STRONG-2020

Valencia Meeting
15-17 December 2020

Theoretical Aspects of Hadron Spectroscopy and Phenomenology

T 4.2 Baryon Spectroscopy: Diffractive and annihilation production and exotic baryons

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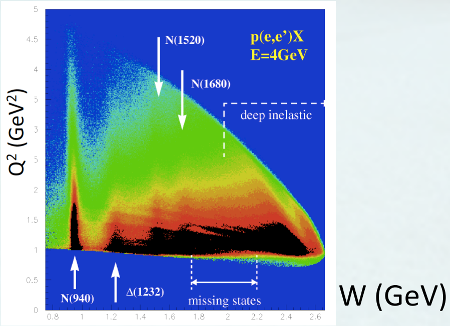
Reporting the activity of: Alessandra Filippi, Bernd Krusche, Lucilla Lanza, Vincent Mathieu

Outline:

- Physics case: pentaquarks, hybrid baryons and the role of the glue
- Hybrid baryons signature
- KY and ππ photo-and electro-production
- Resonances and inclusive electron scattering
- Pentaquark photoproduction
- Outlook & conclusions

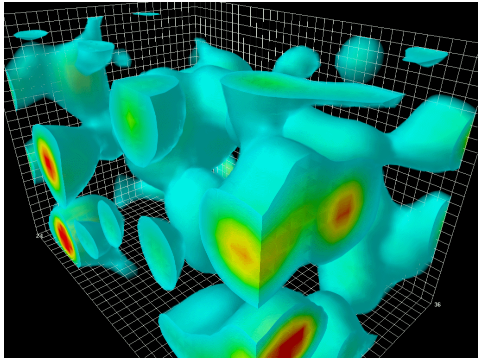


Critical QCD Question Addressed

- **QCD** allows much richer hadron spectrum than **conventional** $q\bar{q}$ mesons and qqq baryons.

Exotic hadrons

glueballs	GG, GGG
multiquark states	$q\,q\,\bar{q}\,\bar{q}$, $q\,q\,q\,q\,\bar{q}$
hybrids	$q\,\bar{q}$ G, $\boldsymbol{q\,q\,q}$ **G**, $q\,q\,\bar{q}\,\bar{q}$ G
molecular hadrons	$[D\bar{D}^*]$, $[\bar{D}^*\,\Sigma_c]$



Derek B. Leinweber – University of Adelaide

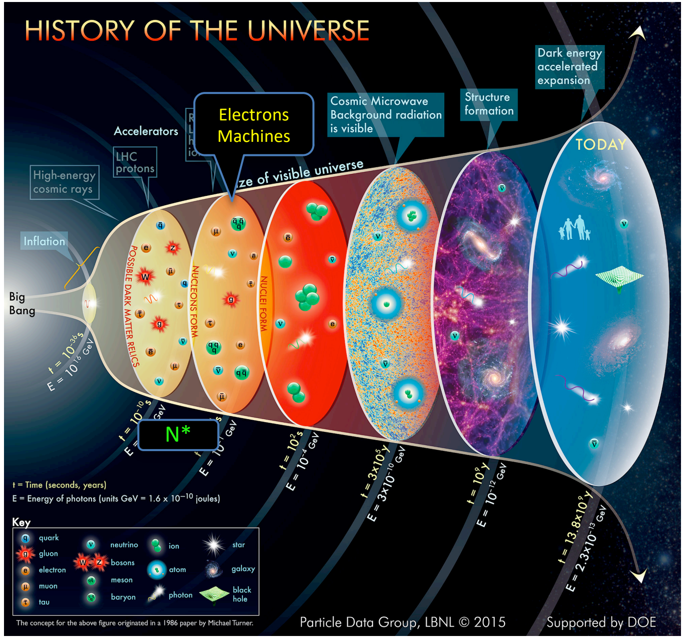
- The light N* spectrum: what is the role of glue?

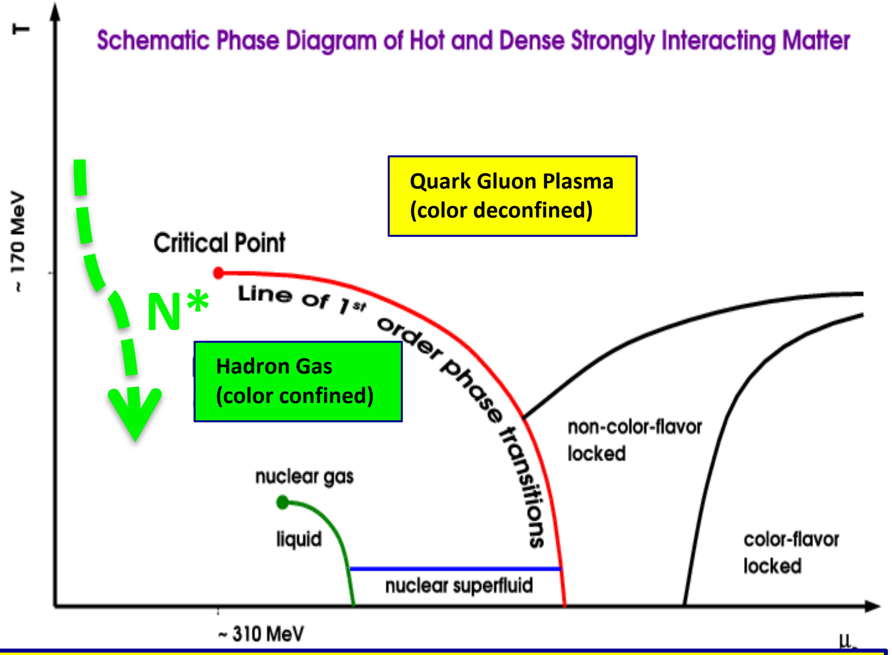
→ **Search for new baryon states**

- The heavy baryon sector: hidden charm pentaquarks

→ **Investigate the properties of pentaquark-like resonances**

N* in the History of the Universe



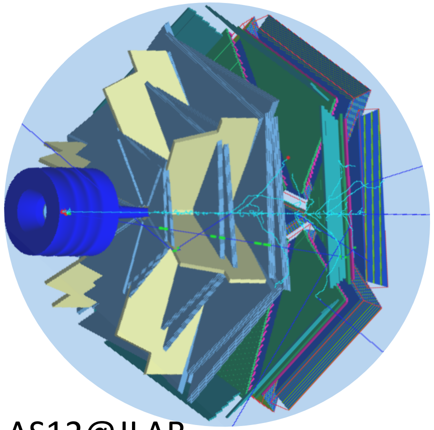


Dramatic events occur in the microsecond old Universe.

- The transition from the QGP to the baryon phase is dominated by excited baryons. A quantitative description requires more states than found to date => **missing baryons.**
- During the transition the quarks acquire **dynamical mass** and the **confinement of color** occurs.

N* Program – meson electro-production

The N* program is one of the key physics foundations of CLAS@JLab, A2@MAMI and CB@ELSA



CLAS12@JLAB

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

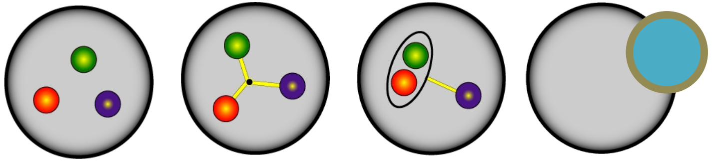
πN, ωN, ϕN, ηN, $\eta' N$, $\pi\pi N$, KY, K*Y, KY*

- 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.

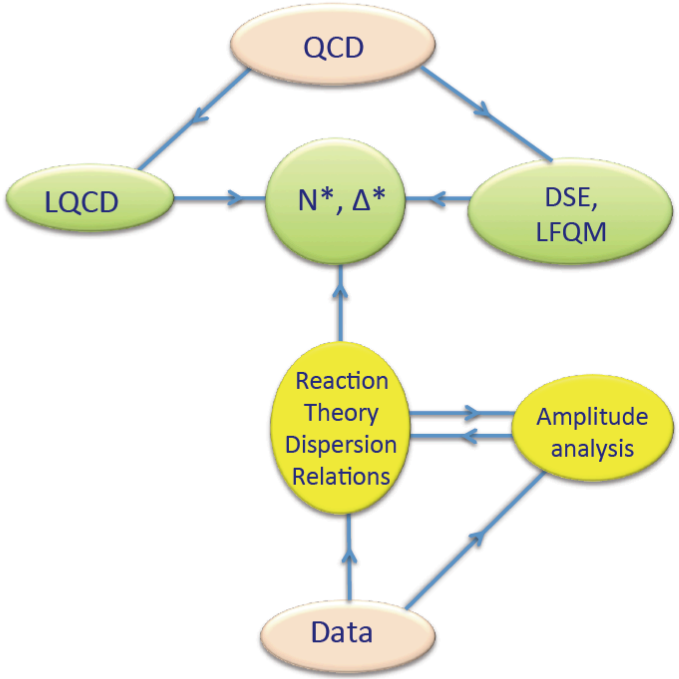
N* degrees of freedom??



