

The 14^o International Workshop on the Physics of Excited Nucleon,
York, UK, 17 – 21 June 2024

A large circular logo with a dark blue center and a yellow crescent shape on the right. The text "NSTAR2024" is written in yellow in the center.

NSTAR2024

Search for Hybrid Baryons and KY Electroproduction at CLAS12

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Outline

Physics Motivation: Study of the nucleon excitation spectrum to understand the dynamical properties of QCD in the non-perturbative regime.

What is the role of glue?

- Search for new Baryon States -> Hybrid States

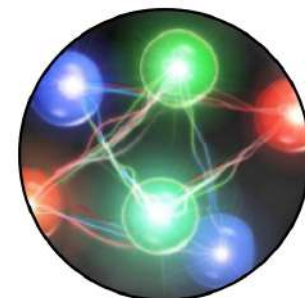
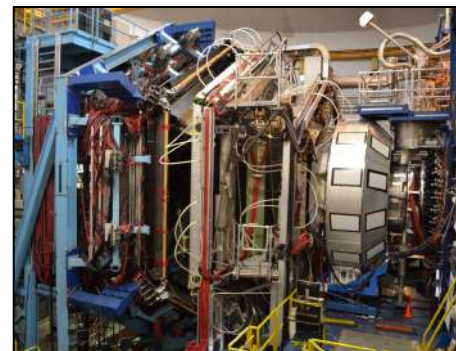
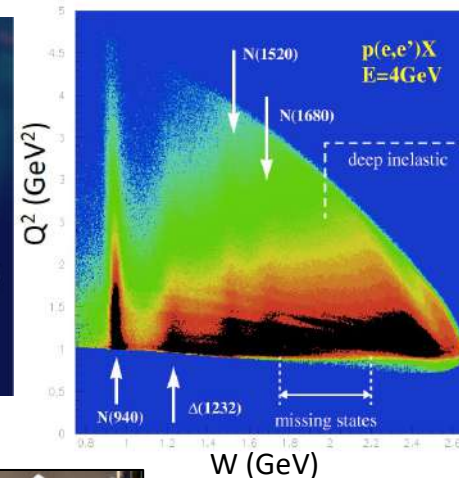
How does the role of the active degrees of freedom in the nucleon spectrum evolve with distance scale?

- Probe underlying degrees of freedom and their emergence from QCD via studies of the Q^2 evolution of electroproduction amplitudes

CLAS12 and Forward Tagger (FT) @ JLab: Experimental Setup description.

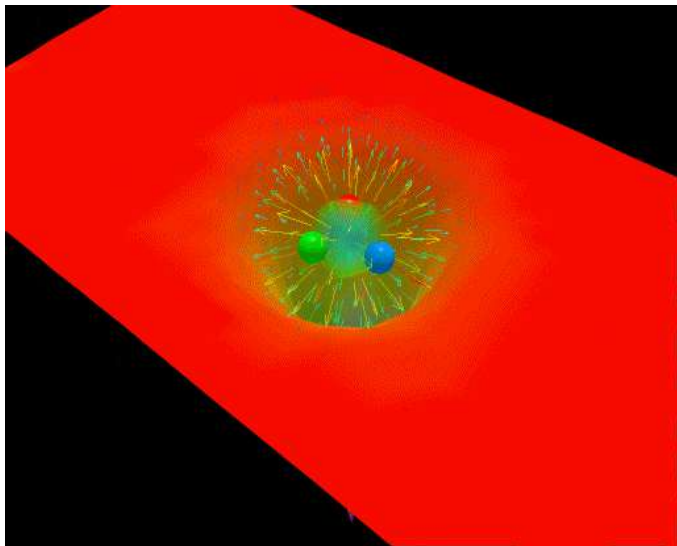
On-going Data Analysis:

- **Results from Physics Runs:** $ep \rightarrow e'KY$ channel studied exploiting data from Fall 2018 Physics Runs in Hall B at Jefferson Lab
- **Beam-Recoil Hyperon Transferred Polarization Analysis**



Critical QCD Questions Addressed

- 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.

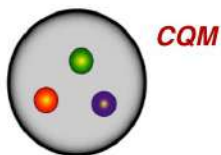
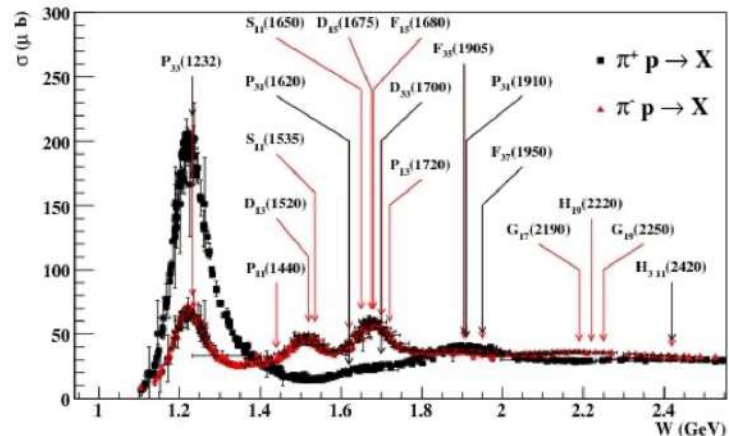
*As such they must be **at the center of any discussion of why the world we actually experience has the character it does.**”*

Nathan Isgur, NStar2000, Newport News, Virginia

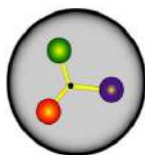
➔ **Search for new baryon states**

Why N*? From the N* Spectrum to QCD

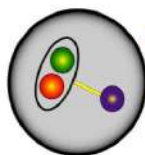
- Understanding the proton's ground state requires understanding its excitation spectrum.
- The N* spectrum reflects the **effective degrees of freedom** and the forces.



CQM



CQM+flux tubes



Quark-diquark clustering



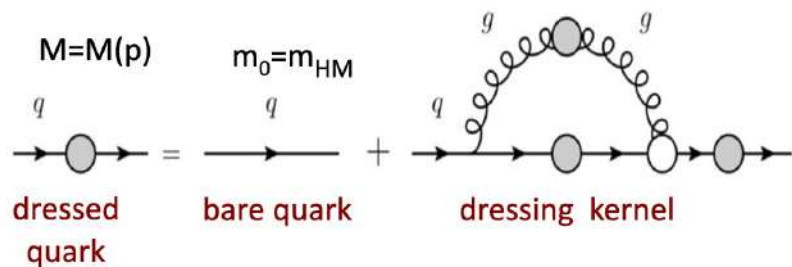
Baryon-meson system



From the Constituent Quark model to QCD.

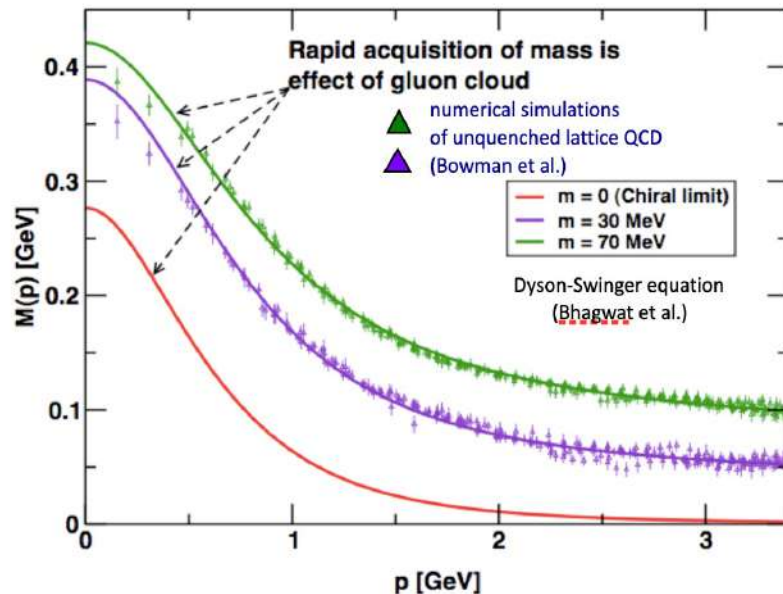
Mass Acquisition

Effective quark mass depends on its momentum



mass composition

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



We need more information about the working of QCD in the non-perturbative regime

Exotic Hadrons

Standard Hadrons come in two varieties: Baryons & Mesons

Exotic Hadrons



Meson and baryon states whose properties cannot be described in terms of q anti- q or qqq degrees of freedom only

Hybrid mesons/baryons:

qqq or $q\bar{q}$ valence quarks plus a valence gluon

Multiquark states:

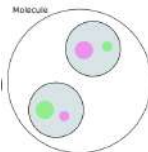
- Baryons with more than 3 valence quarks: **pentaquarks or di-baryons**
- Mesons with more than a quark-antiquark pair: **tetraquarks**

Glueballs:

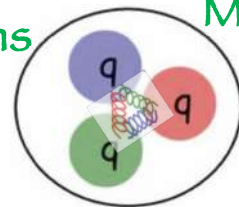
Particles made up of gluonic degrees of freedom only

Molecules...

