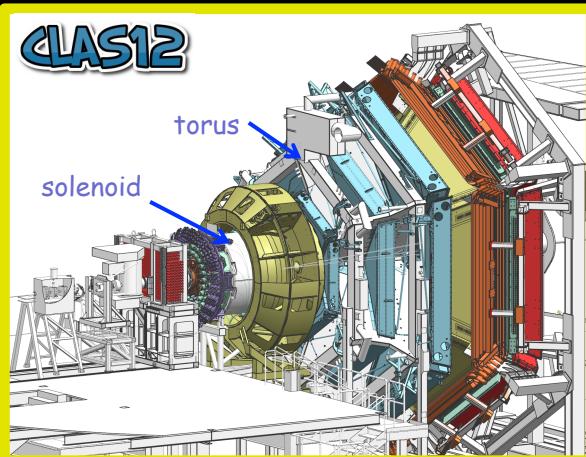
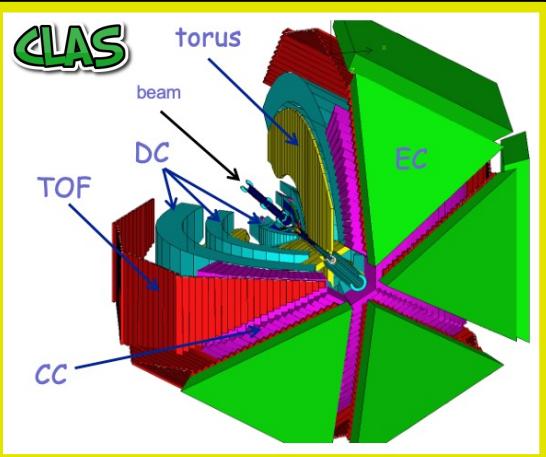


N* Studies from Exclusive Electroproduction off Protons with CLAS and CLAS12



Daniel S. Carman
Jefferson Laboratory



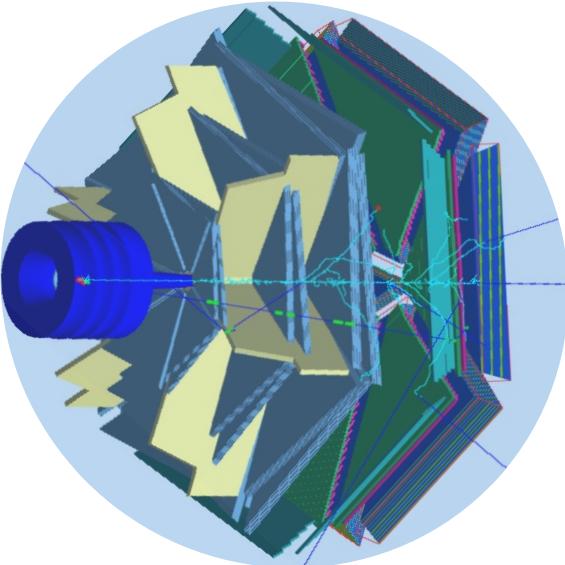
Outline:

- N* Spectrum & Structure
- CLAS $\gamma, p \rightarrow \pi N, \pi\pi N, K\bar{N}$ Data
- CLAS12 N* Program and Results
- Future Plans for N* Studies
- Concluding Remarks

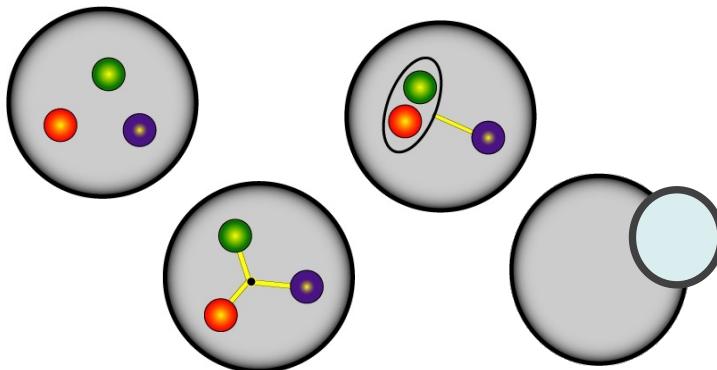


CLAS / CLAS12 N* Program

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



N* degrees of freedom??



- 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* and *structure* of N* states
 - 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

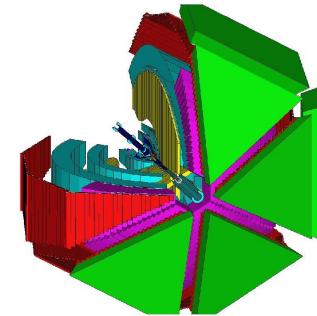
The Q^2 evolution of the extracted N* electrocouplings offers unique insights into the emergence of hadron mass (EHM)

CLAS N* Program Measurement Overview

Reaction	Observable	Q^2 (GeV 2)	W (GeV)	Reference
$e\gamma \rightarrow e\gamma\pi^+\pi^-$	$d\sigma/dM$, $d\sigma/\cos\theta$, $d\sigma/d\alpha$	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)
$e\gamma \rightarrow e\gamma\pi^0$	$\sigma_{LT'}$	0.4- 1.0	1.5 - 1.8	PRC 105, L022201 (2022)
	$d\sigma/d\Omega$	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)
	$\sigma_U, \sigma_{LT}, \sigma_{TT}$	1.0 - 4.6	2.0 - 3.0	PRC 90, 025205 (2014)
	$\sigma_U, \sigma_{LT}, \sigma_{TT}$	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)
$e\gamma \rightarrow e\gamma\pi^+$	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)
	$\sigma_U, \sigma_{LT}, \sigma_{TT}$	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)
	$\sigma_U, \sigma_{LT}, \sigma_{TT}, \sigma_{LT'}$	1.7 - 4.5	1.15 - 1.7	PRC 77, 015208 (2008)
	$\sigma_U, \sigma_{LT}, \sigma_{TT}$	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)
	$\sigma_U, \sigma_{LT}, \sigma_{TT}$	2.12 - 4.16	1.11 - 1.15	PRC 70, 042201 (2004)

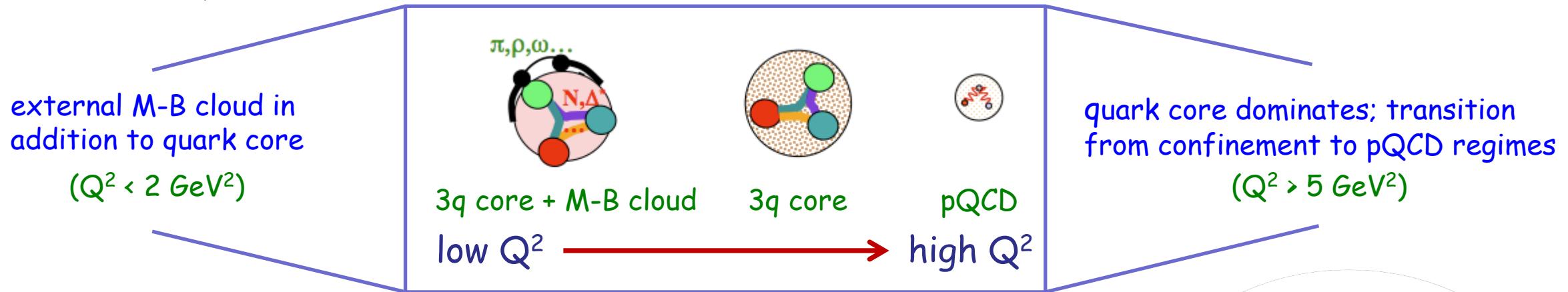
Reaction	Observable	Q^2 (GeV 2)	W (GeV)	Reference
$e\gamma \rightarrow e\gamma\pi^-$	A_t, A_{et}	0.05 - 5.0	1.1 - 2.6	PRC 94, 05520 (2016)
	$\sigma_U, \sigma_{LT}, \sigma_{TT}$	1.6 - 4.6	2.0 - 3.0	PRC 95, 035202 (2017)
	$\sigma_U, \sigma_{LT}, \sigma_{TT}$	0.13 - 3.3	1.5 - 2.3	PRC 76, 015204 (2007)
$e\gamma \rightarrow eK^Y$	$d\sigma/d\Omega$	0.25 - 1.50	1.5 - 1.86	PRL 86, 1702 (2001)
	P^0	0.8 - 3.2	1.6 - 2.7	PRC 90, 035202 (2014)
	$\sigma_U, \sigma_{LT}, \sigma_{TT}, \sigma_{LT'}$	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)
	$\sigma_U, \sigma_{LT}, \sigma_{TT}, \sigma_{LT'}$	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)
	$e\gamma \rightarrow e\omega$	$\sigma_U, \sigma_{LT}, \sigma_{TT}$	1.725 - 4.85	EPJA 24, 445 (2005)
	$e\gamma \rightarrow epp^0$	σ_U	1.6 - 5.6	EPJA 39, 5 (2009)
		σ_L/σ_T	1.5 - 3.0	PLB 605, 256 (2005)
$e\gamma \rightarrow e\phi$	$d\sigma/dt$	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)

CLAS: 1997 - 2012

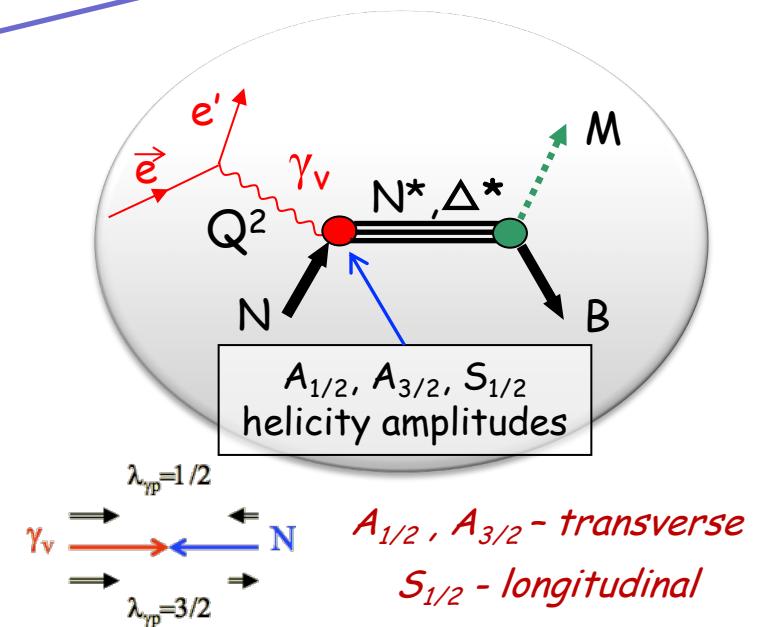


Excited Nucleon Structure

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



- Studies of the $\gamma_\nu p N^*$ 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 and their emergence from QCD



Connecting to Electrocoupling Amplitudes

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

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

- with the following kinematic definitions:

$$q_\gamma = \sqrt{Q^2 + E_\gamma^2}, \quad E_\gamma = \frac{W^2 - Q^2 - M_N^2}{2W}, \quad K = \frac{W^2 - M_N^2}{2W}$$

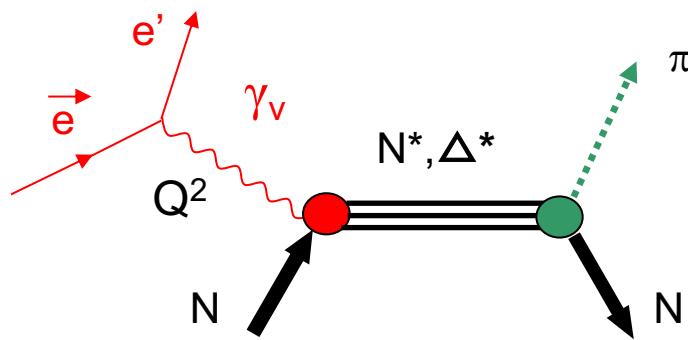
- The electromagnetic decay widths at the resonance point $W=M_r$ are given by:

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

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

Extraction of Electrocouplings

Reaction Channel	N^*, Δ^* States	Q^2 ranges of $\gamma_v p N^*$ Electrocouplings (GeV^2)
$\pi^0 p, \pi^+ n$	$\Delta(1232)3/2^+$ $N(1440)1/2^+, N(1520)3/2^-, N(1535)1/2^-$	0.16 - 6.0 0.30 - 4.16
$\pi^+ n$	$N(1675)5/2, N(1680)5/2^+, N(1710)1/2^+$	1.6 - 4.5
ηp	$N(1535)1/2^-$	0.2 - 2.9
$\pi^+ \pi^- p$	$N(1440)1/2^+, N(1520)3/2^-$ $\Delta(1620)1/2^-, N(1650)1/2^-, N(1680)5/2^+,$ $\Delta(1700)3/2^-, N(1720)3/2^+, N'(1720)3/2^+$	0.25 - 1.5 0.5 - 1.5
http://userweb.jlab.org/~mokeev/resonance_electrocouplings		



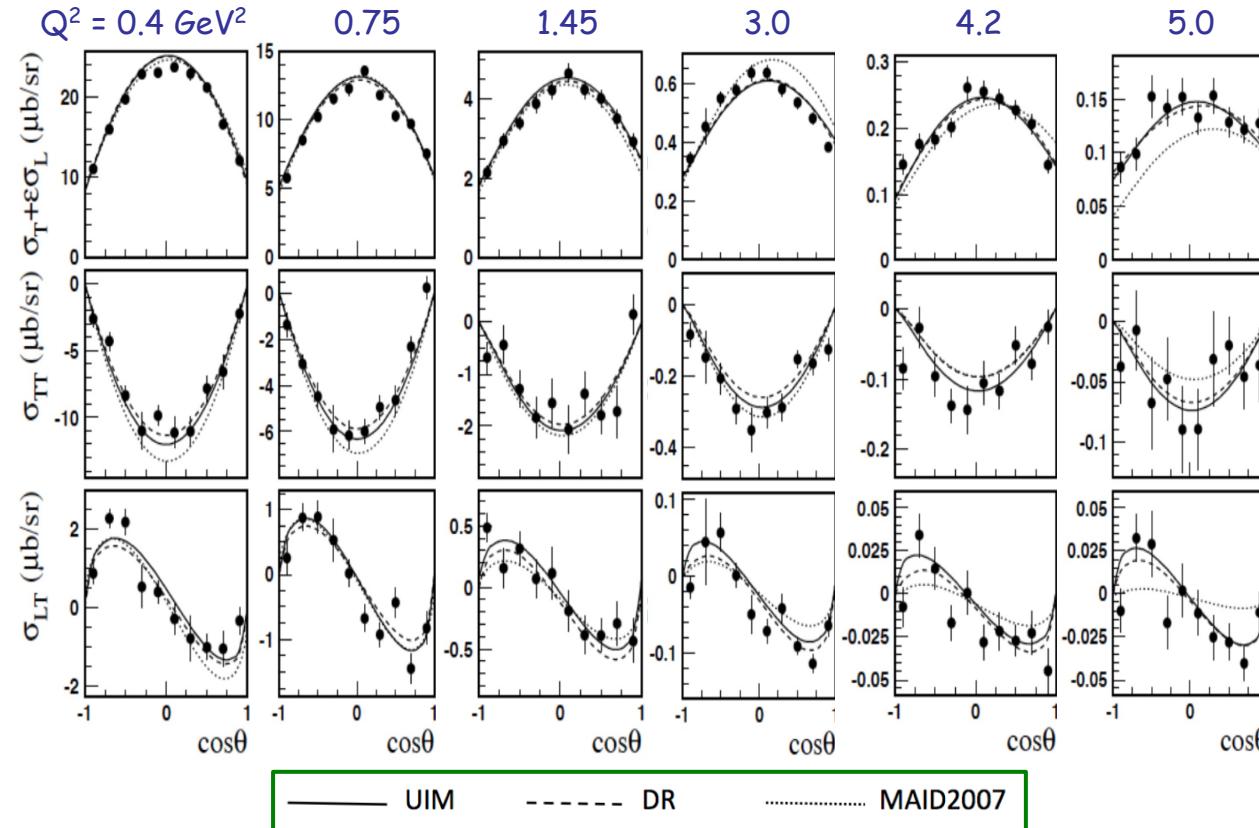
Analysis codes employed for the extractions:

- Unitary Isobar Model (UIM)
 - Fixed-t dispersion relations (DR)
 - Data-driven reaction model for $\pi^+ \pi^- N$ (JM09, JM16, JM19)
- } for πN and ηN

