Nucleon Resonance Studies Via Exclusive KY Electroproduction with CLAS and CLAS12

Daniel S. Carman
Jefferson Laboratory

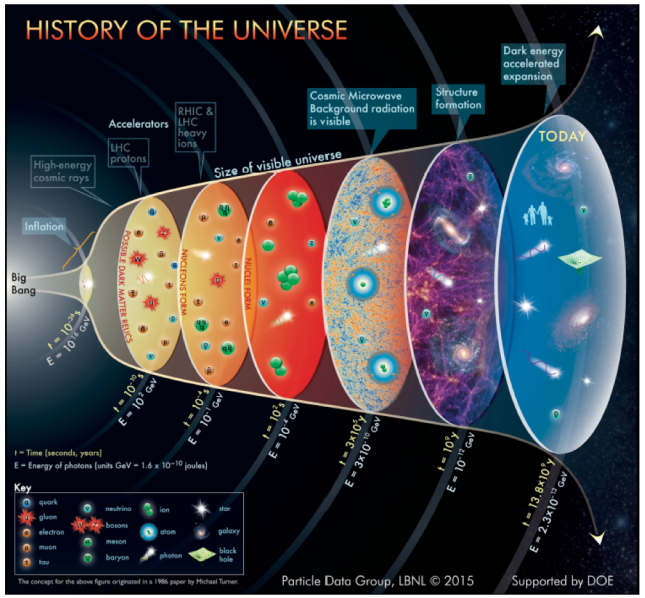
clas
CEBAF Large Acceptance Spectrometer

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



In the early universe:

- Transition occurred from a deconfined quark/gluon phase to hadron phase
- This transition was shaped by the full meson/baryon spectrum

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

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

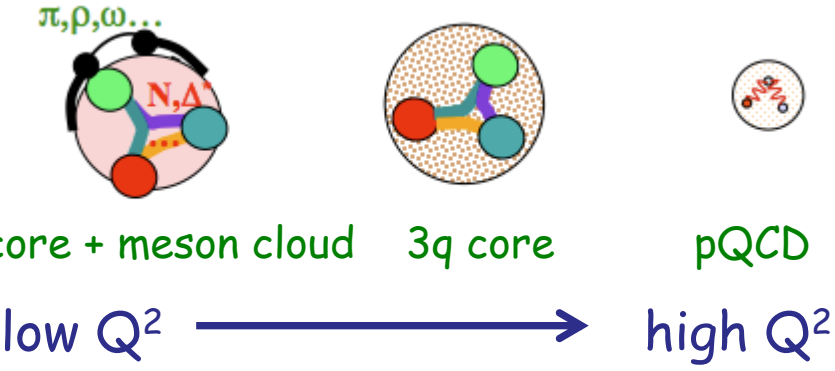
- Goal is to explore the *spectrum* of N* states and their *structure*
  - Probe their underlying degrees of freedom via studies of the Q^2 evolution of the electroproduction amplitudes
    - these amplitudes do not depend on the decay channel but different final states have different hadronic decay parameters and backgrounds
    - insight into strong QCD by mapping the dressed quark mass function from the results on the electrocouplings of different excited nucleon states
    - search for hybrid baryons ($qqqG$) and other non-3q configurations
  - Data can unravel/reveal the spectrum of contributing N* states

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

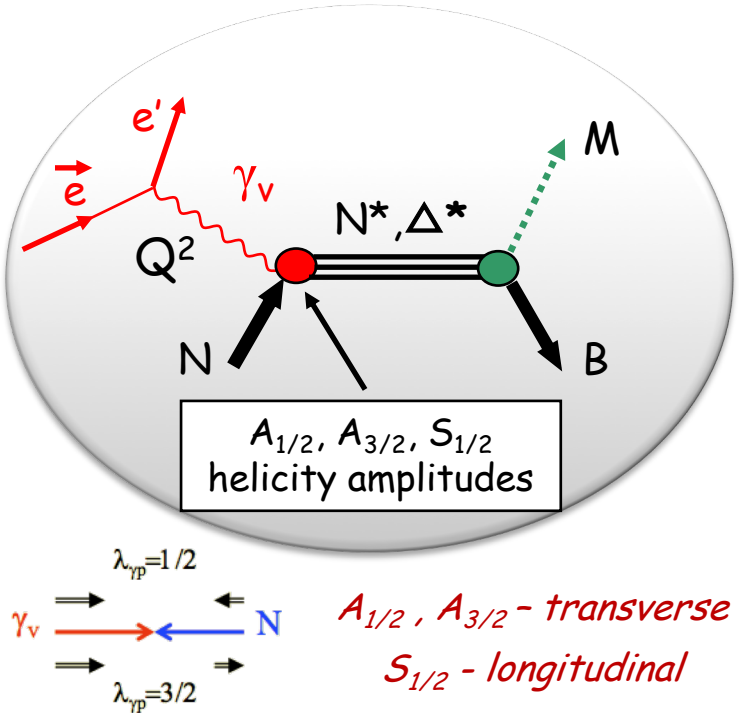
  - High Q^2: ($Q^2 > 5$ GeV^2) quark core dominates; transition from confinement to pQCD regime



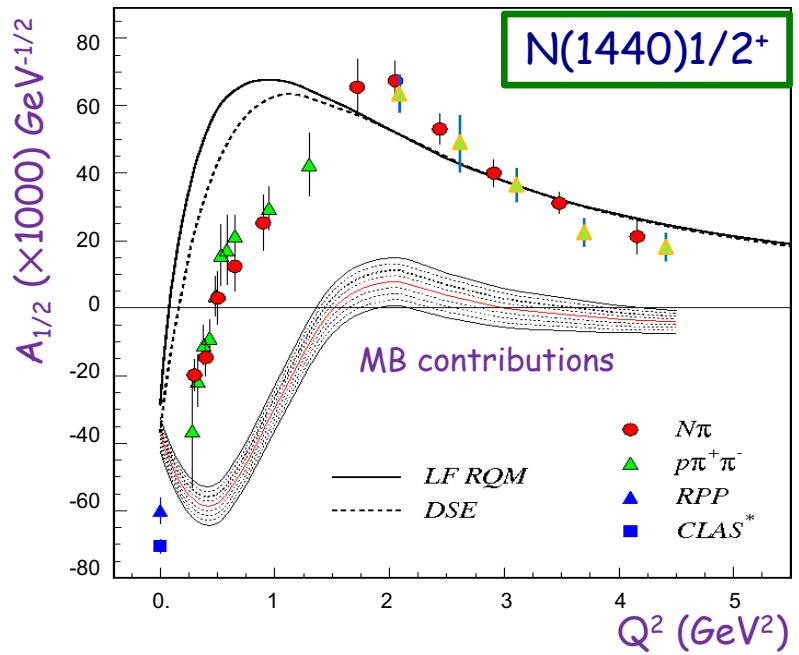
- Studies of the $\gamma_v NN^*$ electrocouplings from low to high Q^2 probe the detailed structure of the N* states

