons.

- At ELSA, excellent data with good statistics in the forward direction.
- Forward region is very sensitive to higher-spin resonances:
  ➜ Observation of $N(2190)G_{17}$ within the Bonn-Gatchina PWA framework
  (Important to confirm high-mass states first observed in πN scattering)

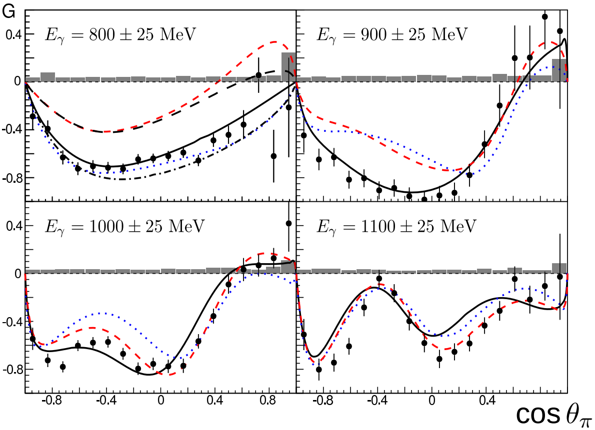


V. C. *et al.* [CBELSA/TAPS], Phys. Rev. C **84**, 055203 (2011)

Asymmetry G in $\vec{\gamma}\vec{p} \to p\,\pi^0$ (CBELSA/TAPS)

ELSA Talks: A. Thiel, HS 1.7 on Monday
A. Wilson, HS 3.7 on Thursday

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

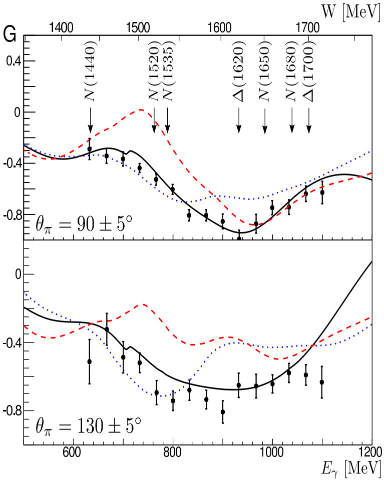


Surprisingly, π production also not well understood at lower energies:

— BoGa
- - SAID
···· MAID

A. Thiel *et al.* [CBELSA/TAPS], PRL **109**, 102001 (2012)

Asymmetry G in $\vec{\gamma}\vec{p} \to p\,\pi^0$ (CBELSA/TAPS)



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

$\theta_\pi = 90 \pm 5°$

$\theta_\pi = 130 \pm 5°$

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

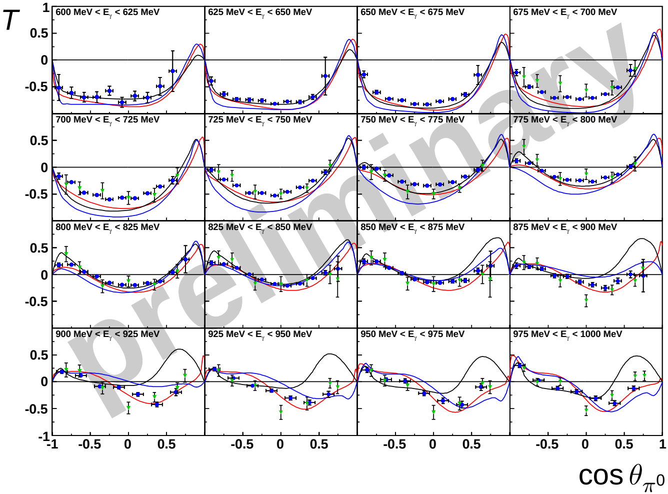
Below 1 GeV, discrepancies can be traced to the E_{0+} and E_{2-} multipoles, which are related to certain resonances:

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

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

A. Thiel *et al.* [CBELSA/TAPS], PRL **109**, 102001 (2012)

Target Asymmetry T in $\gamma \vec{p} \to p\, \pi^0$ (CBELSA/TAPS)



