INPC 2016 – Adelaide

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ELECTROPRODUCTION AND TRANSITION FORM FACTORS:

ON THE ROAD TOWARDS UNDERSTANDING BARYON STRUCTURE

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on behalf of the CLAS Collaboration

September 16, 2016

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CLAS CEBAF Large Acceptance Spectrometer

Jefferson Lab Exploring the Nature of Matter

Department of Energy United States of America

NSF

Idaho State University

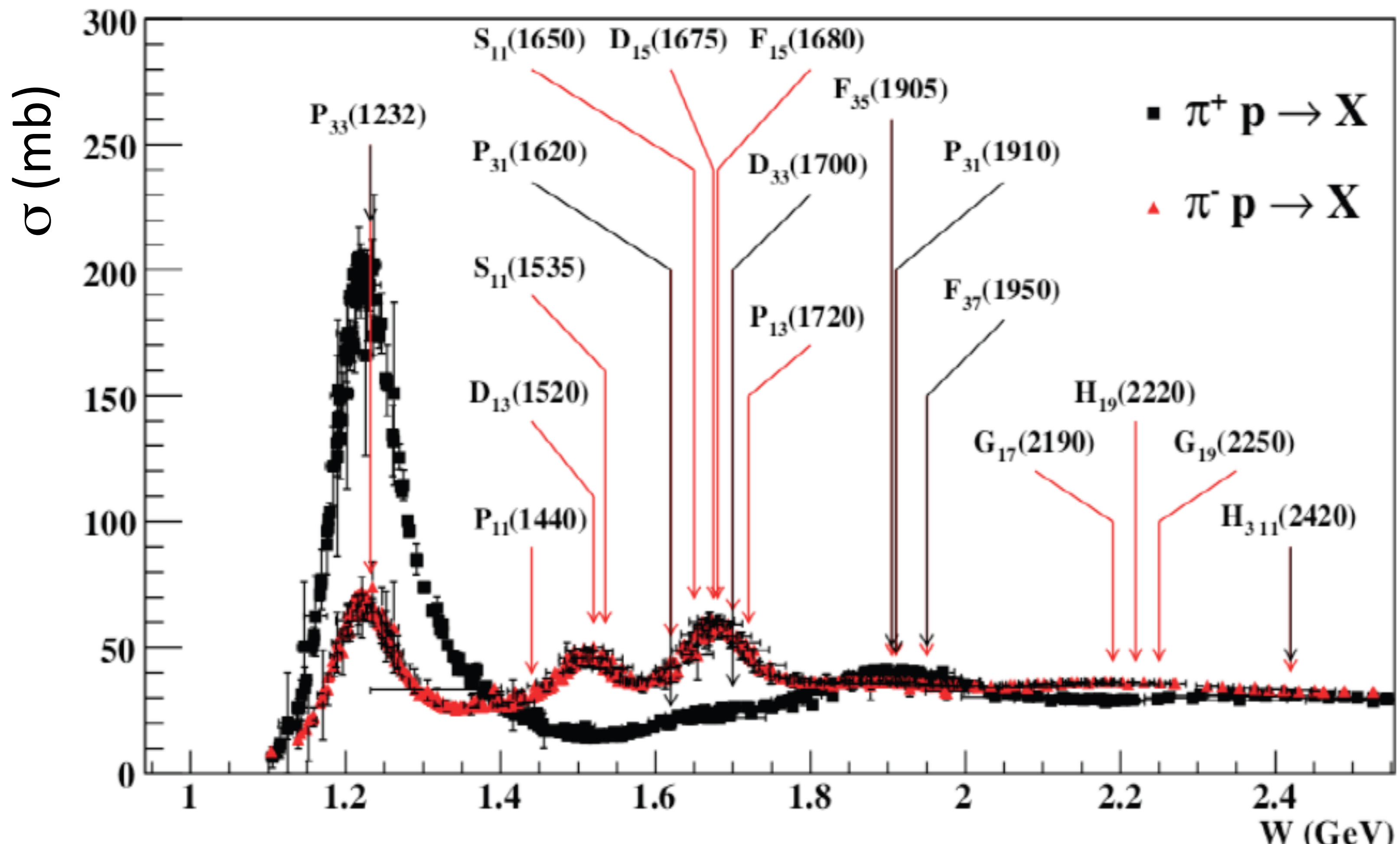
Message to take home

Why N*s are important (quoted from Nathan Isgur[1])

- ***The first is that nucleons are the stuff of which our world is made.***
- ***My second reason is that they are the simplest system in which the quintessentially nonabelian character of QCD is manifest.***
- ***The third reason is that history has taught us that, while relatively simple, baryons are sufficiently complex to reveal physics hidden from us in the mesons.***

[1]Workshop on Excited Nucleons and Hadronic Structure (2000).

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?

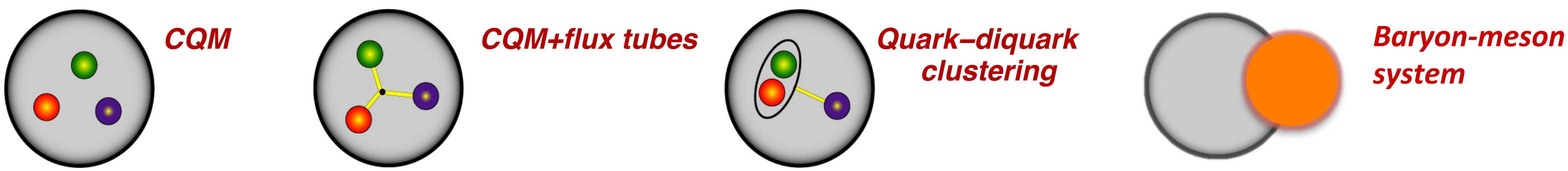
Degrees of Freedom

- **What are the relevant degrees of freedom?**
  - **Meson-Baryon Cloud**
  - **Quark Core**

- **How do the degrees of freedom evolve for differing quantum numbers of an excited baryon (N*) states?**

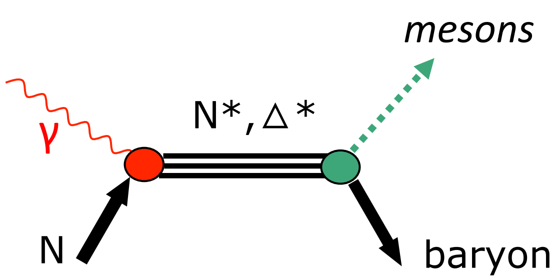
What do we want to learn? (Establish Baryon Spectrum)

- 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)

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

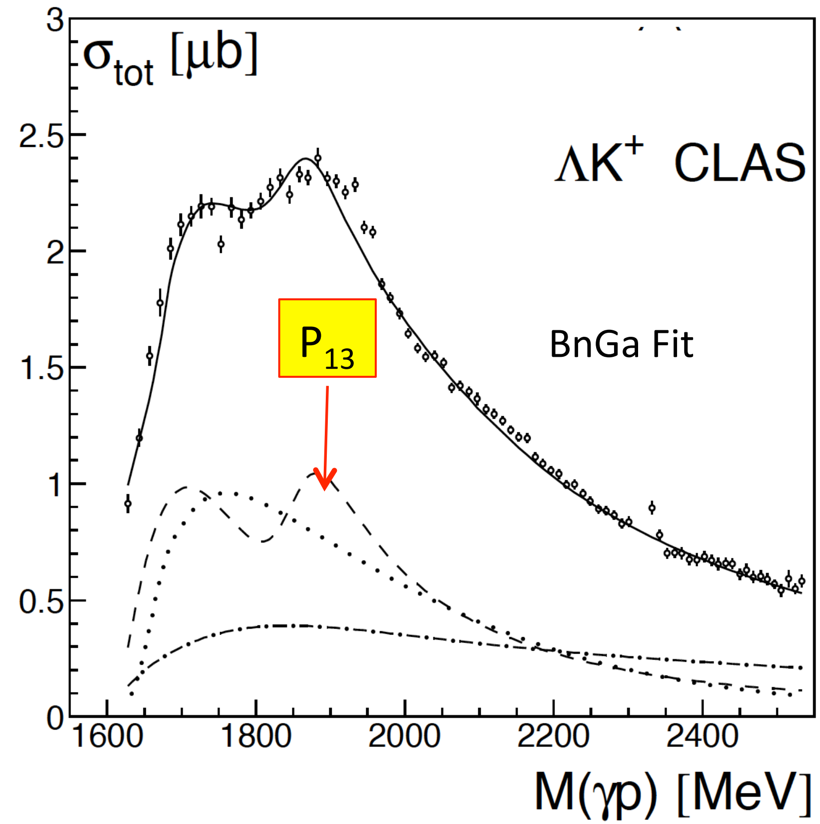
- State was solidly established in Bonn-Gatchina coupled-channel analysis making use of very precise KΛ cross-section and polarization data, lead to the *** rating in PDG2012.

