Advances in the Search for New Baryon States in Experiments with Electromagnetic Probes and New Opportunities with CLAS12

Daniel S. Carman
Jefferson Laboratory

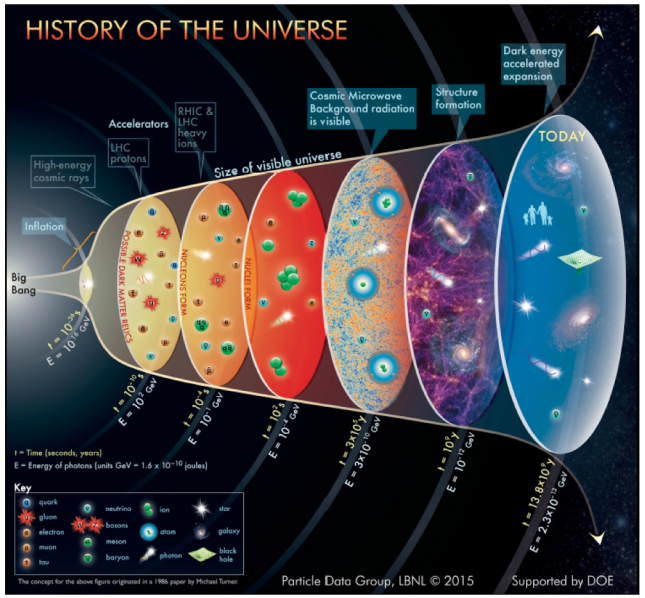
CEBAF Large Acceptance Spectrometer

Outline:

- Advances in N* Studies with CLAS & CLAS12
  - Hall B N* Program
  - Searches for New N* States
- CLAS12 N* Program and Initial Data Studies
- Concluding Remarks

CLAS / CLAS12 N* Program

The N* program is one of the key physics foundations of Hall B



In the early universe:

- Transition occurred from a deconfined quark/gluon phase to hadron phase
- This transition was shaped by the full meson/baryon spectrum

- CLAS & CLAS12 were designed to study exclusive reaction channels over a broad kinematic range:

$$\pi N,\ \omega N,\ \phi N,\ \eta N,\ \eta' N,\ \pi\pi N,\ KY,\ K^*Y,\ KY^*$$

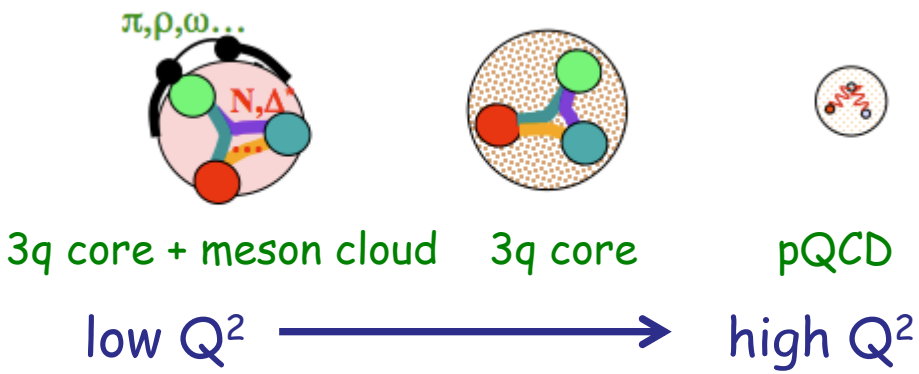
- Goal is to explore the *spectrum* of N* states and their *structure*
  - Probe their underlying degrees of freedom via studies of the Q^2 evolution of the electroproduction amplitudes
    - these amplitudes do not depend on the decay channel but different final states have different hadronic decay parameters and backgrounds
    - insight into strong QCD by mapping the dressed quark mass function from the results on the electrocouplings of different excited nucleon states
    - search for hybrid baryons (qqqG) and other non-3q configurations
  - Data can unravel/reveal the spectrum of contributing N* states

Excited Nucleon Structure

- Nucleon structure is more complex than what can be described accounting for quark degrees of freedom only

  - Low Q^2: ($Q^2 < 2$ GeV^2) structure well described by adding an external meson cloud to inner quark core

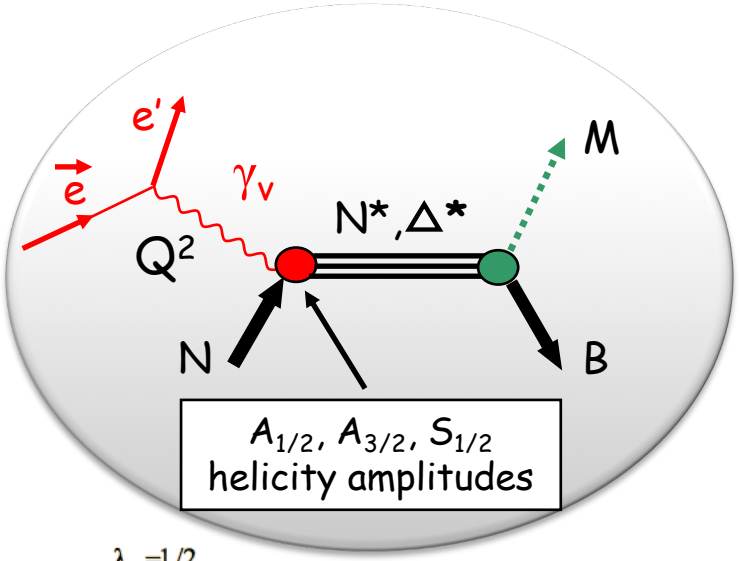
  - High Q^2: ($Q^2 > 5$ GeV^2) quark core dominates; transition from confinement to pQCD regime

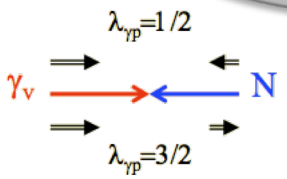


- Studies of the $\gamma_v NN^*$ electrocouplings from low to high Q^2 probe the detailed structure of the N* states

  - The momentum dependence of the dressed quark mass shapes the structure of N* states and the Q^2 evolution of the electrocouplings

  - The electrocouplings are the only source of information on many facets of the non-perturbative strong interaction in the generation of different N* states



