International Workshop on Partial Wave Analyses and Advanced Tools for Hadron Spectroscopy (PWA 12 / ATHOS 7)

Baryon Spectroscopy with CLAS and CLAS12

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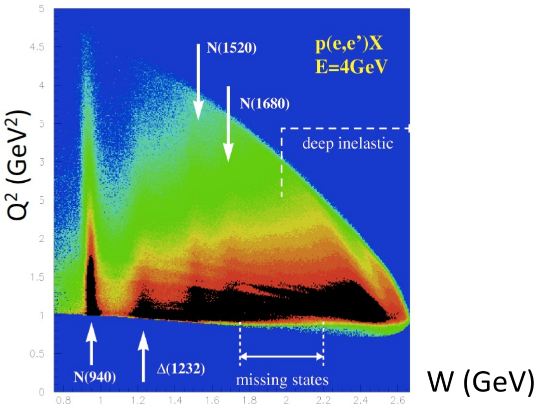
For the CLAS Collaboration

Outline:

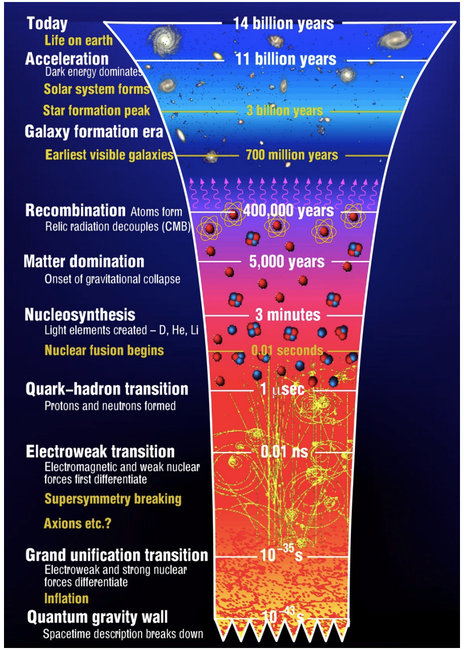
- Establishing N* states
- Identifying the effective degrees of freedom
- Results on photo-and electro-production
- Hybrid baryons signature
- Outlook & conclusions



Jefferson Lab

clas

Strong QCD is born ~ 1μsec after the Big Bang



T ~ 700, 000, 000 yrs: Galaxies

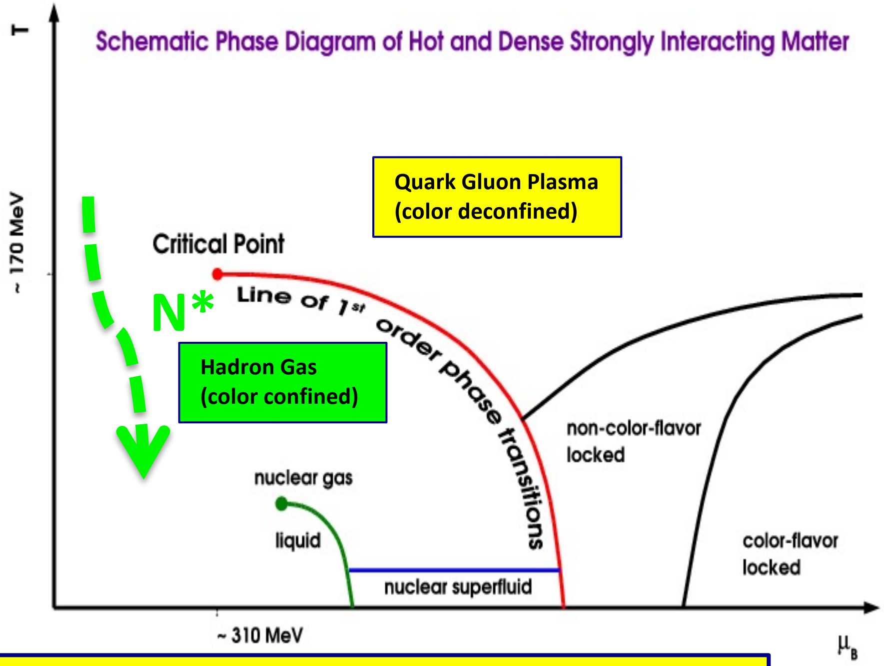
T ~ 400, 000 yrs: Atoms

T ~ : 10^2 s: Nuclei

T ~ 10^{-6} s: Nucleons

T~ 10^{-9} s: QGP

T ~ 10^{-6} s: Transition from the QGP to Nucleons

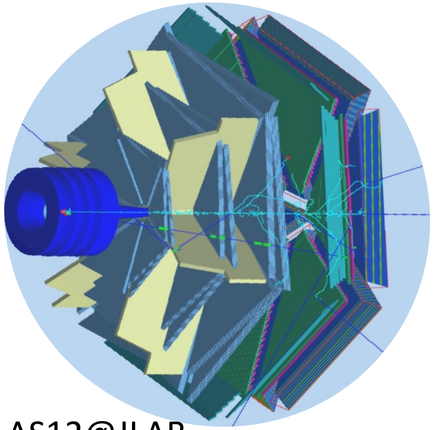


Dramatic events occur in the microsecond old Universe.

- 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 – photo- & electro-production of mesons

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



CLAS12@JLAB

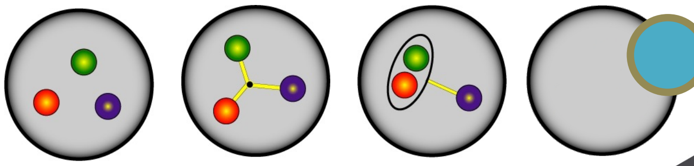
Detectors have been designed to measure cross sections and spin observables over a broad kinematic range for exclusive reaction channels:

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

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

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

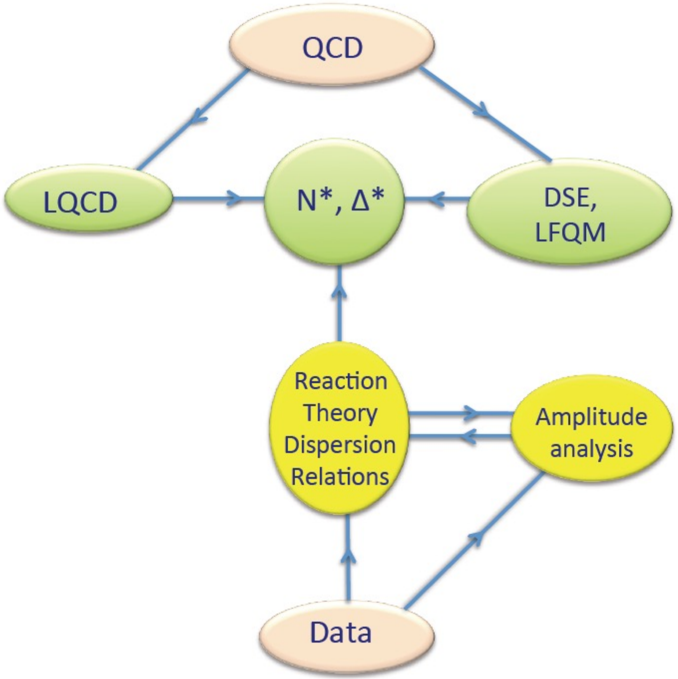
N* degrees of freedom??



Establishing the N* and Δ Spectrum

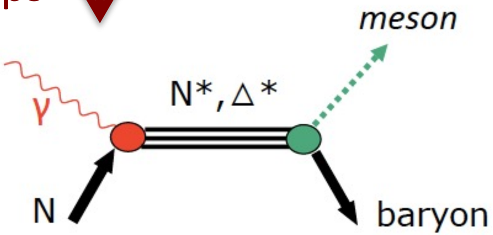
Experimental requirements:

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



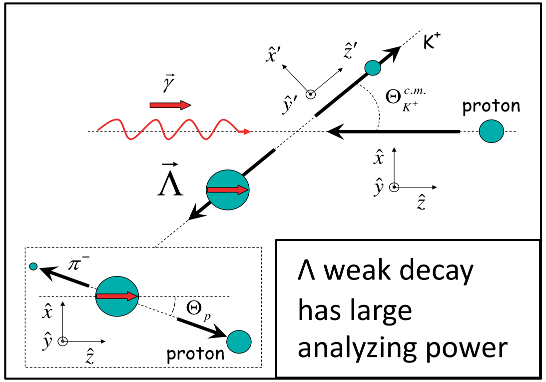
Engaging theoretical groups

Extract s-channel resonances



Hadronic production & Electromagnetic production

Polarization Observables: Complete Experiment



The holy grail of baryon resonance analysis

- 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

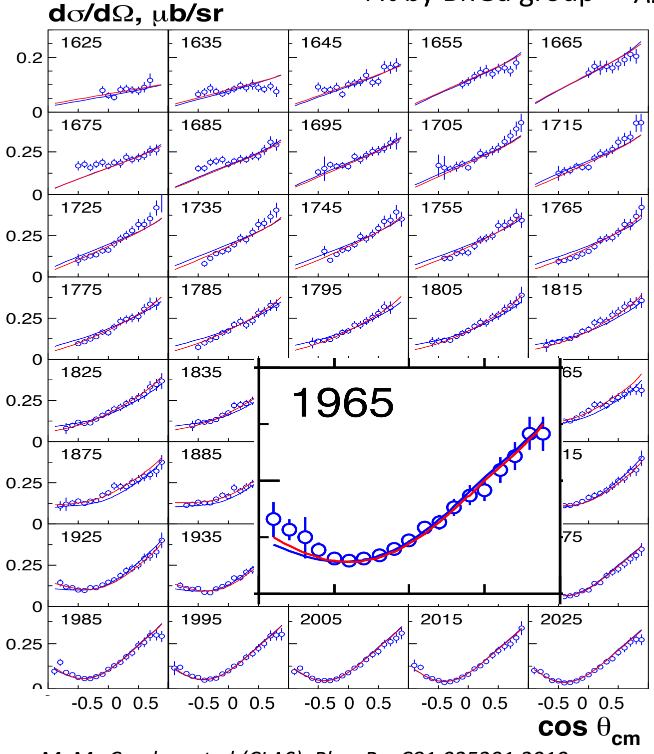
Beam (P^γ)		Target (P^T)			Recoil (P^R)			Target (P^T) + Recoil (P^R)								
					x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
		x	y	z				x	y	z	x	y	z	x	y	z
unpolarized	$d\sigma_0$		$\hat{T}$			$\hat{P}$		$\hat{T}_{x'}$		$\hat{L}_{x'}$		$\hat{\Sigma}$		$\hat{T}_{z'}$		$\hat{L}_{z'}$
$P_L^\gamma \sin(2\phi_\gamma)$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

