Hall B - Run Group K
Color Confinement and Strong QCD
Exclusive Channels Analysis Update

Search for Hybrid Baryons

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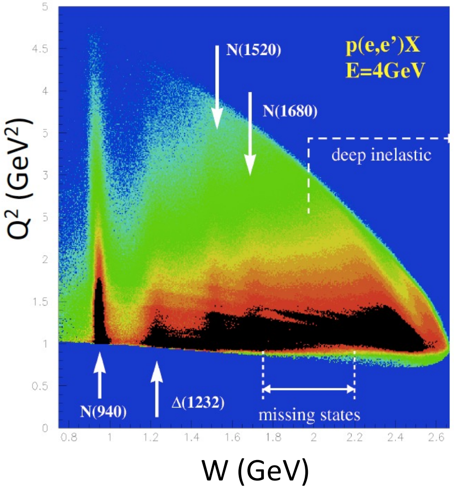
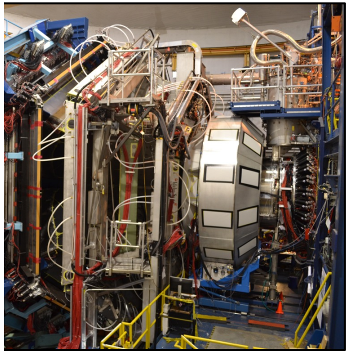




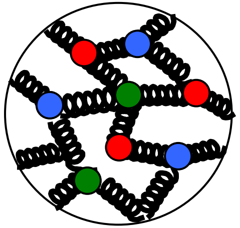
Outline:

- Physics case: N* resonances and search for hybrid baryons
- RG-K data
- Results on KY electroproduction
- Results on η electroproduction
- Summary

Critical QCD Questions Addressed

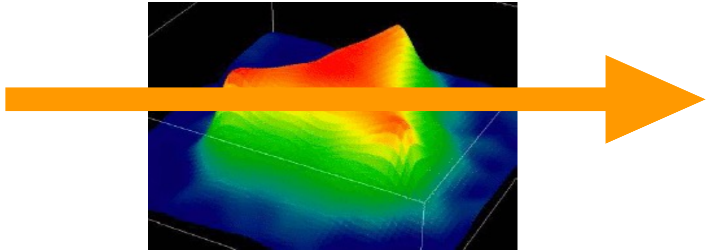
1. **What is the nature of the mass of hadrons?**
   Quarks accounts only for a small fraction of the mass of the proton (m_u=1.7-3.3 MeV, m_d=4.1-5.8 MeV): what leads to the ~GeV mass??
2. **What are the relevant degrees of freedom?**
   At high energy, phenomena can be described in terms of quark and gluons; at low energy, we observed baryons and meson: what are the real degrees of freedom and how the transition from small to large distances occurs??
3. **What is the origin of confinement?**
   Are quarks confined within colorless objects? Can we prove and explain it?
4. **Do quark configuration beyond qqq and $q\bar{q}$ exist?**
   The theory of strong interactions does not prohibit hadronic states with different quark configurations (4q, gg, 2qg). Can we find evidence of the existence of such states?

<< 0.1 fm



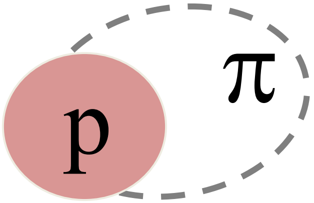
Quarks and Gluons

0.1 – 1 fm



Effective Degrees of Freedom

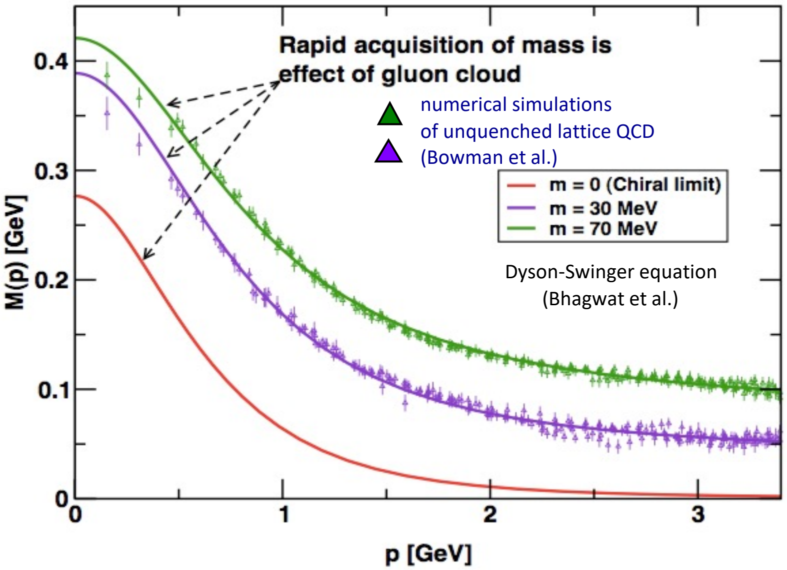
> 1 fm



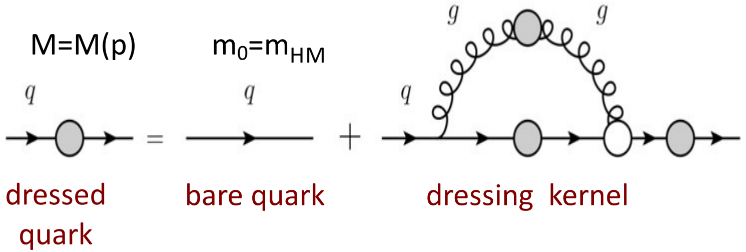
Mesons & Baryons

Critical QCD Questions Addressed

- How do massless quarks acquire mass?



Effective quark mass depends on its momentum



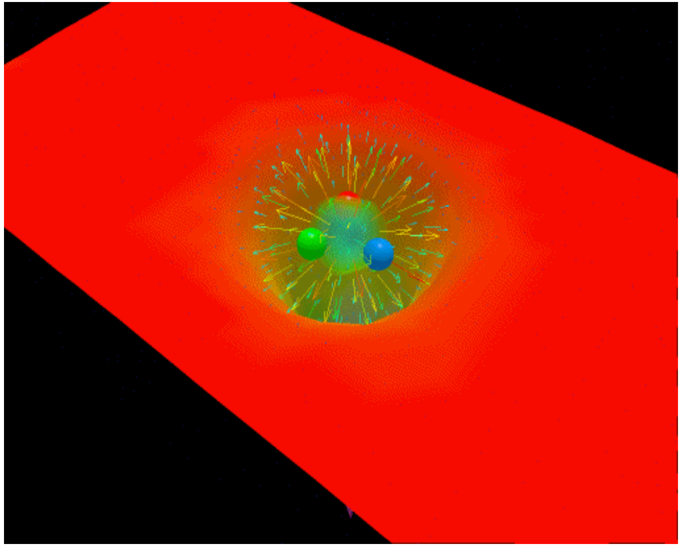
<u>mass composition</u>

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

→ **Measure the Q^2 dependence of electrocoupling amplitudes**

Baryon Spectroscopy

- The light N* spectrum: what is the role of glue?



Derek B. Leinweber – University of Adelaide

“Nucleons are the stuff of which our world is made.

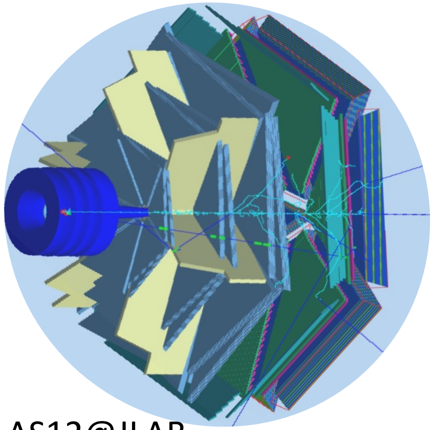
*As such they must be **at the center of any discussion of why the world** we actually experience **has the character it does.**”*

Nathan Isgur, NStar2000, Newport News, Virginia

→ **Search for new baryon states**

N* Program Overview

The N* program is one of the key physics foundations of CLAS and CLAS12



CLAS12@JLAB

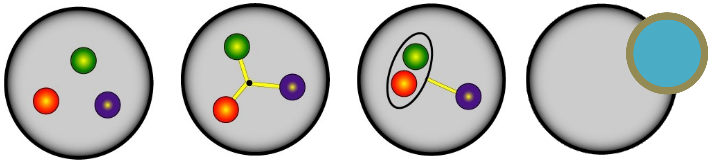
Detectors have been designed to measure cross sections and spin observables over a broad kinematic range for exclusive reaction channels:

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

- N* parameters do not depend on how they decay
- Different final states have different hadronic decay parameters and different backgrounds
- Agreement offers model-independent support for findings

- The program goal is to probe the *spectrum* of N* states and their *structure*
  - Probe the underlying degrees of freedom of the nucleon through studies of photoproduction and the Q^2 evolution of the electro-production amplitudes.

N* degrees of freedom??

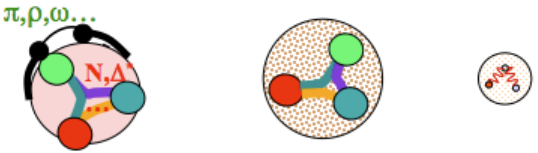


Excited Nucleon Structure

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

  - Low Q^2: *(Q^2 < 5 GeV^2)* — structure well described by adding an external meson cloud to inner quark core

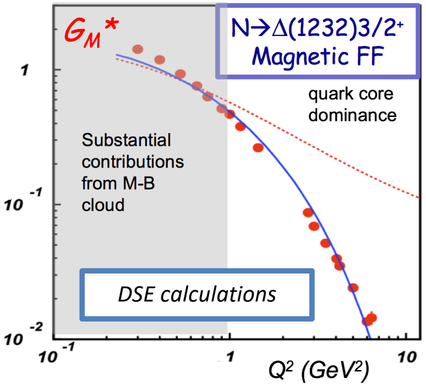
  - High Q^2: *(Q^2 > 5 GeV^2)* — quark core dominates; transition from confinement to pQCD regime

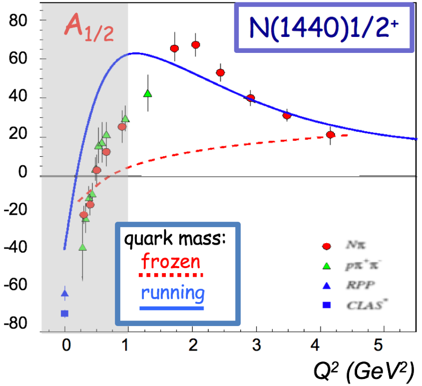


3q core + meson cloud 3q core pQCD

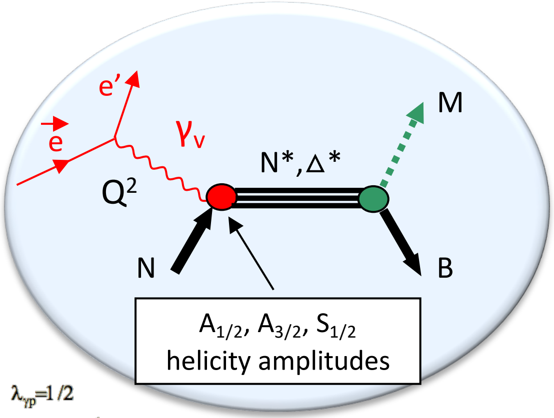
low Q^2 ⟶ high Q^2

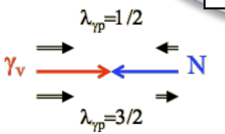
- **Calculations of form factors and electrocoupling amplitudes are sensitive to the underlying quark mass distribution**





