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Progress in diffractive and annihilation production and exotic baryon

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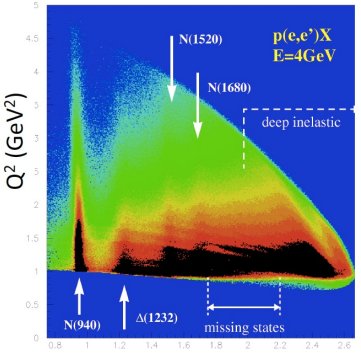
Reporting the activity of: INFN-CT, INFN-FE, INFN-GE, INFN-TO, INFN-RM2, Univ. de Barcelona, Univ. of Bern, Univ. of York.

By: Angela Badalà, Alessandra Filippi, Isabella Garzia, Bernd Krusche, Lucilla Lanza, Vincent Mathieu, Nickolas Zachariou

Outline:

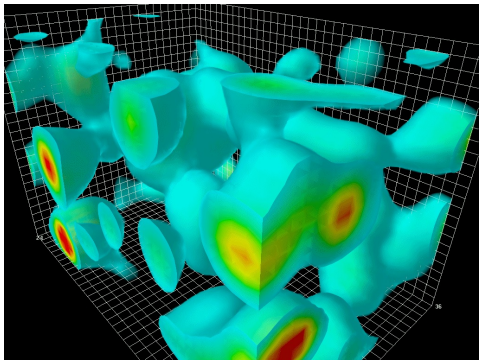
- Physics case: pentaquarks, hybrid baryons and the role of the glue
- Hybrid baryons signature
- πN KY and ππ photo-and electro-production at CLAS
- $\Lambda(1520)$ SDME measurements at GlueX/ Ω production at ALICE
- Pentaquark production at BESIII
- Outlook & conclusions



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, ***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

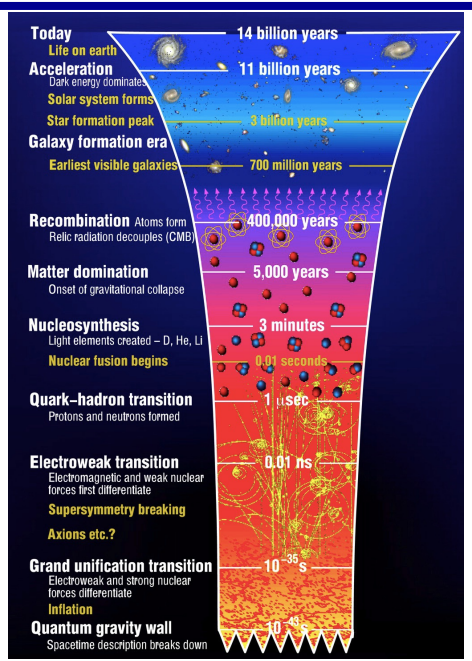
- The light N* spectrum: what is the role of glue?

  → **Search for new baryon states**

- The heavy baryon sector: hidden charm pentaquarks

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

Strong QCD is born ~ 1μsec after the Big Bang



T ~ 700, 000, 000 yrs: Galaxies

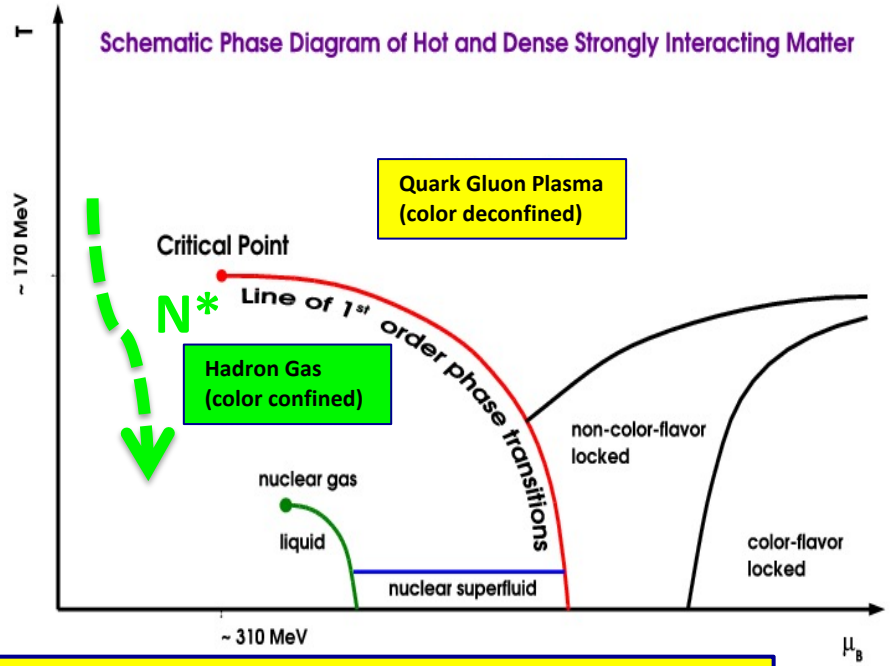
T ~ 400, 000 yrs: Atoms

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

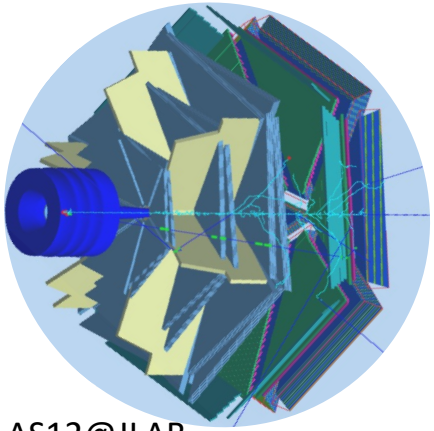


Dramatic events occur in the microsecond old Universe.

- 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

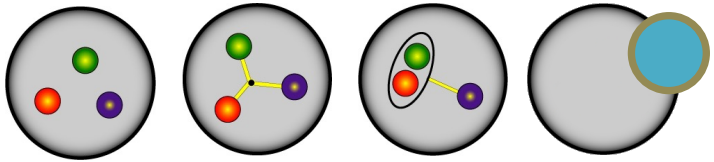
Detectors have been designed to measure cross sections and spin observables over a broad kinematic range for exclusive reaction channels:

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

- 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.

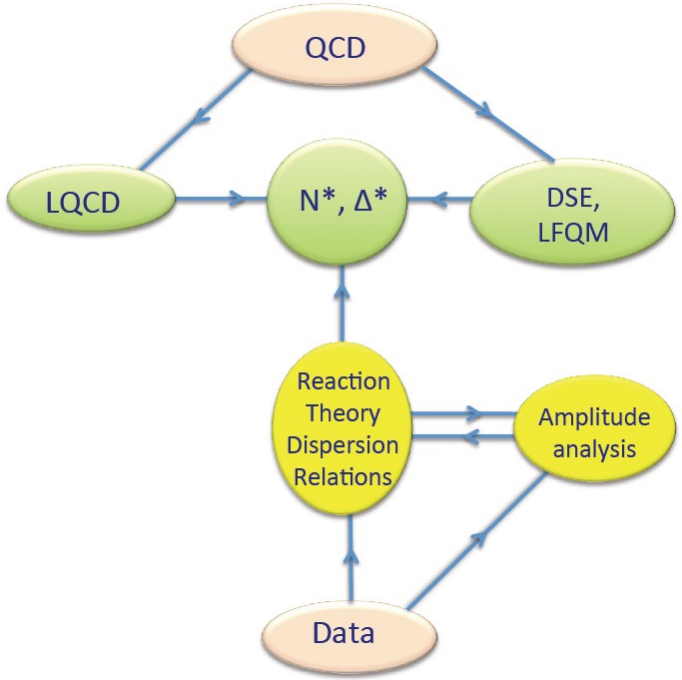
N* degrees of freedom??



