Nucleon Resonance Physics

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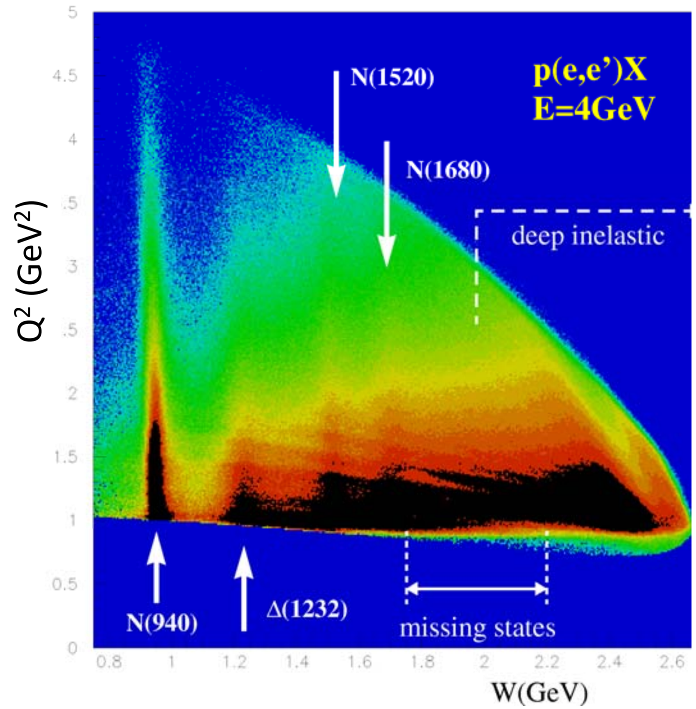
Jefferson Lab

- Introduction
- Establishing the N* spectrum
- Identifying the effective DoF's
- Conclusions & outlook

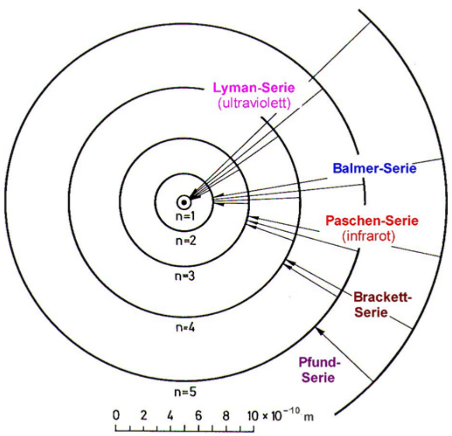


CEBAF Large Acceptance Spectrometer

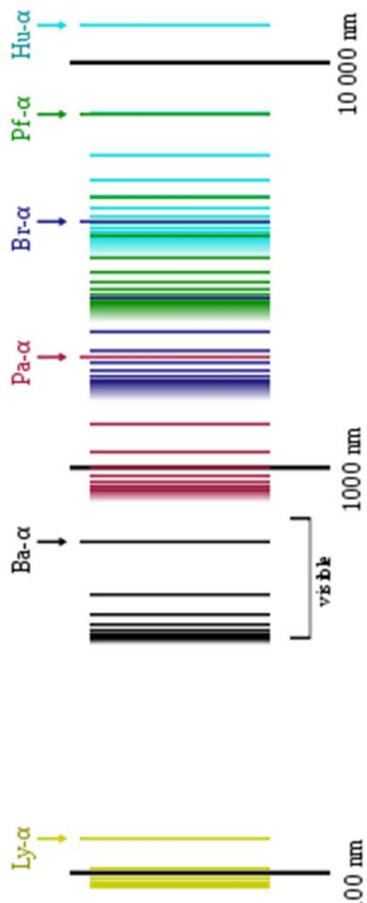
Jefferson Lab
Thomas Jefferson National Accelerator Facility

From the hydrogen spectrum to the N*

N. Bohr, 2013



Spectral series of hydrogen

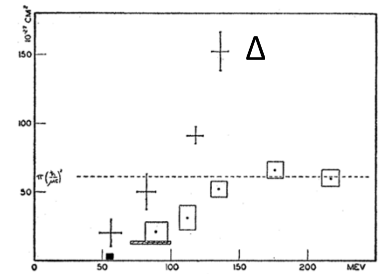


- Understanding the hydrogen atom's ground state requires understanding its excitation spectrum.
  => From the Bohr model of the atom to ***QED***.

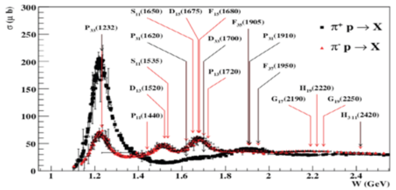
- Understanding the proton's ground state requires understanding its excitation spectrum.
  => From the constituent quark model to ***QCD***.

Some historical markers

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

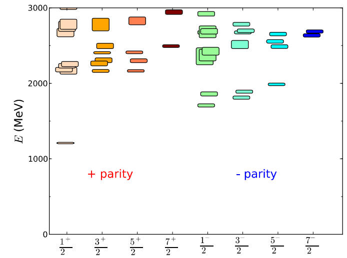


1964: Baryon resonances essential in establishing the quark model and the color degrees of freedom.

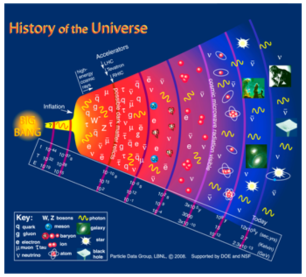


1989: Broad effort to address the "missing baryons" puzzle

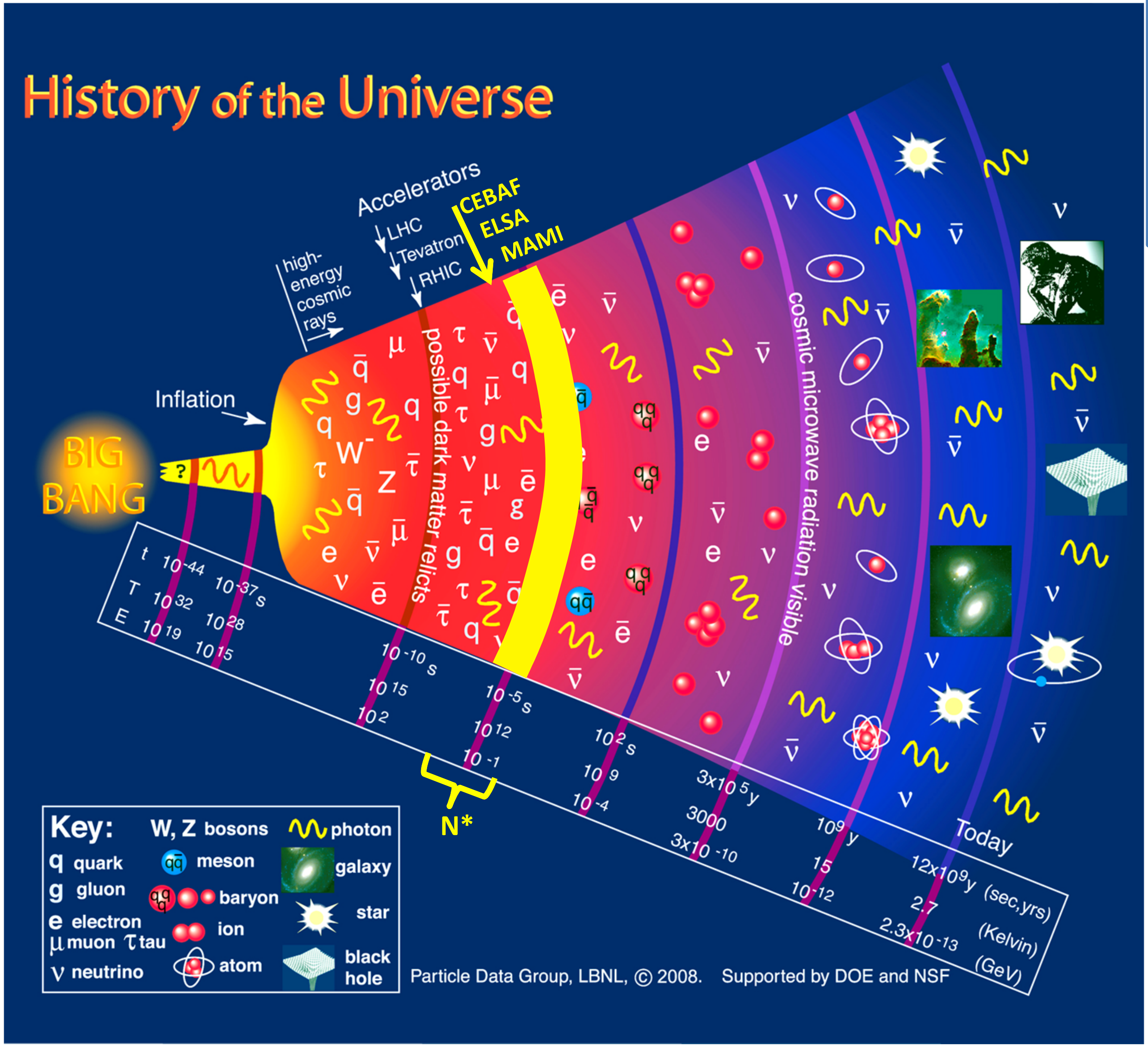
2010: First successful attempt to predict the nucleon spectrum in LQCD



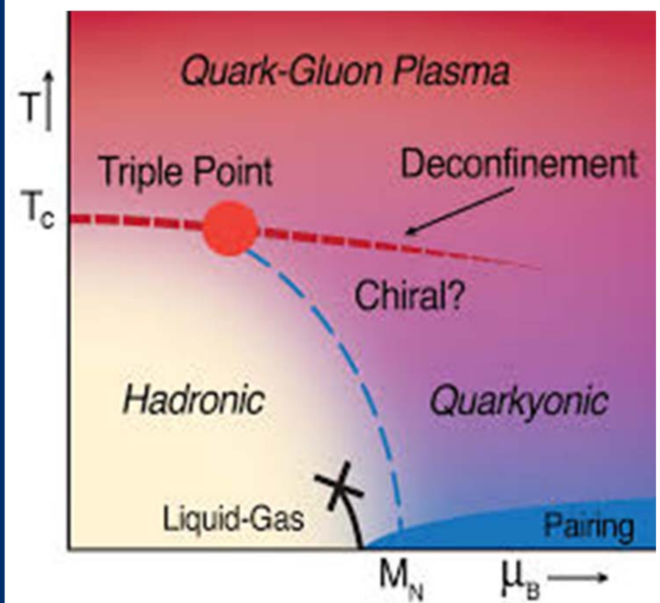
2015: Understanding of the baryon spectrum needed to quantify the transition from the QGP to the confinement phase of nucleons in the early universe.



Excited Baryons in the history of the Universe



Excited baryons are at the transition of the QGP to the confinement of quarks and gluons in hadrons.

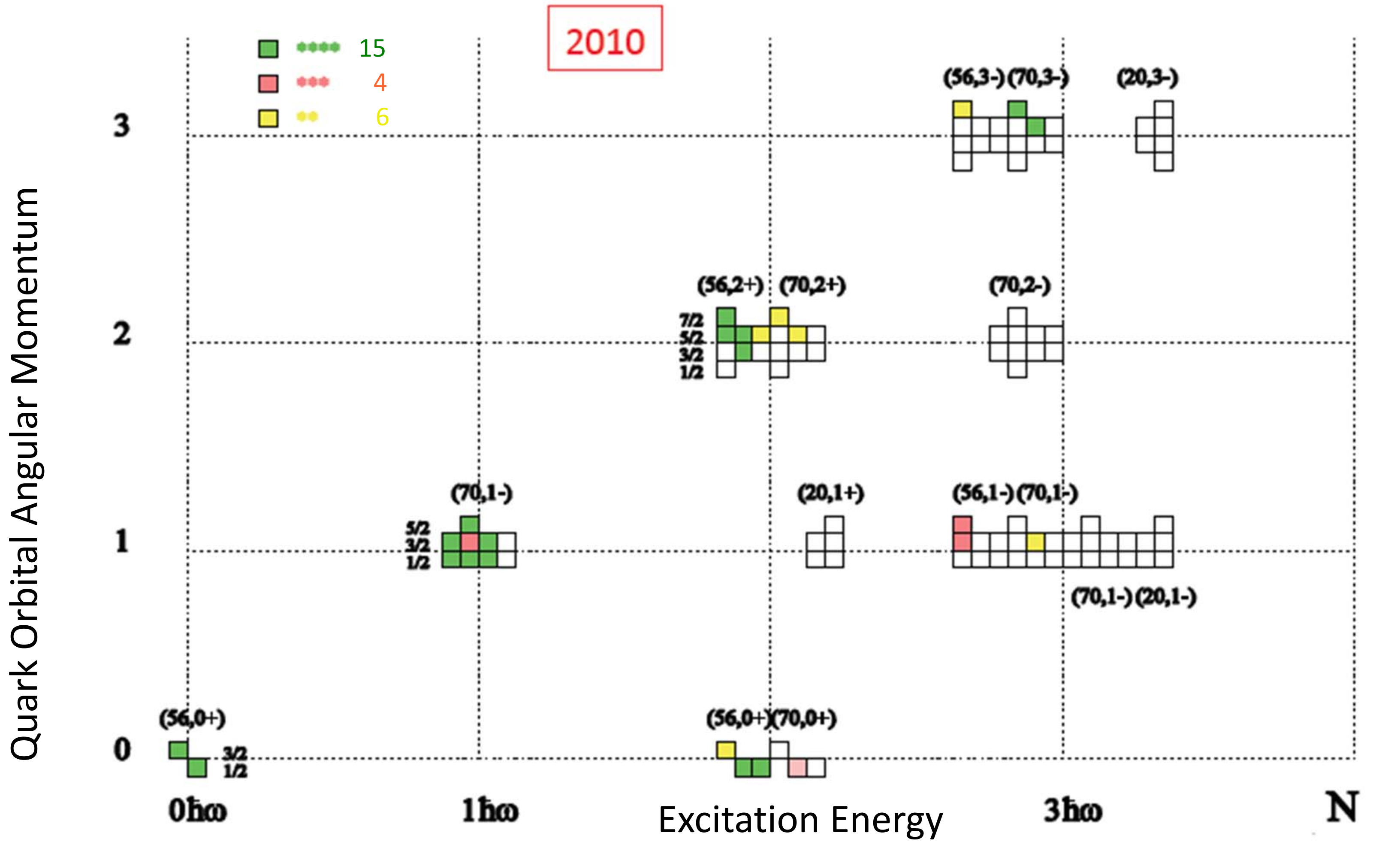


Can we understand this transition from the known excited baryons states?

Constituent Quark Model & SU(6)xO(3)

SU(6)xO(3)

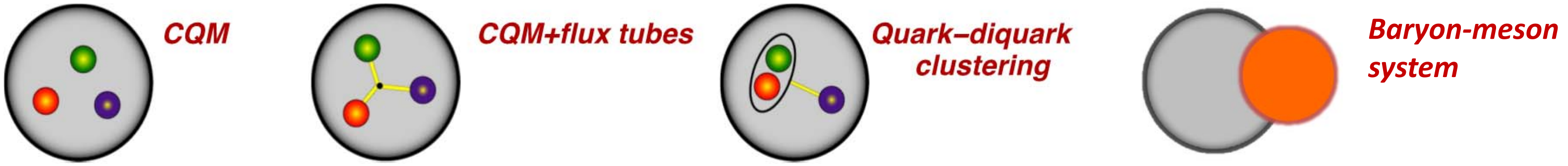
courtesy: D. Menze



Many projected q³ states are still missing or are uncertain.

What do we want to learn?