Aznauryan *et al.*, *Int. J. Mod. Phys. E* 22, 1330015 (2013)
 Mokeev, *FBS* 57, 909 (2016); Mokeev and Carman, *FBS* 63, 59 (2022)

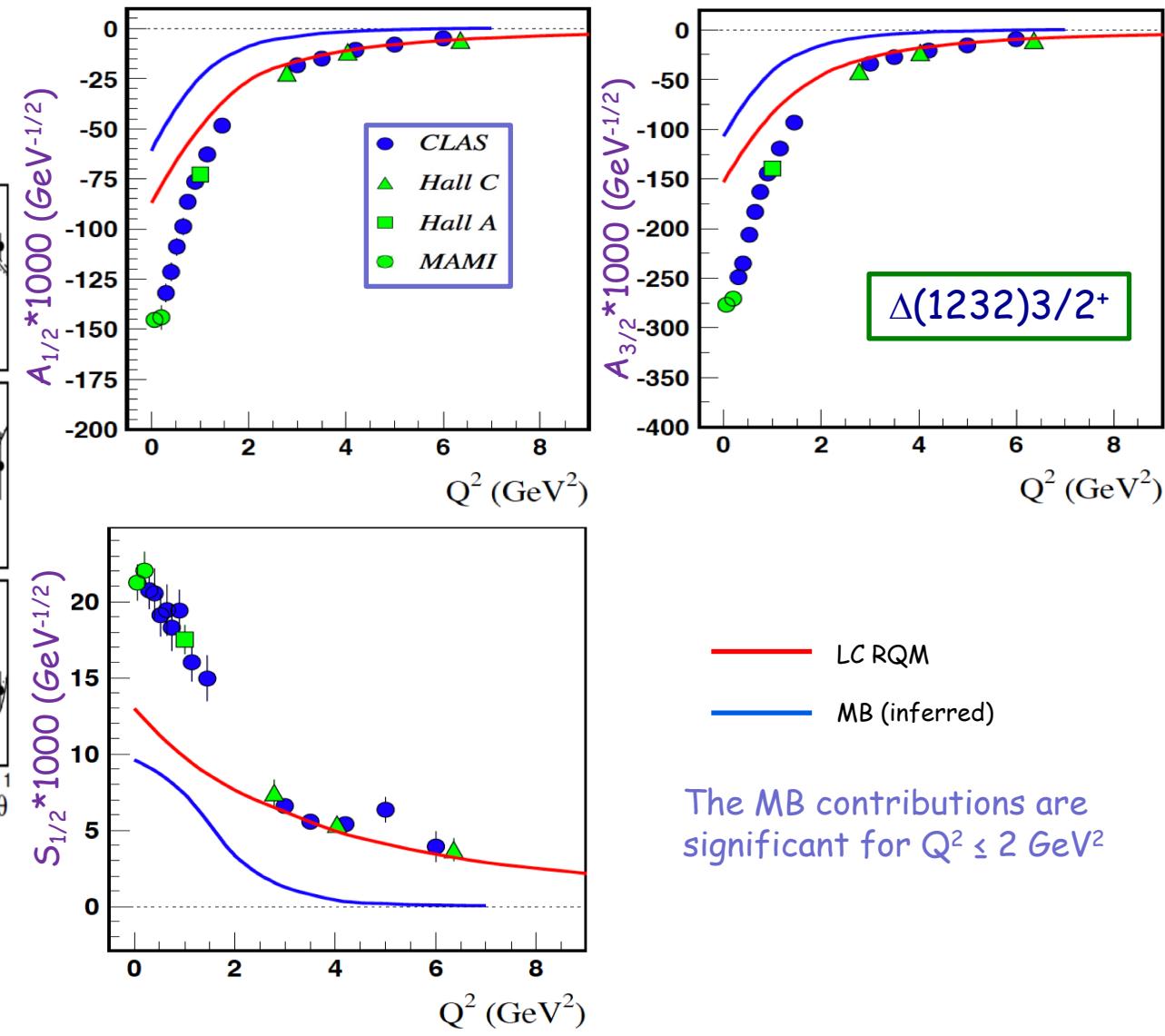
CLAS N* Electrocouplings – First Resonance Region

$\gamma^* p \rightarrow \pi^0 p$

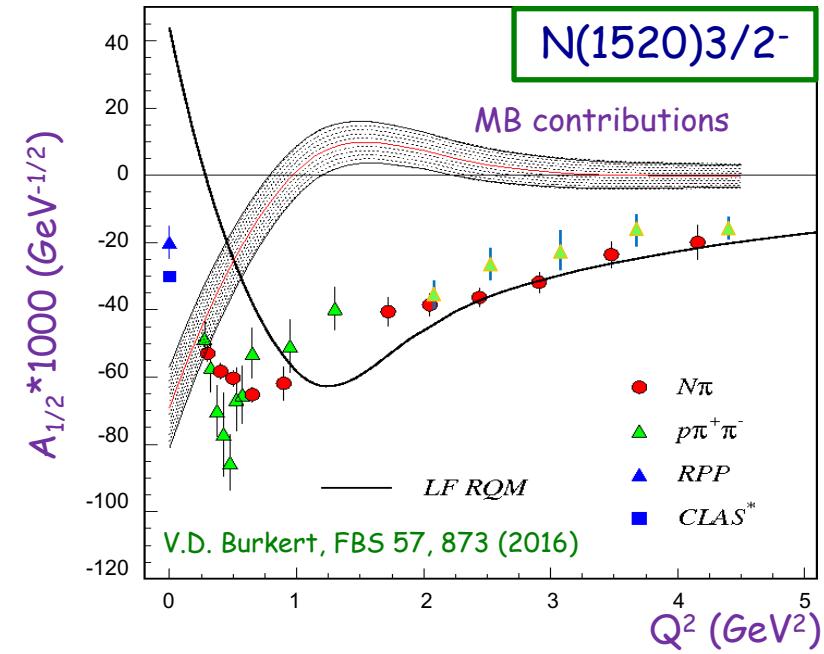
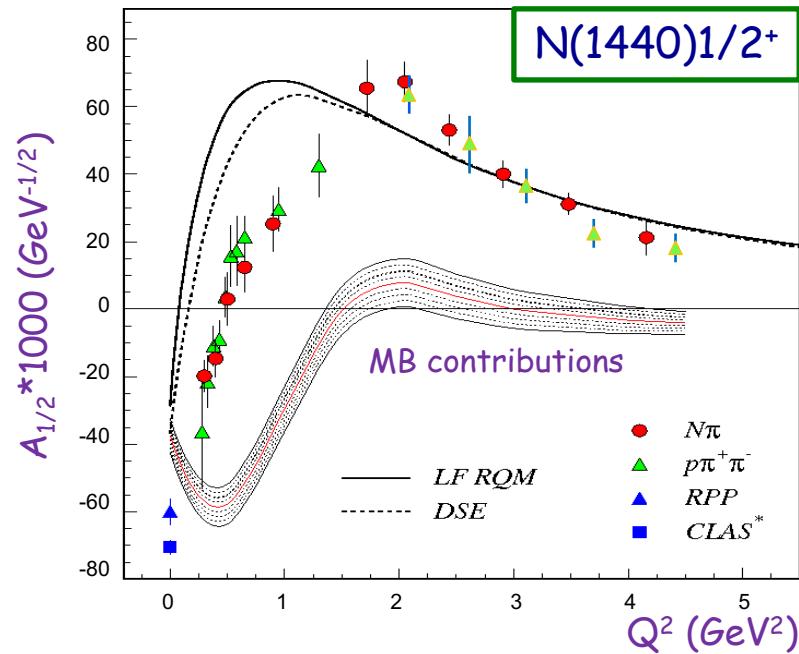


- Good agreement between UIM and DR approaches

Aznauryan et al., PRC 80, 055203 (2009)



CLAS N* Electrocouplings – Second Resonance Region

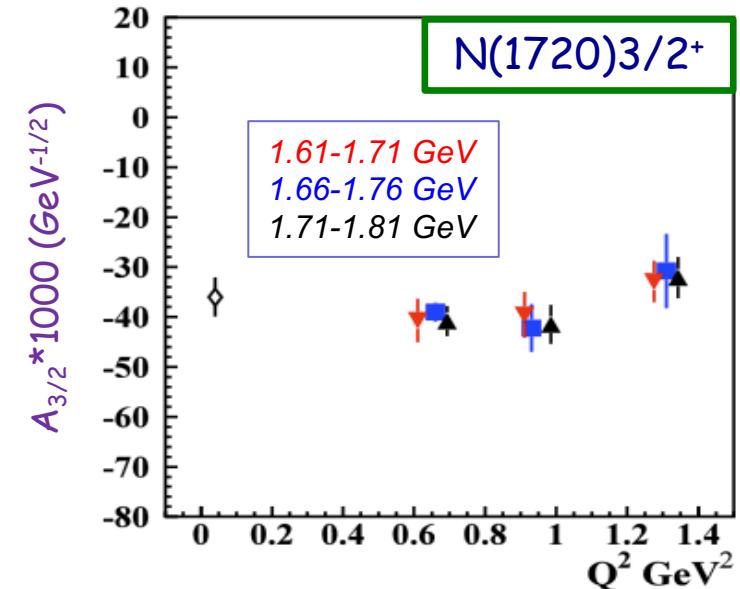
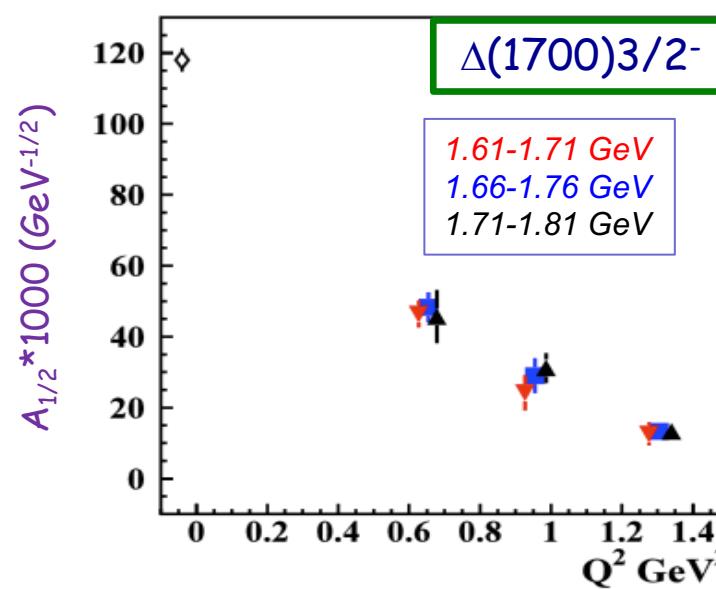
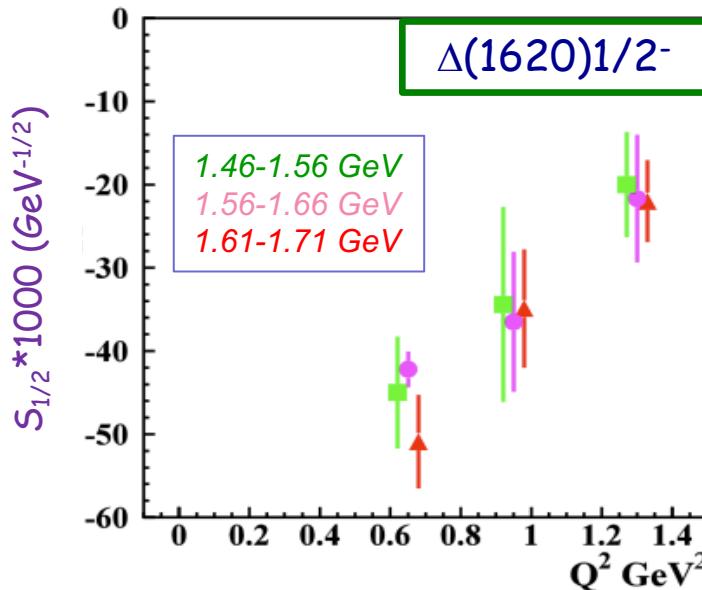


- Electrocouplings reveal different interplay between meson-baryon cloud and quark core:
 - Good agreement of the extracted N^* electrocouplings from $N\pi$ and $N\pi\pi$:
 - Compelling evidence for the reliability of the results
 - Channels have very different mechanisms for the non-resonant background
- 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 the strong QCD dynamics that underlies hadron mass generation

CLAS N* Electrocouplings – Third Resonance Region

$N\pi\pi$ channel gave first electrocoupling results on higher-lying states up to 1.8 GeV

Note: Most high-lying N states decay mainly to $N\pi\pi$ with much smaller strength to $N\pi$*



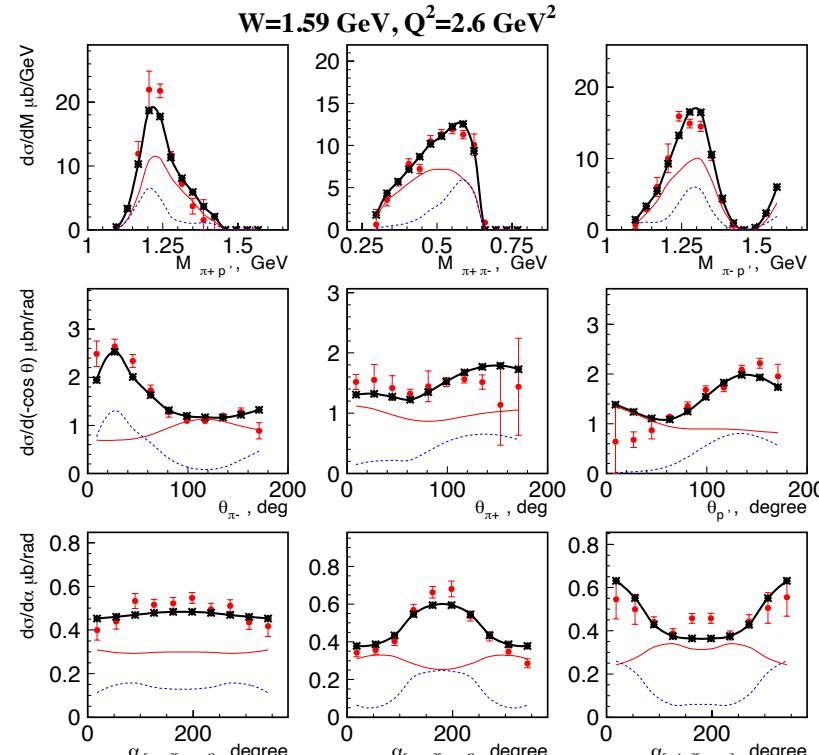
Mokeev, Aznauryan, *IJMPC* 26, 1460080 (2014); Mokeev et al., *PRC* 93, 025206 (2016); Carman, Joo, Mokeev, *FBS* 61, 29 (2020)

Data from the KY channels is critical:

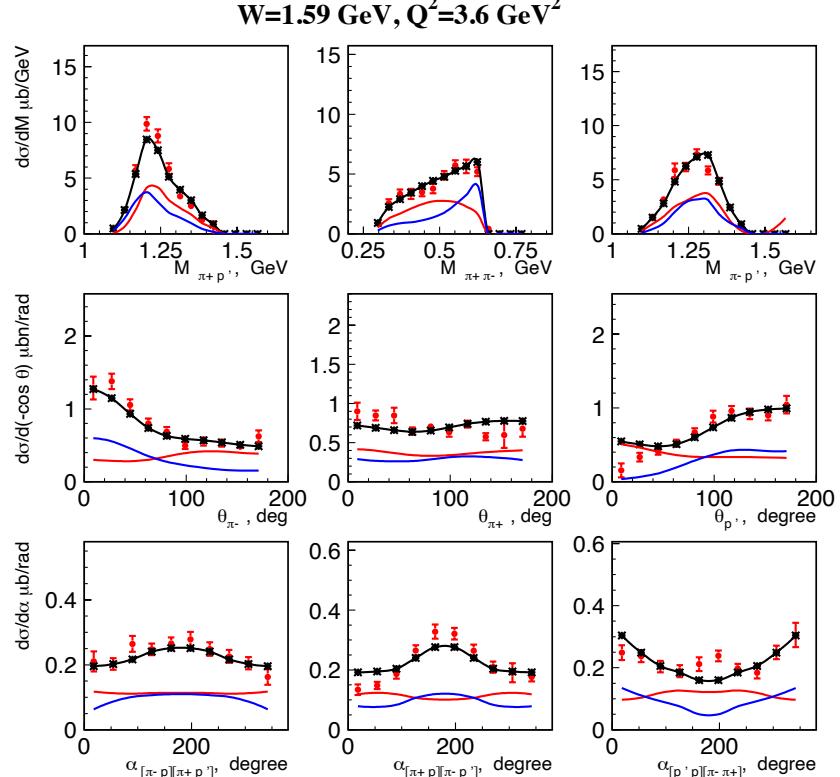
- to provide an independent extraction of the electrocouplings for the higher-lying N* states where $N\pi$ coupling is small
- to elucidate the possible impact of three-quark orbital excitations on EHM

