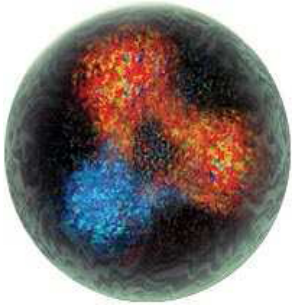
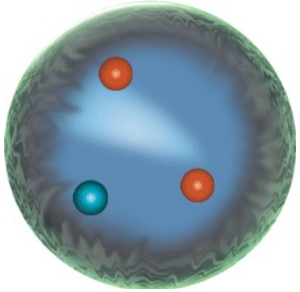


WHAT NUCLEON RESONANCES TEACH US ABOUT NUCLEON STRUCTURE



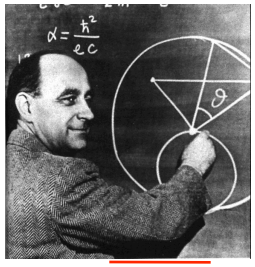
Philip Cole*
Idaho State University
March 27, 2015

*U.S. National Science Foundation grant NSF-PHY-1206082
Talk given in coordination with Volker Burkert

Outline

- Introduction and three big questions
- Overview of effective degrees of freedom
- Establishing the N* spectrum
- Electroexcitation ($Q^2 > 0$) and N* structure
- Towards "complete" experiments
- Conclusions/outlook

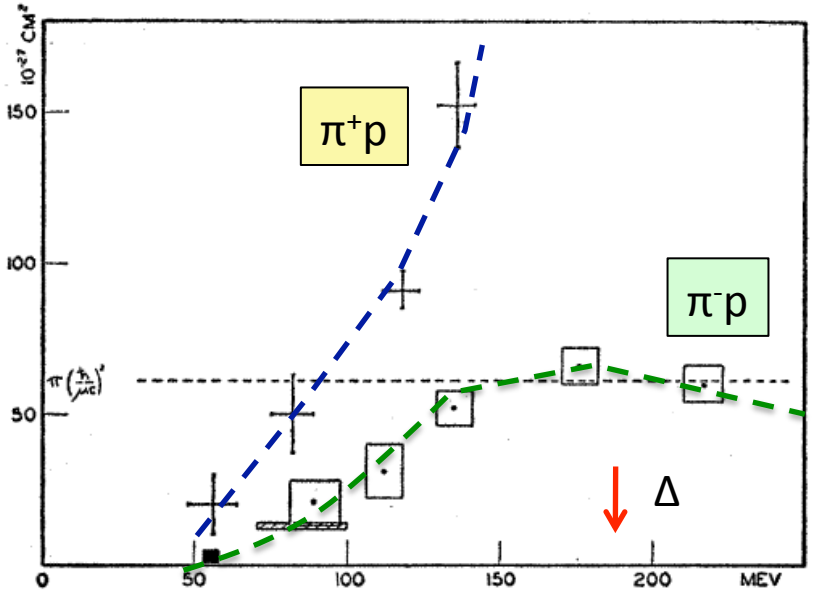
First baryon resonance and beyond

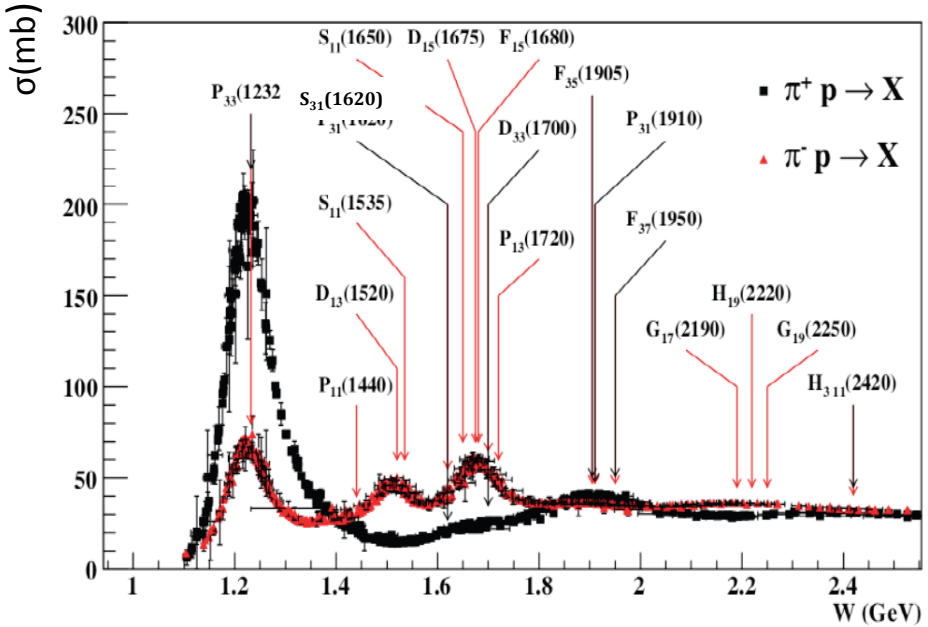


E. Fermi , 1952

Total Cross Sections of Positive Pions in Hydrogen*

H. L. Anderson, E. Fermi, E. A. Long,† and D. E. Nagle
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 21, 1952)

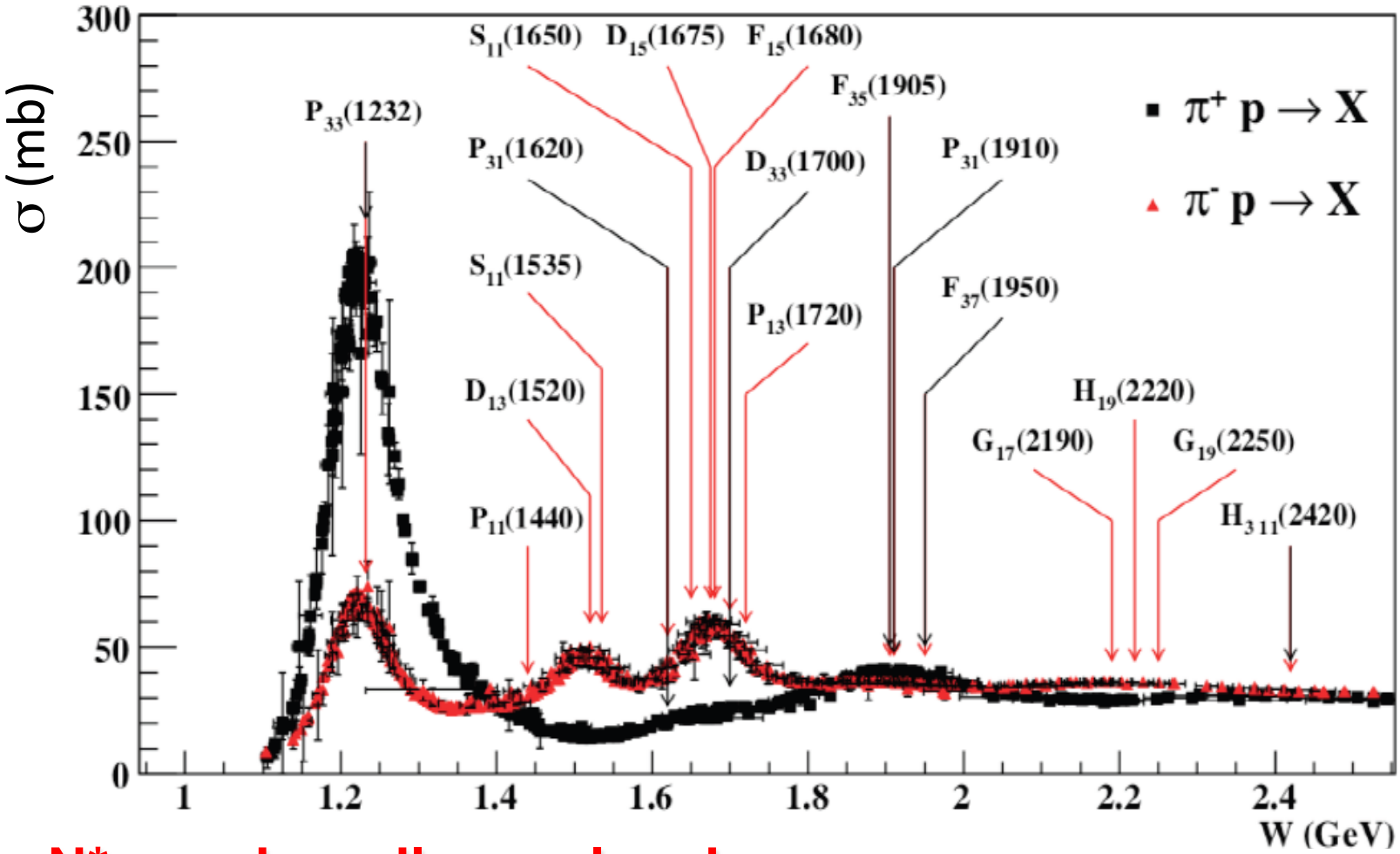




Many states have been discovered in pion-nucleon elastic scattering πN --> πN.

Many states expected from symmetric CQM were not found – are they nonexistent or have they escaped detection because they do not couple to πN?

Baryon resonances (N*s and Δ*s)



- **N*s are broadly overlapping**
- **Hard to disentangle without polarization observables**

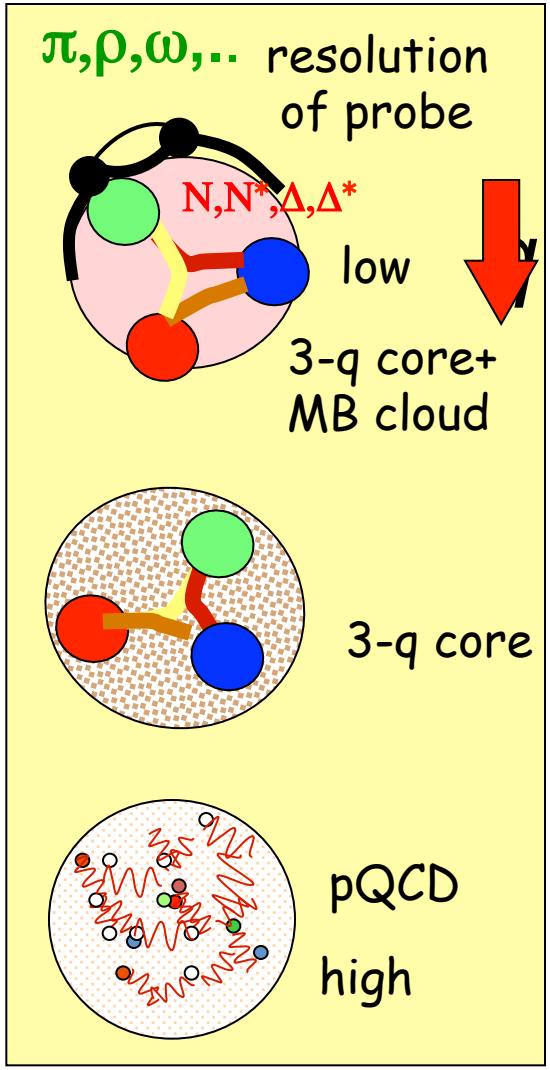
Fundamental questions of bound states in QCD

1. How does nature achieve confinement?

2. How is confinement tied into dynamical chiral symmetry breaking, which describes the origin of most of the visible mass in the universe?

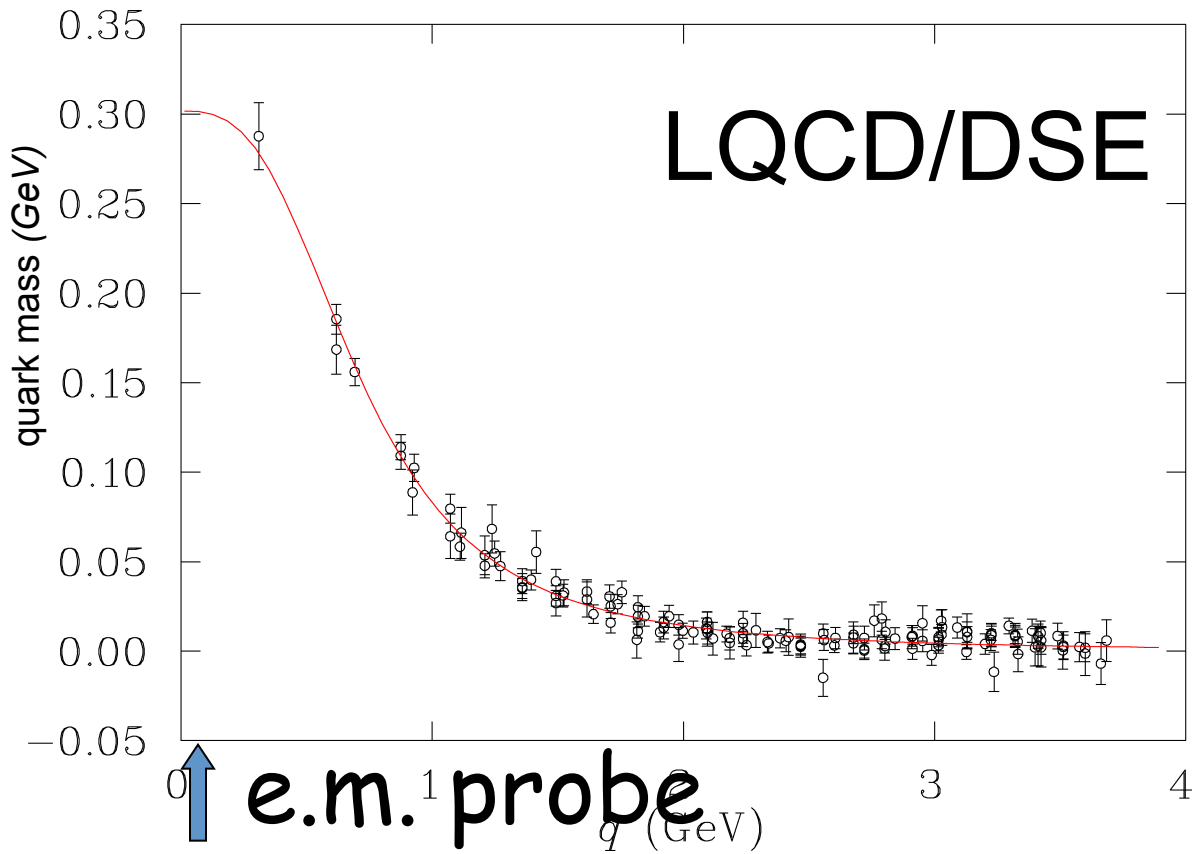
3. Can the fundamental QCD Lagrangian successfully describe the complex structure of all the N* states?

Hadron structure via electromagnetic probes



Allows us to address central the question:

What are the relevant degrees of freedom at varying distance scale?



What do we want to learn?

- Understand the effective degrees-of-freedom underlying the N* spectrum.

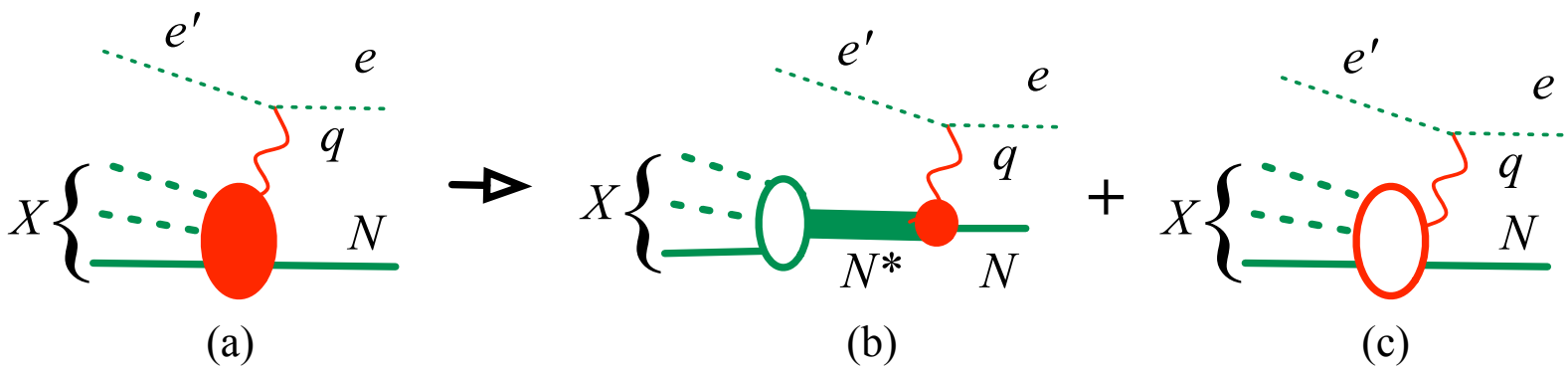
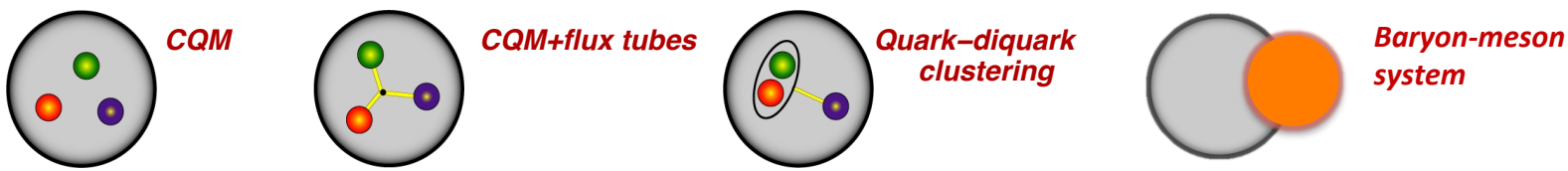


FIG. 2. Diagram (a) represents the scattering of an electron from a nucleon with the creation of a final state X. It is built from two contributions: (b) the excitation of several N^* intermediate states (only one shown in the figure), and (c) background contributions. Note that time flows from right to left in the diagrams.