Establishing the N* and Δ Spectrum

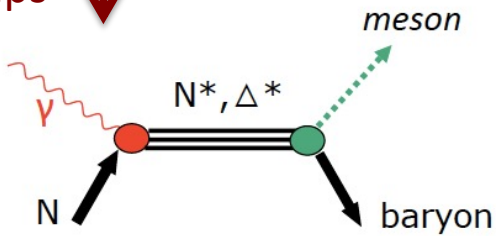
Experimental requirements:

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



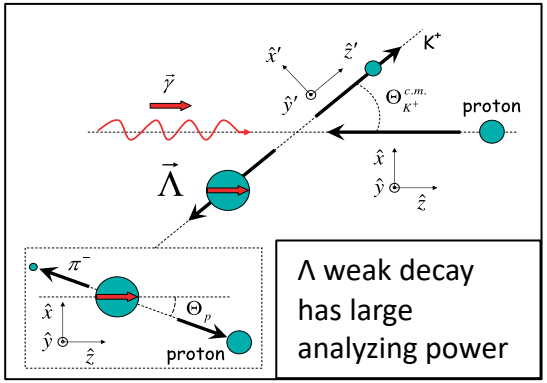
Engaging theoretical groups

Extract s-channel resonances



Hadronic production & Electromagnetic production

Polarization Observables: Complete Experiment



Λ weak decay has large analyzing power

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

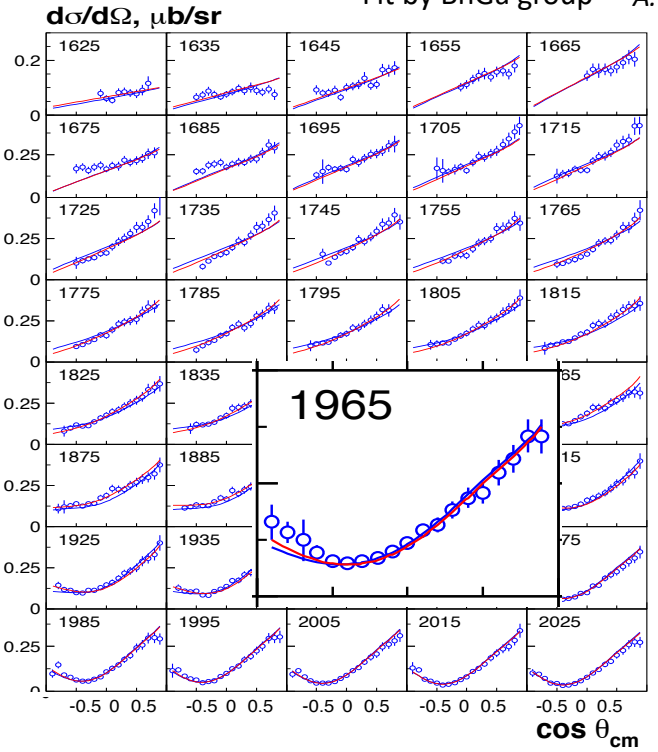
Beam (P^γ)		Target (P^T)			Recoil (P^R)			Target (P^T) + Recoil (P^R)								
		x	y	z	x'	y'	z'	x' x	x' y	x' z	y' x	y' y	y' z	z' x	z' y	z' z
unpolarized	$d\sigma_0$		$\hat{T}$			$\hat{P}$		$\hat{T}_{x'}$		$\hat{L}_{x'}$		$\hat{\Sigma}$		$\hat{T}_{z'}$		$\hat{L}_{z'}$
$P_L^\gamma \sin(2\phi_\gamma)$		$\hat{H}$		$\hat{G}$	$\hat{O}_{x'}$		$\hat{O}_{z'}$		$\hat{\mathbf{C}}_{\mathbf{z'}}$		$\hat{\mathbf{E}}$		$\hat{\mathbf{F}}$		$-\hat{\mathbf{C}}_{\mathbf{x'}}$	
$P_L^\gamma \cos(2\phi_\gamma)$	$-\hat{\Sigma}$		$-\hat{P}$			$-\hat{T}$		$-\hat{\mathbf{L}}_{\mathbf{z'}}$		$\hat{\mathbf{T}}_{\mathbf{z'}}$		$-\mathbf{d}\sigma_\mathbf{0}$		$\hat{\mathbf{L}}_{\mathbf{x'}}$		$-\hat{\mathbf{T}}_{\mathbf{x'}}$
circular P_c^γ		$\hat{F}$		$-\hat{E}$	$\hat{C}_{x'}$		$\hat{C}_{z'}$		$-\hat{\mathbf{O}}_{\mathbf{z'}}$		$\hat{\mathbf{G}}$		$-\hat{\mathbf{H}}$		$\hat{\mathbf{O}}_{\mathbf{x'}}$	

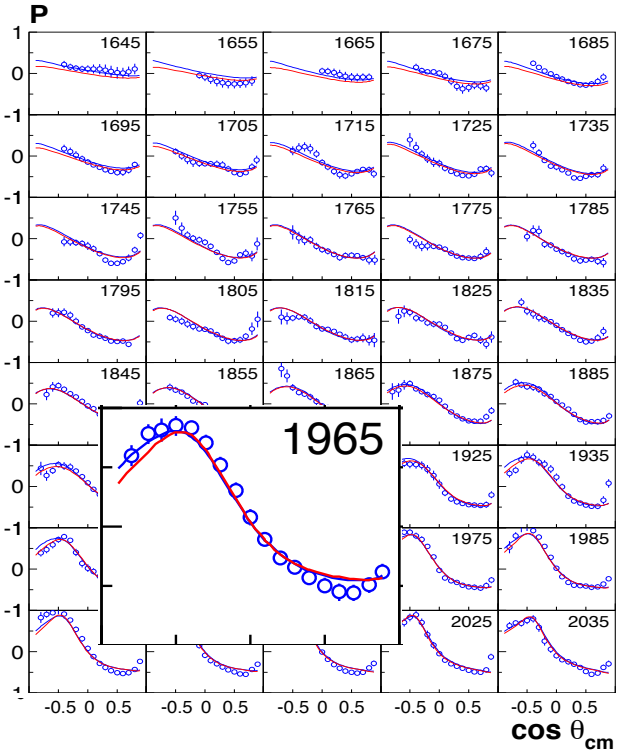
A. Sandorfi, S. Hoblit, H. Kamano, T.-S.H. Lee, J.Phys. 38 (2011) 053001

