Hadron Structure Studies at "CLAS24"

Insights into EHM with an Energy-Upgraded CEBAF

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Spectroscopy with a CEBAF Energy Upgrade

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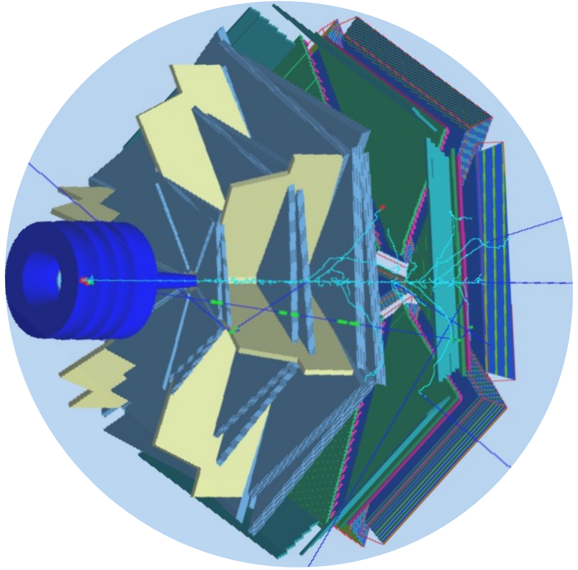
Hybrid
US/Eastern timezone

Outline:

- CLAS/CLAS12 N* Program
- Prospects for N* program at 24 GeV
- JLab Upgrade and "CLAS24" Considerations
- Summary/Concluding Remarks

Hall B N* Program Overview

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

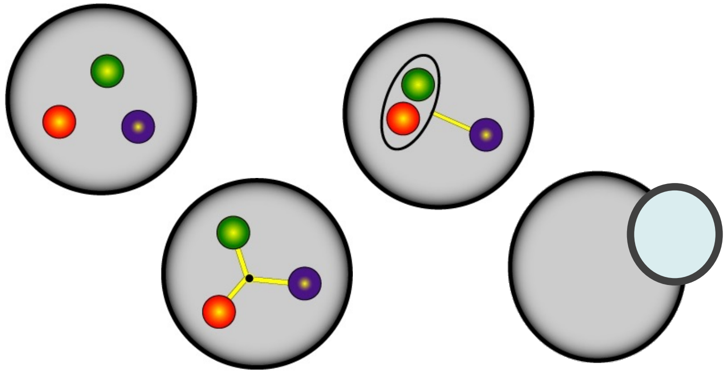


- CLAS & CLAS12 were designed to study exclusive reaction channels over a broad kinematic range:

  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 strong interaction in the regime of large QCD running coupling from the electrocouplings of different N* states

N* degrees of freedom??

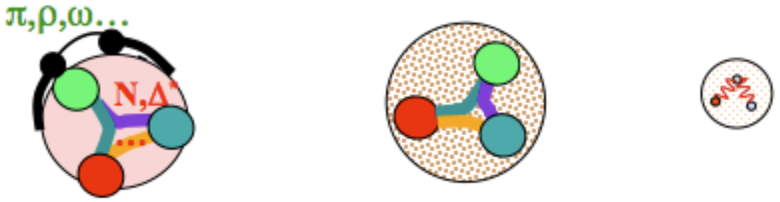


The Q^2 evolution of the extracted N* electrocouplings offers unique insights into the emergence of hadron mass (EHM)

Excited Nucleon Structure

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

structure well described by adding an external M-B cloud to quark core
($Q^2 < 2$ GeV^2)

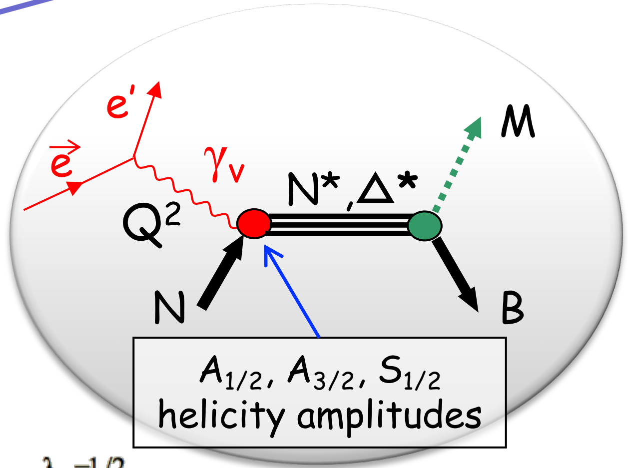


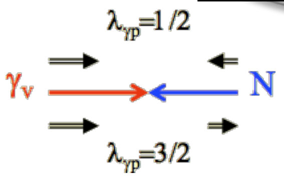
3q core + M-B cloud | 3q core | pQCD

low Q^2 → high Q^2

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

- 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 underlying degrees of freedom 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

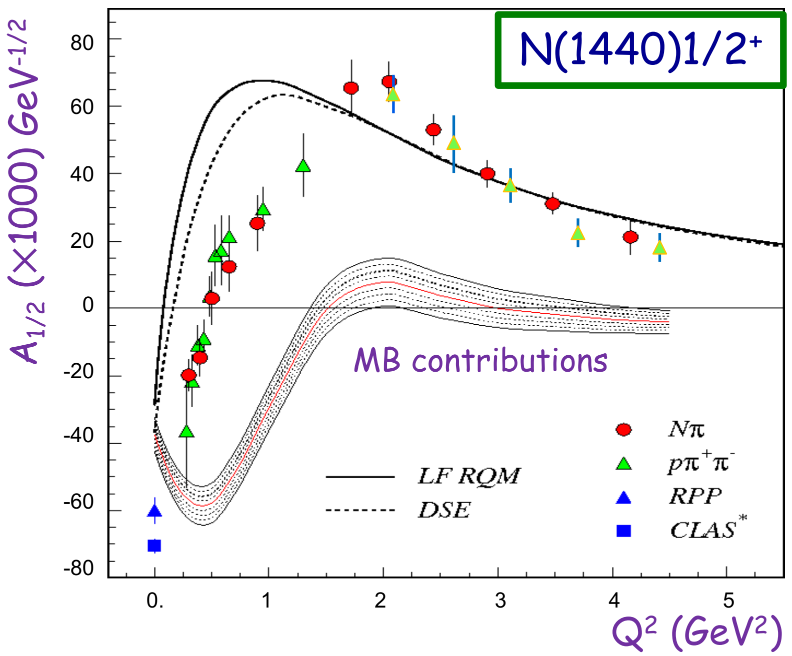


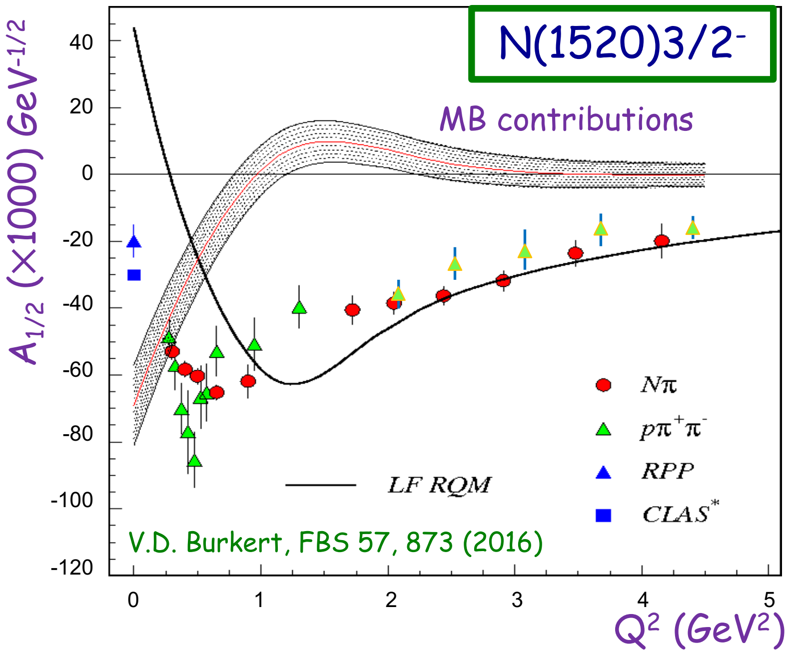


$A_{1/2}$, $A_{3/2}$ – transverse

$S_{1/2}$ - longitudinal

N* Electrocouplings from CLAS





CLAS Electrocoupling Extraction	
Reaction 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+

- Electrocouplings 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
    - KY channels hold promise to enable comparisons to Nππ for higher-lying states where Nπ coupling is small
- Data on the electrocouplings over broad range of Q^2 are needed in order to:
  - Map out the transition from meson-baryon to confined quark degrees of freedom
  - Gain fundamental insight into strong QCD dynamics that underlines hadron mass generation

Emergence of Hadron Mass

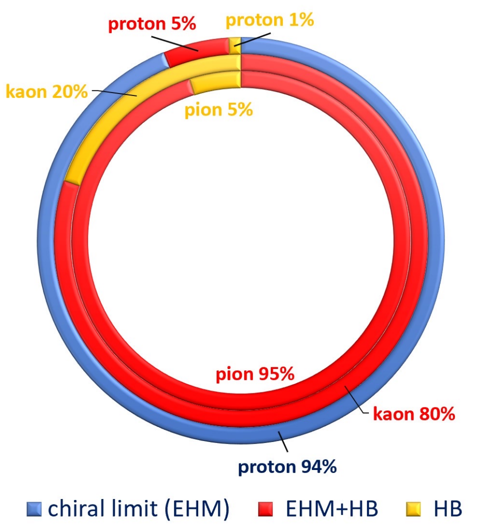
Standard Model paradigm:

- Proton is described by QCD … 3 valence quarks
- Pion is also described by QCD … 1 valence quark and 1 valence antiquark

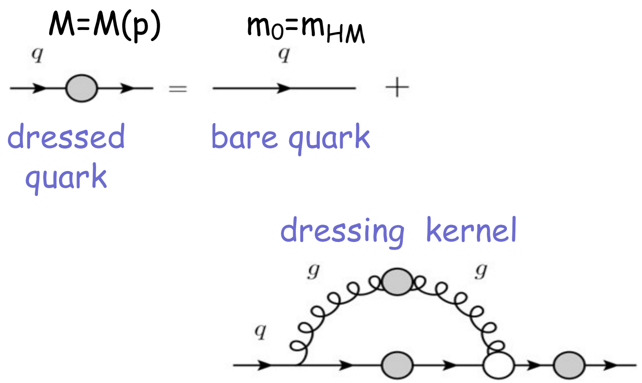
Why is ≈ 1 GeV proton mass paired with ≈ 1/7 GeV pion mass in the same theory of Nature?