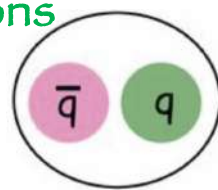
Molecule



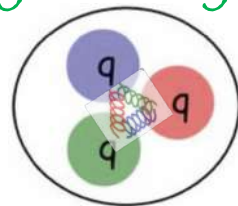
Baryons



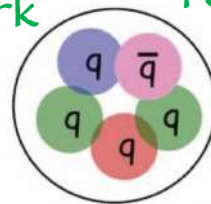
Mesons



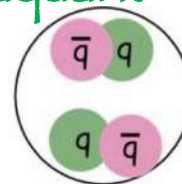
Hybrid baryon



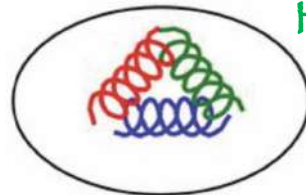
Pentaquark



Tetraquark



Glueball



Hybrid meson

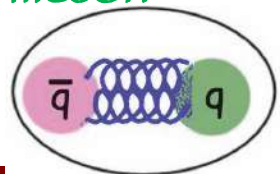


Photo- and Electro- production of mesons on nucleon targets

Meson photo- and electro-
production reactions

for

Light quark baryon
spectroscopy

Two elements provided a crucial boost in the field:

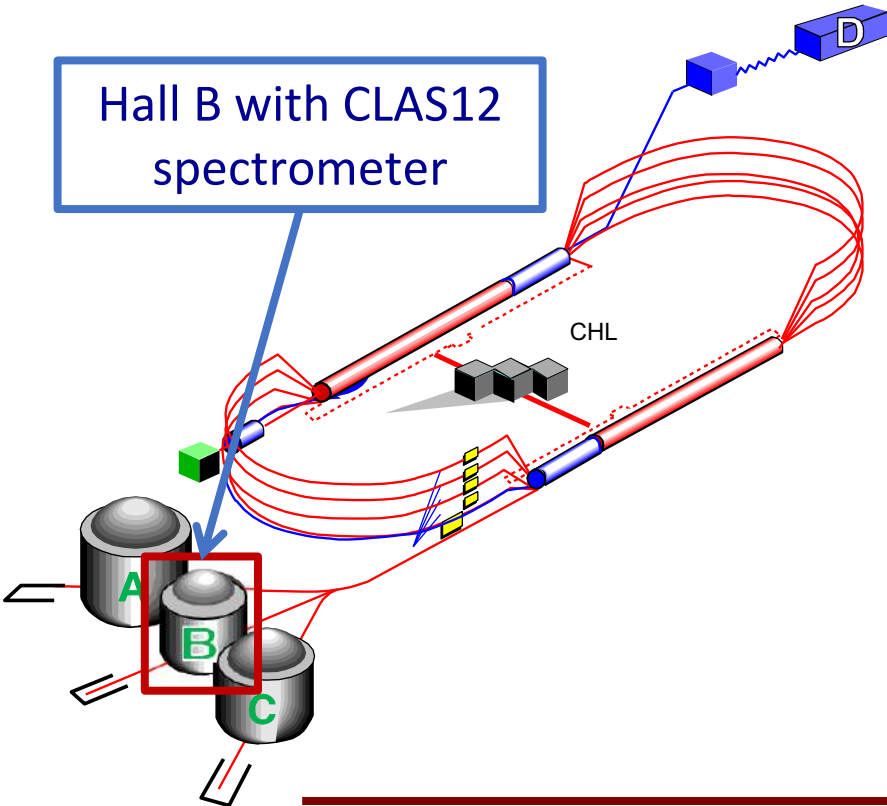
- advent of large solid angle detectors
- polarized beam and targets



single and double
polarization observables

Powerful tool to study the internal structure of the
nucleon

CLAS N* Experimental Program



The N* program is one of the Hall B fundamental

- CLAS & CLAS12 – optimized to study exclusive reaction channels over a broad kinematic range:

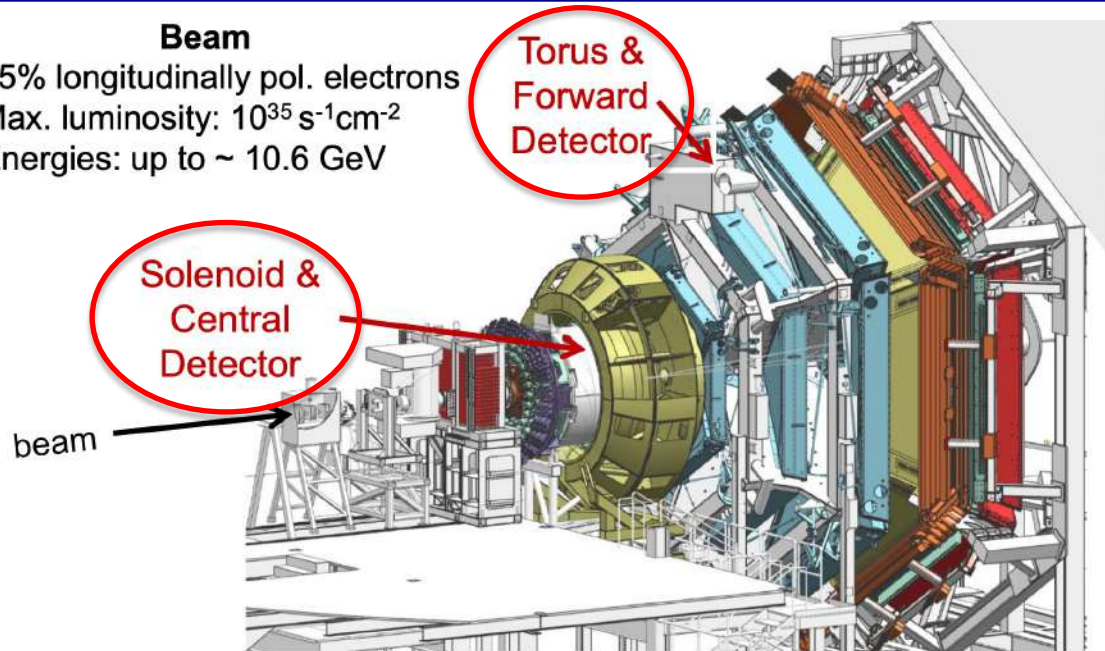
$pN, \omega N, \varphi N, \eta N, \eta' N, \pi\pi N, KY, K^*Y, KY^*$



CLAS12

Beam

- 85% longitudinally pol. electrons
- Max. luminosity: $10^{35} \text{ s}^{-1} \text{ cm}^{-2}$
- Energies: up to $\sim 10.6 \text{ GeV}$



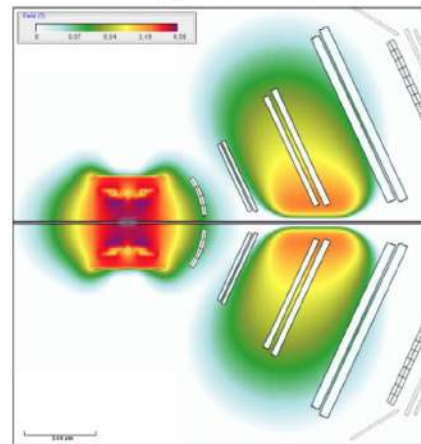
[V.D. Burkert et al., Nucl. Inst. and Meth. A 959, 163419 (2020)]

Ideal instrument to study exclusive meson electroproduction
in the nucleon resonance region