Description of the $\pi^+\pi^-p$ CLAS Data

$\chi^2/d.p. = 2.71$



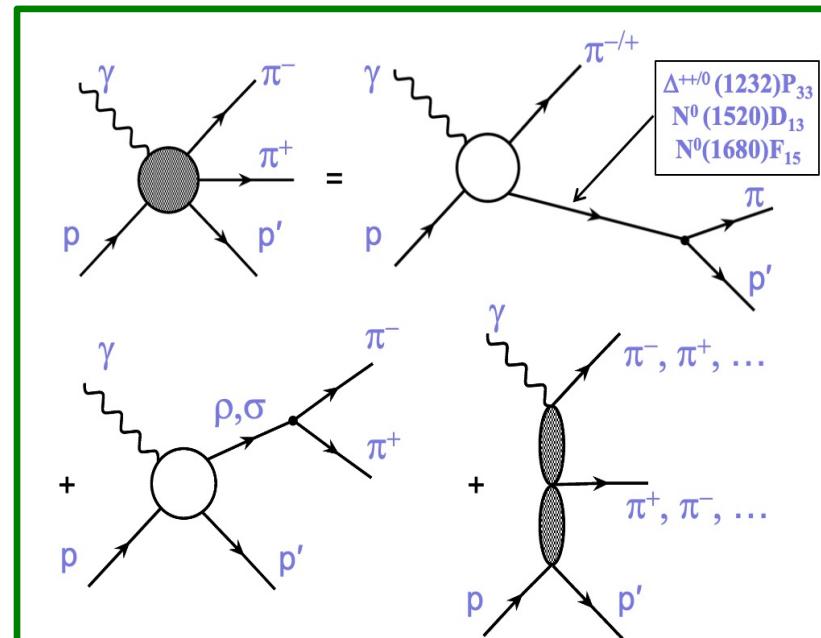
$\chi^2/d.p. = 2.59$



— Full — Resonances — Background

V.I. Mokeev et al., PRC 86, 035203 (2012)

JLab-Moscow Reaction Model



JM model provides reasonable description of data for extraction of resonance electrocouplings

New N'(1720) State from N $\pi\pi$ Analysis

N(1720)3/2⁺ hadronic decays from CLAS data fit with only conventional N* states

	BR($\pi\Delta$), %	BR(pp), %
electroproduction	64-100	<5
photoproduction	14-60	19-69

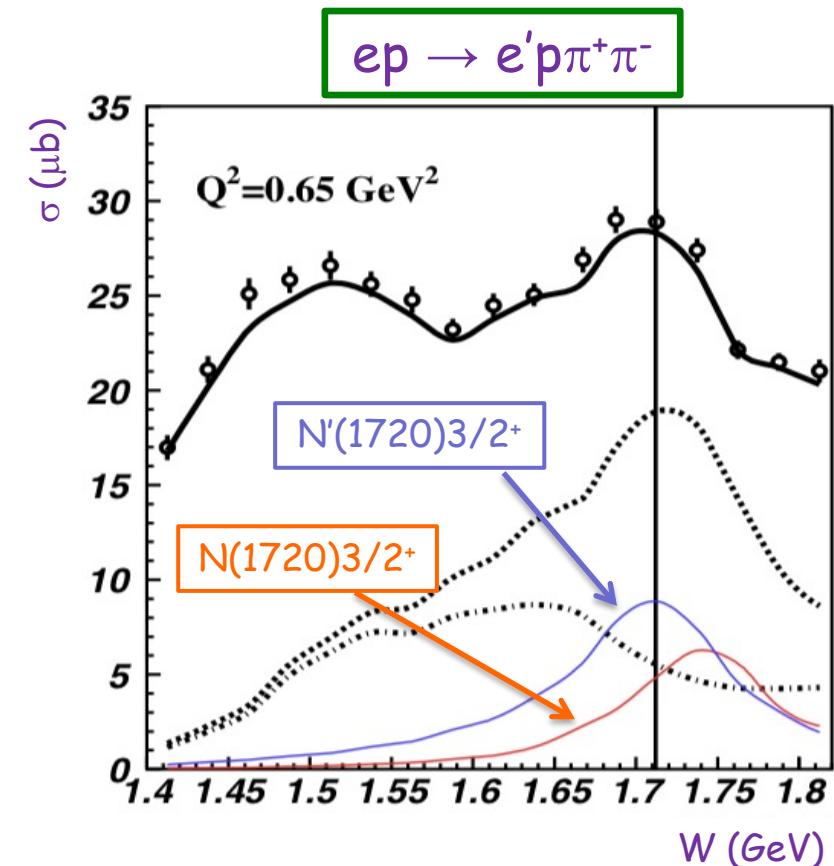
N* hadronic decays from the data fit that incorporates the new N'(1720)3/2⁺ state

Resonance	BR($\pi\Delta$), %	BR(pp), %
N'(1720)3/2 ⁺ electroproduction	47-64	3-10
photoproduction	46-62	4-13
N(1720)3/2 ⁺ electroproduction	39-55	23-49
photoproduction	38-53	31-46
$\Delta(1700)3/2^-$ electroproduction	77-95	3-5
photoproduction	78-93	3-6

Contradictory BR values for N(1720)3/2⁺ decays to $\pi\Delta$ and pp deduced from γp and $\gamma_v p$ data with Q^2 independent resonance masses and hadronic decay widths

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

Good description of both N $\pi\pi$ γp and $\gamma_v p$ data achieved only by including new N'(1720)3/2⁺

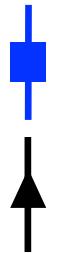
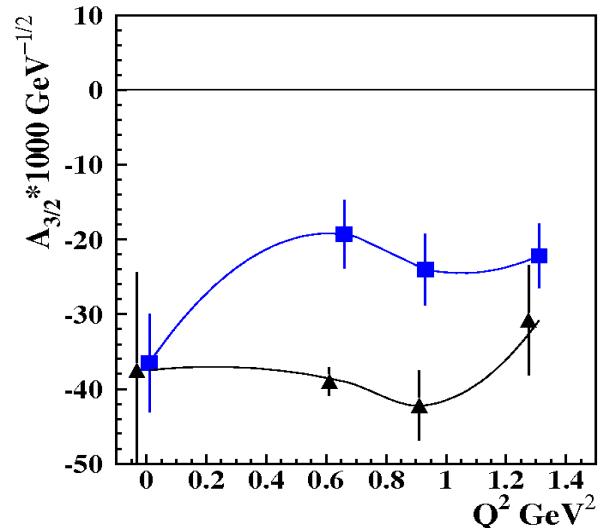
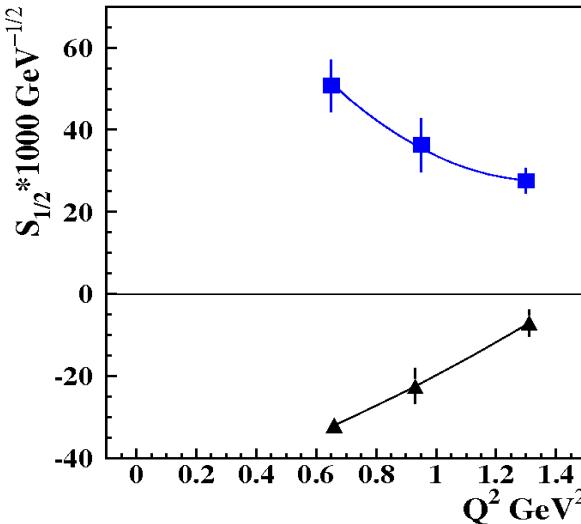
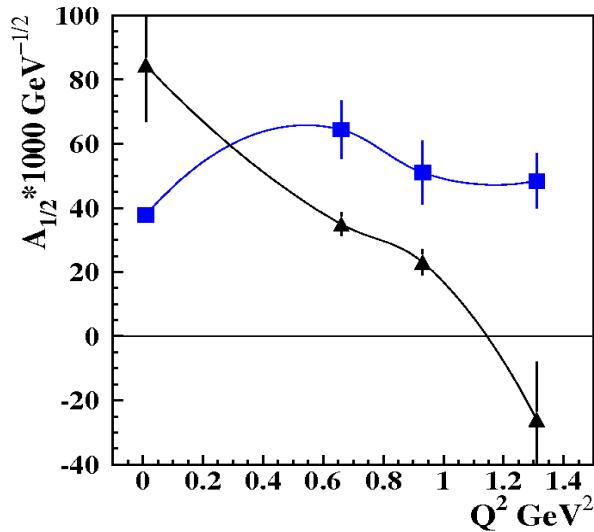


V.I. Mokeev et al., PLB 805, 135457 (2020)

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

New N'(1720) State from $N\pi\pi$ Analysis

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



\blacksquare
N'(1720)3/2⁺

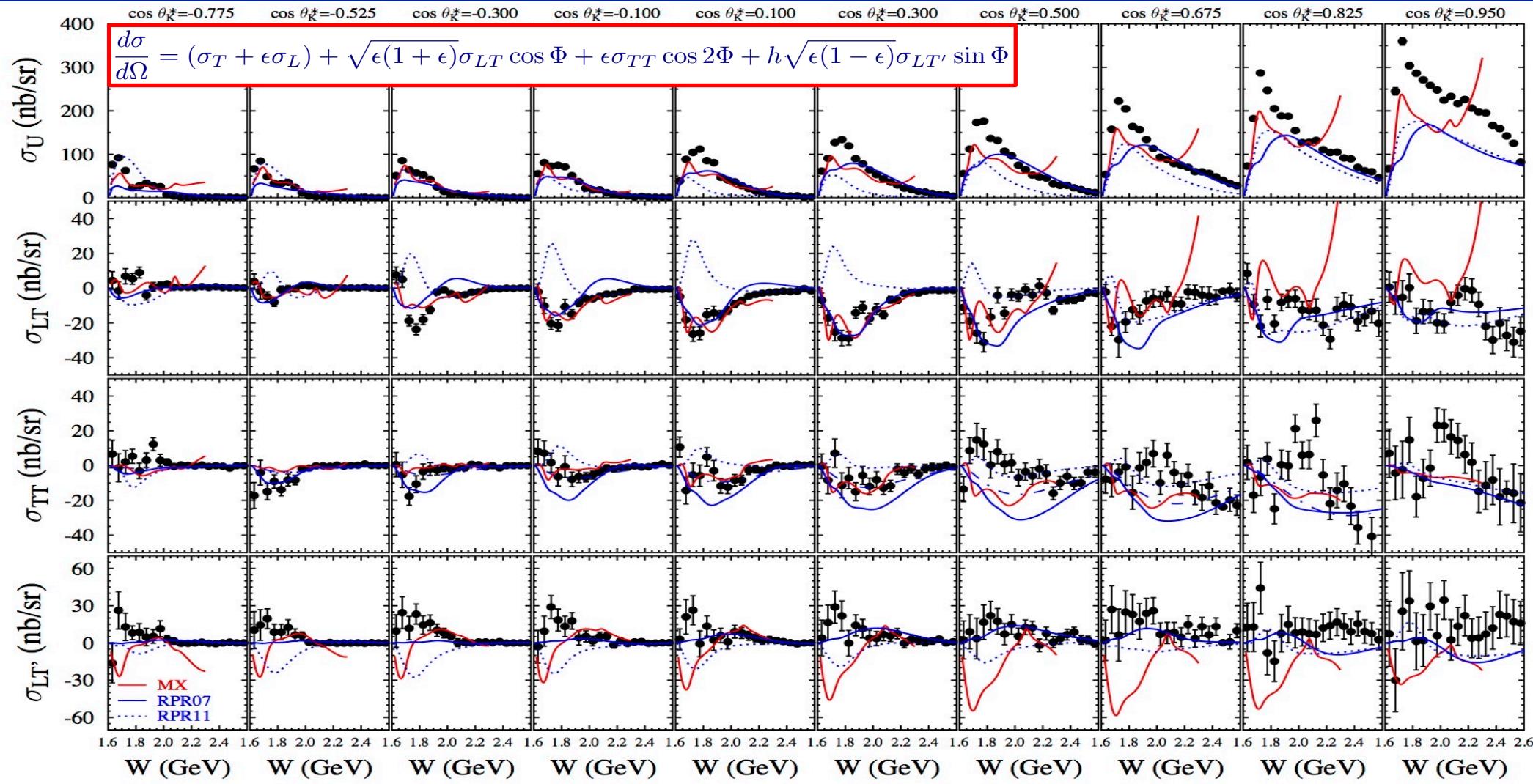
\blacktriangle
N(1720)3/2⁺

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

Description of the $K^+\Lambda$ Data from CLAS



$E = 5.5 \text{ GeV}, W: \text{thr} - 2.6 \text{ GeV}, Q^2 = 1.80, 2.60, 3.45 \text{ GeV}^2$

D.S. Carman et al., PRC 87, 025204 (2013)

Emergence of Hadron Mass

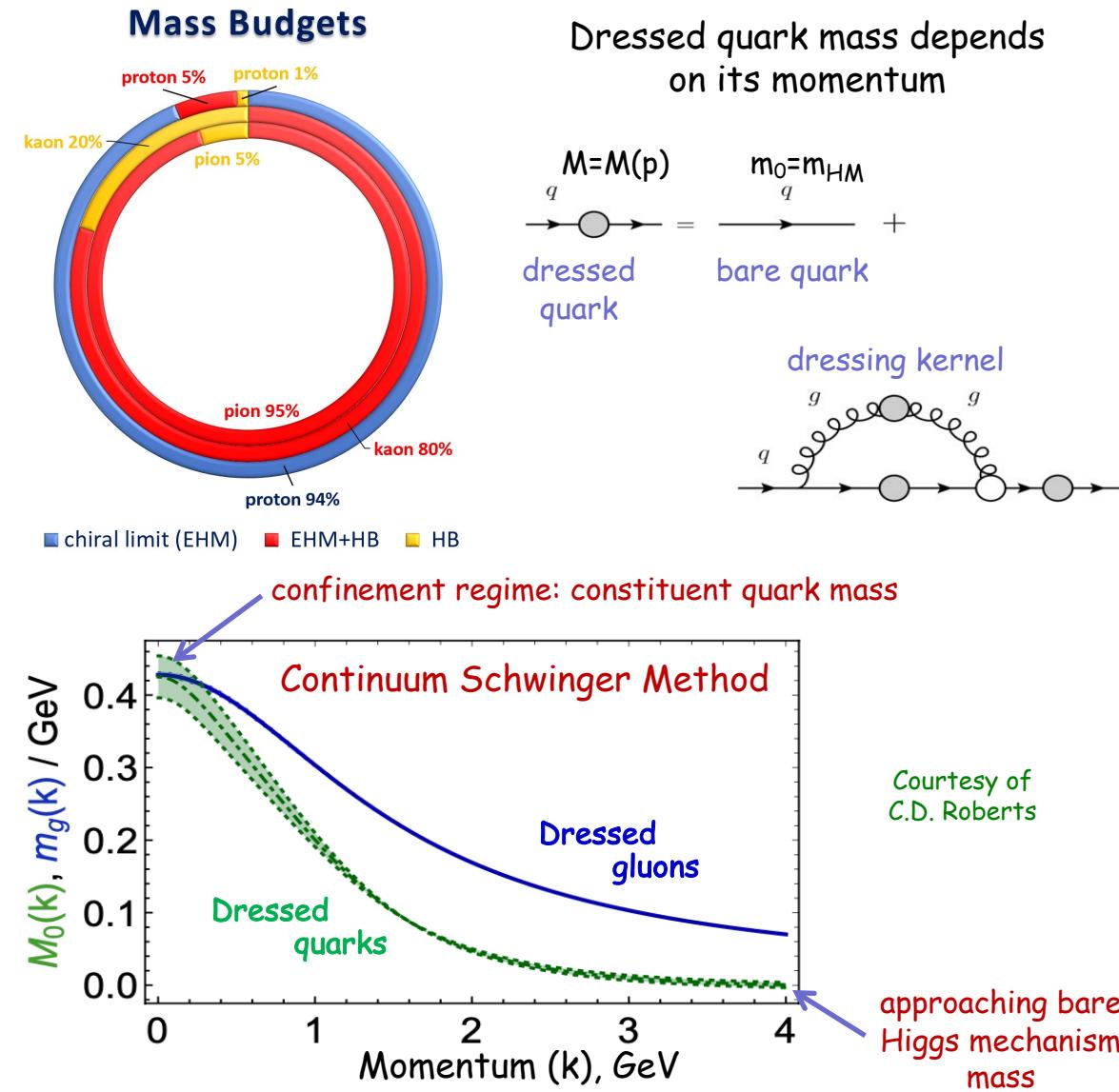
- Mass scale for 3 dressed quarks inside proton is consistent with observed N/N^* masses
- The pion as $q-\bar{q}$ system should have $2/3 M_N$