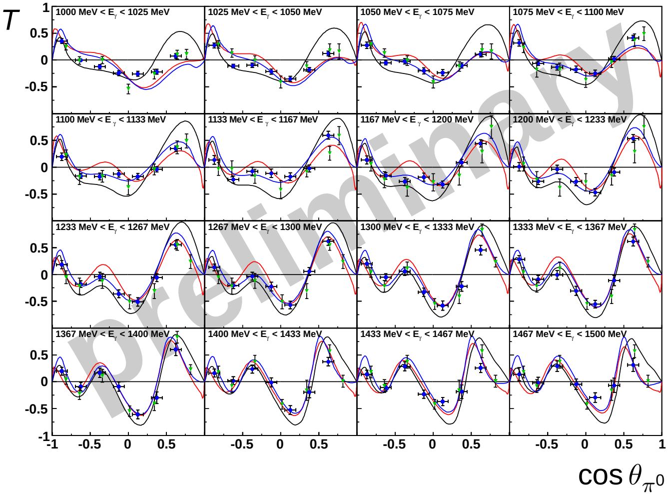
$600 < E_\gamma < 1000$ MeV
in bins of $\Delta E = 25$ MeV

- CBELSA/TAPS
- Daresbury (1977)
  Nucl. Phys. B **121** (1977), 45
- Maid
- Said
- Bonn Gatchina

➜ Good agreement of experimental data. (improved statistics)

J. Hartmann *et al.* [CBELSA/TAPS]

Target Asymmetry T in $\gamma \vec{p} \to p\,\pi^0$ (CBELSA/TAPS)



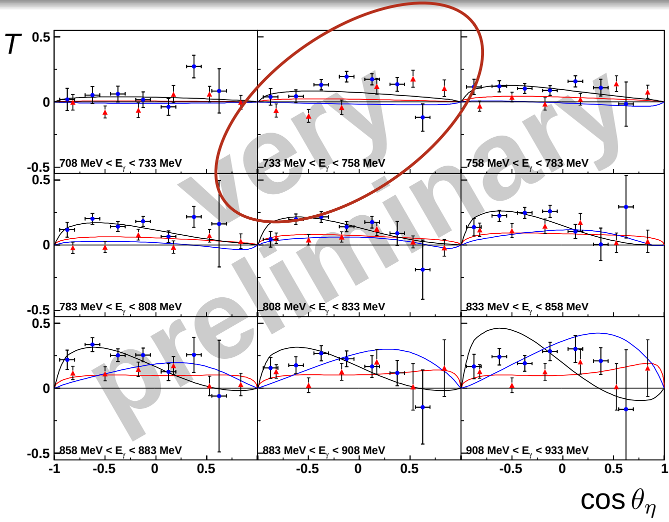
$1000 < E_\gamma < 1500$ MeV

- CBELSA/TAPS
- Daresbury (1977)
  Nucl. Phys. B **121** (1977), 45
- Maid
- Said
- Bonn Gatchina

➜ Good agreement of experimental data.

Model disagreement toward 3rd resonance region: $W > 1.6$ GeV (E_{0+}, E_{2-} multipoles?)

Target Asymmetry T in $\gamma \vec{p} \rightarrow p\,\eta$ (CBELSA/TAPS)



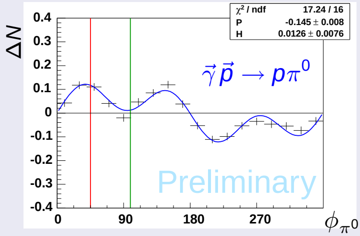
$708 < E_\gamma < 933$ MeV
in bins of $\Delta E = 25$ MeV

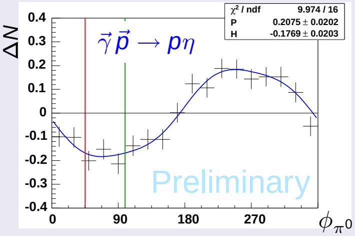
- CBELSA/TAPS
- PHOENICS (1998)
  Phys. Rev. Lett. **81** (1998), 534
- Maid
- Said
- Bonn Gatchina

J. Hartmann *et al.* [CBELSA/TAPS]

Observables P, H (CBELSA/TAPS)

