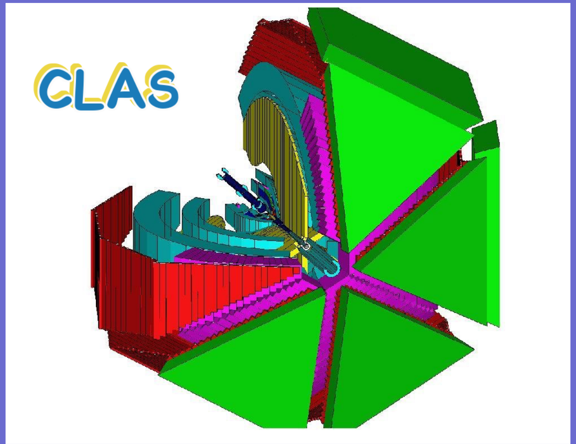
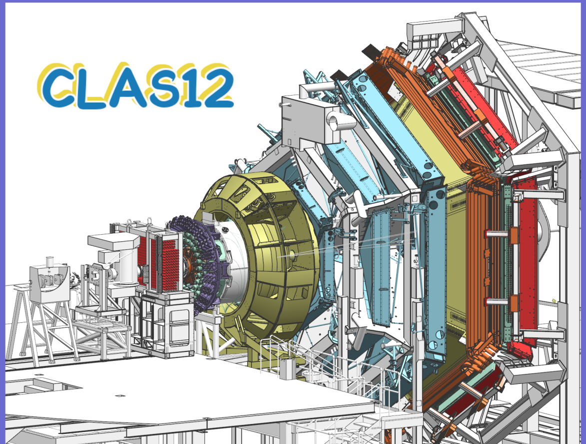
Nucleon Resonance Studies from Exclusive KY Electroproduction





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CEBAF Large Acceptance Spectrometer

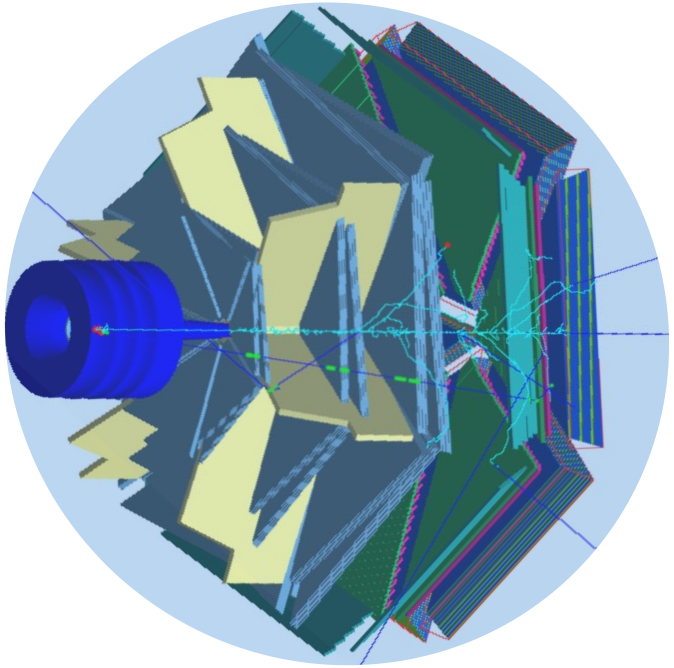
NSTAR2024

Outline:

- N* Spectrum & Structure
- Relevance of KY Electroproduction
- CLAS/CLAS12 N* Program and Results
- Future Plans
- Concluding Remarks

Hall B N* Program Overview

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



- CLAS & CLAS12 - 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
    - search for hybrid baryons (qqqG) and other non-3q configurations

Recent review papers:

D.S. Carman, K. Joo, V.I. Mokeev, Few Body Systems 61, 29 (2020)
V.I. Mokeev and D.S. Carman, Few Body Systems 63, 59 (2022)
D.S. Carman, R.W. Gothe, V.I. Mokeev, C.D. Roberts, Particles 6, 416 (2023)

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, $\cos\theta_m^* = [-1:1]$

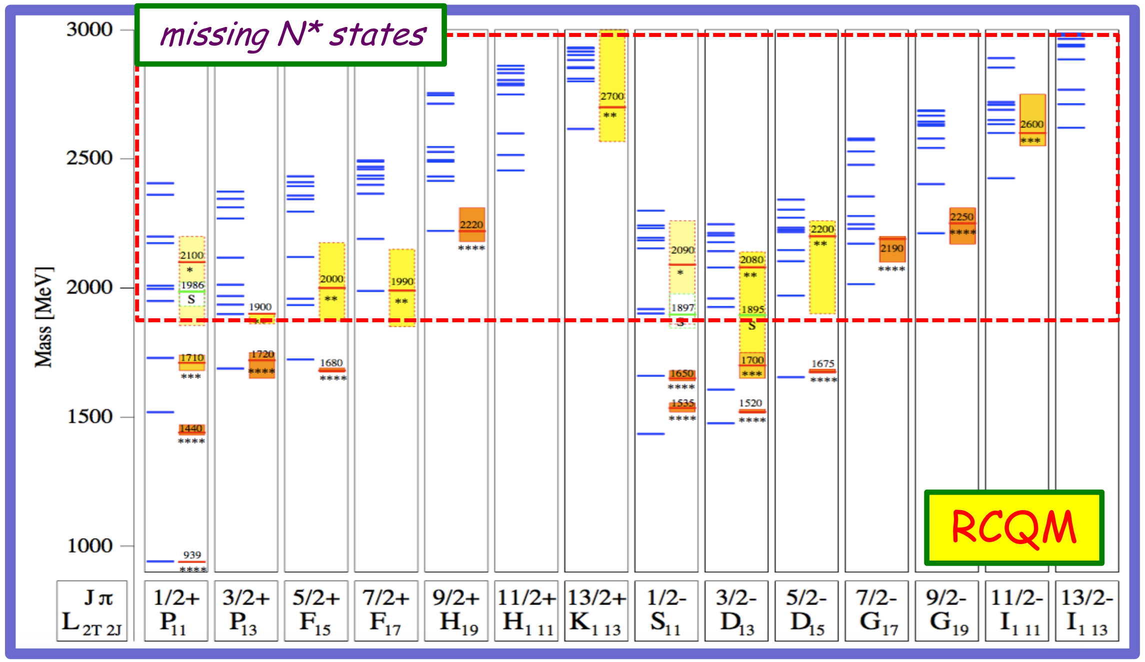
E12-09-003	Nucleon Resonance Studies with CLAS12
E12-06-108A	KY Electroproduction with CLAS12
E12-16-010A	N* Studies Via KY Electroproduction at 6.6 and 8.8 GeV
E12-16-010	A Search for Hybrid Baryons in Hall B with CLAS12

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

Evidence for New N* in KY Channels

State N(mass)J^P	PDG 2010	PDG 2024	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)$7/2^-$	*	***	**		**	***



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

LQCD predictions support CQM

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

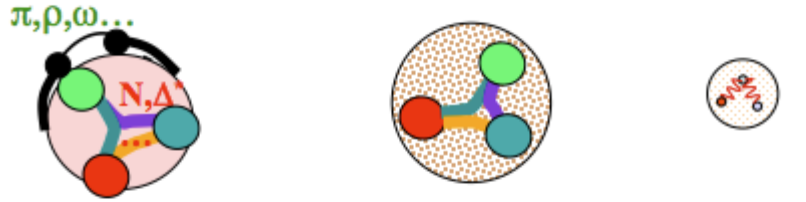
Decisive impact from CLAS KY photoproduction data

- Extend studies to KY electroproduction and to higher masses

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)

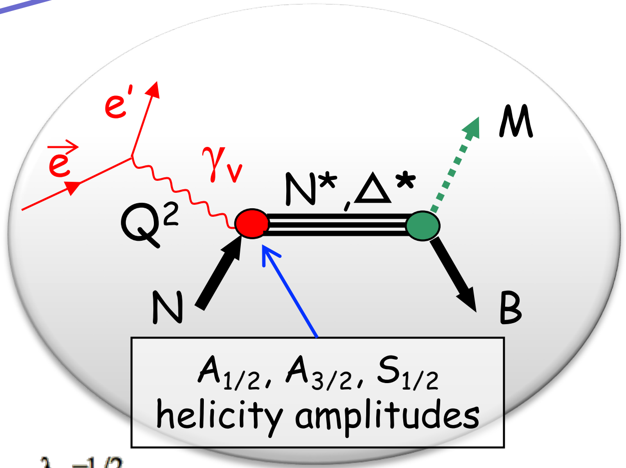


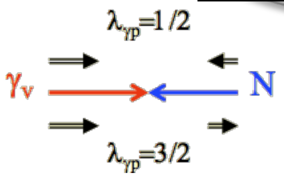
3q core + M-B cloud | 3q core | pQCD

low Q^2 → high Q^2

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

- Studies of the $\gamma_v pN^*$ 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