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



- A vigorous experimental program is underway worldwide with the aim
  - search for undiscovered states in meson **photoproduction** at CLAS, CBELSA, GRAAL, MAMI, and LEPS
  - confirm or dismiss weaker candidates (*, **,***)
  - characterize the systematic of the spectrum

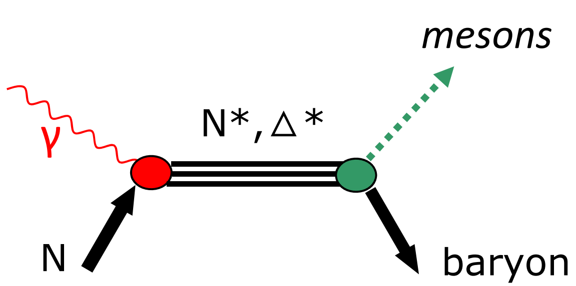
- Measure the strength of resonance excitations versus distance scale in meson **electroproduction** at JLab to identify effective degrees of freedom (JLab).

Establishing the N* and Δ* Spectrum

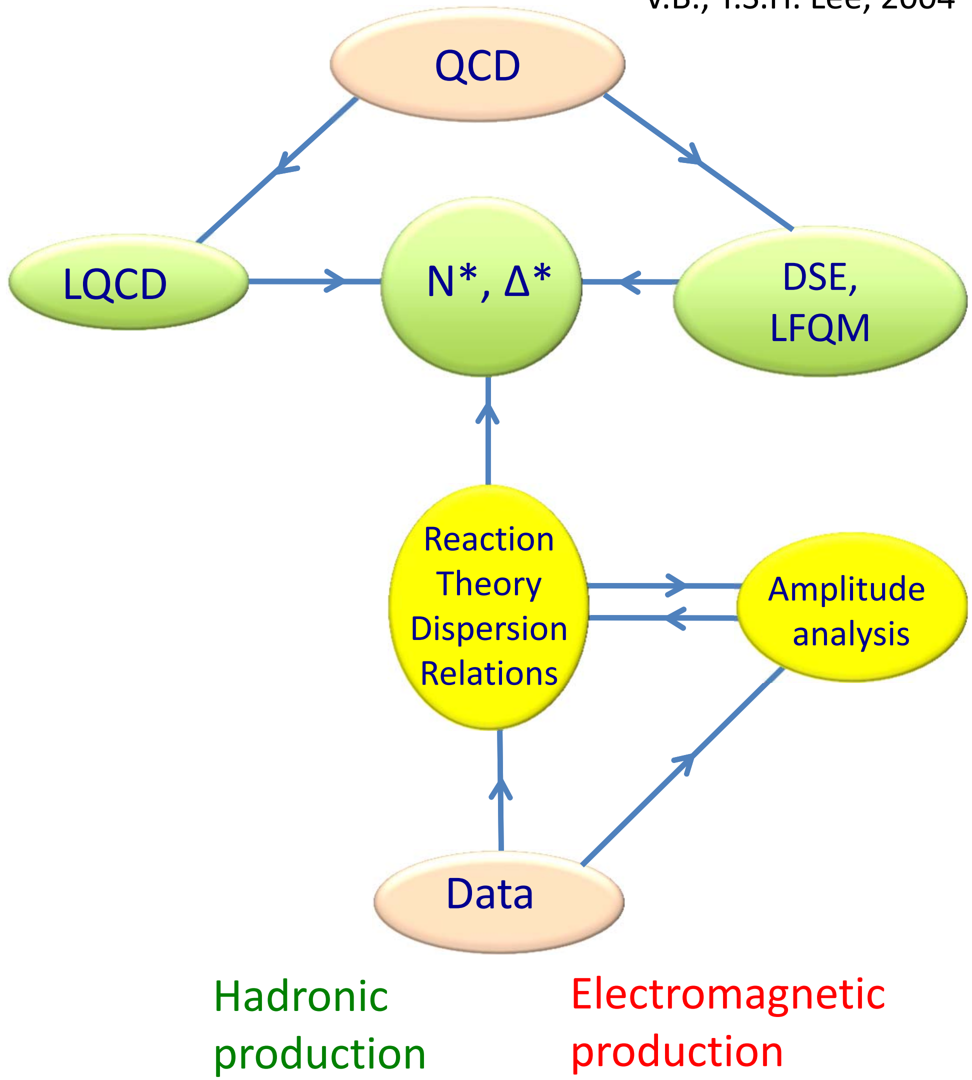
- Multi-GeV polarized cw beam, large acceptance detectors, polarized proton/neutron targets.
- Very precise data for 2- body processes, e.g. γp->Nπ, Nη, KY, in wide kinematics (angle, energy)
- More complex reactions needed to access high mass states, Nππ, Nπη, Nω/ϕ, …

⇓

Extract s-channel resonances

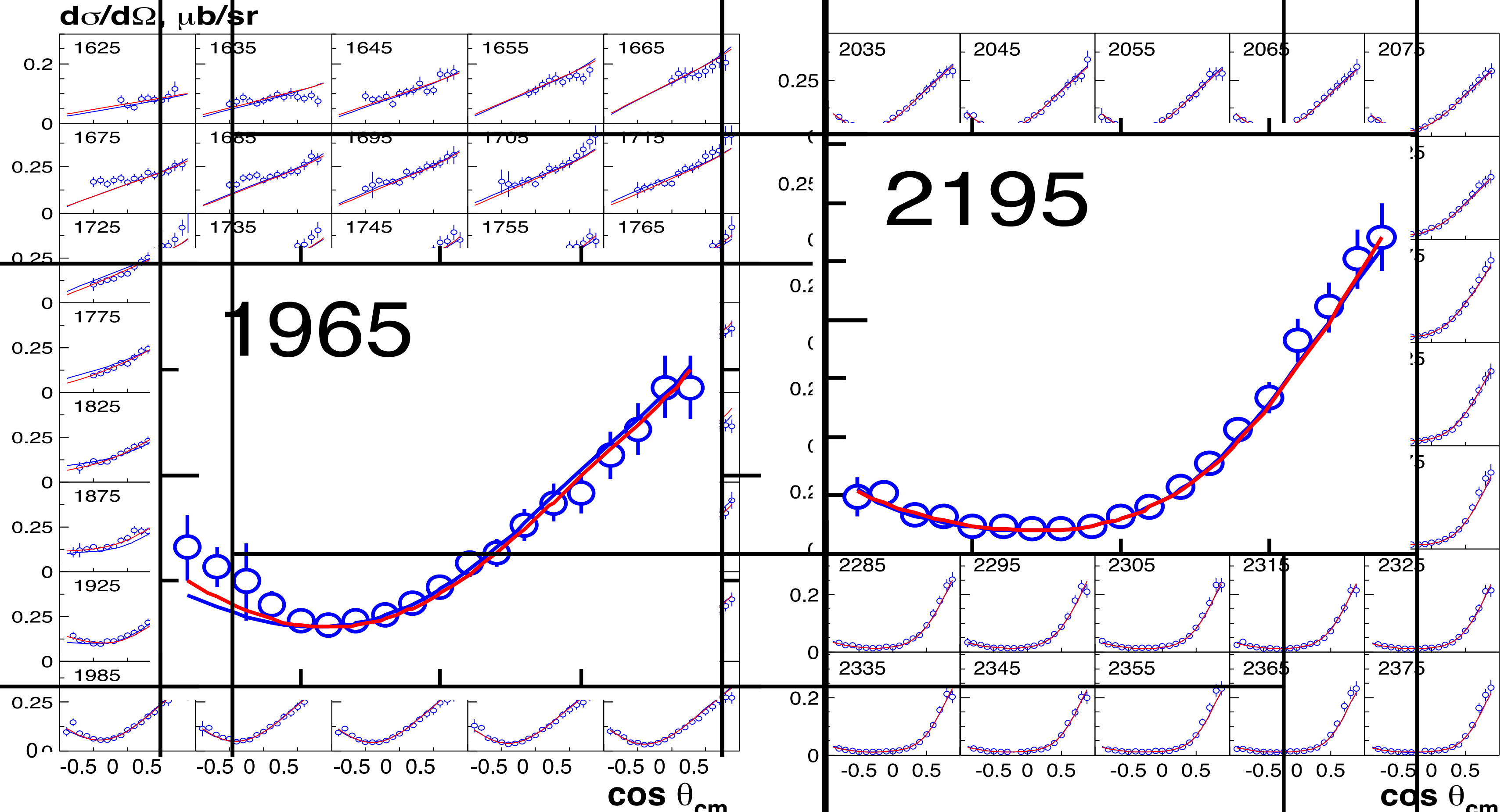


V.B., T.S.H. Lee, 2004



Establishing the N* spectrum, cont'd

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



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

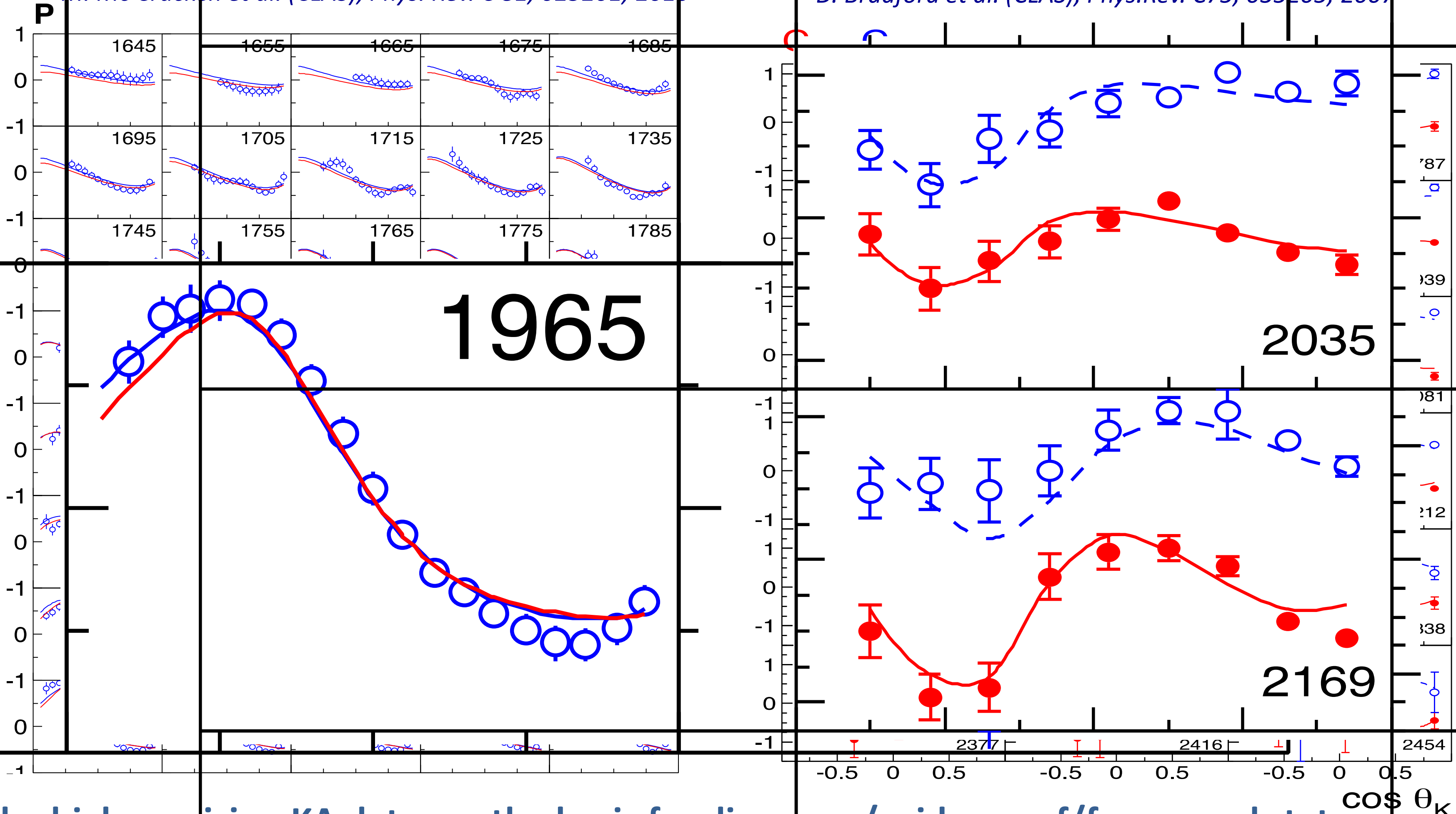
A.V. Anisovich et al (BnGa), EPJ A48, 15 (2012)

Establishing the N* spectrum, cont'd

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

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

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



The high precision KΛ data are the basis for discovery/evidence of/for several states.

Establishing the N* spectrum - N(1900)3/2$^+$

- Bump first seen in SAPHIR $K^+\Lambda$ data but due to systematics in the data misinterpreted as $J^P=3/2^-$.

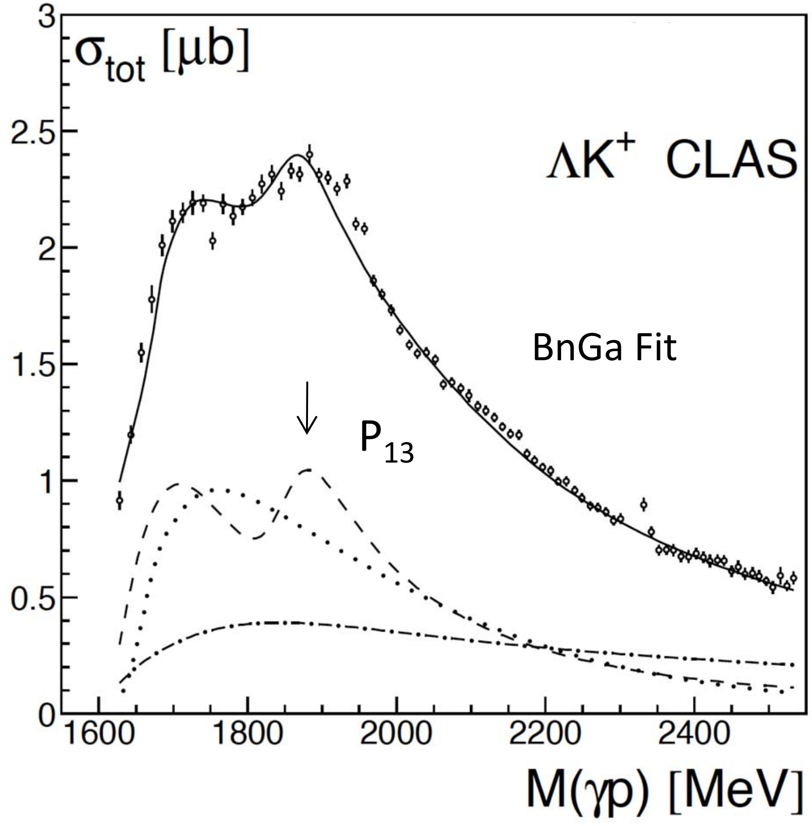
✓ State was solidly established in BnGa multi-channel analysis making use of very precise CLAS $K\Lambda$ crs and polarization data, let to the *** in PDG2012.

