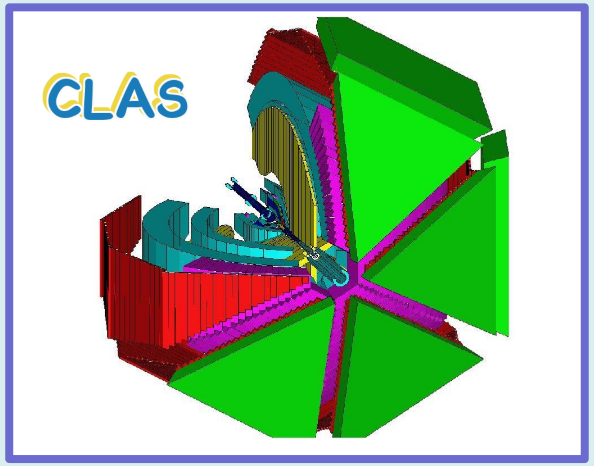
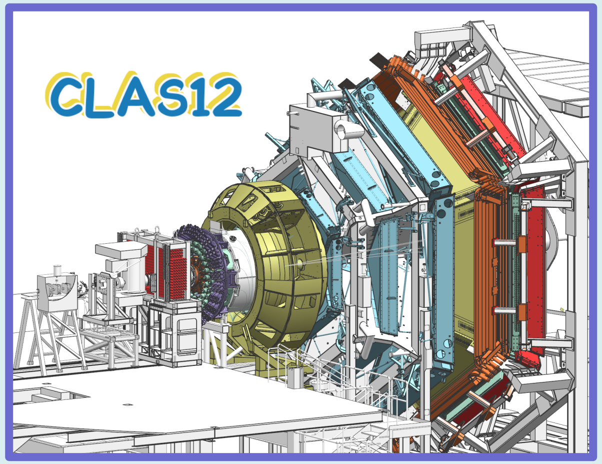
Baryon Spectroscopy and Structure Studies in Hall B





Daniel S. Carman
Jefferson Laboratory

clas
CEBAF Large Acceptance Spectrometer

Outline:

- Relevance of N* studies
- Hall B N* program
- Data from CLAS and CLAS12
- Future plans for N* studies
- Concluding remarks

Relevance of Studies of Excited Nucleon States

WHY N^*'s ARE IMPORTANT

NATHAN ISGUR
Jefferson Lab, 12000 Jefferson Avenue, Newport News, U. S. A.

The study of N^*'s can provide us with critical insights into the nature of QCD in the confinement domain. The keys to progress in this domain are the identification of its important degrees of freedom and the effective forces between them. I report on the growing evidence in support of the flux tube model, and comment on the

- Nucleons (and their excited states) are the stuff from which our world is made ⇒ they must be at the center of any discussion of why our Universe looks as it does.
- They are the simplest system in which the non-abelian character of QCD is manifest.
- Baryons are sufficiently complex to reveal physics hidden from us in mesons.

degrees of freedom and the effective forces between them.

Let me remind you why the basic degrees of freedom of QCD and the elementary gluon-mediated interactions between them are *not* useful starting points for understanding QCD in the confinement regime. It is not difficult

1

N. Isgur, N*2000 proceedings, World Scientific (2020)

particles MDPI

Review

Nucleon Resonance Electroexcitation Amplitudes and Emergent Hadron Mass

Daniel S. Carman [1,*,†], Ralf W. Gothe [2,*,†], Victor I. Mokeev [1,*,†] and Craig D. Roberts [3,4,*,†]

- Studies of the electroexcitation of nucleon resonances allow for essential insight into understanding hadron structure.
- Understanding the dynamics of the strong interaction that governs hadron mass generation is a challenging open problem in the Standard Model.
- Comparisons of data to approaches with a direct connection to QCD are essential … and now becoming possible.

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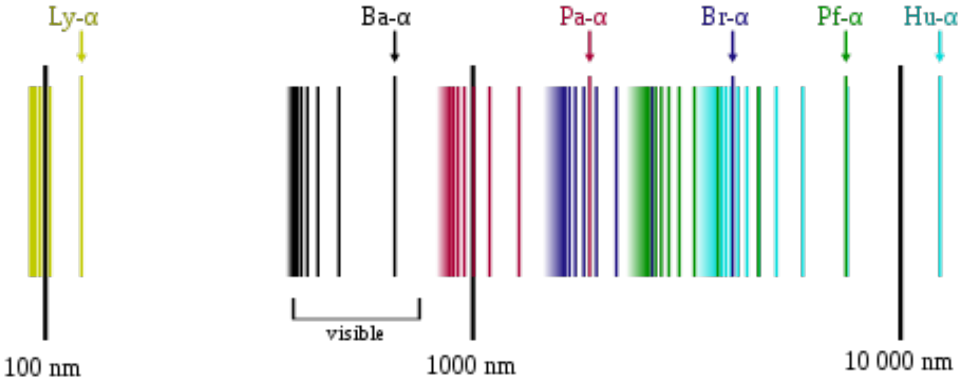
crucial challenge in modern hadron physics [1]. The rapid growth of α_s in the transition from the perturbative to sQCD domains and particularly its saturation, driven by gluon self-interactions, are predicted by CSMs [2,3] and supported by recent experimental results

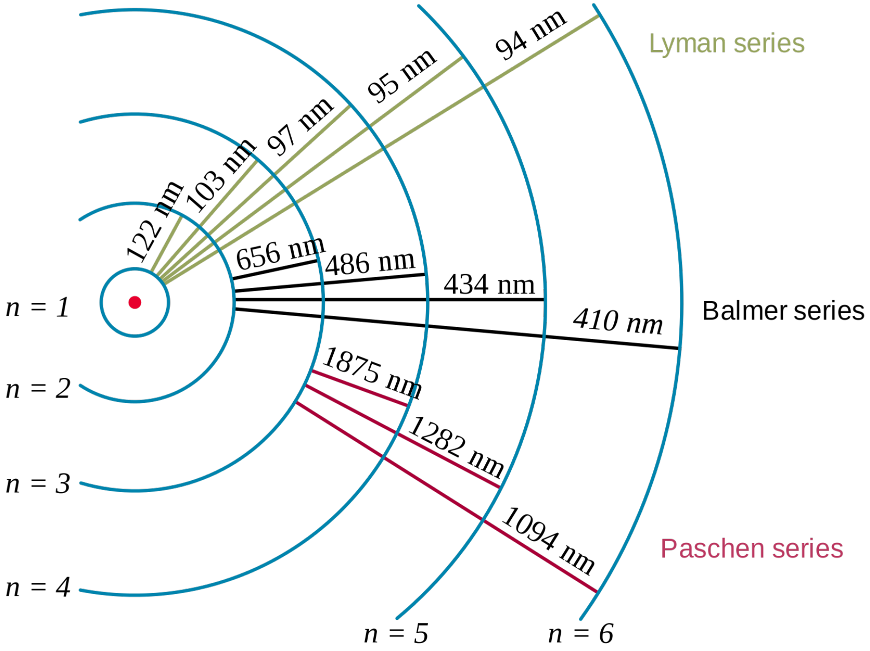
Particles **2023**, *6*, 416–439. https://doi.org/10.3390/particles6010023 https://www.mdpi.com/journal/particles

D.S. Carman, R.W. Gothe, V.I. Mokeev, C.D. Roberts, Particles 6, 416 (2023)

From the Hydrogen Spectrum to the N* Spectrum

N. Bohr





- Understanding the ground state of the hydrogen atom required understanding its excitation energy spectrum

  ⇒ Evolution from the Bohr model of the atom to Quantum Electrodynamics (QED)