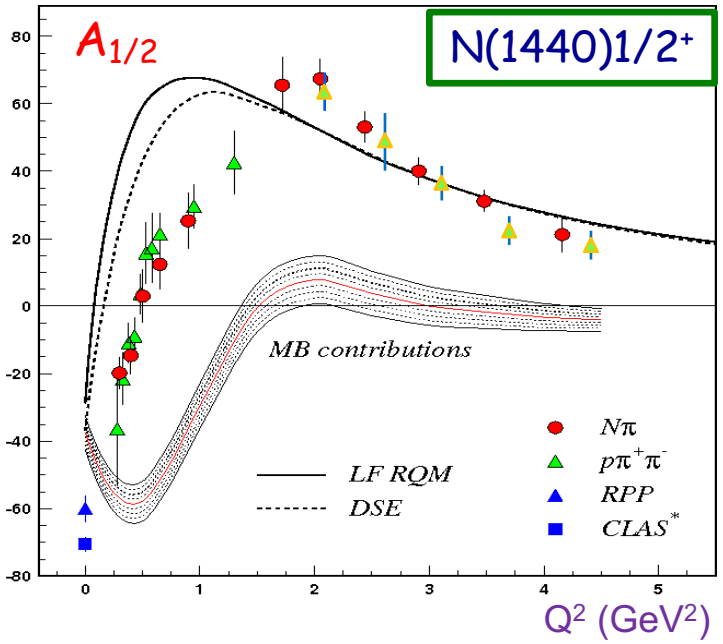


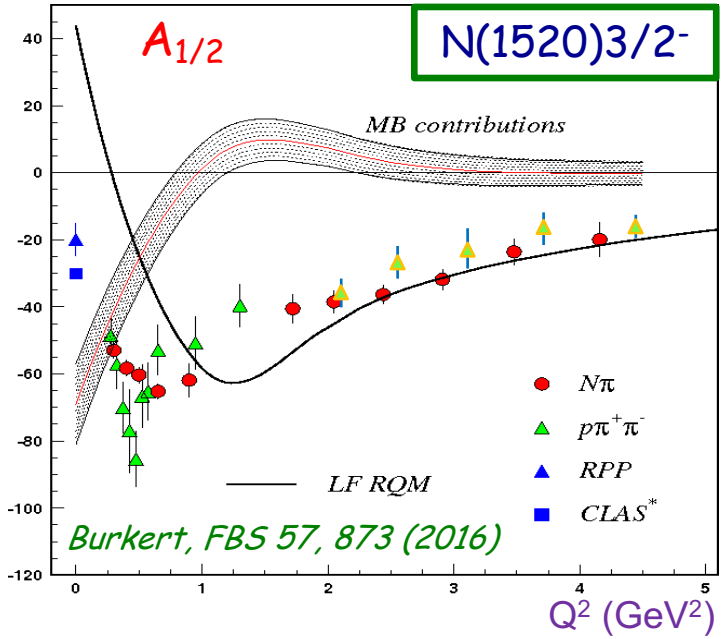
$A_{1/2}$, $A_{3/2}$ - transverse

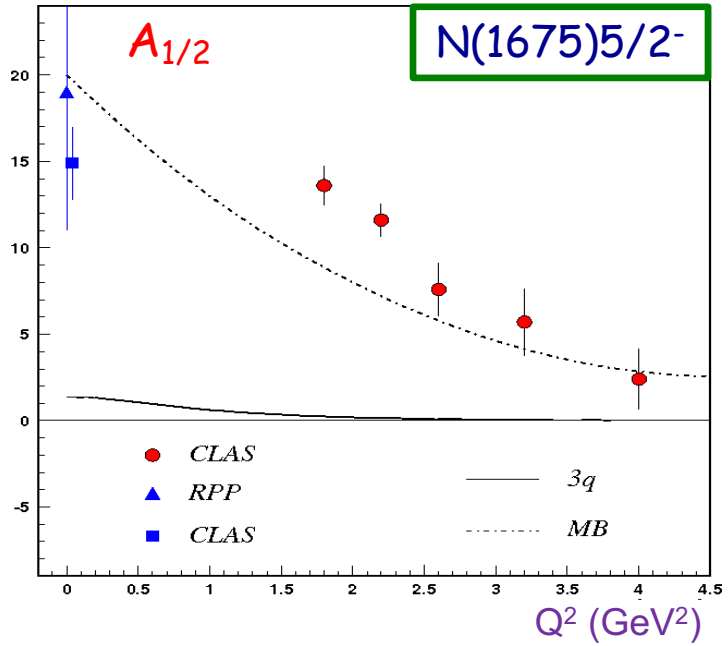
$S_{1/2}$ - longitudinal

N* Electrocouplings from CLAS

*see talk by Victor Mokeev







- Electrocouplings reveal different interplay between meson cloud and quark core
  - Good agreement of the extracted N* electrocouplings from Nπ and Nππ:
    - Compelling evidence for the reliability of the results
    - Channels have very different mechanisms for the non-resonant background
    - KY channels hold promise to enable comparisons to Nππ for higher-lying states where Nπ coupling is weak
- Data on the electrocouplings for Q^2 from 2 - 7 GeV^2 are needed in order to:
  - Map out the transition from meson-baryon to confined quark degrees of freedom
  - Gain insight into the dressed quark mass function at distances where the quark core contribution is largest

Reaction Models

*see talk by Michael Doering

Single Meson Analysis:

- Unitary Isobar Model and Fixed-t Dispersion relation approaches (Kaon-MAID)
- Regge+Resonance model (Ghent)
- Single channel isobar models (T. Mart, O. Maxwell, P. Bydovski)

$\pi^+\pi^-p$ Analysis:

- JM reaction model for combined photo- and electroproduction data

Multi-channel Analysis:

- Bonn-Gatchina multi-channel PWA
- Jülich-Bonn coupled-channel framework
- Argonne-Osaka dynamically coupled-channel model

D.S. Carman, K. Joo, and V.I. Mokeev, FBS 61, 29 (2020)

KY Reaction Model

At present there is no reaction model that adequately describes the KY electroproduction data in the resonance region:

A model that describes the KY data is necessary to extract the electrocouplings from the existing lower Q^2 CLAS data and the planned higher Q^2 CLAS12 data

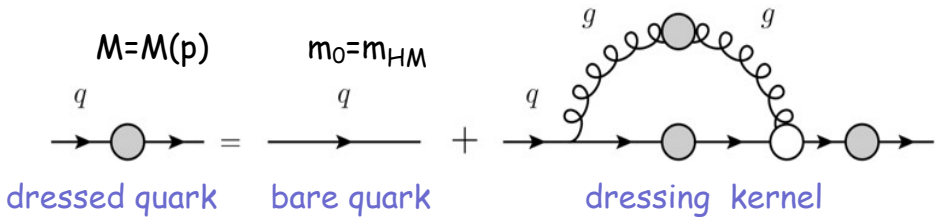
Such a model must incorporate the N* $\gamma_v pN^*$ electrocouplings for W < 1.8 GeV from the available CLAS results

- Explore the possibility to improve the data description by:
  - a) Varying resonant/non-resonant parameters
  - b) Implementing additional phenomenological terms to fit to the data
  - c) Develop approach that simultaneously fits γp and $\gamma^* p$ data
  - d) Account for FSI with open channels
  - e) Make use of available results on the electroproduction and hadronic interaction amplitudes between the following initial/final states:

