QCD@Work - International Workshop on QCD Theory and Experiment

25-28 June 2018 *Matera, Italy*

Light Baryon Spectrum and Structure at CLAS

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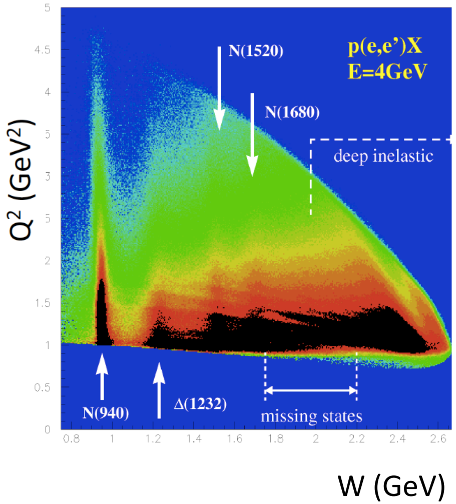


Outline:

- Why study spectroscopy
- Establishing N* states
- Identifying the effective degrees of freedom
- Outlook & conclusions

Jefferson Lab

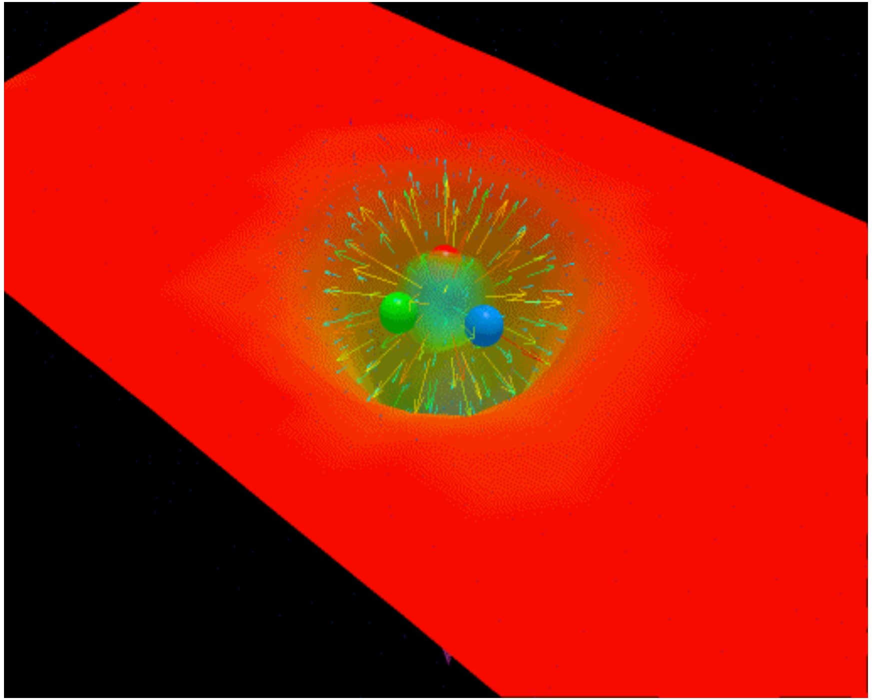
Why N* ?

Baryon Spectroscopy Reveals the Workings of QCD

"Nucleons are the stuff of which our world is made.

As such they must be at the center of any discussion of why the world we actually experience has the character it does."

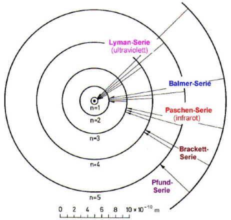
Nathan Isgur, NStar2000, Newport News, Virginia



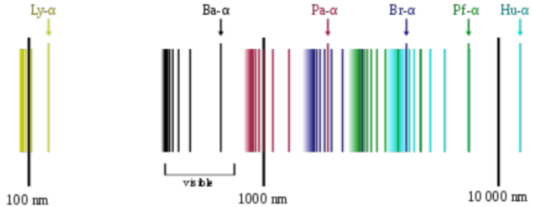
Derek B. Leinweber – University of Adelaide

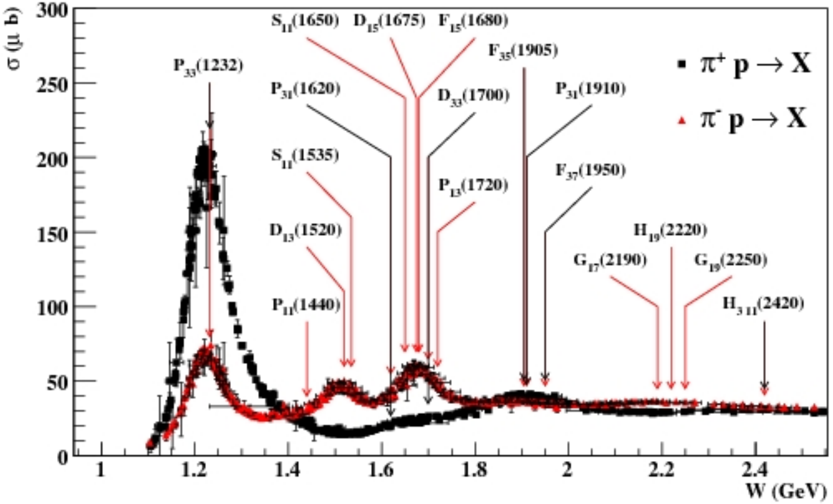
Why N* ? From the Hydrogen Spectrum to QCD

Niels Bohr (1922)



Spectral series of hydrogen





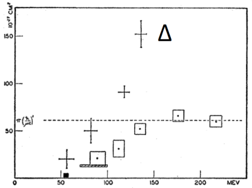
- Understanding the hydrogen atom's ground state requires understanding its excitation spectrum.

→ From Bohr model of the atom to QED.

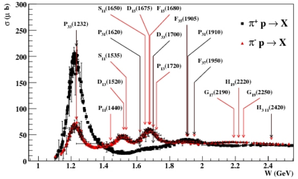
- Understanding the proton's ground state requires understanding its excitation spectrum.

→ From the Constituent Quark model to QCD.

Historical Markers

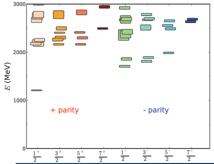


1952: First glimpse of the Δ(1232) in πp scattering shows internal structure of the proton.

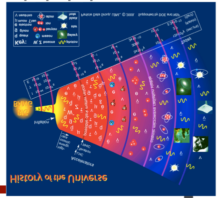


1964: Baryon resonances essential in establishing the quark model and the color degrees of freedom.

1989: Broad effort to address the missing baryon puzzle.

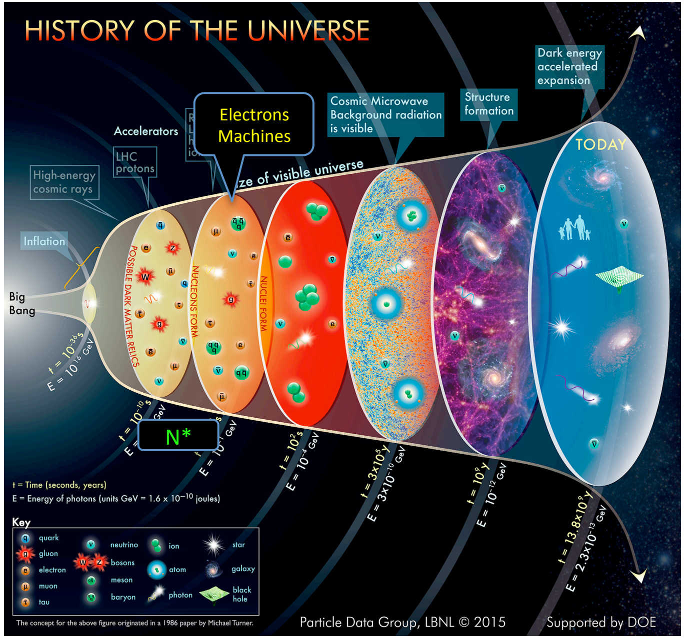


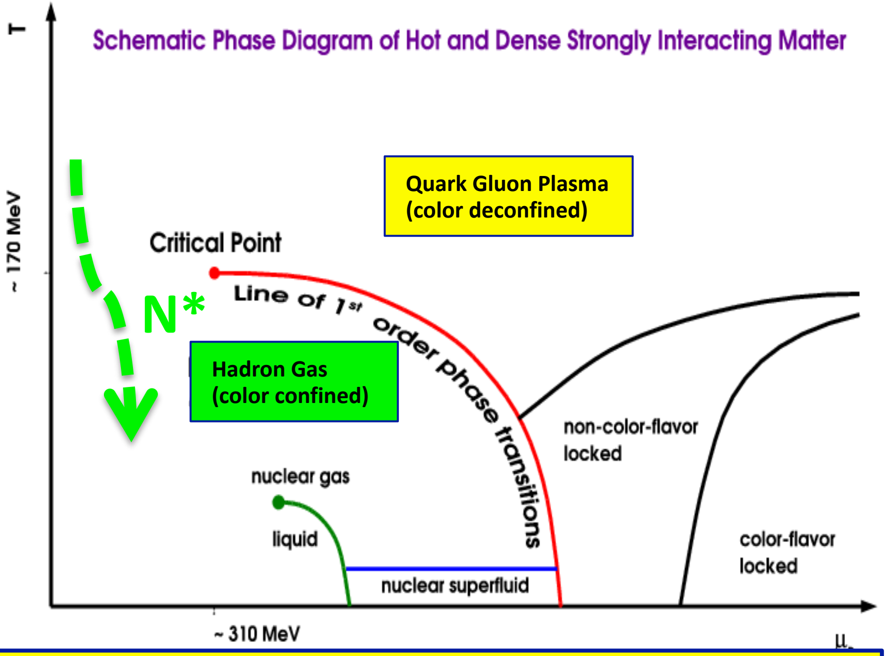
2010: First successful attempt to predict the nucleon spectrum in LQCD.



2015: Understanding of the baryon spectrum is needed to quantify the transition from QGP to the confined phase in the early universe.

N* in the History of the Universe

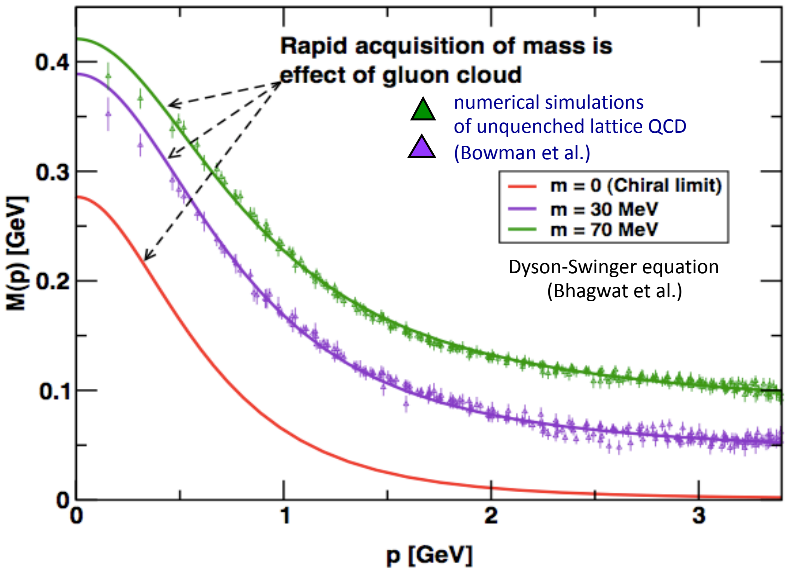


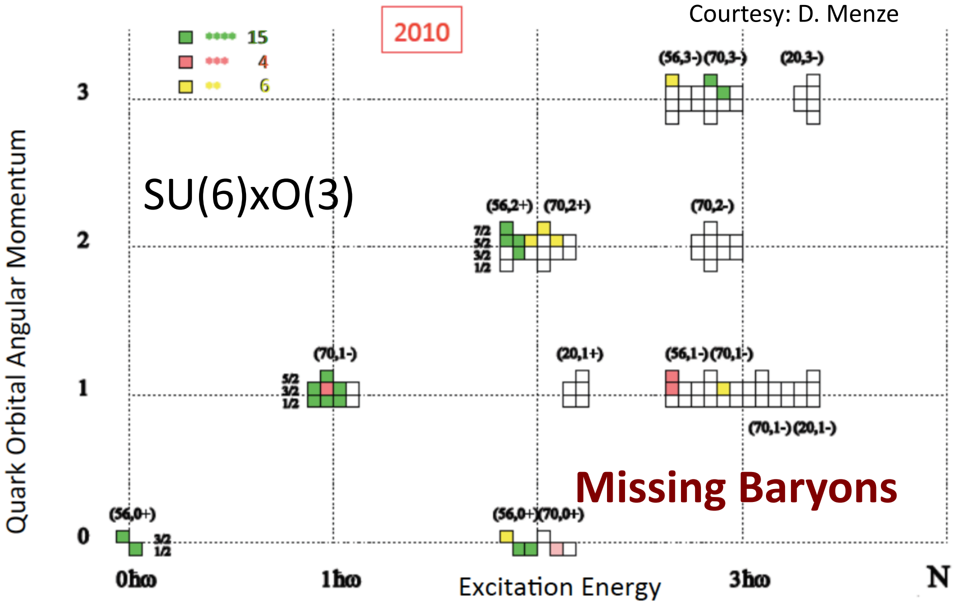


Dramatic events occur in the microsecond old Universe.