$800 < E_\gamma < 900$ MeV





angle of lin. pol. plane:
$\alpha = 45^\circ$

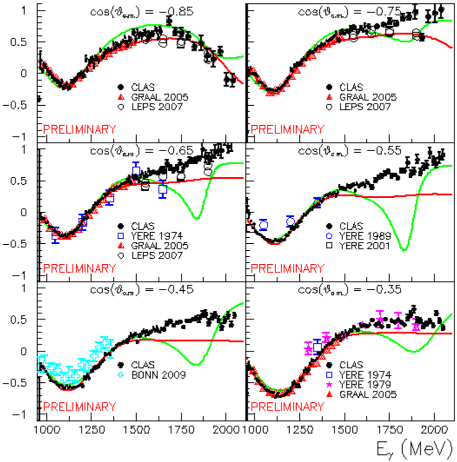
direction of target pol.:
$\beta = 99^\circ$

$$\Delta N(\phi) = C \cdot \frac{(N_{\perp\uparrow} - N_{\perp\downarrow}) - (N_{\parallel\uparrow} - N_{\parallel\downarrow})}{(N_{\perp\uparrow} + N_{\perp\downarrow}) + (N_{\parallel\uparrow} + N_{\parallel\downarrow})}$$
$$= P\,(\sin(\phi - \beta)\cos(2(\phi - \alpha)) + H\,(\cos(\phi - \beta)\sin(2(\phi - \alpha))$$

photon pol.		target pol. axis x	y	z
unpolarized	σ		T	
linear	$-\Sigma$	H	$-P$	$-G$
circular		F		$-E$

Beam Asymmetry Σ in $\vec{\gamma} p \to N\,\pi$ (CLAS g8b)

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



M. Dugger (ASU), CLAS g8b run group

Linear beam polarization:

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

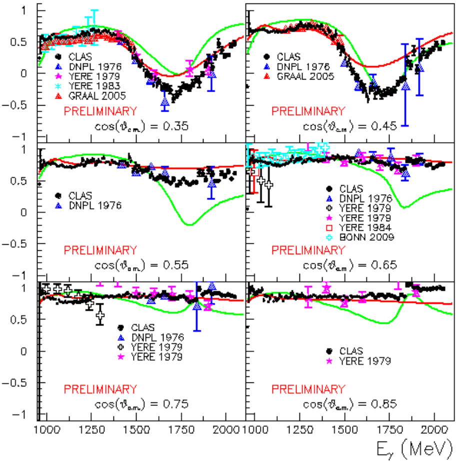
— SAID — MAID • CLAS
($E_\gamma < 2$ GeV, $-0.85 < \cos\theta_\pi < -0.35$)

➜ Serious discrepancies between models and data above 1.4 GeV.

Photoproduction of π mesons still not very well understood.

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

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



M. Dugger (ASU), CLAS g8b run group

$(E_\gamma < 2$ GeV, $0.35 < \cos\theta_\pi < 0.85)$

— SAID — MAID • CLAS

(changes for $\Delta(1700)\,\frac{3}{2}^-$, $\Delta(1905)\,\frac{5}{2}^+$)

Combination of $p\,\pi^0$ and $n\,\pi^+$ helps distinguish between Δ, N^* states:

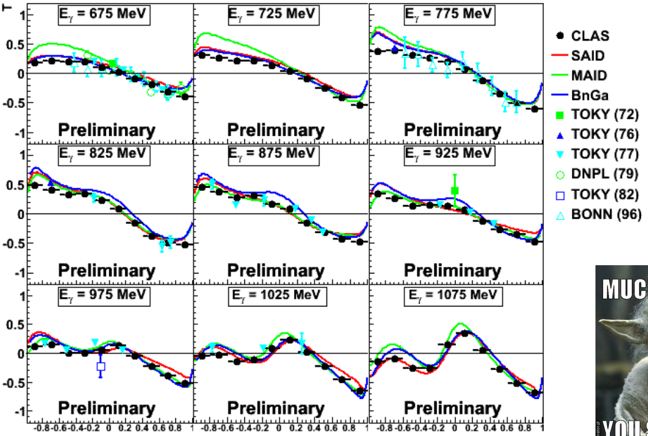
Δ^+ N^*

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

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

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

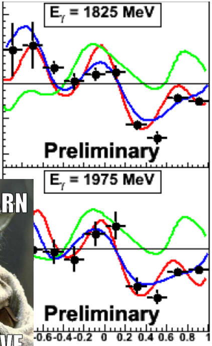
– MAID 07 – SAID – BoGA 12

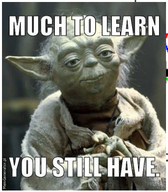


cos $\Theta_{c.m.}$

Early-stage results (g9b)