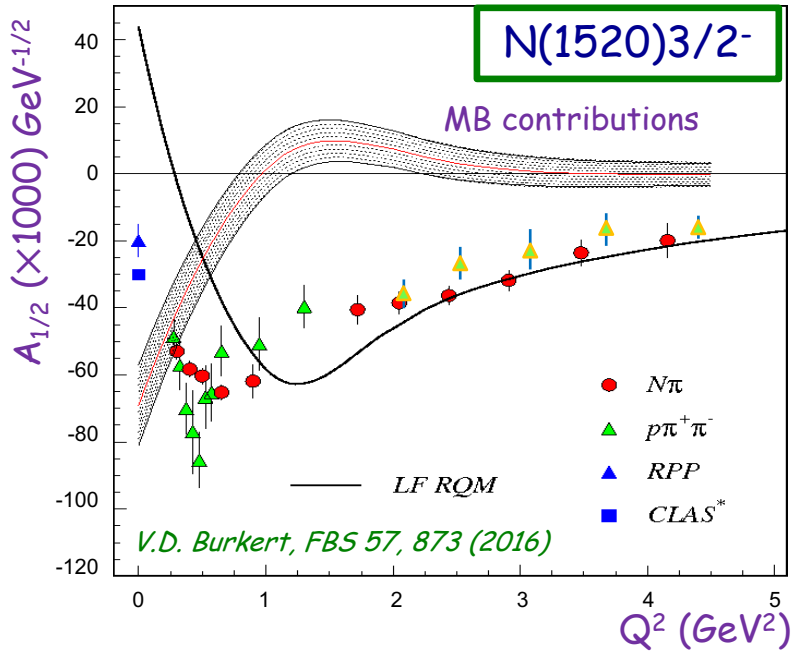
  - The momentum dependence of the dressed quark mass shapes the structure of N* states and the Q^2 evolution of the electrocouplings

  - The electrocouplings are the only source of information on many facets of the non-perturbative strong interaction in the generation of different N* states



N* Electrocouplings from CLAS

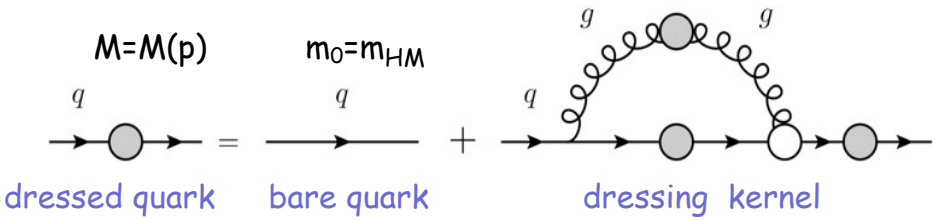




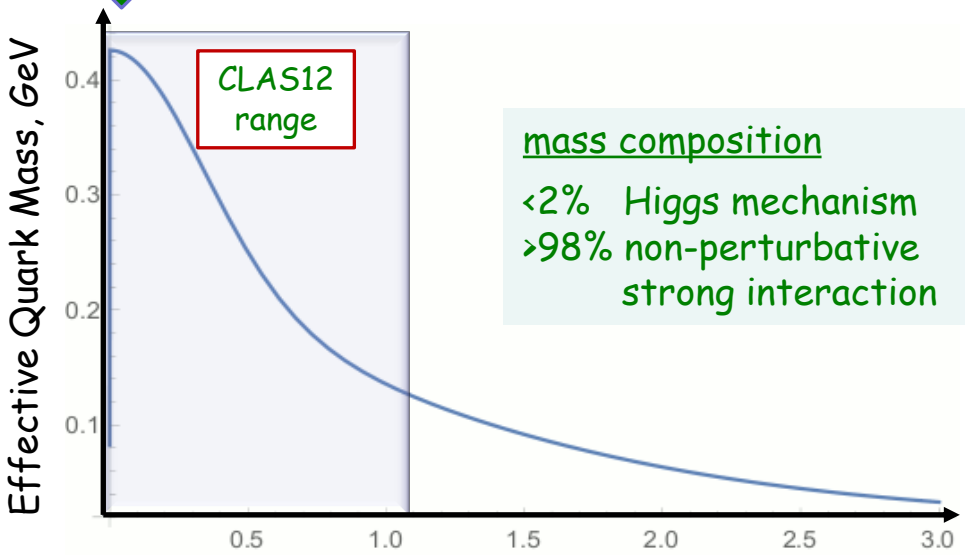
- Electrocouplings reveal different interplay between meson cloud and quark core:
  - Good agreement of the extracted N* electrocouplings from Nπ and Nππ:
    - Compelling evidence for the reliability of the results
    - Channels have very different mechanisms for the non-resonant background
    - KY channels hold promise to enable comparisons to Nππ for higher-lying states where Nπ coupling is small
- Data on the electrocouplings over broad range of Q^2 are needed in order to:
  - Map out the transition from meson-baryon to confined quark degrees of freedom
  - Gain insight into the dressed quark mass function at distances where the quark core contribution is largest