Establishing the N* and Δ Spectrum

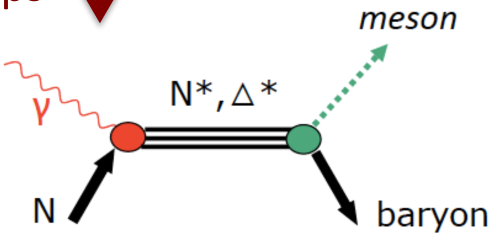
Experimental requirements:

- Precision measurements of photo-induced processes in wide kinematics, e.g.
  $\gamma p \to \pi N, \eta p, KY, ..,$ $\gamma n \to \pi N, K^0Y^0, ..$
- More complex reactions, e.g. $\gamma p \to \omega p, \rho\phi, \pi\pi p, \eta\pi N, K^*Y, ..$ may be sensitive to high mass states through direct transition to ground state or through cascade decays
- Polarization observables are essential



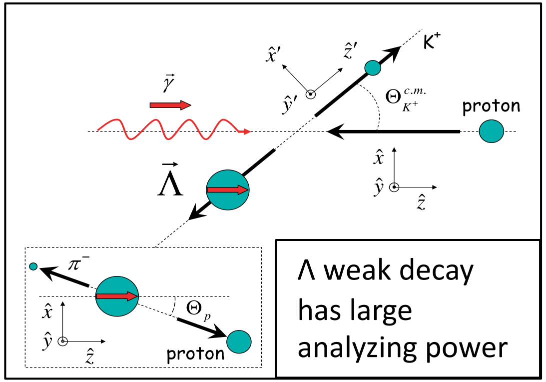
Engaging theoretical groups ↓

Extract s-channel resonances



Hadronic production & Electromagnetic production

Polarization Observables: Complete Experiment



The holy grail of baryon resonance analysis

- KY process described by 4 complex, parity conserving amplitudes
- 8 well-chosen measurements are needed to determine amplitude.
- Up to **16** observables measured directly
- **3** inferred from double polarization observables
- **13** inferred from triple polarization observables

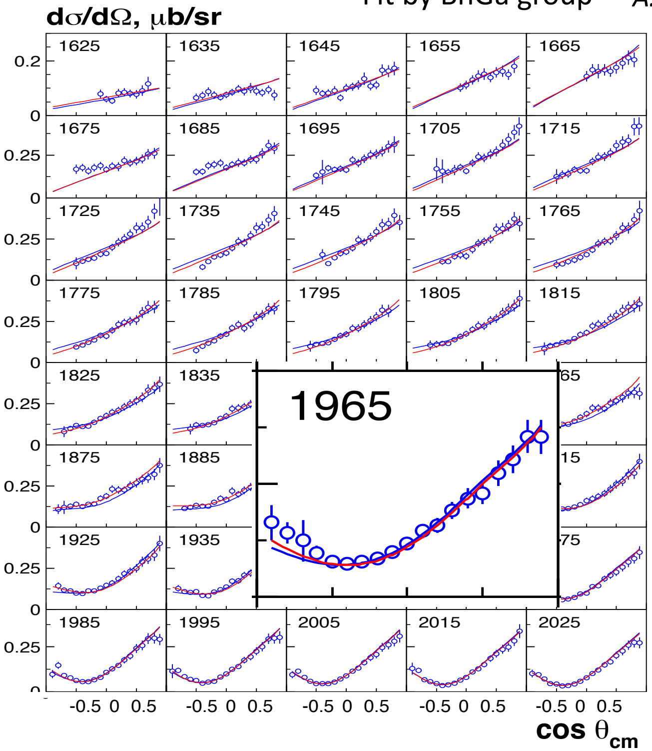
Beam (P^γ)		Target (P^T)			Recoil (P^R)			Target (P^T) + Recoil (P^R)								
					x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
		x	y	z				x	y	z	x	y	z	x	y	z
unpolarized	$d\sigma_0$		$\hat{T}$			$\hat{P}$		$\hat{T}_{x'}$		$\hat{L}_{x'}$		$\underline{\hat{\Sigma}}$		$\hat{T}_{z'}$		$\hat{L}_{z'}$
$P^\gamma_L \sin(2\phi_\gamma)$		$\hat{H}$		$\hat{G}$	$\hat{O}_{x'}$		$\hat{O}_{z'}$		$\hat{\mathbf{C}}_{\mathbf{z'}}$		$\hat{\mathbf{E}}$		$\hat{\mathbf{F}}$		$-\hat{\mathbf{C}}_{\mathbf{x'}}$	
$P^\gamma_L \cos(2\phi_\gamma)$	$-\hat{\Sigma}$		$\underline{-\hat{P}}$			$\underline{-\hat{T}}$		$-\hat{\mathbf{L}}_{\mathbf{z'}}$		$\hat{\mathbf{T}}_{\mathbf{z'}}$		$-\mathbf{d\sigma_0}$		$\hat{\mathbf{L}}_{\mathbf{x'}}$		$-\hat{\mathbf{T}}_{\mathbf{x'}}$
circular P^γ_c		$\hat{F}$		$-\hat{E}$	$\hat{C}_{x'}$		$\hat{C}_{z'}$		$-\hat{\mathbf{O}}_{\mathbf{z'}}$		$\hat{\mathbf{G}}$		$-\hat{\mathbf{H}}$		$\hat{\mathbf{O}}_{\mathbf{x'}}$	

A. Sandorfi, S. Hoblit, H. Kamano, T.-S.H. Lee, J.Phys. 38 (2011) 053001

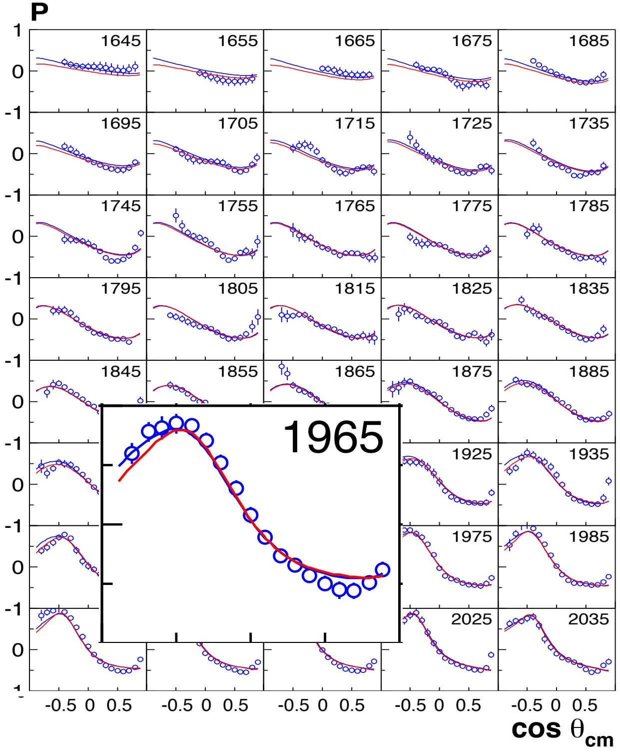
Establishing the N* spectrum – Precision & Polarization are essential

Hyperon photoproduction $\gamma p \rightarrow K^+ \Lambda \rightarrow K^+ p \pi^-$

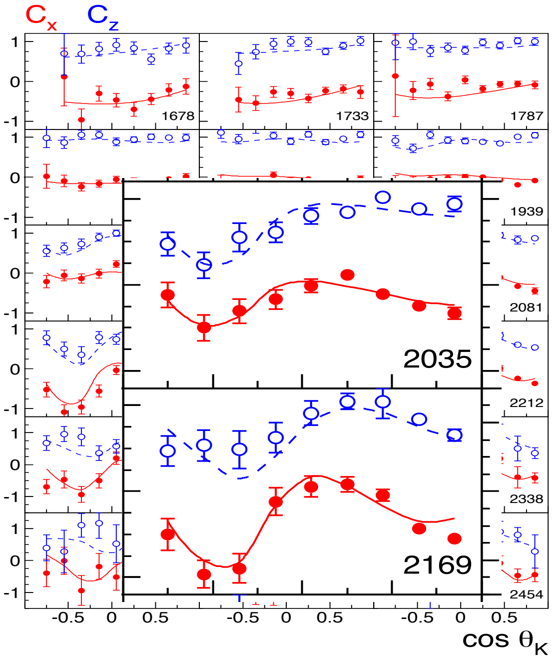
Fit by BnGa group *A.V. Anisovich et al, EPJ A48, 15 (2012)*



M. Mc Cracken et al.(CLAS), Phys.RevC81,025201,2010



γ->Λ **Polarization** transfer



D. Bradford et al. (CLAS), Phys.Rev. C75, 035205, 2007

Evidence for New N* in KY

State N(mass)J^P	PDG pre 2010	PDG 2020	KΛ	KΣ	Nγ	Nπ
$N(1710)1/2^+$	***	****	**	*	****	****
$N(1880)1/2^+$		***	**	*	**	*
$N(2100)1/2^+$	*	***	*		**	***
$N(1895)1/2^-$		****	**	**	****	*
$N(1900)3/2^+$	**	****	**	**	****	**
$N(1875)3/2^-$		***	*	*	**	**
$N(2120)3/2^-$		***	**	*	***	**
$N(2060)5/2^-$		***	*	*	***	**
$\Delta(1600)3/2^+$	***	****			****	***
$\Delta(1900)1/2^-$	**	***		**	***	***
$\Delta(2200)7/2^-$	*	***		**	**	***