Establishing the N* spectrum – Precision & Polarization are essential

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

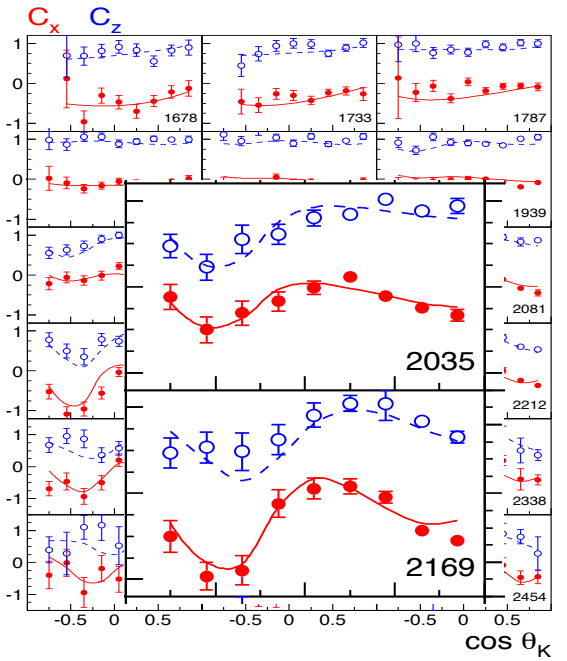
Fit by BnGa group *A.V. Anisovich et al, EPJ A48, 15 (2012)*





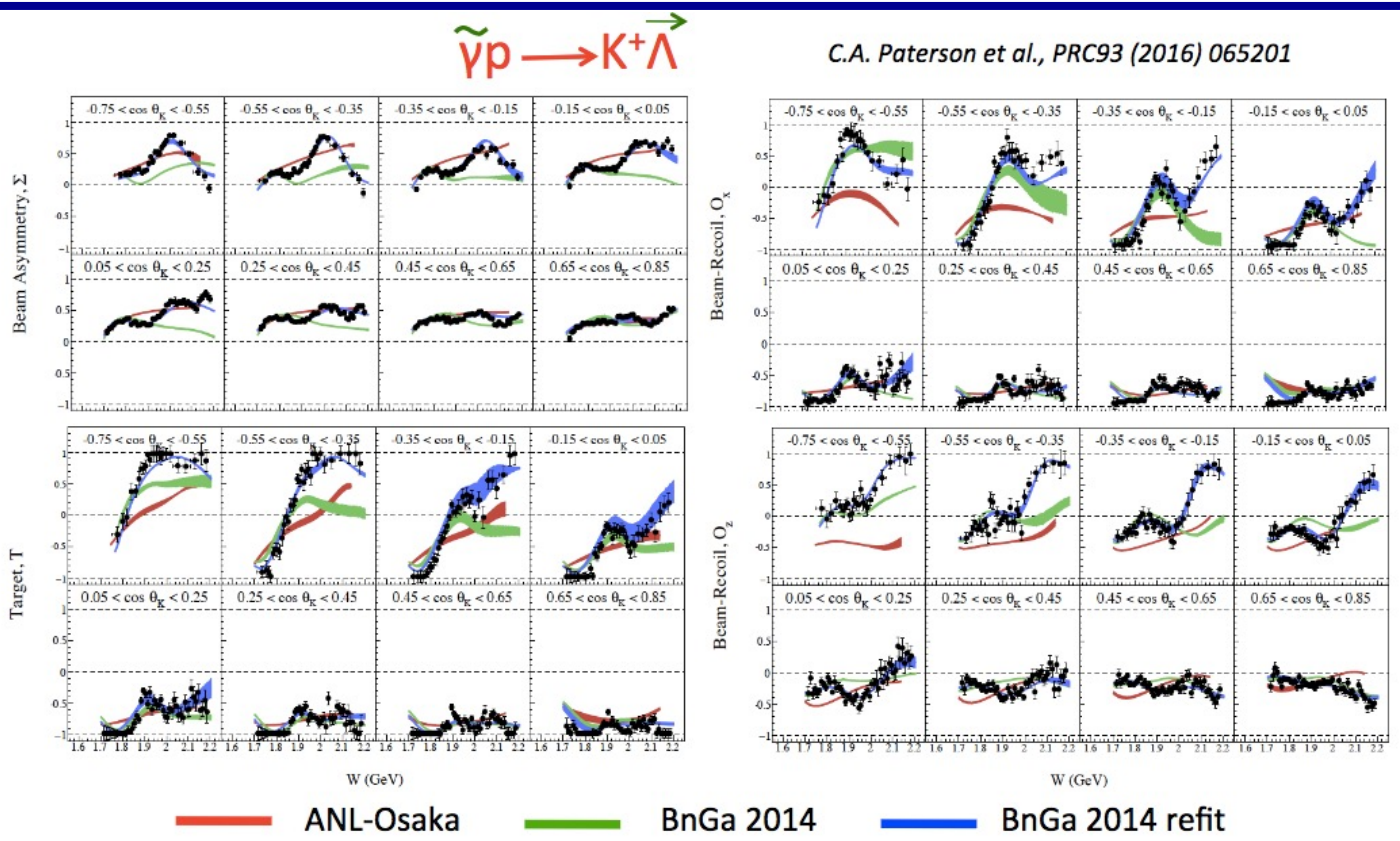
M. Mc Cracken et al.(CLAS), Phys.RevC81,025201,2010

γ->Λ **Polarization** transfer



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

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:
$L_{2I\ 2J}(E) \rightarrow J^P(E)$

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

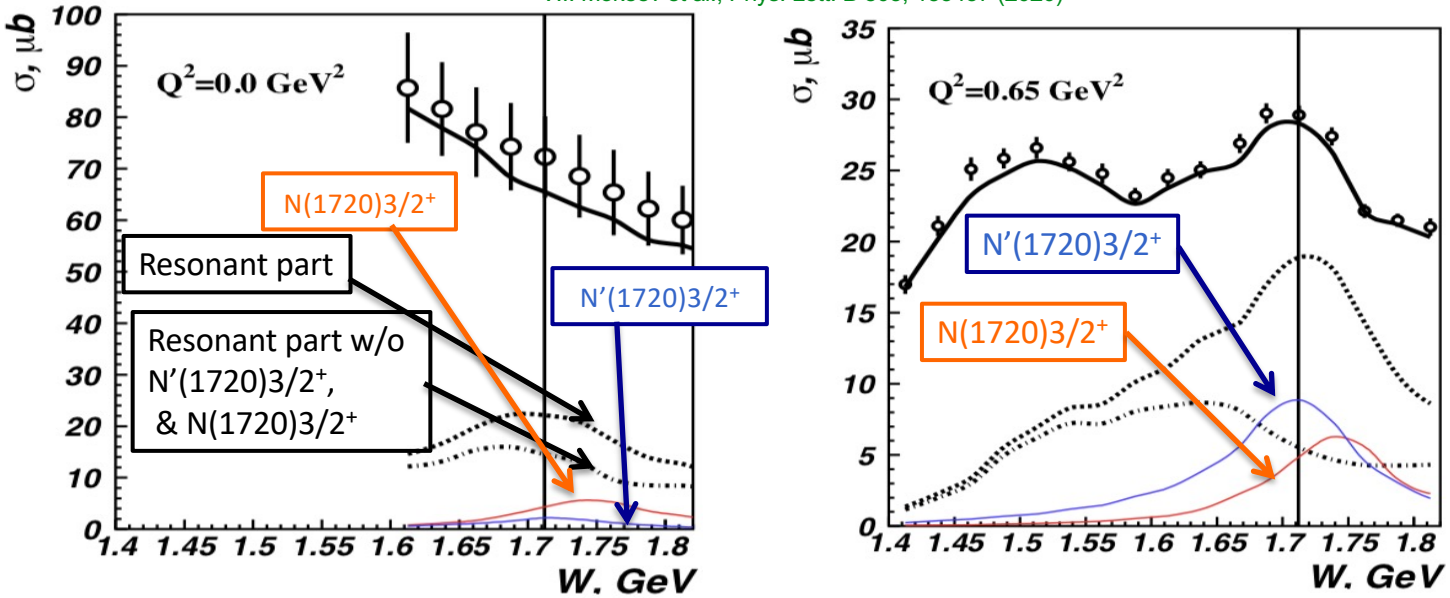
Measure more polarization observables, study these states in electroproduction and extend to higher masses