- Likewise, understanding the ground state of the proton requires understanding its excitation energy spectrum *(the so-called N* states)*

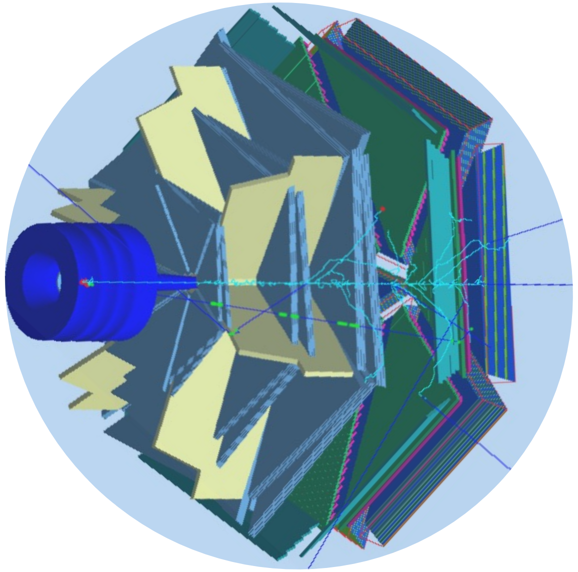
  ⇒ Evolution from the constituent quark model to Quantum Chromodynamics (QCD)

- The study of N* states is critical to charting the true character of the wavefunction of baryons

Many models have the same ground state, but only the one that captures the intricacies of the full excitation energy spectrum truly reflects nature

Hall B N* Program Overview and Goals

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

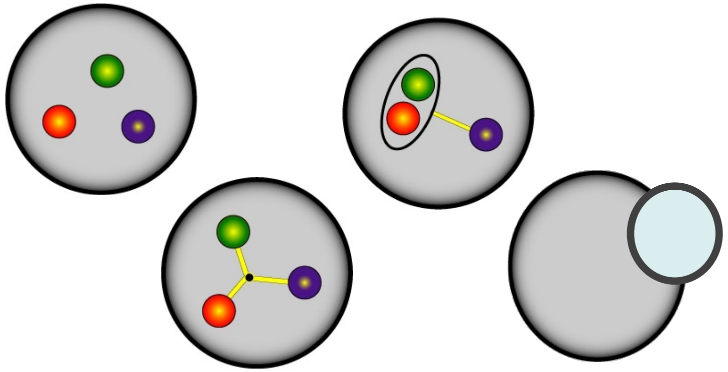


- CLAS & CLAS12 were designed to study exclusive reaction channels over a broad kinematic range:

  πN, ωN, ϕN, ηN, $\eta' N$, $\pi\pi N$, 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
    - provide insight into the origin of hadron mass and N* structure from the results on the electrocouplings of different N* states
    - search for hybrid baryons (qqqG) and other non-3q configurations
  - Data can unravel/reveal the spectrum of N* states

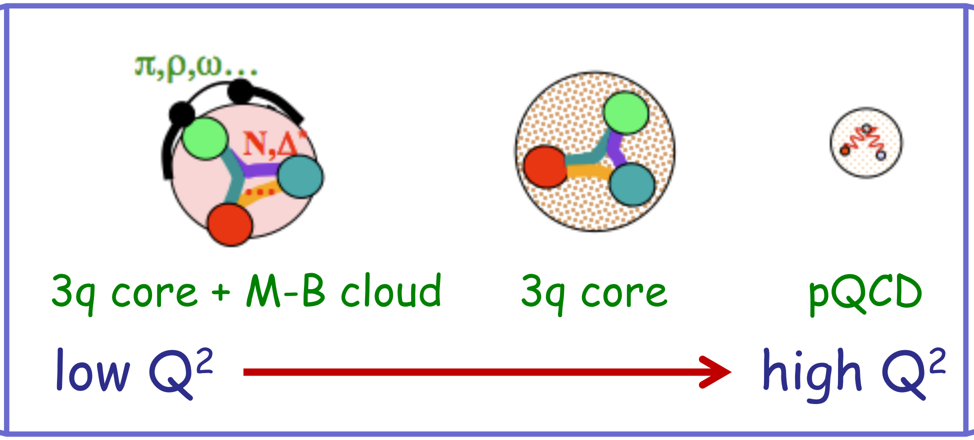
N* degrees of freedom??



Excited Nucleon Structure

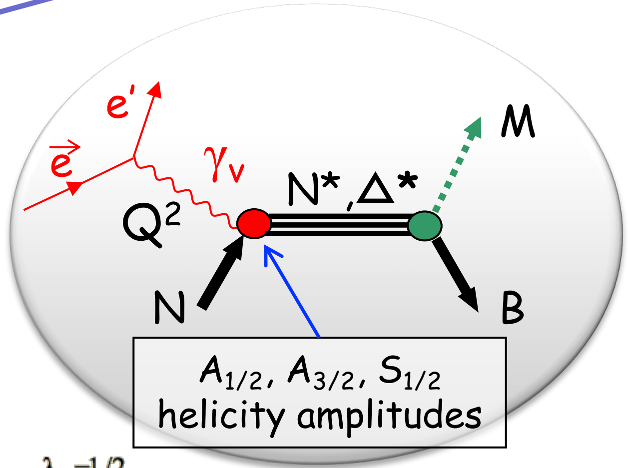
- N* structure is more complex than what can be described accounting for quark degrees of freedom only

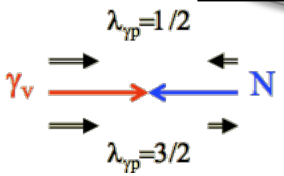
structure well described accounting for external meson-baryon cloud in addition to quark core
($Q^2 < 2$ GeV^2)



quark core dominates; transition from confinement to pQCD regimes
($Q^2 > 5$ GeV^2)

- Studies of the $\gamma_v pN^*$ electrocouplings from low to high Q^2 probe the detailed structure of the N* states
  - The underlying quark and gluon dynamics shape the structure of N* states and the Q^2 evolution of their 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 and their emergence from QCD

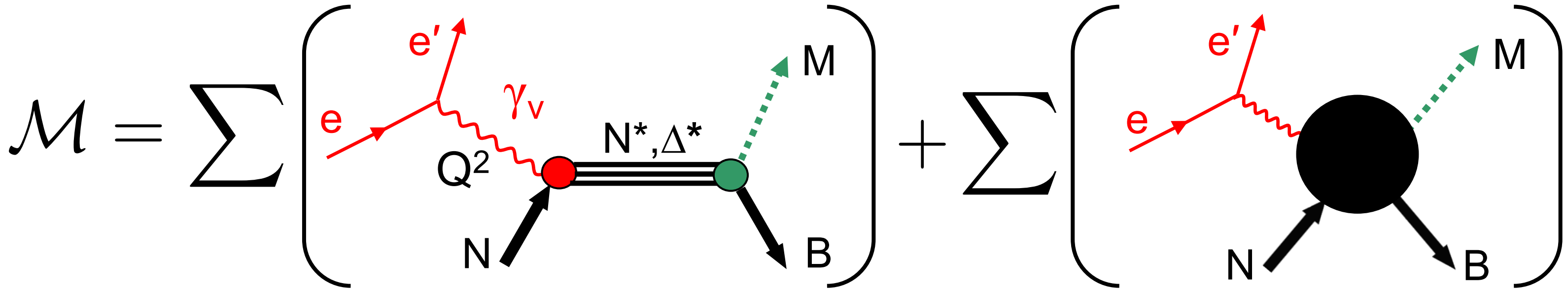




$A_{1/2}$, $A_{3/2}$ – transverse
$S_{1/2}$ - longitudinal

Connecting to Electroproduction Amplitudes

Resonant Amplitudes | Non-Resonant Amplitudes



- Cross sections of resonance r of mass M_r, width $\Gamma_{tot}(M_r)$, and spin J_r:

$$\sigma^r_{L,T}(W,Q^2) = \frac{\pi}{q_\gamma^2} \sum_{N^*,\Delta^*} (2J_r+1) \frac{M_r^2 \Gamma_{tot}(W) \Gamma_\gamma^{L,T}(M_r)}{(M_r^2 - W^2)^2 + M_r^2 \Gamma_{tot}^2(W)} \frac{q_\gamma}{K}$$

