MENU 2016 KYOTO

Baryon Spectroscopy with Electromagnetic Probes

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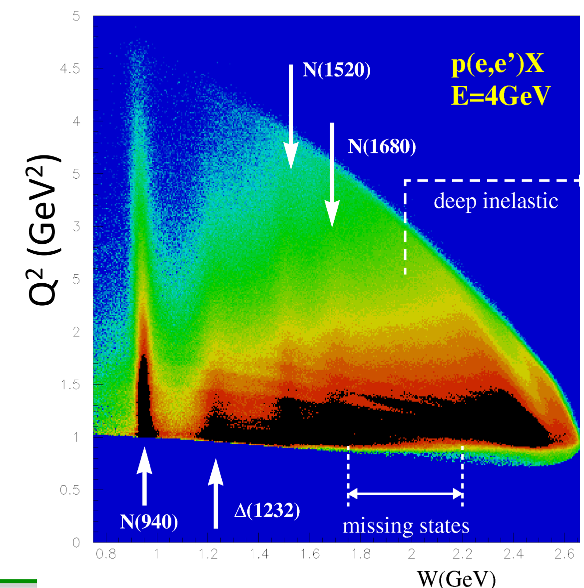
OUTLINE:

- Why study spectroscopy?
- Establishing the N* & Y* States
- Identifying the Effective DoF's
- Conclusions & Outlook

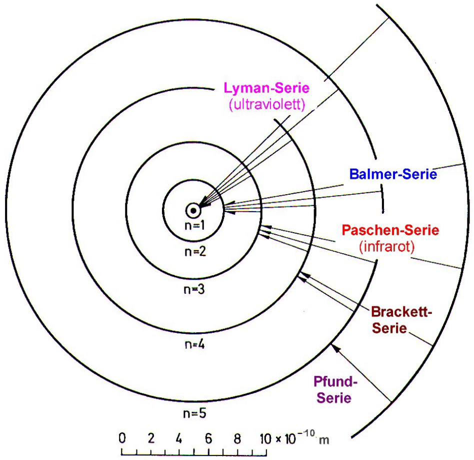


clas CEBAF Large Acceptance Spectrometer

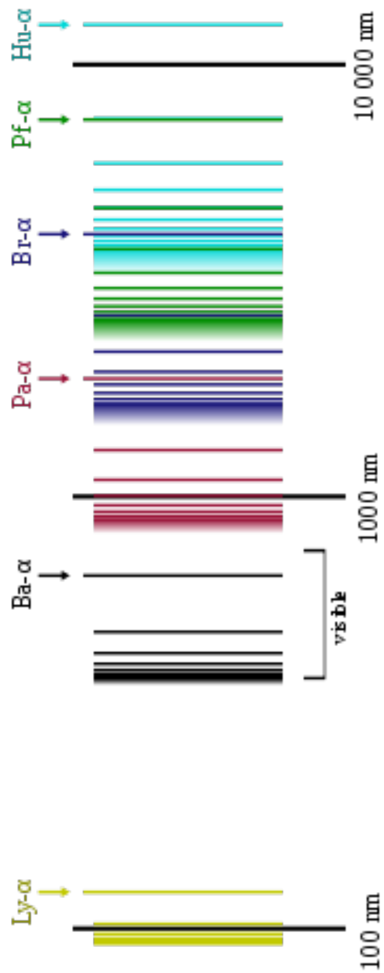
Jefferson Lab Thomas Jefferson National Accelerator Facility

From the hydrogen spectrum to the N*

N. Bohr, 1922 NP



Spectral series of hydrogen

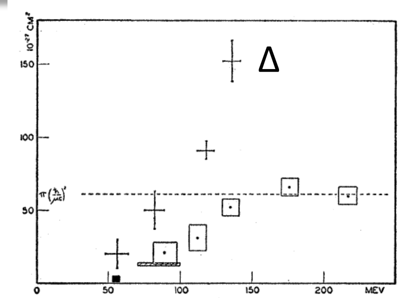


- Understanding the hydrogen atom's ground state requires understanding its excitation spectrum.
  => From the Bohr model of the atom to ***QED***.

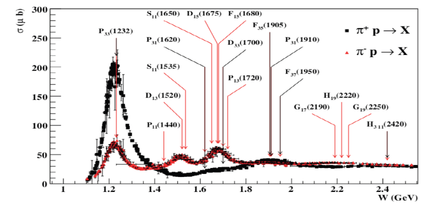
- Understanding the proton's ground state requires understanding its excitation spectrum.
  => From the constituent quark model to ***QCD***.

Some historical markers

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



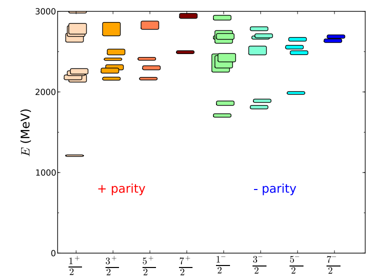
1964: Baryon resonances essential in establishing the quark model and the color degrees of freedom.



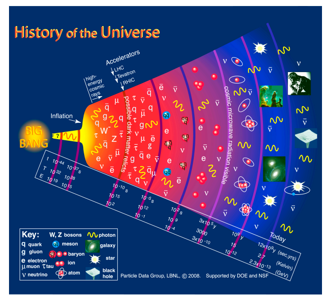
1989: Broad effort to address the "missing baryons" puzzle

CEBAF Large Acceptance Spectrometer

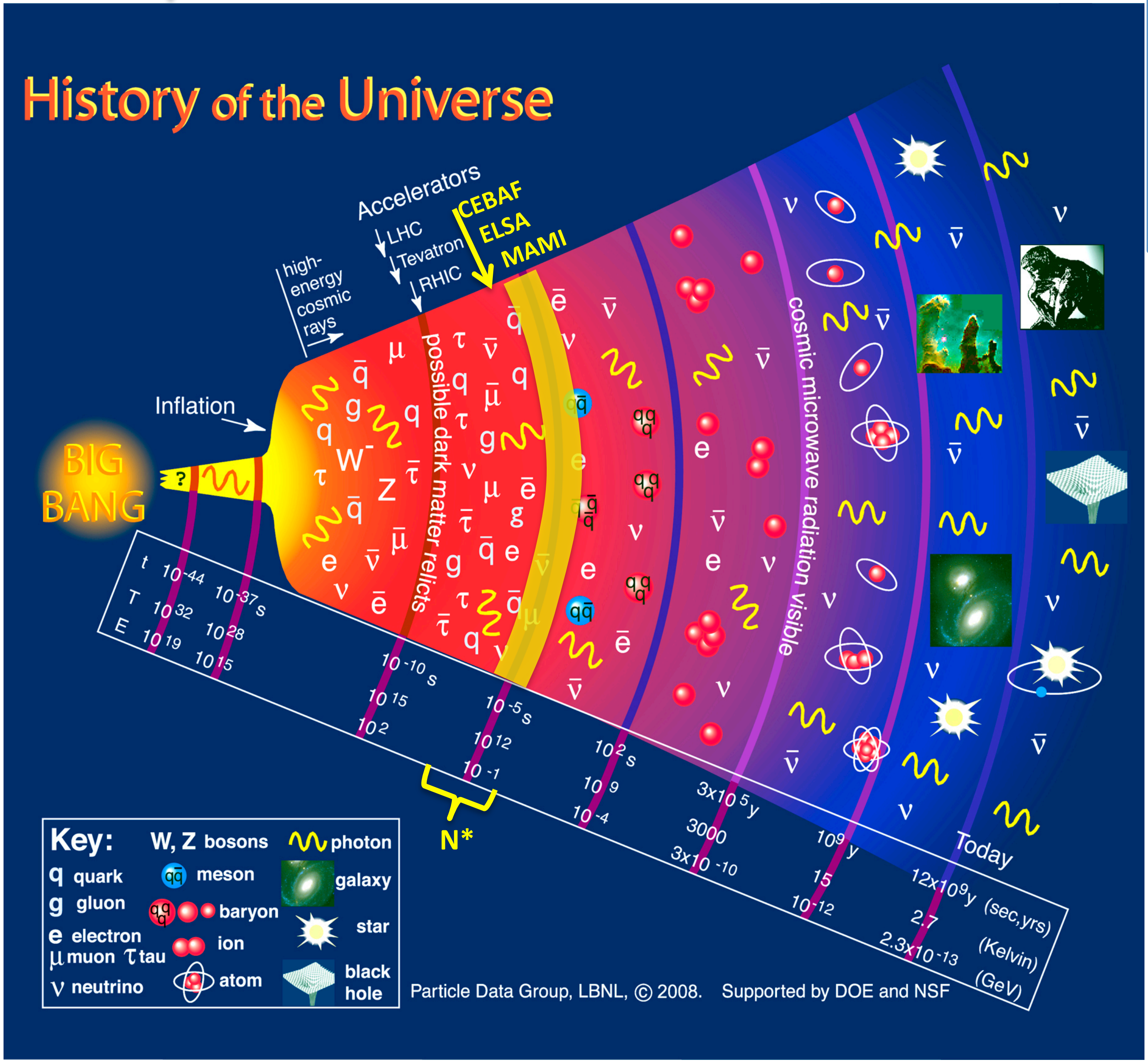
2010: First successful attempt to predict the nucleon spectrum in LQCD



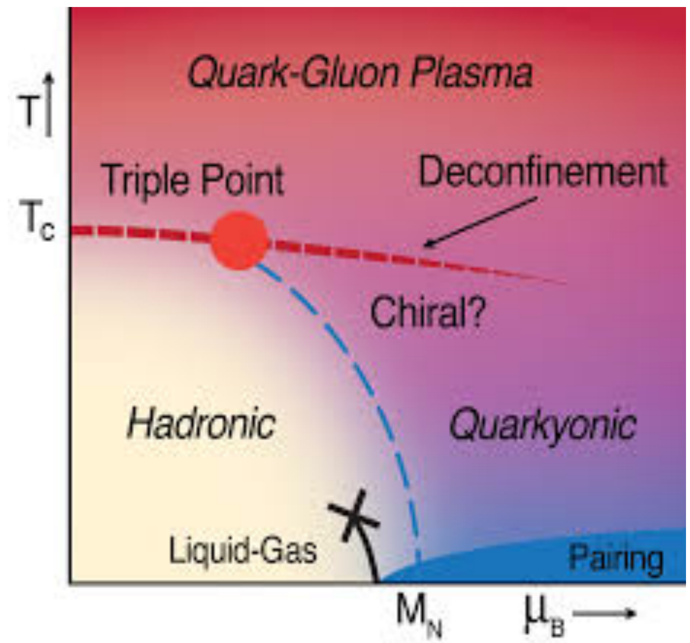
2015: Understanding of the baryon spectrum needed to quantify the transition from the QGP to the confinement phase of nucleons in the early universe.



N*'s in the History of the Universe



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

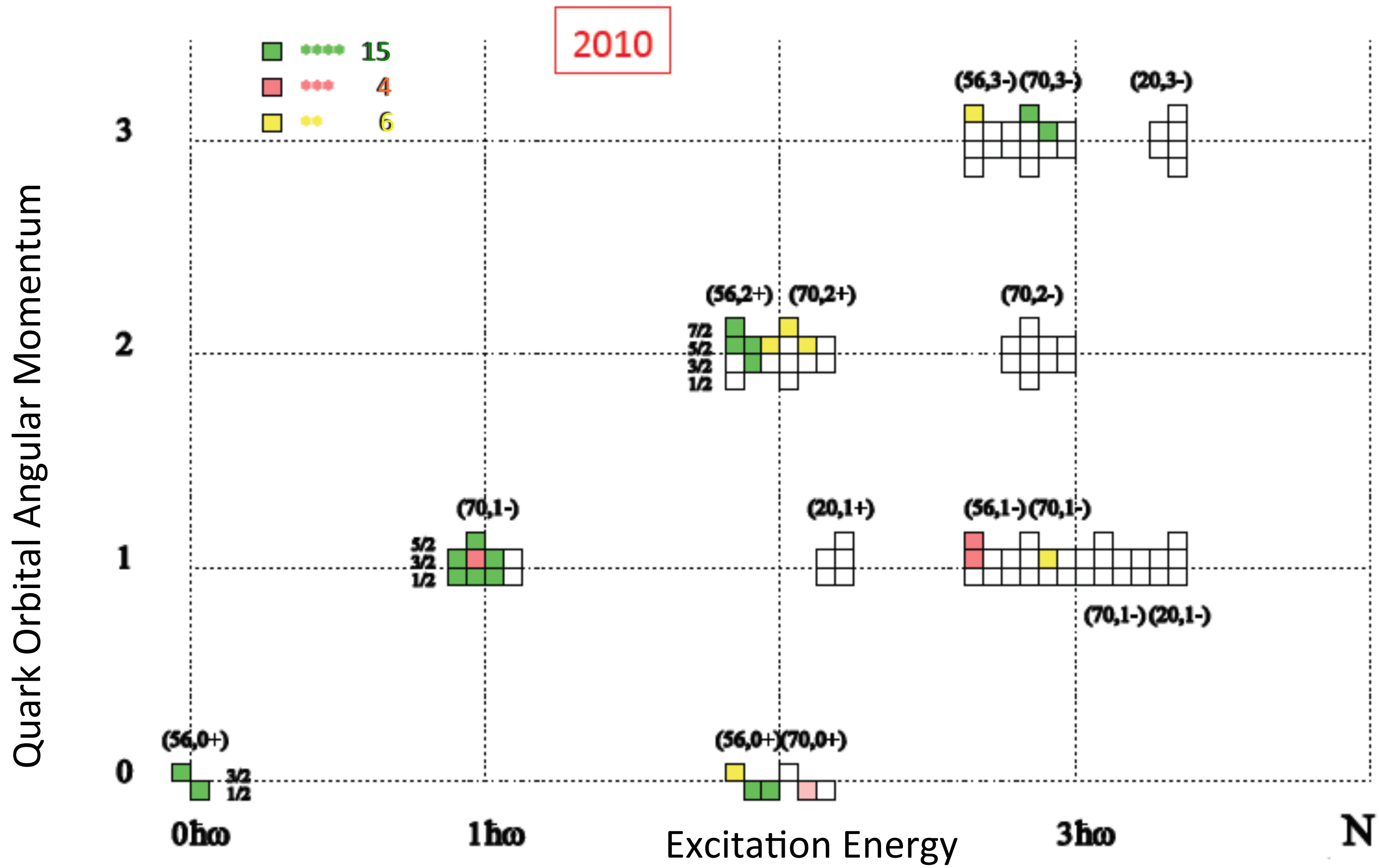


Can we understand this transition from the known excited baryons states?

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

SU(6)xO(3)

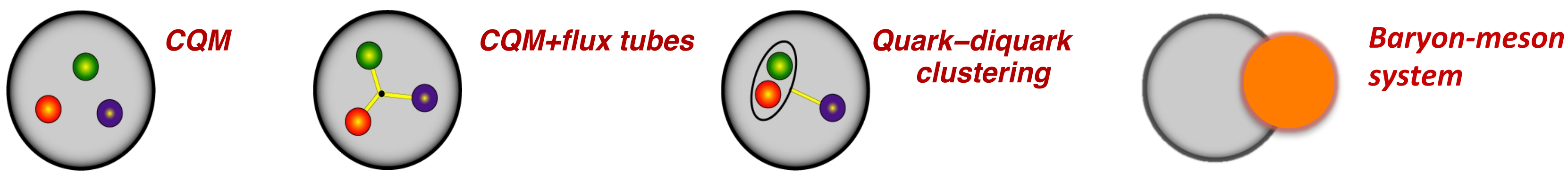
courtesy: D. Menze



Many projected q^3 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 N* and Δ spectrum systematics

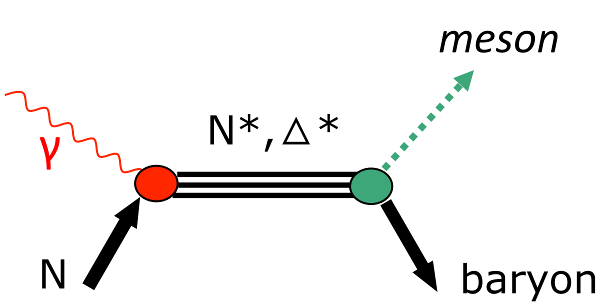
- Measure the strength of resonance excitations versus distance scale in meson **electroproduction** at JLab to identify effective degrees of freedom (JLab).