- Transverse Target Polarization



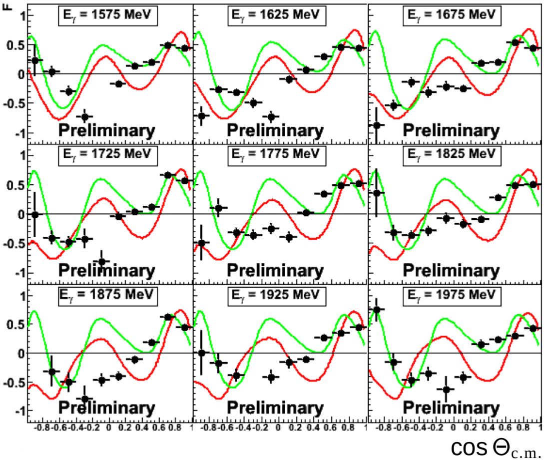


cos $\Theta_{c.m.}$

M. Dugger (ASU), CLAS g8b run group

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

– MAID 07 – SAID 12 BoGa not shown



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

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 g8b run group

Overview of CLAS Polarization Measurements

Measurements off the proton

Eugene Pasyuk, HS 1.1 on Monday

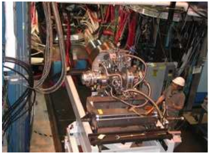
- $\gamma p \rightarrow \boxed{p\,\pi^0,\, n\,\pi^+}$
- $\gamma p \rightarrow p\,\eta,\, p\,\eta'$ (I. Senderovich, HS 1.9)
- $\gamma p \rightarrow \boxed{p\,\pi^+\pi^-}$, $p\,\omega,\, p\,\phi$

➜ Frozen-Spin Target (FROST)

Measurements off the neutron

- $\gamma n \rightarrow p\,\pi^-$
- $\gamma n \rightarrow n\,\pi^+\pi^-$

➜ HD Ice Target



➜ "Complete" experiment possible in Strangeness Photoproduction (Stuart Fegan, HS 1.6 on Monday)

- $\gamma p \rightarrow K\,Y\ (Y = \Lambda,\, \Sigma^0,\, \Sigma^+)$
- $\gamma n \rightarrow K^+\,\Sigma^-,\, K^0\,\Lambda$

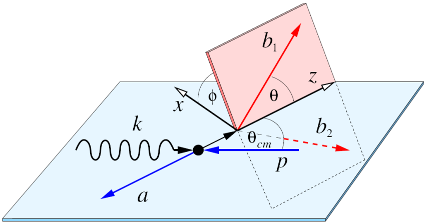
➜ Cross sections ($\Lambda(1405), \Lambda(1520)$): R. Schumacher, Mixed 1.1

Beam-Target Polarization Observables in $\gamma p \to p \pi\pi$

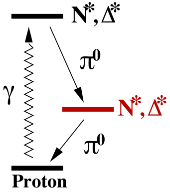
W. Roberts *et al.*, Phys. Rev. C **71**, 055201 (2005)

$$\begin{aligned} I = I_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{P}) & \\ & + \delta_\odot (I^\odot + \vec{\Lambda}_i \cdot \vec{P}^\odot) \\ & + \delta_l [\sin 2\beta (I^s + \vec{\Lambda}_i \cdot \vec{P}^s) + \\ & \qquad \cos 2\beta (I^c + \vec{\Lambda}_i \cdot \vec{P}^c)] \} \end{aligned}$$

$\Leftarrow$ Double-Meson Final States (15 Observables)