- Ground/excited state nucleons probe EHM in an arena where the sum of the dressed quark masses is the dominant contribution to the physical mass
- Studies of differences π vs. K structure are also critical to unravel/test separation of emergent and Higgs mechanisms (AMBER@CERN, EIC/EicC)
- Consistent results on the momentum evolution of the dressed quark mass function from studies of baryons and mesons are of importance for the validation of insight into EHM

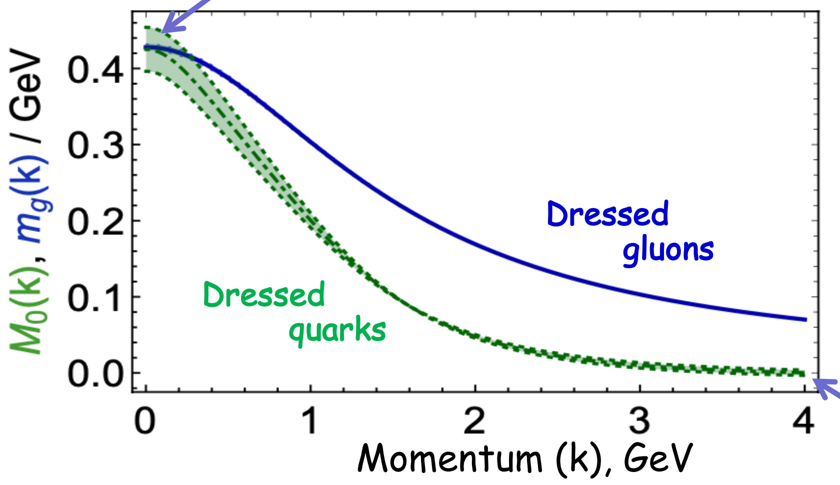
Mass Budgets



Effective quark mass depends on its momentum



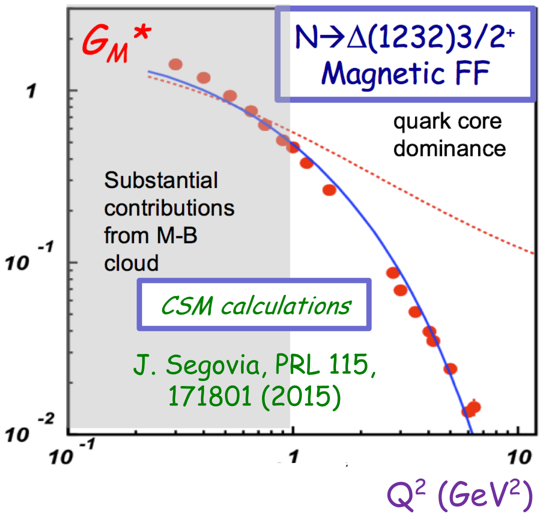
confinement regime: constituent quark mass

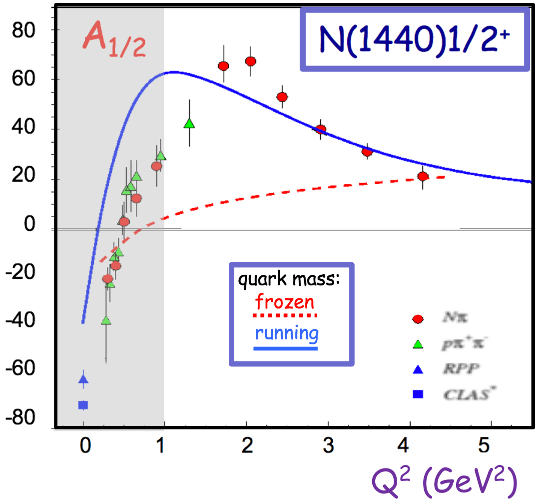


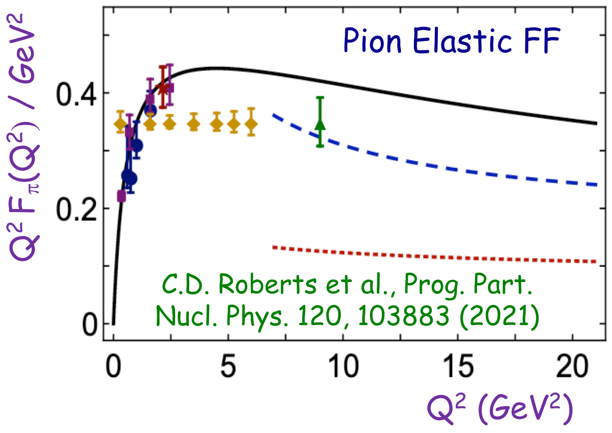
Courtesy of C.D. Roberts

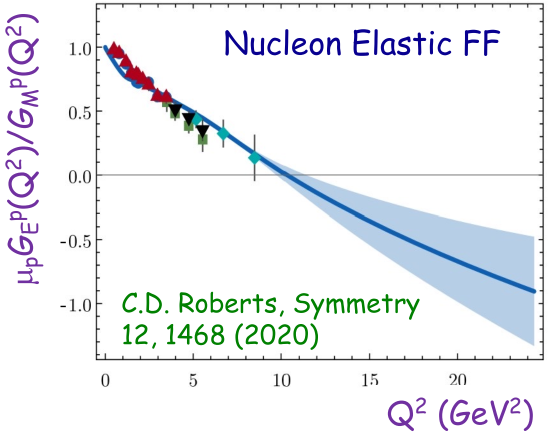
approaching bare Higgs mechanism mass

Data Results vs. QCD Expectations



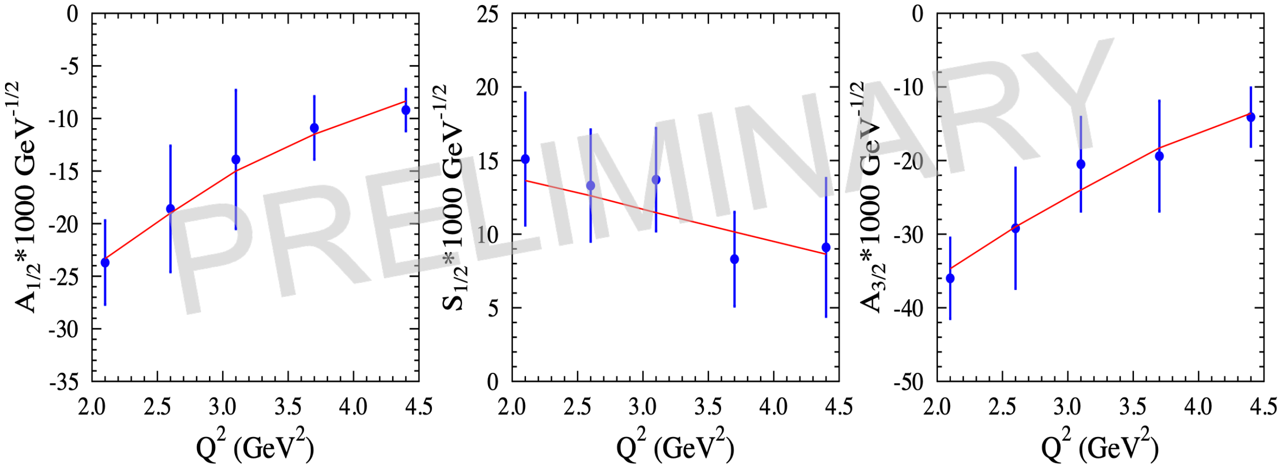






Description of pion, nucleon elastic FF and Δ(1232)3/2+, N(1440)1/2+, Δ(1600)3/2+ electrocouplings achieved ***with the same dressed quark mass function***

Δ(1600)3/2+ Electrocouplings



NEW

continuum QCD predictions:
- Ya Lu et al., Phys. Rev. D 100, 034001 (2019)

Experimental ep → e'pπ+π- data from CLAS:
- V. Mokeev, AMBER@CERN-VII Workshop

Together these different results ***confirm the CSM predictions***, solidifying evidence for the momentum evolution of the dressed quark mass and its role in describing the emergence of hadron mass