- The transition from the QGP to the baryon phase is dominated by excited baryons. A quantitative description requires more states than found to date => **missing baryons.**
- During the transition the quarks acquire **dynamical mass** and the **confinement of color** occurs.

Constituent quark models and SU(6)xO(3)





- Current-quarks of perturbative QCD evolve into constituent quarks at low momentum.

→ Connection between constituent and current quarks.

- QCD-inspired Constituent Quark models: states classified by isospin, parity and spin within each oscillator band. Many projected q^3 states are still missing or uncertain.

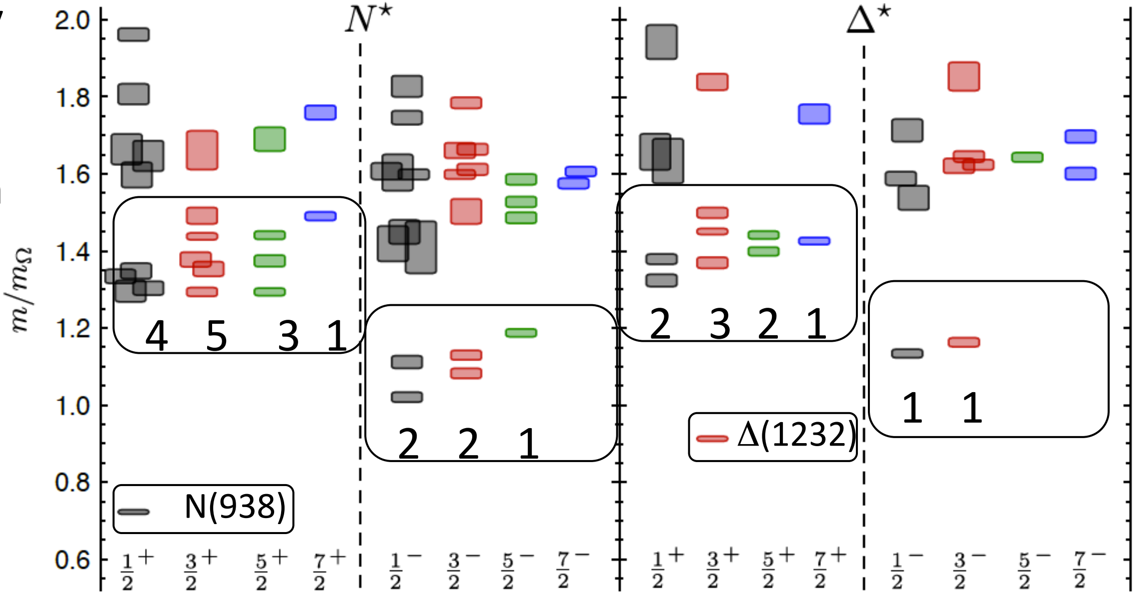
LQCD N* & Δ Spectra

- Exhibit the SU(6)×O(3)-symmetry features

- Counting of levels consistent with non-rel. quark model

- Striking similarity with quark model

- No parity doubling

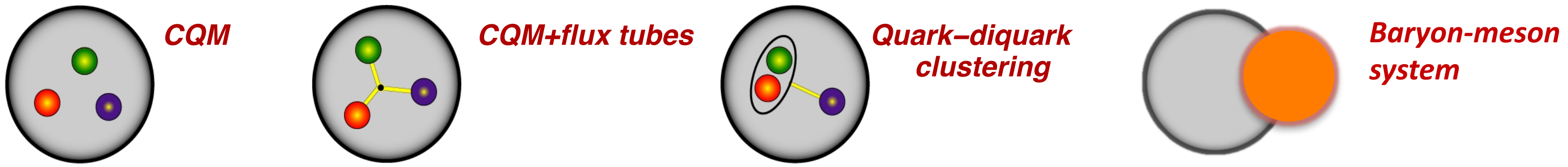


Robert G. Edwards, Jozef J. Dudek, David G. Richards, Stephen J. Wallace
Phys.Rev. D84 (2011) 074508

Problems are not solved!

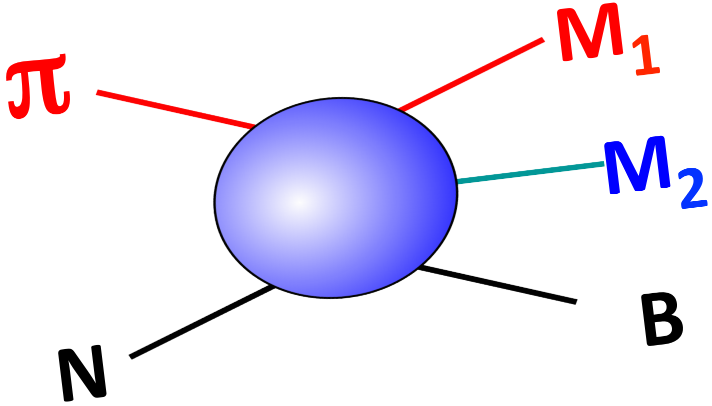
What Do We Want to Learn ?

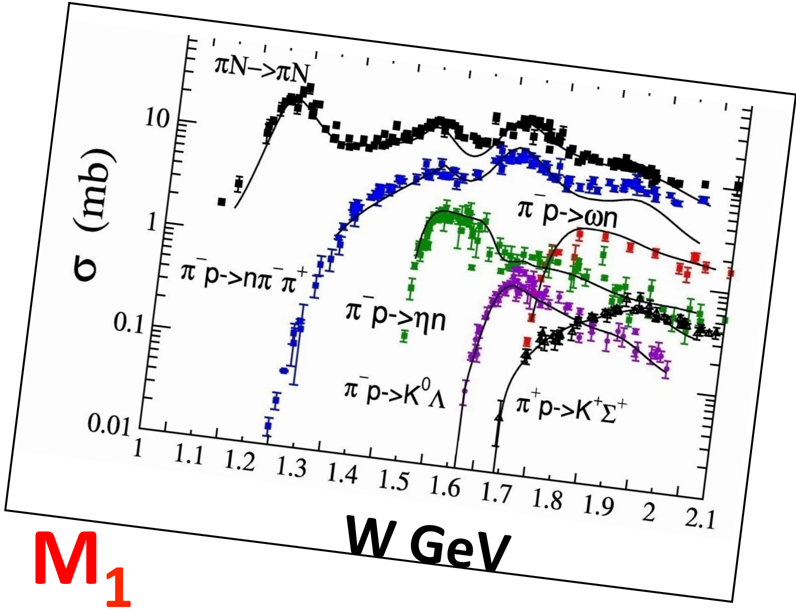
Understand the effective degrees of freedom underlying the N* spectrum and the forces.

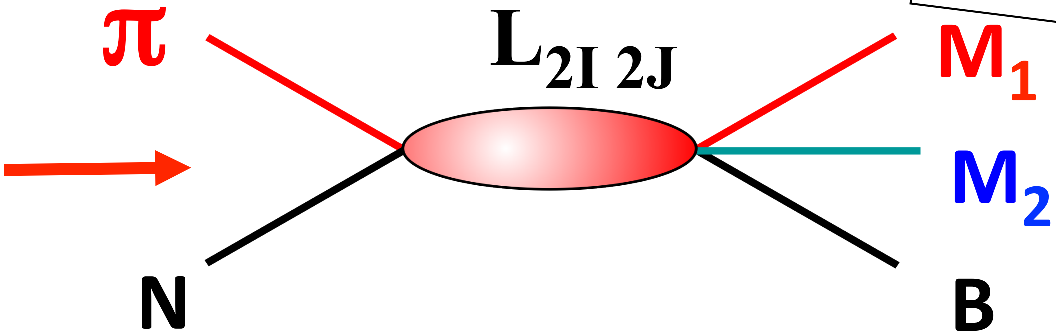


- A vigorous experimental program is worldwide underway with the aim to:
  - search for **undiscovered states** in meson **photoproduction** at CLAS, CBELSA, GRAAL, MAMI, LEPS
  - confirm or dismiss weaker candidates (*, **, ***)
  - characterize the N* and Δ spectrum systematics.
- Measure the strength of resonance excitations versus distance scale in meson **electro-production** at JLab, to reveal the underlying degrees of freedom in the Q^2 evolution of the transition amplitudes.

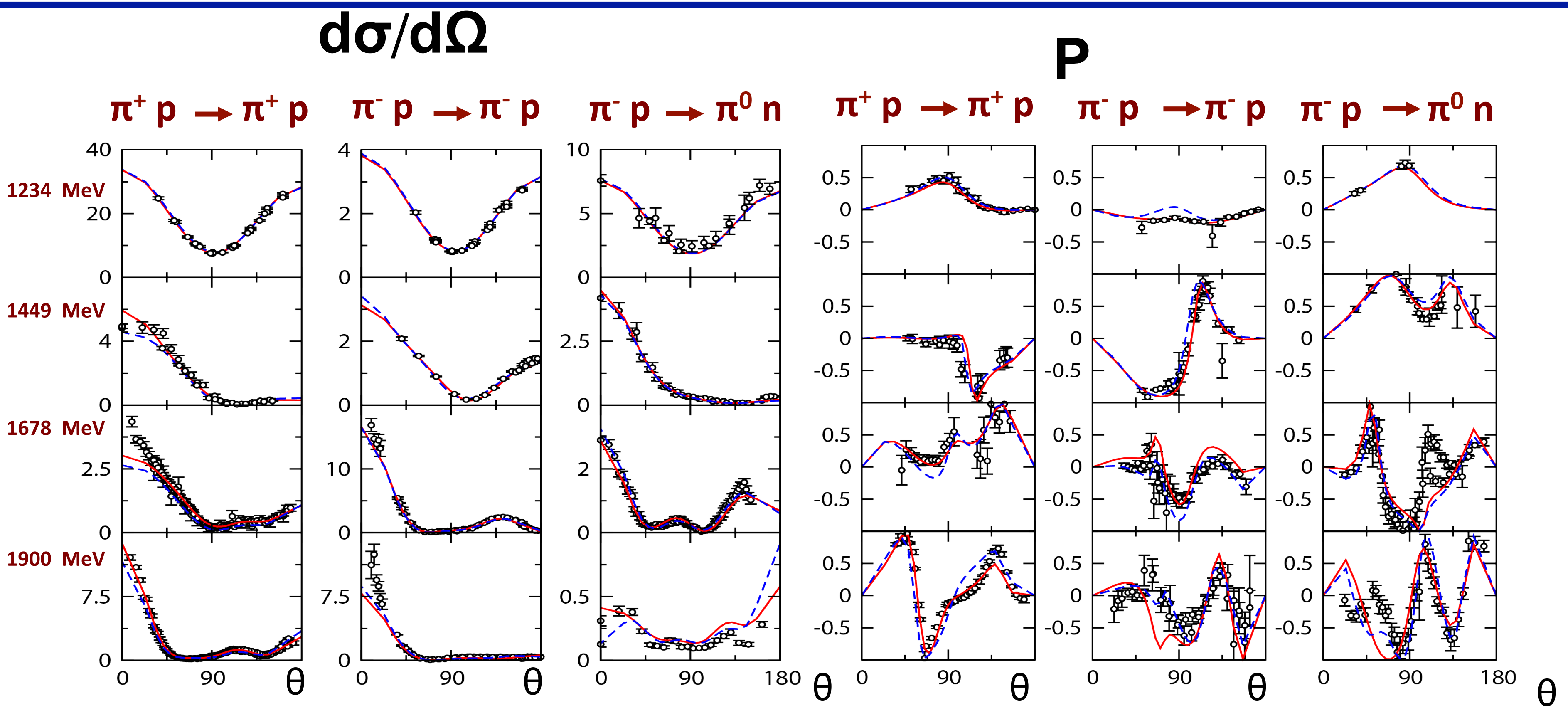
Establishing the N* and Δ Spectrum: πN scattering