- 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.



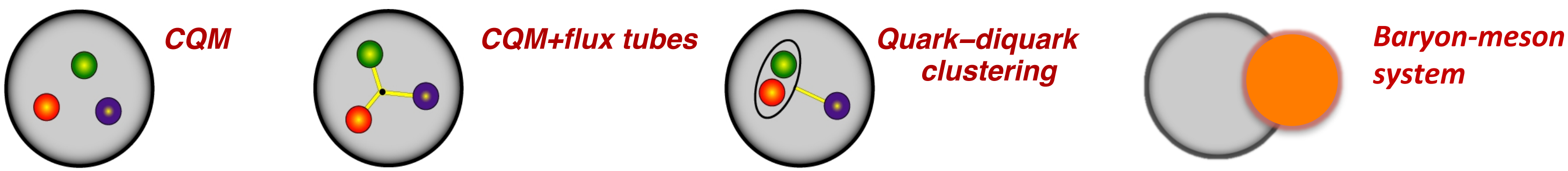
Evidence for new N* states and couplings

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)

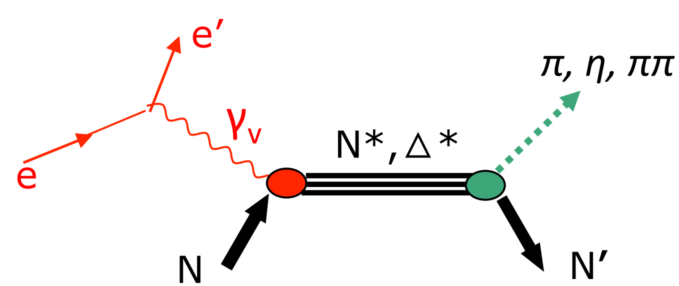
What do we want to learn? (Understand Baryon Structure)

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

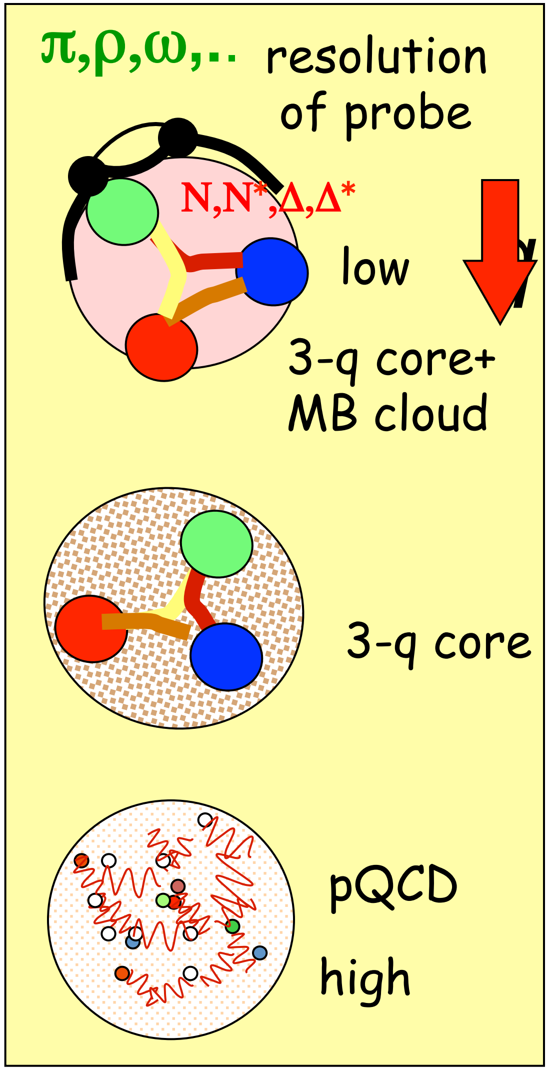


- A vigorous experimental program is underway along two avenues
  - Search for undiscovered states in meson photo-/ electroproduction to systematically characterize the excited baryon spectrum
  - Measure the strength of resonance excitations vs time-distance scale in meson electroproduction (i.e. as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