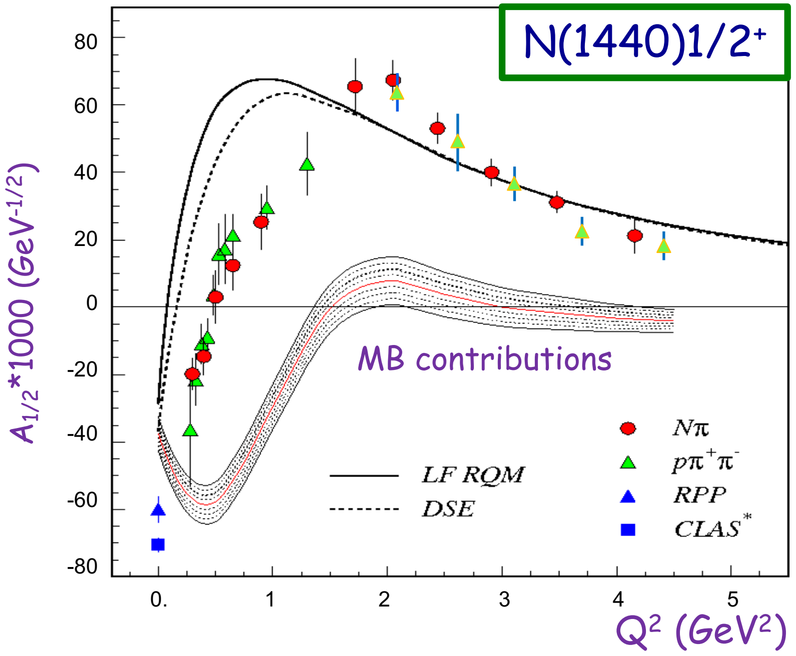


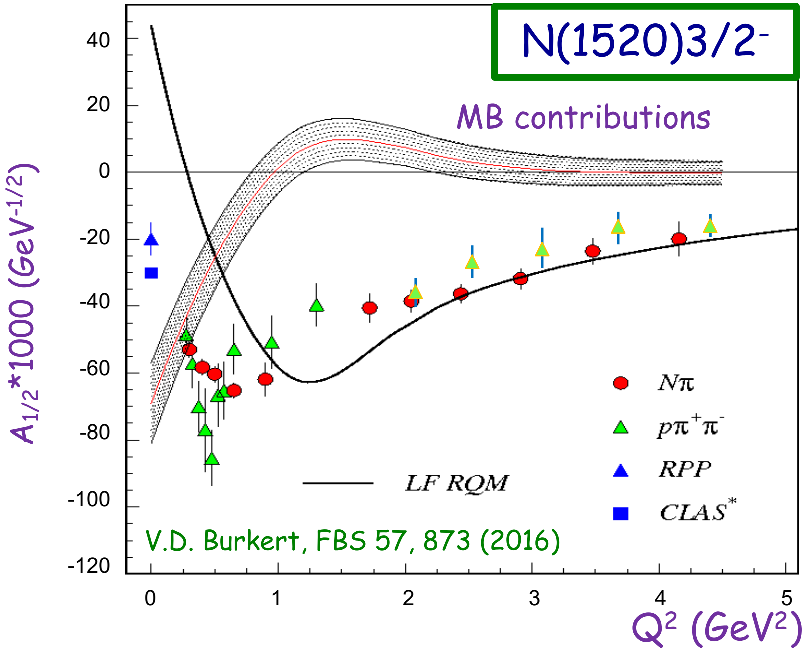


$A_{1/2}$, $A_{3/2}$ – transverse

$S_{1/2}$ - longitudinal

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+

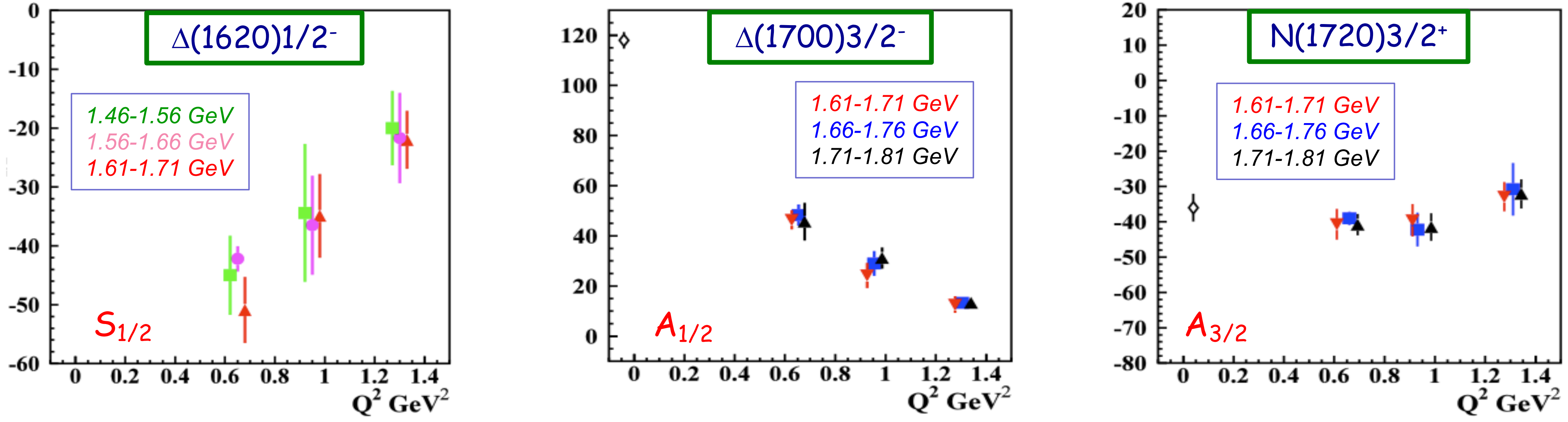
http://userweb.jlab.org/~mokeev/resonance_electrocouplings23

- Electrocouplings 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
- 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

Higher-Lying N* States

$N\pi\pi$ 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 smaller strength to $N\pi$ for some states



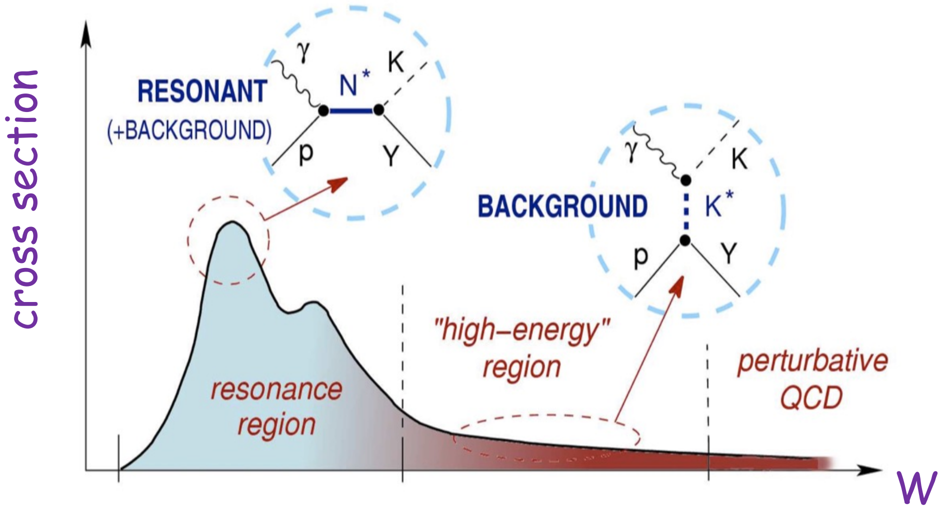
Data from the KY channels is critical:

- to provide an independent extraction of the electrocouplings for higher-lying N* states

V.I. Mokeev, I. Aznauryan, IJMPC 26, 1460080 (2014)
V.I. Mokeev et al., PRC 93, 025206 (2016)
D.S. Carman, K. Joo, V.I. Mokeev, FBS 61, 29 (2020)
V.I. Mokeev et al., PRC 108, 025204 (2023)

KY Reaction Models

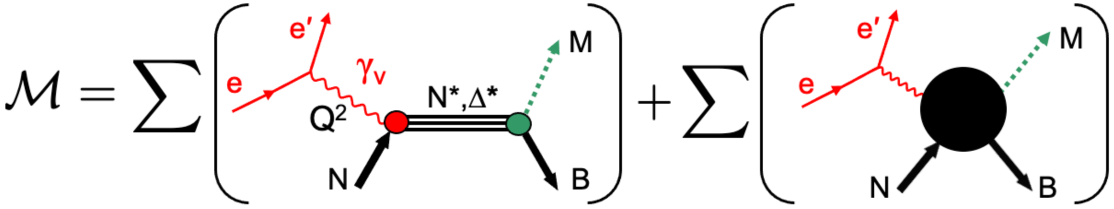
- A model that describes the KY data is necessary to extract the $\gamma_v pN^*$ electrocouplings from the existing lower Q^2 CLAS data and the higher Q^2 CLAS12 data
- No single channel (isobar type) model has yet been shown to adequately describe the KY electroproduction data in the resonance region



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

Multi-Channel:
- Bonn-Gatchina multi-channel PWA
- Jülich-Bonn-GWU coupled-channel framework
- Argonne-Osaka dynamically coupled-channel model
- Dubna-Mainz-Taipei dynamical model

Resonant Amplitudes   Non-Resonant Amplitudes



But there has been some recent progress!

D.S. Carman, K. Joo, V.I. Mokeev, FBS 61, 29 (2020)
M. Mai, Eur. Phys. J. A 59, 286 (2023)
Y.-F. Wang et al, arXiv:2404.17444, (2024)

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

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

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

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

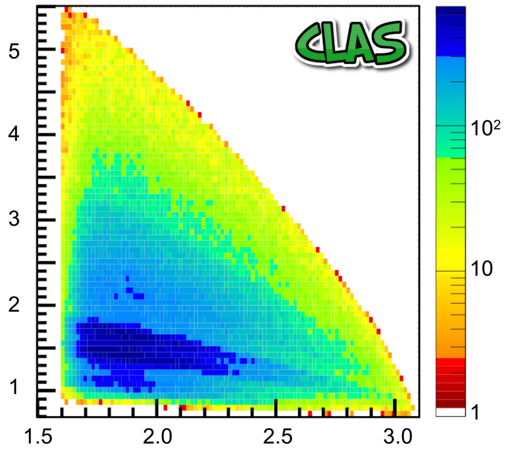
$$\sigma^r_{L,T}(W,Q^2) = \frac{\pi}{q^2_\gamma}\sum_{N^*,\Delta^*}(2J_r+1)\frac{M_r^2\Gamma_{tot}(W)\Gamma_\gamma^{L,T}(M_r)}{(M_r^2-W^2)^2+M_r^2\Gamma^2_{tot}(W)}\frac{q_\gamma}{K}$$

CLAS KY Electroproduction Dataset Overview

#	Run	E_b (GeV)	Trig. (M)
1	e1c	2.567	900
2		4.056	370
3		4.247	620
4		4.462	420
5	e1-6	5.754	4500
6	e1f	5.499	5000

Publications (Polarization):

- $K^+\Lambda$, $K^+\Sigma^0$ beam-recoil polarization transfer
  - W=1.6-2.15 GeV, Q^2=0.3 – 1.5 GeV^2
    D.S. Carman et al. (CLAS), PRL 90, 131804 (2003)
  - W=1.6-2.6 GeV, Q^2=0.7-5.4 GeV^2
    D.S. Carman et al. (CLAS), PRC 79, 065205 (2009)
- $K^+\Lambda$ recoil polarization
  - W=1.6-2.7 GeV, $\langle Q^2\rangle$=1.9 GeV^2
    M. Gabrielyan et al. (CLAS), PRC 90, 035202 (2014)



Q^2 vs. W (GeV)

Publications (Cross Section):