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

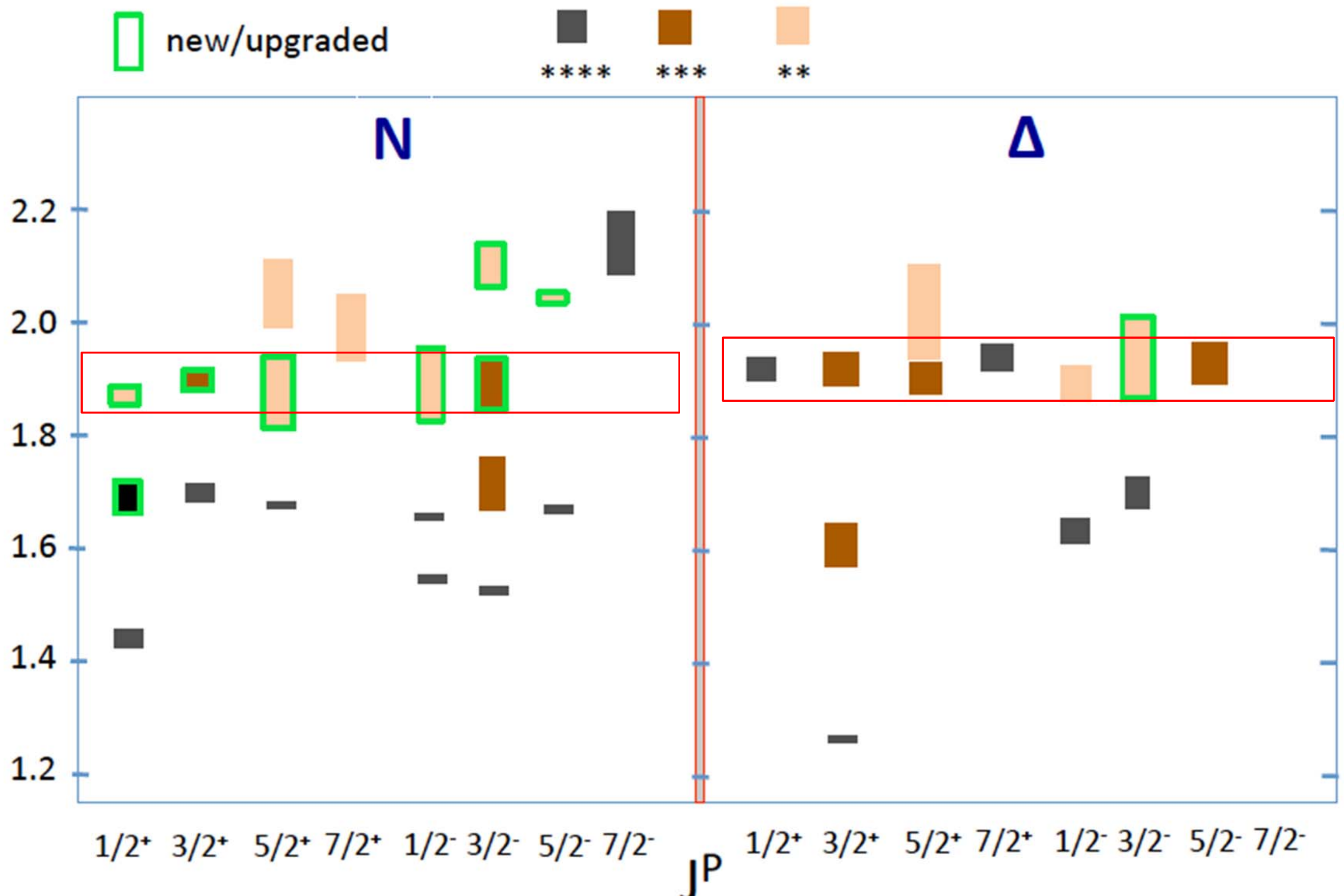
✓ State confirmed in a covariant isobar model single channel analysis of $\gamma p \rightarrow K^+\Lambda$.
T. Mart, M. J. Kholili , PRC86, 022201, 2012

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

=> Candidate for **** state.



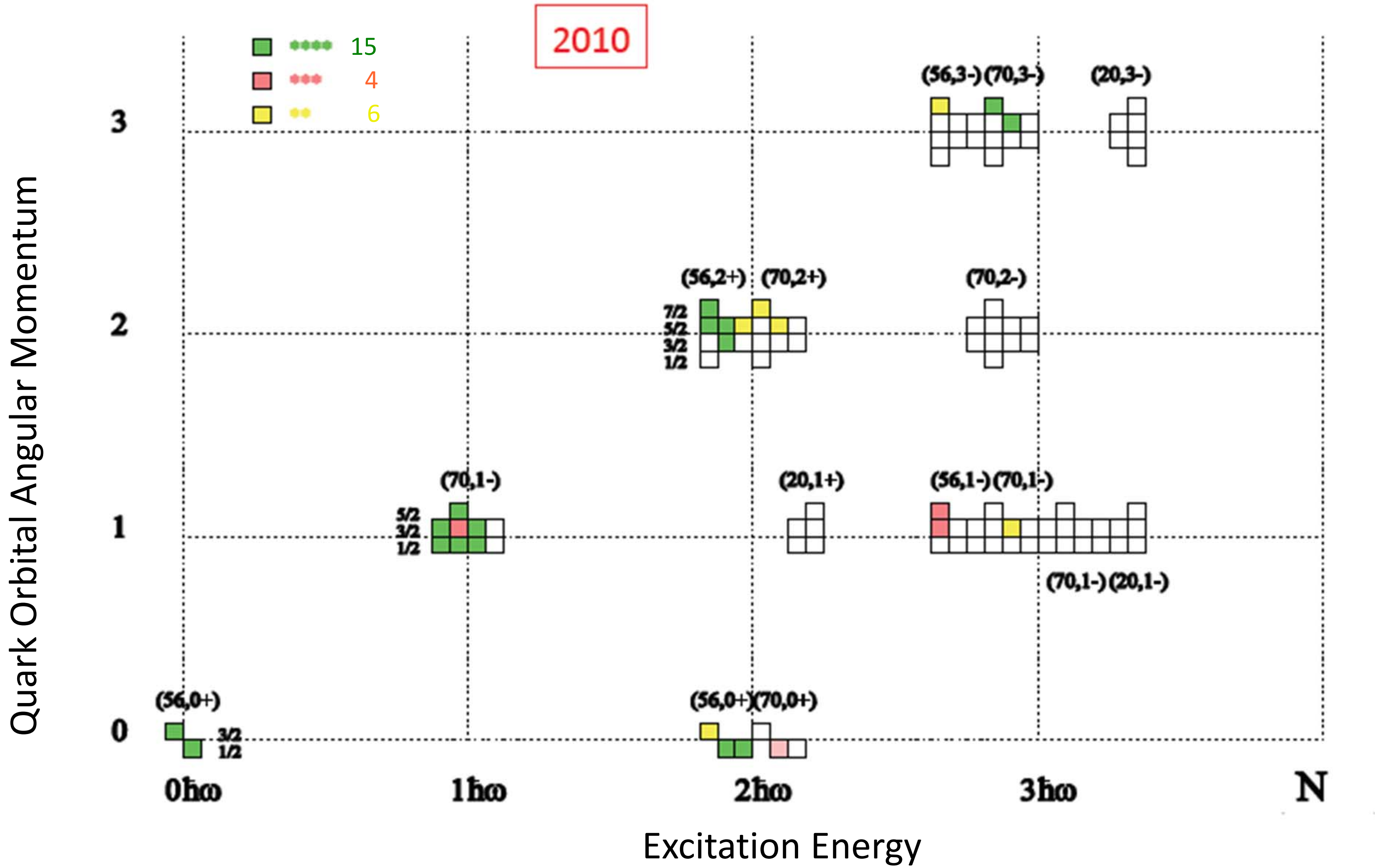
Lower mass N*/Δ* spectrum in 2015



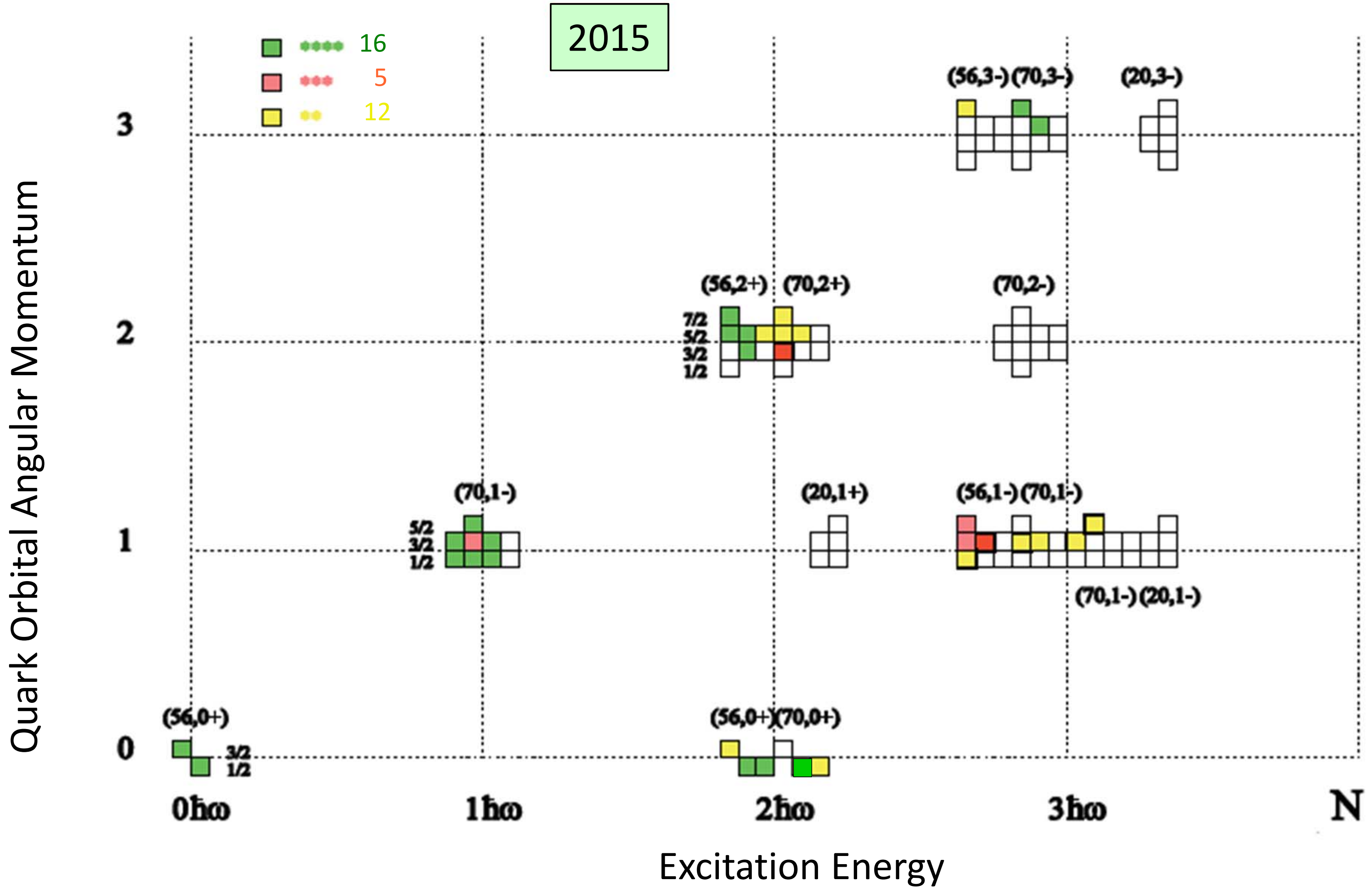
Are we seeing mass degenerate spin multiplets?
Do these states fit into the SU(6) spin-flavor symmetry?

Constituent Quark Model & SU(6)xO(3)

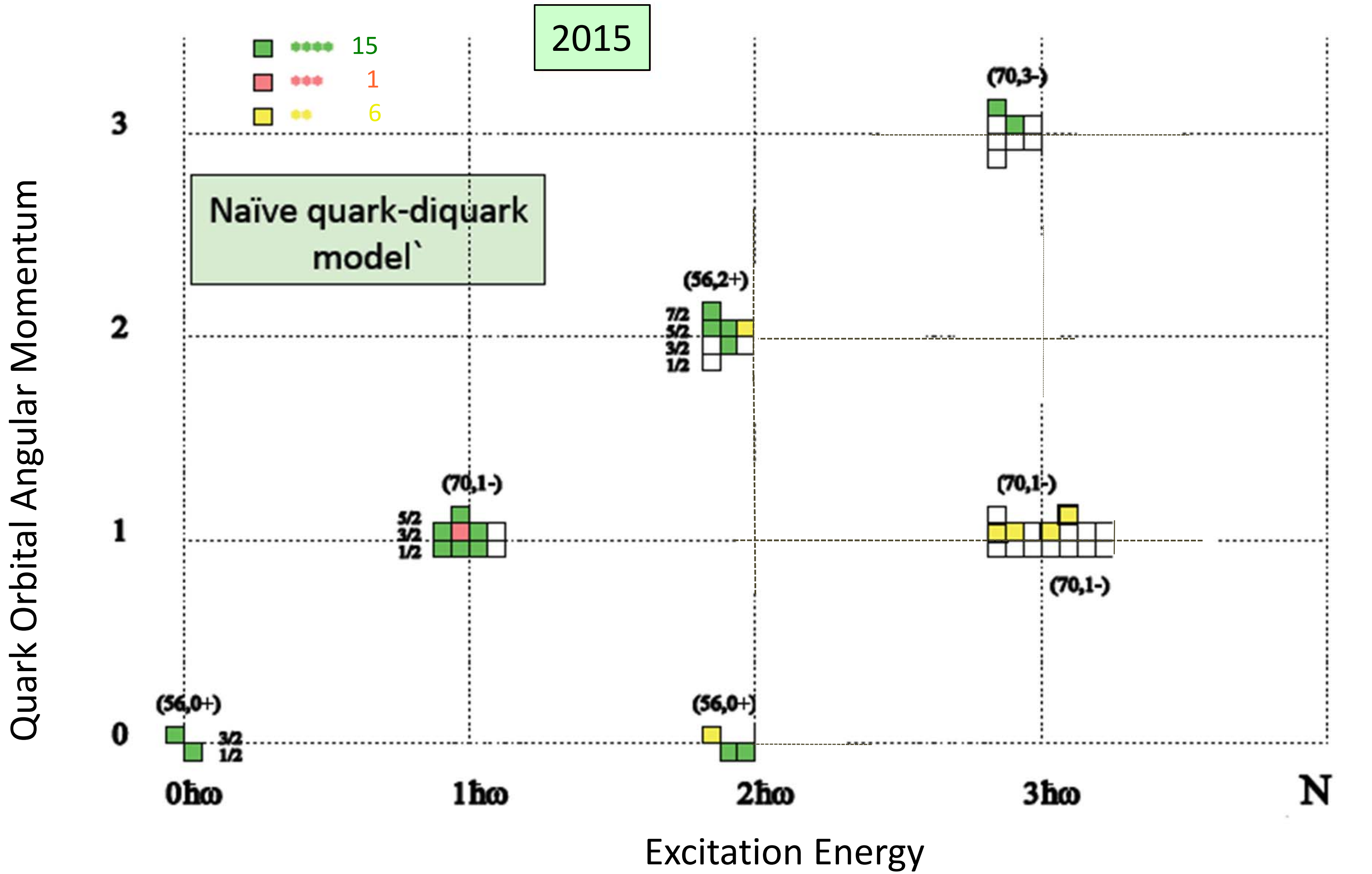
SU(6)xO(3)



Do new states fit into Q³ QM?



