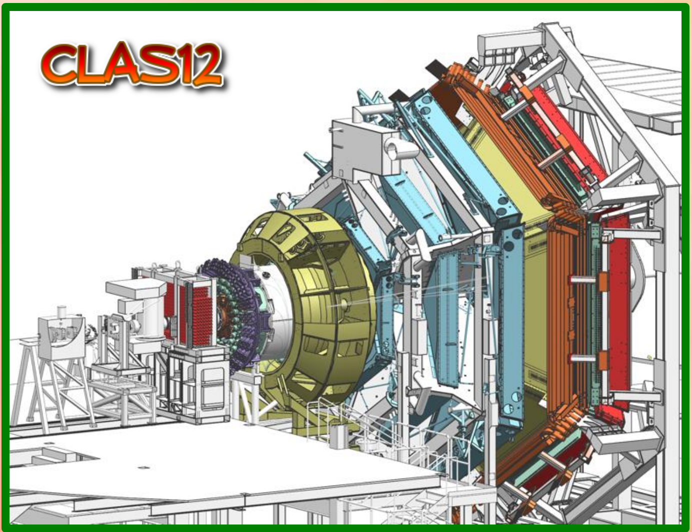
NUCLEON RESONANCE STRUCTURE STUDIES

EXPLORING INCLUSIVE TO EXCLUSIVE REACTIONS



DANIEL S. CARMAN
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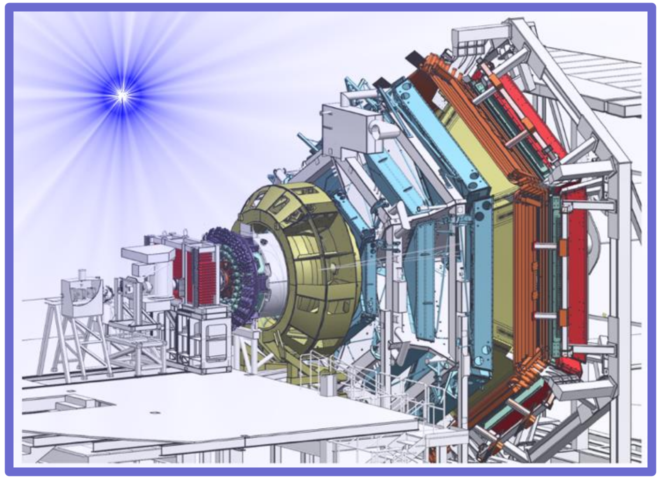
clas
CEBAF Large Acceptance Spectrometer

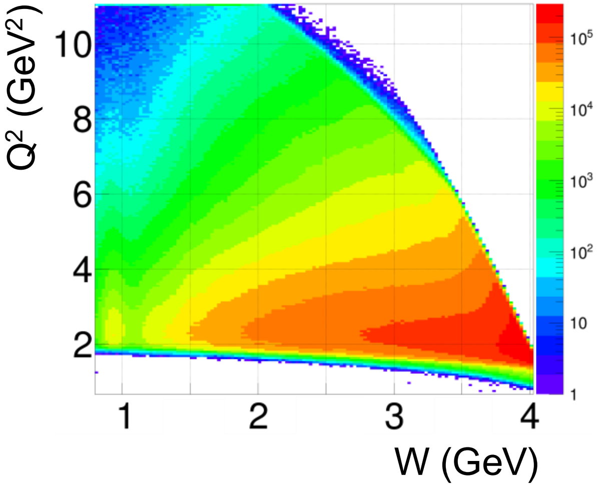
OUTLINE:

- N* structure studies
- CLAS12 N* program
- New CLAS12 results
- Work in progress
- Concluding remarks

Excited Nucleon State Studies

Nucleons (and their excited states) are the stuff from which our world is made ⇒ they must be at the center of any discussion of why our Universe looks as it does.





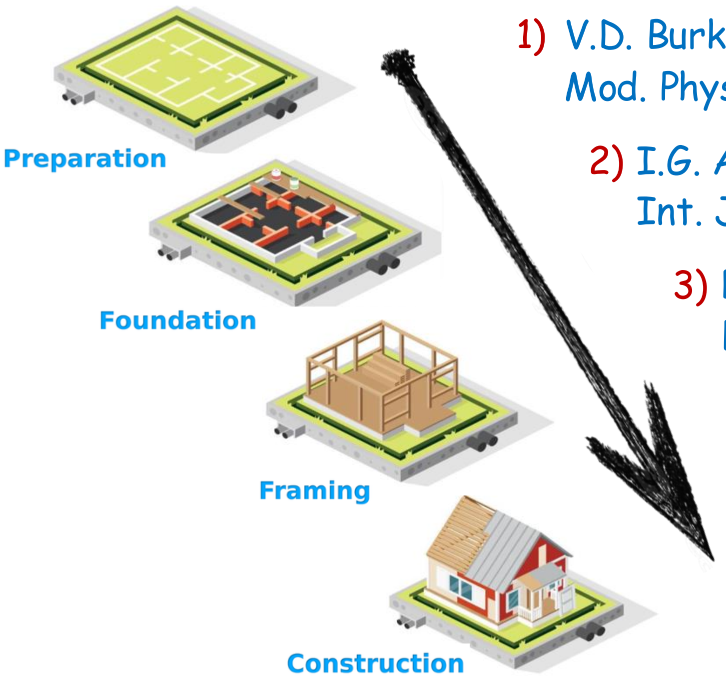
1. Studies of the electroexcitation of nucleon resonances allow for essential insight into understanding the degrees of freedom underlying the N* spectrum
2. Understanding the dynamics of the strong interaction that governs hadrons from the non-perturbative to perturbative regimes is a challenging open problem in the Standard Model.
3. Comparisons of data to approaches with a direct connection to QCD are essential

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

- The CLAS/CLAS12 spectrometers were designed to study e+p reaction channels over a broad kinematic range:

inclusive, πN, ωN, ϕN, ηN, $\eta' N$, $\pi\pi N$, KY, K*Y, KY*

Some History of N* Studies in Hall B



1) V.D. Burkert and T.S.H. Lee, “Electromagnetic Meson Production in the Nucleon Resonance Region”, Int. J. Mod. Phys. E 13, 1035 (2004)

2) I.G. Aznauryan et al., “Studies of Nucleon Resonance Structure in Exclusive Meson Electroproduction”, Int. J. Mod. Phys. E 22, 1330015 (2013)

3) D.S. Carman *et al. (CLAS Collaboration)*, "Separated Structure Functions for Exclusive $K^+\Lambda$ and $K^+\Sigma^0$ Electroproduction at 5.5 GeV at CLAS", Phys. Rev. C 87, 025204 (2013)

4) D.S. Carman, R.W. Gothe, V.I. Mokeev, and C.D. Roberts, "Nucleon Resonance Electroexcitation Amplitudes and Emergent Hadron Mass", Particles 6, 416 (2023)

5) F. Gross, E. Klempt, S.J. Brodsky, A.J. Buras, and V.D. Burkert, “50 Years of Quantum Chromodynamics”, Eur. Phys. J. C 83, 1125 (2023)

CONTINUING ON THE PATH . . .

1) V. Klimenko *et al. (CLAS Collaboration)*, "Inclusive Electron Scattering in the Resonance Region from a Hydrogen Target with CLAS12", arXiv:2501.14996, accepted for publication in Phys. Rev. C (2025)

2) D.S. Carman *et al. (CLAS Collaboration)*, "Recoil Polarization in K^+Y Electroproduction in the Nucleon Resonance Region with CLAS12", arXiv:2505.12030, submitted to Phys. Rev. C (2025)

3) P. Achenbach *et al.*, "Electroexcitation of Nucleon Resonances and the Emergence of Hadron Mass", arXiv:2505.23550, submitted to Symmetry (2025)

CLAS12 N* Program

- Measure exclusive electroproduction of Nπ, Nη, Nππ, KY final states from unpolarized proton target with longitudinally polarized electron beam

E_b = 6.6, 8.8, 11 GeV, $Q^2 \rightarrow$ 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

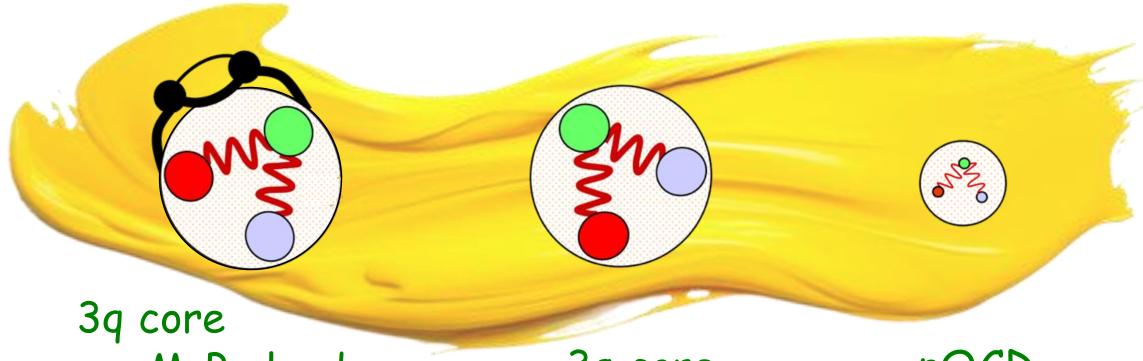
RG-A 50% of total	Spr18 126 mC	10.6 GeV
	Fall18 99 mC	
	Spr19 58 mC	
RG-K 50% of total	Fall18 28 mC	6.5 GeV 7.5 GeV
	Spr24 173 mC	6.4 GeV 8.5 GeV