- $K^+\Lambda$, $K^+\Sigma^0$ cross sections & structure functions
  - $d\sigma/d\Omega$, σ_U, σ_{LT}, σ_{TT}, σ_L, σ_T
    - W=1.6-2.4 GeV, Q^2=0.5-2.8 GeV^2
    P. Ambrozewicz et al. (CLAS), PRC 75, 045203 (2007)
  - $d\sigma/d\Omega$, σ_U, σ_{LT}, σ_{TT}, $\sigma_{LT'}$
    - W=1.6-2.6 GeV, Q^2=1.4-3.9 GeV^2
    D.S. Carman et al. (CLAS), PRC 87, 025204 (2013)
  - $\sigma_{LT'}$
    - W=1.6-2.1 GeV, Q^2=0.65, 1.0 GeV^2
    R. Nasseripour et al. (CLAS), PRC 77, 065208 (2008)
  - $K^+\Lambda$ σ_L/σ_T ratio
    - W=1.72-1.98 GeV, Q^2~0.7 GeV^2
    B.A. Raue & D.S. Carman, PRC 71, 065209 (2005)

CEBAF Large Acceptance Spectrometer

Pseudoscalar Meson Electroproduction Formalism

$$\frac{d\sigma_v}{d\Omega_K^{c.m.}} = \mathcal{K} \sum_{\alpha,\beta} S_\alpha S_\beta \Big[R_T^{\beta\alpha} + \epsilon R_L^{\beta\alpha} + c_+ ({}^cR_{LT}^{\beta\alpha} \cos\Phi + {}^sR_{LT}^{\beta\alpha} \sin\Phi)$$

$$+ \quad \epsilon({}^cR_{TT}^{\beta\alpha} \cos 2\Phi + {}^sR_{TT}^{\beta\alpha} \sin 2\Phi) + hc_-({}^cR_{LT'}^{\beta\alpha} \cos\Phi + {}^sR_{LT'}^{\beta\alpha} \sin\Phi) + hc_0 R_{TT'}^{\beta\alpha} \Big]$$

TABLE I. Polarization observables in pseudoscalar meson electroproduction. A star denotes a response function which does not vanish but is identical to another response function via a relation in App. A.

	Target				Recoil			Target + Recoil								
β	–	–	–	–	x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
α	–	x	y	z	–	–	–	x	y	z	x	y	z	x	y	z
T	R_T^{00}	0	R_T^{0y}	0	0	$R_T^{y'0}$	0	$R_T^{x'x}$	0	$R_T^{x'z}$	0	$*$	0	$R_T^{z'x}$	0	$R_T^{z'z}$
L	R_L	0	R_L^{0y}	0	0	$*$	0	$R_L^{x'x}$	0	$R_L^{x'z}$	0	$*$	0	$*$	0	$*$
${}^cTL$	${}^cR_{TL}^{00}$	0	${}^cR_{TL}^{0y}$	0	0	$*$	0	${}^cR_{TL}^{x'x}$	0	$*$	0	$*$	0	${}^cR_{TL}^{z'x}$	0	$*$
${}^sTL$	0	${}^sR_{TL}^{0x}$	0	${}^sR_{TL}^{0z}$	${}^sR_{TL}^{x'0}$	0	${}^sR_{TL}^{z'0}$	0	$*$	0	$*$	0	$*$	0	$*$	0
${}^cTT$	${}^cR_{TT}^{00}$	0	$*$	0	0	$*$	0	$*$	0	$*$	0	$*$	0	$*$	0	$*$
${}^sTT$	0	${}^sR_{TT}^{0x}$	0	${}^sR_{TT}^{0z}$	${}^sR_{TT}^{x'0}$	0	${}^sR_{TT}^{z'0}$	0	$*$	0	$*$	0	$*$	0	$*$	0
${}^cTL'$	0	${}^cR_{TL'}^{0x}$	0	${}^cR_{TL'}^{0z}$	${}^cR_{TL'}^{x'0}$	0	${}^cR_{TL'}^{z'0}$	0	$*$	0	$*$	0	$*$	0	$*$	0
${}^sTL'$	${}^sR_{TL'}^{00}$	0	${}^sR_{TL'}^{0y}$	0	0	$*$	0	${}^sR_{TL'}^{x'x}$	0	$*$	0	$*$	0	${}^sR_{TL'}^{z'x}$	0	$*$
TT'	0	$R_{TT'}^{0x}$	0	$R_{TT'}^{0z}$	$R_{TT'}^{x'0}$	0	$R_{TT'}^{z'0}$	0	$*$	0	$*$	0	$*$	0	$*$	0

G. Knöchlein, D. Drechsel, L. Tiator, Z. Phys. A 352, 327 (1995)

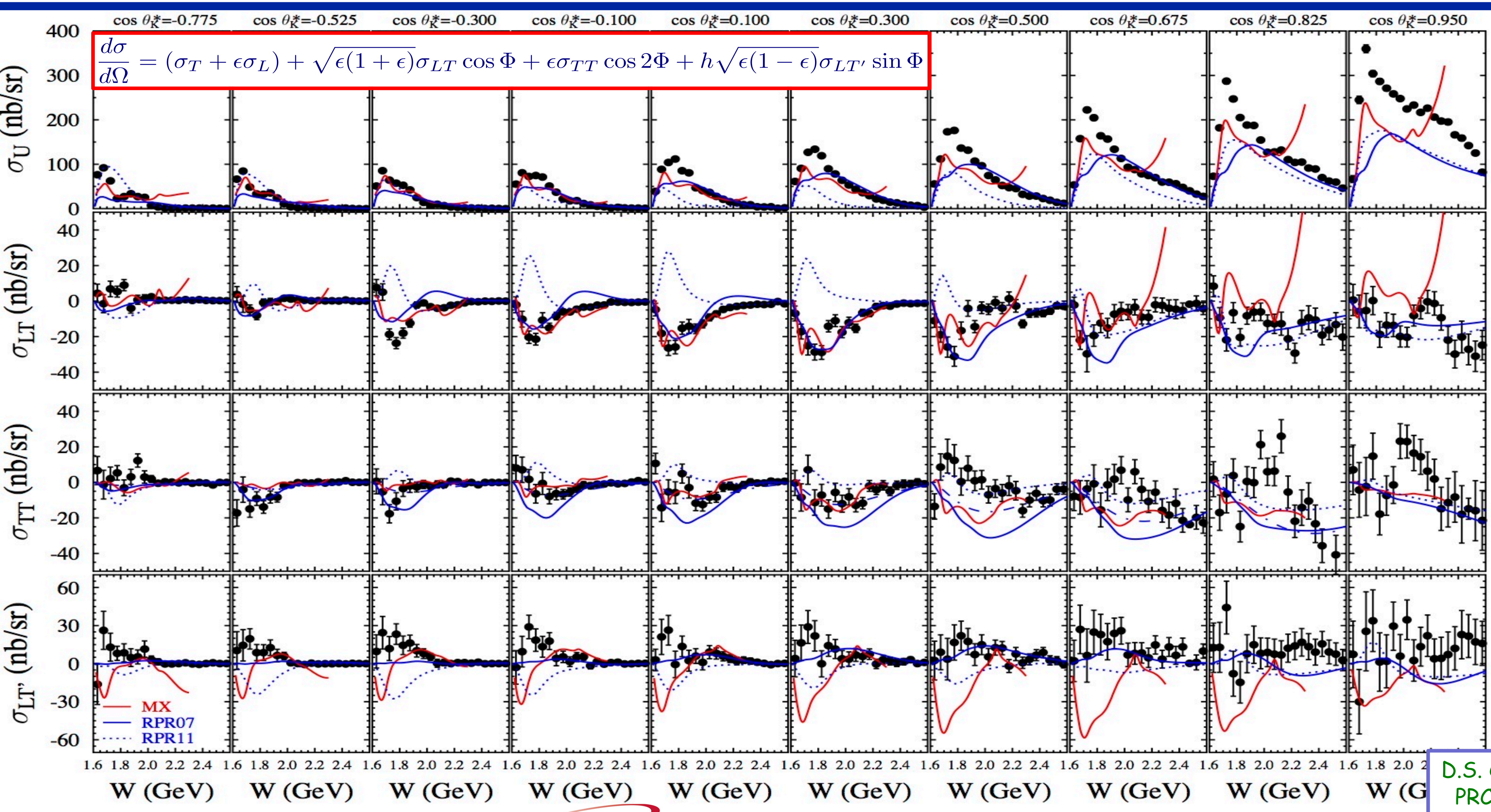
Response functions

$R(Q^2, W, \cos\theta_K^{c.m.})$

CLAS/CLAS12 KY Program

- Differential cross sections
  - σ_L, σ_T, σ_{LT}, σ_{TT}, $\sigma_{LT'}$
- KY recoil polarization
- KY transferred polarization