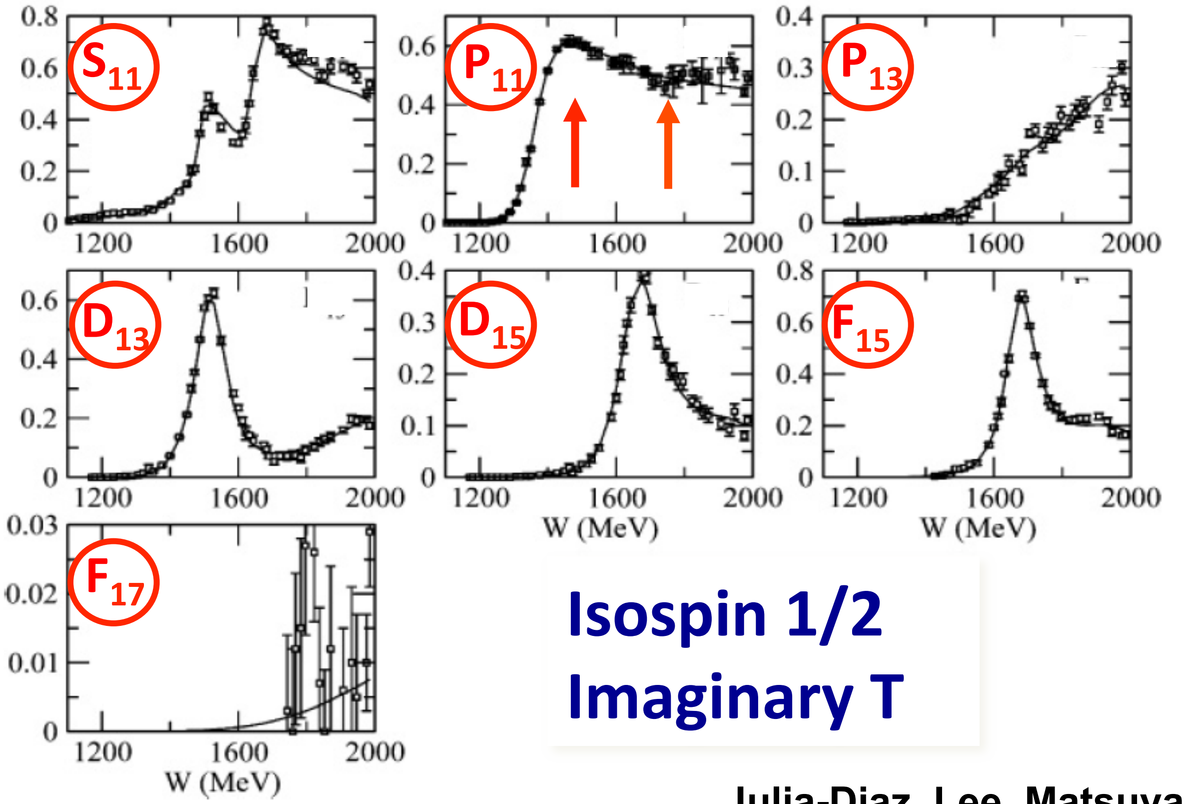




Establishing the N* and Δ Spectrum: πN Scattering



Establishing the N* and Δ Spectrum: πN Amplitudes

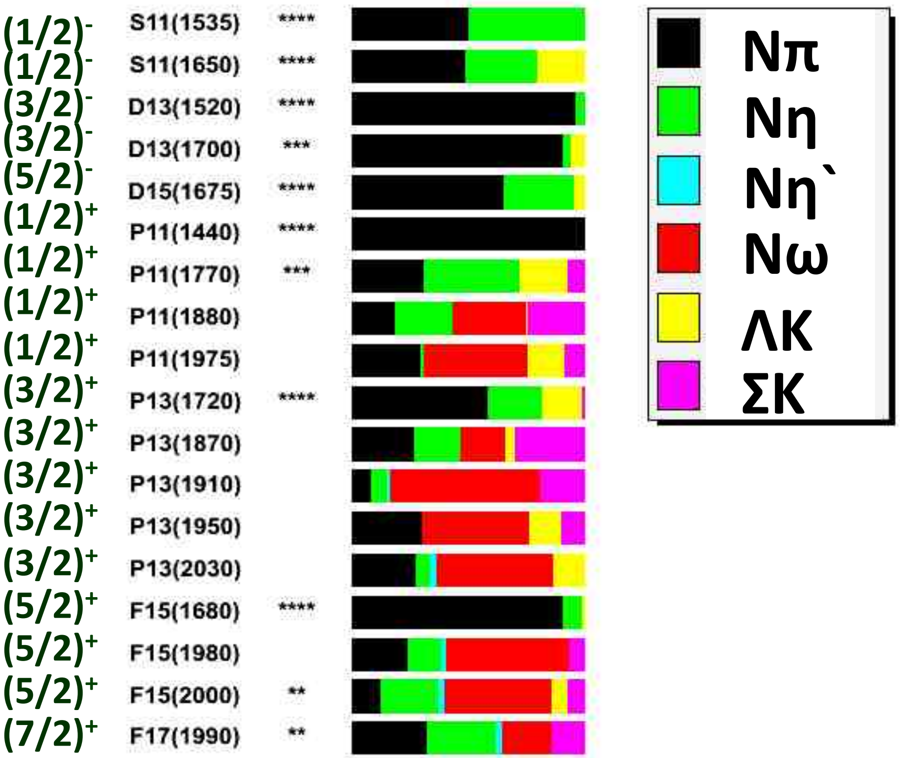


Isospin 1/2
Imaginary T

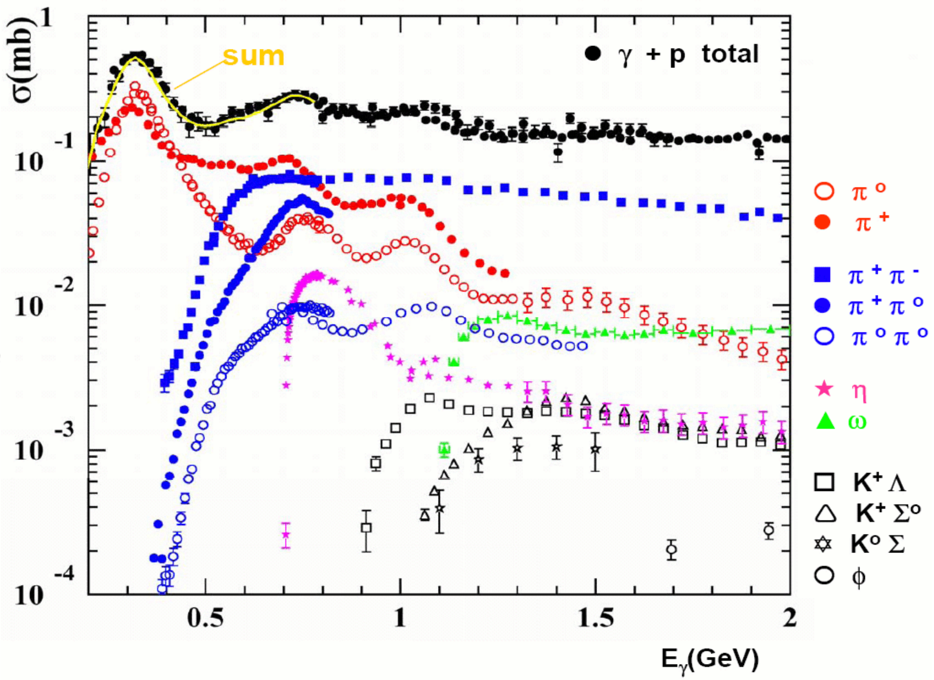
Julia-Diaz, Lee, Matsuyama, Sato

Establishing the N* and Δ Spectrum

Search all channels: not just πN



Photonuclear cross sections



Establishing the N* and Δ Spectrum

Experimental requirements:

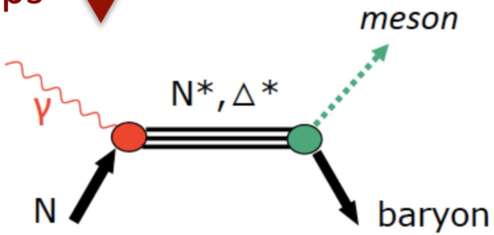
- Precision measurements of photo-induced processes in wide kinematics, e.g.
  γp→πN, ηp, KY, ..,   γn→πN, K^0Y^0, ..

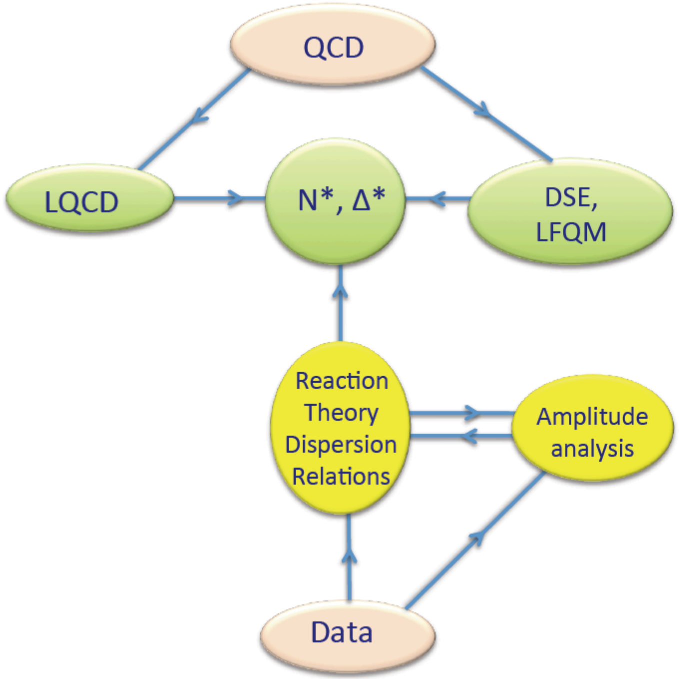
- More complex reactions, e.g. γp → ωp, ρϕ, ππp, ηπN, K*Y, .. may be sensitive to high mass states through direct transition to ground state or through cascade decays

- Polarization observables are essential

Engaging theoretical groups

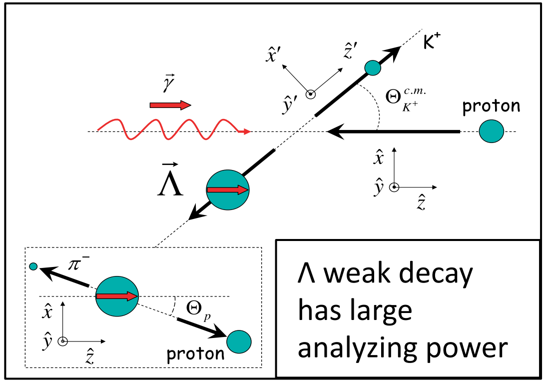
Extract s-channel resonances





Hadronic production & Electromagnetic production

Polarization Observables: Complete Experiment



The holy grail of baryon resonance analysis

- Process described by 4 complex, parity conserving amplitudes
- 8 well-chosen measurements are needed to determine amplitude.
- Up to **16** observables measured directly
- **3** inferred from double polarization observables
- **13** inferred from triple polarization observables

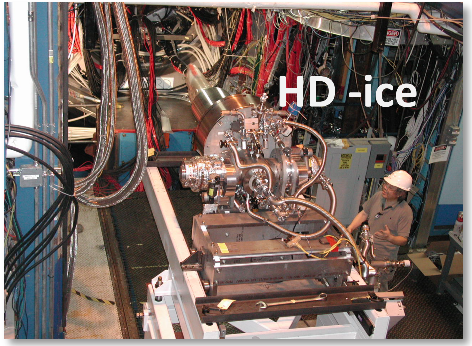
Beam (P^γ)		Target (P^T)			Recoil (P^R)			Target (P^T) + Recoil (P^R)								
					x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
		x	y	z				x	y	z	x	y	z	x	y	z
unpolarized	$d\sigma_0$		$\hat{T}$			$\hat{P}$		$\hat{T}_{x'}$		$\hat{L}_{x'}$		$\hat{\Sigma}$		$\hat{T}_{z'}$		$\hat{L}_{z'}$
$P_L^\gamma \sin(2\phi_\gamma)$		$\hat{H}$		$\hat{G}$	$\hat{O}_{x'}$		$\hat{O}_{z'}$		$\hat{C}_{z'}$		$\hat{E}$		$\hat{F}$		$-\hat{C}_{x'}$	
$P_L^\gamma \cos(2\phi_\gamma)$	$-\hat{\Sigma}$		$-\hat{P}$			$-\hat{T}$		$-\hat{L}_{z'}$		$\hat{T}_{z'}$		$-d\sigma_0$		$\hat{L}_{x'}$		$-\hat{T}_{x'}$
circular P_c^γ		$\hat{F}$		$-\hat{E}$	$\hat{C}_{x'}$		$\hat{C}_{z'}$		$-\hat{O}_{z'}$		$\hat{G}$		$-\hat{H}$		$\hat{O}_{x'}$	