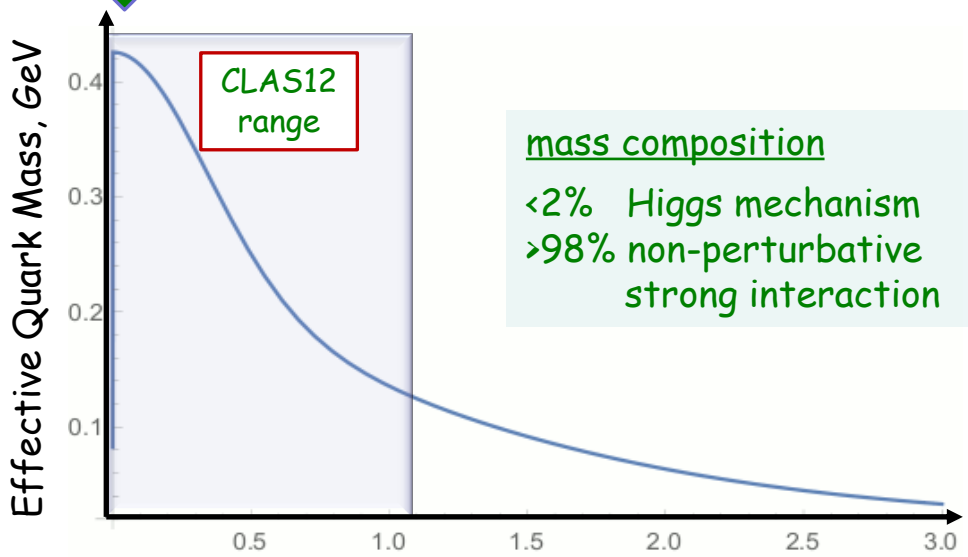
$$\gamma p,\ \pi N,\ \eta N,\ K\Lambda,\ K\Sigma,\ \pi\Delta,\ \rho N,\ \ldots$$

Emergence of Hadron Mass

Effective quark mass depends on its momentum



confinement regime:
- constituent quark mass

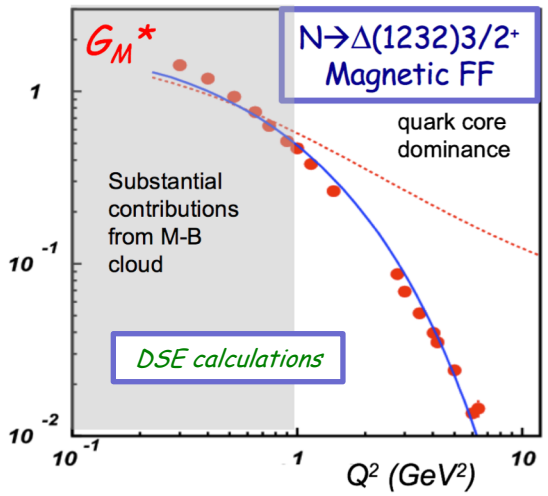


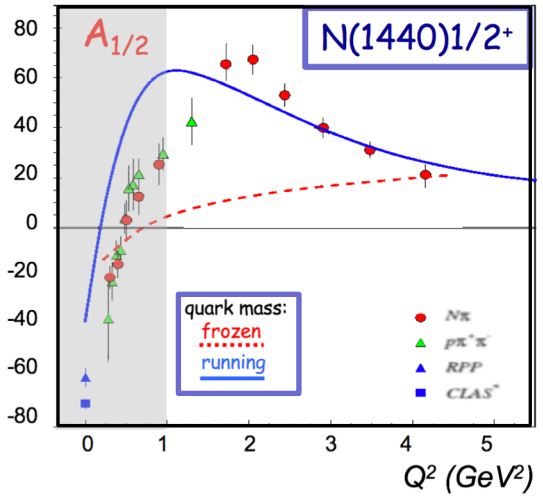
mass composition

<2% Higgs mechanism
>98% non-perturbative strong interaction

approaching bare Higgs mechanism mass

- Calculations of form factors and electrocouplings are sensitive to the evolution of the dressed quark mass function





CLAS results vs. QCD expectations with running quark mass

CLAS12 will cover for the first time the Q^2 range where the dominant part of hadron mass is generated addressing the critical questions:

- *What is the nature of confinement?*
- *How is >98% of visible mass generated?*

N* Excitation Spectrum & Missing States

$|\text{baryon}\rangle : \alpha|qqq\rangle + \beta|qqq(qq)\rangle + \gamma|qqqG\rangle + \ldots$

3 flavors: {u,d,s} → SU(3)

{qqq}: $3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$

SU(6)

quark spin $s_q = \frac{1}{2}$ → SU(2)

$\{\vec{q}\vec{q}\vec{q}\}$: $6 \otimes 6 \otimes 6 = 56 \oplus 70 \oplus 70 \oplus 20$

SU(6) multiplets decompose into flavor SU(3) multiplets as:

2S+1

$56 = {}^4 10 \oplus {}^2 8$

$70 = {}^2 10 \oplus {}^4 8 \oplus {}^2 8 \oplus {}^2 1$

$20 = {}^2 8 \oplus {}^4 1$

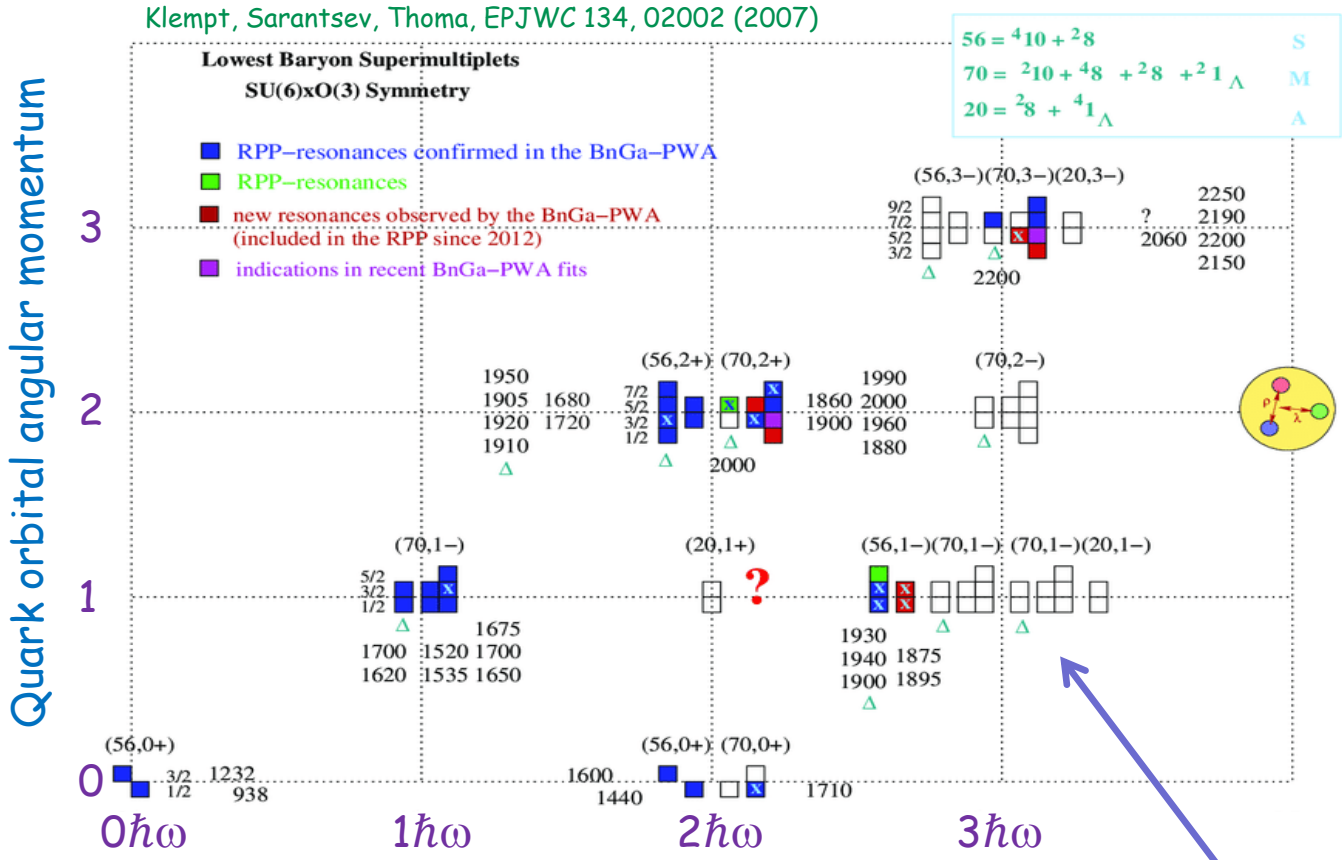
O(3)

baryon spin: $\vec{J} = \vec{L} + \Sigma \vec{s_i}$

parity: $P = (-1)^L$

3-quark Shell Model SU(6) ⊗ O(3) symmetry

Klempt, Sarantsev, Thoma, EPJWC 134, 02002 (2007)