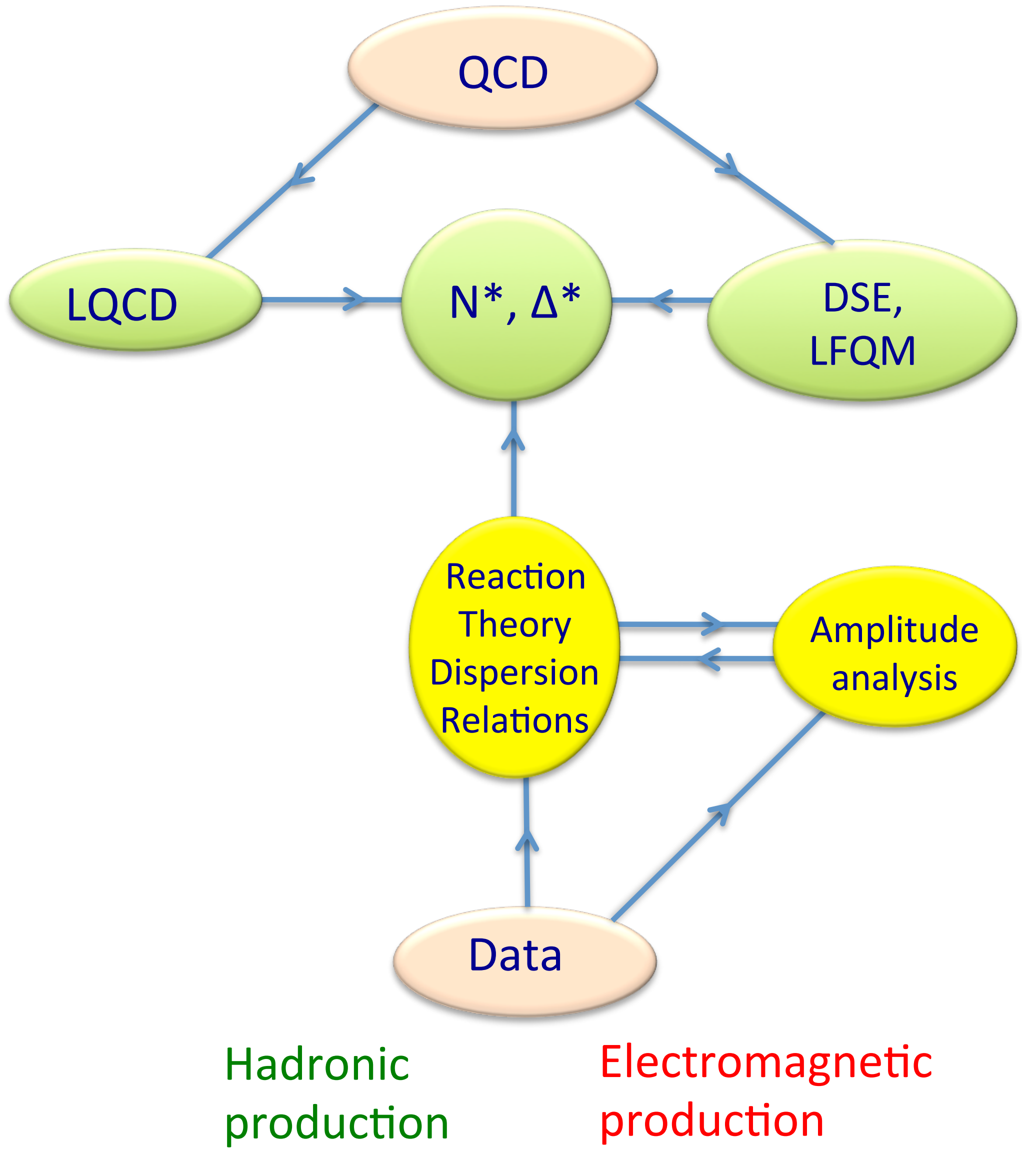
Establishing the N* and Δ* Spectrum

- Multi-GeV polarized CW beam, large acceptance detectors, polarized proton/neutron targets.
- Very precise data for 2-body processes, e.g. $\gamma p \rightarrow N\pi$, $N\eta$, KY, in wide kinematics (angle, energy)
- More complex (multistep) reactions needed to access high mass states, $N\pi\pi$, $N\pi\eta$, $N\omega/\varphi$, …

⇓

Extract s-channel resonances

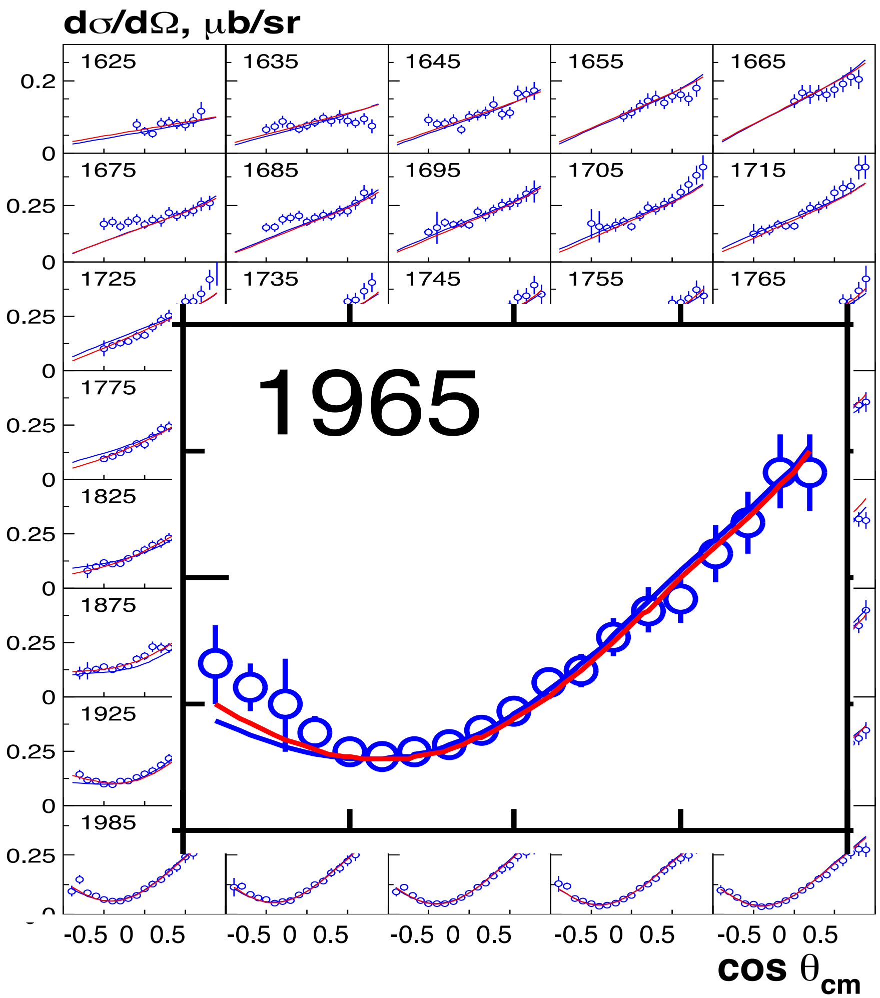




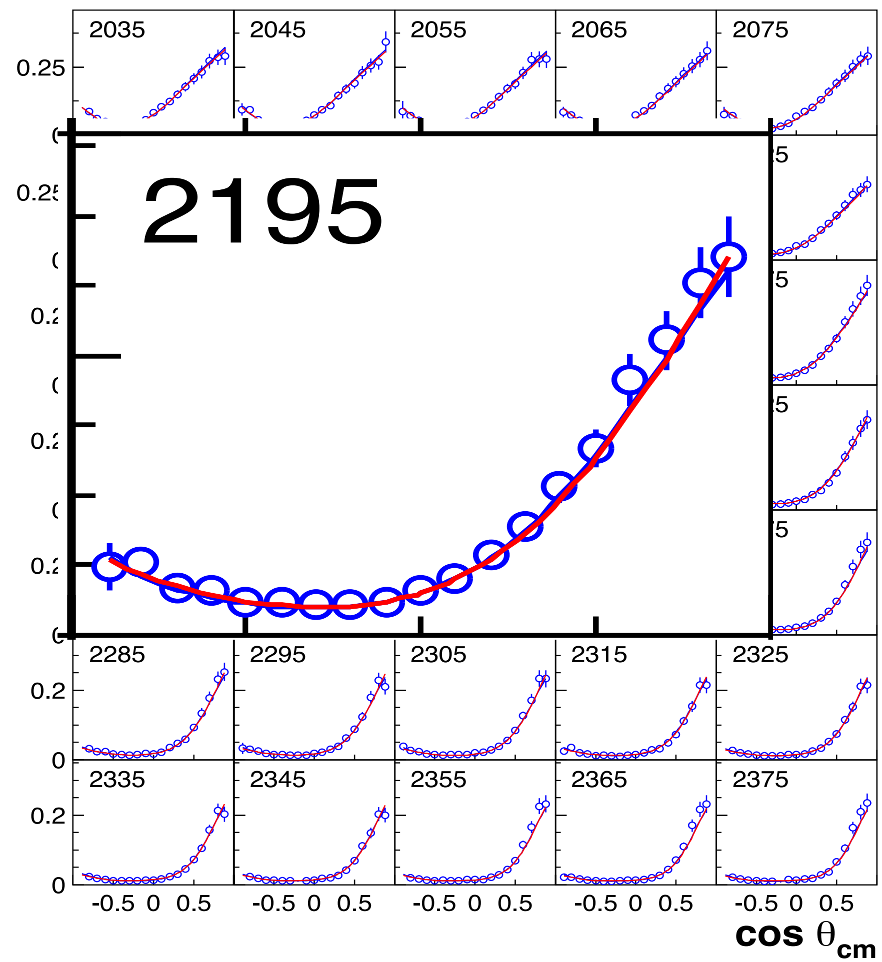
V.Burkert, T.S.H. Lee, 2004

Establishing the N* spectrum, cont'd

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



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

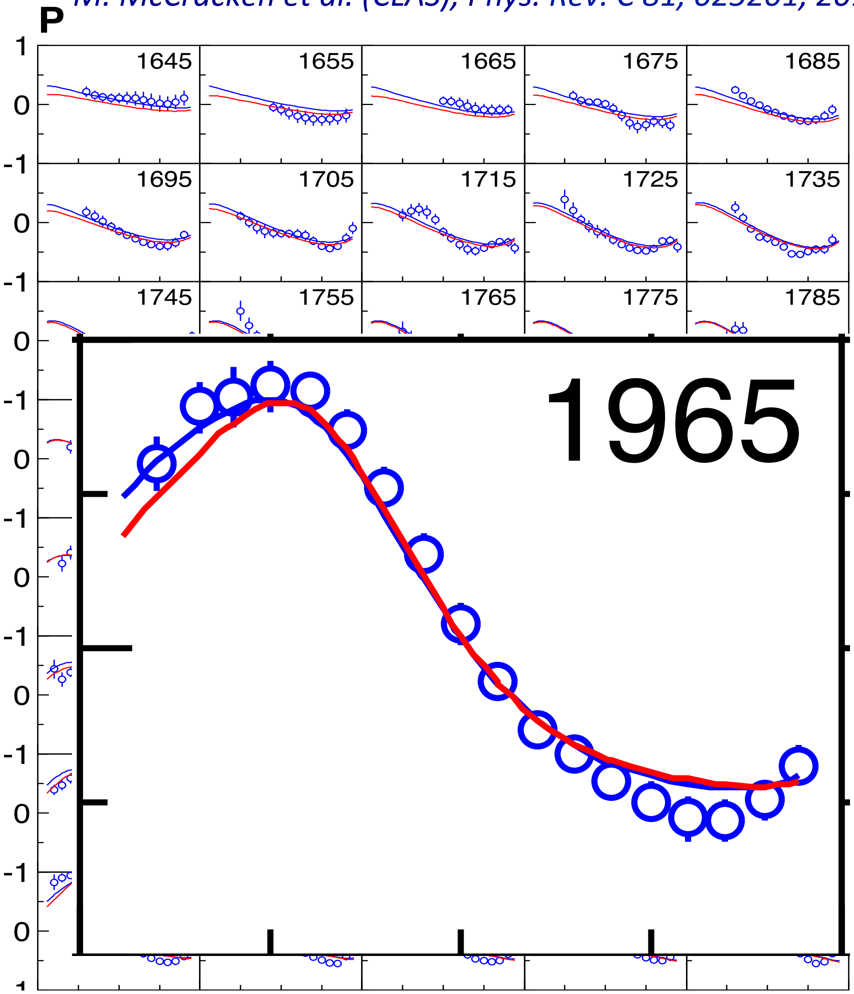


A.V. Anisovich et al (BnGa), EPJ A48, 15 (2012)