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

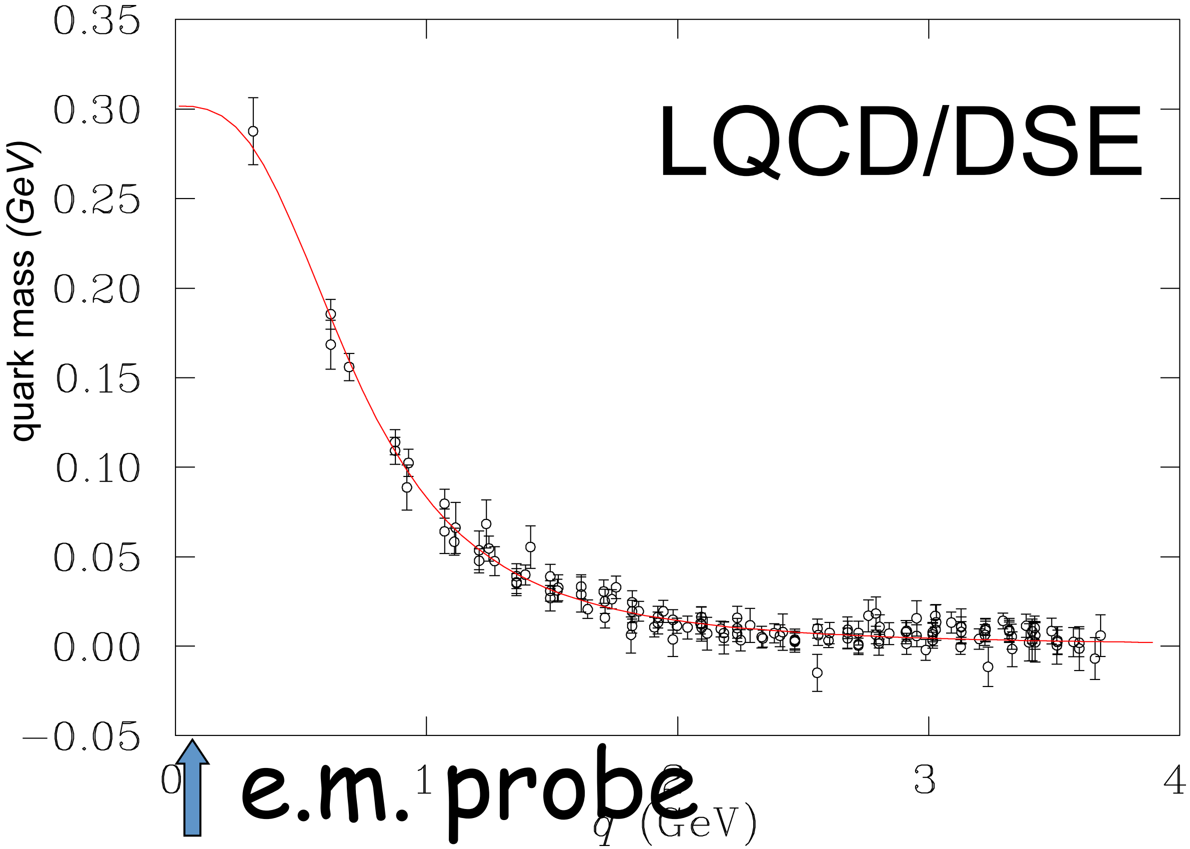


Hadron structure via electromagnetic probes



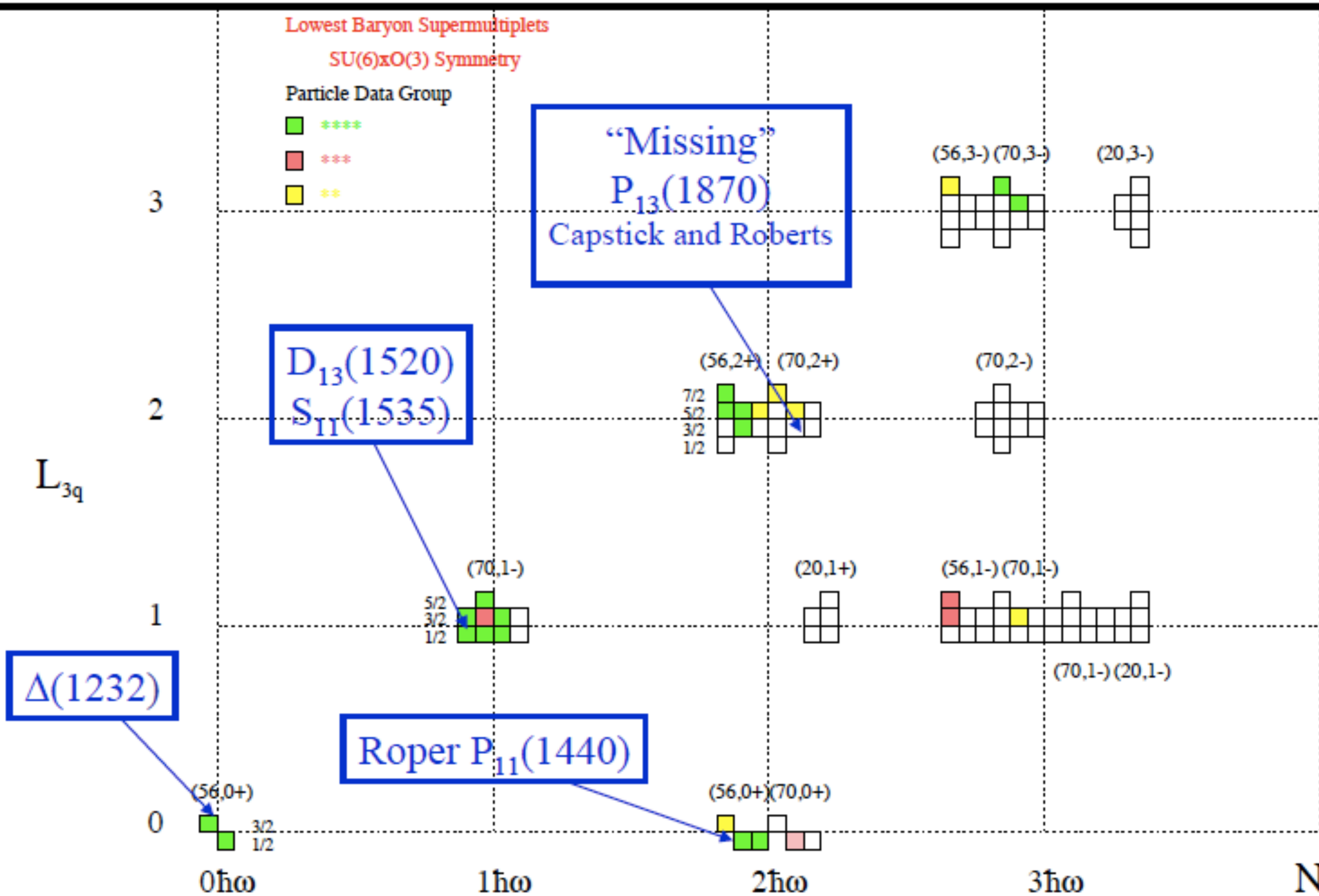
Allows us to address central the question:

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



See Craig Robert's Talk

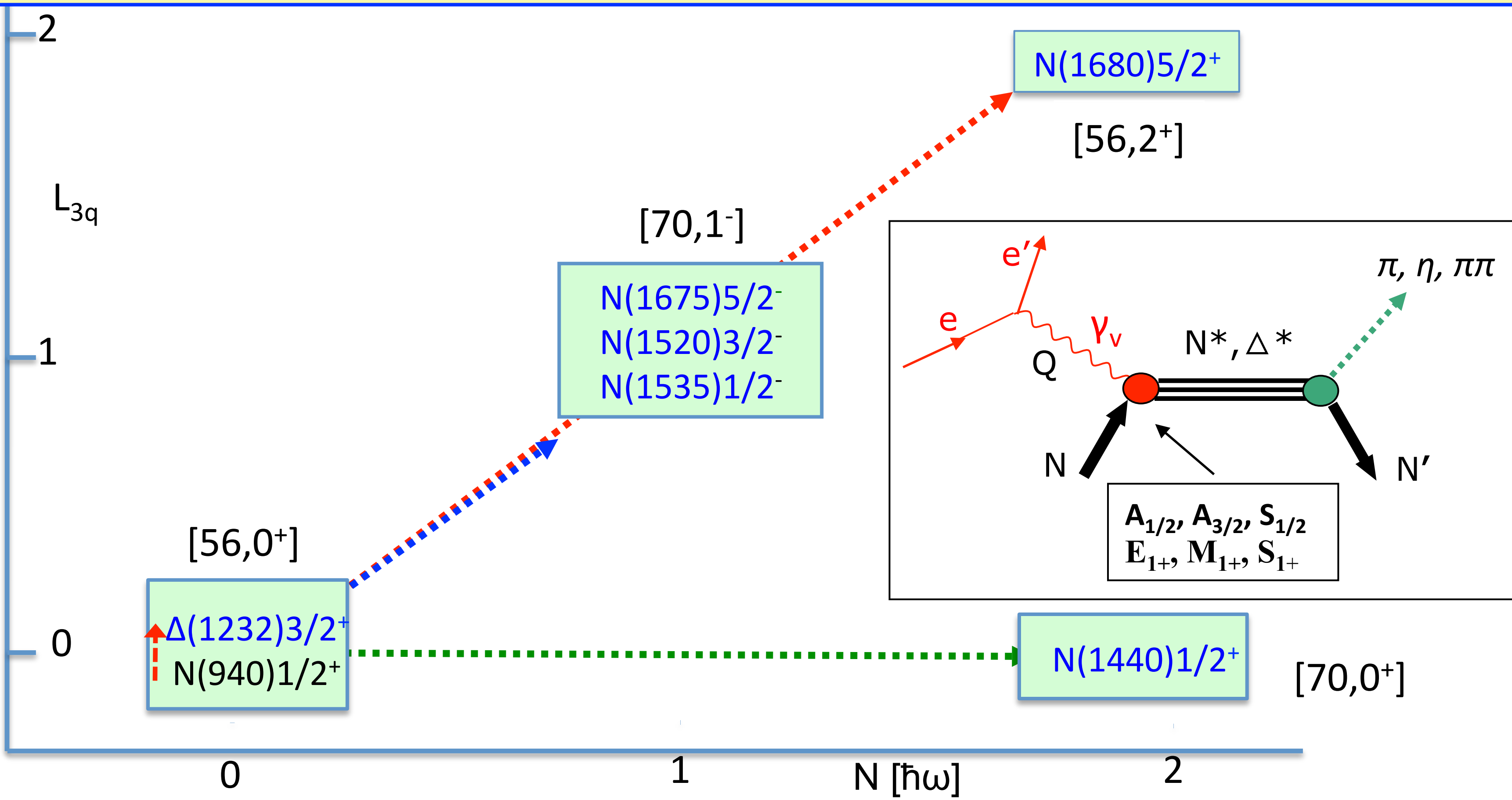
SU(6) x O(3) Classification of Baryons



See David Ireland's Talk

Electroexcitation of N/Δ resonances

- Real photon beam essential for **establishing the N* spectrum**
- Virtual photons probe resonance strength vs time-distance scale for **measuring the N* structure,** confirm/rule out new states from photoproduction