CLAS $K^+\Lambda$ Structure Functions



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

E = 5.5 GeV

W: thr – 2.6 GeV

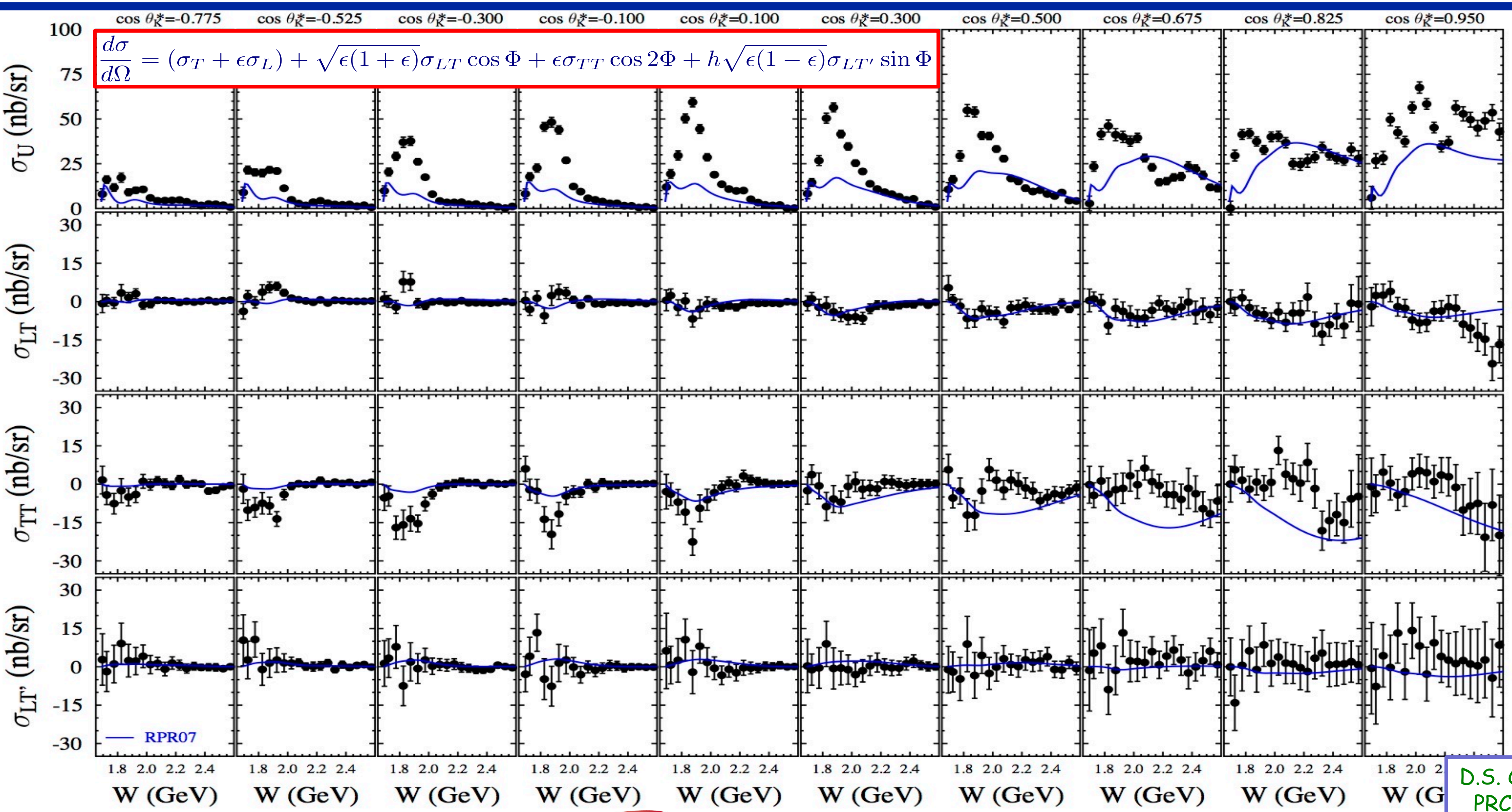
Q^2 = 1.80 GeV^2

2.60 GeV^2

3.45 GeV^2

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

CLAS $K^+\Sigma^0$ Structure Functions



E = 5.5 GeV

W: thr – 2.6 GeV

Q^2 = 1.80 GeV^2

2.60 GeV^2

3.45 GeV^2

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

KY Polarization Formalism

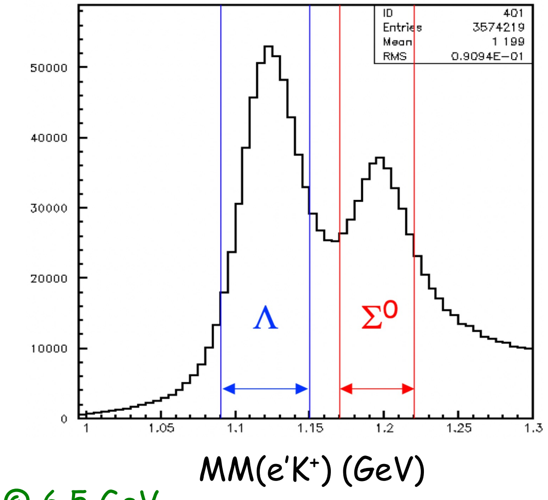
Φ-integrated

$\mathcal{P}^0$ = recoil polarization

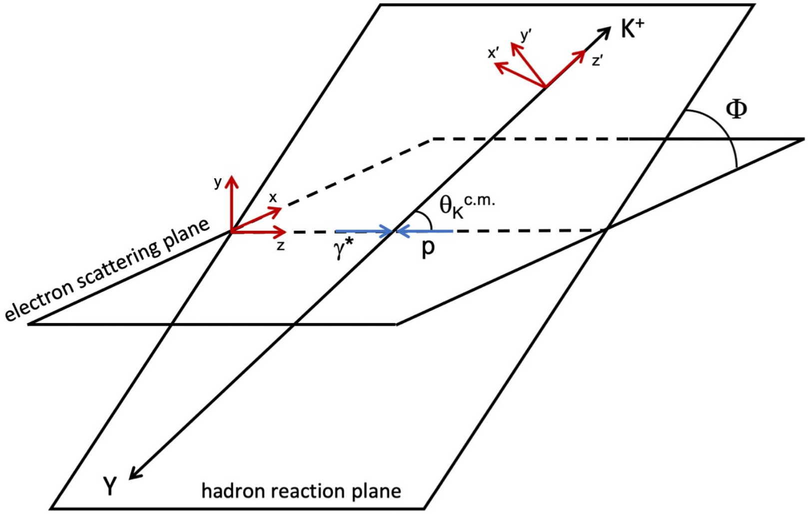
$\mathcal{P}'$ = transferred polarization

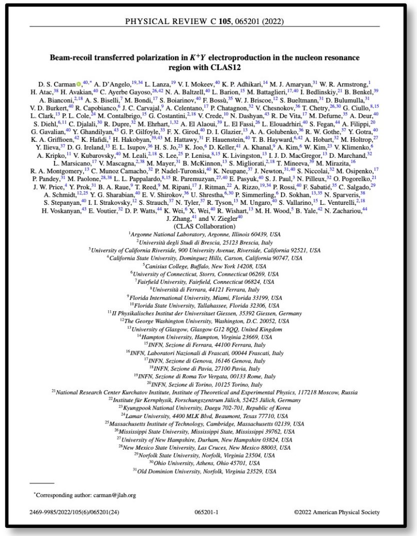
(x′,y′,z′)		(x,y,z)	
$\mathcal{P}^0_{x'}$	0	$\mathcal{P}^0_{x}$	0
$\mathcal{P}^0_{y'}$	$K_I(R_T^{y'0} + \epsilon R_L^{y'0})$	$\mathcal{P}^0_{y}$	$\frac{1}{2}\sqrt{\epsilon(1+\epsilon)}K_I(R_{LT}^{x'0}\cos\theta_K^{c.m.} + R_{LT}^{y'0} + R_{LT}^{z'0}\sin\theta_K^{c.m.})$
$\mathcal{P}^0_{z'}$	0	$\mathcal{P}^0_{z}$	0
$\mathcal{P}'_{x'}$	$K_I\sqrt{1-\epsilon^2}R_{TT'}^{x'0}$	$\mathcal{P}'_{x}$	$\frac{1}{2}\sqrt{\epsilon(1-\epsilon)}K_I(R_{LT'}^{x'0}\cos\theta_K^{c.m.} - R_{LT'}^{y'0} + R_{LT'}^{z'0}\sin\theta_K^{c.m.})$
$\mathcal{P}'_{y'}$	0	$\mathcal{P}'_{y}$	0
$\mathcal{P}'_{z'}$	$K_I\sqrt{1-\epsilon^2}R_{TT'}^{z'0}$	$\mathcal{P}'_{z}$	$\sqrt{1-\epsilon^2}K_I(-R_{TT'}^{x'0}\sin\theta_K^{c.m.} + R_{TT'}^{z'0}\cos\theta_K^{c.m.})$

$ep \rightarrow e'K^+Y$



CLAS12 @ 6.5 GeV

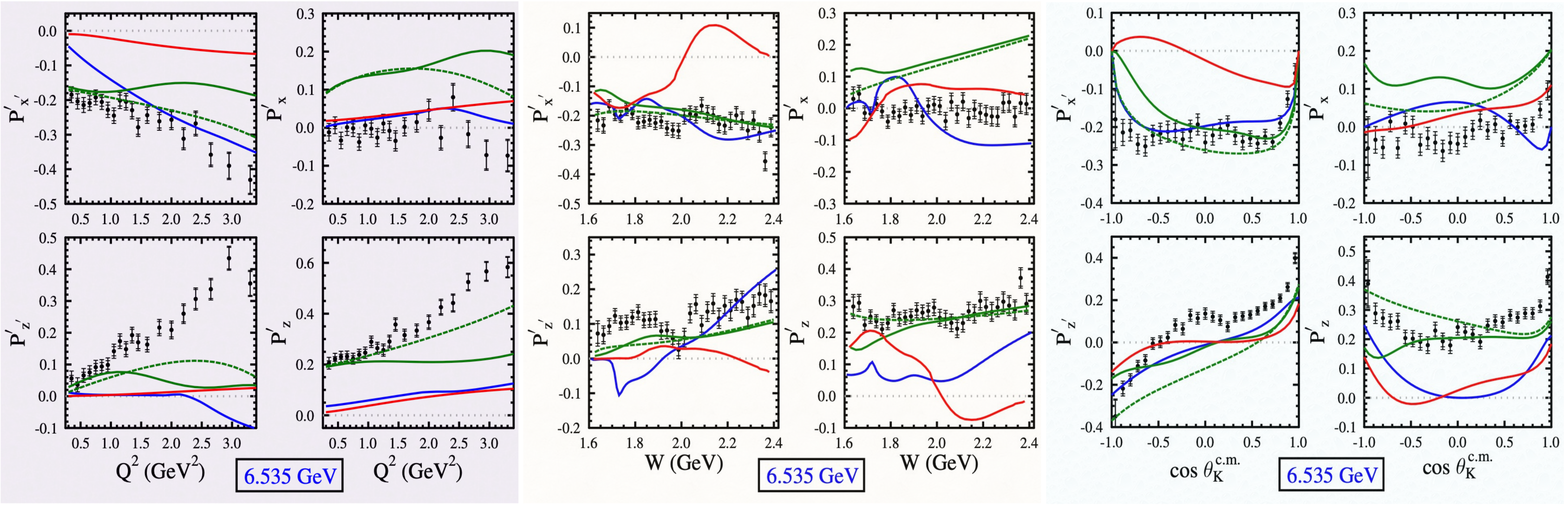



PHYSICAL REVIEW C 105, 065201 (2022)

Beam-recoil transferred polarization in K^+Y electroproduction in the nucleon resonance region with CLAS12

D.S. Carman et al. (CLAS), PRC 79, 065205 (2022)