The "missing resonance" problem

New N′(1720) State from Nππ Analysis

N(1720)3/2⁺ hadronic decays from CLAS data fit with only conventional N* states		
	BR(πΔ), %	BR(ρp), %
electroproduction	64-100	<5
photoproduction	14-60	19-69

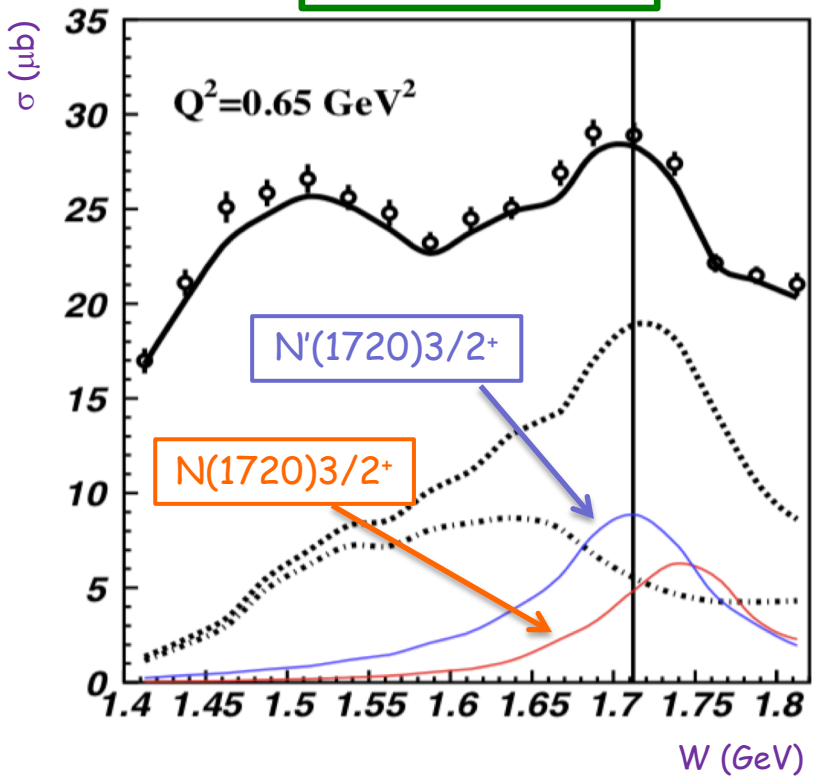
Contradictory BR values for N(1720)3/2⁺ decays to πΔ and ρp deduced from γp and γ_vp data with Q^2 independent resonance masses and hadronic decay widths

- impossible to describe the data with conventional N* states only

N* hadronic decays from the data fit that incorporates the new N′(1720)3/2⁺ state		
Resonance	BR(πΔ), %	BR(ρp), %
N′(1720)3/2⁺ electroproduction photoproduction	47-64 46-62	3-10 4-13
N(1720)3/2⁺ electroproduction photoproduction	39-55 38-53	23-49 31-46
Δ(1700)3/2⁻ electroproduction photoproduction	77-95 78-93	3-5 3-6

Good description of both Nππ γp and γ_vp data achieved only by including new N′(1720)3/2⁺

$ep \rightarrow e'p\pi^+\pi^-$

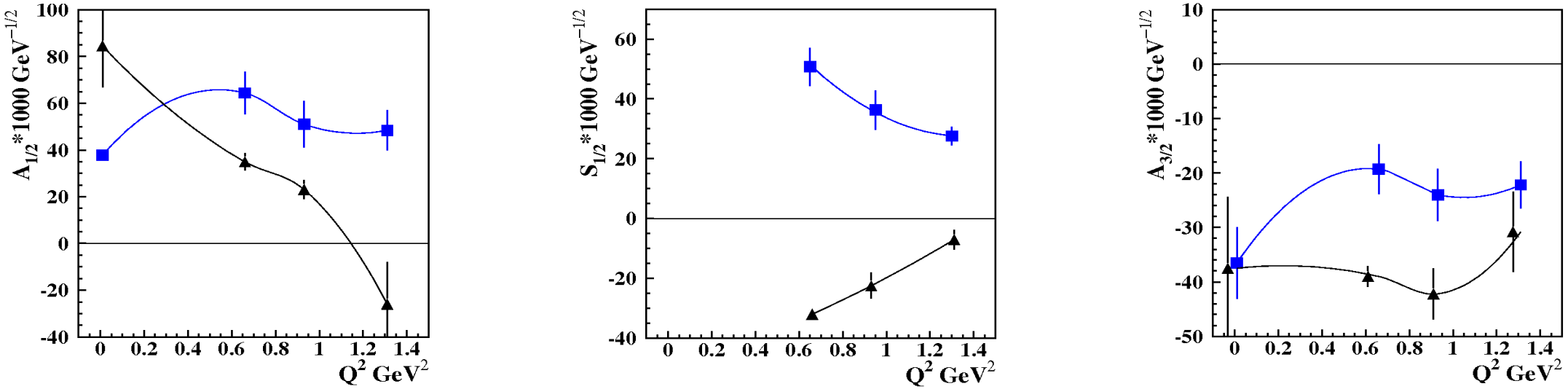


V.I. Mokeev et al., PLB 805, 135457 (2020)

⇒ both photo- and electroproduction data are essential for a full understanding of the N* spectrum

New N′(1720) State from Nππ Analysis

The photo-/electrocouplings of the N′(1720)3/2⁺ and conventional N(1720)3/2⁺ states



N′(1720)3/2⁺

N(1720)3/2⁺

Resonance	Mass, GeV	Total width, MeV
N′(1720)3/2⁺	1.715-1.735	120±6
N(1720)3/2⁺	1.743-1.753	112±8

V.I. Mokeev et al., PLB 805, 135457 (2020)

- N′(1720)3/2⁺ is the only new resonance for which data on electroexcitation amplitudes have become available
- Gaining insight into the ``missing" resonance structure will shed light on the peculiar structural features that have made them so elusive, as well as on the emergence of new resonances from QCD

CLAS12 N* Program

- Measure exclusive electroproduction of $N\pi$, $N\eta$, $N\pi\pi$, KY final states from an unpolarized proton target with longitudinally polarized electron beam