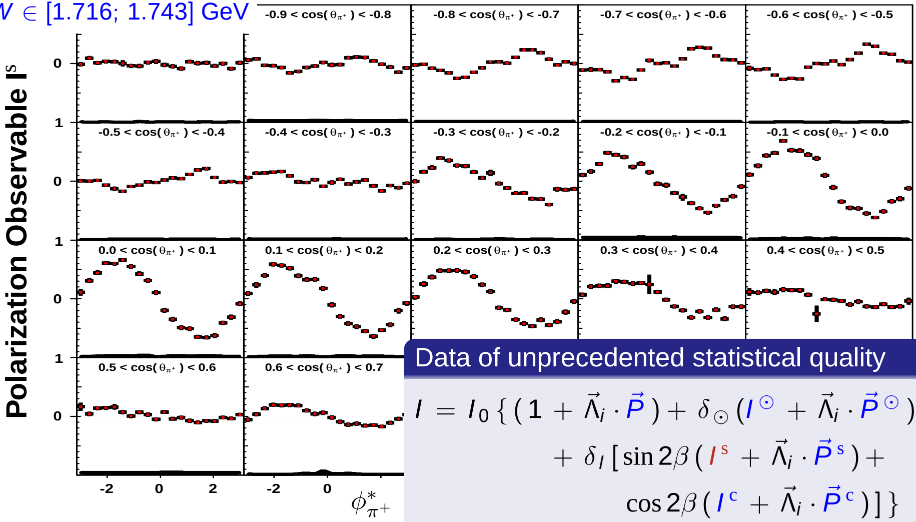


At higher excitation energies:
Multi-meson final states important.



➜ Search for states in decay cascades!

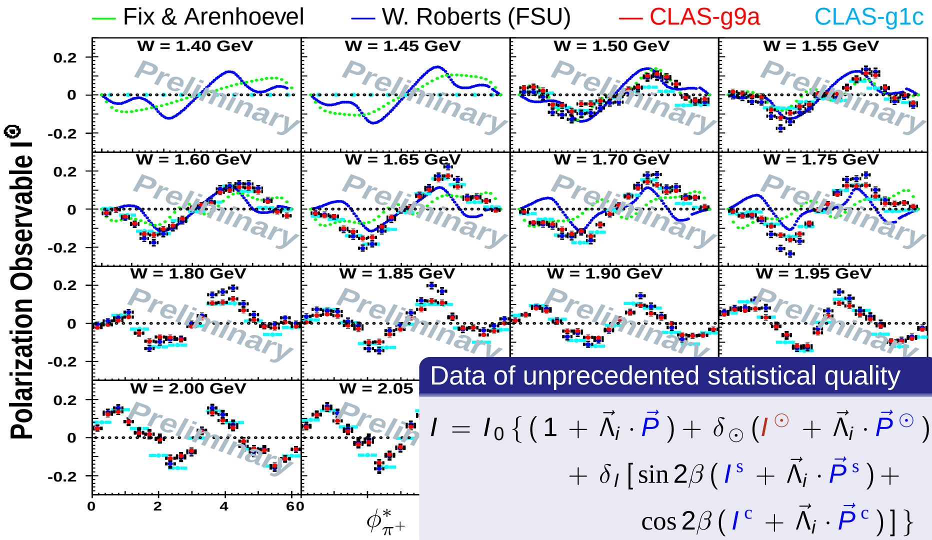
$W \in [1.716;\ 1.743]$ GeV



Data of unprecedented statistical quality

$$I = I_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_\odot (I^\odot + \vec{\Lambda}_i \cdot \vec{P}^\odot) + \delta_l [\sin 2\beta (I^s + \vec{\Lambda}_i \cdot \vec{P}^s) + \cos 2\beta (I^c + \vec{\Lambda}_i \cdot \vec{P}^c)] \}$$

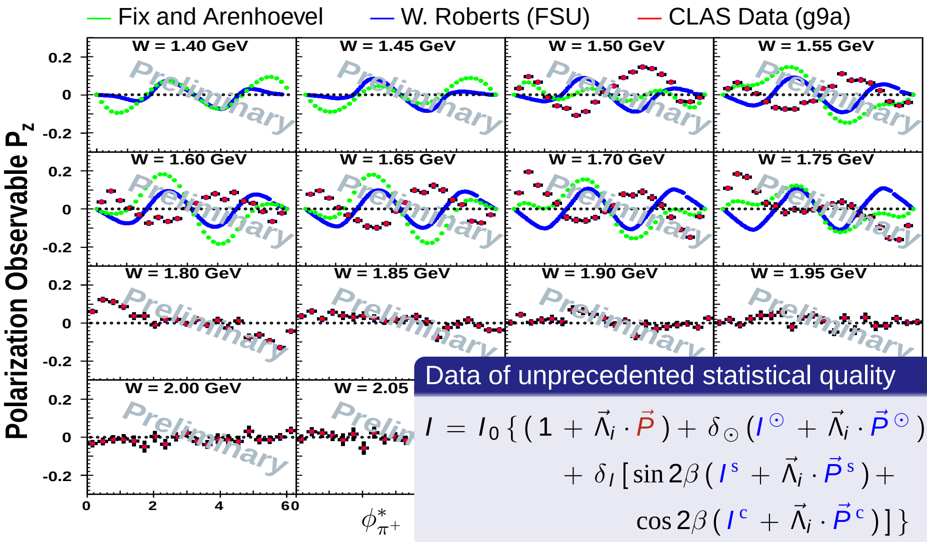
Charles Hanretty *et al.*, CLAS-g8b run group