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

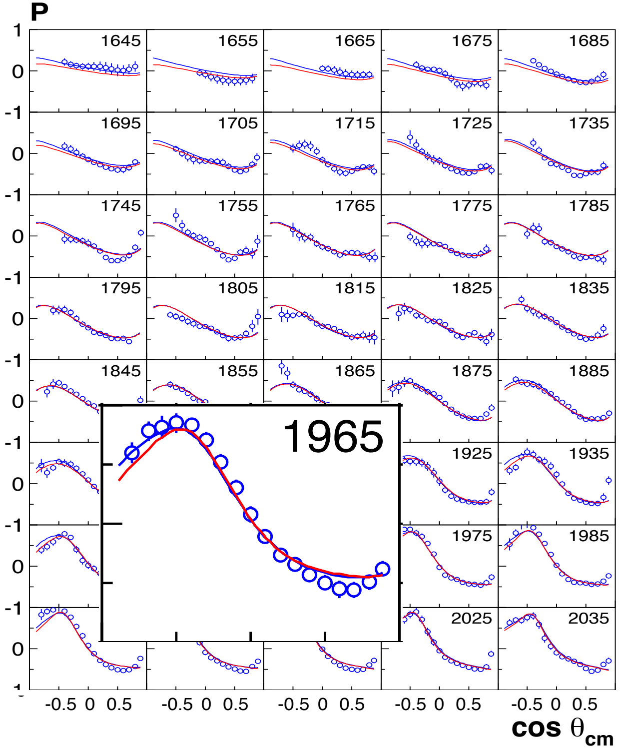
Establishing the N* spectrum – Precision & Polarization are essential

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

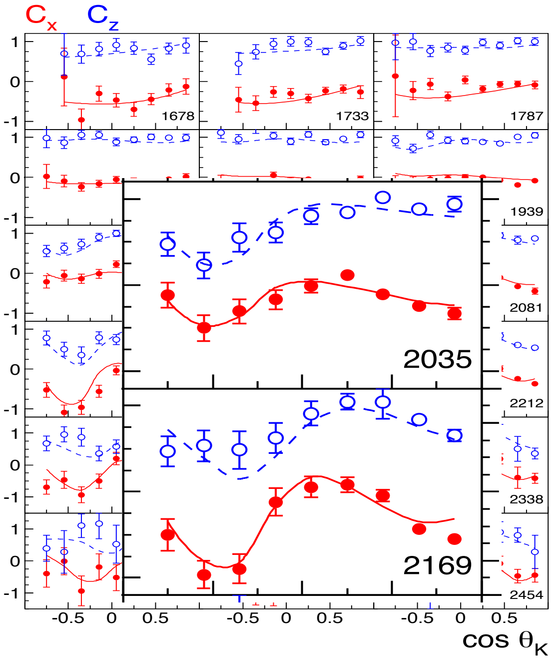
Fit by BnGa group *A.V. Anisovich et al, EPJ A48, 15 (2012)*



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

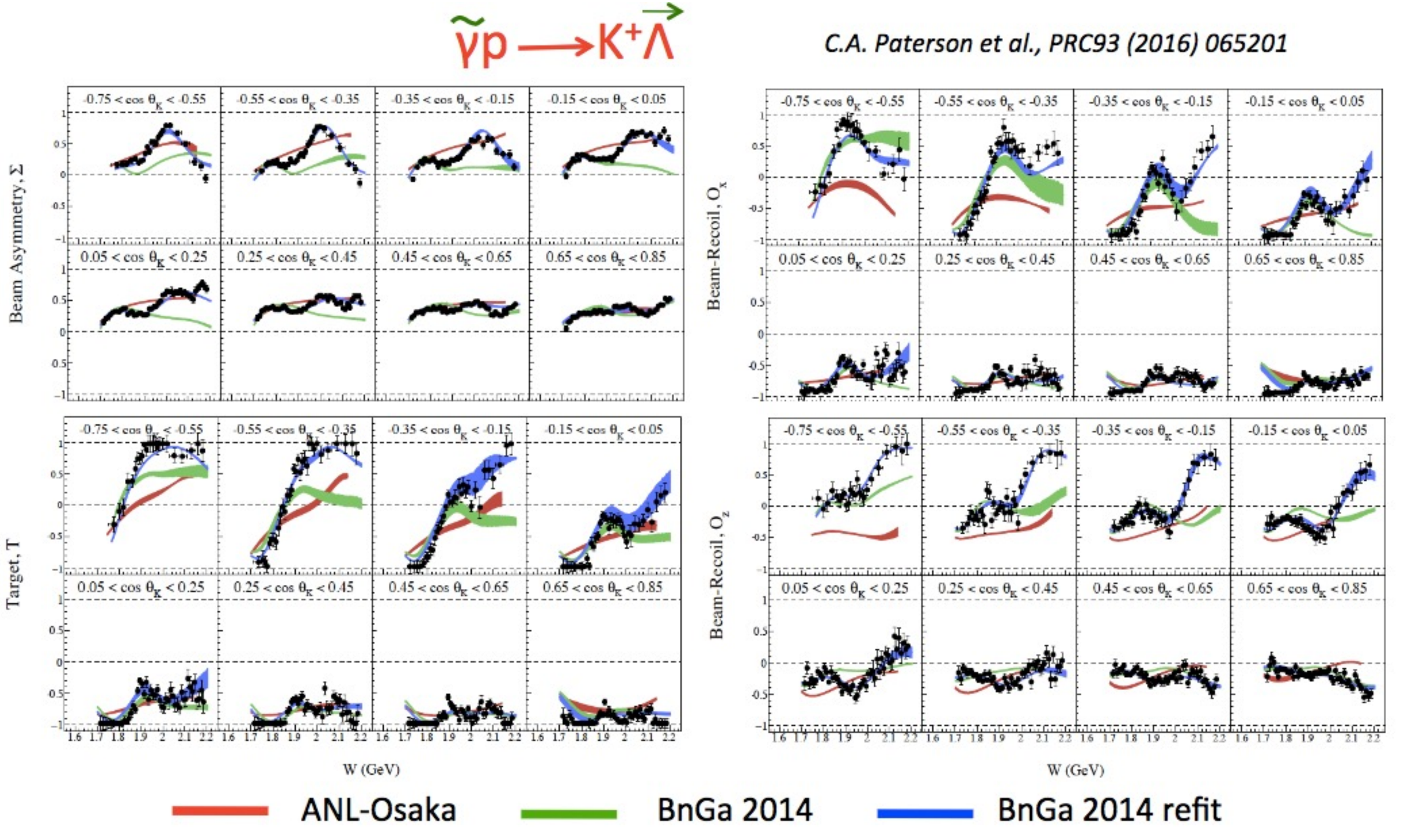


γ->Λ **Polarization** transfer



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

More N* from polarized $K^+ \Lambda$ photoproduction?



New Multipole Extraction

PRC96,055202 (2017)

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)$5/2^-$		***	*	*	***	**
Δ(1600)$3/2^+$	***	****			****	***
Δ(1900)$1/2^-$	**	***		**	***	***
Δ(2200)$7/2^-$	*	***		**	**	***

Naming scheme has changed:
$L_{2I\ 2J}(E) \longrightarrow J^P(E)$

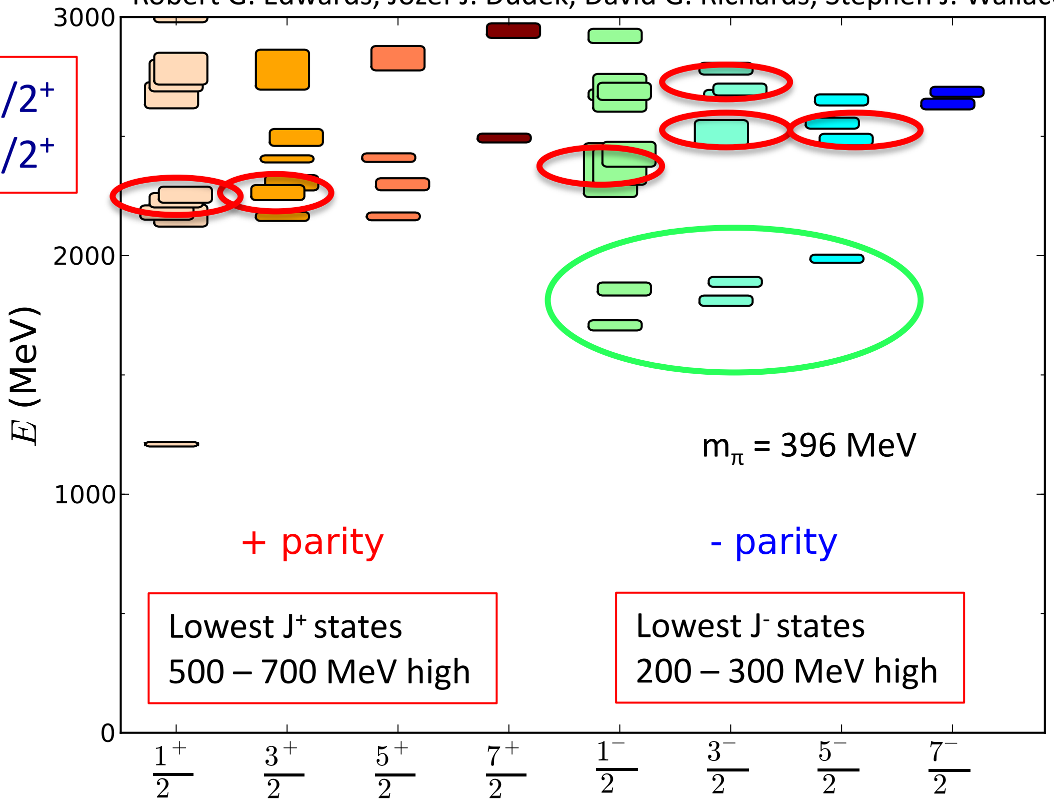
P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

