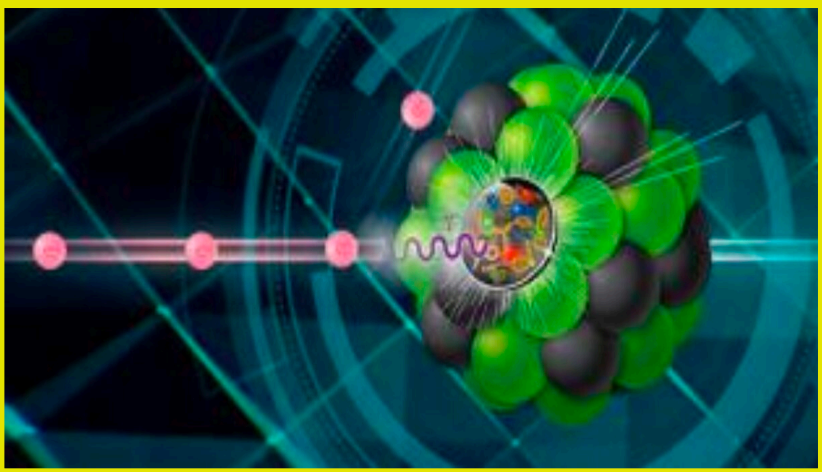
Strangeness Electroproduction with CLAS/CLAS12 as a Tool for N* Exploration

MASS IN THE STANDARD MODEL AND CONSEQUENCES OF ITS EMERGENCE



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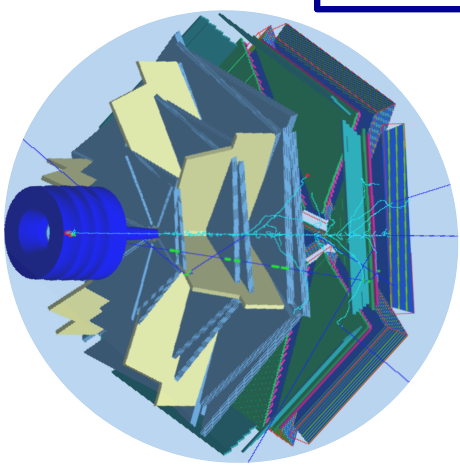
Outline

- N* Spectrum & Structure
- CLAS $\gamma_v p \rightarrow \pi N$, $\pi\pi N$, KY Data
- CLAS12 N* Program and Plans
- Concluding Remarks

CLAS / CLAS12 N* Program

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

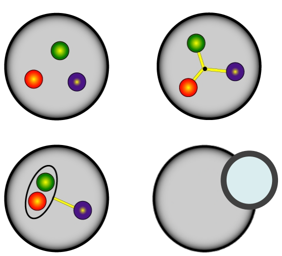


- CLAS & CLAS12 were designed to measure cross sections and spin observables over a broad kinematic range for exclusive reaction channels:

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
    - insight into EHM by mapping the dressed quark mass function from the results on the electrocouplings of different excited nucleon states
  - Data can unravel/reveal the spectrum of contributing states in a complementary manner relative to photoproduction

N* degrees of freedom??

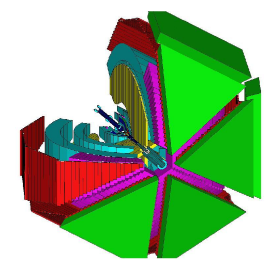


CLAS N* Program Measurement Overview

Reaction	Observable	Q^2 (GeV^2)	W (GeV)	Reference
$ep \to ep\pi^+\pi^-$	$d\sigma/dM$, $d\sigma/d\cos\theta$, $d\sigma/d\alpha$	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)
$ep \to ep\pi^0$	$d\sigma/d\Omega$	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)
$ep \to en\pi^+$	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)

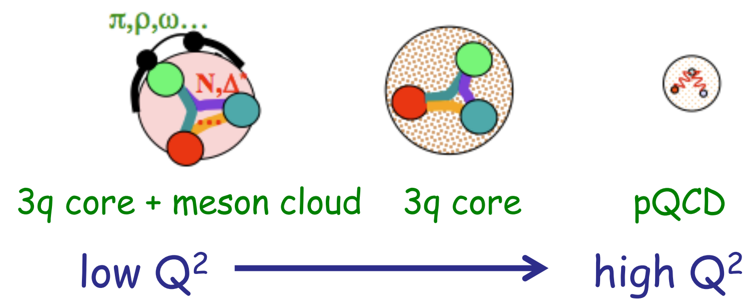
Reaction	Observable	Q^2 (GeV^2)	W (GeV)	Reference
$en \to ep\pi^-$	A_t, A_{et}	0.05 - 5.0	1.1 - 2.6	PRC 94, 05520 (2016)
$ep \to ep\eta$	σ_U, σ_{LT}, σ_{TT}	1.6 - 4.6	2.0 - 3.0	PRC 95, 035202 (2017)
	σ_U, σ_{LT}, σ_{TT}	0.13 - 3.3	1.5 - 2.3	PRC 76, 015204 (2007)
	$d\sigma/d\Omega$	0.25 -1.50	1.5 - 1.86	PRL 86, 1702 (2001)
$ep \to eK^+Y$	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)
$ep \to ep\omega$	σ_U, σ_{LT}, σ_{TT}	1.725 - 4.85	1.85 - 2.77	EPJA 24, 445 (2005)
$ep \to ep\rho^0$	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)
$ep \to ep\phi$	$d\sigma/dt$	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