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

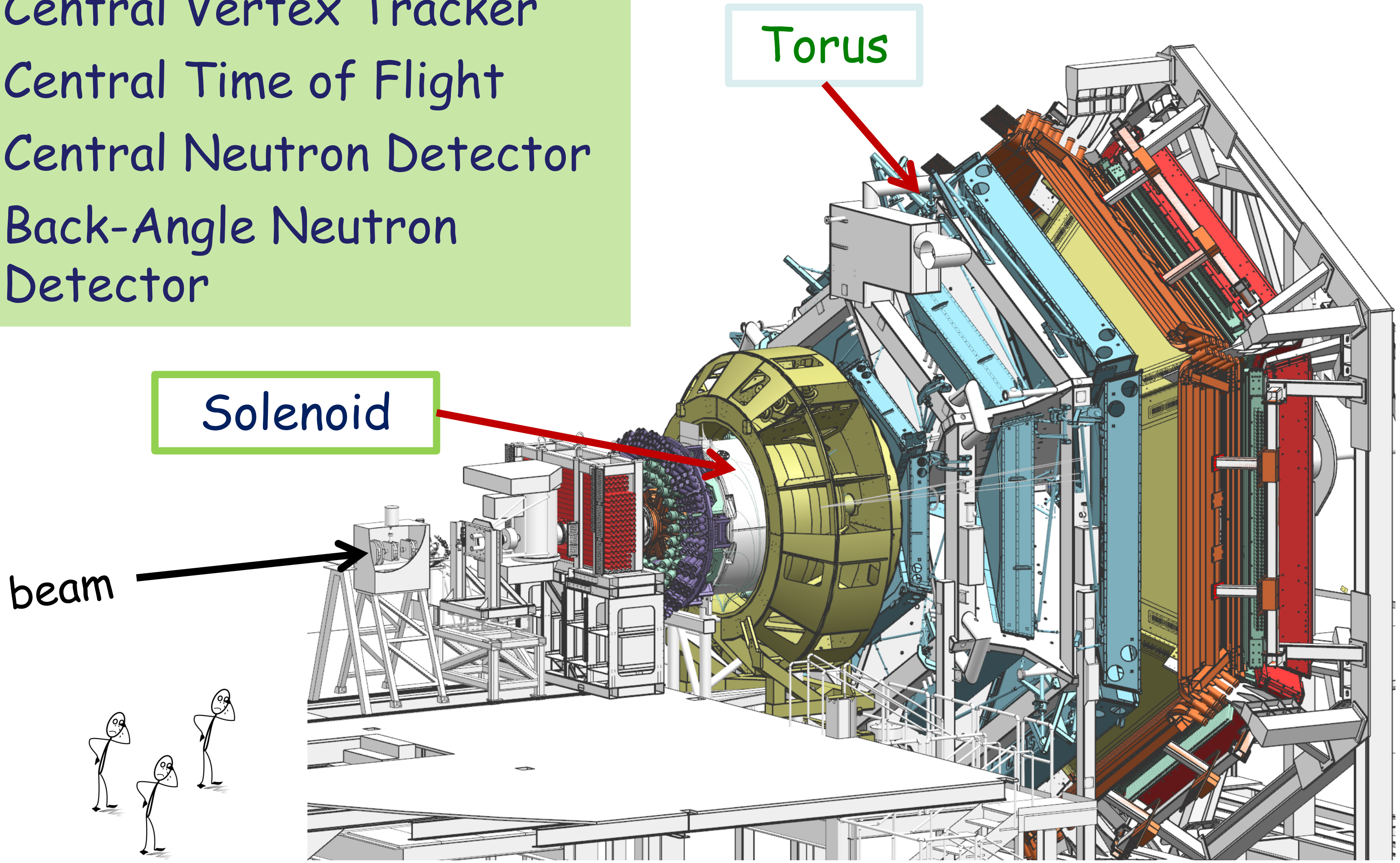
RG-A	Spr. 18 126 mC	10.4 GeV, 10.6 GeV 50% of total
	Fall 18 99 mC	
	Spr. 19 58 mC	
RG-K	Fall 18 28 mC	6.5 GeV, 7.5 GeV 10% of total

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 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
   - expect precision in electroproduction to match photoproduction for Q^2 < 2-3 GeV^2
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
   - different N* quantum numbers allow study of different qq correlations

CLAS12 Spectrometer

CENTRAL

- Beamline
- Target
- Central Vertex Tracker
- Central Time of Flight
- Central Neutron Detector
- Back-Angle Neutron Detector



FORWARD

- High Threshold Cherenkov
- Forward Tagger
- Drift Chambers
- Low Threshold Cherenkov
- Ring Imaging Cherenkov
- Forward Time of Flight
- EM Calorimeter

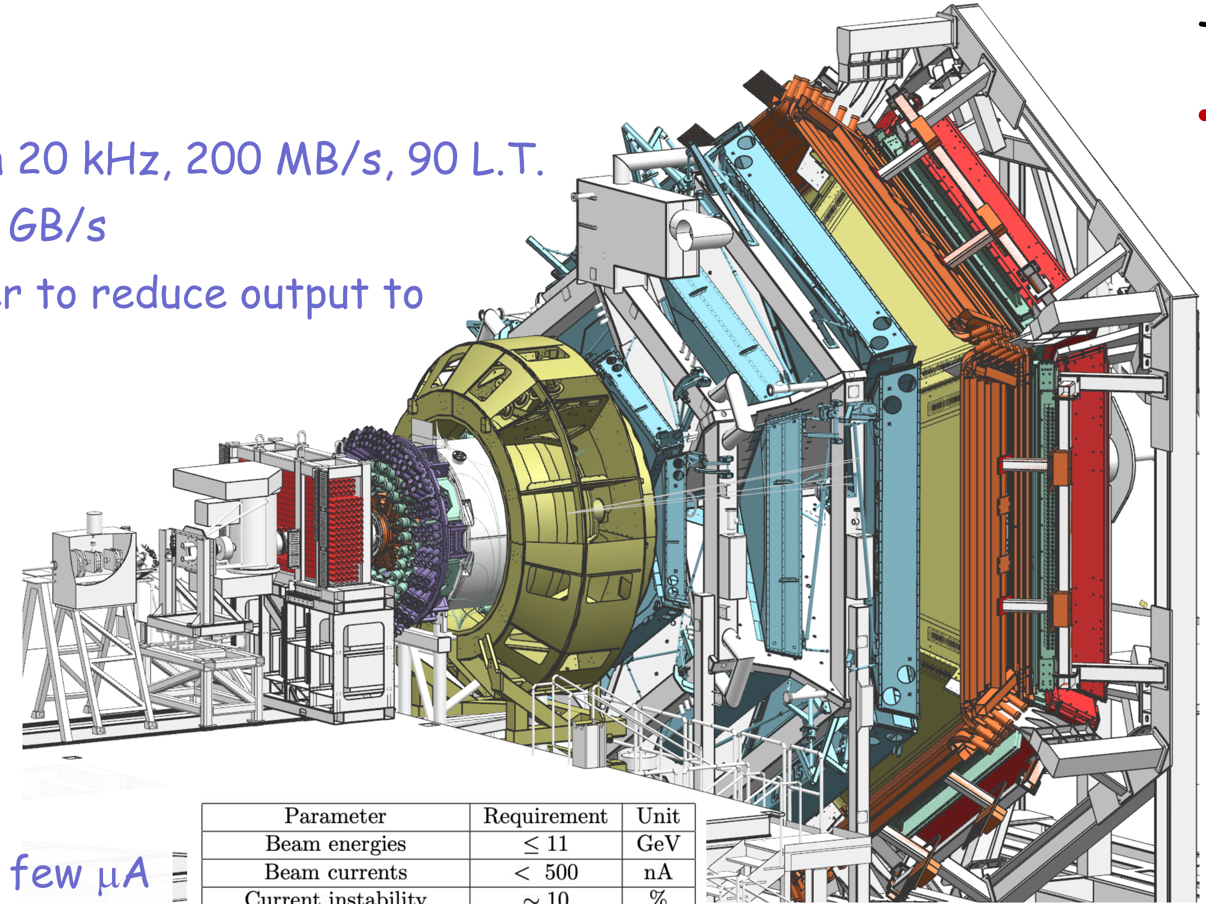
$$\mathcal{L}_{max} = 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

	Forward	Central
Angular coverage	5° – 35°	35° – 135°
Momentum resolution	$\delta p/p < 1\%$	$\delta p/p < 5\%$
θ resolution	1 mrad	5 – 10 mrad
ϕ resolution	1 mrad/sinθ	5 mrad/sinθ

Hall B “CLAS24” Upgrade

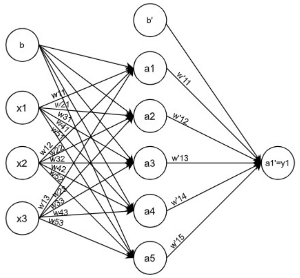
DAQ:

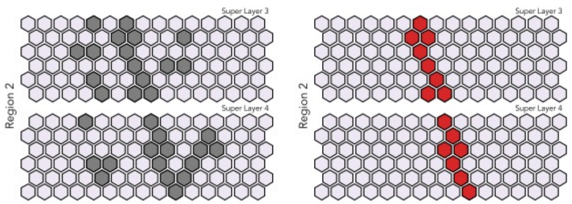
- Present operation 20 kHz, 200 MB/s, 90 L.T.
- Push to 30 kHz, 1 GB/s
- Develop L3 trigger to reduce output to tape/storage



Tracking:

- AI-based cluster finder; necessary to keep tracking efficiency $\varepsilon >$ 85% for higher luminosity operations