Emergence of Hadron Mass

Effective quark mass depends on its momentum



confinement regime:
- constituent quark mass



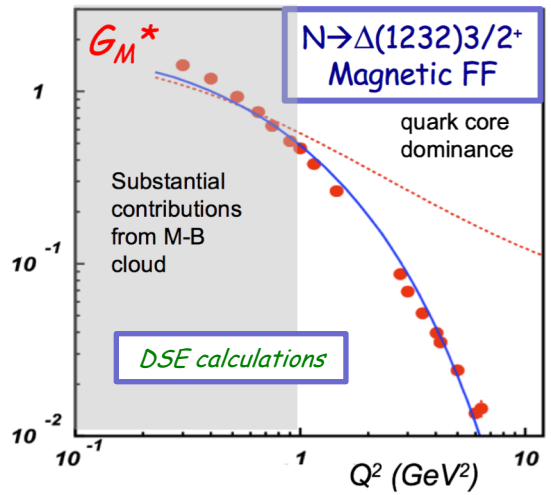
mass composition

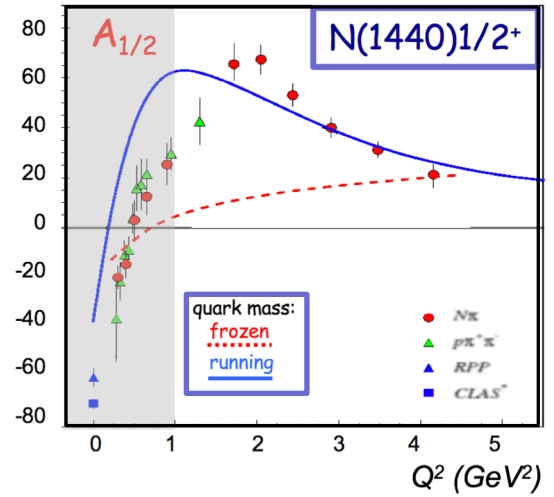
<2% Higgs mechanism
>98% non-perturbative strong interaction

approaching bare Higgs mechanism mass

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

J. Segovia, PRL 115, 171801 (2015)





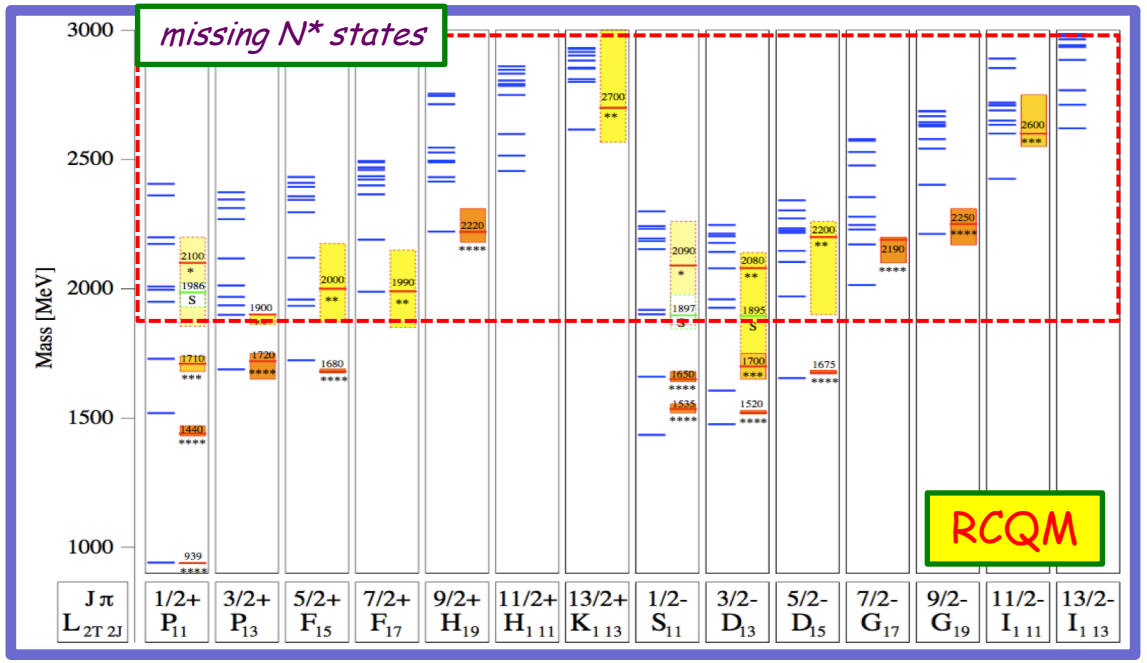
CLAS results vs. QCD expectations with running quark mass

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	KΛ	KΣ	γN
N(1710)1/2+	***	****	****	**	*	****
N(1875)3/2-		***	**	*	*	**
N(1880)1/2+		***	*	**	**	**
N(1895)1/2-		****	*	**	**	****
N(1900)3/2+	**	****	**	**	**	****
N(2000)5/2+	*	**	*			**
N(2060)5/2-		***	**	*	*	***
N(2100)1/2+	*	***	***	*		**
N(2120)3/2-		***	**	**	*	***
Δ(1600)3/2+	***	****	***			****
Δ(1900)1/2-	**	***	***		**	***
Δ(2200)7/2-	*	***	**		**	***



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

Recent LQCD predictions support CQM

Dudek, Edwards, PRD 85, 054016 (2012)

Decisive impact from CLAS KY photoproduction data - Extend studies to KY 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

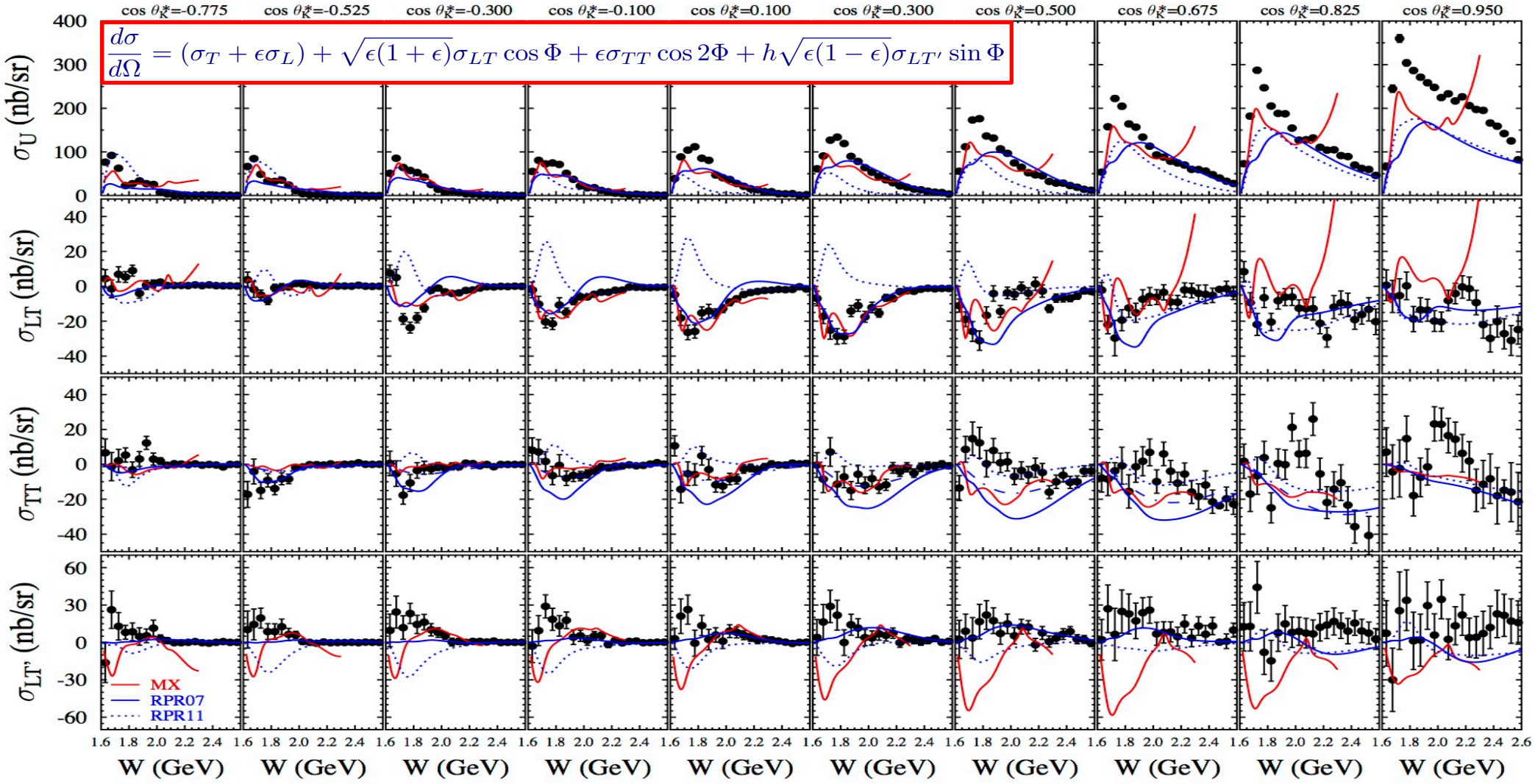
Publications (Polarization):