Excited Nucleon Structure

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

meson-baryon cloud surrounding inner quark core

(Q^2 < 1 GeV^2)



quark core dominates; transition from confinement to pQCD regime

(Q^2 > 5 GeV^2)

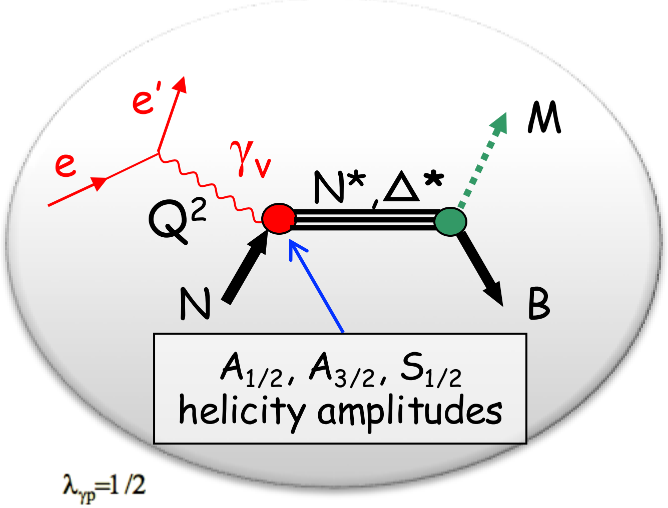
3q core
+ M-B cloud

3q core

pQCD

low Q^2 → high Q^2

- Fits to the measured cross sections using an advanced reaction model provide access to the $\gamma_v pN^*$ electrocouplings

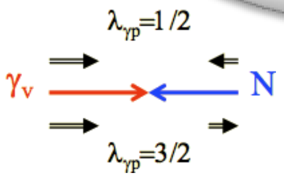


EM decay widths (N*→ Nγ)

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

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

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



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

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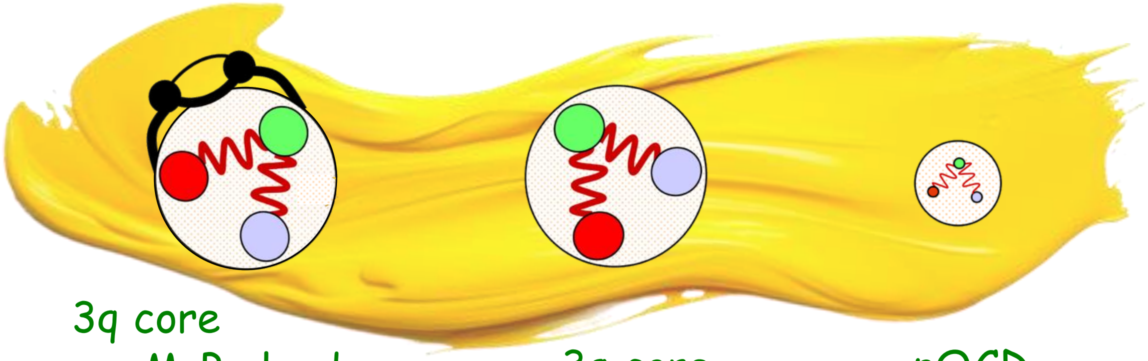

3q core + M-B cloud

3q core

pQCD

quark core dominates; transition from confinement to pQCD regime

($Q^2 > 5$ GeV^2)

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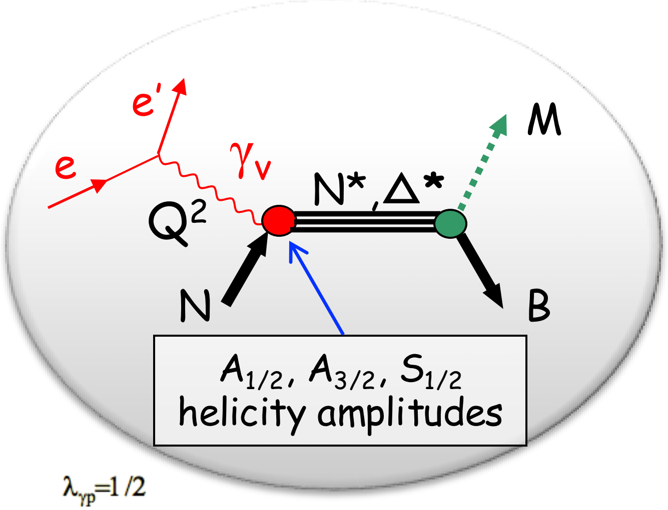
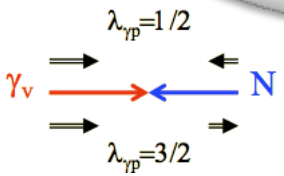
- Fits to the measured cross sections using an advanced reaction model provide access to the $\gamma_v pN^*$ electrocouplings



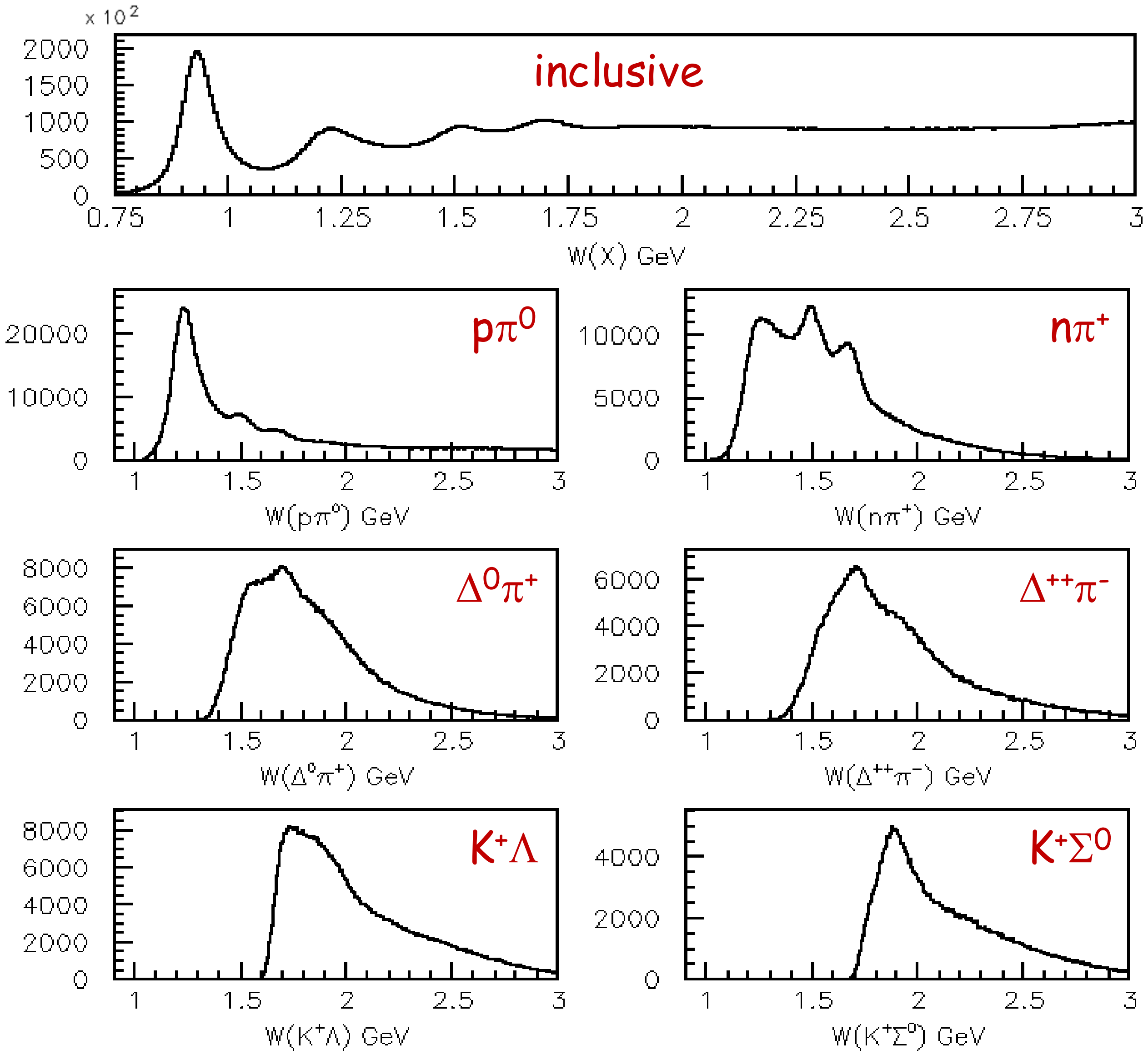
The momentum dependence of the underlying degrees of freedom shapes the structure of N* states and the Q^2 evolution of the electrocouplings