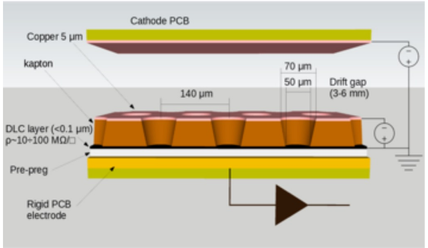


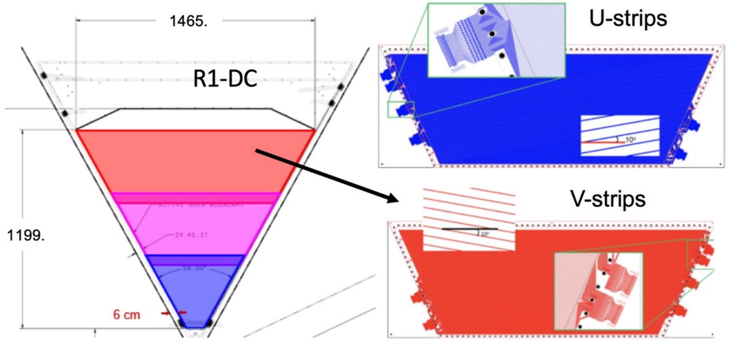
- Inclusion of new high-resolution μ-strip detectors (μRWell) to separate track from background hit segments

Beamline:

- Beam currents to few μA
- P_b > 80%
- Maintain beam stability and emittance specs
- Upgrade instrumentation

Parameter	Requirement	Unit
Beam energies	≤ 11	GeV
Beam currents	< 500	nA
Current instability	~ 10	%
Accuracy of current measurement	~ 1	%
Beam widths (σ_x, σ_y)	< 300	μm
Position stability	< 200	μm
Divergence	< 100	μrad
Beam halo $(> 5\sigma)$	$< 10^{-4}$	
Beam polarization	>80	%
Accuracy of polarization measurement	< 3	%





Hall B "CLAS24" Upgrade

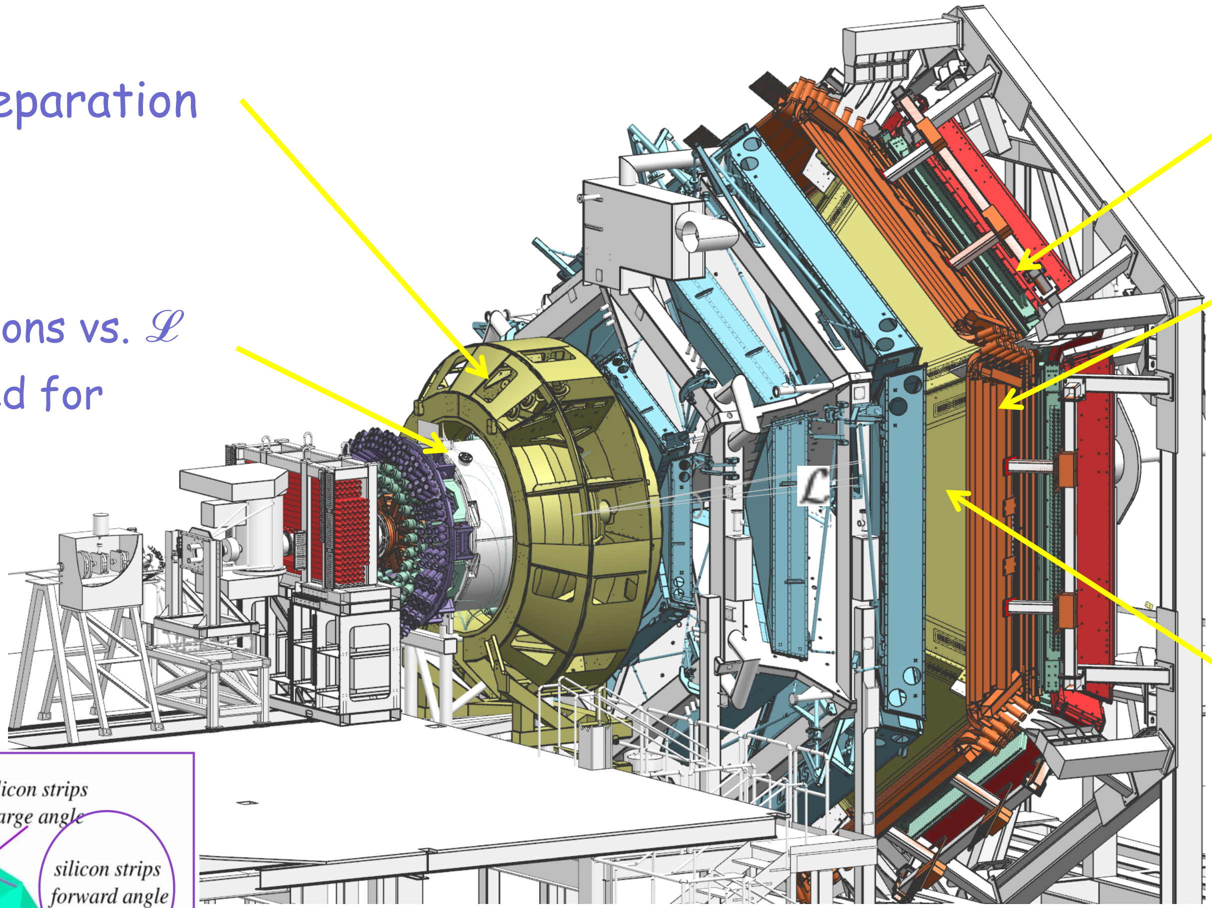
HTCC:

- Designed for e/π separation
- p_π thr @ ~4.5 GeV

Central Detector:

- r = 25 cm; rate limitations vs. $\mathscr{L}$
- Detailed studies needed for CTOF, CND, CVT

CTOF 3σ sep.	π/K	0.58 GeV
	K/p	0.93 GeV
	π/p	1.14 GeV



ECAL:

- Shower containment of 22 R.L. – should work for E_b=24 GeV

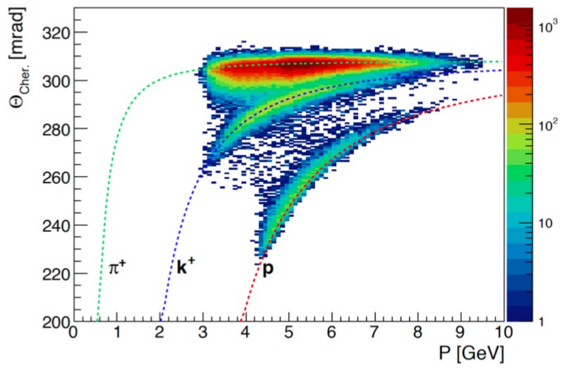
FTOF:

- Higher $\mathscr{L}$ ⇒ higher PMT currents ⇒ reduced PMT life

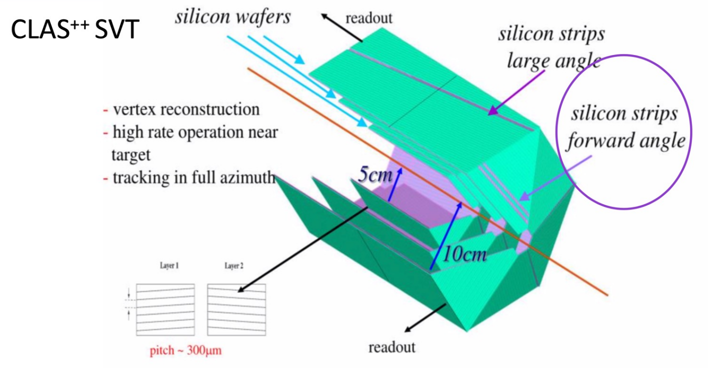
FTOF 4σ sep.	π/K	2.8 GeV
	K/p	4.8 GeV
	π/p	5.4 GeV

RICH:

- Currently in only 2 of 6 sectors; momentum range of PID superior to FTOF alone



Other Considerations:

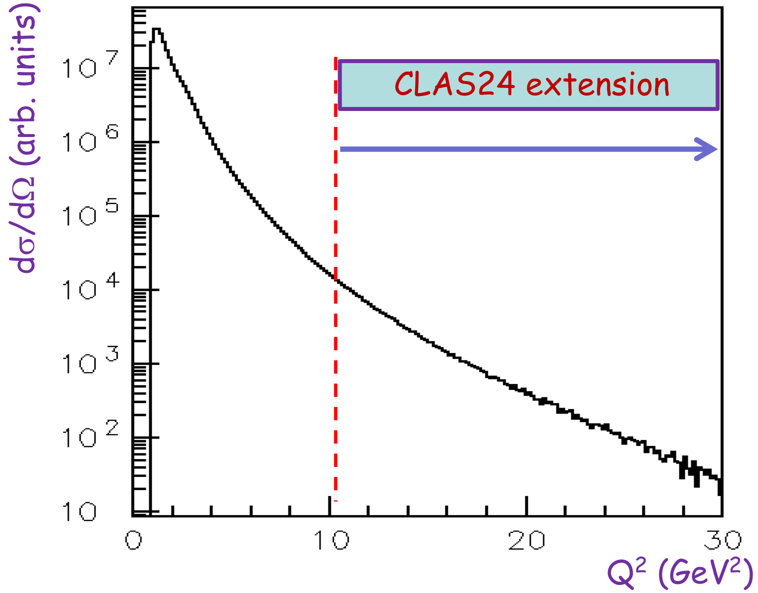


V. Burkert - Messina workshop – Mar. 22

- Entirely new large-acceptance detector ***not*** realistic

Strategy: consider smaller-scale upgrades

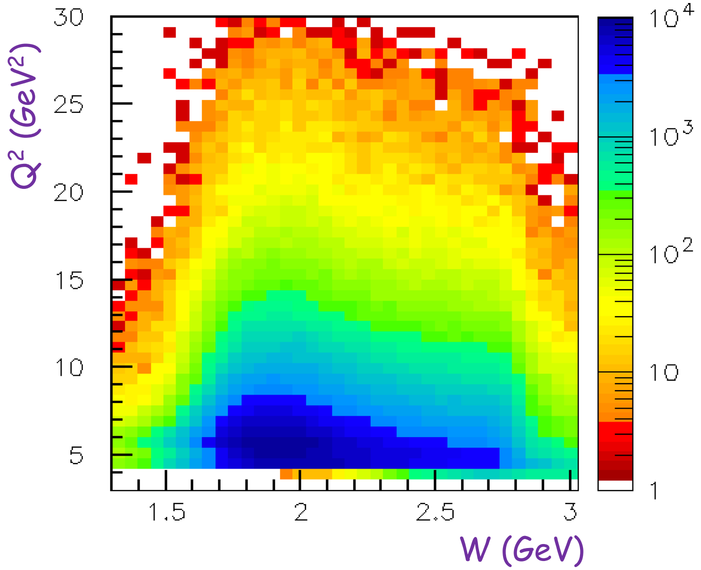
Hall B "CLAS24" Upgrade – Scattered Electron