- What configurations are seen in nature, do they depend on distance scale, what are the underlying symmetries?
- Is chiral symmetry restored at high masses?

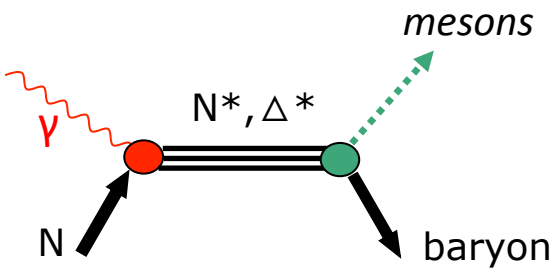
What do we want to learn?

- Understand the effective degrees-of-freedom underlying the N* spectrum.



- A vigorous experimental program is underway along two avenues
  - Search for undiscovered states in meson photoproduction to systematically characterize the excited baryon spectrum

$$\vec{\gamma}\vec{N} \rightarrow N\pi \qquad \vec{\gamma}\vec{N} \rightarrow N\pi\pi$$

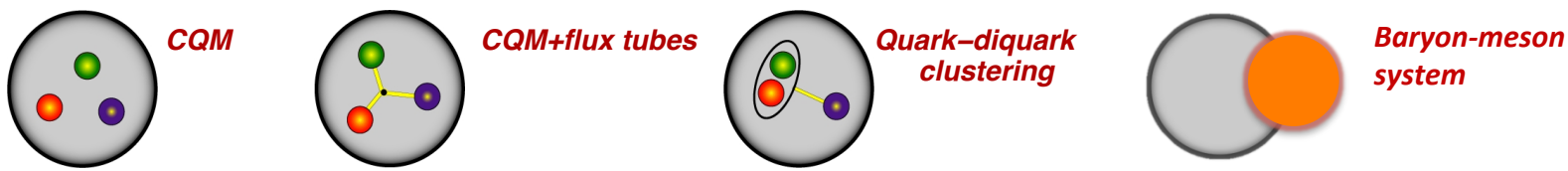


- the photon beam can be circularly or linearly polarized
- the nucleon may be transversely or longitudinally polarized

(either target or beam may be polarized, both may be polarized, or neither the target nor the beam be polarized as the case may be)

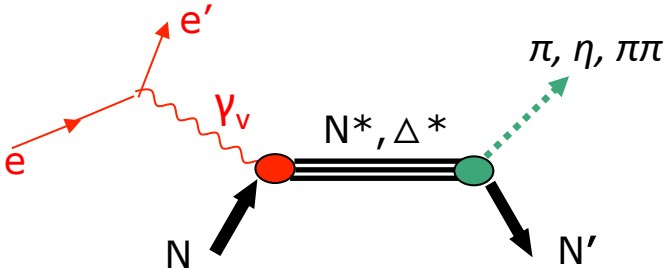
What do we want to learn?

- Understand the effective degrees-of-freedom underlying the N* spectrum.



- A vigorous experimental program is underway along two avenues
  - Search for undiscovered states in meson photoproduction to systematically characterize the excited baryon spectrum
  - Measure the strength of resonance excitations vs time-distance scale in meson electroproduction (i.e. as a function of $Q^2 = -q^2$)

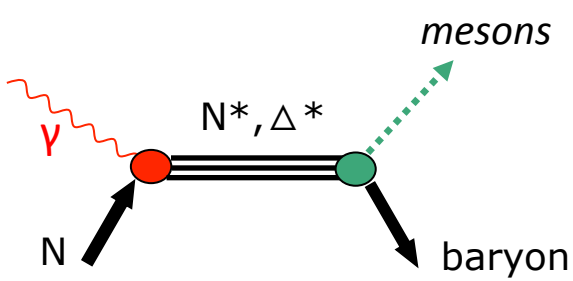
$\gamma_v N \rightarrow N\pi$ $\gamma_v N \rightarrow N\pi\pi$



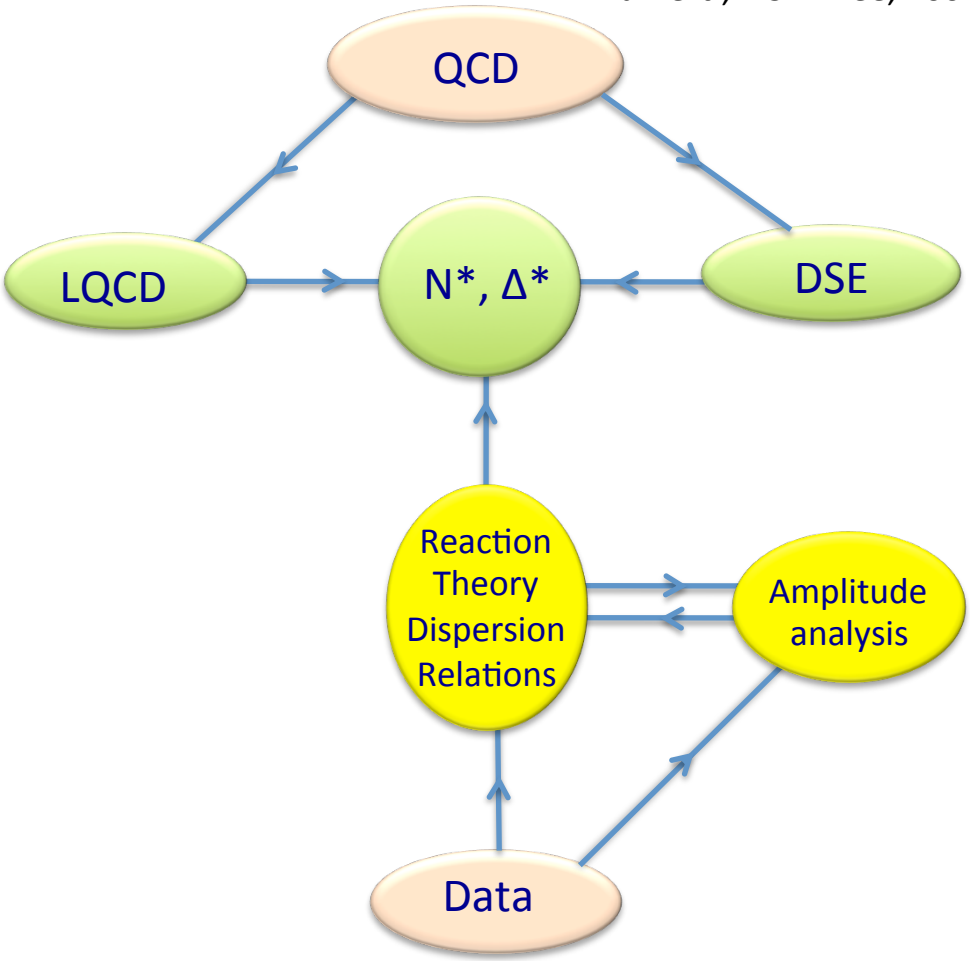
Modern tools for N* and Δ* studies

- Multi-GeV polarized cw beam, large acceptance detectors, polarized proton/neutron targets.
- Electromagnetically induced two-body processes, e.g. γp --> Nπ, Nη, KY in wide kinematics
- More complex reactions needed to access high mass states, Nππ, Nπη, Nω/ϕ, …

Extract s-channel resonances



V. Burkert., T.S.H. Lee, 2004



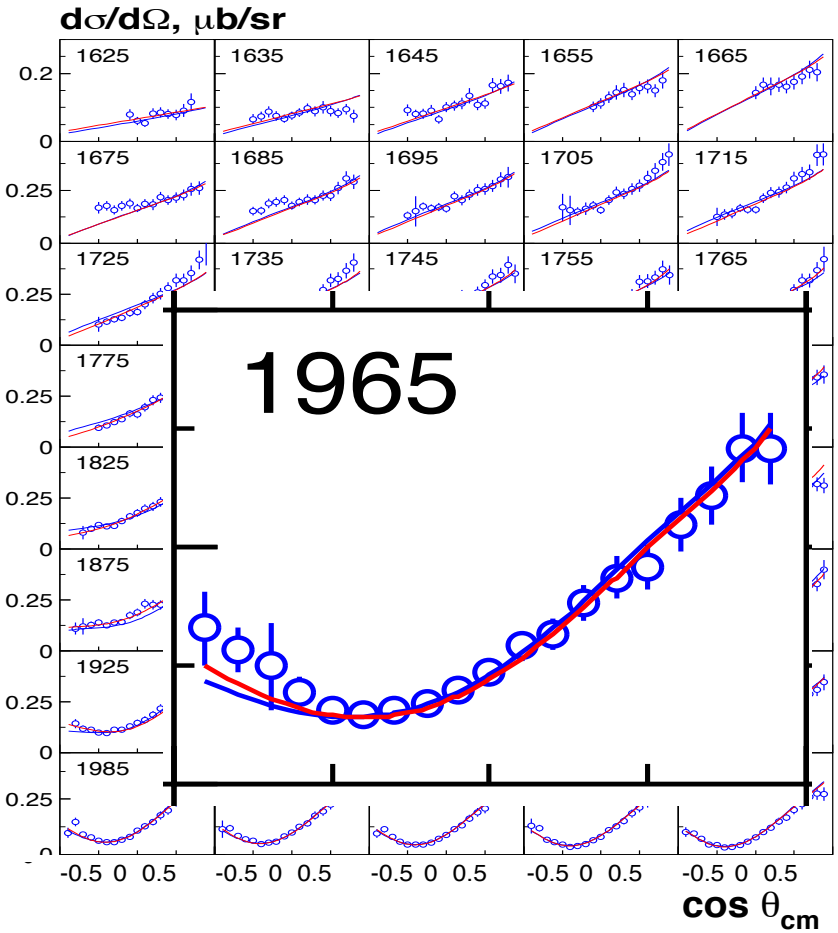
Hadronic production

Electromagnetic production

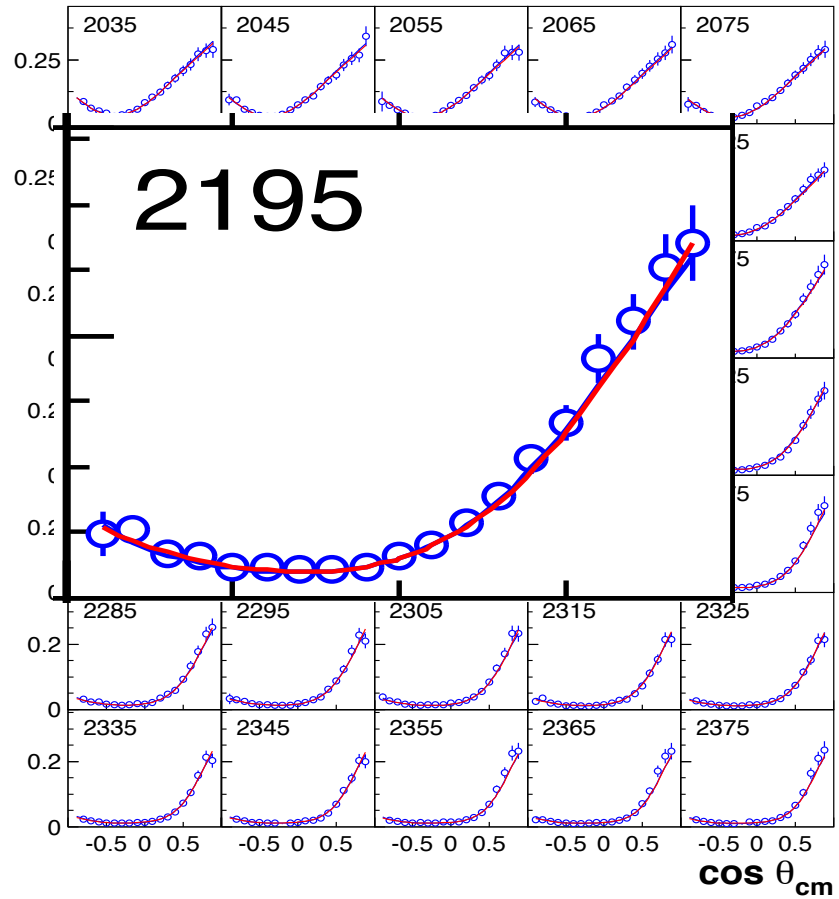
Establishing the nucleon spectrum

Most states discovered in πN, experiments focus now on γN.

Essential new data on hyperon production $\gamma p \rightarrow K^+\Lambda \rightarrow K^+p\pi^-$



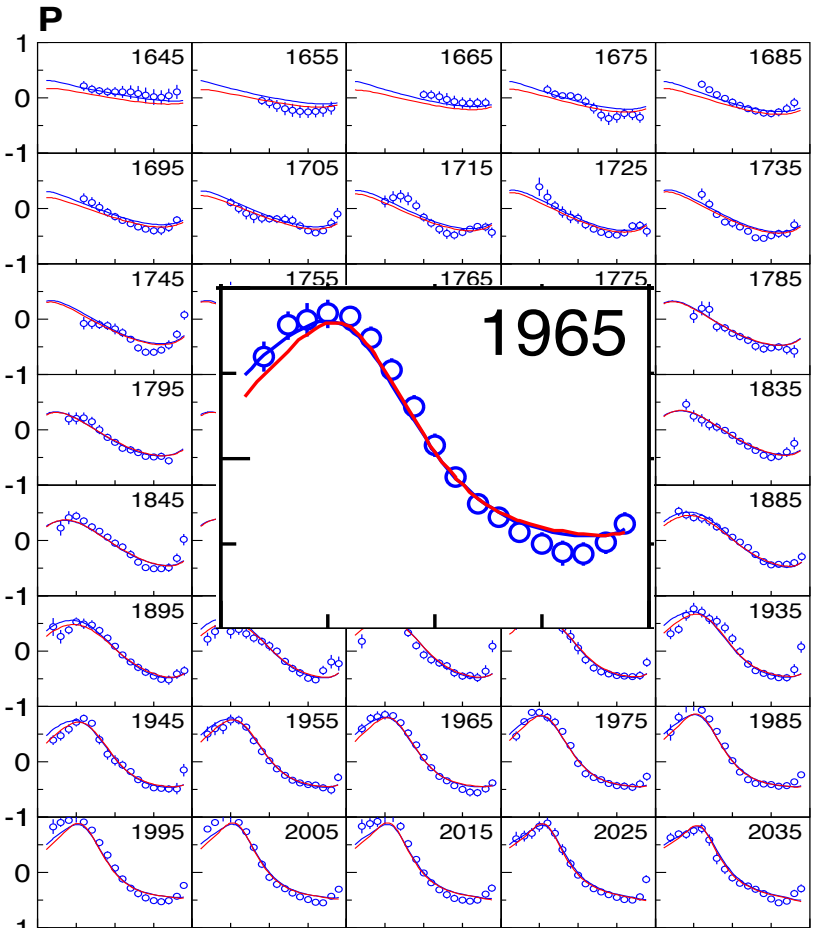
M. Mc racken et al.(CLAS), Phys. Rev C81, 025201, 2010