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

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

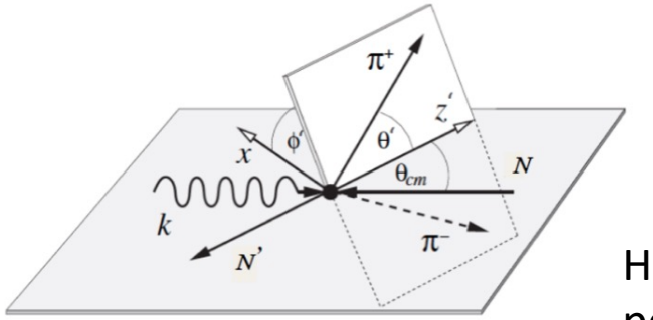
$\pi^+\pi^-p$ electroproduction

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/n target

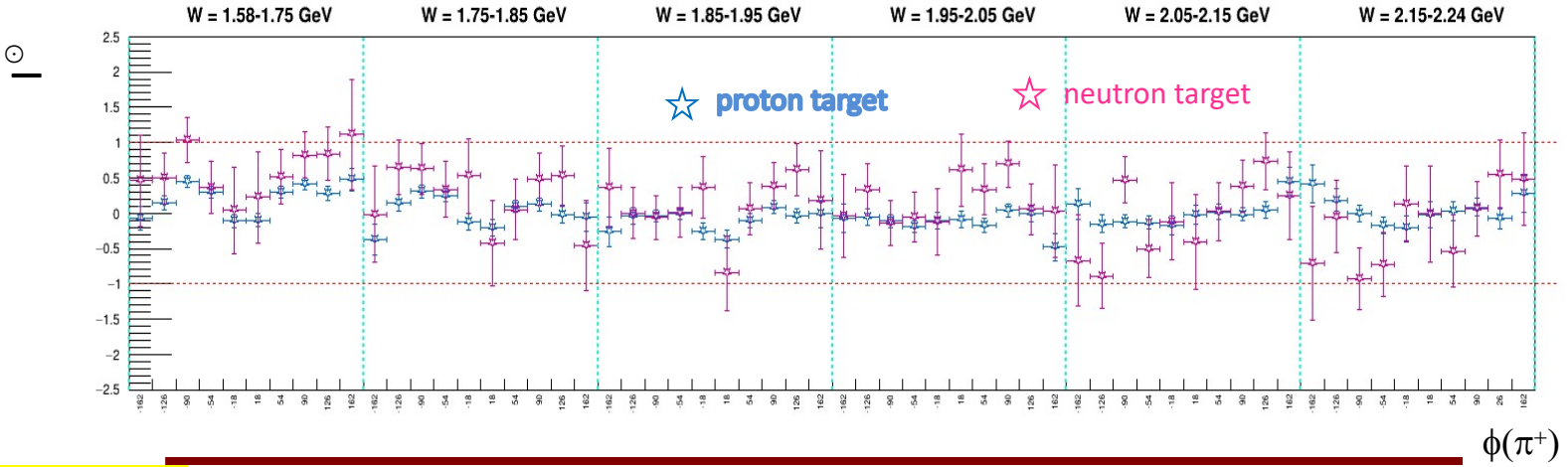


Measurements of polarization observables

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

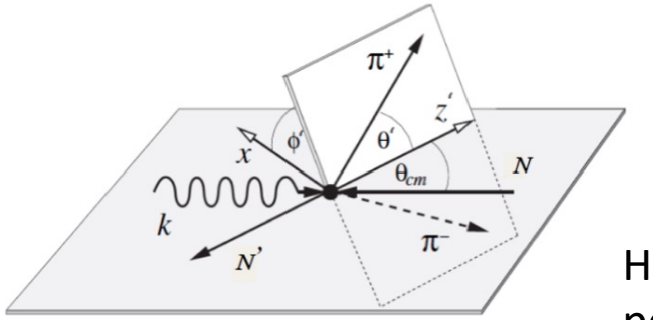
HD-ice frozen-spin polarized target

$I^\odot$ polarized p



Courtesy of A. Filippi

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

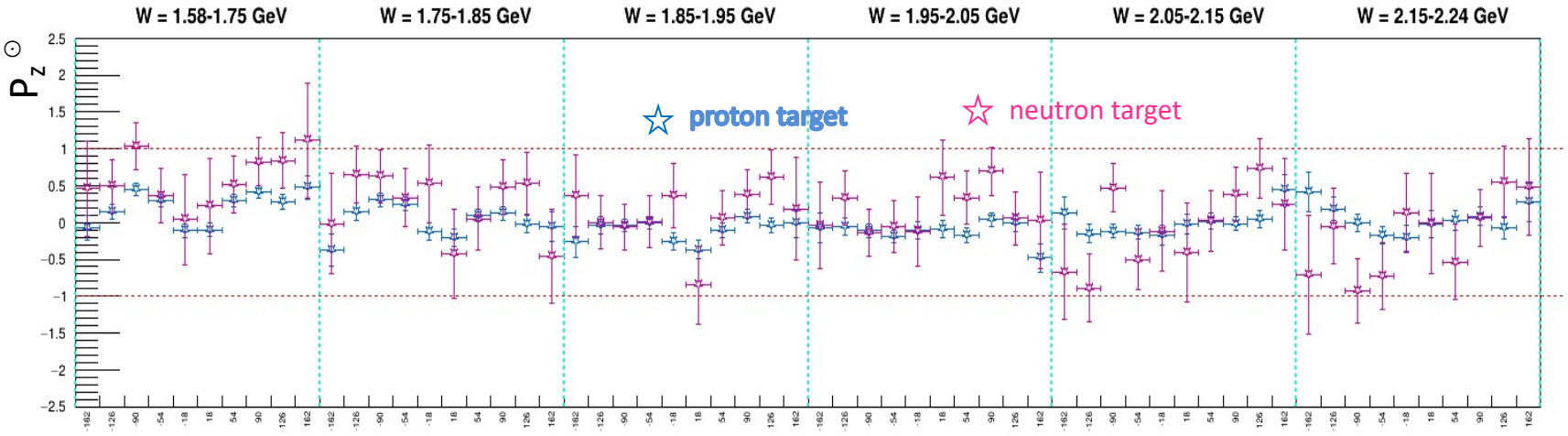


Measurements of polarization observables