- The EM decay widths ($N^* \to N\gamma$) at $W=M_r$ are given by:

$$\Gamma_\gamma^L(M_r,Q^2) = 2\frac{q^2_{\gamma,r}(Q^2)}{\pi} \frac{2M_N}{(2J_r+1)M_r} |S_{1/2}(Q^2)|^2$$

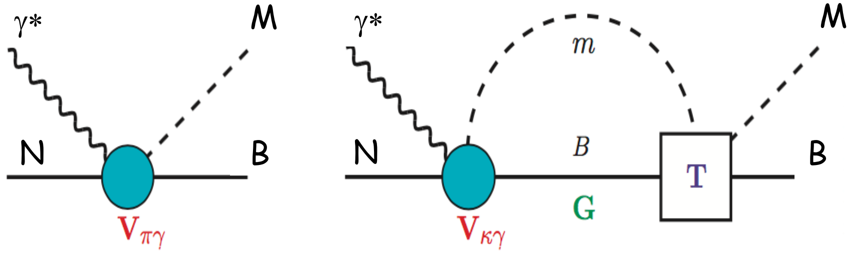
$$\Gamma_\gamma^T(M_r,Q^2) = \frac{q^2_{\gamma,r}(Q^2)}{\pi} \frac{2M_N}{(2J_r+1)M_r} (|A_{1/2}(Q^2)|^2 + |A_{3/2}(Q^2)|^2)$$

Single Channel Models:

- Simplicity (isobar, effective Lagrangian, multipoles)
- Single framework to study different channels
- Not a complete physics model but have proven to be useful and relevant

Coupled-Channel Models:

- Simultaneous fits to multiple independent channels (photo-, electro-, and hadroproduction)
- Treatment of FSI and re-scattering effects



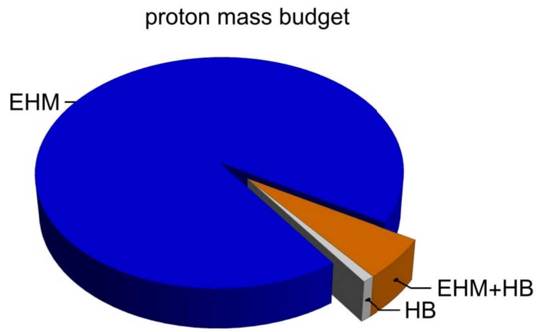
Coupled-channel approaches:

ANL-Osaka, Dubna-Mainz-Taipei, Julich-Bonn-Washington

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

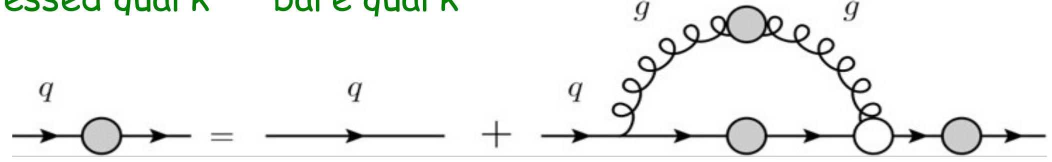
Emergence of Hadron Mass

- Standard Model of Particle Physics has one obvious mass-generating mechanism:
  - Higgs Boson … impacts are critical to the evolution of Universe as we know it
- However, the Higgs boson alone is responsible for just ~1% of the visible mass in the Universe
  - Proton mass budget … only 9 MeV/939 MeV is directly from Higgs



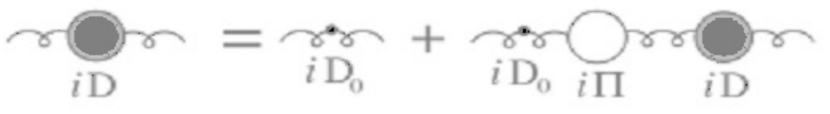
- Studies of ground/excited state nucleons probe EHM in a regime where the dressed quark masses are the dominant contribution to their physical mass
- Studies of pions and kaons are complementary to N/N* studies are also critical to unravel separation of EHM and Higgs mechanisms (AMBER@CERN, EIC/EicC)