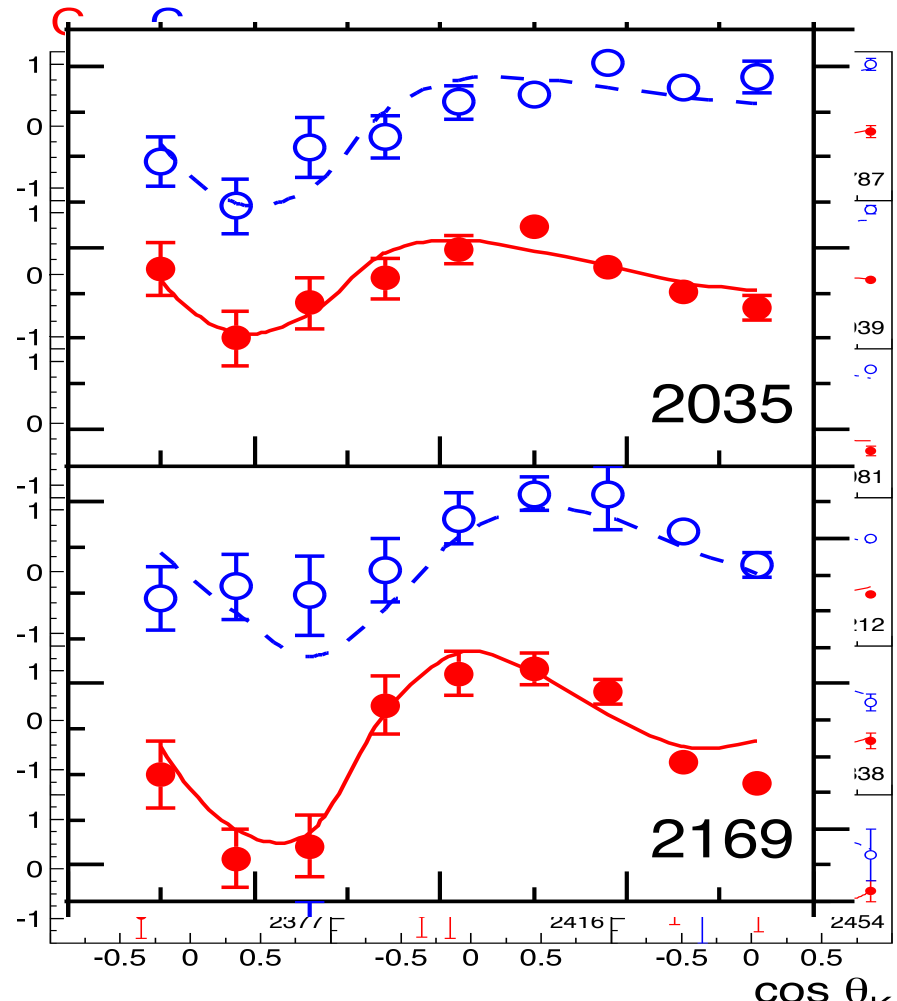
Establishing the N* spectrum, cont'd

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

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



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



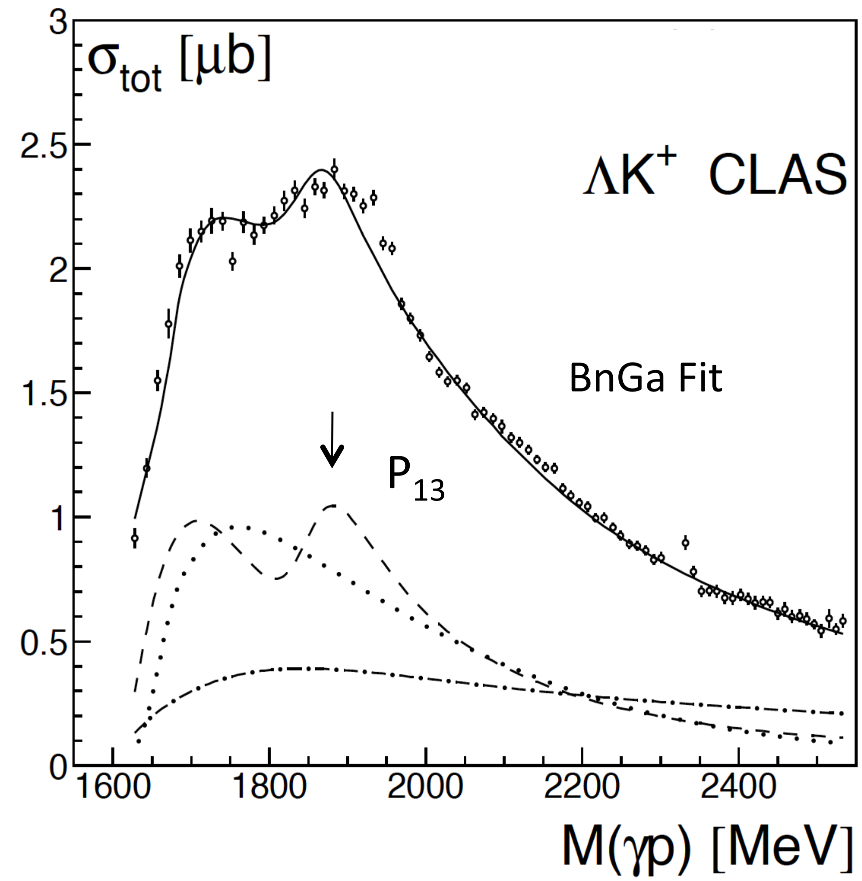
The high precision KΛ data are the basis for discovery/evidence of/for several states.

Establishing the N* spectrum, cont'd

N(1900)3/2⁺

- Bump first seen in SAPHIR $K^+\Lambda$ data but due to systematics in the data misinterpreted as $J^P=3/2^-$. (a D-wave resonance)
- State was solidly established in BnGa multi-channel analysis making use of very precise CLAS $K\Lambda$ σ and polarization data, led to the *** in PDG2012. (a P-wave resonance)
- State confirmed in an effective Langrangian resonance model analysis of $\gamma p \to K^+\Lambda$.
  O. V. Maxwell, PRC85, 034611, 2012
- State confirmed in a covariant isobar model single channel analysis of $\gamma p \to K^+\Lambda$.
  T. Mart, M. J. Kholili , PRC86, 022201, 2012
- First baryon resonance observed and multiply confirmed in electromagnetic meson production.

  => Candidate for **** state.



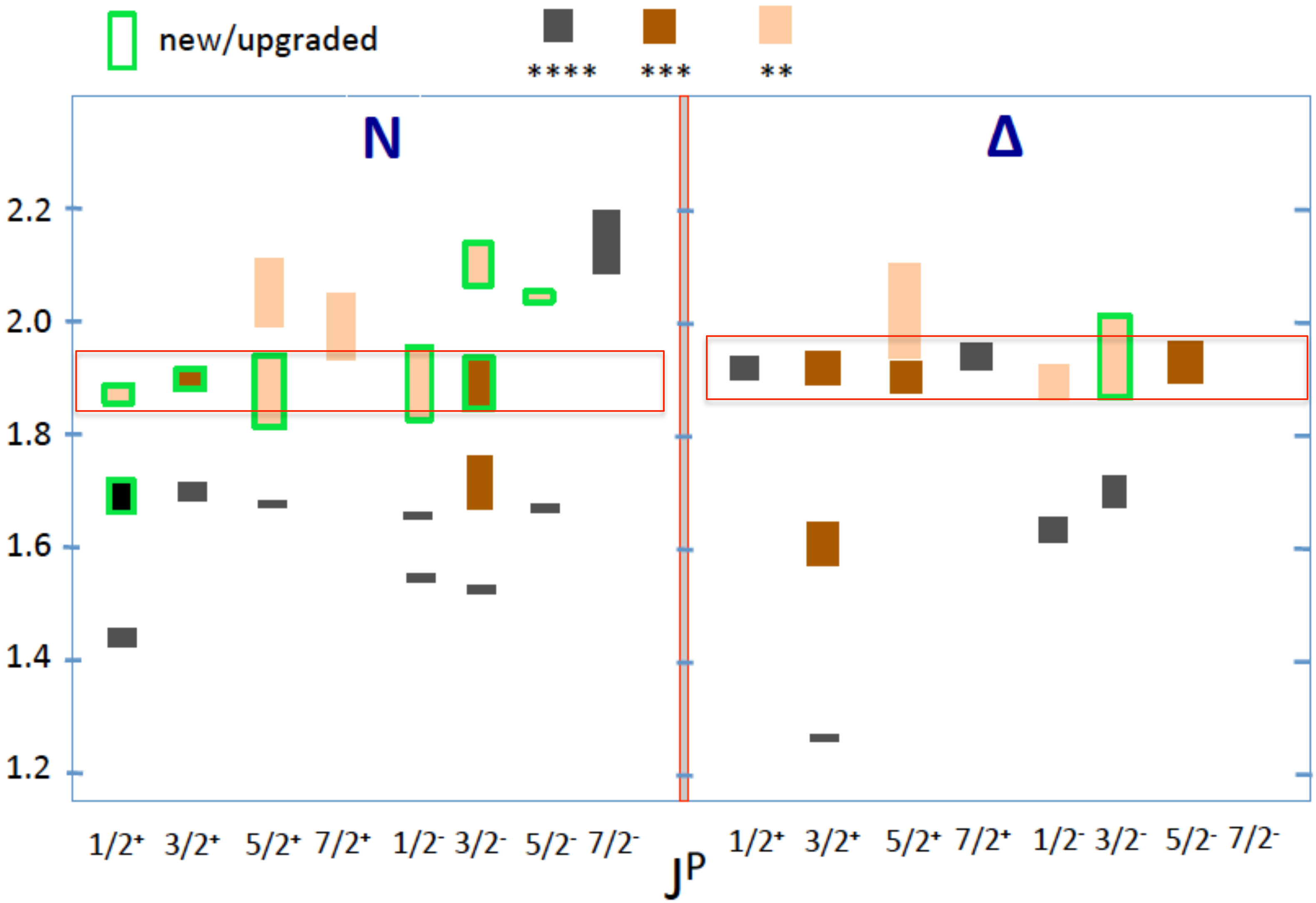
Updated Spectrum of Baryon Resonances

- From 2000-2010, no new baryon resonances were considered by the PDG
  - Used πN-scattering and some π-photoproduction only
- Matured multi-channel models now include much photoproduction data
- E.g. Bonn-Gatchina PWA, A. V. Anisovich et al. EPJA 48, 15 (2012).

	Particle Data Group 2010	BnGa analyses	Particle Data Group 2012	GWU'06
$N(1860)5/2^+$		*	**	
$N(1875)3/2^-$		***	***	
$N(1880)1/2^+$		**	**	
$N(1895)1/2^-$		**	**	
$N(1900)3/2^+$	**	***	***	no evidence
$N(2060)5/2^-$		***	**	
$N(2150)3/2^-$		**	**	
$\Delta(1940)3/2^-$	*	*	**	no evidence

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

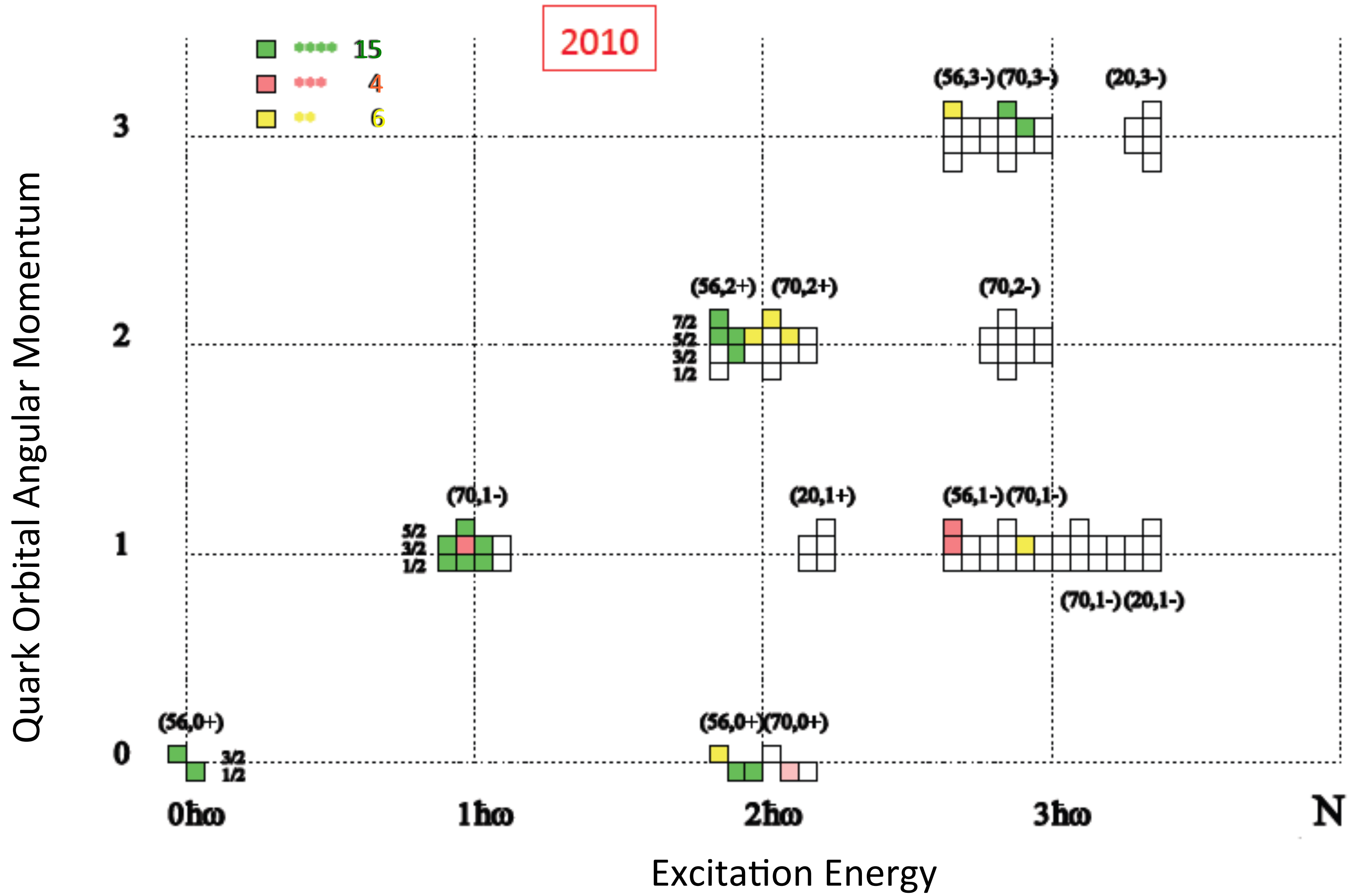
Lower mass N*/Δ* spectrum in 2015



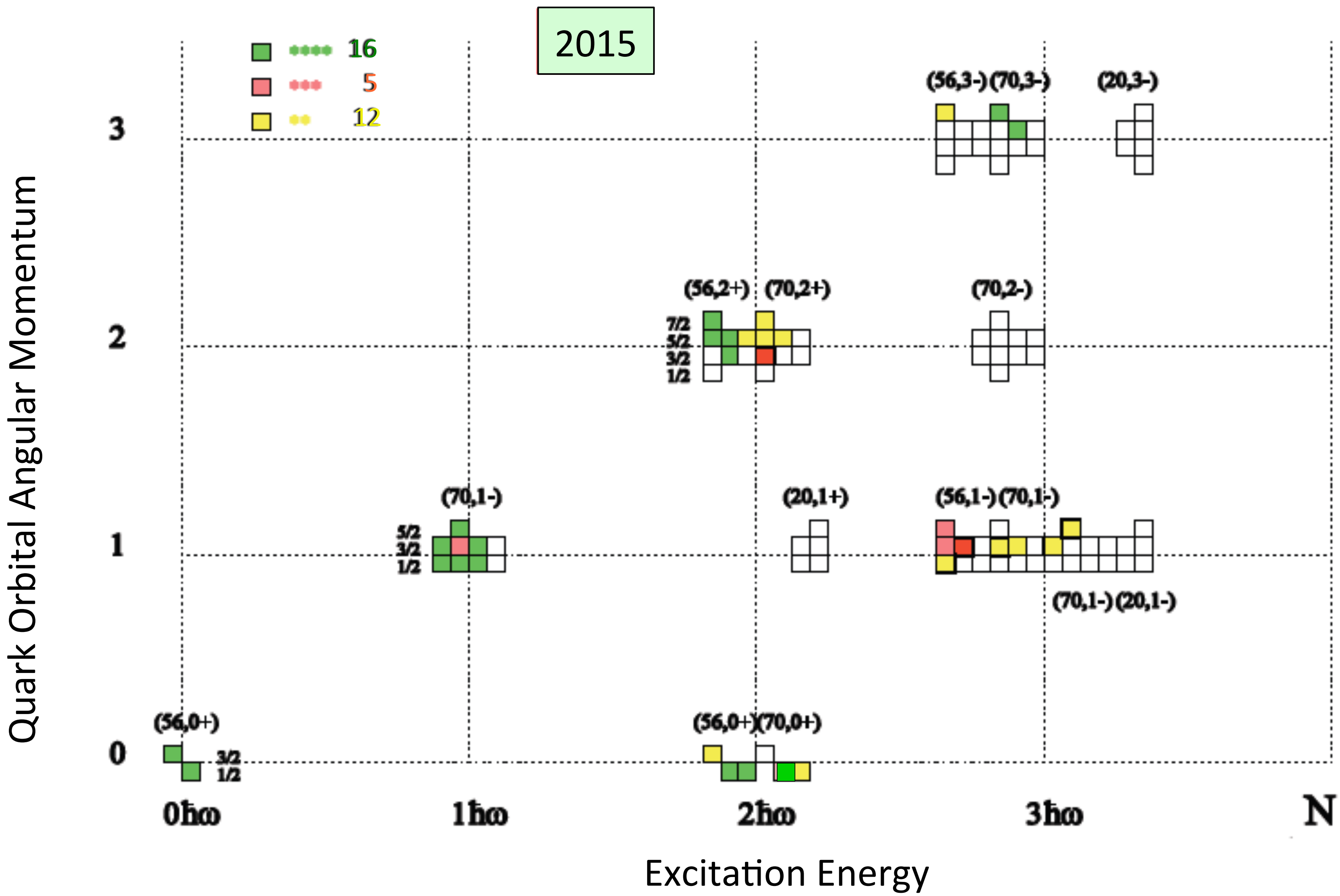
Are there mass degenerate spin multiplets?
Do these states fit into the SU(6) spin-flavor symmetry? Lattice?