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

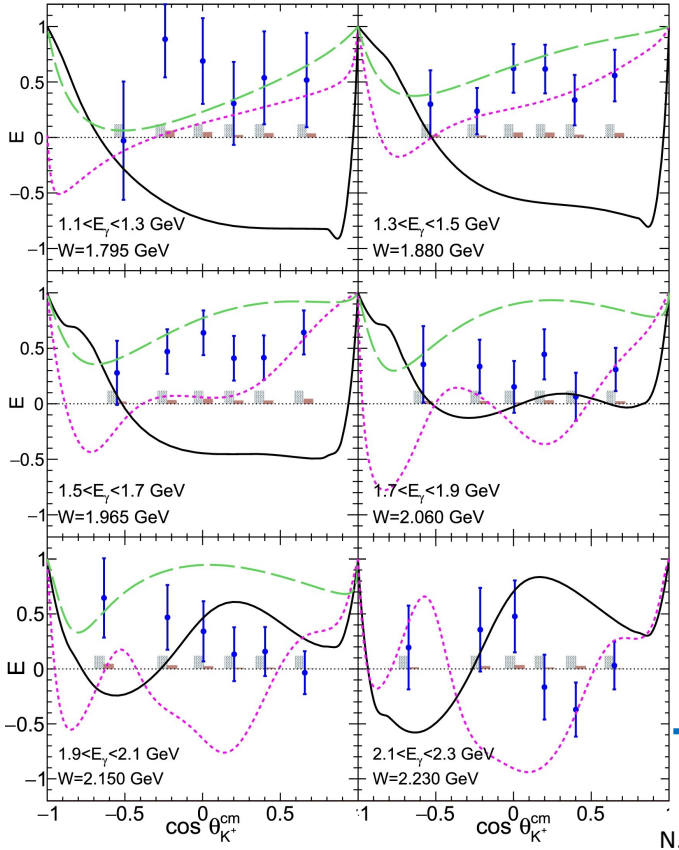
HD-ice frozen-spin polarized target

$P_z^\odot$ polarized target



Courtesy of A. Filippi

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



Beam-Target helicity asymmetry E

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

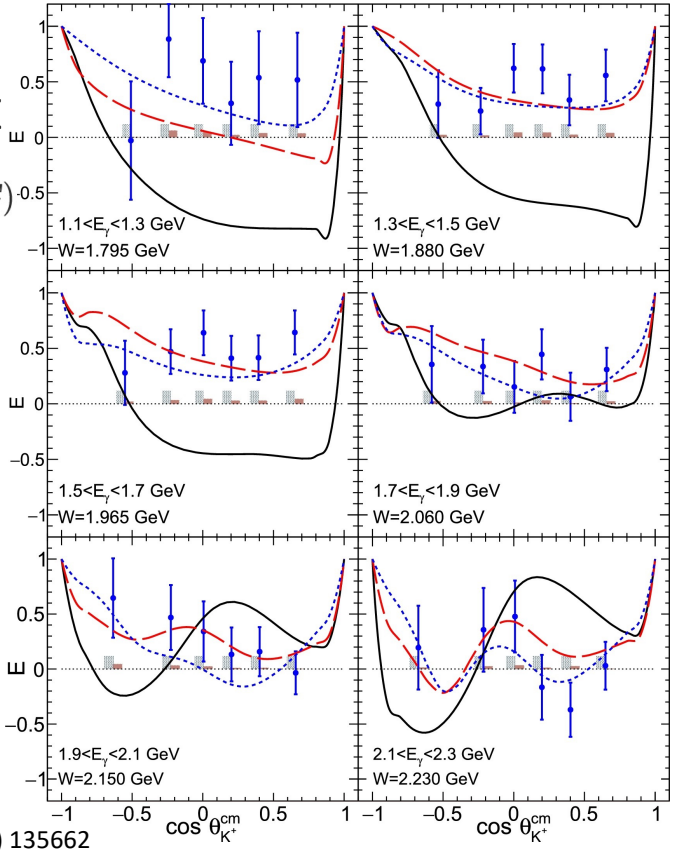
Kaon-Maid2000

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

Courtesy of N. Zachariou

Single Polarization observable Σ: $\vec{\gamma}\, n \rightarrow k^+ \Sigma^-$

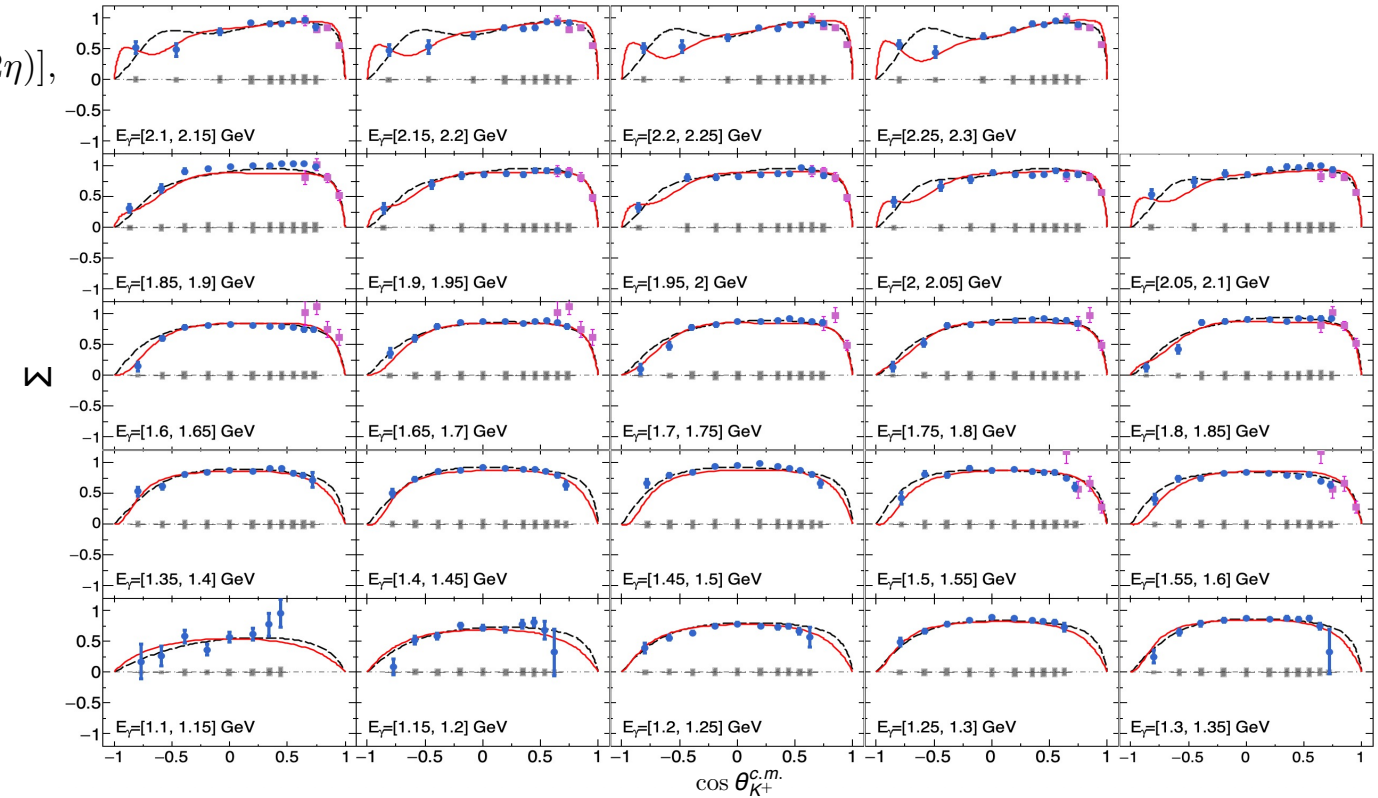
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 [1 - P_{lin} \boldsymbol{\Sigma} \cos(2\eta)],$$