dressed quark bare quark dressing kernel

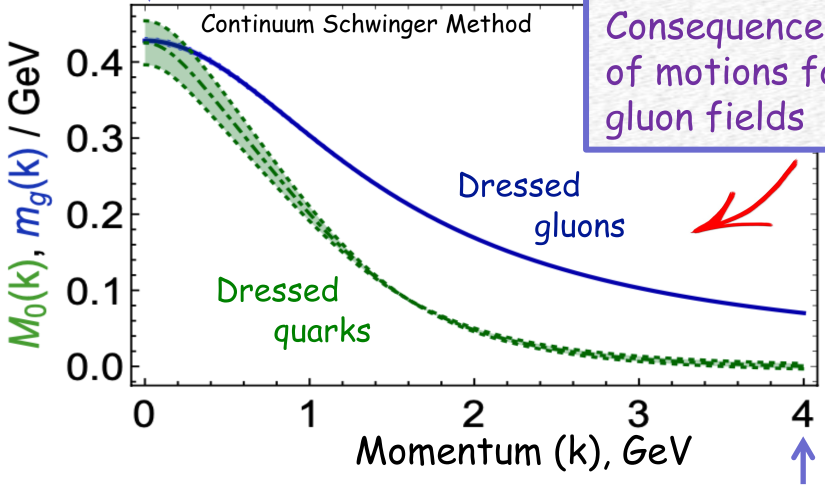


M=M(p) $m_0=m_{HM}$

dressed gluon bare gluon dressing kernel



confinement regime: constituent quark mass



Consequence of equations of motions for quark and gluon fields

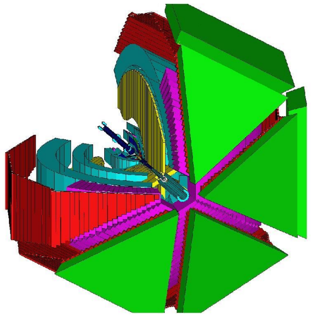
approaching bare Higgs mass

CLAS N* Program Measurement Overview

Reaction	Observable	Q^2 (GeV^2)	W (GeV)	Reference
ep --> $ep\pi^+\pi^-$	$d\sigma/dM$, $d\sigma/\cos\theta$, $d\sigma/d\alpha$	0.4 - 1.0	1.3 - 1.825	PRC 98, 025203 (2018)
		2.0 - 5.0	1.4 - 2.0	PRC 96, 025209 (2017)
		0.25 - 0.60	1.34 - 1.56	PRC 86, 035203 (2012)
		0.2 - 0.6	1.3 - 1.57	PRC 79, 015204 (2009)
		0.5 - 1.5	1.4 - 2.1	PRL 91, 022002 (2003)
ep --> $ep\pi^0$	$d\sigma/d\Omega$	0.4- 1.0	1.0 - 1.8	PRL 101, 015208 (2020)
	A_t, A_{et}	1.0 - 6.0	1.1 - 3.0	PRC 95, 035207 (2017)
	σ_U, σ_{LT}, σ_{TT}	1.0 - 4.6	2.0 - 3.0	PRC 90, 025205 (2014)
	σ_U, σ_{LT}, σ_{TT}	2.0 - 4.5	1.08 - 1.16	PRC 87, 045205 (2013)
	$d\sigma/dt$	1.0 - 4.6		PRL 109, 112001 (2012)
	$d\sigma/d\Omega$	3.0 - 6.0	1.1 - 1.4	PRL 97, 112003 (2006)
	A_t, A_{et}	0.187 - 0.77	1.1 - 1.7	PRC 78, 045204 (2008)
	$\sigma_{LT'}$	0.4 - 0.65	1.34 - 1.46	PRC 72, 058202 (2005)
	A_t, A_{et}	0.5 - 1.5	1.1 - 1.3	PRC 68, 035202 (2003)
	σ_U, σ_{LT}, σ_{TT}	0.4 - 1.8	1.1 - 1.4	PRL 88, 122001 (2002)
ep --> $en\pi^+$	A_t, A_{et}	1.0 - 6.0	1.1 - 3.0	PRC 95, 035206 (2017)
	A_t, A_{et}	0.05 - 5.0	1.1 - 2.6	PRC 94, 05520 (2016)
	A_t, A_{et}	0.0065 - 0.35	1.1 - 2.0	PRC 94, 045207 (2016)
	σ_U, σ_{LT}, σ_{TT}	1.8 - 4.5	1.6 - 2.0	PRC 91, 045203 (2015)
	$d\sigma/dt$	1.6 - 4.5	2.0 - 3.0	EPJA 49, 16 (2013)
	$\sigma_{LT'}$	0.4 - 0.65	1.1 - 1.3	PRC 85, 035208 (2012)
	σ_U, σ_{LT}, σ_{TT}, $\sigma_{LT'}$	1.7 - 4.5	1.15 - 1.7	PRC 77, 015208 (2008)
	σ_U, σ_{LT}, σ_{TT}	0.25 - 0.65	1.1 - 1.6	PRC 73, 025204 (2006)
	$\sigma_{LT'}$	0.4 - 0.65	1.34 - 1.46	PRC 72, 058202 (2005)
	σ_U, σ_{LT}, σ_{TT}	2.12 - 4.16	1.11 - 1.15	PRC 70, 042201 (2004)
	A_{et}	0.35 - 1.5	1.12 - 1.72	PRL 88, 082001 (2002)

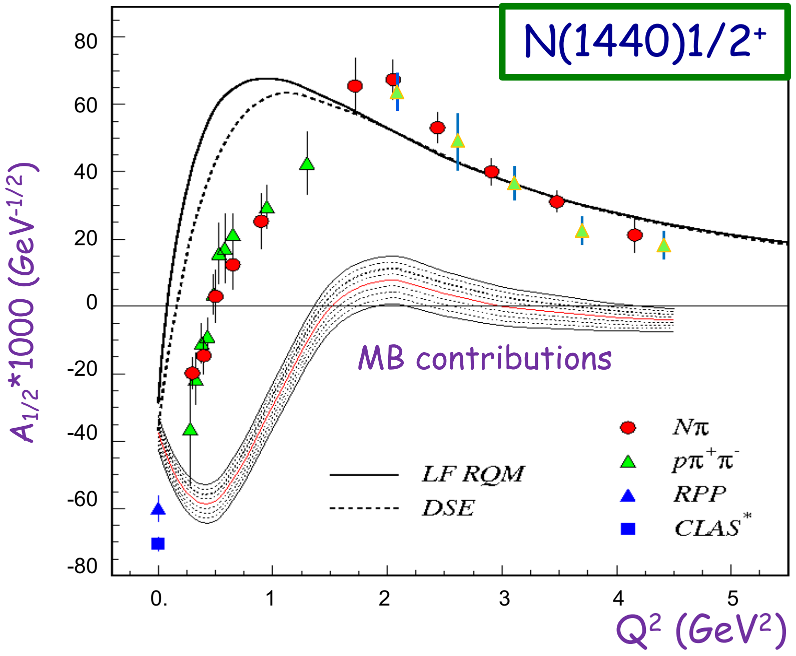
Reaction	Observable	Q^2 (GeV^2)	W (GeV)	Reference
en --> $ep\pi^-$	A_t, A_{et}	0.05 - 5.0	1.1 - 2.6	PRC 94, 05520 (2016)
ep --> $ep\eta$	σ_U, σ_{LT}, σ_{TT}	1.6 - 4.6	2.0 - 3.0	PRC 95, 035202 (2017)
	σ_U, σ_{LT}, σ_{TT}	0.13 - 3.3	1.5 - 2.3	PRC 76, 015204 (2007)
	$d\sigma/d\Omega$	0.25 -1.50	1.5 - 1.86	PRL 86, 1702 (2001)
ep --> eK^+Y	P^0	0.8 - 3.2	1.6 - 2.7	PRC 90, 035202 (2014)
	σ_U, σ_{LT}, σ_{TT}, $\sigma_{LT'}$	1.4 - 3.9	1.6 - 2.6	PRC 87, 025204 (2013)
	P'_x, P'_z	0.7 - 5.4	1.6 - 2.6	PRC 79, 065205 (2009)
	$\sigma_{LT'}$	0.65, 1.0	1.6 - 2.05	PRC 77, 065208 (2008)
	σ_U, σ_{LT}, σ_{TT}, $\sigma_{LT'}$	0.5 - 2.8	1.6 - 2.4	PRC 75, 045203 (2007)
	P'_x, P'_z	0.3 - 1.5	1.6 - 2.15	PRL 90, 131804 (2003)
ep --> $ep\omega$	σ_U, σ_{LT}, σ_{TT}	1.725 - 4.85	1.85 - 2.77	EPJA 24, 445 (2005)
ep --> $ep\rho^0$	σ_U	1.6 - 5.6	1.8 - 2.8	EPJA 39, 5 (2009)
	σ_L/σ_T	1.5 - 3.0	1.85 - 2.2	PLB 605, 256 (2005)
ep --> $ep\phi$	$d\sigma/dt$	1.4 - 3.8	2.0 - 3.0	PRC 78, 025210 (2008)
	$d\sigma/dt'$	0.7 - 2.2	2.0 - 2.6	PRC 63, 059901 (2001)

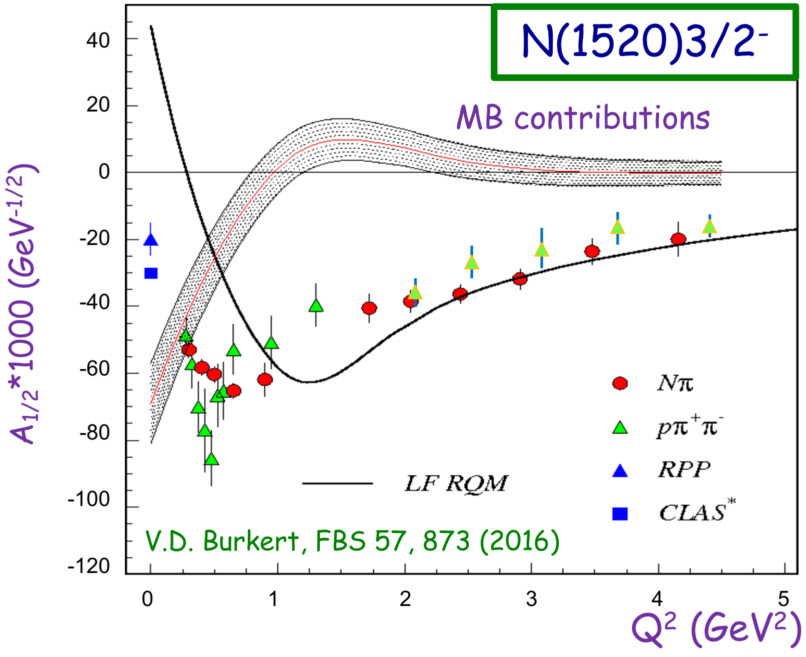
"Mining" of old CLAS data still in progress with several analyses currently ongoing



