

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



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.

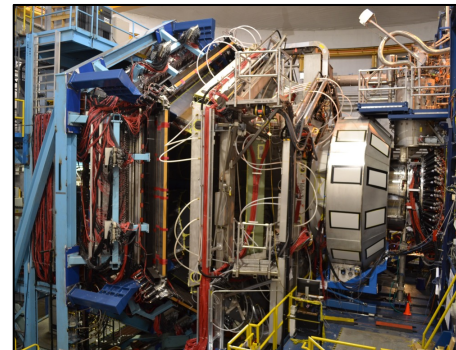
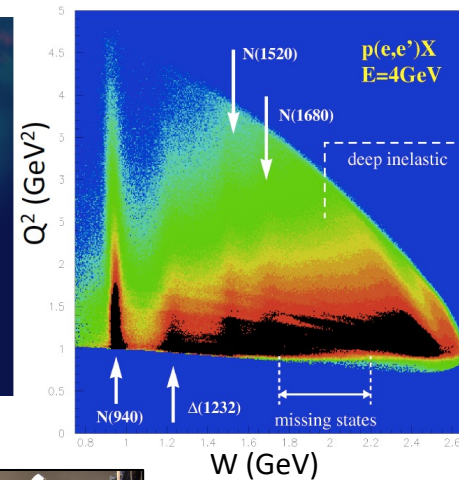
What is the role of glue?

- 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.

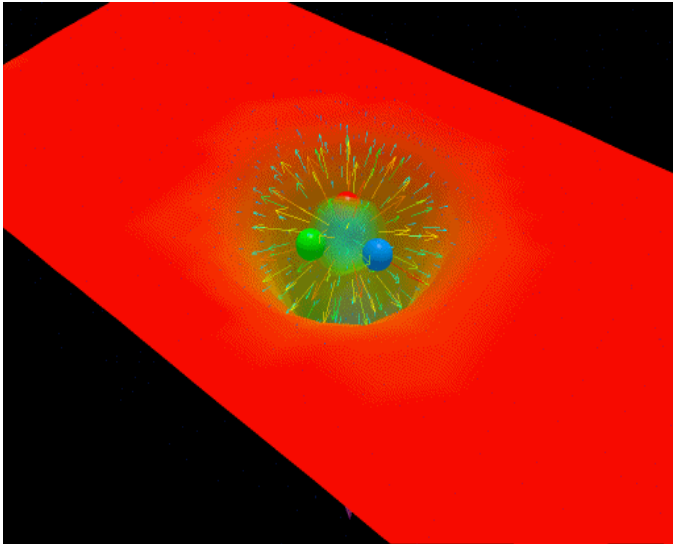
On-going Data Analysis:

- **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.

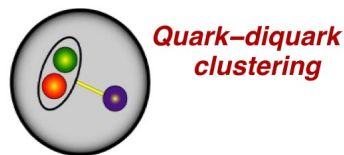
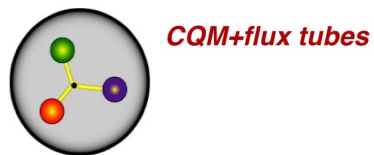
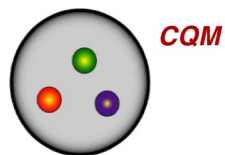
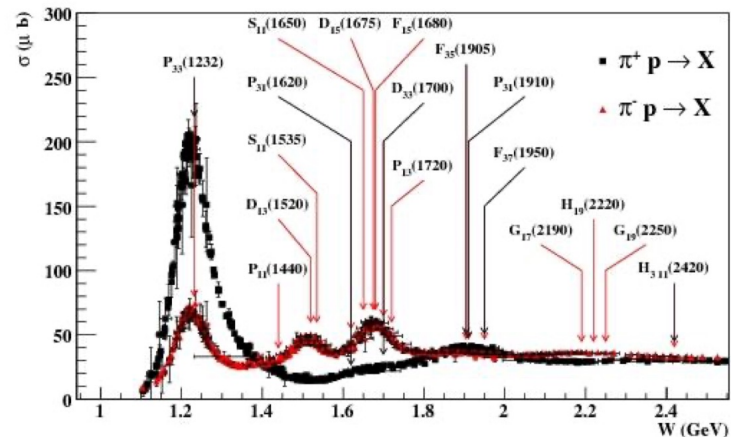
*As such they must be **at the center of any discussion of why the world we actually experience has the character it does.**”*

Nathan Isgur, NStar2000, Newport News, Virginia

➔ **Search for new baryon states**

Why N*? From the N* Spectrum to QCD

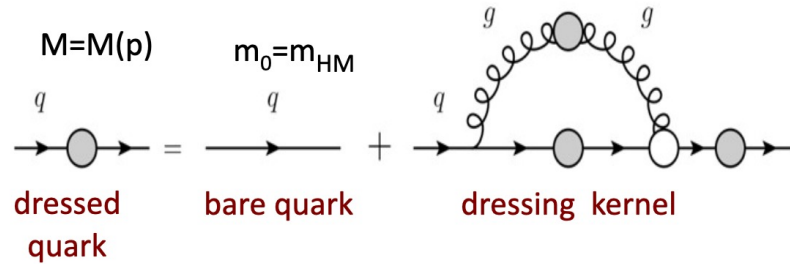
- Understanding the proton's ground state requires understanding its excitation spectrum.
- The N* spectrum reflects the **effective degrees of freedom** and the forces.



→ From the Constituent Quark model to QCD.

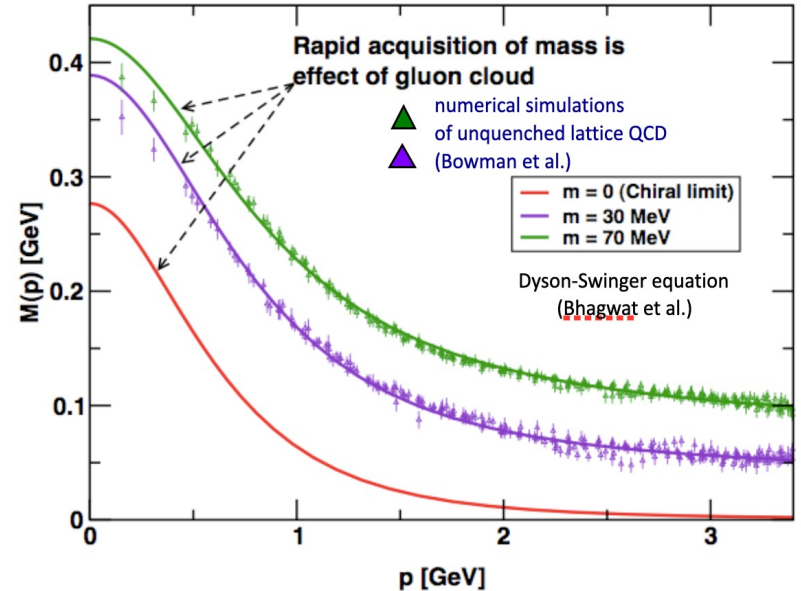
Mass Acquisition

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:

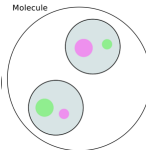
- Baryons with more than 3 valence quarks: **pentaquarks or di-baryons**
- Mesons with more than a quark-antiquark pair: **tetraquarks**

Glueballs:

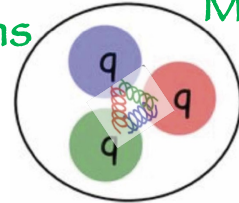
Particles made up of gluonic degrees of freedom only

Molecules...

