
# Review of light baryon spectroscopy

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

UNIVERSITY OF CONNECTICUT 1881

Stefan Diehl

*Justus Liebig University Giessen*

*University of Connecticut*

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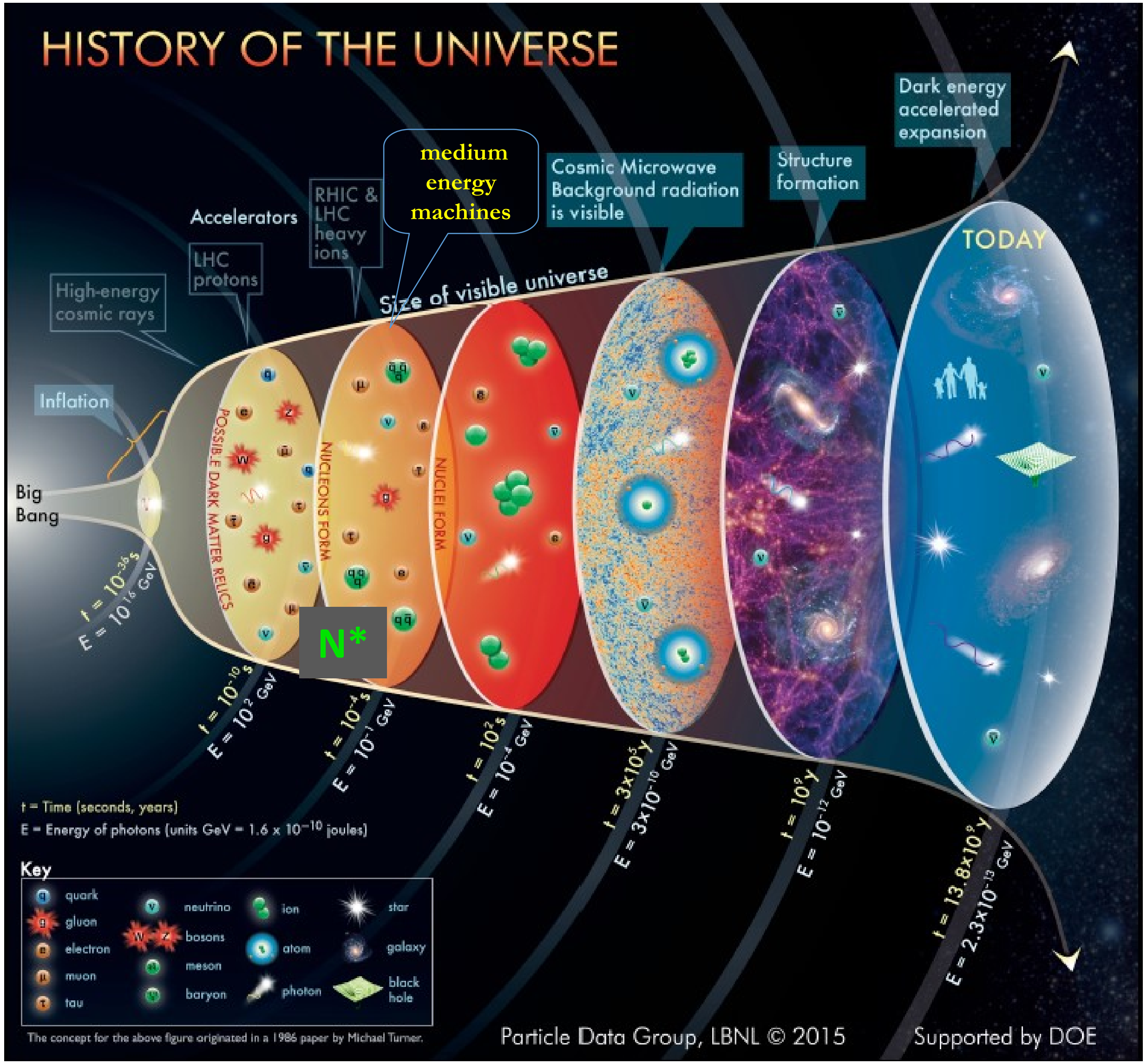
# Evolution of the Universe




## Time after the Big Bang

**T ~ $10^{-8}$ s: QGP**

**T ~ $10^{-6}$ s: N*, B***

- → confinement emerges
- → light quarks acquire mass
- → chiral symmetry is broken

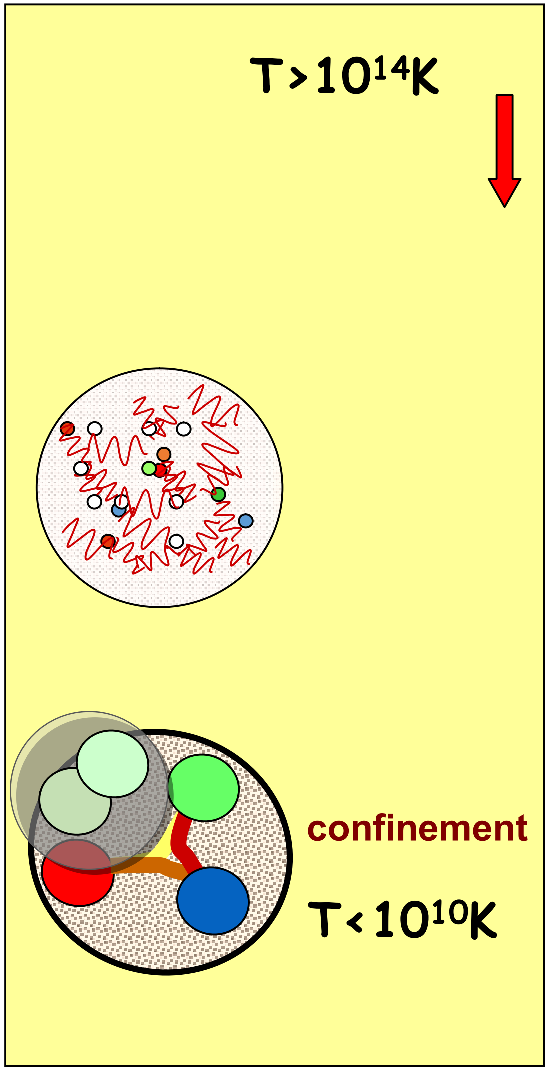
**T ~ $10^{-4}$ s: Nucleons**

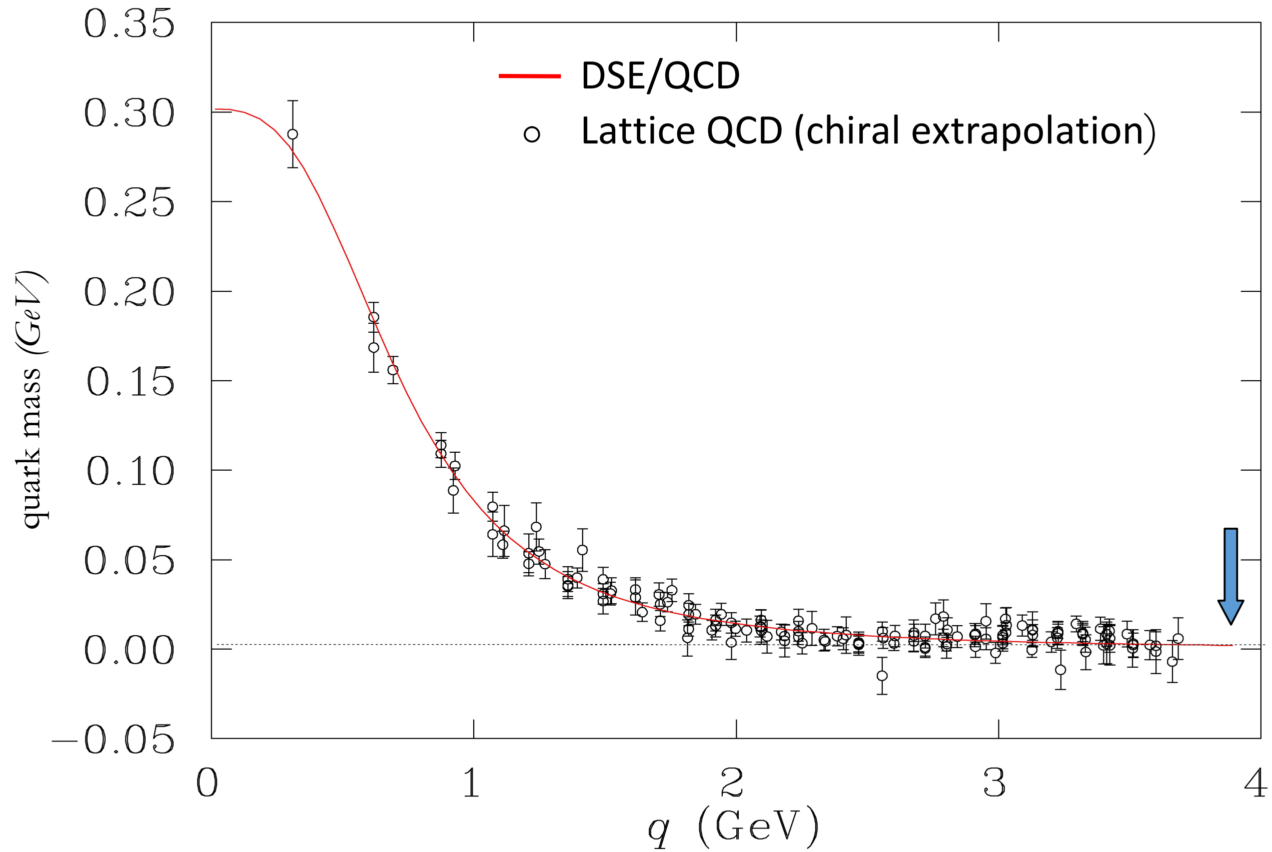
- → only protons and neutrons remain

**T ~ : $10^{2}$ s: Nuclei**

**T ~ 300,000 yrs: Atoms**

# How do light quarks aquire mass?

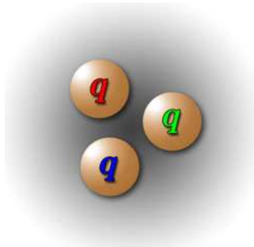



As the temperature drops, quarks couple to gluons, become massive and form resonances with other quarks before freezing out as stable nucleons.

**=> Measure observables that are sensitive to the quark mass.**

# QCD and Confinement – Open Questions

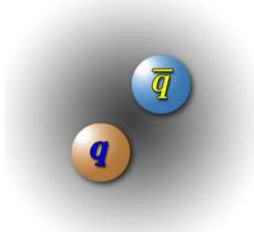



What is the origin of confinement?

How are confinement and chiral symmetry breaking connected?

How does QCD give rise to hadrons?

Interaction between quarks unknown throughout > 98 % of a hadron's volume



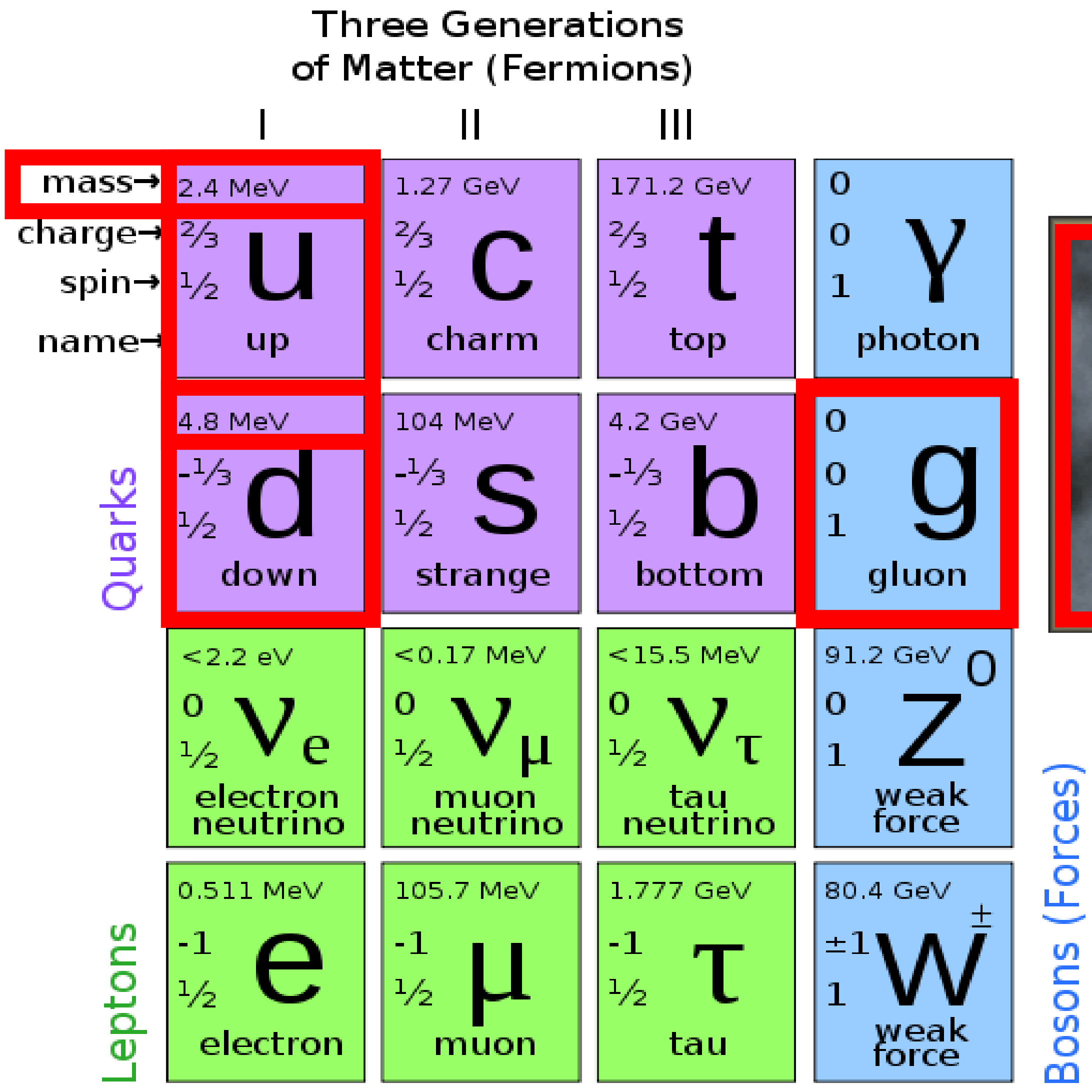

Baryons in PDG insufficient to explain transition
=> missing states!