A. Sandorfi, S. Hoblit, H. Kamano, T.-S.H. Lee, J.Phys. 38 (2011) 053001

Experimental set-up

Polarized Frozen-spin Targets & **C**EBAF **L**arge **A**cceptance **S**pectrometer

or



+

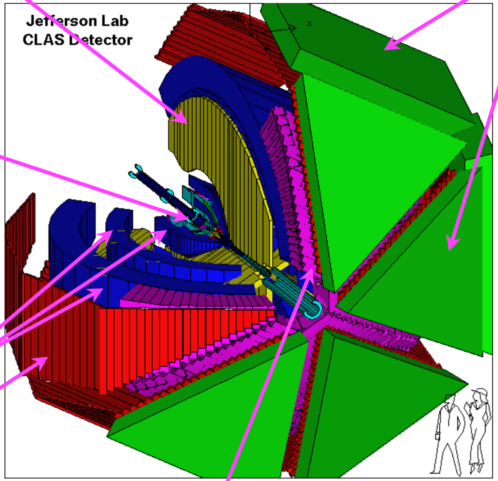
start counter

Torus magnet

6 superconducting coils

Electromagnetic calorimeters

Lead/scintillator, 1296 photomultipliers



Drift chambers

35,000 cells

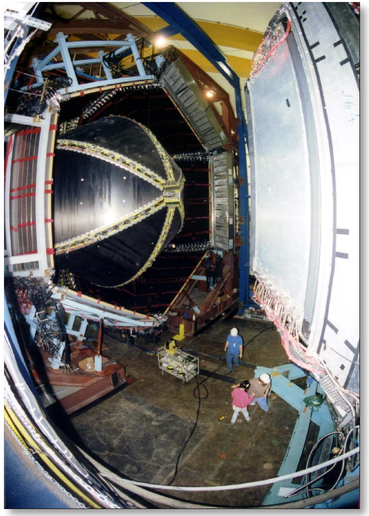
Time-of-flight counters

plastic scintillators,
684 photomultipliers

Gas Cherenkov counters

e/π separation, 256 PMTs

Open CLAS detector



CLAS N* Experimental Program

✔-published, ✓-acquired

Proton targets

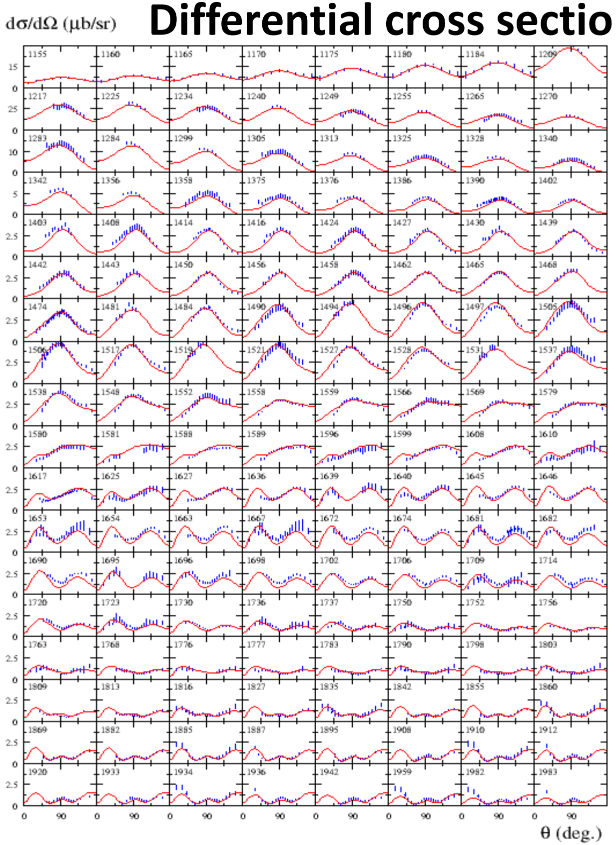
	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
$p\pi^0$	✔	✔	✓		✓	✓	✓	✓								
$n\pi^+$	✔	✔	✓		✔	✓	✓	✓								
$p\eta$	✔	✓	✓		✔	✓	✓	✓								
$p\eta'$	✔	✓	✓		✓	✓	✓	✓								
$N\pi\pi$	✔	✓	✓		✓	✓	✓	✓								
$p\ \omega/\phi$	✔	✓			✔				✔SDME							
$K^+\Lambda$	✔	✔	✔	✔	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔	✔	✔
$K^+\Sigma^0$	✔	✔	✔	✔	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔	✔	✔
$K^{0*}\Sigma^+$	✔	✓									✓	✓				
$K^{+*}\Lambda$	✔	✓		✔												

Neutron targets

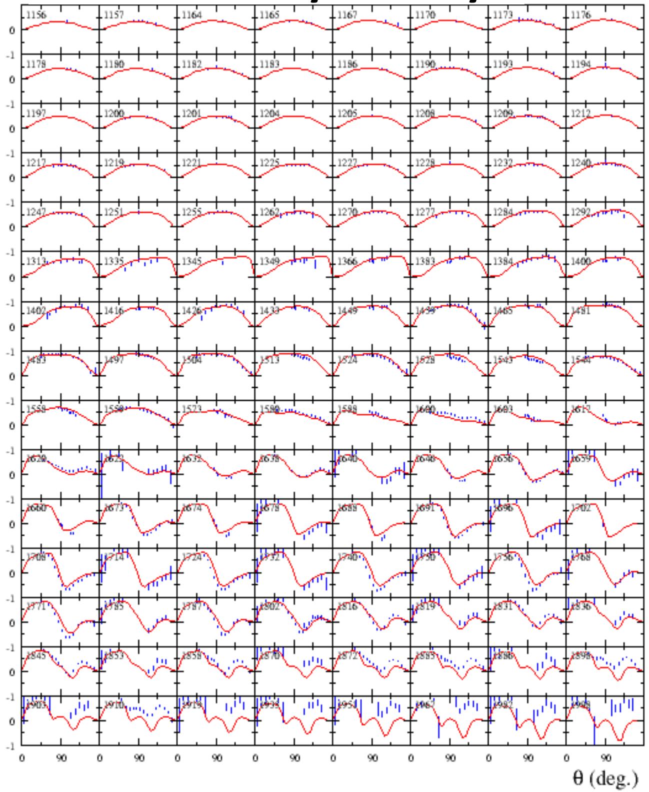
	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
$p\pi^-$	✔	✓			✔	✓	✓									
$p\rho^-$	✔	✓			✓	✓	✓									
$K^-\Sigma^+$	✓	✓			✓	✓	✓									
$K^0\Lambda$	✔	✓		✓	✔	✓	✓				✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓		✓	✔	✓	✓				✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓														

Establishing the N* and Δ Spectrum: $\gamma + p \rightarrow \pi^0 + p$

Differential cross section



Σ Beam Asymmetry

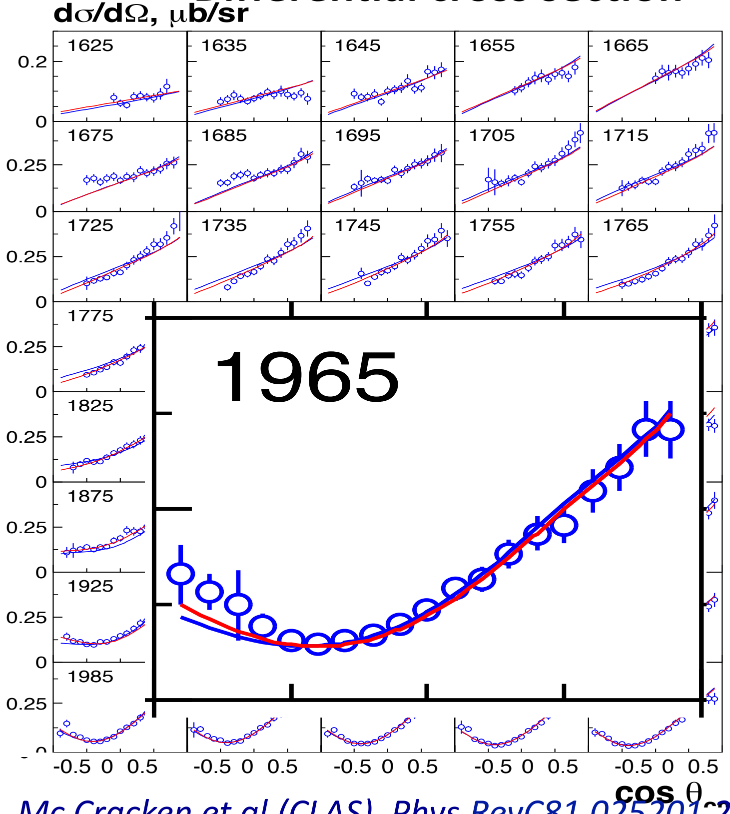


Kamano
Nakamura
Lee &
Sato, 2012

T single
G E F double
polarization
observables
also available

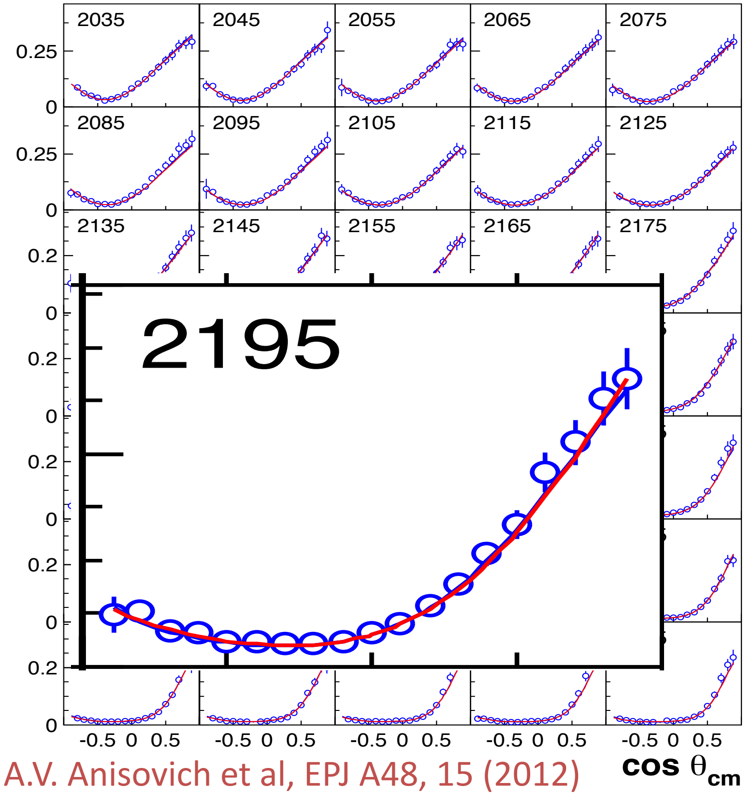
Strangeness production: $\vec{\gamma} + \vec{p} \rightarrow K^+ + \vec{\Lambda} \rightarrow K^+ + p + \pi^-$

Differential cross section



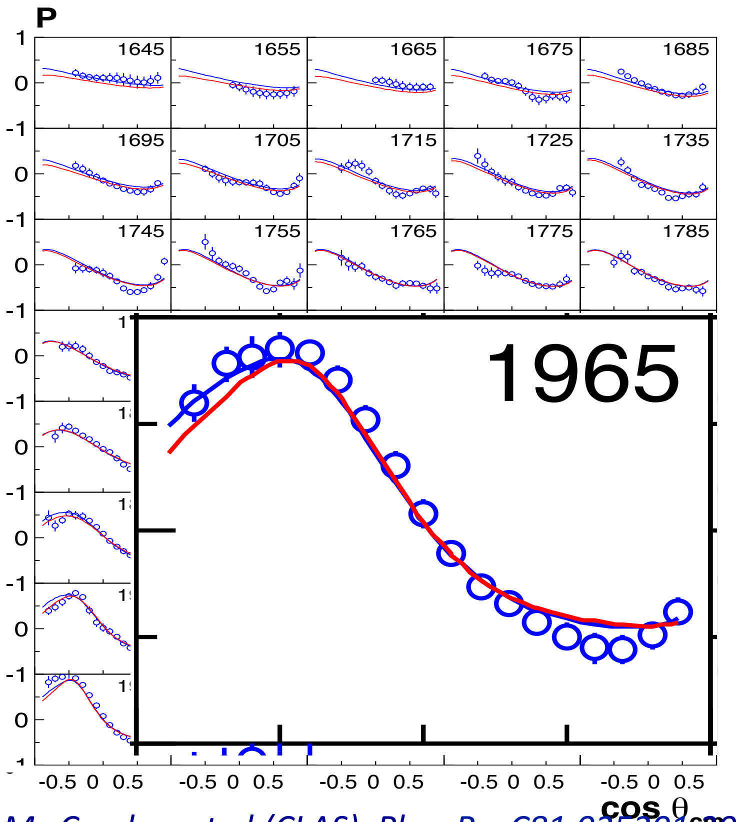
M. Mc Cracken et al.(CLAS), Phys.RevC81,025201,2010