CLAS results vs. QCD expectations with running quark mass

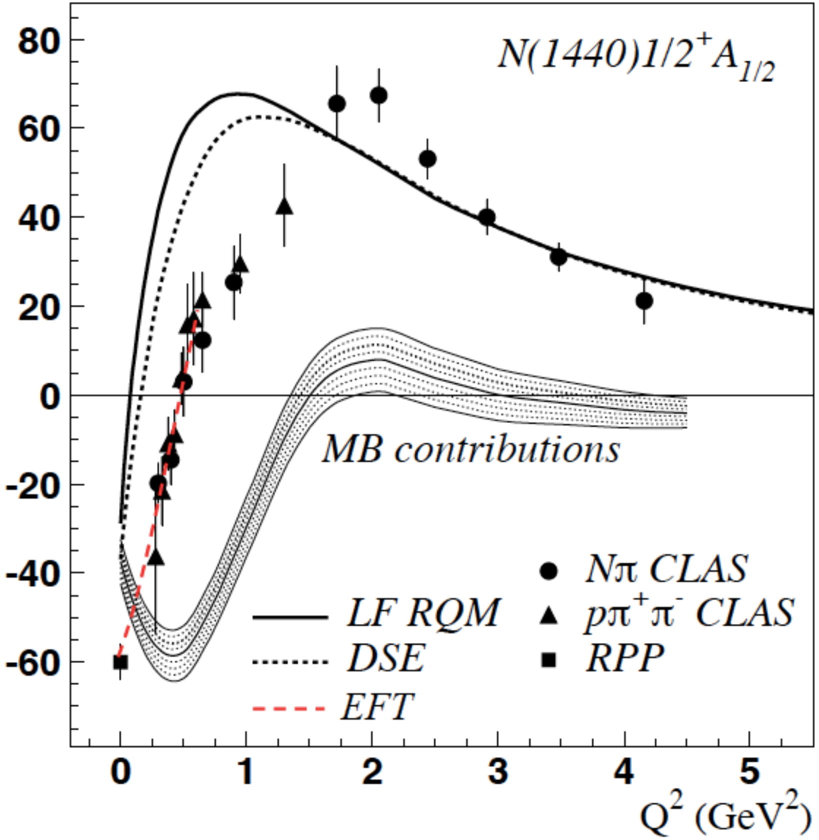




$A_{1/2}$, $A_{3/2}$ – transverse

$S_{1/2}$ - longitudinal

Roper - 1st nucleon radial excitation?



V.B., C. Roberts, Rev.Mod.Phys. 91 (2019) no.1, 011003

***LF RQM**: I. Aznauryan, V.B. arXiv:1603.06692*
***DSE**: J. Segovia, C.D. Roberts et al., PRC94 (2016) 042201*
***EFT**: T. Bauer, S. Scherer, L. Tiator, PRC90 (2014) 015201*

➔ Non-quark contributions are significant at $Q^2 < 2.0$ GeV^2. The behavior at $Q^2 < 0.5$ can be modeled in EFT.

➔ The 1st radial excitation of the q^3 core emerges as the probe penetrates the MB cloud

"Nature" of the Roper – is consistent with the 1st radial excitation of its quark core surrounded by a meson-baryon "cloud".

Hybrid Hadrons: Hadrons with Explicit Gluonic Degrees of Freedom

Hybrid hadrons with dominant gluonic contributions are predicted to exist by QCD.

Experimentally:

- **Hybrid mesons** $|q\bar{q}g\rangle$ states may have exotic quantum numbers J^{PC} not available to pure $|q\bar{q}\rangle$ states GlueX, MesonEx, COMPASS, PANDA ….
- **Hybrid baryons** $|qqqg\rangle$ have the same quantum numbers J^P as $|qqq\rangle$ electroproduction with CLAS12 (Hall B).

Theoretical predictions:

✧ MIT bag model - T. Barnes and F. Close, Phys. Lett. 123B, 89 (1983).

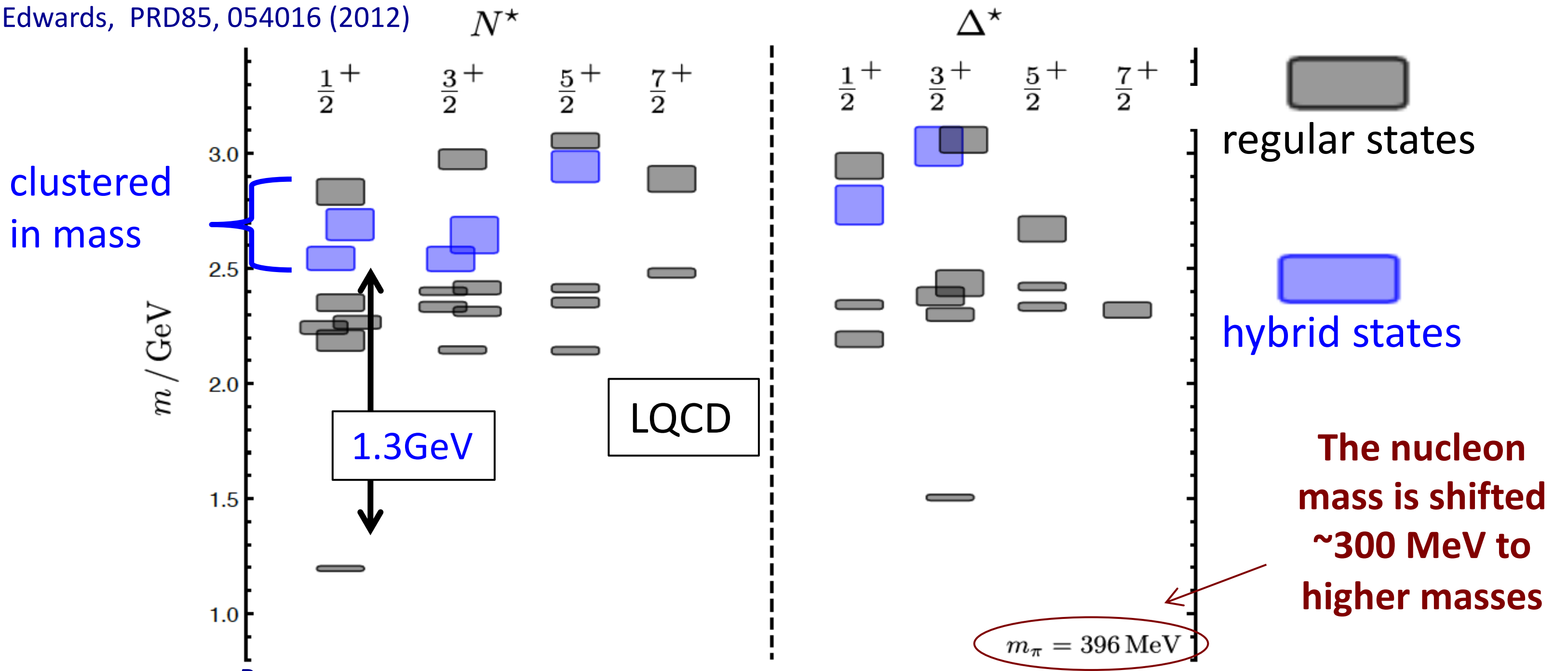
✧ QCD Sum Rule - L. Kisslinger and Z. Li, Phys. Rev. D 51, R5986 (1995).

✧ Flux Tube model - S. Capstick and P. R. Page, Phys. Rev. C 66, 065204 (2002).

✧ LQCD - J.J. Dudek and R.G. Edwards, PRD85, 054016 (2012).

Hybrid Baryons in LQCD

J.J. Dudek and R.G. Edwards, PRD85, 054016 (2012)



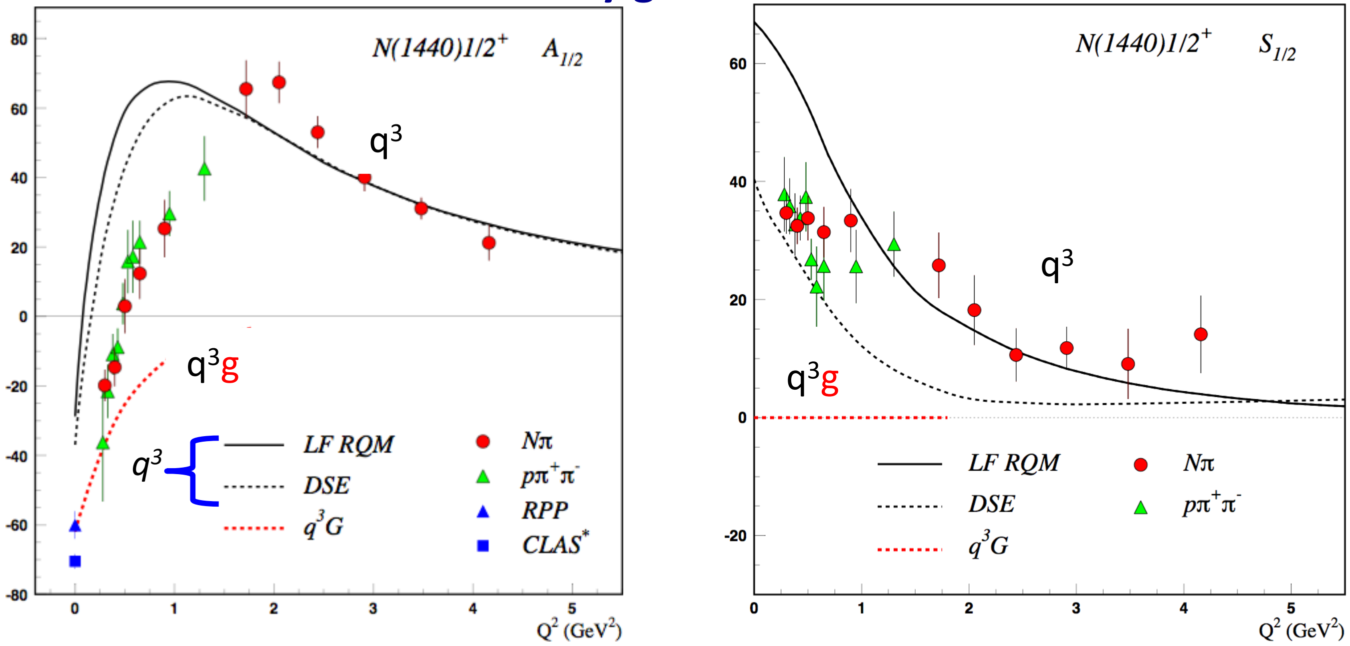
Hybrid states have same J^P values as qqq baryons. How to identify them?

- Overpopulation of N $1/2^+$ and N $3/2^+$ states compared to QM projections.
- **$A_{1/2}$ ($A_{3/2}$) and $S_{1/2}$ show different Q^2 evolution.**

Separating q^3g from q^3 states ?

CLAS results on electrocouplings clarified nature of the Roper.

Will CLAS12 data be able to identify gluonic contributions ?



For hybrid "Roper", $A_{1/2}(Q^2)$ drops off faster with Q^2 and $S_{1/2}(Q^2) \sim 0$.

Hybrid Baryon Signatures

Based on available knowledge, the ***signatures*** for hybrid baryons consist of***:***

• **Extra resonances** with $J^p=1/2^+$ and $J^p=3/2^+$, with masses > 1.8 GeV and decays into $N\pi\pi$ or KY final states.

•A **drop** of the transverse helicity amplitudes $A_{1/2}(Q^2)$ and $A_{3/2}(Q^2)$ faster than for ordinary three quark states, because of extra glue-component in valence structure.

•A **suppressed** longitudinal amplitude $S_{1/2}(Q^2)$ in comparison with transverse electro-excitation amplitude ($J^P=1/2^+$).