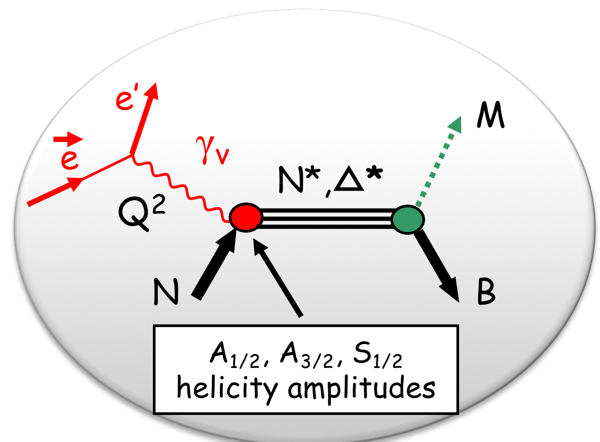


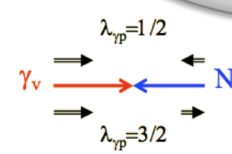
Excited Nucleon Structure

- Nucleon structure is more complex than what can be described accounting for quark degrees of freedom only
  - Low Q^2: ($Q^2 < 2$ GeV^2) structure well described by adding an external meson cloud to inner quark core
  - High Q^2: ($Q^2 > 5$ GeV^2) quark core dominates; transition from confinement to pQCD regime



- Studies of the $\gamma_v NN^*$ electrocoupling amplitudes from low to high Q^2 probe the detailed structure of the N* states
  - The momentum dependence of the dressed quark mass 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