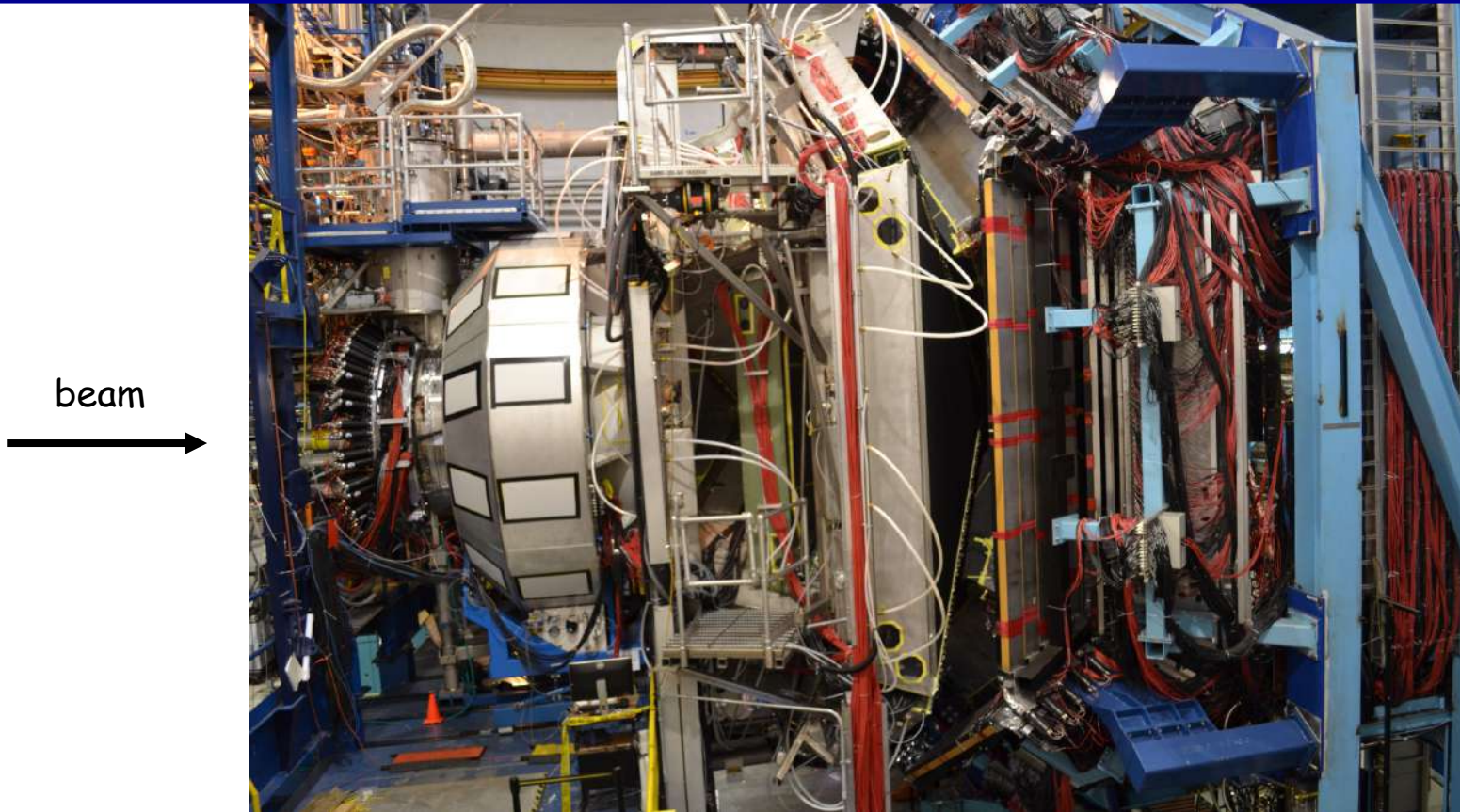
Targets (org. by Run Groups)

- Proton (RG-A/K)
- Deuteron (RG-B)
- Nuclei (RG-M/D/E)
- Long. pol. NH_3/ND_3 (RG-C)

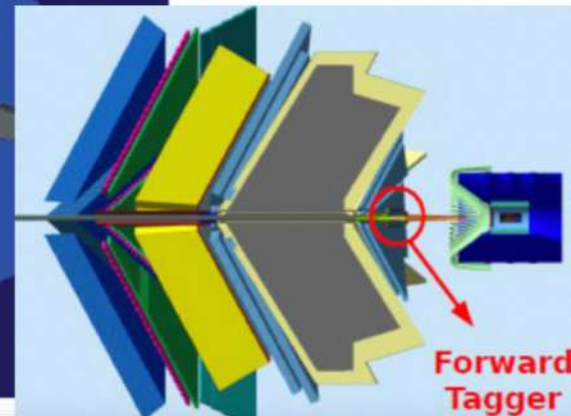
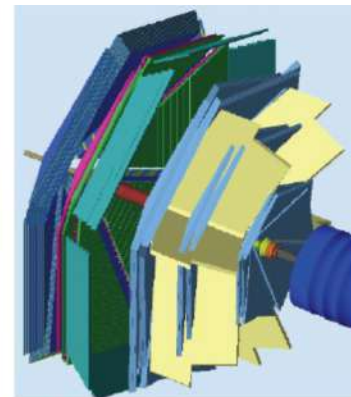
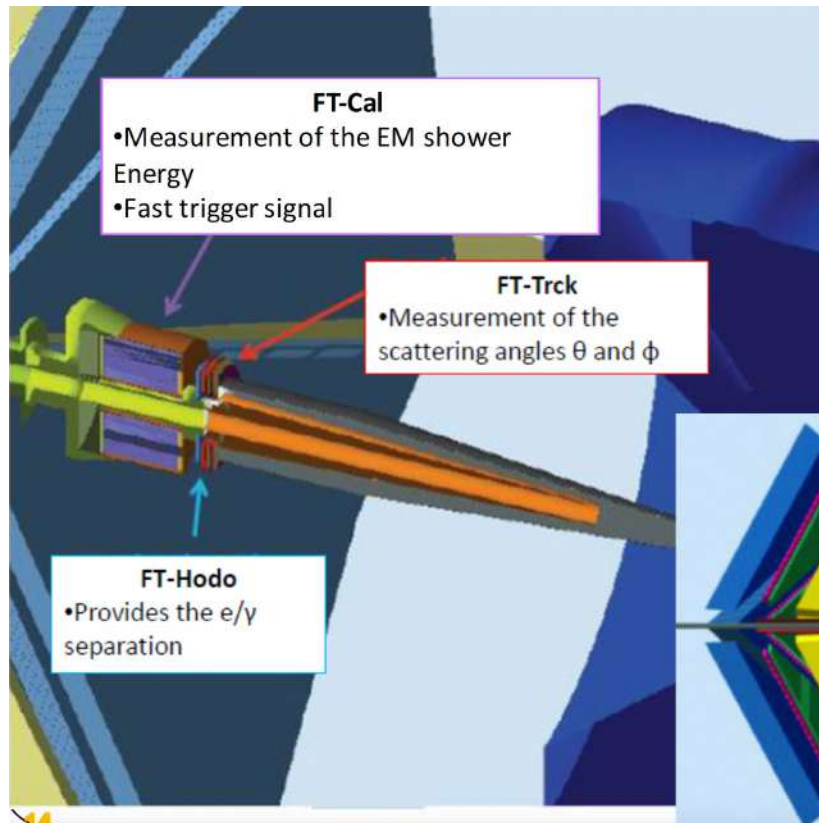
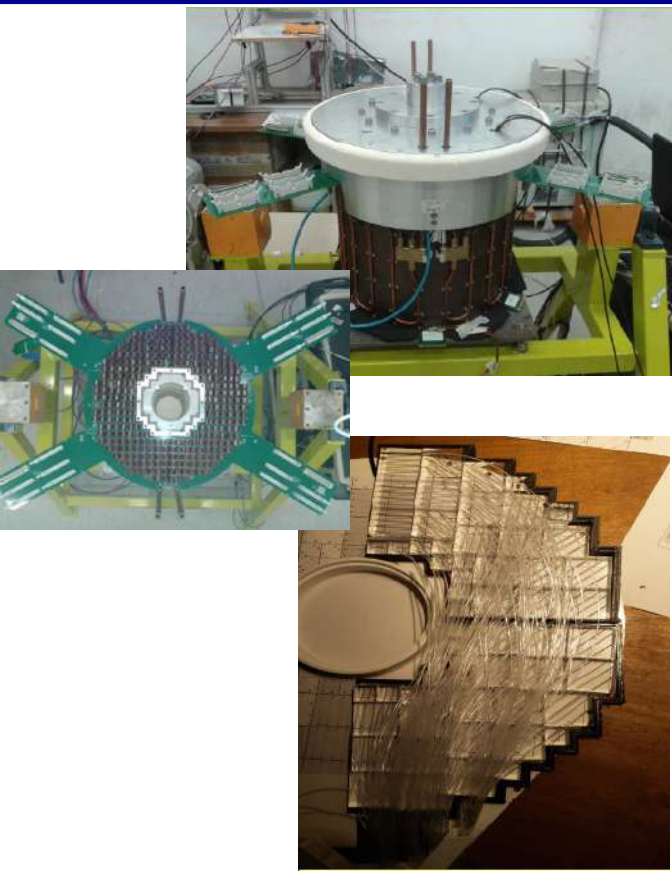
Magnetic Field