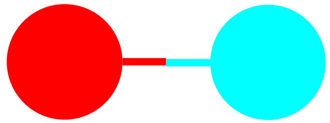
Explaining the excitation spectrum of hadrons is the key to our understanding of QCD in the low-energy regime (Hadron Models, Lattice QCD, ...)

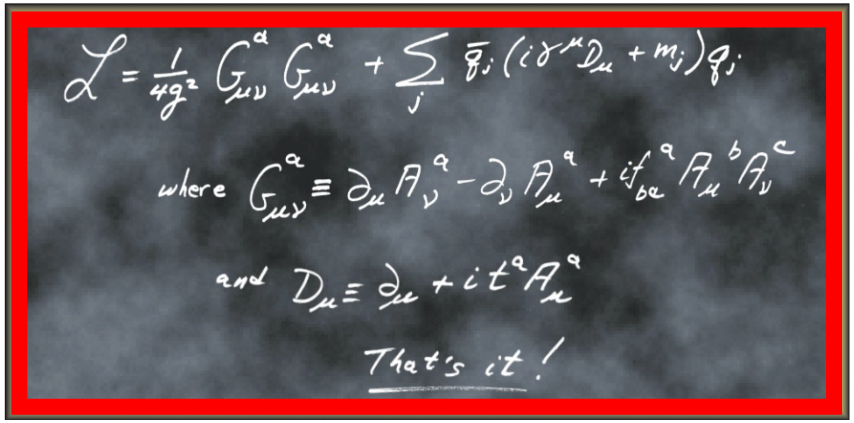
➜ Complementary to Deep Inelastic Scattering (DIS) where information on collective degrees of freedom is lost

With a few GeV electron machine, explore events to unravel mechanisms of confinement

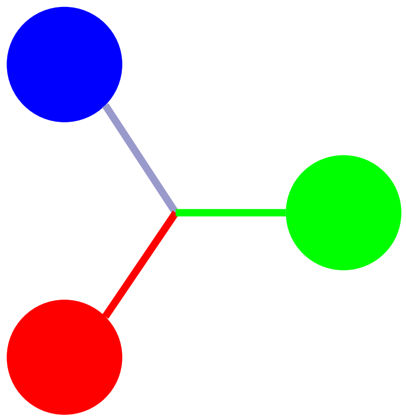
# Build your Mesons and Baryons …



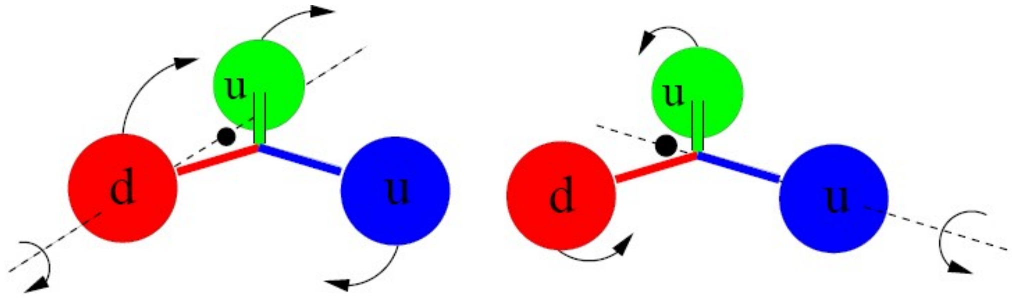



Frank Wilczek, Physics Today, August 2000

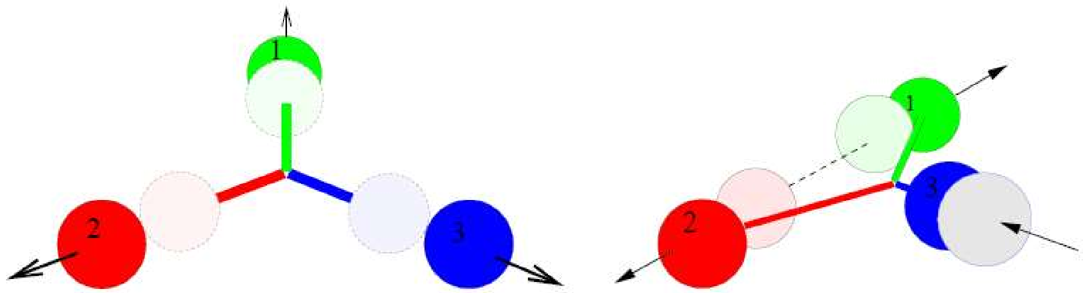


# N and Δ Excited Baryon States …

- Orbital excitations (two distinct kinds in contrast to mesons)



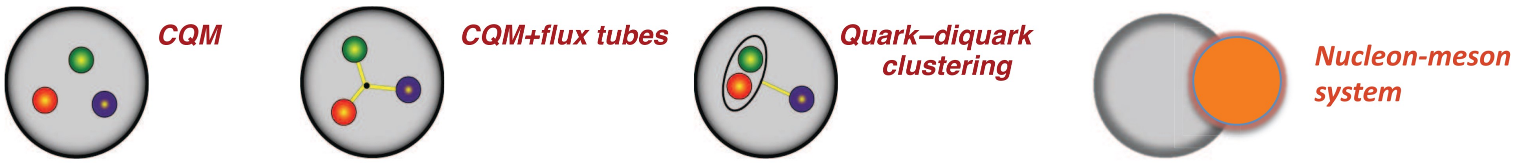

- Radial excitations (also two kinds in contrast to mesons)



# Experimental questions related to hadrons

## Baryons

What are the fundamental degrees of freedom inside a proton or a neutron?
How do they change with varying quark masses?




## Mesons

What is the role of glue in a quark-antiquark system and how is this related to the confinement of QCD?

What are the properties of predicted states beyond simple quark-antiquark systems (hybrids, glueballs, multi-quark states, ...)?

# Goals of the N* program

1. Spectroscopy (mainly driven by real photon scattering)

   ➜ Search for previously unobserved or so-called *missing resonances*

   ➜ Measure the N* spectrum more precisely

   ➜ Provides information on the nature of the effective degrees of freedom in strong QCD

2. Structure of excited baryons (mainly driven by electron scattering)

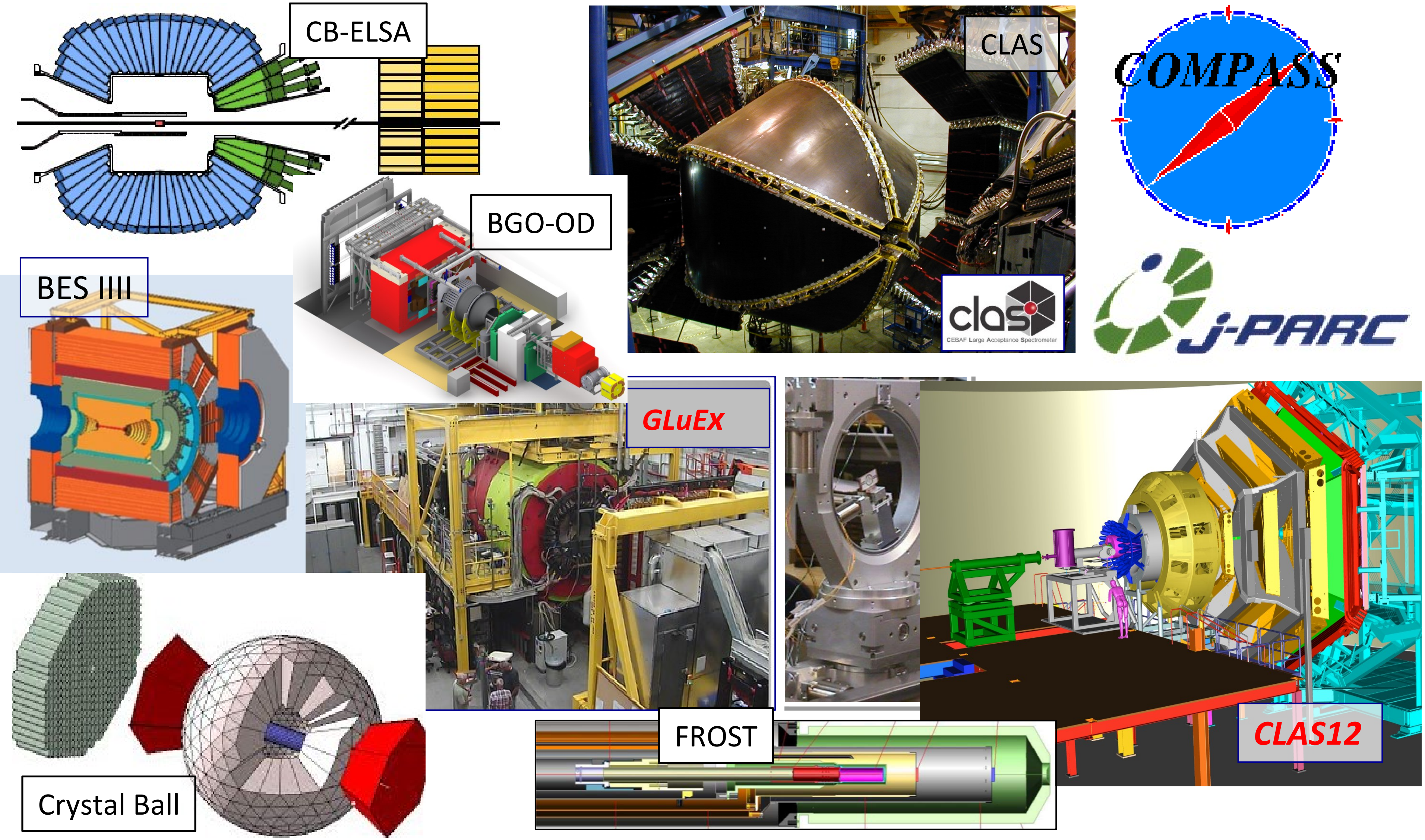
   ➜ Electron beams are ideal to measure resonance form factors and their $Q^2$ dependence

   ➜ Provides information on the confining (effective) forces of the 3-quark system.

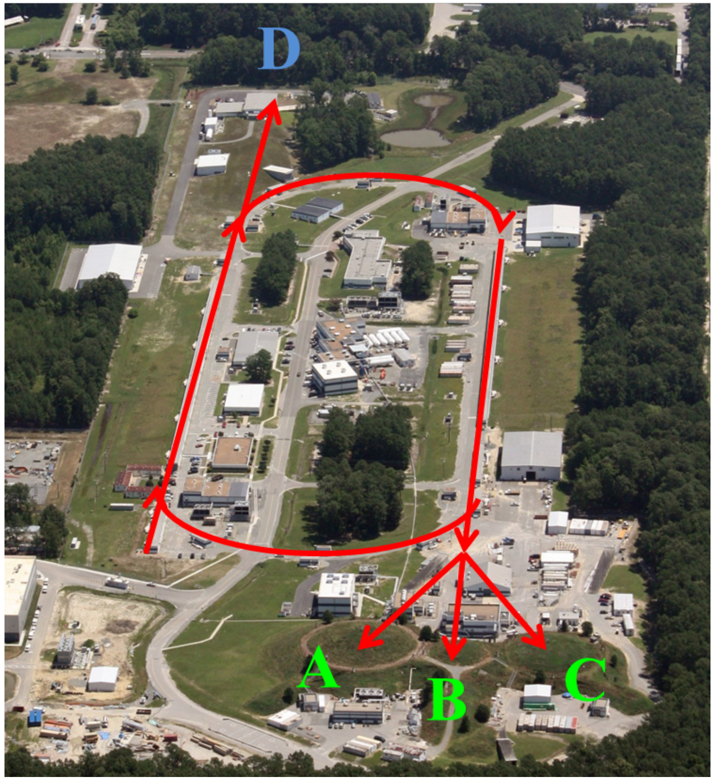
   ➜ Studying underlying symmetries of hadron system

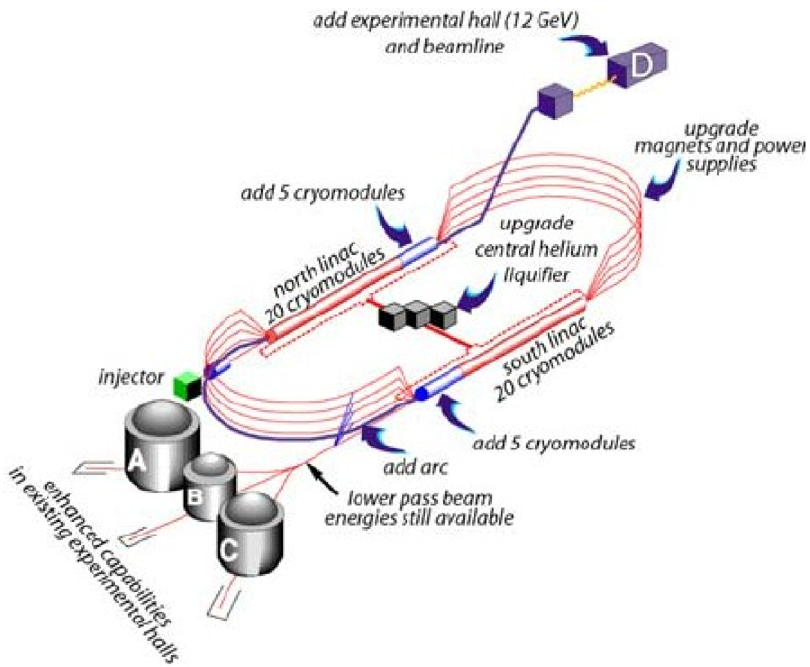
   ➜ Understanding the effective degrees of freedom