See Annalisa D’Angelo’s Talk

Summary of the Results on $\gamma_v pN^*$ Electrocouplings from CLAS

Exclusive meson electroproduction channels	Excited proton states	Q^2-ranges for extracted $\gamma_v NN^*$ electrocouplings, GeV^2
$\pi^0 p$, $\pi^+ n$	$\Delta(1232)3/2^+$ $N(1440)1/2^+$, $N(1520)3/2^-$, $N(1535)1/2^-$	0.16-6.0 0.30-4.16
$\pi^+ n$	$N(1675)5/2^-$, $N(1680)5/2^+$ $N(1710)1/2^+$	1.6-4.5
ηp	$N(1535)1/2^-$	0.2-2.9
$\pi^+\pi^- p$	$N(1440)1/2^+$, $N(1520)3/2^-$ $\Delta(1620)1/2^-$, $N(1650)1/2^-$, $N(1680)5/2^+$, $\Delta(1700)3/2^-$, $N(1720)3/2^+$, $N'(1720)3/2^+$	0.25-1.50 0.5-1.5

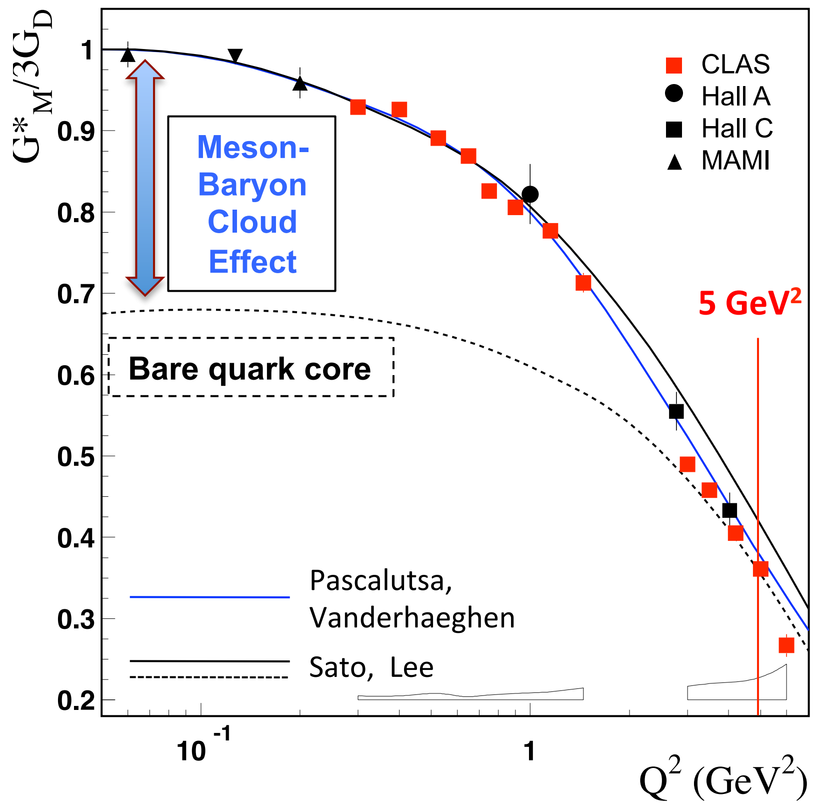
The values of resonance electrocouplings can be found in:
https://userweb.jlab.org/~mokeev/resonance_electrocouplings/

PLANS:

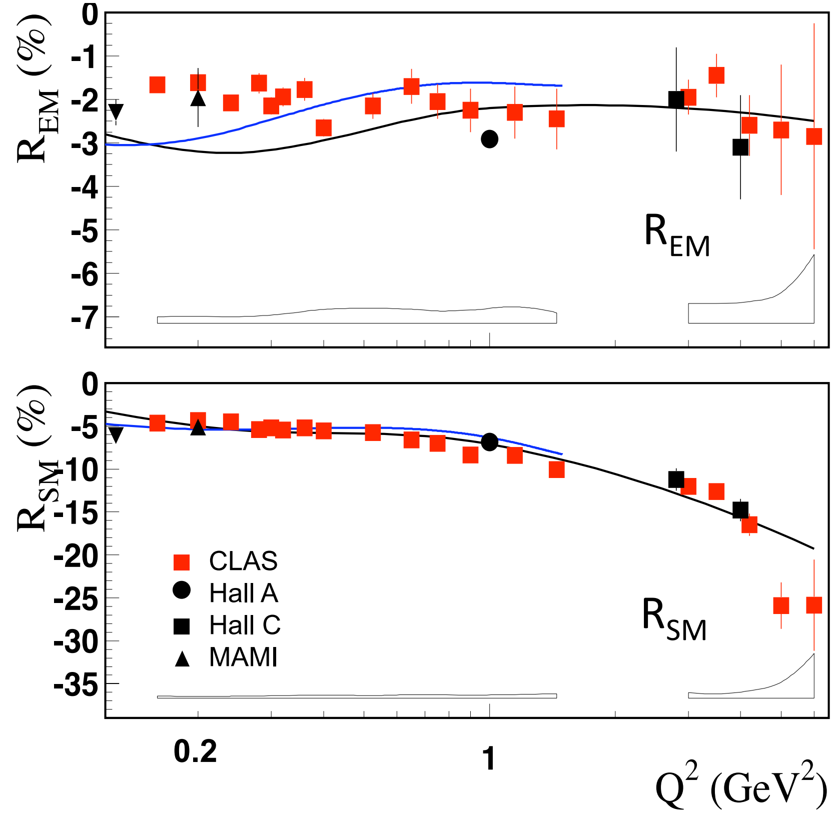
$\gamma_v pN^*$ electrocoupling of all prominent nucleon resonances in mass range $M_{N^*} < 2.0$ GeV will be determined from independent analyses of $N\pi$, $N\pi\pi$, and KY channels measured with the CLAS12 detector.