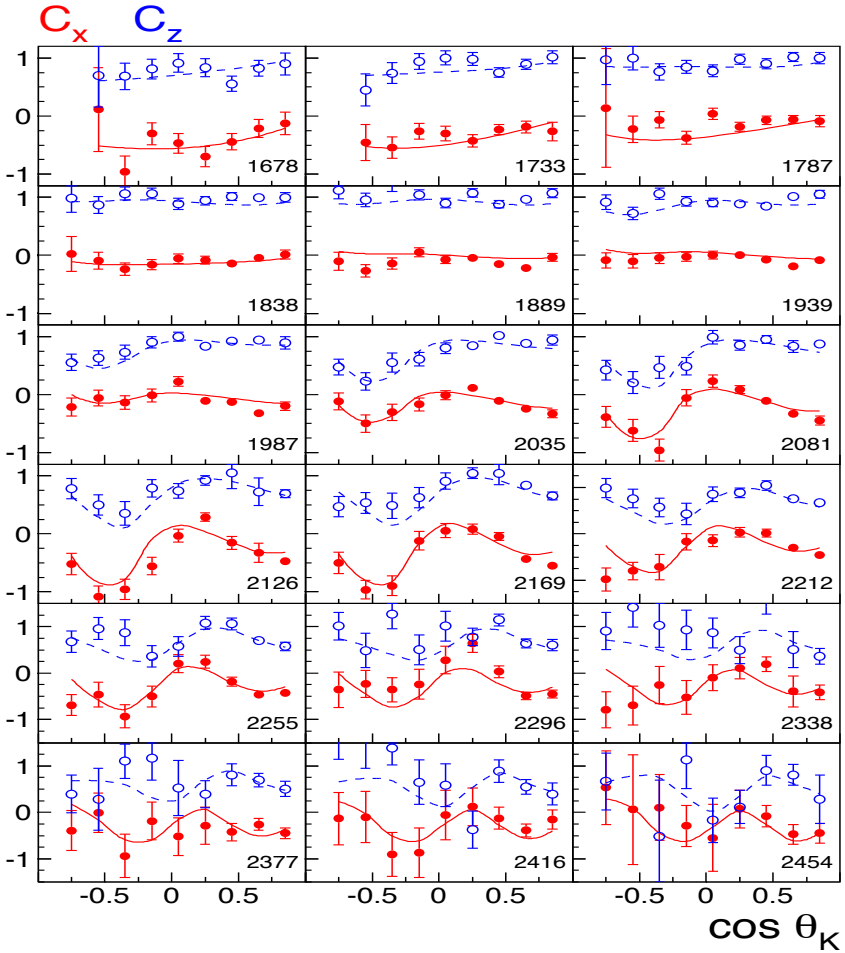
A.V. Anisovich et al (BnGa), EPJ A48, 15 (2012)

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

Λ Recoil polarization



γ->Λ Polarization transfer



M. McCracken et al. (CLAS), Phys. Rev. C 81, 025201, 2010

D. Bradford et al. (CLAS), Phys.Rev. C75, 035205, 2007

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

The N(1900)3/2$^+$ state

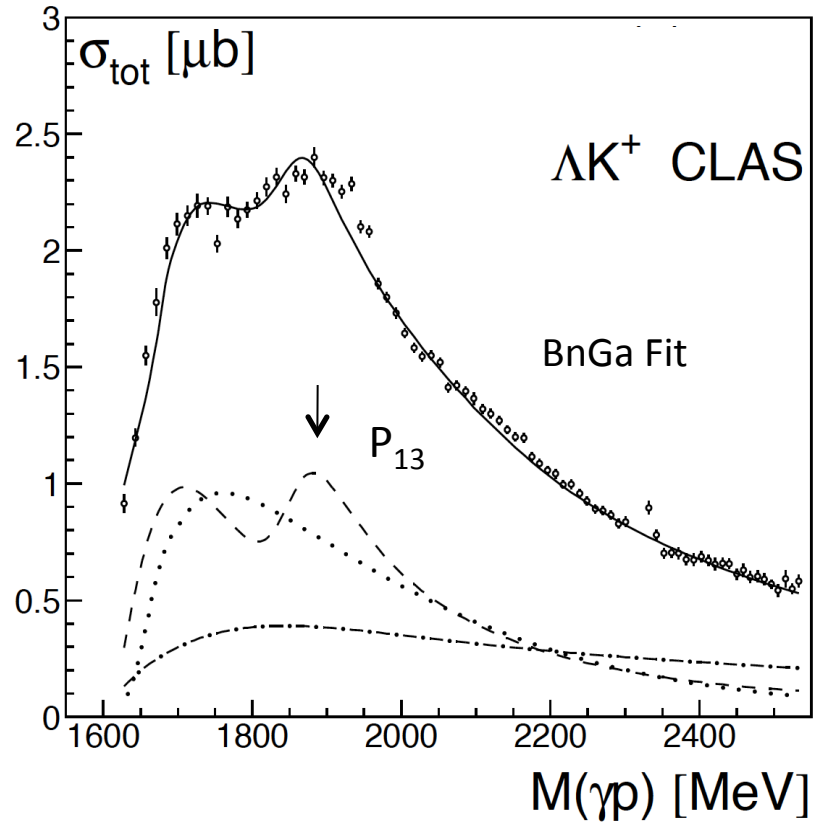
- State was solidly established in BnGa coupled-channel analysis making use of very precise KΛ cross-section and polarization data, lead to the *** rating in PDG2012.

- State confirmed in an effective Langrangian resonance model analysis of $\gamma p \rightarrow K^+\Lambda$.
  O. V. Maxwell, PRC85, 034611, 2012

- State confirmed in a covariant isobar model single channel analysis of $\gamma p \rightarrow K^+\Lambda$.
  T. Mart, M. J. Kholili , PRC86, 022201, 2012

- First baryon resonance observed and multiply confirmed in electromagnetic meson production.

  => Good candidate for **** state.



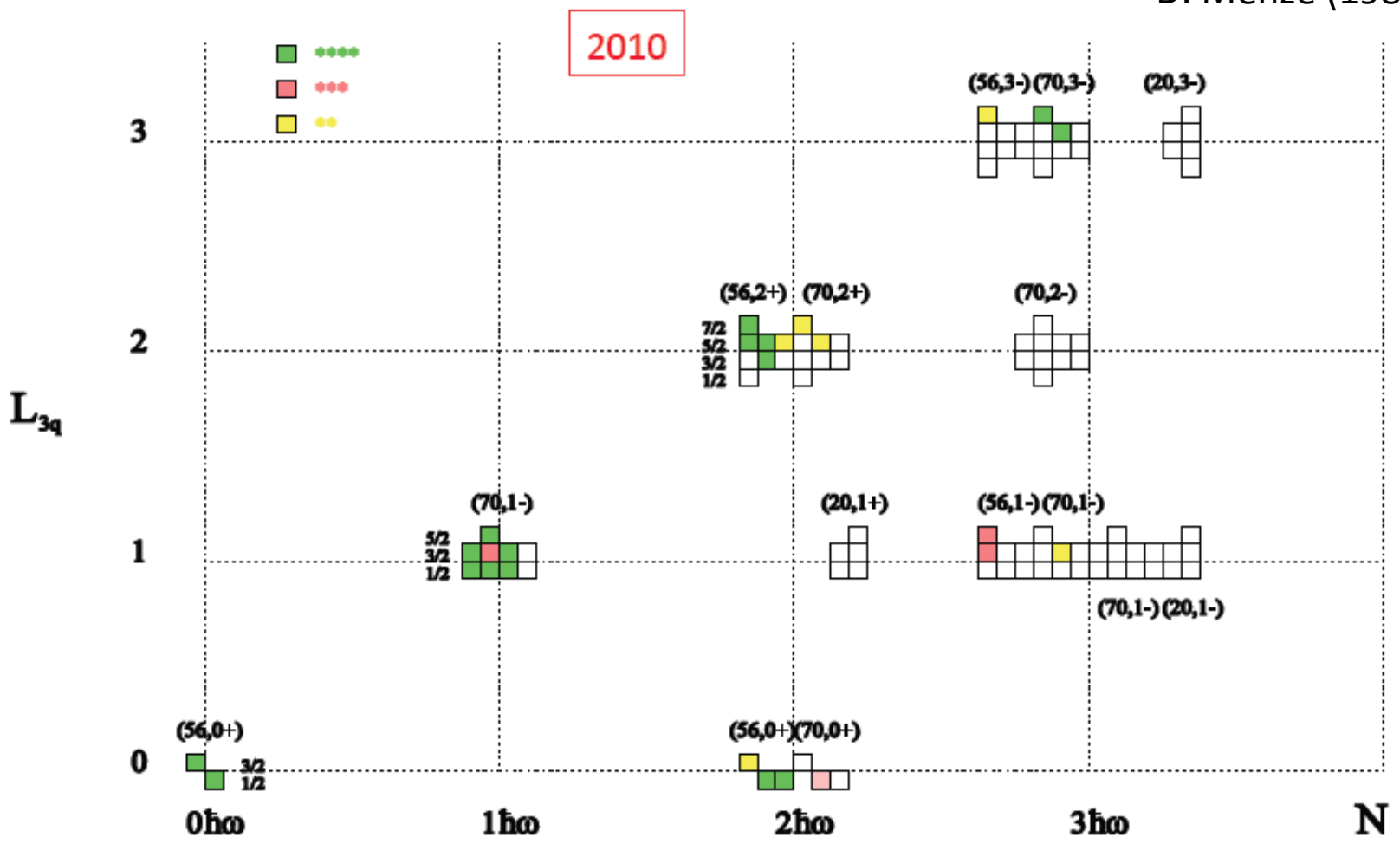
Evidence for new N* states and couplings

State N((mass)J^P	PDG 2010	PDG 2012	KΛ	KΣ	Nγ
N(1710)$1/2^+$	*** (not seen in GW analysis)	***	***	**	***
N(1880)$1/2^+$		**	**	*	**
N(1895)$1/2^-$		**	**	*	***
N(1900)$3/2^+$	**	***	***	**	***
N(1875)$3/2^-$		***	***	**	***
N(2150)$3/2^-$		**	**		**
N(2000)$5/2^+$	*	***	**	*	**
N(2060)$5/2^-$		***		**	***

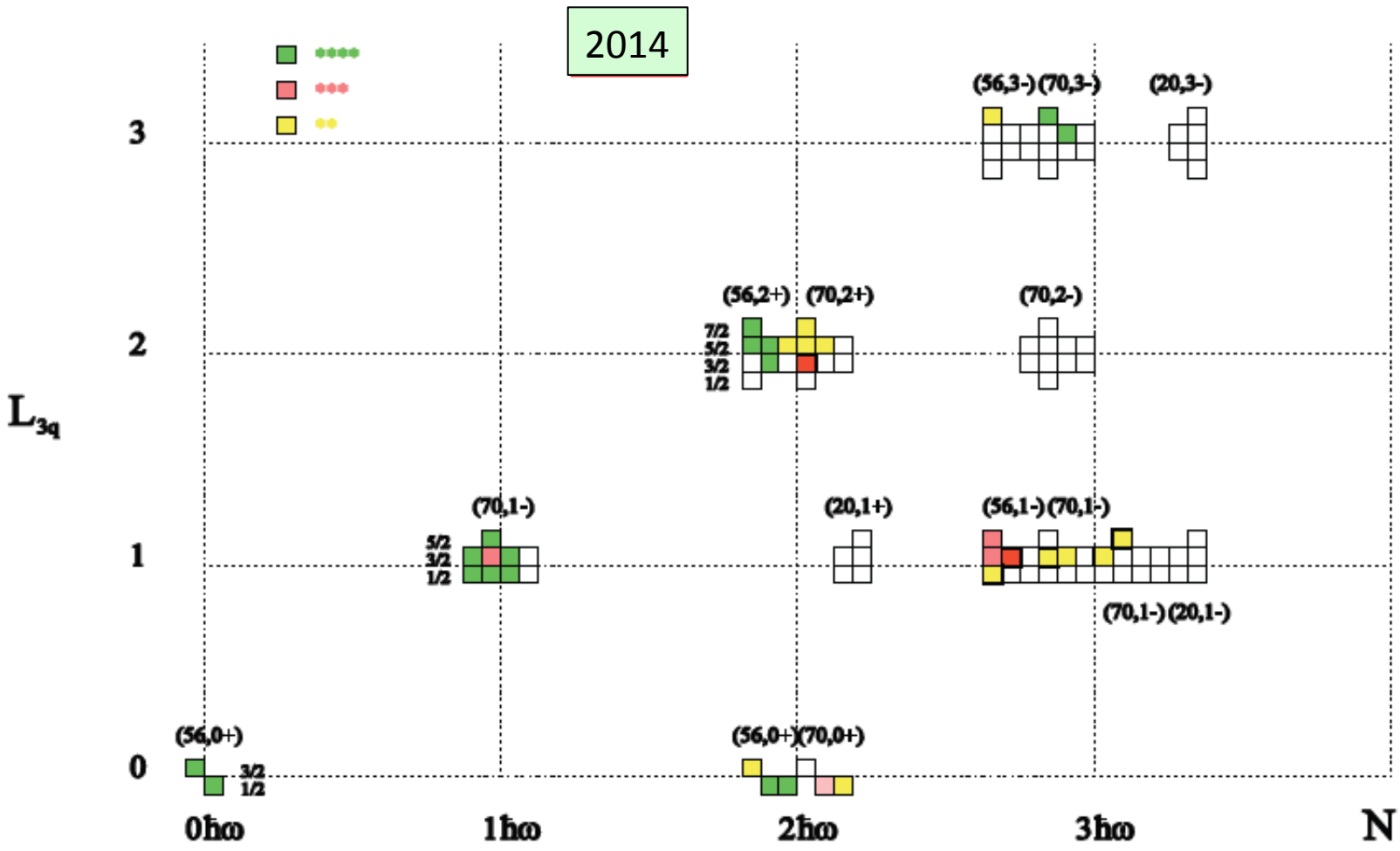
Bonn-Gatchina Analysis – A.V. Anisovich et al., EPJ A48, 15 (2012)
(First coupled-channel analysis that includes nearly all new photoproduction data)

Do new states fit into CQM?

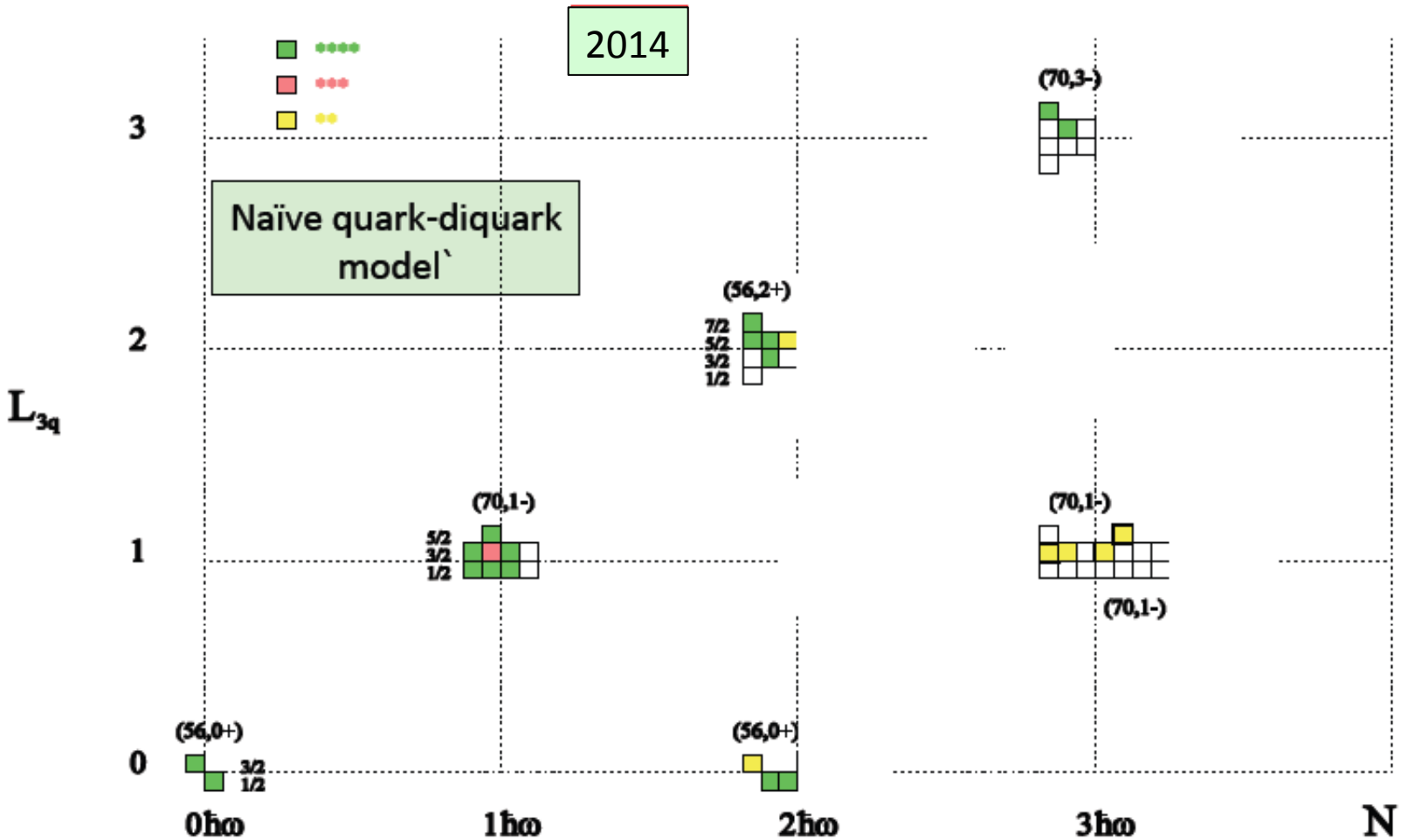
D. Menze (1980's)



Do new states fit into CQM?