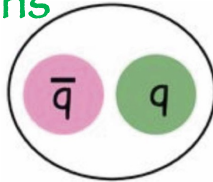
Molecule



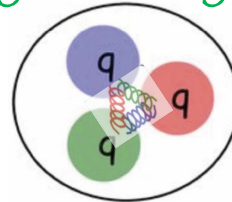
Baryons



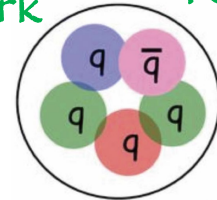
Mesons



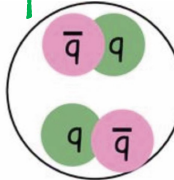
Hybrid baryon



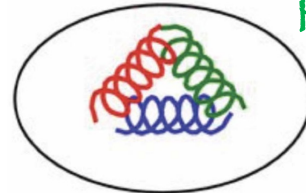
Pentaquark



Tetraquark



Glueball



Hybrid meson

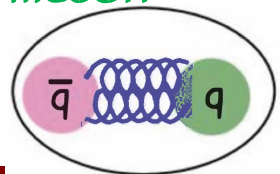


Photo- and Electro- production of mesons on nucleon targets

Meson photo- and electro-
production reactions

for

Light quark baryon
spectroscopy

Two elements provided a crucial boost in the field:

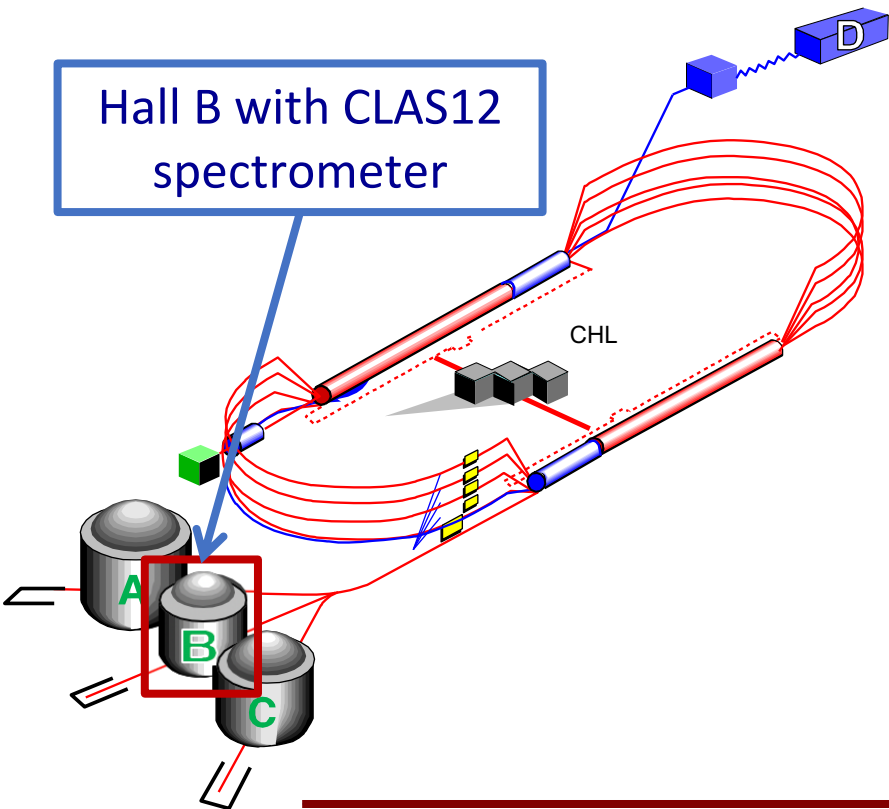
- advent of large solid angle detectors
- polarized beam and targets



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:

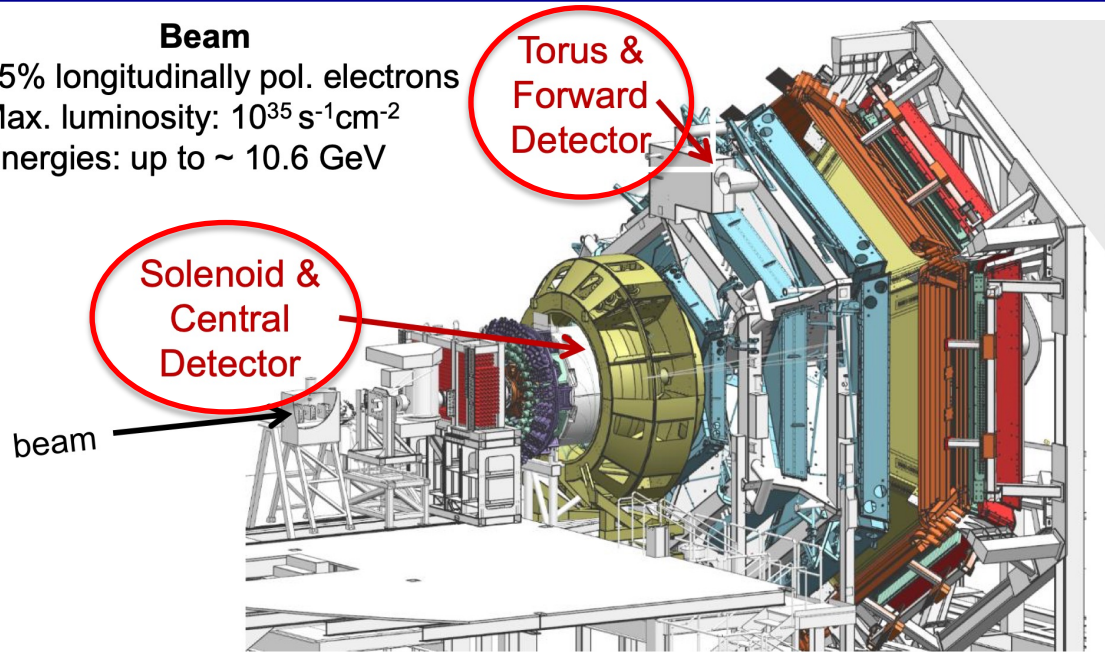
$\pi N, \omega N, \varphi N, \eta N, \eta' N, \pi\pi N, KY, K^*Y, KY^*$



CLAS12

Beam

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

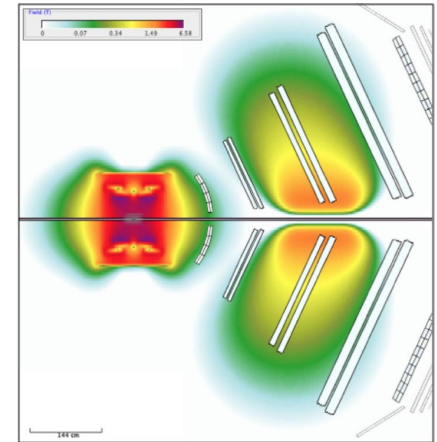


[V.D. Burkert et al., Nucl. Inst. and Meth. A 959, 163419 (2020)]

Targets (org. by Run Groups)