$A_{1/2}$, $A_{3/2}$ – transverse

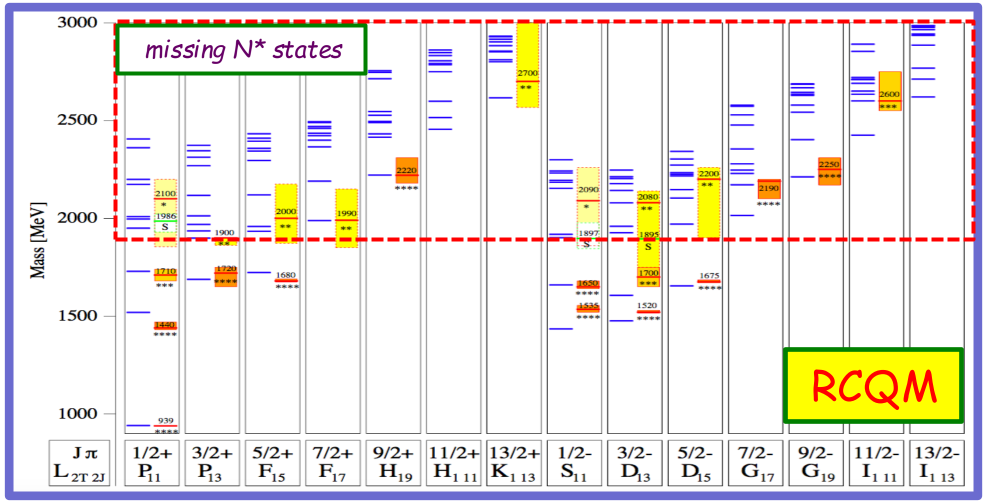
$S_{1/2}$ - longitudinal

Inclusive vs. Exclusive Channels



Inclusive ep → e'X spectrum is the sum over all exclusive channels:

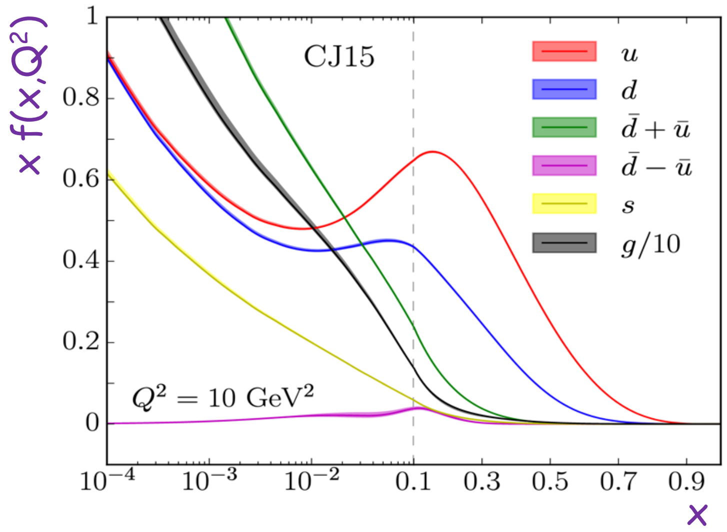
- Different exclusive channels couple to different intermediate N* states
- N* couplings to different final states provides complementary information with different systematics
- KY channels provide important cross-check of 2π channel for higher-lying resonances - *the land of the "missing" resonances*



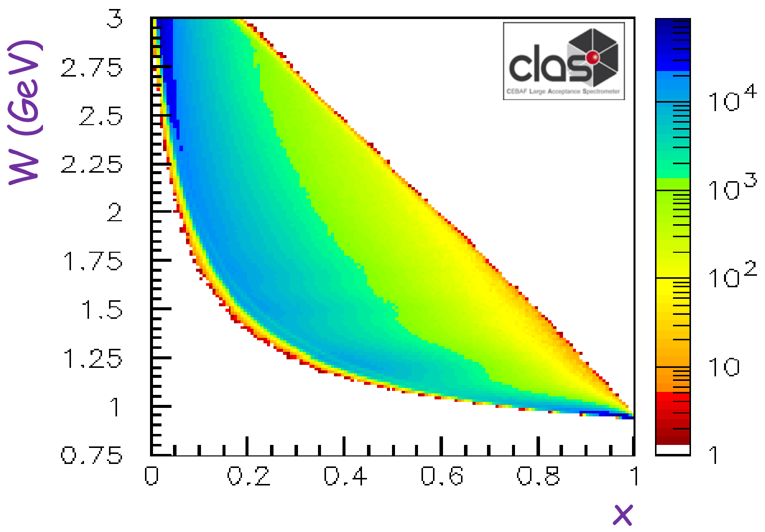
U. Löring, B. Metsch, H.R. Petry, Eur. Phys. J. A 10, 395 (2001)

Inclusive Observables in Resonance Region

- An important goal of nuclear physics is to understand nucleon structure in terms of *Parton Distribution Functions (PDFs)*
- Global QCD analyses have provided detailed information on the nucleon PDFs over a broad kinematic range:
  - Over the past 50 years, the p(e,e')X reaction has been probed: $x \in [\sim 10^{-4}, 0.9]$, $Q^2 \in [1, 10^4]$ GeV^2
- However, most of the data is in the DIS region (low x, high W)
  - In the nucleon resonance region W < 2.5 GeV (large x), the PDFs have been much less explored *(strong QCD regime)*
  - Difficult to separate perturbative/non-perturbative processes *(higher-twist effects, target mass corrections, N*s, …)*



A. Accardi et al., PRD 11, 114017 (2016)

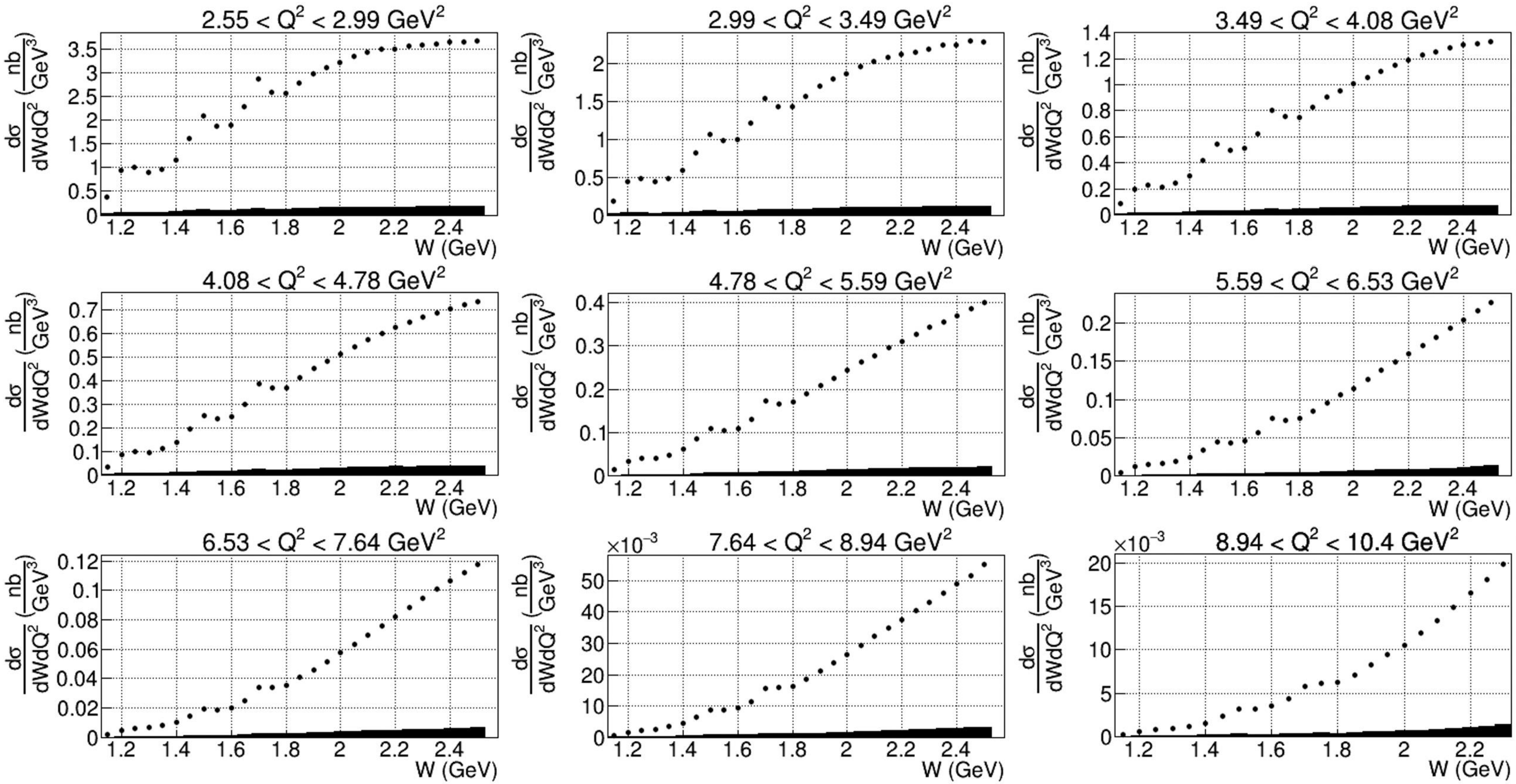


Several model approaches are available:

CSM, lQCD, quark-hadron duality, QCD-kindred, phenomenological fits, …

inclusive electron scattering cross sections provide "stress testing" ground

CLAS12 Inclusive Electron Cross Sections



FIRST ABSOLUTE CROSS SECTIONS FROM CLAS12

Systematic Uncertainties:

Bin-by-bin: 5.8%

Scale: 3.7%

RG-A – F18

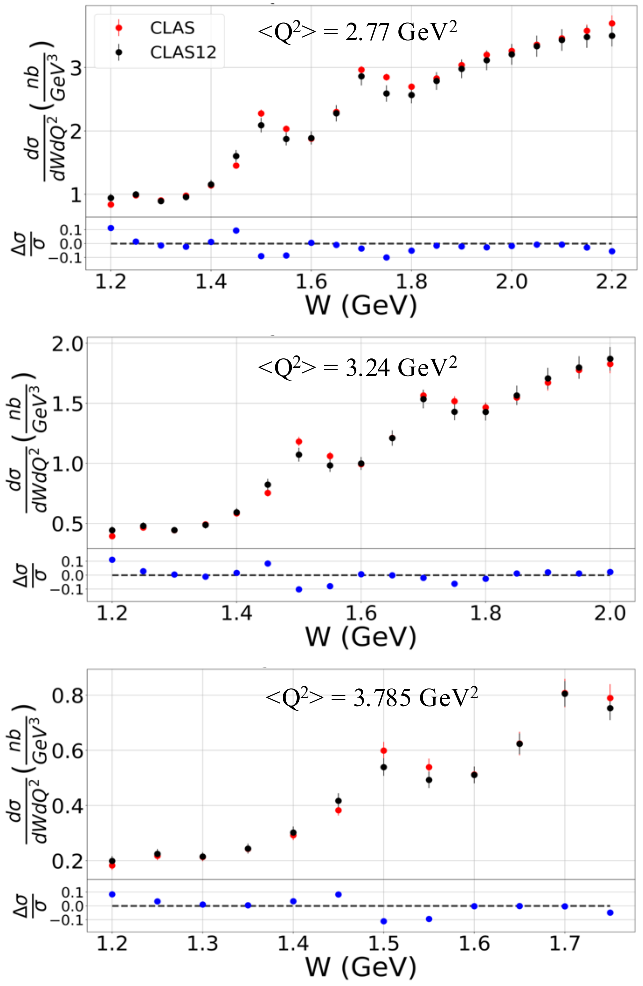
10.6 GEV

V. Klimenko et al. (CLAS), arXiv:2501.14996, accepted for publication in PRC (2025)

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

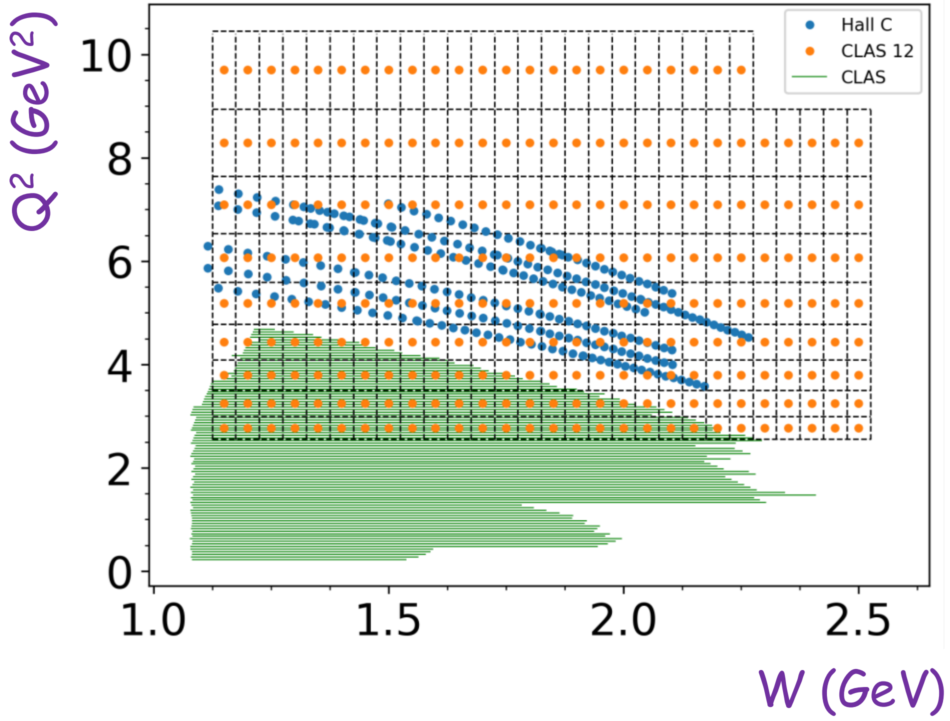
Comparisons of Inclusive Cross Sections

CLAS12 vs. CLAS



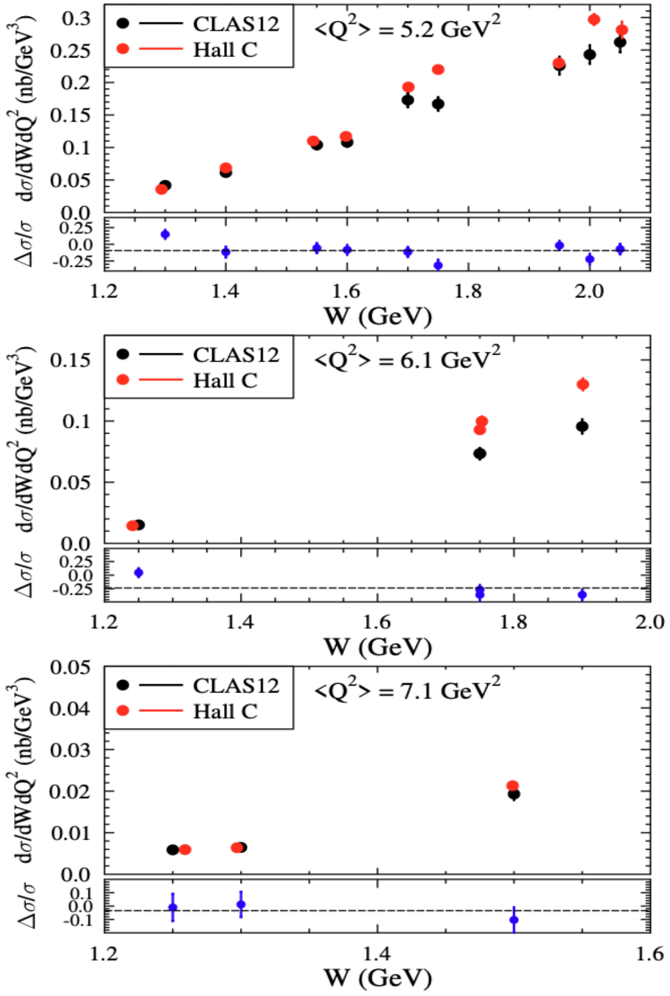
M. Osipenko et al. (CLAS), PRD 67, 092001 (2003)

Kinematic Comparison



The new CLAS12 data span the full nucleon resonance region with uniform binning in W for the full range of $Q^2 \in [2.5{:}10.4]$ GeV^2