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

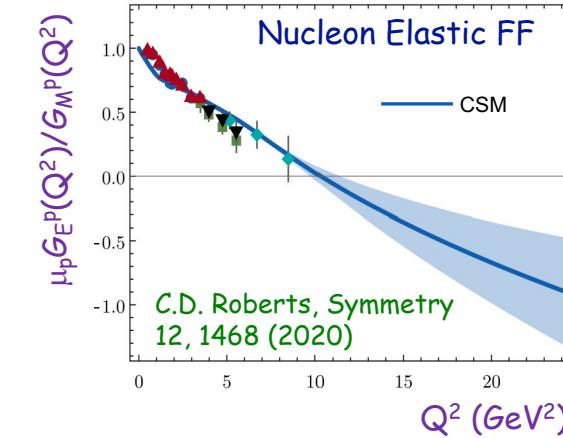
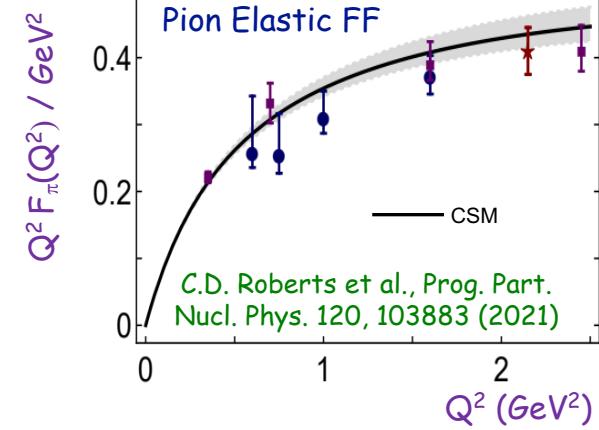
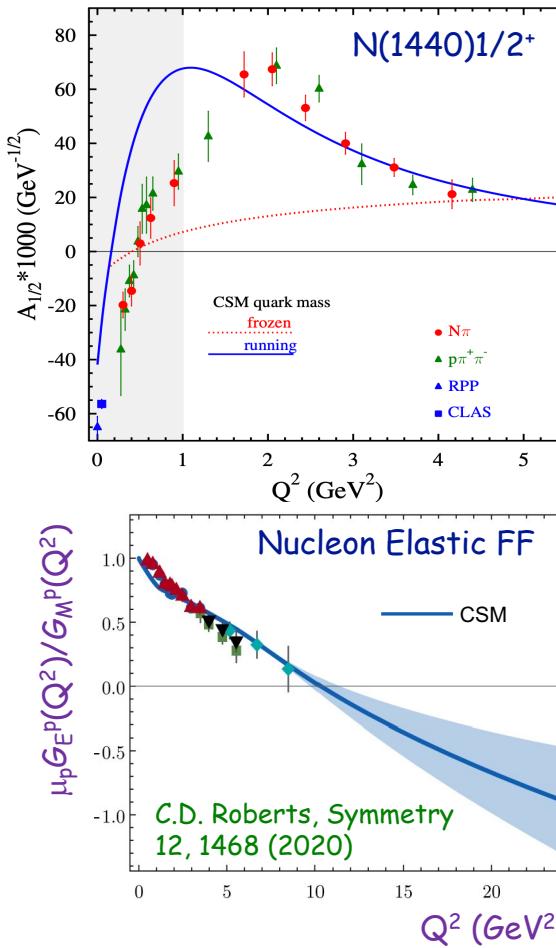
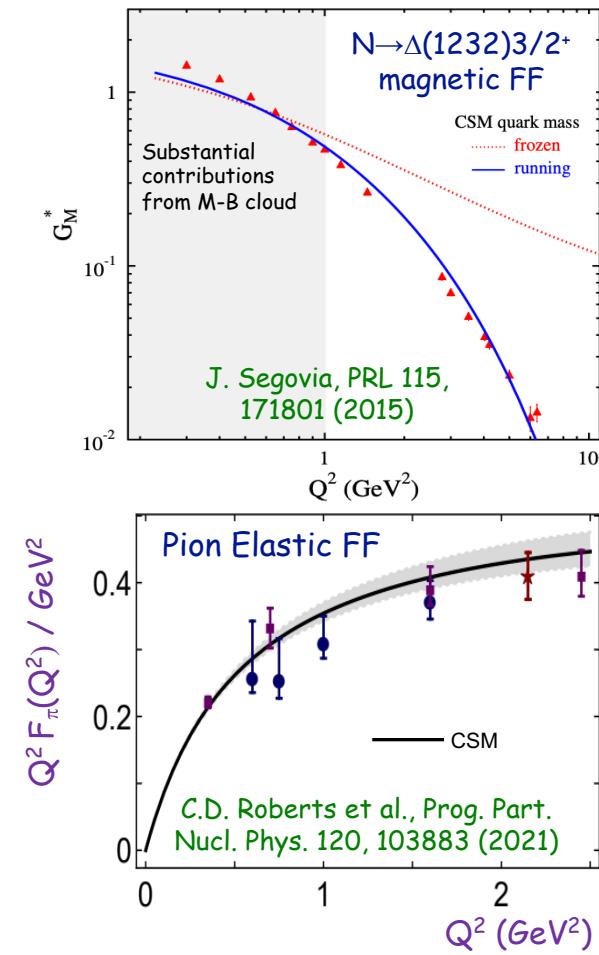
- The lightest hyperon $\approx 20\%$ above nucleon mass

Why is $m_s/m_{u,d}$ current quark mass ≈ 30 ?

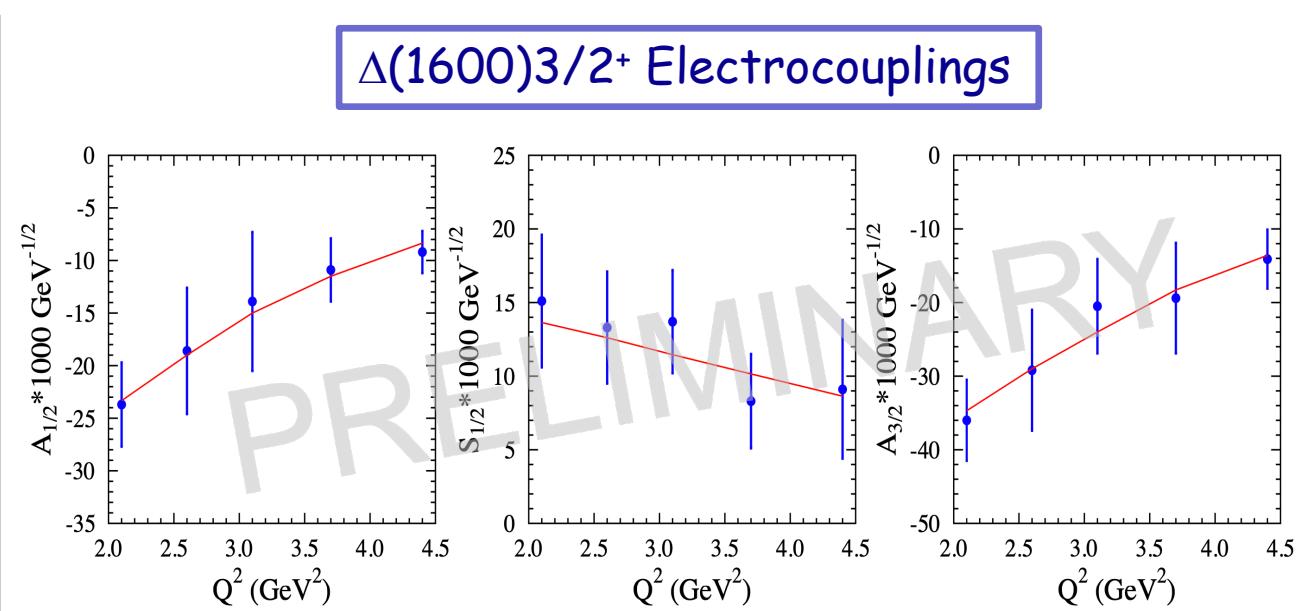
- Studies of ground/excited state nucleons probe EHM in a regime where the sum of the dressed quark masses is the dominant contribution to the physical resonance mass
- Studies of differences π vs. K structure are also critical to unravel/test separation of emergent and Higgs mechanisms (AMBER@CERN, EIC/EicC) - complementary to N^* studies
- 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



Data Results vs. Theory Expectations



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



$\Delta(1600) 3/2^+$ Electrocoupings

NEW

continuum QCD predictions:

Y. Lu et al., PRD 100, 034001 (2019)

Experimental $e p \rightarrow e' p\pi^+\pi^-$ data from CLAS:

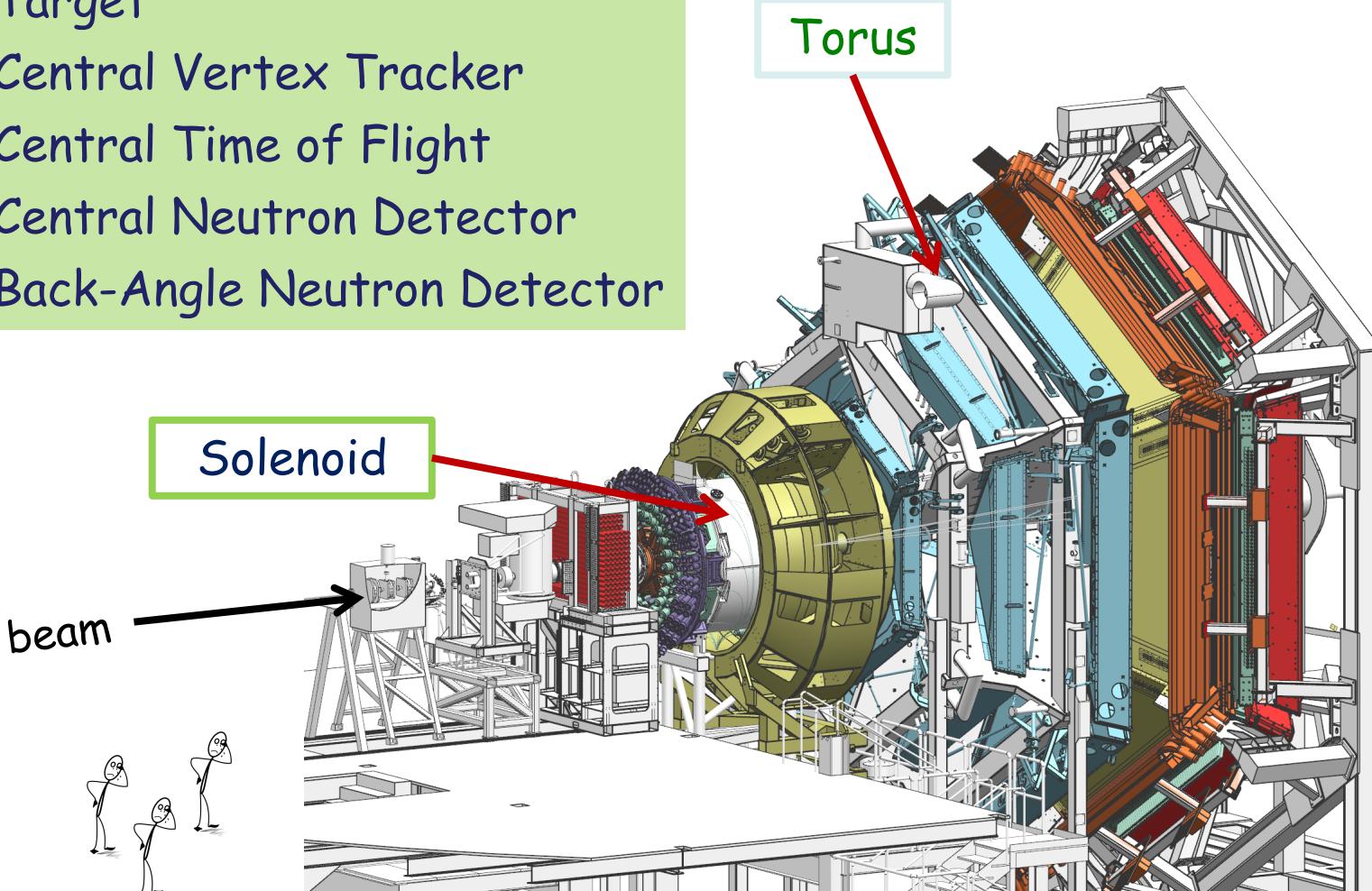
V. Mokeev, AMBER@CERN-VII Workshop

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 Spectrometer

C
E
N
T
R
A
L

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



V.D. Burkert et al., Nucl. Inst. and Meth. A 959, 163419 (2020)

FORWARD

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

	Forward	Central
Angular coverage	$5^\circ - 35^\circ$	$35^\circ - 135^\circ$
Momentum resolution	$\delta p/p < 1\%$	$\delta p/p < 5\%$
θ resolution	1 mrad	5 - 10 mrad
ϕ resolution	1 mrad/ $\sin\theta$	5 mrad/ $\sin\theta$

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

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

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

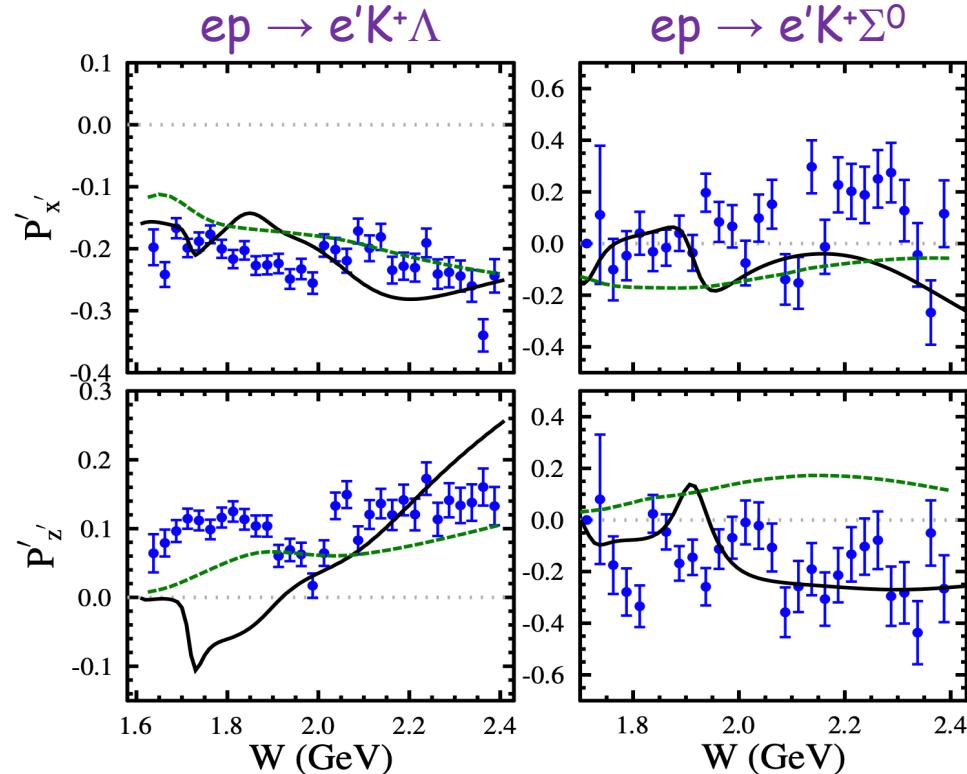
RG-A	Spr. 18 126 mC	10.2 GeV, 10.6 GeV 50% of total
	Fall 18 99 mC	
	Spr. 19 58 mC	
RG-K	Fall 18 28 mC	6.5 GeV, 7.5 GeV 10% of total

continuing in Fall 23

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

CLAS12 K⁺Y Transferred Polarization

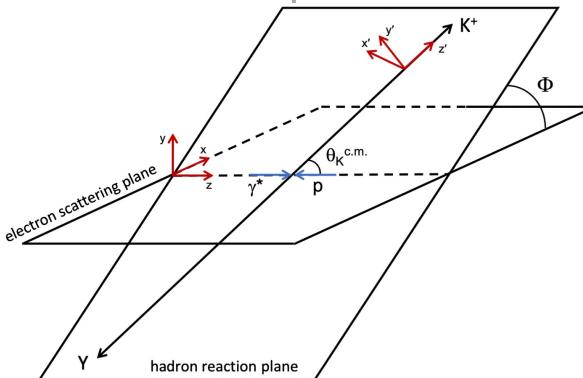
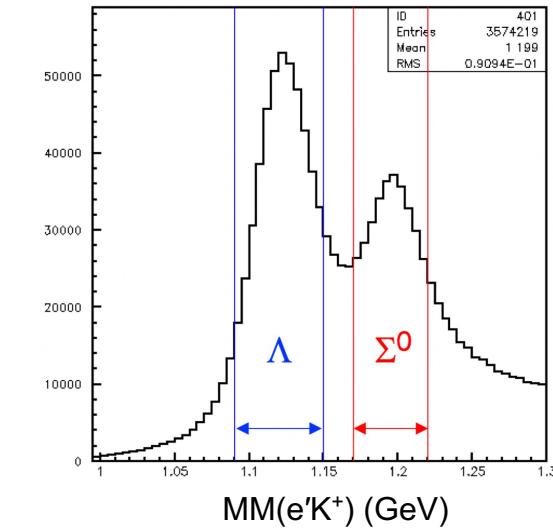
CLAS12 RG-K @ 6.535 GeV