The RG-K proposal focused on: $e\ p \rightarrow e\ K^+\Lambda$, $e\ K^+\Sigma^0$

The study also includes other single meson channels (πp, ηp, KY…) and $\pi\pi p$.

CLAS12 – RG-K 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, 7.5, 8.8 Q^2 = 0.05 → 6 GeV^2, W → 3.0 GeV, $\cos\theta_m^*$ = [-1:1]

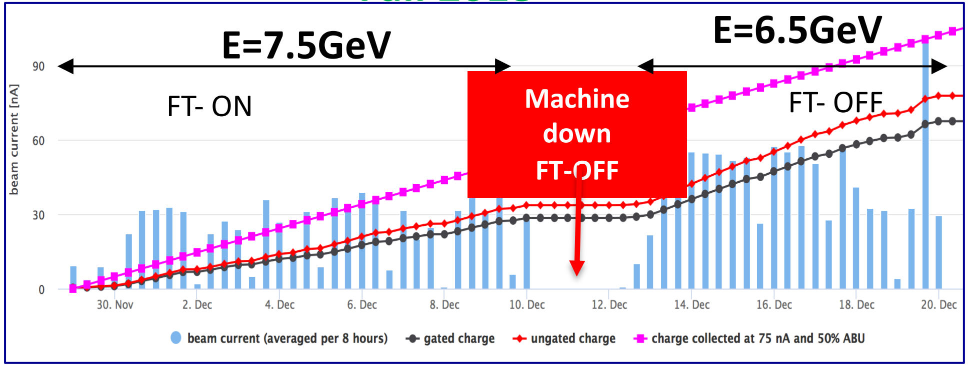
E12-16-010	**A Search for Hybrid Baryons in Hall B with CLAS12**
E12-16-010A	N* Studies Via KY Electroproduction at 6.6 and 8.8 GeV

By Dan Carman

1. Study higher-lying N* states:
   - confirm signals of new baryon states observed in $\gamma p \to KY$
   - 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

Run Group K Production

Fall 2018

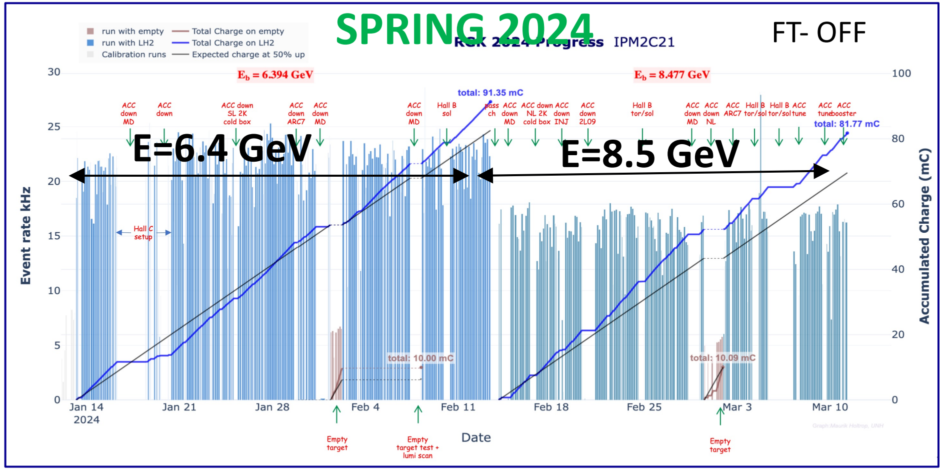


45mC of accumulated charge

Fall 2018		
Beam Energy	Beam Current	Collected Events
7.5 GeV	35 nA	3.5 G
7.5 GeV	45 nA	4.3 G
6.5 GeV	60 nA	7.8 G

EVENTS
15.6 G

SPRING 2024



193mC of accumulated charge

Spring 2024		
Beam Energy	Beam Current	Collected Events
6.4 GeV	65 nA	38.3 G
8.5 GeV	75 nA	21.7 G

EVENTS
60 G

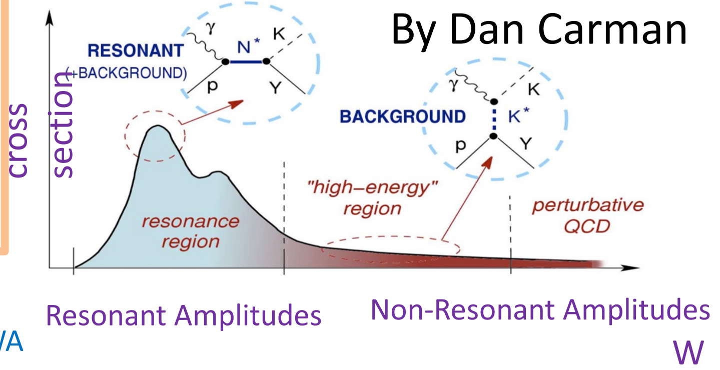
Fall 2018 → **SPRING 2024**

X4 more statistics: 50% of total assigned

KY Reaction Models

- A model that describes the KY data is necessary to extract the $g_v pN^*$ 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

By Dan Carman



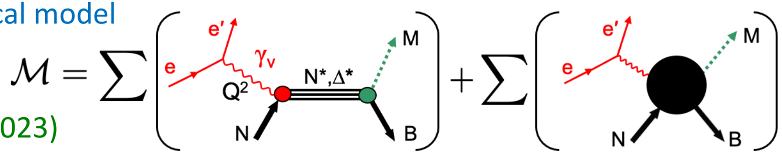
Single Channel:

- 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

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)

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

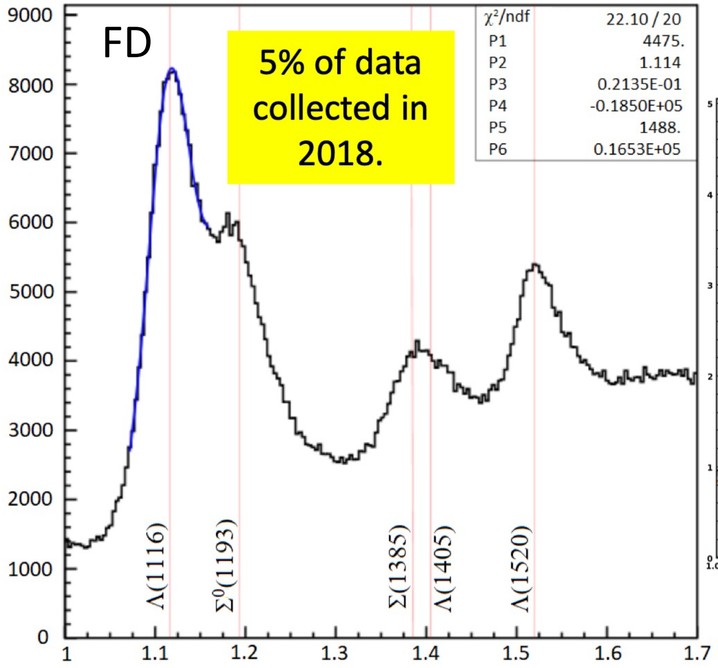
$$\sigma^r_{L,T}(W,Q^2) = \frac{\pi}{q_\gamma^2} \sum_{N^*,\Delta^*} (2J_r+1) \frac{M_r^2 \Gamma_{tot}(W) \Gamma_\gamma^{L,T}(M_r)}{(M_r^2 - W^2)^2 + M_r^2 \Gamma_{tot}^2(W)} \frac{q_\gamma}{K}$$

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

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

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

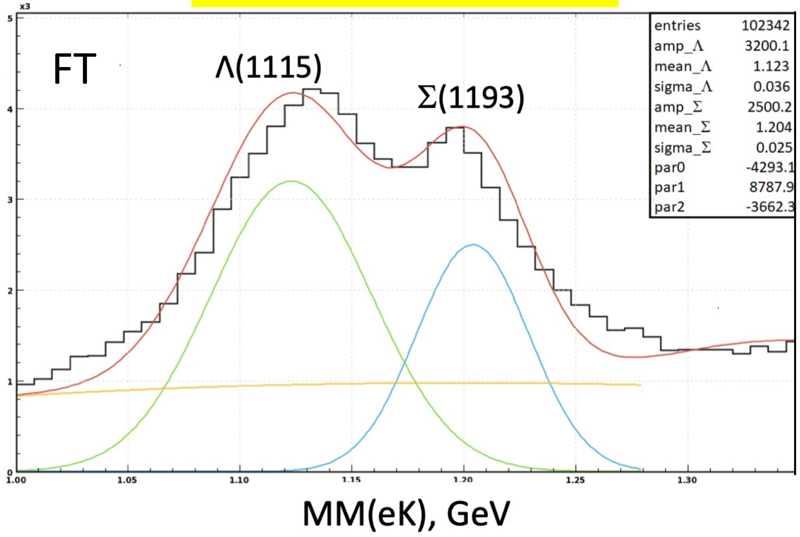
KY Events selection: electron in the FD(CLAS)/FT



1.6 GeV < W < 3 GeV

Courtesy of D. Carman

Exclusive Kinematics



Preliminary results obtained with data collected in 2018

p(e,e'K⁺)X E_{beam} = 7.546 GeV

Pseudoscalar Meson Electroproduction Formalism

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

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

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

By Dan Carman

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

Response functions

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

CLAS/CLAS12 KY Program

- Differential cross sections
  - $\sigma_L, \sigma_T, \sigma_{LT}, \sigma_{TT}, \sigma_{LT'}$
- KY recoil polarization
- KY transferred polarization

KY Polarization Formalism

RG-K Fall 2018 pass1 data

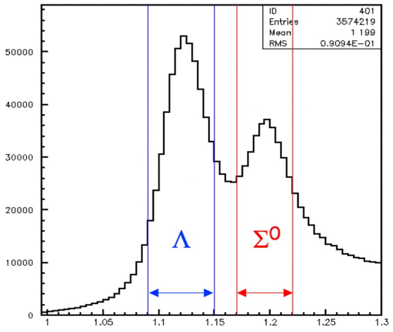
By Dan Carman

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

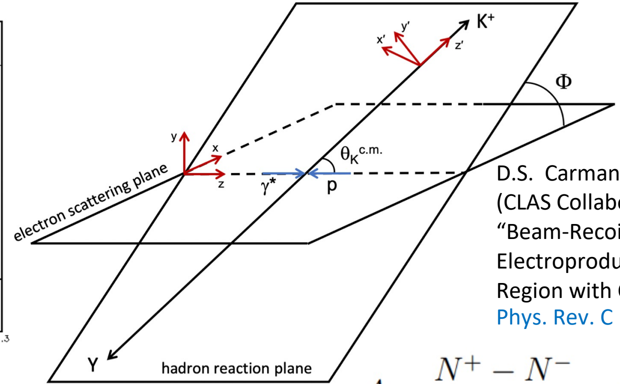
$\mathcal{P}'$ = transferred polarization

ep → e'K⁺Y

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



CLAS12 @ 6.5 GeV MM(e'K⁺) (GeV)



D.S. Carman, A. D'Angelo, L. Lanza V. Mokeev (CLAS Collaboration)
"Beam-Recoil Transferred Polarization in K+Y Electroproduction in the Nucleon Resonance Region with CLAS12"
Phys. Rev. C 105, 065201 (2022)

$$A = \frac{N^+ - N^-}{N^+ + N^-} = \nu_Y \alpha_\Lambda P_b \mathcal{P}'_Y \cos\theta_p^{RF}$$