CLAS12 Spectrometer



Experimental Setup: Forward Tagger



Electron Beam with CLAS12

Run Group Proposal (RG K) “Color Confinement and Strong QCD”:

Search for Hybrid Baryons (qqqg)

KY Electroproduction for the N^* study

DVCS

SIDIS

RUN CONDITIONS	
Torus Current	100% (3375 A) - negative out-bending
Solenoid	-100 %
FT	ON @ 7.5 GeV -> OFF @ 6.5 GeV and 8.5 GeV
Beam/Target	Polarized electrons, un-polarized LH ₂ target
Luminosity	<ul style="list-style-type: none">• $\sim 5 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ @ 7.5 GeV $\sim 0.87 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ @ 6.5 GeV$0.87 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ @ 6.4 GeV $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ @ 8.5 GeV FULL LUMINOSITY

Fall 2018: EVENTS **15.6 G**

Spring 2024: EVENTS **60 G** (Statistics increased by a factor 4)

50% of the total

Hybrid Hadrons

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

Experimentally:

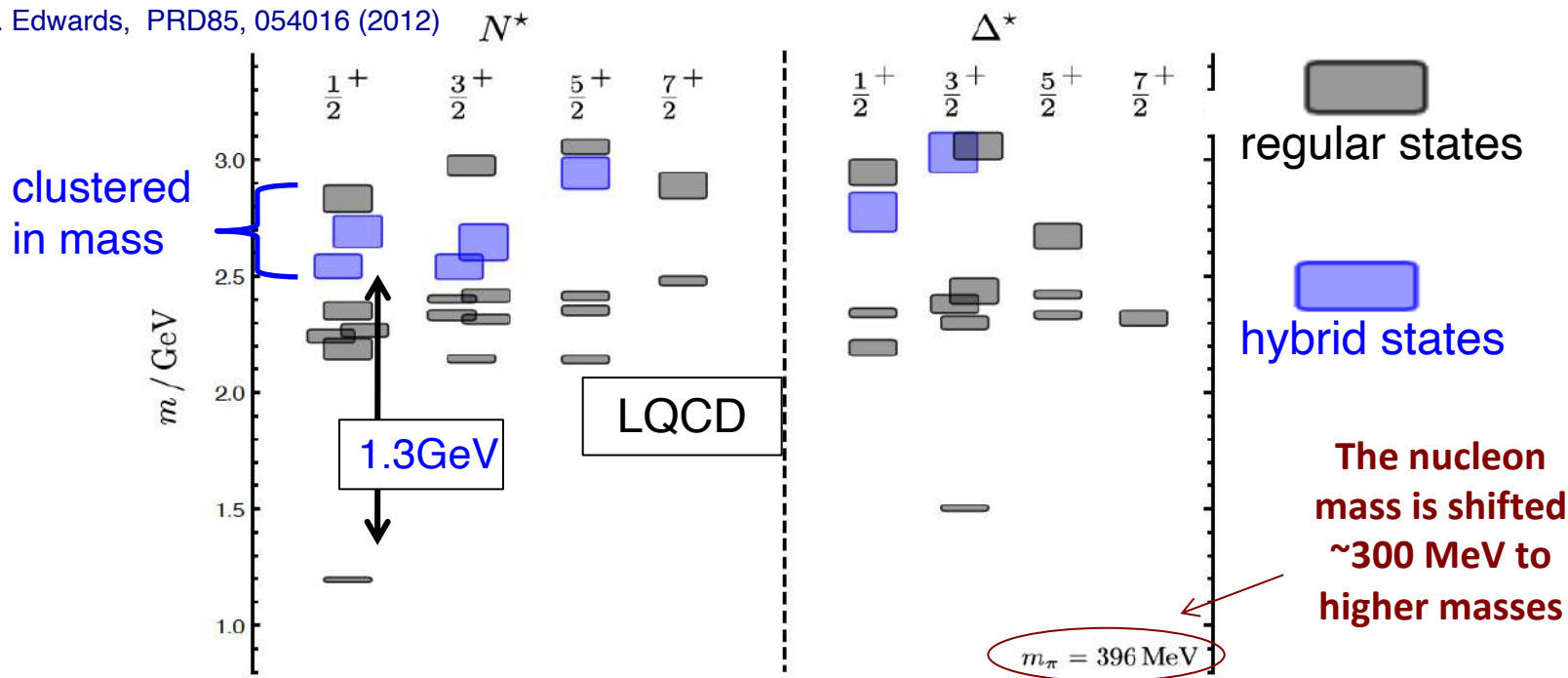
- **Hybrid mesons** $|q\bar{q}g\rangle$ states may have exotic quantum numbers J^{PC} not available to pure $|q\bar{q}\rangle$ states
GlueX, MesonEx, COMPASS, PANDA
- **Hybrid baryons** $|qqqg\rangle$ have the same quantum numbers J^P as $|qqq\rangle$ electroproduction with CLAS12 (Hall B).

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)



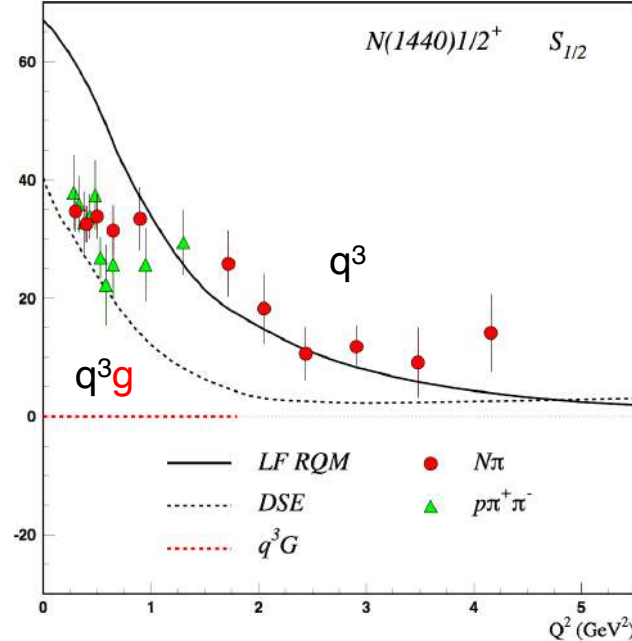
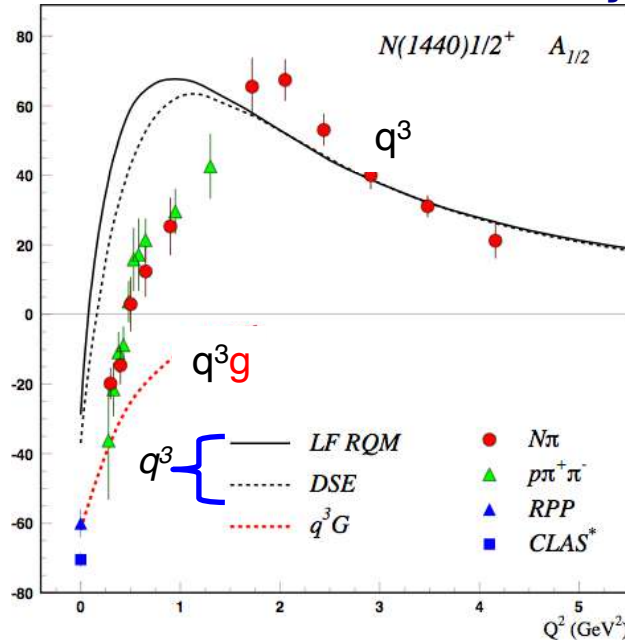
Hybrid states have same J^P values as qqq baryons. How to identify them?

- 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 ?