Σ Beam Asymmetry

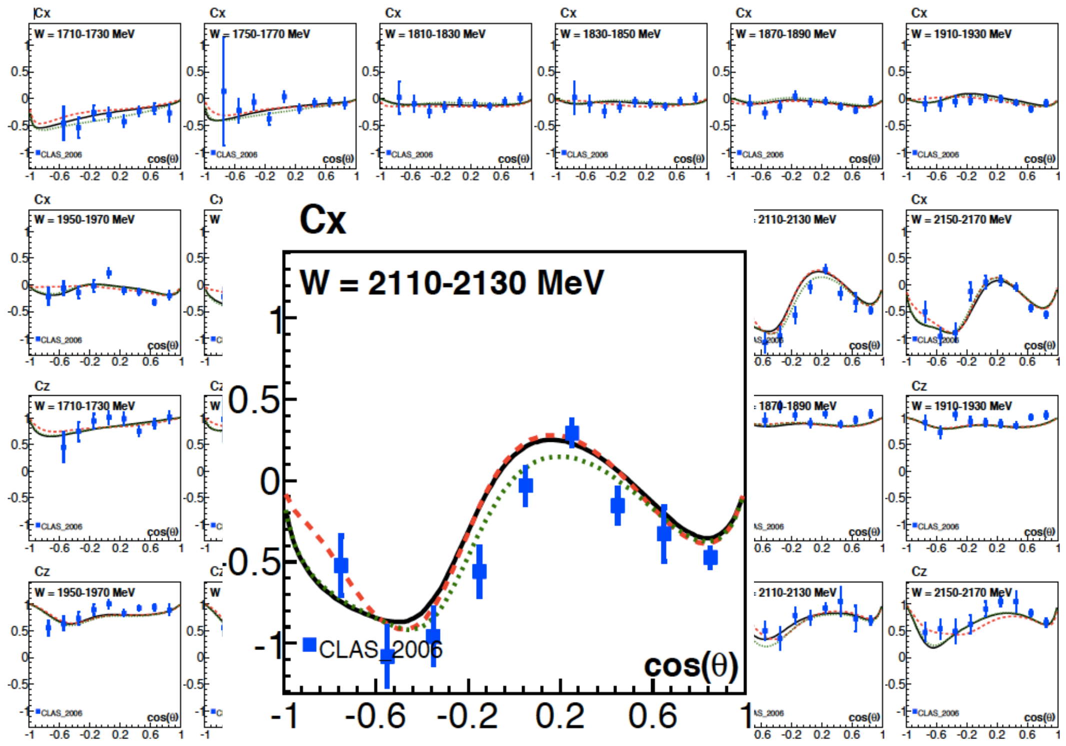


A.V. Anisovich et al, EPJ A48, 15 (2012)

Strangeness production: $\vec{\gamma} + \vec{p} \rightarrow K^+ + \vec{\Lambda} \rightarrow K^+ + p + \pi^-$



M. Mc Cracken et al.(CLAS), Phys.RevC81,025201,2010

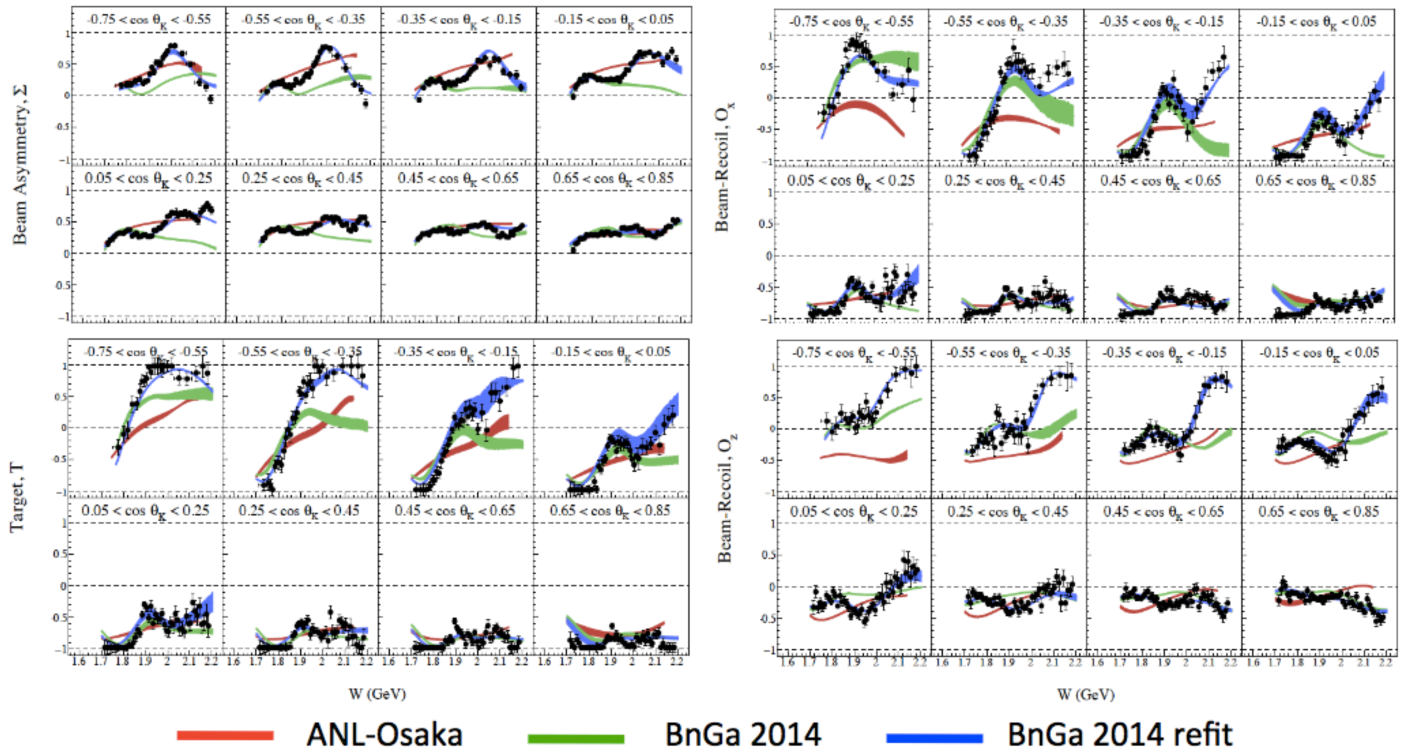


A.V. Anisovich et al, EPJ A48, 15 (2012); PRC96,055202 (2017)

More N* from polarized $K^+ \Lambda$ photoproduction?

$\tilde{\gamma} p \longrightarrow K^+ \vec{\Lambda}$

C.A. Paterson et al., PRC93 (2016) 065201

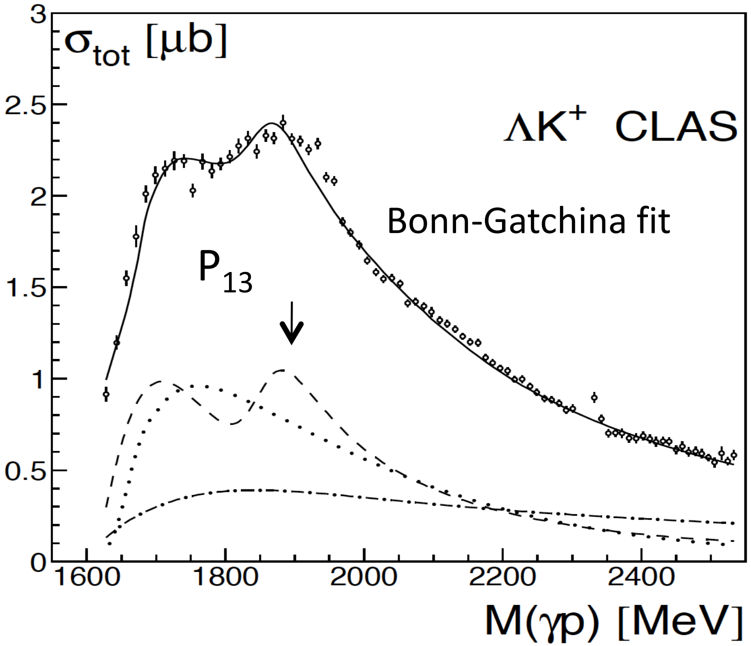


New Multipole Extraction

PRC96,055202 (2017)

The N(1900)3/2⁺ State

- Bump first seen in SAPHIR $K^+ \Lambda$ data but due to systematics in the data misinterpreted as $J^P = 3/2^-$ (D–wave resonance).
- State was solidly established in Bn-Ga coupled-channel analysis making use of very precise KΛ polarized data, resulting in *** assignment in PDG2012. (P-wave resonance) and confirmed by recent multipole extraction (PRL 119, 062004, 2017)
- State confirmed in an effective Langrangian resonance model analysis $\gamma p \rightarrow K^+ + \Lambda$ (*O. V. Maxwell, PRC85,034611, 2012*)
- State confirmed in a covariant isobar model single channel analysis $\gamma p \rightarrow K^+ + \Lambda$ (*T. Mart & M. J. Kholili, PRC86, 022201, 2012*).
- First baryon resonance observed and multiply confirmed in electromagnetic production. → **Candidate for **** state**



Updated Spectrum of Baryon Resonances

- From 2000 to 2010 no new Baryon resonances were considered by the PDG.
  - Used πN- scattering data and some π-photoproduction only.
- Mature multi-channel models now include many photoproduction data.
- E.g. Bonn-Gatchina PWA analysis, A. Anisovich et al. EPJ A 48, 15 (2012), PRL 119, 062004, 2017)

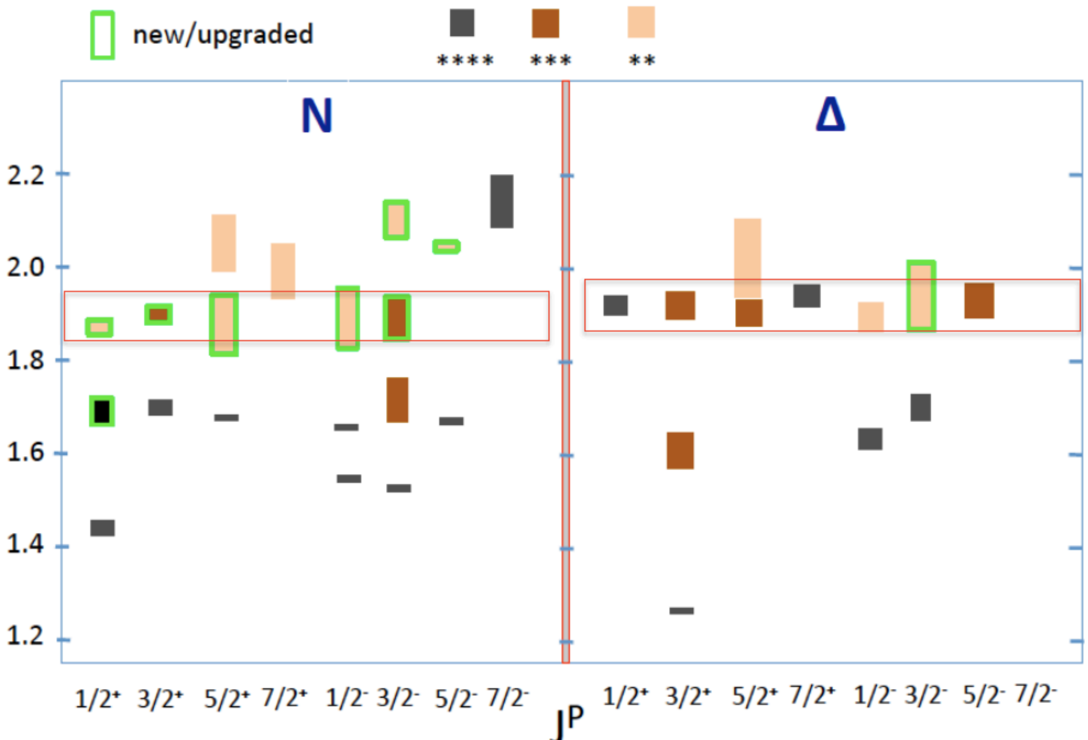
	Particle Data Group 2010	BnGa analyses	Particle Data Group 2012
$N(1860)5/2^+$		*	**
$N(1875)3/2^-$		***	***
$N(1880)1/2^+$		**	**
$N(1895)1/2^-$		**	**
$N(1900)3/2^+$	**	***	***
$N(2060)5/2^-$		***	**
$N(2150)3/2^-$		**	**
$\Delta(1940)3/2^-$	*	*	**

Naming scheme has changed:

$L_{2I\ 2J}(E) \longrightarrow J^P(E)$

- Results from photoproduction now add to the PDG tables and determine properties of baryon resonances