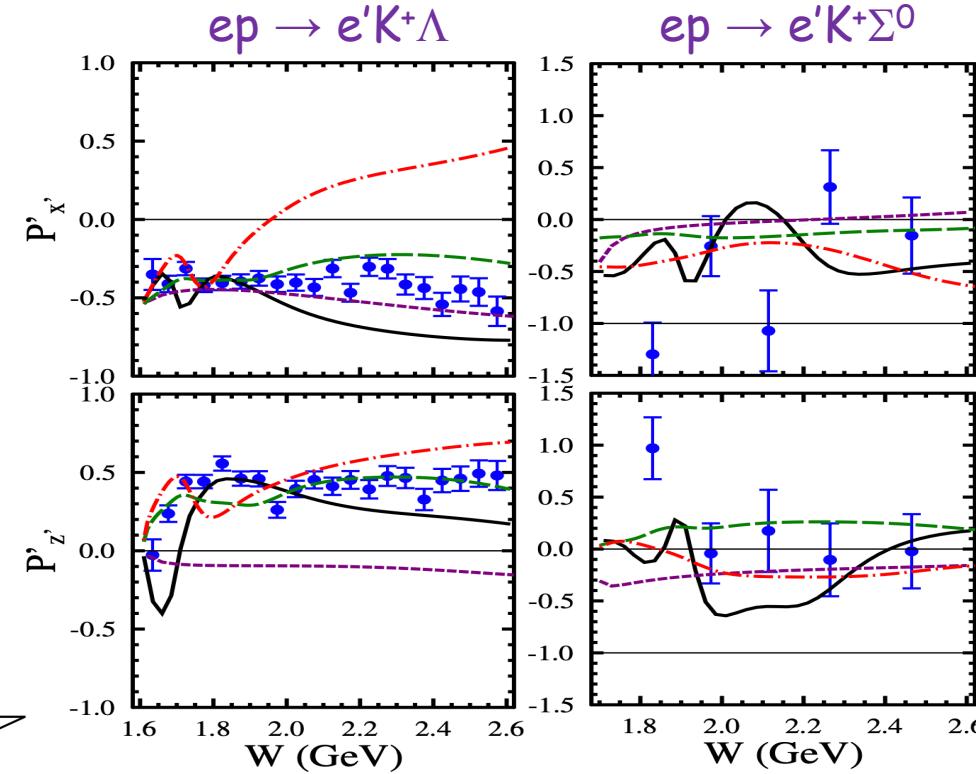
D.S. Carman et al., PRC 105, 065201 (2022)

KAON-MAID
RPR

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



CLAS e1-6 @ 5.754 GeV



D.S. Carman et al., PRC 79, 065205 (2009)

Mart/Bennhold
RPR-1

RPR-2
Regge

CLAS12 Inclusive Cross Sections

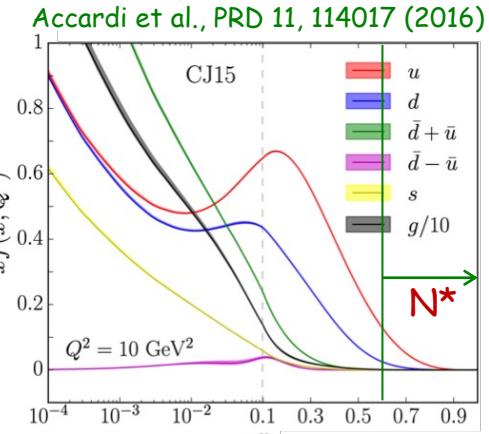
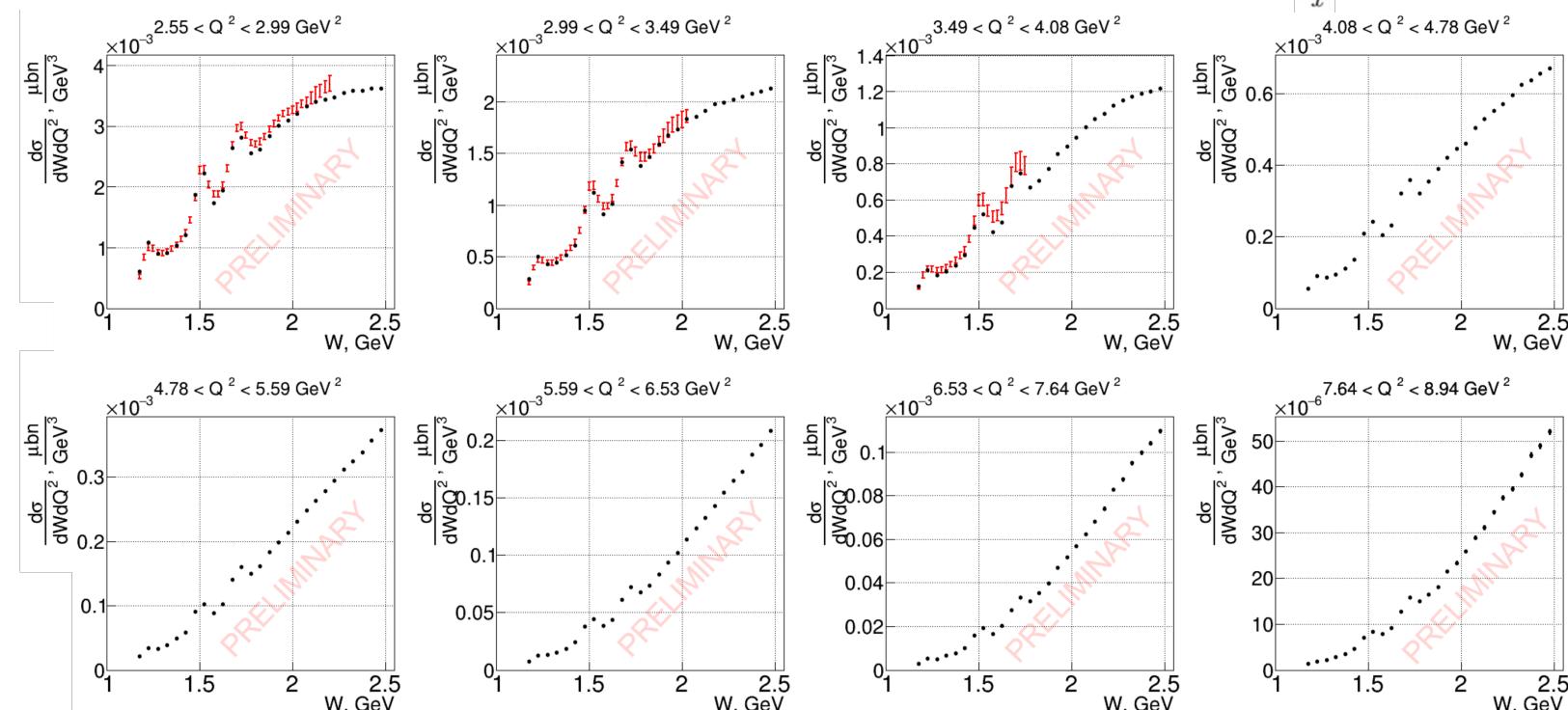
Extending knowledge of the nucleon Parton Distribution Functions in the resonance region:

- Global QCD analyses have provided detailed information on the nucleon PDFs in a wide range of longitudinal momentum fraction, x , from 10^{-4} to 0.9
- At large x , in the nucleon resonance region ($W < 2.5$ GeV), the PDFs are significantly less explored
- Extractions in this region require accounting for higher-twist effects, target-mass corrections, and the nucleon resonance electro-excitations

$p(e, e')X$

- Preliminary CLAS12 data @ $E_b = 10.6$ GeV
V. Klimenko - in progress
- CLAS data @ $E_b = 1.5 - 4.4$ GeV
M. Osipenko et al., PRD 67, 092001 (2003)

First broad W coverage data over the full resonance region to $Q^2=9$ GeV 2 - spanning the transition from quark-gluon confinement toward pQCD



Resonant Contributions to Inclusive $F_2(W, Q^2)$ Structure Function

$$F_2 = \mathcal{K} \frac{1 + \frac{\sigma_L}{\sigma_T}}{1 + \epsilon \cdot \frac{\sigma_L}{\sigma_T}} \sigma_U$$

CLAS σ_U data: M. Osipenko et al., PRD 67, 092001 (2003)

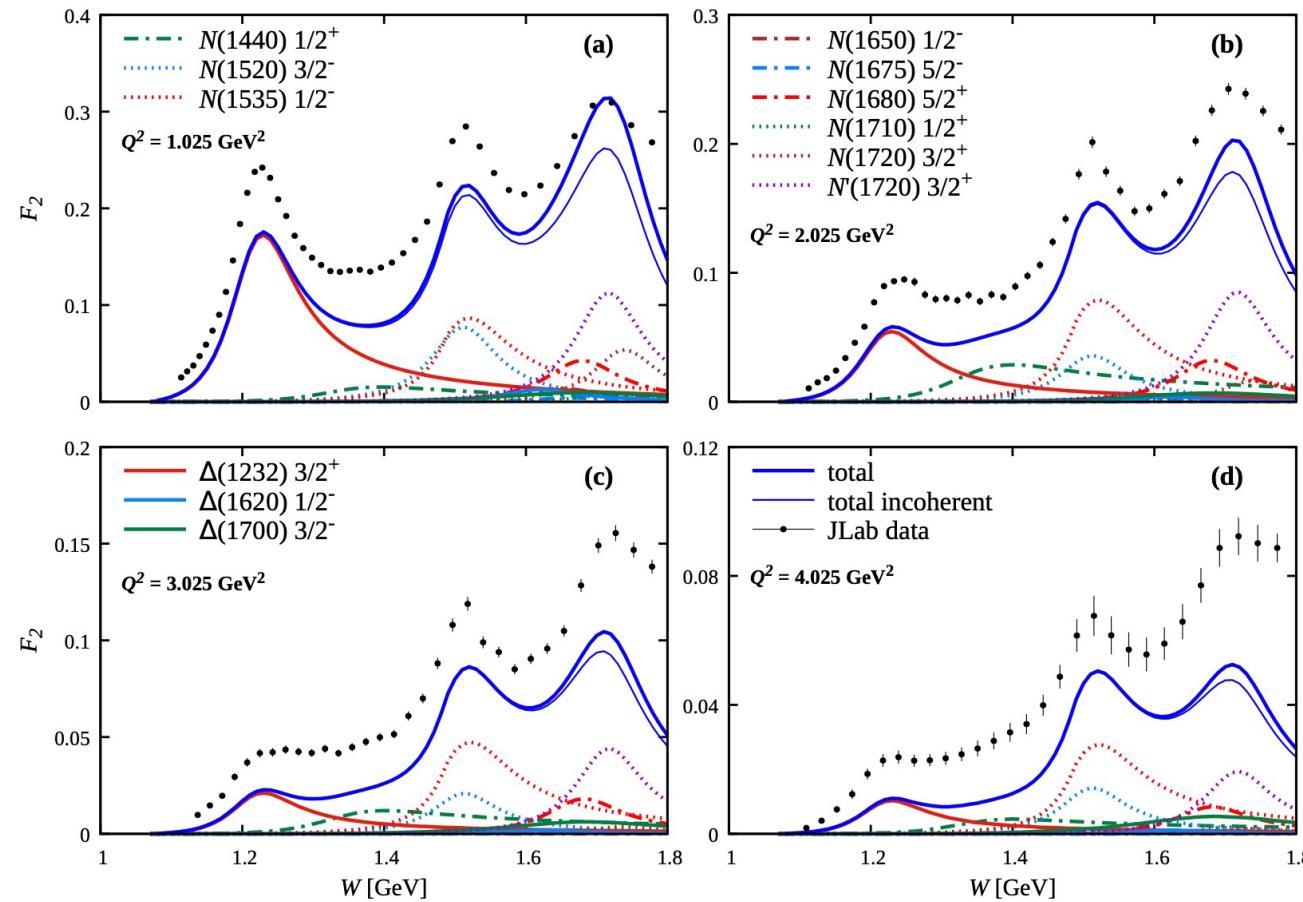
Hall C σ_L/σ_T data: Y. Liang, Ph.D. thesis (2003)

N^* contributions computed with $\gamma_v p N^*$ electrocouplings from CLAS data

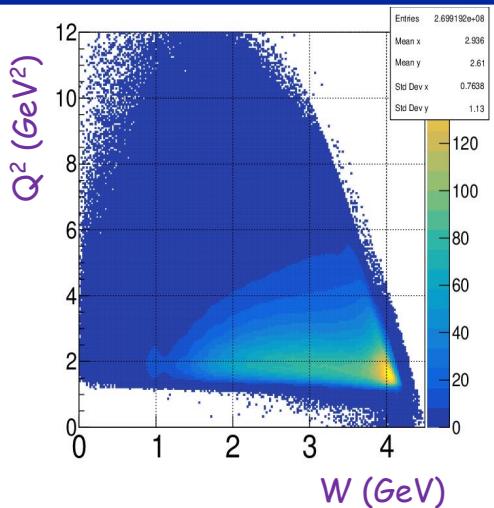
A.N. Hiller Blin et al., PRC 100, 035201 (2019)

Insight into EHM:

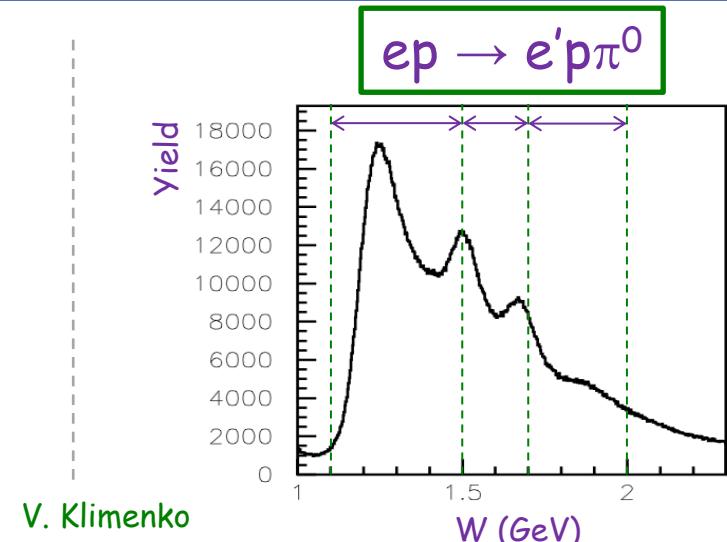
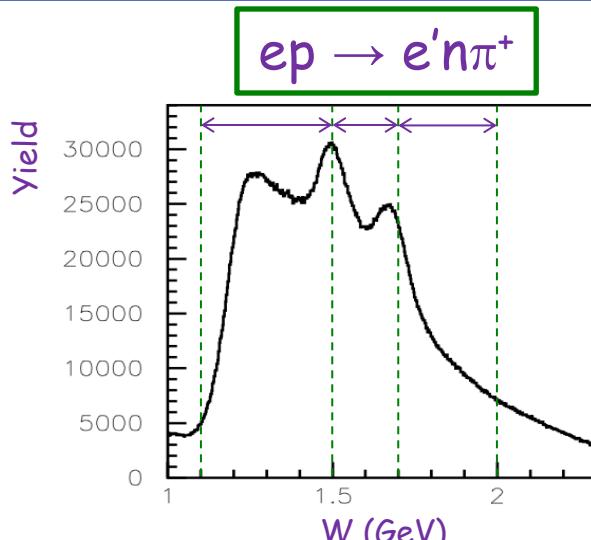
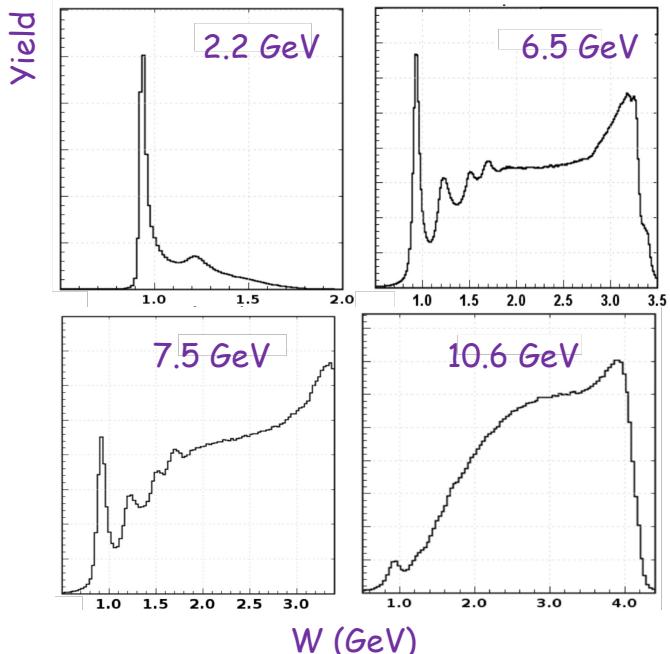
- The non-resonant parts of F_2 can be computed with the dressed quark mass function. The full F_2 structure function will be confronted to the data estimated from the resonant/non-resonant contributions.
- CLAS12 data on the structure function moments in a broad range of $Q^2 < 10 \text{ GeV}^2$ may shed light on momentum dependence of dressed gluon mass.



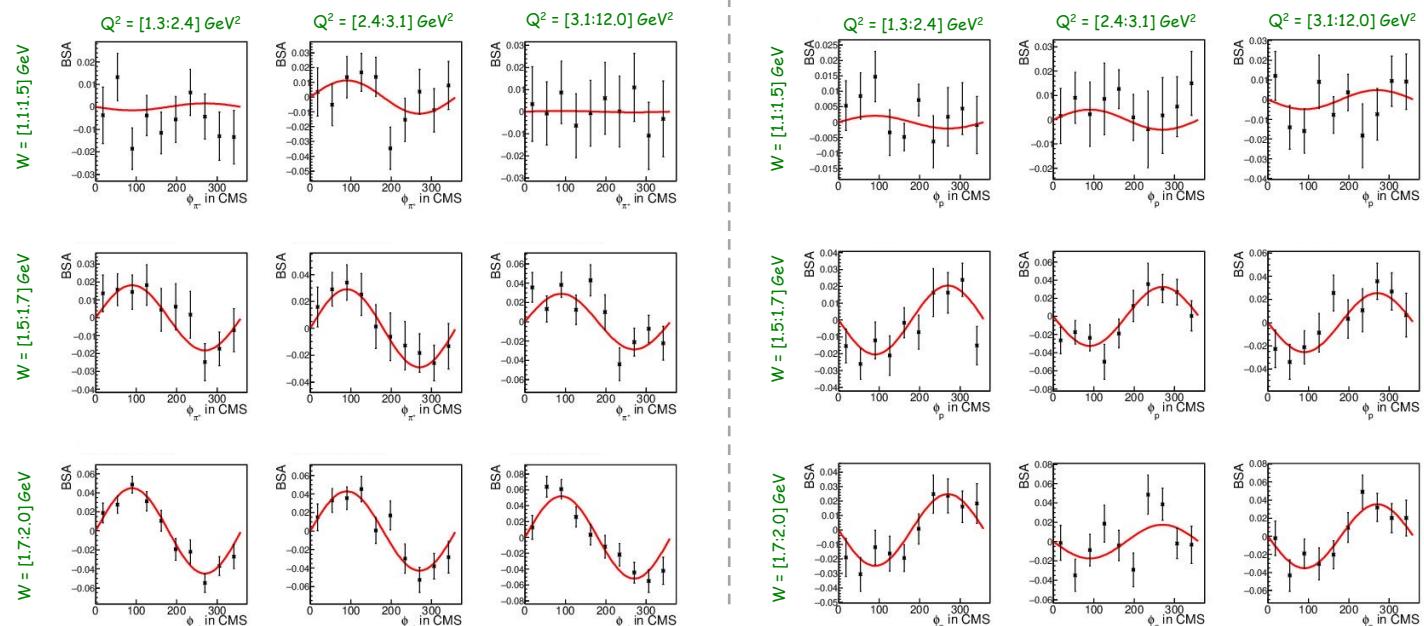
CLAS12 N π Beam Spin Asymmetries



Trigger based on scattered electron

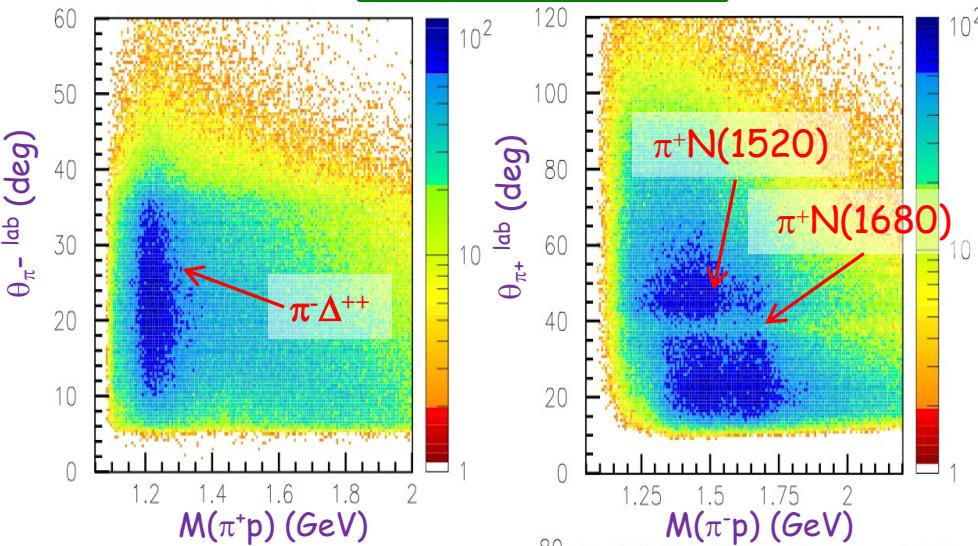


V. Klimenko

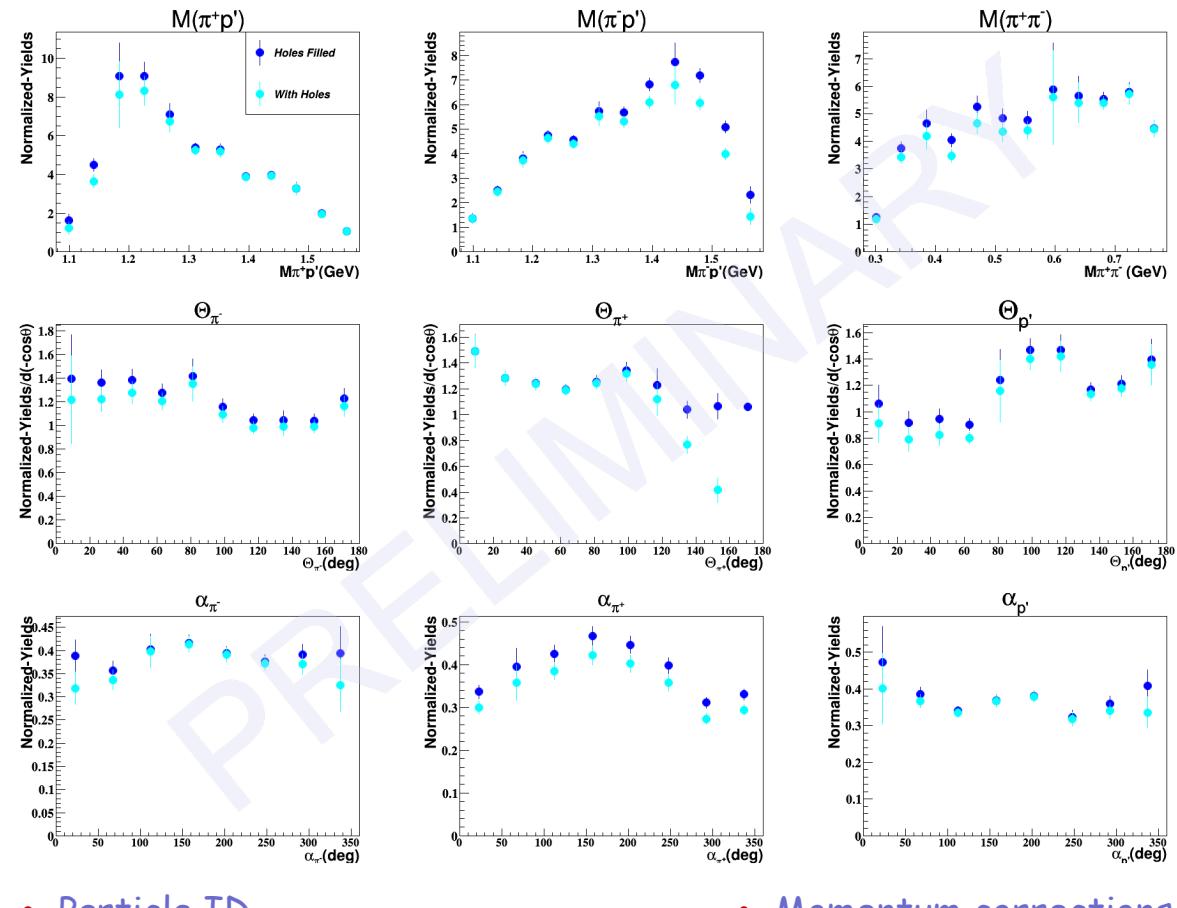


CLAS12 $p\pi^+\pi^-$ Cross Sections

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



Normalized yields: $Q^2:[3.0-3.5] \text{ GeV}^2$, $W:[1.725:1.750] \text{ GeV}$



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

Extraction of cross sections advancing

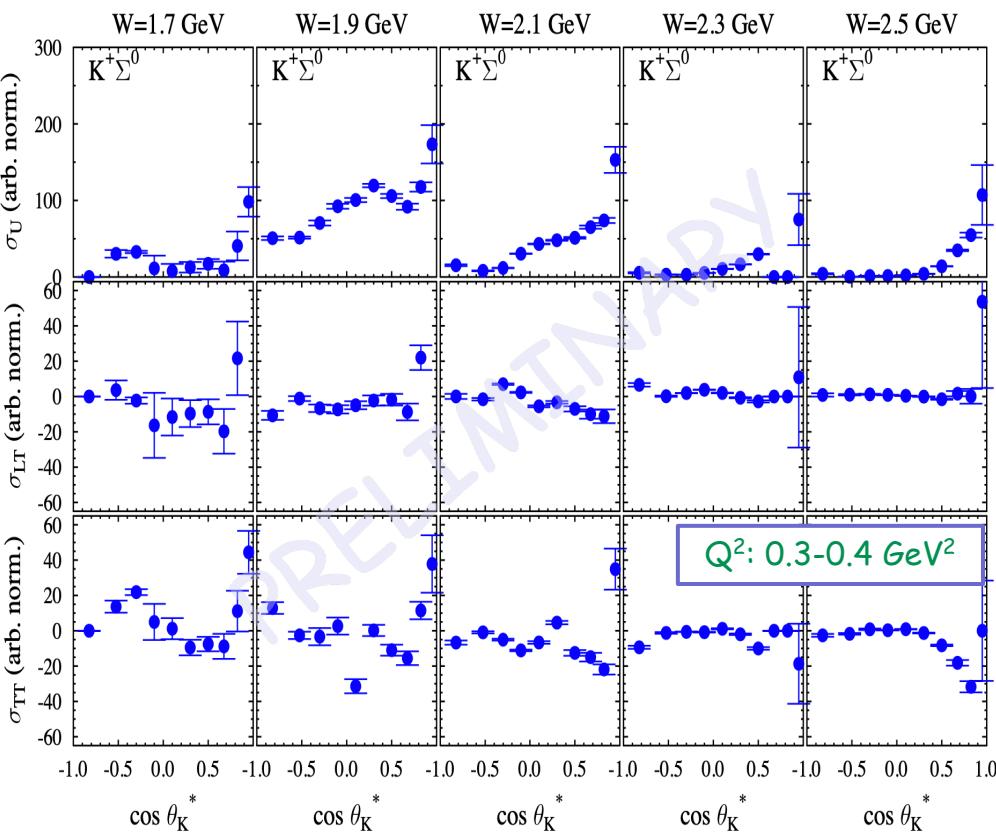
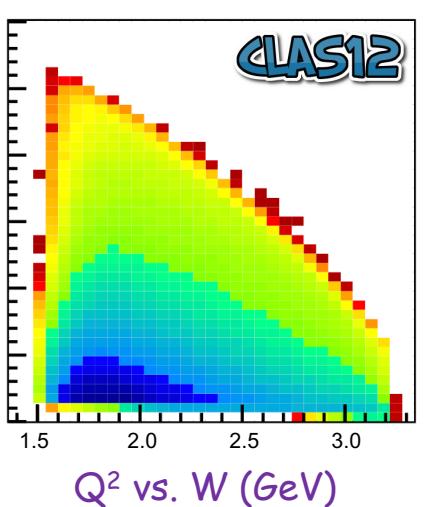
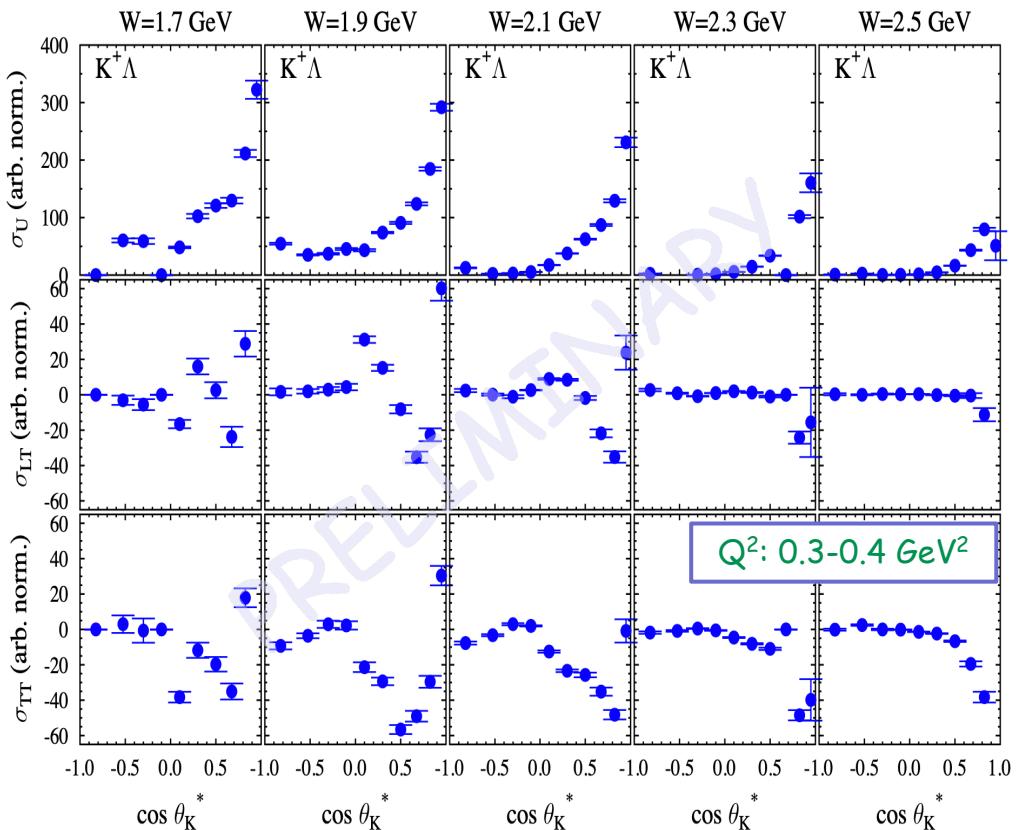
K. Neupane