CLAS12 Beam-Recoil Λ Transferred Polarization



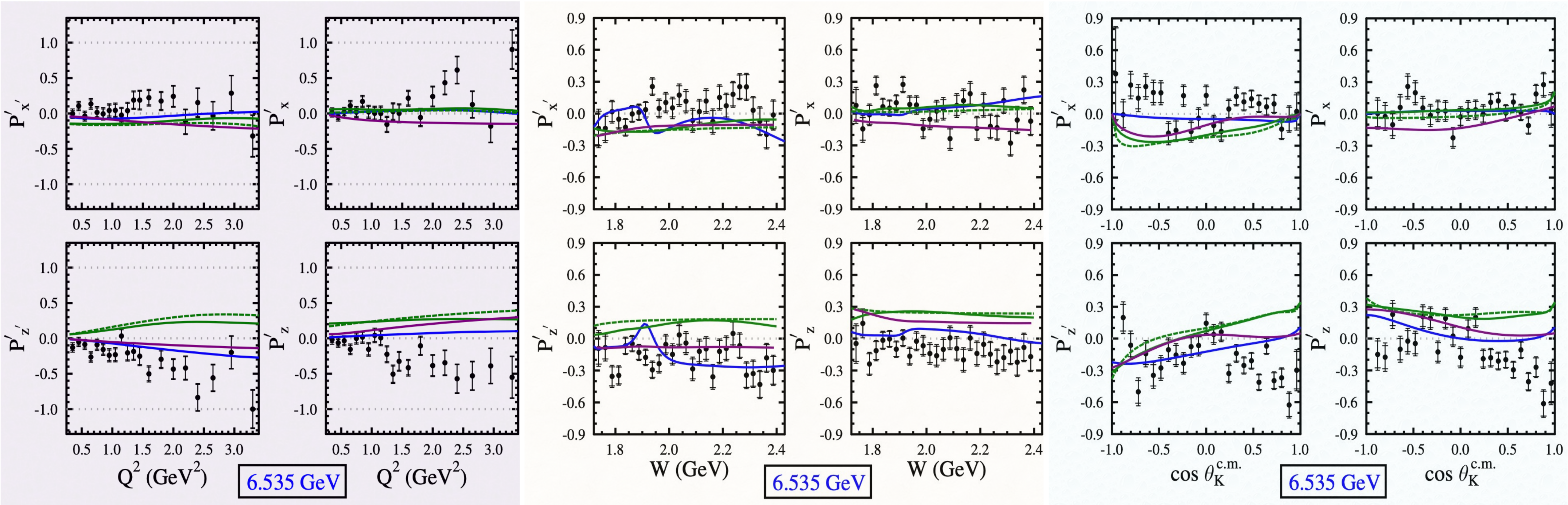
Model	Year	Type	Fit Data	N* States
Kaon-MAID	2000	Isobar	none	1/2, 3/2
RPR	2011	Isobar+Regge	CLAS γp	1/2, 3/2, 5/2
BS3	2018	Isobar	CLAS γp & ep	1/2, 3/2, 5/2

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

Development of reaction models in progress:

- T. Mart
- M. Döring, M. Mai
- P. Bydžovský, D. Skoupil

CLAS12 Beam-Recoil Σ^0 Transferred Polarization



Model	Year	Type	Fit Data	N* States
SL	1996	Isobar	none	1/2, 3/2
Kaon-MAID	2000	Isobar	none	1/2, 3/2
RPR	2007	Isobar+Regge	CLAS γp	1/2, 3/2, 5/2

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

$K^+\Sigma^0$ final state has sensitivity to both N* and Δ* resonances ⇒ isospin filter compared to $K^+\Lambda$ final state

CLAS12 L/T from Transferred Polarization

Φ-integrated

$$\mathcal{P}'_{z'} = \pm\mathcal{P}'_z = \pm\frac{c_0 R^{z'0}_{TT'}}{R^{00}_T + \epsilon R^{00}_L} = \pm\frac{c_0 R^{z'0}_{TT'}}{\sigma_U/\mathcal{K}}$$

At $\cos\theta_K^{c.m.} = 1, \quad R^{z'0}_{TT'} = R^{00}_T$

$$\mathcal{P}'_{z'} = \mathcal{P}'_z = \frac{c_0 R^{00}_T}{R^{00}_T + \epsilon R^{00}_L} = \frac{c_0\sigma_T}{\sigma_T + \epsilon\sigma_L}$$

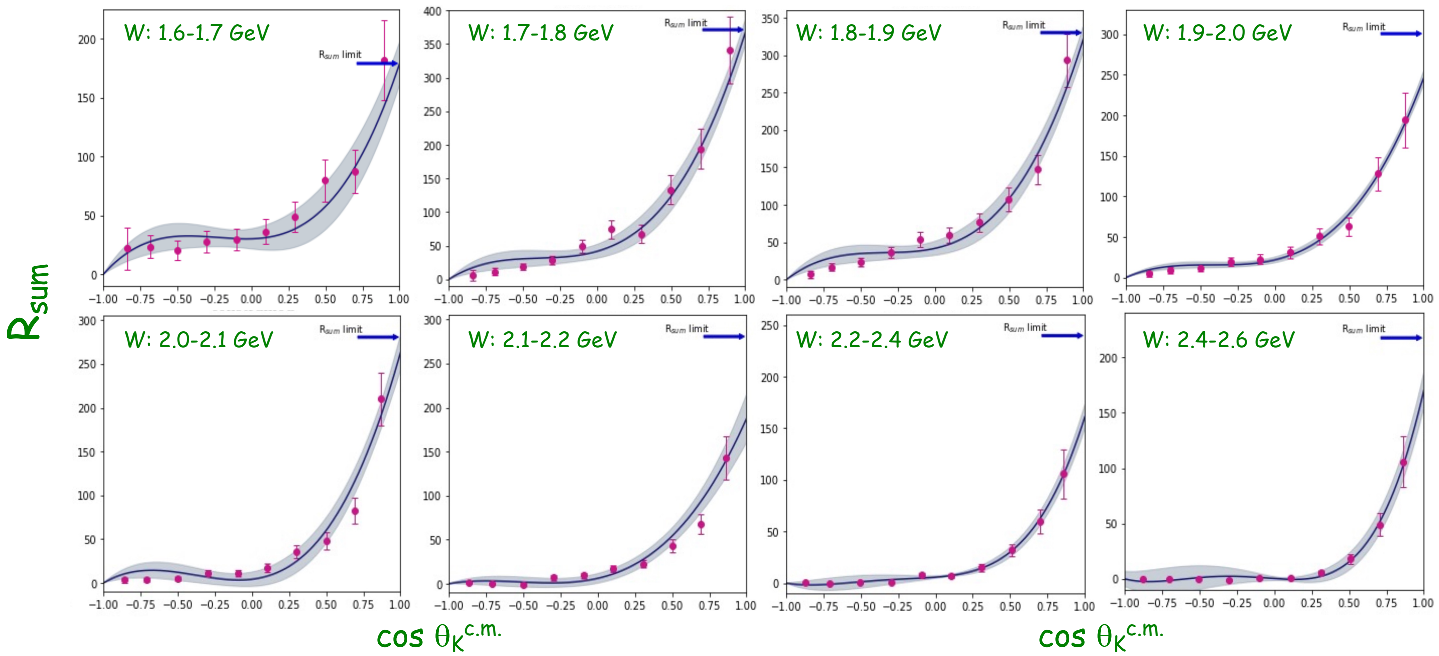
$$\Rightarrow \quad R = \frac{\sigma_L}{\sigma_T} = \frac{1}{\epsilon}\left(\frac{c_0}{\mathcal{P}'_{z'}} - 1\right)$$

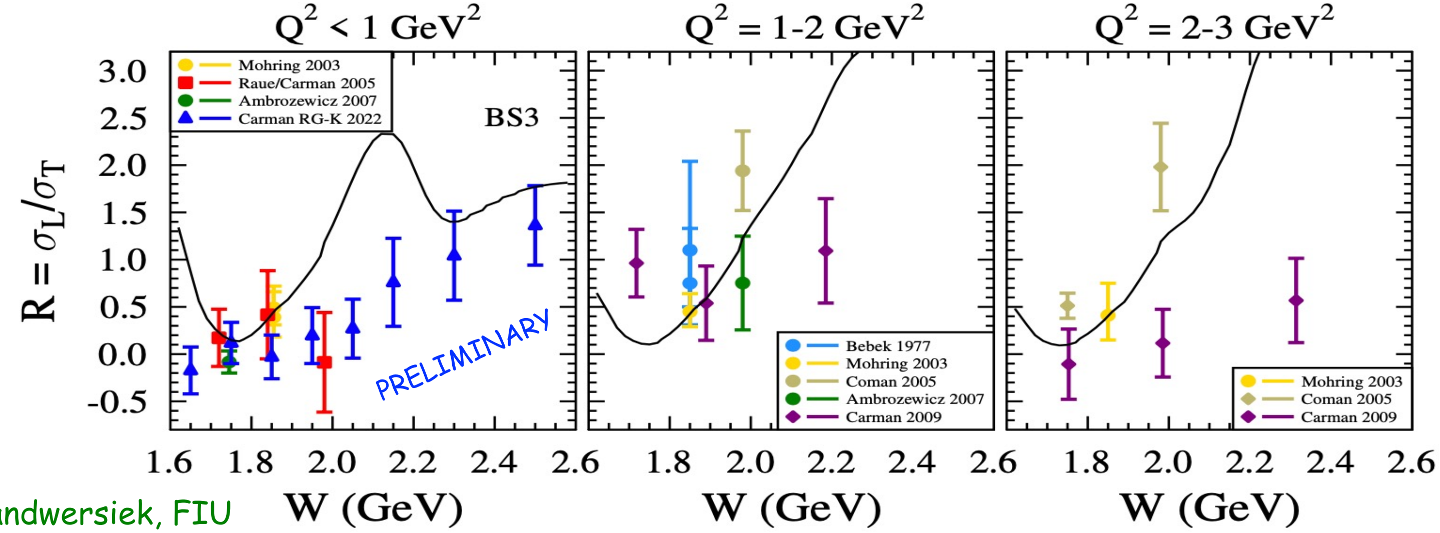
Define: $\mathrm{R_{sum}} = \frac{(\mathcal{P}'_{z'} + \mathcal{P}'_z)\sigma_U}{c_0}$