CLAS12 vs. Hall C



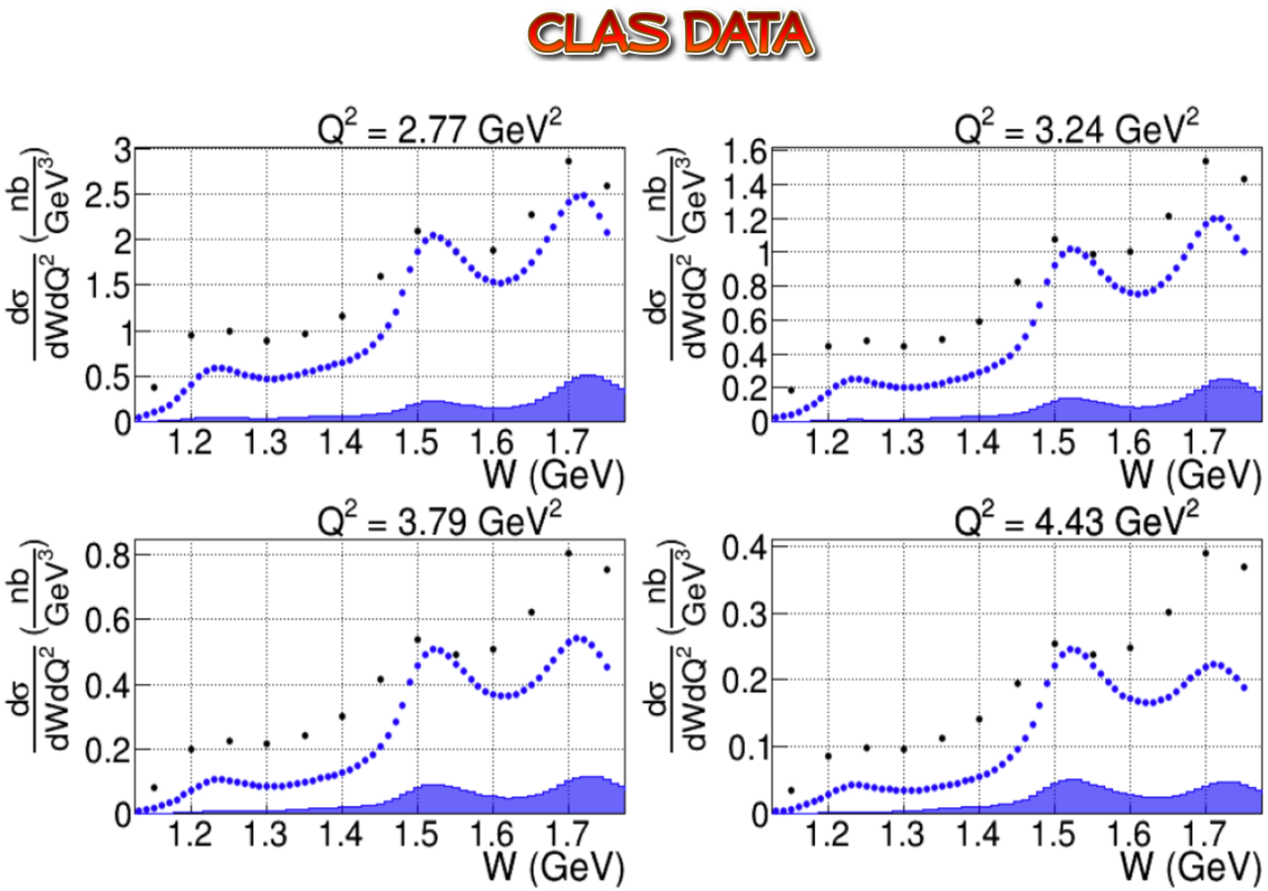
S.P. Malace et al., PRC 80, 035207 (2009)

Connecting Inclusive and Exclusive Data

- Information on the Q^2 evolution of the $\gamma_v pN^*$ electrocouplings for all prominent N* is needed for a realistic evaluation of the resonant contributions to inclusive electron scattering

- The electrocouplings have been determined from CLAS data for most N* states in the range W to 1.8 GeV from exclusive channels (πN, $\pi^+\pi^- N$) for Q^2 up to 5 GeV^2

- Resonance contributions show strong evolution with Q^2
  - different in the 1st, 2nd, 3rd resonance regions



A. N. Hiller Blin et al., PRC 107, 035202 (2023)

Accounting for resonant contributions will ultimately allow for access to probe nucleon PDFs at high x

Pseudoscalar Meson Electroproduction

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

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

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

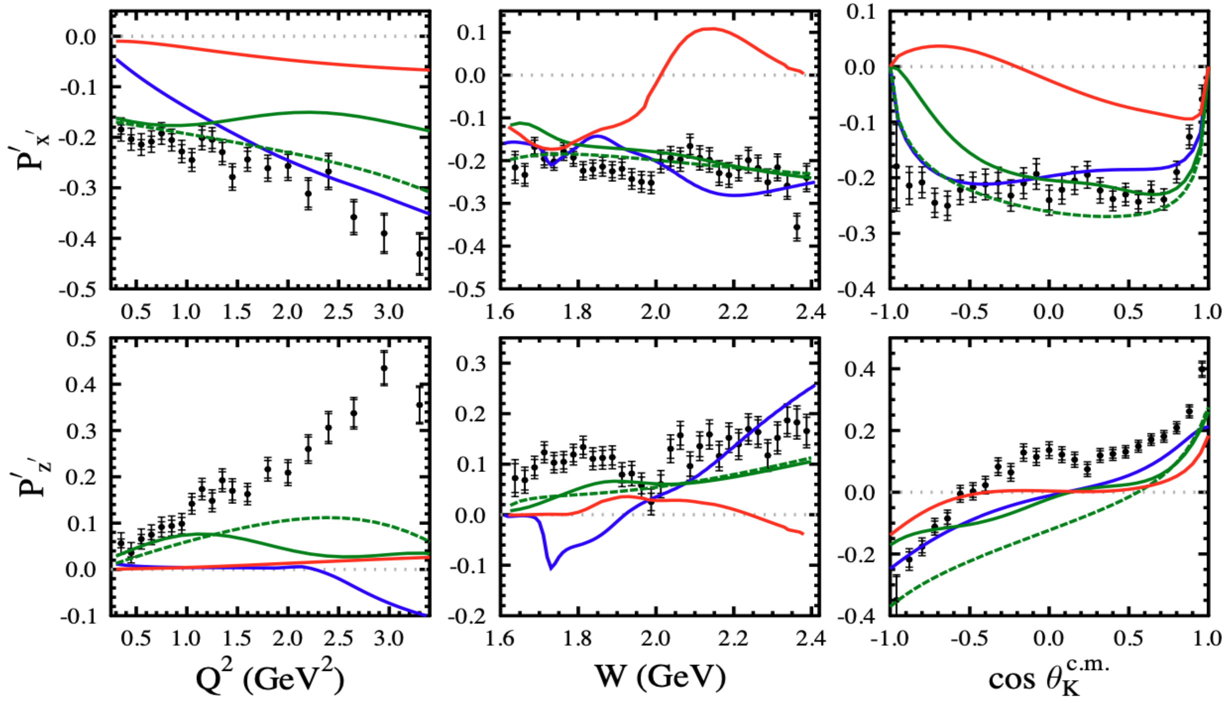
$R(Q^2, W, \cos\theta_K^{c.m.})$

CLAS/CLAS12 KY Program

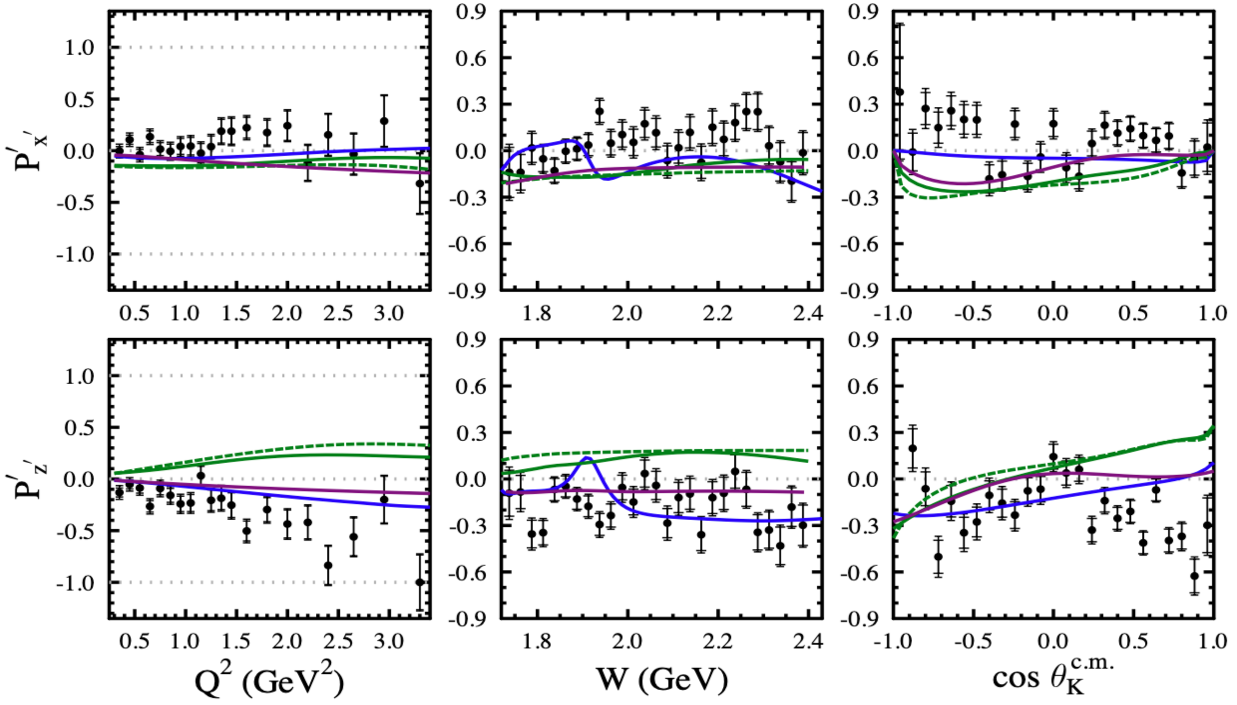
- Differential cross sections
  - σ_L, σ_T, σ_{LT}, σ_{TT}, $\sigma_{LT'}$
- KY recoil polarization
- KY transferred polarization