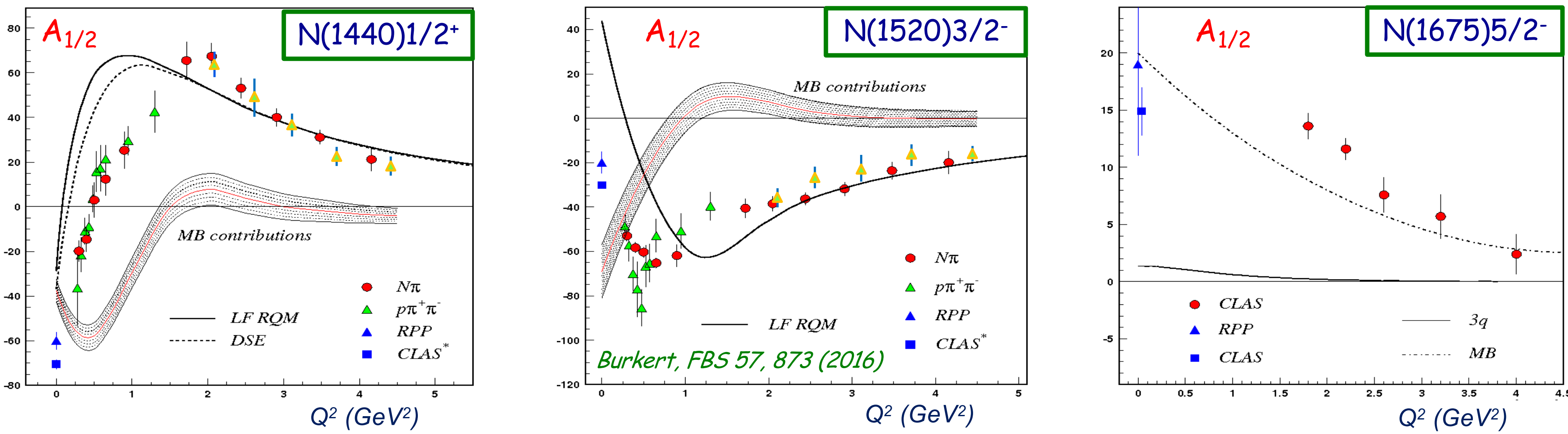




$A_{1/2}$, $A_{3/2}$ - transverse

$S_{1/2}$ - longitudinal

Lower-Lying N* States



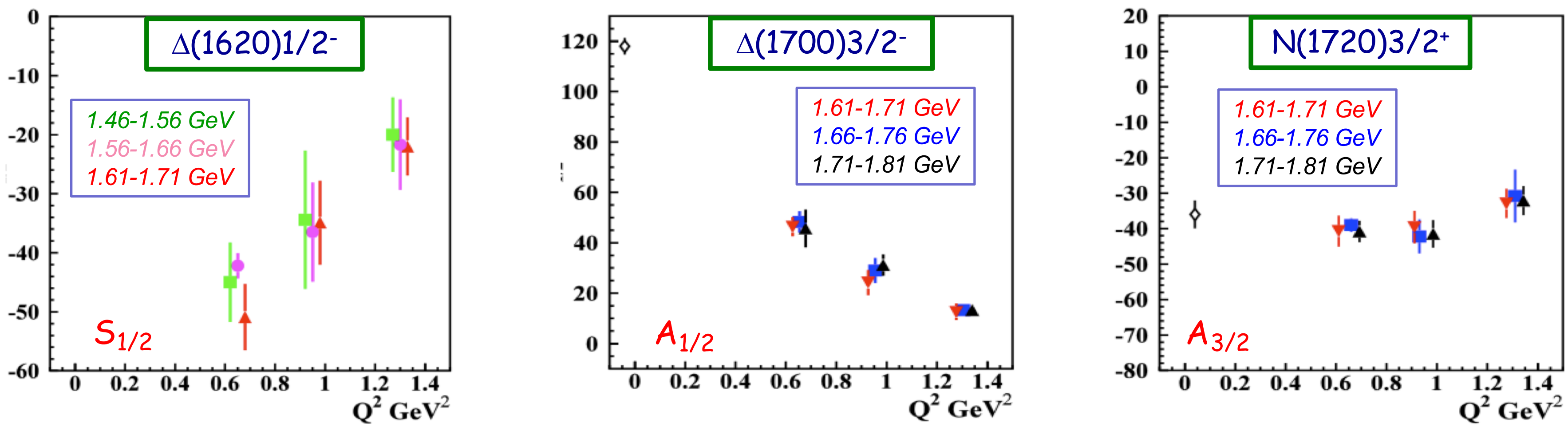
- Electrocouplings reveal different interplay between meson cloud and quark core:
  - Data on the electrocouplings at $Q^2 > 2.0$ GeV^2 are needed in order to gain insight into the dressed quark mass function at the distances where the quark core contribution dominates
- Good agreement of the extracted N* electrocouplings from Nπ and Nππ:
  - Compelling evidence for the reliability of the results
  - Channels have very different mechanisms for the non-resonant background

Precision studies of N* structure are a key part of the CLAS12 experimental program

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 much smaller strength to $N\pi$*

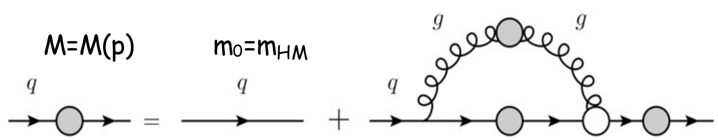


Mokeev, Aznauryan, IJMPC 26, 1460080 (2014); Mokeev et al., PRC 93, 025206 (2016); Carman, Joo, Mokeev, FBS 61, 29 (2020)

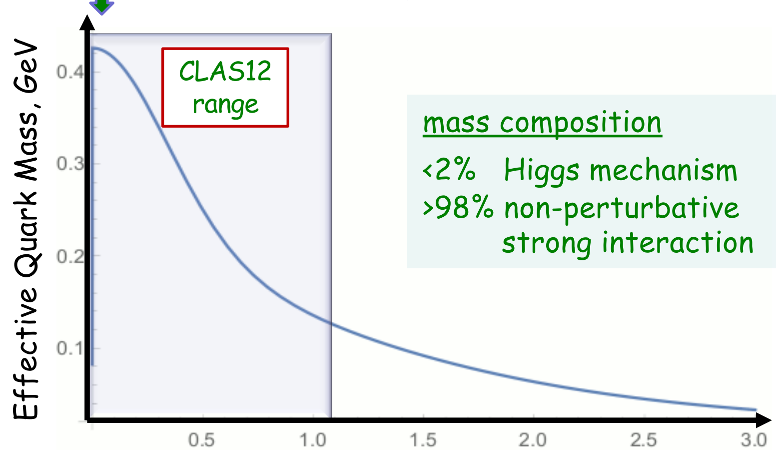
Data from the KY channels is critical:
- to provide an independent extraction of the electrocouplings for the higher-lying N* states
- to elucidate the possible impact of the three-quark orbital excitation on EHM

Emergence and Distribution of Mass

Effective quark mass depends on its momentum



confinement regime:
- constituent quark mass



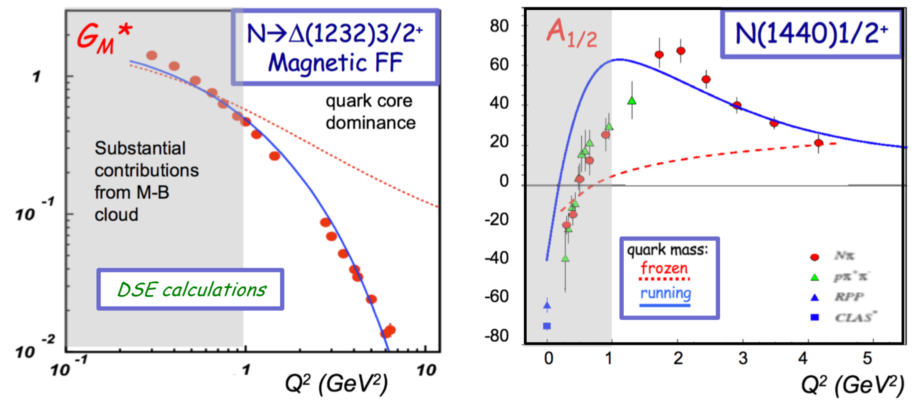
approaching bare Higgs mechanism mass

mass composition

<2% Higgs mechanism

>98% non-perturbative strong interaction

- Calculations of form factors and electrocouplings are sensitive to the evolution of the dressed quark mass function