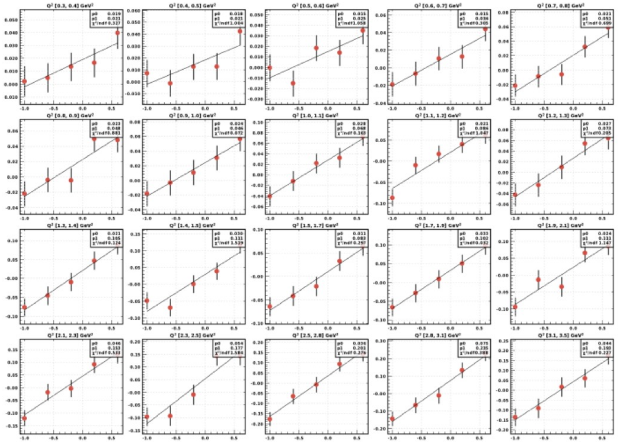
Beam-Recoil Transferred Polarization in K^+Y Electroproduction

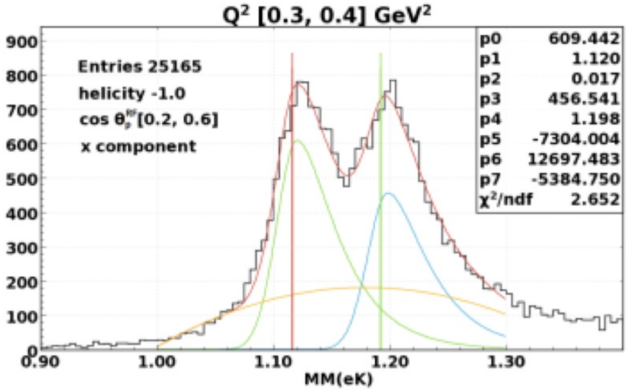
By Lucilla Lanza

The **independent analysis** consists of the direct exploitation of equation

$$A = \frac{N^+ - N^-}{N^+ + N^-} = \nu_Y \alpha_\Lambda P_b \mathcal{P}'_Y \cos\theta_p^{RF}$$

The events in each kinematic bin of Q², W and cos ϑ_K^* were divided into 5 cos ϑ_p^{RF} bins for each beam helicity…

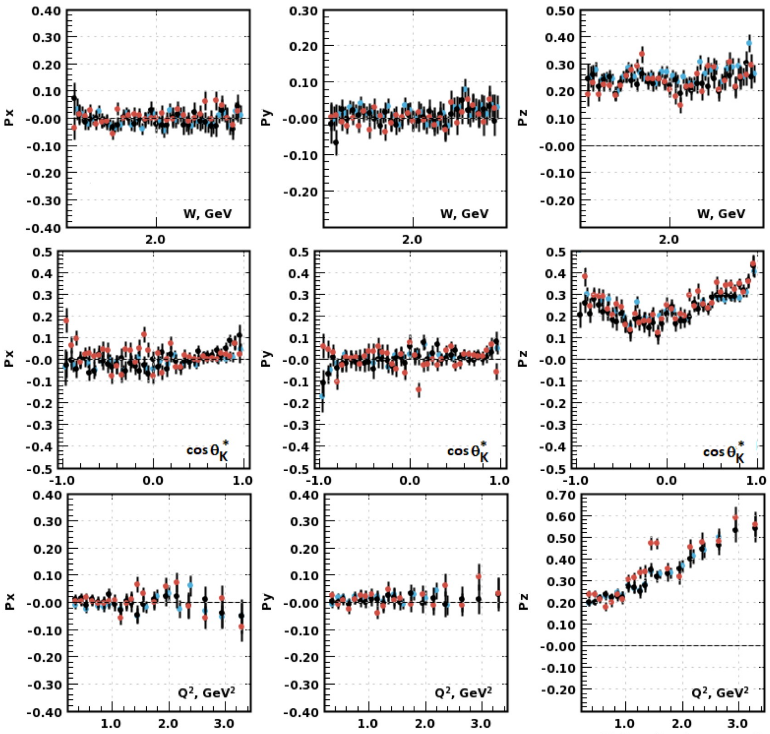




… and the number of Λ events was extracted using a fit of the MM(eK⁺) spectrum

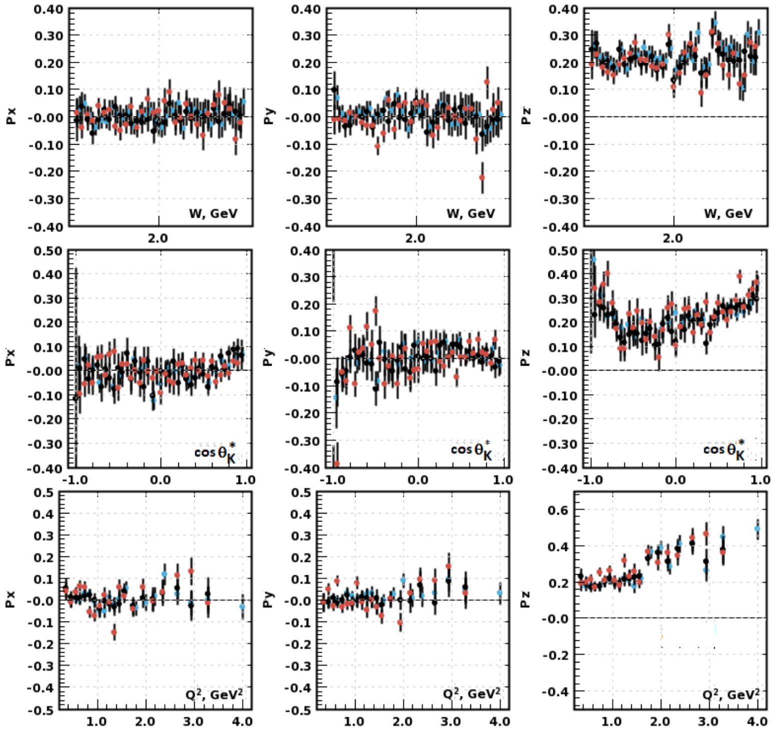
Beam-Recoil Transferred Polarization in K^+Y Electroproduction

$\mathcal{P}'$



6.5 GeV

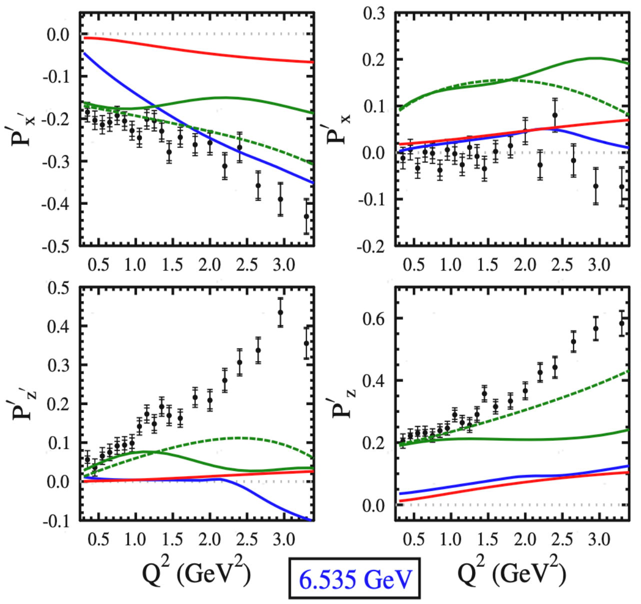
By Dan Carman and Lucilla Lanza

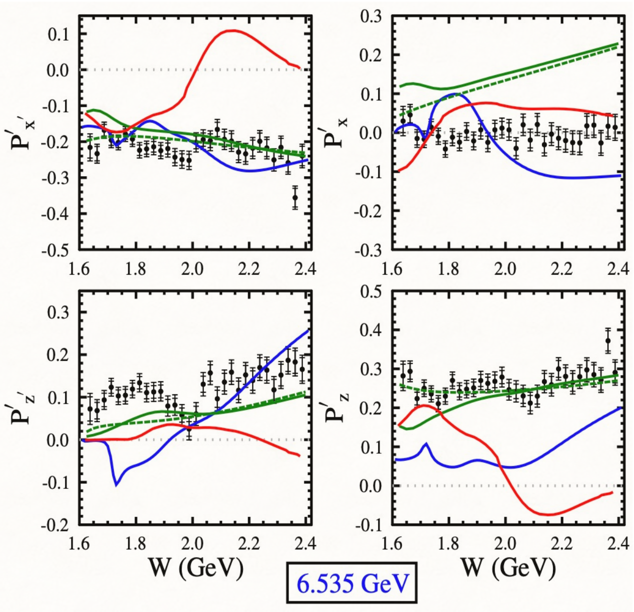


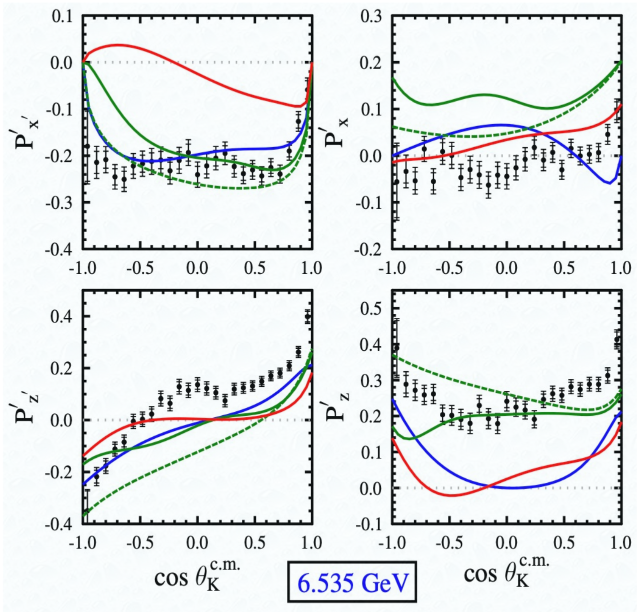
7.5 GeV

Blue dots : Approach 1
Red dots : Approach 2
Black dots : Approach 1 (different fitting procedure)

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

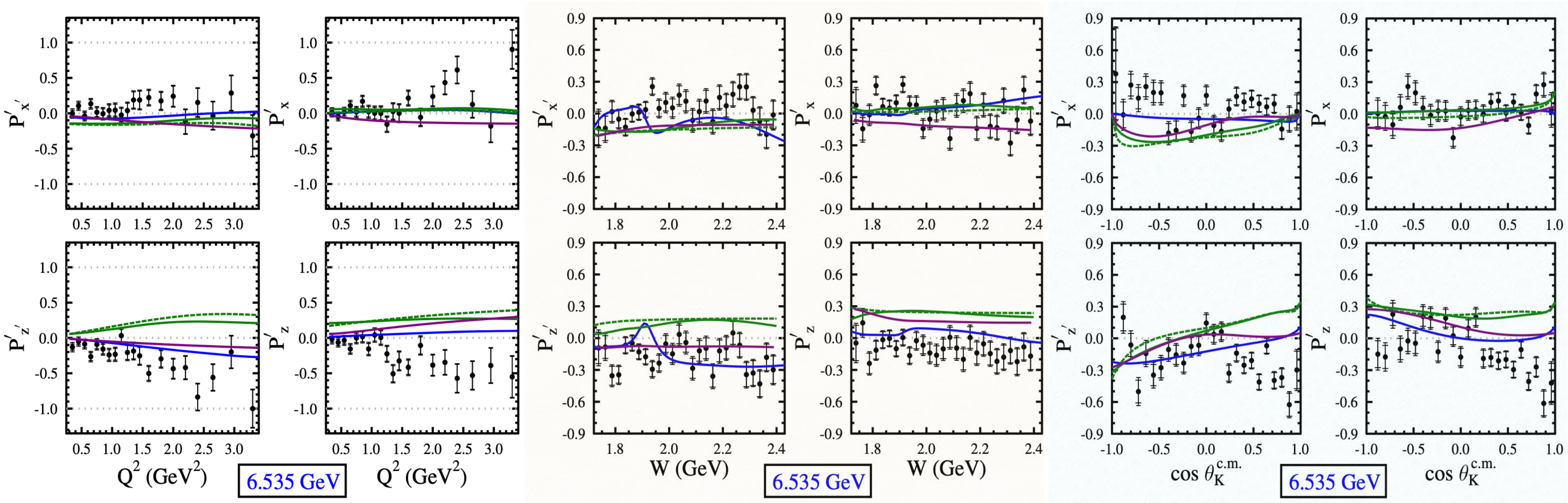
D.S. Carman et al. (CLAS12), PRC 105, 065201 (2022)