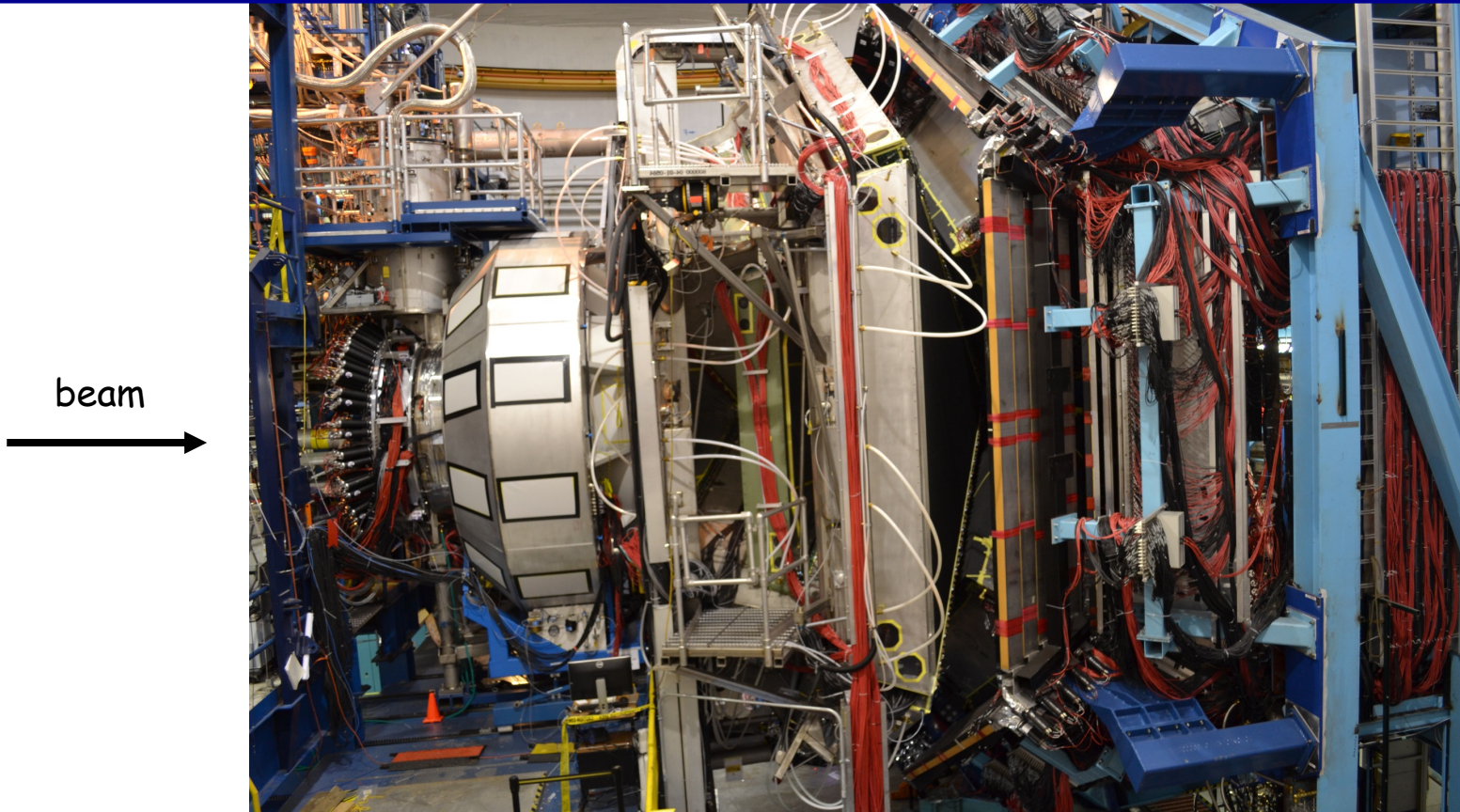
- Proton (RG-A/K)
- Deuteron (RG-B)
- Nuclei (RG-M/D/E)
- Long. pol. NH_3/ND_3 (RG-C)

Magnetic Field

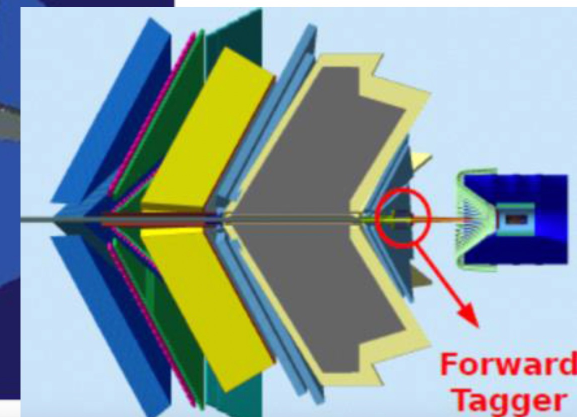
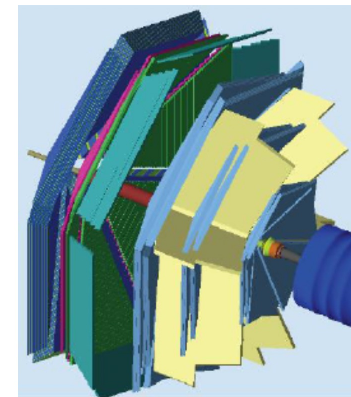
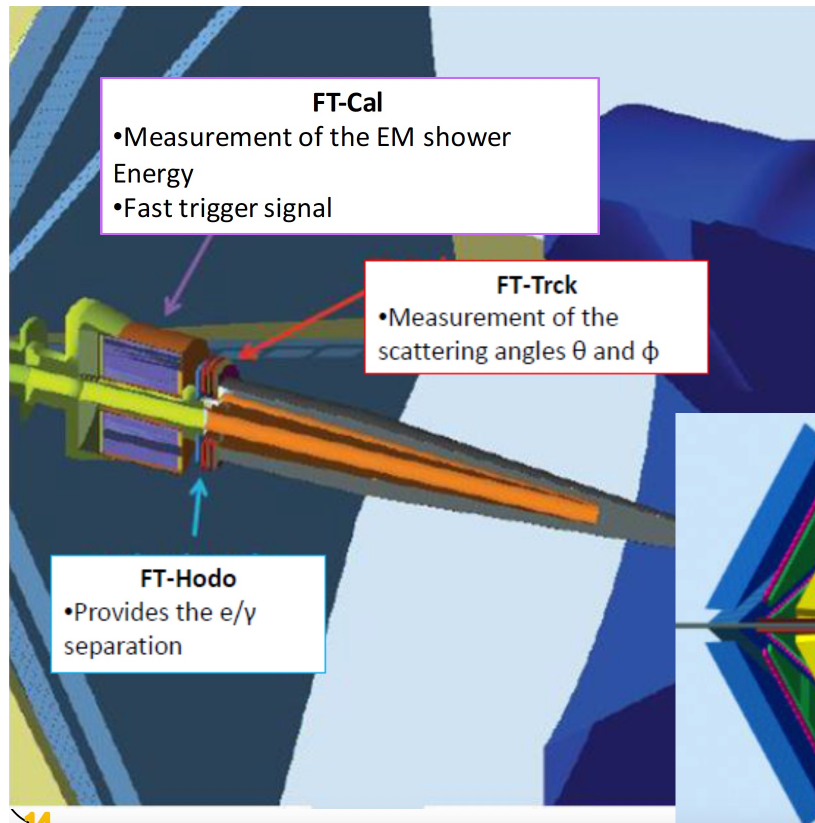
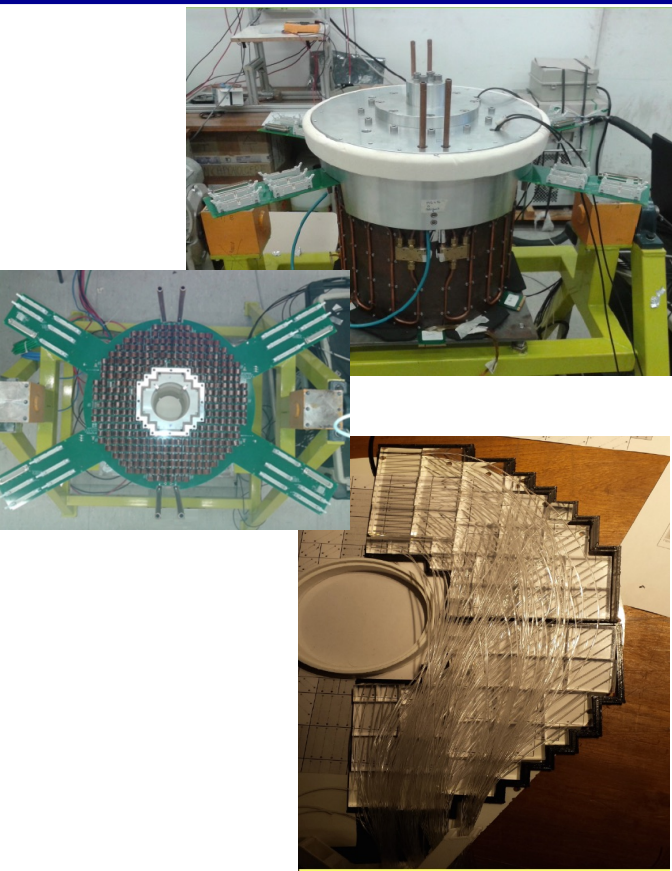


Ideal instrument to study exclusive meson electroproduction
in the nucleon resonance region

CLAS12 Spectrometer



Experimental Setup: Forward Tagger



RGK @ 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 | • $\sim 5 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ @ 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:

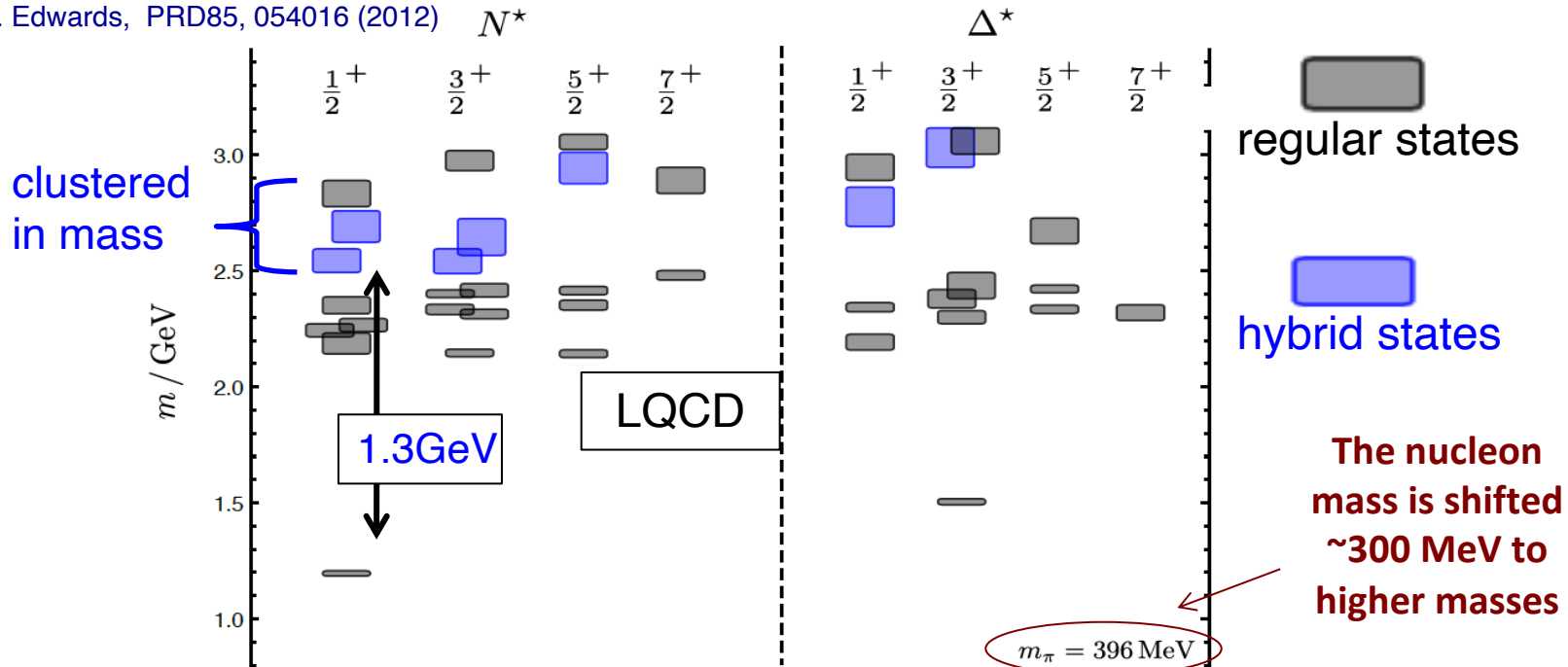
- **Hybrid mesons** $|q\bar{q}g\rangle$ states may have exotic quantum numbers J^{PC} not available to pure $|q\bar{q}\rangle$ states
GlueX, MesonEx, COMPASS, PANDA
- **Hybrid baryons** $|qqqg\rangle$ have the same quantum numbers J^P as $|qqq\rangle$ electroproduction with CLAS12 (Hall B).

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)



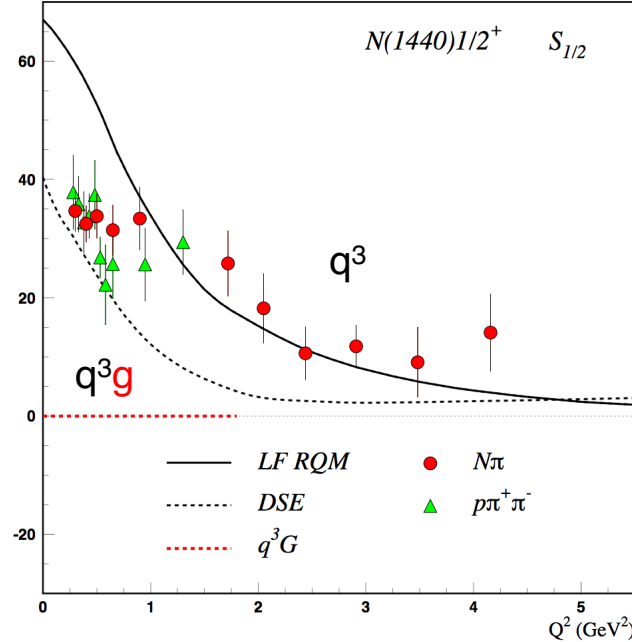
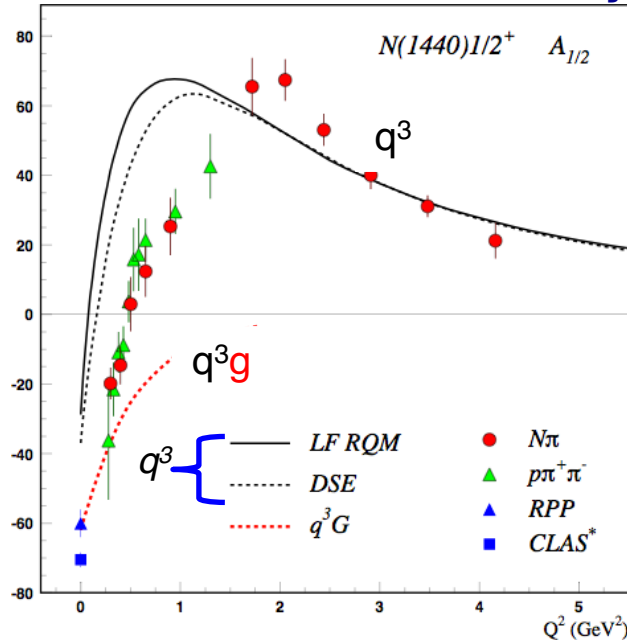
Hybrid states have same J^P values as qqq baryons. How to identify them?

- 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.

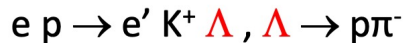
Will CLAS12 data be able to identify gluonic contributions ?



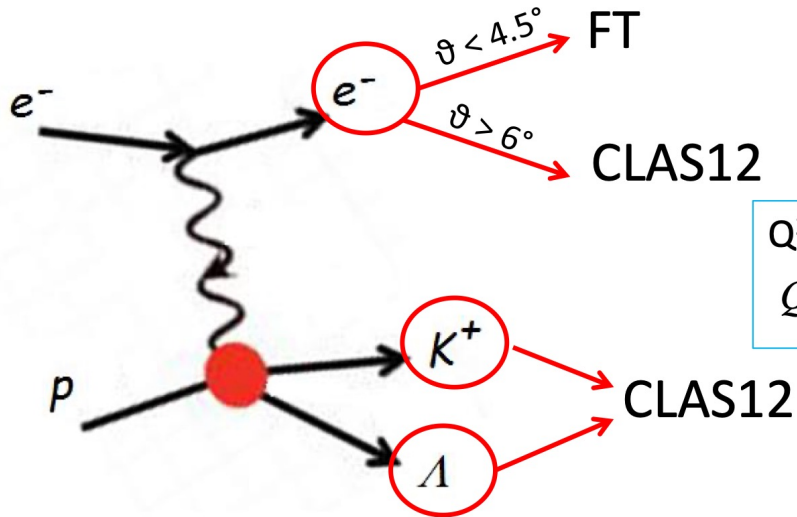
For hybrid “Roper”, $A_{1/2}(Q^2)$ drops off faster with Q^2 and $S_{1/2}(Q^2) \sim 0$.

