QNP 2024

QNP2024 – The 10° International Conference on Quarks and Nuclear Physics,
Facultat de Biologia, Universitat de Barcelona, Spain, 8 – 12 July 2024

N* studies using KY Electroproduction at CLAS12

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e- JLab12

clas

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Outline

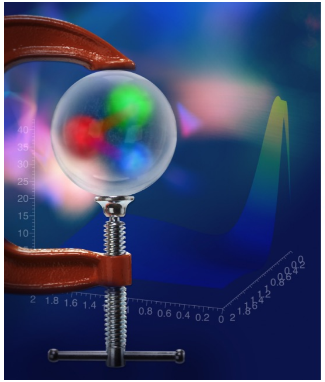
Physics Motivation: Study of the nucleon excitation spectrum to understand the dynamical properties of QCD in the non-perturbative regime.

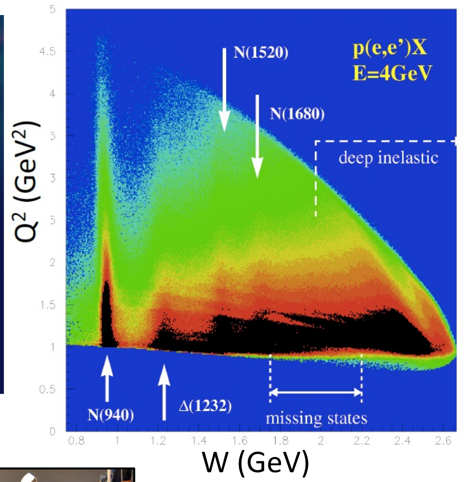
What is the role of glue?

- 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

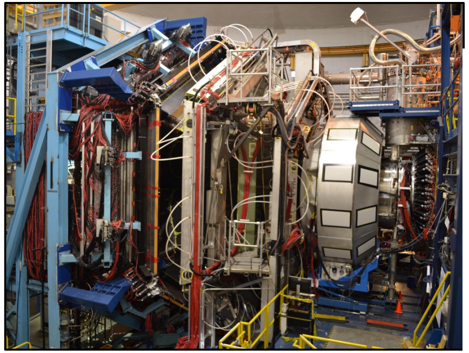




CLAS12 and Forward Tagger (FT) @ JLab: Experimental Setup description.

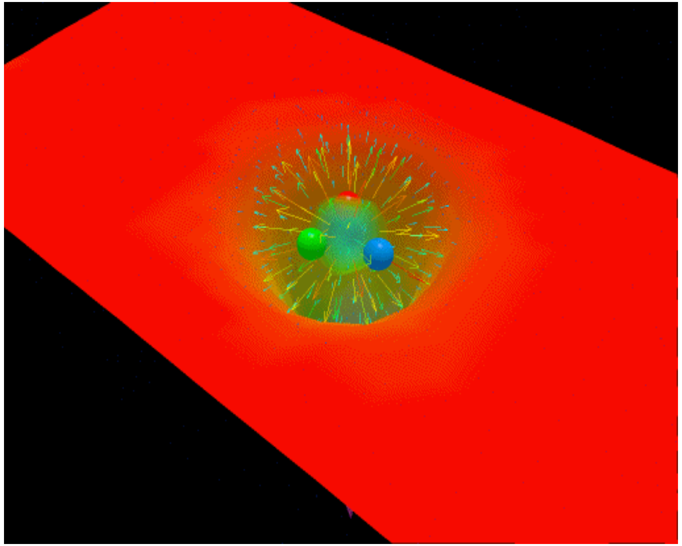
On-going Data Analysis:

- **Results from Physics Runs**: ep -> 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.****"*

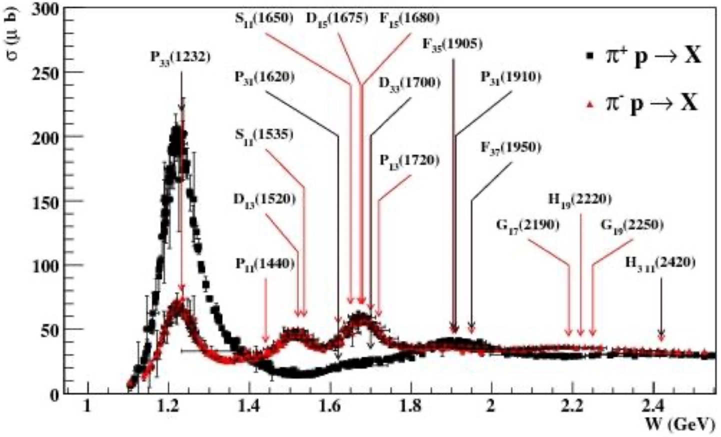
Nathan Isgur, NStar2000, Newport News, Virginia

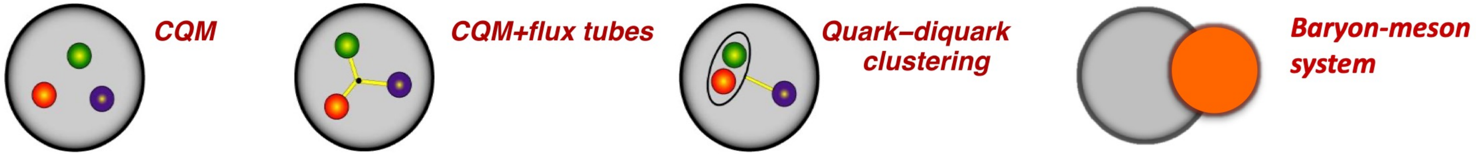
→ **Search for new baryon states**

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.

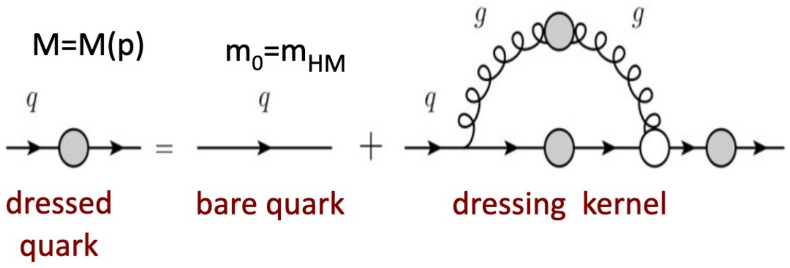




⟶ From the Constituent Quark model to QCD.

Mass Acquisition

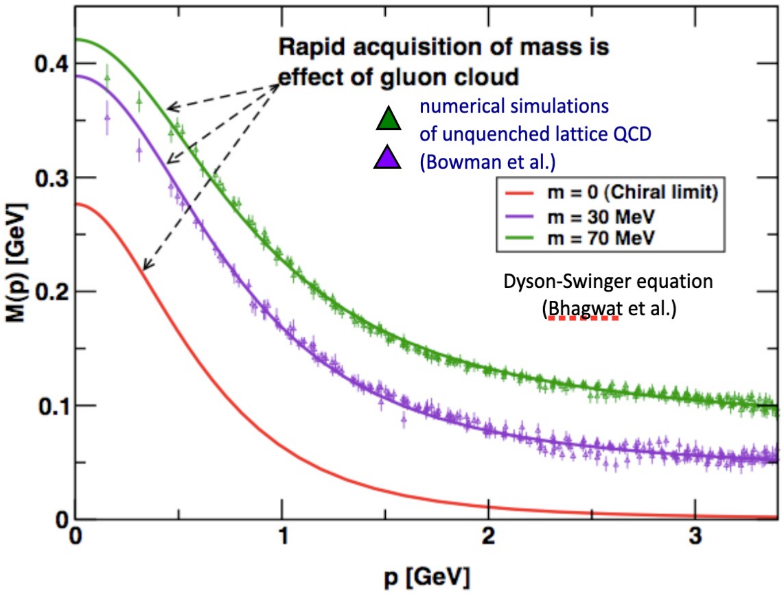
Effective quark mass depends on its momentum



<u>mass composition</u>

<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

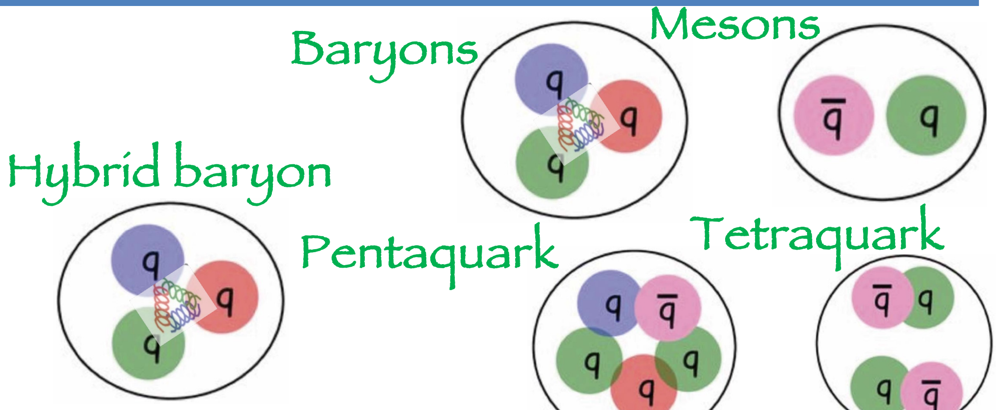
Exotic Hadrons ⇨ Meson and baryon states whose properties cannot be described in terms of q anti-q or qqq degrees of freedom only