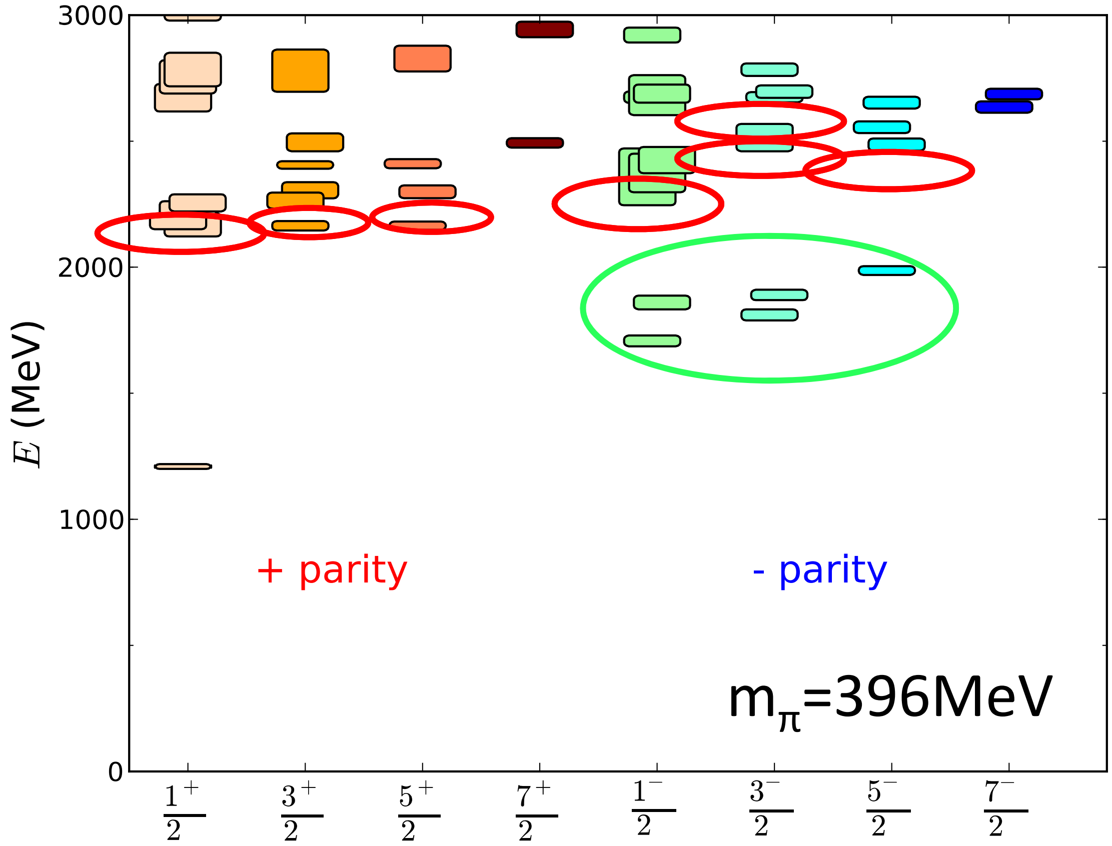
Do new states fit into Q-Q² model?



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$^-$

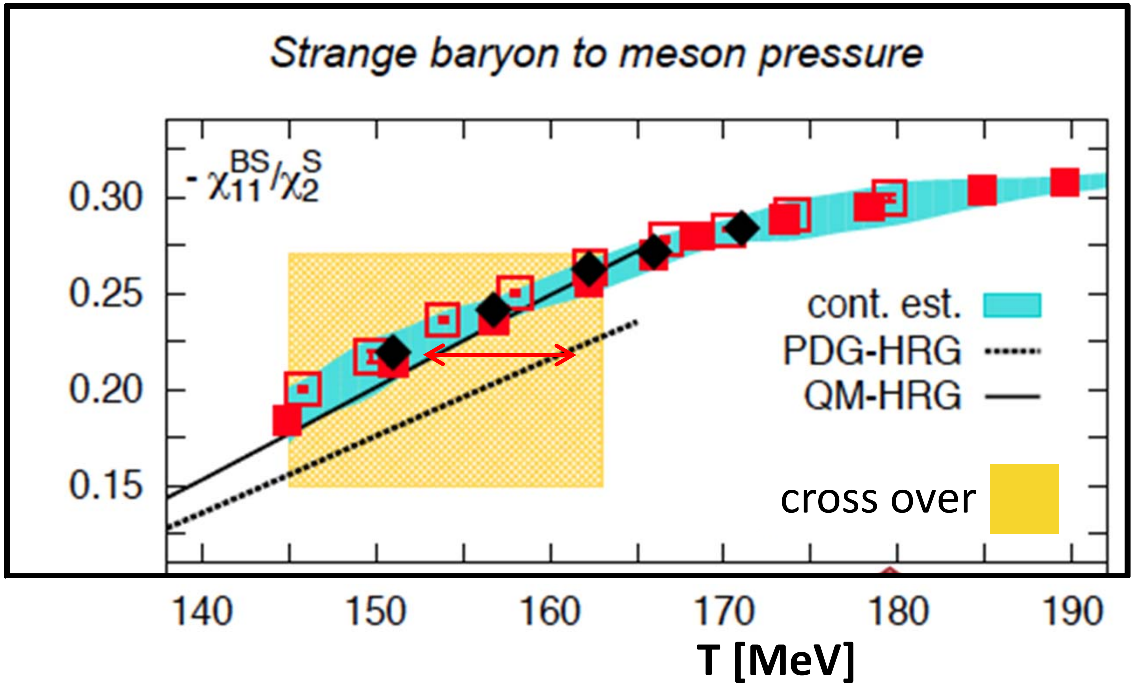
Known states:
N(1675)5/2$^-$
N(1700)3/2$^-$
N(1520)3/2$^-$
N(1650)1/2$^-$
N(1535)1/2$^-$

Lowest J$^+$ states 500 -700 MeV high

Lowest J$^-$ states 200-300 MeV too high

Ignoring the mass scale, new candidate states fit with the J^P values predicted from LQCD. The field would really benefit from more realistic Lattice masses for N* states.

Missing baryons resonances in HIC



from Hot QCD

A. Bazavov et al., Phys.Rev.Lett. 113 (2014) 7, 072001

Transition shifted by about 8 MeV to lower temperature (later times) due to missing excited strange baryons

➔ **The number of known excited strange baryon states (PDG) is insufficient to account for the QCD phase cross over from the QGP phase to the baryon phase.**

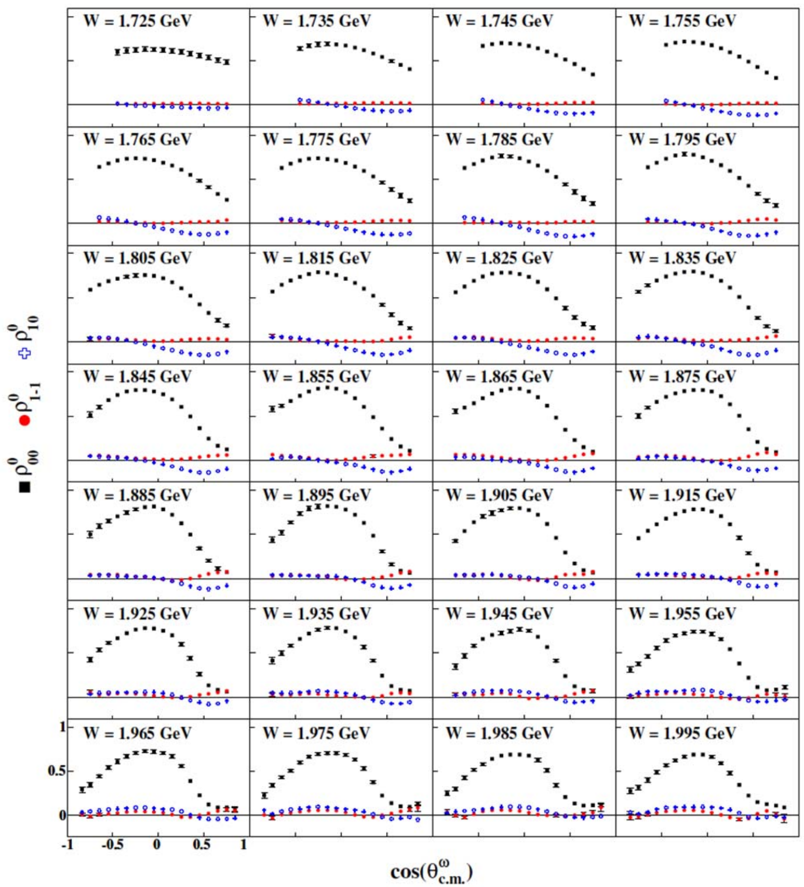
- *Evidence for missing strange baryons*
- *Evidence observed also for missing charm and light quark baryons*
- *Motivates an excited baryon program of all quark flavors.*

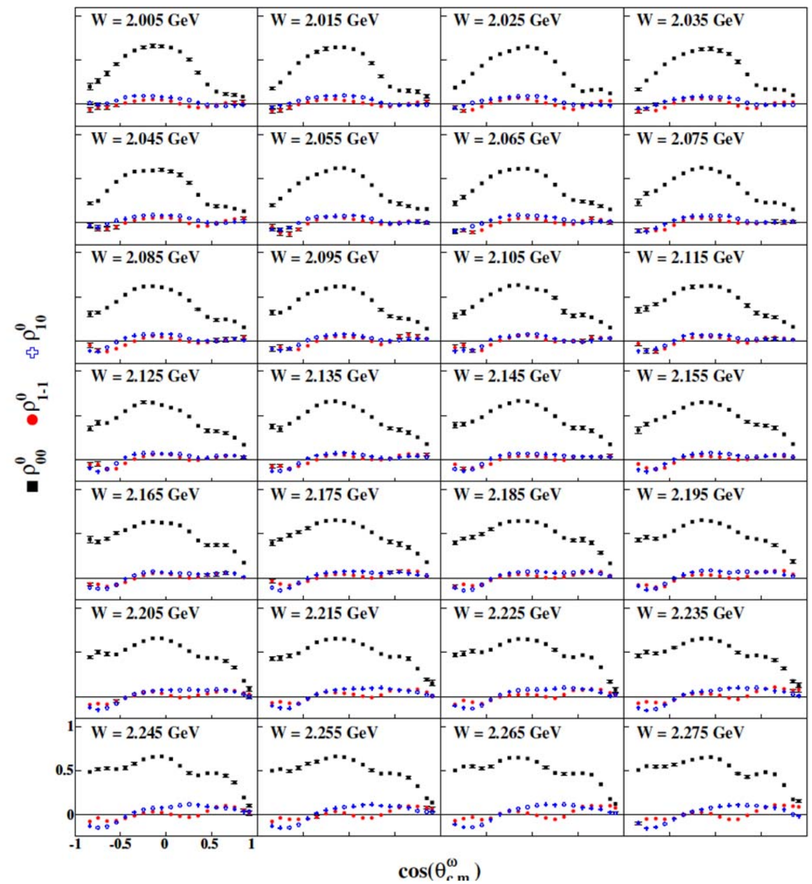
The RHIC operation plan for 2016 includes an energy scan to map out this behavior.

High precision data to establish the N* spectrum

SDME from $\gamma p \rightarrow p\omega \rightarrow p\pi^+\pi^-\pi^0$

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

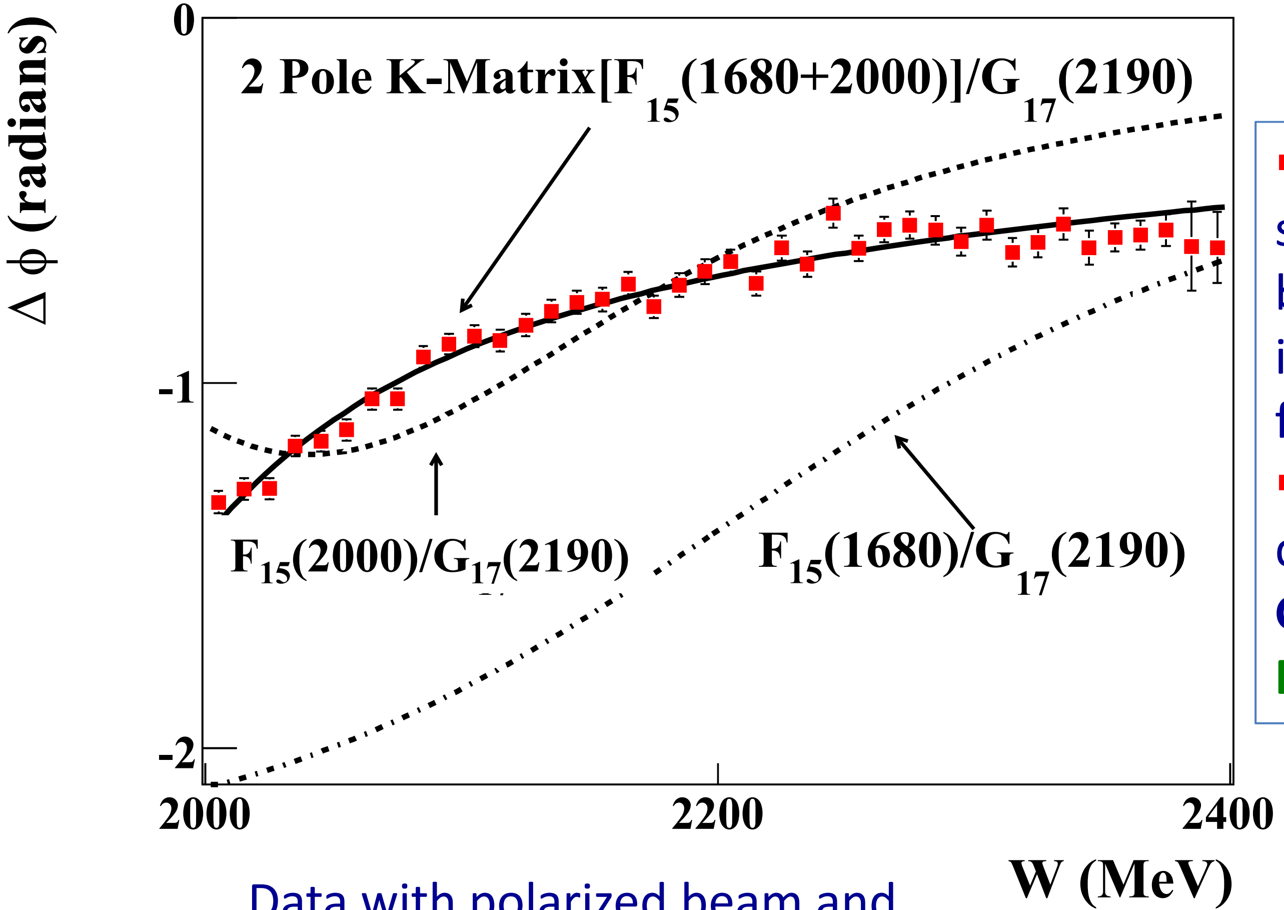




- To fully exploit N* sensitivities of $p\omega$ channel, data should be included in multi-channel analysis

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

- Data used as input to a single channel event-based, energy-independent PWA (the first ever for baryons).
- ω photoproduction is dominated **F_{15}(1680), G_{17}(2190)**, and "missing" **F_{15}(2000)**

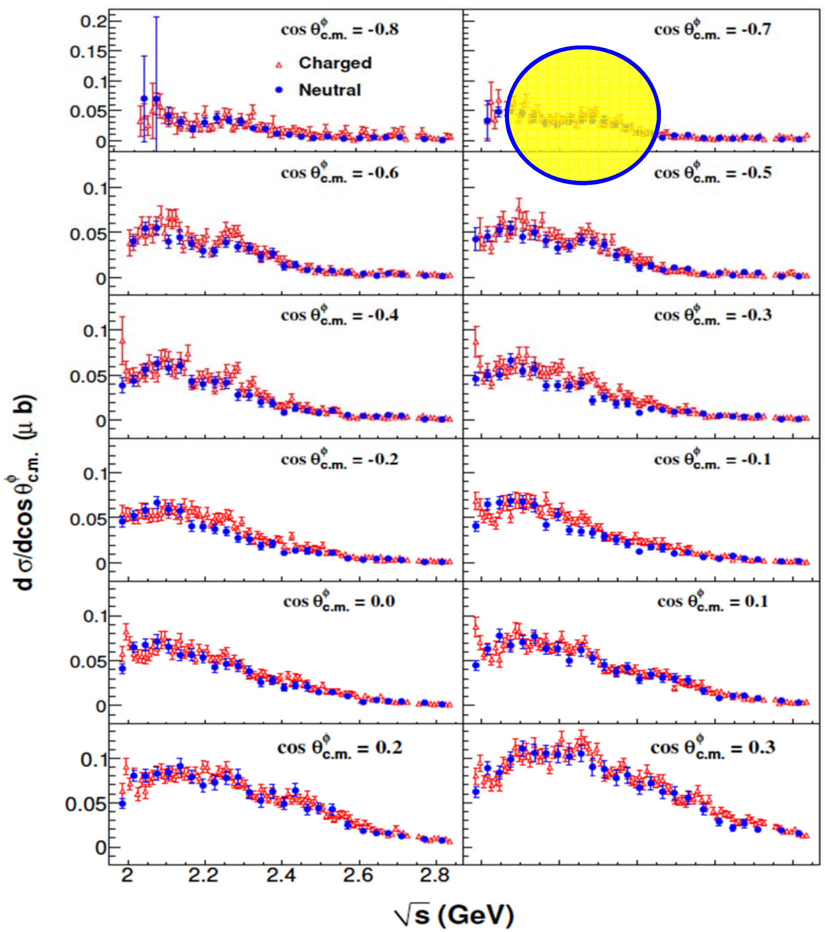
Data with polarized beam and polarized target underway.