- $K^+\Lambda$, $K^+\Sigma^0$ beam-recoil polarization transfer
  - W=1.6-2.15 GeV, Q^2=0.3 – 1.5 GeV^2
    D.S. Carman et al., PRL 90, 131804 (2003)
  - W=thr-2.6 GeV, Q^2=1.6-2.6 GeV^2
    D.S. 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
    M. Gabrielyan et al., PRC 90, 035202 (2014)

Publications (Cross Section):

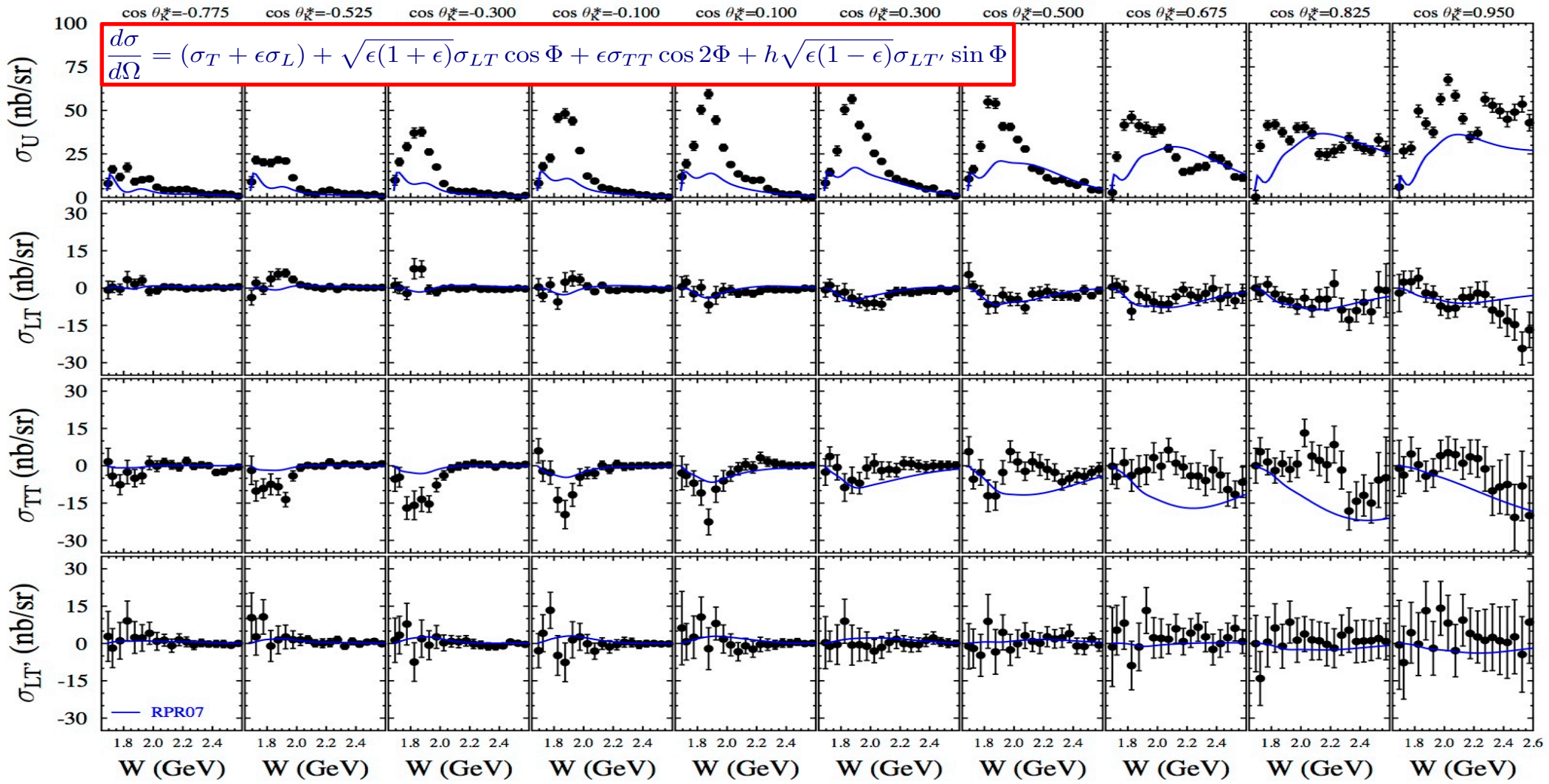
- $K^+\Lambda$, $K^+\Sigma^0$ cross sections & structure functions
  - $d\sigma/d\Omega$, σ_U, σ_{LT}, σ_{TT}, σ_L, σ_T
    - W=thr-2.4 GeV, Q^2=0.5-2.8 GeV^2
    P. Ambrozewicz et al., PRC 75, 045203 (2007)
  - $d\sigma/d\Omega$, σ_U, σ_{LT}, σ_{TT}, $\sigma_{LT'}$
    - W=thr-2.6 GeV, Q^2=1.4-3.9 GeV^2
    D.S. 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
  B.A. Raue & D.S. 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
  R. Nasseripour et al., PRC 77, 065208 (2008)