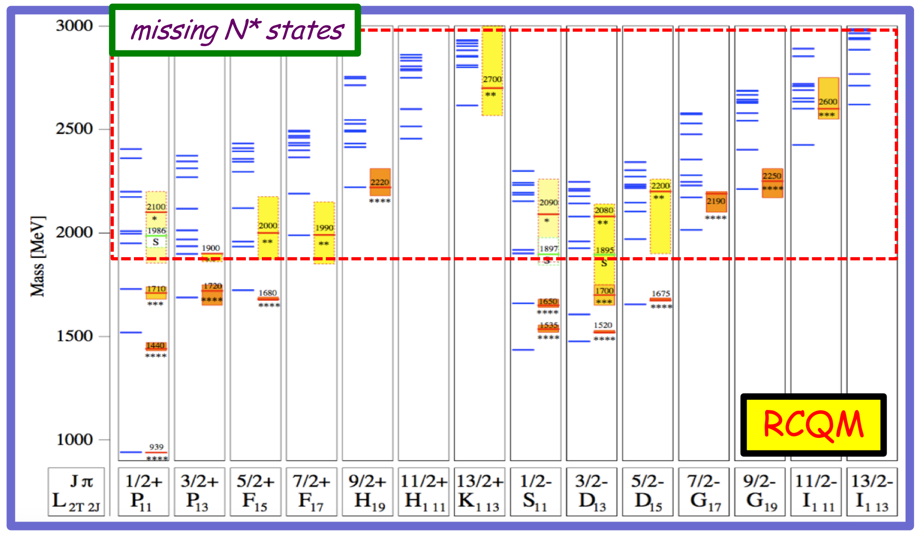
CLAS results vs. QCD expectations with running quark mass

CLAS12 will cover for the first time the Q^2 range where the dominant part of hadron mass is generated addressing the critical questions:

- *What is the nature of confinement?*
- *How is >98% of visible mass generated?*

Evidence for New N* in the KY Channels

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)

Extend these studies to electroproduction and to higher masses

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
    [Carman et al., PRL 90, 131804 (2003)]
  - W=thr-2.6 GeV, Q^2=1.6-2.6 GeV^2
    [Carman et al., PRC 79, 065205 (2009)]
- $K^+\Lambda$ recoil polarization
  - W=1.6-2.7 GeV, $\langle Q^2\rangle$=1.9 GeV^2
    [Gabrielyan et al., PRC 90, 035202 (2014)]

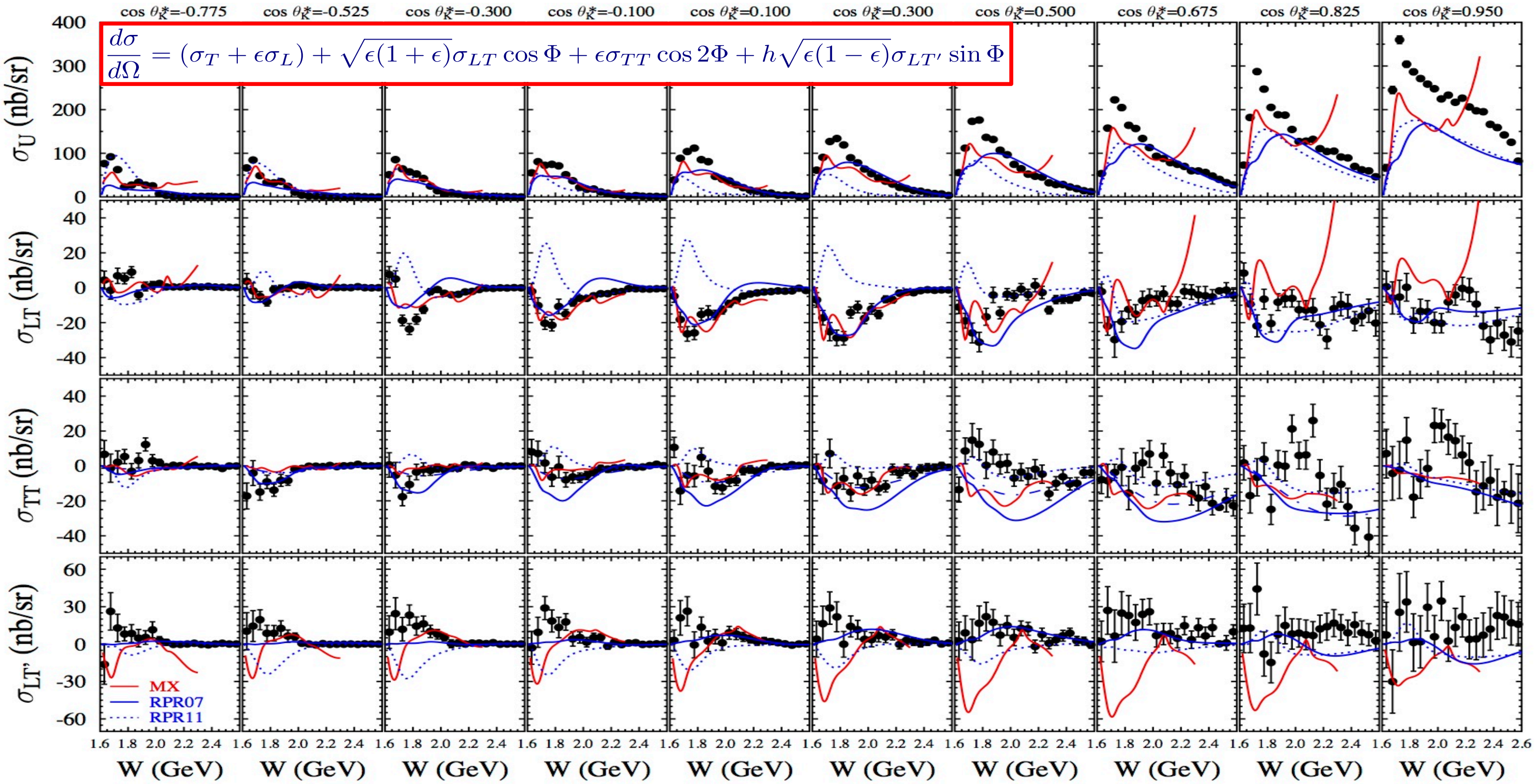
Publications (Cross Section):