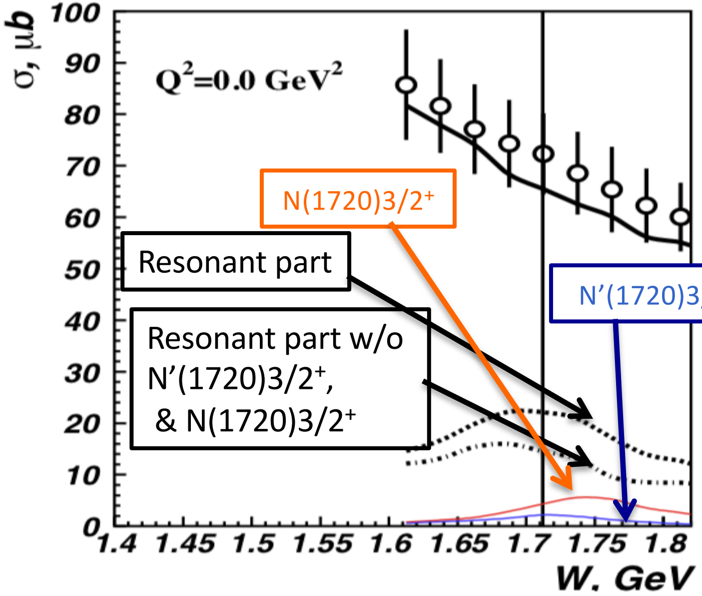
Study these states in electroproduction and extend to higher masses

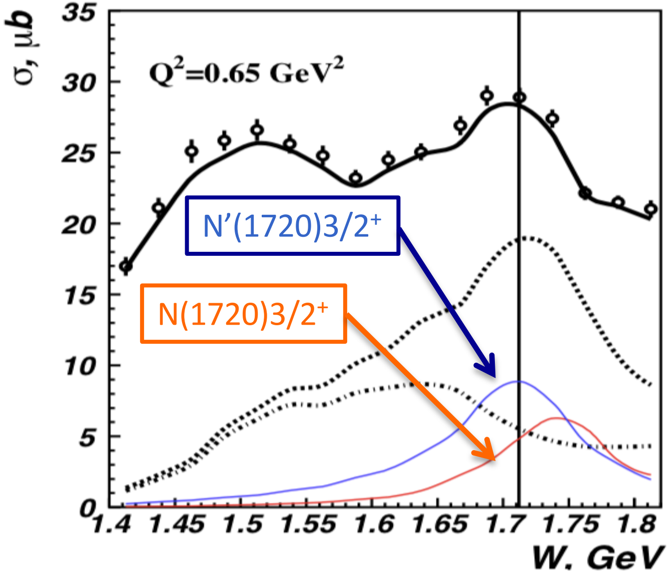
$\pi^+\pi^-p$ CLAS data - Newly Discovered N'(1720)3/2⁺

$\pi^+\pi^-p$ photoproduction

$\pi^+\pi^-p$ electroproduction

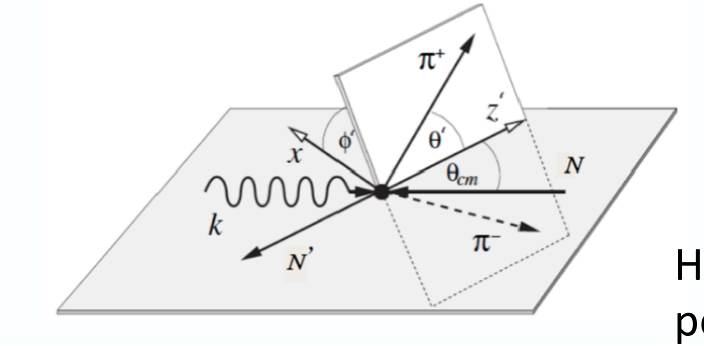
V.I. Mokeev et al., Phys. Lett. B 805, 135457 (2020)





- Evidence of a new N'(1720)3/2⁺ resonance from the combined analysis of CLAS photo- and electroproduction of the $\pi^+\pi^-p$ channel
- First result on Q^2 evolution of new resonance electrocoupling

$\pi^+\pi^-$ photoproduction – polarized p target

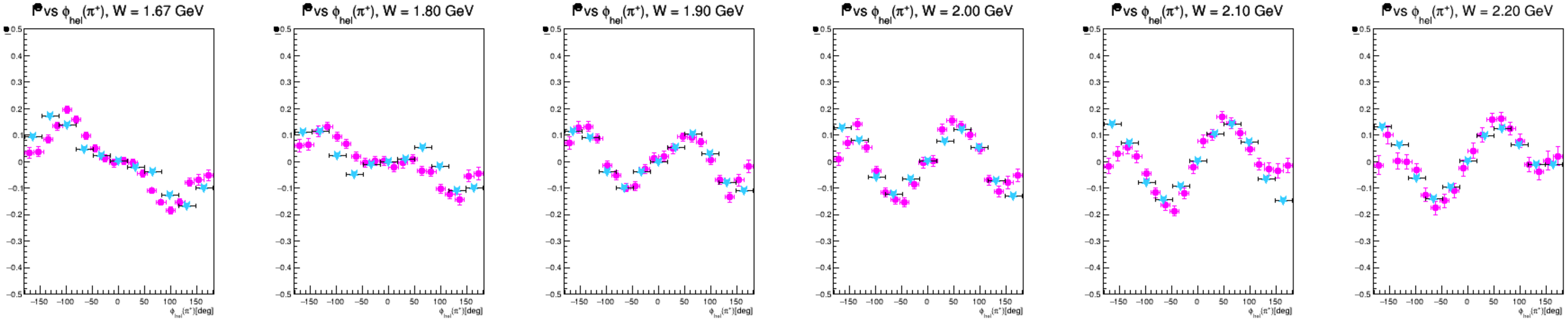


Measurements of polarization observables

$$\frac{d\sigma}{dx_i} = \sigma_0\{(1 + \Lambda_z \cdot \mathbf{P_z}) + \delta_\odot(\mathbf{I}^\odot + \Lambda_z \cdot \mathbf{P}_z^\odot)\}$$

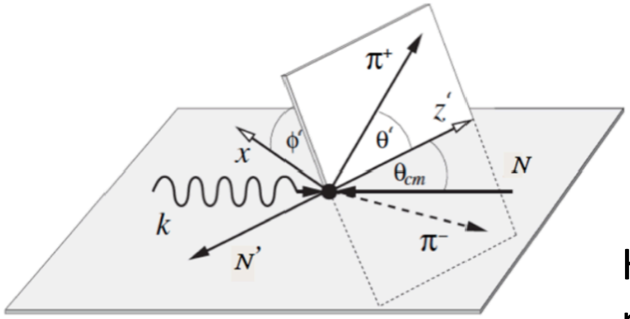
HD-ice frozen-spin polarized target

$I^\odot$ polarized p



Preliminary results by: A. Filippi

$\pi^+\pi^-$ photoproduction – polarized p target

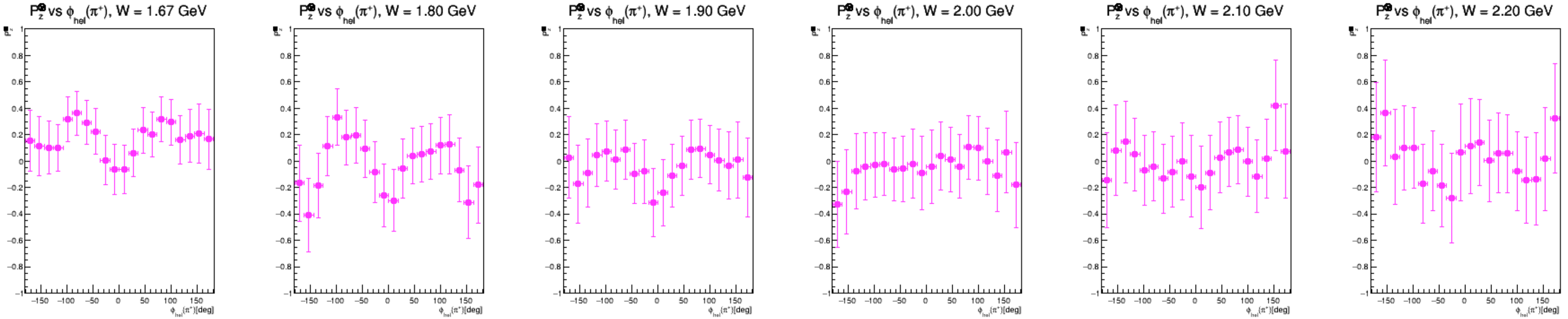


Measurements of polarization observables

$$\frac{d\sigma}{dx_i} = \sigma_0\{(1 + \Lambda_z \cdot \mathbf{P_z}) + \delta_\odot(\mathbf{I}^\odot + \Lambda_z \cdot \mathbf{P}_z^\odot)\}$$