Development of reaction models in progress:

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

By Dan Carman

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. (CLAS12), PRC 105, 065201 (2022)

$K^+\Sigma^0$ final state has sensitivity to both N* andΔ* resonances ⇒ more isospin states 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 $\cos\theta_K^{c.m.} = 1, \quad R^{z'0}_{TT'} = R^{00}_T$

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

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

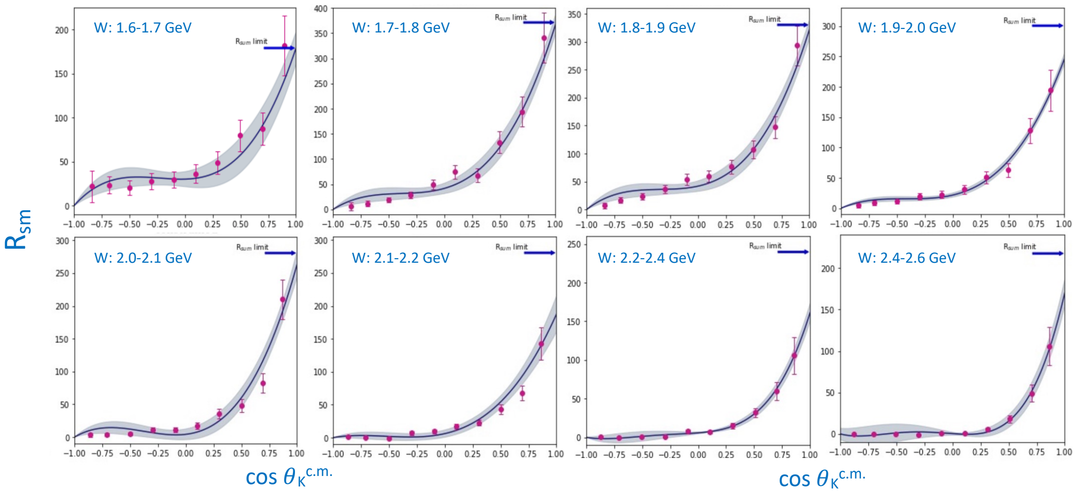
Define: $$\mathrm{R}_{\mathrm{sum}} = \frac{(\mathcal{P}'_{z'} + \mathcal{P}'_z)\sigma_U}{c_0}$$

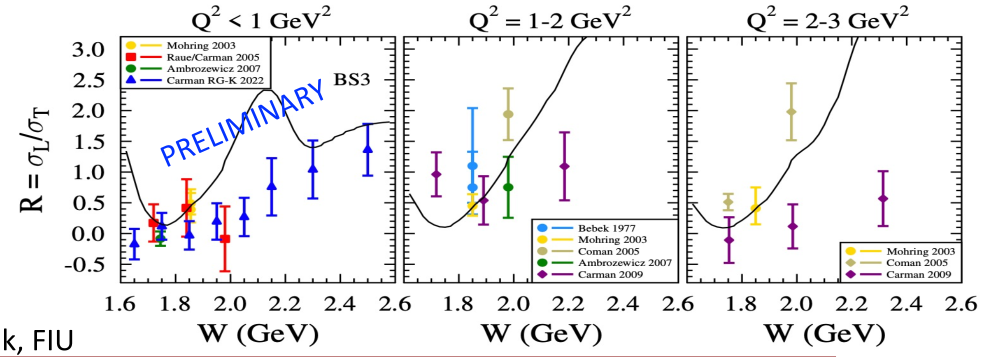
Extrapolate R_{sum} to $\theta_K^{c.m.} = 0°$ to extract R vs. W

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

B.A. Raue and D.S. Carman, PRC 71, 065209 (2005)

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

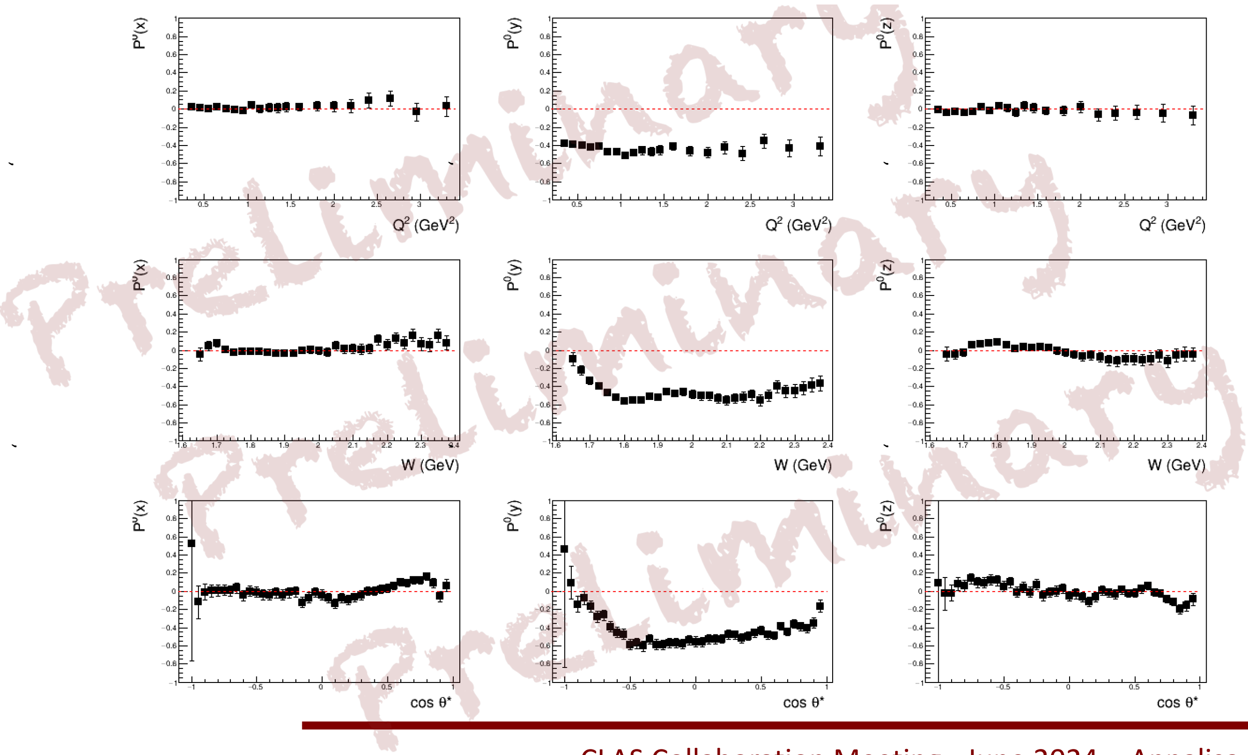




By J. Landwersiek, FIU

K^+Y Induced Polarization CLAS12

$$\frac{N^+ - N^-}{N^+ + N^-} = \frac{\nu_Y \alpha P_Y}{2}, \nu_Y = 1 \; or \; \nu_Y = -0.256, \alpha = 0.732$$



x and z components still not fully compatible with 0

as expected from theory

The analysis will be improved once the **Spring 2024** data will be available for analysis

By Lucilla Lanza

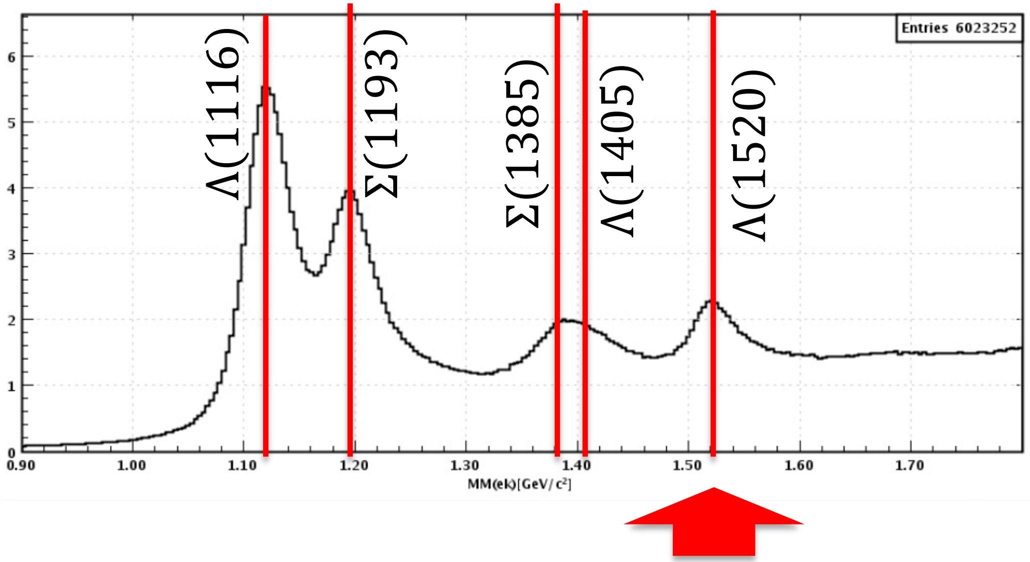
$\Lambda(1520)$

Other channels could be exploited as final states for possible new resonances..

$$ep \rightarrow eK^{+}\Lambda(1520) \rightarrow eK^{+}\,K^{-}p$$

The existence of several non-strange N* resonances with significant (~5%) branching ratios into the $K^{+}\Lambda\,(1520)$ decay channel has been predicted

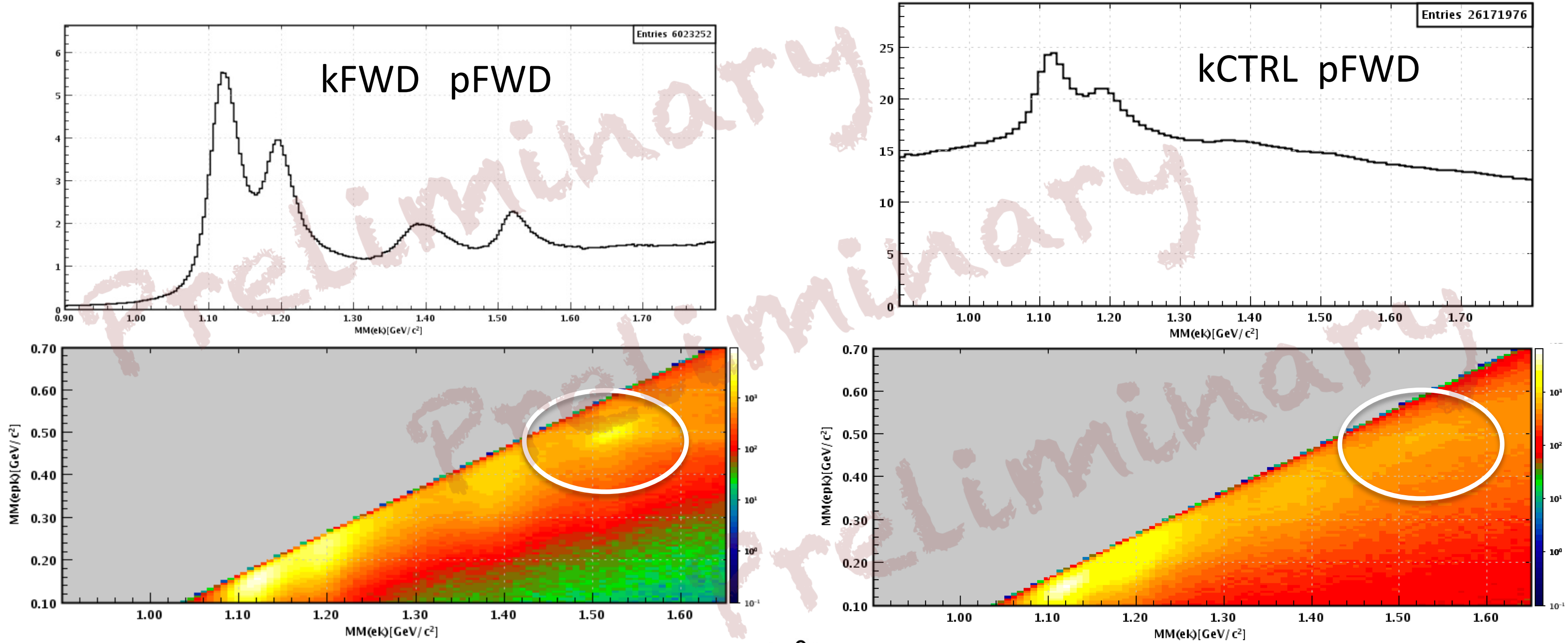
kFWD pFWD



$\Lambda(1520)$ arises as a separate structure

→ S. Barrow et al., CLAS Coll., Phys.Rev.C64:044601,2001
→ Simon Chapstick and W. Roberts, Phys. Rev. D **58** 074011