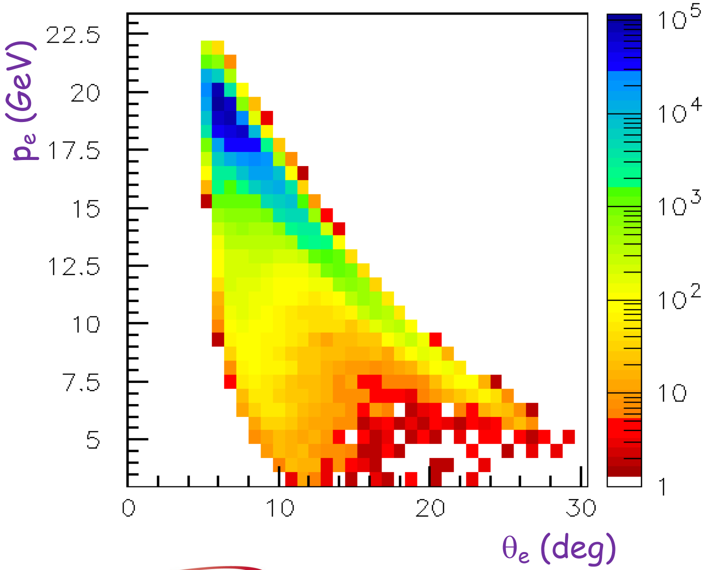


The electroproduction cross section for any exclusive meson production reaction falls off rapidly vs. Q^2

Over the range of Q^2 accessible at E_b=24 GeV, the cross section drops by *~6 orders of magnitude*

This drives the necessary luminosity for the experiment – consideration of $\mathcal{L} \gtrsim 10^{36}$ $cm^{-2}s^{-1}$



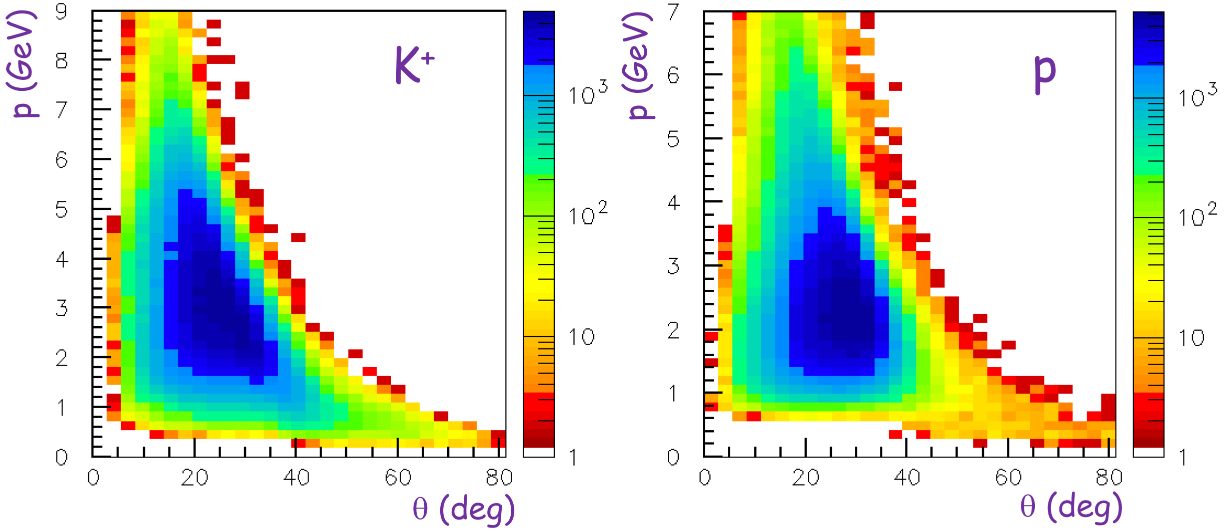


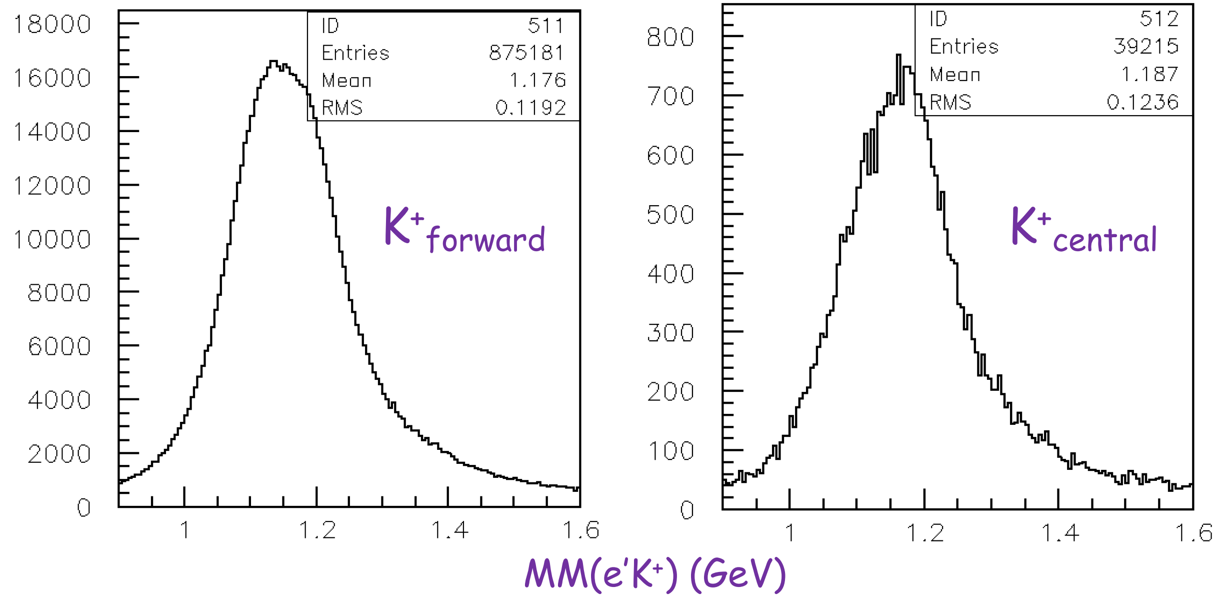
Work in progress:

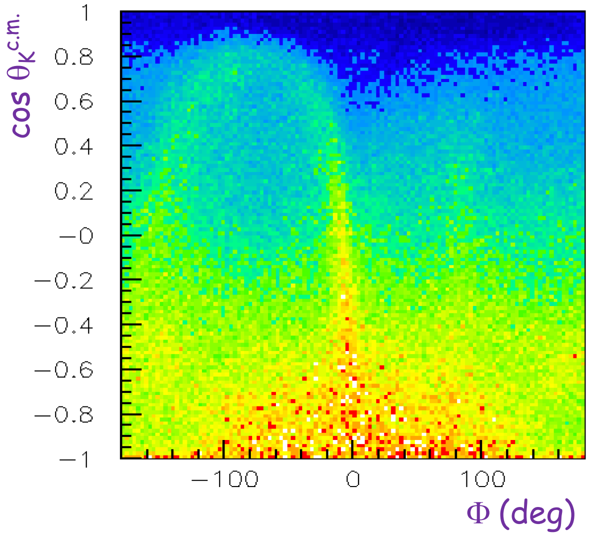
- Simulation studies in progress for a number of exclusive channels:
  - π^+n, π^0p, $\pi^+\pi^-p$, $K^+\Lambda$, $K^+\Sigma^0$, (e,e′X)
- Goals:
  - Determine necessary collected charge for a viable experiment
  - Optimize CLAS24 configuration
  - Develop analysis approach for exclusive processes