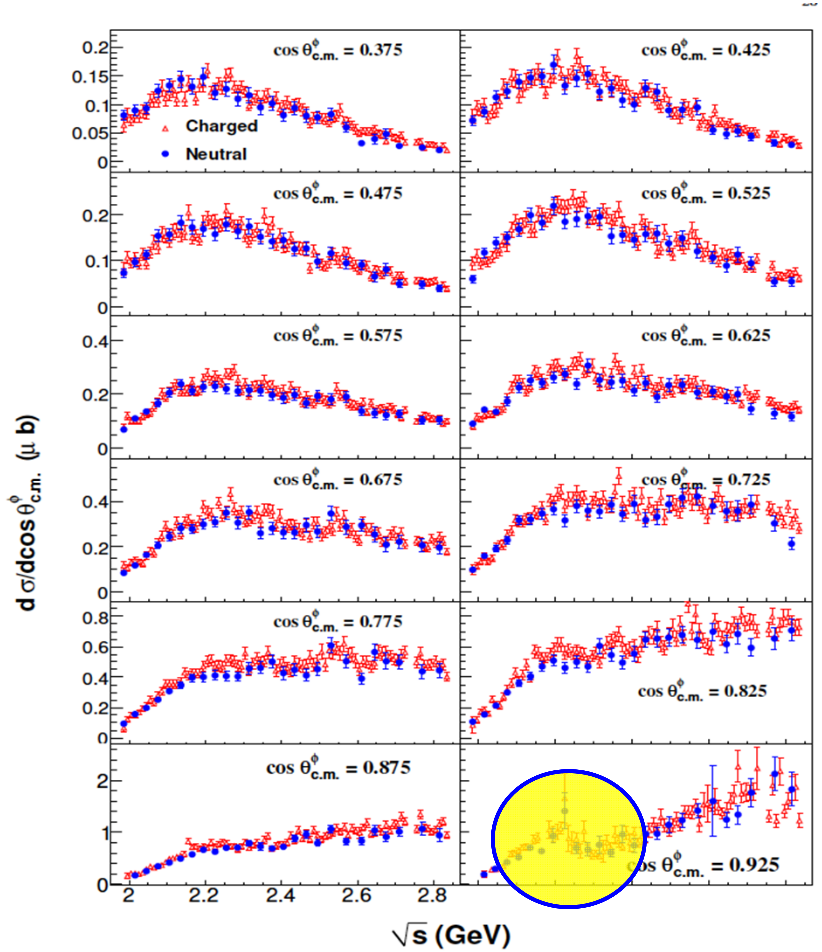
First observation of G_{17}(2190) -> Nω, PDG2014

Spin Density M.E. for γp pφ pKK

$\phi \rightarrow K^+K^-$, $\phi \rightarrow K^0_s K^0_l$

B. Dey et al. (CLAS), PR C89 (2014) 5, 055208
K.P. Adhikari et al. (CLAS), PR C89 (2014) 5, 055206

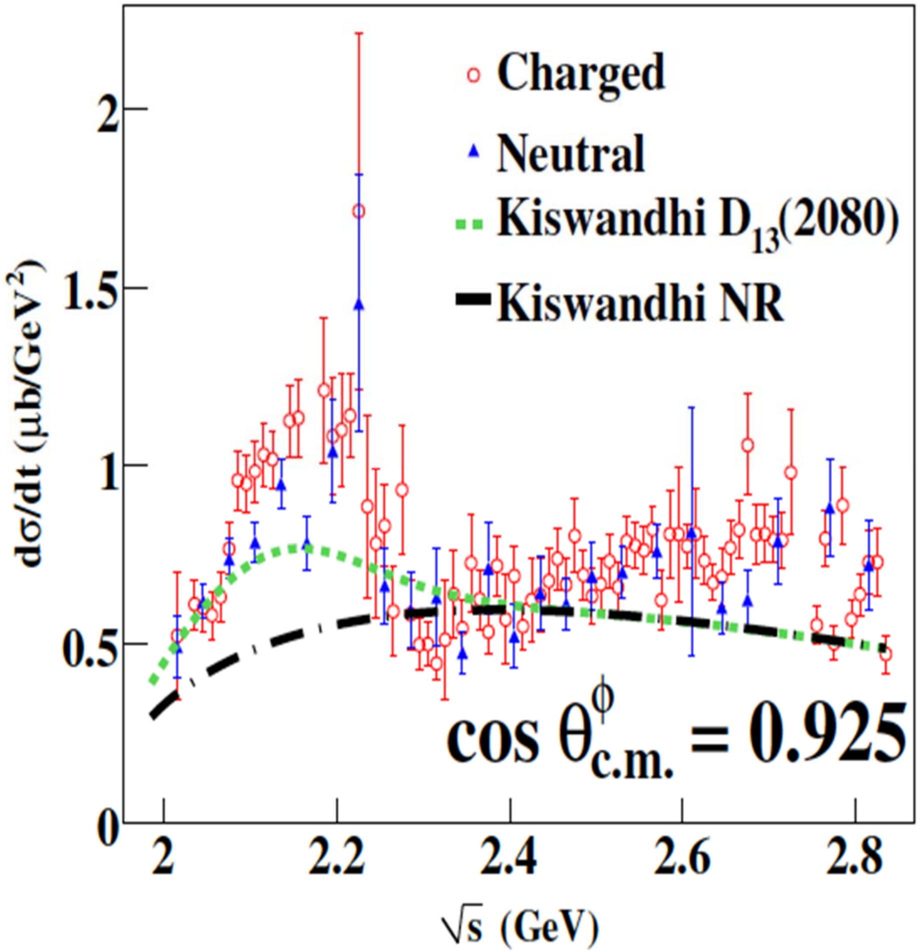




Channel could be be sensitive to N*'s with large s-sbar content and MB molecules or pseudo-pentaquarks?

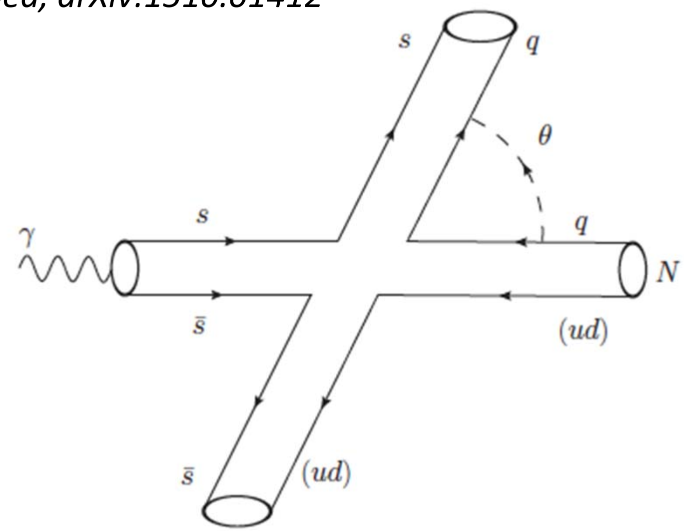
Pseudo pentaquark in $\gamma p \;\; p\phi \;\; pKK$?

$\phi \rightarrow K^+K^-$, $\phi \rightarrow K^0_s K^0_l$



Structure may not be an s-channel resonance. Could it be diquark-anti-triquark pair similar to what is proposed for the P_c^+ resonances.

R. Lebed, arXiv:1510.01412

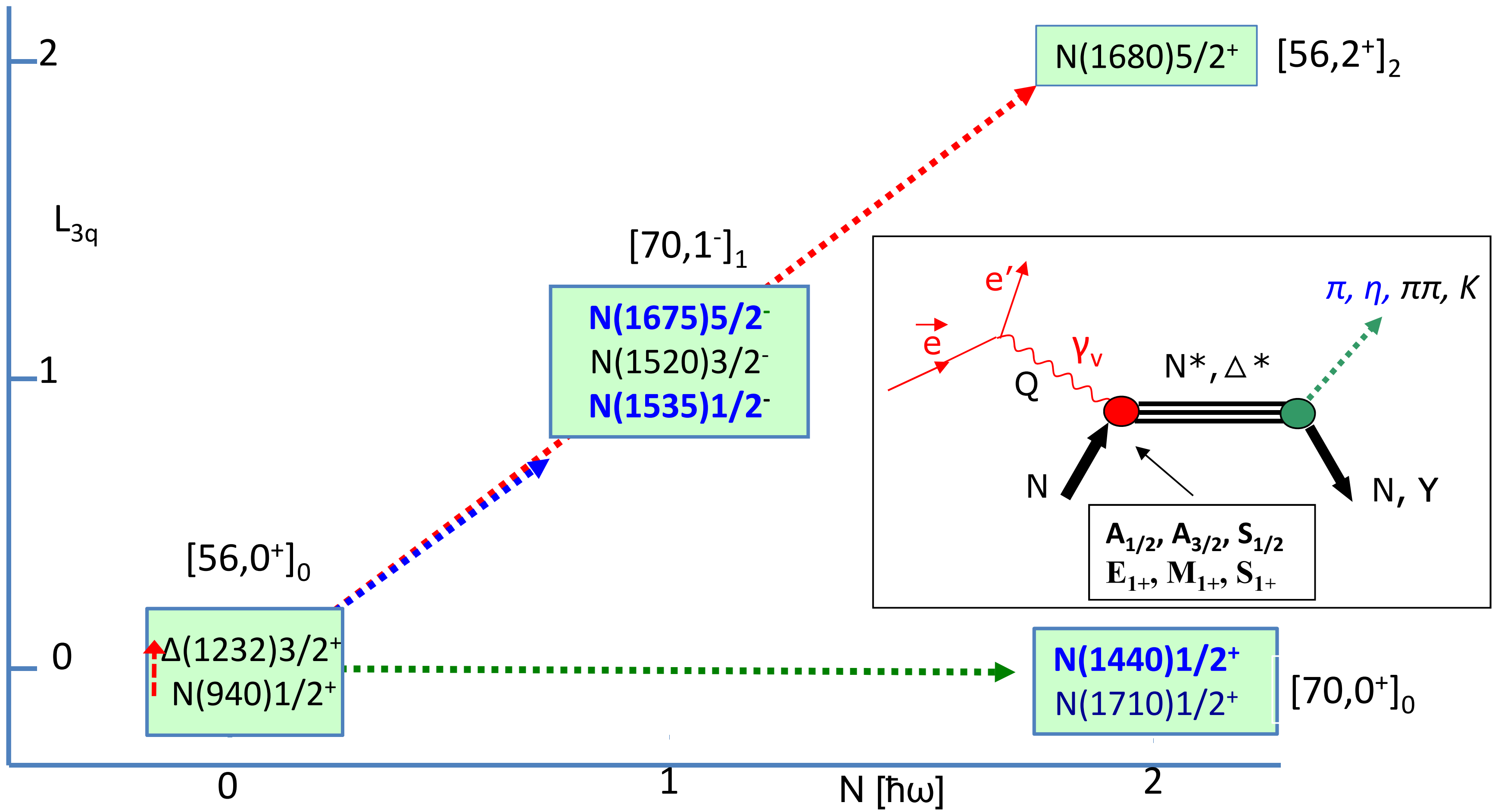


Maintain approximate collinearity

Electroexcitation of N/Δ resonances

Central question in hadron physics

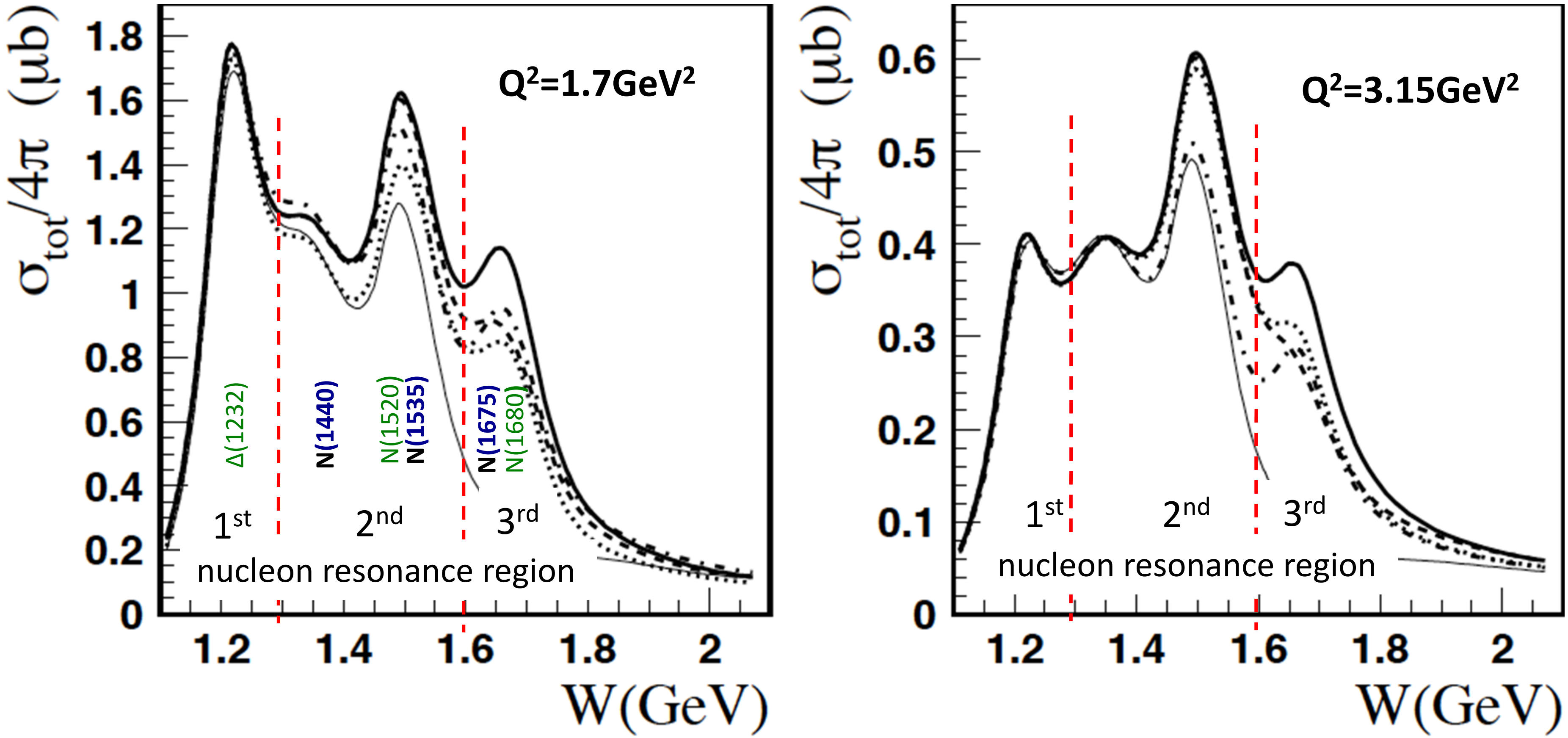
What are the effective degrees of freedom at varying distance scale?