Lower Mass N*/Δ spectrum in 2015

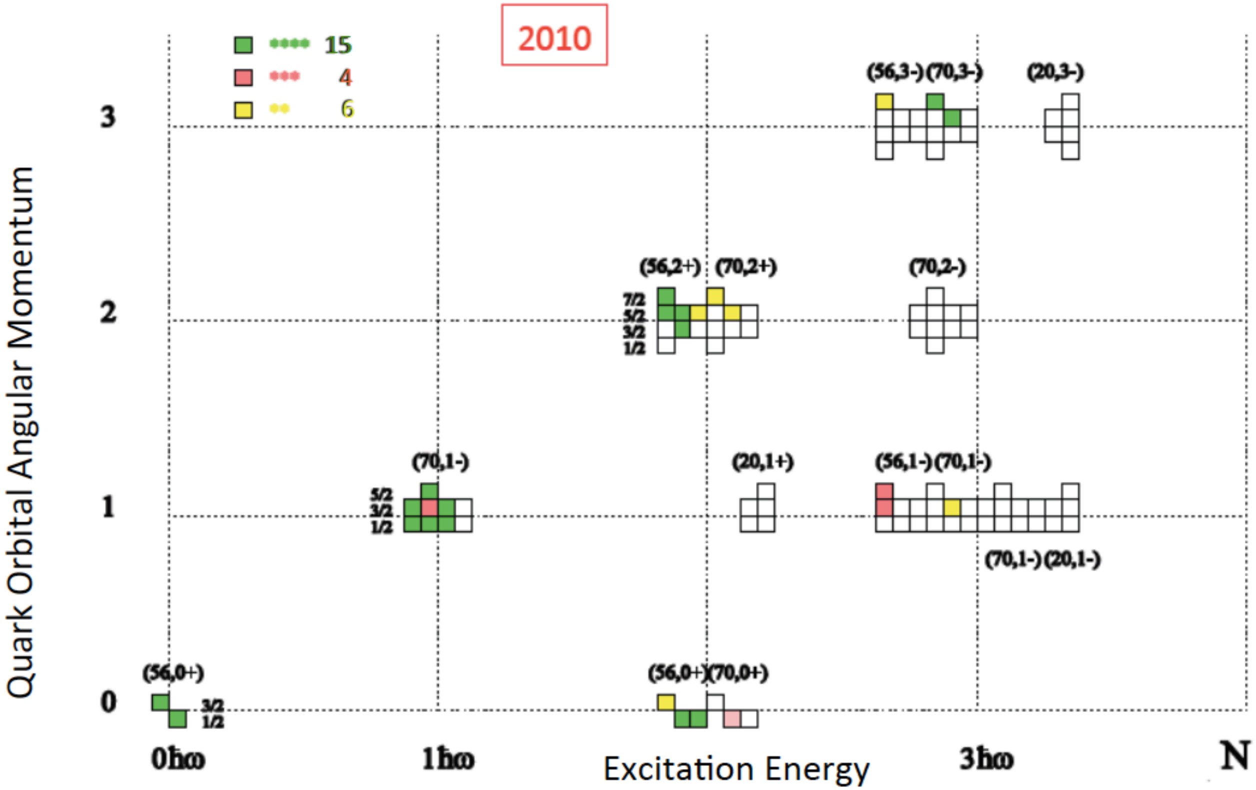


Are there mass degenerate spin multiplets?

Do these states fit into the SU(6) state symmetry? Lattice?

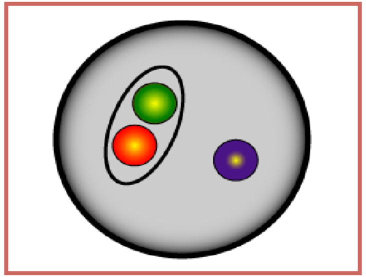
Constituent Quark Models & QCD

SU(6)xO(3)

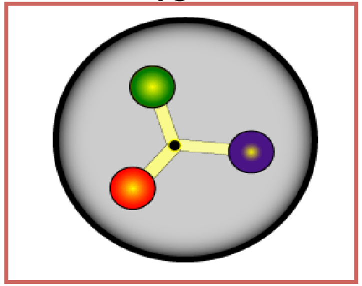


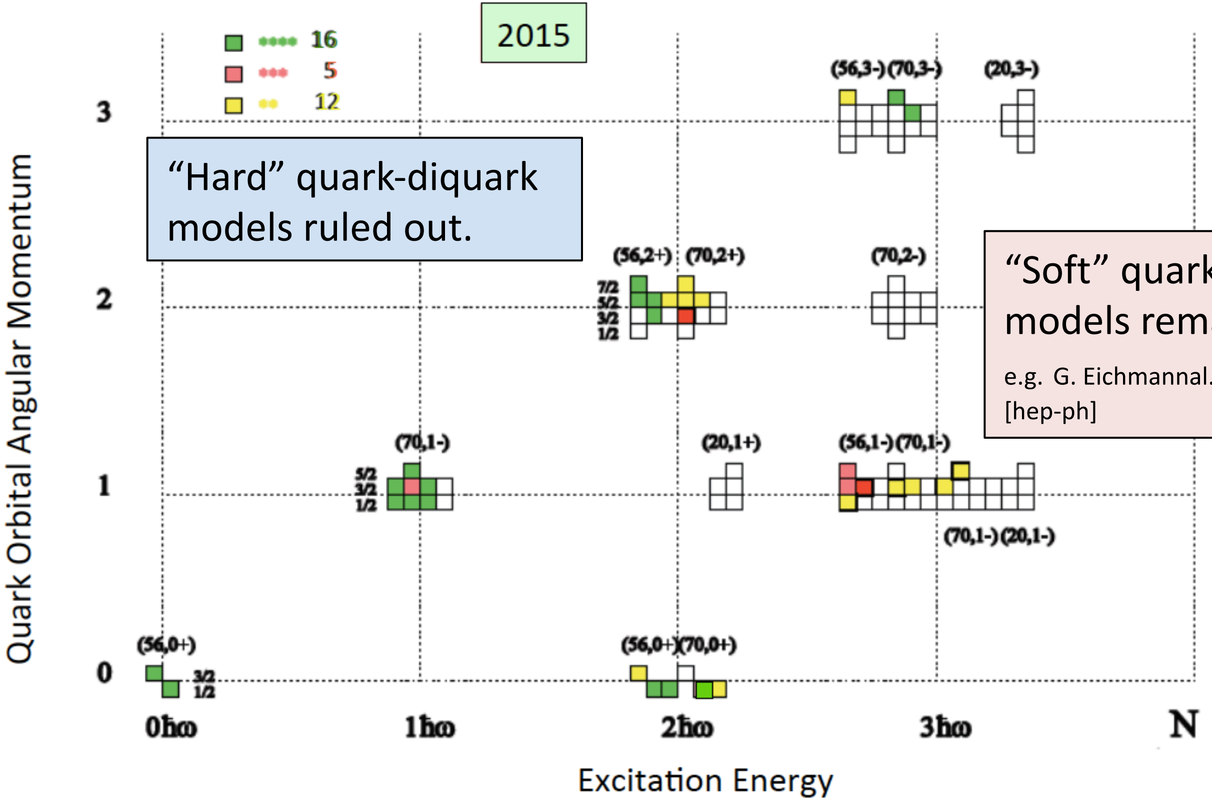
Do New States Fit into Q^3 QM ?

SU(6)xO(3)



vs





"Hard" quark-diquark models ruled out.

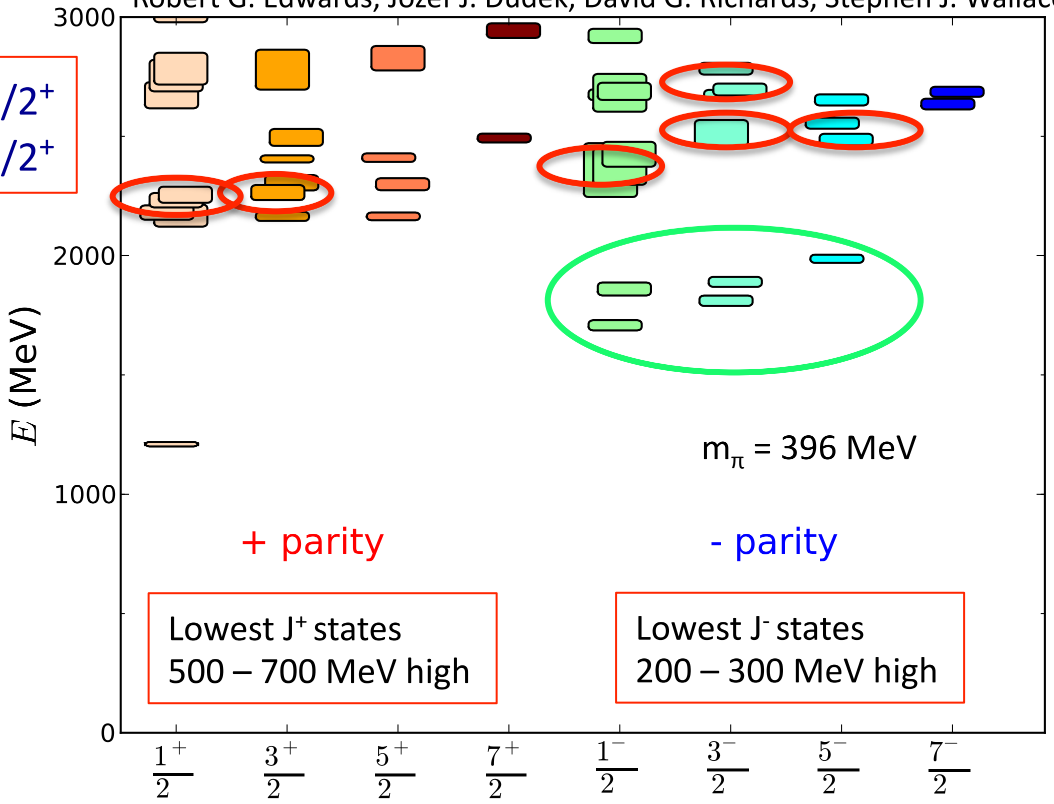
"Soft" quark-diquark models remain viable.

e.g. G. Eichmannal. et arXiv:1607.05748 [hep-ph]

Do New States Fit into LQCD Projections ?

Robert G. Edwards, Jozef J. Dudek, David G. Richards, Stephen J. Wallace **Phys.Rev. D84 (2011) 074508**

N(1900)3/2$^+$
N(1880)1/2$^+$



N(2060)5/2$^-$
N(2120)3/2$^-$
N(1875)3/2$^-$
N(1895)1/2$^-$

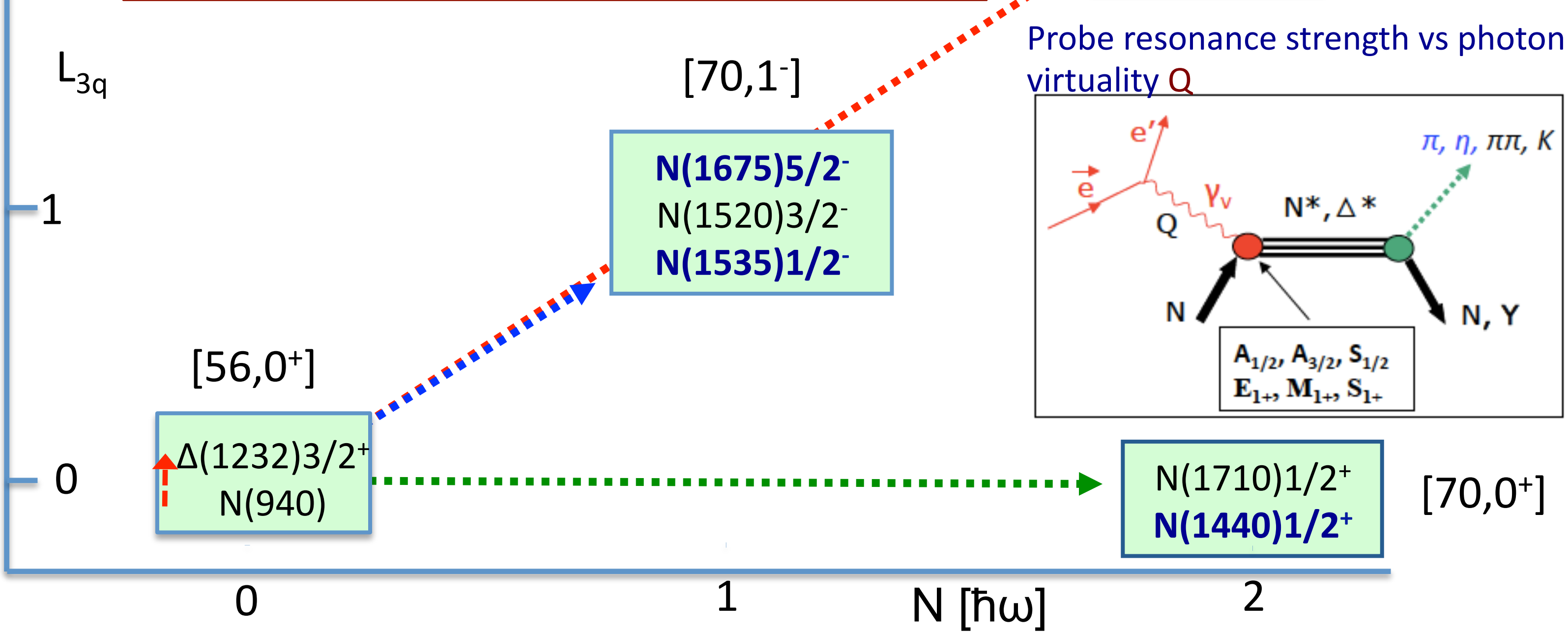
Ignoring the mass scale, new candidates fit the J^P values predicted from LQCD.

The field would really benefit from more realistic Lattice masses for N* states.