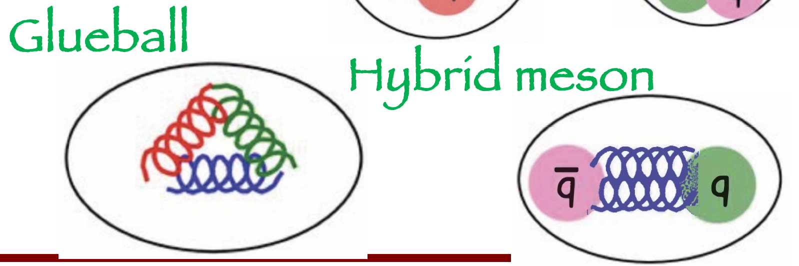
Hybrid mesons/baryons:
qqq or $q\bar{q}$ valence quarks plus a valence gluon

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…





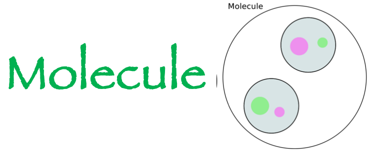


Photo- and Electro- production of mesons on nucleon targets

Meson photo- and electro-production reactions

for

Light quark baryon spectroscopy

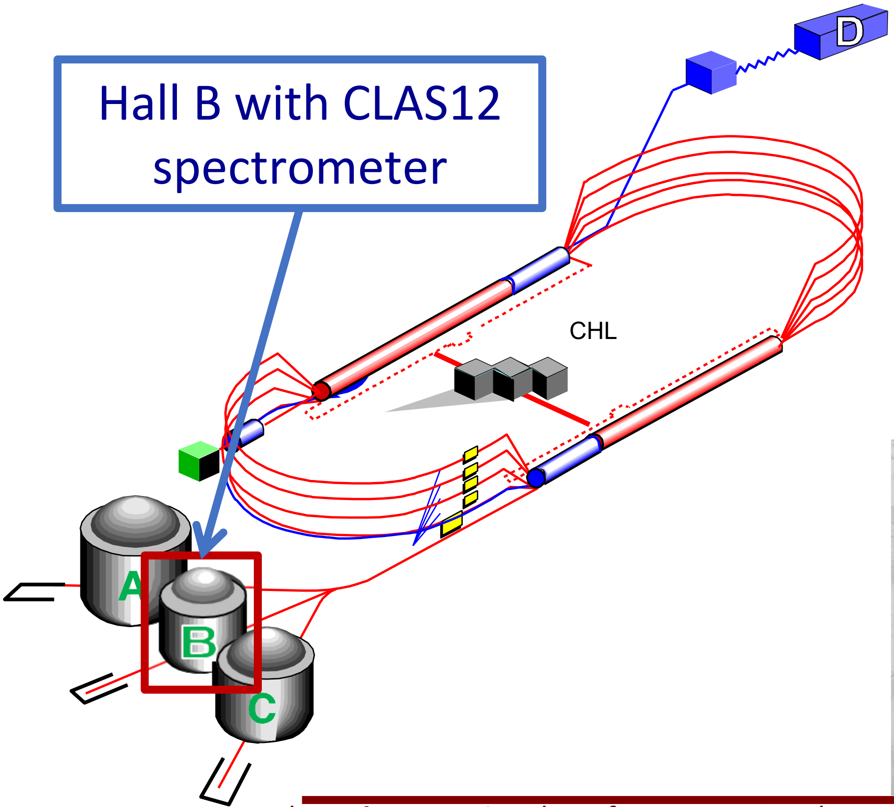
Two elements provided a crucial boost in the field:

- 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

Hall B with CLAS12 spectrometer



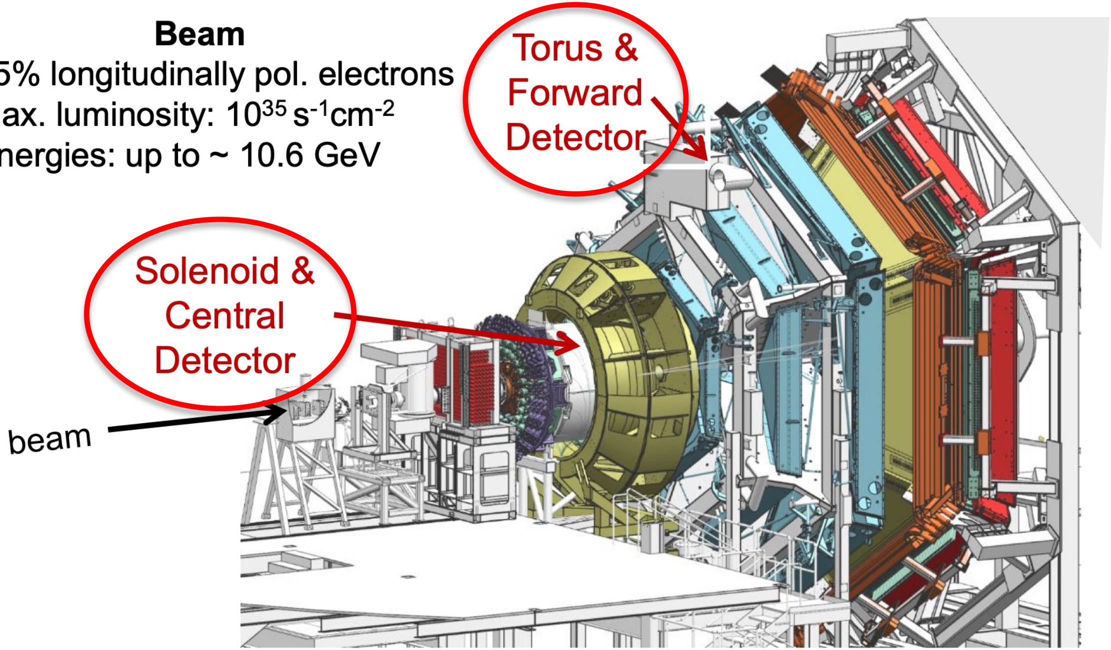
The N* program is one of the Hall B fundamental

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

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

CLAS12

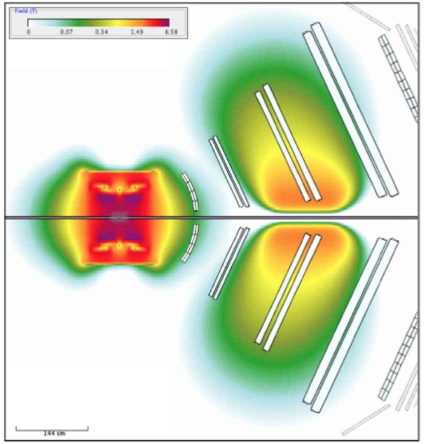
Beam
- 85% longitudinally pol. electrons
- Max. luminosity: $10^{35}\ s^{-1}cm^{-2}$
- Energies: up to ~ 10.6 GeV



[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)