Impact on D_{13} and P_{13} partial waves

Bonn-Gatchina fit

Isobar Model

N(1720)3/2+,
Δ(1900)1/2−
N(1895)1/2−



Courtesy of N. Zachariou

N. Zachariou et al arXiv:2106.13957v2 submitted to Phys. Lett. B (2021)

Double Polarization observable G: $\vec{\gamma}\,\vec{p} \rightarrow \pi^0 p$

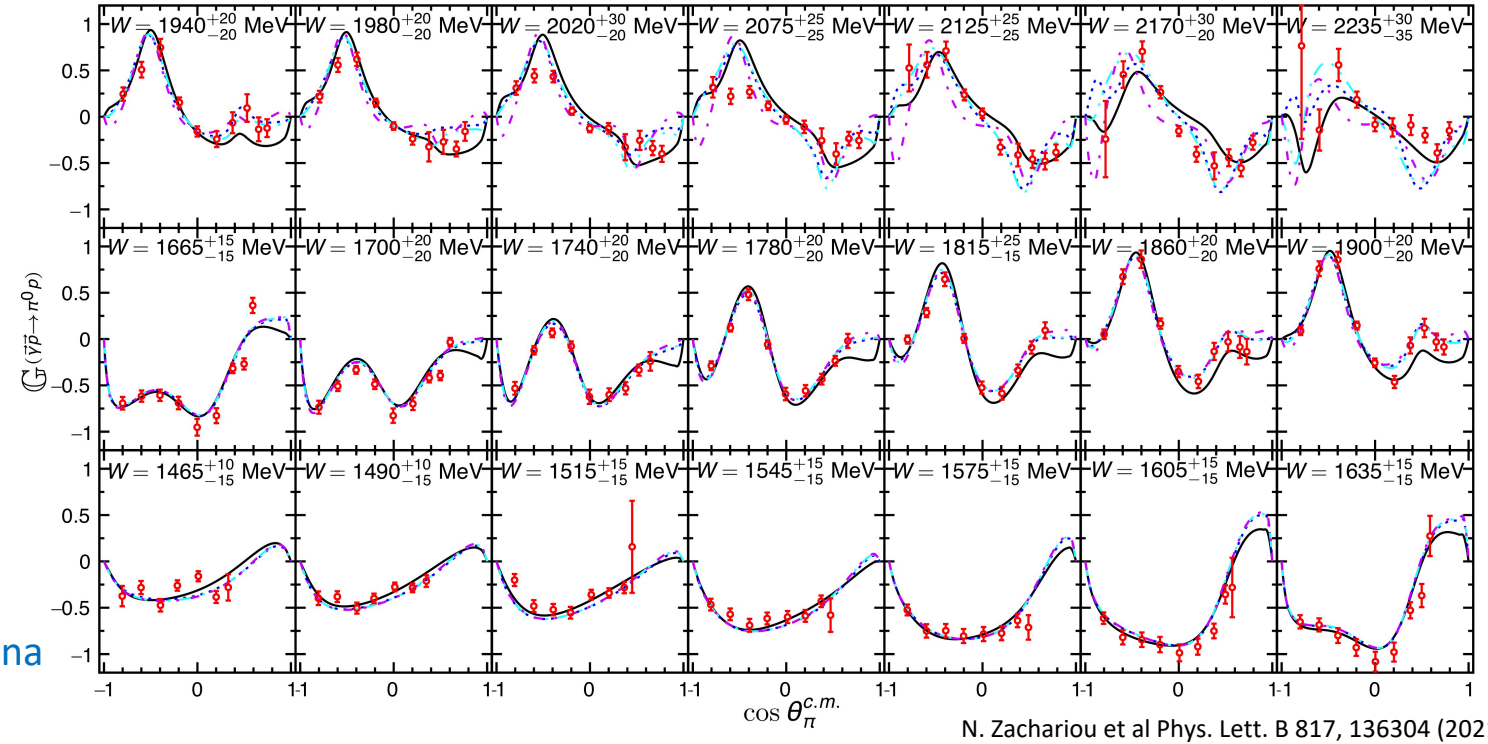
$$\frac{d\sigma}{d\Omega}(W, \vartheta_\pi^{c.m.}, \eta) = \frac{d\sigma}{d\Omega}(W, \vartheta_\pi^{c.m.})|_0 \left(p_\gamma \Sigma^{eff} cos(2\eta) + p_\gamma p_z^{eff} \mathbb{G} sin(2\eta)\right)$$

New important addition to the world data.

Extended kinematic coverage to higher energies and all angles.