(1997-2012)

N* Electrocouplings from CLAS





CLAS Electrocoupling Extraction	
Channel	N*, Δ* States
$\pi^0 p$, $\pi^+ n$	Δ(1232)3/2+, N(1440)1/2+, N(1520)3/2-, N(1535)1/2-
$\pi^+ n$	N(1675)5/2+, N(1680)5/2+, N(1710)1/2+
ηp	N(1535)1/2-
$\pi^+\pi^- p$	N(1440)1/2+, N(1520)3/2- Δ(1620)1/2-, N(1650)1/2-, N(1680)5/2+, Δ(1700)3/2-, N(1720)3/2+, N'(1720)3/2+
http://userweb.jlab.org/~mokeev/resonance_electrocouplings23	

- Electrocouplings of different N* states reveal different interplay between meson-baryon 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

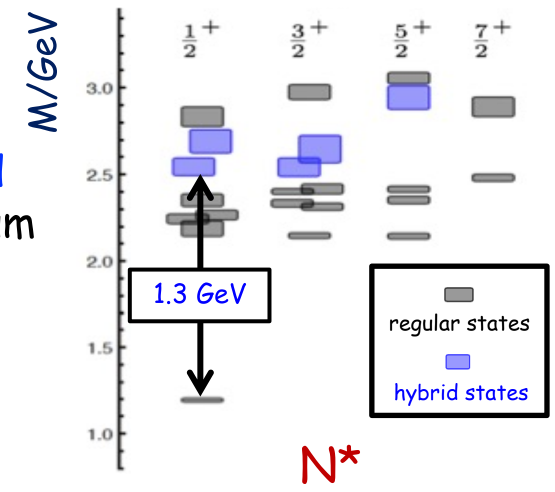
Hunting for Glue in Excited Baryons

Can glue be a structural component of excited baryon states?

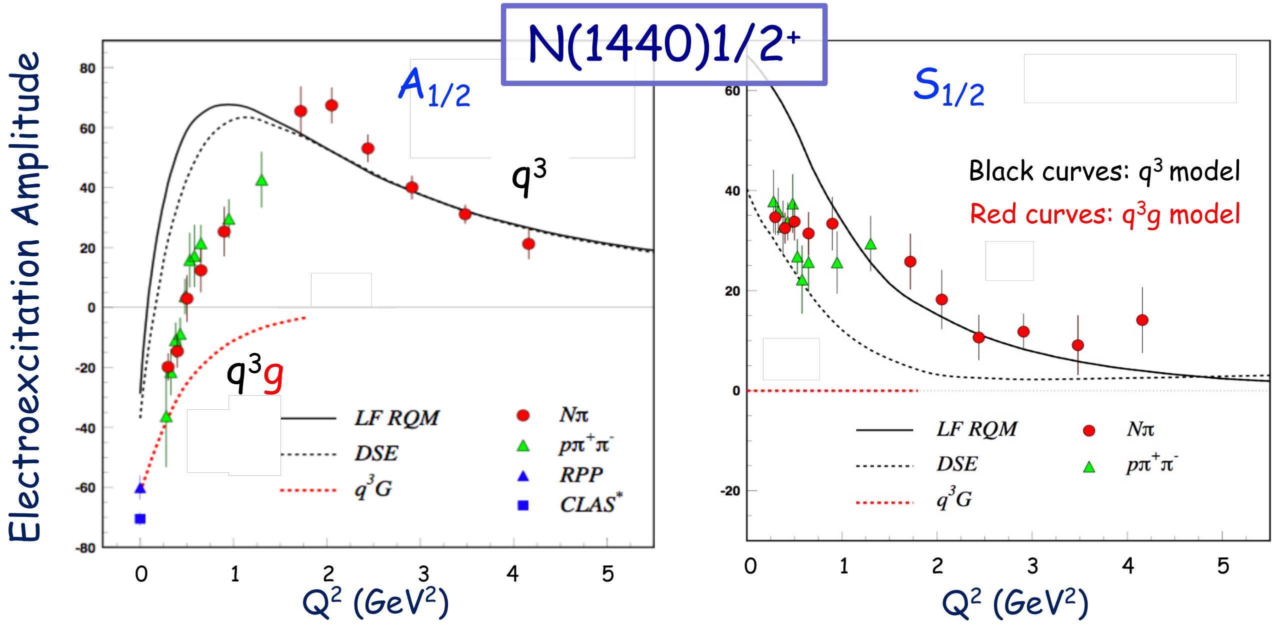
LQCD predicts hybrid baryons in N* spectrum

JLab LQCD group results

m_π=396 MeV



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



The signatures for hybrid baryons include:

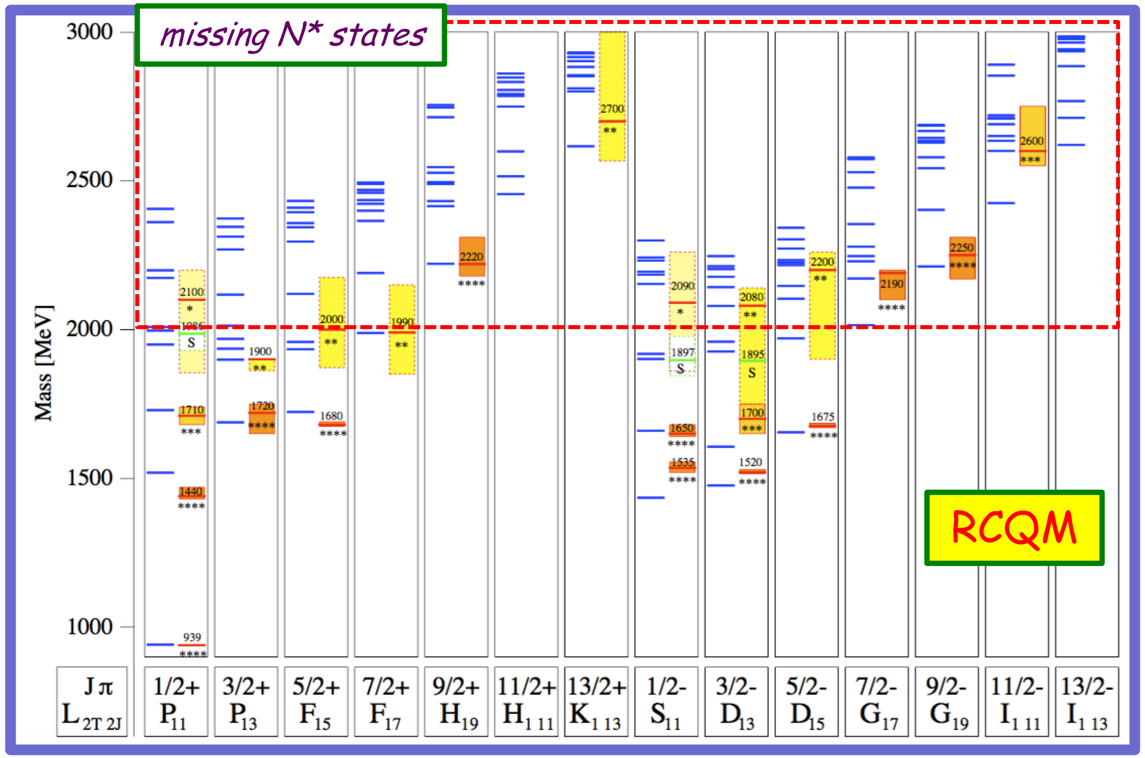
- Extra resonances with $J^\pi=1/2^+, 3/2^+$ in mass range 2.0-2.5 GeV and decays into Nππ or KY final states
- Drop of $A_{1/2}(Q^2)$ and $A_{3/2}(Q^2)$ faster than for ordinary 3q states due to extra glue-component in valence structure
- Suppressed $S_{1/2}(Q^2)$ relative to $A_{1/2}(Q^2)$ amplitude