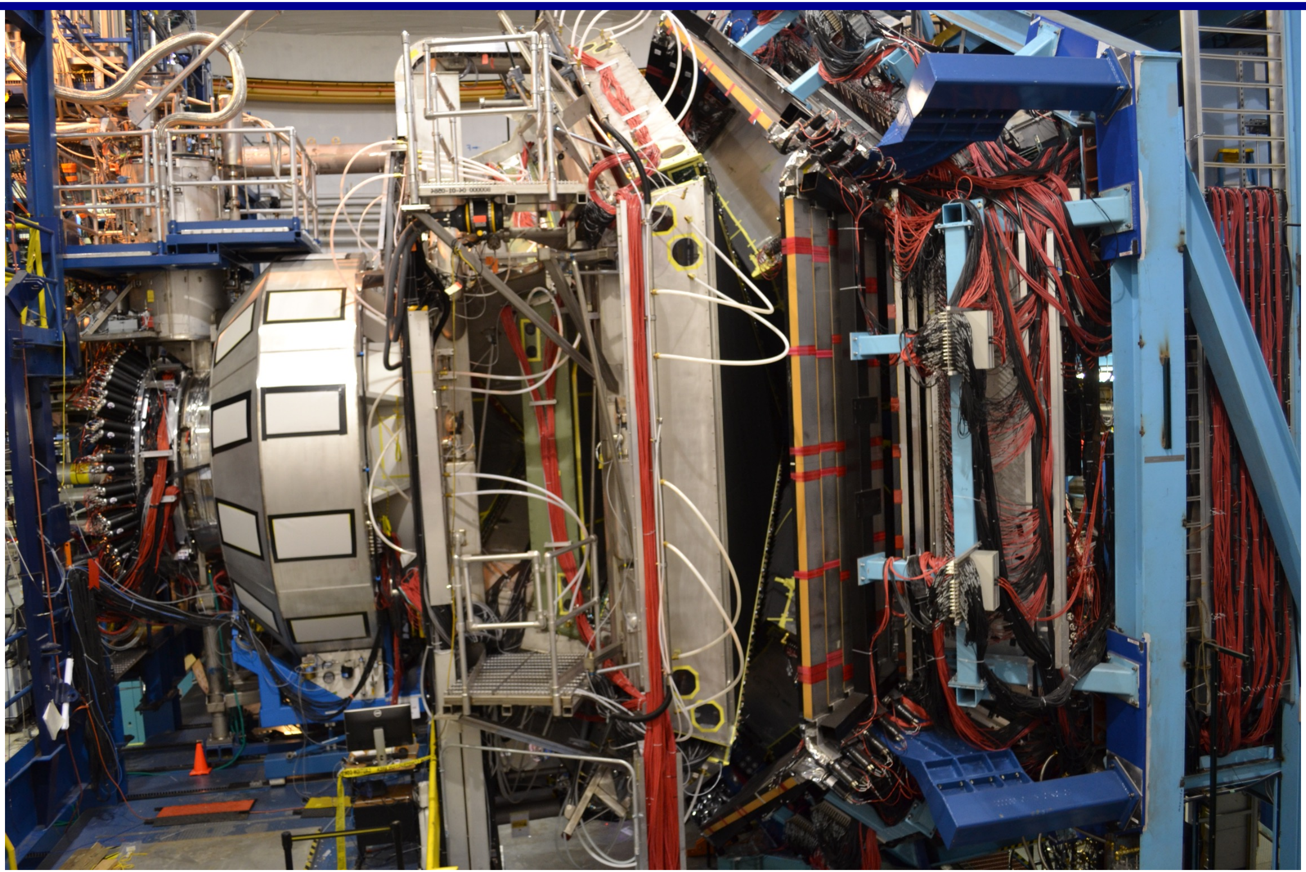
Magnetic Field



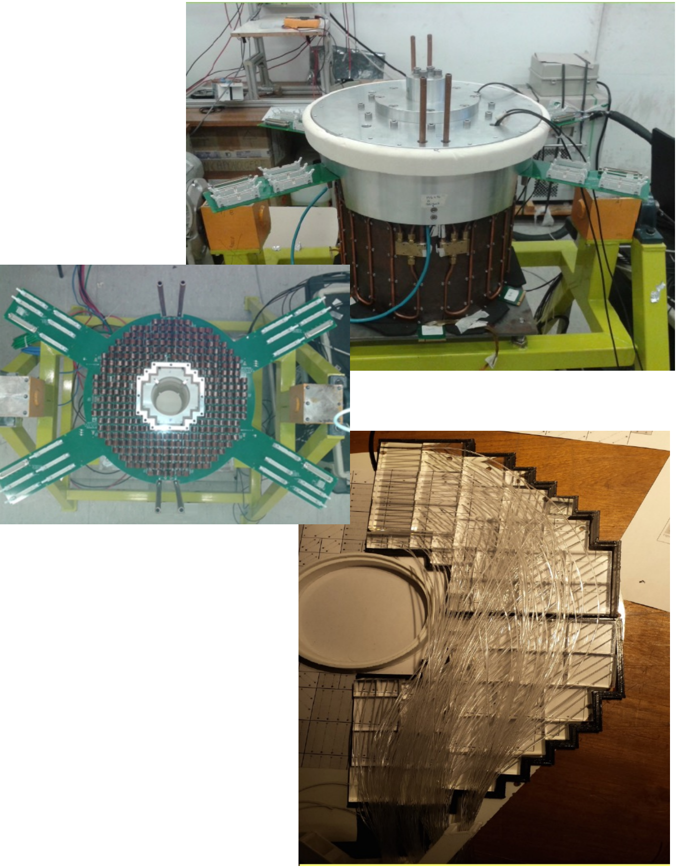
Ideal instrument to study exclusive meson electroproduction in the nucleon resonance region

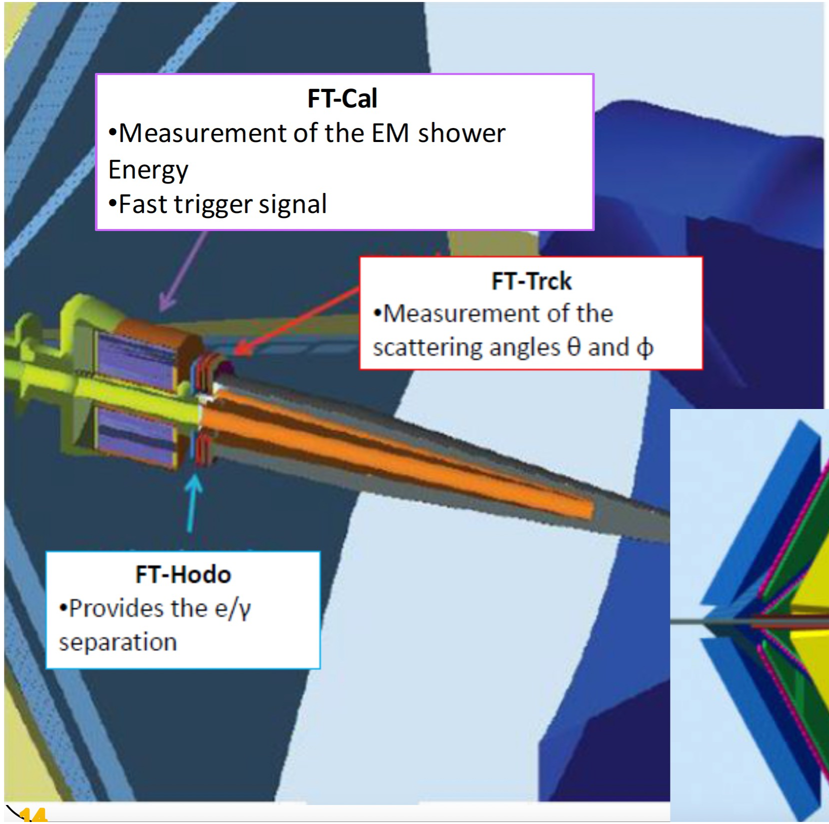
CLAS12 Spectrometer

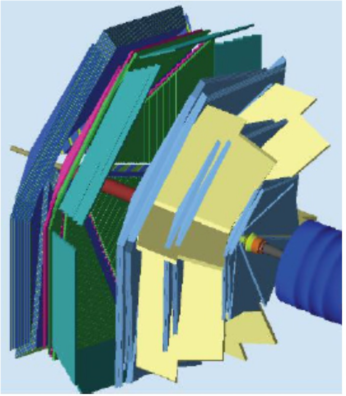
beam →

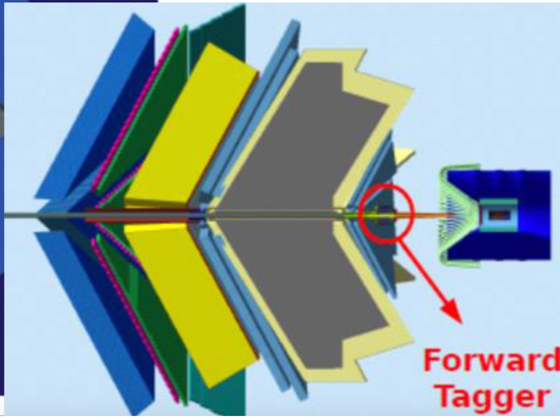


Experimental Setup: Forward Tagger









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	• ~ 5 10^{34} $cm^{-2}s^{-1}$ @ 7.5 GeV ~ 0.87 10^{34} $cm^{-2}s^{-1}$ @ 6.5 GeV 0.87 10^{35} $cm^{-2}s^{-1}$ @ 6.4 GeV 10^{35} $cm^{-2}s^{-1}$@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** $|q\bar{q}g>$ states may have exotic quantum numbers J^{PC} not available to pure $|q\bar{q}>$ states
  GlueX, MesonEx, COMPASS, PANDA ….

- **Hybrid baryons** |qqqg> have the same quantum numbers J^P as |qqq> electroproduction with CLAS12 (Hall B).

Theoretical predictions:

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

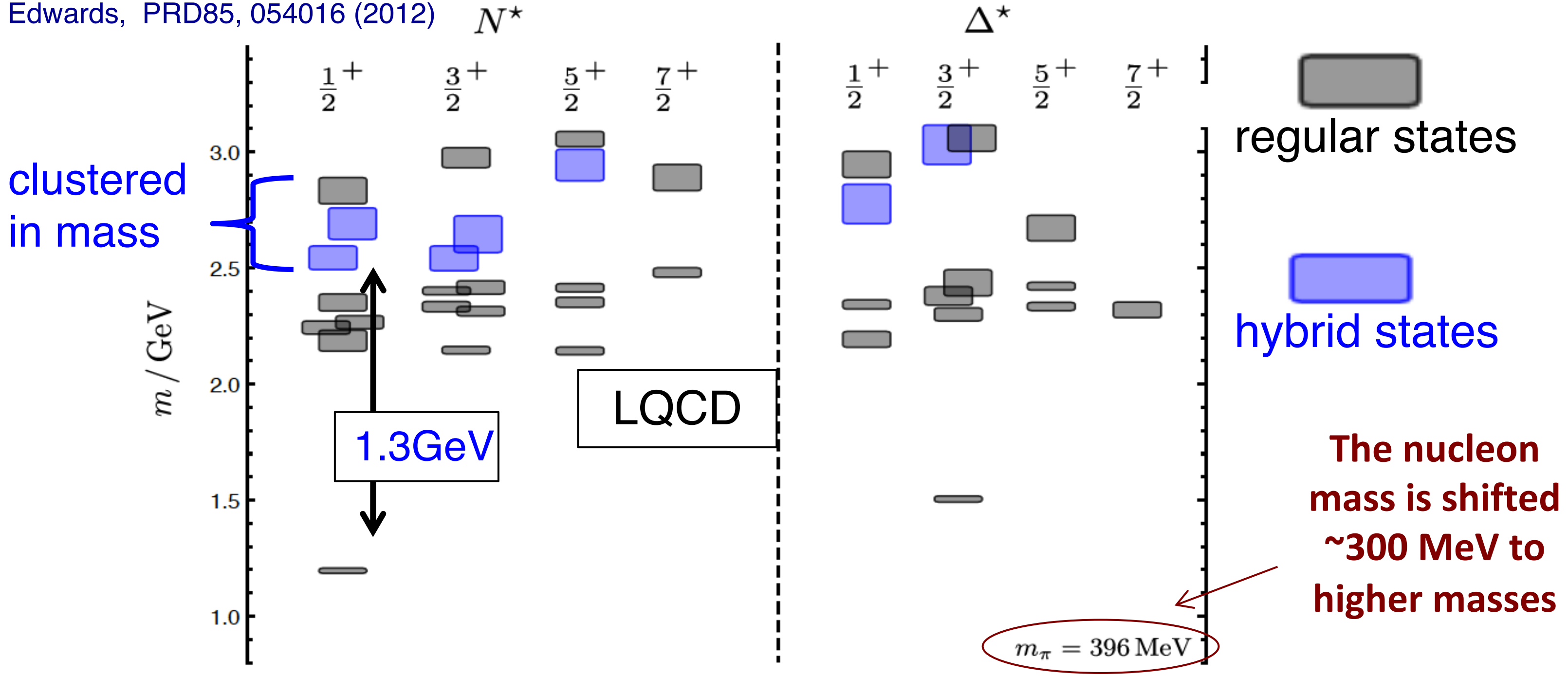
✧ QCD Sum Rule - L. Kisslinger and Z. Li, Phys. Rev. D 51, R5986 (1995).

✧ 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)



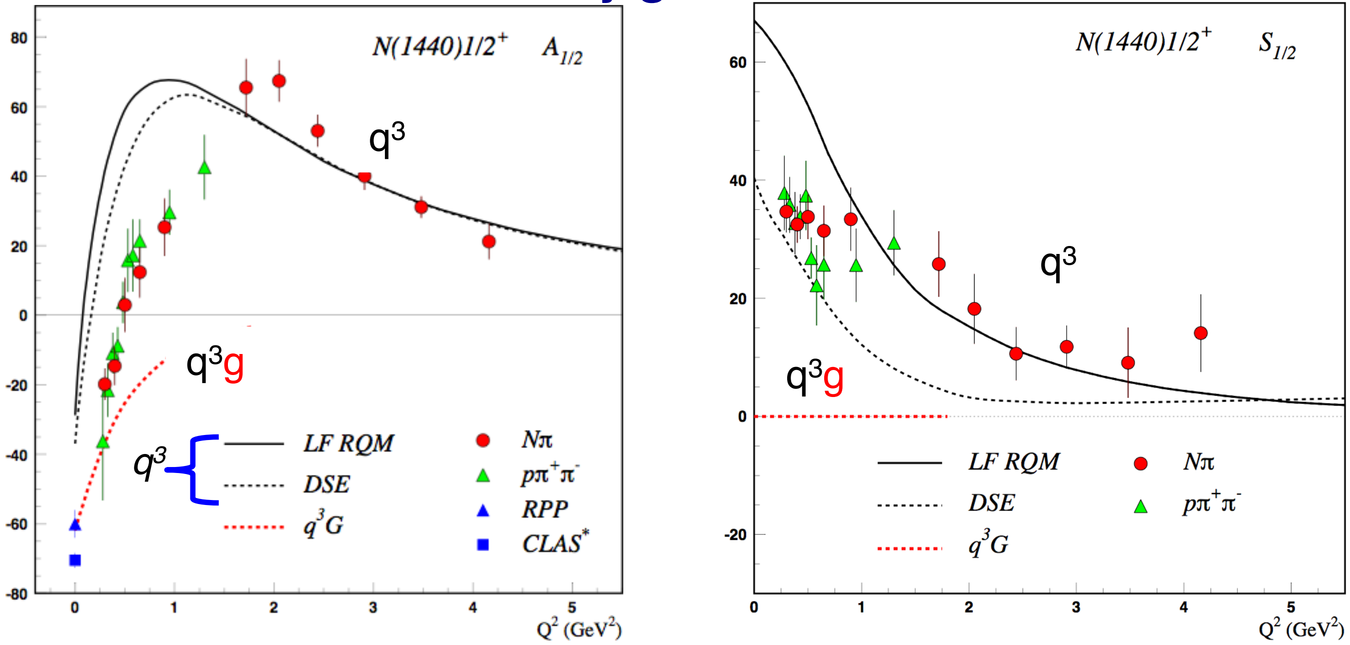
Hybrid states have same J^P values as qqq baryons. How to identify them?

- 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 ?



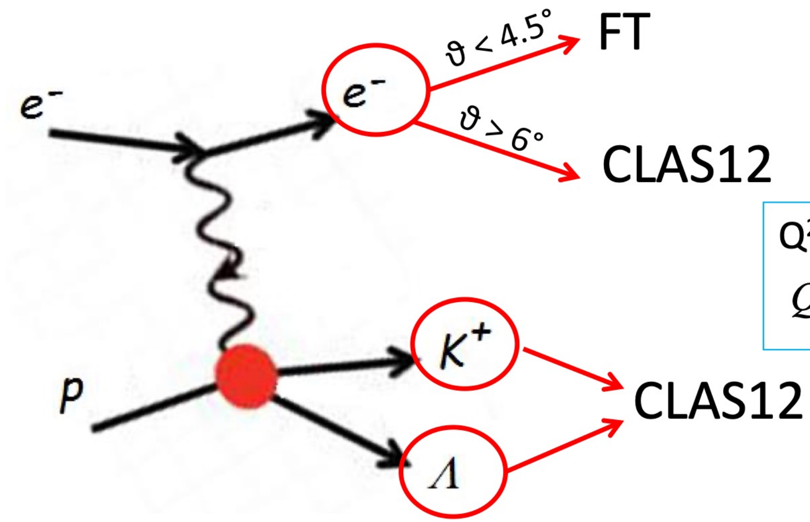
For hybrid "Roper", $A_{1/2}(Q^2)$ drops off faster with Q^2 and $S_{1/2}(Q^2) \sim 0$.

KY channel, low Q^2 region

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

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

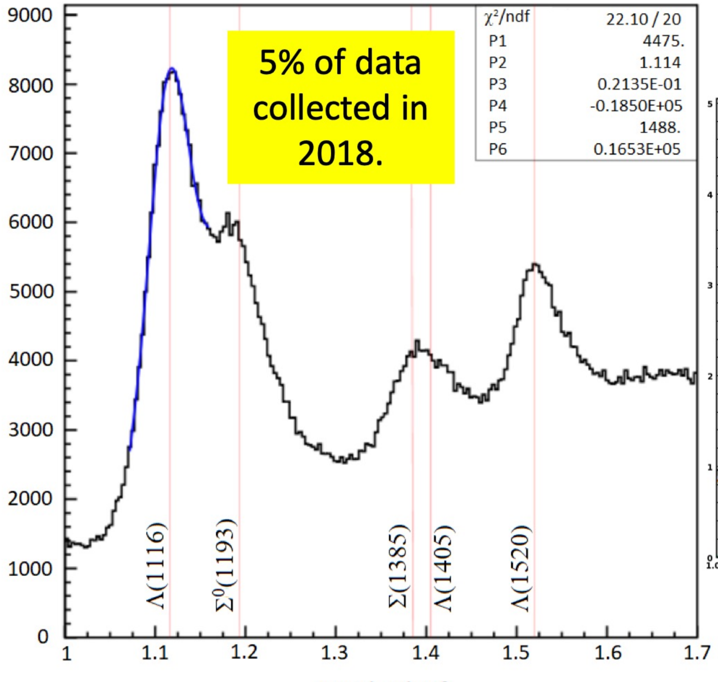
FT allows to probe the **crucial Q^2 range** where hybrid baryons may be identified due to their fast dropping $A_{1/2}(Q^2)$ amplitude and the suppression of the scalar $S_{1/2}(Q^2)$ amplitude.