# Experiments to explore excited baryons



# Thomas Jefferson National Accelerator Facility (Jefferson Lab)




➡ CEBAF Upgrade completed in September 2017

→ electron beam

→ $E_{max}$ = 12 GeV

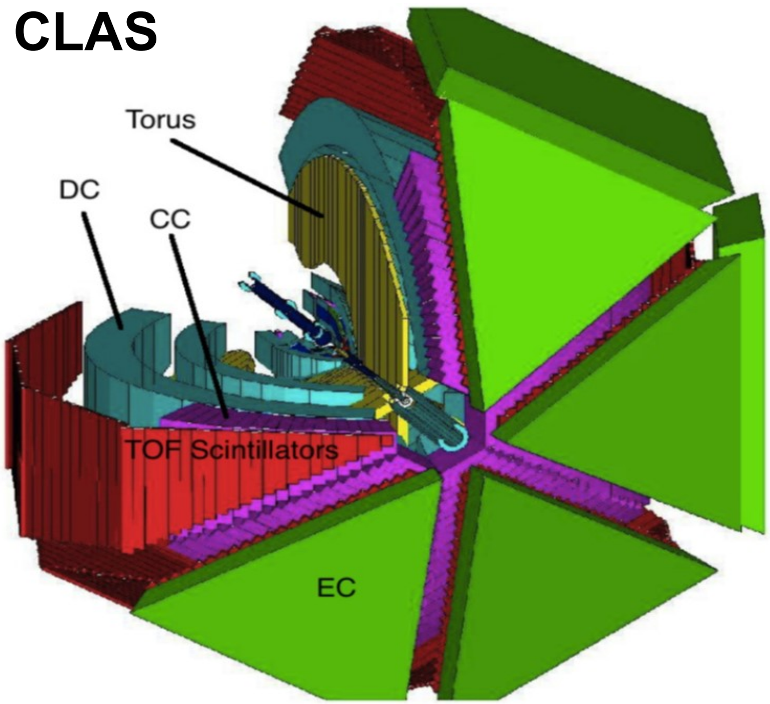
→ $I_{max}$ = 90 μA

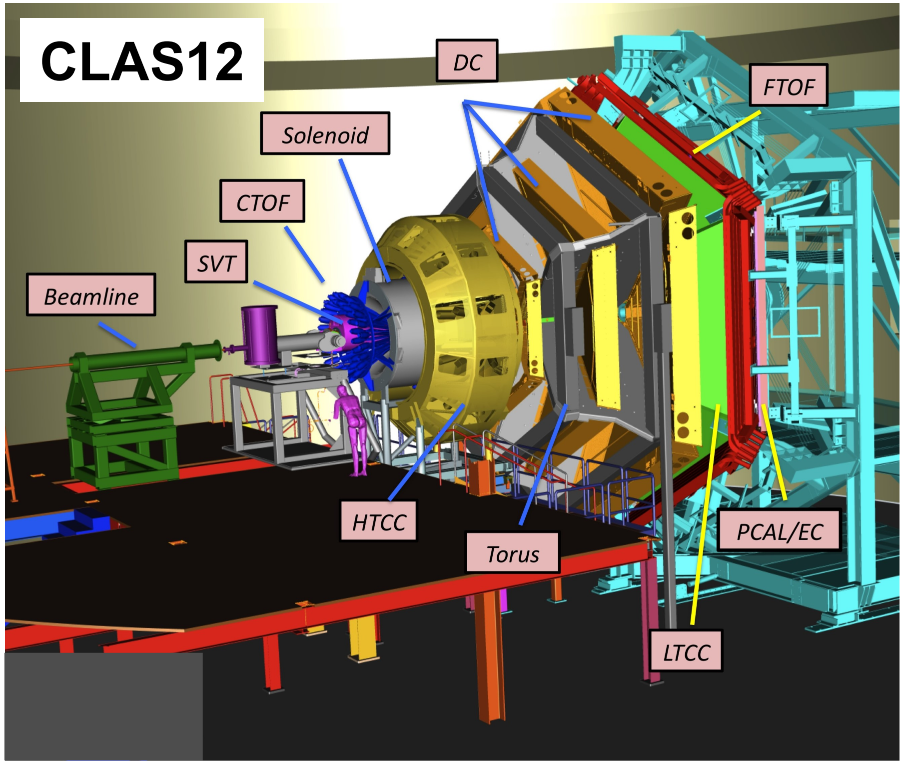
→ $Pol_{max}$ ~ 90%

## Physics Operation

- 4 halls running simultaneously since January 2018
- Highest intensity tagged photon beam at 9 GeV
- World-record polarized electron beams
- Nuclear experiments at ultra-high luminosities, up to $10^{39}$ electrons-nucleons /cm$^2$/s

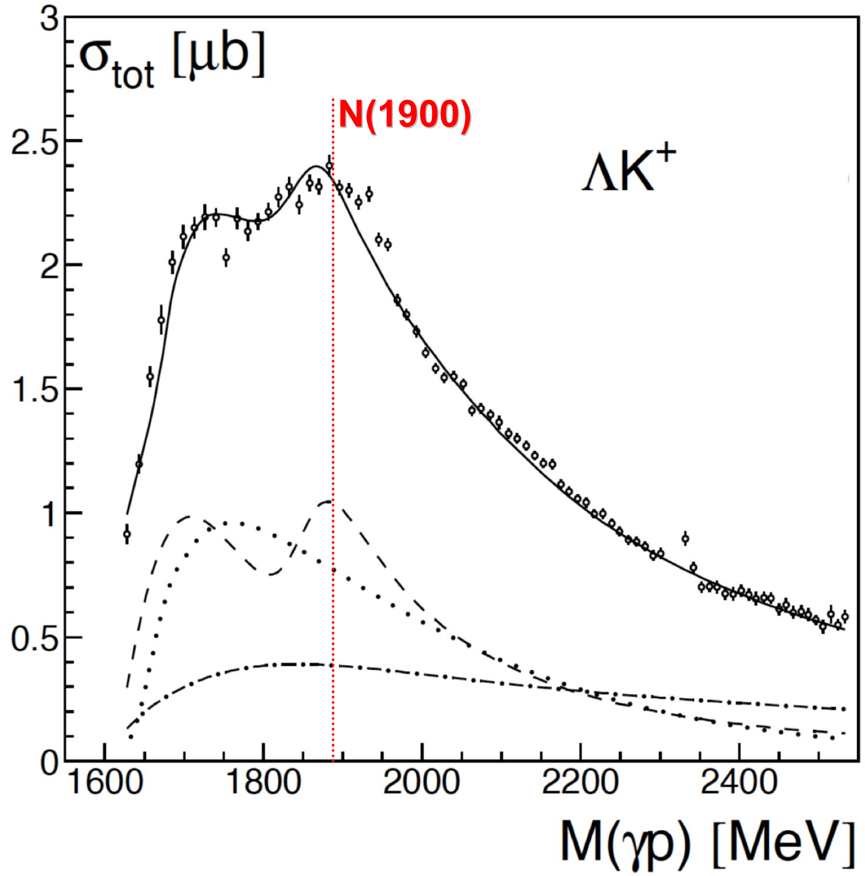
# CLAS / CLAS12 in Hall B at Jefferson Lab




- $\mathcal{L} = 1 \times 10^{35}$ cm$^{-2}$s$^{-1}$
- Inclusive electron trigger (all calibration reactions will be analyzed in parallel)
- Electrons in the forward detector
- Protons in the central detector and forward detector
- Photons in the forward detector and forward tagger

# Establishing the N* spectrum: The N(1900) 3/2+ state




- First baryon resonance observed and fully established with multiple confirmations in electromagnetic meson production.
- 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 $\gamma p \rightarrow K^+\Lambda$.

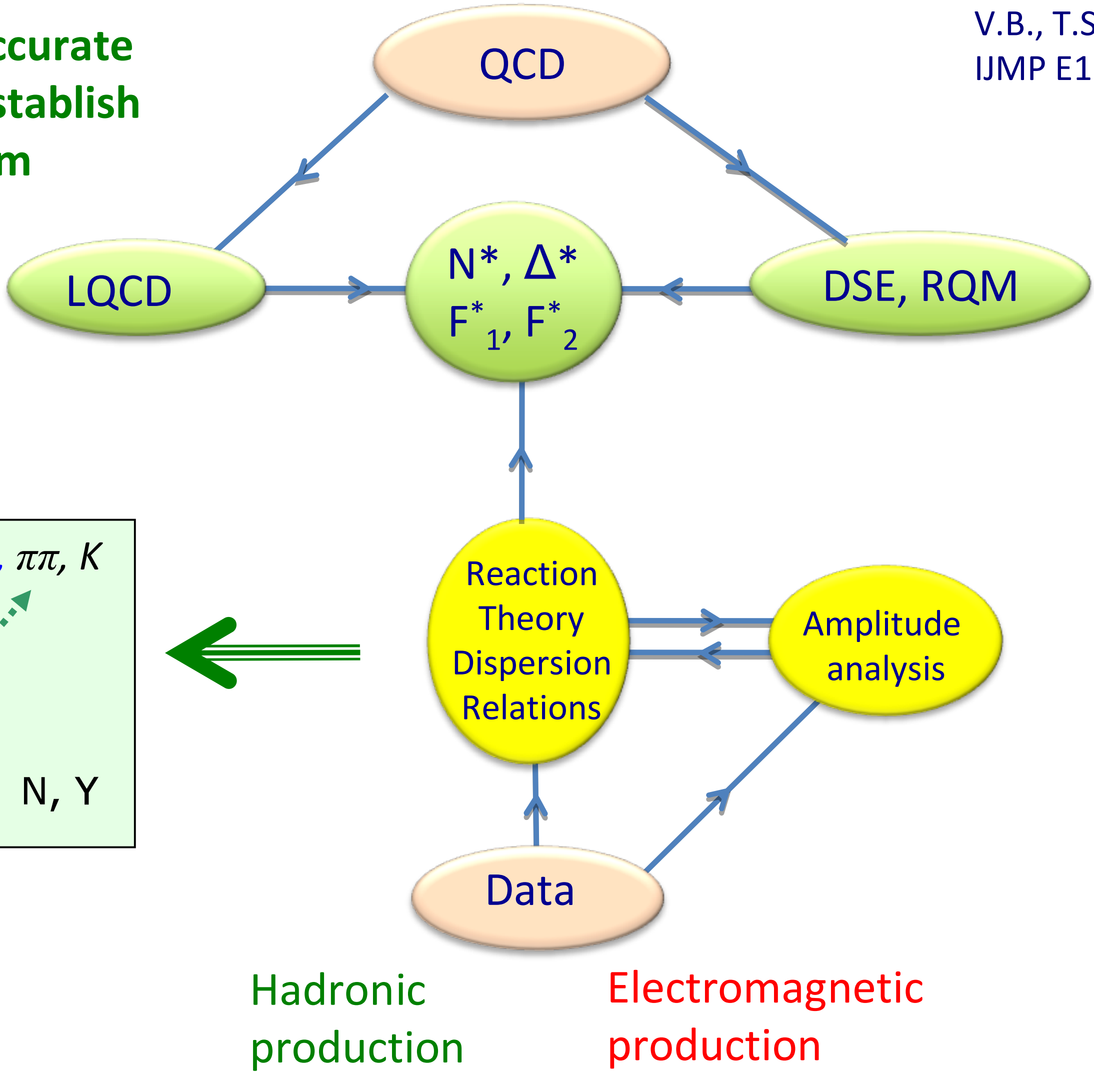
  *T. Mart, M. J. Kholili , PRC86, 022201, 2012*

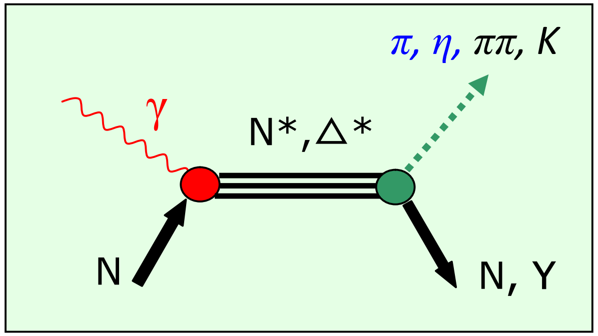
**A more detailed analysis is required!**

# Establishing the N* and Δ* Spectrum

**Precision data require accurate analysis procedures to establish the baryon spectrum**

V.B., T.S.-H. Lee
IJMP E13 (2004)