$K^+\Lambda$ Structure Functions



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

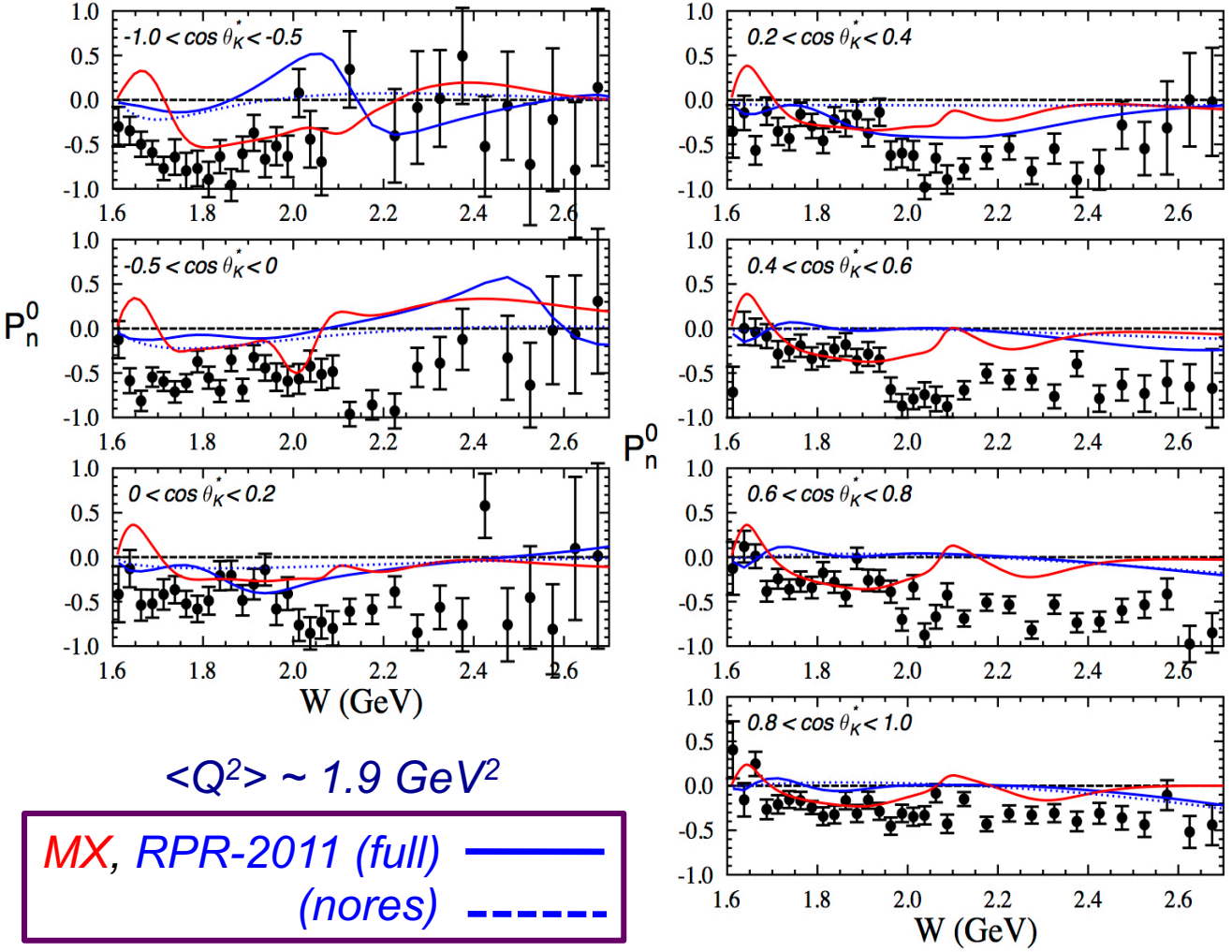
$K^+\Sigma^0$ Structure Functions



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

$K^+\Lambda$ Polarization Observables

Recoil Polarization

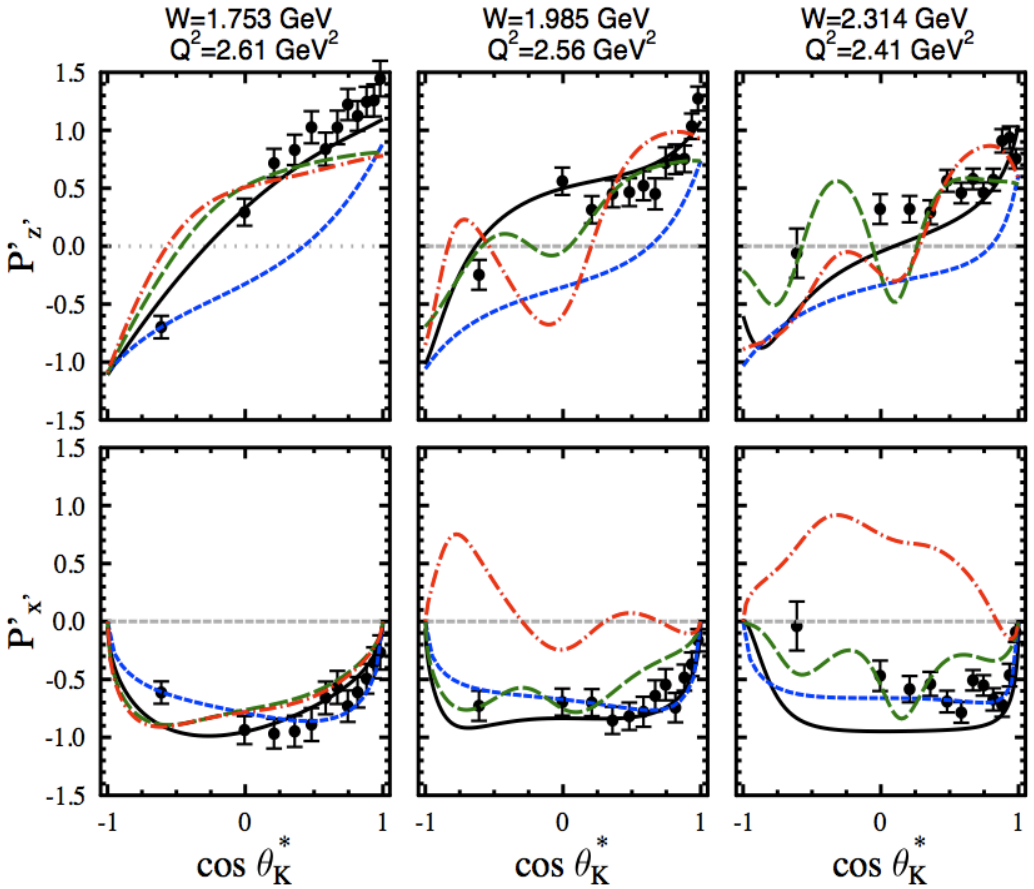


<Q^2> ~ 1.9 GeV^2

MX, RPR-2011 (full) ——
(nores) ------

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

Beam-Recoil Transferred Polarization



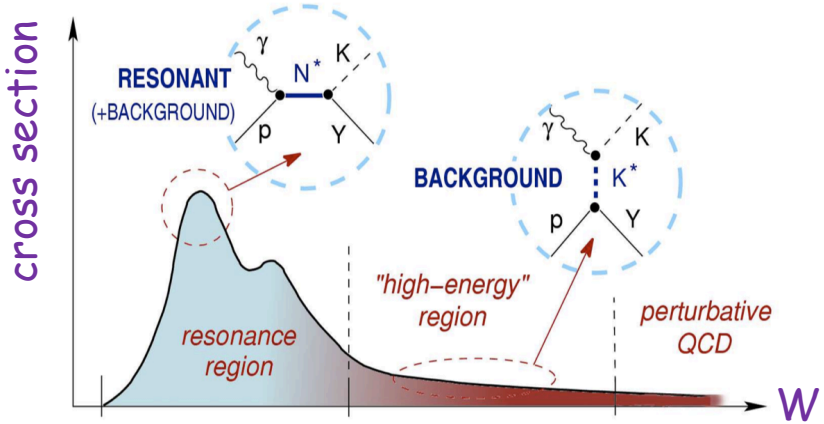
Isobar Model - Mart
Regge Model - GLV
RPR07 w $P_{11}(1900)$ - Ghent
RPR07 w $D_{13}(1900)$ - Ghent

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

KY Reaction Models

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 $\gamma_v pN^*$ electrocouplings from the existing lower Q^2 CLAS data and the planned higher Q^2 CLAS12 data



Single Meson Analysis:

- 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 Analysis:

- Bonn-Gatchina multi-channel PWA
- Jülich-Bonn-GWU coupled-channel framework
- Argonne-Osaka dynamically coupled-channel model

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

Such a model must incorporate the $\gamma_v pN^*$ electrocouplings from the available CLAS results for W < 1.8 GeV and estimates for the excited states in the mass range up to 3 GeV

- Need to allow for possibility to:
  a) Vary resonant/non-resonant parameters
  b) Implement additional phenomenological terms to fit to the data
  c) Simultaneously fit the γp and $\gamma^* p$ data

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

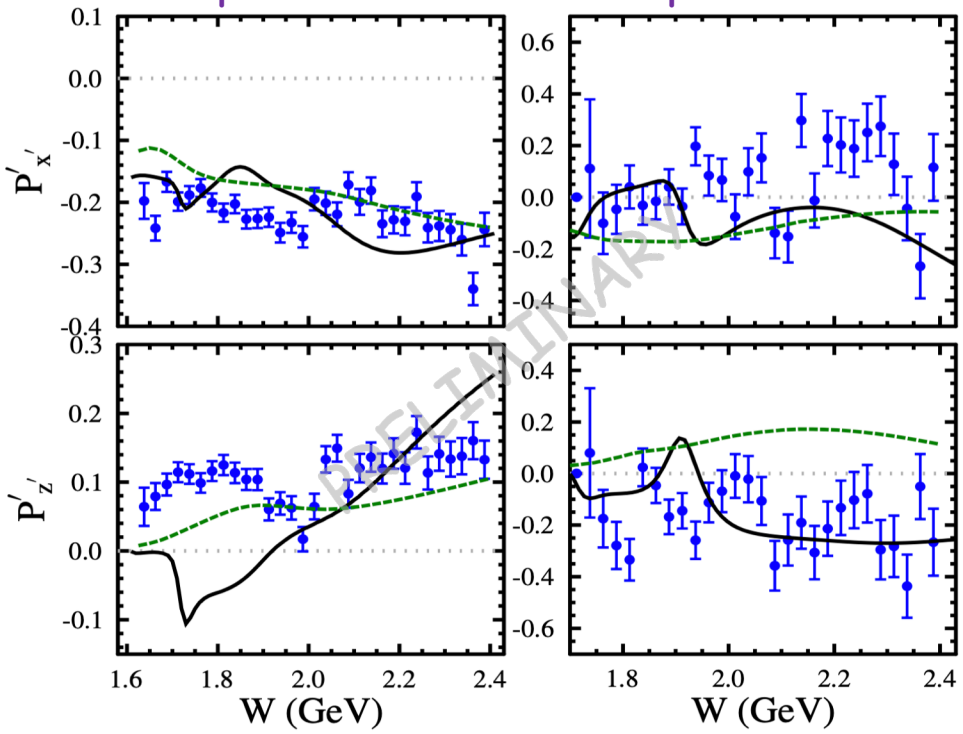
RG-A	Spr. 18 126 mC	10.4 GeV, 10.6 GeV 50% of total
	Fall 18 99 mC	
	Spr. 19 58 mC	
RG-K	Fall 18 28 mC	6.5 GeV, 7.5 GeV 10% of total