Extrapolate R_{sum} to $\theta_K^{c.m.} = 0°$ to extract R vs. W

Fit function: $R_{sum} = a_0 + a_1 x + a_2 x^2 + a_3 x^3$

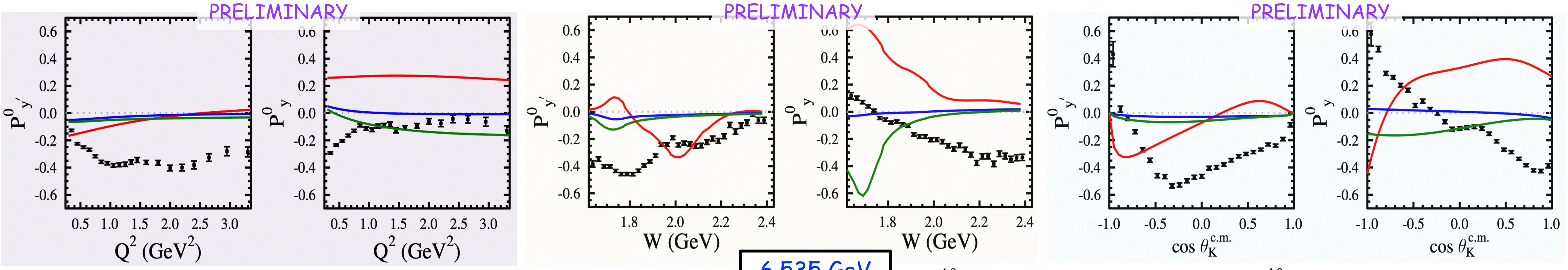
B.A. Raue and D.S. Carman, PRC 71, 065209 (2005)
D.S. Carman et al. (CLAS), PRC 79, 065205 (2009)





J. Landwersiek, FIU

CLAS12 Recoil Λ Polarization

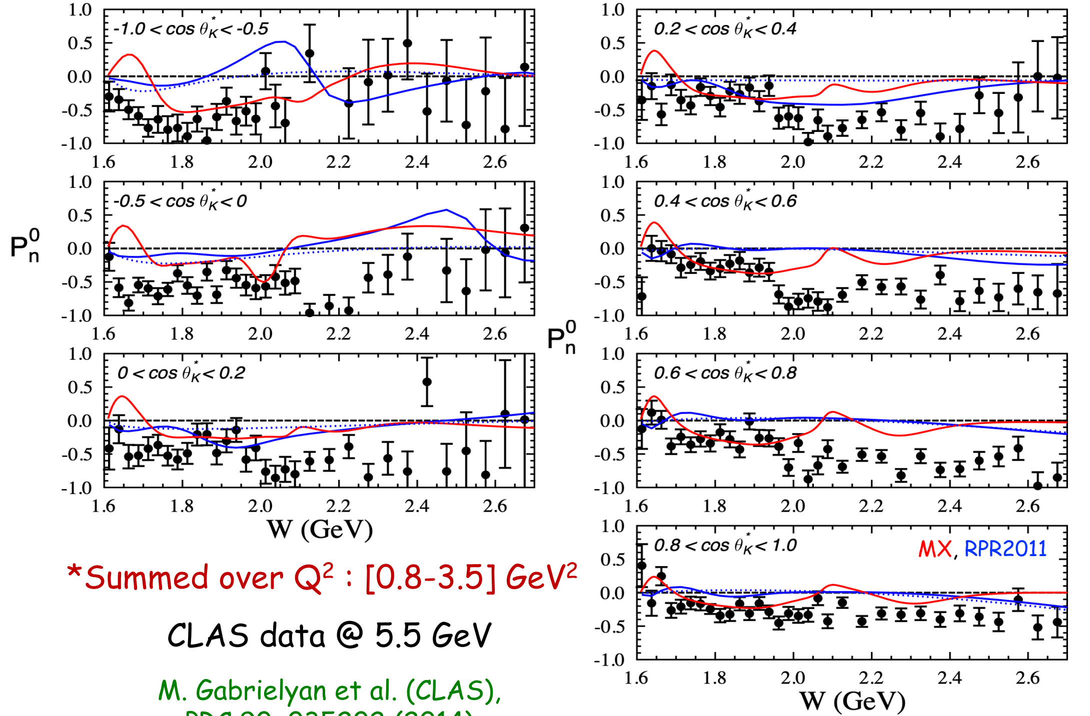


6.535 GeV

Model	Year	Type	Fit Data	N* States
SL	1996	Isobar	none	1/2, 3/2
SL-A	1998	Isobar+Regge	none	1/2, 3/2, 5/2
BS3	2018	Isobar	CLAS γp & ep	1/2, 3/2, 5/2

- CLAS12 data from 2018 test run – 10% of PAC approved beam time – amounts to 5x existing data
- New 6.4 GeV/8.5 GeV data from Jan. – Mar. 2024 amounts to another 5x increase in statistics

  ⇒ multi-dimensional analyses possible



*Summed over Q^2 : [0.8-3.5] GeV^2

CLAS data @ 5.5 GeV

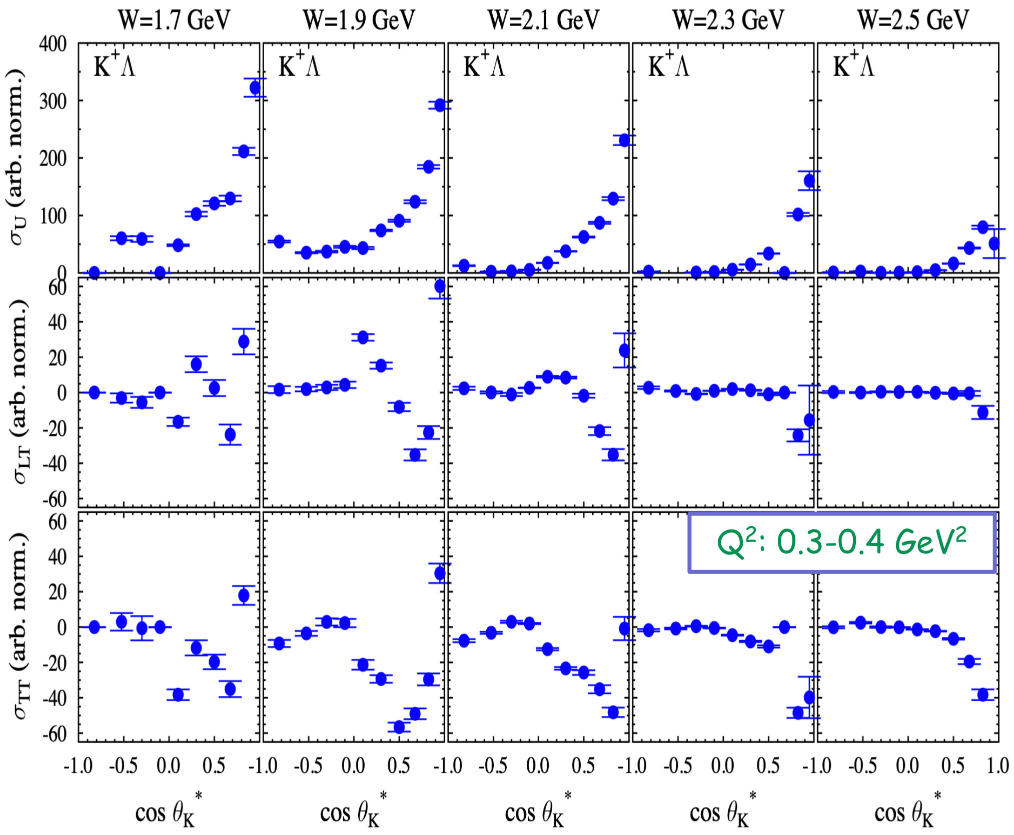
M. Gabrielyan et al. (CLAS), PRC 90, 035202 (2014)

CLAS12 KY Cross Sections

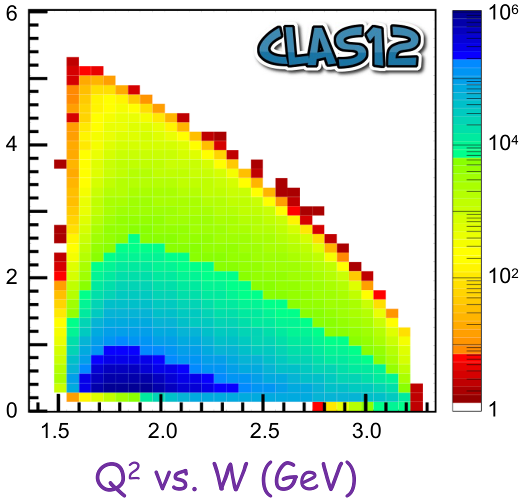
ep → e'K⁺Λ

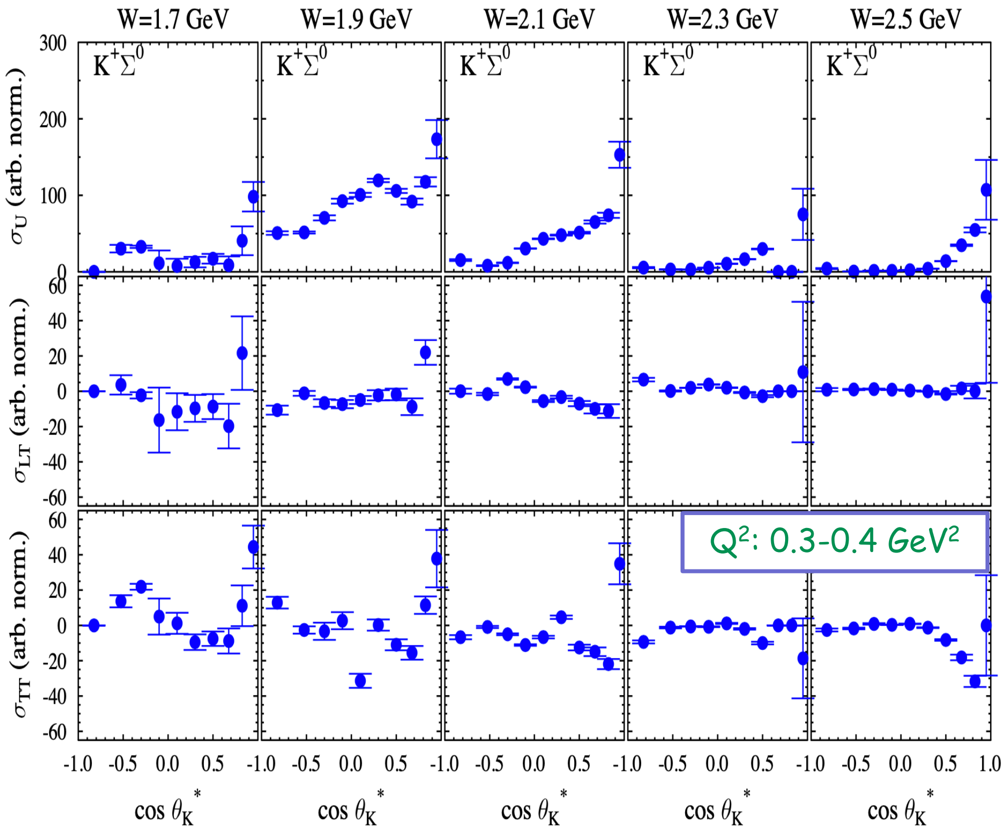
$$\frac{d\sigma}{d\Omega} = (\sigma_T + \epsilon\sigma_L) + \sqrt{\epsilon(1+\epsilon)}\sigma_{LT}\cos\Phi + \epsilon\sigma_{TT}\cos 2\Phi$$