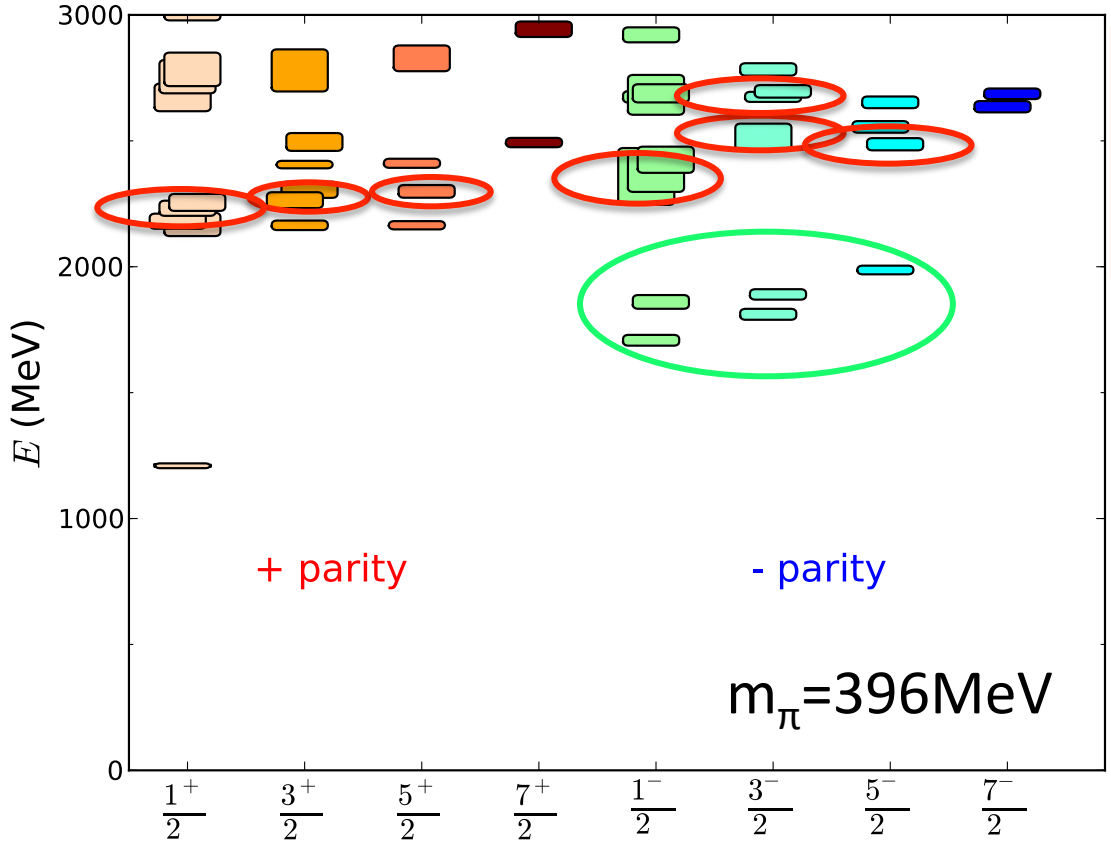
Do new states fit into CQM?



Do new states fit into LQCD projections?

R. Edwards et al., Phys.Rev. D84 (2011) 074508

N(1860)5/2$^+$
N(1900)3/2$^+$
N(1880)1/2$^+$



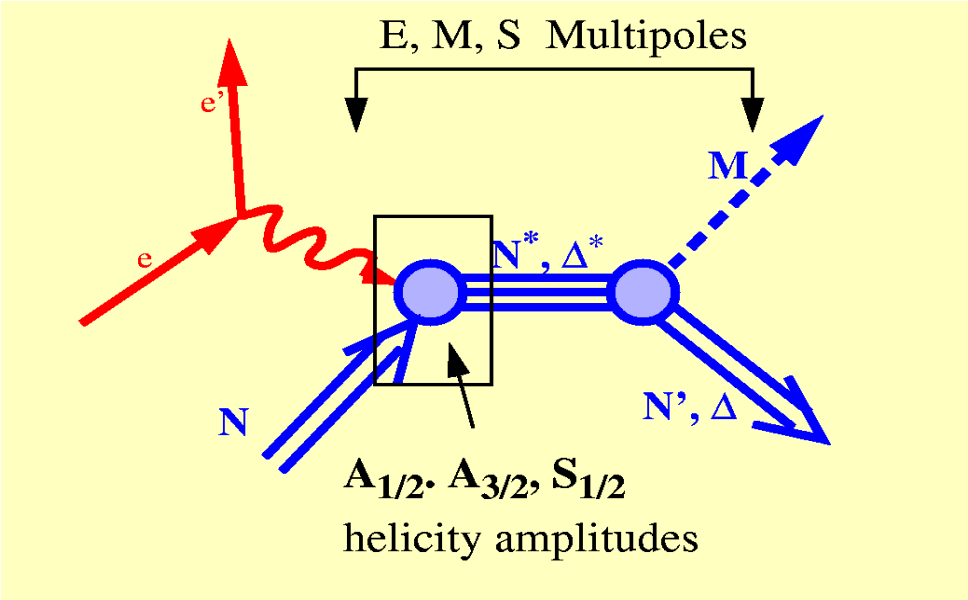
N(2060)5/2$^-$
N(2120)3/2$^-$
N(1875)3/2$^-$
N(1895)1/2$^-$

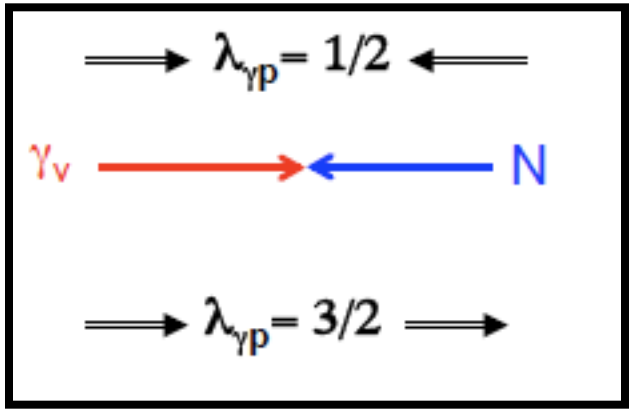
Known states:
N(1675)5/2$^-$
N(1700)3/2$^-$
N(1520)3/2$^-$
N(1650)1/2$^-$
N(1535)1/2$^-$

LQCD states ~ 300 MeV too high

Ignoring the mass scale, new candidate states fit with the J^P values predicted from LQCD.

Electroproduction





The helicity amplitudes are related to the matrix elements of the electromagnetic current via:

$A_{1/2}$: $\langle N^*, S_z^* = +\tfrac{1}{2} | \varepsilon_\mu^{(+)} J^\mu_{em} | N, S_z = -\tfrac{1}{2} \rangle$

$A_{3/2}$: $\langle N^*, S_z^* = +3/2 | \varepsilon_\mu^{(+)} J^\mu_{em} | N, S_z = +\tfrac{1}{2} \rangle$

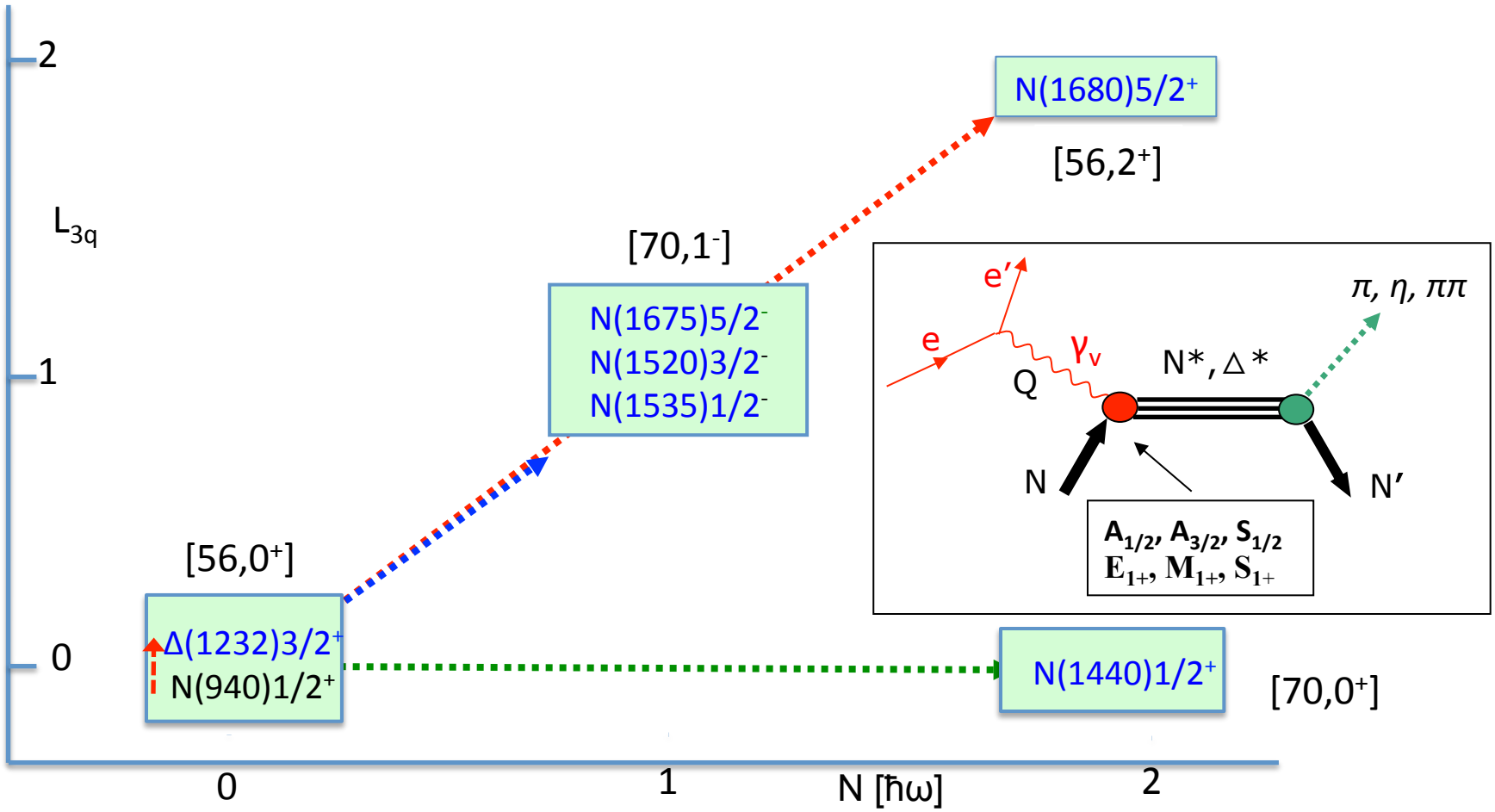
$S_{1/2}$: $\langle N^*, S_z^* = +\tfrac{1}{2} | \varepsilon_\mu^{(0)} J^\mu_{em} | N, S_z = +\tfrac{1}{2} \rangle$

Transverse
- $A_{1/2}$
- $A_{3/2}$

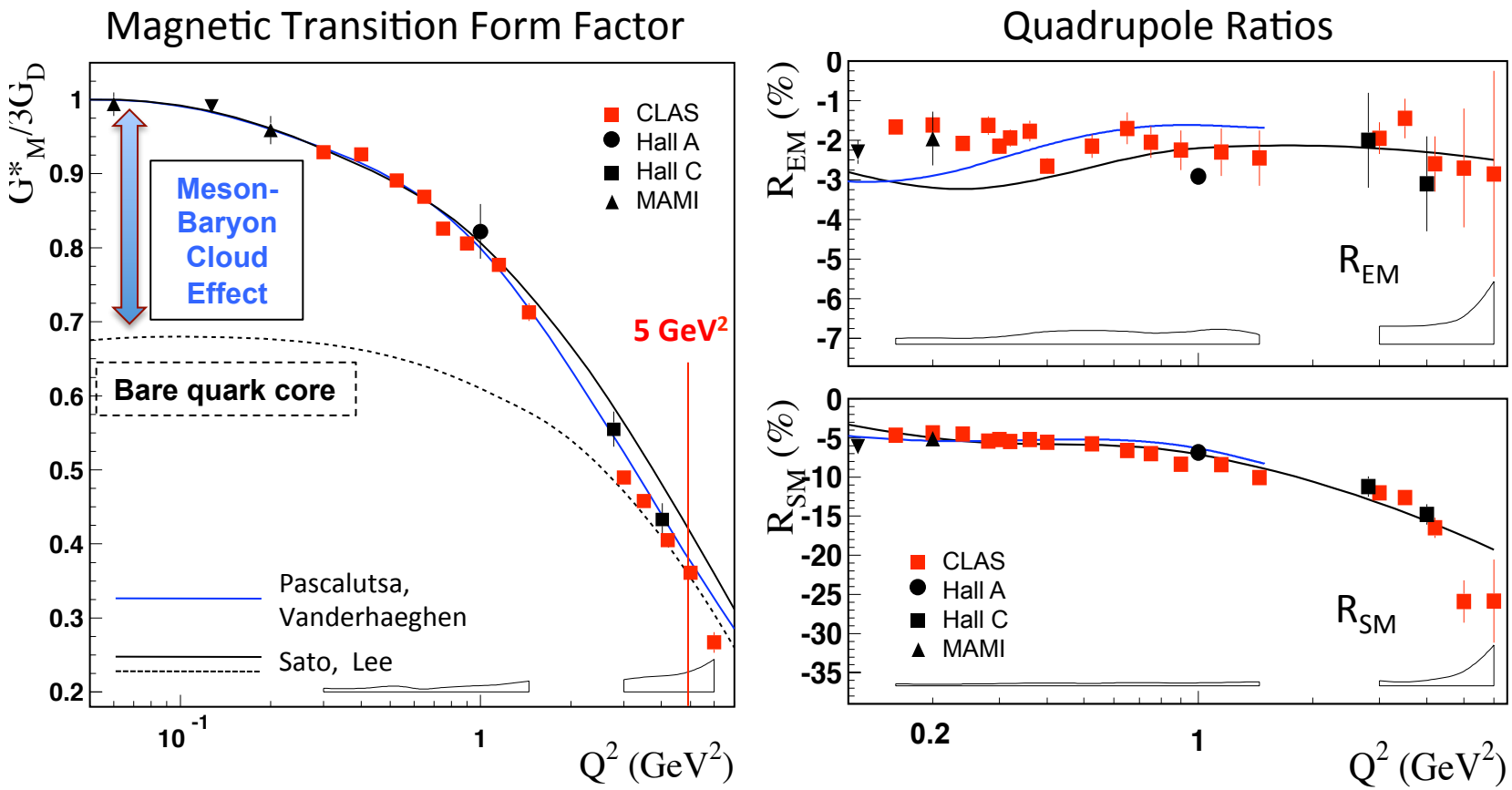
Longitudinal
- $S_{1/2}$

Electroexcitation of N/Δ resonances

- Real photon beam essential to establish the N* spectrum
- Virtual photons probe resonance strength vs time-distance scale