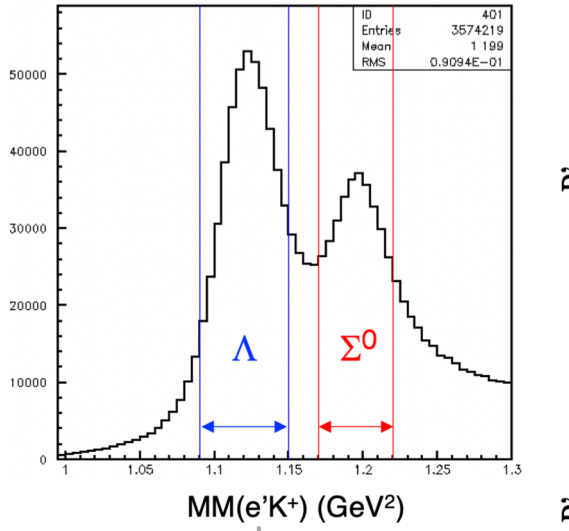
1. Study higher-lying N* states:
   - confirm signals of new baryon states observed in $\gamma p \rightarrow KY$ with data of comparable statistical precision
   - search for predicted qqqg hybrid baryons
2. Understand effect of meson cloud on N* structure:
   - use transition regime to explore emergence 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

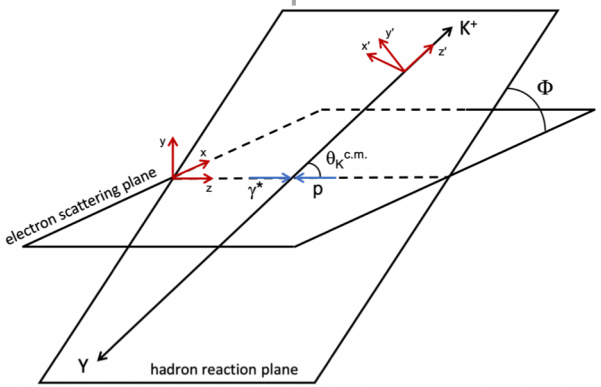
CLAS12 Transferred Polarization $\vec{e}p \rightarrow e'K^+\vec{Y}$