The Δ(1232)3/2+ transition

Magnetic Transition Form Factor



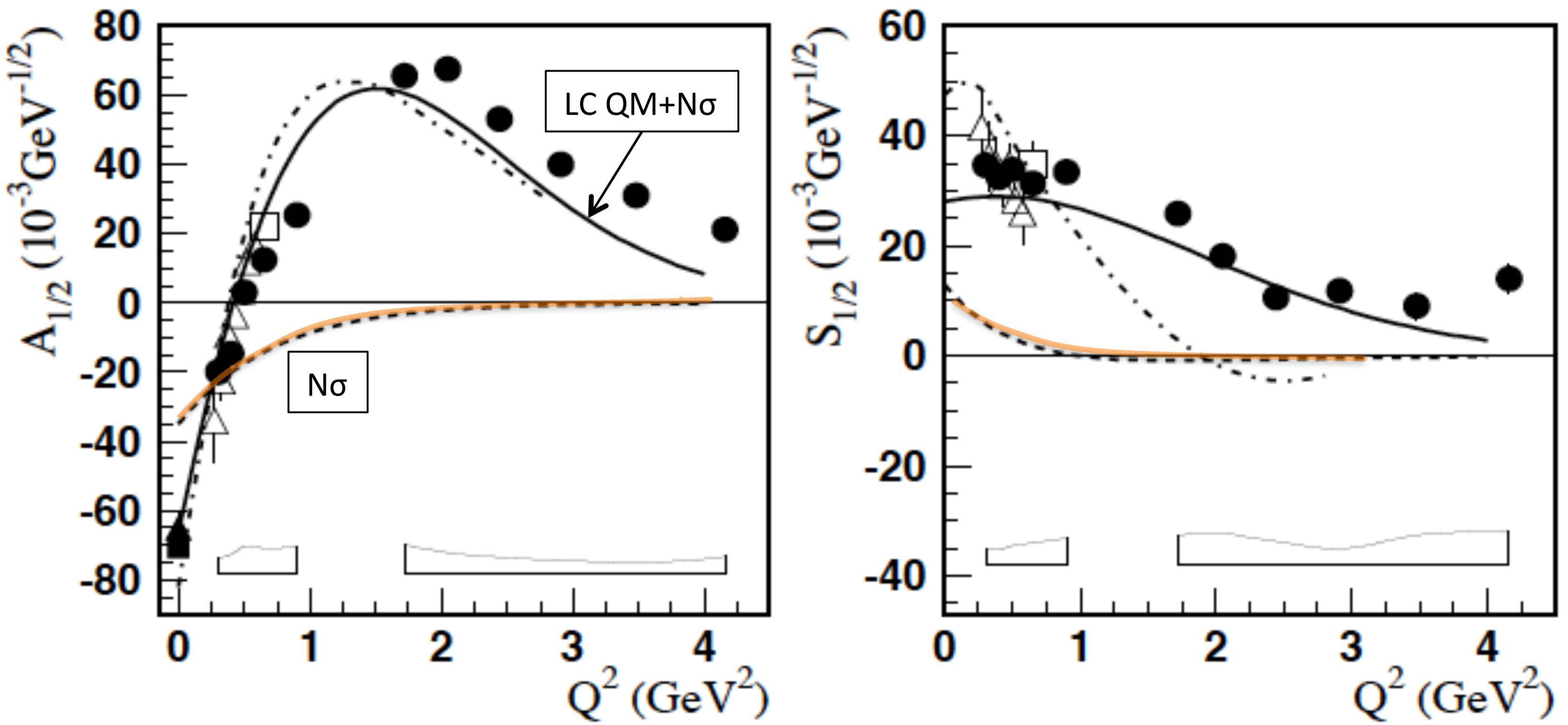
Quadrupole Ratios



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

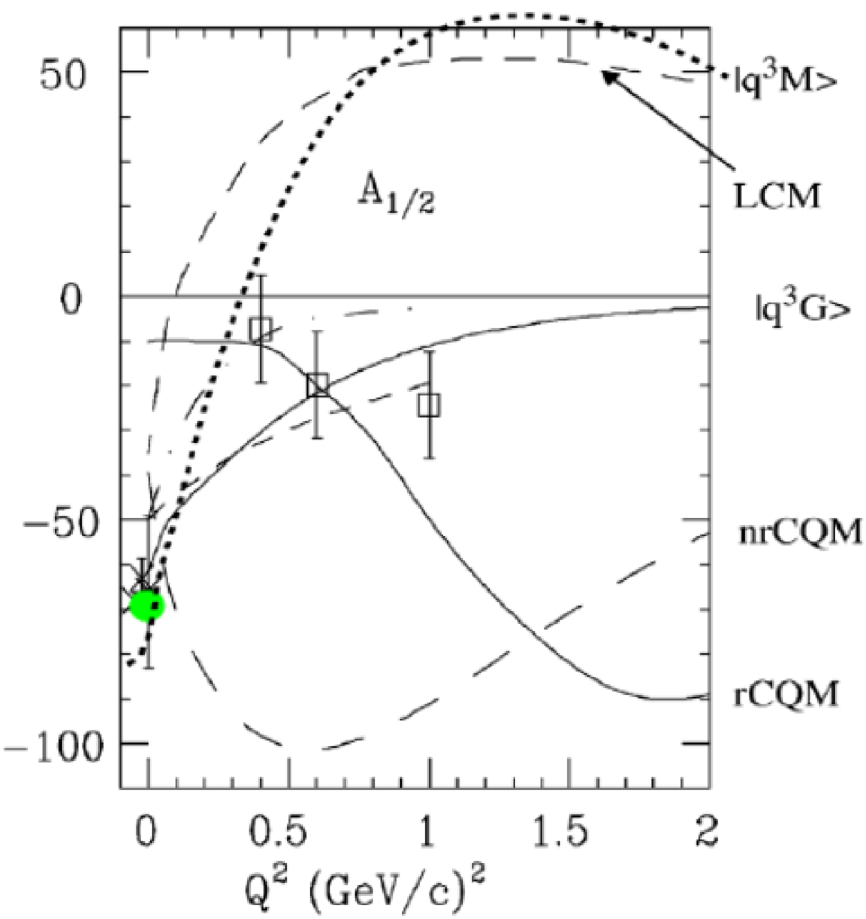
Aznauryan et al. (CLAS), PRC80, 055203 (2009) , V. Mokeev et al. (CLAS), PRC86, 035203 (2012)



- $A_{1/2}$ 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.