E_b = 6.6, 8.8, 11 GeV, Q^2 = 0.05 → 12 GeV^2, W → 3.0 GeV, cos θ_m^* = [-1:1]

E12-09-003	Nucleon Resonance Studies with CLAS12
E12-06-108A	KY Electroproduction with CLAS12
E12-16-010A	N* Studies Via KY Electroproduction at 6.6 and 8.8 GeV
E12-16-010	A Search for Hybrid Baryons in Hall B with CLAS12

RG-A	Spr. 18 126 mC	10.4 GeV, 10.6 GeV 50% of total
	Fall 18 99 mC	
	Spr. 19 58 mC	
RG-K	Fall 18 28 mC	6.5 GeV, 7.5 GeV 10% of total

1. Study higher-lying N* states:
   - confirm signals of new baryon states observed in $\gamma p \to KY$
   - search for predicted qqqG hybrid baryons
2. Understand effect of meson cloud on N* structure:
   - use transition regime (Q^2 = 2-7 GeV^2) to explore emergence of external meson cloud from the core of confined quarks and gluons
   - expect precision in electroproduction to match photoproduction for Q^2 up to ~3 GeV^2
3. Probe dressed quark mass function and di-quark correlations in N* structure:
   - important aspect of N* structure and $\gamma_v NN^*$ amplitudes
   - provide insight into hadron mass emergence vs. Q^2
   - different N* quantum numbers allow study different qq correlations

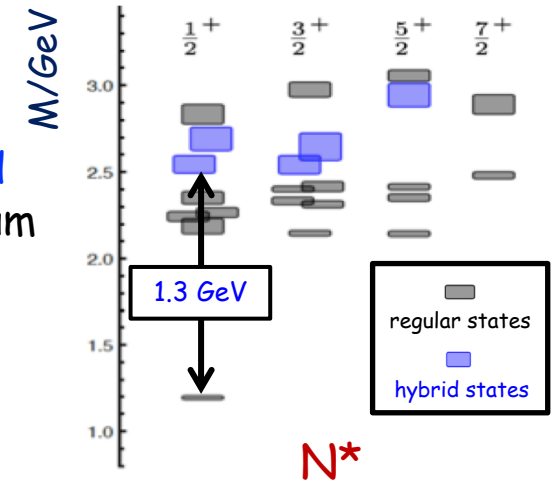
Hunting for Glue in Excited Baryons

Can glue be a structural component of excited baryon states?

LQCD predicts hybrid baryons in N* spectrum

JLab LQCD group results

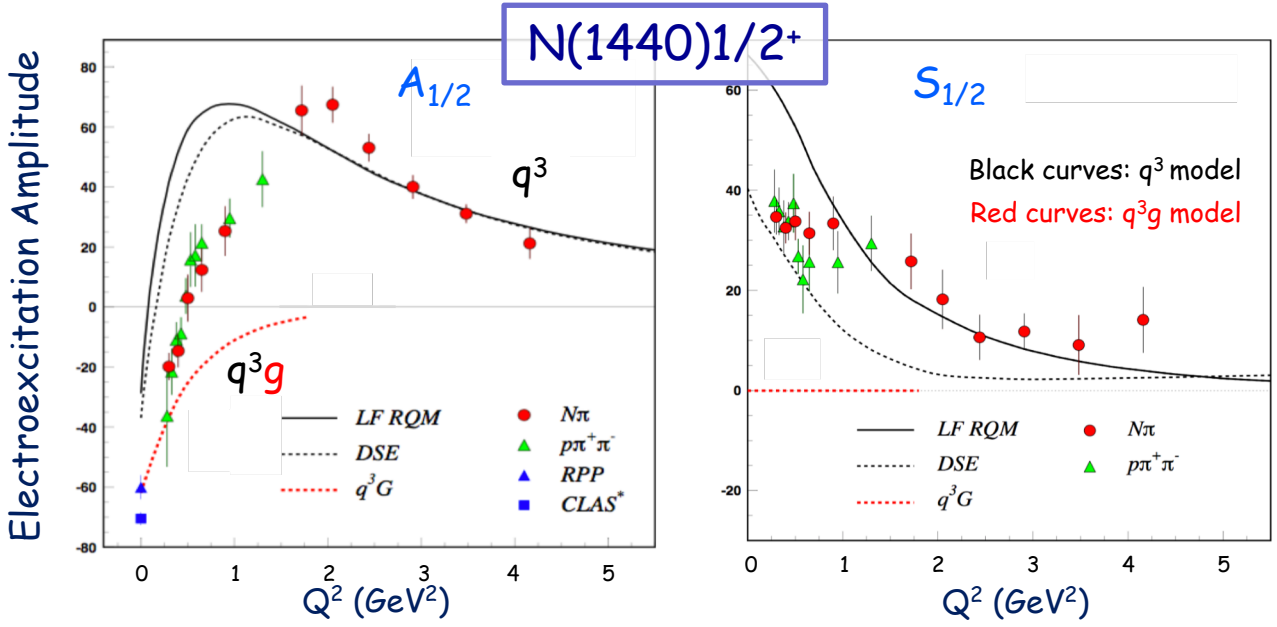
m_π=396 MeV



The signatures for hybrid baryons include:

- Extra resonances with $J^\pi=1/2^+$, $3/2^+$ in mass range 2.0-2.5 GeV and decays into $N\pi\pi$ or KY final states
- Drop of $A_{1/2}(Q^2)$ and $A_{3/2}(Q^2)$ faster than for ordinary 3q states due to extra glue-component in valence structure
- Suppressed $S_{1/2}(Q^2)$ relative to $A_{1/2}(Q^2)$ transverse amplitude

The hybrid nature of baryons appears in the Q^2 evolution of their transition amplitudes



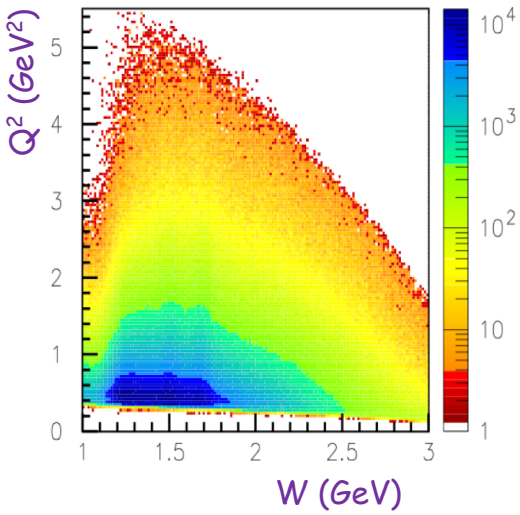
Quark model predictions on the Q^2 evolution of the electrocouplings are necessary for hybrid identification

Z.P. Li, V. Burkert, Z.J Li, PRD 46, 70 (1992)