Q^2 range of interest: 0.05 - 2 GeV^2

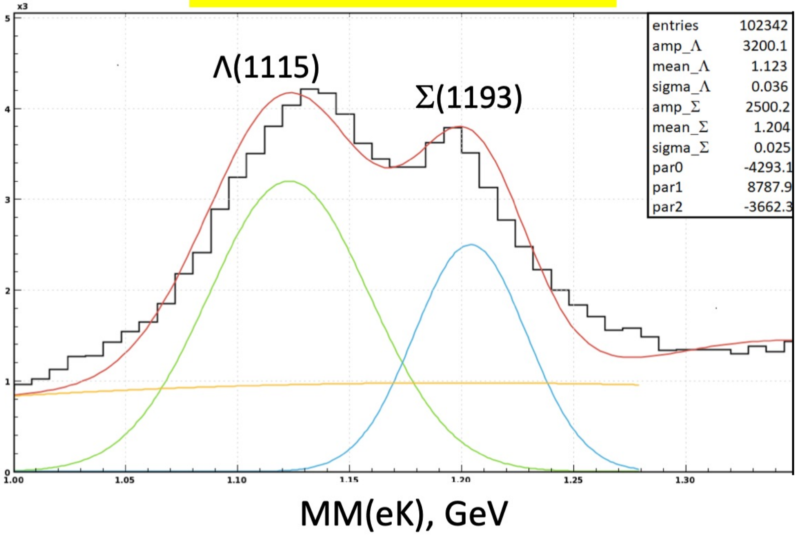
$$Q^2 = 4E_{Beam}E_{e'}\sin^2\frac{\vartheta}{2} \Rightarrow \vartheta < 5°$$

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



1.6 GeV < W < 3 GeV MM(eK) Kf Courtesy of D. Carman

Exclusive Kinematics

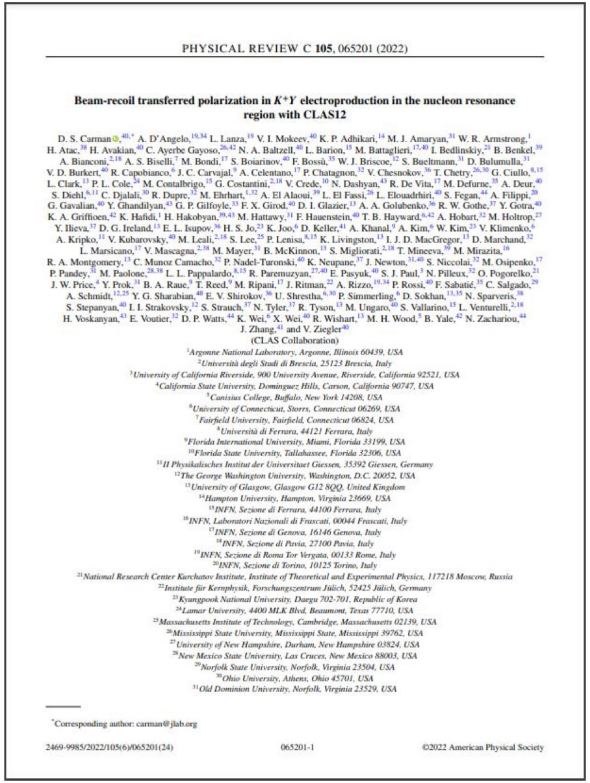


Preliminary results obtained with data collected in 2018

p(e,e'K⁺)X

E_{beam} = 7.546 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,[40,*] A. D'Angelo,[19,34] L. Lanza,[19] V. I. Mokeev,[40] K. P. Adhikari,[14] M. J. Amaryan,[31] W. R. Armstrong,[1] H. Atac,[38] H. Avakian,[40] C. Ayerbe Gayoso,[26,42] N. A. Baltzell,[40] L. Barion,[15] M. Battaglieri,[17,40] I. Bedlinskiy,[21] B. Benkel,[39] A. Bianconi,[2,18] A. S. Biselli,[7] M. Bondi,[17] S. Boiarinov,[40] F. Bossù,[35] W. J. Briscoe,[12] S. Bueltmann,[31] D. Bulumulla,[31] V. D. Burkert,[40] R. Capobianco,[6] J. C. Carvajal,[9] A. Celentano,[17] P. Chatagnon,[32] V. Chesnokov,[36] T. Chetry,[26,30] G. Ciullo,[8,15] L. Clark,[13] P. L. Cole,[24] M. Contalbrigo,[15] G. Costantini,[2,18] V. Crede,[10] N. Dashyan,[43] R. De Vita,[17] M. Defurne,[35] A. Deur,[40] S. Diehl,[6,11] C. Djalali,[30] R. Dupre,[32] M. Ehrhart,[1,32] A. El Alaoui,[39] L. El Fassi,[26] L. Elouadrhiri,[40] S. Fegan,[44] A. Filippi,[20] G. Gavalian,[40] Y. Ghandilyan,[43] G. P. Gilfoyle,[33] F. X. Girod,[40] D. I. Glazier,[13] A. A. Golubenko,[36] R. W. Gothe,[37] Y. Gotra,[40] K. A. Griffioen,[42] K. Hafidi,[1] H. Hakobyan,[39,43] M. Hattawy,[31] F. Hauenstein,[40] T. B. Hayward,[6,42] A. Hobart,[32] M. Holtrop,[27] Y. Ilieva,[37] D. G. Ireland,[13] E. L. Isupov,[36] H. S. Jo,[23] K. Joo,[6] D. Keller,[41] A. Khanal,[9] A. Kim,[6] W. Kim,[23] V. Klimenko,[6] A. Kripko,[11] V. Kubarovsky,[40] M. Leali,[2,18] S. Lee,[25] P. Lenisa,[8,15] K. Livingston,[13] I. J. D. MacGregor,[13] D. Marchand,[32] L. Marsicano,[17] V. Mascagna,[2,38] M. Mayer,[31] B. McKinnon,[13] S. Migliorati,[2,18] T. Mineeva,[39] M. Mirazita,[16] R. A. Montgomery,[13] C. Munoz Camacho,[32] P. Nadel-Turonski,[40] K. Neupane,[37] J. Newton,[31,40] S. Niccolai,[32] M. Osipenko,[17] P. Pandey,[31] M. Paolone,[28,38] L. L. Pappalardo,[8,15] R. Paremuzyan,[27,40] E. Pasyuk,[40] S. J. Paul,[3] N. Pilleux,[32] O. Pogorelko,[21] J. W. Price,[4] Y. Prok,[31] B. A. Raue,[9] T. Reed,[9] M. Ripani,[17] J. Ritman,[22] A. Rizzo,[19,34] P. Rossi,[40] F. Sabatié,[35] C. Salgado,[29] A. Schmidt,[12,25] Y. G. Sharabian,[40] E. V. Shirokov,[36] U. Shrestha,[6,30] P. Simmerling,[6] D. Sokhan,[13,35] N. Sparveris,[38] S. Stepanyan,[40] I. I. Strakovsky,[12] S. Strauch,[37] N. Tyler,[37] R. Tyson,[13] M. Ungaro,[40] S. Vallarino,[15] L. Venturelli,[2,18] H. Voskanyan,[43] E. Voutier,[32] D. P. Watts,[44] K. Wei,[6] X. Wei,[40] R. Wishart,[13] M. H. Wood,[5] B. Yale,[42] N. Zachariou,[44] J. Zhang,[41] and V. Ziegler[40]
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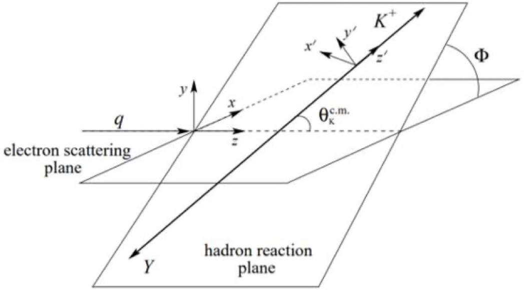
2469-9985/2022/105(6)/065201(24) 065201-1

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 LH_2 target
- Extract beam-recoil transferred polarization from longitudinally polarized beam electron to final state hyperon vs. Q^2, W, cos θ_K c.m.

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

$\mathcal{P}'$ = transferred polarization

(x',y',z')

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

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

$\mathcal{P}^0_{x'}$	0
$\mathcal{P}^0_{y'}$	$K_I(R_T^{y'0} + \epsilon R_L^{y'0})$
$\mathcal{P}^0_{z'}$	0

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

Theoretical expectation:

$\mathcal{P}'_x$	$\frac{1}{2}\sqrt{\epsilon(1-\epsilon)}K_I(R^{x'0}_{TL'}\cos\theta^*_K - R^{y'0}_{TL'} + R^{z'0}_{TL'}\sin\theta^*_K)$
$\mathcal{P}'_y$	0
$\mathcal{P}'_z$	$\sqrt{1-\epsilon^2}K_I(-R^{x'0}_{TT'}\sin\theta^*_K + R^{z'0}_{TT'}\cos\theta^*_K)$

$\mathcal{P}'_{x'}$	$K_I\sqrt{1-\epsilon^2}R^{x'0}_{TT'}$
$\mathcal{P}'_{y'}$	0
$\mathcal{P}'_{z'}$	$K_I\sqrt{1-\epsilon^2}R^{z'0}_{TT'}$

How to extract the polarization from data (approach 1):