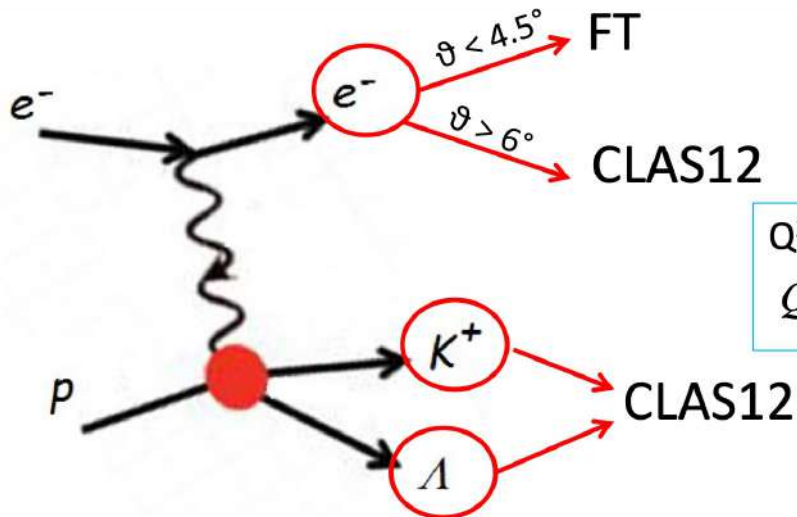
For hybrid “Roper”, $A_{1/2}(Q^2)$ drops off faster with Q^2 and $S_{1/2}(Q^2) \sim 0$.

Hybrid Baryons

Data from KY are critical to provide the extraction of the electrocoupling amplitudes:

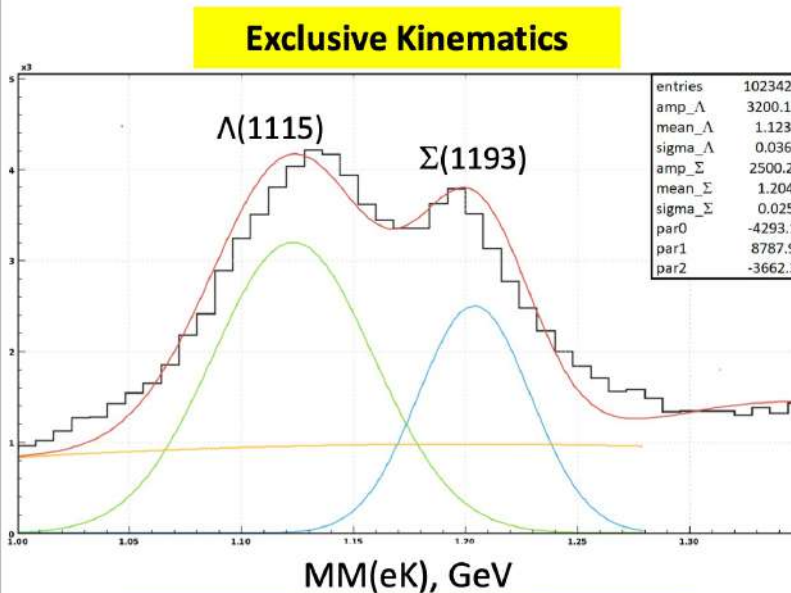
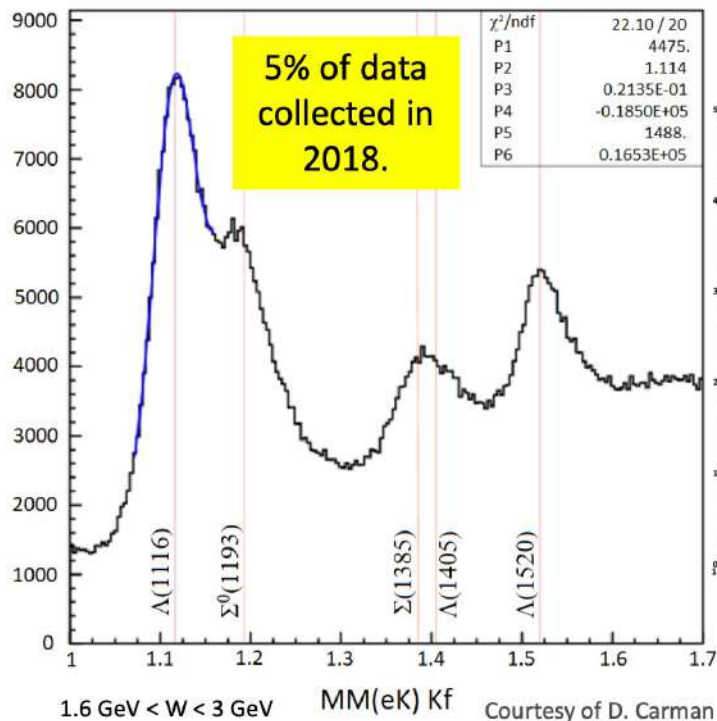
$$e p \rightarrow e' K^+ \Lambda, \Lambda \rightarrow p \pi^-$$

FT allows to probe the **crucial Q^2 range** where hybrid baryons may be identified due to their fast dropping $A_{1/2}(Q^2)$ amplitude and the suppression of the scalar $S_{1/2}(Q^2)$ amplitude.



$$Q^2 \text{ range of interest: } 0.05 - 2 \text{ GeV}^2$$
$$Q^2 = 4E_{\text{Beam}}E_{e'} \sin^2 \frac{\vartheta}{2} \Rightarrow \vartheta < 5^\circ$$

Preliminary Results: electron in the FD(CLAS)/FT



Preliminary results obtained with data collected in 2018

$p(e, e'K^+)X$

$E_{\text{beam}} = 7.546 \text{ GeV}$

Beam-Recoil Transferred Polarization in K^+Y Electroproduction in the Nucleon Resonance Region with CLAS12

PHYSICAL REVIEW C **105**, 065201 (2022)

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

D. S. Carman,^{10*} A. D'Angelo,^{10,11} L. Lanza,¹⁰ V. I. Mokeev,¹² M. J. Amarian,¹³ W. R. Armstrong,¹⁴ H. Asak,¹⁵ H. Avakian,¹⁶ C. Ayerbe Gayoso,^{17,18} N. A. Babatz,¹⁹ L. Barion,²⁰ M. Bangert,²¹ J. I. Bellisley,²² B. Binkert,²³ A. Bianconi,^{24,25} A. S. Biehl,²⁶ M. Bondi,²⁷ S. Bostinarov,²⁸ F. Bossi,²⁹ W. J. Briscoe,³⁰ S. Buchmann,³¹ D. Buhanella,^{32,33} V. D. Burkert,³⁴ R. Caprihanco,³⁵ J. C. Carvajal,³⁶ A. Celentano,³⁷ P. Chaturvedi,³⁸ V. Chetani,³⁹ T. Chetty,⁴⁰ G. Cifali,⁴¹ L. Clark,⁴² P. L. Cole,⁴³ M. Costantini,⁴⁴ G. Costantini,⁴⁵ V. Cude,⁴⁶ A. Dabayan,⁴⁷ R. De Vita,⁴⁸ M. Dehghan,⁴⁹ A. Deh,⁵⁰ S. Diehl,^{51,52} C. Djaili,⁵³ R. Dugre,⁵⁴ M. Echevaria,⁵⁵ A. El Alaoui,⁵⁶ L. El Fassi,⁵⁷ L. Elouadhi,⁵⁸ S. Fegan,⁵⁹ A. Filippek,⁶⁰ G. Gerasimov,⁶¹ Y. Ghardiyan,⁶² G. P. Gilfoyle,⁶³ F. X. Girod,⁶⁴ D. I. Glazier,⁶⁵ A. A. Golubenko,⁶⁶ R. W. Gothe,⁶⁷ Y. Gotsis,⁶⁸ K. A. Griffioen,⁶⁹ K. Haid,⁷⁰ H. Hakobyan,⁷¹ M. Hattori,⁷² F. Haxenja,⁷³ T. B. Hayward,^{74,75} A. K. Hohn,⁷⁶ M. Hultgren,⁷⁷ Y. Iliev,⁷⁸ D. G. Ireland,⁷⁹ E. L. Isupov,⁸⁰ H. S. Jo,⁸¹ K. Joshi,⁸² D. Keller,⁸³ A. Khanal,⁸⁴ A. Kim,⁸⁵ W. Kim,⁸⁶ V. Kimesnikov,⁸⁷ A. Kipko,⁸⁸ Y. Kobayashi,⁸⁹ M. Lesli,⁹⁰ S. Lee,⁹¹ P. Lesica,⁹² K. Livingston,⁹³ J. I. D. MacGregor,⁹⁴ D. Marchand,⁹⁵ L. Maricani,⁹⁶ V. Mascia,⁹⁷ M. Mayer,⁹⁸ B. McKinnon,⁹⁹ S. Mignani,¹⁰⁰ Y. Mironov,¹⁰¹ M. Mizumoto,¹⁰² E. A. Montgomery,¹⁰³ C. Minor Camacho,¹⁰⁴ P. Nadel-Tal,¹⁰⁵ K. Naganuma,¹⁰⁶ J. J. Newke,¹⁰⁷ S. Nicolini,¹⁰⁸ M. D. O'Connell,¹⁰⁹ P. Pandey,¹¹⁰ M. Pascale,¹¹¹ L. L. Pappalardo,¹¹² R. Paremarayan,¹¹³ E. Parys,¹¹⁴ S. J. Paul,¹¹⁵ N. Pilkev,¹¹⁶ D. Pogonitsa,¹¹⁷ J. W. Price,¹¹⁸ Y. Prok,¹¹⁹ B. A. Rase,¹²⁰ T. Reed,¹²¹ M. Ripani,¹²² J. Rissman,¹²³ A. Rizzo,¹²⁴ P. Rossi,¹²⁵ F. Sabatini,¹²⁶ C. Salgado,¹²⁷ A. Schmidt,¹²⁸ Y. G. Sharfian,¹²⁹ E. Y. Shmukov,¹³⁰ U. Shroff,¹³¹ P. Sommerer,¹³² D. Sotkin,¹³³ N. Spivakov,¹³⁴ S. Sreynyan,¹³⁵ I. I. Strakovsky,¹³⁶ S. Strauch,¹³⁷ N. Tyler,¹³⁸ R. Tyson,¹³⁹ M. Ugaev,¹⁴⁰ S. Vallarino,¹⁴¹ L. Venuti,¹⁴² H. Voskanyan,¹⁴³ E. Voutier,¹⁴⁴ D. P. Watts,¹⁴⁵ K. Wei,¹⁴⁶ R. Weihart,¹⁴⁷ M. H. Wood,¹⁴⁸ B. Yalc,¹⁴⁹ N. Zachariou,¹⁵⁰ J. Zhang,¹⁵¹ and V. Ziegler¹⁵²
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³²Kyungpook National University, Daegu 702-701, Republic of Korea