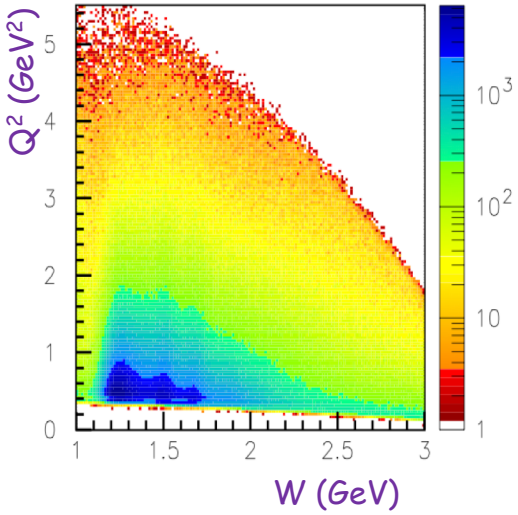
CLAS12 Kinematic Coverage

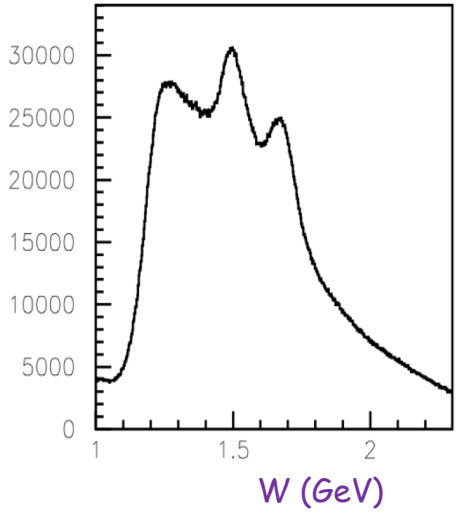
*see talk by Ralf Gothe

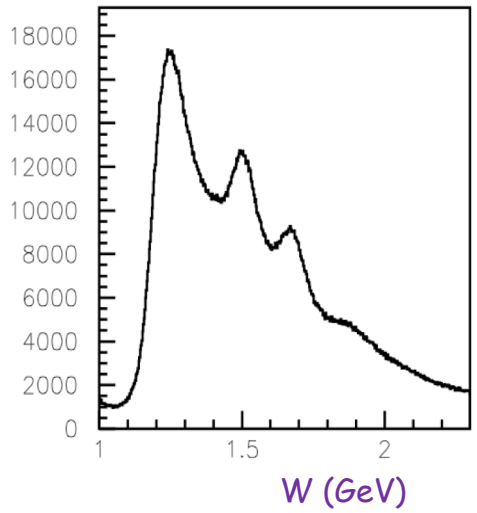
$ep \rightarrow e'n\pi^+$



$ep \rightarrow e'p\pi^0$



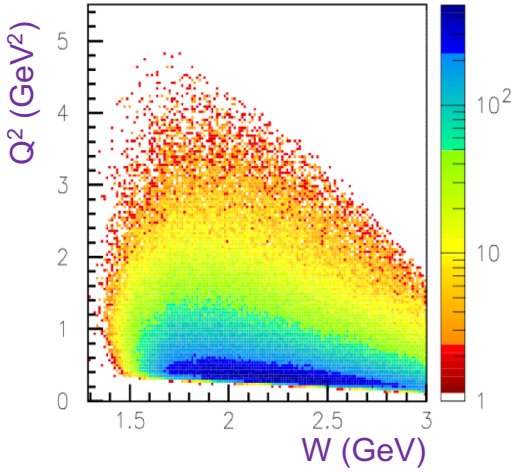




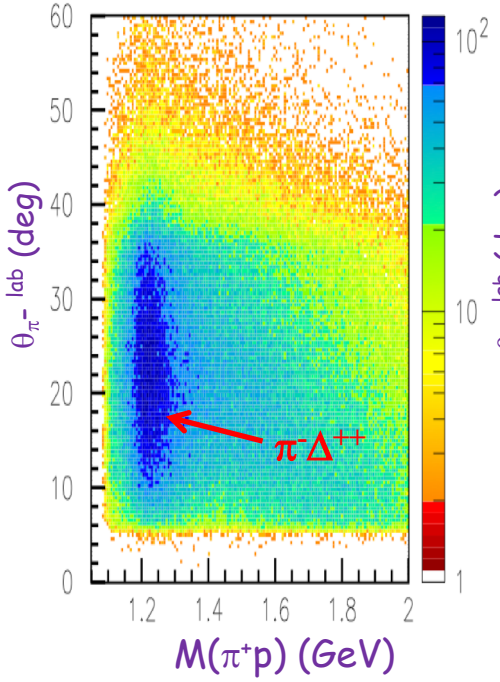
6.535 GeV data from CLAS12 RG-K

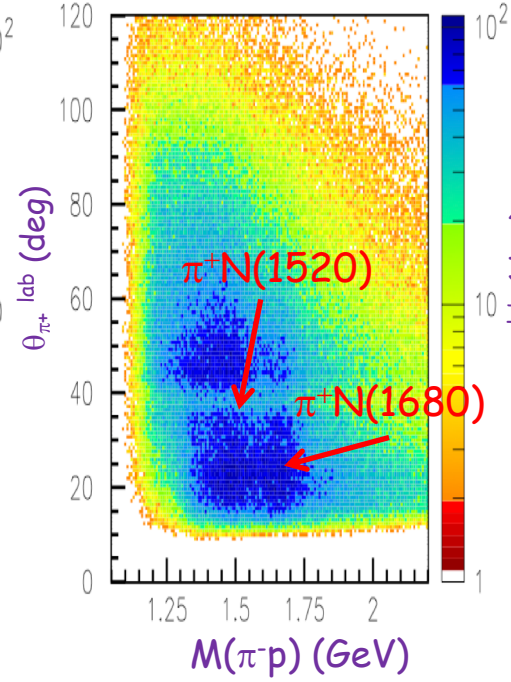
Studies in progress:

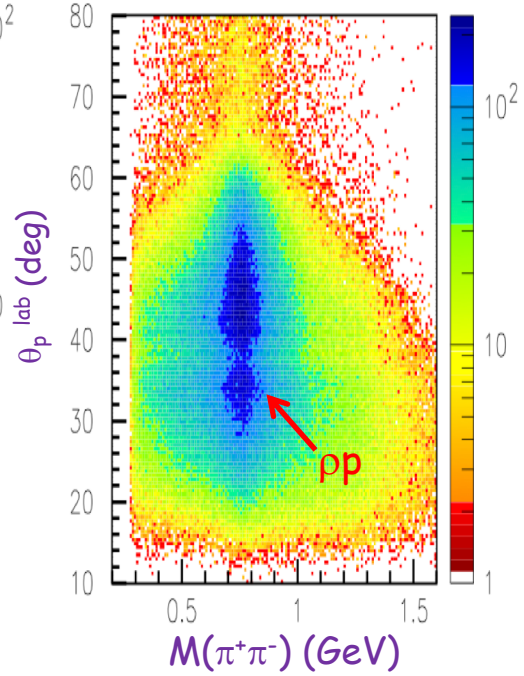
- BSA for single pion production
- Cross section extractions