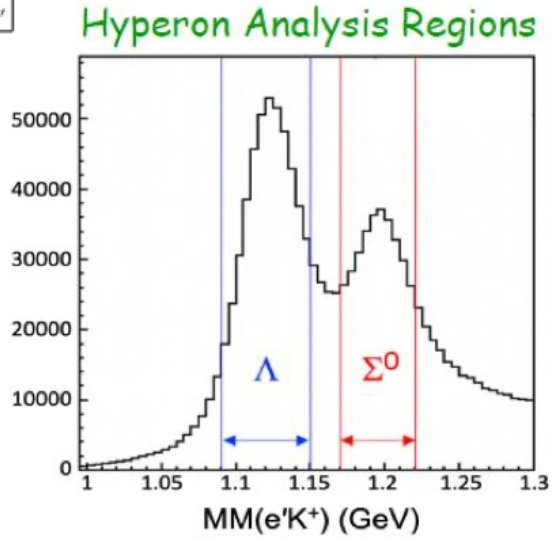
$$\frac{dN}{d\cos\theta_P^{RF}} = N_0\left(1 + \nu_Y \alpha P_Y \cos\theta_p^{RF}\right)$$

Where α_Λ =0.732, P=0.8567 and ϑ_p^{RF} is the angle between the spin quantization axis and the Λ decay proton in the yperon rest frame

$$A_{meas} = \frac{(N^+_\Lambda + N^+_\Sigma + N^+_B) - (N^-_\Lambda + N^-_\Sigma + N^-_B)}{N_\Lambda + N_\Sigma + N_B} = \alpha P_b[P'_{meas}]\cos\theta_P^{RF}$$

$$P'_\Lambda = P'_{meas}\left(1 + F_\Sigma + F_B\right) - \nu_\Sigma P'_\Sigma F_\Sigma$$

$$F_\Sigma = \frac{N_\Sigma}{N_\Lambda}, \qquad F_B = \frac{N_B}{N_\Lambda}$$



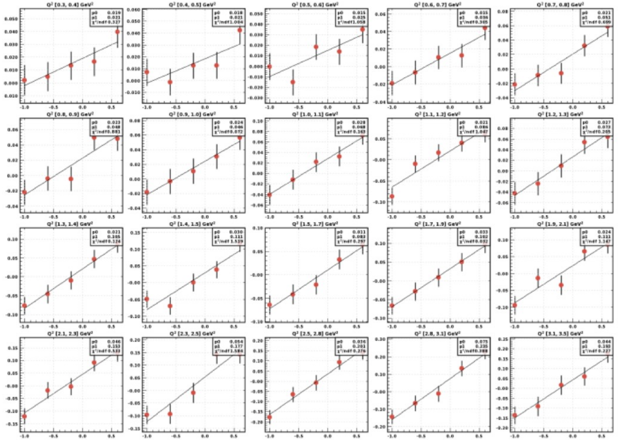
Binning is performed over the three kinematic variables Q^2, W and cos ϑ_K^*

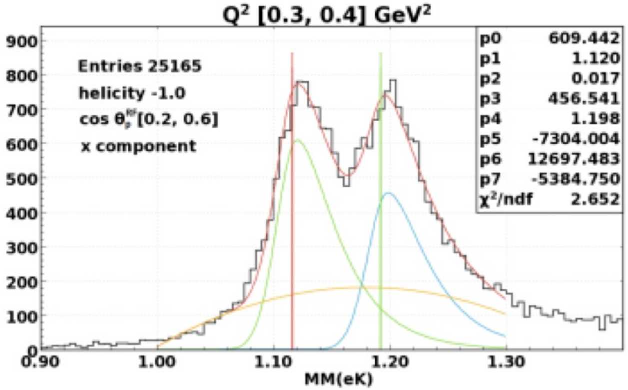
Beam-Recoil Transferred Polarization in K^+Y Electroproduction in the Nucleon Resonance Region with CLAS12

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 ϑ_K^*** were divided into 5 cos ϑ_p^{RF} bins for each beam helicity…

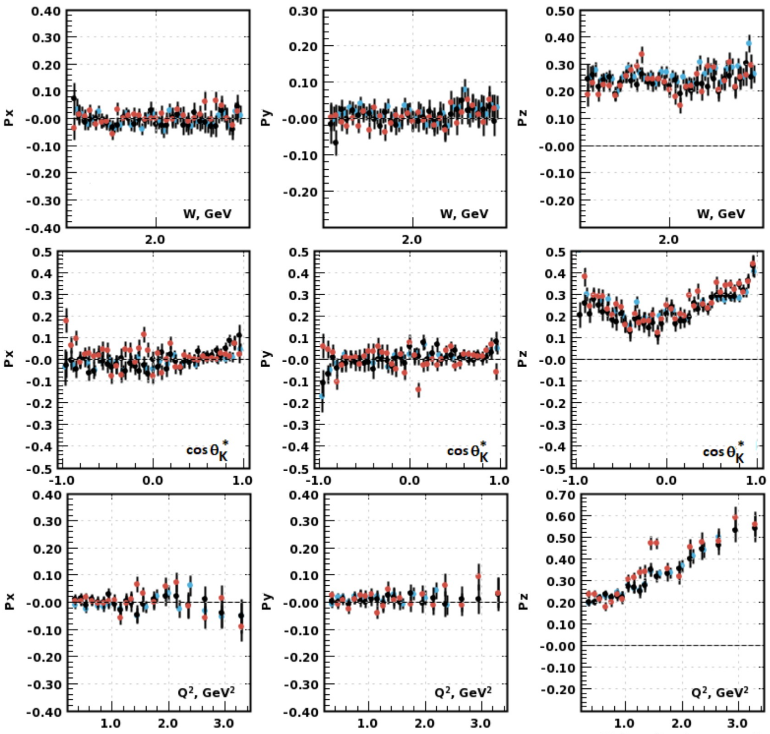




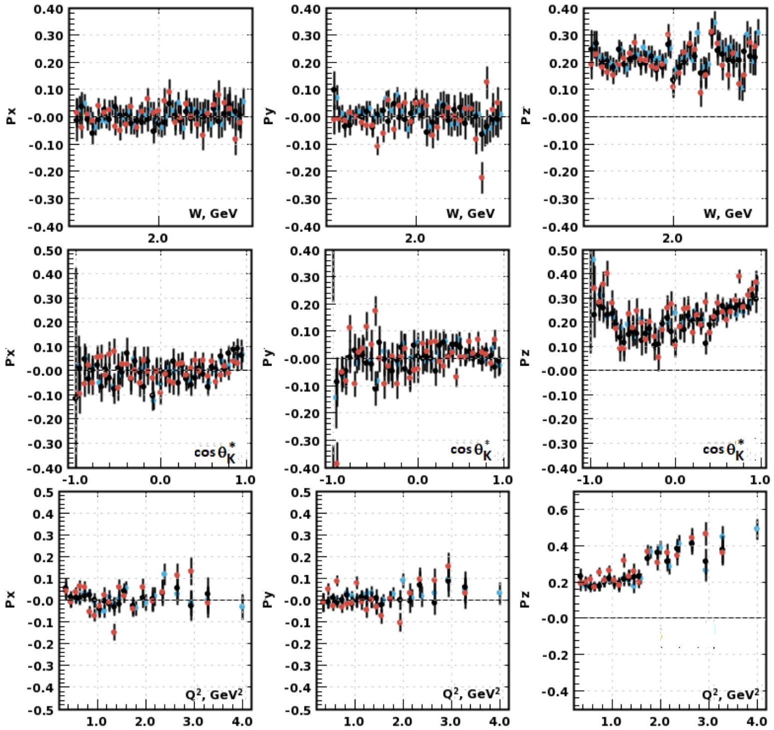
… and the number of Λ events was extracted using a fit of the MM(eK^+) spectrum

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

$\mathcal{P}'$



6.5 GeV



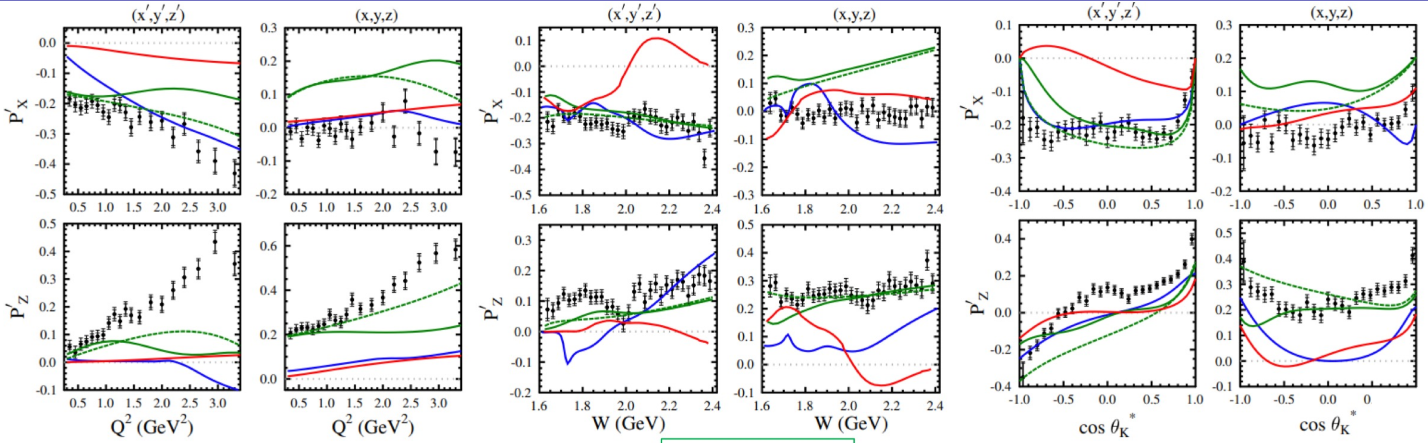
7.5 GeV

Blue dots : Approach 1

Red dots : Approach 2

Black dots : Approach 1 (different fitting procedure)