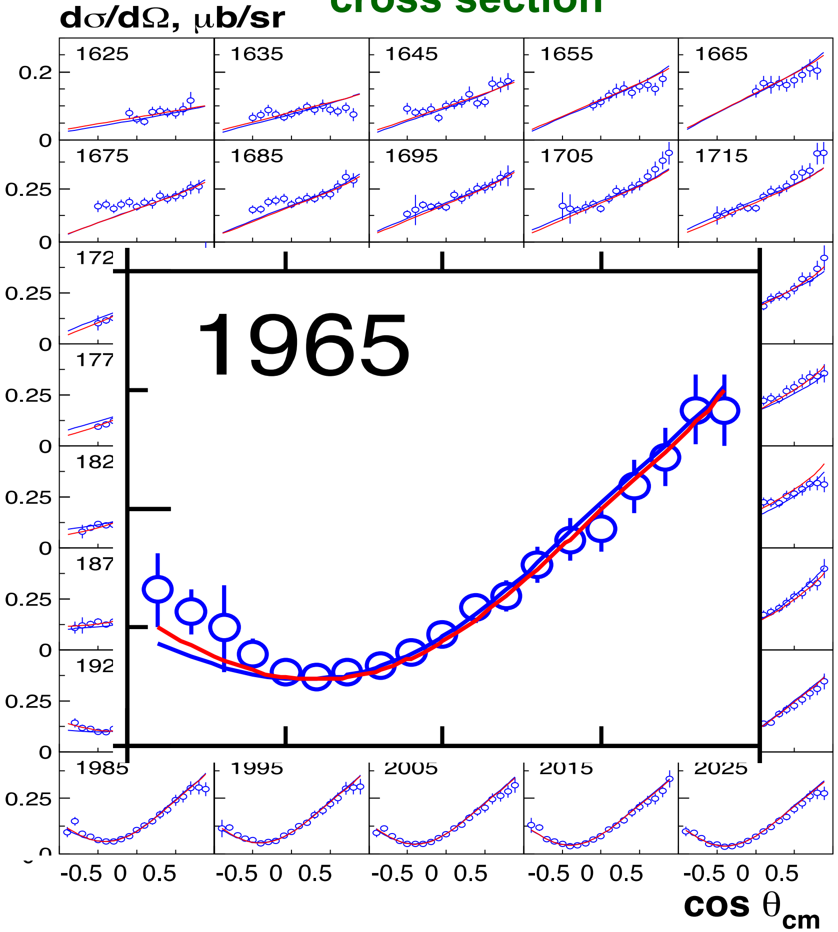


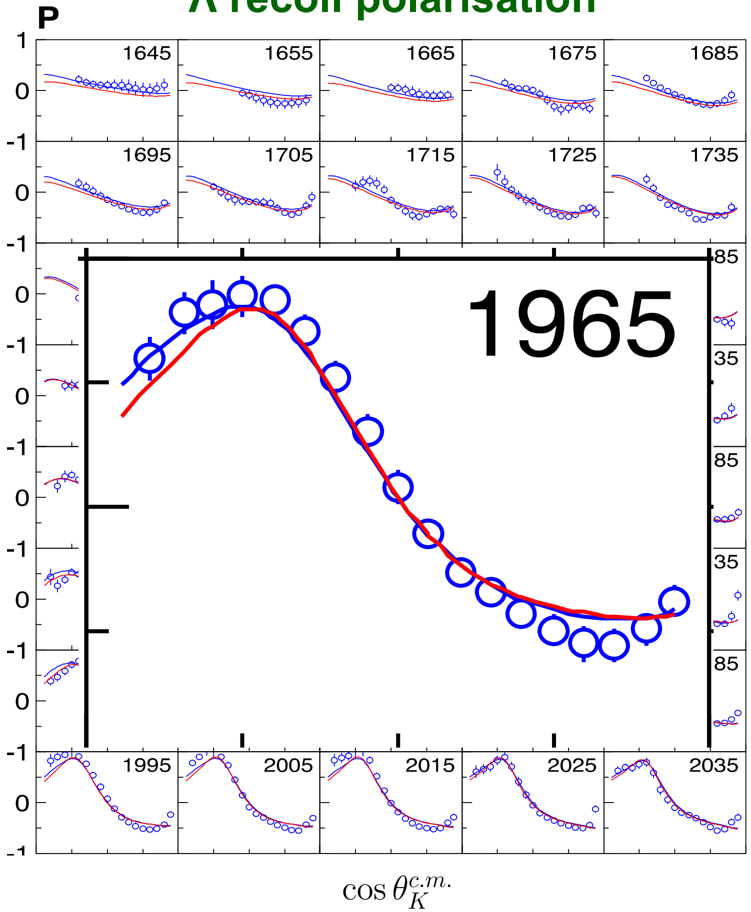
# Establishing the N* spectrum

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

**cross section**




**Λ recoil polarisation**

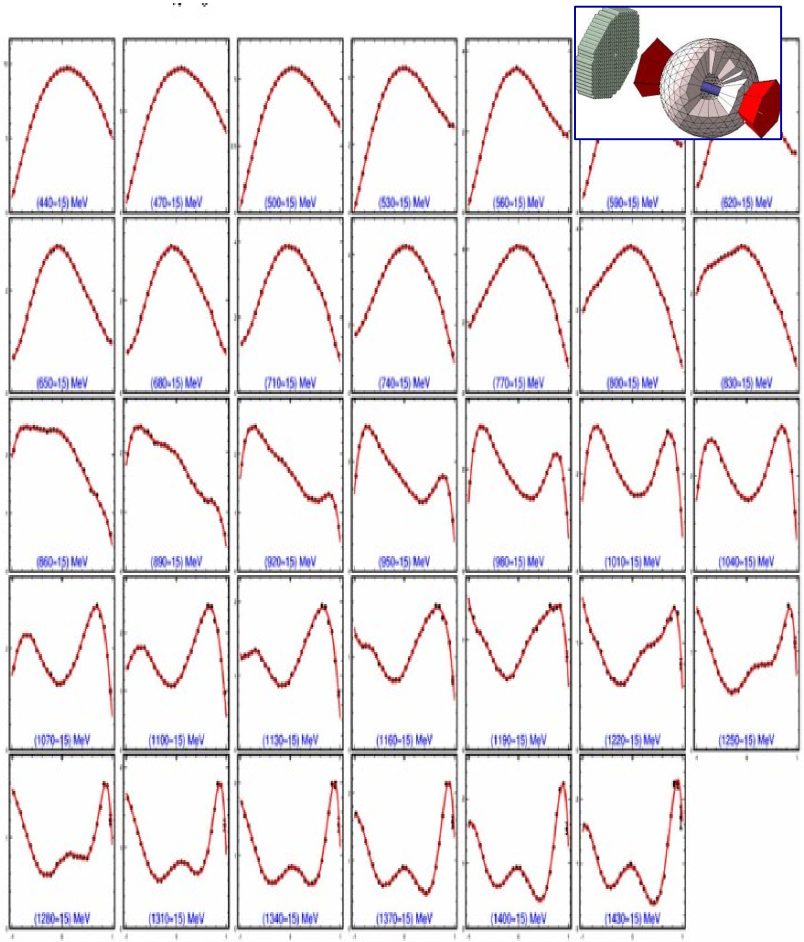



*M. Mc Cracken et al. (CLAS), Phys.RevC81, 025201 (2010)*

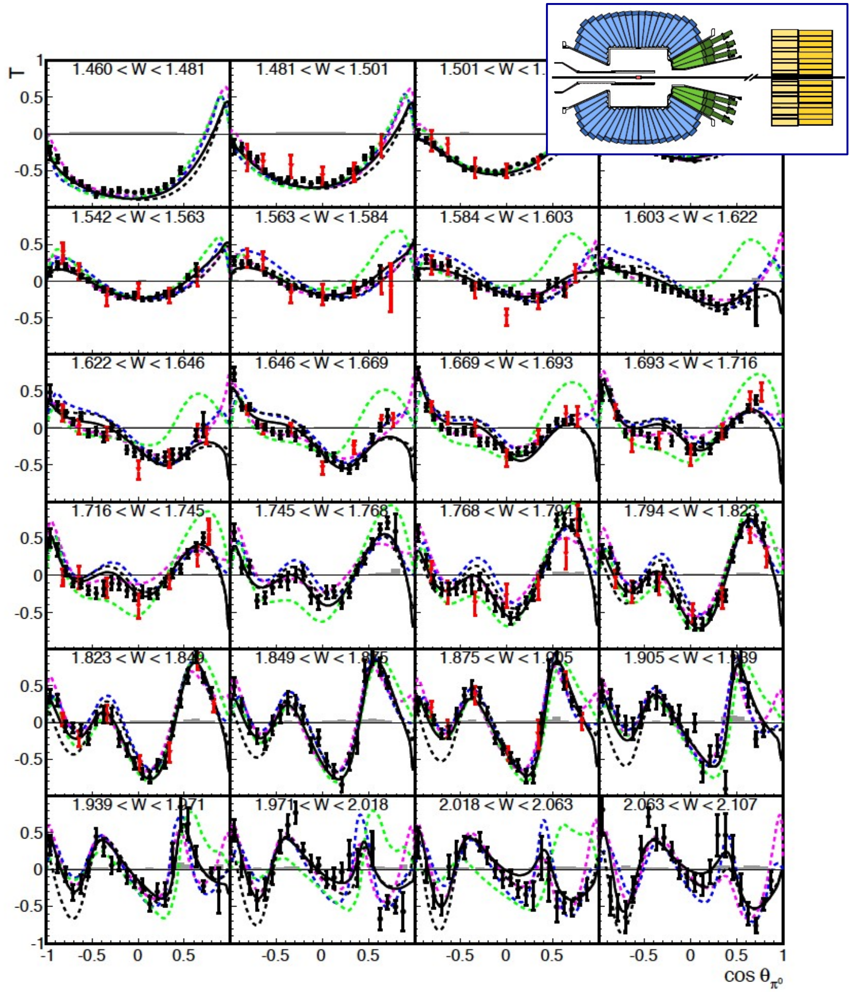
*Fit: A.V. Anisovich et al, EPJ A48, 15 (2012)*

# Example of CB-ELSA and MAMI-CB Data

Differential p$\pi^0$ cross section at MAMI-CB fitted with L = 4 Legendre expansion.



Target Asymmetry in $\pi^0$ production off protons.



# Polarization observables in KΛ/KΣ production

Including additional polarization observables has let
to the discovery of new states?

beam asymmetry → Σ
recoil polarisation → P
pol. transfer from a circ. pol. photon beam to a recoiling Λ → $C_x$, $C_z$
transverse target asymmetry → T
beam recoil double polarisation → $O_x$, $O_z$

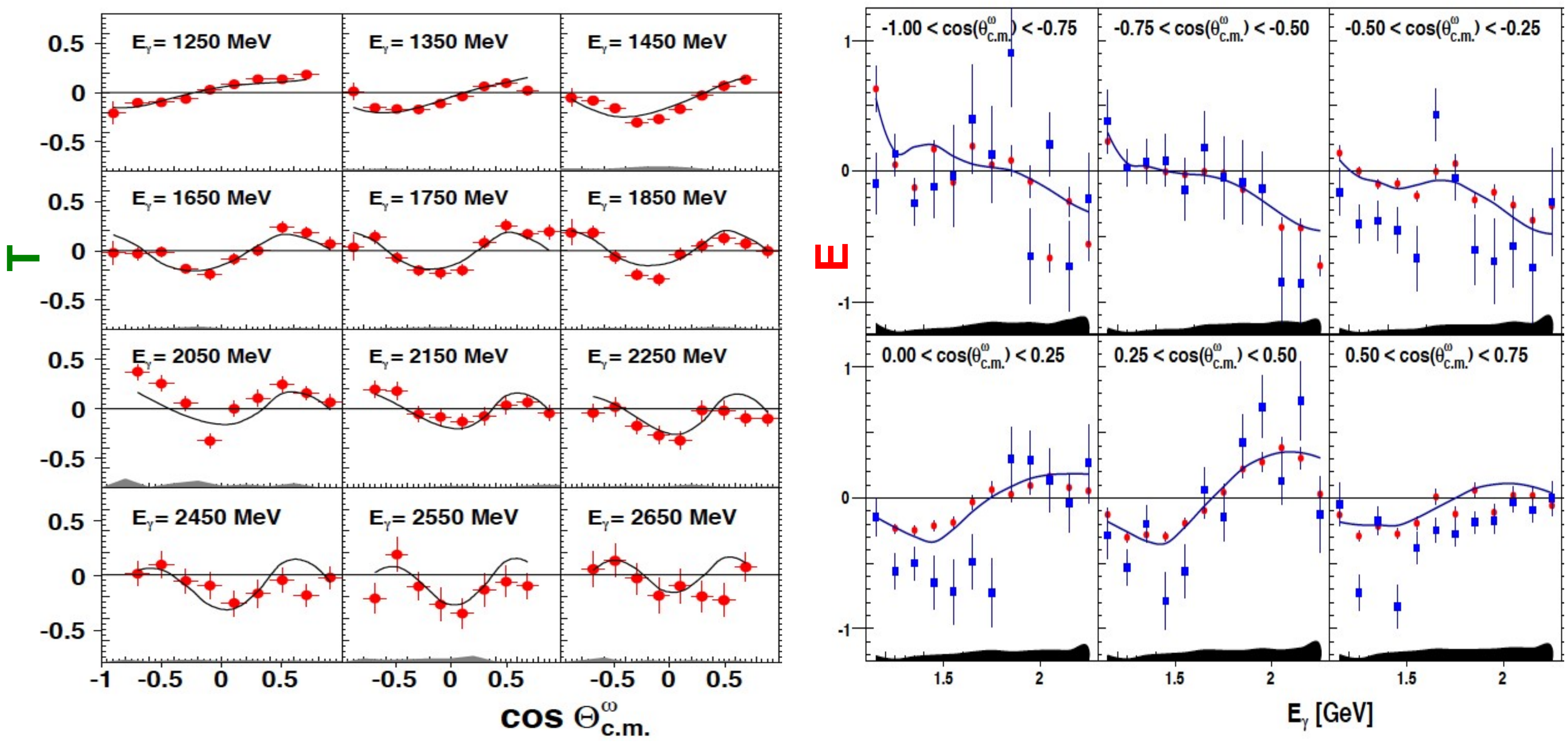
| Experiment | Final State | $W$ range (GeV) | $\Sigma$ | $P$ | $C_x$ | $C_z$ | $T$ | $O_x$ | $O_z$ |
|---|---|---|---|---|---|---|---|---|---|
| CLAS g11 | $K\Lambda$ | 1.62–2.84 | | ⋆ | | | | | |
| | $K\Sigma^0$ | 1.69–2.84 | | ⋆ | | | | | |
| CLAS g1c | $K\Lambda$ | 1.68–2.74 | | ⋆ | ⋆ | ⋆ | | | |
| | $K\Sigma^0$ | 1.79–2.74 | | ⋆ | ⋆ | ⋆ | | | |
| LEPS | $K\Lambda$ | 1.94–2.30 | ⋆ | | | | | | |
| | $K\Sigma^0$ | 1.94–2.30 | ⋆ | | | | | | |
| GRAAL | $K\Lambda$ | 1.64–1.92 | ⋆ | ⋆ | | | ⋆ | ⋆ | ⋆ |
| | $K\Sigma^0$ | 1.74–1.92 | ⋆ | ⋆ | | | | | |
| CLAS g8 | $K\Lambda$ | 1.71–2.19 | ⋆ | ⋆ | | | ⋆ | ⋆ | ⋆ |
| | $K\Sigma^0$ | 1.75–2.19 | ⋆ | ⋆ | | | ⋆ | ⋆ | ⋆ |