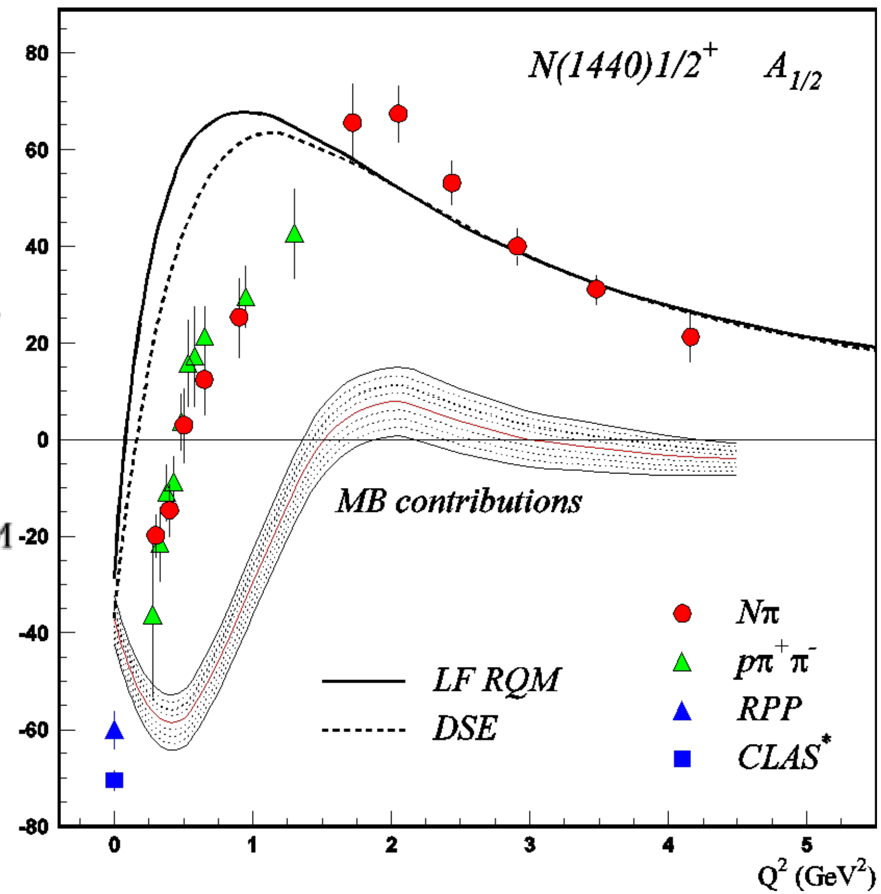
Roper resonance in 2002 & 2016

2002



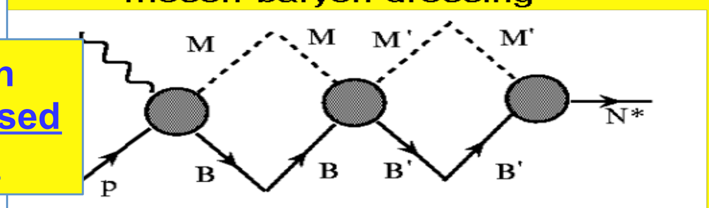
V. Burkert, Baryons 2002

2016



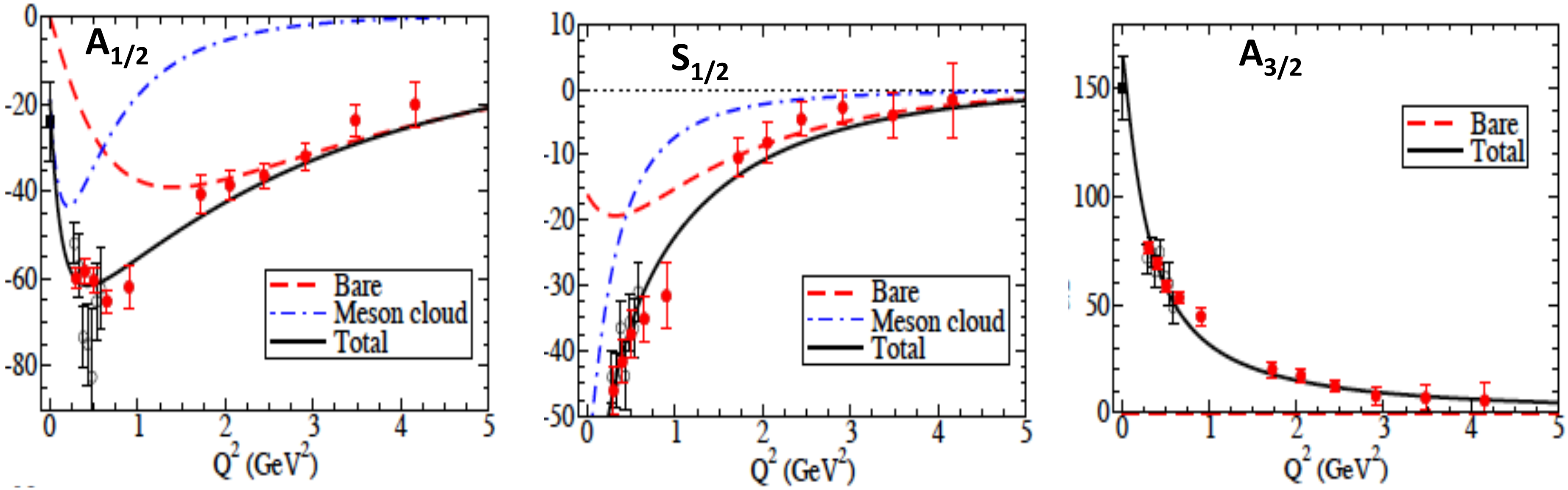
V. D. Burkert

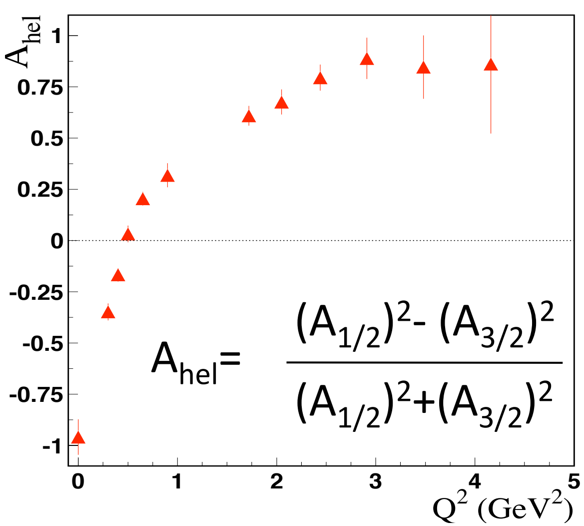
The mechanisms of the meson-baryon dressing



DSE describe successfully the nucleon elastic and the transition N→Δ(1232)3/2⁺, N→N(1535)1/2⁻ form factors with the same dressed quark mass function (J.Segovia, et al., PRL 115, 171801 (2015)).

Electrocouplings of N(1520)3/2⁻





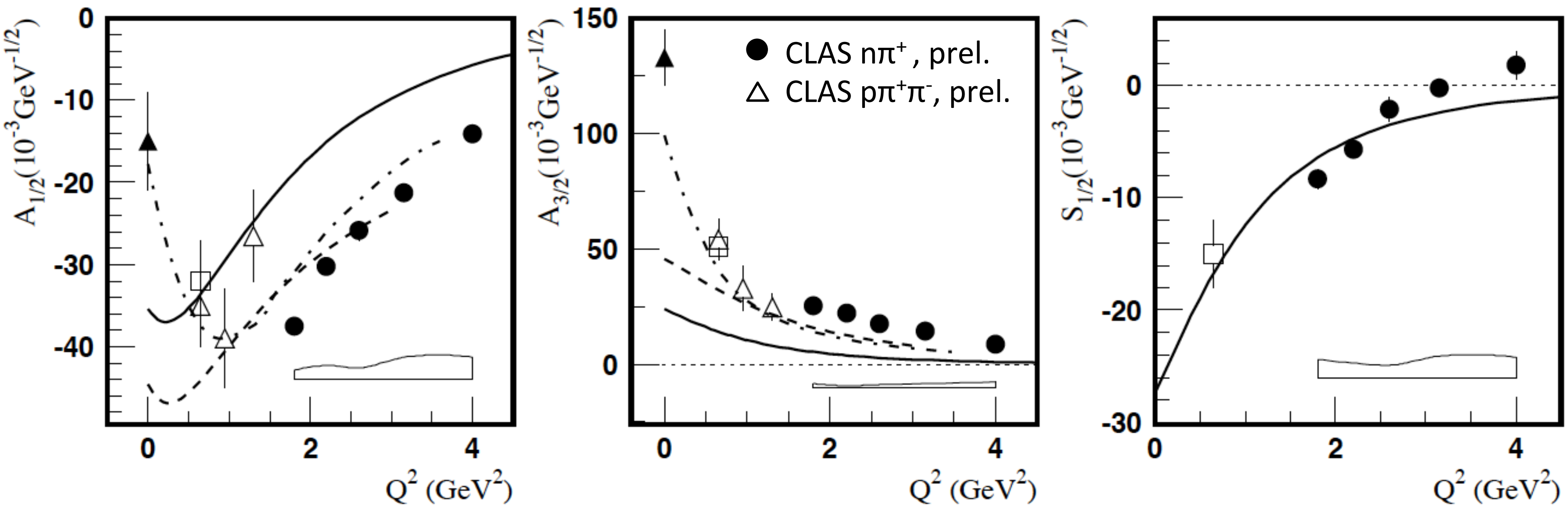
$$A_{hel} = \frac{(A_{1/2})^2 - (A_{3/2})^2}{(A_{1/2})^2 + (A_{3/2})^2}$$

- 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.

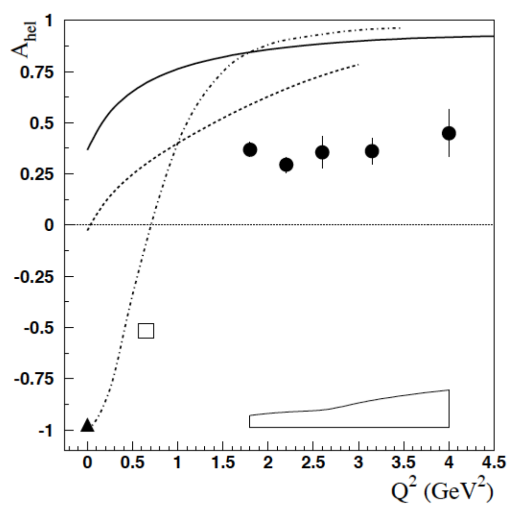
$A_{1/2}$ strength at high Q^2 dominantly from quarks
$A_{3/2}$ strength dominantly from MB contributions.

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

Electrocouplings of N(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.
- Are there significant meson-baryon contributions at large Q^2?