Hybrid Baryons

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



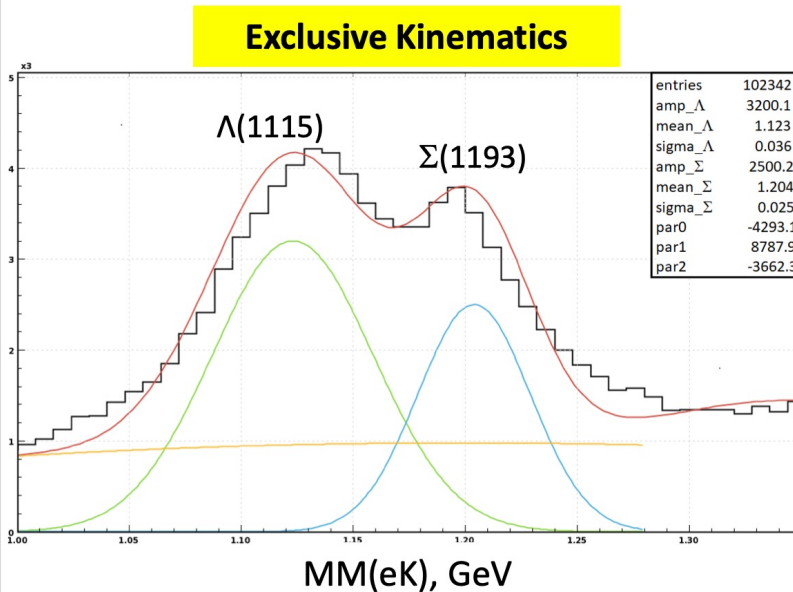
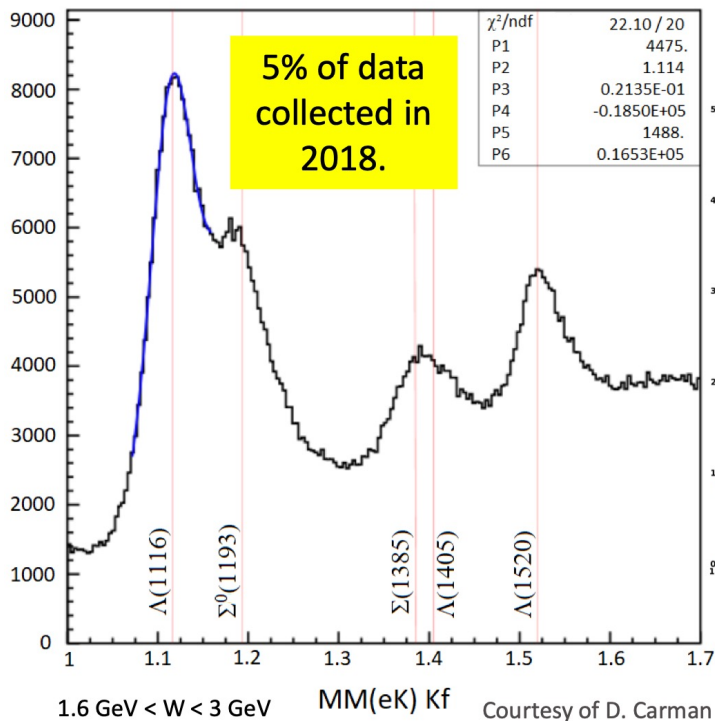
FT allows to probe the **crucial Q^2 range** where hybrid baryons may be identified due to their fast dropping $A_{1/2}(Q^2)$ amplitude and the suppression of the scalar $S_{1/2}(Q^2)$ amplitude.



Q^2 range of interest: 0.05 - 2 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



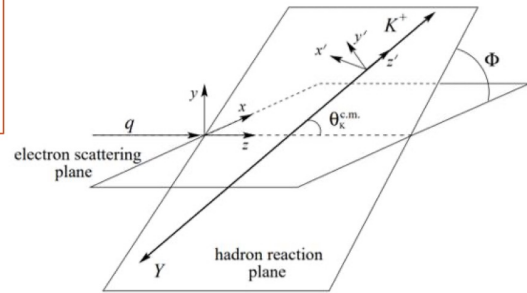
Preliminary results obtained with data collected in 2018

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

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

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

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. Q², W, cos θ_ν^{c.m.}

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

P' = transferred polarization

(x', y', z')

P⁰ = 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 ⁰ _{x'} | 0 |
| P ⁰ _{y'} | K _I (R _T ^{y'0} + εR _L ^{y'0}) |
| P ⁰ _{z'} | 0 |

➡ D. Carman's talk

PHYSICAL REVIEW C 105, 065201 (2022)

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

D. S. Carman,^{40,*} A. D'Angelo,^{18,34} L. Lanza,³⁵ V. I. Mokeev,⁴⁰ K. P. Adhikari,¹⁴ M. J. Amarian,³¹ W. R. Armstrong,¹ H. Atac,³⁶ H. Avakian,⁴⁰ C. Ayerbe Gayoso,⁴² N. A. Balzelli,¹⁰ L. Barton,¹⁰ M. Battaglieri,^{17,41} I. Bedini,²¹ B. Benke,¹⁹ A. Bianconi,^{2,18} A. S. Biselli,¹ M. Bondi,¹ S. Botarino,⁴⁰ F. Bossi,¹⁹ W. J. Briscoe,²³ S. Buehlmann,³¹ D. Bulumulla,^{1,19} V. D. Burkert,⁹ R. Capobianco,¹ J. C. Carvajal,¹ A. Celestano,¹ P. Chatagnon,¹ V. Cheshkov,²⁹ T. Chery,²⁹ G. Ciullo,^{4,19} L. Clark,¹⁹ P. L. Cole,²⁸ M. Costantini,¹⁸ G. Costantini,¹⁸ V. Crede,³⁸ N. Dadyman,¹⁹ R. De Vita,¹⁷ M. DeFurno,²⁹ A. Dea,⁴⁰ S. Diehl,^{1,11} C. Djalaoui,³⁰ R. Dupre,²⁵ M. Echarri,^{1,12} A. El Alaoui,³⁰ L. El Fassi,¹⁸ L. Elouadrhiri,⁴⁰ S. Fegan,⁴⁴ A. Filippi,²⁰ G. Gavalian,⁴⁰ Y. Ghandiyani,⁴¹ G. P. Gilfoyle,¹³ F. X. Girod,³⁰ D. I. Glazier,¹³ A. A. Golbenko,²⁰ R. W. Gothe,²³ Y. Goto,⁴⁰ K. A. Griffioen,⁵ K. Hafidi,¹ H. Hakobyan,^{30,43} M. Hattawy,¹ F. Hausmaninger,⁴⁰ T. B. Hayward,^{4,18} A. Hohari,²³ M. Holtrop,²⁷ Y. Ilieva,¹⁷ D. G. Ireland,¹¹ E. L. Isupov,⁴⁰ H. S. Jo,²³ K. Jo,⁹ D. Keller,⁴⁴ A. Khanal,⁴⁰ A. Kim,¹ W. Kim,²³ V. Klenchenko,⁴⁰ A. Kripko,¹⁷ V. Kubarovsky,⁴⁰ M. Leati,^{2,19} S. Lee,²⁷ P. Lenisa,^{4,15} K. Livingston,¹¹ J. J. D. MacGregor,¹⁷ D. Marchand,²⁰ L. Mariciano,¹⁷ V. Mascagnan,¹⁹ M. Mayer,¹⁹ B. McKimmon,¹ S. Miglio,^{17,19} T. Mineeva,¹ M. Mirzita,²⁰ R. A. Moutongonyi,¹ C. Muñoz Camacho,¹⁹ P. Nadel-Turcosi,⁴⁰ K. Neeganeh,¹ J. Nowak,¹⁹ S. Nicolosi,¹⁷ M. Ojpaske,¹⁷ P. Pandey,¹ M. Paolone,^{28,38} L. L. Pappalardo,^{4,13} R. Paremyazyan,^{27,40} E. Paryuk,⁴⁰ S. J. Paul,¹ N. Pilleux,¹⁵ O. Pogorelec,²¹ J. W. Price,¹ Y. Prok,¹ B. A. Raue,¹ T. Reed,¹ M. Ripani,¹⁷ J. Rimani,²³ A. Rizzo,^{19,29} P. Rossi,⁴⁰ F. Sabatié,¹ C. Salgado,²⁹ A. Schmidt,^{17,29} Y. G. Sharabian,⁴⁰ E. V. Shirokov,⁴⁰ P. Sommering,¹⁷ D. Sokhan,^{13,39} N. Sparrere,⁴⁰ S. Stapanian,⁴⁰ I. I. Strakovsky,¹² S. Strauch,¹ N. Tyler,¹⁷ R. Tyson,¹ M. Ungars,⁴⁰ S. Vallarino,¹³ L. Venturini,^{2,18} H. Voskanyan,⁴¹ E. Voutier,²⁷ D. P. Watts,⁴⁴ K. Wei,⁴⁰ R. Wharton,¹⁷ M. H. Wood,³ B. Yale,⁴² N. Zachariou,⁴⁴ J. Zhang,⁴¹ and V. Ziegler⁴⁰ (CLAS Collaboration)