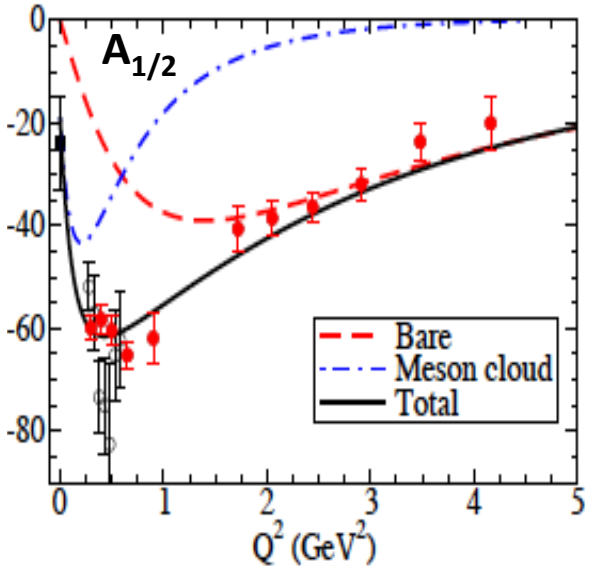


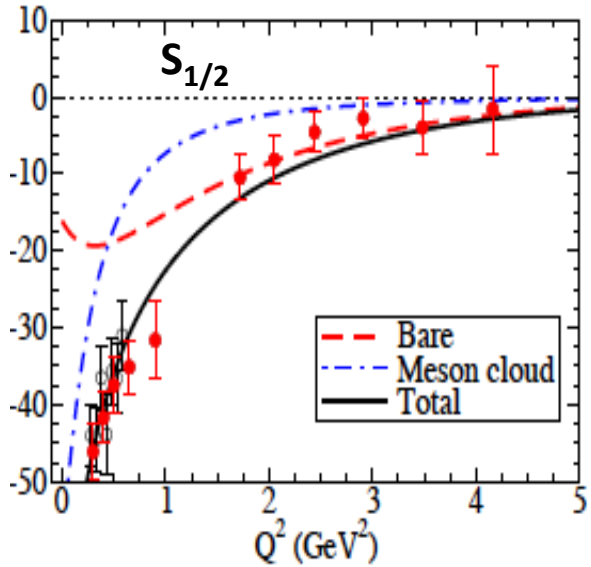
The Δ(1232)3/2⁺ transition

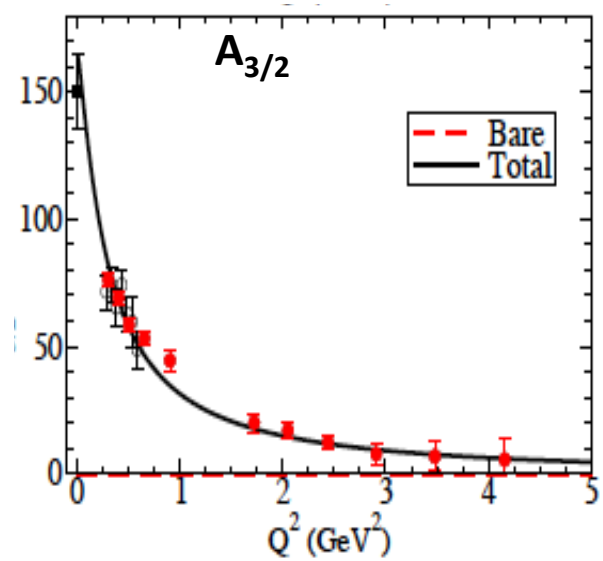


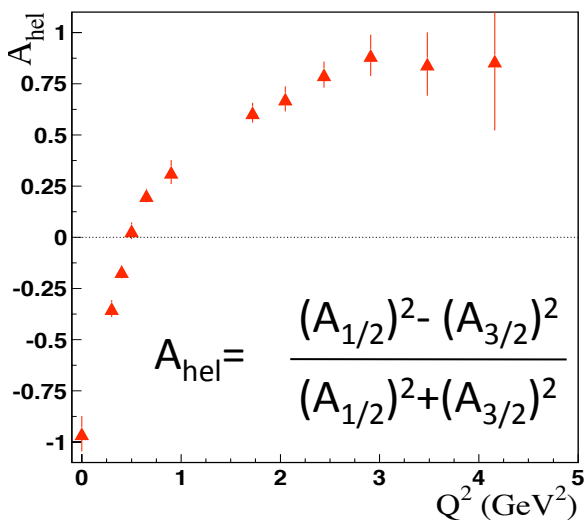
- 35% MB contributions needed to describe magnetic dipole transition at Q^2=0.
- For G^*_M the MB contribution are decreasing with increasing Q^2 to 10% @ 5 GeV²
- $R_{EM} = E_{1+}/M_{1+}$ and $R_{SM} = S_{1+}/M_{1+}$ are small and can be described with MB contributions only

Electrocouplings of N(1520)3/2$^-$









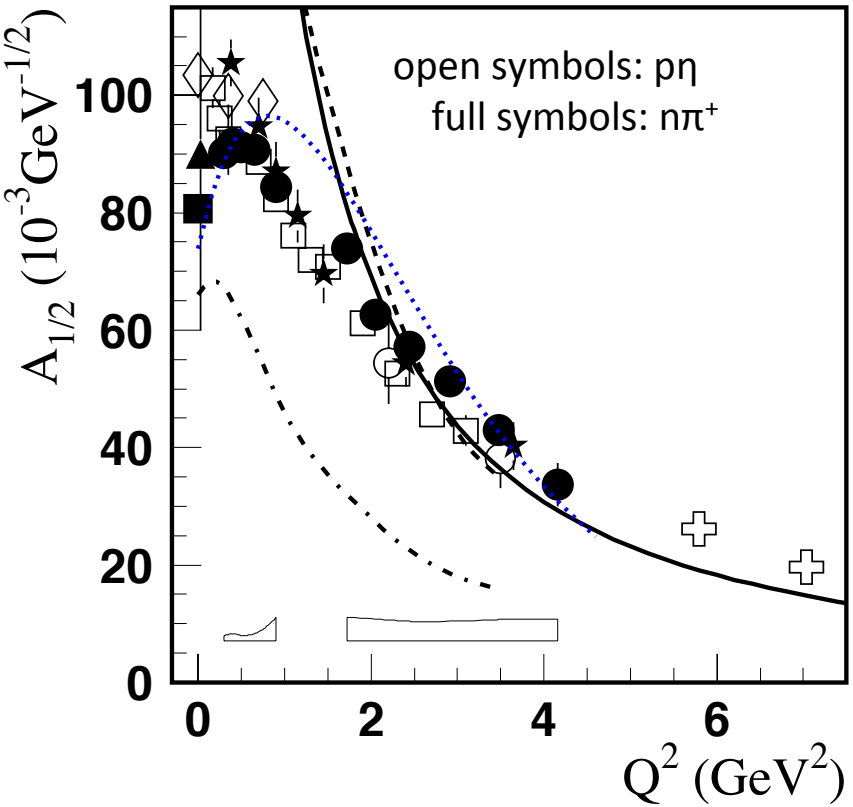
$$A_{hel} = \frac{(A_{1/2})^2 - (A_{3/2})^2}{(A_{1/2})^2 + (A_{3/2})^2}$$

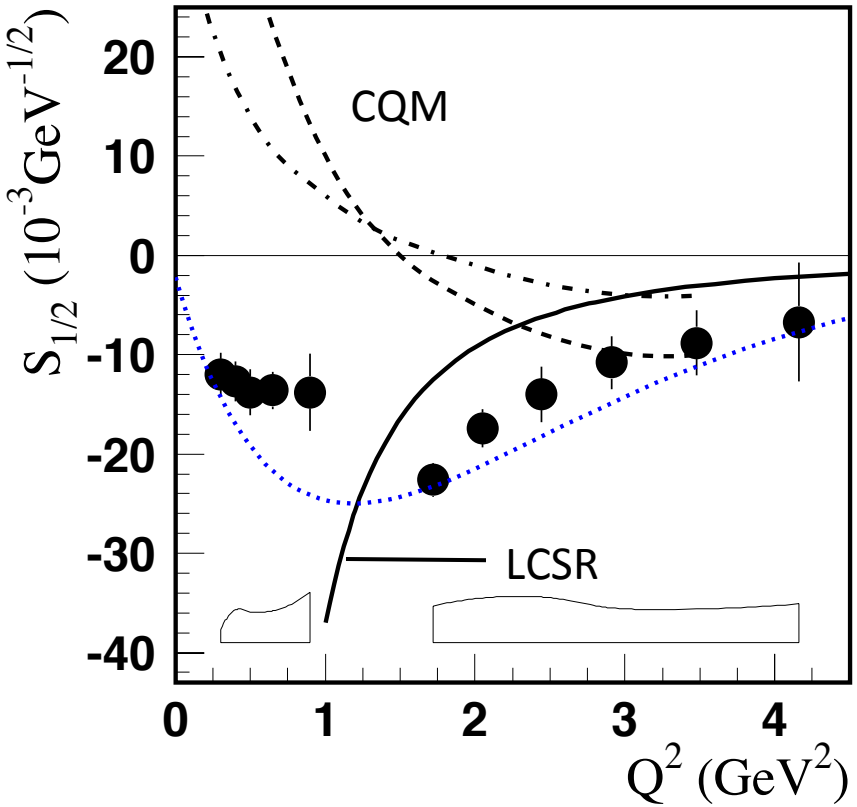
- First data set that enabled the determination of $S_{1/2}(Q^2)$
- Firmly established switch from $A_{3/2}$ dominance at $Q^2=0$ to $A_{1/2}$ dominance at $Q^2 > 1$ GeV^2.

$A_{1/2}$ strength at high Q^2 dominantly from quarks
$A_{3/2}$ strength dominantly from MB contributions.

G. Ramalho and M. T. Peña, arXiv:1309.0730

Electrocouplings of N(1535)1/2$^-$





- Chiral unitary (dynamical) models show the state may have a significant coupling to KΛ and pϕ which could indicate sizeable qqqs$\bar{s}$ component in the wave function.
- Could explain the large pη branching ratio (~50%) and negative sign of $S_{1/2}$ at low Q^2.
- Are there high mass N* states with significant N*--> pϕ coupling?

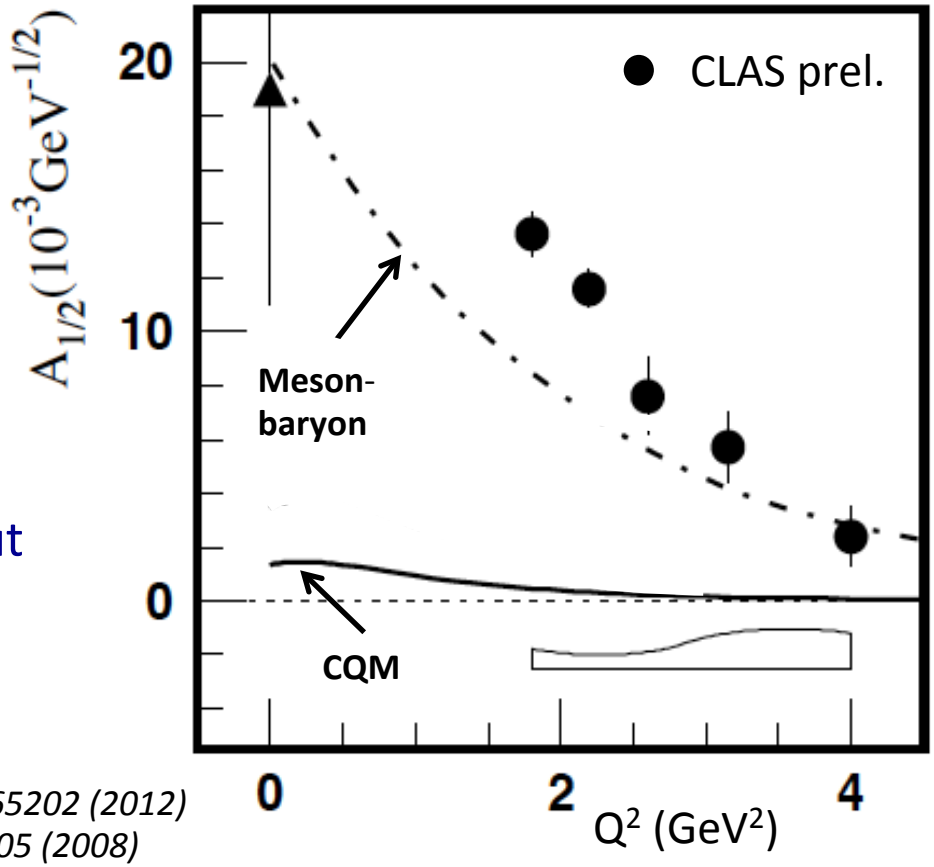
=> Include γp-> pϕ data in coupled-channel PWA.

Meson-Baryon contributions to $\gamma p \rightarrow N(1675)5/2^-$

How can we be sure that we need MB contributions to resonance excitations?

Moorhouse selection rule:
=> Quark contributions to
$\gamma_v pN(1675)$ transition:
$A^p_{1/2}=A^p_{3/2}=0$

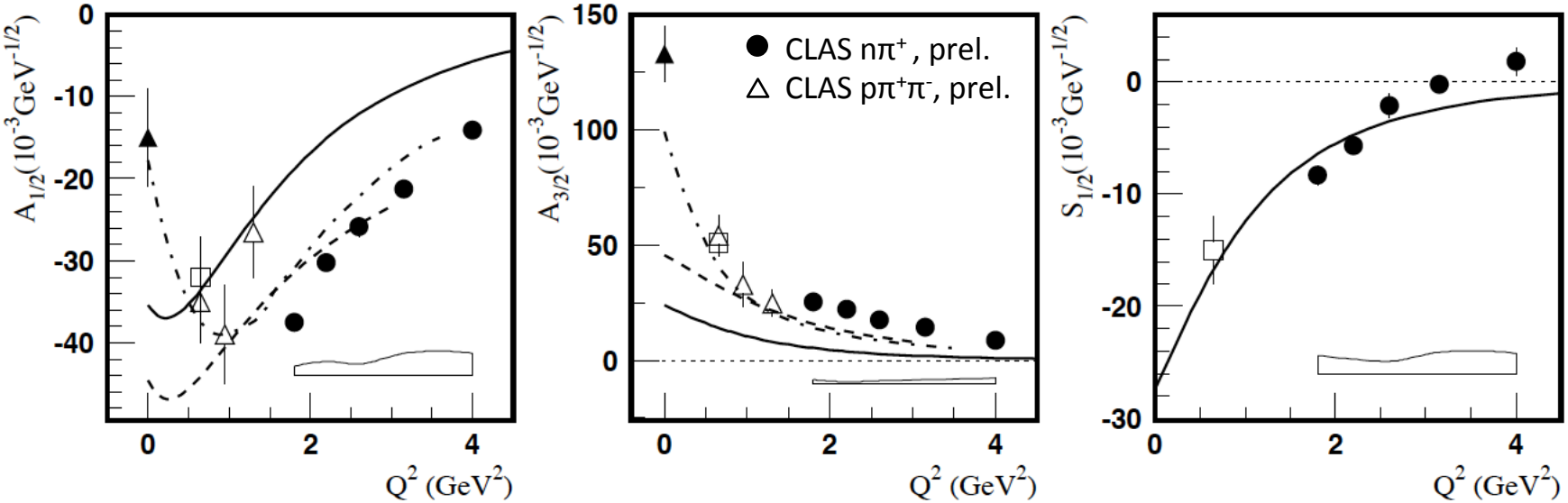
Explicit CQM calculations give finite but very small quark contributions.



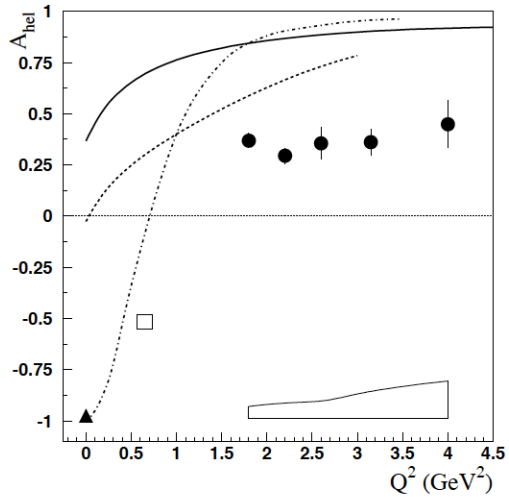
E. Santopinto and M. M. Giannini, PRC 86, 065202 (2012)
B. Juliá-Díaz, T.-S.H. Lee, et al., PR C 77, 045205 (2008)

- Input to calibrate dynamical coupled-channel model calculations.