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

clas
CEBAF Large Acceptance Spectrometer

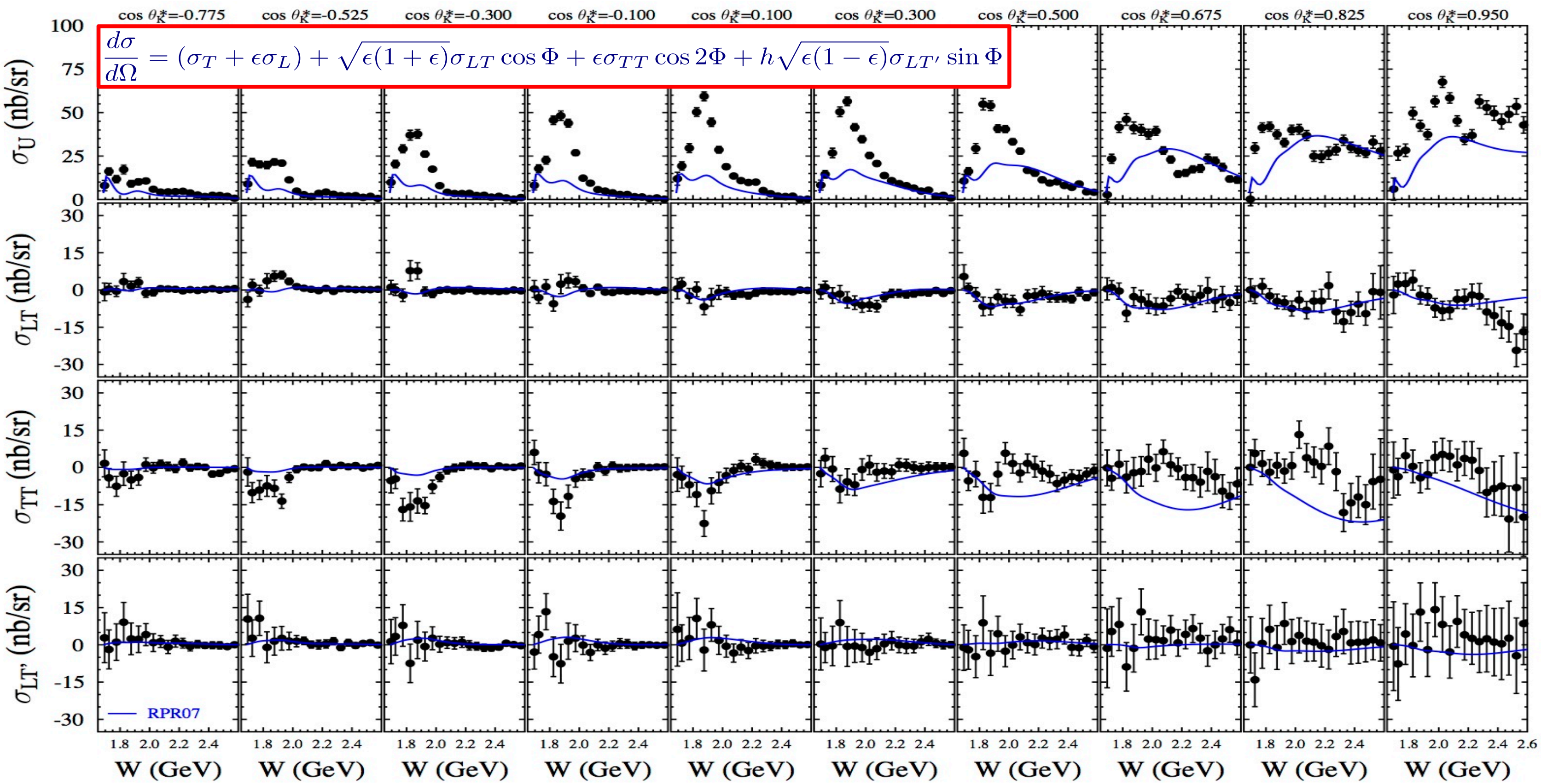
$K^+\Lambda$ Structure Functions

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



E = 5.5 GeV, W: thr – 2.6 GeV, Q^2 = 1.80, 2.60, 3.45 GeV^2 *Carman et al., PRC 87, 025204 (2013)*