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²⁵Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

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²⁷University of New Hampshire, Durham, New Hampshire 03824, USA

²⁸New Mexico State University, Las Cruces, New Mexico 88003, USA

²⁹Norfolk State University, Norfolk, Virginia 23504, USA

³⁰Ohio State University, Athens, Ohio 45701, USA

³¹Old Dominion University, Norfolk, Virginia 23529, USA

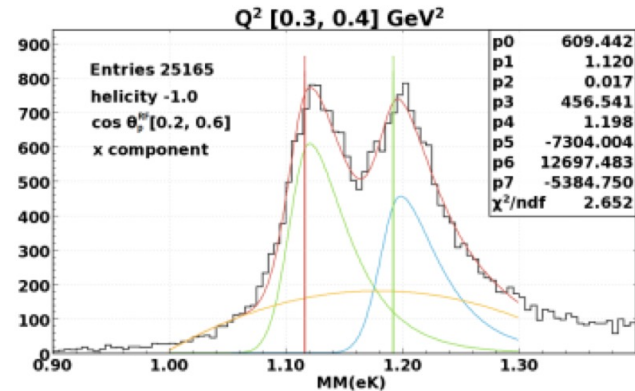
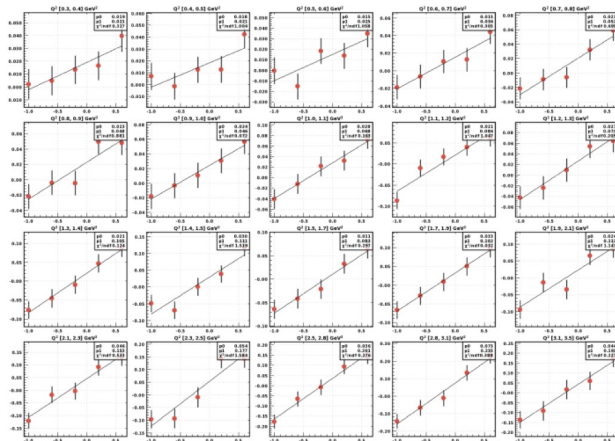
*Corresponding author: carman@jlab.org

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

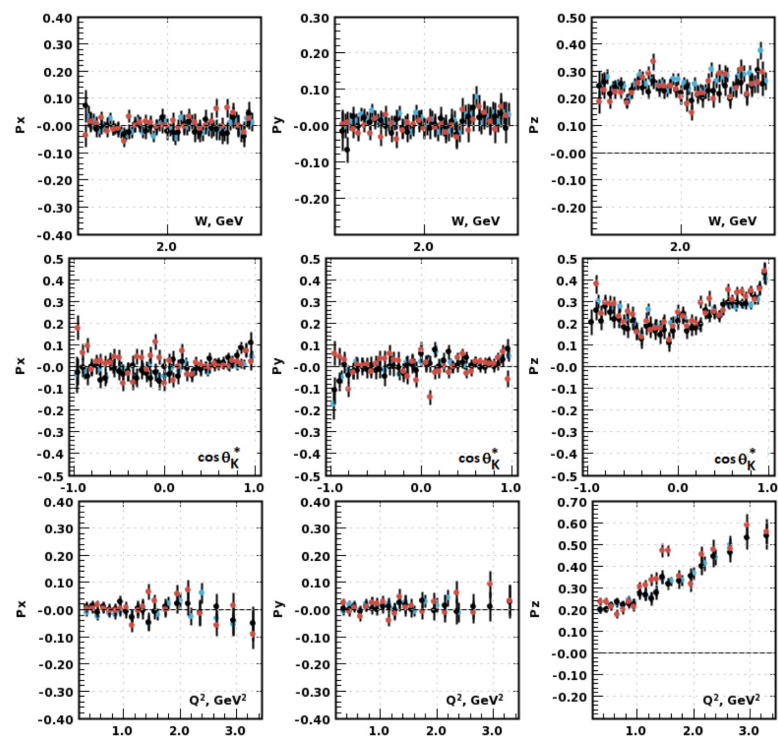
$$A = \frac{N^+ - N^-}{N^+ + N^-} = \nu_Y \alpha_\Lambda P_b P'_Y \cos \theta_p^{RF}$$

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...



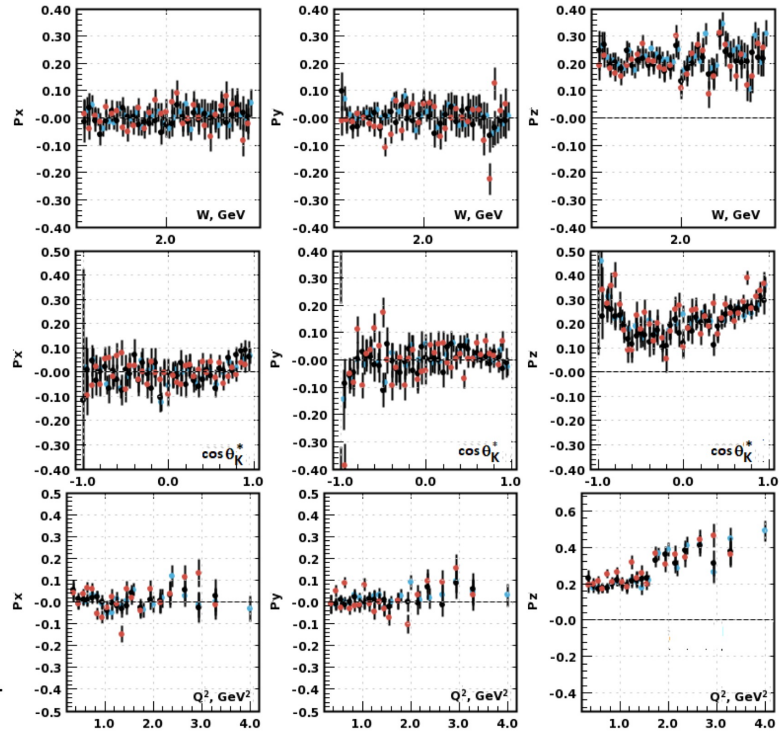
... and the number of Λ events was extracted using a fit of the $MM(eK^+)$ spectrum

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



6.5 GeV

P'