Electrocouplings of N(1680)5/2$^+$



$$\frac{A_{1/2}^2 - A_{3/2}^2}{A_{1/2}^2 - A_{3/2}^2}$$

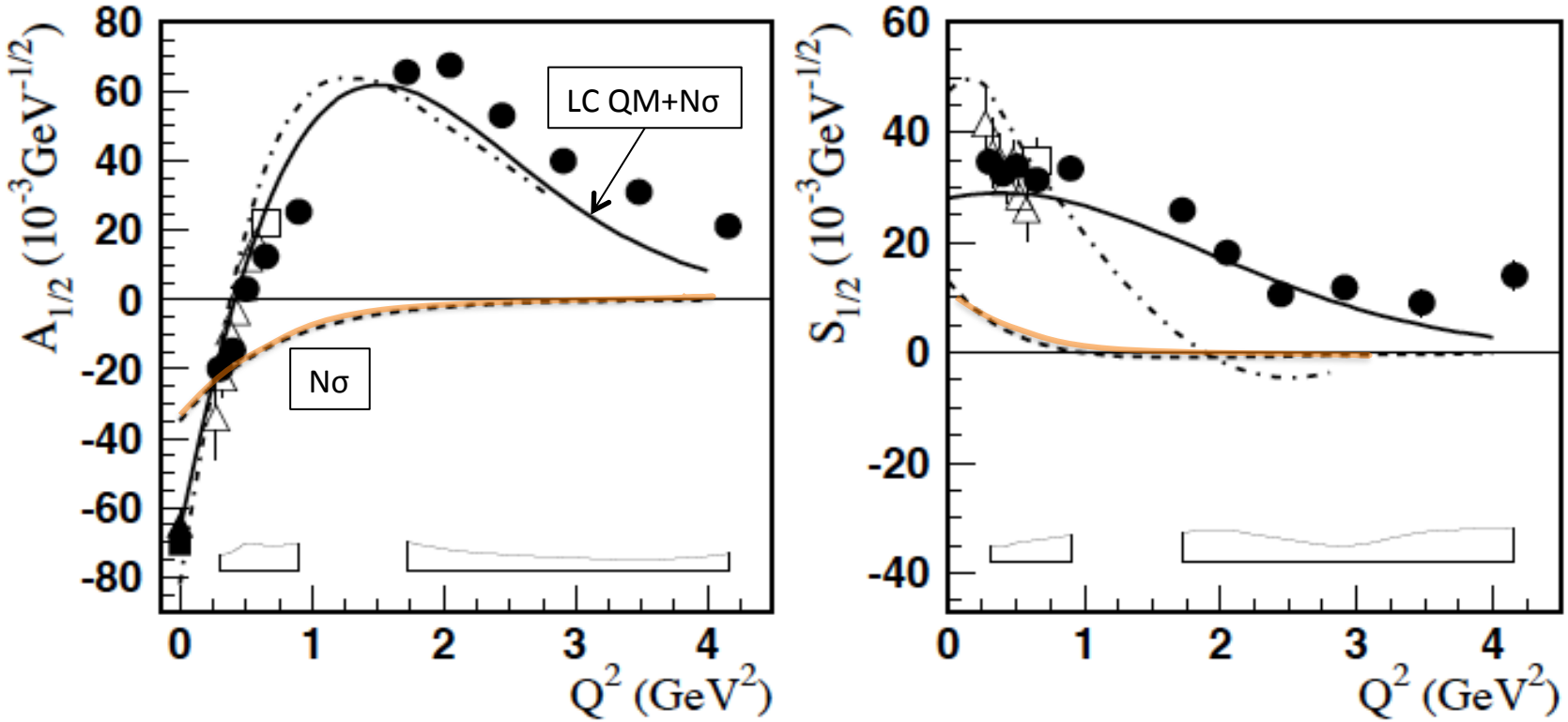


- The observed helicity switch from 3/2 to 1/2 dominance is not as rapid as predicted by QM and as seen for the N(1520)3/2$^-$ state.

Significant meson-baryon contributions at large Q^2?

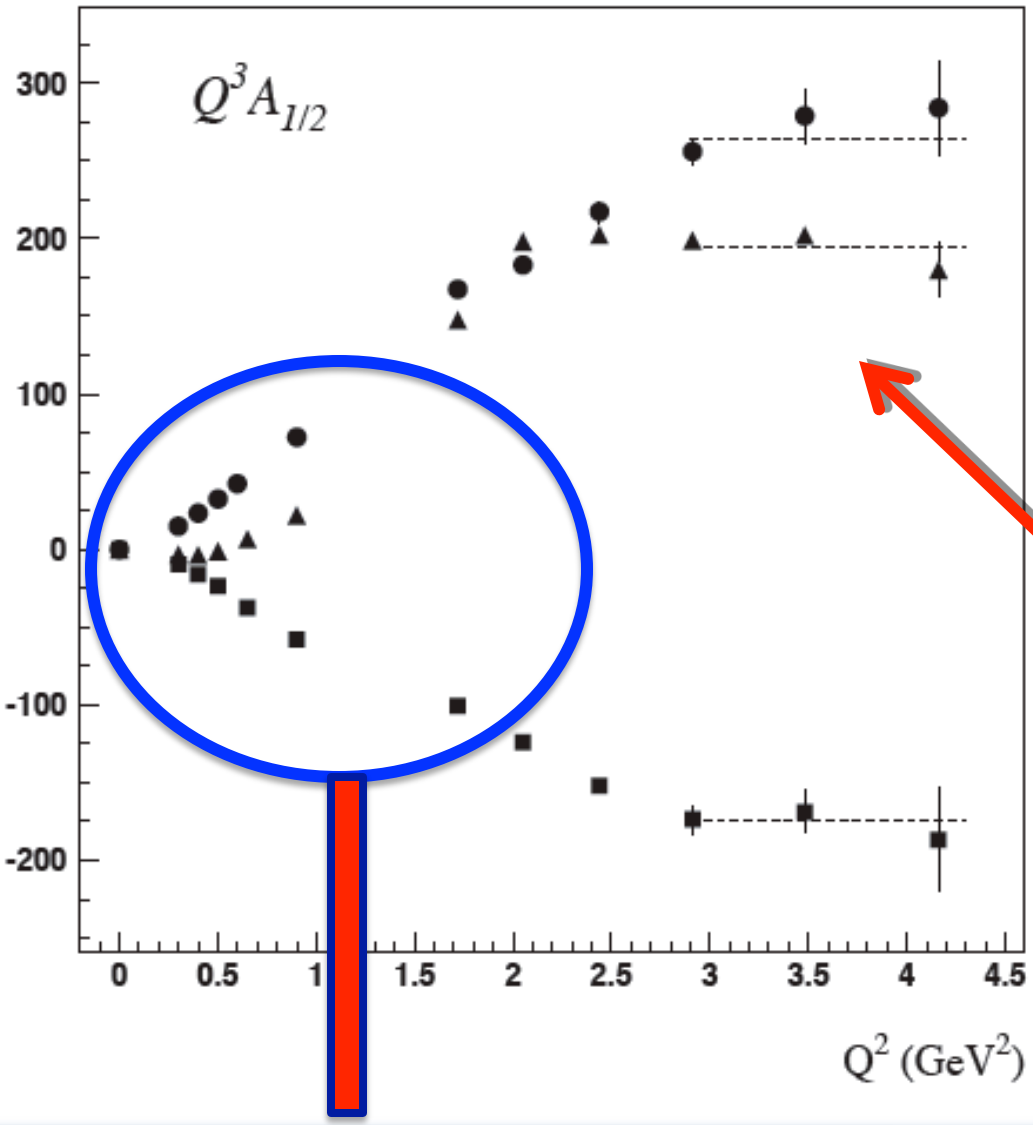
Electrocouplings of 'Roper' N(1440)1/2$^+$

Aznauryan et al. (CLAS), PRC80, 055203 (2009) , V. Mokeev et al. (CLAS), PRC86, 035203 (2012)



- $A_{1/2}$ exhibits unusual Q^2 behavior, disappears at Q^2=0.5, becomes large at $Q^2 > 1.5$ GeV^2.
- In nrCQM the state is the first radial excitation of the nucleon => $A_{1/2}(0) > 0$.
- nrQM failure led to more exotic explanations, e.g. hybrid state, pure Nσ molecule, Nρ.
- LC QM + Nσ reproduce main features at small and at large Q^2.

$A_{1/2}$ electrocouplings



▲ $P_{11}(1440)$

■ $D_{13}(1520)$

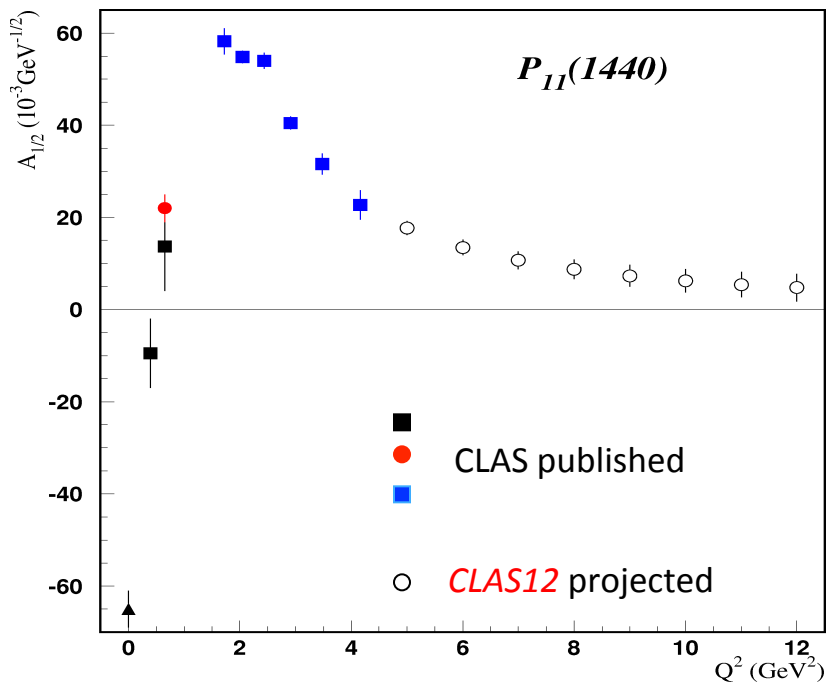
● $S_{11}(1535)$

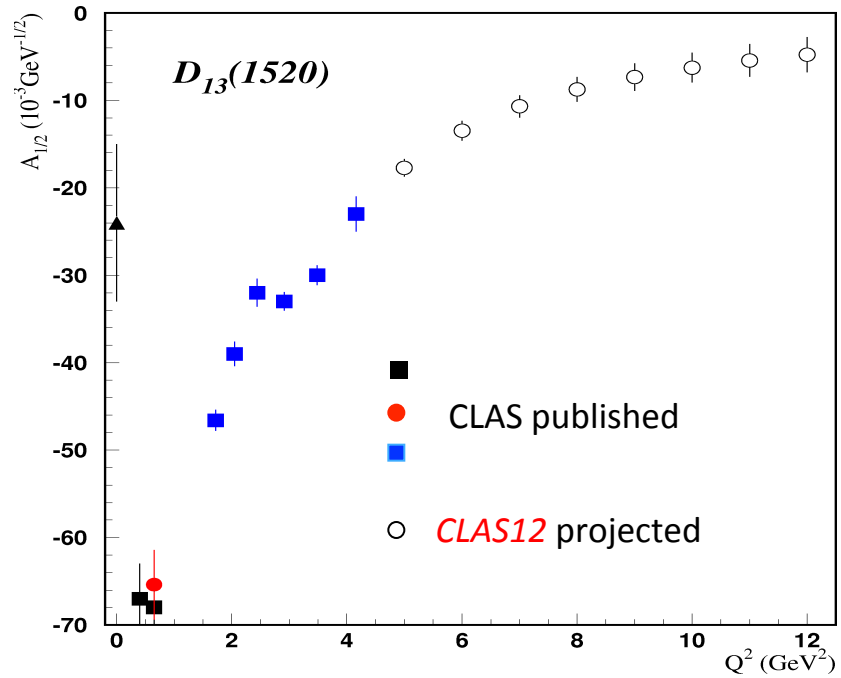
scaled by Q^3

Projections for N* transitions

For the foreseeable future, CLAS12 will be the only facility worldwide, which will be able to access the N* electrocouplings in the Q^2 regime of 5 GeV^2 to 10 GeV^2, where the quark degrees of freedom are expected to dominate. The approved experimentes "*Nucleon Resonance Studies with CLAS12*" and "*Exclusive N* → KY Studies with CLAS12*" have 60 days of beamtime:

- https://www.jlab.org/exp_prog/proposals/09/PR12-09-003.pdf
- https://www.jlab.org/exp_prog/proposals/14/E12-06-108A.pdf





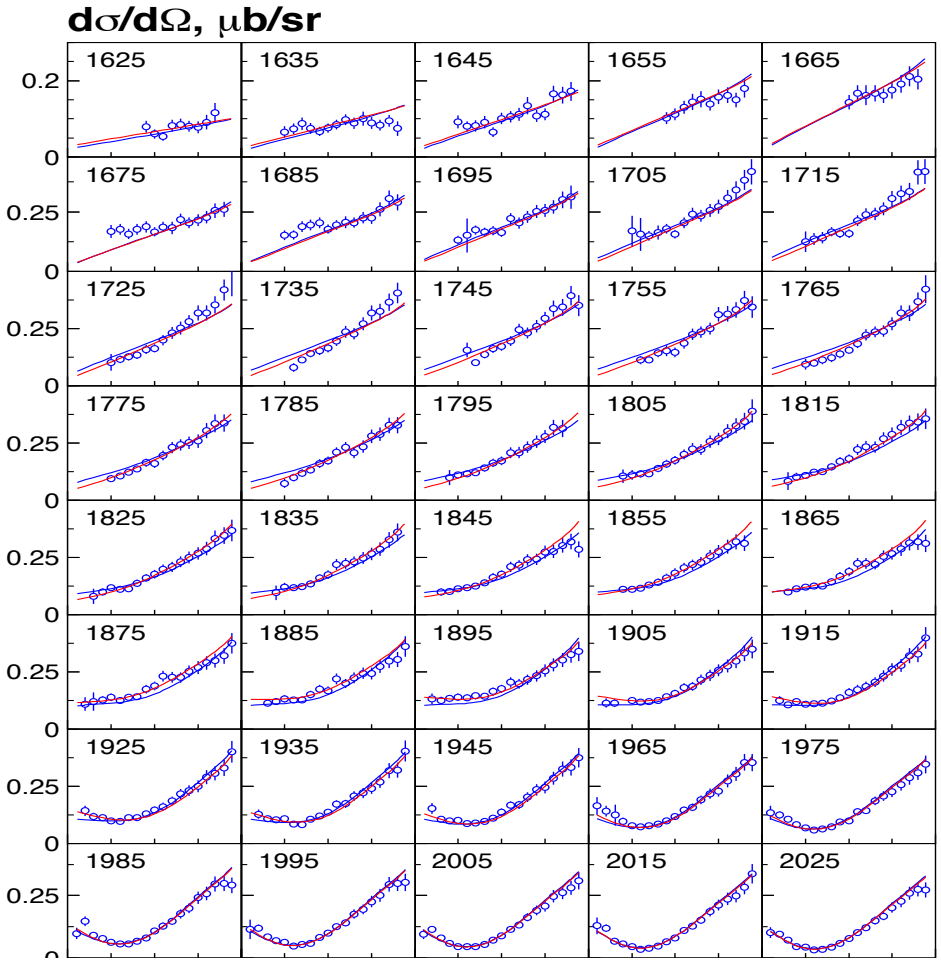
Confirming the nucleon spectrum

$\gamma p \rightarrow K^+\Lambda \rightarrow K^+ p \pi^-$

Electroproduction data are further needed to confirm the existence of N*s that decay through the $K^+\Lambda$ channel in the nucleon spectrum for varying Q^2 bins.

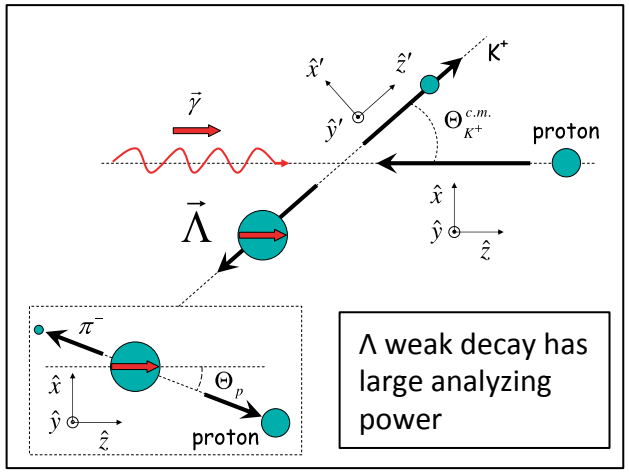
Providing constraints on:

- N* hadronic decay widths
- N* masses should be the same in all Q^2 bins.