CLAS12 RG-K @ 6.535 GeV

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

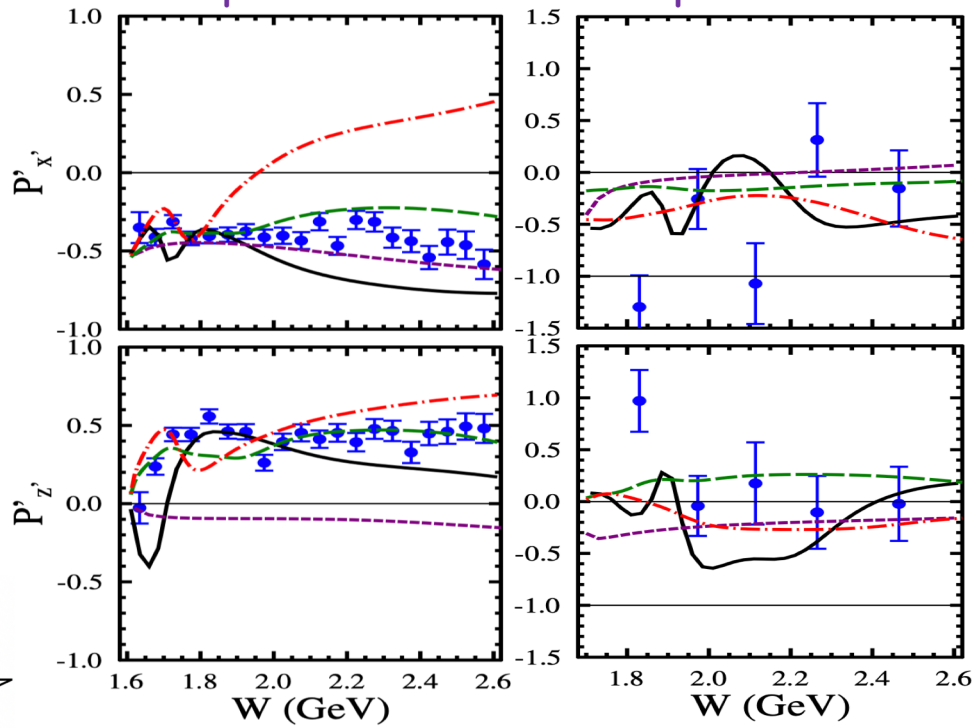






CLAS e1-6 @ 5.754 GeV

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



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

KAON-MAID
RPR

Under CLAS12 analysis review

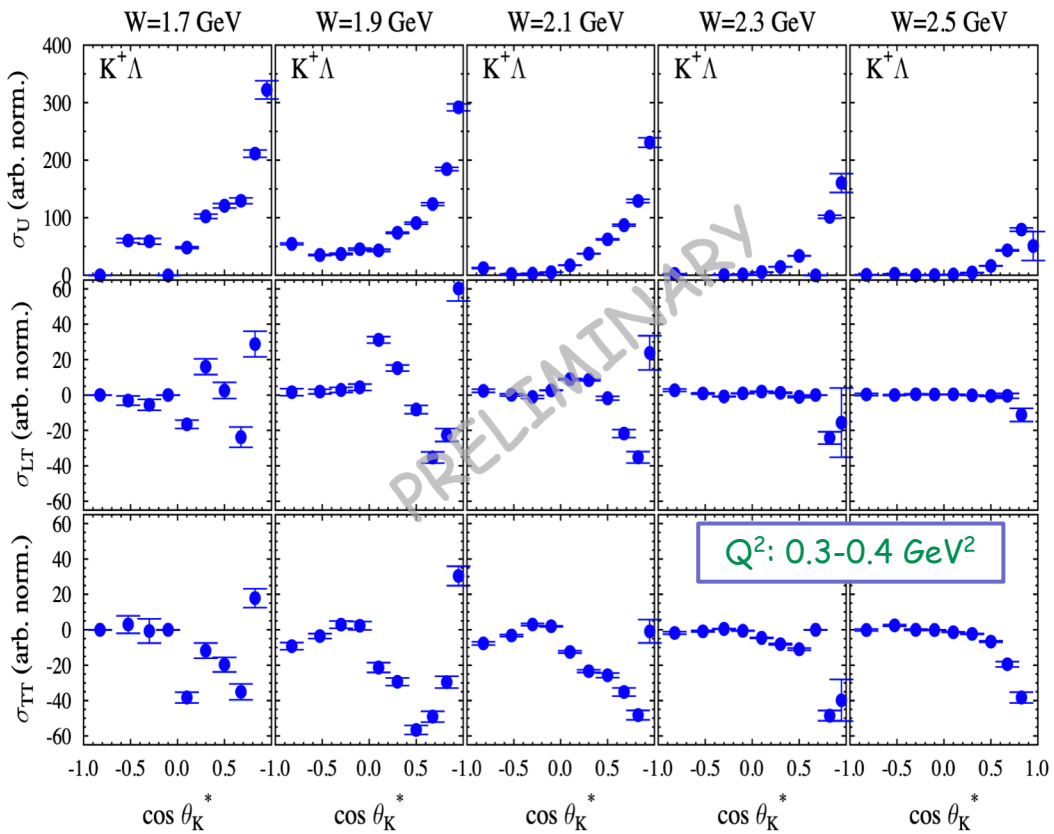
Mart/Bennhold RPR-2
RPR-1 Regge

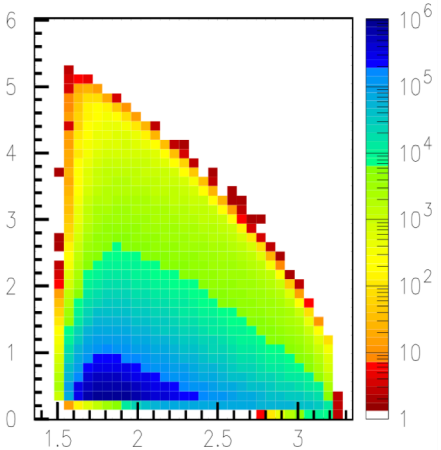
CLAS12 KY Cross Section Measurements

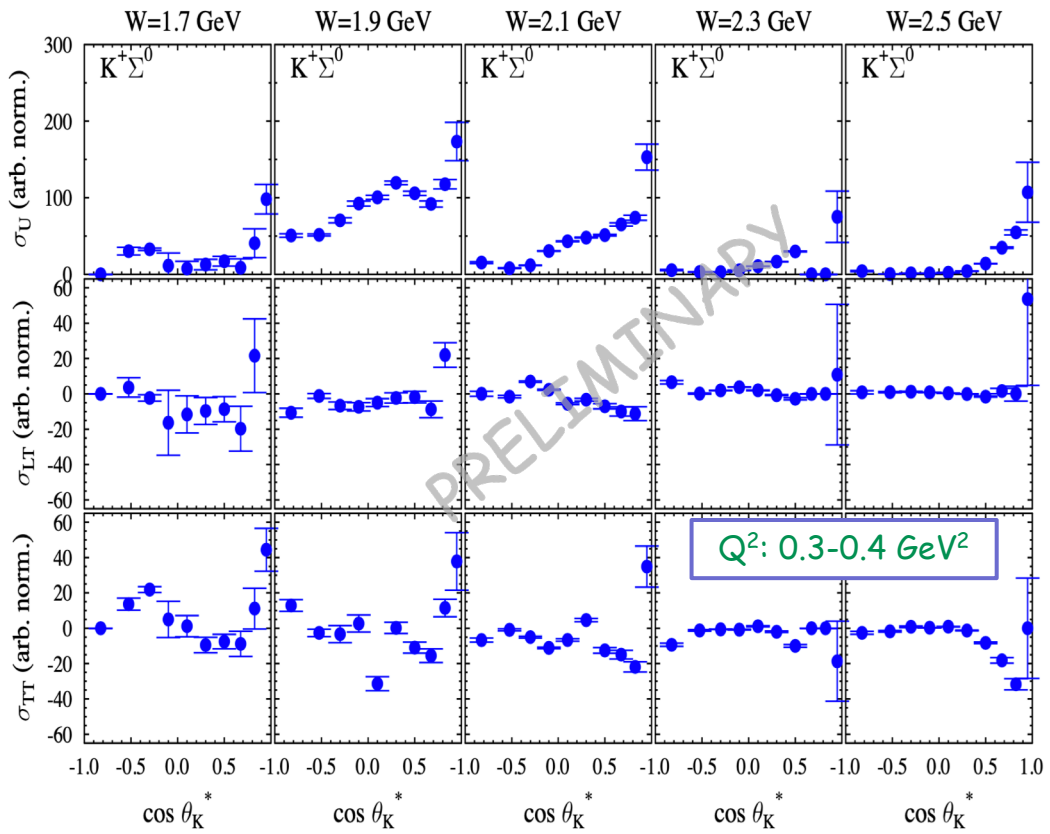
$ep \rightarrow e'K^+\Lambda$

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

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





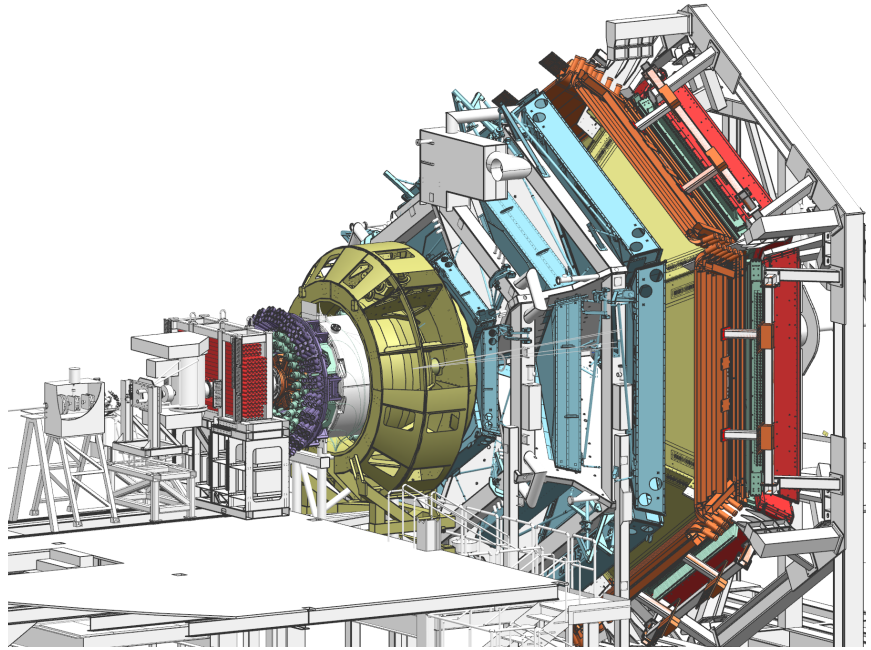


6.535 GeV RG-K

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

CLAS12 N* Analysis - Near-Term Plans

- KY Phase 1: (next 12 months)
  - Beam-recoil transferred polarization
    - Publication submitted by the end of the year *(now under CLAS review)*
  - 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* program:

- Active analyses on inclusive (e,e') cross sections and $\pi^+ n$, $\pi^0 p$, $\pi^+\pi^- p$ BSAs and differential cross sections

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 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