Measure more polarization observables, study these states in electroproduction and extend to higher masses

Do New States Fit into LQCD Projections ?

Robert G. Edwards, Jozef J. Dudek, David G. Richards, Stephen J. Wallace **Phys.Rev. D84 (2011) 074508**

N(1900)3/2$^+$
N(1880)1/2$^+$



N(2060)5/2$^-$
N(2120)3/2$^-$
N(1875)3/2$^-$
N(1895)1/2$^-$

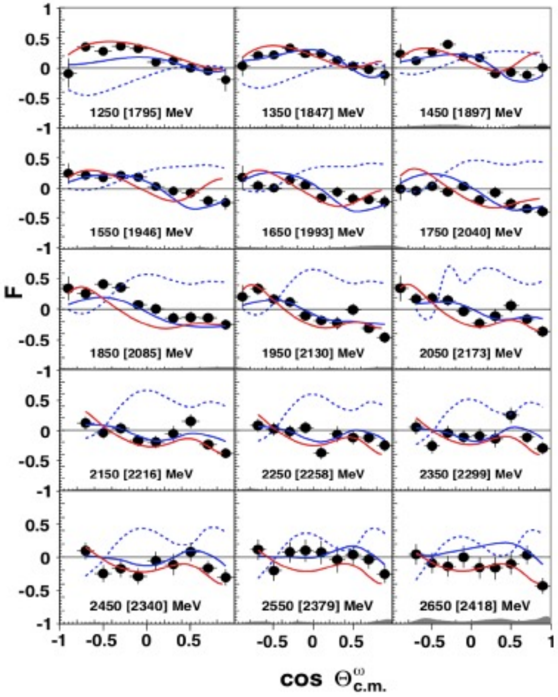
Ignoring the mass scale, new candidates fit the J^P values predicted from LQCD.

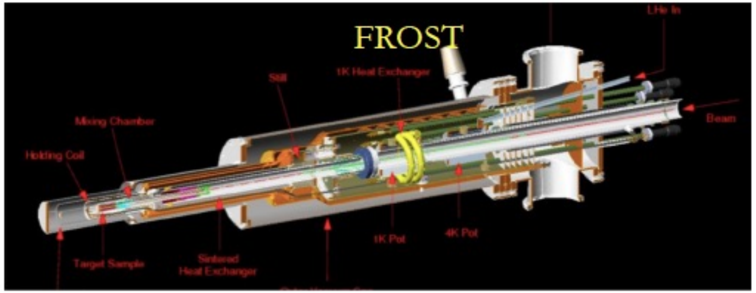
The field would really benefit from more realistic Lattice masses for N* states.

Known states:
N(1675)5/2$^-$
N(1700)3/2$^-$
N(1520)3/2$^-$
N(1650)1/2$^-$
N(1535)1/2$^-$

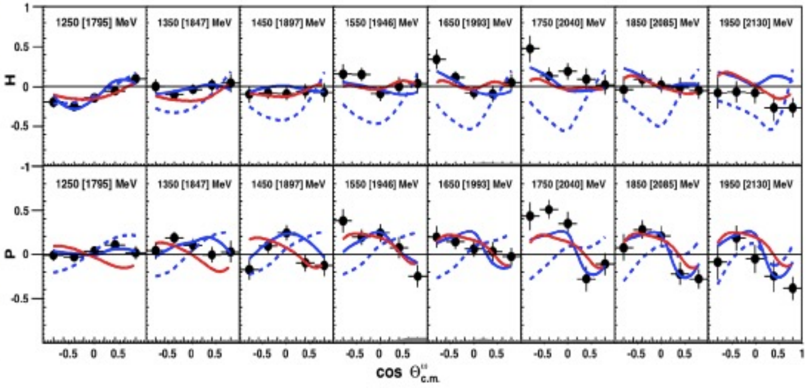
Beam-target asymmetries $\vec{\gamma}\,\vec{p} \rightarrow p\,\omega$

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}\{(1 - \delta_l\,\Sigma\cos 2\beta)$$
$$+\Lambda\cos\alpha\,(-\delta_l\,H\sin 2\beta + \delta_\odot\,F)$$
$$-\Lambda\sin\alpha\,(-T + \delta_l\,P\cos 2\beta)\},$$





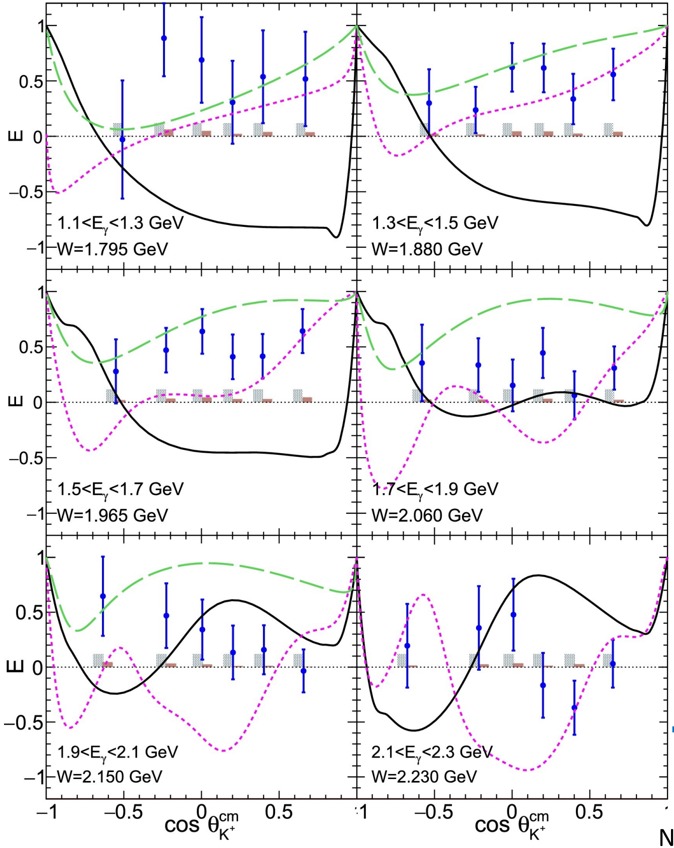
P. Roy et al. (CLAS), Phys.Rev. Lett. 122 (2019) 162301



PWA: BnGa, Wei

Both PWA need newly discovered nucleon resonances: $N(1880)1/2^+$, $N(1895)1/2^-$, $N(1875)3/2^-$, N(2120)3/2-. Also strong evidence is found for **$N(2000)5/2^+$** (previously also seen in unpolarized CLAS ω data)

Search for Neutron States: $\vec{\gamma}\,\vec{n} \to K^+\,\Sigma^-$



Beam-Target helicity asymmetry E

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_0 \left(1 - P_T^{eff} P_\odot E\right)$$