CLAS12 KY Transferred Polarization

$K^+\Lambda$



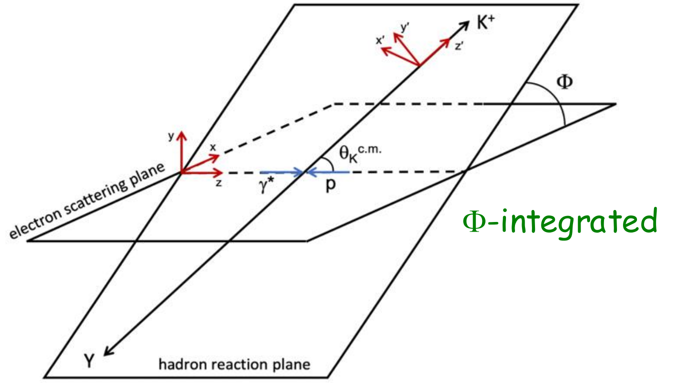
$K^+\Sigma^0$



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

Model	Year	Type	Fit Data	N* States
SL	1996	Isobar	none	1/2, 3/2
Kaon-MAID	2000	Isobar	none	1/2, 3/2, 5/2
RPR	2011	Isobar+Regge	CLAS γp	1/2, 3/2, 5/2
BS3	2018	Isobar	CLAS γp + ep	1/2, 3/2, 5/2

RG-K – W18
6.5 GEV



Φ-integrated

L/T from Λ Transferred Polarization

For $\cos\theta_K^{c.m.} = 1$: ① $\mathcal{P}'_{z'} = \mathcal{P}'_z$, ② $R_{TT'}^{z'0} = R_T^{00}$

$$\Rightarrow \mathcal{P}'_{z'} = \mathcal{P}'_z = \frac{c_0 R_T^{00}}{R_T^{00} + \epsilon R_L^{00}} = \frac{c_0 \sigma_T}{\sigma_T + \epsilon \sigma_L}$$

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

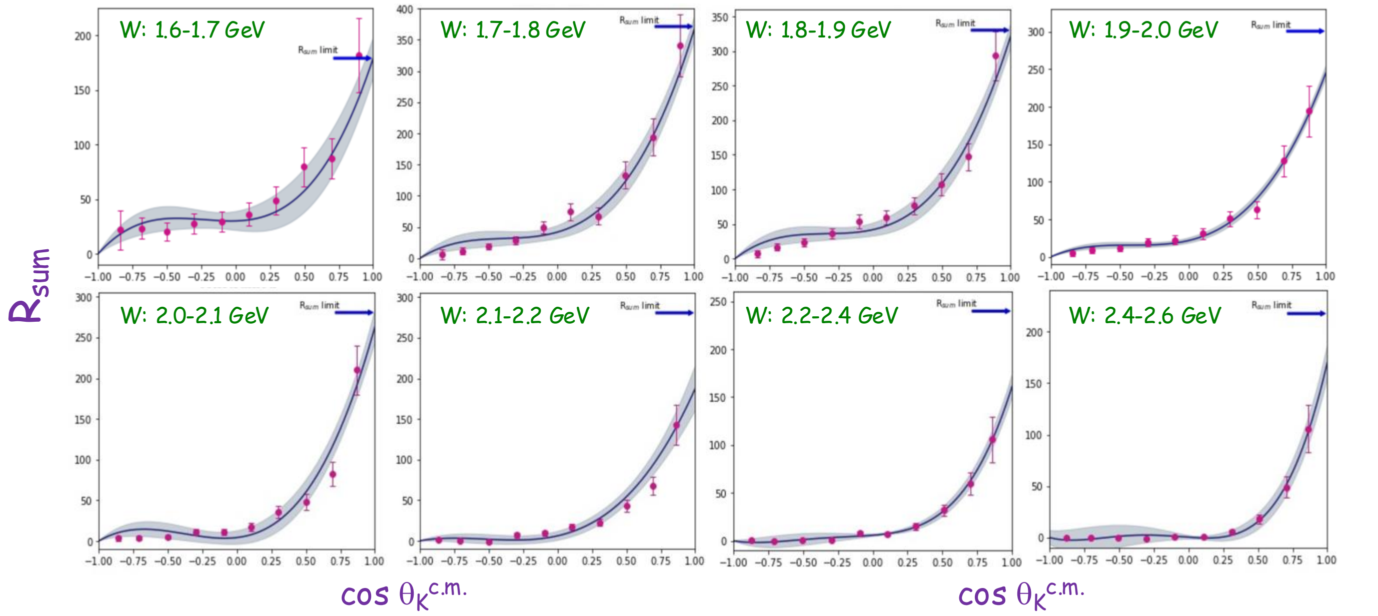
MATHEMATICAL CHICANERY

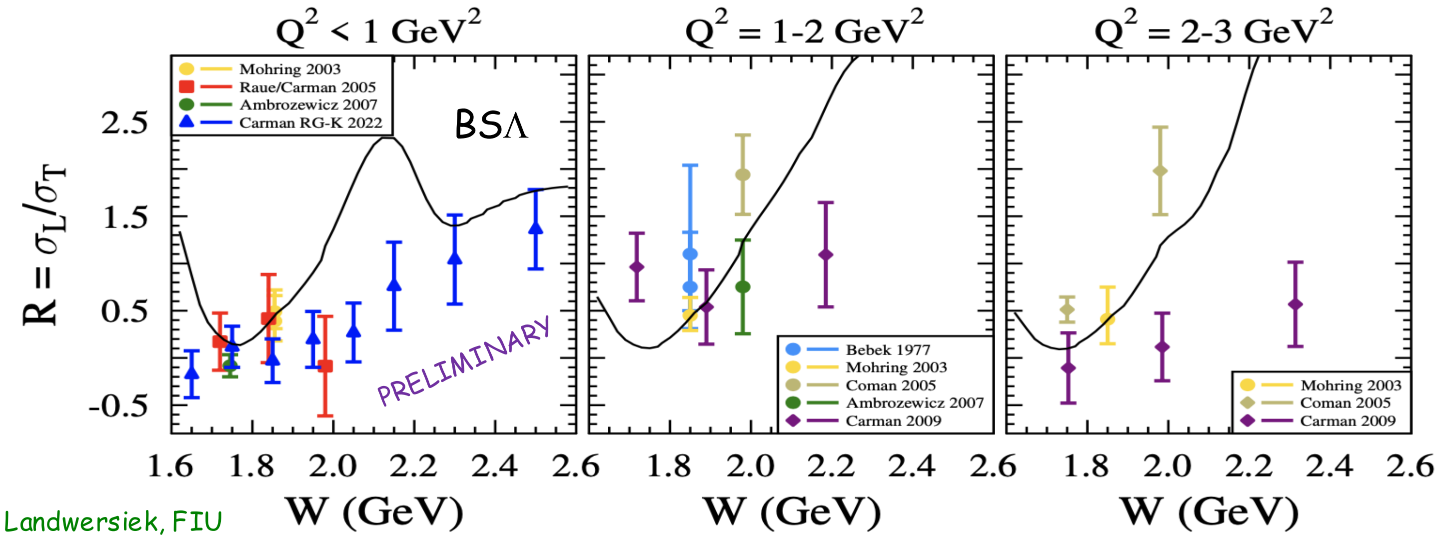
$$\mathrm{R}_{\mathrm{sum}} = \frac{(\mathcal{P}'_{z'} + \mathcal{P}'_z)\sigma_U}{c_0}$$

Fit function: $\mathrm{R}_{\mathrm{sum}} = a_0 + a_1 x + a_2 x^2 + a_3 x^3$

$$\boxed{R(\theta_K^{c.m.} = 0^\circ) = \frac{2\sigma_U}{\mathrm{R}_{\mathrm{sum}}} - 1}$$