HD-ice frozen-spin polarized target

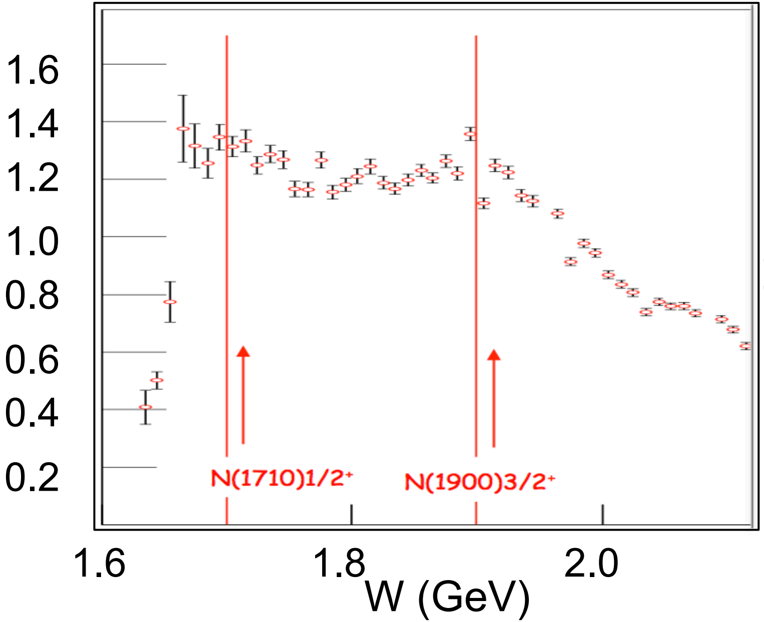
polarized p $P_z^\odot$



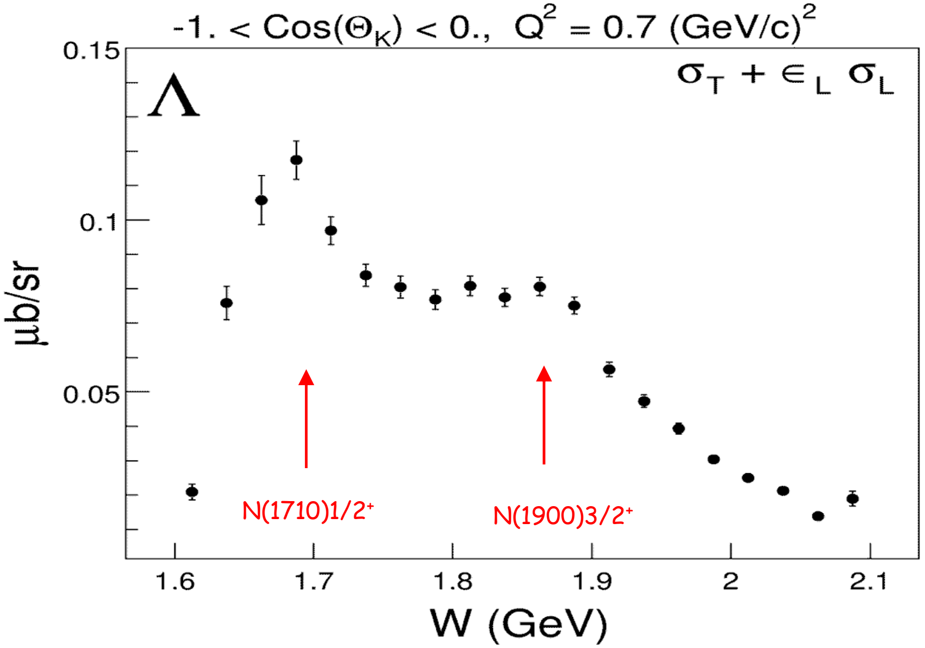
Preliminary results by: A. Filippi

Studying Baryons in $\gamma^* p \rightarrow K\Lambda/\Sigma$?

Photoproduction



Electroproduction



- Strangeness electroproduction is a fertile ground in studying S=0 baryon states with masses above 1.6 GeV.

Hybrid Baryons: Baryons 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 → 0^{--}, 1^{-+}, 1^{--}, ….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).

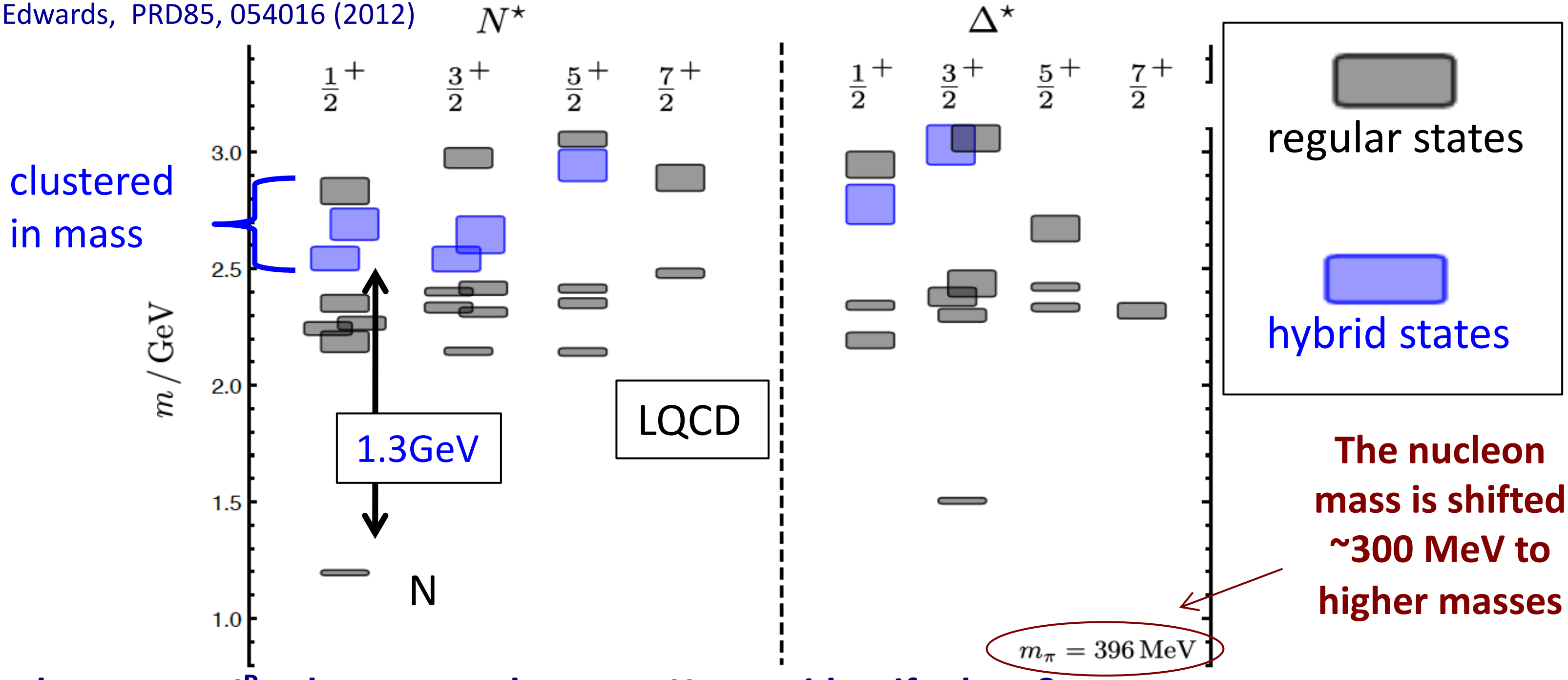
✧ QCD Sum Rule - L. Kisslinger and Z. Li, Phys. Rev. D 51, R5986 (1995).

✧ 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)



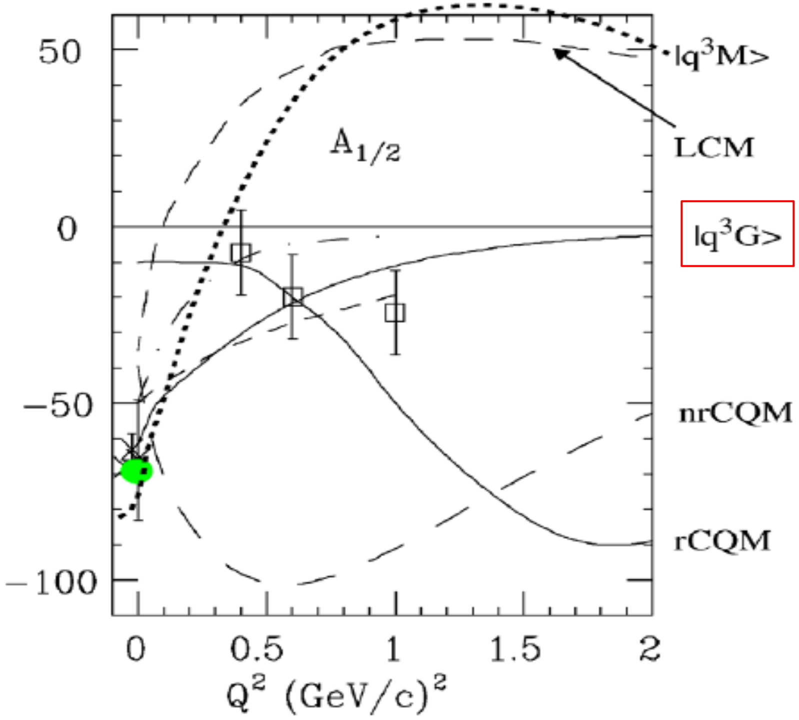
The nucleon mass is shifted ~300 MeV to higher masses