Hall B "CLAS24" Upgrade - Hadrons

Test study: $e + p \rightarrow e' + K^+ + Y$, $Y = \Lambda, \Sigma^0$



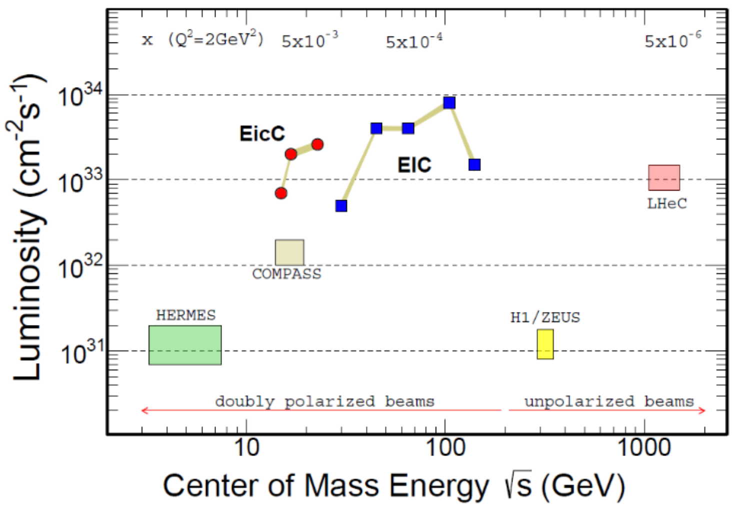




- Current CLAS12 momentum resolution is ~1%
  - Doubling the energy likely precludes missing mass analysis for high purity signal separation
  - Improvements in acceptance can compensate to a degree (and needs study)
  - The two-body acceptance for "CLAS24" $e'h^\pm$ is ~20% and for $e'h_1^\pm h_2^\pm$ is ~5% with unchanged CLAS12 configuration
- The initial steps would be an extension of the program with CLAS12 with improvements in tracking, vertexing, and PID

JLab – Luminosity Frontier

Energy and luminosity increase are needed in order to obtain information on the $\gamma_v pN^*$ electrocouplings at $Q^2>10$ GeV^2, allowing us to map out the momentum dependence of the dressed quark mass within the entire range of distances where the dominant part of hadron mass is generated

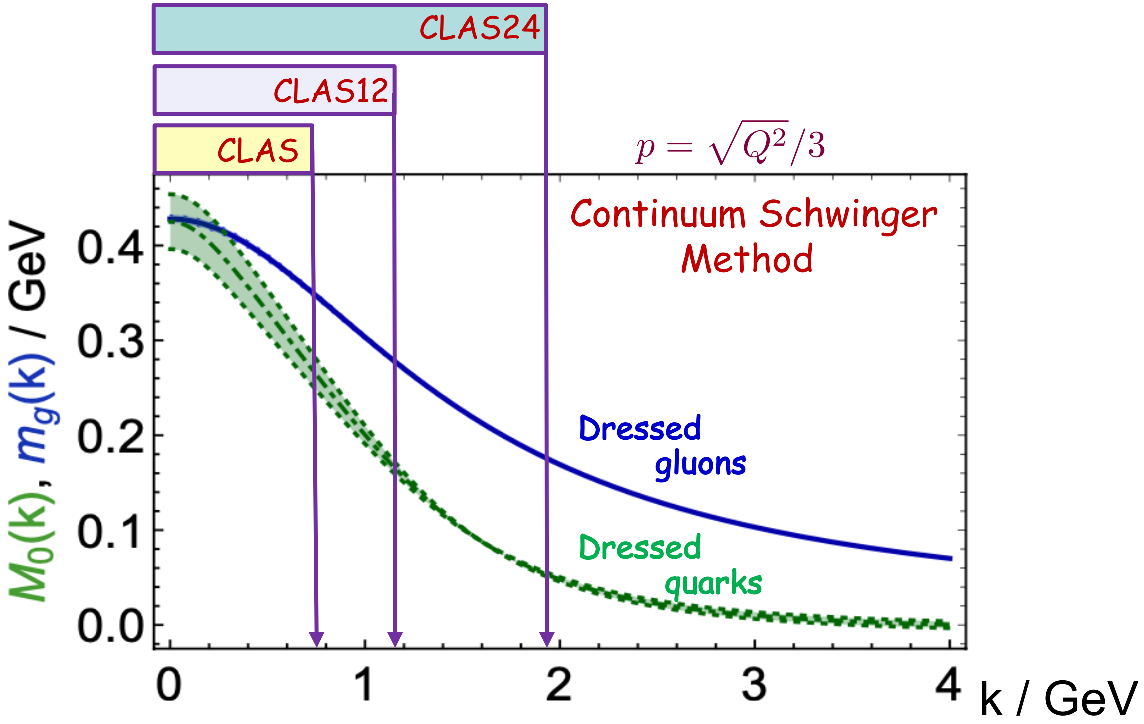


Both EIC and EIcC would need much higher luminosity to carry out such a program

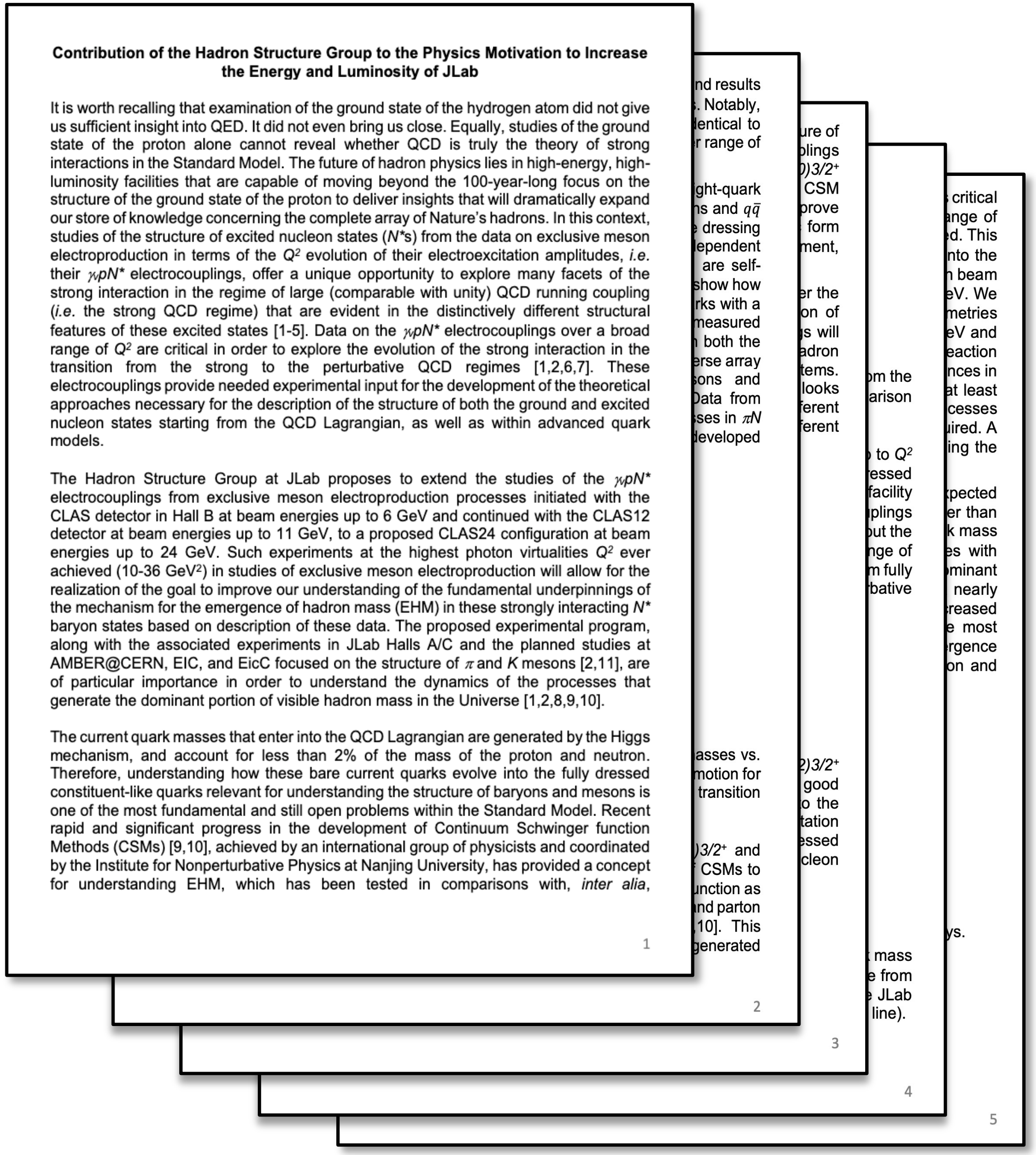
The luminosity "frontier" is a *unique* advantage of JLab

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

- Beam energy (~)24 GeV
- Nearly 4π coverage
- High luminosity
- Studies of exclusive reactions



Hadron Structure Studies with CLAS24



Contribution of the Hadron Structure Group to the Physics Motivation to Increase the Energy and Luminosity of JLab

It is worth recalling that examination of the ground state of the hydrogen atom did not give us sufficient insight into QED. It did not even bring us close. Equally, studies of the ground state of the proton alone cannot reveal whether QCD is truly the theory of strong interactions in the Standard Model. The future of hadron physics lies in high-energy, high-luminosity facilities that are capable of moving beyond the 100-year-long focus on the structure of the ground state of the proton to deliver insights that will dramatically expand our store of knowledge concerning the complete array of Nature's hadrons. In this context, studies of the structure of excited nucleon states (N^*s) from the data on exclusive meson electroproduction in terms of the Q^2 evolution of their electroexcitation amplitudes, *i.e.* their $\gamma_v pN^*$ electrocouplings, offer a unique opportunity to explore many facets of the strong interaction in the regime of large (comparable with unity) QCD running coupling (*i.e.* the strong QCD regime) that are evident in the distinctively different structural features of these excited states [1-5]. Data on the $\gamma_v pN^*$ electrocouplings over a broad range of Q^2 are critical in order to explore the evolution of the strong interaction in the transition from the strong to the perturbative QCD regimes [1,2,6,7]. These electrocouplings provide needed experimental input for the development of the theoretical approaches necessary for the description of the structure of both the ground and excited nucleon states starting from the QCD Lagrangian, as well as within advanced quark models.