# Target T and beam-target E spin asymmetries

$\gamma p \rightarrow p\omega$

transverse target

longitudinal target



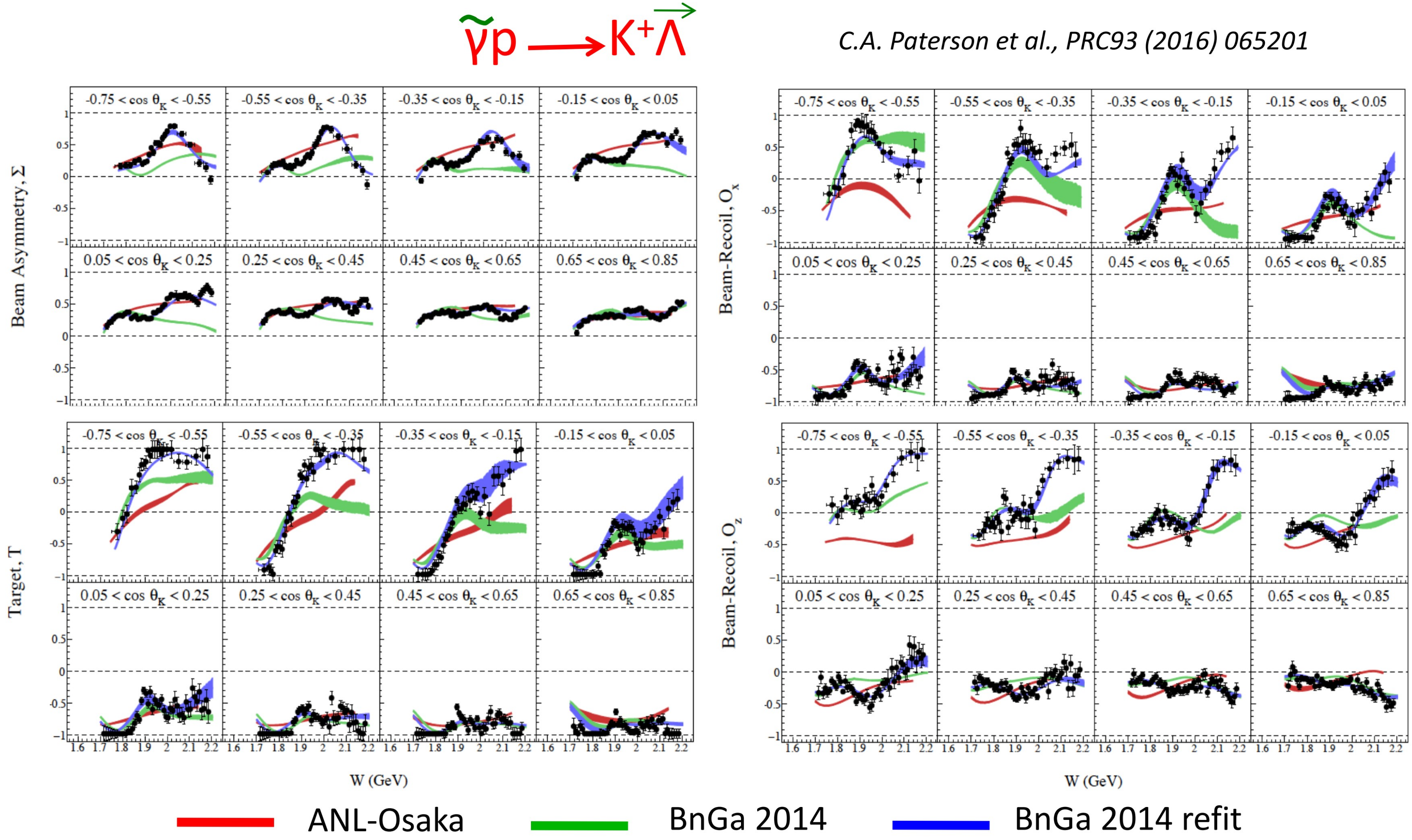

*P. Roy et al. PRC97 (2018) no.5, 055202*

*Fit: Bonn-Gatchina*

# More N*'s from polarized K⁺Λ production?

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

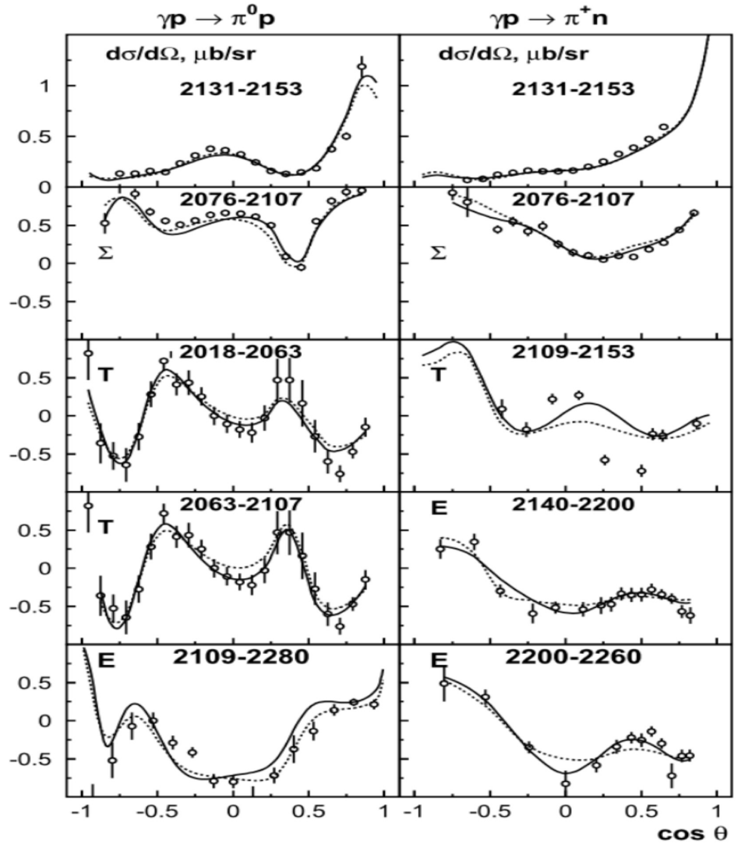
*C.A. Paterson et al., PRC93 (2016) 065201*

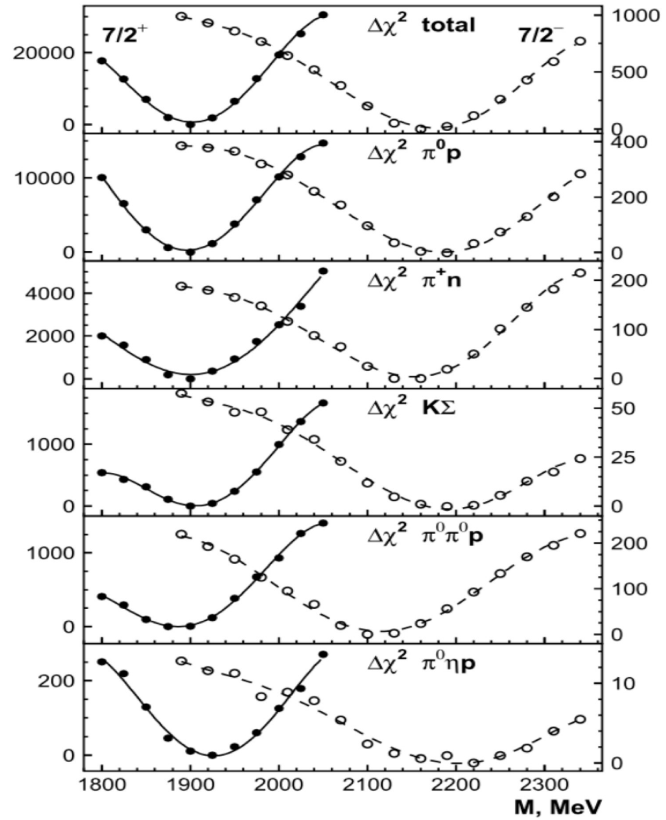


# Search for the Δ(2200)7/2- resonance

*A.V. Anisovich et al., Phys.Lett. B766 (2017) 357-361*

**Use all available pπ$^0$, nπ$^+$ data, σ and single and double polarization data on T, Σ, E**




Analysis verifies the strong 4* Δ(1950) 7/2+ state and finds evidence for Δ(2200) 7/2-

**M = 2176 (40) MeV**
**Γ = 210 (70) MeV**
**BR(Nπ) = 3.5(1.5)%**

# New evidence for excited nucleons

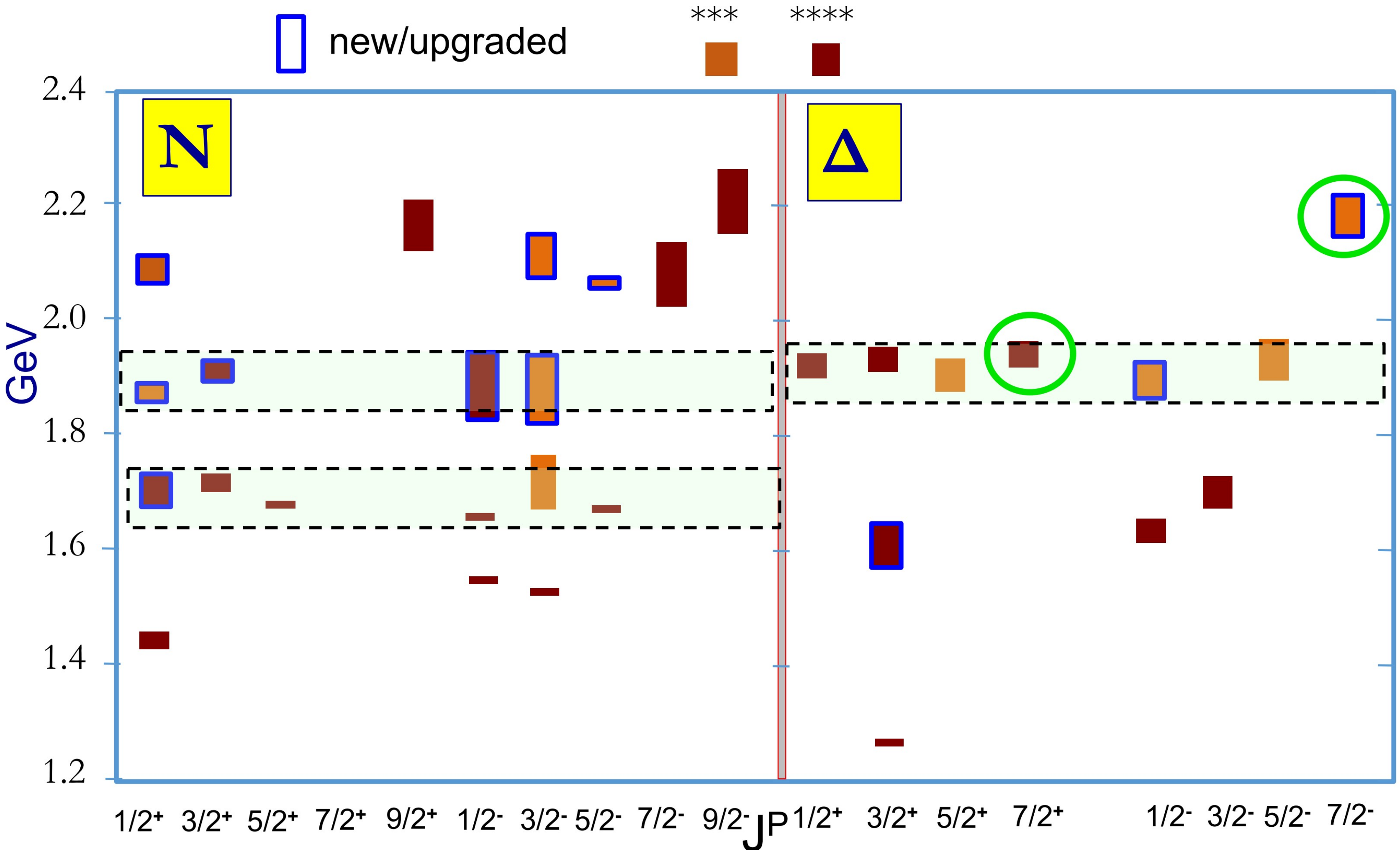
| State N((mass)$J^P$ | PDG pre 2012 | PDG 2018 evidence | Mass (Pole) |
|---|---|---|---|
| N(1710)$1/2^+$ | *** | **** | 1700 |
| N(1880)$1/2^+$ | | *** | 1860 |
| N(2100)$1/2^+$ | * | *** | 2100 |
| N(1895)$1/2^-$ | | **** | 1910 |
| N(1900)$3/2^+$ | ** | **** | 1920 |
| N(1875)$3/2^-$ | | *** | 1900 |
| N(2120)$3/2^-$ | | *** | 2100 |
| N(2060)$5/2^-$ | | *** | 2070 |
| Δ(2200)$7/2^-$ | * | *** | 2150 |

**** - existence is certain
*** - existence is likely
** - evidence of existence is fair
* - evidence of existence is poor

**The most recent photoproduction data led to the discovery of new states and fully established poorly known states up to 2200 MeV.**

*http://pdg.lbl.gov/2019/reviews/rpp2018-rev-n-delta-resonances.pdf*

# The N/Δ spectrum in PDG 2018

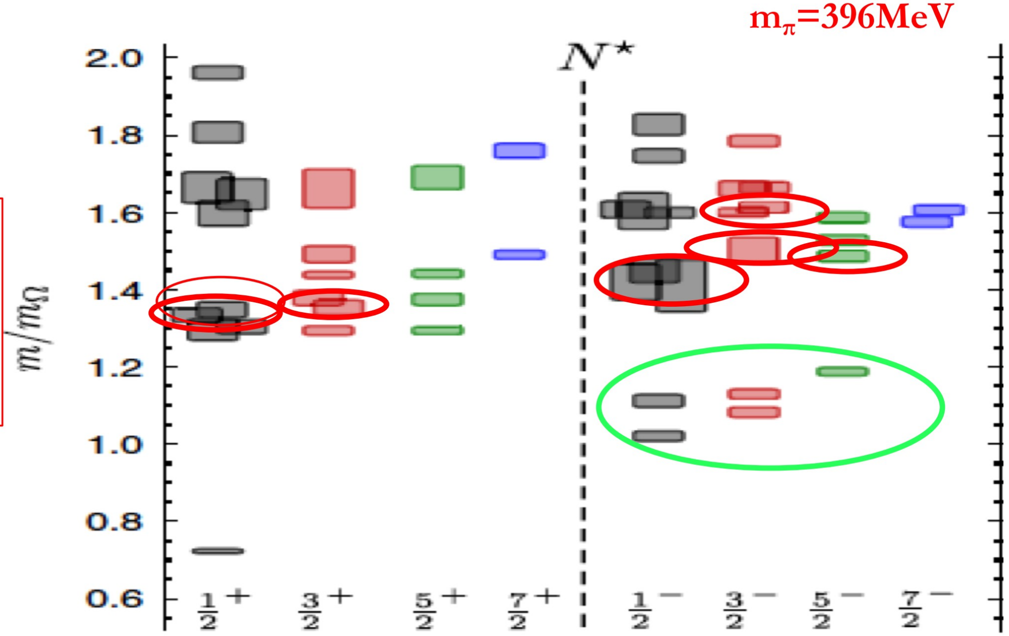



○ **The parity partners Δ(1950)7/2$^+$ and Δ(2200)7/2$^-$ show no mass degeneracy.**

# Do the new states agree with the LQCD predictions?

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

$m_\Omega$ = 1672 MeV




Fit needed
N(1900)3/2$^+$
N(2100)1/2$^+$
N(1880)1/2$^+$

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

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 high

**Ignoring the absolute mass scale, new states correlate with the J$^P$ values predicted from LQCD.**

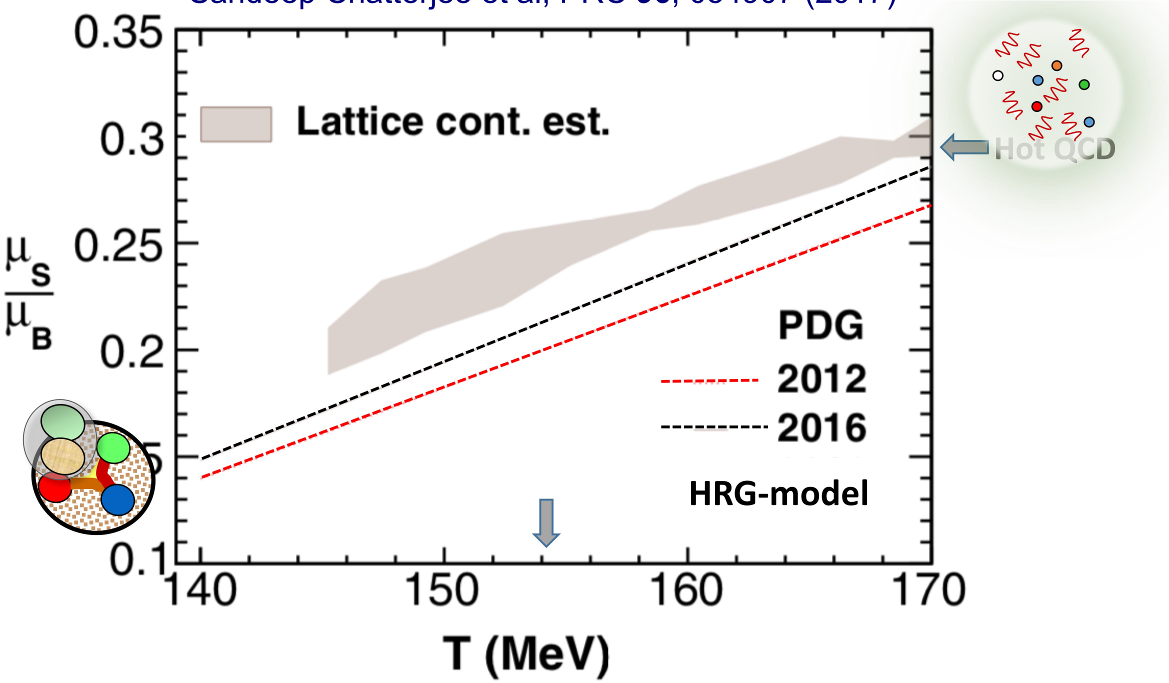
**We need LQCD projections at or near the physical pion mass**