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. Can we do it?**

Electrocouplings of the 'Roper' in 2002

N(1440)1/2$^+$

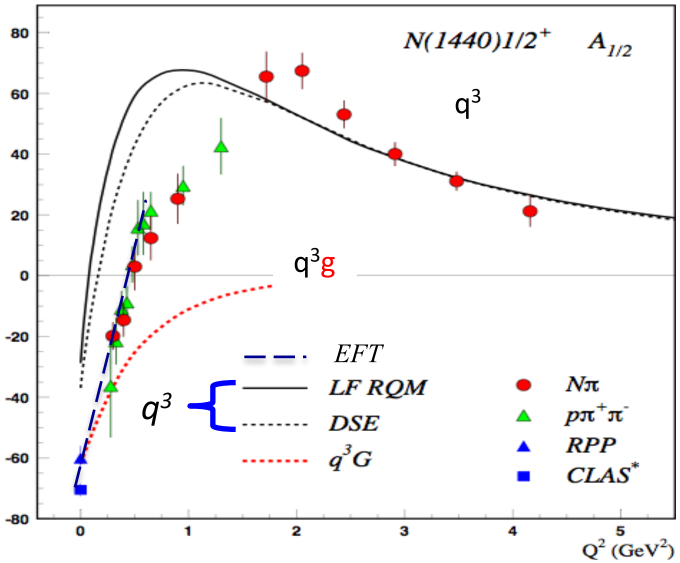


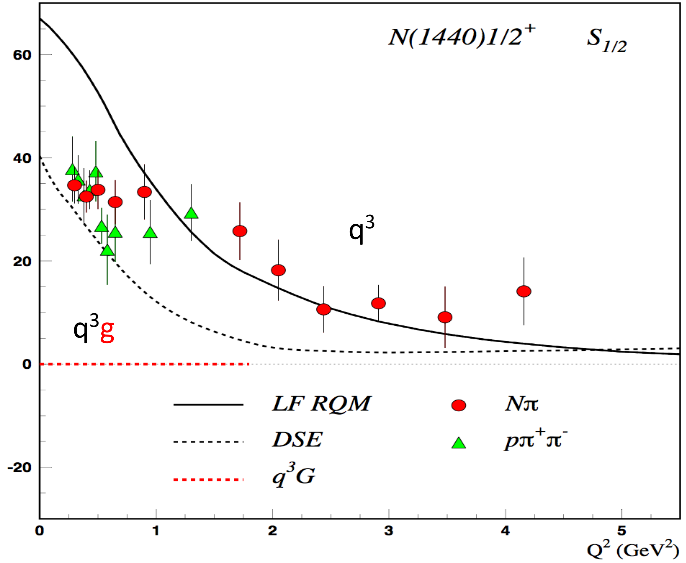
In 2002 Roper amplitude $A_{1/2}$ measurements were more consistent with hybrid state but data were limited with large uncertainties.

Lowest mass hybrid baryon should be $J^P = 1/2^+$ (same as Roper)

Separating q^3g from q^3 States?

Precise CLAS results on electrocouplings clarified nature of the Roper





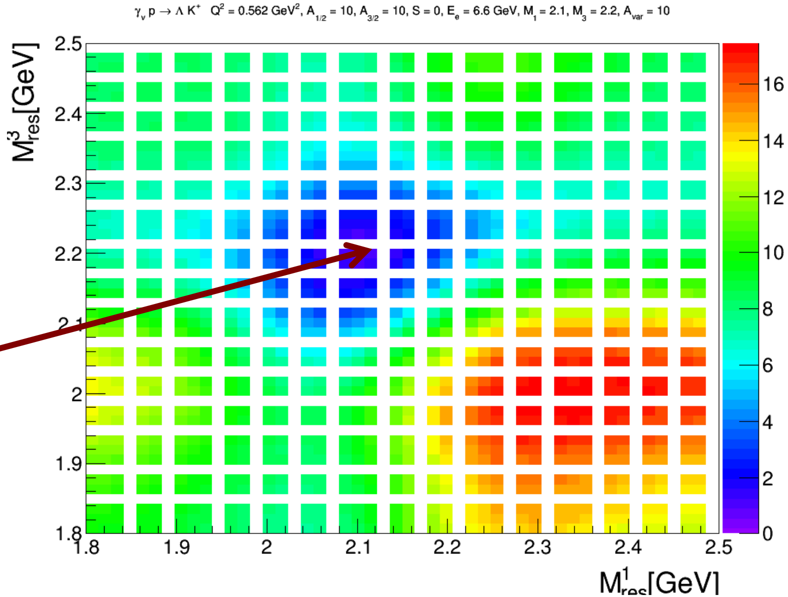
- $A_{1/2}$ and $S_{1/2}$ amplitudes at high Q^2 >2 GeV^2 indicate 1st radial q^3 excitation
- Significant meson-baryon coupling at small Q^2

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

MC Quasi-data Blind Extraction: $J^P=1/2^+$ + $J^P=3/2^+$

Two hybrid baryon resonances with $J^p = 1/2^+$ and $J^p = 3/2^+$ were inserted in the $ep \longrightarrow e K^+\Lambda$ Gent RPR2011 reaction amplitude and **quasi-data** were generated $\longrightarrow$ $d\sigma_{q.d.}$

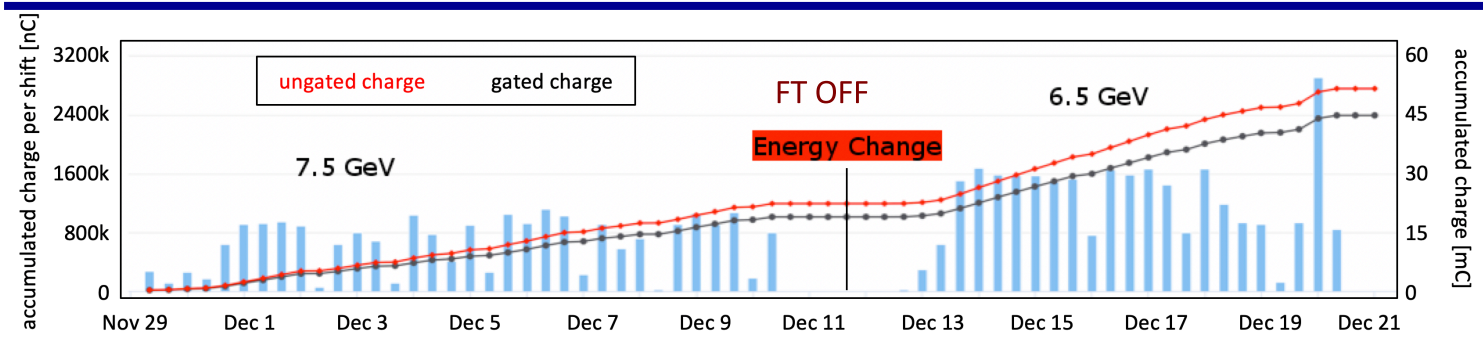
Typical 3-dim map of χ^2 as a function of the two resonance masses, evolving in time for increasing $A_{1/2}$ ($A_{3/2}$) strength.



χ^2 minimum

CLAS12 detector ability to identify new resonances

CLAS12 - Run Group K Data Production



Q~45mC = 7% of Expected 648mC

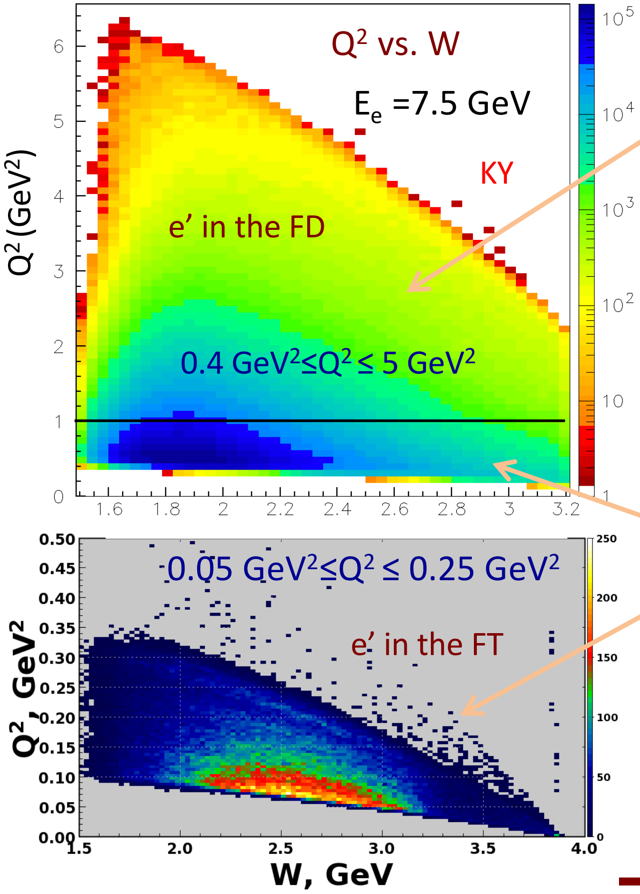
Opportunistic Run

RUN CONDITIONS – FALL 2018	
Torus Current	100% (3375 A) - negative outbending
Solenoid	-100 %
FT	ON @ 7.5 GeV -> OFF @ 6.5 GeV
Beam/Target	Polarized electrons, unpolarized LH_2 target
Luminosity	~ 5 10^{34} $cm^{-2}s^{-1}$ @ 7.5 GeV 10^{35} $cm^{-2}s^{-1}$ @ 6.5 GeV FULL LUMINOSITY

12 PAC days

EVENTS
15.6 G

RG-K Kinematic Coverage



Q^2>1 GeV^2:

- Evolution of active degrees of freedom in the N* structure

Q^2<1 GeV^2:

search for:

- hybrid baryon signature
- meson-baryon contributions to the N* structure

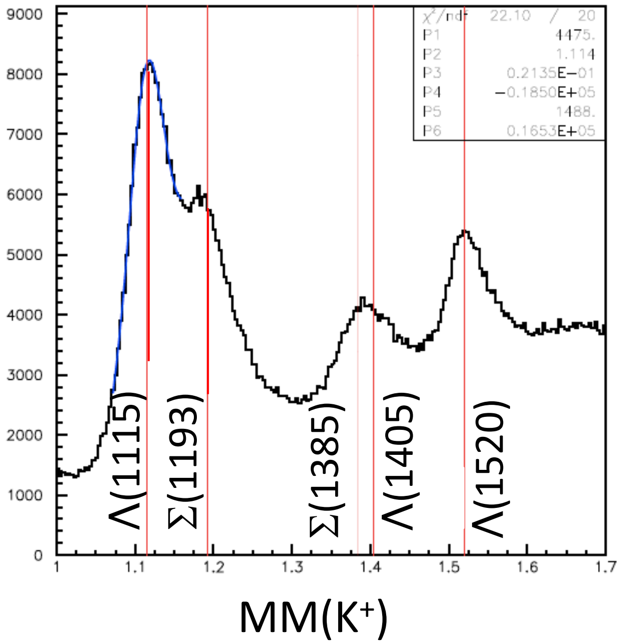
Reactions of interest for the N*/hybrid program:

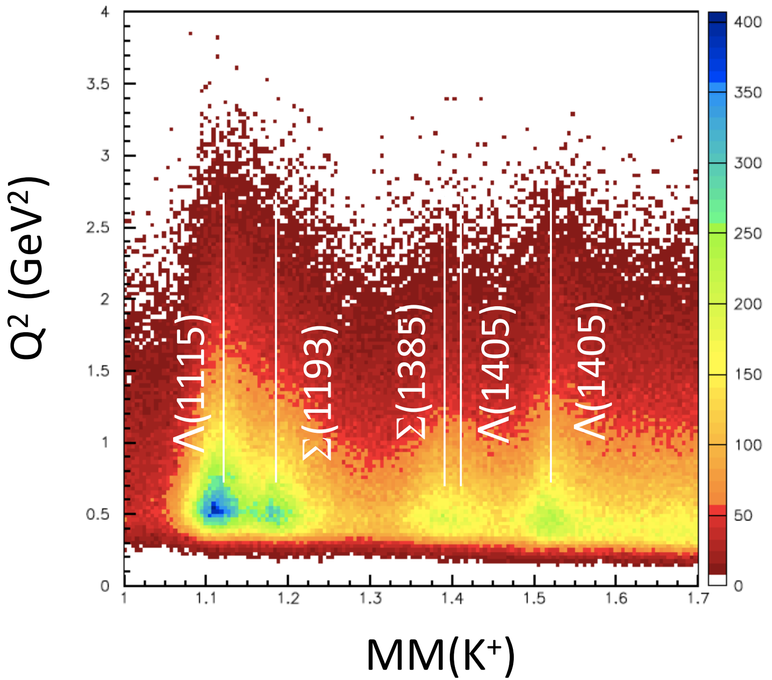
$ep \rightarrow ep\pi^+\pi^-$

$ep \rightarrow eK^+Y$

RGK 7.5 GeV p(e,e'K⁺)X electron in CLAS

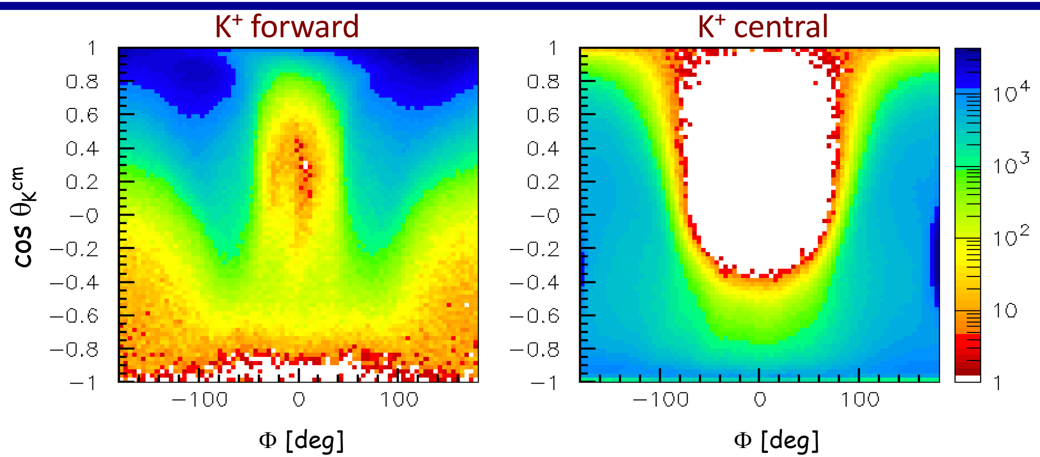
1.6 GeV < W < 3 GeV





80K KΛ events from 1 G triggers in CLAS → 4 M total KΛ events already collected

K^+Y Analysis Status/Plans



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

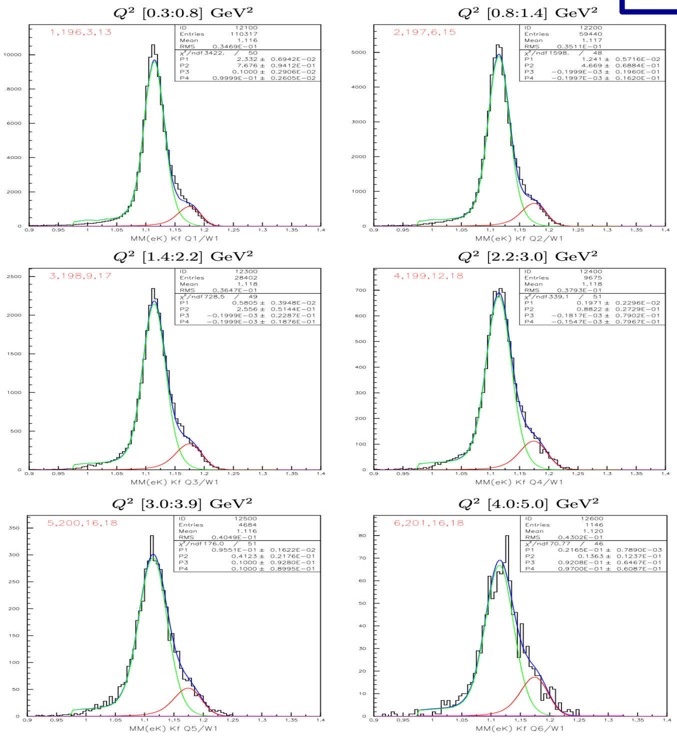
- Analysis objectives: (RG-K datasets at both 6.6 and 8.8 GeV)
  - Extract the *separated structure functions* $\sigma_T + \epsilon\sigma_L$, σ_{TT}, σ_{LT}, $\sigma_{LT'}$ in bins of Q^2, W, cos θ_K^{cm}, Φ
  - Extract the *recoil and beam-recoil hyperon polarization* in bins of Q^2, W, cos θ_K^{cm}
- To extract the resonance electrocouplings to access the N* structure information, development of a suitable KY reaction model is essential (work in progress by several phenomenology/theory groups)

Work in conjunction with RG-A KY analysis

K^+Y Yield Extraction Fits

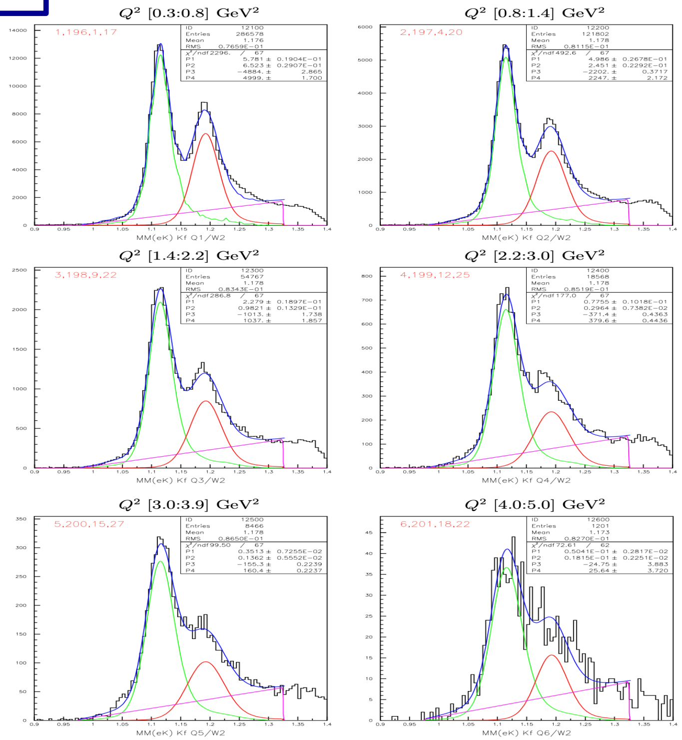
7.5 GeV

W = 1.725 GeV



MM(e'K+) [GeV]

W = 1.925 GeV



MM(e'K+) [GeV]