$K^+\Sigma^0$ Structure Functions



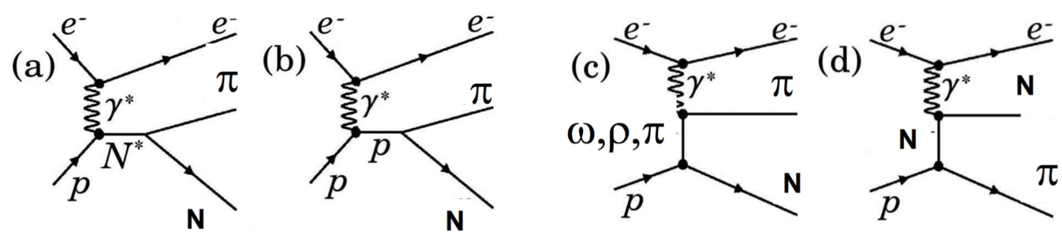
E = 5.5 GeV, W: thr – 2.6 GeV, Q^2 = 1.80, 2.60, 3.45 GeV^2 *Carman et al., PRC 87, 025204 (2013)*

Reaction Models

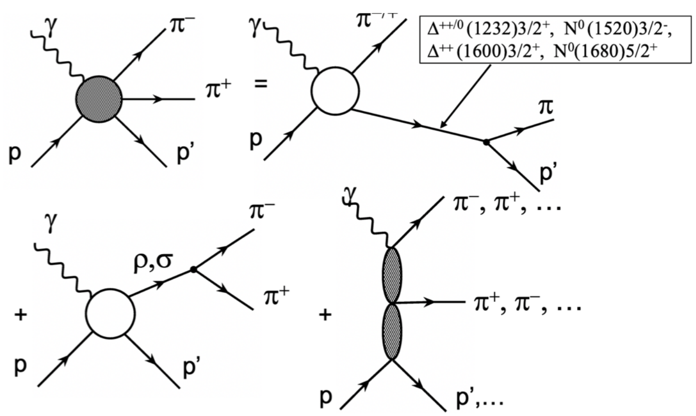
Fixed-t Dispersion Relations (DR)

- The real parts of 18 invariant Nπ electroproduction amplitudes are computed from their imaginary parts, employing model-independent fixed-t dispersion relations
- The imaginary parts of the Nπ electroproduction amplitudes at W>1.3 GeV are dominated by the resonant parts and were computed from N* parameters fit to the data

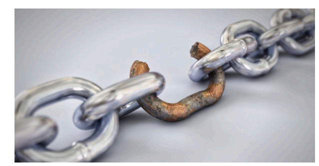
Unitary Isobar Model (UIM)



JLab-Moscow Model (JM)



KY Reaction Model



At present there is no reaction model that adequately describes the KY electroproduction data in the resonance region

A model that describes the KY data well is necessary to extract the electrocouplings from the existing lower Q^2 CLAS data and the planned higher Q^2 CLAS12 data

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

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]

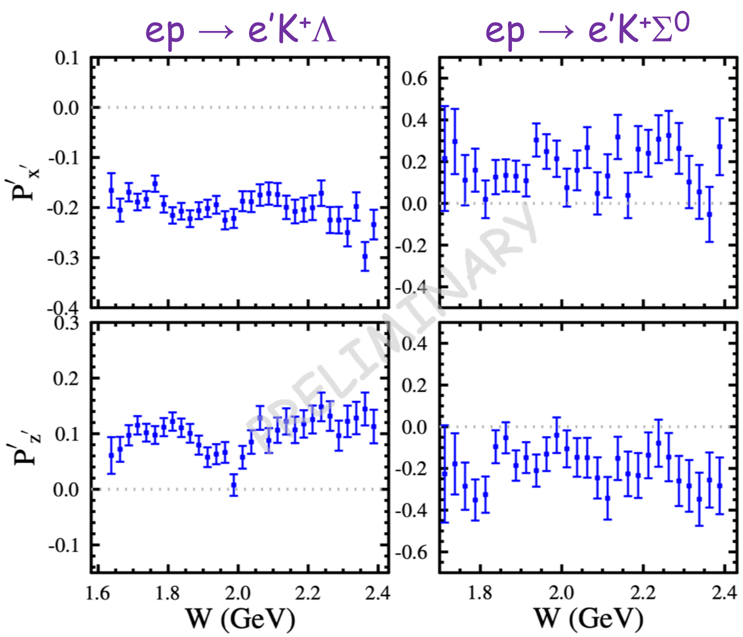
E12-09-003	Nucleon Resonance Studies with CLAS12
E12-06-108A	KY Electroproduction with CLAS12
E12-16-010A	N* Studies Via KY Electroproduction at 6.6 and 8.8 GeV
E12-16-010	A Search for Hybrid Baryons in Hall B with CLAS12