# Search for missing excited states

**How many exited baryon states exist in nature?**

strangeness / baryon chemical potential

Sandeep Chatterjee et al, PRC **96**, 054907 (2017)




*The transition near the cross over temperature is not described with accounting for only the currently established excited baryon states.*

**not included:**

| PDG 2016 with *, ** | |
|---|---|
| $N(1860)$ | $N(1880)$ |
| $N(1895)$ | |
| $N(2000)$ | $N(2040)$ |
| $N(2060)$ | $N(2100)$ |
| $N(2120)$ | $N(2300)$ |
| $N(2570)$ | $N(2700)$ |
| $\Delta(1750)$ | $\Delta(1900)$ |
| $\Delta(1940)$ | $\Delta(2000)$ |
| $\Delta(2150)$ | $\Delta(2200)$ |
| $\Delta(2300)$ | $\Delta(2350)$ |
| $\Delta(2390)$ | $\Delta(2400)$ |
| $\Delta(2750)$ | $\Delta(2950)$ |
| $N(1875)$ | |

**PDG 2018 with** ***, ****

**➔ We get closer**

# Search for excited baryons in 2-body channels

✓ - *data acquired* ✔ - *analyzed/published*

CEBAF Large Acceptance Spectrometer

2018

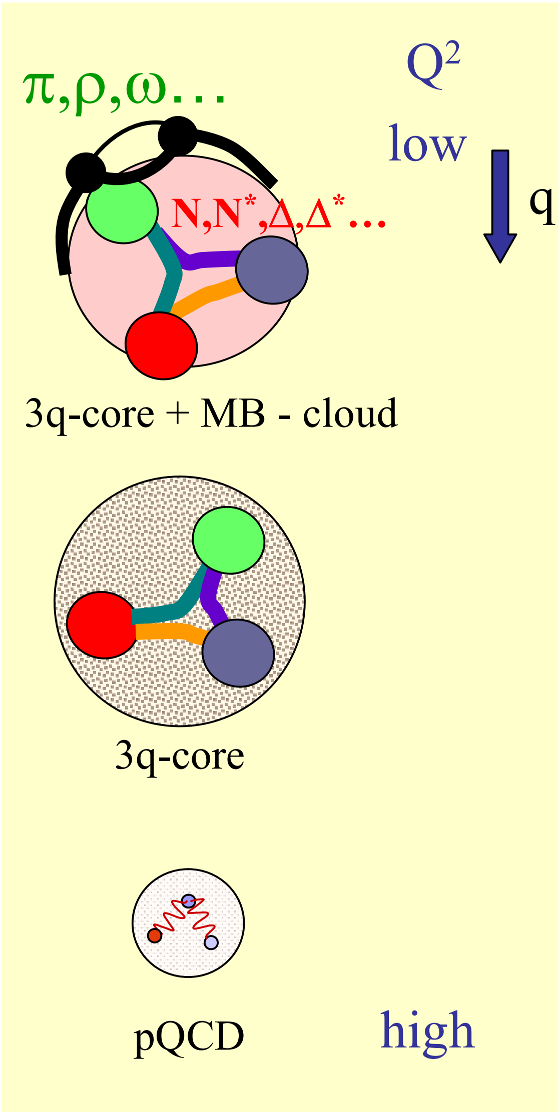
$\gamma p \rightarrow X$

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

$\gamma n \rightarrow X$

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

# Structure of Excited Baryons with Electromagnetic Probes

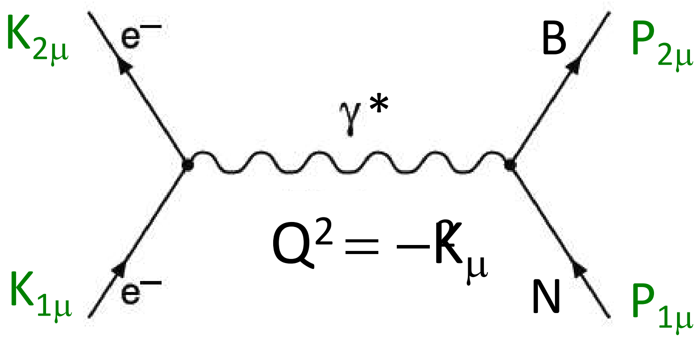



- Meson photoproduction very effective in searching for and identifying new resonances.
- To probe the internal structure and relevant degrees of freedom versus distance scale, a hard scale is needed, which is provided in electron scattering.

➔ Study the structure of the nucleon spectrum in the domain where dressed quarks are the major active degree of freedom.

➔ Explore the formation of excited nucleon states in interactions of dressed quarks and their emergence from QCD.

➔ Reveal the nature of the N* states



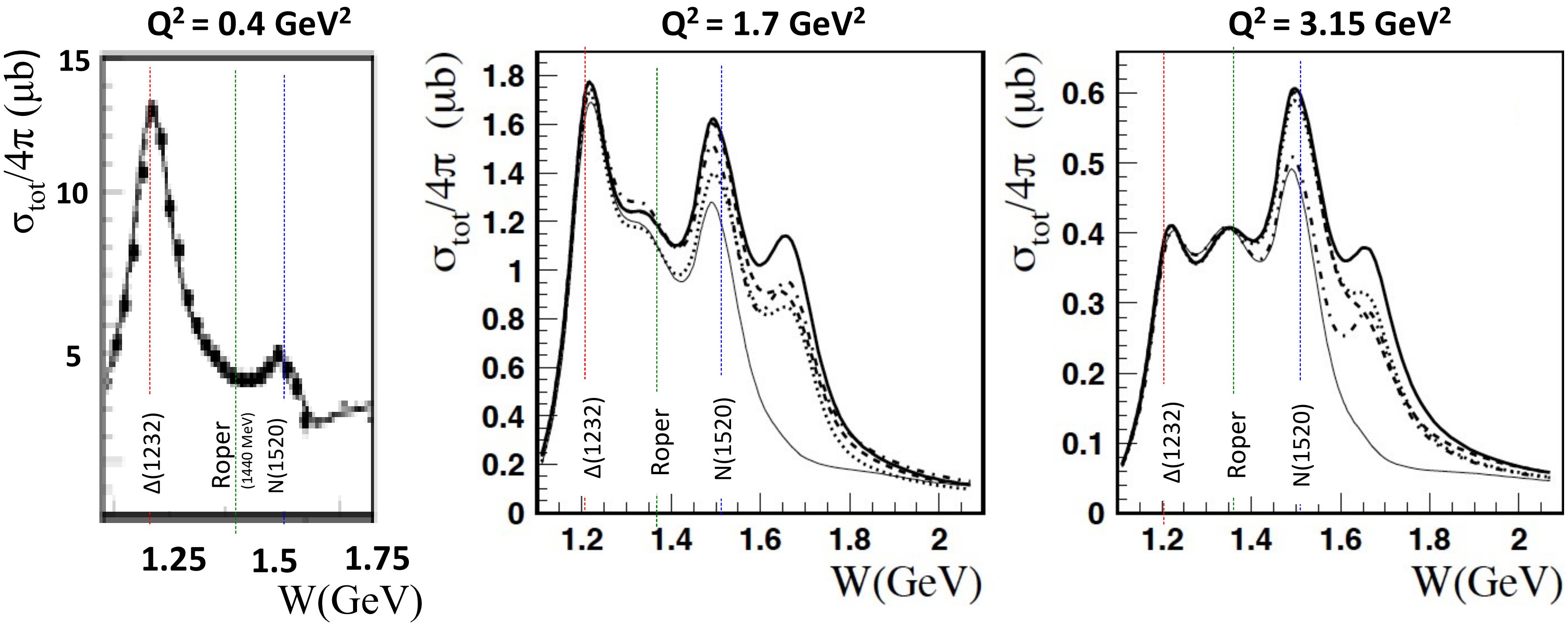
# Integrated cross section at W < 2GeV

## $\gamma^* p \rightarrow \pi^+ n$

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

CEBAF Large Acceptance Spectrometer

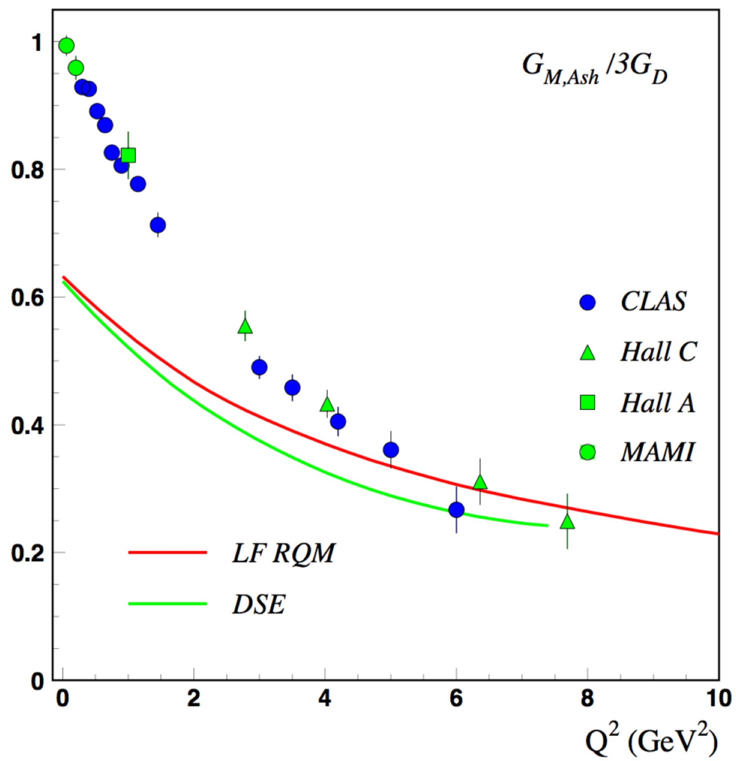
**Why study more than one resonance, aren't they all the same?**



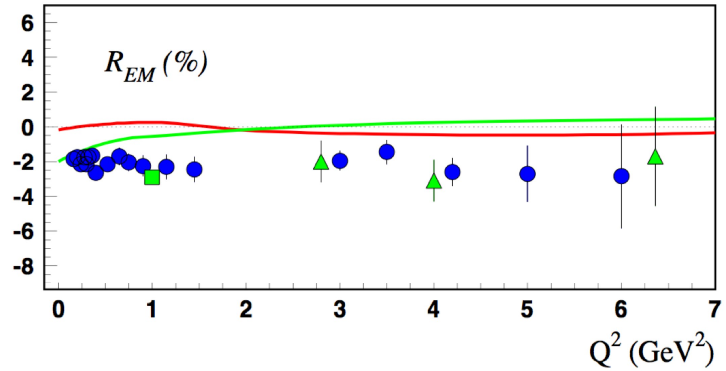

**→ States with different quantum numbers respond differently to increase in $Q^2$**

# NΔ(1232)3/2+ transition form factors

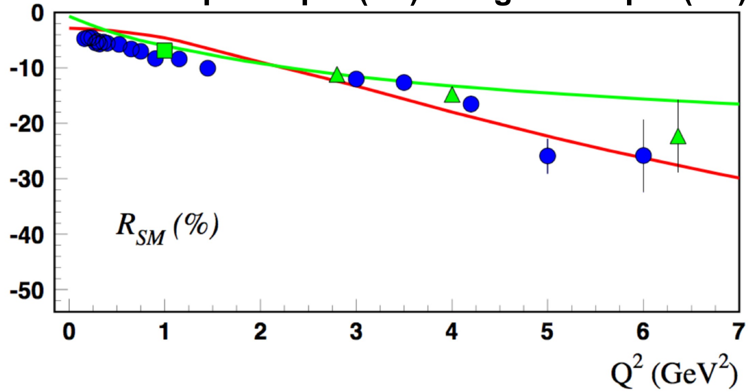
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \cdot \frac{\epsilon G_E^2(Q^2) + \tau G_M^2(Q^2)}{\epsilon(1+\tau)}$$




**electric quadrupol (E2) / magnetic dipol (M1)**



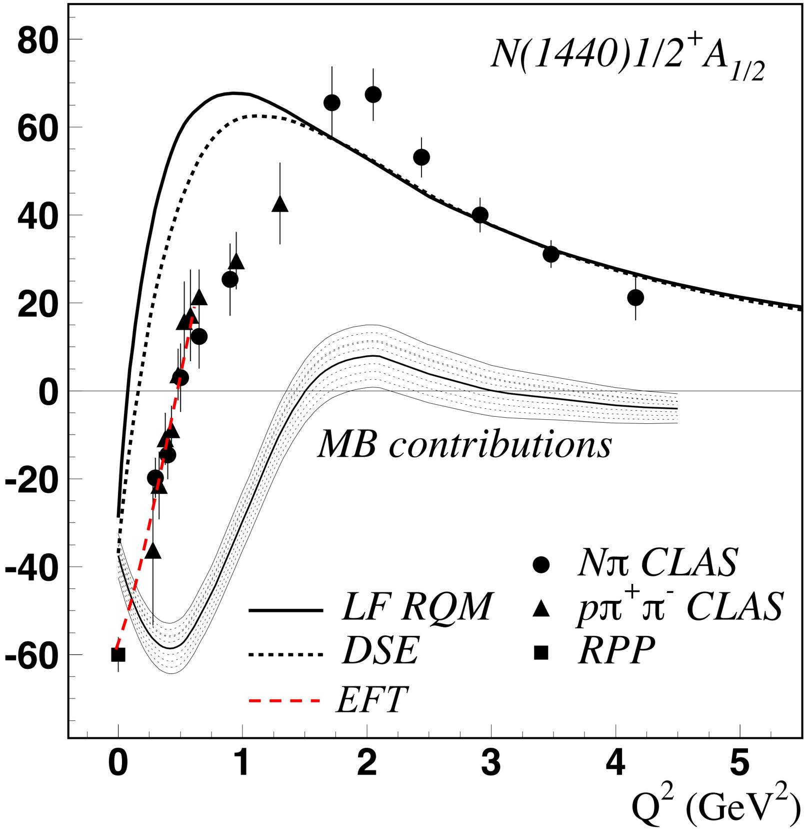

**coulomb quadrupol (C2) / magnetic dipol (M1)**




***light front RQM**: I. Aznauryan, V.Burkert arXiv:1603.06692* ***DSE:** J. Segovia, C.D. Roberts et al., PRC94 (2016) 042201*