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³⁴Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

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³⁶University of New Hampshire, Durham, New Hampshire 03824, USA

³⁷New Mexico State University, Las Cruces, New Mexico 88003, USA

³⁸North Carolina State University, Raleigh, Virginia 27695, USA

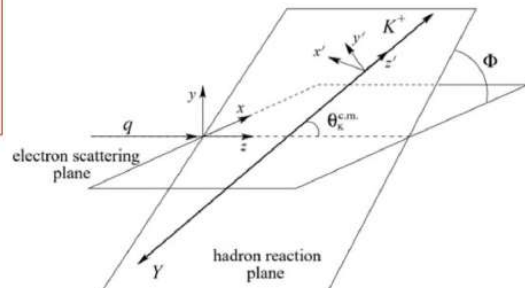
³⁹Ohio State University, Columbus, Ohio 43210, USA

⁴⁰Old Dominion University, Norfolk, Virginia 23529, USA

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)

Analysis of CLAS12 RG-K data from Fall 2018

- 6.535 GeV and 7.546 GeV electrons on LH₂ target
- Extract beam-recoil transferred polarization from longitudinally polarized beam electron to final state hyperon vs. Q^2 , W , $\cos \theta_{\nu}$ c.m.



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

P' = transferred polarization

(x', y', z')

P^0 = recoil polarization

$$P'_{x'} = K_I \sqrt{1 - \epsilon^2} R_{TT}^{x'0},$$

$$P'_{y'} = 0$$

$$P'_{z'} = K_I \sqrt{1 - \epsilon^2} R_{TT}^{z'0},$$

$$P_{x'}^0 = 0$$

$$P_{y'}^0 = K_I (R_T^{y'0} + \epsilon R_L^{y'0})$$

$$P_{z'}^0 = 0$$

*Corresponding author: carman@jlab.org

2409-989X/2022/105(6)/065201(24)

065201-1

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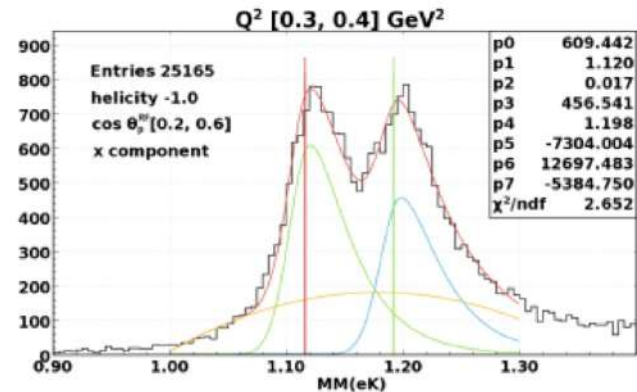
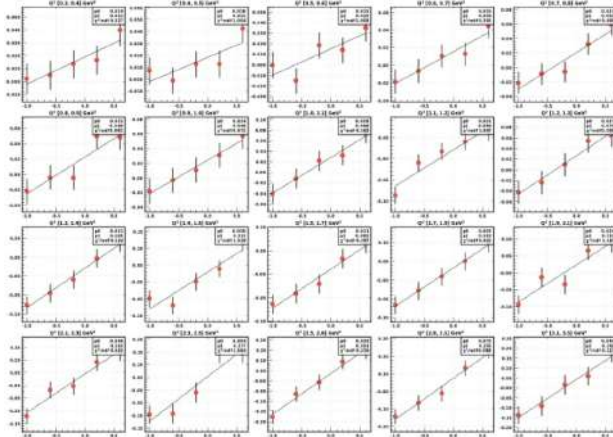
➡ D. Carman's talk

Beam-Recoil Transferred Polarization in K^+Y Electroproduction in the Nucleon Resonance Region with CLAS12

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

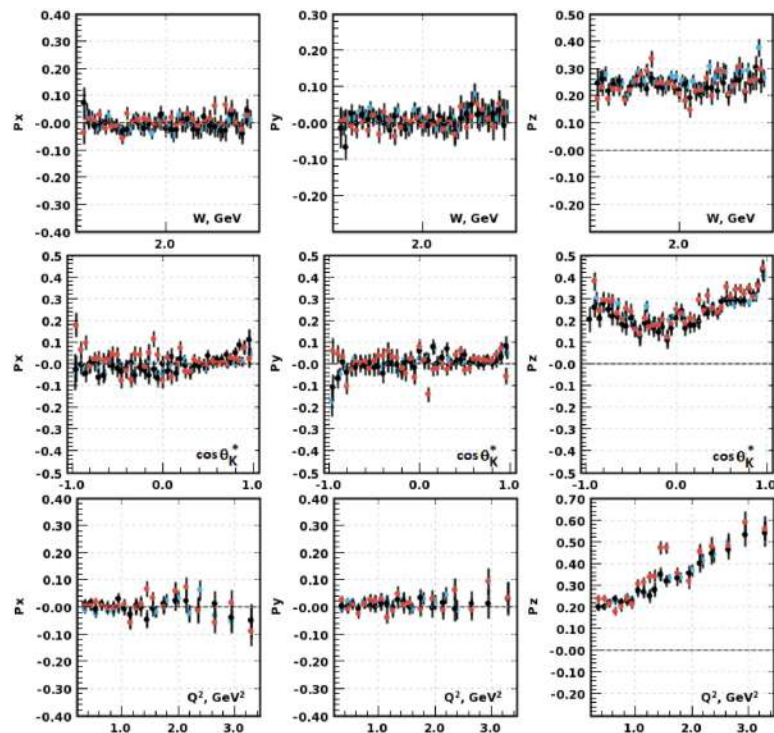
$$A = \frac{N^+ - N^-}{N^+ + N^-} = \nu_Y \alpha_\Lambda P_b \mathcal{P}'_Y \cos \theta_p^{RF}$$

The events in each kinematic bin of Q^2 , W and $\cos \vartheta_K^*$ were divided into 5 $\cos \vartheta_p^{RF}$ bins for each beam helicity...