ep → e'K⁺Σ⁰



PRELIMINARY





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

CLAS12 6.535 GeV RG-K

Q^2: [0.3:3.5] GeV^2

CLAS 5.479 GeV Q^2: [1.4:3.9] GeV^2

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

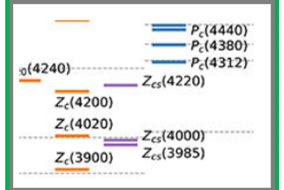
JLab Beyond the 12 GeV Era

JLab considering upgrade to 22 GeV

High Energy Workshop Series 2022

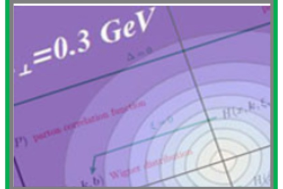
JLab Upgrade: Science at the luminosity frontier

Hadron Spectroscopy with a CEBAF Energy Upgrade



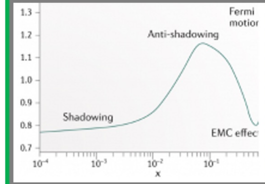
- 38 participants
- 8 talks

The Next Generation of 3D Imaging



- 55 participants
- 14 talks

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

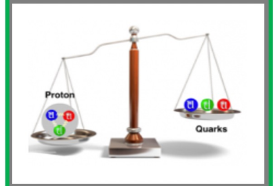


- 43 participants
- 14 talks

Physics Beyond the Standard Model

- 37 participants
- 6 talks

J/Psi and Beyond



- 38 participants
- 7 talks

Strong Interaction Physics at the Luminosity Frontier with 22 GeV Electrons at Jefferson Lab

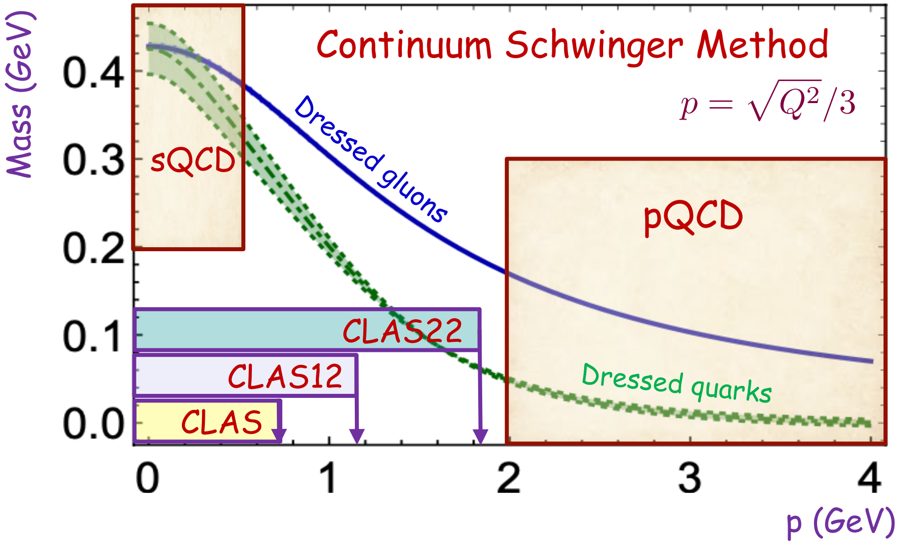
arXiv: 2306.09360 (in press Eur. Phys. J. A)

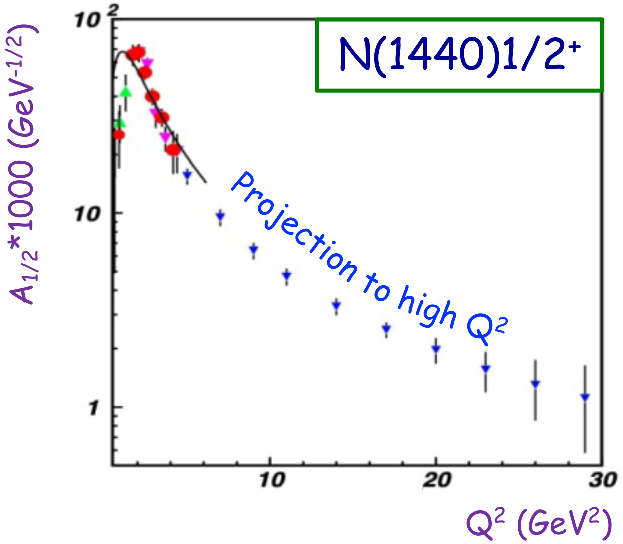
Energy and luminosity increase are needed to explore N* structure at $Q^2 > 10$ GeV^2

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





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
  - With the development of a reaction model the KY channels should be an important ingredient to understand the spectrum and structure of 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 – this talk has focused on the KY channels
  - Consistent results from analyses of the electrocouplings determined from KY and $\pi^+\pi^-p$ for 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 at 22 GeV @ *the luminosity frontier*

Backup Slides

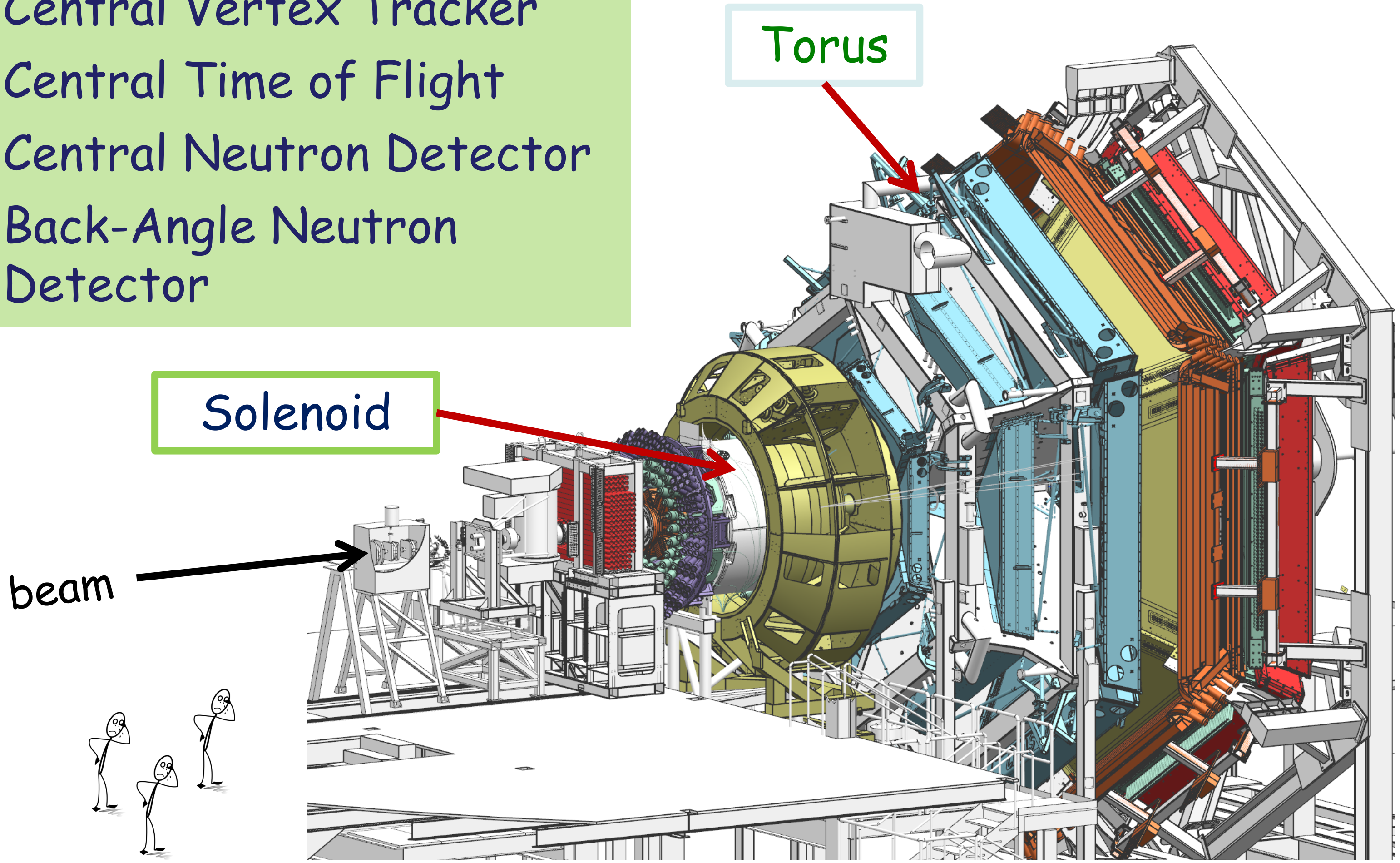
CLAS12 Spectrometer Model

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



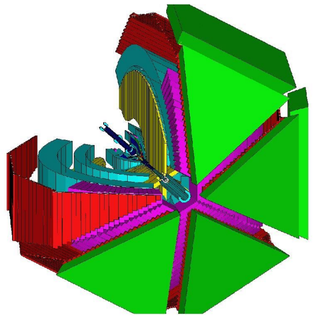
	Forward	Central
Angular coverage	$5^\circ - 35^\circ$	$35^\circ - 135^\circ$
Momentum resolution	$\delta p/p < 1\%$	$\delta p/p < 5\%$
θ resolution	1 mrad	5 – 10 mrad
ϕ resolution	1 mrad/sinθ	5 mrad/sinθ

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}, σ_{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)

CLAS: 1997 - 2012



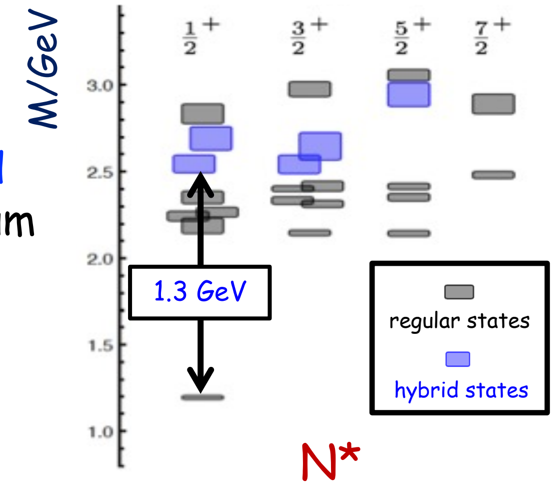
Hunting for Glue in Excited Baryons

Can glue be a structural component of excited baryon states?