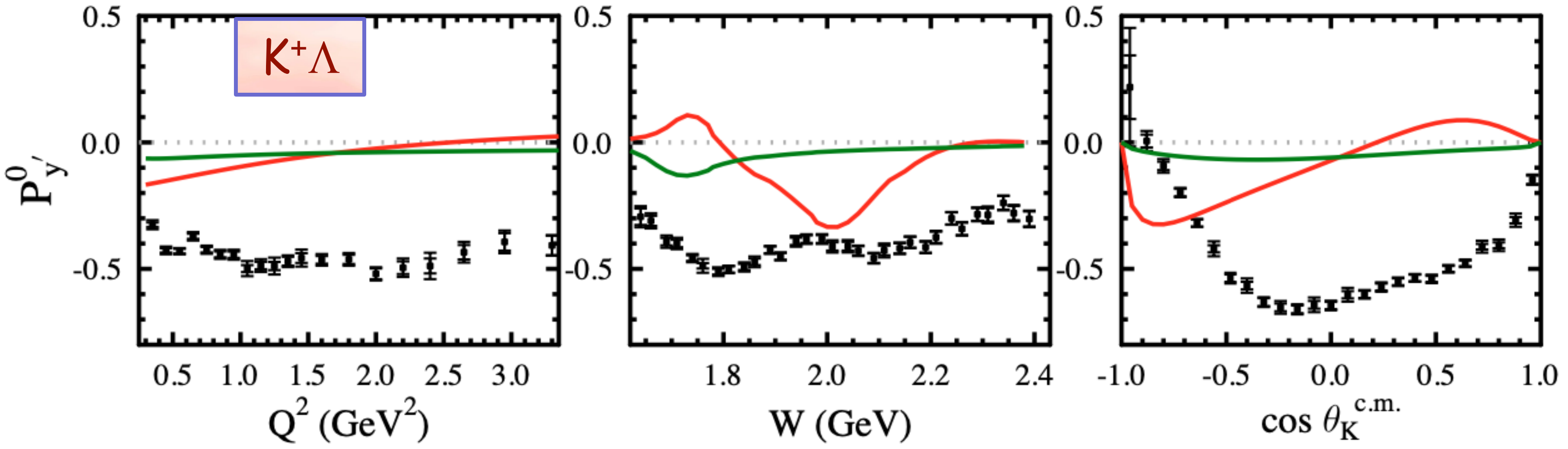
B.A. Raue and D.S. Carman, PRC 71, 065209 (2005)
D.S. Carman et al. (CLAS), PRC 79, 065205 (2009)

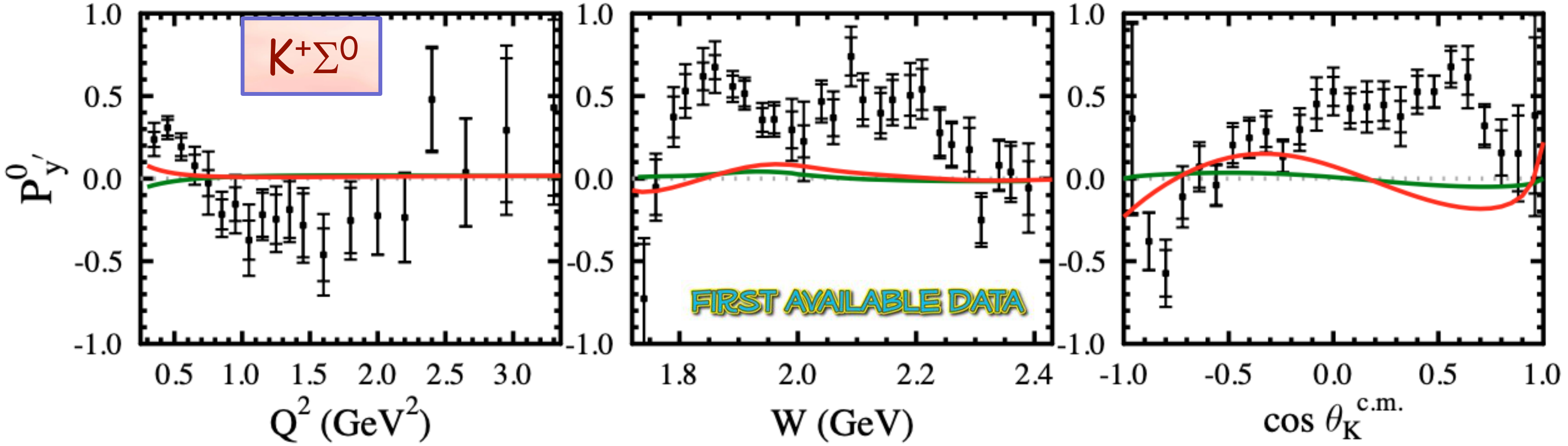


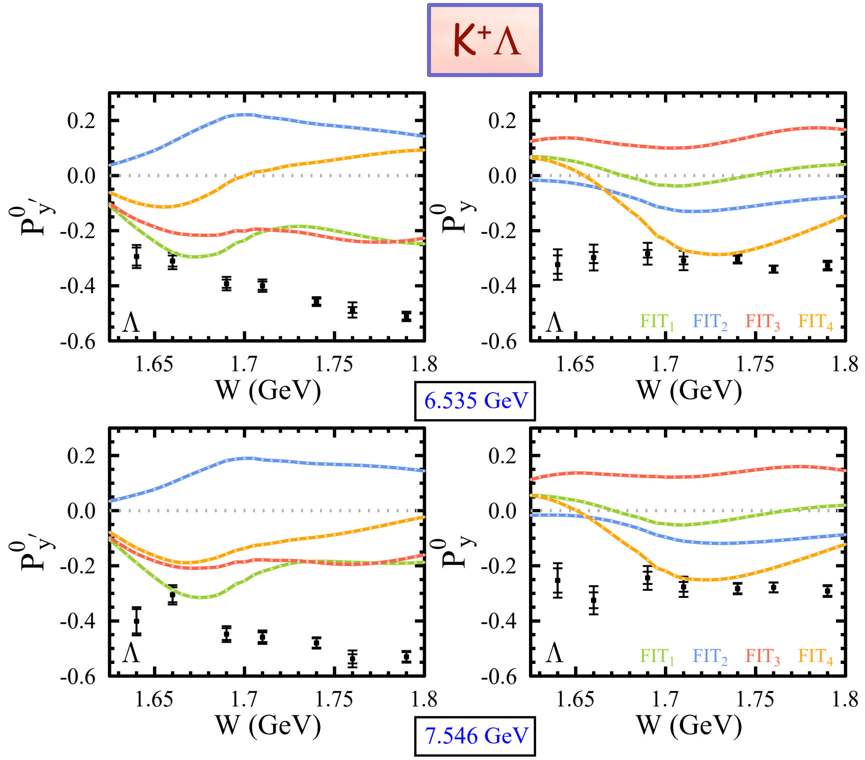


J. Landwersiek, FIU

CLAS12 KY Recoil Polarization







JBW coupled-channel model

D. Rönchen, M. Döring, U.-G. Meißner, EPJA 54110 (2018)
M. Mai et al., EPJA 59286 (2023)

Isobar models:

BSΛ: D. Skoupil and P. Bydžovský, PRC 97, 025202 (2018)
BSΣ: D. Petrillis and D. Skoupil, PRC 110, 065204 (2024)
SL: J.C. David, C. Fayard, G.H. Lamont, and B. Saghai, PRC 53, 2613 (1996)