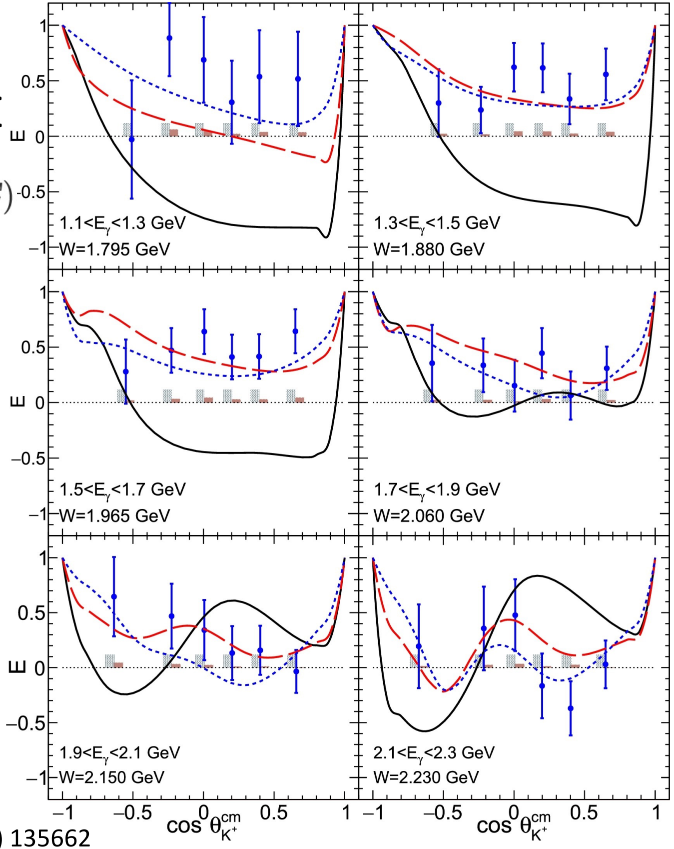
Kaon-Maid2000

Kaon-Maid2017

Bonn-Gatchina 2017

Bonn-Gatchina 2019
N(1895)1/2⁻ N(1720)3/2⁺
N(1900)3/2⁺
modified photo-couplings

Bonn-Gatchina 2019
+ N(2170) 3/2⁺

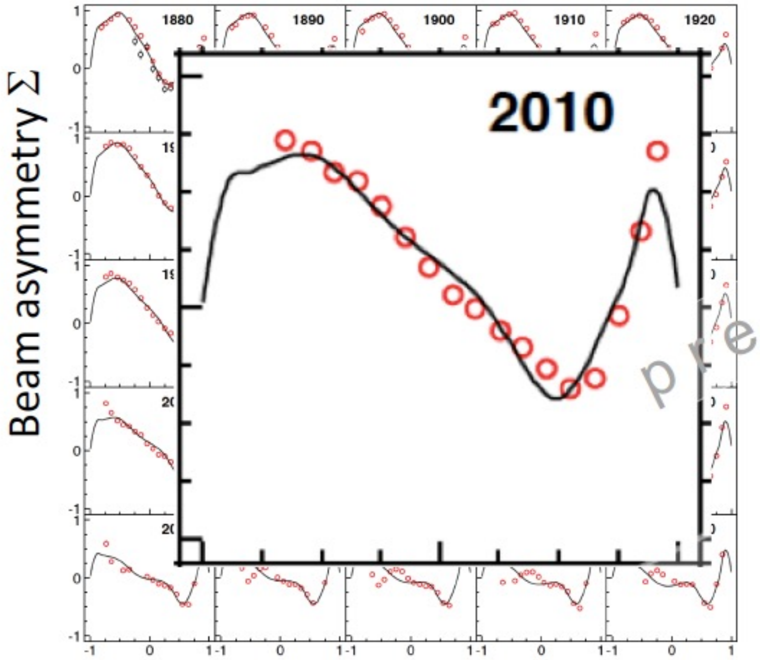


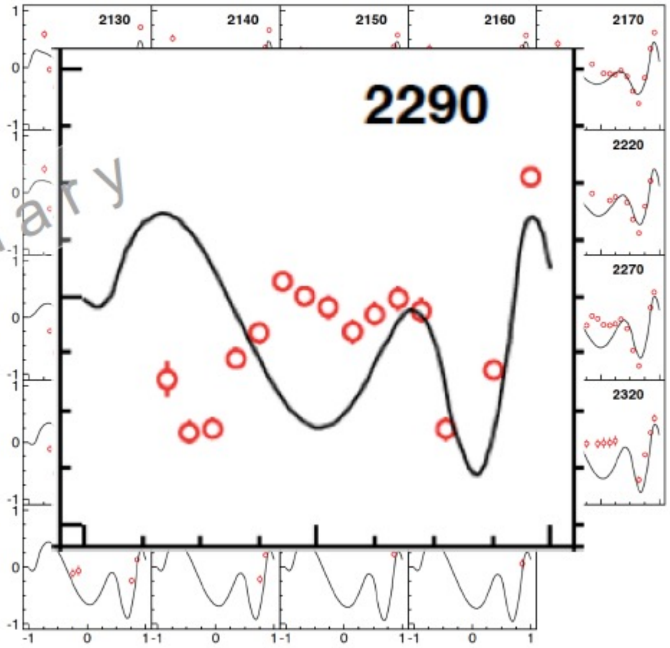
N. Zachariou et al Phys lett B 808 (2020) 135662

Search for Neutron States: $\vec{\gamma}\, n \rightarrow \pi^- p$

$\Sigma\ (\gamma n \to \pi^- p)$

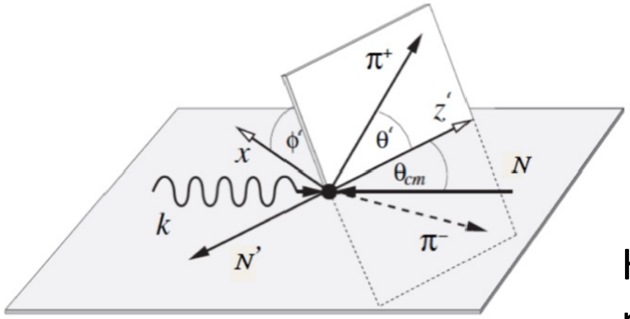
Fit: Bonn-Gatchina, 2018





Fit requires additional new resonances above 2100 MeV

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

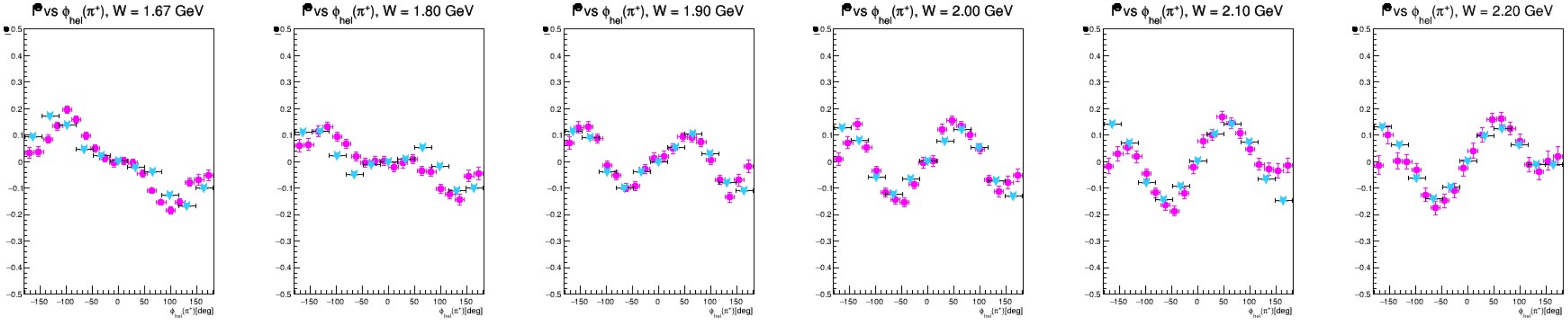


Measurements of polarization observables

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

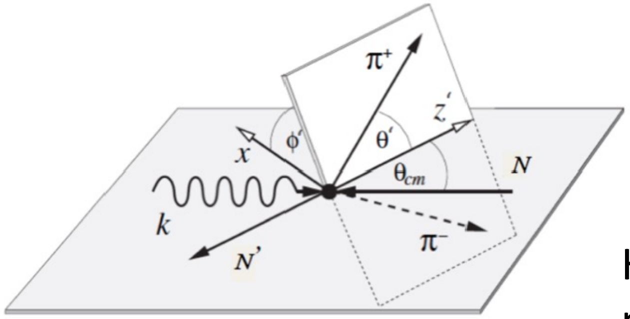
HD-ice frozen-spin polarized target

$I^\odot$ polarized p



Preliminary results by: A. Filippi (g14 data-set)