Total cross section at W < 2.1 GeV

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

Data: *K. Park et al., PR C77 (2008) 015208; K. Park et al. PR C91 (2015) 045203*

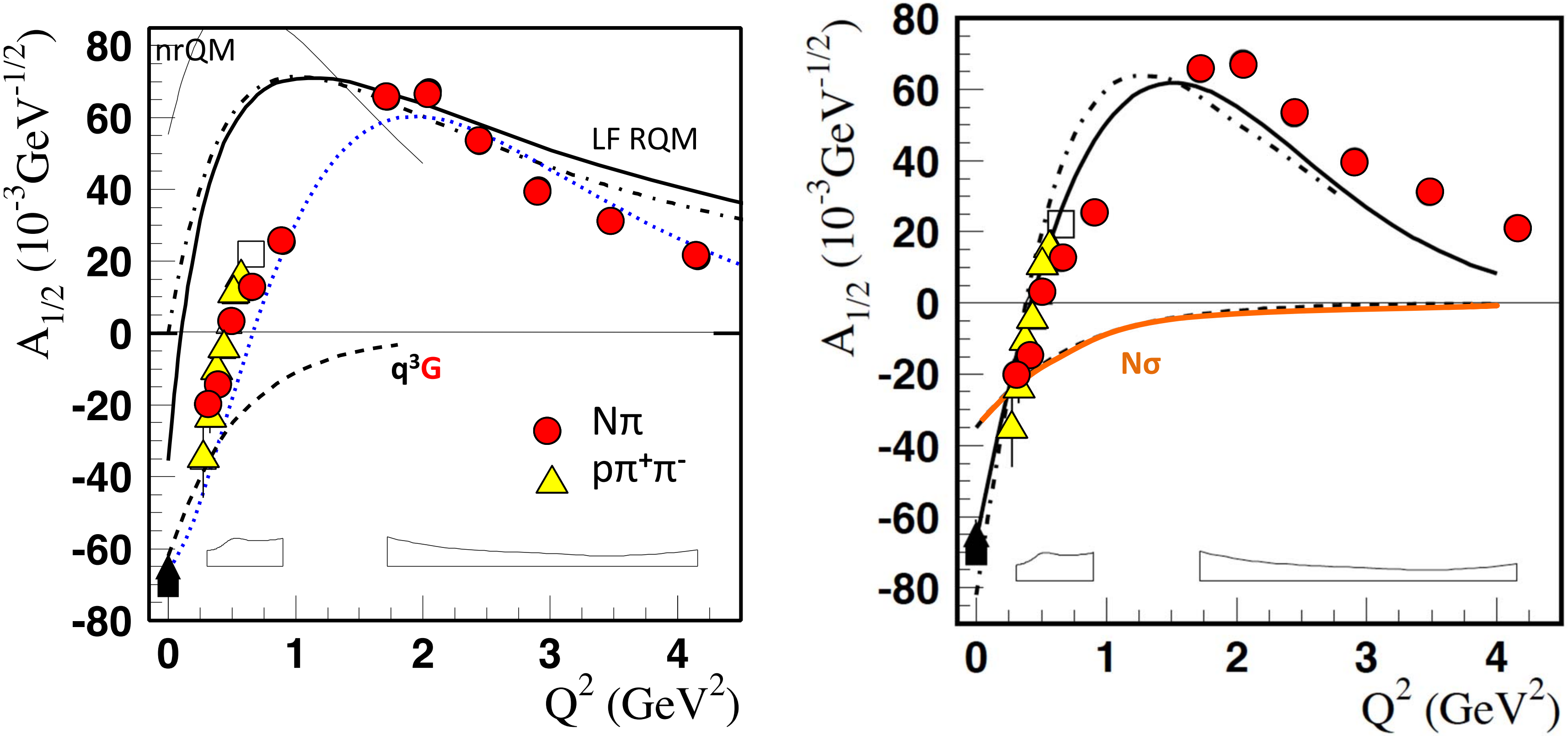


Analysis with UIM & fixed-t DR; Recent review: *I. Aznauryan, V. Burkert, Prog.Part.Nucl.Phys. 67 (2012) 1-54*

Electrocouplings of 'Roper' in 2012

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

L. Tiator et al., Chin.Phys. C33 (2009) 1069 (MAID fit)



I. Aznauryan, PR C76 (2007) 025212

Z.P. Li, V. Burkert, Zh. Li, PR D46 (1992) 70

I.T. Obukhovsky, et al., PR D84, 014004 (2011)

The "Roper" resonance in 2015

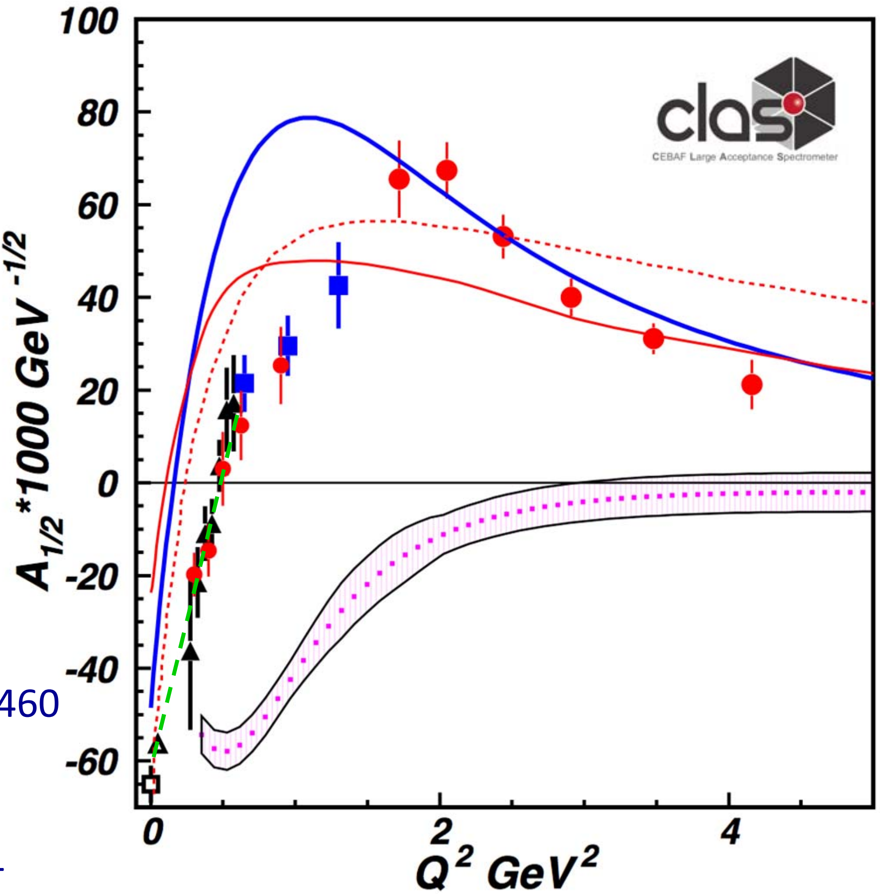
——— Nπ loops to model MB cloud; **running quark mass**, in LF RQM. I.G. Aznauryan, V. D. Burkert, Phys. Rev. C85, 055202 (2012).

.... Nσ loops to model MB cloud in LF RQM**; frozen constituent quark mass**. I.T. Obukhovsky, et al., Phys. Rev. D89, 014032 (2014).

——— **Quark core** contributions from DSE/QCD J. Segovia et al., arXiv:1504.04386

——— MB cloud **inferred from the CLAS data** as the difference between the data and quark core evaluated in DSE/QCD, V. Mokeev et al., arXiv:1509.05460

- - - - - **EFT employing** π, ρ, N, N'. T. Bauer, S. Scherer, L. Tiator, PR C90 (2014) 1, 015201



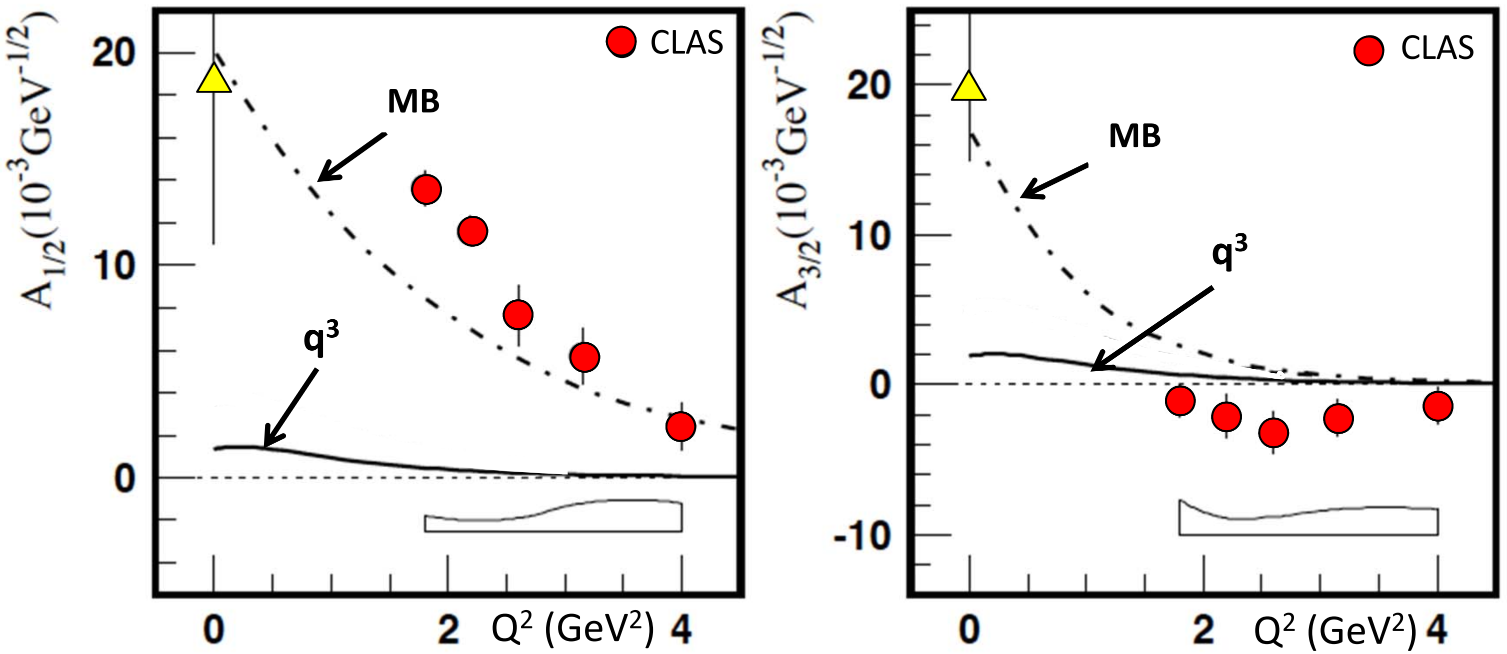
The structure of the Roper is driven by the interplay of the core of three dressed quarks in the 1st radial excitation and the external meson-baryon cloud.

MB contribution to $\gamma_v pN(1675)5/2^-$

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

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

I.G. Aznauryan, V.D. Burkert, PR C92 (2015) 1, 015203 ; K. Park et al. (CLAS), PR C91 (2015) 045203



- Measures the meson-baryon contribution to $\gamma^* pN(1675)5/2^-$ directly
- Can be verified on $\gamma^* nN(1675)5/2^-$ 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)*

Light-cone N* transition charge densities

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

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

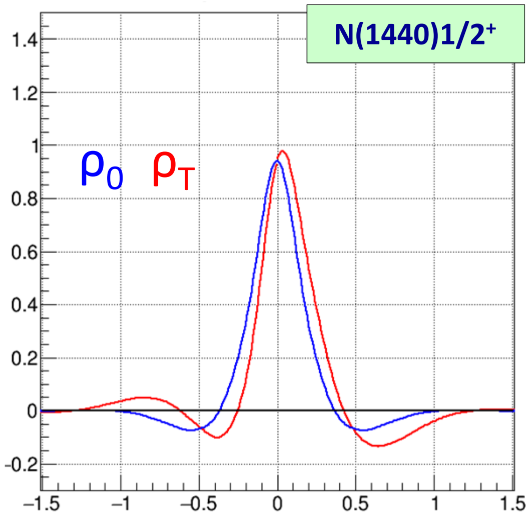
L. Tiator, M. Vanderhaeghen
Phys.Lett. B672 (2009) 344-348

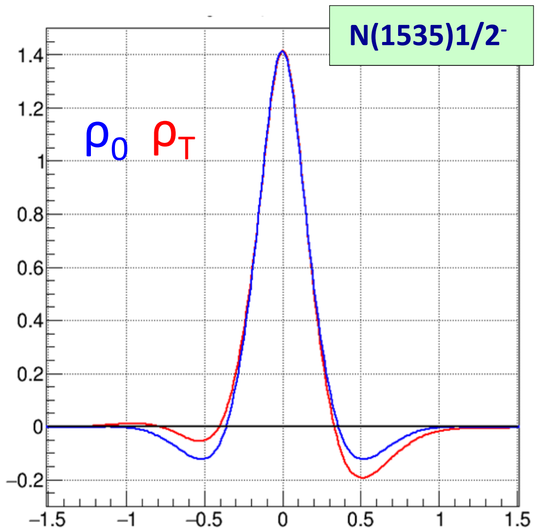
$$\rho_0^{NN^*}(\vec{b}) = \int_0^\infty \frac{dQ}{2\pi} Q\, J_0(b\,Q) F_1^{NN^*}(Q^2)$$

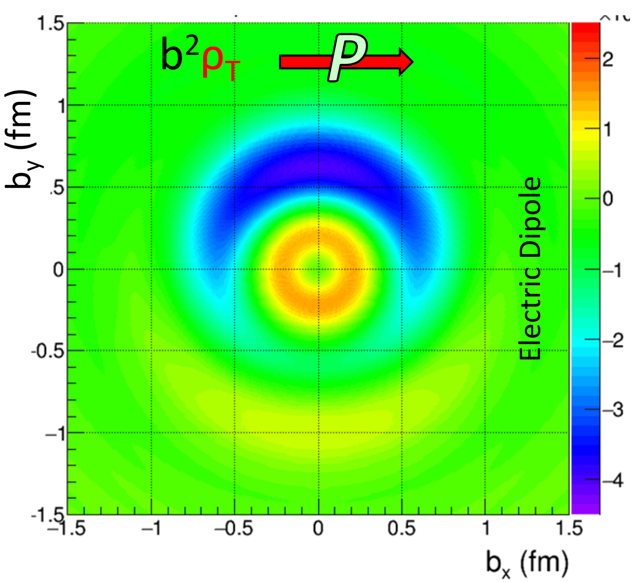
Exp: $0 < Q^2 < 4.5\text{-}7\ \text{GeV}^2$

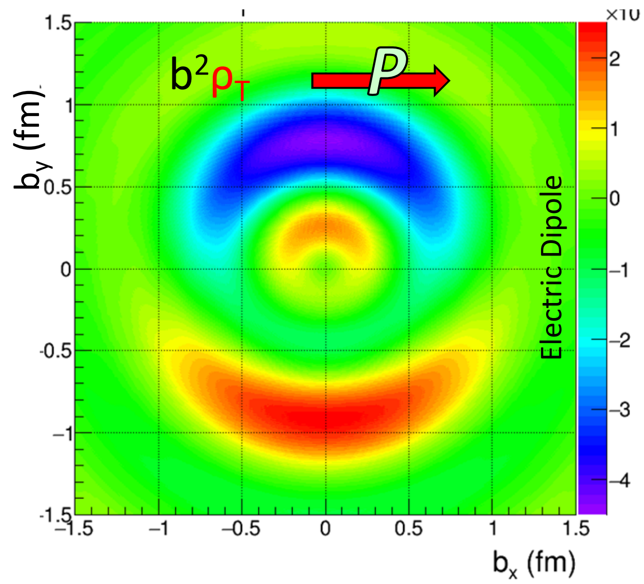
$$\rho_T^{NN^*}(\vec{b}) = \rho_0^{NN^*}(b) + \sin(\phi_b - \phi_S)\int_0^\infty \frac{dQ}{2\pi}\frac{Q^2}{(M^* + M_N)} J_1(b\,Q) F_2^{NN^*}(Q^2)$$

$J_m = +½ \to -½$









What have we have learned from N* studies?