Λ(1520)



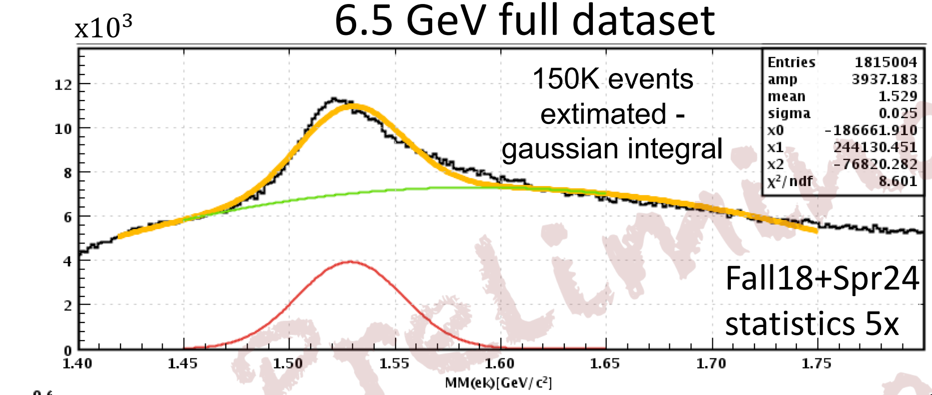
Five structures: Λ(1116), Σ^0(1193), Σ(1385), Λ(1405), Λ(1520)

By Lucilla Lanza

$$ep \rightarrow eK^+\Lambda(1520) \rightarrow eK^+\,K^-p$$

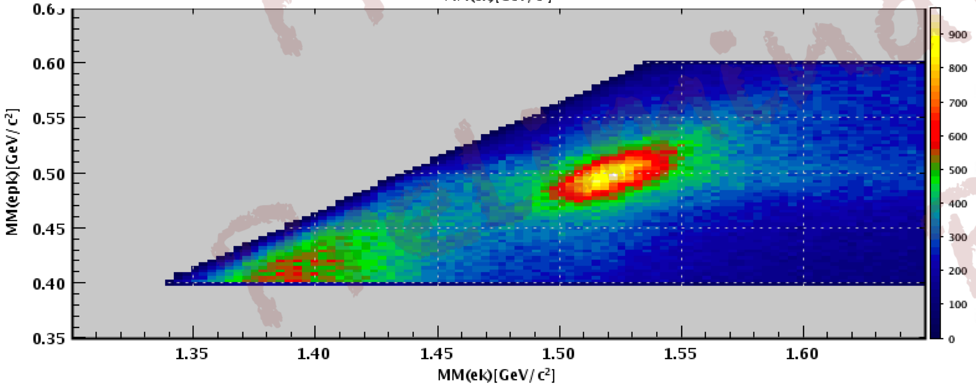
Λ(1520)

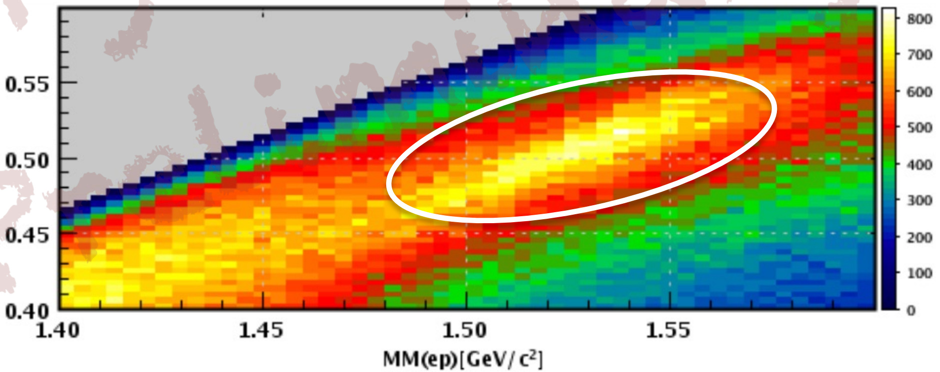
6.5 GeV full dataset



It is possible to isolate $\Lambda(1520)$ also in events with an electron detected in the FT

7.5 GeV dataset





$$ep \rightarrow eK^{+}\Lambda(1520) \rightarrow eK^{+}\,K^{-}p$$

By Lucilla Lanza

Unique Opportunity of Nη Final States

- **Key Idea:** Nη final states provide a cleaner probe of nucleon resonances compared to Nπ final states
- η is isospin singlet (I = 0) → "isospin filter" (Nη final states access only I = 1/2 nucleon resonances)
- Complements Nπ studies in a coupled-channel approach

Particle	J^P	Overall	$N\gamma$	$N\pi$	$N\eta$
$N(1440)$	$1/2^+$	****	****	****	
$N(1520)$	$3/2^-$	****	****	****	****
$N(1535)$	$1/2^-$	****	****	****	****
$N(1650)$	$1/2^-$	****	****	****	****
$N(1675)$	$5/2^-$	****	****	****	*
$N(1680)$	$5/2^+$	****	****	****	*
$N(1700)$	$3/2^-$	***	**	***	*
$N(1710)$	$1/2^+$	****	****	****	***
$N(1720)$	$3/2^+$	****	****	****	*
$N(1860)$	$5/2^+$	**	*	**	*
$N(1875)$	$3/2^-$	***	**	**	*
$N(1880)$	$1/2^+$	***	**	*	*
$N(1895)$	$1/2^-$	****	****	*	****

**** Existence is certain.
*** Existence is very likely.
** Evidence of existence is fair.
* Evidence of existence is poor.

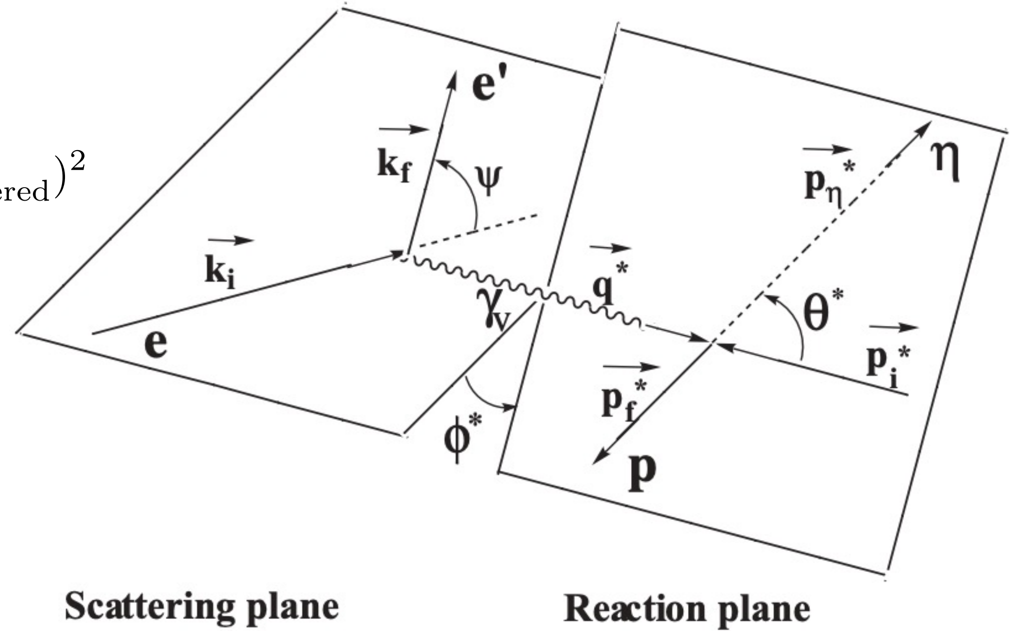
Particle	Jp	Fraction Γ_i/Γ for Decay Modes	
		Nπ	Nη
N(1440)	$1/2^+$	55-75 %	<1%
N(1520)	$3/2^-$	55-65%	0.07-0.09 %
N(1535)	$1/2^-$	32-52 %	30-55%
N(1650)	$1/2^-$	50-70 %	15-35%
N(1675)	$5/2^-$	38-42 %	<1%
N(1680)	$5/2^+$	60-70 %	<1%
N(1700)	$3/2^-$	7-17 %	1-2%
N(1710)	$1/2^+$	5-20 %	10-50%
N(1720)	$3/2^+$	8-14 %	1-5%
N(1875)	$3/2^-$	3-11 %	3-16%
N(1880)	$1/2^+$	3-31 %	1-55%
N(1895)	$1/2^-$	2-18 %	15-45%
N(1900)	$3/2^+$	1-20 %	2-14%
N(2060)	$5/2^-$	7-12 %	2-38%
N(2100)	$1/2^+$	8-32 %	5-45%

η Electroproduction Kinematics

- **Key Idea:** The η electroproduction reaction is studied in the center-of-mass frame, with key kinematic variables W, Q^2, cos(θ*), and ϕ*.
- Center-of-mass frame: resonance is at rest

ep → e'p'η

$$W = \sqrt{s} = \left| P^{\mu}_{\gamma_\mu} + P^{\mu}_{\text{target}} \right|$$
$$Q^2 = -q^2 = -(P^{\mu}_{e,\text{beam}} - P^{\mu}_{e',\text{scattered}})^2$$
$$\cos\theta^*$$
$$\phi^*$$



By Izzy Illari

Beam Spin Asymmetry (A_{LU}) in η Electroproduction

- **Key Idea:** First ever measurement of the beam spin asymmetry in exclusive η electroproduction in a previously unexplored kinematic region (1.6 ≤ W ≤ 2.2 GeV).
- Longitudinally polarized electron beam on unpolarized stationary proton target
- Complements existing cross section and polarization observable measurements

Polarized cross sections:

$$\sigma^{\pm} = \sigma_T + \epsilon\sigma_L + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi^* + \epsilon\sigma_{TT}\cos 2\phi^* \pm h_e\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}\sin\phi^*$$

Beam Spin Asymmetry A_{LU}:

$$A_{LU} = \frac{1}{P_b}\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \boxed{\frac{1}{P_b}\frac{N^+ - N^-}{N^+ + N^-}}$$

$N^{\pm}$ = η signal yield for (±1) helicity

P_b = beam polarization (= 0.8517)