Beam-Recoil Λ Transferred Polarization



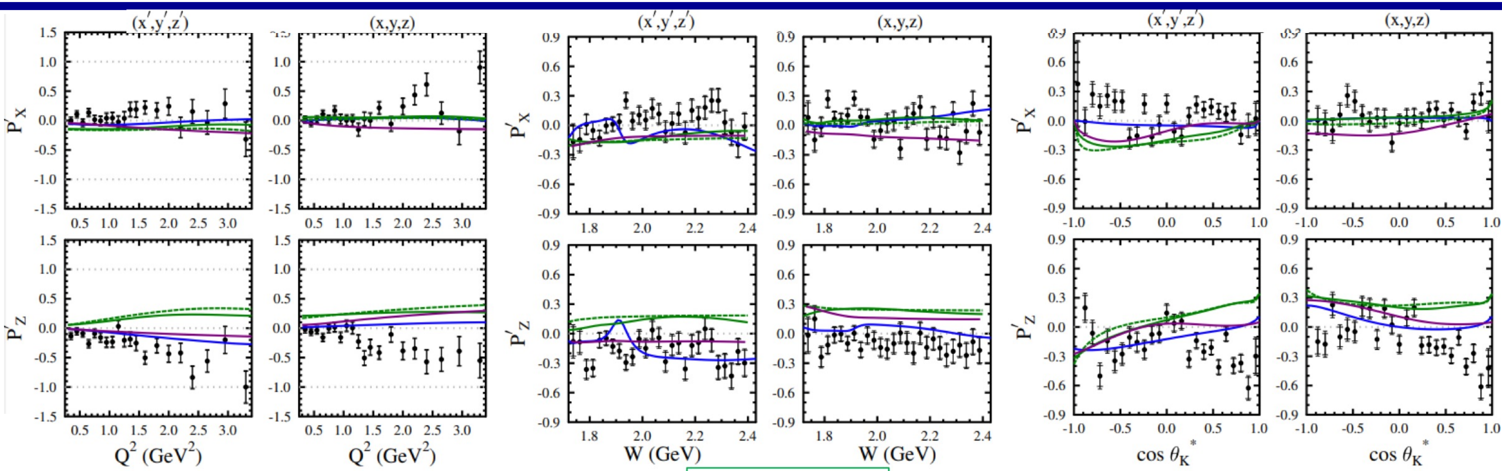
6.535 GeV

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. (CLAS Collaboration)*, "Beam-Recoil Transferred Polarization in K⁺Y Electroproduction in the Nucleon Resonance Region with CLAS12", Phys. Rev. C 105, 065201 (2022)

Λ polarization results extend available data from previous experiments (e.g. CLAS e1-6 @ 5.754 GeV)

Beam-Recoil Σ^0 Transferred Polarization



6.535 GeV

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

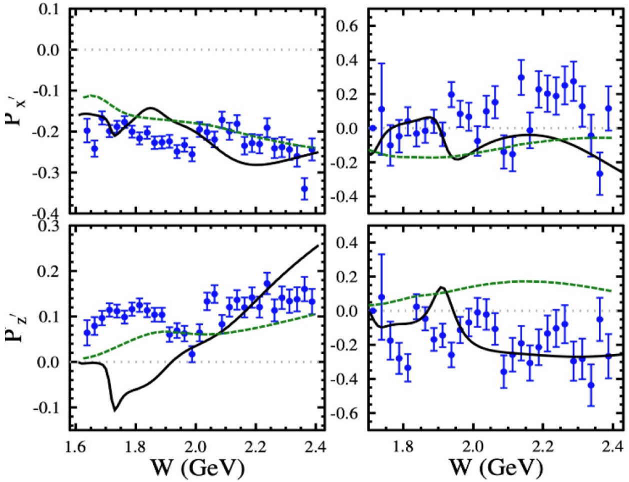
D.S. Carman *et al. (CLAS Collaboration)*, "Beam-Recoil Transferred Polarization in K⁺Y Electroproduction in the Nucleon Resonance Region with CLAS12", Phys. Rev. C 105, 065201 (2022)

Σ^0 are the first statistically meaningful datasets that can be compared with model predictions.

K^+Y Transferred Polarization CLAS12 vs. CLAS

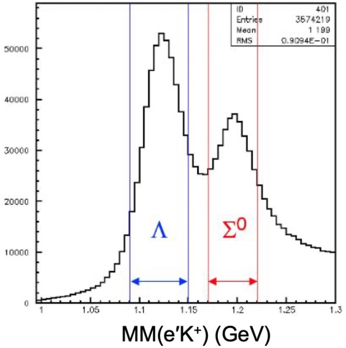
CLAS12 (RG-K)

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



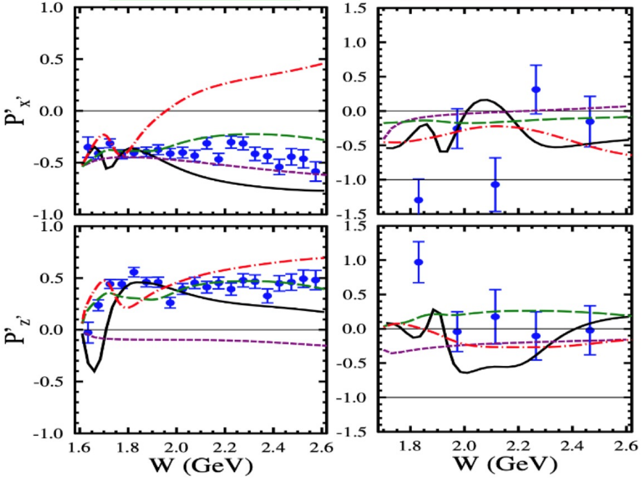
[D.S. Carman et al., Phys. Rev. C 105, 065201 (2022)]

ep → e'K^+Y



CLAS (e1-6)

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



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

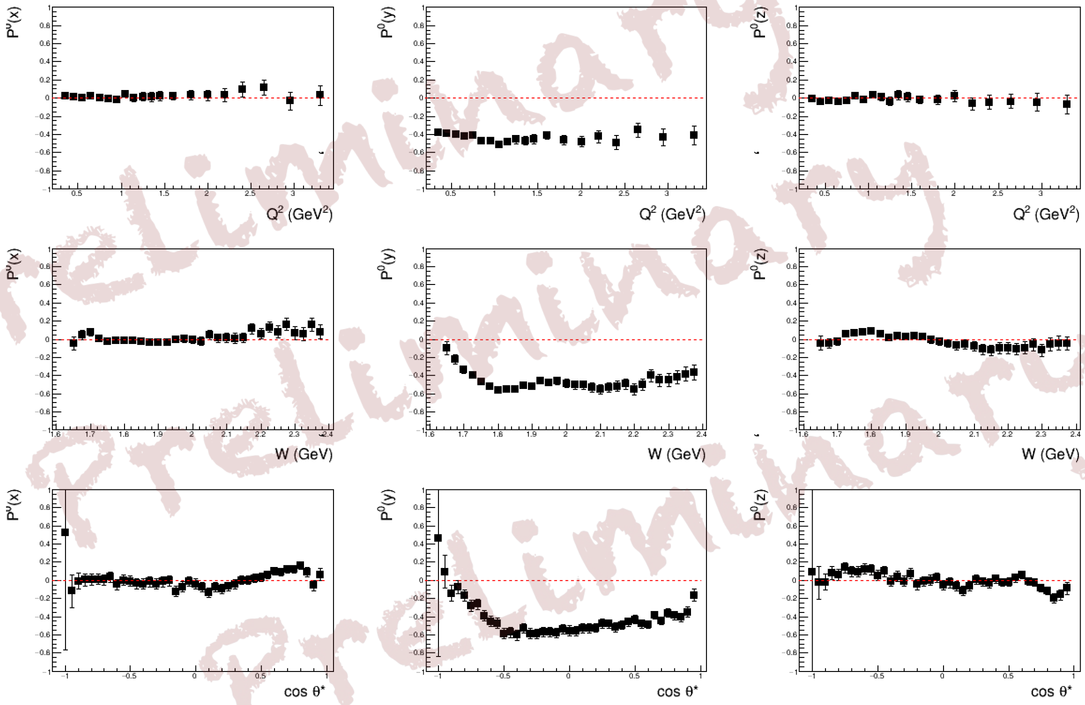
KAON-MAID
RPR

World data set will get extended by orders of magnitude

Mart/Bennhold RPR-2
RPR-1 Regge

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

Φ-integrated

	(x',y',z')		(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

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

Λ(1520)