SAID ZA19

Bonn-Gatchina



Courtesy of N. Zachariou

N. Zachariou et al Phys. Lett. B 817, 136304 (2021)

Double Polarization observable G: $\vec{\gamma}\,\vec{p} \rightarrow \pi^+ n$

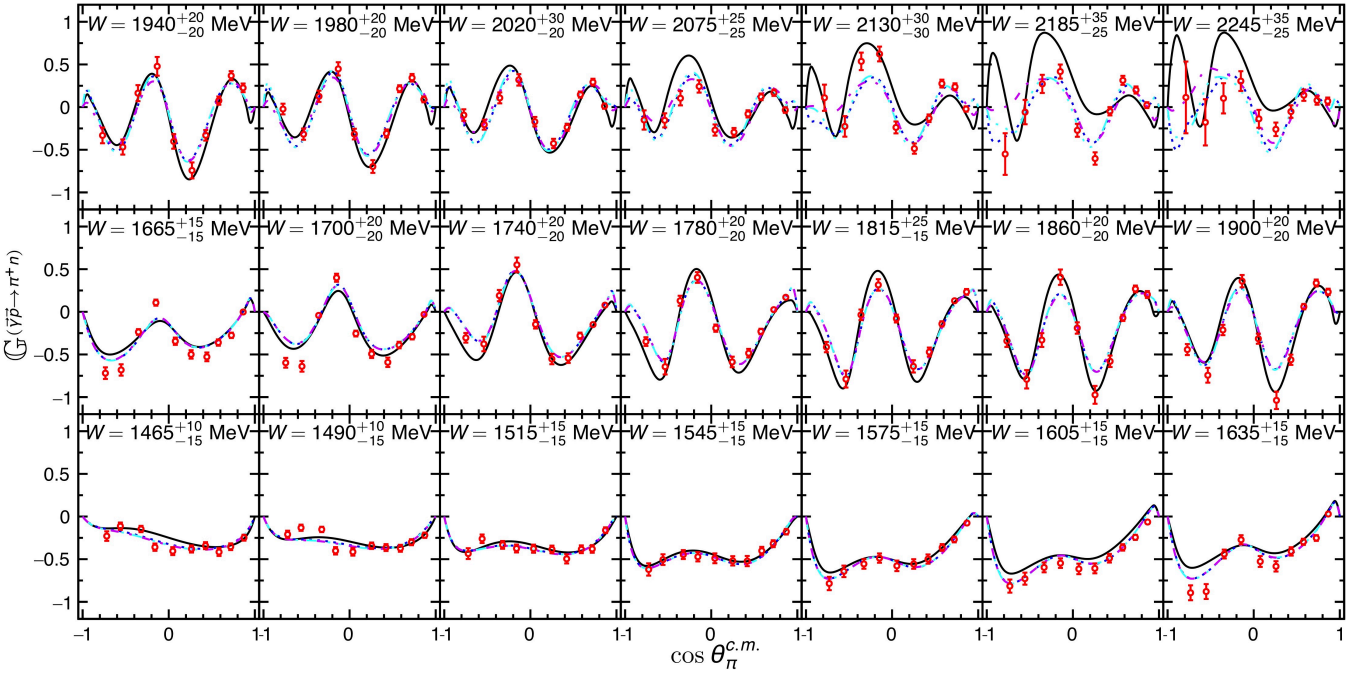
$$\frac{d\sigma}{d\Omega}(W, \vartheta_\pi^{c.m.}, \eta) = \frac{d\sigma}{d\Omega}(W, \vartheta_\pi^{c.m.})|_0 \left(p_\gamma \Sigma^{eff} cos(2\eta) + p_\gamma p_z^{eff} \mathbb{G} sin(2\eta)\right)$$