Extractions of the Q^2 evolution of the electrocouplings are necessary for hybrid identification

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

Evolution of the N* Spectrum

State N(mass)J^P	PDG 2010	PDG 2020	πN	$K\Lambda$	$K\Sigma$	γN
N(1710)$1/2^+$	***	****	****	**	*	****
N(1875)$3/2^-$		***	**	*	*	**
N(1880)$1/2^+$		***	*	**	**	**
N(1895)$1/2^-$		****	*	**	**	****
N(1900)$3/2^+$	**	****	**	**	**	****
N(2000)$5/2^+$	*	**	*			**
N(2060)$5/2^-$		***	**	*	*	***
N(2100)$1/2^+$	*	***	***	*		**
N(2120)$3/2^-$		***	**	**	*	***
Δ(1600)$3/2^+$	***	****	***			****
Δ(1900)$1/2^-$	**	***	***		**	***
Δ(2200)$7/2^-$	*	***	**		**	***



U. Löring, B.C. Metsch, H.R. Petry, Eur. Phys. J. A 10, 395 (2001)

Recent LQCD predictions support CQM

J. Dudek, R. Edwards, PRD 85, 054016 (2012)

CLAS12 N* Program

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

E_b = 6.6, 8.8, 11 GeV, $Q^2 = 0.05 \rightarrow 12$ GeV^2, $W \rightarrow 3.0$ GeV, $\cos\theta_m^* = [-1:1]$

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	10.2 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
	Spr24 173 mC	6.4 GeV, 8.5 GeV 50% of total

1. Study higher-lying N* states:
   - confirm signals of new baryon states observed in $\gamma p \rightarrow KY$
   - explore full regime of "missing" quark model states
2. Understand active degrees of freedom that account for N* structure vs. distance scale:
   - explore dynamical structure of N* states from low to high Q^2 – meson-baryon cloud to quark degrees of freedom
   - search for predicted qqqg hybrid baryons
3. Probe quark dressing effects and di-quark correlations in N* structure:
   - important aspect of N* structure and electrocoupling amplitudes
   - provide insight into emergence of hadron mass vs. Q^2
   - N* states of different structure allow study of different qq correlations

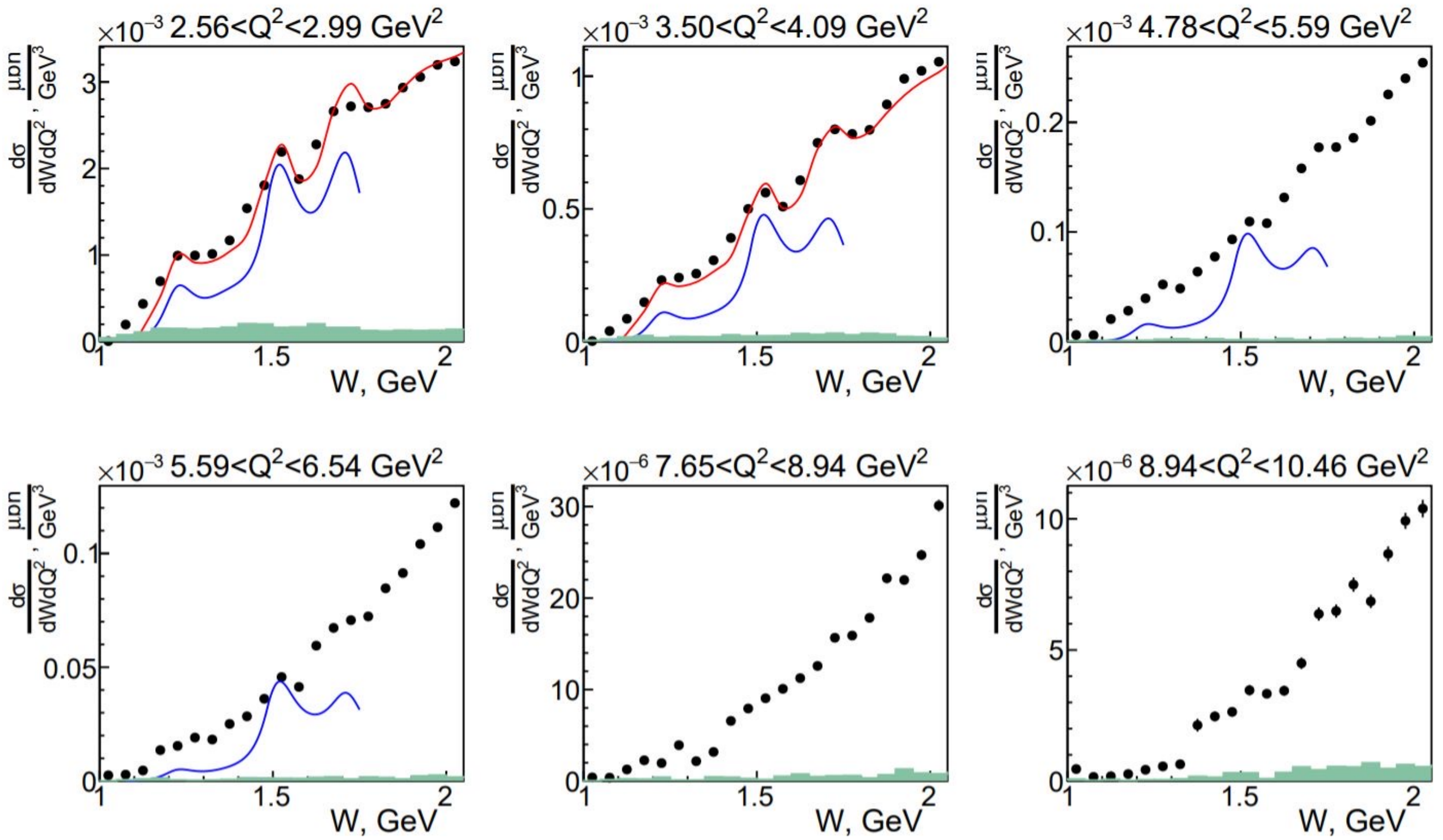
Inclusive Cross Sections from CLAS12

- First results on (e,e'X) inclusive cross sections in the resonance region at Q^2 from 2-10 GeV^2 with a broad coverage over W in any Q^2-bin

interpolation of CLAS results
M. Osipenko et al. (CLAS), PRD 67, 092001 (2003)
A.A. Golubenko et al., Prog. Part. Nucl. 50, 587 (2019)

- Evaluated resonance contributions probe the nucleon PDF to provide new opportunities to explore quark hadron duality

resonant contribution computed with $\gamma_v pN^*$ electrocouplings from CLAS data
A.N. Hiller Blin et al., PRC 104 025201 (2021)