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

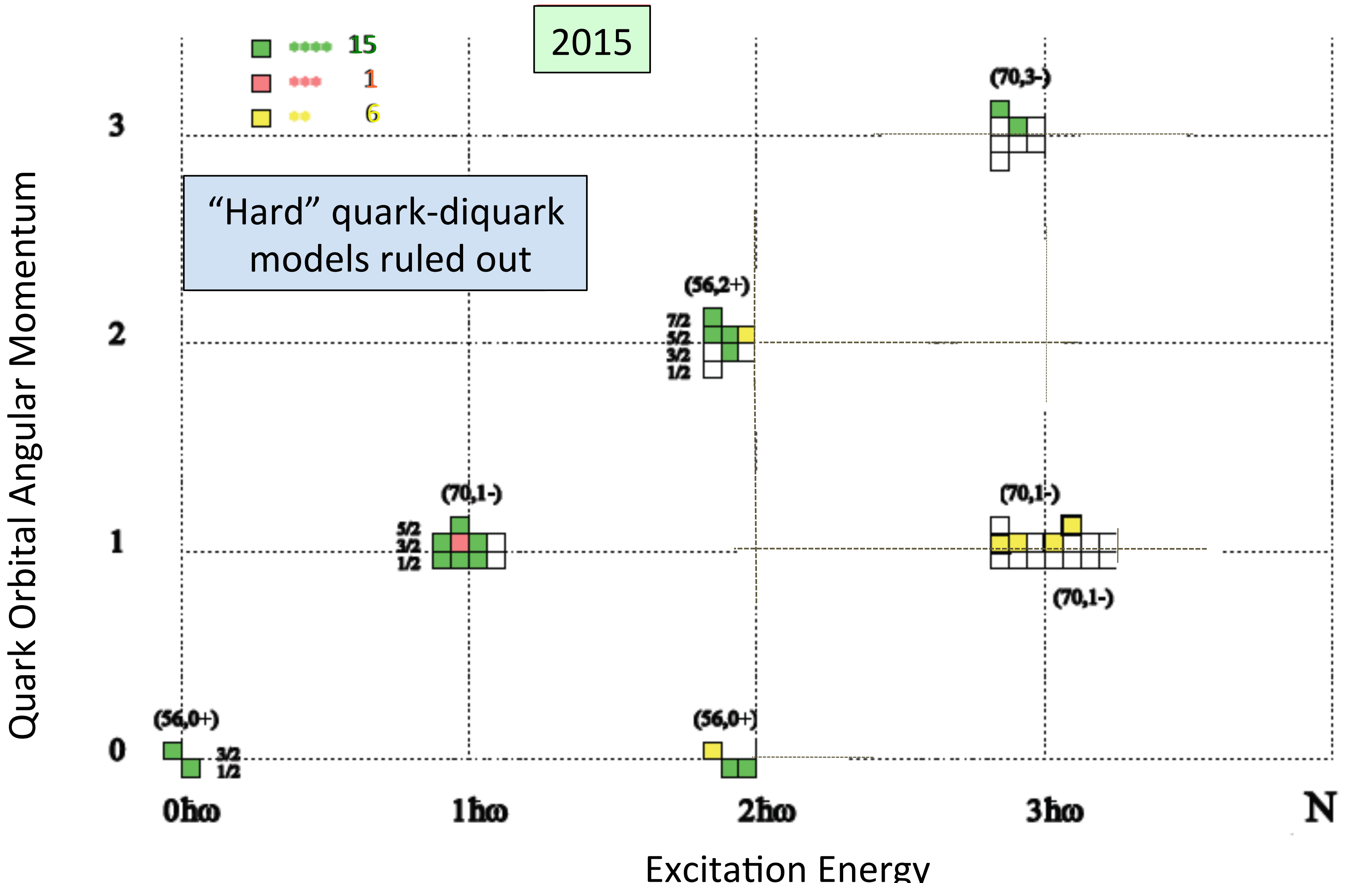
SU(6)xO(3)



Do new states fit into Q³ QM?



Do new states fit into Q-Q^2 model?

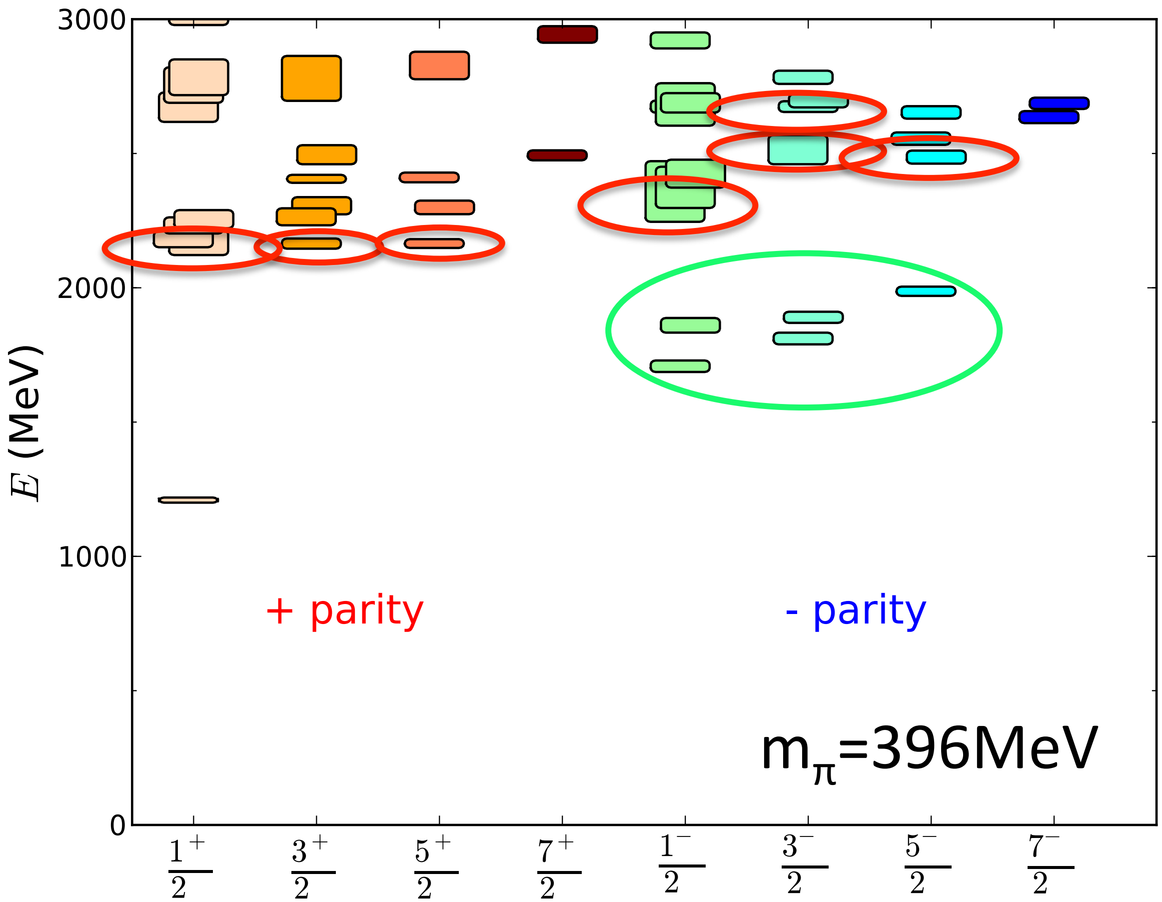


"Soft" quark-diquark models may remain viable,
e.g. G. Eichmann et al, arXiv:1607.05748 [hep-ph]

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$^-$

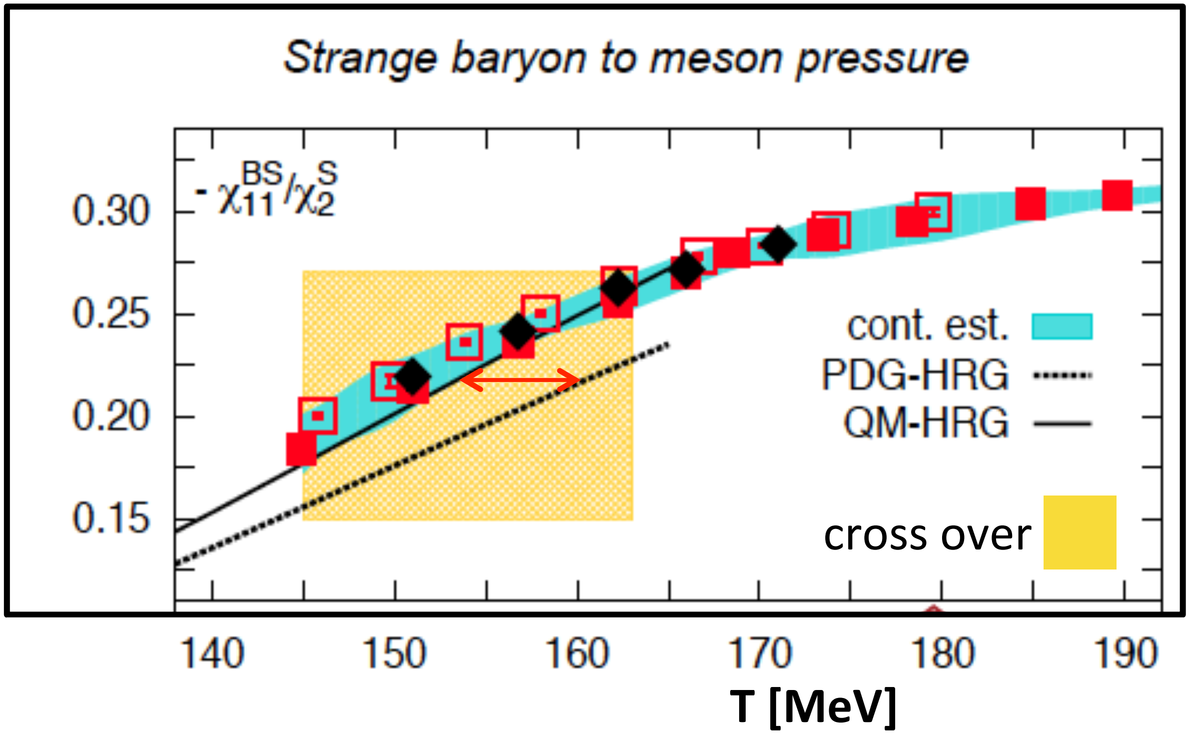
Lowest J$^+$ states 500 -700 MeV high

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 in QCD Phase Transition

From Hot QCD: Fluctuation Ratio of Baryon Number to Strangeness at hadron freeze-out



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

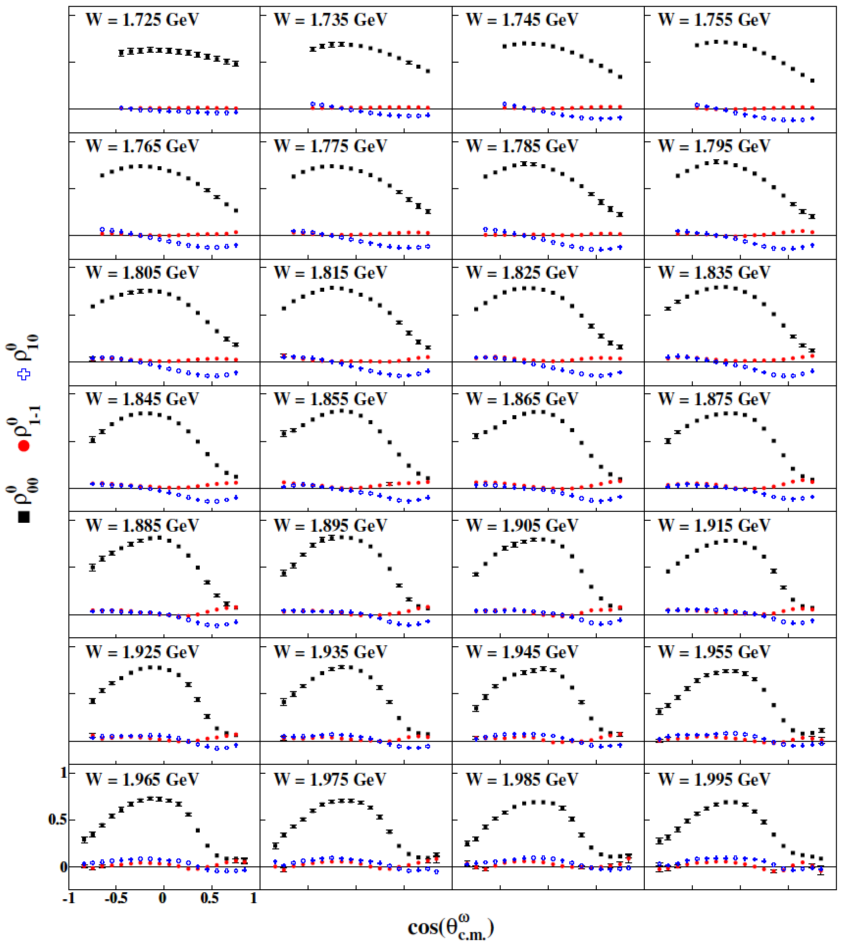
The RHIC operation plan for 2016 includes an energy scan to map out this behavior.