Complete photoproduction experiments

$$\gamma + p \longrightarrow K^+ + \Lambda\,(p\pi^-)$$



- Process described by 4 complex 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'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	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

Towards "complete" experiments

Observables	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
✔ published	✔ acquired or under analysis															
$p\pi^0$	✔	✔	✓	(✓)	✓	✓	✓	✓								
$n\pi^+$	✔	✔	✓	(✓)	✓	✓	✓	✓								
$p\eta$	✔	✓	✓	(✓)	✓	✓	✓	✓								
$p\eta'$	✔	✓	✓	(✓)	✓	✓	✓	✓								
$p\omega/\phi$	✔	✓	✓	(✓)	✓	✓	✓	✓								
$K^+\Lambda$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^+\Sigma^0$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^{0*}\Sigma^+$	✔	✓									✓	✓				
$p\pi^-$	✔	✓		(✓)	✓	✓	✓									
$p\rho^-$	✓	✓		(✓)	✓	✓	✓									
$K^-\Sigma^+$	✓	✓		(✓)	✓	✓	✓									
$K^0\Lambda$	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓									✓	✓				

Proton targets

Tensor polarization, SDME

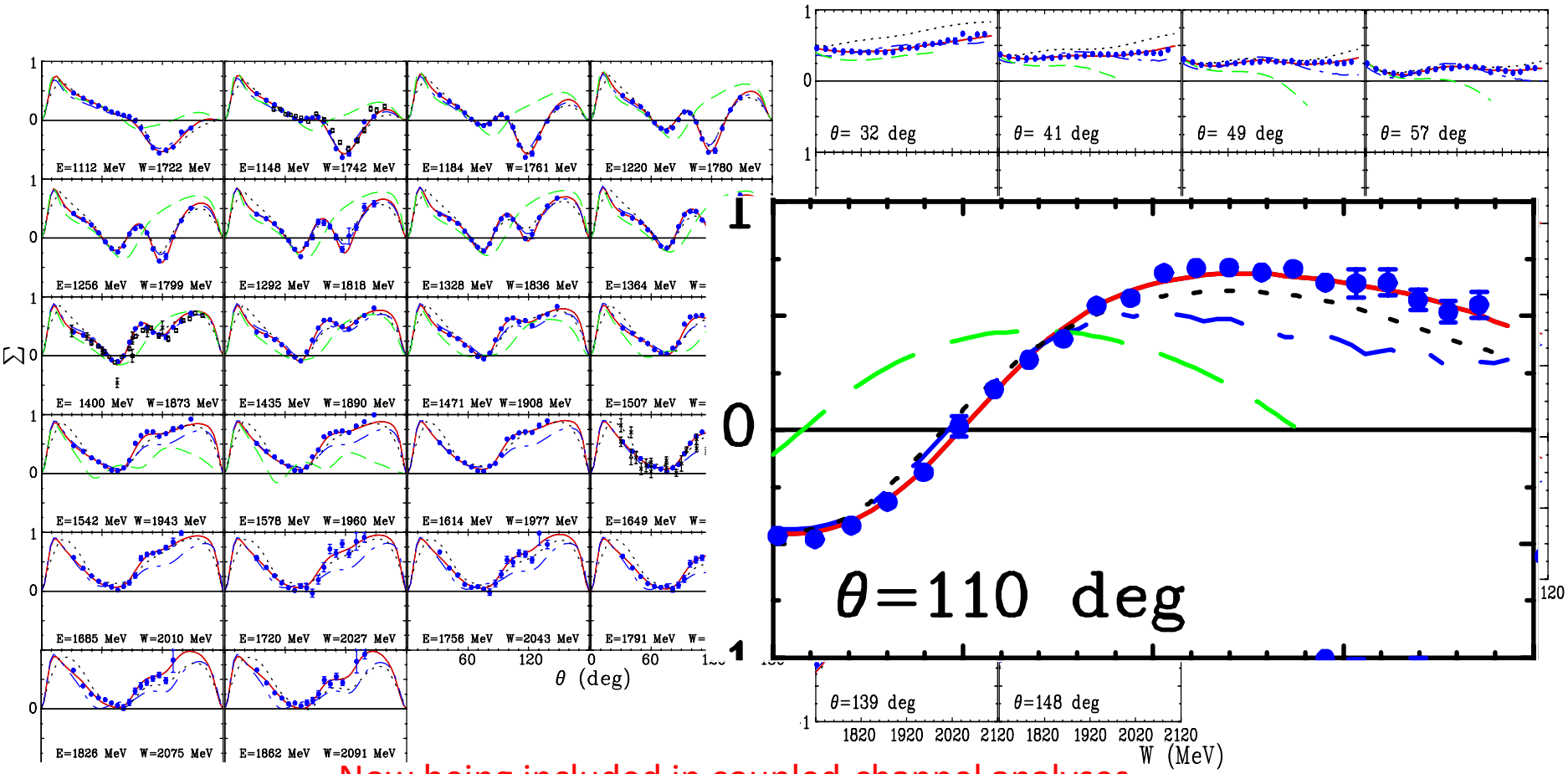
Neutron targets

Polarized photon beam asymmetry Σ

World data $\vec{\gamma}p \longrightarrow \pi^+ n$

M. Dugger et al. (CLAS), PRC 88, 065203 (2013)

1.72 < W < 2.10 GeV



Now being included in coupled-channel analyses

N* states in $\gamma p \rightarrow p\omega \rightarrow p\pi^+\pi^-\pi^0$?

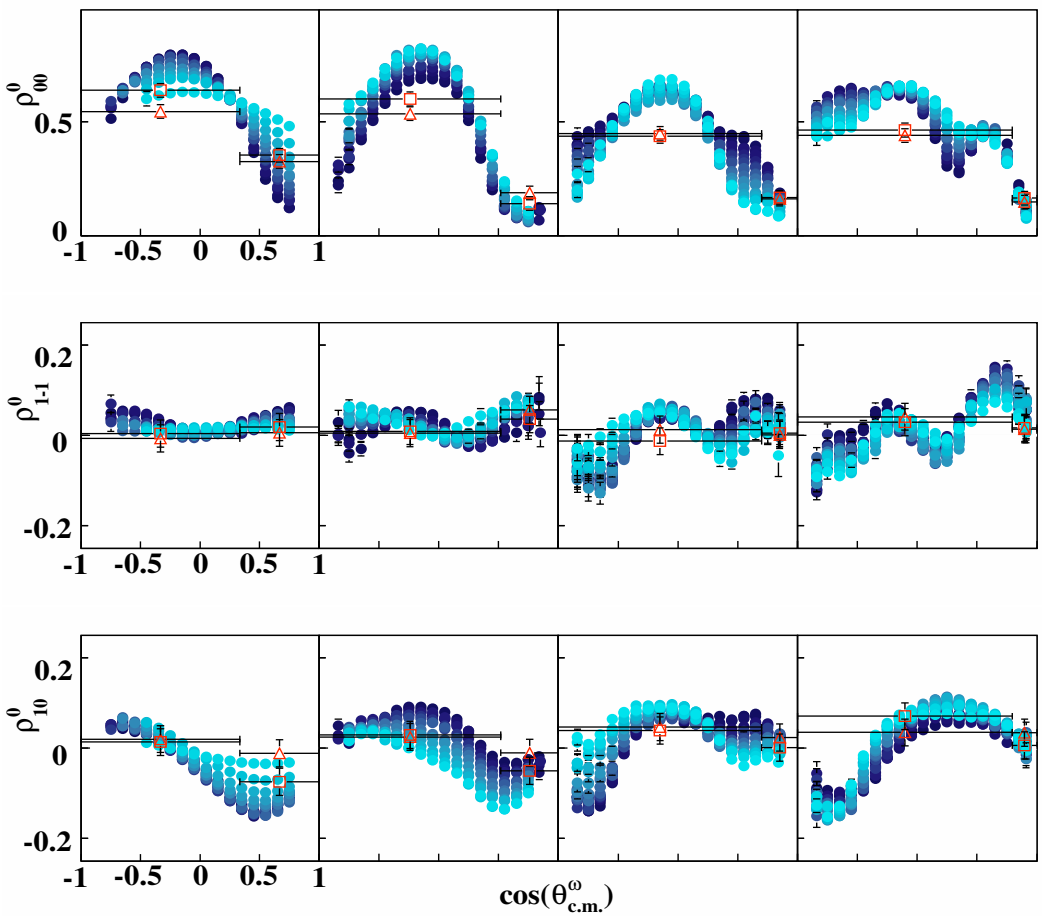
$$\mathcal{I}(\sqrt{s}, \cos\theta^{\phi}_{\text{c.m.}}) \sim \frac{1}{2}(1-\rho^0_{00}) + \frac{1}{2}(3\rho^0_{00}-1)\cos^2\zeta - \sqrt{2}Re\rho^0_{10}\sin 2\zeta\cos - \rho^0_{1-1}\cos 2\varphi, \quad (38)$$

- Very precise cross sections in W, $\cos\theta_\omega$. From ω decays => SDME ρ^0_{00}, ρ^0_{1-1}, ρ^0_{10}, shown in **blue - blue** shades.

- Channel in preparation by BnGa and other groups for analysis in coupled channel framework.

- Single channel analysis shows evidence for (missing) N(2000)5/2$^+$ state.

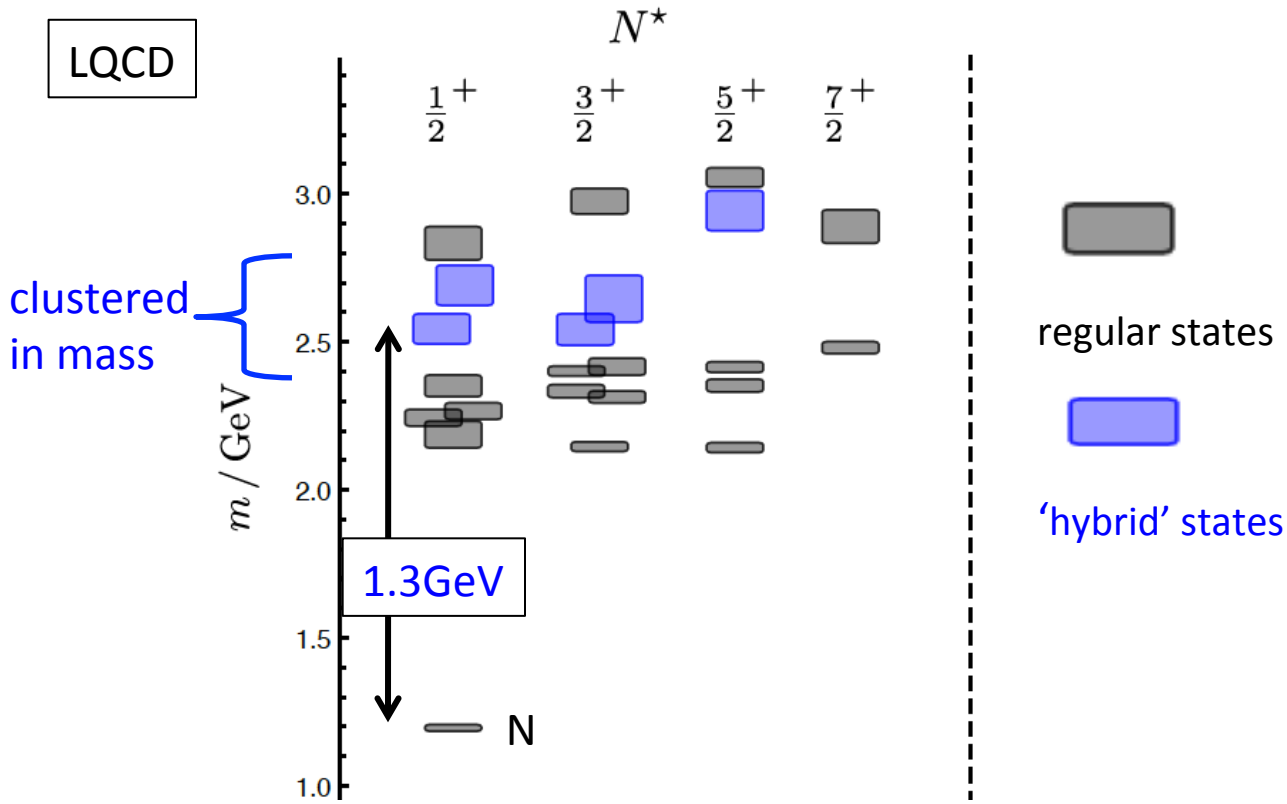
W=1.7 – 2.4 GeV, ΔW=10 MeV bins



M. Williams, et al. (CLAS), Phys. Rev. C80:065209, 2009

Gluonic baryons q^3G

J.J. Dudek and R.G. Edwards, PRD85 (2012) 054016 *T. Barnes and F.E. Close, PLB128, 277 (1983)*



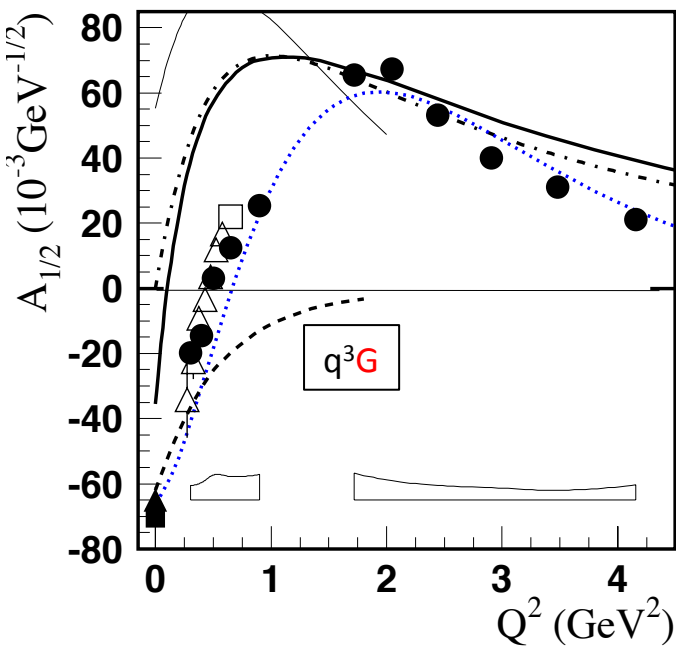
Gluonic states q^3G have same J^P values as q^3 baryons. Lowest state should be a $J^P = 1/2^+$ Roper-like state. How to identify them?

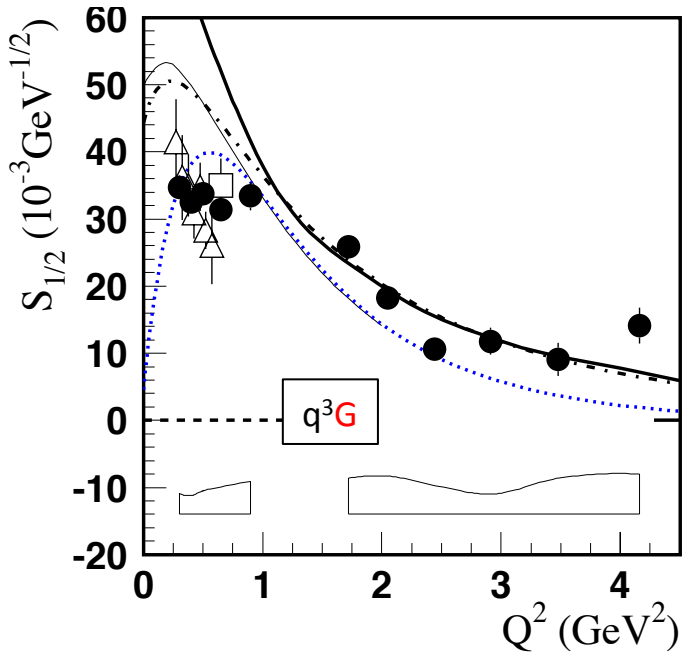
- Overpopulation of $N1/2^+$ and $N3/2^+$ states compared to QM projections?
- Transition form factors in electroproduction?

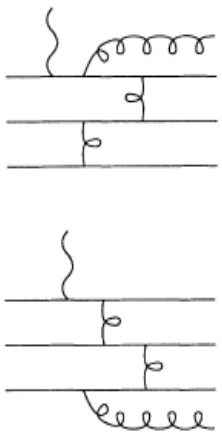
Separating q^3G from q^3 states?

Z.P. Li, V. Burkert, Zh. Li, PRD 46, 70, 1992; C.E. Carlson, N. Mukhopadhyay, PRL 67, 3745, 1991

Lowest mass $|q^3G\rangle$ with $J^P = 1/2^+$ behave like the Δ(1232)





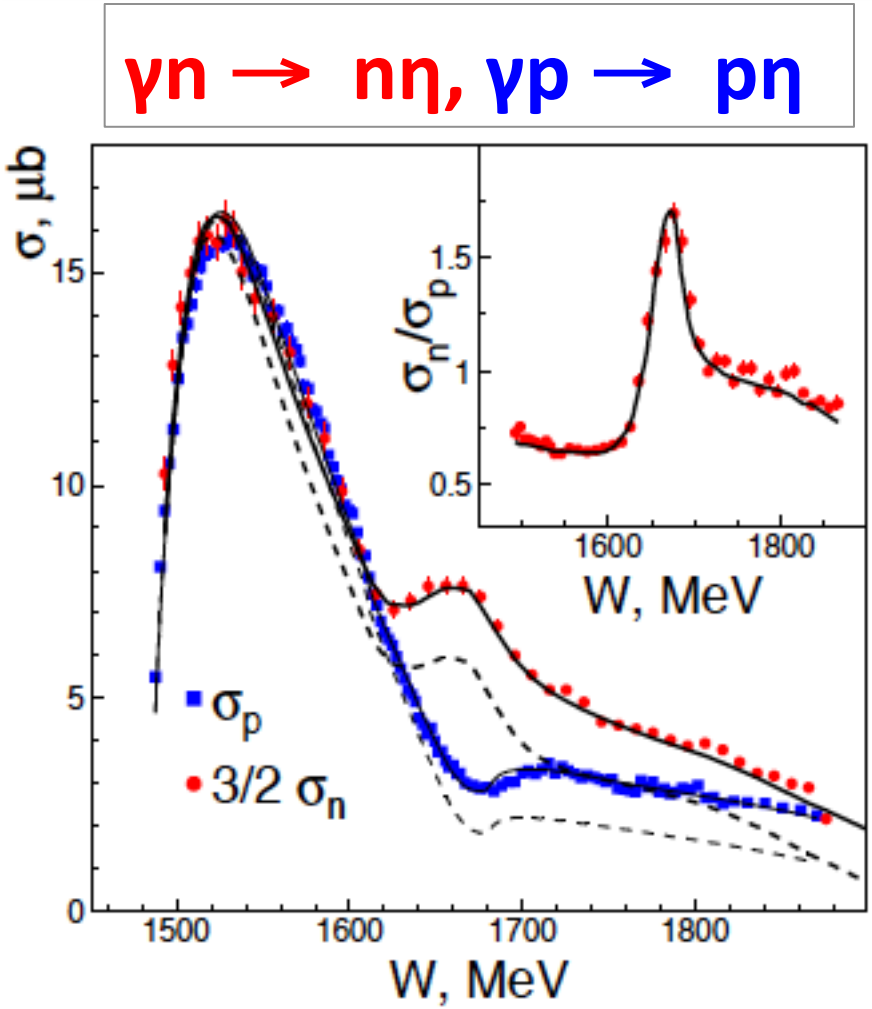


For Roper-like hybrid states $A_{1/2}(Q^2)$ expected to drop very fast with Q^2, and $S_{1/2}(Q^2) = 0$

- $A_{1/2}(Q^2)$ and $S_{1/2}(Q^2)$ are inconsistent with the Roper as a gluonic state.