New Run Group Proposal (RG K)

"Color Confinement and Strong QCD"

Hybrid Baryons PR12-16-010	Search for hybrid baryons (qqqg) focusing on 0.05 $GeV^2 < Q^2 < 2.0$ GeV^2 in mass range from 1.8 to 3 GeV in KΛ, Nππ, Nπ *(A. D'Angelo)*
KY Electroproduction PR12-16-010A	Study N* structure for states that couple to KY through measurements of cross sections and polarization observables that will yield Q^2 evolution of electrocoupling amplitudes *(D. Carman)*
DVCS PR12-16-010B	Access GPDs H, E, $\tilde{H}$, $\tilde{E}$ using DVCS process ep → epγ and the DVMP process ep → $ep\pi^0$ *(L.Elouadrhiri)*

Run Group conditions:
E_b = 6.6 GeV, 50 days
E_b = 8.8 GeV, 50 days

- Torus I = -3375 A (negatives outbending)
- FT, MM, RICH
- Polarized electrons, unpolarized LH_2 target
- L = $1x10^{35}$ $cm^{-2}s^{-1}$

First run group proposal for less than 5-pass beam

CLAS12 N* Program

E12-09-003	E12-06-108A
Nucleon Resonance Studies with CLAS12	KY Electroproduction with CLAS12
Burkert, Mokeev, Stoler, Joo, Gothe, Cole	*Carman, Mokeev, Gothe*

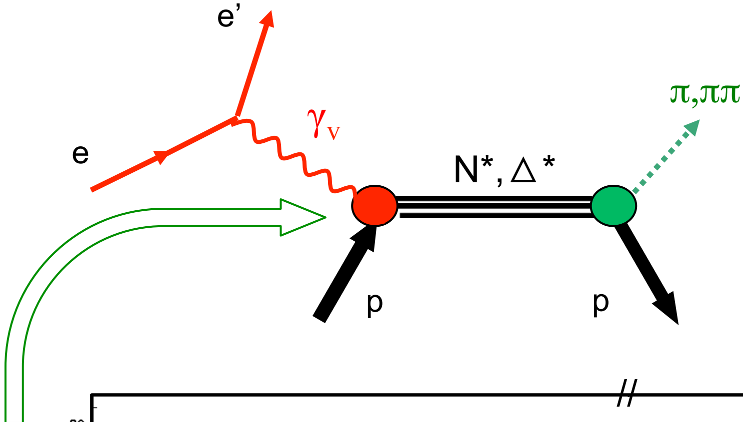
- Measure exclusive electroproduction cross sections from an unpolarized proton target with longitudinally polarized electron beam for $N\pi$, $N\eta$, $N\pi\pi$, KY:

$$E_b = 11 \text{ GeV},\ Q^2 = 5 \rightarrow 12 \text{ GeV}^2,\ W \rightarrow 3.0 \text{ GeV},\ \cos\theta_m^* = [-1:1]$$

- Key Motivations:
  - *Study spectrum and structure of all prominent N* states vs. Q^2*
    - *A unique opportunity to explore the nature of confinement that is responsible for >98% of resonance masses and the emergence of N* states from QCD*
  - *KY data complement the $N\pi\pi$ data as independent information for high-mass states inaccessible with $N\pi$ final states*
    - *Promising way to confirm signals of new N* states observed in photoproduction using search in multiple independent Q^2 bins*

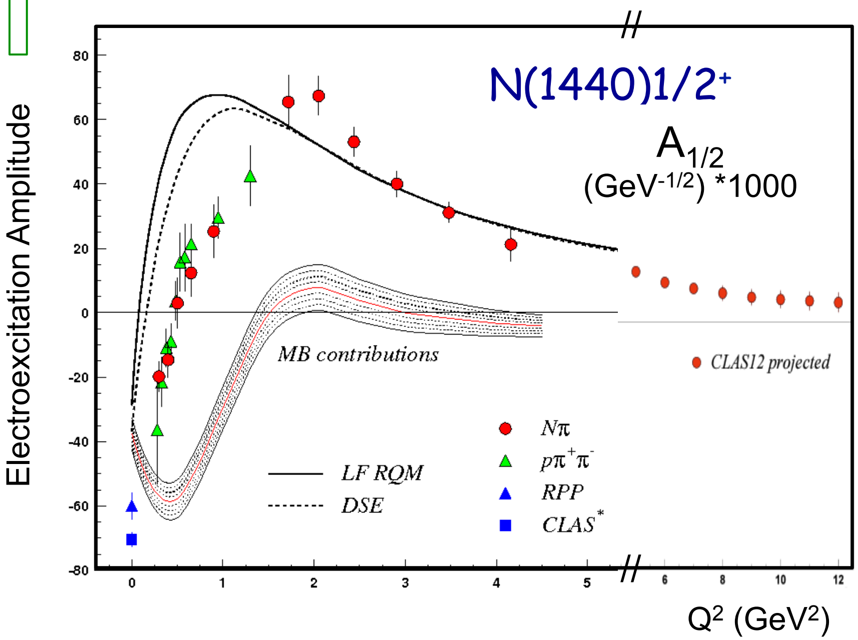
Resonances with the CLAS12 at high Q^2<12 GeV^2 :
Emergence and Distribution of Mass

Resonance electro-excitation (●) and decay (●) amplitudes



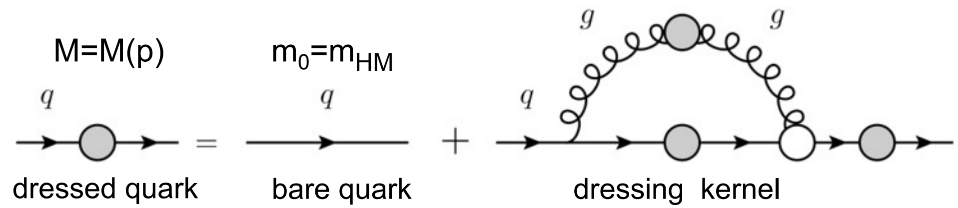
N* electroexcitation studies with CLAS12 in Hall B at JLab will address the critical open questions:

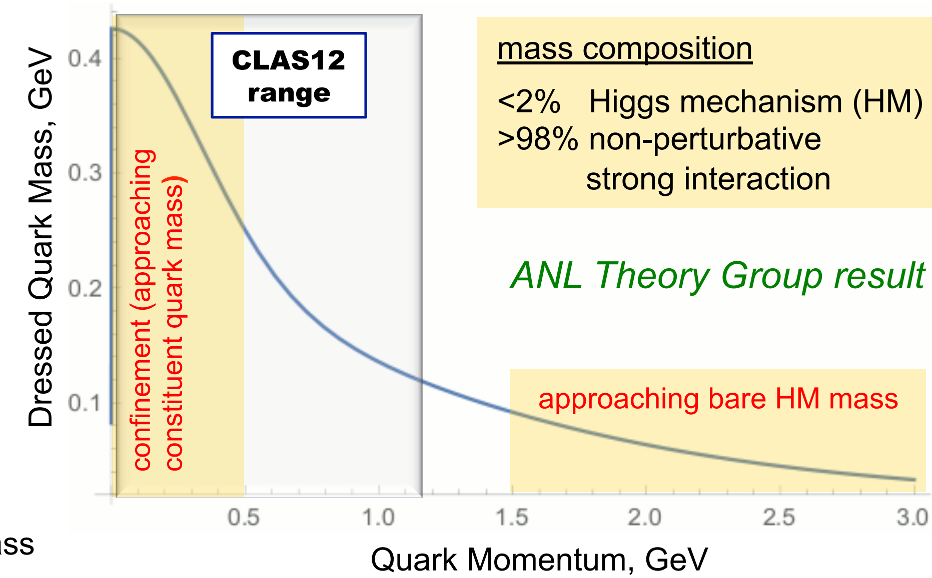
What is the essence of confinement, how is >98% of visible mass generated, and how is it distributed within a hadron?



CLAS results versus QCD expectations with running quark mass

Dressed quark mass depends on its momentum





What have we have learned from N* studies?

- Evidence for many new states revealed in multichannel analysis – major impact from high precision KΛ and KΣ photoproduction reactions at CLAS.

- The CLAS data on γ_vNN* 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 $Q^2 > 5.0\ \mathrm{GeV}^2$.

What do we seek to learn from N* studies?

- N* studies with the CLAS12 at low/intermediate Q^2 will allow us to
  - **search** for hybrid baryons
  - **explore t**he emergence of Meson-Baryon Cloud
- Resonance electrocouplings at for low to high Q^2 will allow us to
  - **study** the confinement regime for the quark core.
  - **map** the quark mass function in the transition from confinement to perturbative QCD

Interactions between and among valence quarks and gluons?