$ep \rightarrow e'p\pi^+\pi^-$

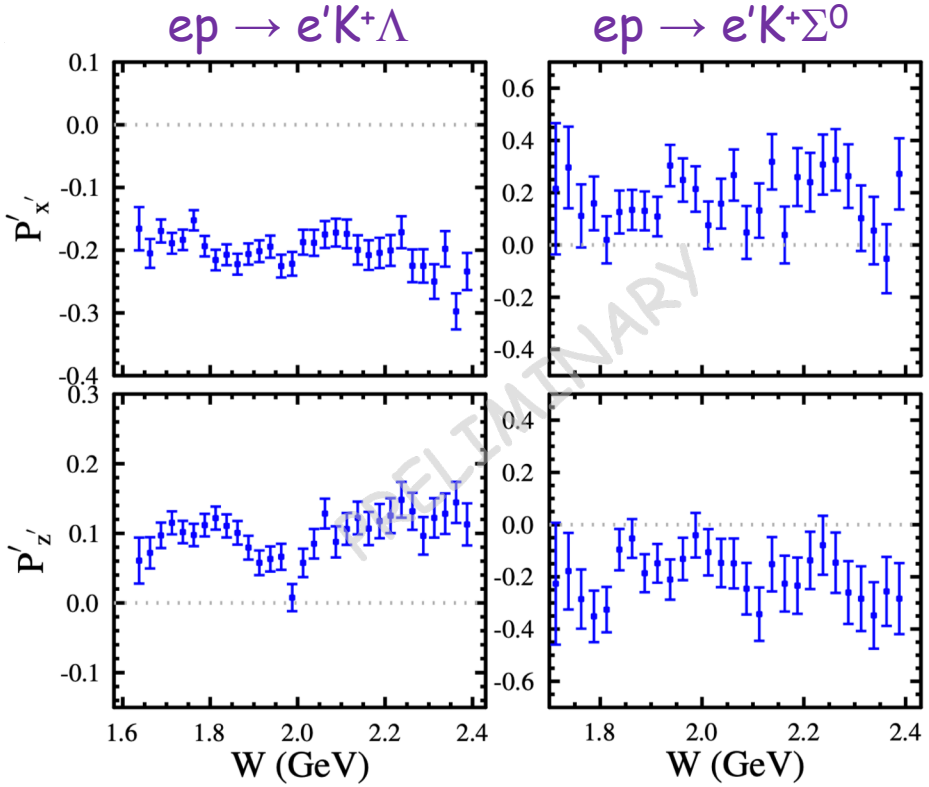






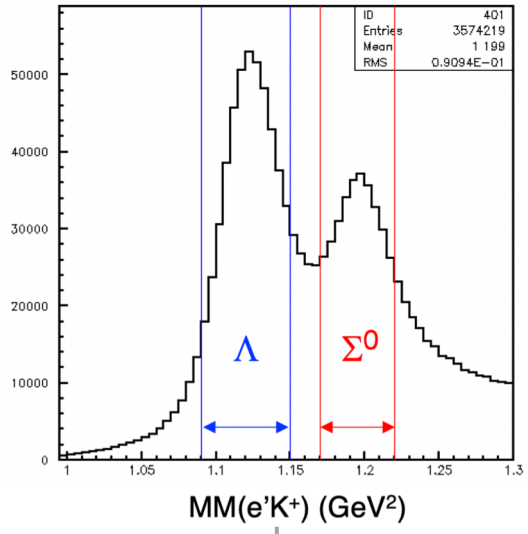
Beam-Recoil Transferred Polarization $\vec{e}p \rightarrow e'K^+\vec{Y}$

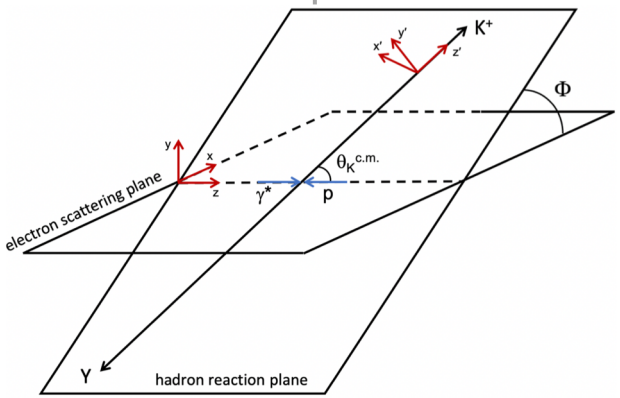
CLAS12 RG-K @ 6.535 GeV



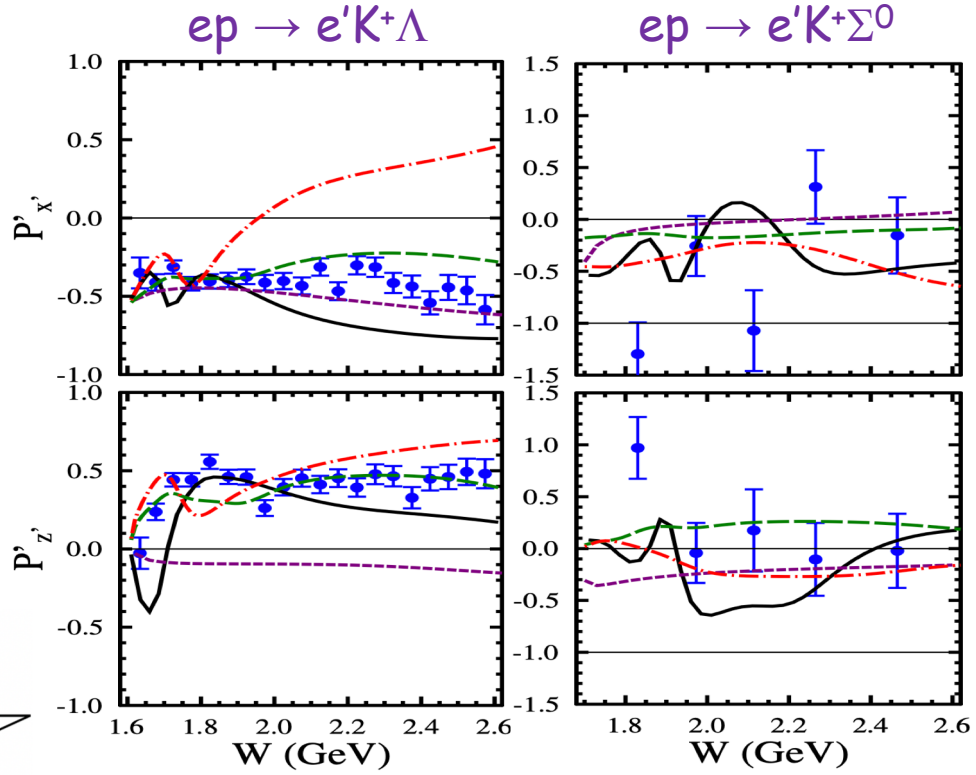
Publication in preparation

Raw uncorrected polarization





CLAS e1-6 @ 5.754 GeV



D.S. Carman et al., PRC79, 065205 (2009)