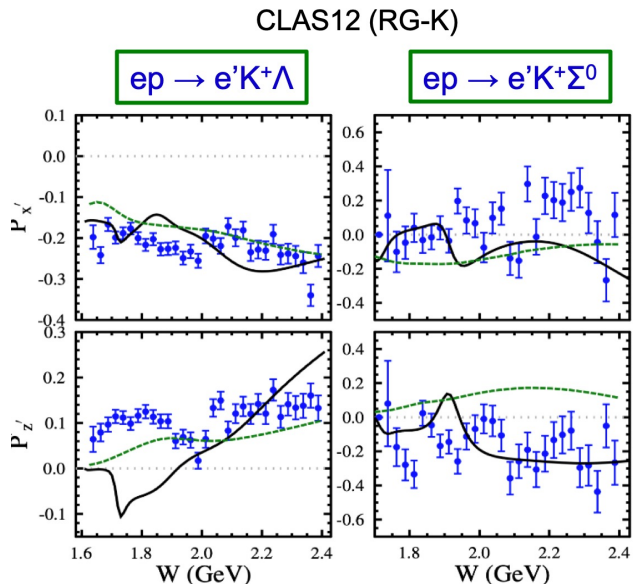


7.5 GeV

Blue dots : Approach 1
Red dots : Approach 2

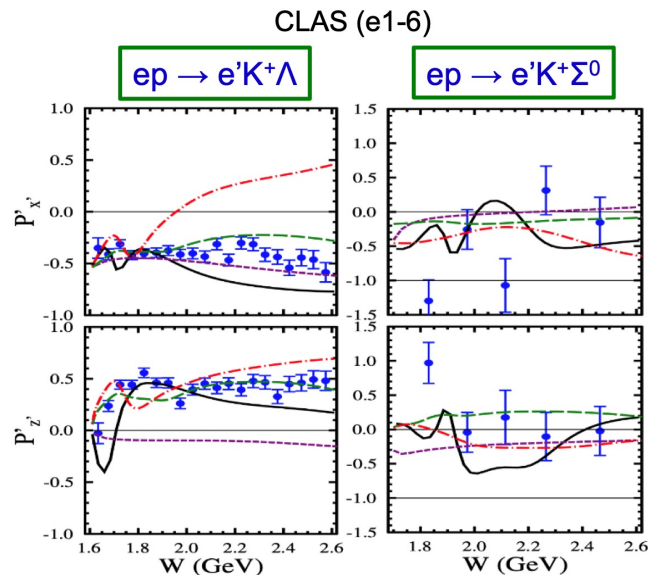
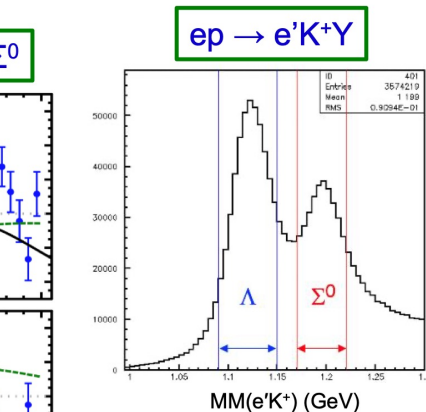
Black dots : Approach 1 (different fitting procedure)

K⁺Y Transferred Polarization CLAS12 vs. CLAS



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

KAON-MAID
RPR



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

Mart/Bennhold
RPR-1

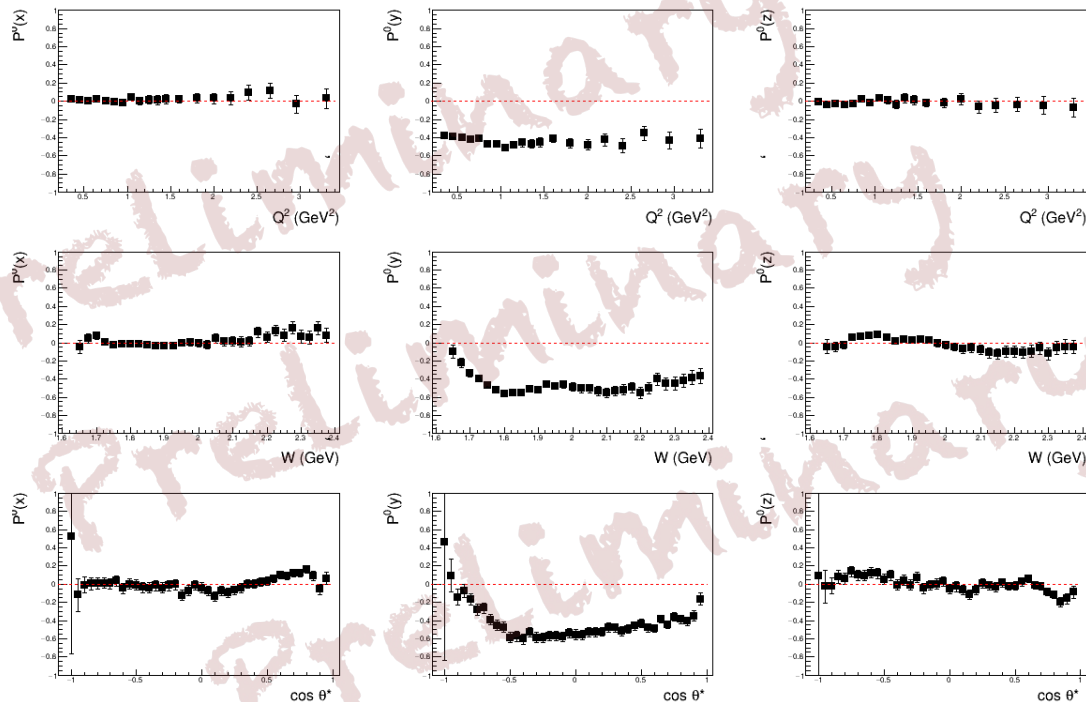
RPR-2
Regge

World data set will get extended
by orders of magnitude

➡ 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 | | 0 |
| P_y^0 | $K_I(R_T^{y'0} + \epsilon R_L^{y'0})$ | | $\frac{1}{2} \sqrt{\epsilon(1+\epsilon)} K_I (R_{LT}^{z'0} \cos \theta_K^{z'm} + R_{LT}^{y'0} \sin \theta_K^{z'm})$ |
| P_z^0 | 0 | | 0 |