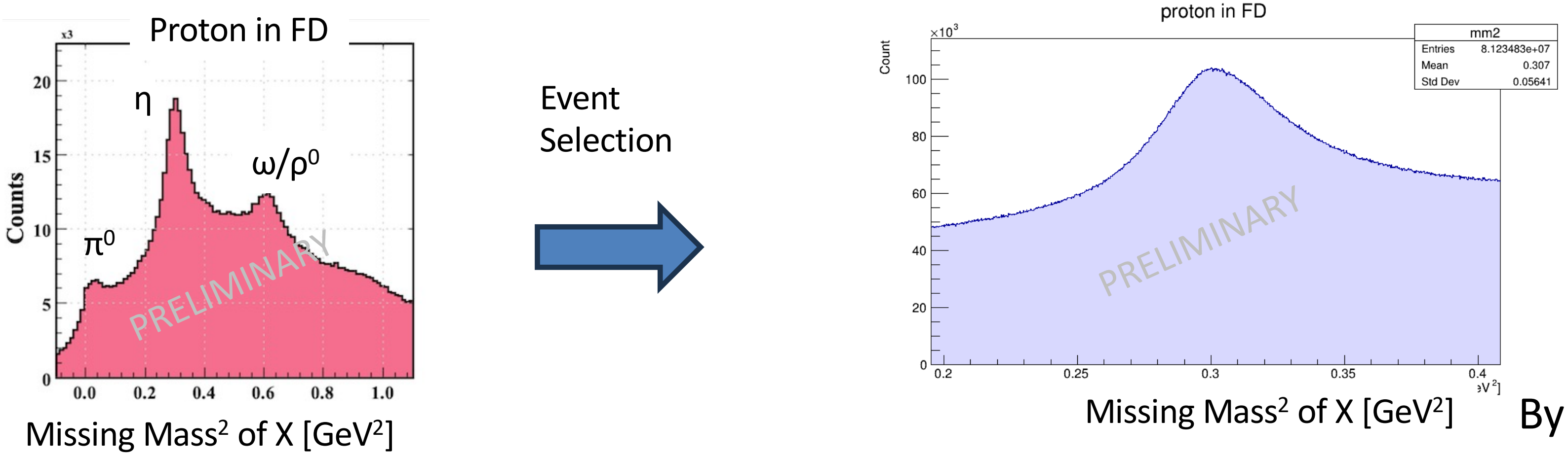
Sin ϕ* Moment:

$$A_{LU} = \frac{A_{LU}^{\sin\phi^*}\sin\phi^*}{1 + A_{UU}^{\cos\phi^*}\cos\phi^* + A_{UU}^{\cos 2\phi^*}\cos 2\phi^*} \approx \boxed{A_{LU}^{\sin\phi^*}}\sin\phi^*$$

By Izzy Illari

Event Selection and η Identification

- **Key Idea:** η mesons are identified using the missing mass technique in the ep → e'p'X reaction (e and p in the FD)
- Reconstruct the missing mass squared (MM^2) of the undetected particle X
- η signal appears as a peak around $MM^2 = 0.3$ GeV^2
- Apply analysis cuts:
  - W < 2 GeV (nucleon resonance region)
  - 0.15 $GeV^2 < MM^2 < 0.45$ GeV^2 (η peak region)
- Implement standard RGK fiducial cuts and cuts developed for analysis

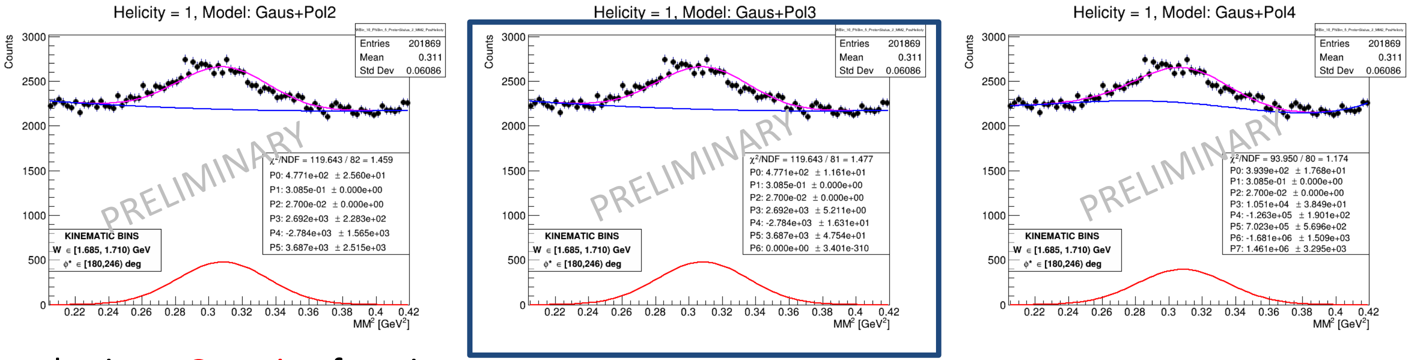


By Izzy Illari

Signal Extraction and Background Fit

- Key Idea: Extracting the η signal yield requires fitting the missing mass squared distribution with a combination of signal and background fits.

pol3 as “benchmark”

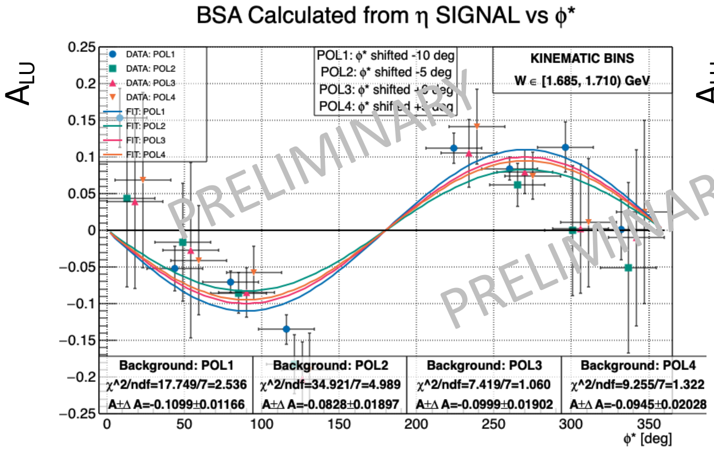


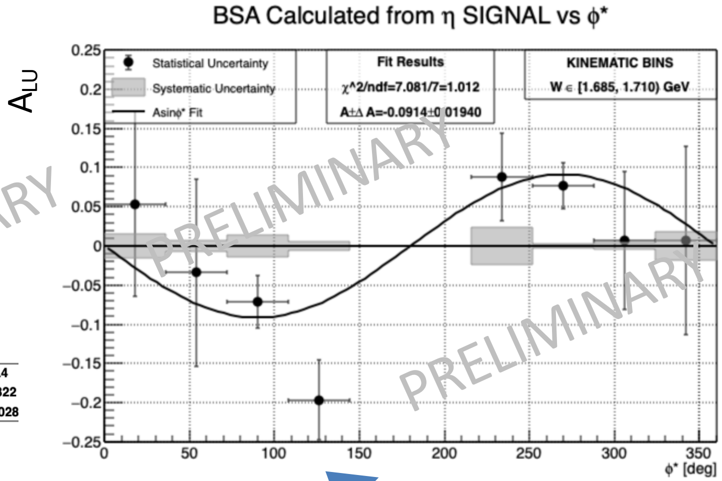
- Signal: Fitted using a Gaussian function
- Background: Fitted using polynomial functions of various orders (pol2, pol3, pol4)
- pol3 chosen as the "benchmark" fits, balancing bias and variance
- Systematic uncertainty analysis is preliminary
  - Dominant source considered is the yield extraction procedure, estimated by comparing different background fits (pol2, pol3, pol4)

By Izzy Illari

Representative Fit to Beam Spin Asymmetry

- **Key Idea:** The BSA is extracted by fitting the asymmetry as a function of ϕ* with a sine function.
- Data are binned over W and ϕ*, integrated over Q^2 and cosθ*





$$A_{LU} = \frac{1}{P_b}\frac{N^+ - N^-}{N^+ + N^-}$$

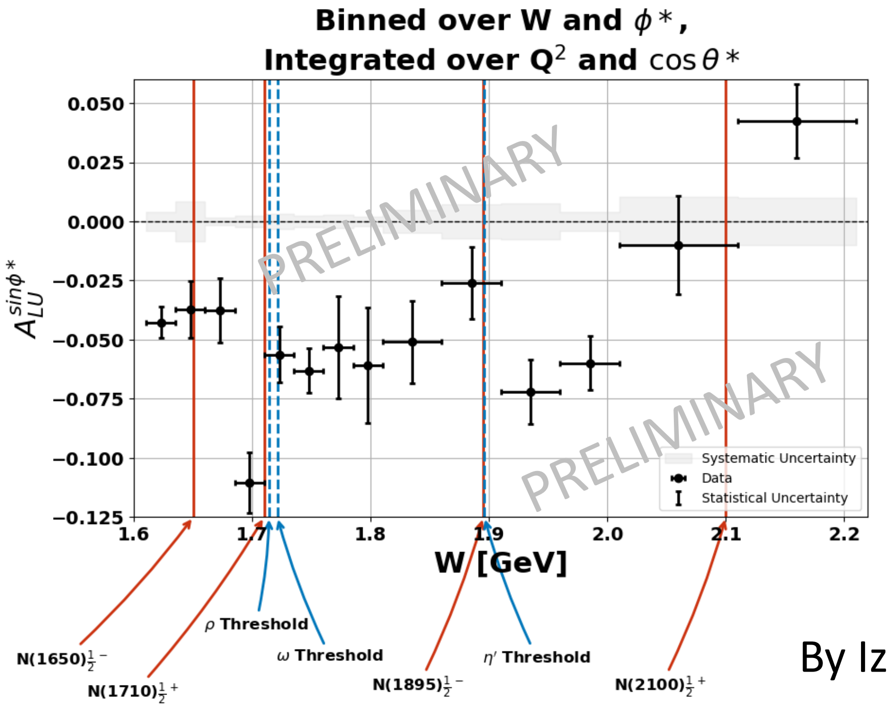
$$A_{LU} \approx A_{LU}^{\sin\phi*} \sin\phi*$$

By Izzy Illari

Sine Moment of the Beam Spin Asymmetry ($A_{LU}^{\sin\phi^*}$)

- **Key Idea:** The sine moment of the asymmetry, $A_{LU}^{\sin\phi^*}$, is extracted to study the dependence on the center-of-mass energy W.