- $G_M$ shows dominance of $q^3$ contribution at $Q^2 > 3$ GeV$^2$
- $R_{EM}$ = -2% consistent with MB, no trend towards asymptotic behavior ($R_{EM} \rightarrow +100\%$ )
- $R_{SM}$ ~ consistent with $q^3$ dominance, DSE has different trend at high $Q^2$

# Solving the Roper N(1440)1/2+ Puzzle




*V. Burkert, C. Roberts, Rev.Mod.Phys. 91 (2019) no.1, 011003*

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

***DSE:*** *J. Segovia et al., PRL 115 (2015); 1504.04386*

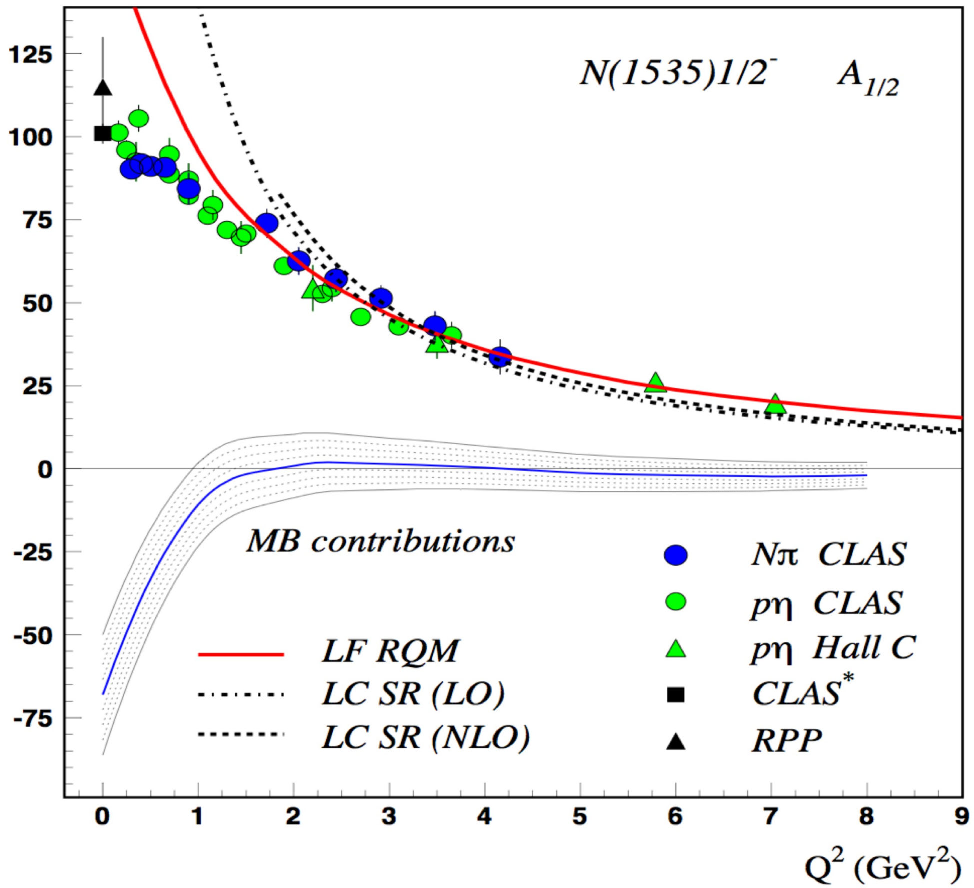
***EFT:*** *T. Bauer, S. Scherer, L. Tiator, PRC90 (2014) 015201*

- Quark core contributions dominate at $Q^2 > 2$ GeV$^2$
- Non-quark contributions are significant at $Q^2 < 2.0$ GeV$^2$
- The behavior at $Q^2 < 0.5$ can be modeled in EFT

**The 1st radial excitation of the 3-quark core seen when the probe penetrates the MB cloud.**

**"Nature" of the Roper – is consistent with the 1st radial excitation of its quark core surrounded by a meson-baryon "cloud"**

# N(1535)1/2- – Parity partner of the nucleon



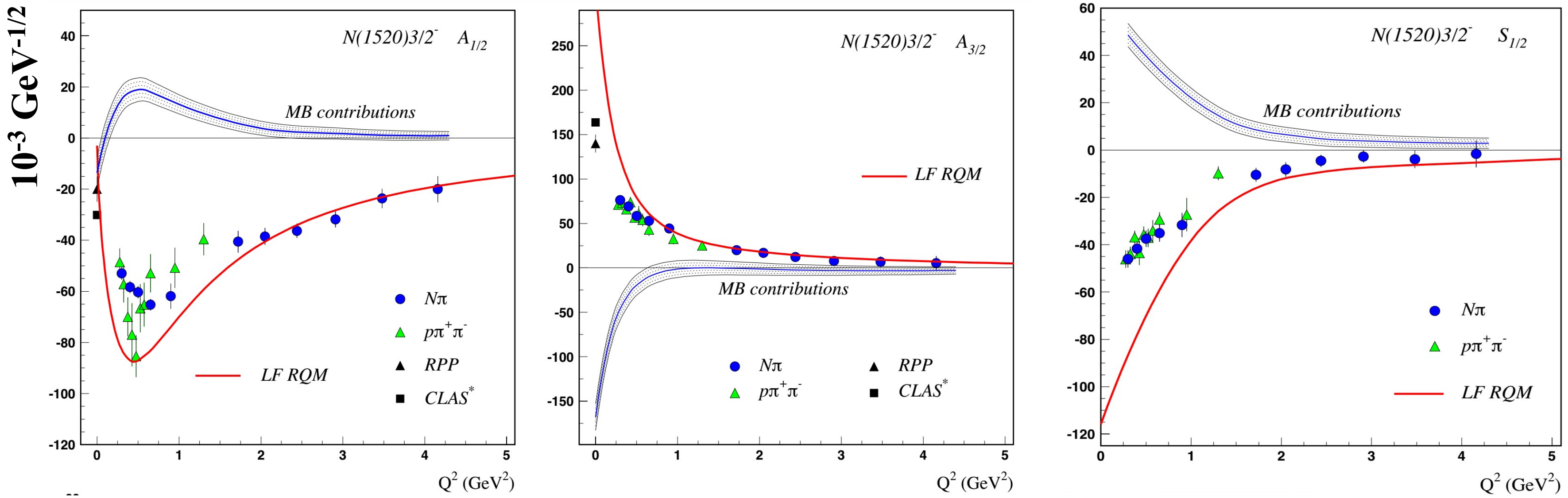

***light front RQM (LF RQM):*** *I. Aznauryan, V. Burkert, arXiv:1603.06692*

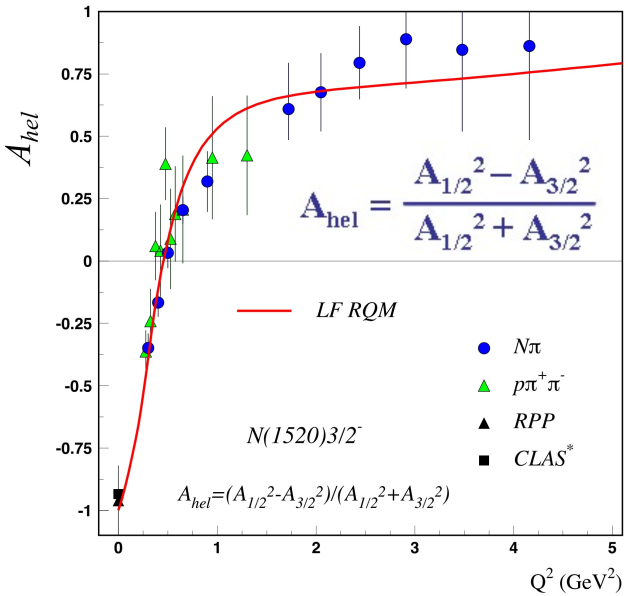
***light cone sum rule (LC SR):*** *I. Anikin, V. Braun, N. Offen, PRD92 (2015) 014018*

- LF RQM describes data at $Q^2 > 1.0$ GeV$^2$
- LC SR with direct link to sQCD describe transition at $Q^2 > 1.5$ GeV$^2$
- Non-quark contributions concentrated at $Q^2 < 1.0$ GeV$^2$

**N(1535)1/2- quark core excitation is consistent with the 1st orbital excitation of the nucleon**

# Electrocoupling Amplitudes for γp → N(1520) $D_{13}$ Transition



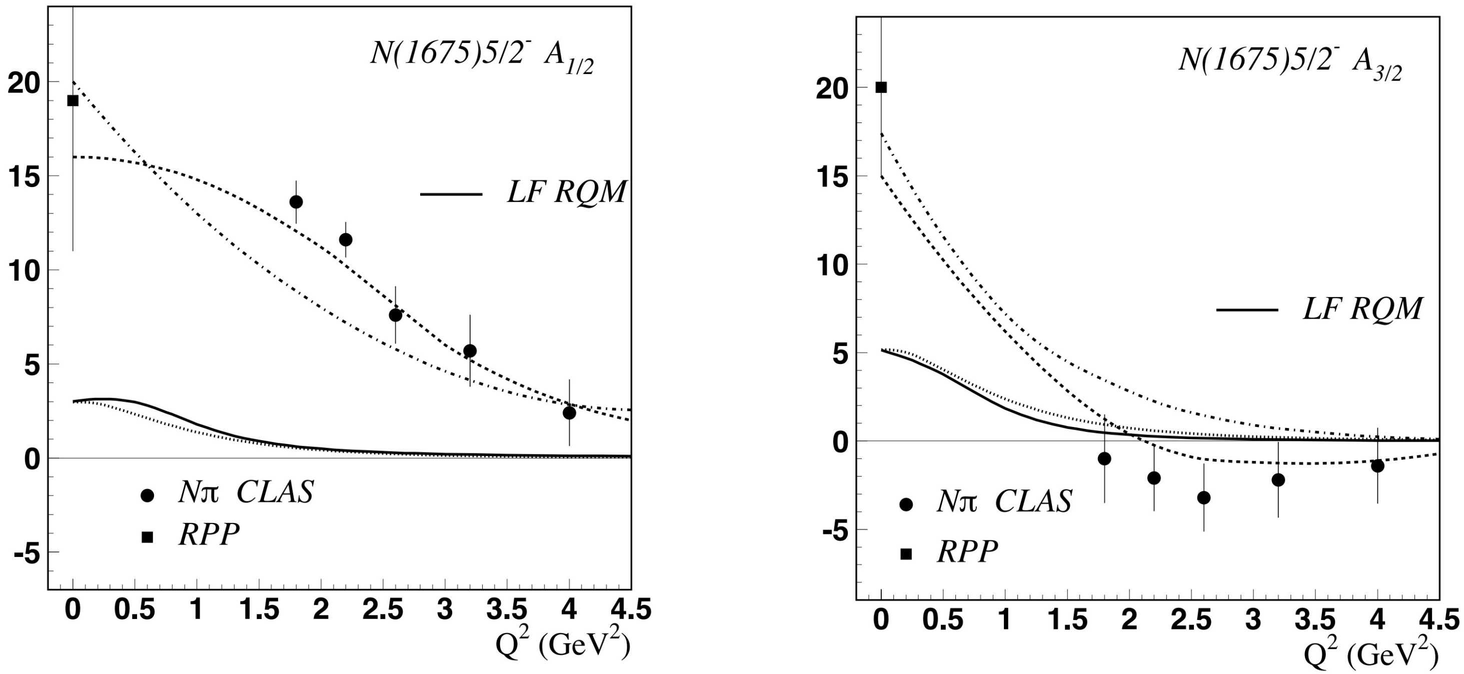




- $A_{1/2}$ amplitude dominant at $Q^2 > 1$ GeV$^2$
- $A_{3/2}$ is only significant contributor at $Q^2 < 3$ GeV$^2$
- There is clear evidence for a helicity switch from λ = 3/2 (at photon point) to λ = 1/2 at high $Q^2$:
  - ➔ Rapid change in helicity structure when going from photo- to electroproduction of a nucleon resonance
  - ➔ Stringent prediction of the chiral QM!