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

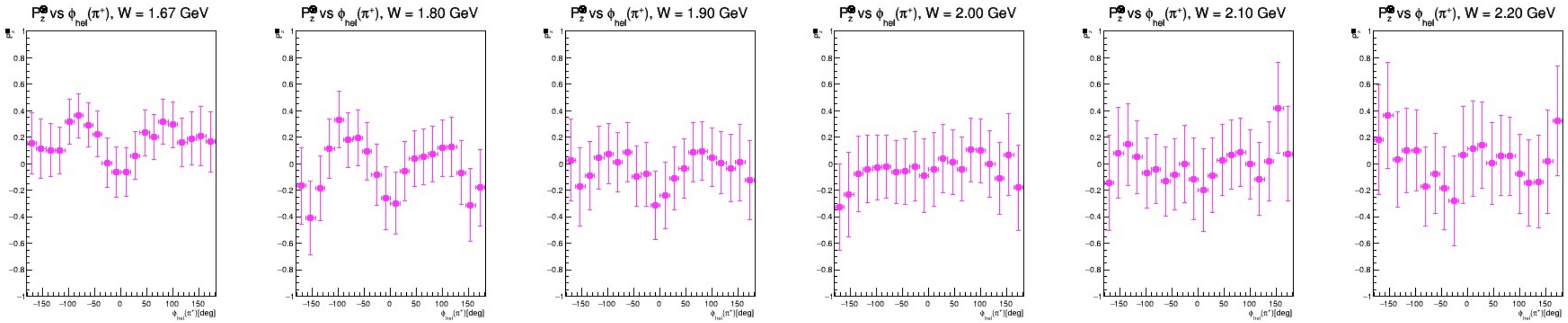


Measurements of polarization observables

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

HD-ice frozen-spin polarized target

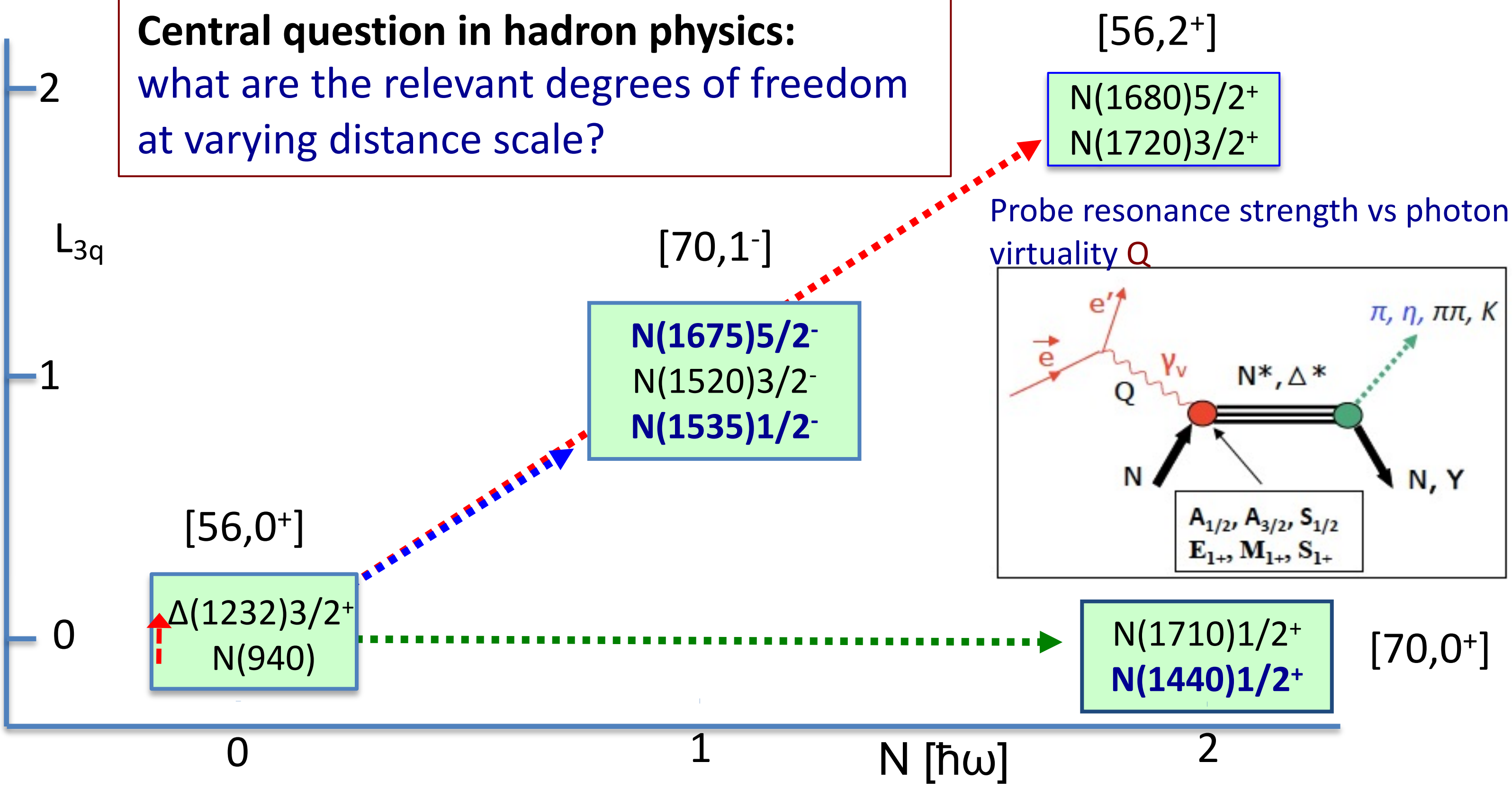
polarized p $P_z^\odot$



Preliminary results by: A. Filippi (g14 data-set)

Electroexcitation of N*/Δ resonances

Central question in hadron physics:
what are the relevant degrees of freedom at varying distance scale?



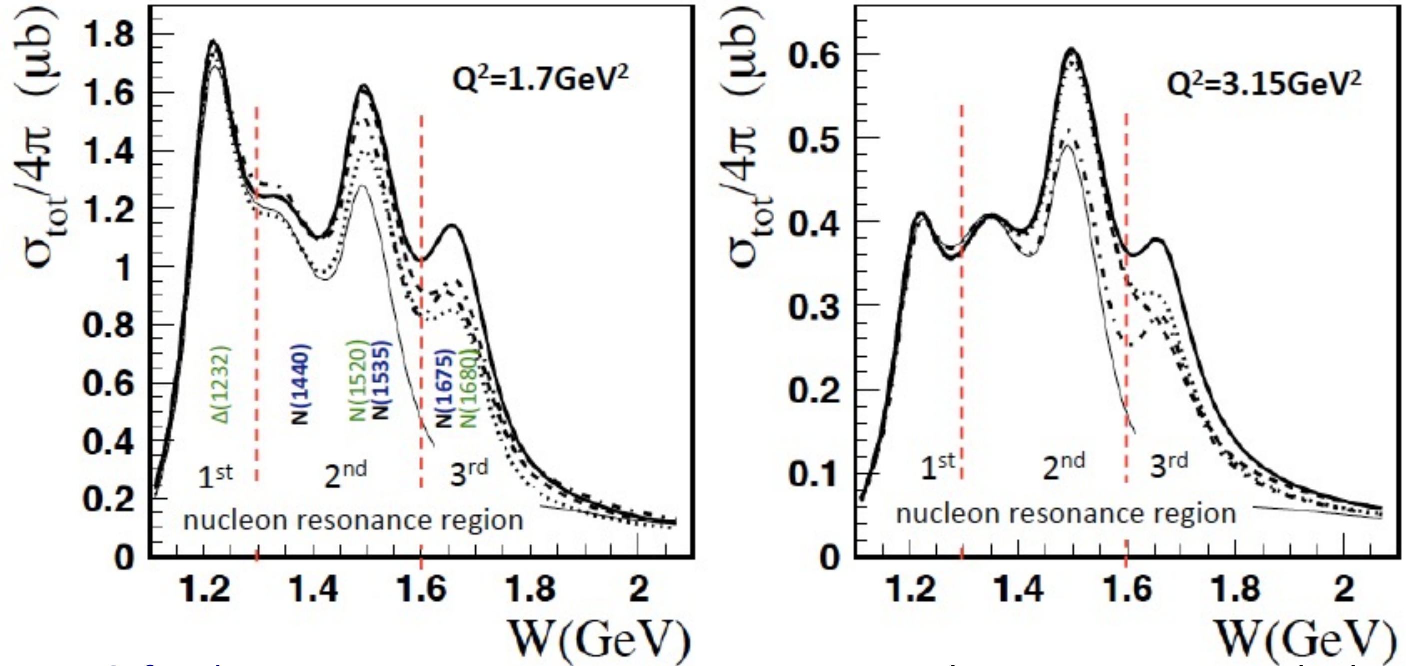
Probe resonance strength vs photon virtuality Q

Total cross section at W < 2.1 GeV

$\gamma^* + p \longrightarrow \pi^+ + n$

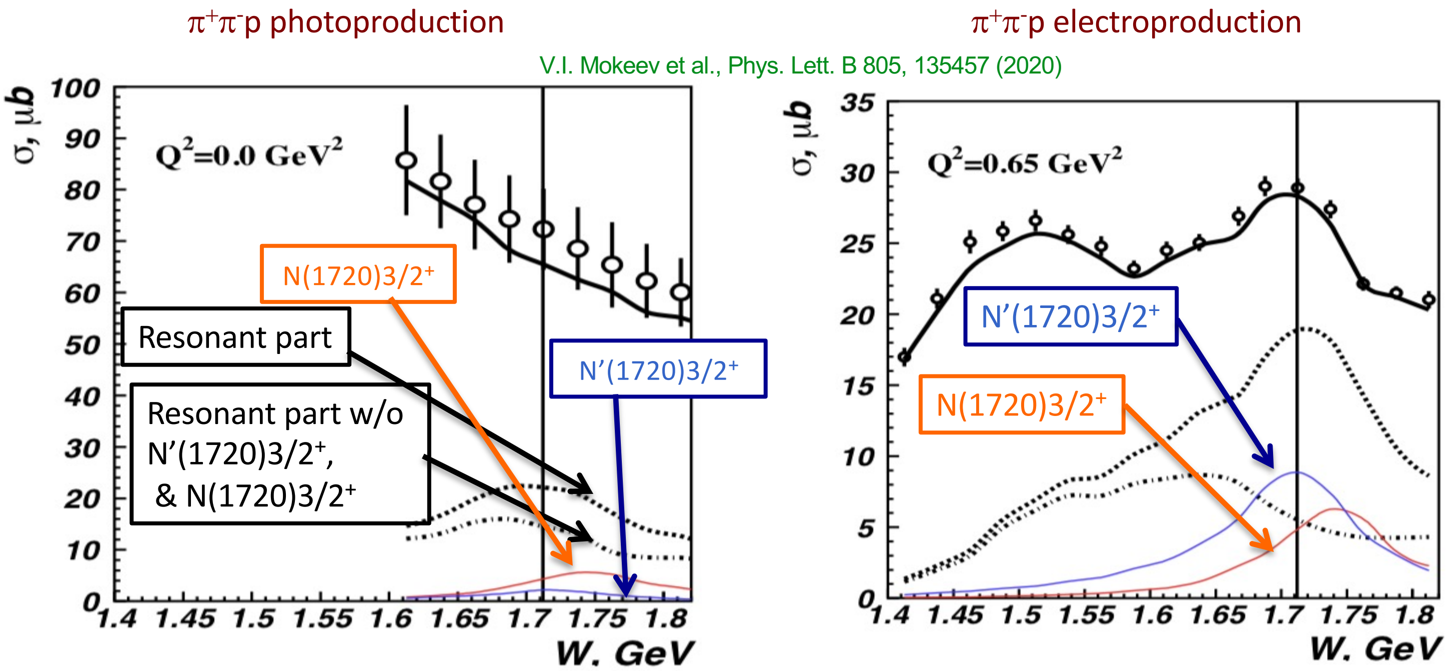
Different states respond differently to changes in Q^2