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

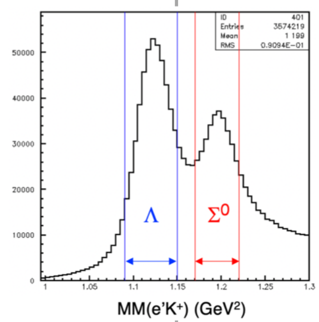
1. Study higher-lying N* states:
   - confirm signals of new baryon states observed in $\gamma p \to KY$ with data of comparable statistical precision
   - search for predicted qqqg hybrid baryons
2. Understand effect of meson cloud on N* structure:
   - use transition regime to explore emergence of external meson cloud from the core of confined quarks and gluons
   - expect precision in electroproduction to match photoproduction for $Q^2 < 2$-3 GeV^2
3. Probe dressed quark mass function and di-quark correlations in N* structure:
   - important aspect of N* structure and $\gamma_v NN^*$ amplitudes
   - provide insight into EHM vs. Q^2
   - different N* quantum numbers allow study different qq correlations

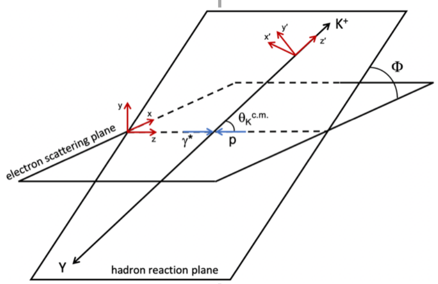
CLAS12 Transferred Polarization $\vec{e}p \rightarrow e'K^+\vec{Y}$

CLAS12 RG-K @ 6.535 GeV

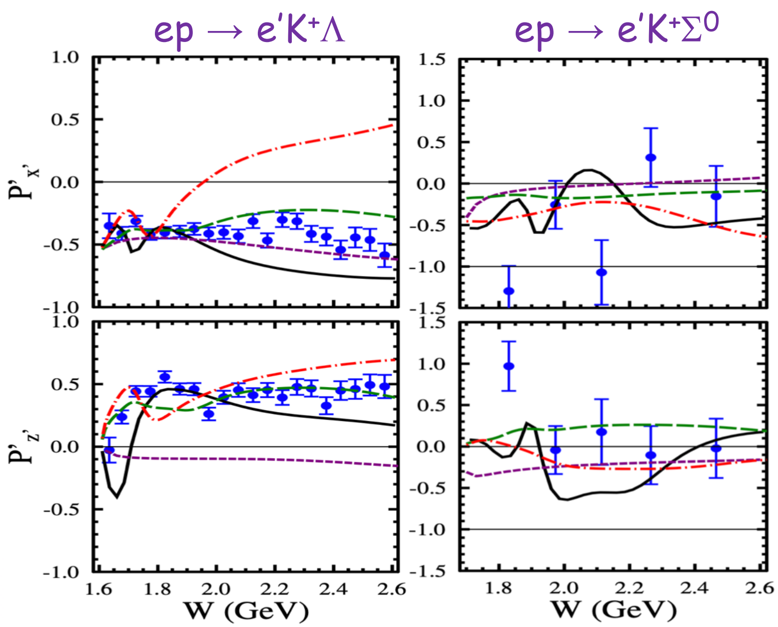


Raw uncorrected polarization





CLAS e1-6 @ 5.754 GeV



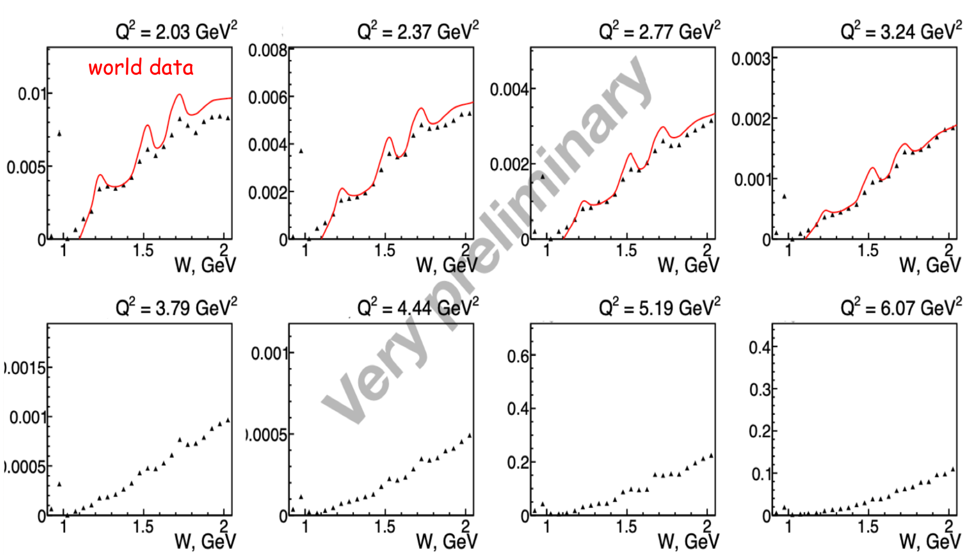
D.S. Carman et al., PRC79, 065205 (2009)