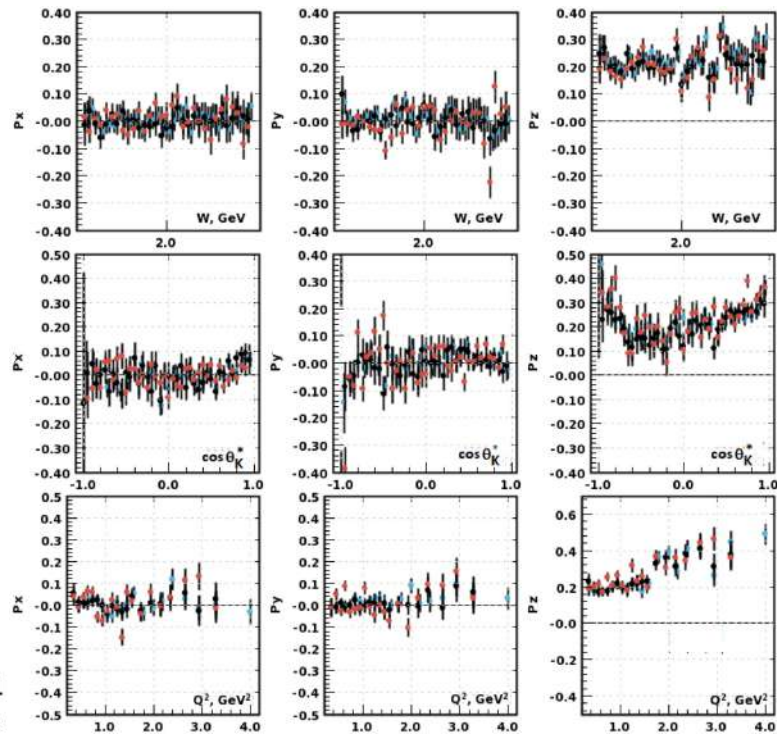


... and the number of Λ events was extracted using a fit of the $MM(eK^+)$ spectrum

Beam-Recoil Transferred Polarization in K^+Y Electroproduction in the Nucleon Resonance Region with CLAS12



P'

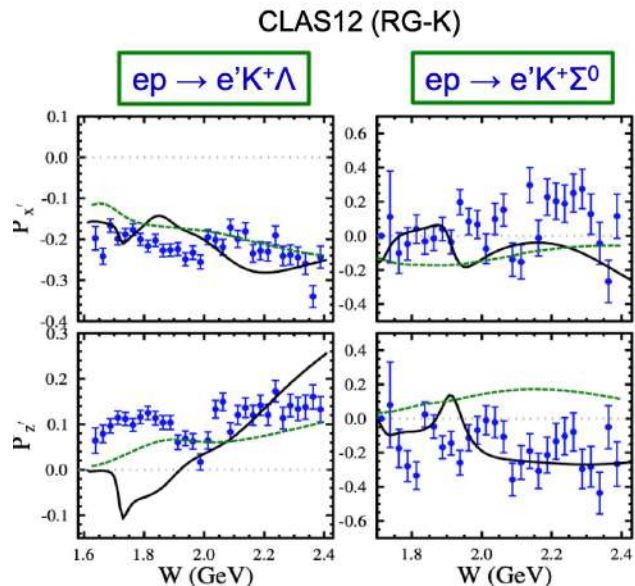


Blue dots : Approach 1

Red dots : Approach 2

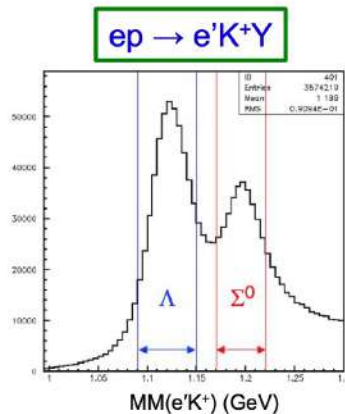
Black dots : Approach 1 (different fitting procedure)

K⁺Y Transferred Polarization CLAS12 vs. CLAS

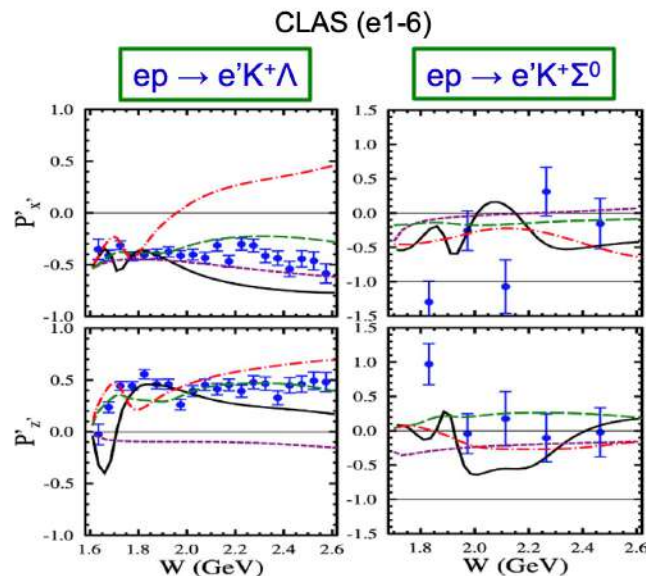


[D.S. Carman et al., Phys. Rev. C 105, 065201 (2022)]

KAON-MAID
RPR



World data set will get extended
by orders of magnitude



[D.S. Carman et al., Phys. Rev. C 79, 065205 (2009)]

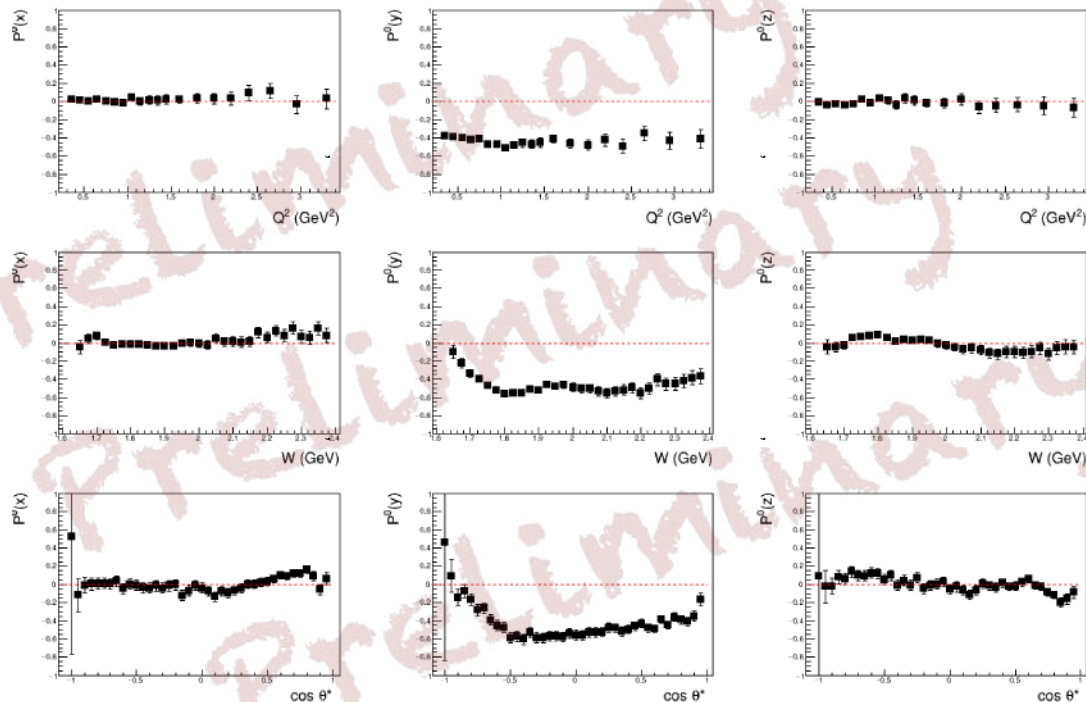
Mart/Bennhold
RPR-1

RPR-2
Regge

D. Carman's talk

K⁺Y Induced Polarization CLAS12

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



x and z components still not fully compatible with 0 as expected from theory

(x,y,z)		Φ -integrated	(x,y,z)
P_x^0	0	P_x^0	0
P_y^0	$K_I(R_L^{p'0} + \epsilon R_L^{y'0})$	P_y^0	$\frac{1}{2} \sqrt{\epsilon(1+\epsilon)} K_I(R_L^{p'0} \cos \theta_K^{m-} + R_L^{y'0} + R_L^{z'0} \sin \theta_K^{m-})$
P_z^0	0	P_z^0	0