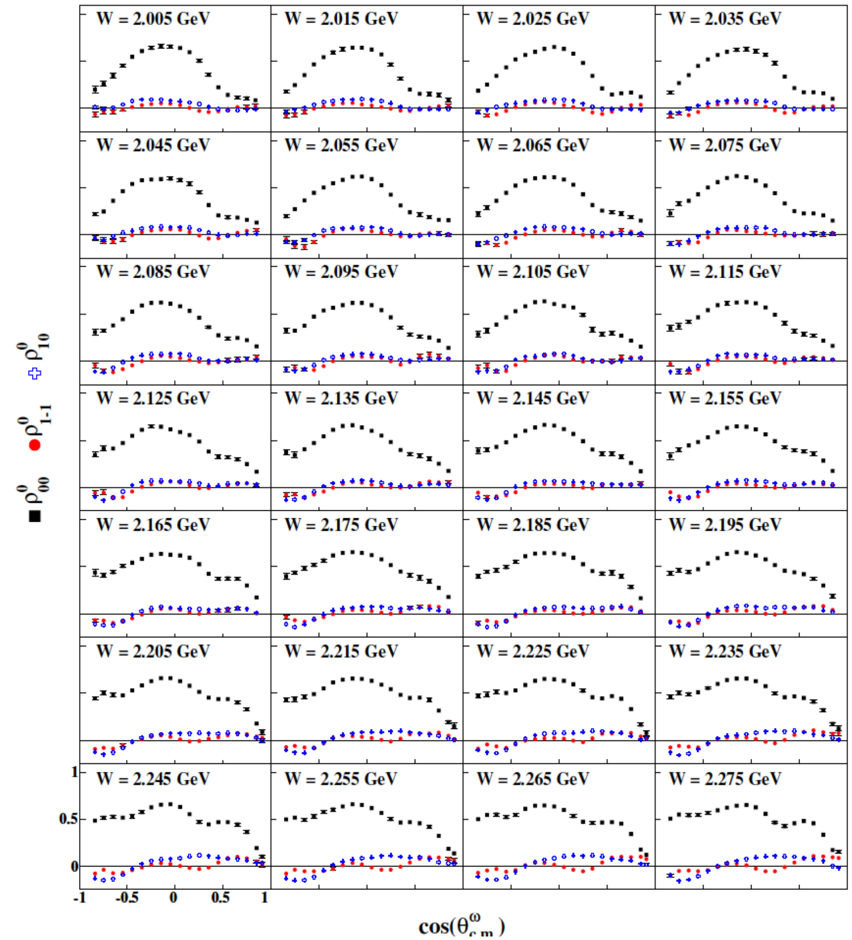
N* states in $\gamma\, p \rightarrow p\omega \rightarrow p\, \pi^+ \pi^- \pi^0$

- Pioneering work: precision vector meson data to search for higher mass N*'s

SDME extraction

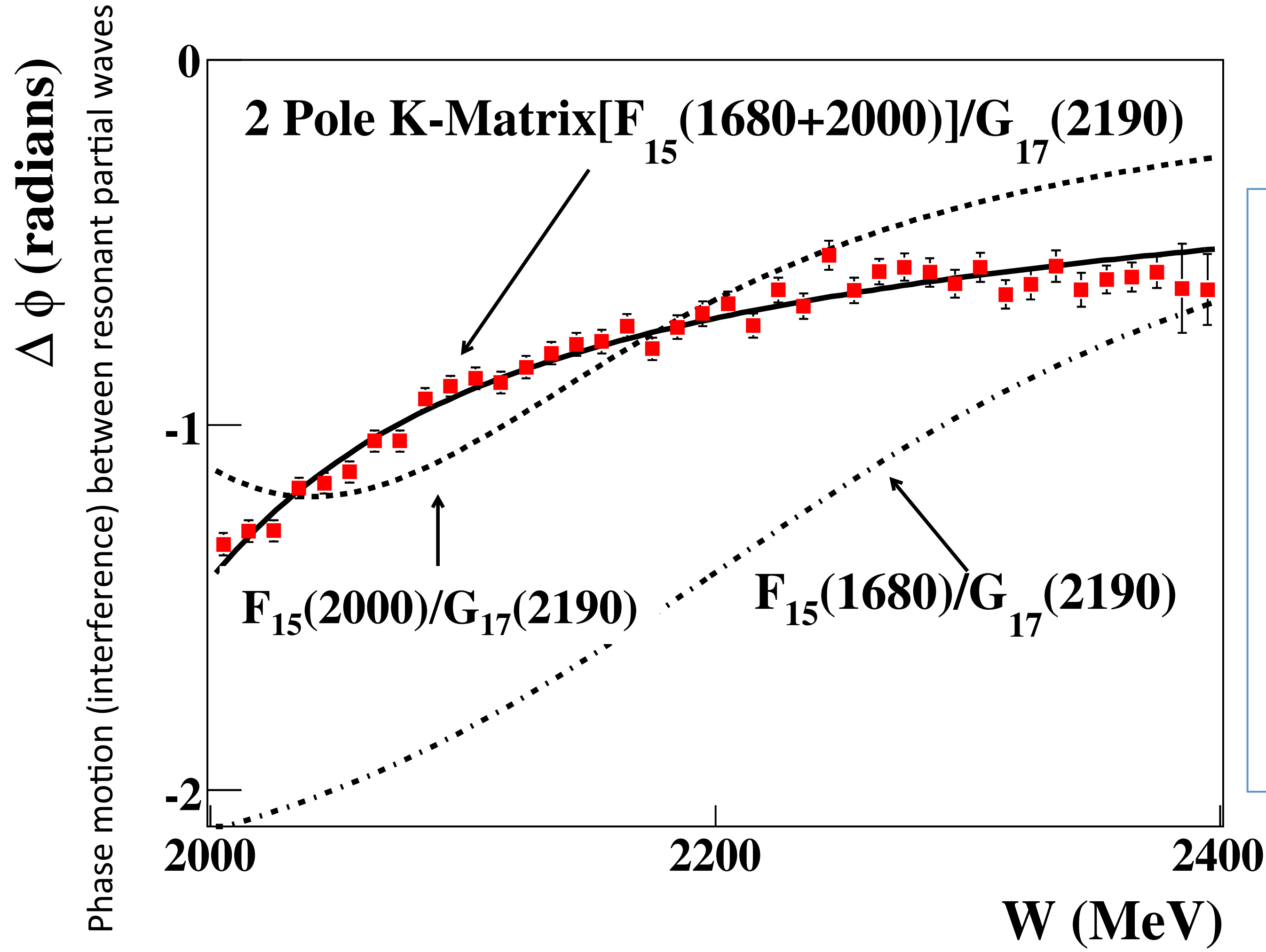
M. Williams, et al. (CLAS) ,
Phys.Rev. C80 (2009) 065208





- No Isospin filter sensitive only to N* states
- No multi-channel analysis done, but pioneering work on single-channel event-based analysis

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



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)**

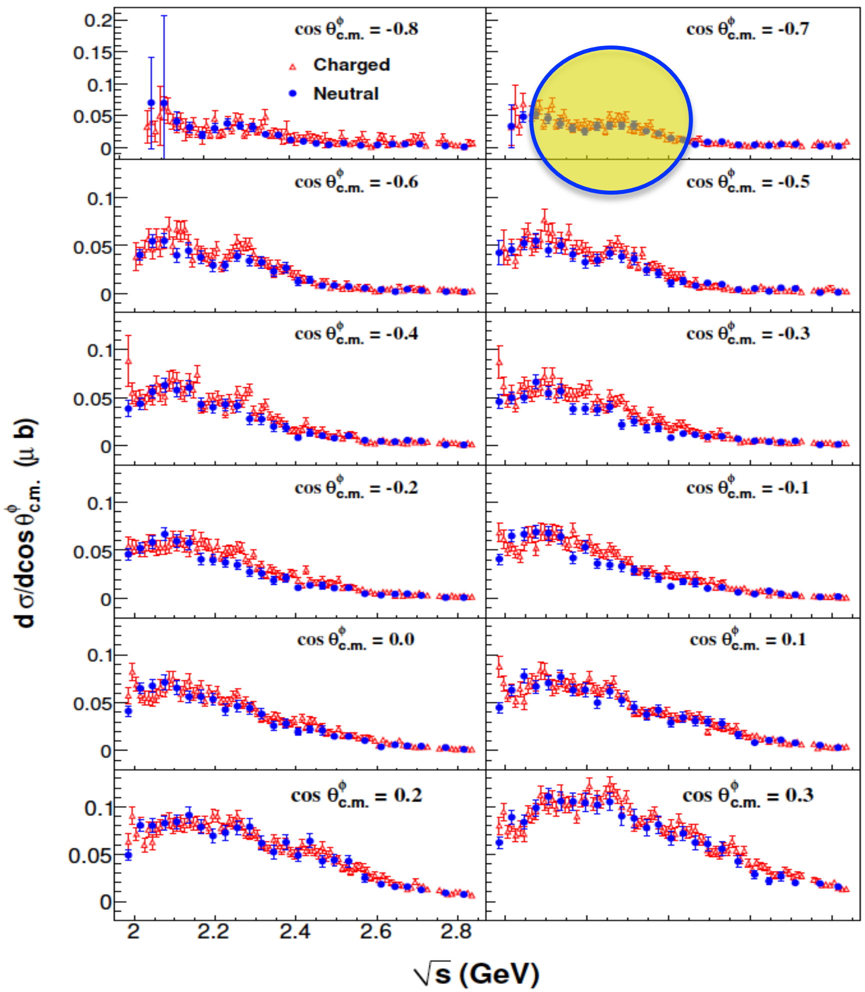
Results with polarized beam and polarized target forthcoming...

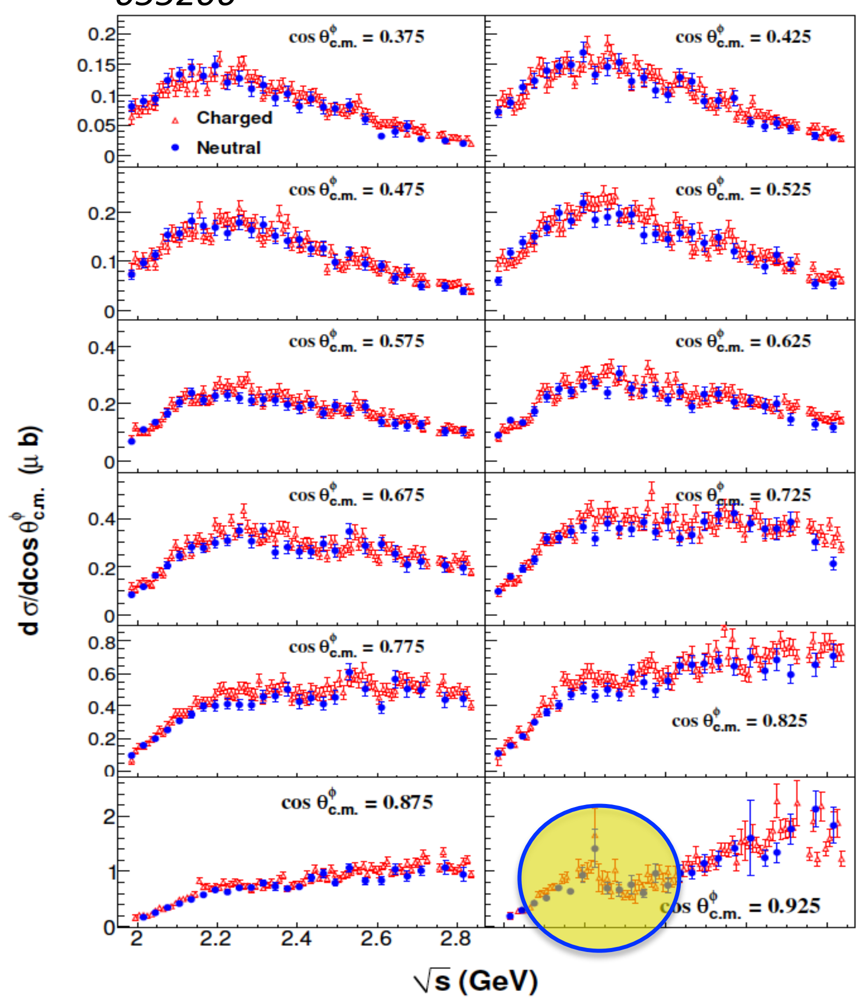
First observation of G_{17}(2190) -> Nω, PDG2014

Pseudo-pentaquark in $\gamma p \to p\,\phi$

$\phi \to K^+K^-$, $\phi \to K^0_S K^0_L$

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

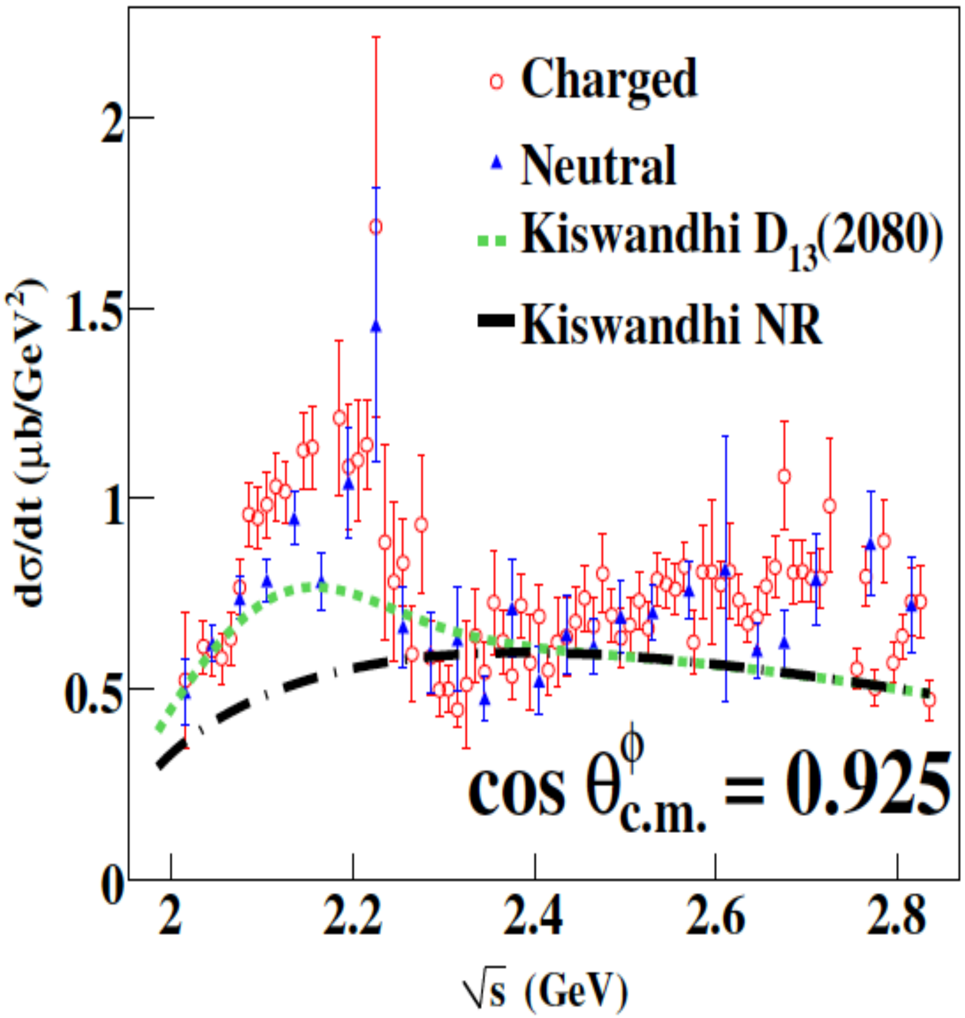




Channel could be be sensitive to: N*'s with large s-sbar content, MB molecules, pseudo-pentaquarks?