Known states:
N(1675)5/2$^-$
N(1700)3/2$^-$
N(1520)3/2$^-$
N(1650)1/2$^-$
N(1535)1/2$^-$

Electroexcitation of N*/Δ resonances

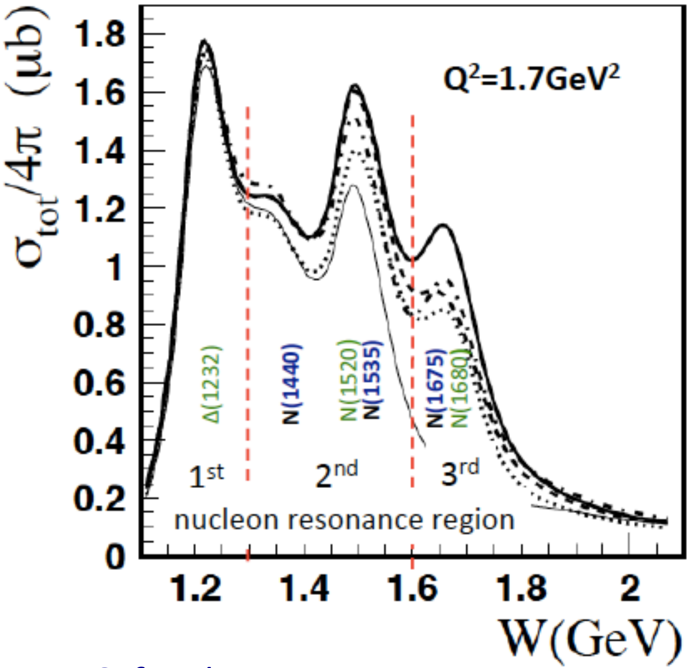
Central question in hadron physics:
what are the relevant degrees of freedom at varying distance scale?

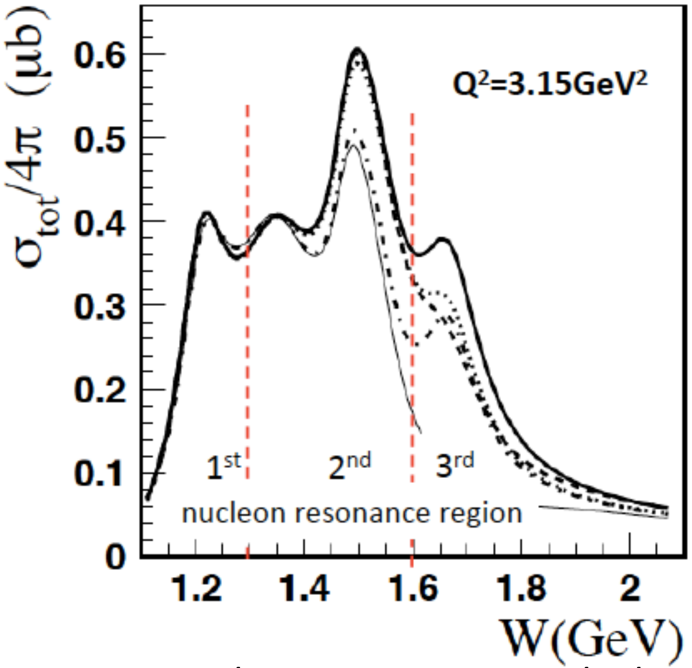


Total cross section at W < 2.1 GeV

$\gamma^* + p \longrightarrow \pi^+ + n$

Data: *K. Park et al. PRC 77 (2008) 015208; K. Park et al. PRC 91 (2015) 045203*





Analysis with UIM & fixed-t DR; Recent review: I. Aznauryan, V. Burkert, Prog. Part. Nucl. Phys. 67 (2012) 1.

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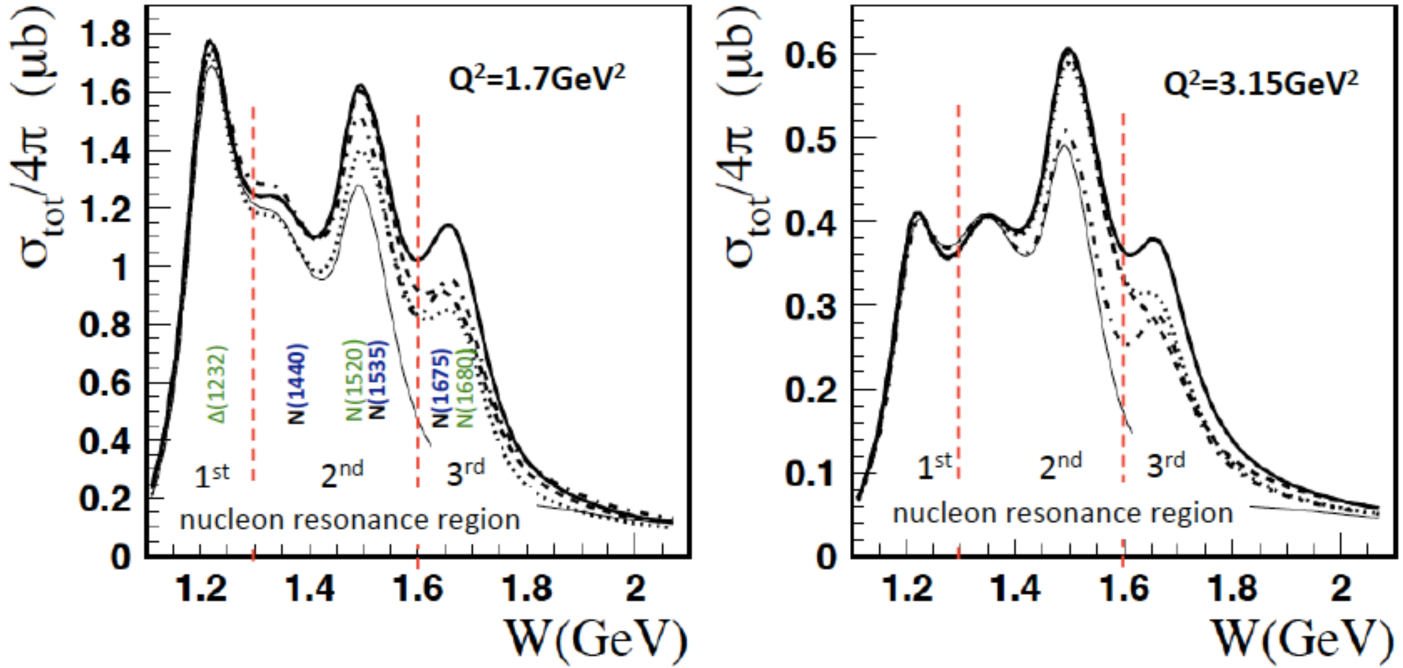
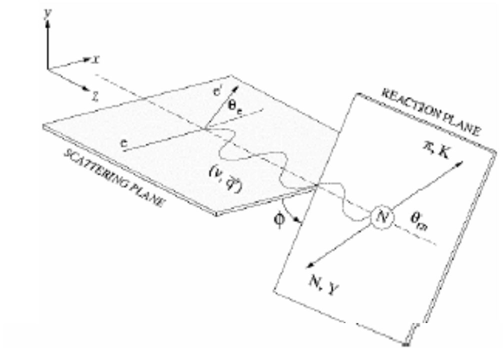


Different states respond differently to changes in Q^2

Electroexcitation kinematics



$$\frac{d^4\sigma}{dQ^2 dW\, d\Omega_K} = \Gamma(Q^2, W) \times \frac{d\sigma}{d\Omega_K}\left(Q^2, W, \Theta_K, \varepsilon, \phi\right)$$

Virtual photon flux

Electroproduction cross section

Transverse

Transverse-tra e interference

Helicity structure

$$\frac{d\sigma}{d\Omega_K} = \sigma_T + \varepsilon_L \sigma_L + \varepsilon \sigma_{TT} \cos(2\phi) + \sqrt{2\varepsilon_L(\varepsilon+1)}\,\sigma_{LT} \cos(\phi) + h\sqrt{2\varepsilon_L(1-\varepsilon)}\,\sigma_{LT'}$$

σ_u "Unseparated"

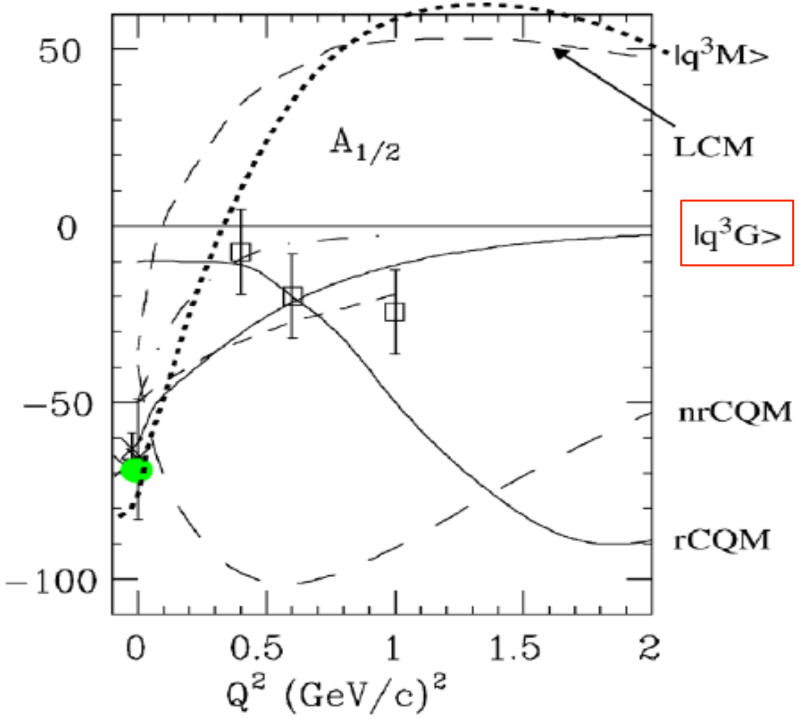
Longitudinal (sensitive to J=0$^{\pm}$ exchange in t-channel: mesons, diquarks)

Transverse-longitudinal interference

Measured σ are decomposed using UIM or fixed-t DR to extract N* & Δ helicity amplitudes.

Electrocouplings of the 'Roper' in 2002

N(1440)1/2$^+$



In 2002 Roper amplitude $A_{1/2}$ measurements were more consistent with hybrid state but data were limited with large uncertainties.

Electrocouplings of the 'Roper' in 2016

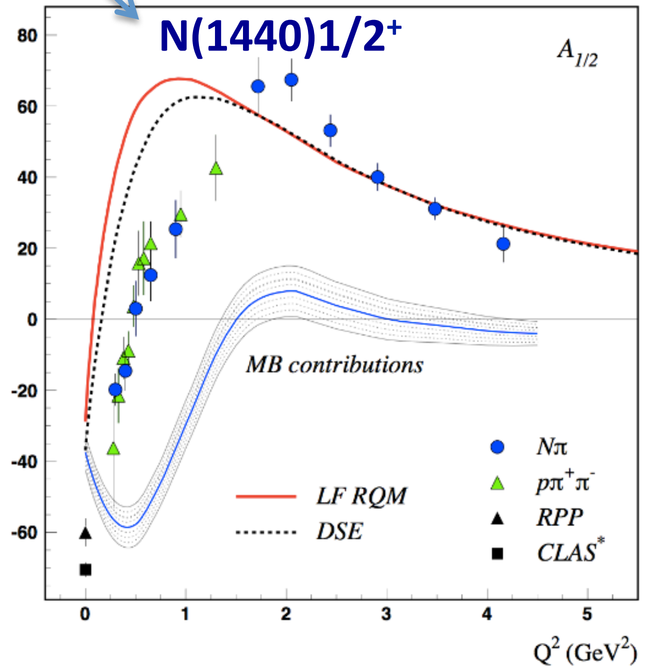
LF RQM: I. Aznauryan, V.B. arXiv:1603.06692

Quark-core contributions from DSE/QCD
J. Segovia et al. PRL 115 (2015) 171801.

***Meson Baryon cloud** inferred from CLAS data as the difference between data and the quark-core evaluation in DSE/QCD.*
V. Mokeev et al., PR C 93 (2016) 025206.

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

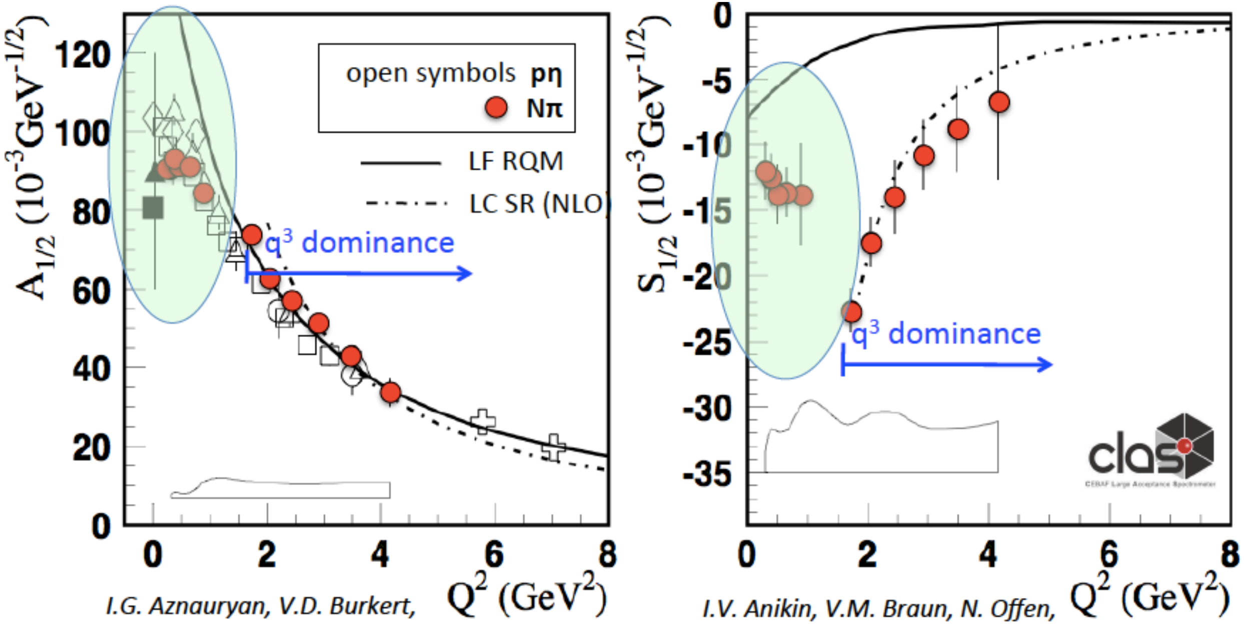
The 1st radial excitation of the q3 core emerges as the probe penetrates the MB cloud.