• Major progress made during past ~5 years in the search for new N* and Δ* states. All new states can be accommodated in CQM and LQCD. Naïve (non-dynamical) quark-diquark model is ruled out.

• Knowledge of Q^2 - dependence is absolutely necessary to understand the nature (internal structure) of excited states. The Roper **IS** the 1st radial excitation of the q^3 core, obscured at large distances by meson cloud effects.

• Leading amplitude of prominent low mass states, e.g N(1440)$1/2^+$ and N(1535)$1/2^-$ well described at $Q^2 > 2\text{-}3$GeV by QCD modeling in DSE/QCD, LC SR and LF RQM.

• Light-front transition charge densities for the Roper and N(1535) show significant differences in transverse spatial distributions.

Where are we going?

• Baryon resonances of all flavors were driving the evolution of the universe at the transition from the QGP to confined quarks in nucleons. A quantitative understanding of this transition requires the search for the missing excited states of all flavors.

• Much of the published data with potential of accessing new states have not been implemented in multi channel analyses (e.g. pω, pϕ, K*Λ) but they are important in the search for higher mass states. Precise polarization data critical and are in production.

• Need to measure electro-excitation of states at higher W and in large Q^2 range. Need to include Include Nπ, Nππ, KΛ/KΣ final states.

• Electro-excitation of prominent states up to highest Q^2 to probe the transition from the dressed to the bare quark core with CLAS12.

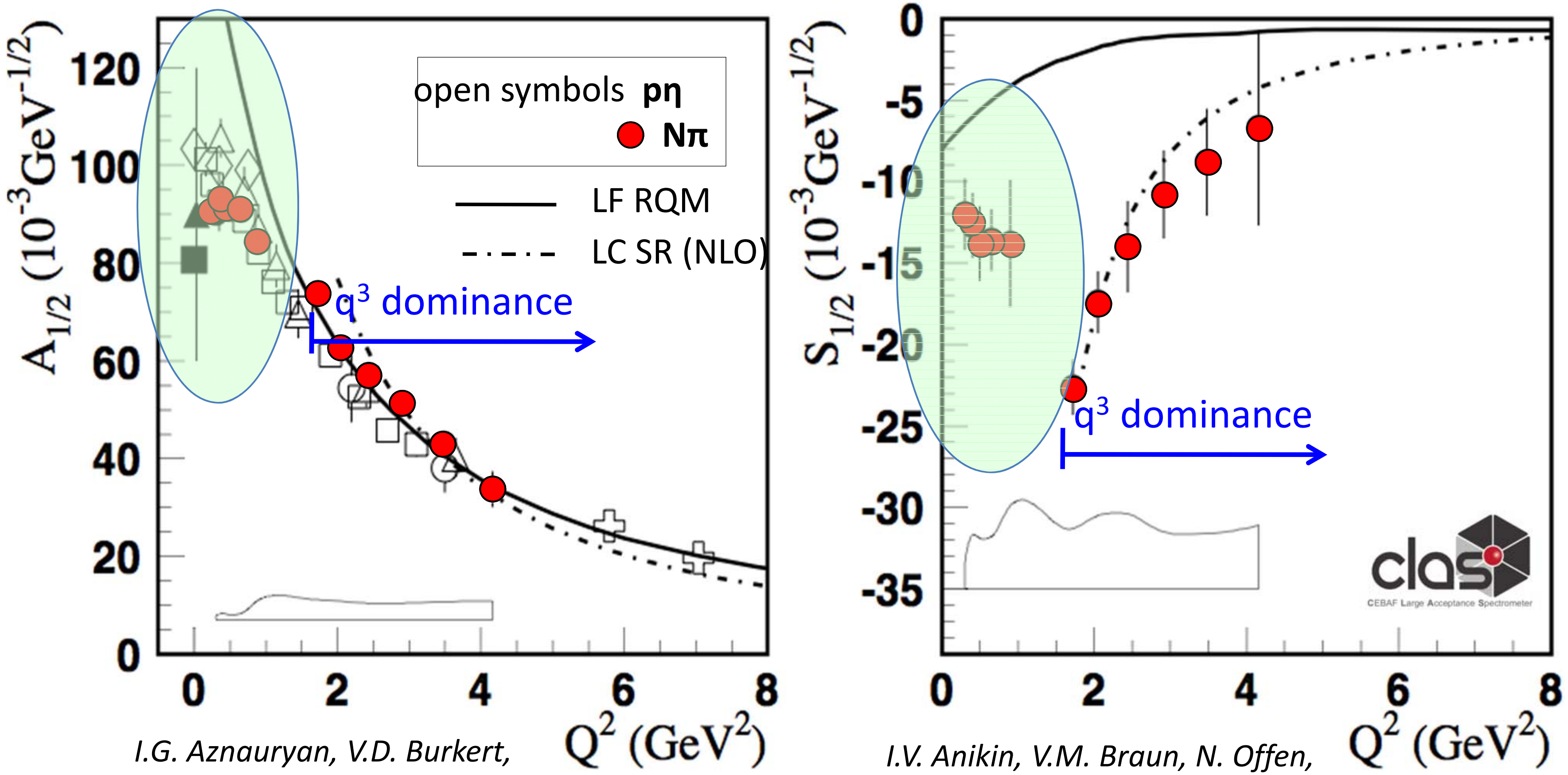
• Search for hybrid baryons (q^3G). Electro-excitation needed to distinguish hybrid baryons from q^3 states with CLAS12.

Questions for Discussion

- Implementation of momentum-dependent quark mass into model calculations.
- Using Breit-Wigner masses versus poles positions in analysis of electroproduction data.
- Long-wavelength limit (Siegert's theorem)
  - Is it unique limit for each resonance or does mixing play a role? How to treat states that mix, e.g. $N(1535)1/2^-$ and $N(1650)1/2^-$
- Extension of pwa in meson photo- to electroproduction

Electrocouplings of $\gamma_v pN(1535)1/2^-$

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

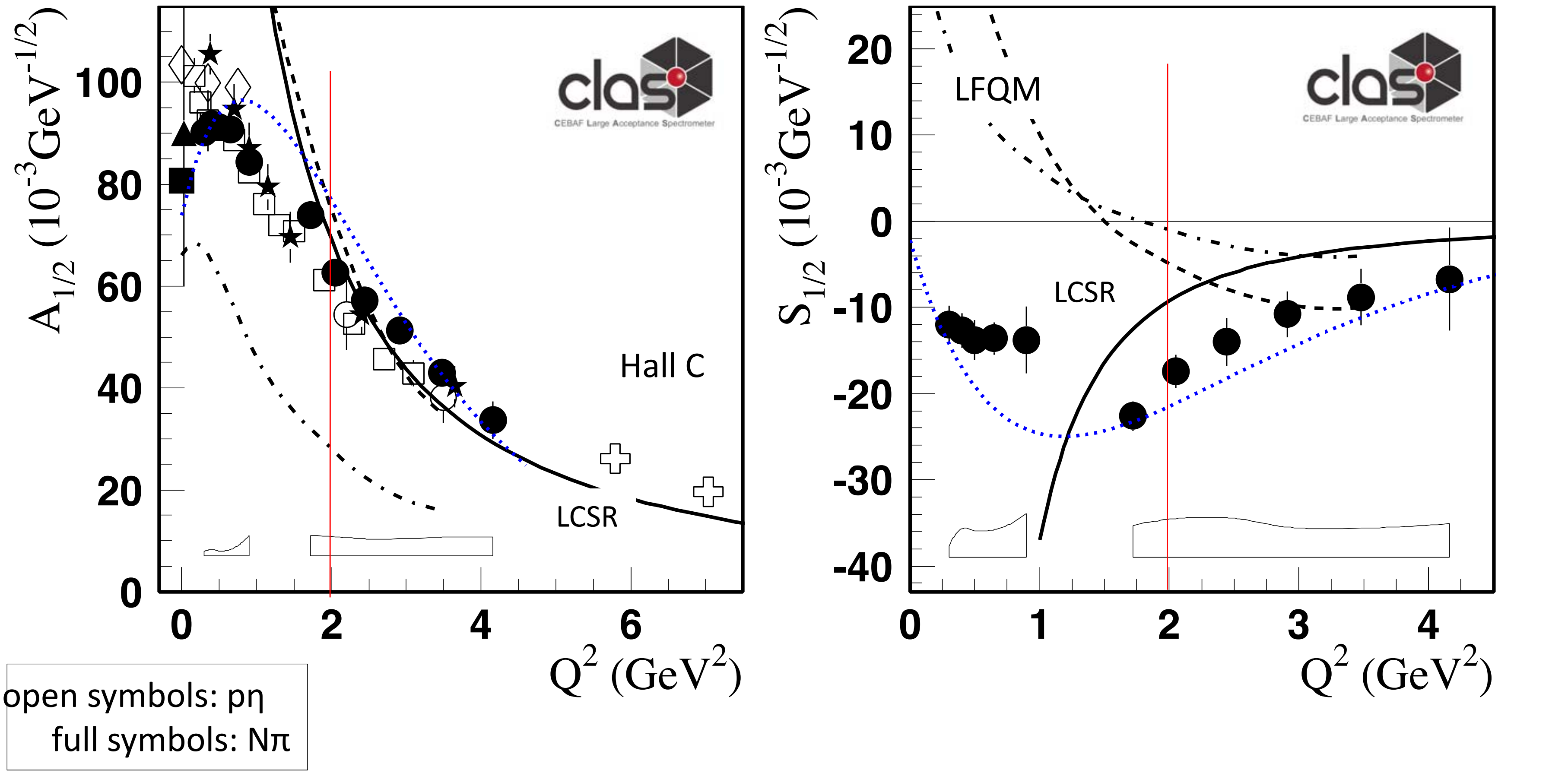


I.G. Aznauryan, V.D. Burkert, PR C85 (2012) 055202

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

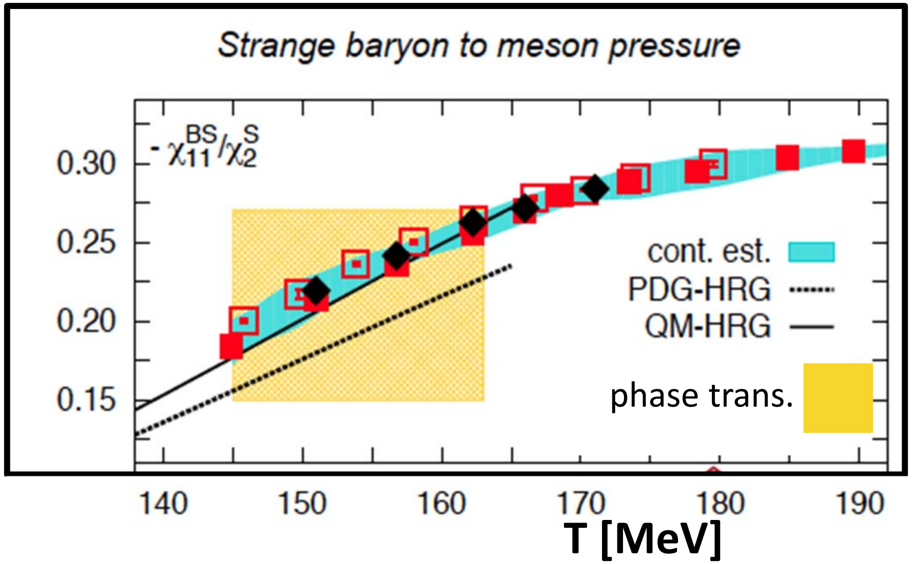
- MB contributions may account for discrepancies at low Q^2.
- MB contributions from chiral unitary model analyses due to KΛ and pϕ components.

Electrocouplings of $\gamma_v pN(1535)1/2^-$

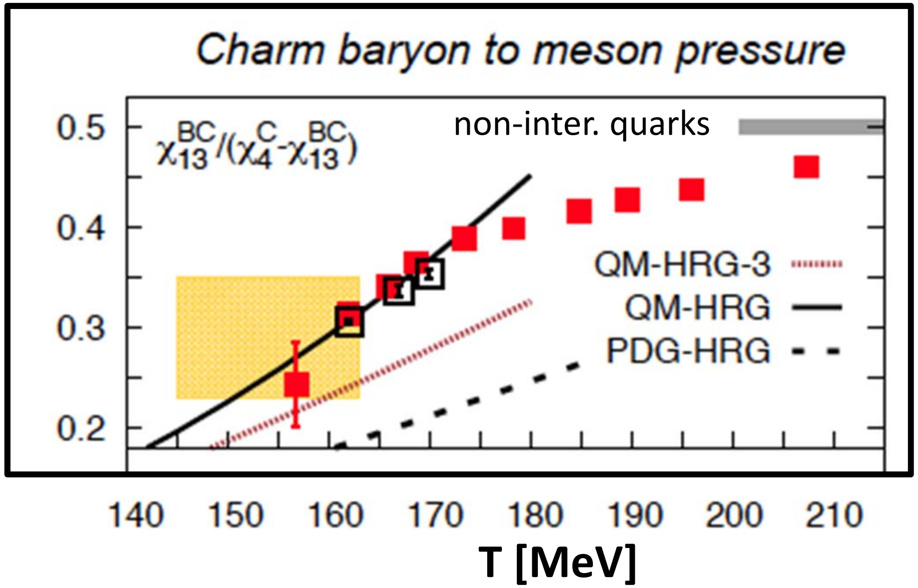


- Chiral unitary model analyses: state may have a significant coupling to KΛ and pϕ
- Sizeable $qqqs\bar{s}$ admixture in the wave function?
- Large $s\bar{s}$ could explain sign of $S_{1/2}$ at Q^2 < 2 GeV^2 contrasting LFQM predictions.

Missing baryon resonances and HIC



A. Bazavov et al., Phys.Rev.Lett. 113 (2014) 7, 072001



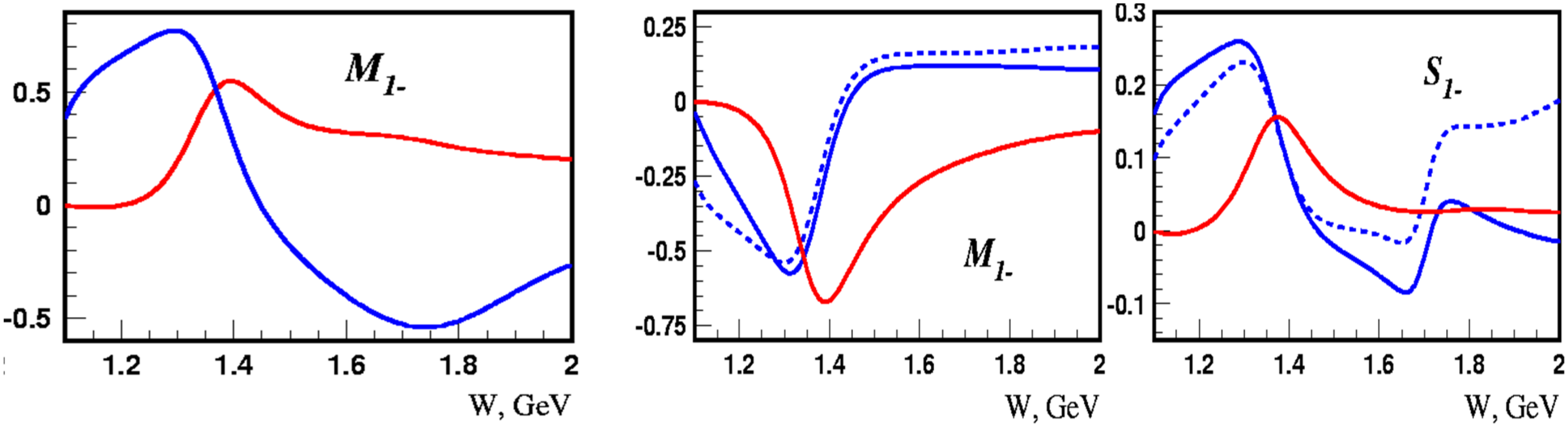
A. Bazavov et al., Phys.Lett. B737 (2014) 210-215

The number of observed excited baryon states (PDG) is insufficient to account for the cross over from non-interacting quarks (QGP) to the baryon phase.