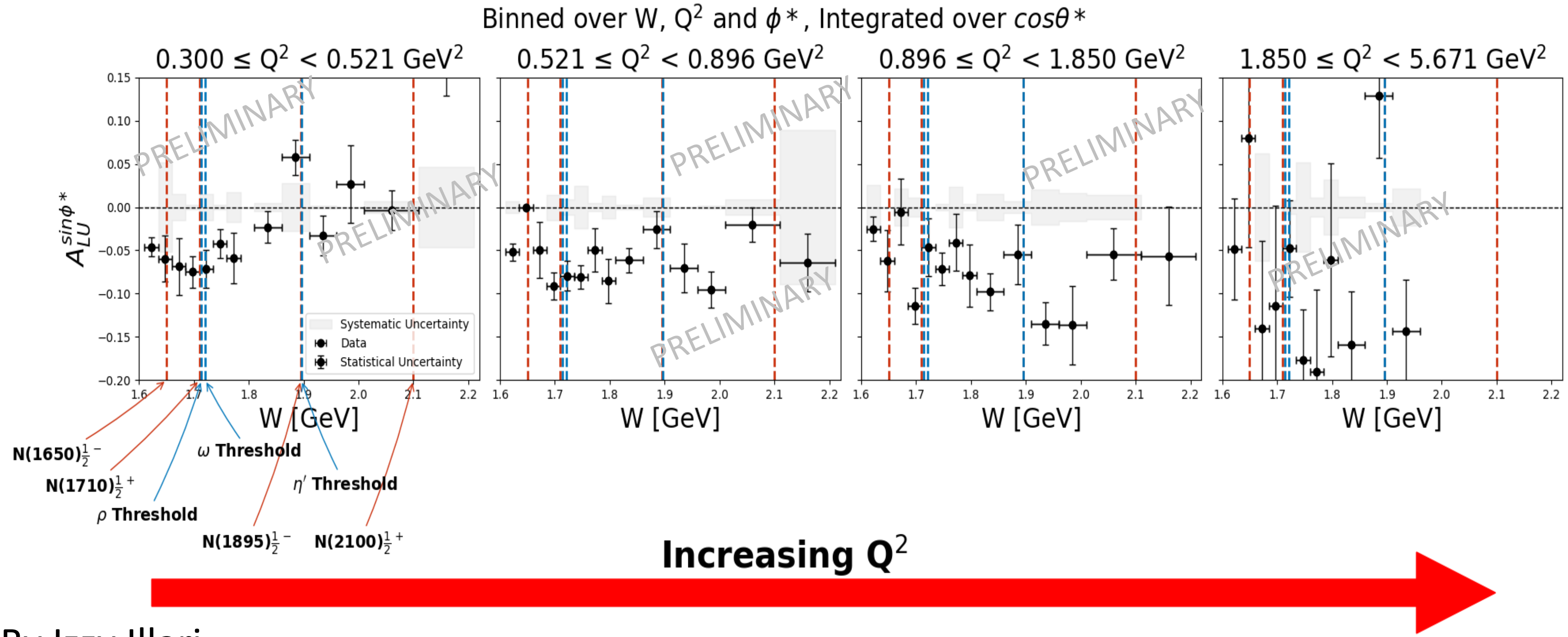
- Data binned over W and ϕ*, integrated over Q^2 and cosθ*
- Error bars represent statistical uncertainties
- Grey histograms around zero line indicate systematic uncertainties
- Red lines: selected nucleon resonances
- Blue lines: selected meson production thresholds
- Vertical lines suggest interesting physics at specific W values but do not definitively explain the observed behavior



By Izzy Illari

Q^2 Dependence of the Sine Moment ($A_{LU}^{\sin\phi^*}$)

- **Key Idea:** Binning the data over Q^2 allows for investigating the dependence of $A_{LU}^{\sin\phi^*}$ on the four-momentum transfer squared.

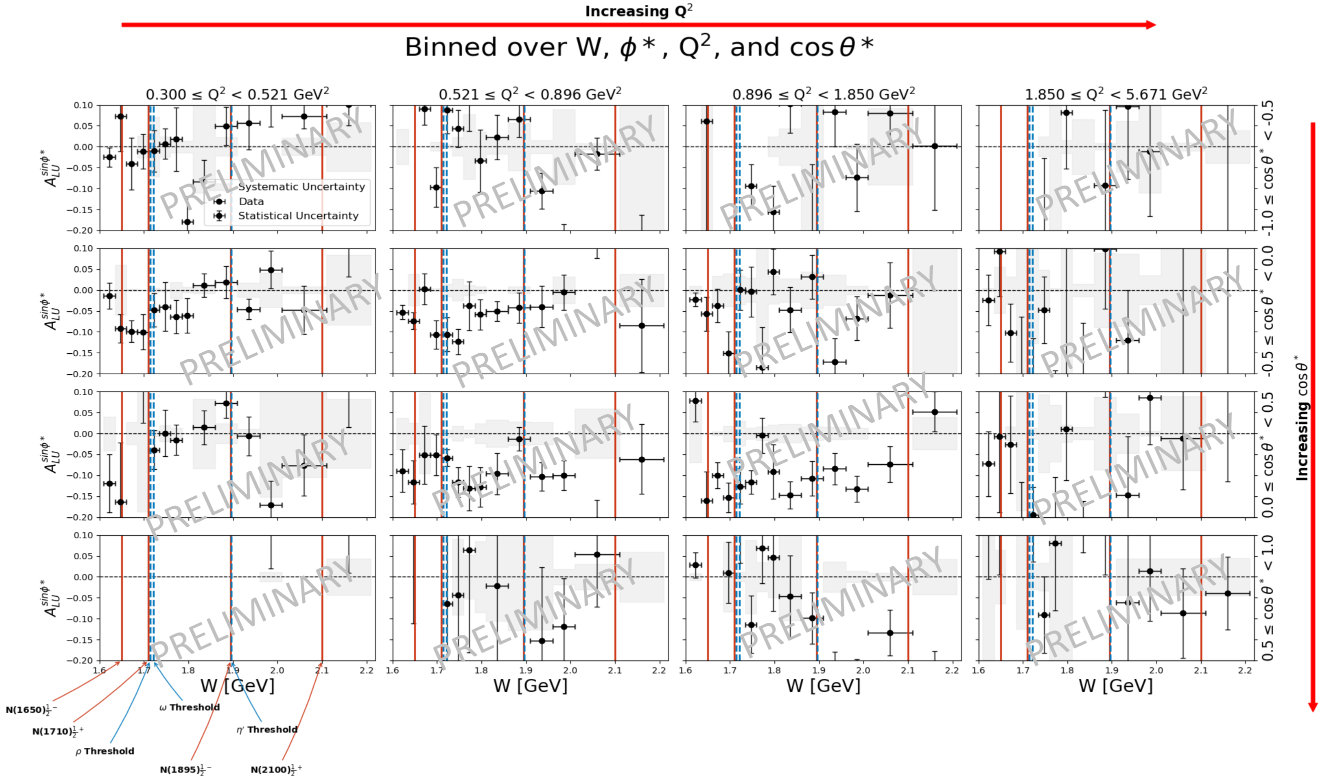


By Izzy Illari

Full Kinematic Dependence of the Sine Moment

Key Idea: A comprehensive study of the sine moment's dependence on the kinematic phase space.

Limited by Fall 2018 statistics

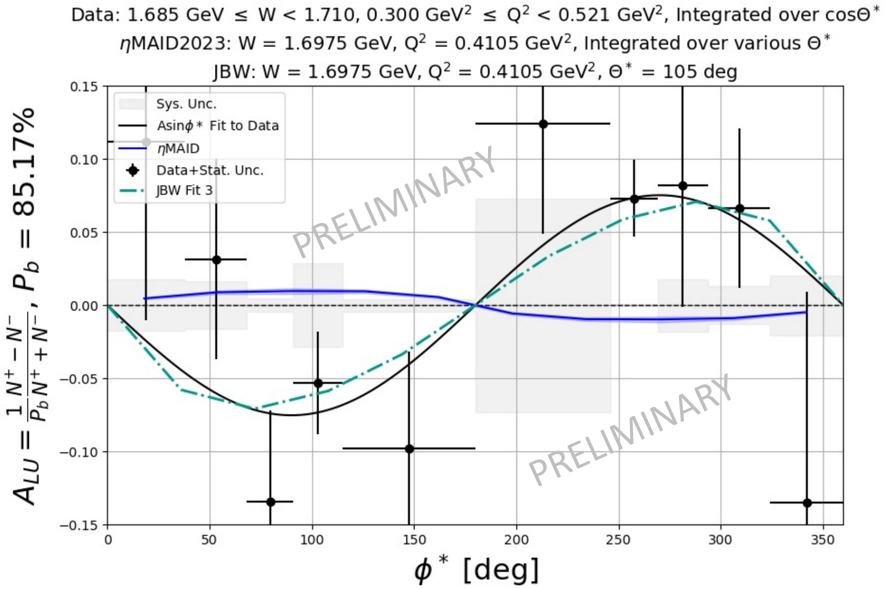


X4 Statistics is available from Spring 2024 data

By Izzy Illari

Comparison with Theoretical Models: An Example

- **Key Idea:** The beam spin asymmetry data has the potential to constrain and improve theoretical models of η electroproduction.
  - Data binned over W, ϕ*, and Q^2 and integrated over cosθ*
  - Jülich-Bonn-Washington (JBW)
  - EtaMAID
  - Illustrative example of the potential for this data to constrain and improve theoretical models
  - Limitations in the models (small Nη datasets, lack of polarization observables) prevent definitive conclusions at this stage

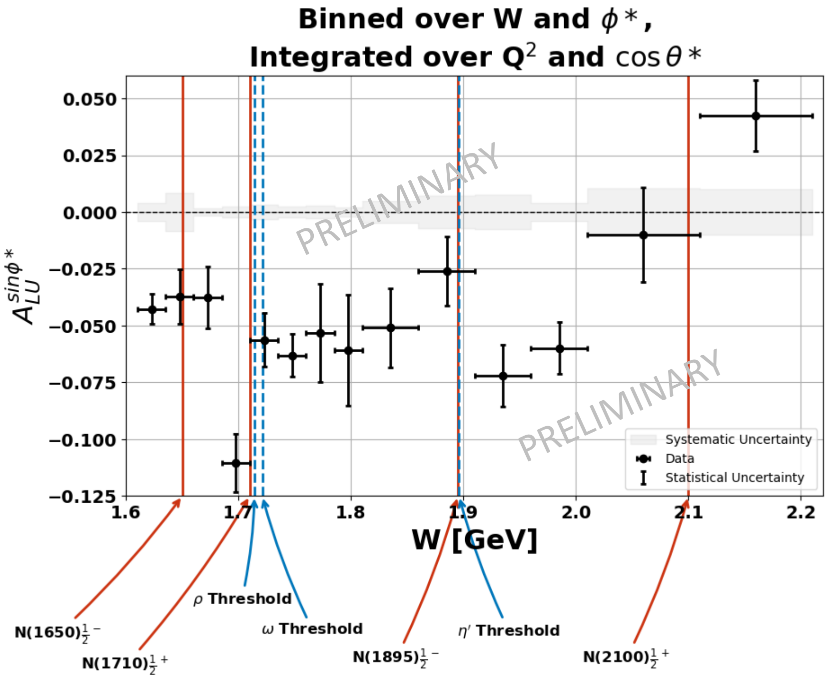


By Izzy Illari

Summary of Key Findings and Impact

- **Key Idea:** The beam spin asymmetry measurements in η electroproduction offer valuable data for theoretical models and could be provide new insights into nucleon resonances.

- **Findings:**
  - Consistently negative $A_{LU}^{\sin\phi^*}$ values across the W range
  - Dip-like structure near N(1710)
  - Cusp-like behavior near N(1895)
- **Impact:**
  - Expands kinematic reach in η electroproduction BSA measurements
  - Provides new data to evaluate and constrain theoretical models
- **Next Steps and Path to Publication:**
  - Perform Fast MC simulations to determine acceptances
  - Prepare a CLAS12 Analysis Note
  - Explore collaborations with Eta-MAID and JBW



By Izzy Illari

Summary and Outlook

Summarizing:

- The study of N* states is one of the crucial topics of the CLAS and CLAS12 physics programs:
  - -CLAS has produced a huge amount of data up to $Q^2 < 5$ GeV^2
  - -CLAS12 was designed to extend these studies for $0.05 < Q^2 < 12$ GeV^2
- The first results of the CLAS12 N* program have been obtained with the analysis of KY polarization transfer data and ηp A_{LU} asymmetries from the RGK Fall 2018 Run
  - -The RGK available dataset is 5x larger than the analyzed one
  - -Only 10% of expected full statistics has been analyzed.
- On going analyses:
  - -First paper on KY electroproduction has been published on PRC
  - -Other analyses based on the existing RG-K data are in progress ($\pi\pi p$, KY, ηp, DVCS, $\pi^0 p$)
  - -All analysis channels will benefit from Spring 2024 collected data in the short time

And in the future…

- Future work with these data is expected to face up he most challenging problems of the Standard Model on the nature of hadron mass, confinement, and the emergence of N* states from quarks and gluons

Stay tuned for further updates…