# N+(1675)5/2- photo/electrocoupling amplitudes

**proton target**: **q³** transverse amplitudes are suppressed due to a selection rule

➔ **Expect MB contributions to dominate at all $Q^2$**




K. Park et al.; PRC 91 (2015) 045203

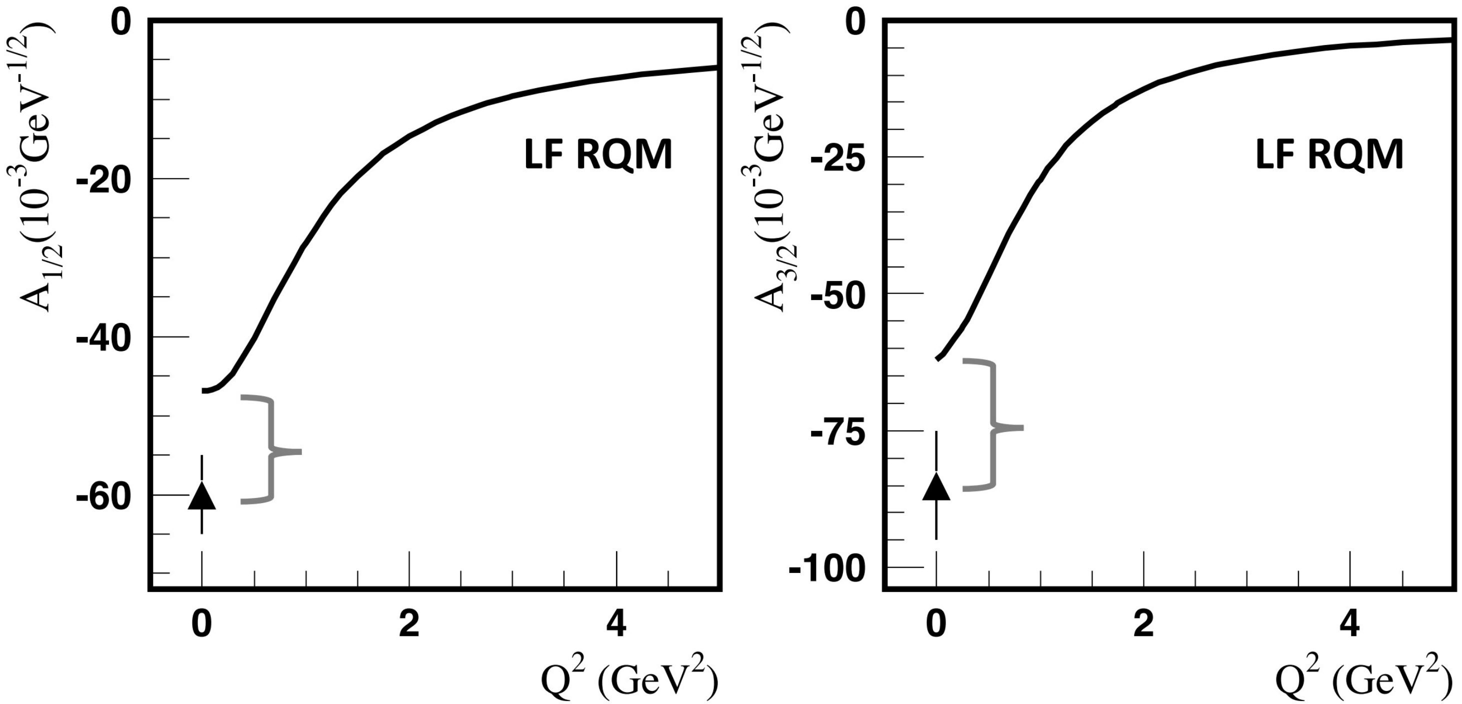
➔Meson-baryon contributions significant

➔ State is not a MB resonance

# $N^0(1675)5/2^-$ photo/electrocoupling amplitudes

**neutron target:** **$q^3$** transverse amplitudes are not suppressed

➔ **Expect $q^3$ contributions to dominate at all $Q^2$**



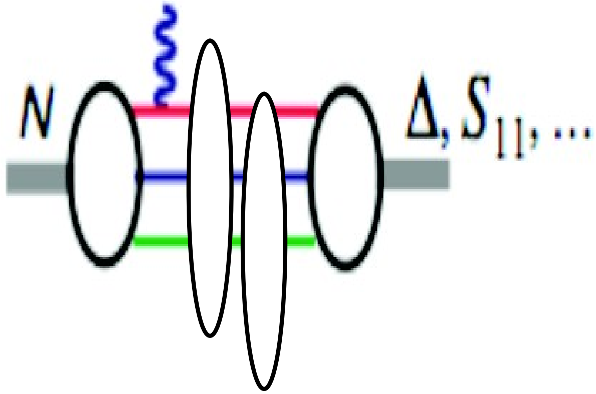

➔ LF RQM predicts large amplitudes on neutrons

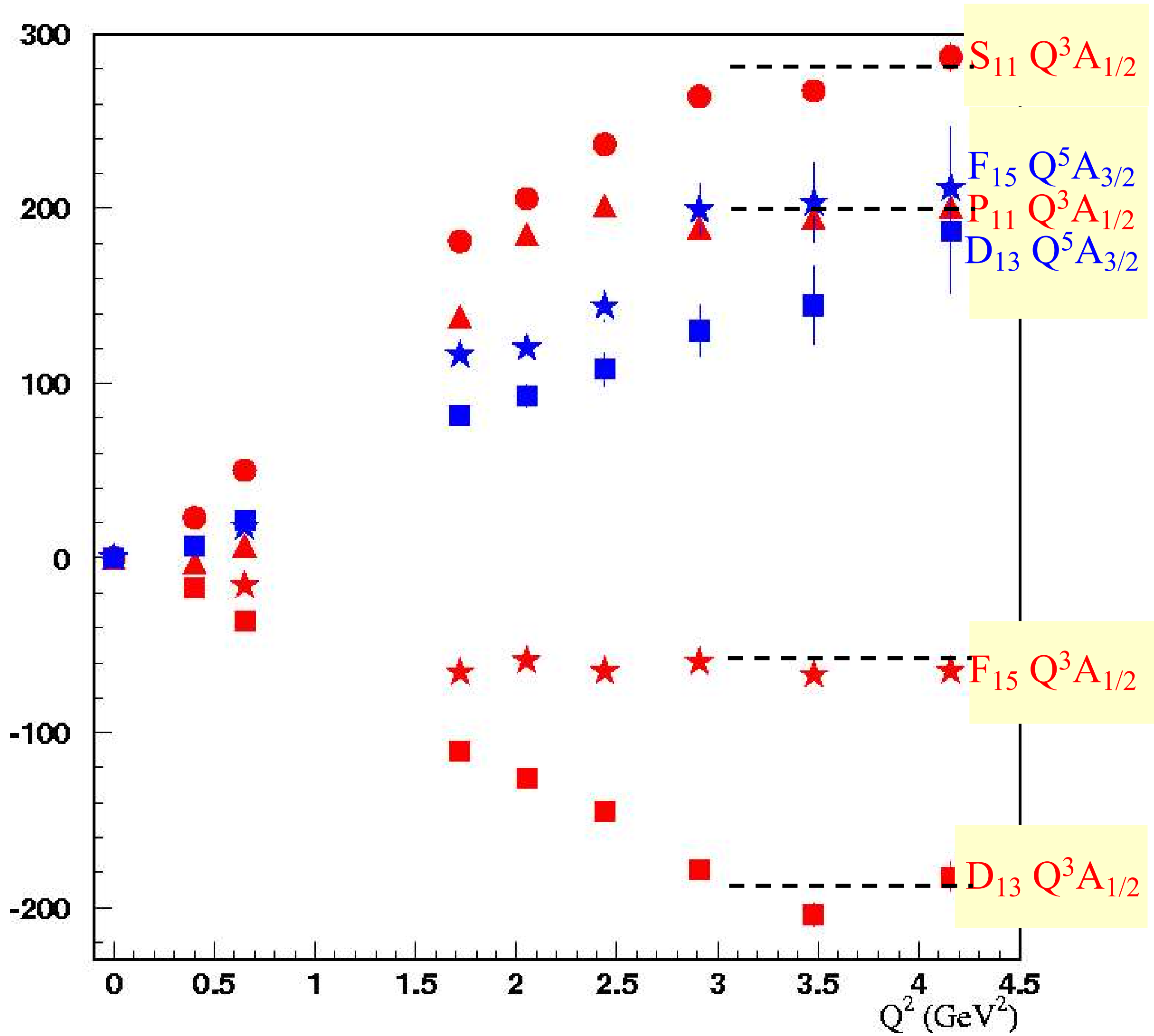
➔ Effect has been observed at the photon point

➔ Meson-baryon contributions significant, not dominant (~25%)

# Evidence for the Onset of Precocious Scaling?

I. G. Aznauryan *et al.,* Phys. Rev. C80, 055203 (2009)



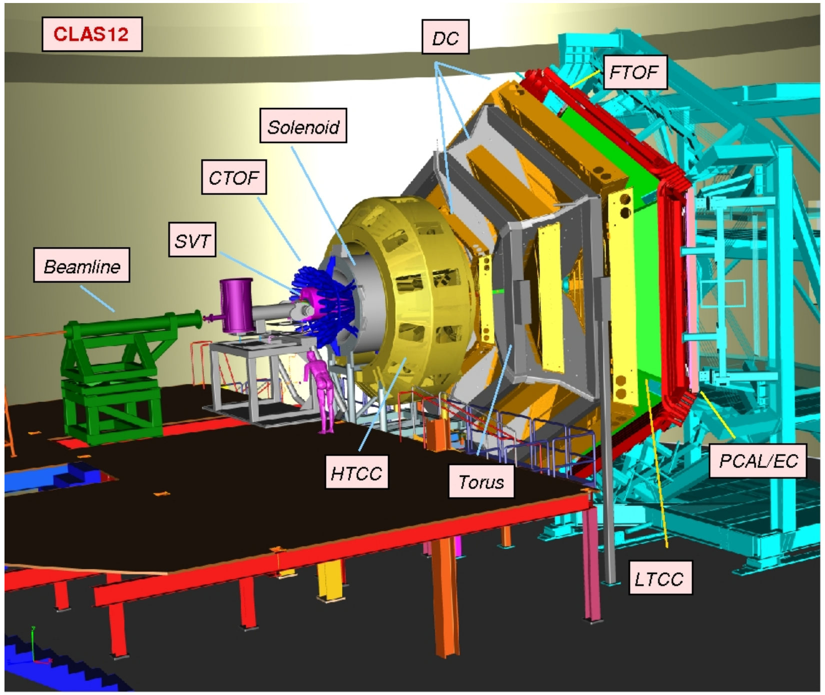




- $A_{1/2} \propto 1/Q^3$
- $A_{3/2} \propto 1/Q^5$

# Outlook

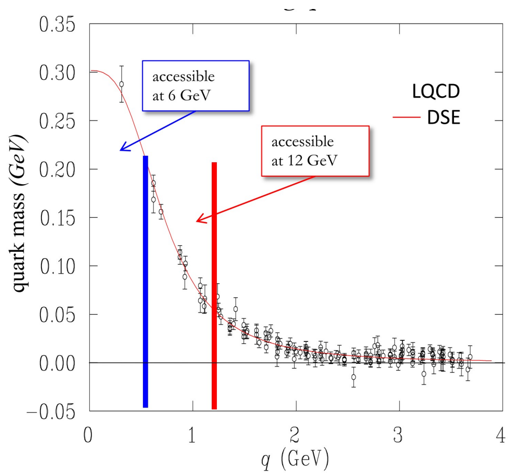
- The search for new N* states continues with the precision data from CBELSA, MAMI, JLAB, LEPS, J-PARC, ..

## CLAS12 N* program has just started …




- Extend the $Q^2$ to a higher range
- Study the hyper-baryon spectrum
- Map out the transition of strong QCD to pertubative QCD

➔ Probe the running quark mass



# Summary

- First high precision photo- and electroproduction data have become available and led to a new wave of significant developments in N* program.
- Large amounts of high precision data and multi-channel PWA have been essential in the discovery of new N* resonances.
- So far there is only qualitative agreement of the measured spectrum with LQCD predictions.
- Electroexcitation of nucleon resonances are sensitive to the effective degrees of freedom versus distance scale.
- The N* experimental program at higher energies gives access to domains where the transition from dressed to elementary quarks should occur.

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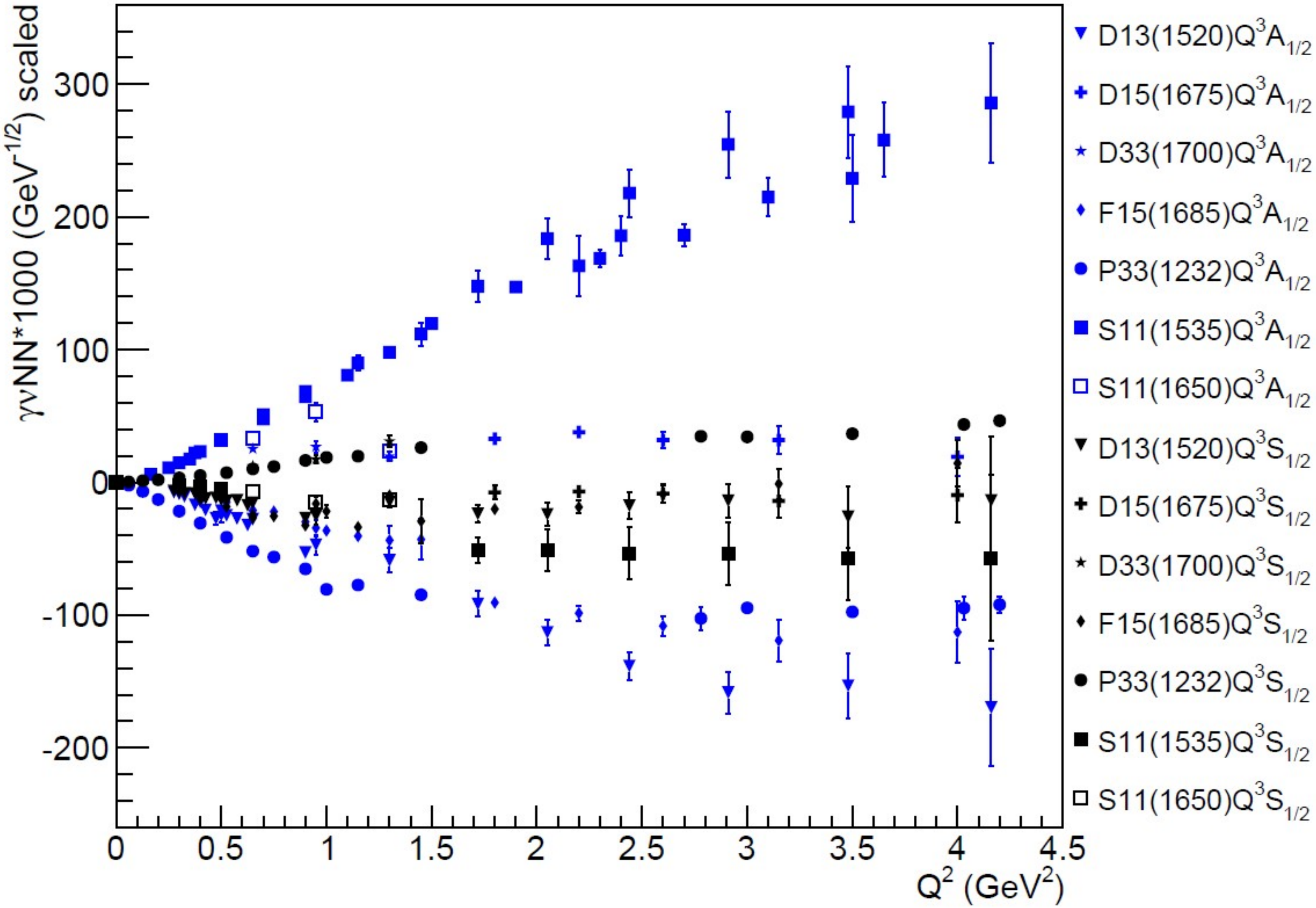
# Evidence for the Onset of Precocious Scaling?




V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)   Ye Tian