CLAS12 Preliminary - under internal review

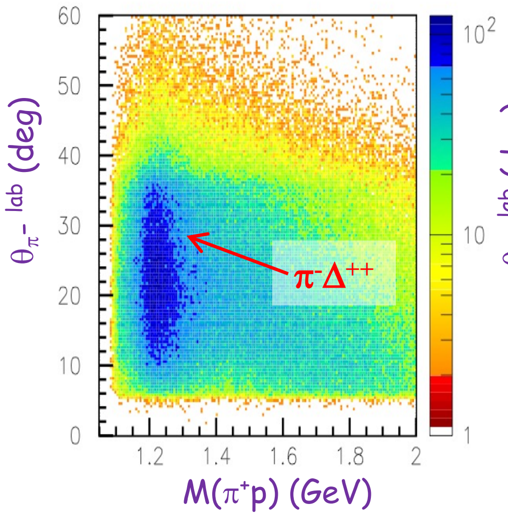
V. Klimenko, UConn

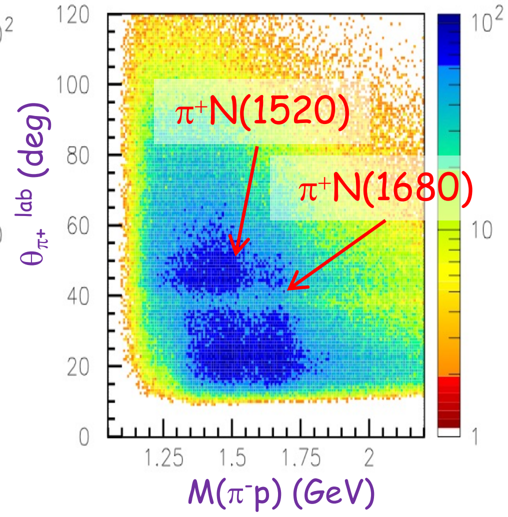
*talk on Tuesday afternoon

- Studies of inclusive structure function moments will shed light on the nucleon structure evolution in the transition from the strongly coupled to pQCD regimes

Two Pion Cross Sections from CLAS12

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

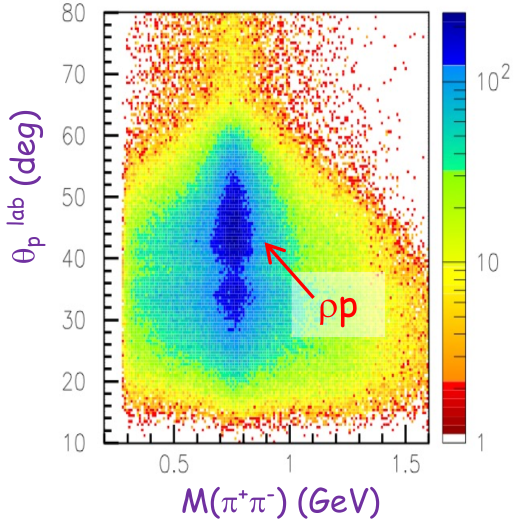




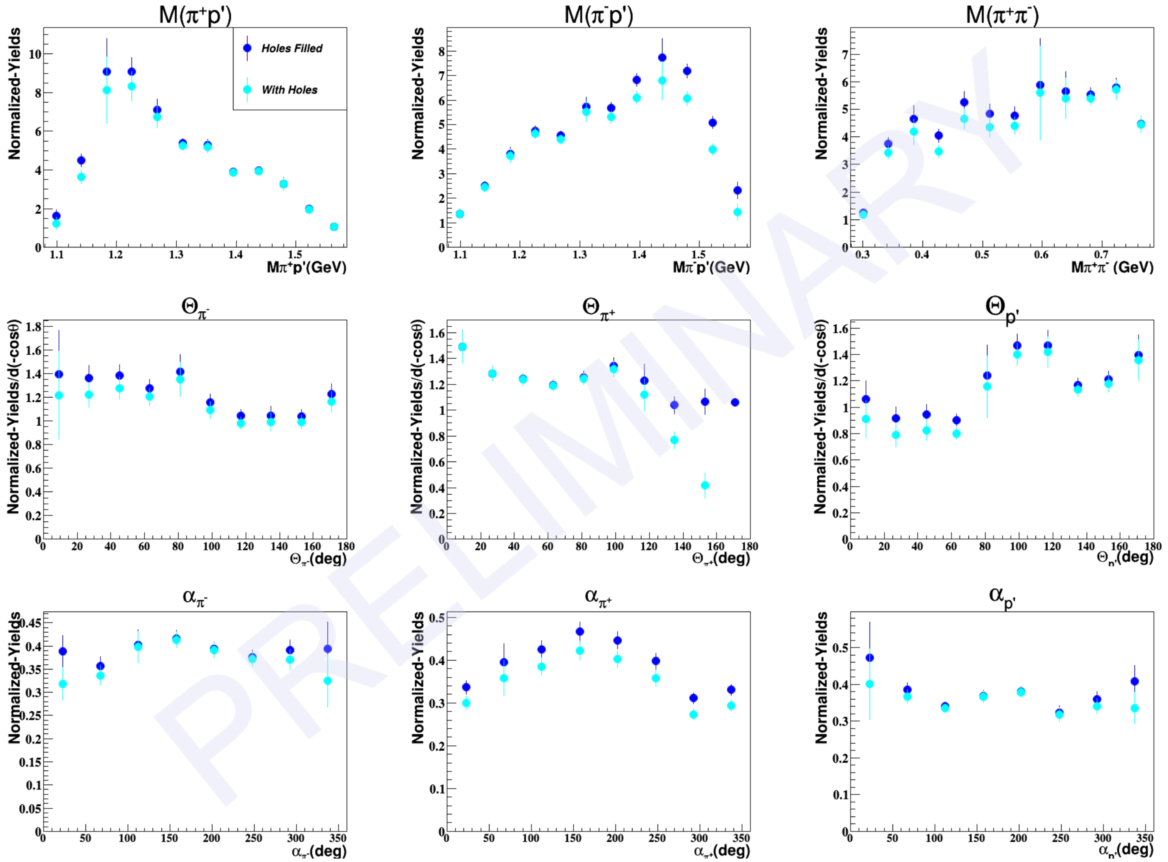
Topologies:

1) Fully exclusive
2) Missing π^-
3) Missing π^+
4) Missing p

RG-A @ 10.6 GeV



Normalized yields: Q^2:[3.0-3.5] GeV^2, W:[1.725:1.750] GeV

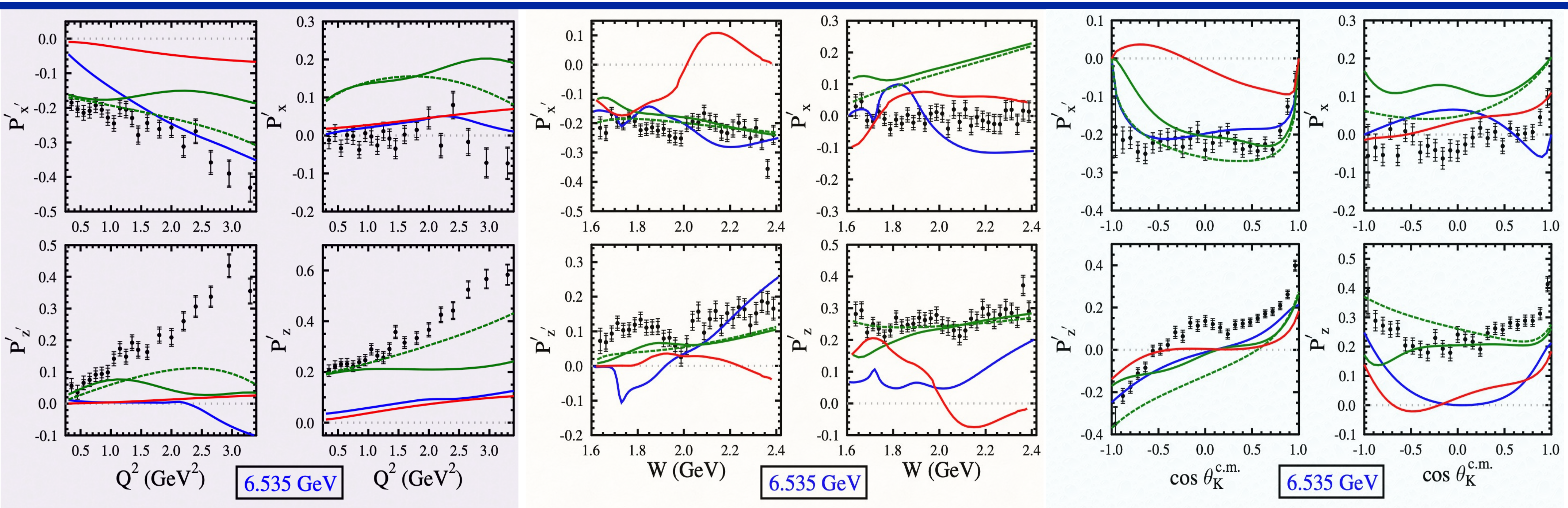


- Particle ID
- Yield extraction
- Monte Carlo acceptance (TWOPEG)
- Momentum corrections
- Radiative corrections
- Systematic studies

Extraction of cross sections advancing

K. Neupane, USC

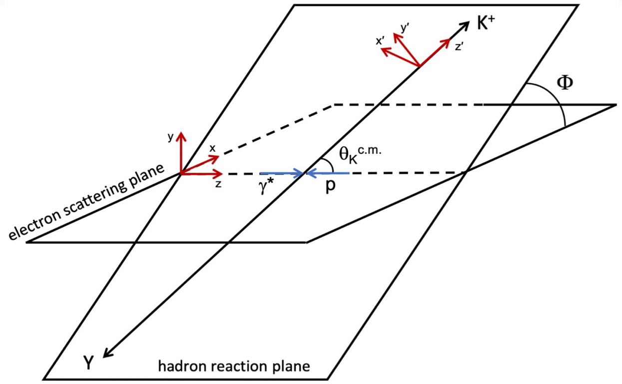
Beam-Recoil Λ Transferred Polarization from CLAS12



D.S. Carman et al. (CLAS), PRC 105, 065201 (2022)

RG-K @ 6.5 GeV

Model	Year	Type	Fit Data	N* States
Kaon-MAID	2000	Isobar	none	1/2, 3/2
RPR	2011	Isobar+Regge	CLAS γp	1/2, 3/2, 5/2
BS3	2018	Isobar	CLAS γp + ep	1/2, 3/2, 5/2



Concluding Remarks

- Nucleons and their excited states are the most fundamental three-body systems in Nature. If we don't understand how QCD builds each state in the spectrum, then our understanding of QCD is incomplete.

- 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 - electrocouplings of most N* states up to 1.8 GeV have been extracted from these data for the first time

- The CLAS12 N* program is extending these studies for $0.05 < Q^2 < 12$ GeV^2:
  - Analysis of the collected data is underway – first analyses from CLAS12 N* program focused on inclusive, 2π, and KY final states
  - These data will be important input to address the most challenging problems of the Standard Model on the nature of hadron mass, confinement, and the emergence of N* states
  - Consistent results on the N* electroexcitation amplitudes from different reaction channels will validate insights learned on the emergence of hadron mass from QCD-connected models
    - complementary to studies of EHM of the structure of pions and kaons

- Considering a future for JLab beyond 12 GeV era – JLab at 22 GeV @ *the luminosity frontier*

A. Accardi et al., arXiv: 2306.09360 (in press Eur. Phys. J. A)

Backup Slides

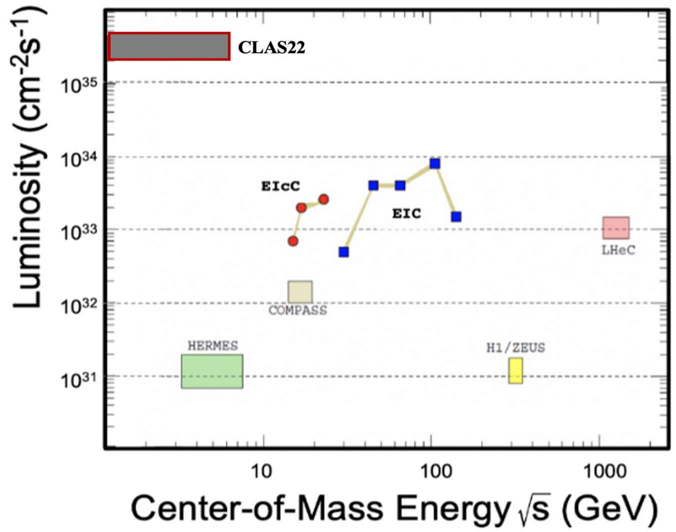
JLab Energy Upgrade

Energy and luminosity increase are needed to explore N* structure at $Q^2 > 10$ GeV^2

Goal to map out the dressed quark mass over the entire range of quark momenta where the dominant part of hadron mass is generated

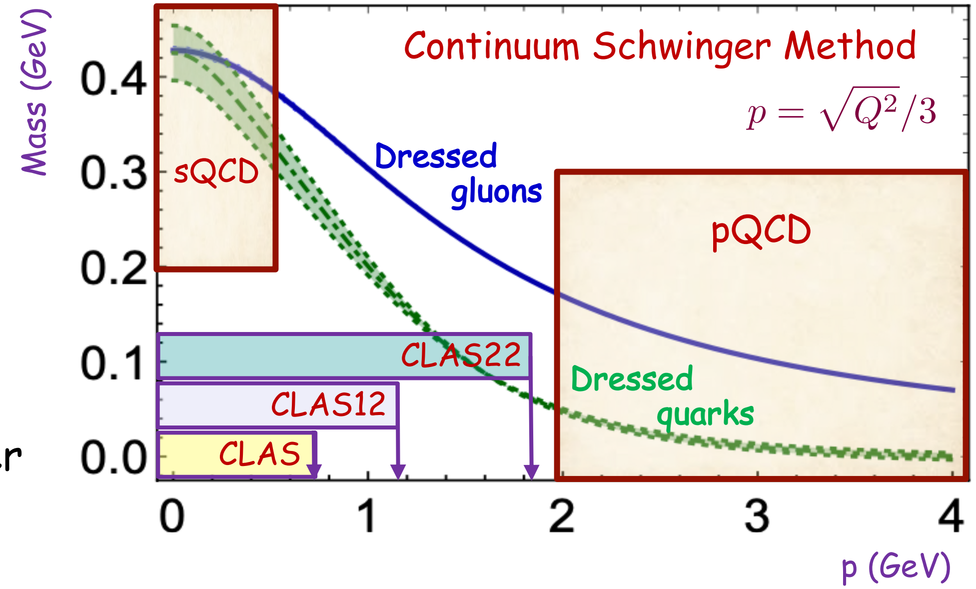
The electroproduction measurements foreseen at JLab in Hall B after completion of the 12 GeV program:

- Beam energy 22 GeV
- Nearly 4π coverage
- High luminosity
- Studies of exclusive reactions



Both EIC and EIcC would need much higher luminosity to carry out such a program

The luminosity frontier is a *unique* advantage of JLab



For program details see:

https://userweb.jlab.org/~carman/clas22