Mart/Bennhold	RPR-2
RPR-1	Regge

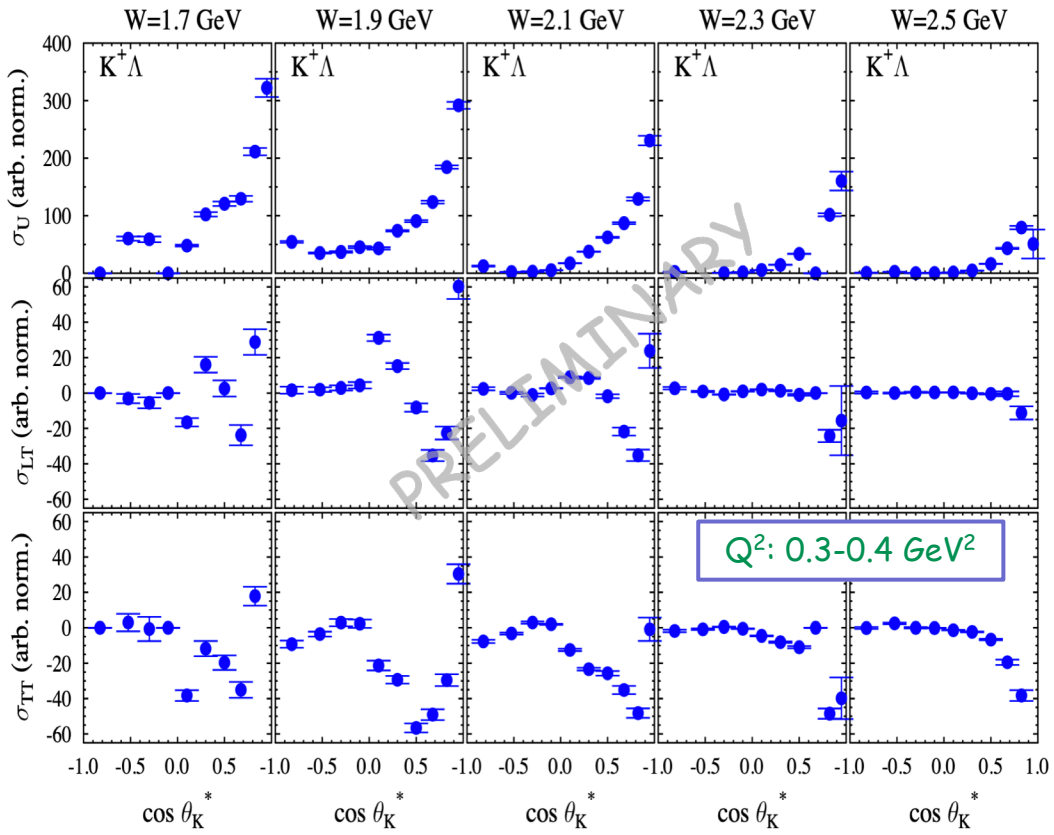
CLAS12 Cross Section Measurements

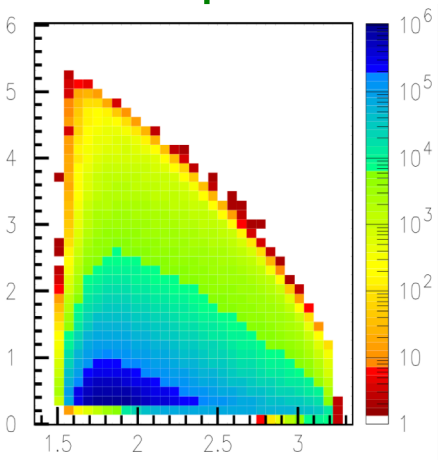
*see talk by Nick Markov

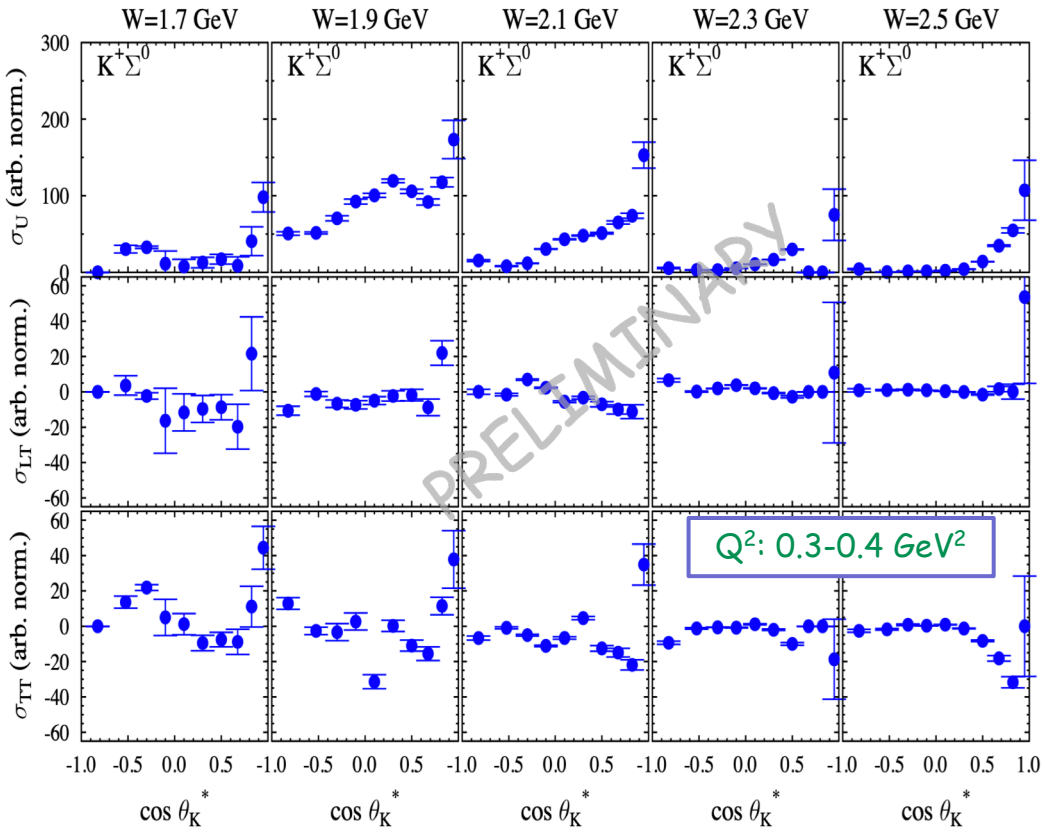
$ep \rightarrow e'K^+\Lambda$

$$\frac{d\sigma}{d\Omega} = (\sigma_T + \epsilon\sigma_L) + \sqrt{\epsilon(1+\epsilon)}\sigma_{LT}\cos\Phi + \epsilon\sigma_{TT}\cos 2\Phi$$

$ep \rightarrow e'K^+\Sigma^0$







6.535 GeV RG-K

$\sigma_{T,L,LT,TT} = f(Q^2, W, \cos\theta_K^*)$

Concluding Remarks

- The study of N* states is one of the key foundations of the CLAS physics program:
  - CLAS has provided a huge amount of data up to $Q^2 \sim 5\ GeV^2$ - dominating the world database
  - With the available reaction models for $N\pi$ and $N\pi\pi$, the electrocouplings of most N* states up to 1.8 GeV have been extracted from these data for the first time
  - A reaction model for the KY channels is needed to better understand the spectrum and structure of higher-lying N* states
- The CLAS12 N* program will extend these studies for $0.05 < Q^2 < 12\ GeV^2$:
  - Analysis of the collected data is underway – I have just skimmed the surface of our work
  - Program allows us to obtain ultimate information on the spectrum of high-lying resonances and continue search for missing conventional states and gluonic hybrids
  - Consistent results on the dressed quark mass function from the electrocouplings of different N* states will validate insight into sQCD – important to address the most challenging problems of the SM on the nature of confinement and the emergence of hadron mass