Data: *K. Park et al. PRC 77 (2008) 015208; K. Park et al. PRC 91 (2015) 045203*



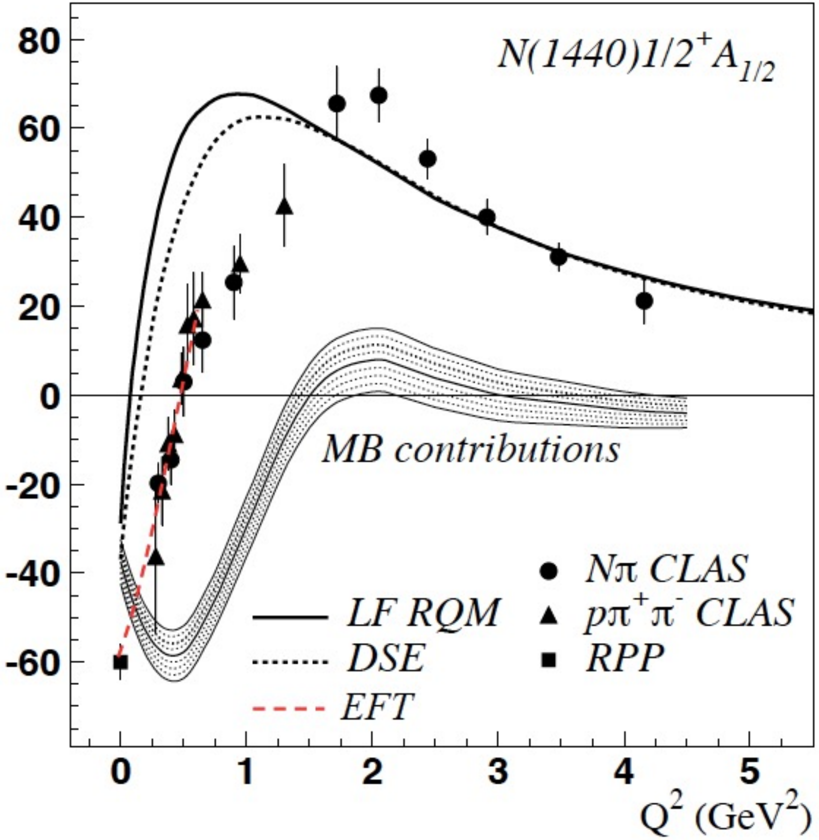
Analysis with UIM & fixed-t DR; *Recent review:* *I. Aznauryan, V. Burkert, Prog. Part. Nucl. Phys. 67 (2012) 1.*

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



- 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

Roper - 1st nucleon radial excitation?



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

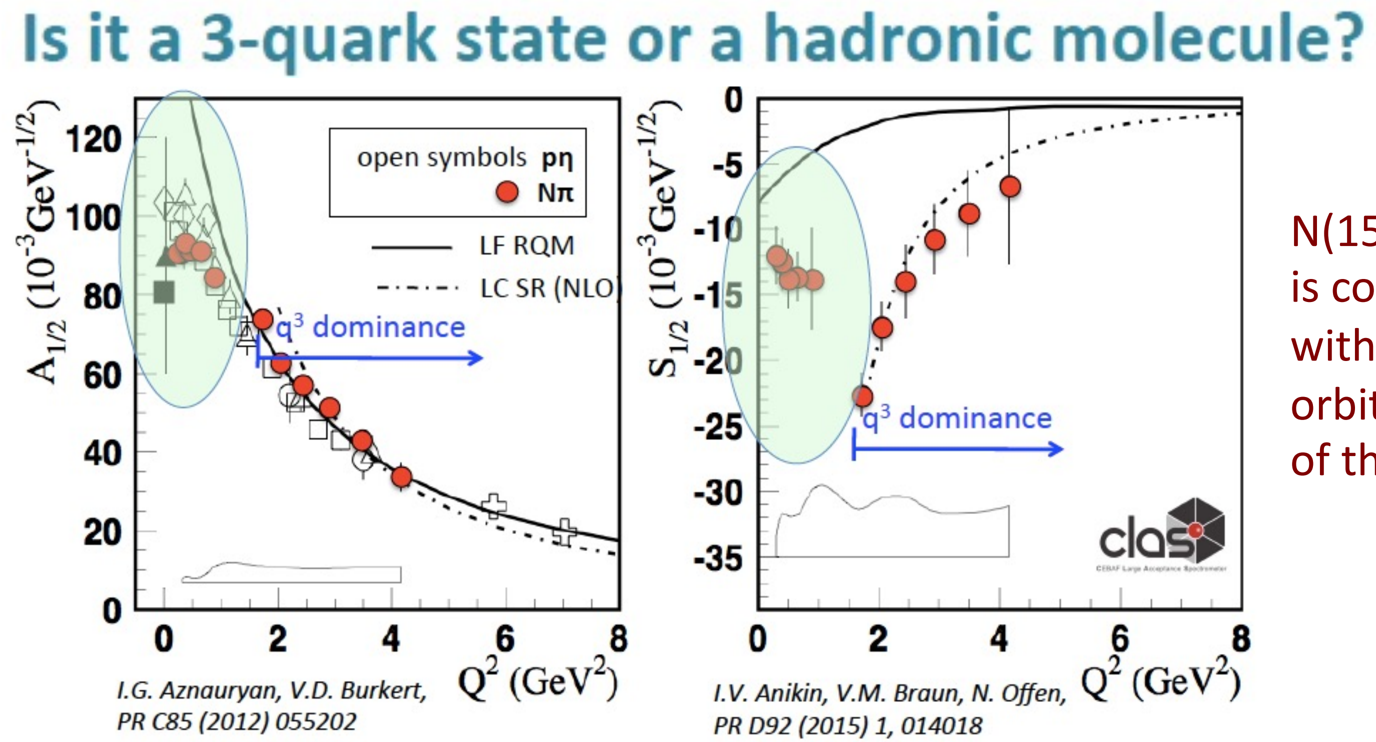
LF RQM: *I. Aznauryan, V.B. arXiv:1603.06692*
DSE: *J. Segovia, C.D. Roberts et al., PRC94 (2016) 042201*
EFT: *T. Bauer, S. Scherer, L. Tiator, PRC90 (2014) 015201*

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

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

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

MB Contribution to electro-excitation of N(1535)1/2$^-$



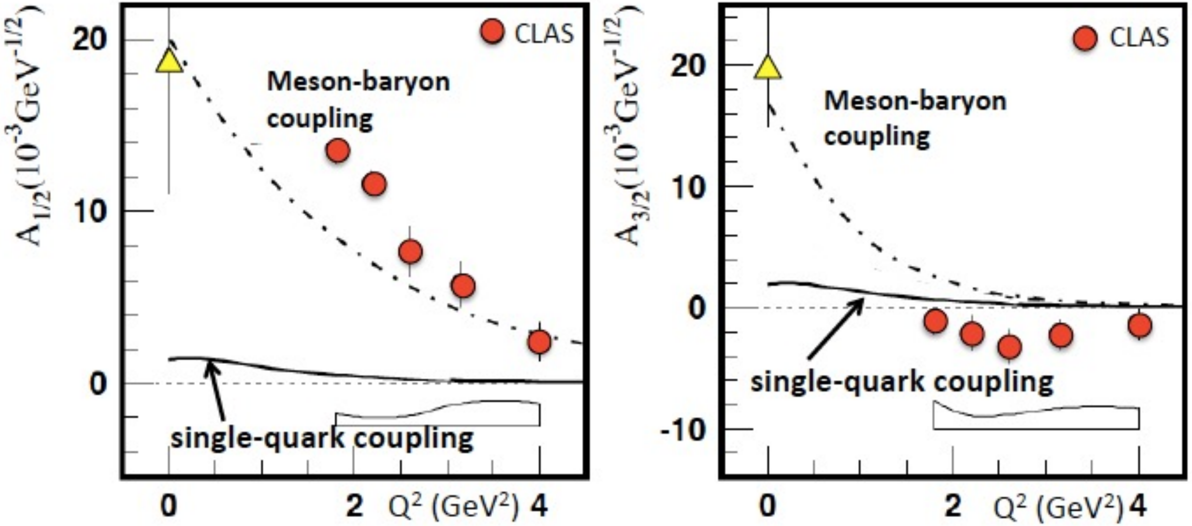
N(1535)1/2$^-$ is consistent with the 1st orbital excitation of the nucleon.

- Meson-baryon cloud may account for discrepancies at low Q^2.

MB Contribution to electro-excitation of N(1675)$5/2^-$

Quark components to the helicity amplitudes of the N(1675) $5/2^-$ are strongly suppressed for **proton target.**

Single Quark Transition:
$A^p_{1/2} = A^p_{3/2} = 0$



- Measures the meson-baryon contribution to the γ^* p N(1675)$5/2^-$ directly.
- Can be verified on γ^* n N(1675)$5/2^-$ which is not suppressed

——— *E. Santopinto and M. M. Giannini, PRC 86, 065202 (2012)*

– · – · *B. Juliá-Díaz, T.-S.H. Lee, et al., PRC 77, 045205 (2008)*

Hybrid Baryons: Baryons with Explicit Gluonic Degrees of Freedom

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

Experimentally:

- **Hybrid mesons** $|q\bar{q}g>$ 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).