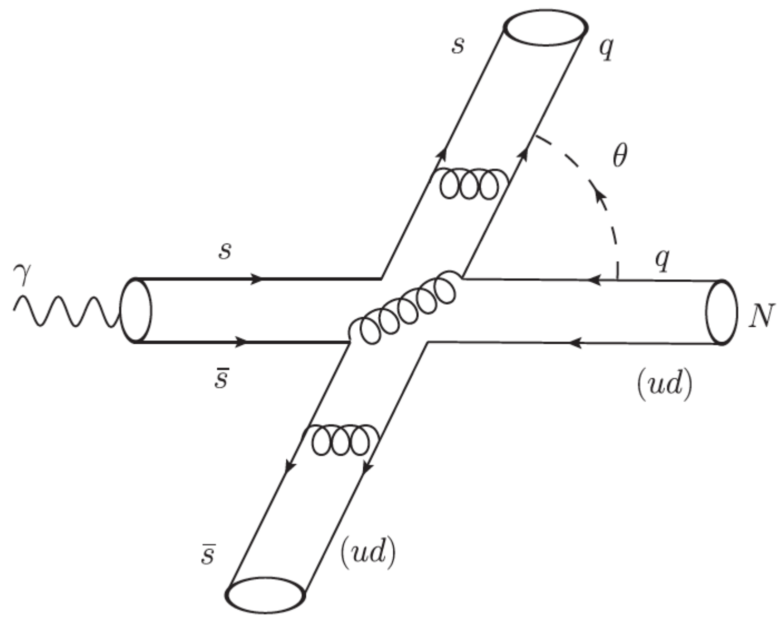
Pseudo-pentaquark in $\gamma p \rightarrow p\,\phi$

$\phi \rightarrow K^+K^-$, $\phi \rightarrow K^0_S K^0_L$



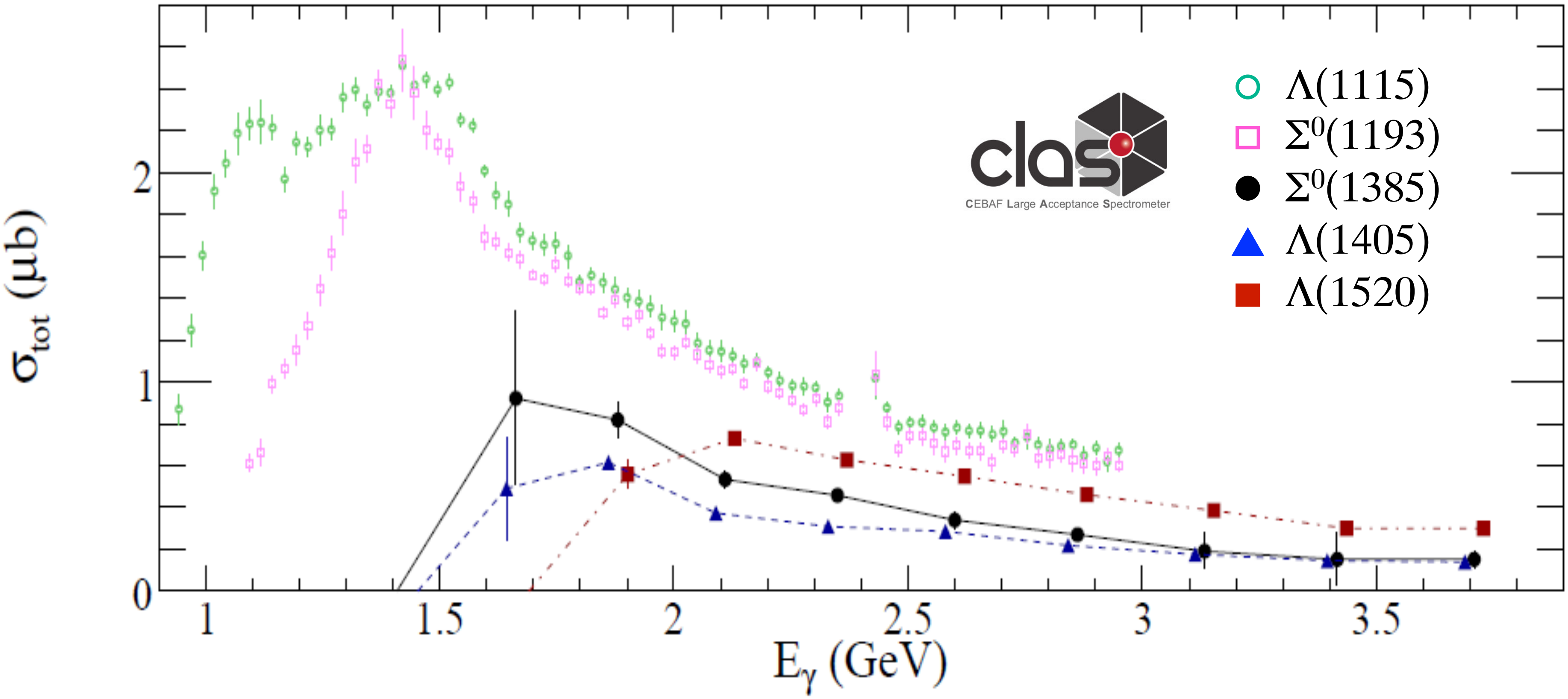
Structure may not be an s-channel resonance. Could it be a color diquark - anti-triquark pair, similar to that proposed for the P_c^+ LHCb resonances.

R. Lebed, Phys Rev D 92, 11406 (2015)



Near-collinearity minimizes momentum transfer → shows up at extreme angles

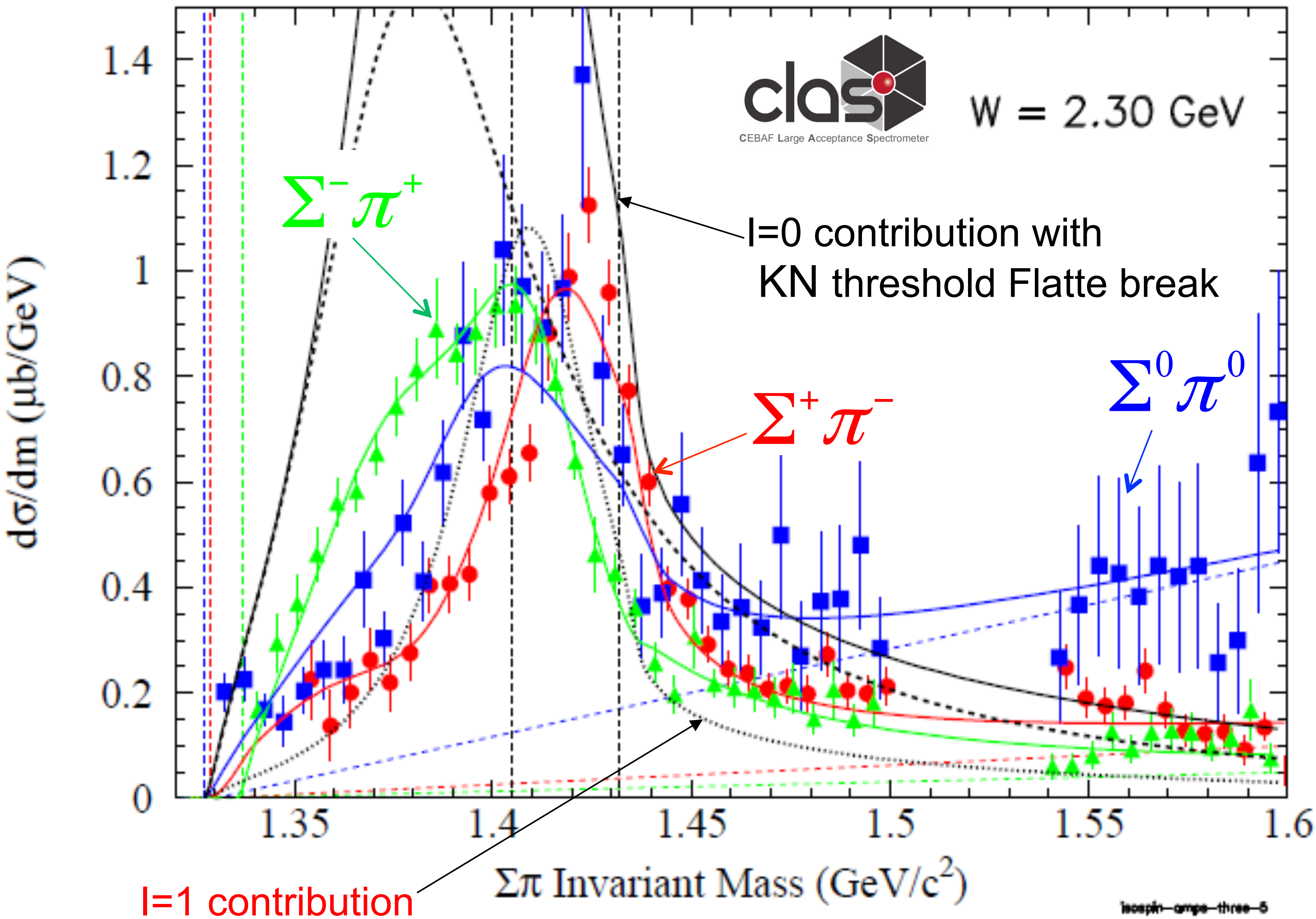
Exploring the S = -1 Hyperons



- $\gamma + p \rightarrow \mathrm{K}^+ + \mathrm{Y}^{(*)}$
- All three Y^*s have similar total cross sections
- Ground state Λ and Σ^0 are comparable to Y^* in size[1]

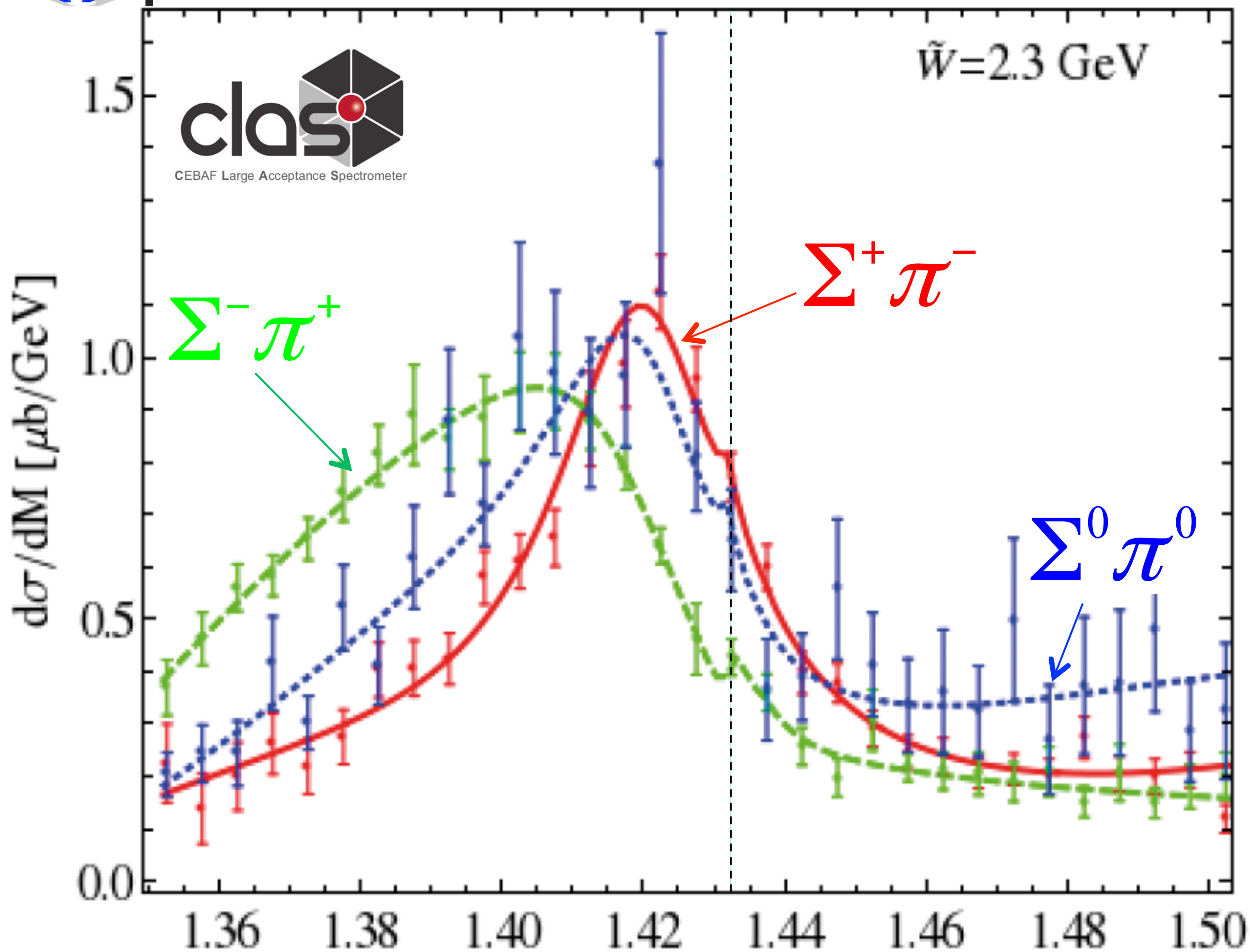
1. R. Bradford et al. (CLAS) Phys. Rev. **C 73**, 035202 (2006)
   K. Moriya *et al.* (CLAS), Phys. Rev. C **88**, 045201 (2013).

Dynamical nature of the Λ(1405)



K. Moriya *et al.* (CLAS), Phys. Rev. C **87**, 035206 (2013)
R. A. Sch. & K. Moriya, Nucl. Phys A **914**, 51 (2013)

Dynamical nature of the Λ(1405)



- Example: Mai & Meissner approach:
- Chiral unitary MB model for: $\bar{K}$N scattering + SIDDHARTA kaonic atom data + CLAS photo-production results at NLO
- Confirms the 2-pole nature of Λ(1405)
- Pole positions:

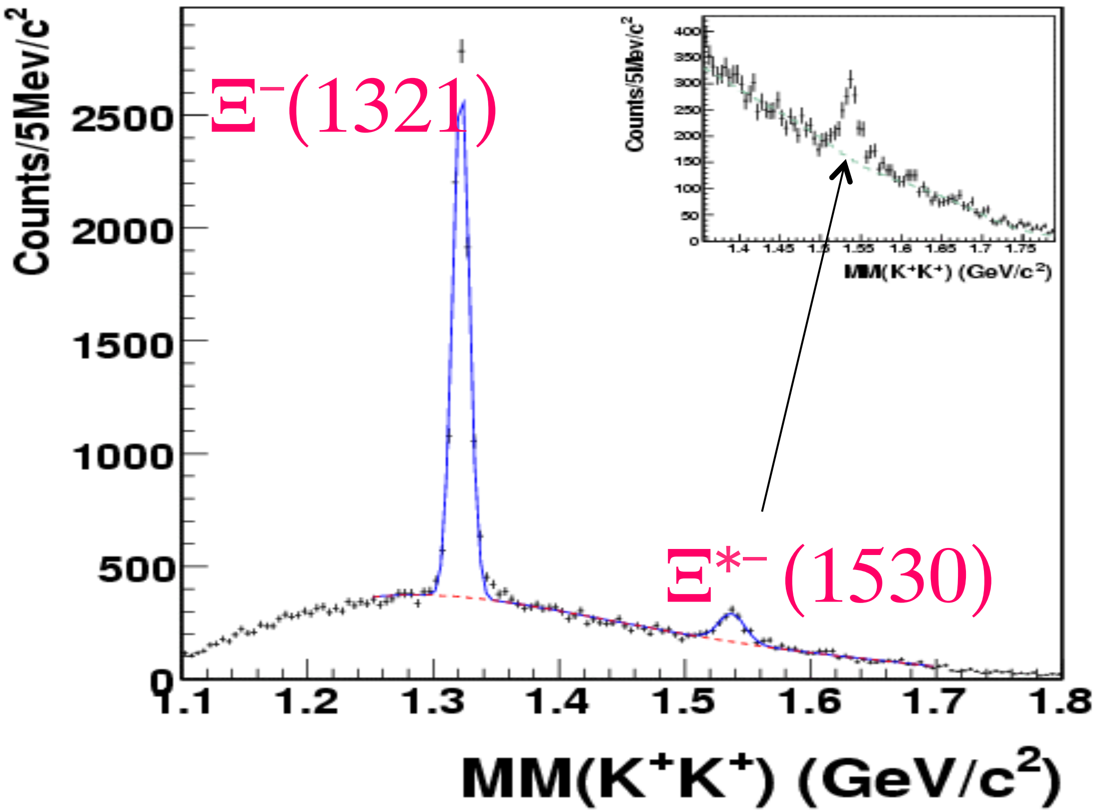
Solution	Pole 1	Pole 2
#2	$1434^{+2}_{-2} - i\,10^{+2}_{-1}$	$1330^{+4}_{-5} - i\,56^{+17}_{-11}$
#4	$1429^{+8}_{-7} - i\,12^{+2}_{-3}$	$1325^{+15}_{-15} - i\,90^{+12}_{-18}$