CLAS12 K⁺Y Cross Section Measurements

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

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

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



6.535 GeV RG-K

D.S. Carman, in progress

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



JLab Beyond the 12 GeV Era

JLab considering accelerator upgrade
to electron beam energies of 20+ GeV

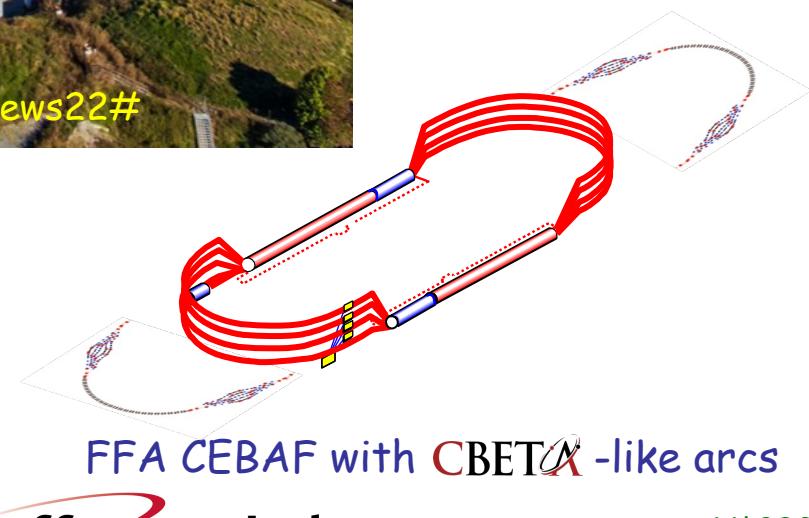
High Energy Workshop Series 2022

JLab Upgrade: Science at the luminosity frontier



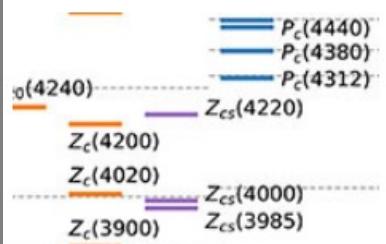
Physics with CEBAF at 12 GeV and
Future Opportunities
e-Print: 2112.00060 [nucl-ex]

(accepted for publication to Progress in
Particle and Nuclear Physics - in press)



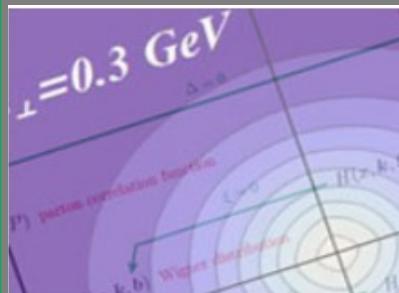
FFA CEBAF with CBETA-like arcs

Hadron Spectroscopy
with a CEBAF Energy
Upgrade



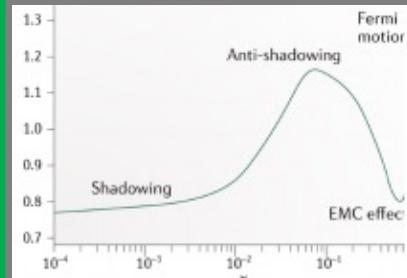
- 38 participants
- 8 talks

The Next Generation of
3D Imaging



- 55 participants
- 14 talks

Science at Mid-x: Anti-
Shadowing and the Role
of the Sea



- 43 participants
- 14 talks

Physics Beyond the
Standard Model



- 37 participants
- 6 talks

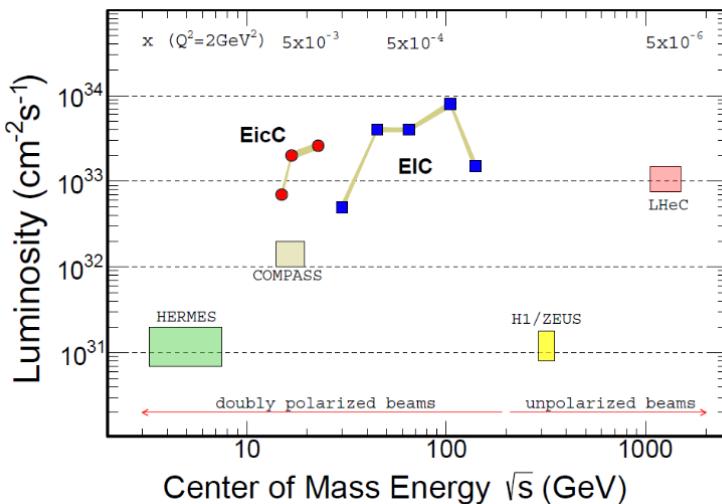
J/Psi and Beyond



- 38 participants
- 7 talks

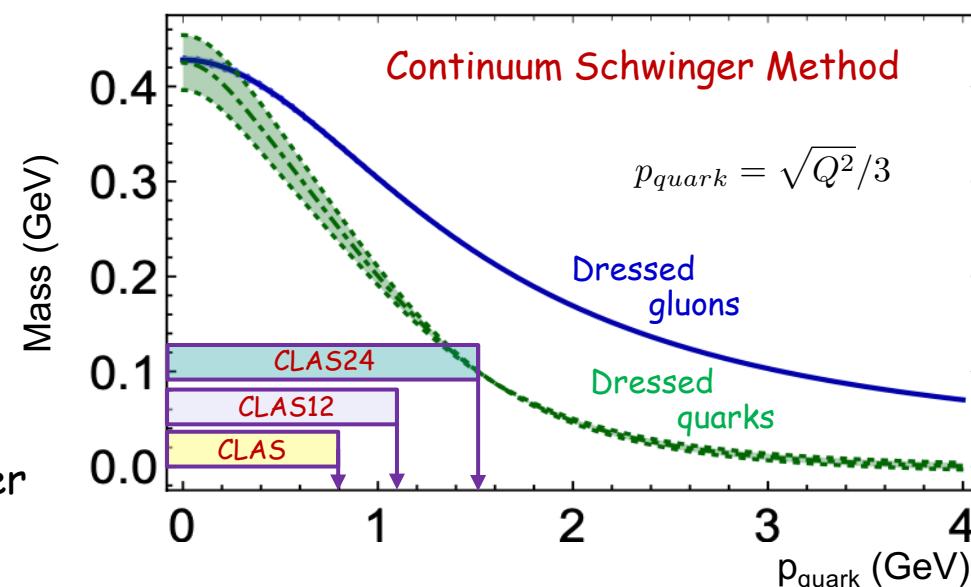
Considerations for N* Program at 20+ GeV

Energy and luminosity increase are needed to obtain $\gamma_V p N^*$ electrocouplings at $Q^2 > 10 \text{ GeV}^2$ to map out the dressed quark mass over the entire range of 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

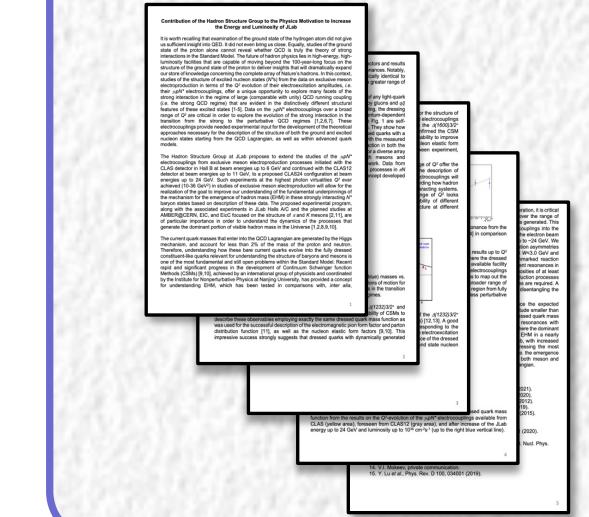


The electroproduction measurements foreseen at JLab in Hall B after completion of the 12 GeV program:

- Beam energy 20+ GeV
- Nearly 4π coverage
- High luminosity
- Studies of exclusive reactions

For program details see:

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



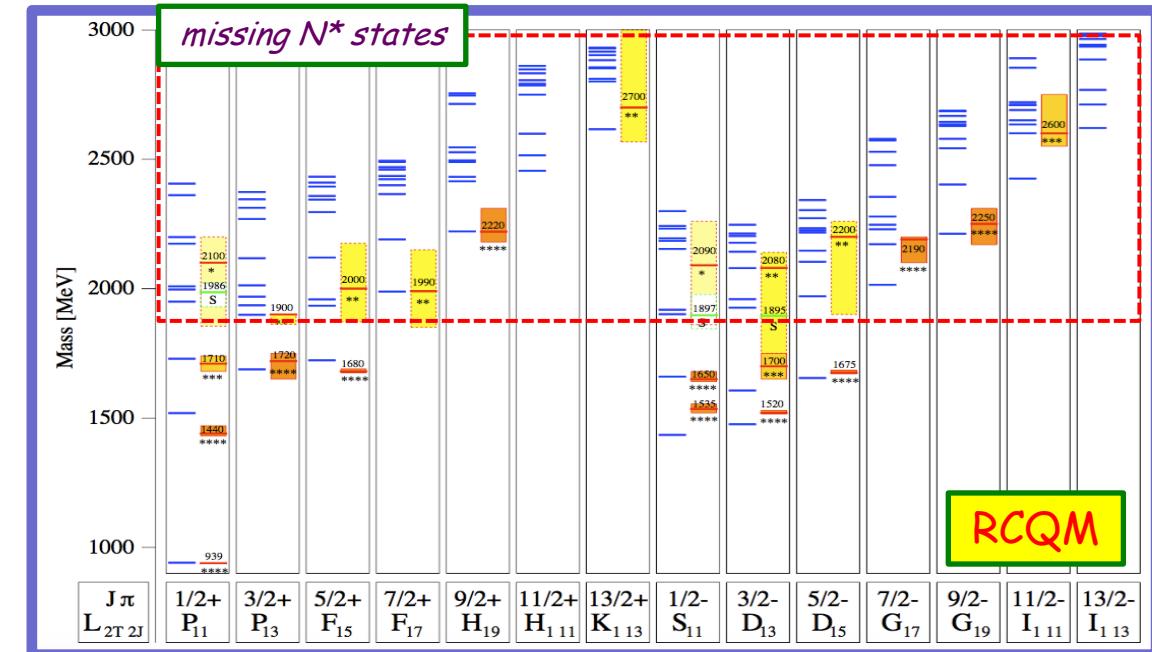
Concluding Remarks

- 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 $Q^2 \sim 5 \text{ GeV}^2$ - electrocouplings of most N^* states $< 1.8 \text{ GeV}$ have been extracted from these data for the first time
 - With the development of a reaction model the KY channels should be an important ingredient to understand the spectrum and structure of higher-lying N^* states
- The CLAS12 N^* program will extend these studies for $0.05 < Q^2 < 12 \text{ GeV}^2$:
 - Analysis of the collected data is advancing - first CLAS12 N^* paper published on KY polarization
 - Consistent results on the dressed quark mass function from analyses of the electrocouplings of different N^* states will validate fundamental insight into emergence of hadron mass (EHM)
 - complementary to studies of EHM of the structure of pions and kaons
 - 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
- Considering a future for JLab beyond 12 GeV era - **JLab 20+ GeV @ the luminosity frontier**

BACKUP SLIDES

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 ⁻		***	**	**	*	***
$\Delta(1600)3/2^+$	***	****	***			****
$\Delta(1900)1/2^-$	**	***	***		**	***
$\Delta(2200)7/2^-$	*	***	**		**	***



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

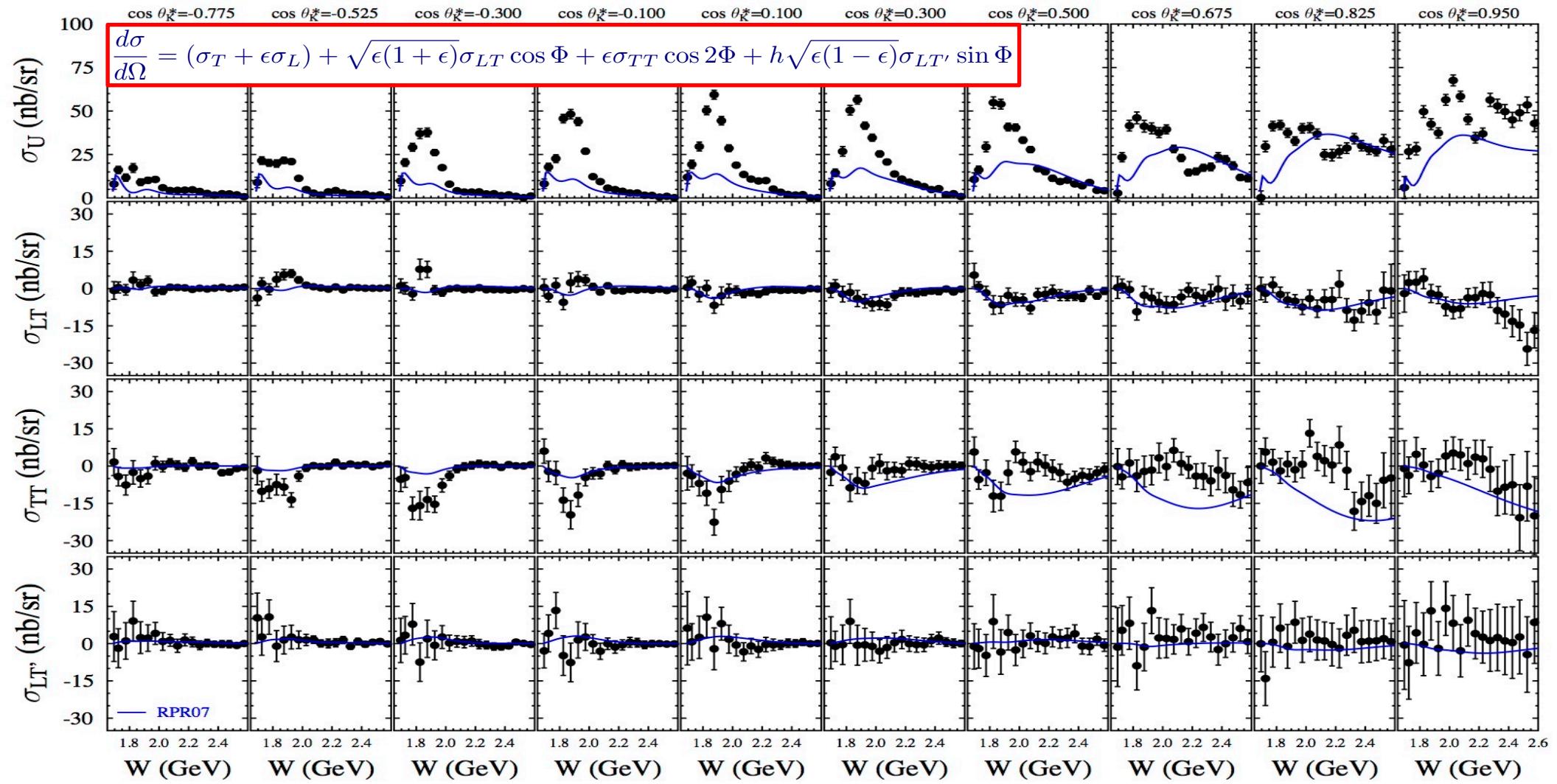
Recent LQCD predictions support CQM

Dudek, Edwards, PRD 85, 054016 (2012)