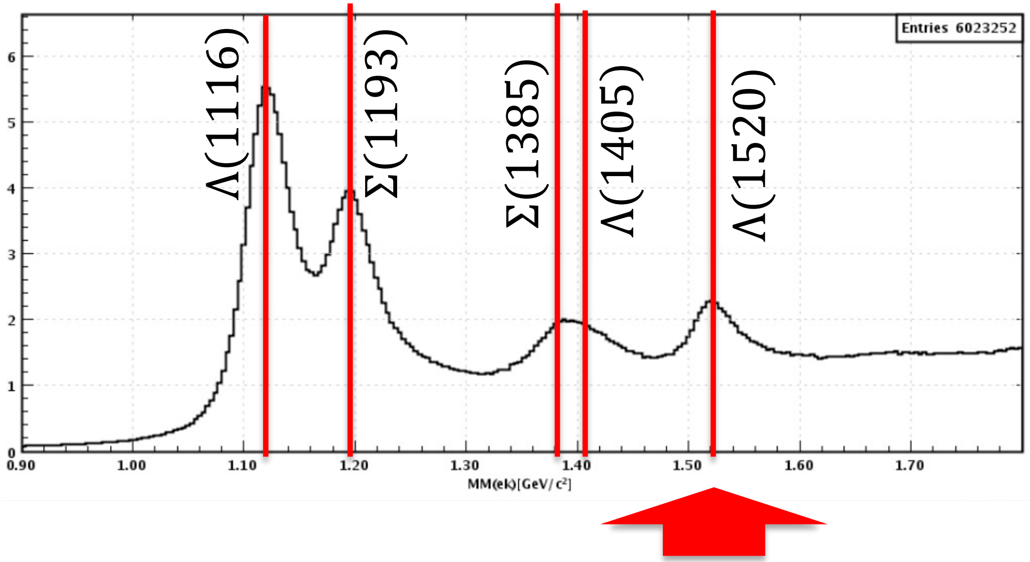
Other channels could be exploited as final states for possible new resonances..

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

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

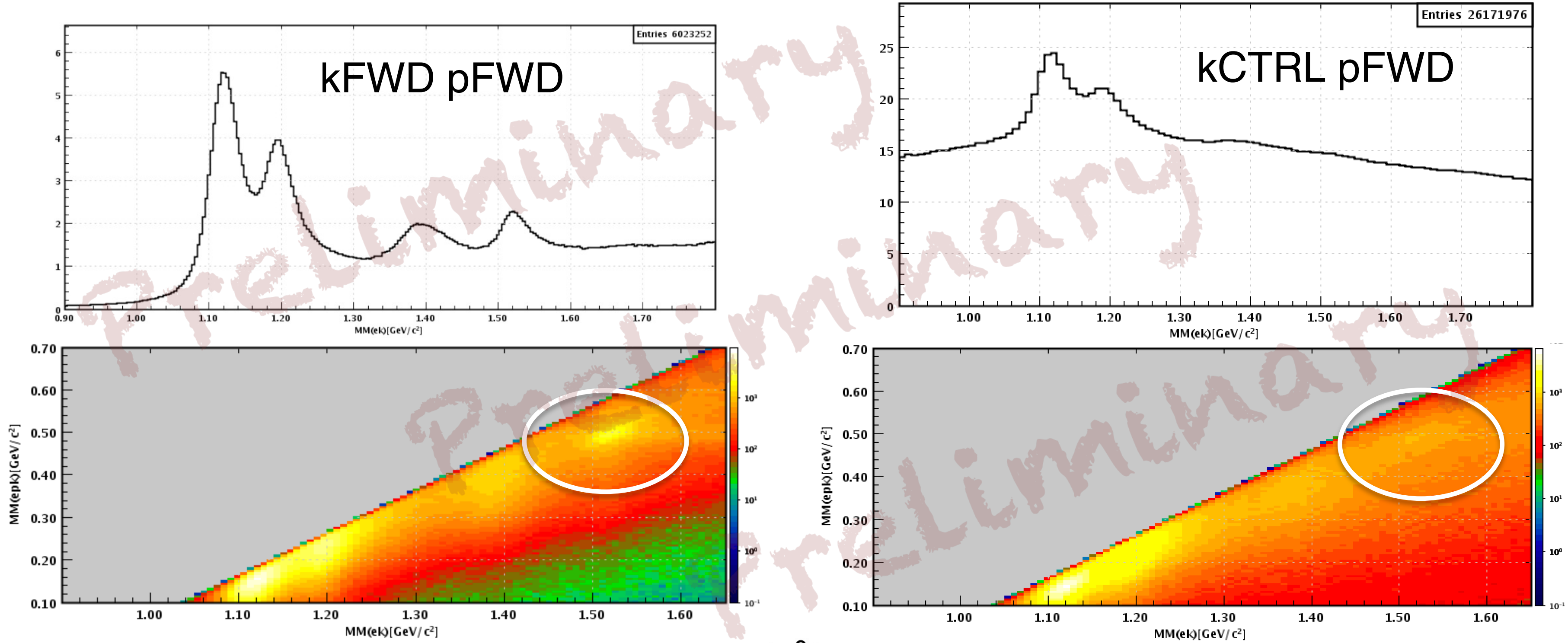
→ S. Barrow et al., CLAS Coll., Phys.Rev.C64:044601,2001
→ Simon Chapstick and W. Roberts, Phys. Rev. D **58** 074011

kFWD pFWD



Λ(1520) arises as a separate structure

Λ(1520)

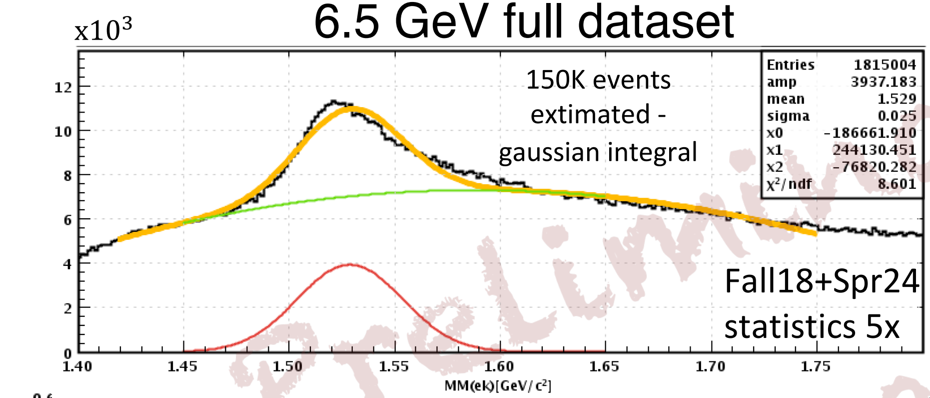


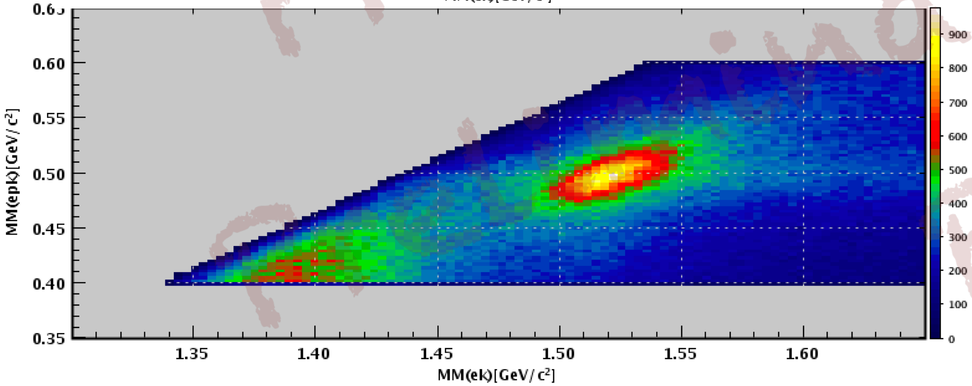
Five structures: Λ(1116), Σ^0(1193), Σ(1385), Λ(1405), Λ(1520)

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

Λ(1520)

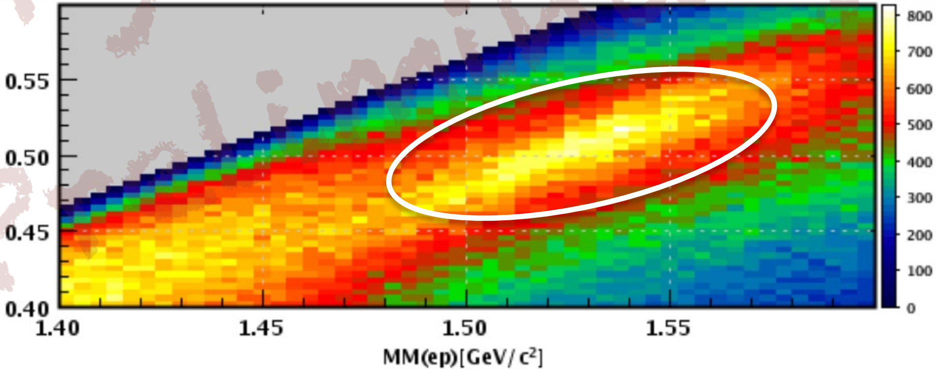
6.5 GeV full dataset





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

7.5 GeV dataset



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

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 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 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…

Summary and Outlook

Summarizing:

- The study of N* states is one of the crucial topics of the CLAS and CLAS12 ... ams:
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  - -More data...

And in the future

- Future work w... ce up he most challenging problems of the Standard Model on the nature ... ement, and the emergence of N* states from quarks and gluons

Thank you for the attention!

Stay tuned for further updates…