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

➡ D. Carman's talk

$\Lambda(1520)$

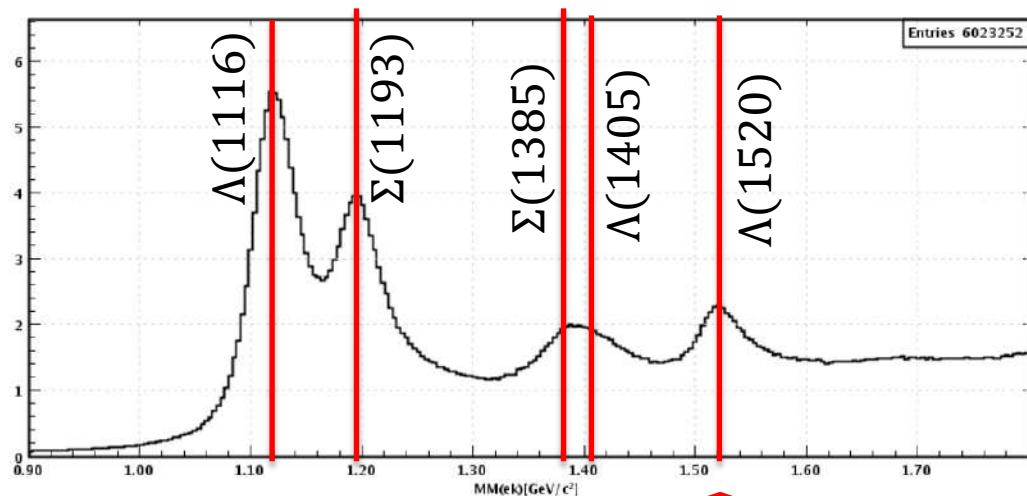
kFWD pFWD

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

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

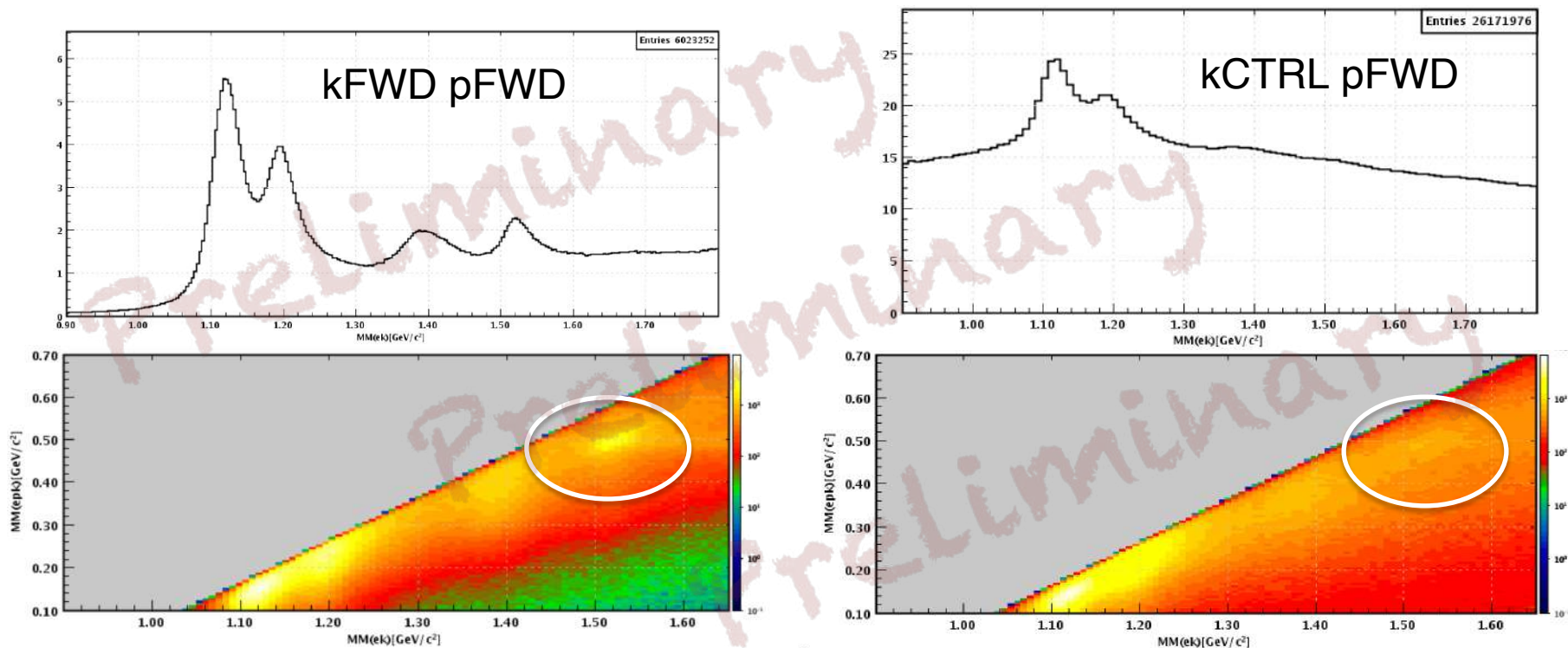
The existence of several nonstrange N^* resonances with significant ($\sim 5\%$) branching ratios into the decay channel $K^+ \Lambda(1520)$ has been predicted

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



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

$\Lambda(1520)$

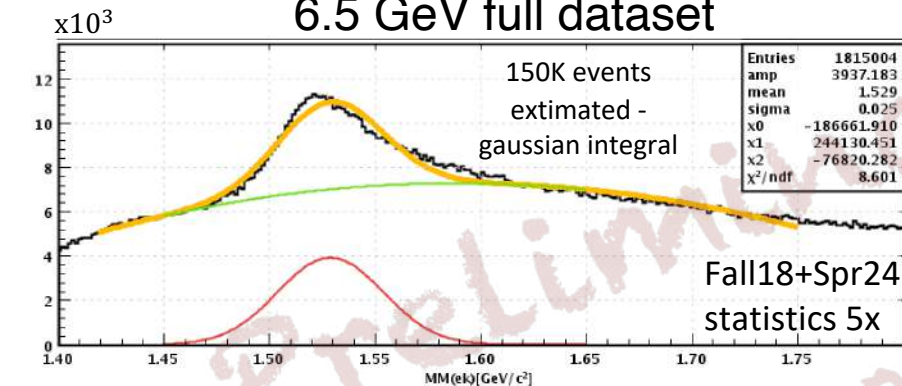


Five structures: $\Lambda(1116)$, $\Sigma^0(1193)$, $\Sigma(1385)$, $\Lambda(1405)$, $\Lambda(1520)$

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

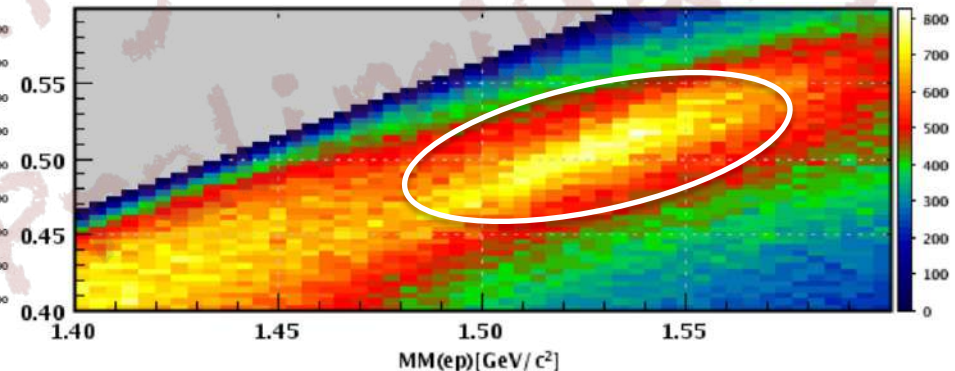
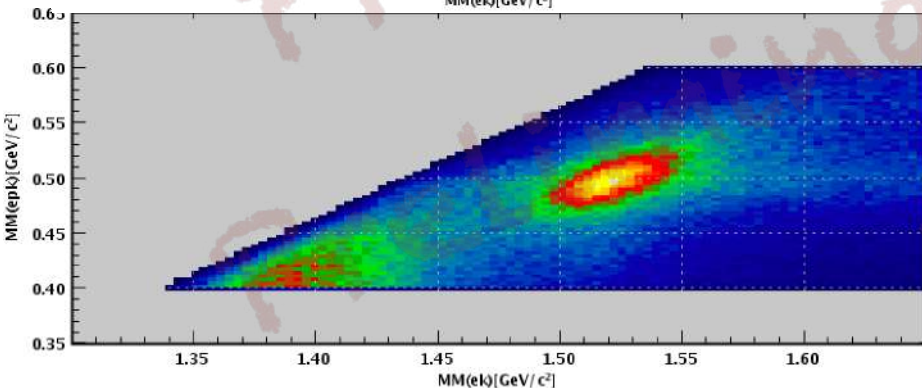
$\Lambda(1520)$

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



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

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 $Q^2 < 5 \text{ GeV}^2$
 - CLAS12 was designed to extend these studies for $0.05 < Q^2 < 12 \text{ GeV}^2$
- The first results of the CLAS12 N^* program have been obtained with the analysis of KY polarization transfer data from the RGK Fall 2018 Run
 - The RGK dataset is 5x larger than the available KY world data in the resonance region
 - Only 10% of expected 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
 - More data have been collected in Spring 2024

And in the future...

- Future work with these data is expected to face up the 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...