Decisive impact from CLAS photoproduction data

- Extend studies to electroproduction and to higher masses

Description of the $K^+\Sigma^0$ Data from CLAS

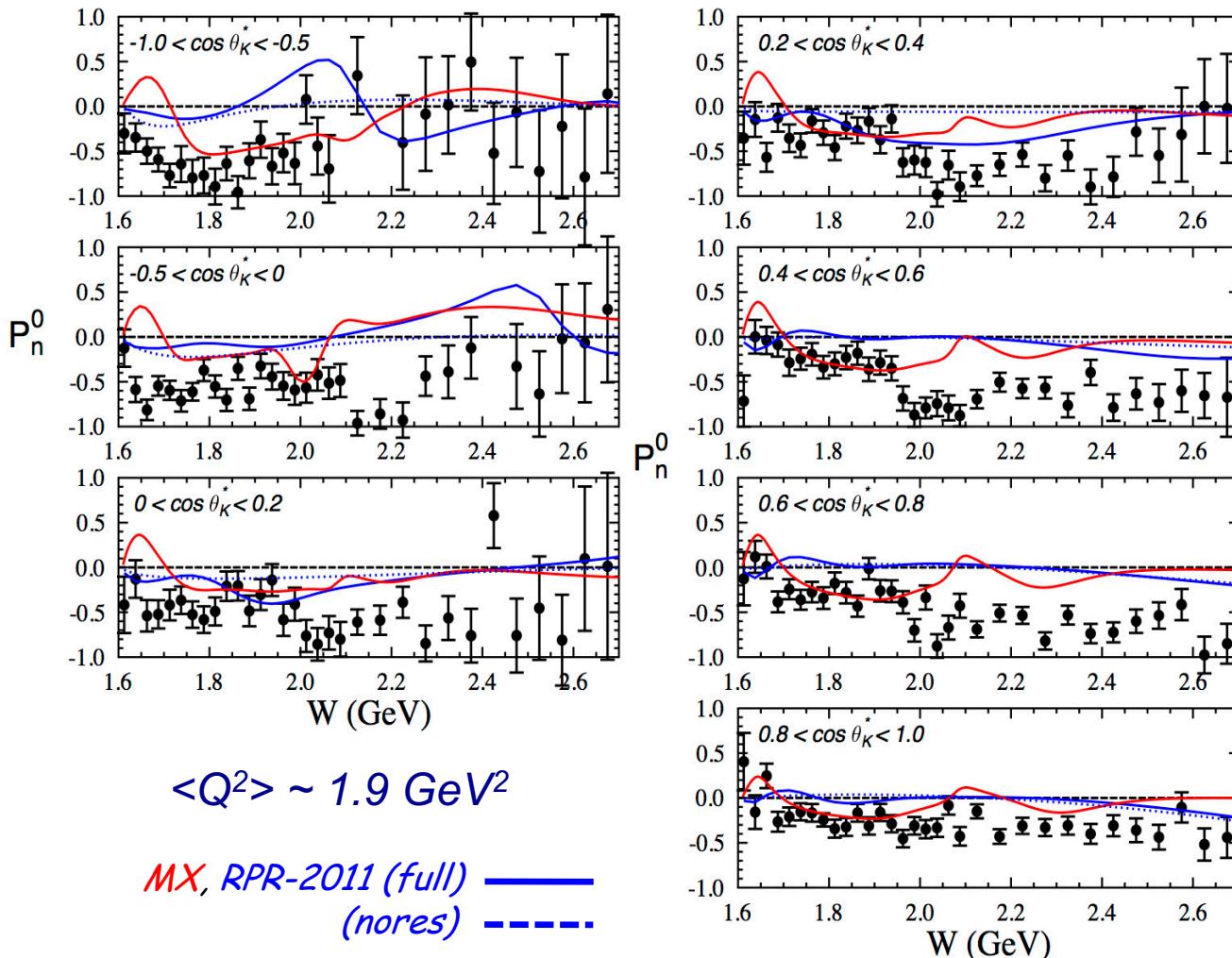


$E = 5.5 \text{ GeV}, W: \text{thr} - 2.6 \text{ GeV}, Q^2 = 1.80, 2.60, 3.45 \text{ GeV}^2$

D.S. Carman et al., PRC 87, 025204 (2013)

K⁺Λ Polarization Observables

Recoil Polarization

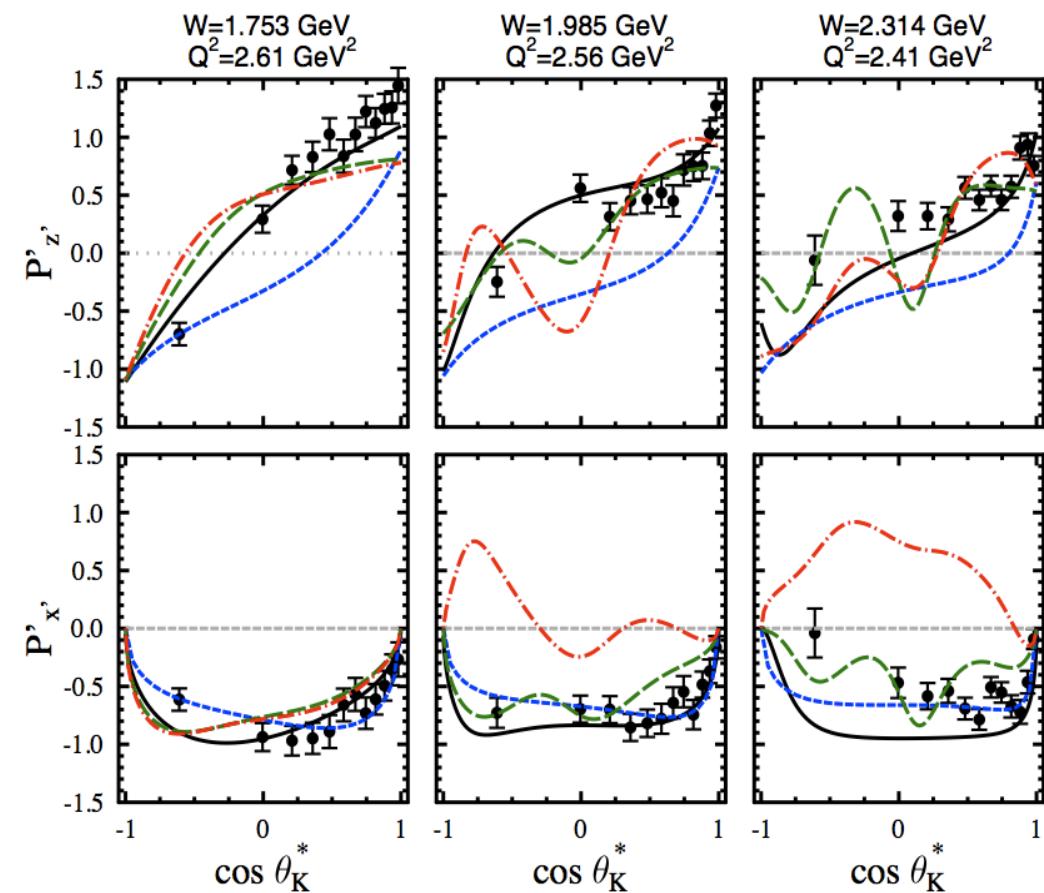


M. Gabrielyan et al., PRC 90, 035202 (2014)

Daniel S. Carman

Jefferson Lab

Beam-Recoil Transferred Polarization



Isobar Model - Mart
Regge Model - GLV

RPR07 w $P_{11}(1900)$ - Ghent
RPR07 w $D_{13}(1900)$ - Ghent

D.S. Carman et al., PRC 79, 065205 (2009)

N*2022 - Oct. 17 - 21, 2022

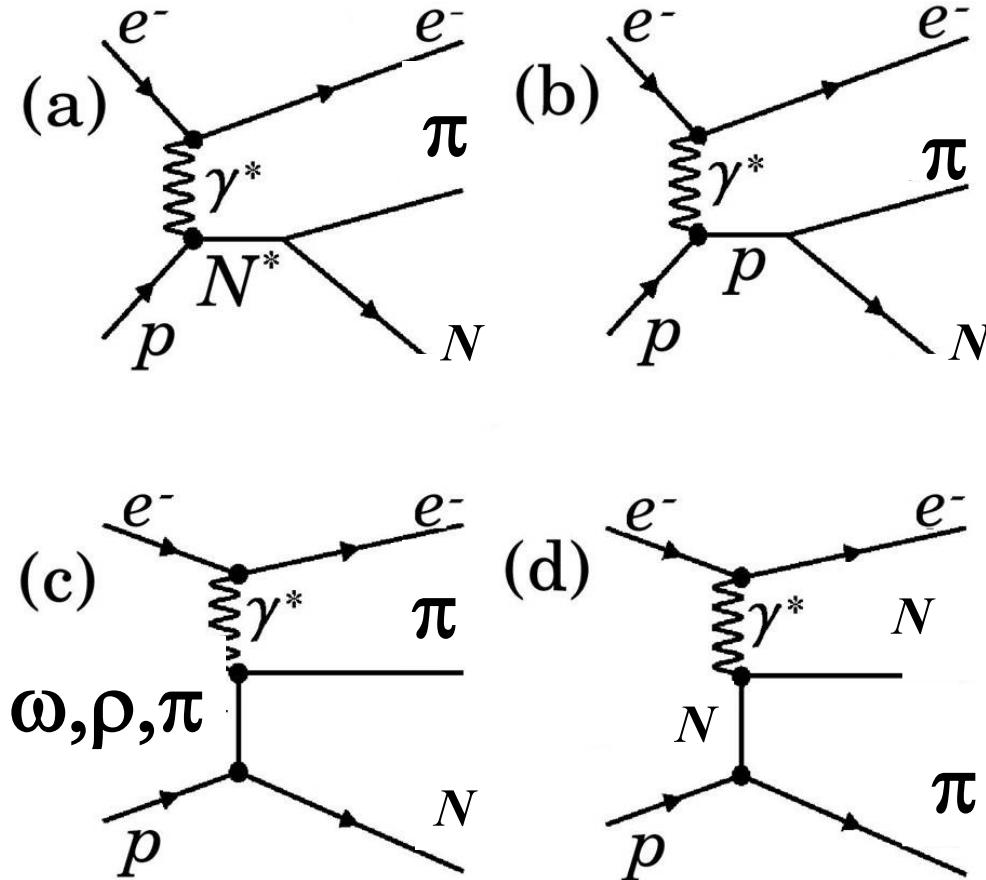
Page 30

Approaches for Extraction of $\gamma_v p N^*$ Electrocouplings from $N\pi$ Exclusive Electroproduction off Protons

Dispersion Relations (DR)

- The real parts of invariant $N\pi$ electroproduction amplitudes are computed from their imaginary parts employing fixed-t dispersion relations.
- The imaginary parts of the $N\pi$ electroproduction amplitudes at $W > 1.3$ GeV are saturated by the resonant parts and were computed from N^* parameters fit to the data.

Unitary Isobar Model (UIM)

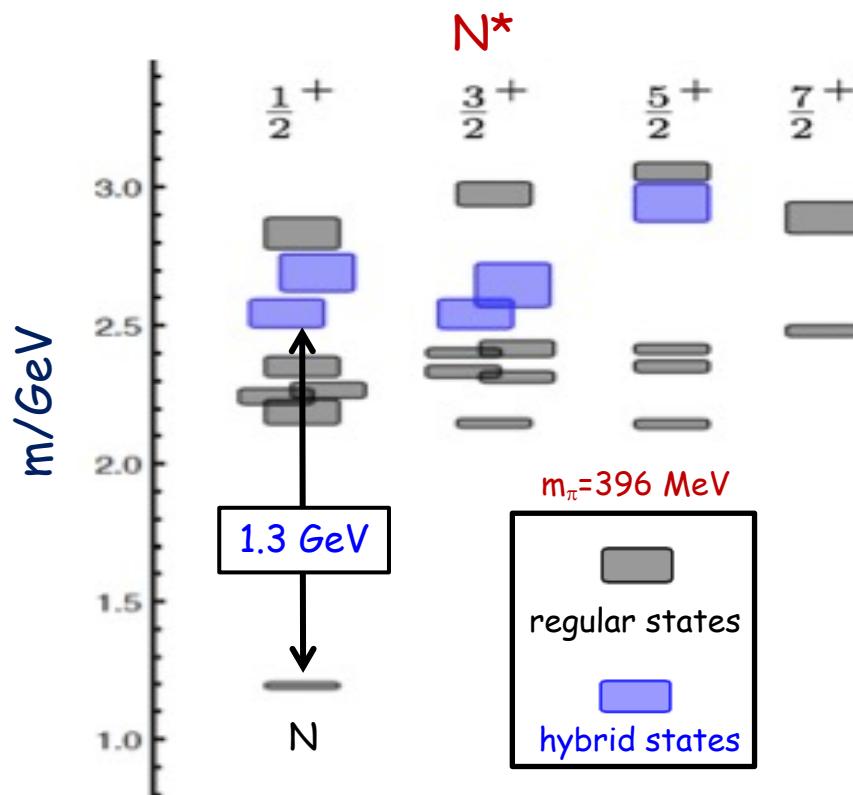


I.G. Aznauryan, PRC 67, 015209 (2003); I.G. Aznauryan et al., PRC 80, 055203 (2009)

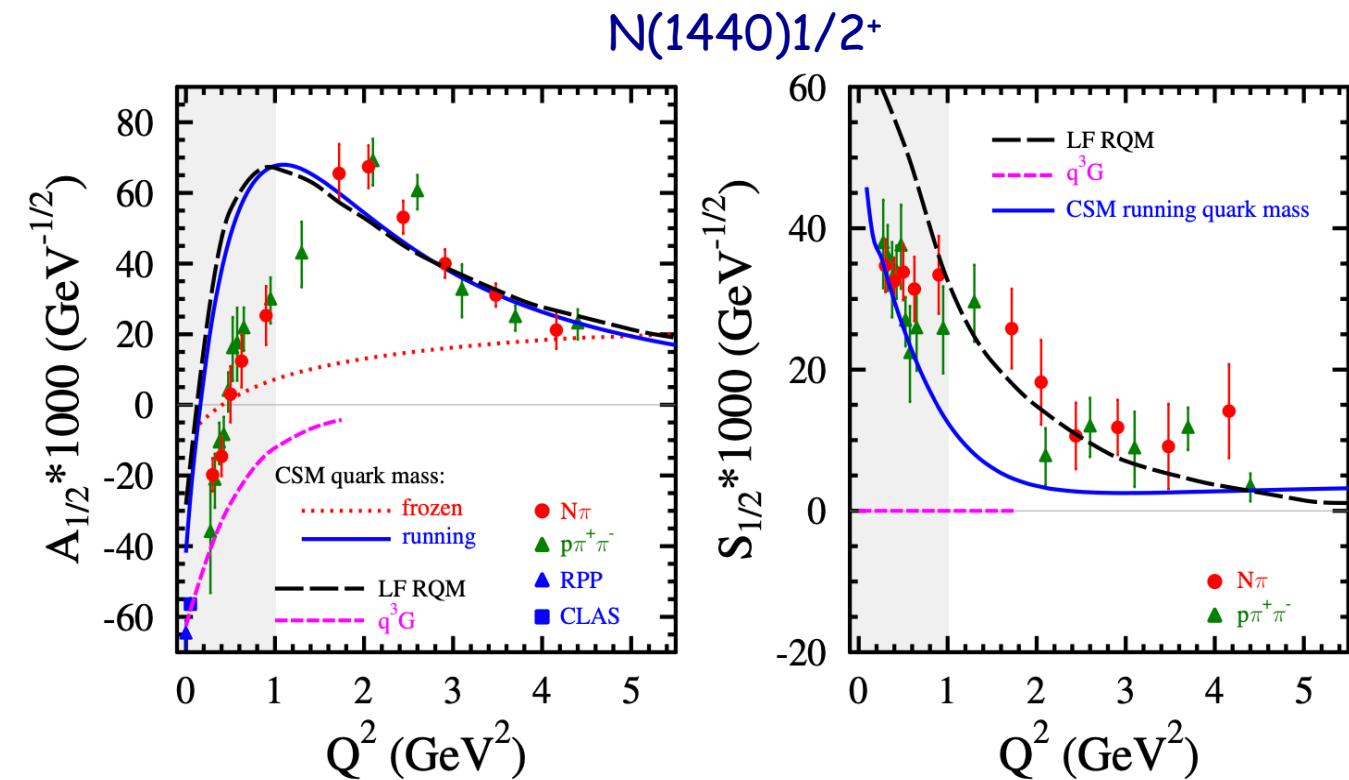
Hunting for Glue in Excited Baryons

Can glue be a structural component of excited baryon states?

N^* spectrum from Lattice QCD predicts the existence of hybrid baryons



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



Dudek, Edwards, PRD 85, 054016 (2012)

Daniel S. Carman

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N*2022 - Oct. 17 - 21, 2022

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CLAS12 is the ideal laboratory to perform search