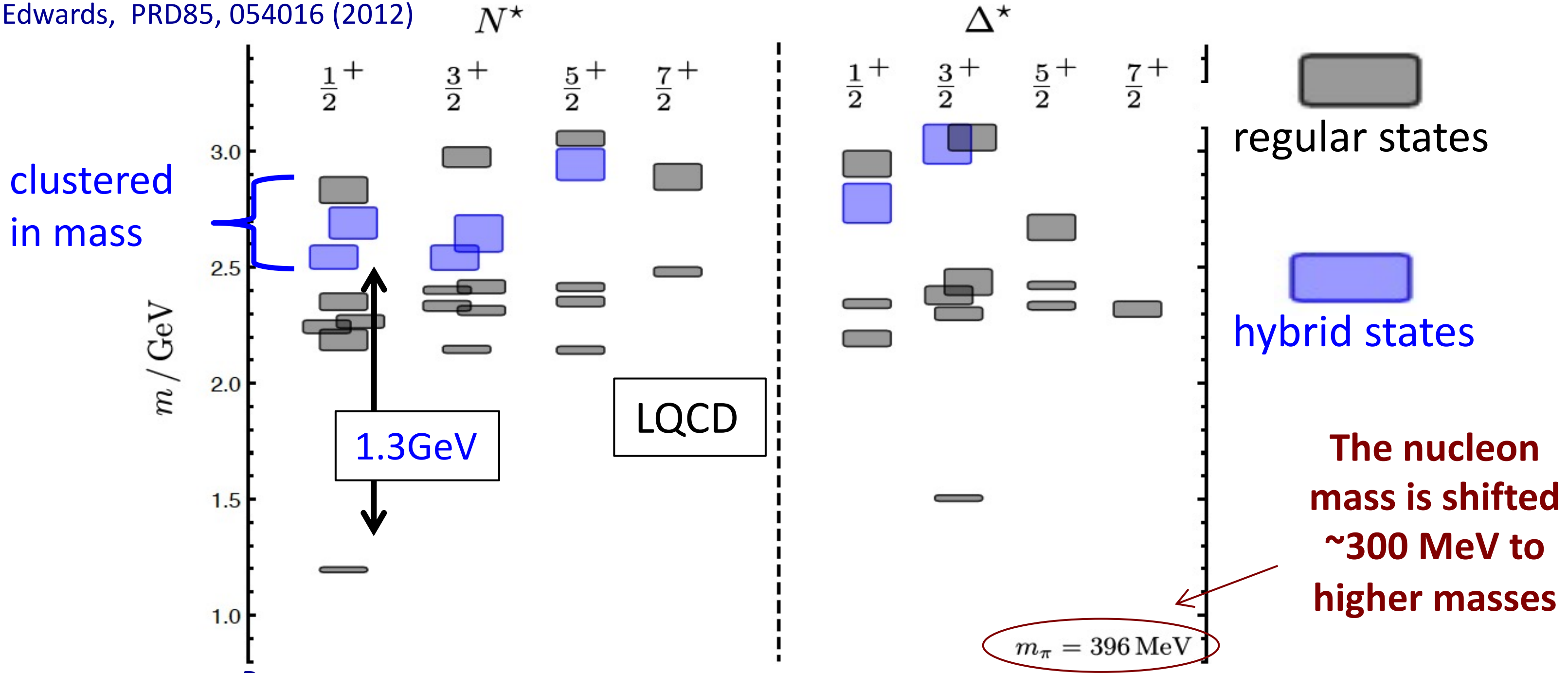
✧ QCD Sum Rule - L. Kisslinger and Z. Li, Phys. Rev. D 51, R5986 (1995).

✧ 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)



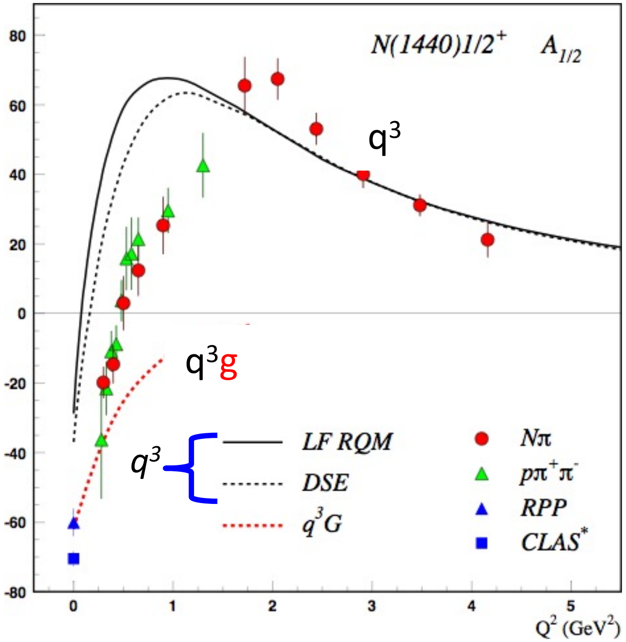
Hybrid states have same J^P values as qqq baryons. How to identify them?

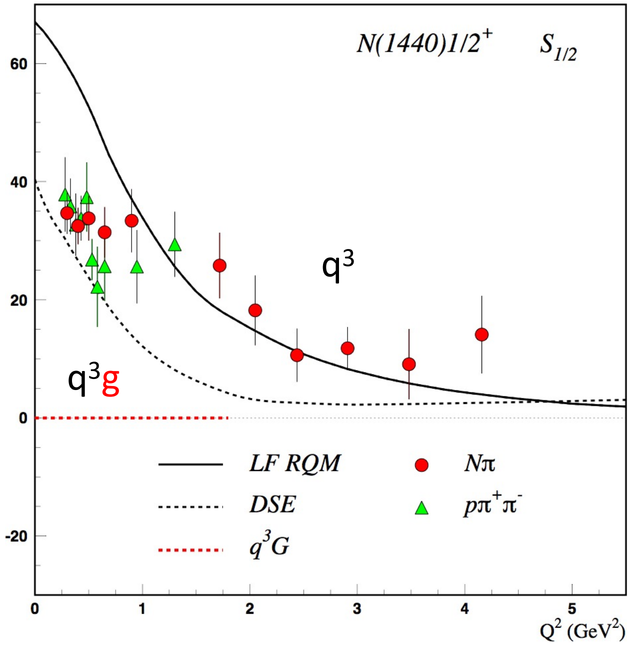
- Overpopulation of N $1/2^+$ and N $3/2^+$ states compared to QM projections.
- **$A_{1/2}$ ($A_{3/2}$) and $S_{1/2}$ show different Q^2 evolution.**

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 ?

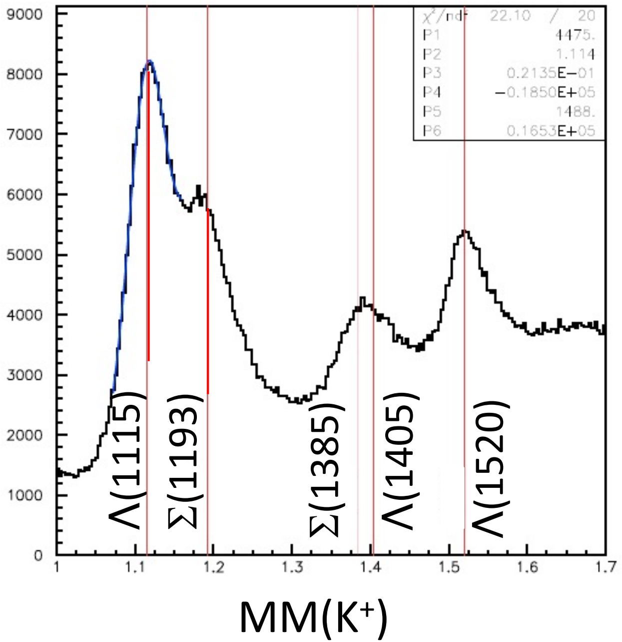


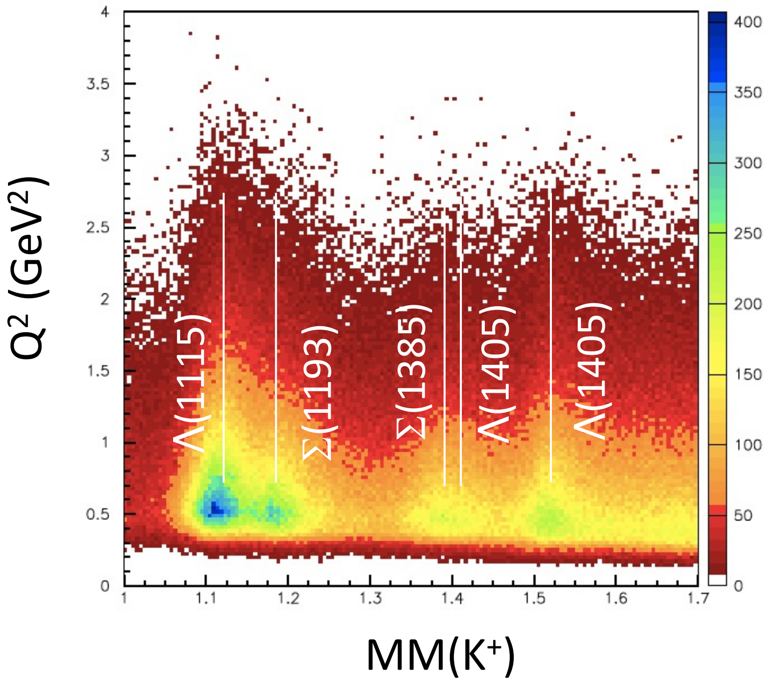


For hybrid "Roper", $A_{1/2}(Q^2)$ drops off faster with Q^2 and $S_{1/2}(Q^2)$ ~ 0.