The structure of the Roper is driven by the interplay of the core of three dressed quarks in the 1st radial excitation and the external meson-baryon cloud.

MB Contribution to electro-excitation of N(1535)1/2⁻

Is it a 3-quark state or a hadronic molecule?



I.G. Aznauryan, V.D. Burkert, PR C85 (2012) 055202

I.V. Anikin, V.M. Braun, N. Offen, PR D92 (2015) 1, 014018

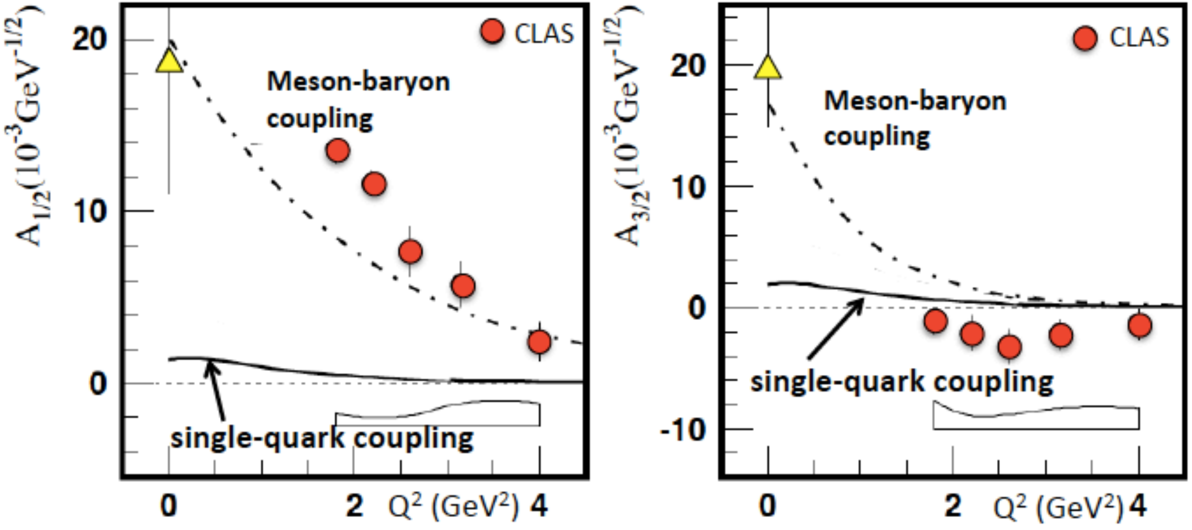
N(1535)1/2⁻ is consistent with the 1st orbital excitation of the nucleon.

- Meson-baryon cloud may account for discrepancies at low Q^2.

MB Contribution to electro-excitation of N(1675)5/2$^-$

Quark components to the helicity amplitudes of the N(1675) 5/2$^-$ are strongly suppressed for **proton target.**

Single Quark Transition:
$A^p_{1/2} = A^p_{3/2} = 0$



- Measures the meson-baryon contribution to the γ^* p N(1675)5/2$^-$ directly.
- Can be verified on γ^* n N(1675)5/2$^-$ which is not suppressed

——— *E. Santopinto and M. M. Giannini, PRC 86, 065202 (2012)*

– · – · *B. Juliá-Díaz, T.-S.H. Lee, et al., PRC 77, 045205 (2008)*

Hybrid Baryons: Baryons with Explicit Gluonic Degrees of Freedom

Hybrid hadrons with dominant gluonic contributions are predicted to exist by QCD.

Experimentally:

- **Hybrid mesons** $|q\bar{q}g\rangle$ states may have exotic quantum numbers J^{PC} not available to pure $|q\bar{q}\rangle$ states GlueX, MesonEx, COMPASS, PANDA ….

- **Hybrid baryons** $|qqqg\rangle$ have the same quantum numbers J^P as $|qqq\rangle$ electroproduction with CLAS12 (Hall B).

Theoretical predictions:

✧ MIT bag model - T. Barnes and F. Close, Phys. Lett. 123B, 89 (1983).

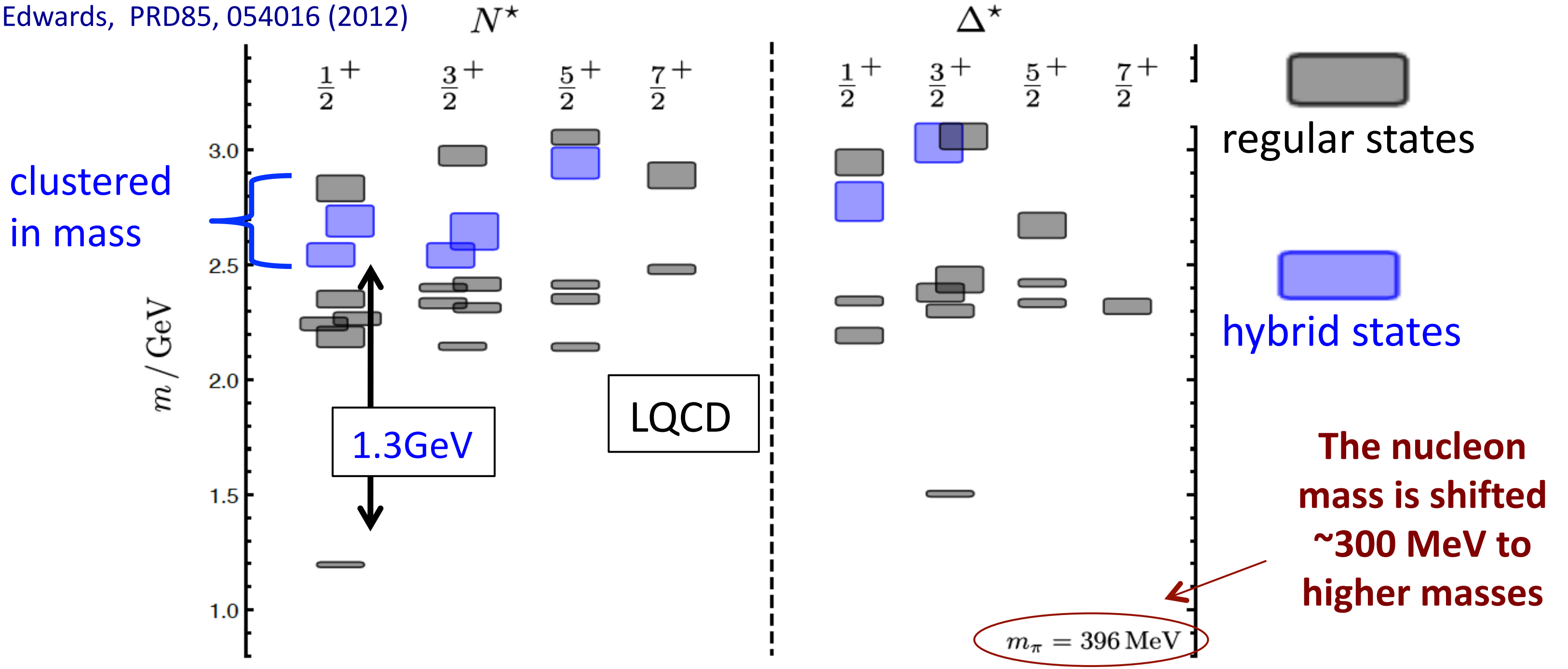
✧ QCD Sum Rule - L. Kisslinger and Z. Li, Phys. Rev. D 51, R5986 (1995).

✧ Flux Tube model - S. Capstick and P. R. Page, Phys. Rev. C 66, 065204 (2002).

✧ LQCD - J.J. Dudek and R.G. Edwards, PRD85, 054016 (2012).

Hybrid Baryons in LQCD

J.J. Dudek and R.G. Edwards, PRD85, 054016 (2012)



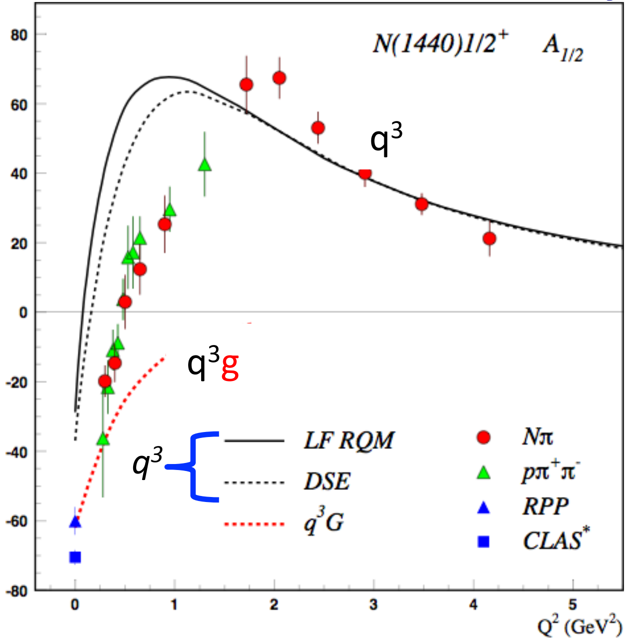
Hybrid states have same J^P values as qqq baryons. How to identify them?

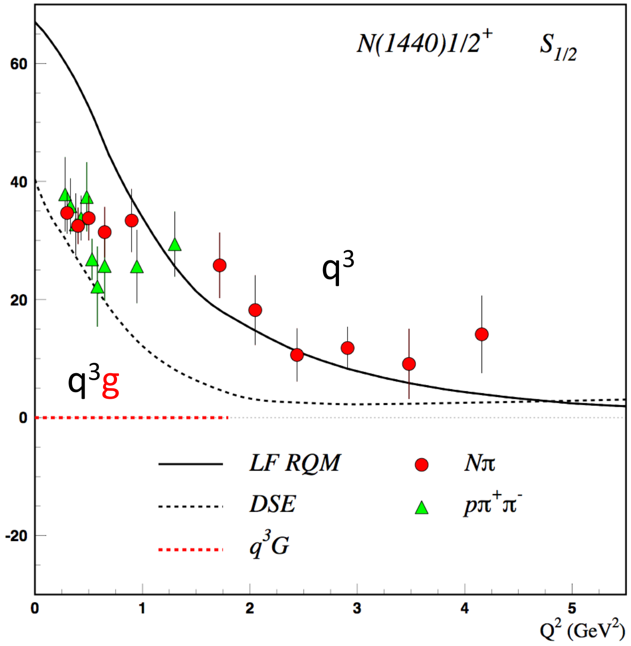
- Overpopulation of N $1/2^+$ and N $3/2^+$ states compared to QM projections.
- **$A_{1/2}$ ($A_{3/2}$) and $S_{1/2}$ show different Q^2 evolution.**

Separating q^3g from q^3 states ?

CLAS results on electrocouplings clarified nature of the Roper.

Will CLAS12 data be able to identify gluonic contributions ?





For hybrid "Roper", $A_{1/2}(Q^2)$ drops off faster with Q^2 and $S_{1/2}(Q^2) \sim 0$.

Baryon Spectroscopy Status Today

- Major progress made in the last years in the search for N* and Δ states.
  All states can be accommodated in CQM and LQCD schemes.
  - Naïve (non-dynamical) di-quark models are ruled out.

- Knowledge of Q^2-dependence of electrocouplings is absolutely necessary to understand the nature (the internal structure) of the excited states.
  - Roper IS the first radial excitation of the q^3 core, obscured at large distances by meson-cloud effects.

- Leading electrocoupling amplitudes of prominent low-mass states (e.g. N(1535)$1/2^-$) is well modeled by DSE/QCD, LC SR and LF RQM for Q^2> 2 GeV.

- Search for hybrid baryons with explicit gluonic degrees of freedom would be possible investigating the low Q^2 evolution of high-mass resonance (2-3 GeV) electrocoupligs:
  - Looking for suppressed $A^{1/2}$, $A^{3/2}$, $S^{1/2}$ at low Q^2.