Below KN threshold, narrow

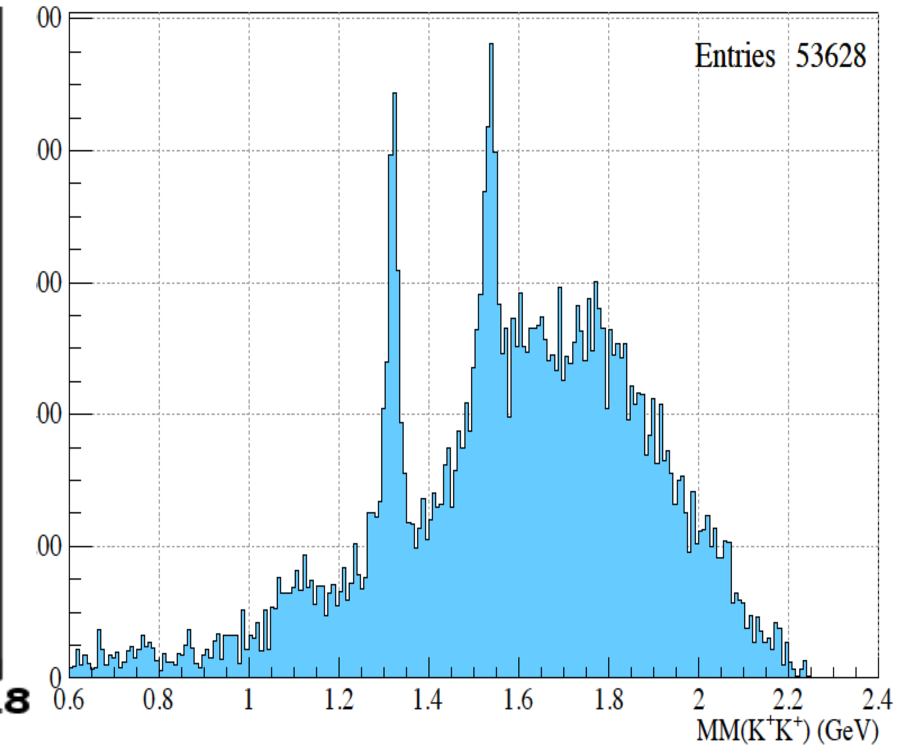
At Σπ threshold, broad

M. Mai and U. Meissner, EPJA 51, 30 (2015),
See also: L. Roca and E. Oset, Phys Rev C 87, 055201 (2013),
S. X. Nakamura & D. Jido, PTEP 023D01 (2014).
Data: K. Moriya *et al.* (CLAS), Phys. Rev. C **87**, 035206 (2013).

S=−2 Hyperons: $\Xi^{-(*)}$ States Missing

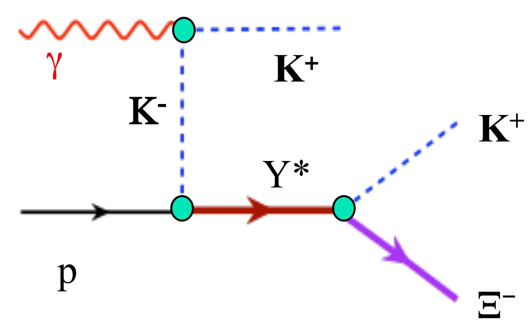


L. Guo et.al. Phys Rev C **76** 025208 (2007)



J. Goetz thesis (2010); CLAS g12 data set

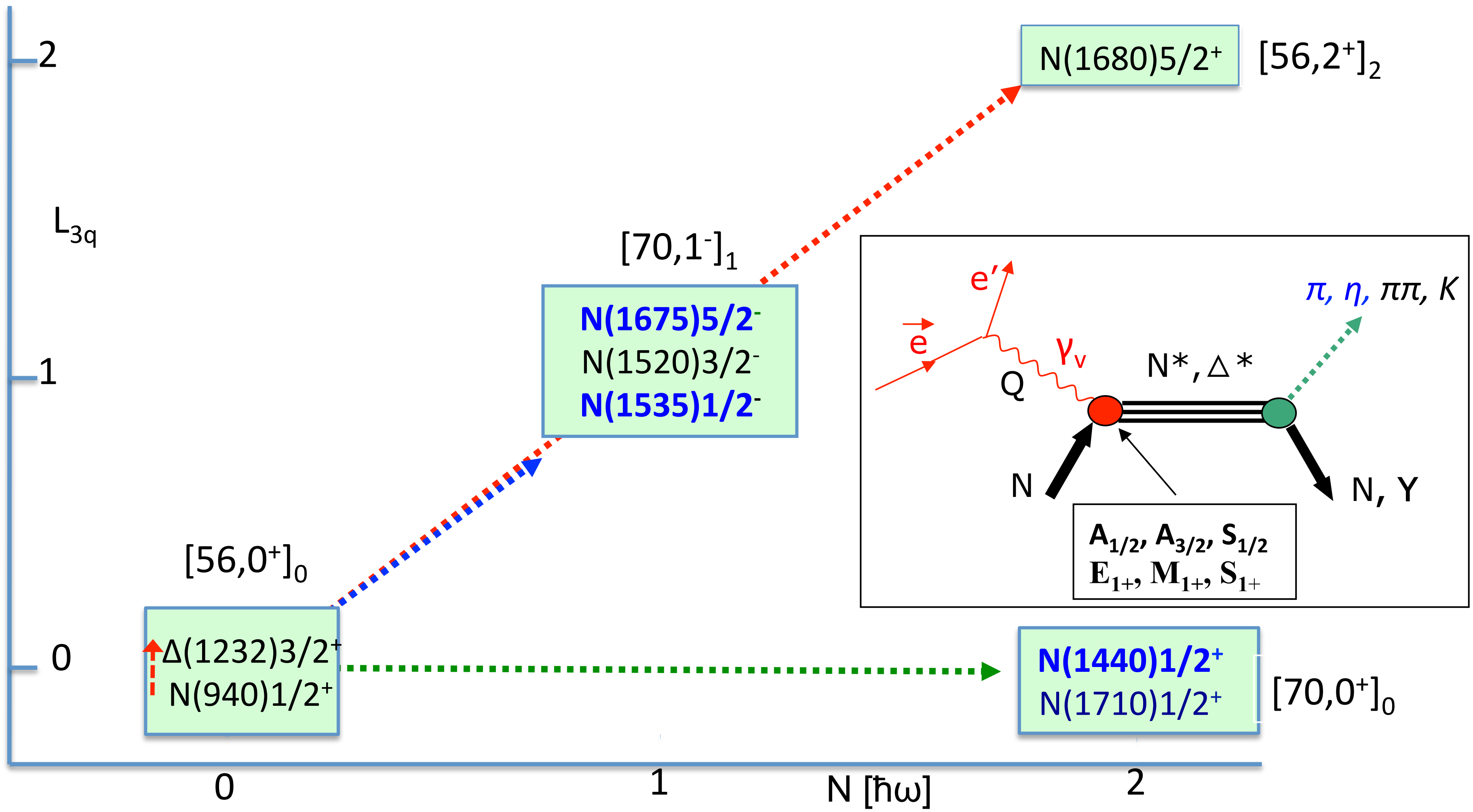
- Detect via $\gamma\, p \longrightarrow K^+K^+(\Xi^-)$
- Only two narrow states seen: $\Xi^-(1321)$, $\Xi^-(1530)$
- Other states? Failed searches (CLAS g12 group w/ 5 GeV beam)



Electroexcitation of N/Δ resonances

Central question in hadron physics

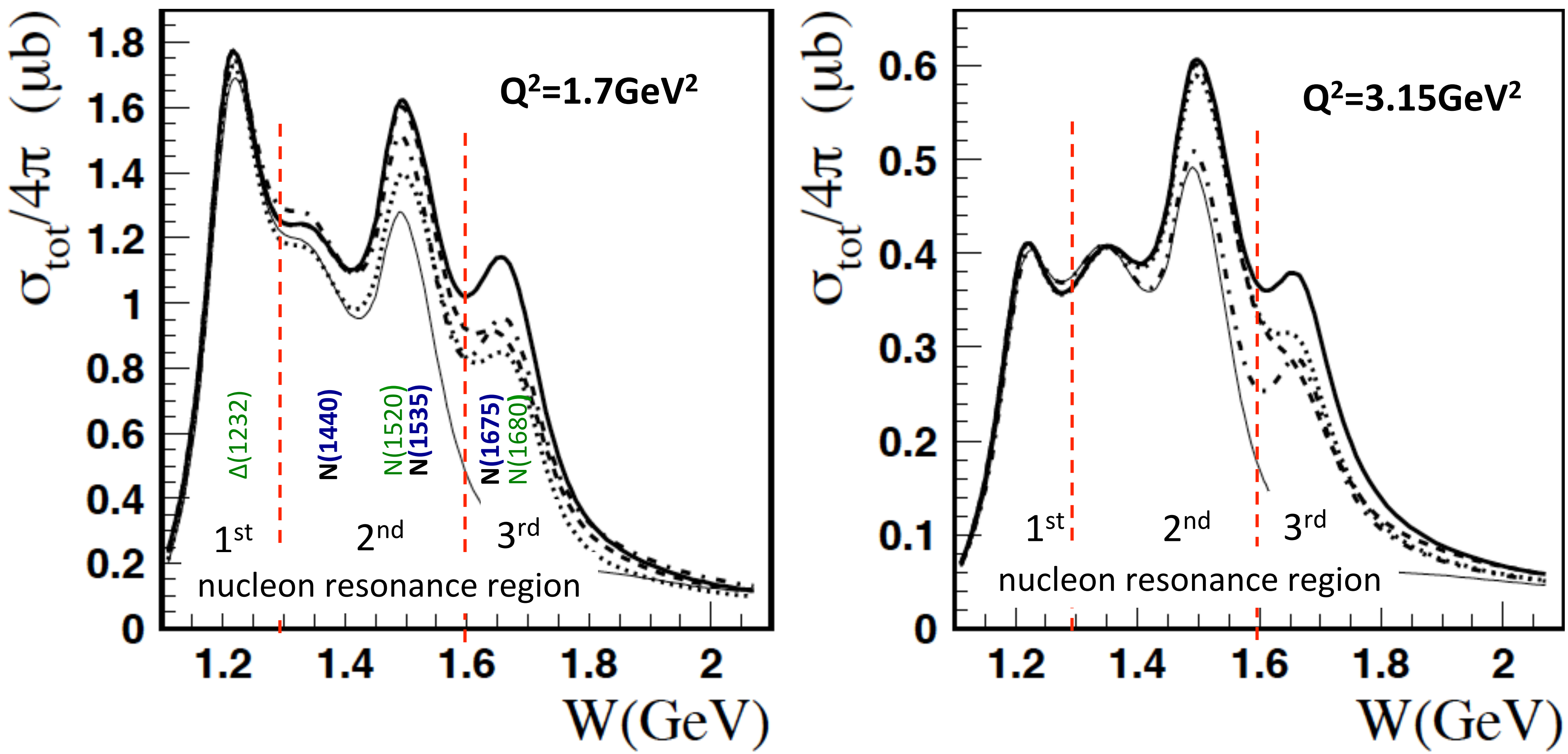
What are the effective degrees of freedom at varying distance scale?



Total cross section at W < 2.1 GeV

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

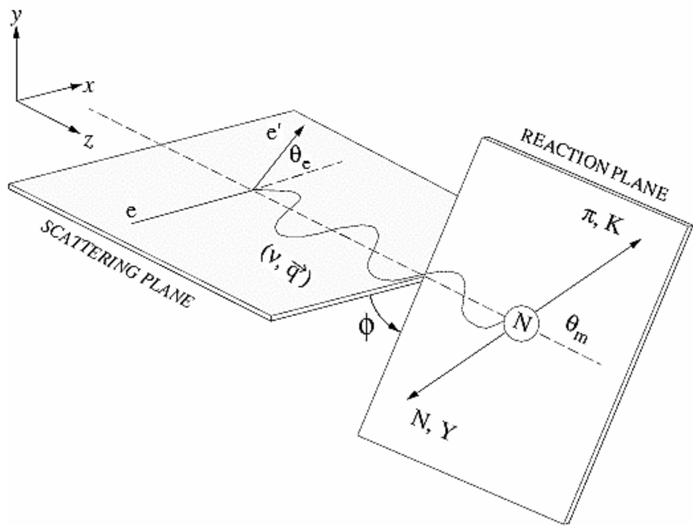
Data: *K. Park et al., PR C77 (2008) 015208; K. Park et al. PR C91 (2015) 045203*



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

Electroexcitation Kinematics

For unpolarized target & polarized e⁻ beam:



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

Virtual photon flux

Electroproduction cross section

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

Transverse

Transverse-transverse interference

Helicity structure

σ_u "Unseparated"

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

Transverse-longitudinal interference

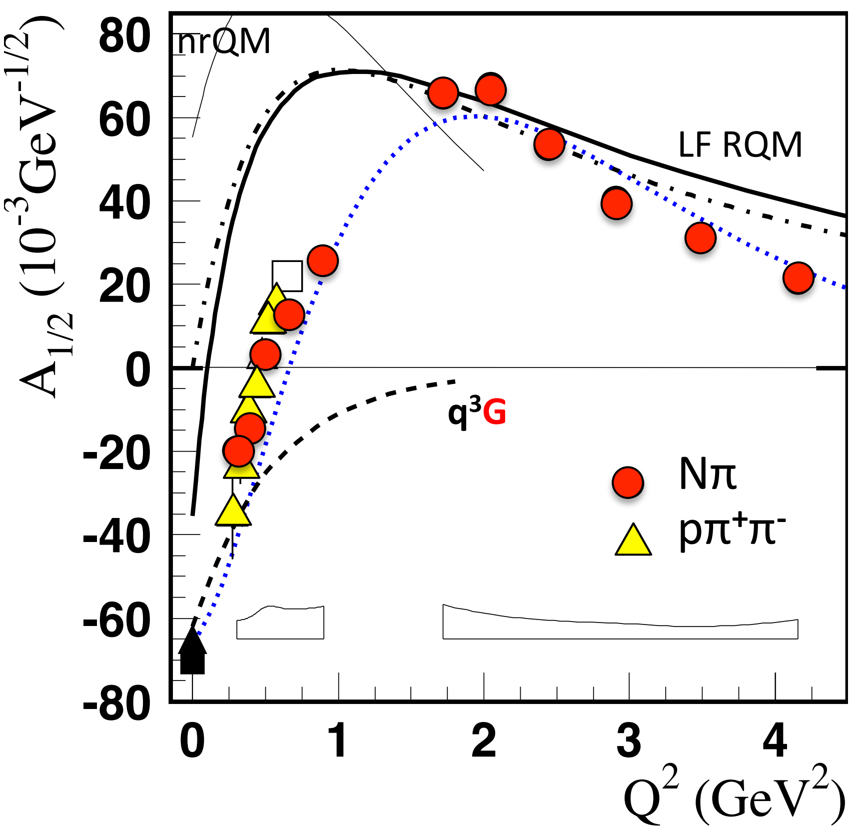
Measured σ's are decomposed using UIM or fixed-t DR to extract N* & Δ helicity couplings