Mart/Bennhold	RPR-2
RPR-1	Regge

CLAS12 Cross Section Measurements

10.6 GeV RG-A

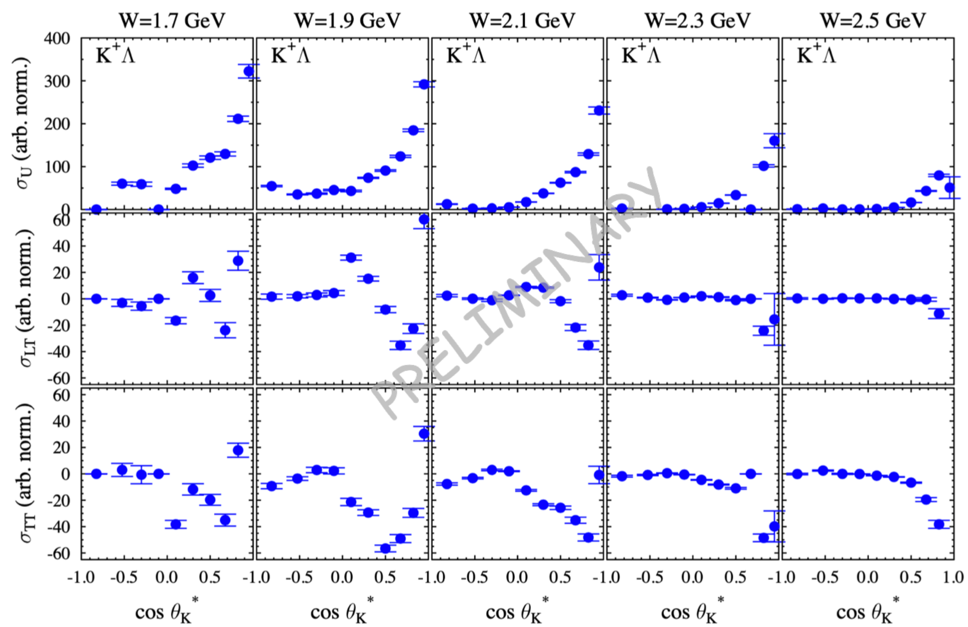
ep → e′X



- Use to understand yield normalization with CLAS12
- Gain insight into ground state nucleon PDF in the resonance region and insight into quark-hadron duality in the resonance and DIS regions

ep → e′K⁺Λ

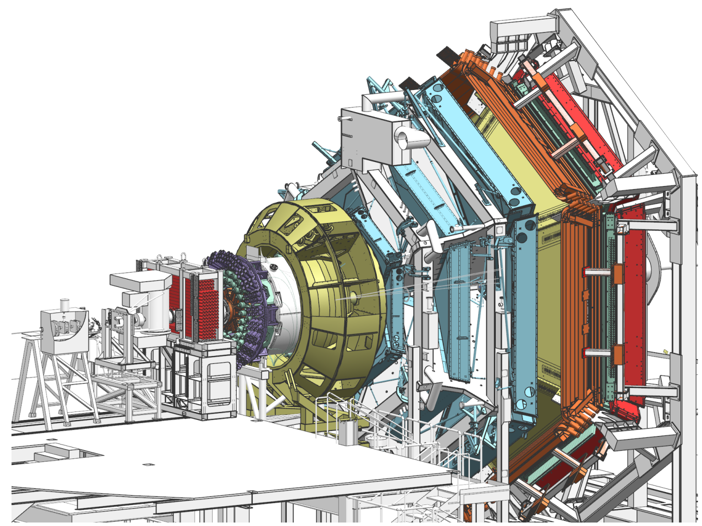
6.5 GeV RG-K



Q^2: 0.3-0.4 GeV^2

CLAS12 N* Analysis - Near-Term Plans

- KY Phase 1: (next 12 months)
  - Beam-recoil transferred polarization
    - Publication submitted by the end of the year
  - Recoil polarization
    - Analysis to be completed spring 2022
  - Fifth structure function
    - Analysis to be completed summer 2022
- KY Phase 2: (next 2-3 years)
  - Cross sections and separated structure functions
    - Analysis done in first half of 2023
  - L/T separation (6.6, 8.8, 11 GeV)
    - Analysis over next three years



Note: This work is part of the overall plans of the CLAS/CLAS12 N*/Hadron Structure Group:

- Active analyses on inclusive (e,e'), π^+n, π^0p, $\pi^+\pi^-p$ – BSA and differential cross sections
- Stay tuned – more to say at upcoming (virtual) Strong QCD Workshop hosted by Nanjing U., Jun. 7-10

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 understanding 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 on the dressed quark mass function from analyses of the electrocouplings of different N* states will validate insight into EHM in a nearly model-independent way
  - These studies from CLAS12 will probe the Q^2 range where the dominant part of hadron mass is generated
  - 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