- *Evidence for missing strange and charmed baryons*
- *Discrepancy observed also for light quark baryons*
- ***Motivates an excited baryon program of all quark flavors.***

Roper M_{1-} Multipole amplitude for $\gamma^* p \rightarrow \pi^+ n$

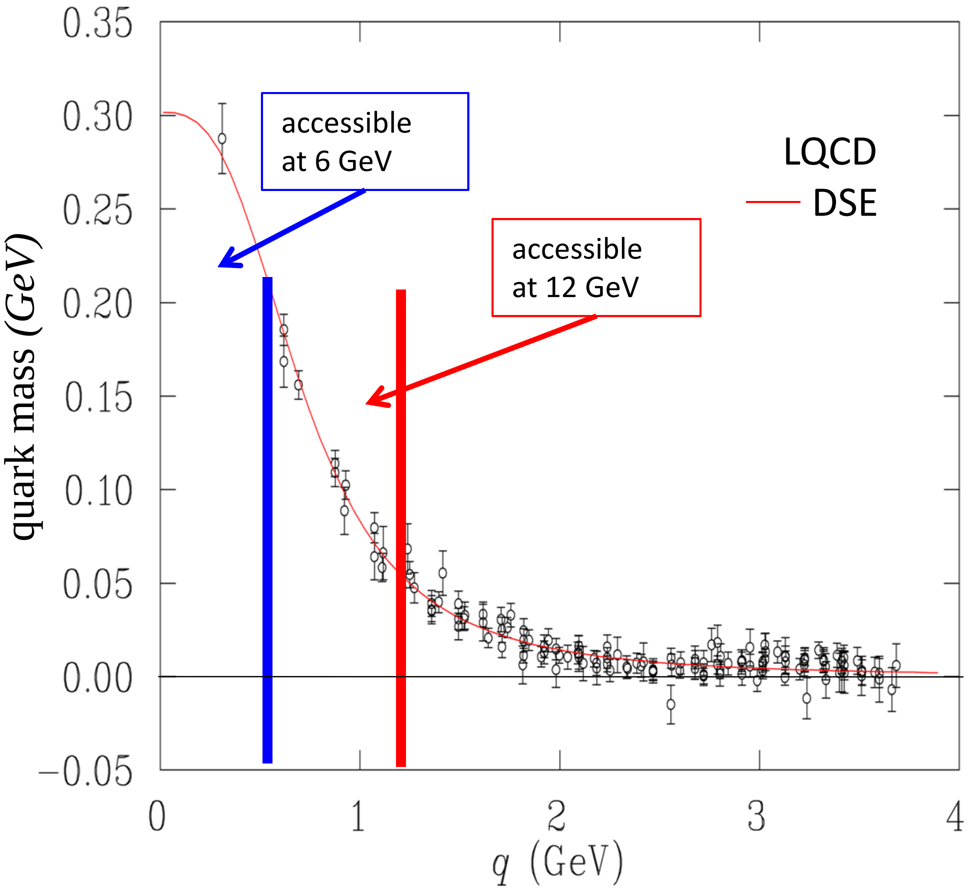
$Q^2 = 0$ **$Q^2 = 2.05\ GeV^2$**

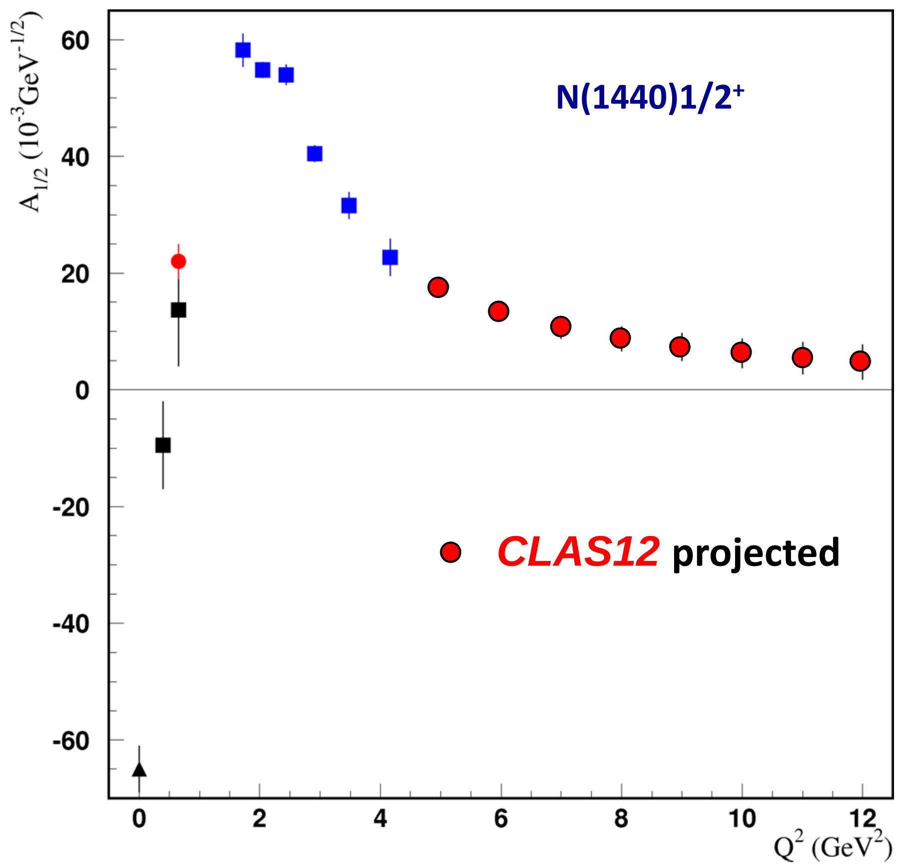


- **At Q^2=1.7 - 4.2, resonance behavior is seen in these amplitudes more clearly than at Q^2 =0**
- **DR and UIM give close results for real parts of multipole amplitudes**

Im ———
Re UIM ———
Re DR ....

Probing the running quark mass at JLab12

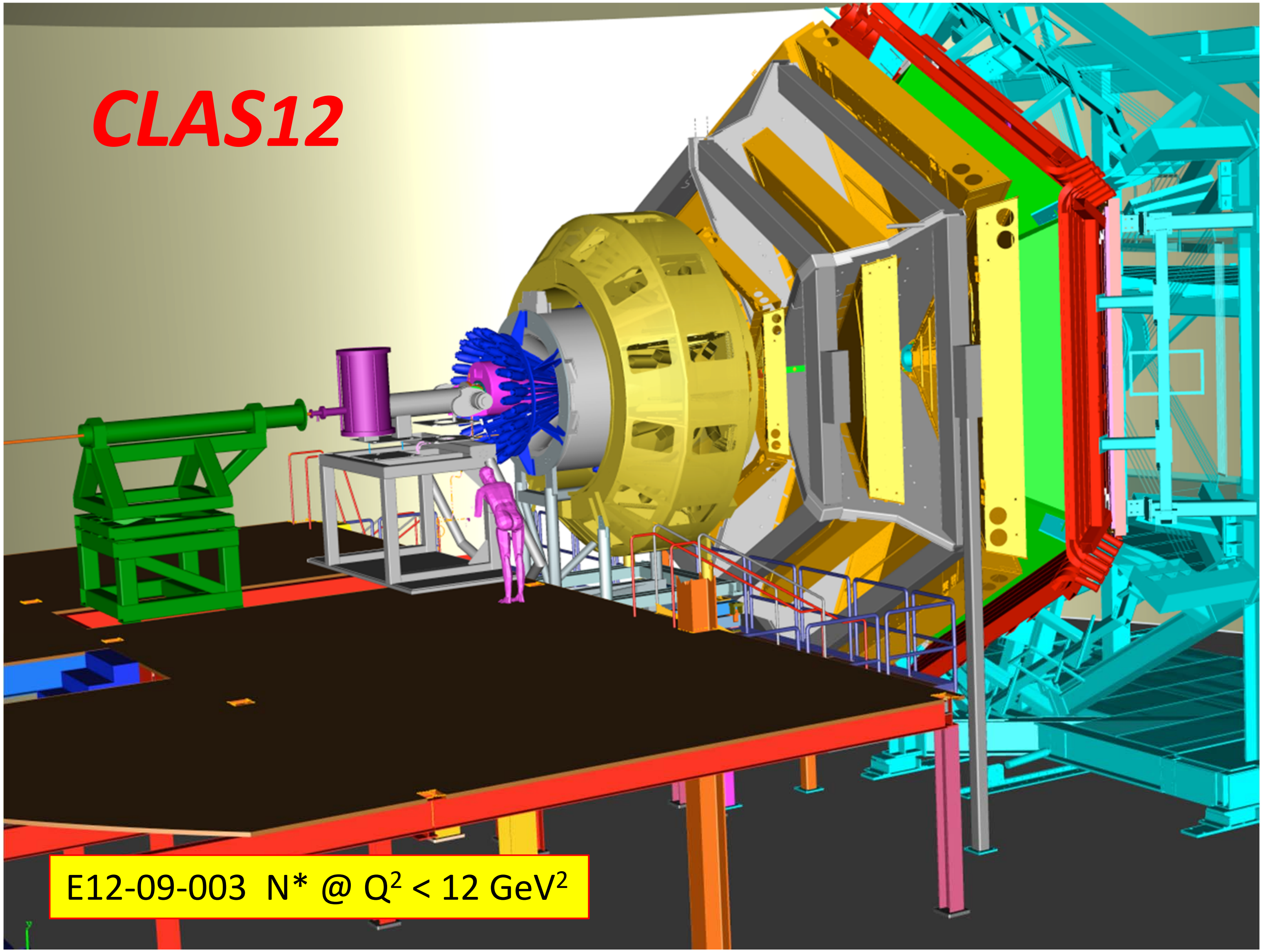




R. Gothe et al. E12-09-003

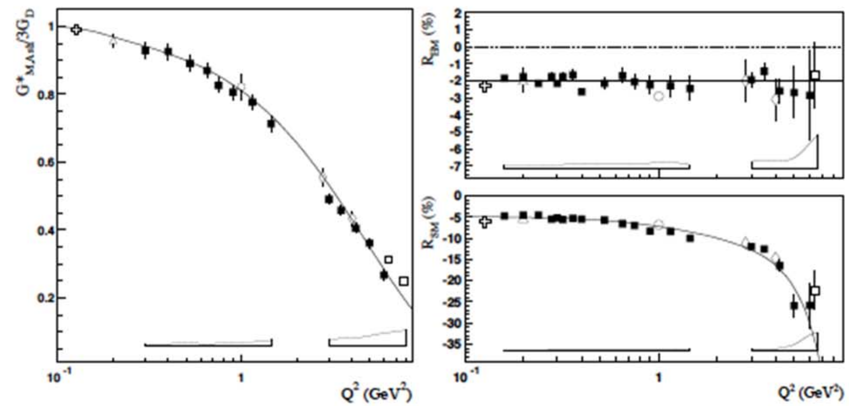
Nucleon resonance transitions amplitudes probe the quark mass function from constituent quarks to dressed quarks and elementary quarks.

N* Transition FF Physics @ JLAB12

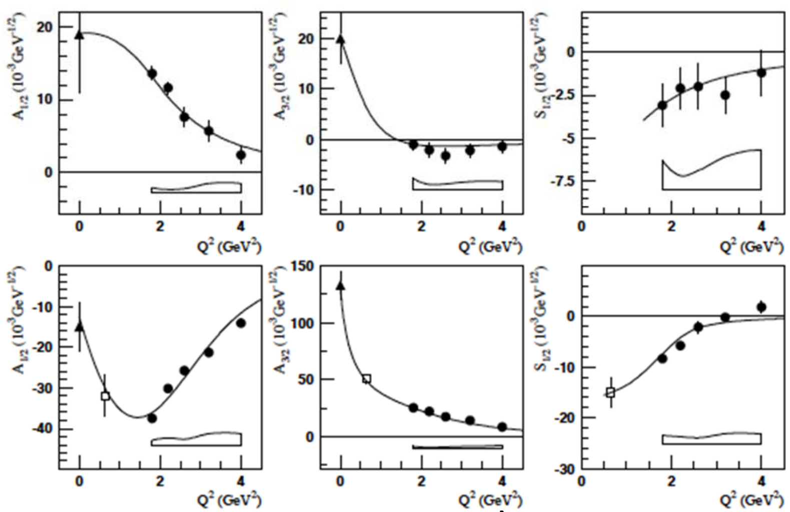


Electrocouplings in RPP 2015

Δ(1232)



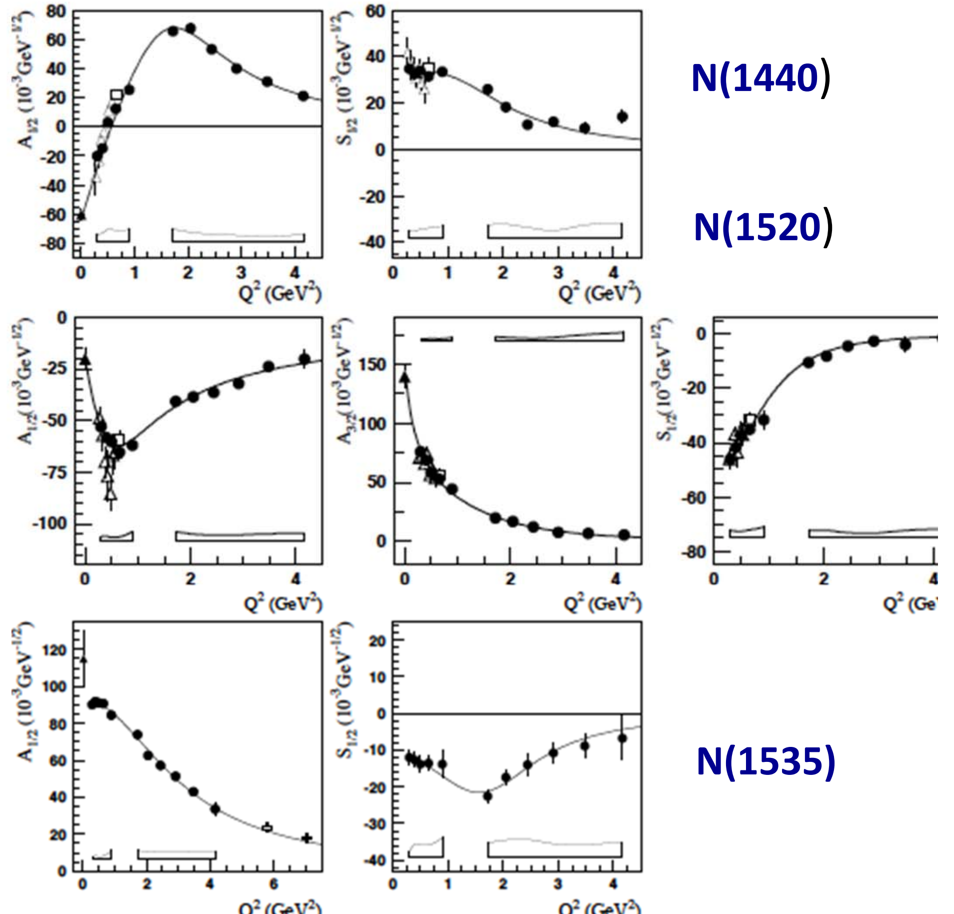
N(1675)



N(1680)

N AND Δ RESONANCES

Revised May 2015 by V. Burkert (Jefferson Lab), E. Klempt (University of Bonn), M.R. Pennington (Jefferson Lab), L. Tiator (University of Mainz), and R.L. Workman (George Washington University).



N(1440)

N(1520)

N(1535)