- Electroexcitation could be a powerful tool for identifying gluonic baryons

An "exotic" resonance at 1670 MeV ?



- Integrated cross section in η photo-production off neutrons shows peak at 1670 MeV that is not seen on the proton.

- Speculations that this may be a $J^P=1/2^+$ a non-exotic member of a decuplet of penta-quark states predicted at this mass by χQSM.

- Coupled-channel analysis shows this as **interference effects of the *N(1535)1/2*$^-$ and *N(1650)1/2*$^-$ states**. Different signs of the helicity amplitudes generate constructive and destructive effects on neutron and proton, respectively.

D. Werthmüller et al., PRL 111, 232001 (2013)

BnGa: A.V. Anisonov et al., arXiv:1402.7164 (2014)

Studies of Nucleon Resonance Structure in Exclusive Meson Electroproduction

Studies of Nucleon Resonance Structure in Exclusive Meson Electroproduction

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ABSTRACT

Studies of the structure of excited baryons are key to the N^* program at Jefferson Lab. Within the first year of data taking with the Hall B CLAS12 detector following the 12 GeV upgrade, a dedicated experiment will aim to extract the N^* electrocouplings at high photon virtualities Q^2. This experiment will allow exploration of the structure of N^* resonances at the highest photon virtualities ever yet achieved, with a kinematic reach up to $Q^2 = 12\ \mathrm{GeV}^2$. This high-Q^2 reach will make it possible to probe the excited nucleon structures at distance scales ranging from where effective degrees of freedom, such as constituent quarks, are dominant through the transition to where nearly massless bare-quark degrees of freedom are relevant. In this document, we present a detailed description of the physics that can be addressed through N^* structure studies in exclusive meson electroproduction. The discussion includes recent advances in reaction theory for extracting N^* electrocouplings from meson electroproduction off protons, along with QCD-based approaches to the theoretical interpretation of these fundamental quantities. This program will afford access to the dynamics of the nonperturbative strong interaction responsible for resonance formation, and will be crucial in understanding the nature of confinement and dynamical chiral symmetry breaking in baryons, and how excited nucleons emerge from QCD.

http://arxiv.org/abs/1212.4891

- I. G. Aznauryan, A. Bashir, V. Braun, S.J. Brodsky, V.D. Burkert, L. Chang, Ch. Chen, B. El-Bennich, I.C. Cloët, P.L. Cole, R.G. Edwards, G.V. Fedotov, M.M. Giannini, R.W. Gothe, F. Gross, Huey-Wen Lin, P. Kroll, T.-S.H. Lee, W. Melnitchouk, V.I. Mokeev, M.T. Peña, G. Ramalho, C.D. Roberts, E. Santopinto, G F. de Teramond, K. Tsushima, D.J. Wilson **(99 pages)**
- Posted on arXiv on 20 Dec 2012.
- Revised on 3 April 2013
- Published in the **International Journal of Modern Physics E (IJMPE)** Volume 22, Issue 06, June 2013 .

What have we have learned from N* studies?

- Evidence for many new states revealed in coupled-channel analysis involving high precision KΛ and KΣ photoproduction reactions.
- States can be accommodated within the SU(6)xO(3) group and LQCD spin-parity projections but not in the naïve quark-diquark picture.
- Meson photoproduction is reaching the "holy grail" of complete measurements, allowing major advances in the search for new states.
- For access to high mass excited nucleon states precision vector meson production data need to be incorporated in coupled-channel analyses.
- Low Q^2 behavior may be essential to identify hybrid baryons.
- The CLAS data on $\gamma_v NN^*$ electrocouplings have revealed that the N* structure as being a complex interplay between the inner core of three dressed quarks and the external meson-baryon cloud. The relative contribution of quark degrees of freedom increases with Q^2 and is expected to be dominant at $Q^2 > 5.0$ GeV^2.

High Q^2 data are needed to access and quantify the short distance behavior (=>JLab@12GeV)

Thanks

Additional slides

N* Light Cone transition charge densities

$$A_{1/2} = e\frac{Q_-}{\sqrt{K}\,(4M_N M^*)^{1/2}}\left\{F_1^{NN^*} + F_2^{NN^*}\right\},$$

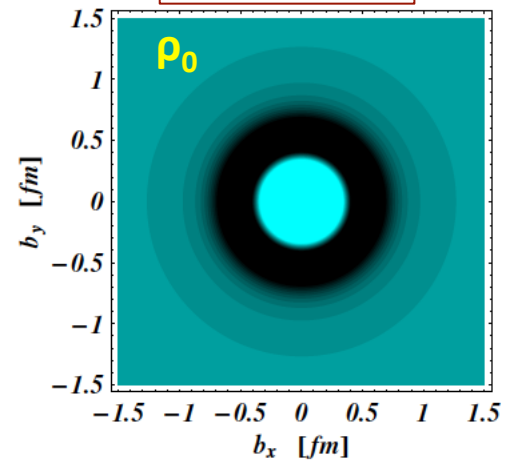
$$S_{1/2} = e\frac{Q_-}{\sqrt{2K}\,(4M_N M^*)^{1/2}}\left(\frac{Q_+Q_-}{2M^*}\right)\frac{(M^*+M_N)}{Q^2}\left\{F_1^{NN^*} - \frac{Q^2}{(M^*+M_N)^2}F_2^{NN^*}\right\}$$

L. Tiator, M. Vanderhaeghen, 2009

$$\rho_0^{NN^*}(\vec{b}) = \int_0^\infty \frac{dQ}{2\pi} Q\, J_0(b\,Q) F_1^{NN^*}(Q^2)$$

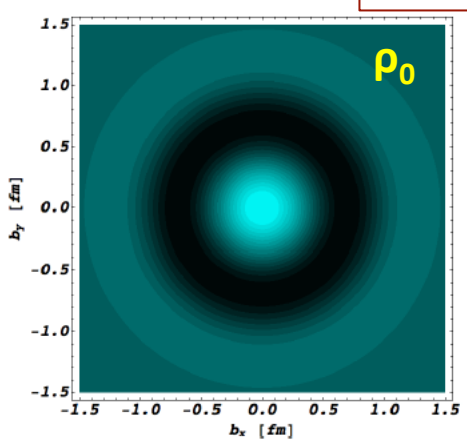
$$\rho_T^{NN^*}(\vec{b}) = \rho_0^{NN^*}(b) + \sin(\phi_b - \phi_S)\int_0^\infty \frac{dQ}{2\pi}\frac{Q^2}{(M^*+M_N)} J_1(b\,Q) F_2^{NN^*}(Q^2)$$

N(1440)1/2+

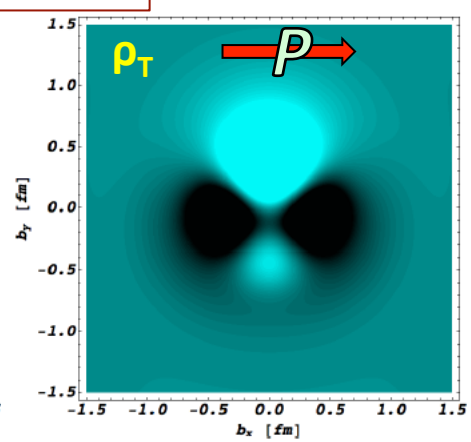


+1/2 => +1/2

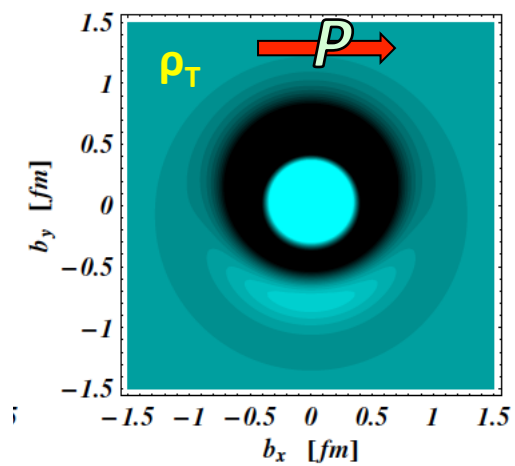
N(1520)3/2-



+1/2 => +1/2



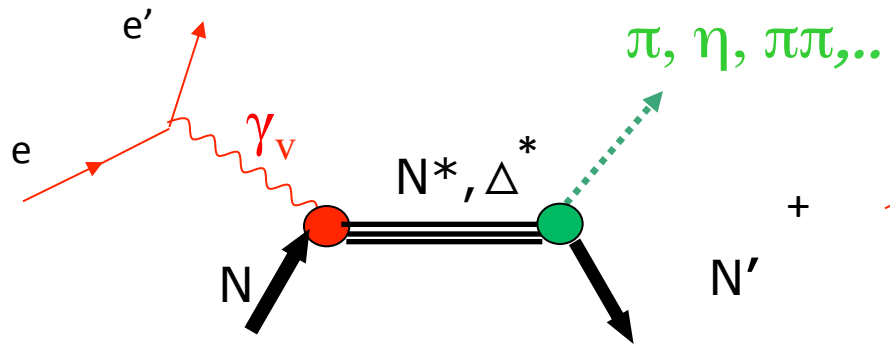
+1/2 => -1/2
Electric QM



+1/2 => -1/2
Electric DM

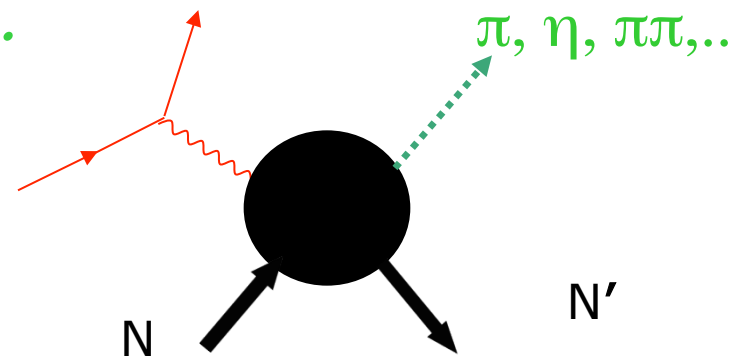
$\gamma_v NN^*$ Electrocouplings from Exclusive Meson Electroproduction Data

Resonant amplitudes



+

Non-resonant amplitudes



- Real $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$, $S_{1/2}(Q^2)$
  or
- $G_1(Q^2)$, $G_2(Q^2)$, $G_3(Q^2)$
  or
- $G_M(Q^2)$, $G_E(Q^2)$, $G_C(Q^2)$

I.G .Aznauryan and V.D .Burkert, Progr. Part. Nucl. Phys. 67, 1 (2012).

Definition of N* photo-/electrocouplings employed in the CLAS data analyses :

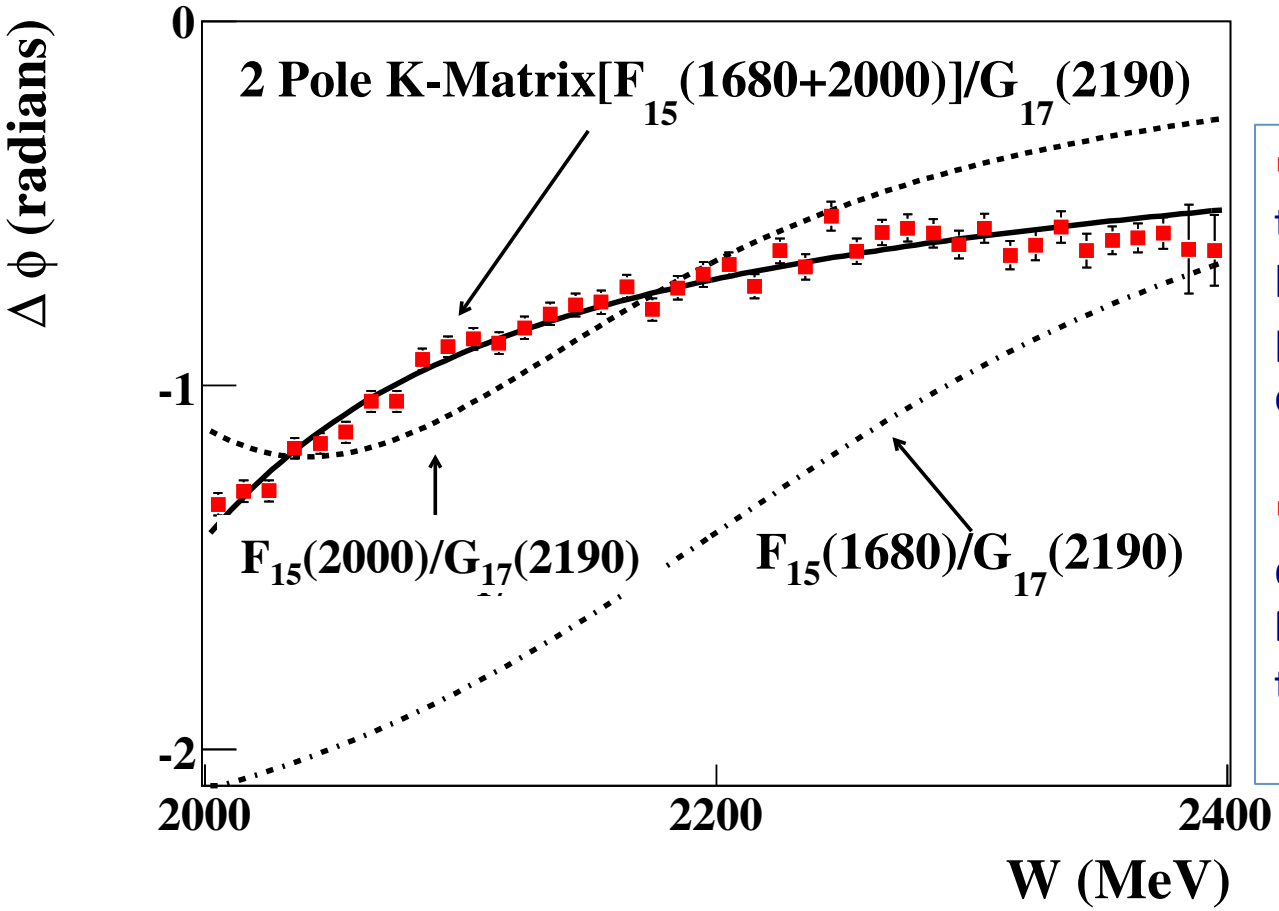
$$\Gamma_\gamma = \frac{q_\gamma^2}{\pi} \frac{2M_N}{(2J_r+1)M_{N^*}} \left[|A_{1/2}|^2 + |A_{3/2}|^2 \right]$$

Γ_γ stands for N* electro-magnetic decay widths at $W=M_{N^*}$ in real energy axis.

Consistent results on $\gamma_v NN^*$ electrocouplings from different meson electroproduction channels and from different analysis approaches will demonstrate the reliable extraction of these quantities.

N* states in $\gamma p \rightarrow p\omega \rightarrow p\pi^+\pi^-\pi^0$

Process acts as isospin filter and is sensitive only to N* states



M. Williams, et al. (CLAS), Phys.Rev. C80 (2009) 065208

- The data are used as input to a single channel event-based, energy independent partial wave analysis (the first ever for baryons).

- ω photoproduction is dominated by the well known **F_{15}(1680) and G_{17}(2190)**, and the "missing" ** **F_{15}(2000)** (2012 PDG: N(2000)5/2$^+$)

Diff. CS and SDME for $\gamma p \rightarrow p\phi \rightarrow pK^+K^-(K_sK_l)$

B. Dey et al., (CLAS), arXiv:1403.2110