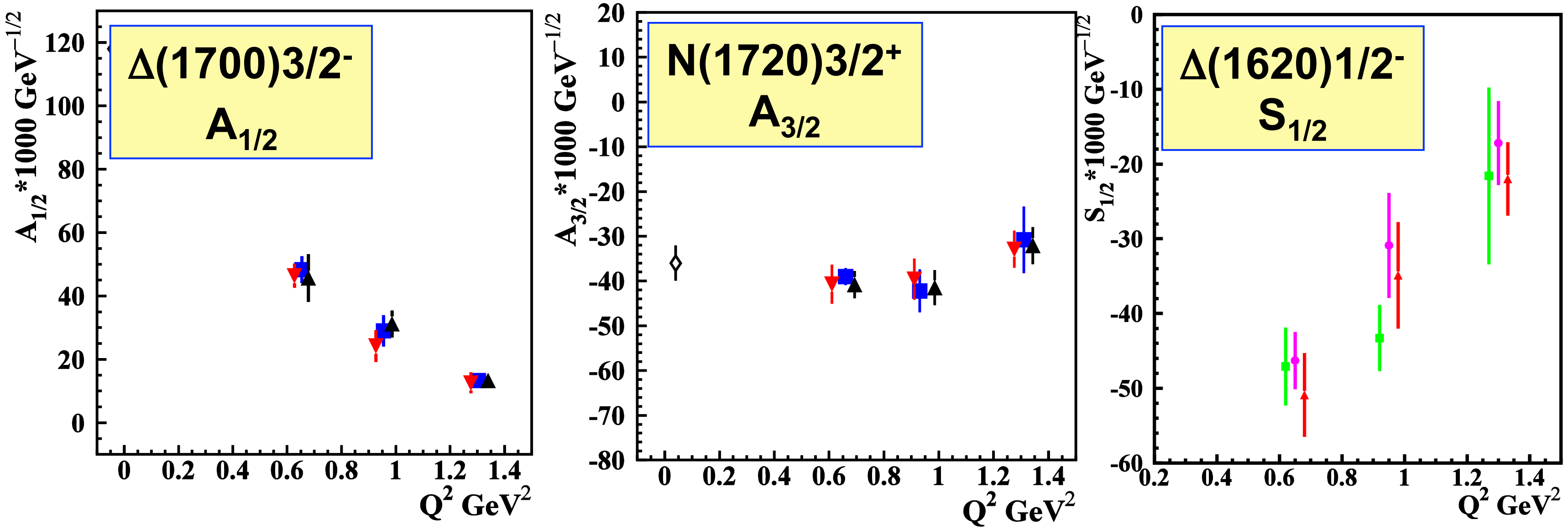
THANKS

The Advertiser 15 September 2016

Electrocouplings in the Third Resonance Region
(CLAS $\pi^+\pi^- p$ Electroproduction Data)

V.I. Mokeev and I.G. Aznauryan., Int. J. Mod. Phys. Conf. Ser. 26. 146080 (2014)

V.I. Mokeev et al., PRC 93, 054016 (2016)



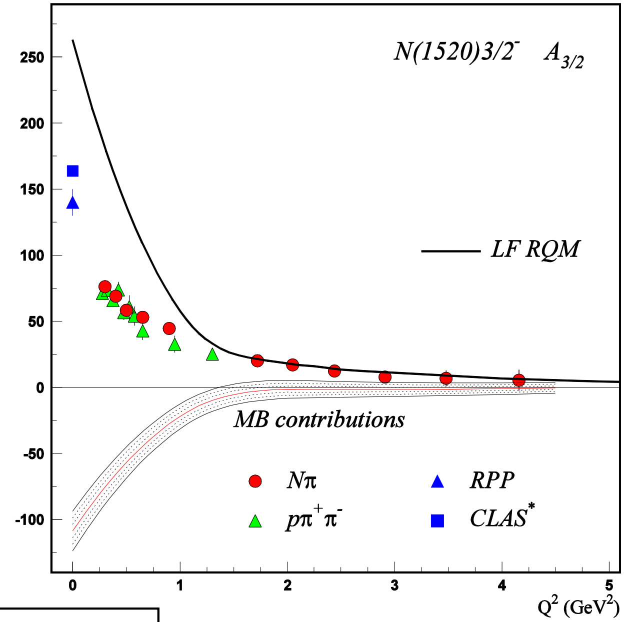
<u>**Independent fits in different W-intervals**</u>

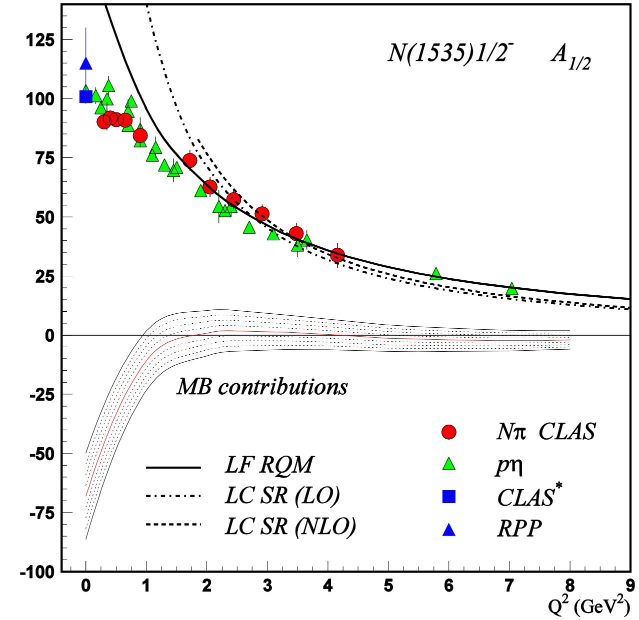
green: 1.51<W<1.61 GeV **red: 1.61<W<1.71 GeV** **black: 1.71<W<1.81 GeV**
magenta: 1.56<W<1.66 GeV **blue: 1.66<W<1.76 GeV**

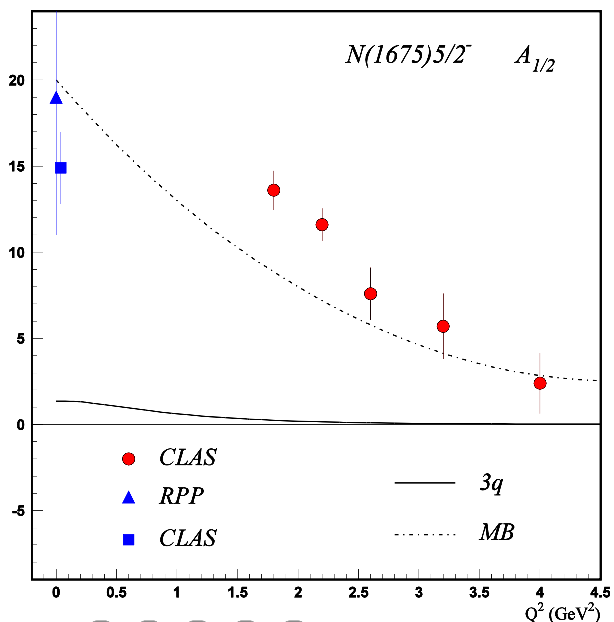
- N* states in the 3rd resonance region which decay preferentially to the $N\pi\pi$ final states.
- The electrocouplings for the **D(1620)1/2$^-$**, **N(1650)1/2$^-$**, **N(1680)5/2$^+$**, **D(1700)3/2$^-$**, and **N(1720)3/2$^+$** resonances have become available for the first time.

$\gamma_v pN^*$ Electrocouplings from $N\pi$, $\pi^+\pi^- p$, and ηp Electroproduction

H Denizli et al., Phys. Rev. C76, 015204 (2007).
I.G. Aznauryan et al., Phys. Rev. C80, 055203 (2009).
V.I. Mokeev et al., Phys. Rev . C86, 035203 (2012).
K. Park et al., Phys. Rev. C91, 052014 (2015).
V.I. Mokeev et al., Phys. Rev . C93, 054016 (2016).







Consistent values of resonance electrocouplings from analyses of $N\pi$/ $\pi^+\pi^- p$ and $N\pi$/$N\eta$ exclusive channels strongly support:

- **reliable electrocoupling extraction;**
- **capabilities of the reaction models to obtain resonance electrocouplings in independent analyses of these channels;**

First results on electrocouplings of the 3rd resonance region N* states have become available