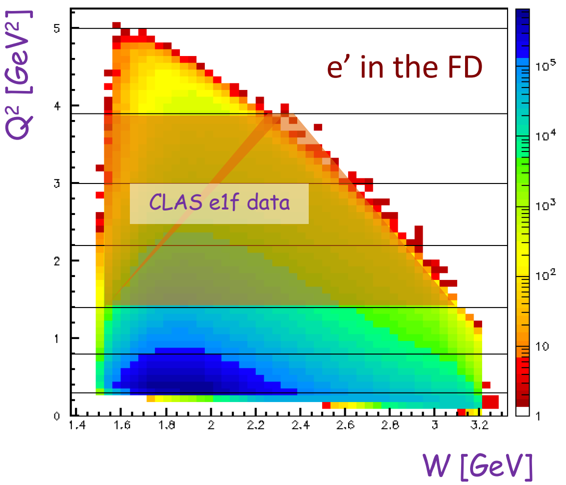
Fit MM(e'K+) with MC K^+Y templates convoluted with Gaussian + bck to minimize χ^2

K^+Y Yield Estimates

Estimate for full 6.5 RG-K dataset (analyzed stat. x10)

Q^2 GeV^2	W GeV	RG-K $K^+\Lambda$ Yield	RG-K $K^+\Sigma^0$ Yield	CLAS e1f $K^+\Lambda$ Yield	CLAS e1f $K^+\Sigma^0$ Yield
0.3 - 0.8	1.7 - 1.75	967810	123250	-	-
0.8 - 1.4		514170	74980	-	-
1.4 - 2.2		240520	41050	10092	1032
2.2 - 3.0		81630	14170	7808	810
3.0 - 3.9		39550	6620	3925	450
4.0 - 5.0		8970	2190	-	-
0.3 - 0.8	1.9 - 1.95	1241070	824020	-	-
0.8 - 1.4		536520	309710	-	-
1.4 - 2.2		245160	124080	11365	3843
2.2 - 3.0		83430	37440	7954	2537
3.0 - 3.9		37790	17190	3466	1122
4.0 - 5.0		5420	2290	-	-

Kinematic phase space for RG-K @ 6.5 GeV



	Total Yield
$K^+\Lambda$	35618500
$K^+\Sigma^0$	17702300

Full statistics for RG-K will allow for:

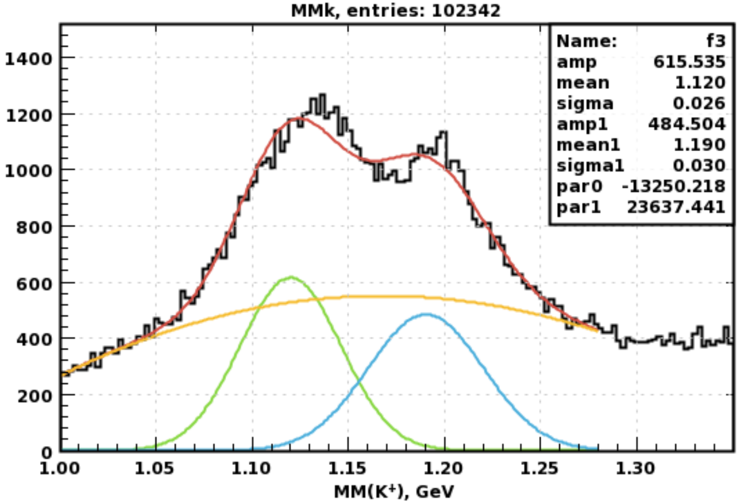
- KY electroproduction measurements up to $Q^2 = 3$ GeV^2 with statistics comparable to photoproduction

K^+Y Yield at Low Q^2 - Electron Detected in FT

Estimate for full 7.5 RG-K dataset (analyzed stat. x10)

Q^2 GeV^2	W GeV	RG-K $K^+\Lambda$ Yield	RG-K $K^+\Sigma^0$ Yield
0.05– 0.25	1.6 – 3	361250	196250

W (GeV)	RG-K $K^+\Lambda$ Yield	RG-K $K^+\Sigma^0$ Yield
thresh. – 2.0	75580	7830
2.0 – 2.5	198130	95410
2.5 – 3.2	101670	78360



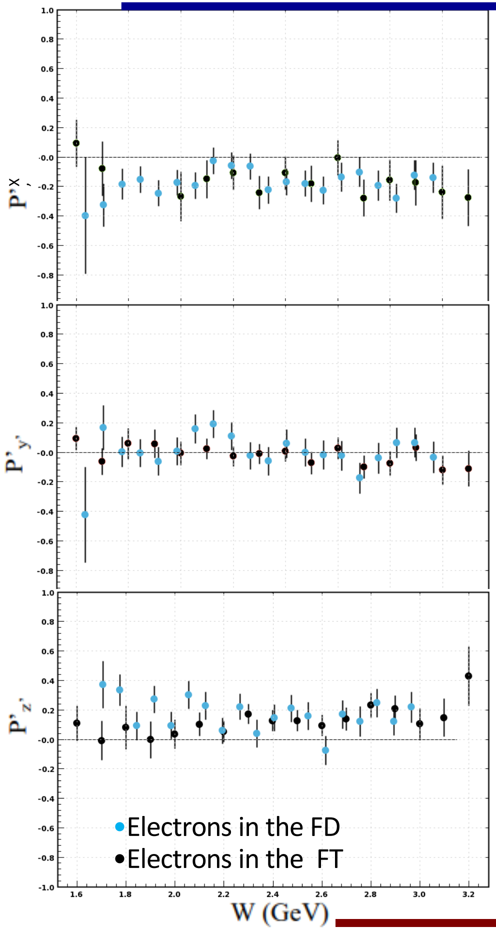
Fully exclusive kinematics

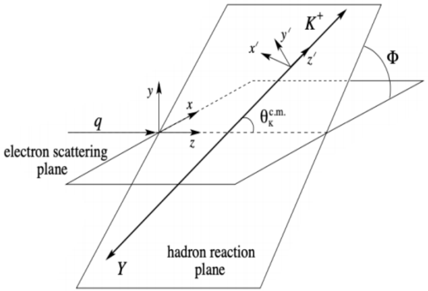
CLAS12 momentum correction implementation will allow for analysis via $e'K^+$ final state to maximize statistics

Full statistics for RG-K will allow for:

- KY electroproduction measurements down to Q^2 = 0.05 GeV^2

Transferred Λ Polarization





Hyperon polarization integrated over the Φ angle (x’, y’, z’)

~0.9

$$A_\Lambda = \alpha_\Lambda P_b \mathcal{P}'_\Lambda \cos\theta_p^{RF}$$

Angle between the quantization axes (x’, y’, z’) and the proton from the Λ decay

0.750

$$A_{meas} = \frac{(N_Y^+ + N_{Y'}^+ + N_{bck}^+) - (N_Y^- + N_{Y'}^- + N_{bck}^-)}{N_Y + N_{Y'} + N_{bck}}$$

$$\mathcal{P}'_{x'} = \sqrt{1-\epsilon^2} \cdot \frac{R_{TT'}^{x'0}}{R_T^{00} + \epsilon R_L^{00}}$$

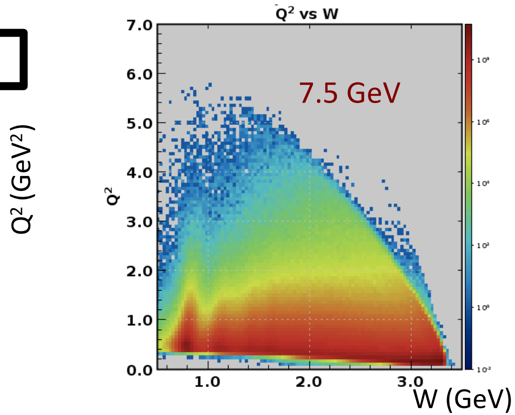
$$\mathcal{P}'_{y'} = 0$$

$$\mathcal{P}'_{z'} = \sqrt{1-\epsilon^2} \cdot \frac{R_{TT'}^{z'0}}{R_T^{00} + \epsilon R_L^{00}}$$

Preliminary results by Lucilla Lanza

Inclusive Electron Scattering

Electron in ECAL



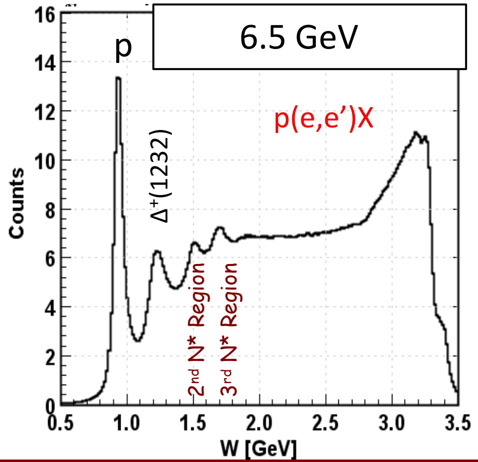
Electron Identification:

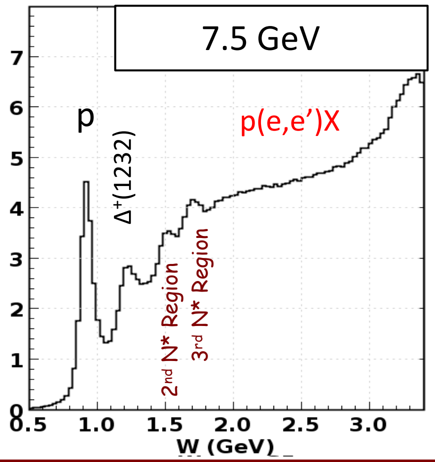
- Energy deposition in ECAL

  Separate showering from minimum-ionizing particles

- Matched hit in HTCC
- Track in Drift Chamber

Large acceptance spectrometer covers broad range in Q^2 and W



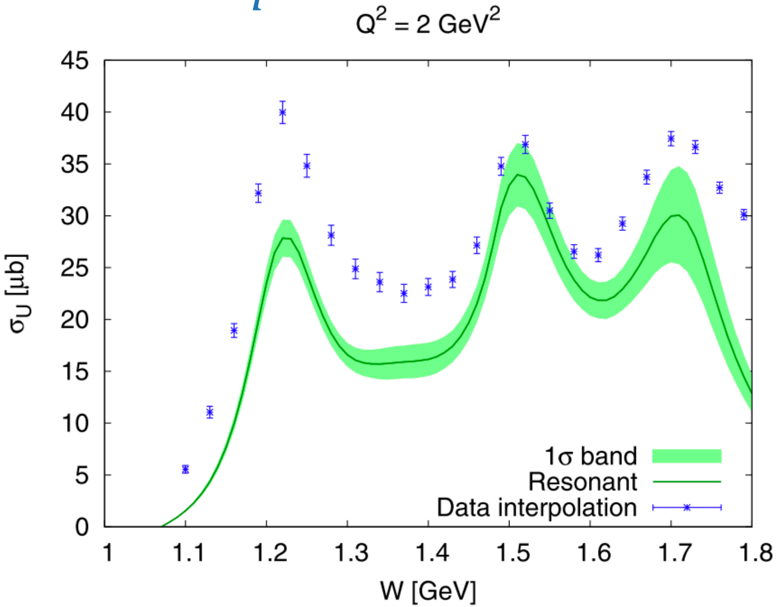


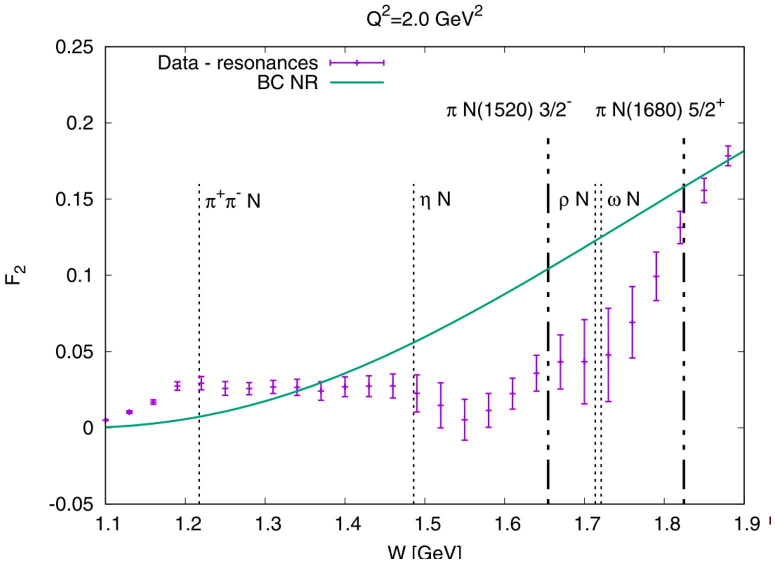
Nucleon resonance contributions to unpolarized inclusive electron scattering

Hiller-Blin et al (JPAC) PRC100 (2019) 035201

N^* and Δ^* electrocoupling from CLAS analyses used to evaluated resonance contribution in inclusive $e^- p \to X$

Difference between resonance and data compared to background parametrisation from Christy&Boosted PRC81 2010

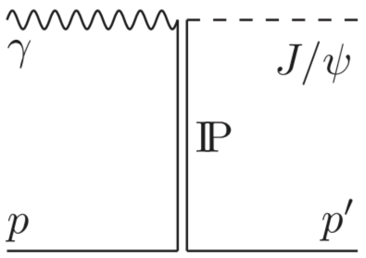


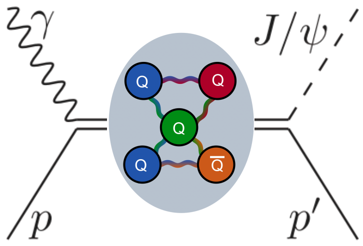


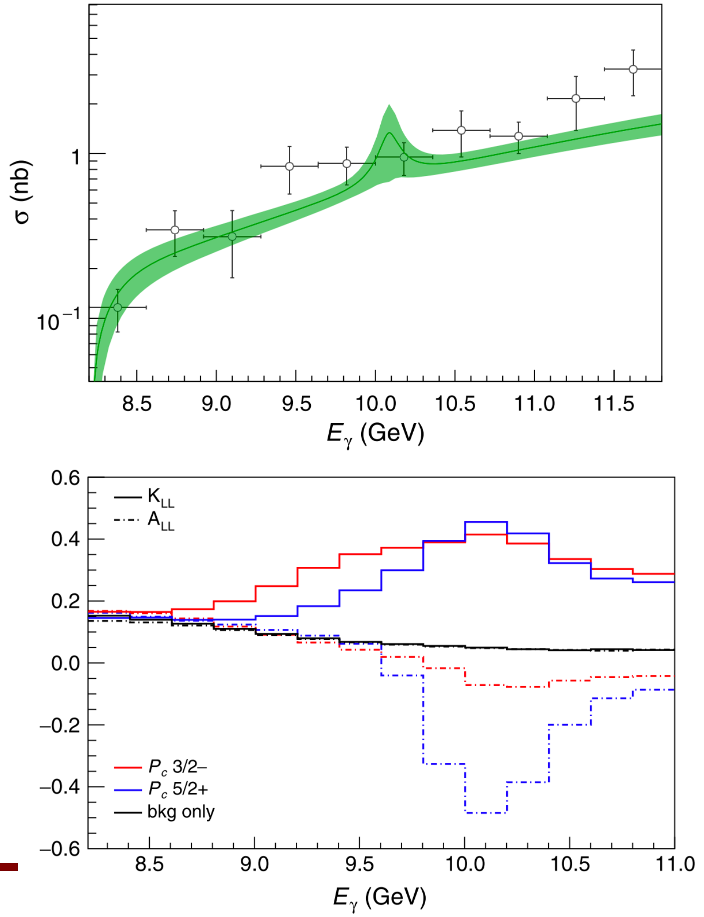
Double polarization observables in pentaquark photoproduction

Winney et al (JPAC) PRC100 (2019) 034019

Model for pentaquark production + background







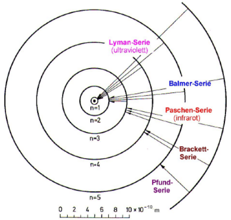
Prediction from polarized observables

Summary

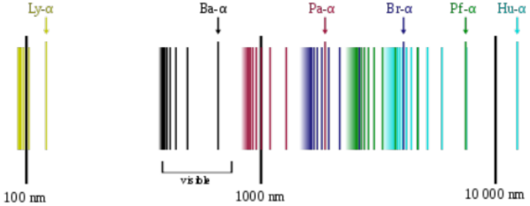
- We started a program to search for new states of baryonic matter: **hybrid baryons.**
- Complementing the international program to search for **hybrid mesons.**
- Identification of hybrid baryons will verify fundamental expectations of **strong QCD on the role of glue.**
- Data on polarization observables are being obtained on $\pi\pi$ photoproduction and KY electroproduction which are expected to provide important constraints to theoretical models to identify **new N* baryon resonances in the 2.1 – 2.3 GeV mass range**.
- New theoretical results have been obtained by JPAC for the **inclusive unpolarized electroproduction**.
- **Double polarization observables in pentaquark** photoproduction have also been evaluated.

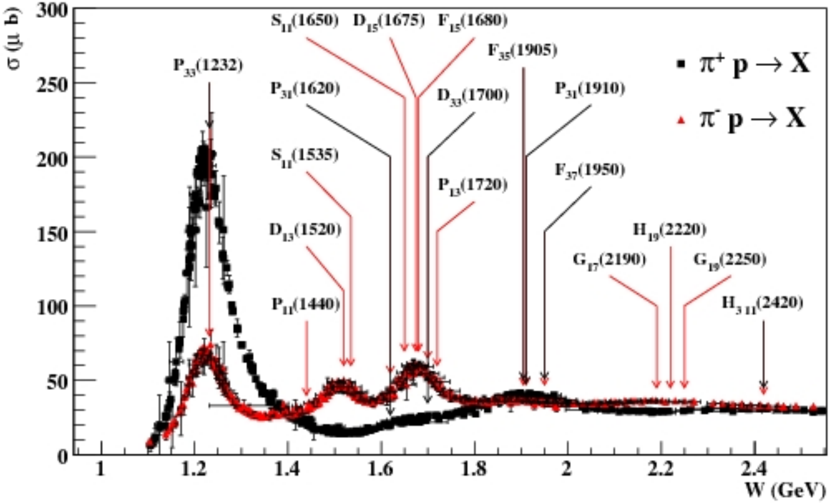
Why N* ? From the Hydrogen Spectrum to QCD

Niels Bohr (1922)



Spectral series of hydrogen





- Understanding the hydrogen atom's ground state requires understanding its excitation spectrum.

  ⟶ From Bohr model of the atom to QED.

- Understanding the proton's ground state requires understanding its excitation spectrum.

  ⟶ From the Constituent Quark model to QCD.