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

 D. Carman's talk

$\Lambda(1520)$

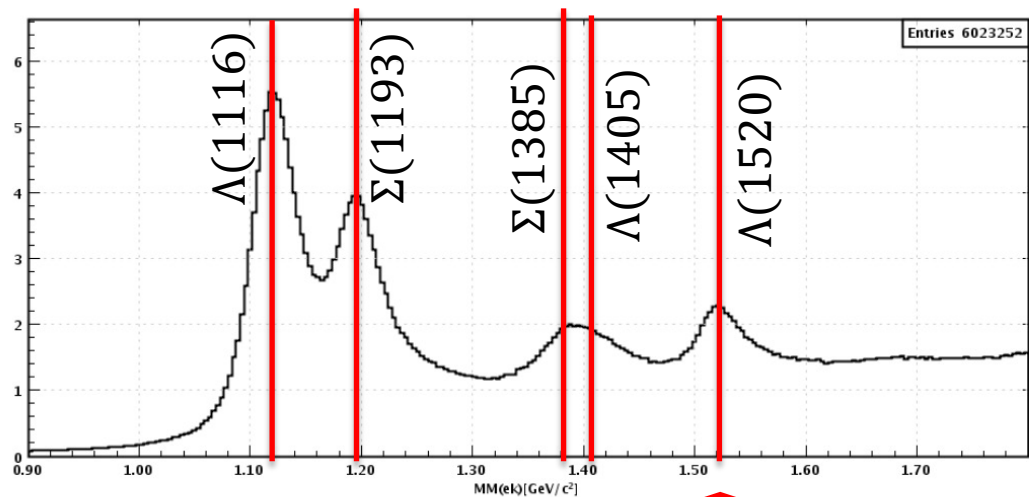
kFWD pFWD

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

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

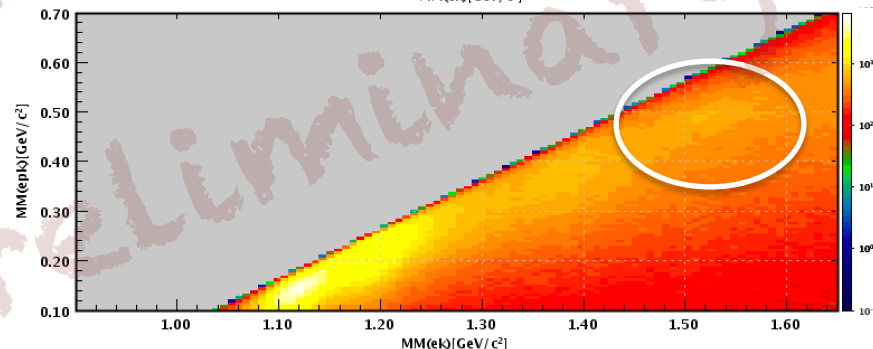
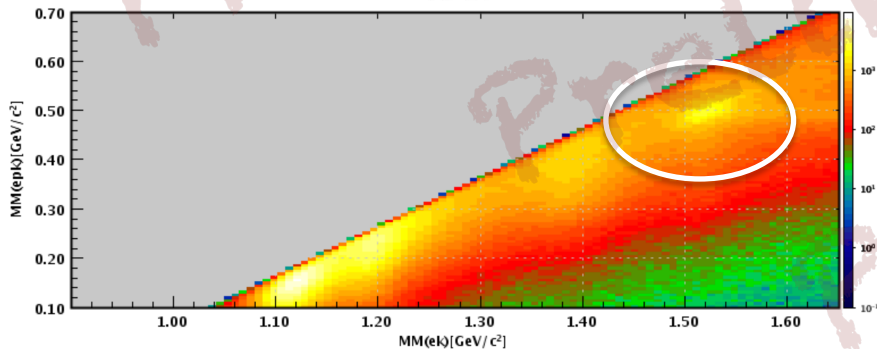
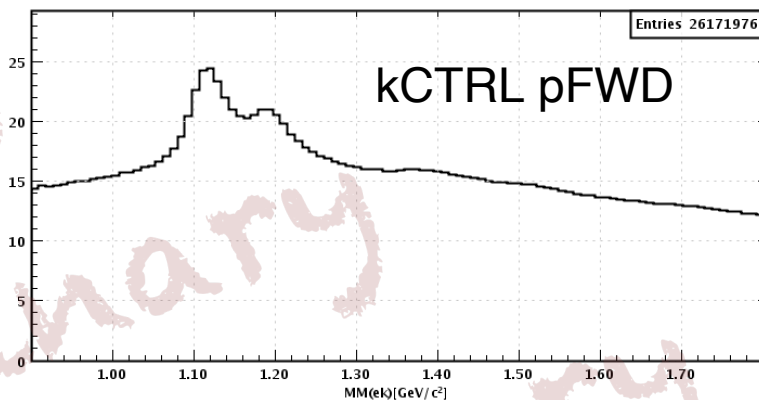
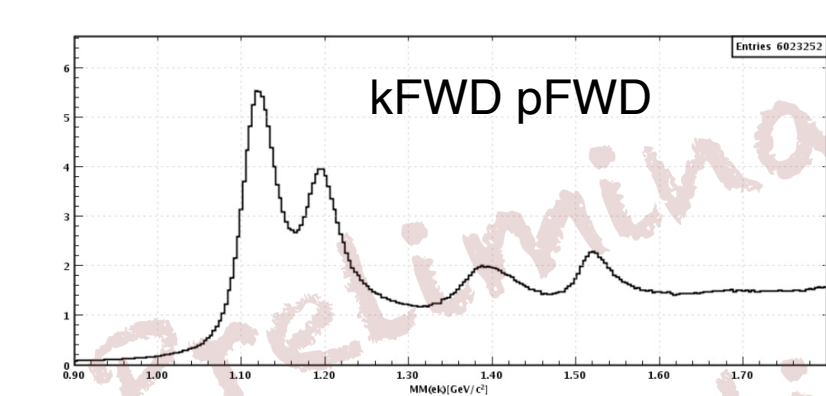
The existence of several nonstrange N^* resonances with significant ($\sim 5\%$) branching ratios into the decay channel $K^+\Lambda(1520)$ has been predicted

- 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

$\Lambda(1520)$

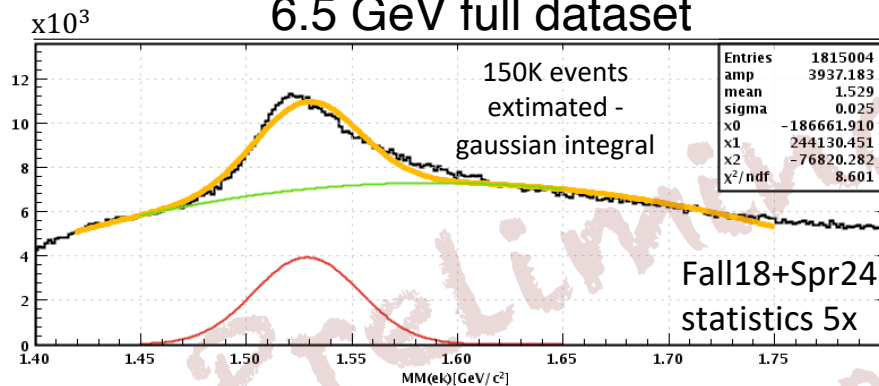


Five structures: $\Lambda(1116)$, $\Sigma^0(1193)$, $\Sigma(1385)$, $\Lambda(1405)$, $\Lambda(1520)$

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

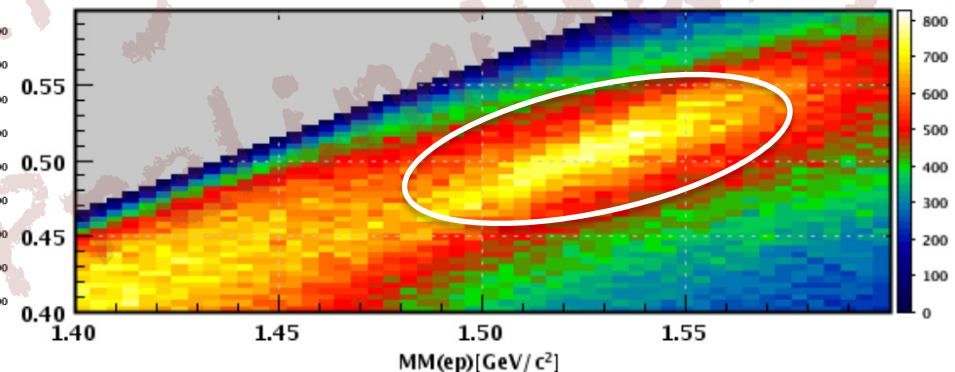
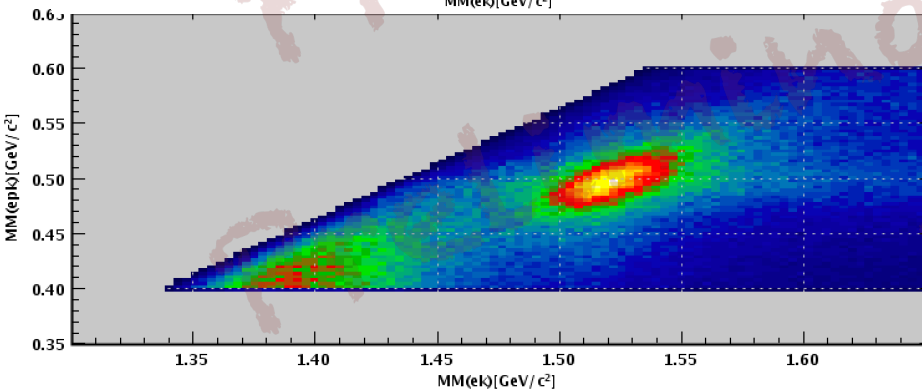
$\Lambda(1520)$

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...

Summary and Outlook

Summarizing:

- The study of N^* states is one of the **crucial topics** of the CLAS and CLAS12 programs:
 - CLAS has produced a huge amount of data up to Q2 5 GeV2
 - CLAS12 was designed to extend these studies for 0.05 Q2 12 GeV2
- The first results of the CLAS12 N^* program have been published in the form of a preprint. The data were transferred from the RGK Fall 2018 Run:
 - The RGK dataset is 5x larger than the CLAS dataset
 - Only 10% of expected statistics** were collected
- On going analyses:
 - First paper on the N^* program** is being prepared
 - Other analyses are progressing well
 - More data are being collected

And in the future

- Future work will focus on the most challenging problems of the Standard Model on the nature of confinement, and the emergence of N^* states from quarks and gluons

THANK YOU FOR
THE ATTENTION!

Stay tuned for further updates...