CLAS12 K^+ electroproduction data

1.6 GeV < W < 3 GeV





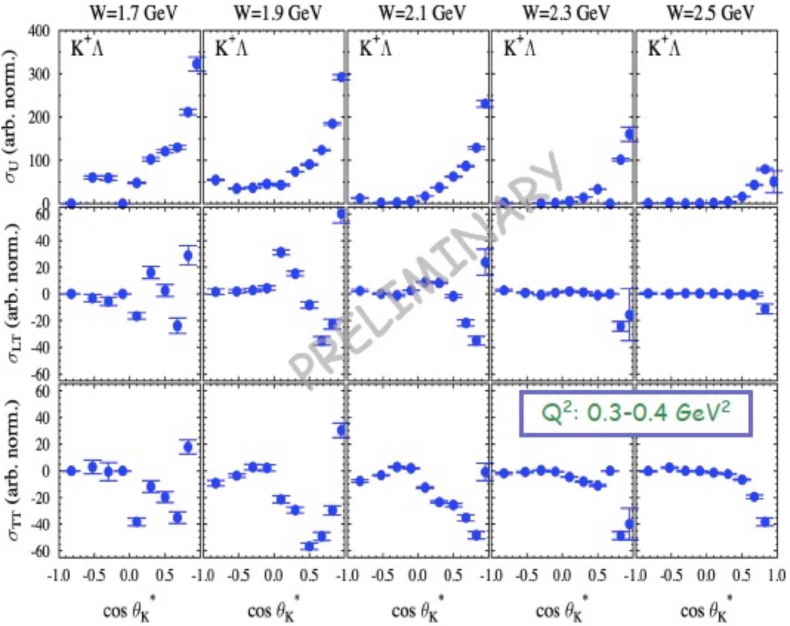
4 M total $K\Lambda$ events already collected

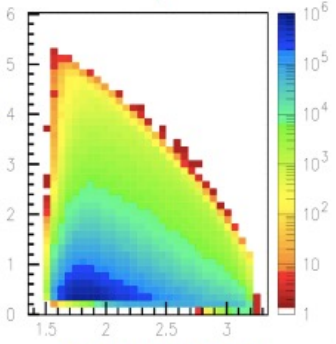
CLAS12 KY electro-production Cross Section Measurements

$ep \rightarrow e'K^+\Lambda$

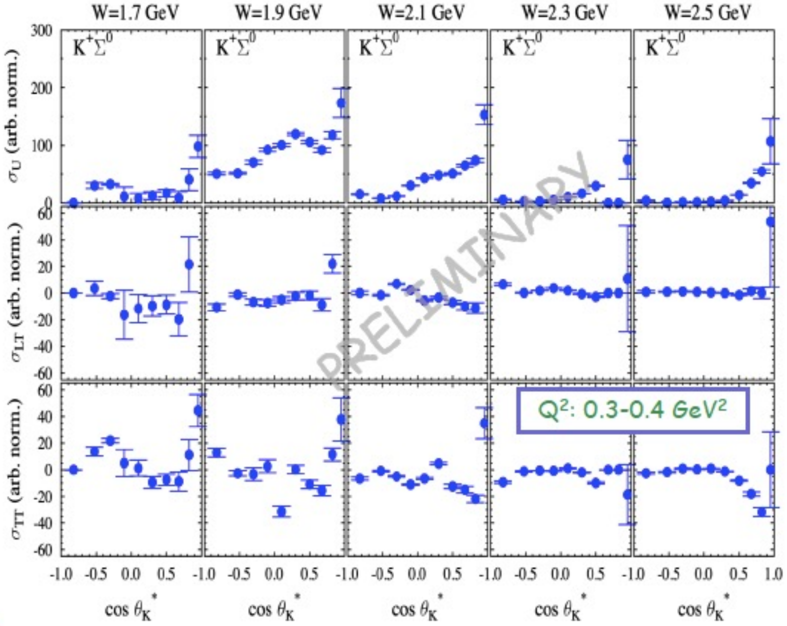
$$\frac{d\sigma}{d\Omega} = (\sigma_T + \epsilon\sigma_L) + \sqrt{\epsilon(1+\epsilon)}\sigma_{LT}\cos\Phi + \epsilon\sigma_{TT}\cos 2\Phi$$

$ep \rightarrow e'K^+\Sigma^0$





Q² vs. W (GeV)



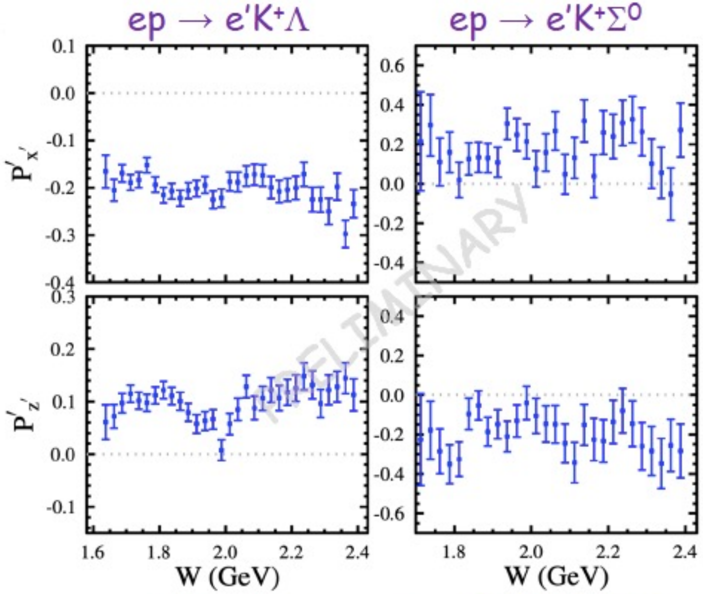
6.535 GeV RG-K

$\sigma_{T,L,LT,TT} = f(Q^2, W, \cos\theta_K^*)$

By Dan Carman

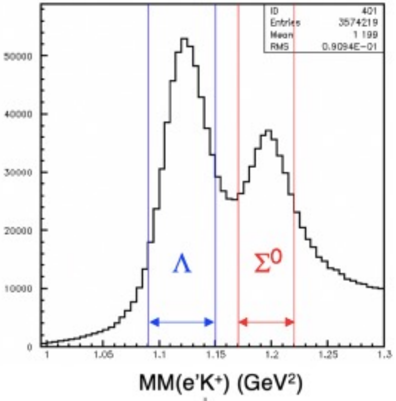
CLAS12 KY electro-production Cross Section Measurements

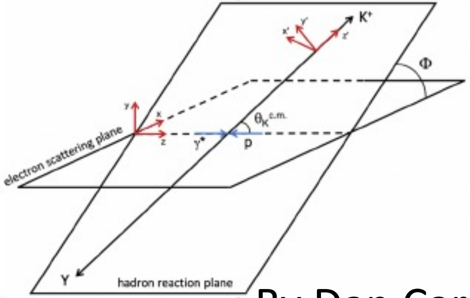
CLAS12 RG-K @ 6.535 GeV



Publication in preparation

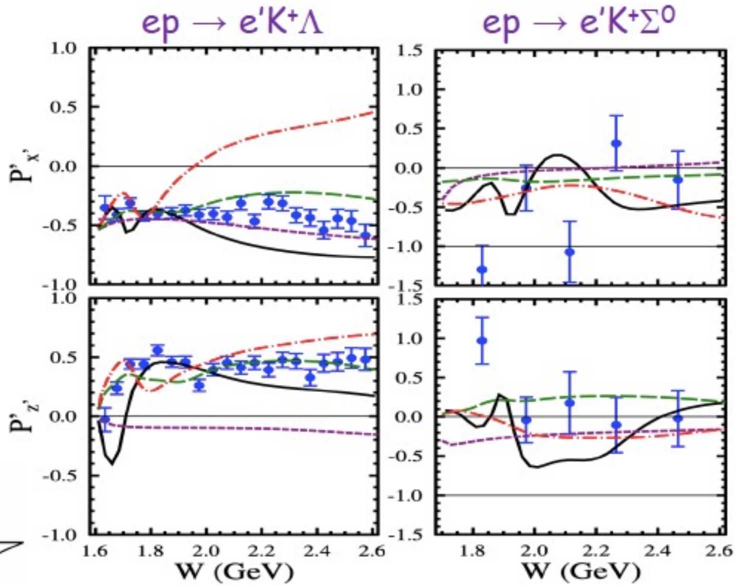
Raw uncorrected polarization





By Dan Carman

CLAS e1-6 @ 5.754 GeV



D.S. Carman et al., PRC79, 065205 (2009)

Mart/Bennhold RPR-2
RPR-1 Regge

Baryon Spectroscopy Status Today

- Major progress made in the last years in the search for N* and Δ states.
  All states can be accommodated in CQM and LQCD schemes.
  - Polarization observables in photo-production have provided crucial constraints

- Knowledge of Q^2-dependence of electro-couplings is absolutely necessary to understand the nature (the internal structure) of the excited states.
  - Roper IS the first radial excitation of the q^3 core, obscured at large distances by meson-cloud effects.
  - Leading electrocoupling amplitudes of prominent low-mass states (e.g. $N(1535)1/2^-$) is well modeled by DSE/QCD, LC SR and LF RQM for $Q^2 > 2$ GeV.

- Search for hybrid baryons with explicit gluonic degrees of freedom would be possible investigating the low Q^2 evolution of high-mass resonance (2-3 GeV) electrocoupligs:
  - Looking for suppressed $A^{1/2}$, $A^{3/2}$, $S^{1/2}$ at low Q^2.

Upcoming results from CLAS12 will play a key role: stay tuned!