Data of unprecedented statistical quality

$$I = I_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_{\odot} (I^{\odot} + \vec{\Lambda}_i \cdot \vec{P}^{\odot}) + \delta_l [\sin 2\beta (I^s + \vec{\Lambda}_i \cdot \vec{P}^s) + \cos 2\beta (I^c + \vec{\Lambda}_i \cdot \vec{P}^c)] \}$$

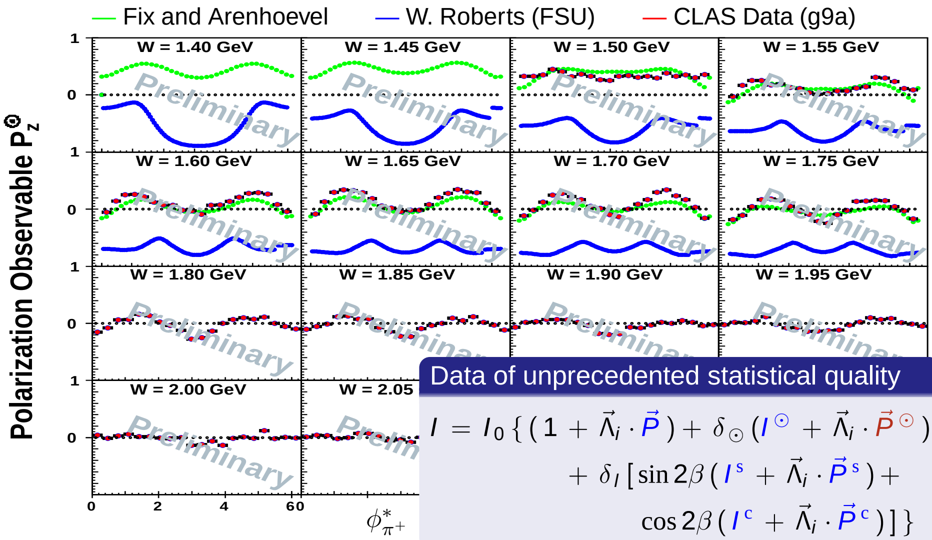
Sungkyun Park *et al.*, CLAS-g9a run group



Data of unprecedented statistical quality

$$I = I_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_\odot (I^\odot + \vec{\Lambda}_i \cdot \vec{P}^\odot) + \delta_l [\sin 2\beta (I^s + \vec{\Lambda}_i \cdot \vec{P}^s) + \cos 2\beta (I^c + \vec{\Lambda}_i \cdot \vec{P}^c)] \}$$

Sungkyun Park *et al.*, CLAS-g9a run group



Data of unprecedented statistical quality

$$I = I_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_{\odot} (I^{\odot} + \vec{\Lambda}_i \cdot \vec{P}^{\odot}) + \delta_l [\sin 2\beta (I^{s} + \vec{\Lambda}_i \cdot \vec{P}^{s}) + \cos 2\beta (I^{c} + \vec{\Lambda}_i \cdot \vec{P}^{c})] \}$$

Sungkyun Park *et al.*, CLAS-g9a run group

Outline

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 relevant degress of freedom in excited baryons.
  ➜ Some states might be generated dynamically ...

$N(1860)\,\frac{5}{2}^+$	$**$	πN	γN				
$N(1875)\,\frac{3}{2}^-$	$***$	πN	γN		ΛK	ΣK	
$N(1880)\,\frac{1}{2}^+$	$**$	πN	γN		ΛK	ΣK	
$N(1895)\,\frac{1}{2}^-$	$**$	πN	γN	ηN	ΛK	ΣK	
$N(1900)\,\frac{3}{2}^+$	$***$	πN	γN	ηN	ΛK	ΣK	$\Delta\pi$
$N(2060)\,\frac{5}{2}^-$	$**$	πN	γN	ηN		ΣK	
$\Delta(1940)\,\frac{3}{2}^-$	$* \longrightarrow **$	πN	γN				$\Delta\eta$ (!)

New States in PDG 2012.