RG-K – W18
6.5 GEV

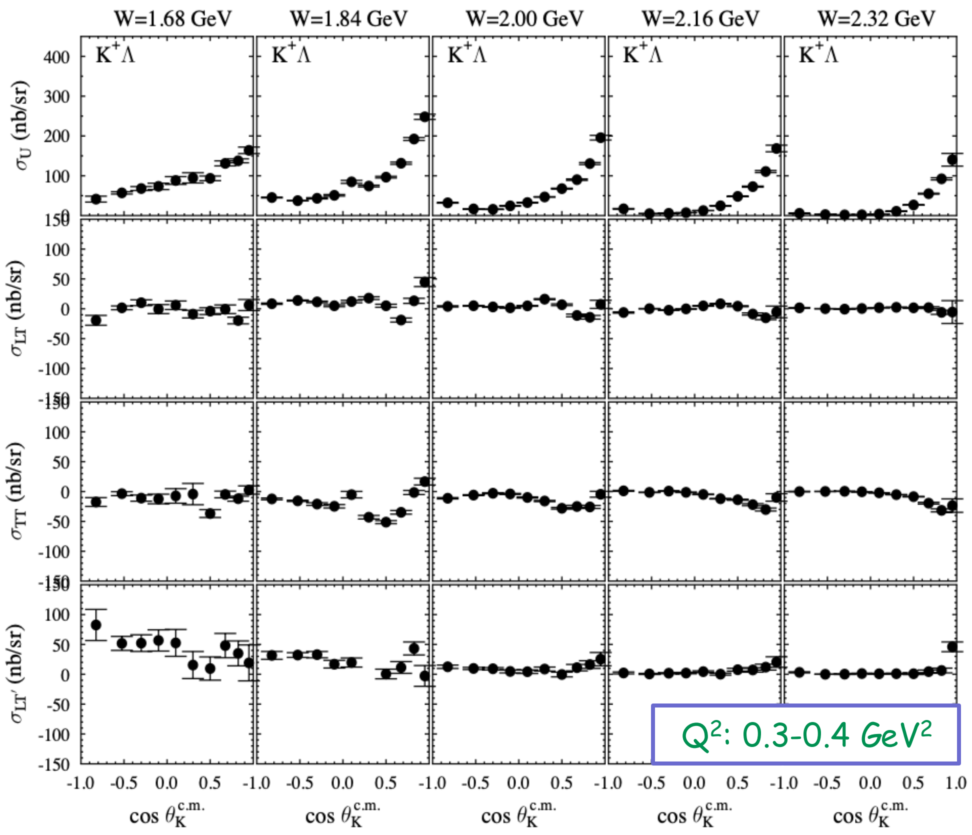
Latest analysis of KY channels
arXiv:2505.12030, submitted to PRC (2025)

CLAS12 KY Cross Sections

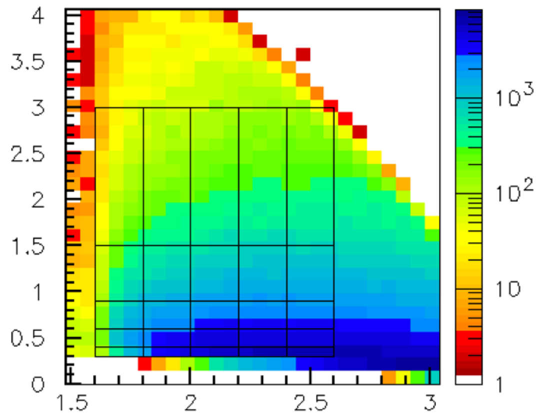
$ep \to e'K^+\Lambda$

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

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

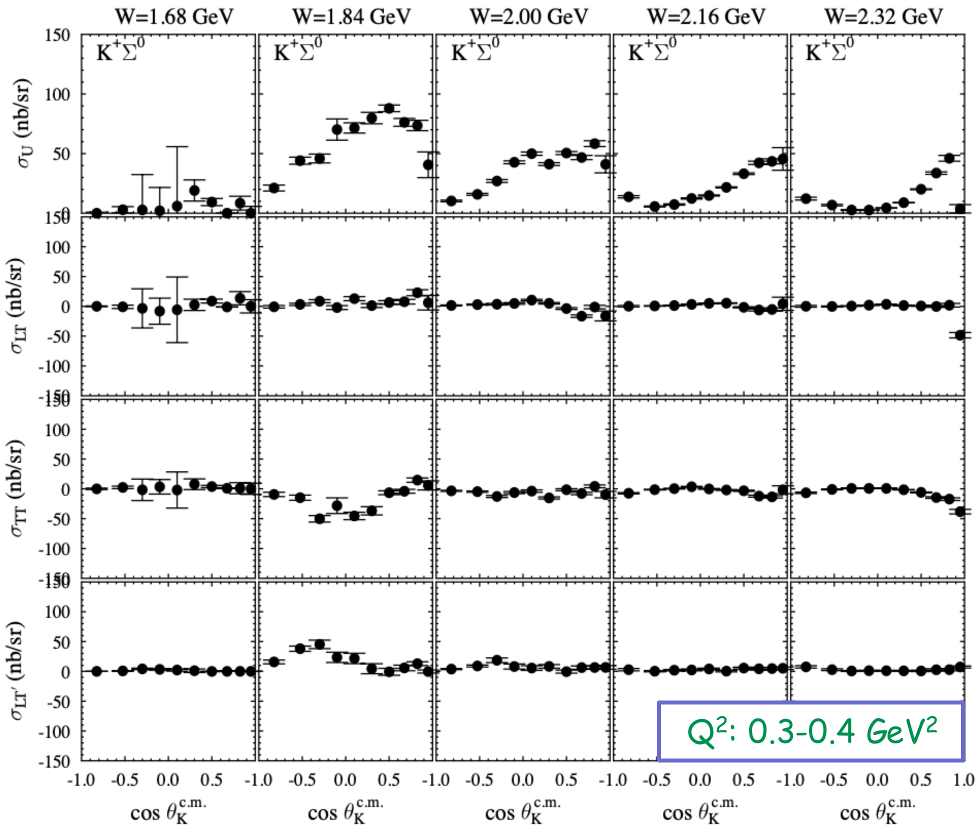


PRELIMINARY



JLab, JMU, Rome

RG-K – W18
6.5 GEV



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

Analysis of Spr24 RG-K dataset upcoming with 10x the statistics

Concluding Remarks

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

- The study of N* states is one of the key foundations of the CLAS physics program:
  - CLAS has provided a huge amount of data up to $Q^2 \sim 5$ GeV^2 - electrocouplings of most N* states up to 1.8 GeV have been extracted from these data for the first time

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

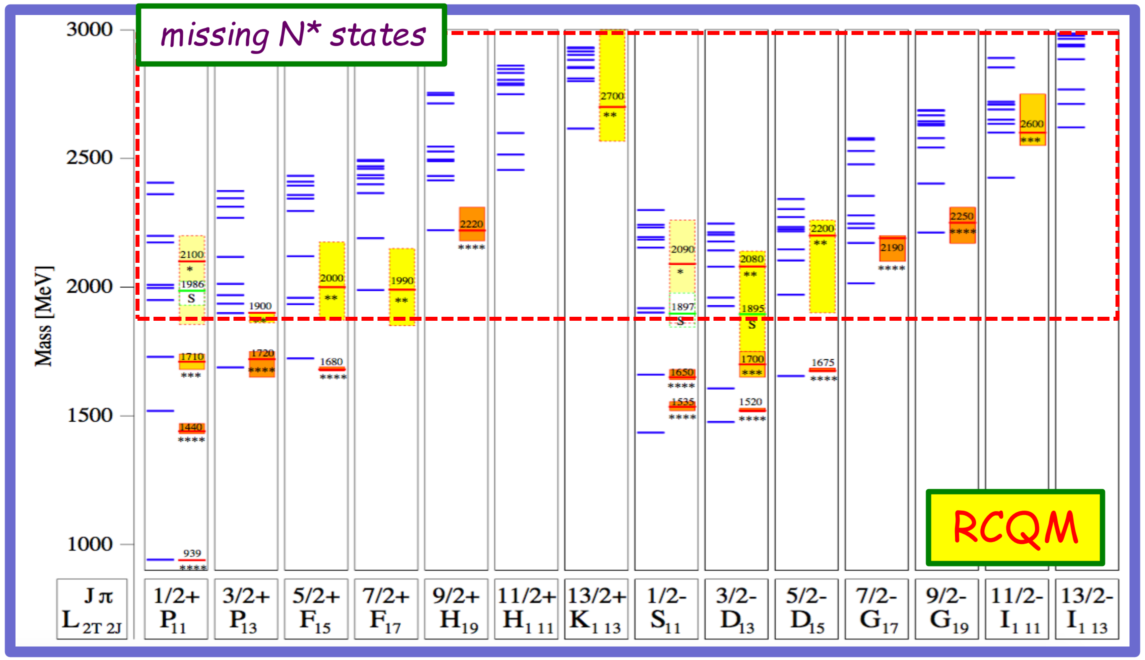
- Considering a future for JLab beyond 12 GeV era – *JLab at 22 GeV @ the luminosity frontier*

A. Accardi et al., EPJA 60, 173 (2024)

Backup Slides

Evidence for New N* in KY Channels

State N(mass)J^P	PDG 2010	PDG 2024	πN	$K\Lambda$	$K\Sigma$	γN
$N(1710)1/2^+$	***	****	****	**	*	****
$N(1875)3/2^-$		***	**	*	*	**
$N(1880)1/2^+$		***	*	**	**	**
$N(1895)1/2^-$		****	*	**	**	****
$N(1900)3/2^+$	**	****	**	**	**	****
$N(2000)5/2^+$	*	**	*			**
$N(2060)5/2^-$		***	**	*	*	***
$N(2100)1/2^+$	*	***	***	*		**
$N(2120)3/2^-$		***	**	**	*	***
$\Delta(1600)3/2^+$	***	****	***			****
$\Delta(1900)1/2^-$	**	***	***		**	***
$\Delta(2200)7/2^-$	*	***	**		**	***



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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