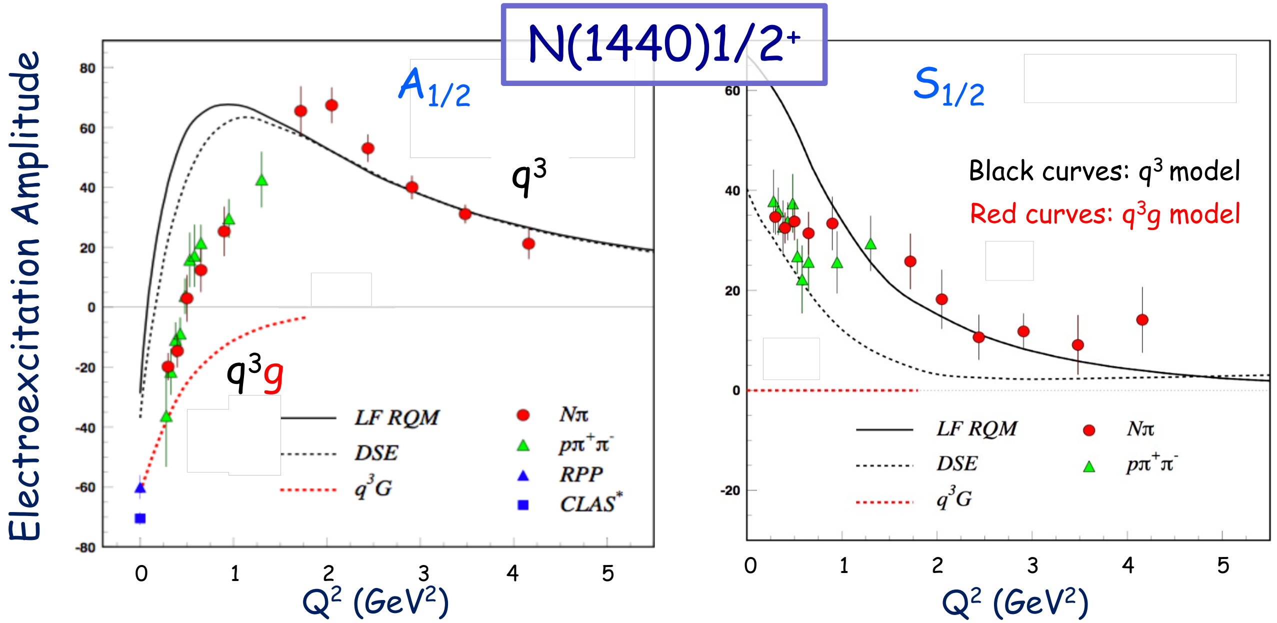
LQCD predicts hybrid baryons in N* spectrum

JLab LQCD group results

m_π=396 MeV



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



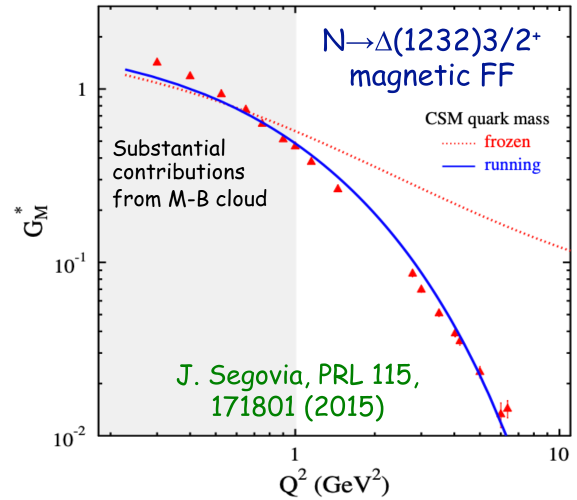
The signatures for hybrid baryons include:

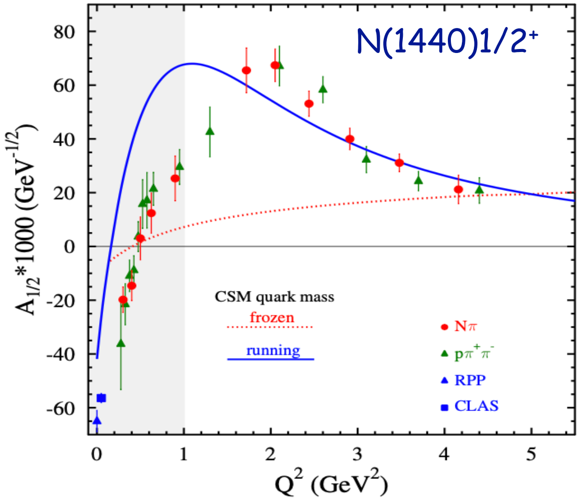
- Extra resonances with $J^\pi=1/2^+, 3/2^+$ in mass range 2.0-2.5 GeV and decays into $N\pi\pi$ or KY final states
- Drop of $A_{1/2}(Q^2)$ and $A_{3/2}(Q^2)$ faster than for ordinary 3q states due to extra glue-component in valence structure
- Suppressed $S_{1/2}(Q^2)$ relative to $A_{1/2}(Q^2)$ transverse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

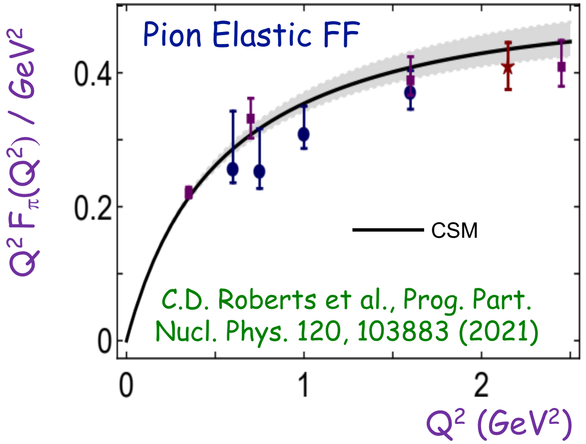
Quark model predictions on the Q^2 evolution of the electrocouplings are necessary for hybrid identification

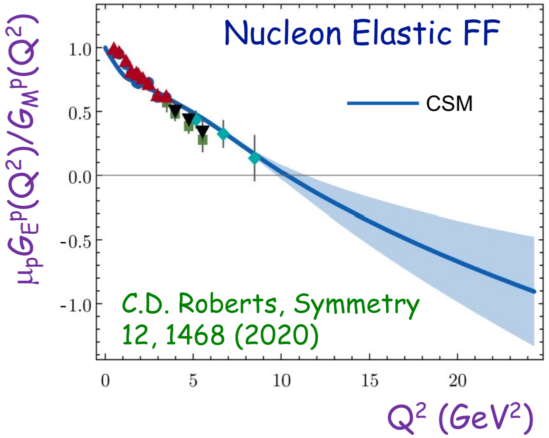
Z.P. Li, V. Burkert, Z.J Li, PRD 46, 70 (1992)

Data Results vs. Theory Expectations



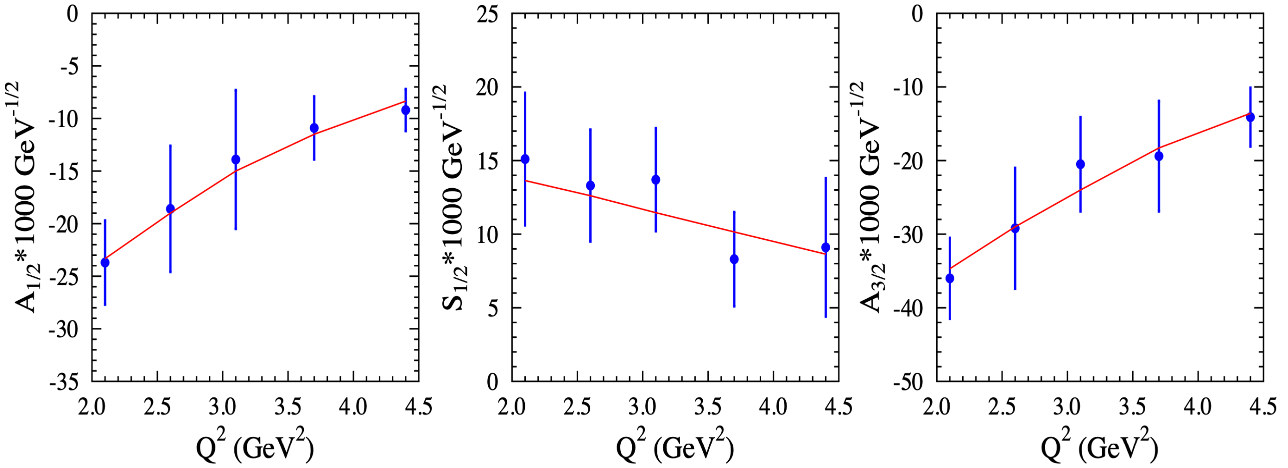






Description of pion, nucleon elastic FF and Δ(1232)3/2+, N(1440)1/2+, Δ(1600)3/2+ electrocouplings achieved ***with the same dressed quark mass function***

Δ(1600)3/2+ Electrocouplings



NEW

continuum QCD predictions:
Y. Lu et al., PRD 100, 034001 (2019)

Experimental ep → e'p$\pi^+\pi^-$ data from CLAS:
V. Mokeev et al., PRC 108, 025204 (2023)

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