The Hadron Structure Group at JLab proposes to extend the studies of the $\gamma_v pN^*$ electrocouplings from exclusive meson electroproduction processes initiated with the CLAS detector in Hall B at beam energies up to 6 GeV and continued with the CLAS12 detector at beam energies up to 11 GeV, to a proposed CLAS24 configuration at beam energies up to 24 GeV. Such experiments at the highest photon virtualities Q^2 ever achieved (10-36 GeV^2) in studies of exclusive meson electroproduction will allow for the realization of the goal to improve our understanding of the fundamental underpinnings of the mechanism for the emergence of hadron mass (EHM) in these strongly interacting N^* baryon states based on description of these data. The proposed experimental program, along with the associated experiments in JLab Halls A/C and the planned studies at AMBER@CERN, EIC, and EicC focused on the structure of π and K mesons [2,11], are of particular importance in order to understand the dynamics of the processes that generate the dominant portion of visible hadron mass in the Universe [1,2,8,9,10].

The current quark masses that enter into the QCD Lagrangian are generated by the Higgs mechanism, and account for less than 2% of the mass of the proton and neutron. Therefore, understanding how these bare current quarks evolve into the fully dressed constituent-like quarks relevant for understanding the structure of baryons and mesons is one of the most fundamental and still open problems within the Standard Model. Recent rapid and significant progress in the development of Continuum Schwinger function Methods (CSMs) [9,10], achieved by an international group of physicists and coordinated by the Institute for Nonperturbative Physics at Nanjing University, has provided a concept for understanding EHM, which has been tested in comparisons with, *inter alia*,

1

Hadron Structure Group in Hall B developing physics case to support CLAS24 upgrade

<u>List of Participating Institutions:</u>

- Jefferson Lab (Hall B and Theory Division)
- University of Connecticut
- Genova University and INFN of Genova
- Lamar University
- Ohio University
- Skobeltsyn Nuclear Physics Institute and Physics Department at Lomonosov Moscow State University
- University of South Carolina
- INFN Sez di Roma Tor Vergata and Universita di Roma Tor Vergata
- Nanjing University and affiliated institutes
- Tubingen University
- Tomsk State University and Tomsk Polytechnic University
- James Madison University
- George Washington University

https://userweb.jlab.org/~carman/clas24

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 - electrocouplings of most N* states < 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 and advancing well
  - Experimental results on N* electrocouplings from different final states will provide new insights into strong QCD and validate insight into the emergence of hadron mass (EHM)
  - Studies of the hadron sector are complementary to studies in the meson sector
- A possible CLAS24 N* program will provide a culmination to this work:
  - Bridging the gap between 12 GeV and EIC energies (20-140 GeV) will provide information on the dressed quark mass function at the full range of distances where dominant part of hadron mass is generated
  - Program addresses the most challenging problems of the Standard Model on the nature of >98% of hadron mass and quark-gluon confinement
  - Capability to measure exclusive reactions for Q^2 to ~30 GeV^2 at $\mathcal{L} > 10^{36}$ cm^{-2}s^{-1} and 4π coverage *will make JLab24 the ultimate QCD machine* to explore hadron generation in the strong QCD regime

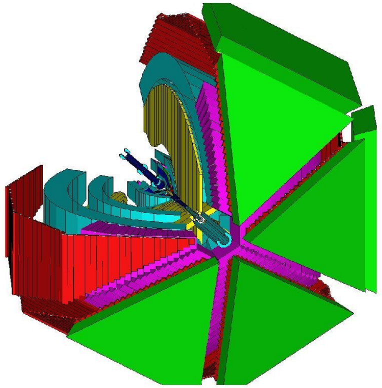
Backup Slides

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 continues with several analyses still ongoing



$\Delta(1600)3/2^+$ Electrocouplings from CLAS

Γ_{tot}, MeV	$\Gamma\ \pi\Delta$, MeV	$\Gamma\ \rho\pi$, MeV	Mass, GeV
248±25 259±21	158±25 169±22	0 0	1.564±0.026 1.57±0.018
BF	48-82% 52-81%	0 0	

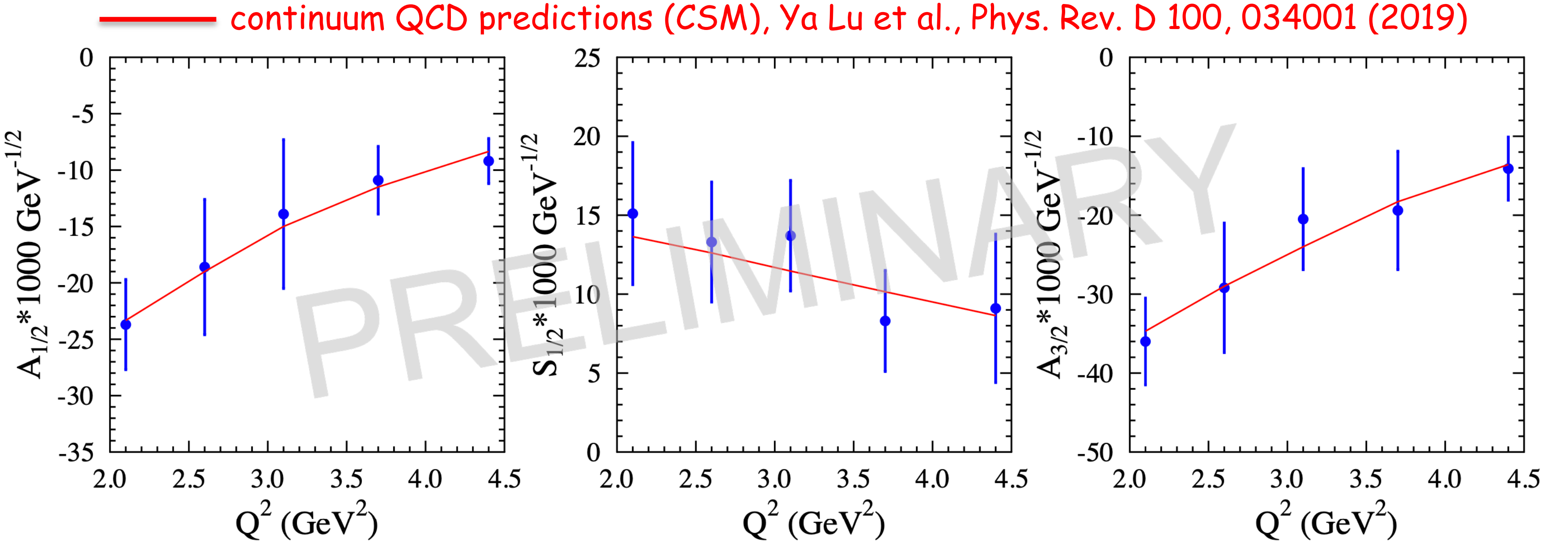
ep → e' p π^+ π^- data from CLAS

W fit range: [1.51 : 1.61] GeV:

blue: 2.0 < Q^2 < 3.5 GeV^2

red: 3.0 < Q^2 < 5.0 GeV^2

V. Mokeev, AMBER@CERN-VII Workshop

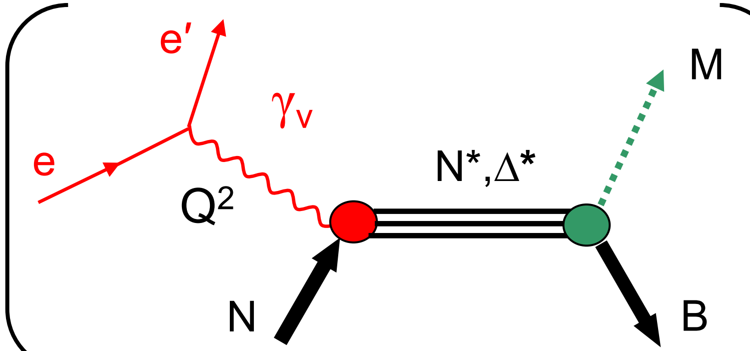


The CLAS $\Delta(1600)3/2^+$ electrocoupling results *confirm the CSM prediction*, solidifying evidence for the momentum evolution of the dressed quark mass and its role in describing the emergence of hadron mass

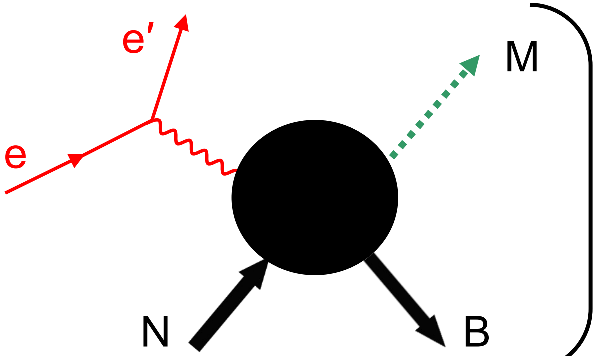
Connecting to Electrocoupling Amplitudes