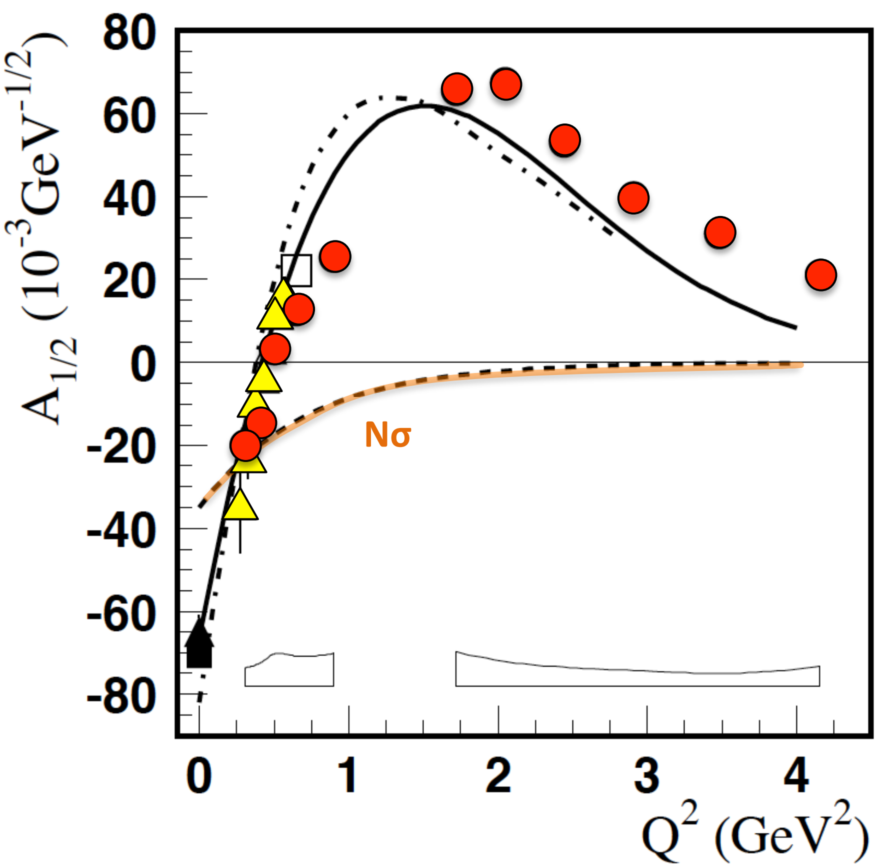
Electrocouplings of 'Roper' in 2012

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

N(1440)1/2$^+$

CEBAF Large Acceptance Spectrometer





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).

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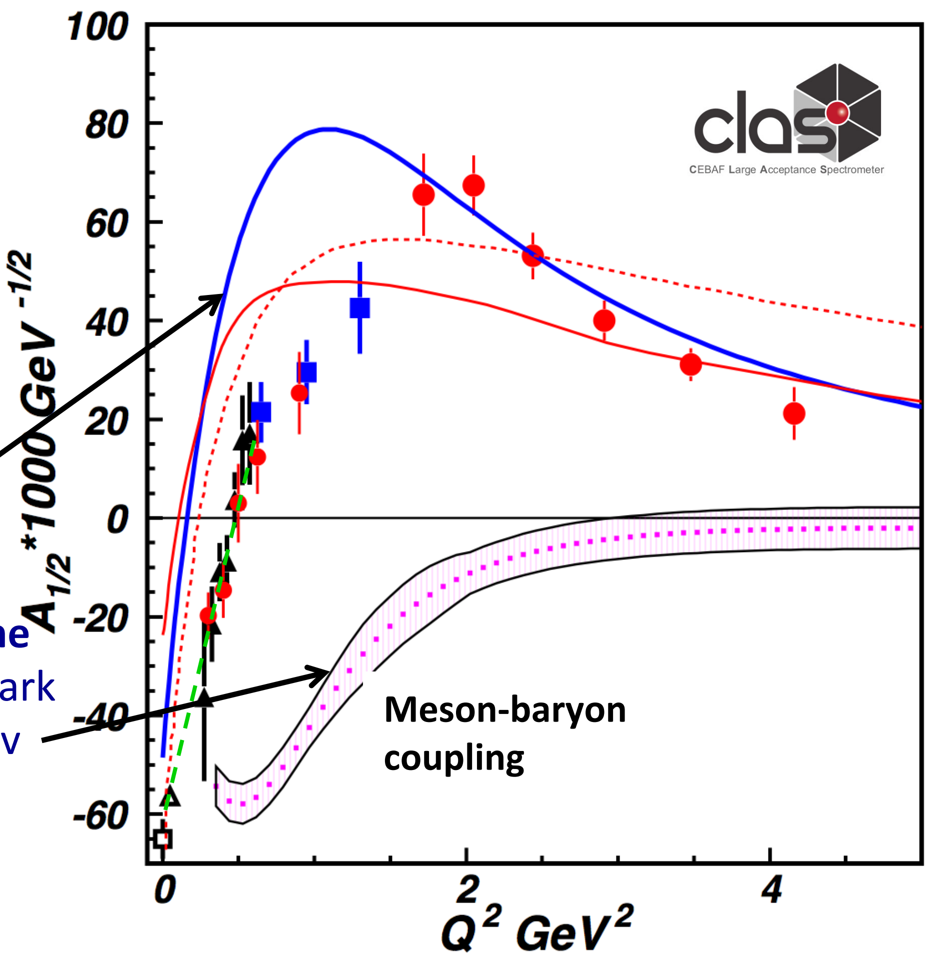
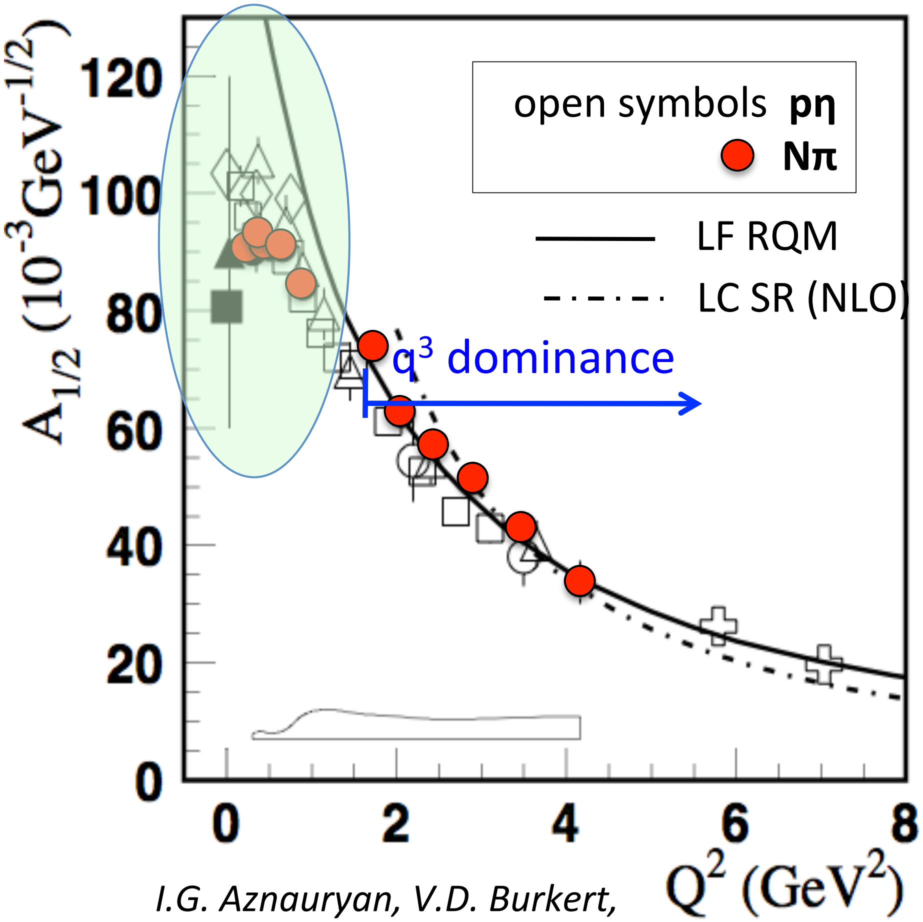


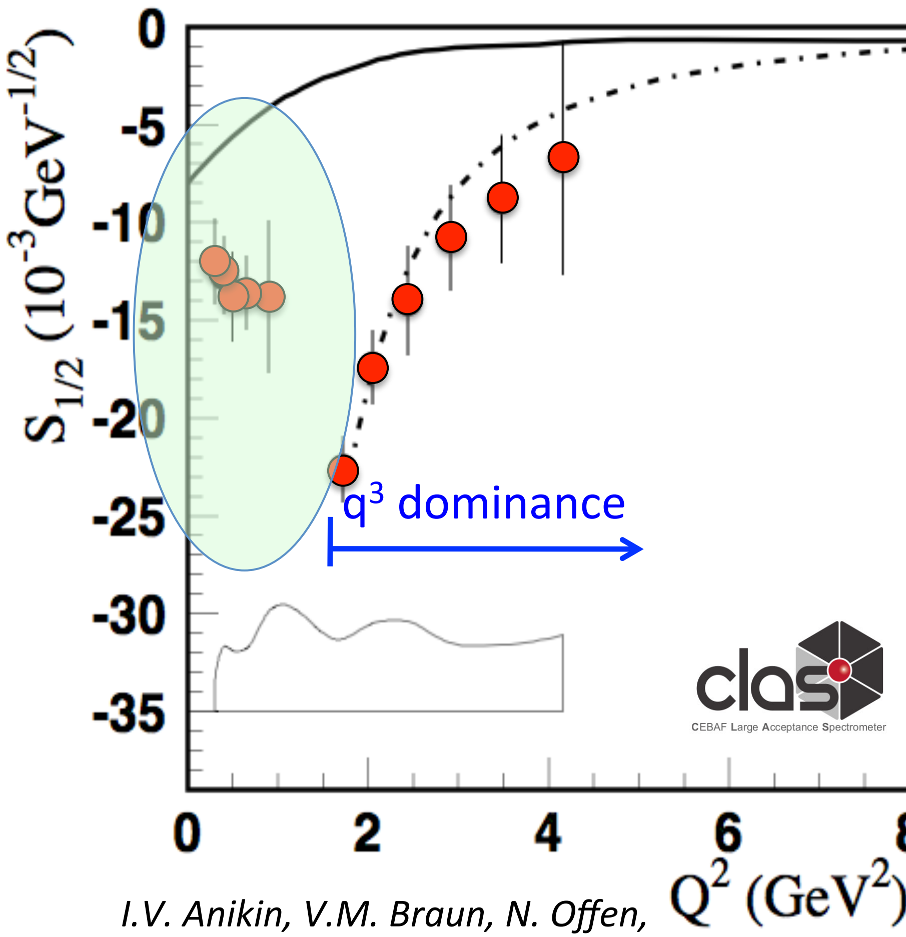
The structure of the Roper is driven by the interplay of the core of three dressed quarks in the 1st radial excitation and the external meson-baryon cloud.

Electrocouplings of γ_v p 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

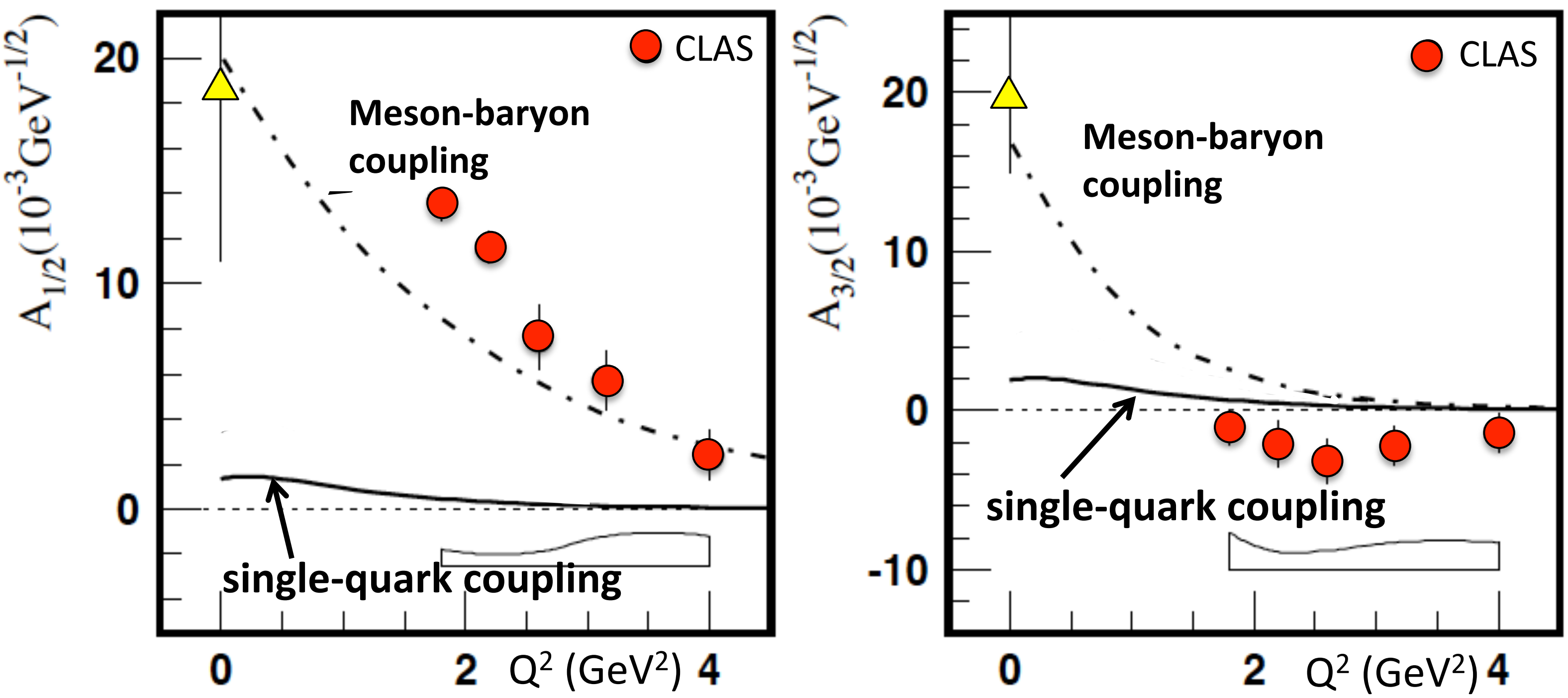
- Meson Baryon (MB) contributions may account for discrepancies at low Q^2.
- MB contributions from chiral unitary model analyses due to KΛ and pϕ components.

MB Cloud Contribution to γ_v p 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:
$A^p_{1/2} = A^p_{3/2} = 0$

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 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)*

Baryon Spectroscopy Status Today

- 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 models are ruled out.
- High-mass N* and Y* states remain elusive experimentally, and some states are interesting composite objects ($\Lambda(1405)$)
- 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 amplitudes of prominent low mass states, e.g. N(1440) $1/2^+$ and N(1535) $1/2^-$ well described at $Q^2 > 2$-3GeV by QCD modeling in DSE/QCD, LC SR and LF RQM.
- In the JLab 12 GeV era, CLAS12 can further push the limits of unraveling the internal structure of the N* states. (cf. R. Gothe, Pl. 1)

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- BACKUP SLIDES

N* Transition FF Physics @ JLAB12