Resonant Amplitudes   Non-resonant Amplitudes

$$\mathcal{M} = \sum$$



$$+ \sum$$



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

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

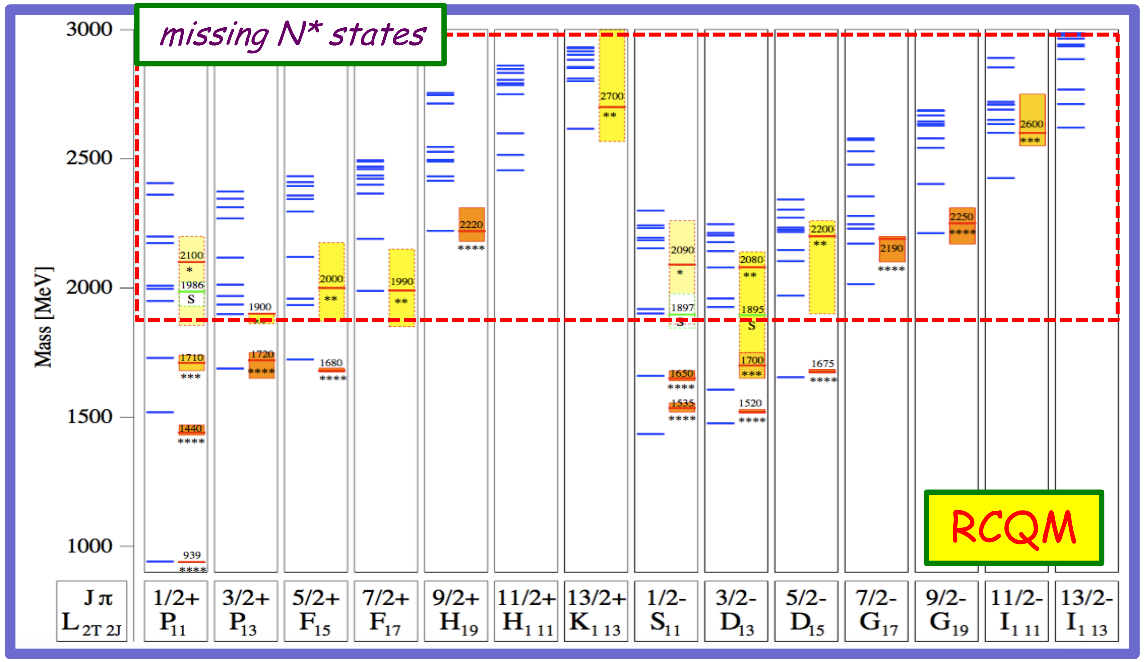
- The electromagnetic decay widths ($N^* \rightarrow N\gamma$) at the resonance point $W=M_r$ are given by:

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

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

Evolution of the N* Spectrum

State N(mass)J^P	PDG 2010	PDG 2020	πN	KΛ	KΣ	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)$7/2^-$	*	***	**		**	***



Löring, Metsch, Petry, Eur. Phys. J. A 10, 395 (2001)

Recent LQCD predictions support CQM

Dudek, Edwards, PRD 85, 054016 (2012)

Decisive impact from CLAS KY photoproduction data - Extend studies to 2π and KY electroproduction and to higher masses

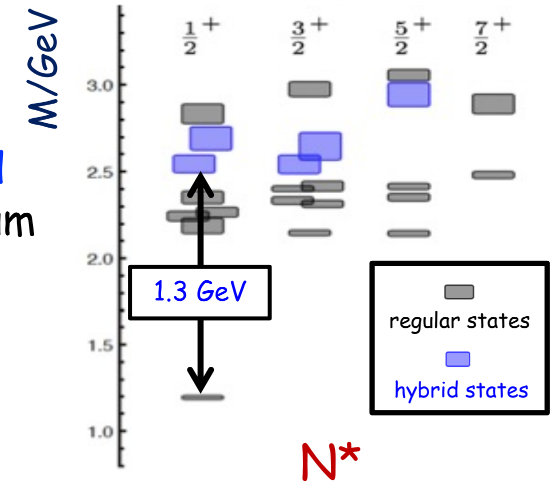
Hunting for Glue in Excited Baryons

Can glue be a structural component of excited baryon states?

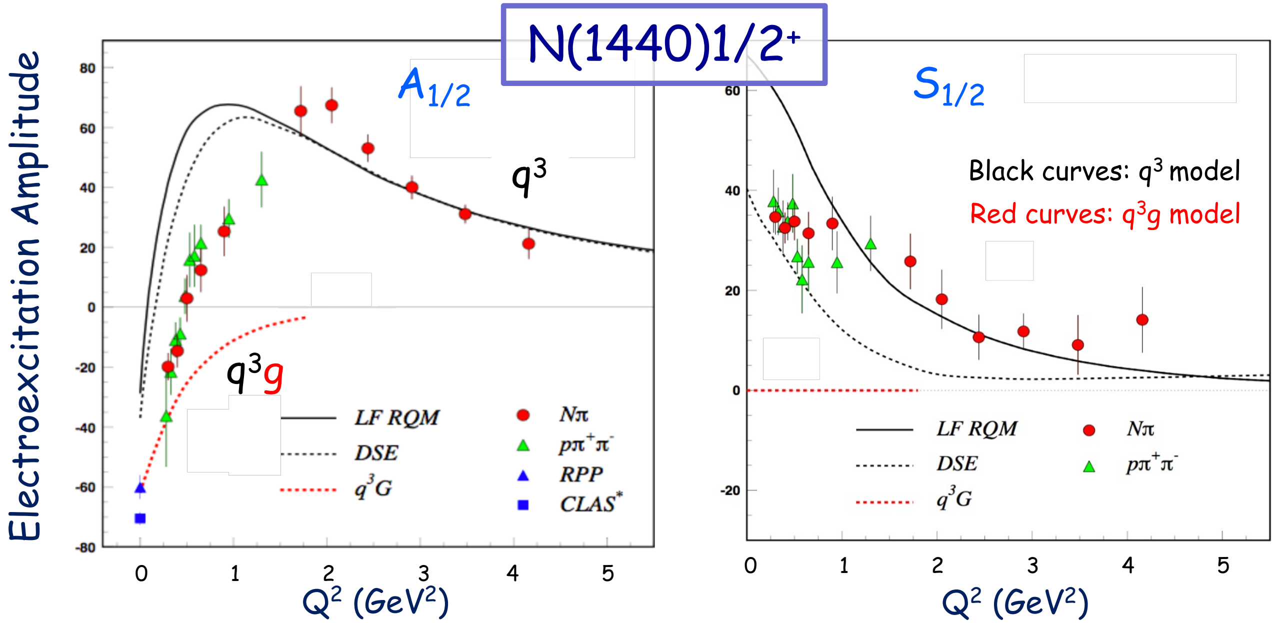
LQCD predicts hybrid baryons in N* spectrum

JLab LQCD group results

m_π=396 MeV



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



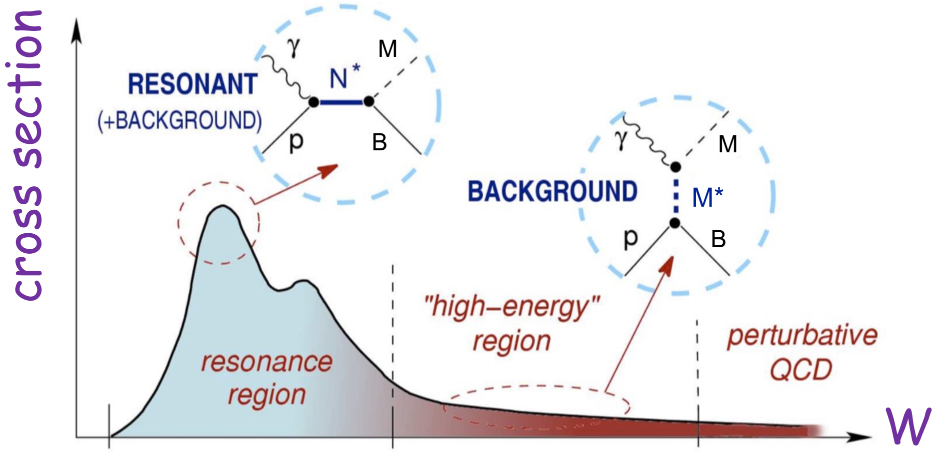
The signatures for hybrid baryons include:

- Extra resonances with $J^\pi=1/2^+, 3/2^+$ in mass range 2.0-2.5 GeV and decays into $N\pi\pi$ 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

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)

Reaction Models



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:

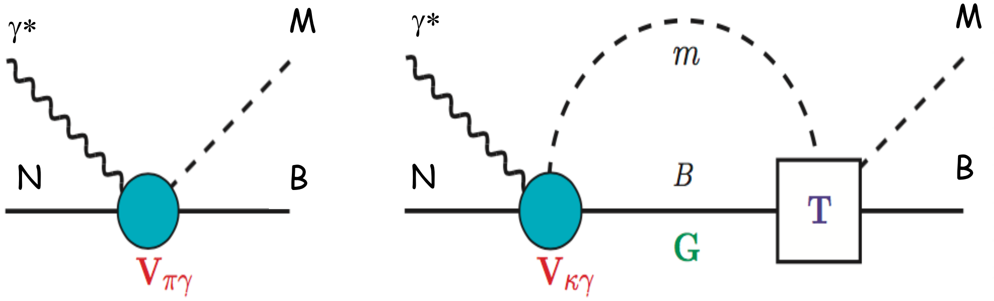
- Simultaneous fits to multiple independent channels
- Treatment of FSI and re-scattering effects

Resonances:

- Select N* states for inclusion (J=1/2, 3/2, 5/2)
- EM form factors from Bonn CQM
- Constrain electrocouplings to available data
- Fit to data to fix parameters (decay widths, couplings strengths)

Background:

- Model amplitude for non-resonant diagrams (t- and u-channel)
- Parameterize by coupling strengths/phases
- Tune to high-energy data above the resonance region



Coupled-channel approaches:

ANL-Osaka (EBAC), Dubna-Mainz-Taipei, Julich-Bonn

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