SAID ZA19

Bonn-Gatchina

N(2190)7/2−

Δ(2200)7/2

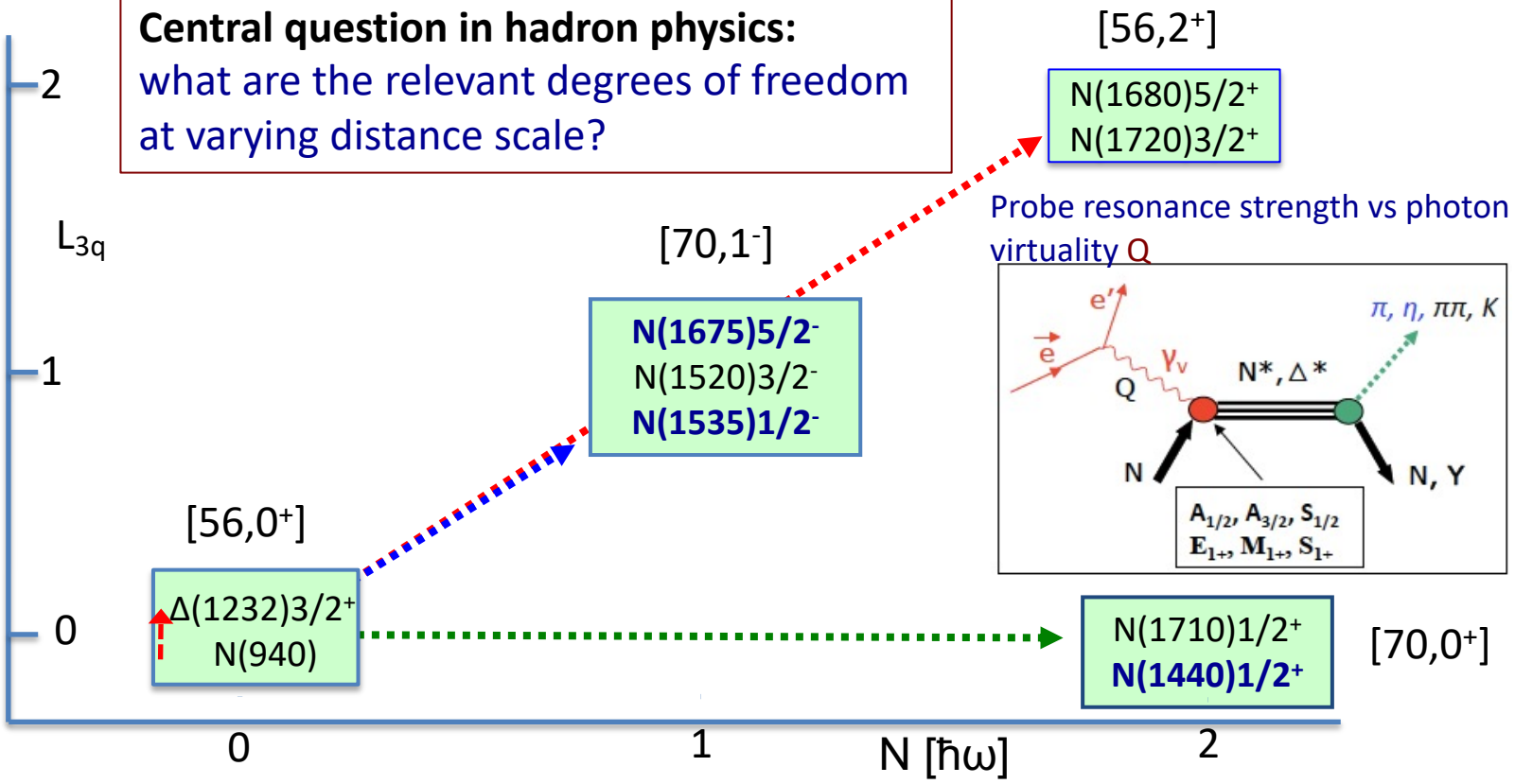


Courtesy of N. Zachariou

N. Zachariou et al Phys. Lett. B 817, 136304 (2021)

Electroexcitation of N*/Δ resonances

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

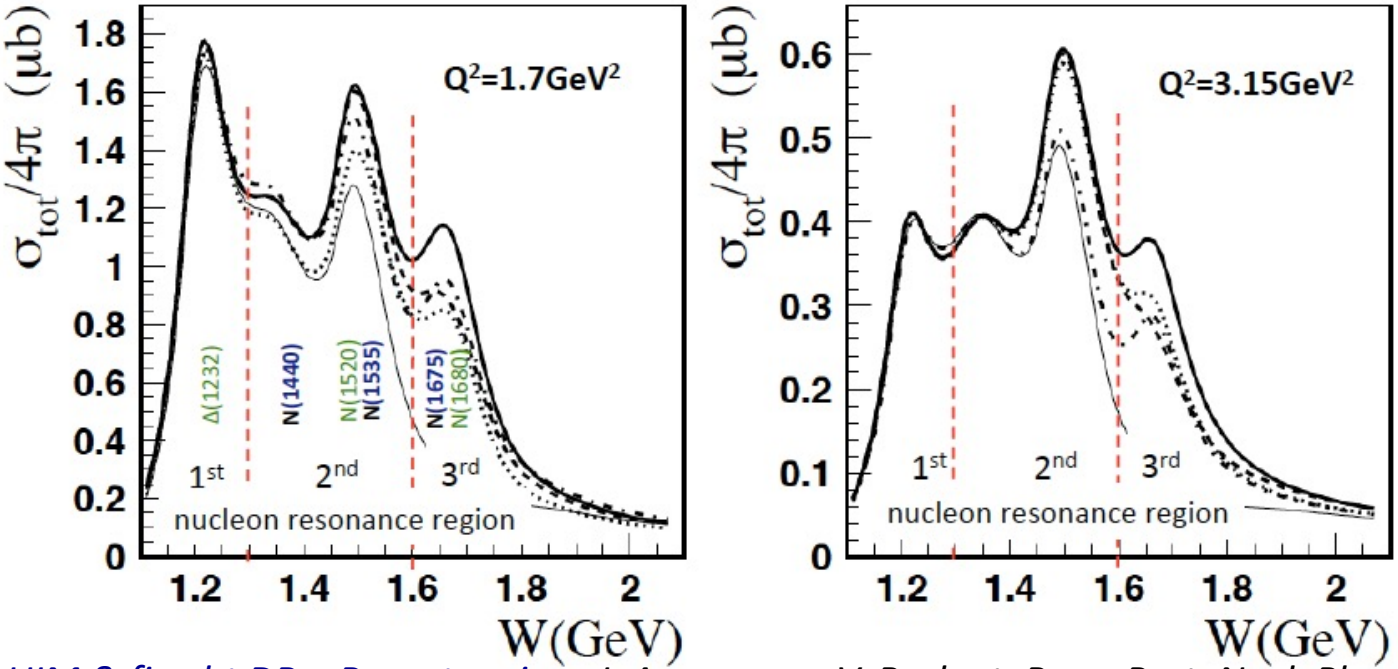


Total cross section at W < 2.1 GeV

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

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.

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 GlueX, MesonEx, COMPASS, PANDA ….

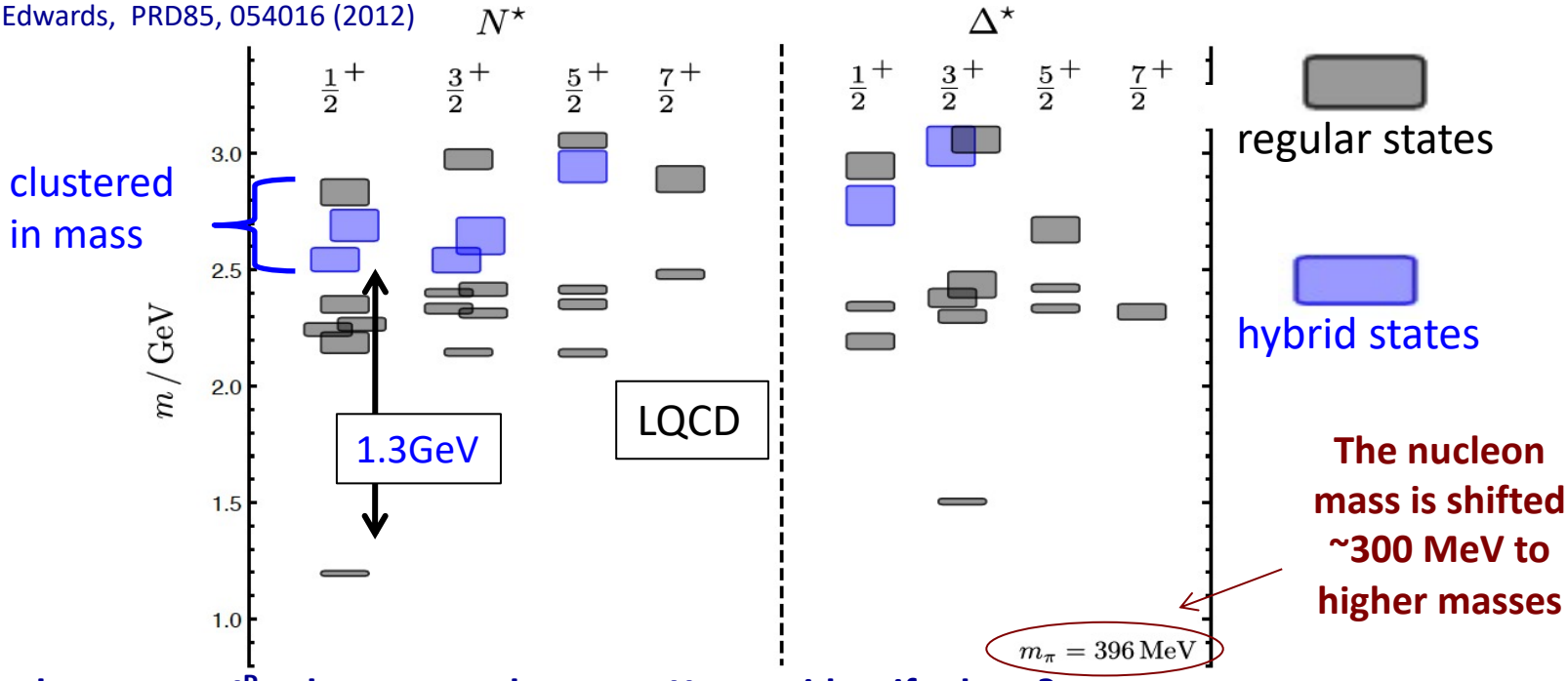
- **Hybrid baryons** $|qqqg\rangle$ have the same quantum numbers J^{P} as $|qqq\rangle$ electroproduction with CLAS12 (Hall B).

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)



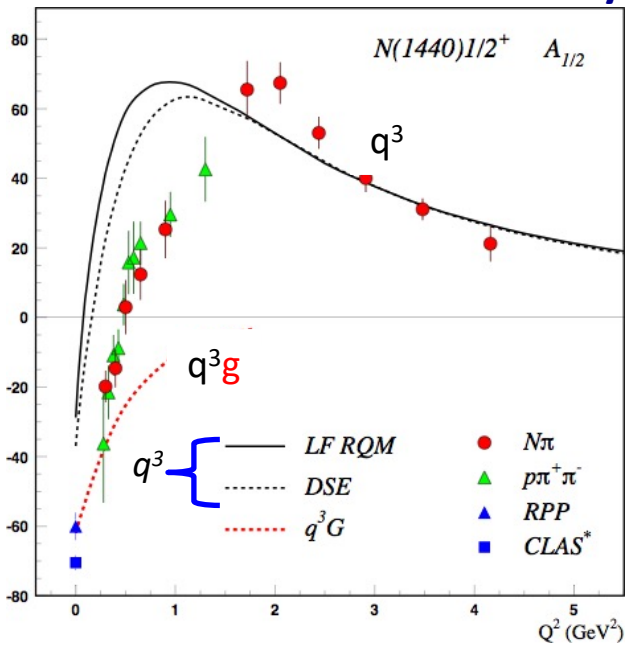
Hybrid states have same J^P values as qqq baryons. How to identify them?

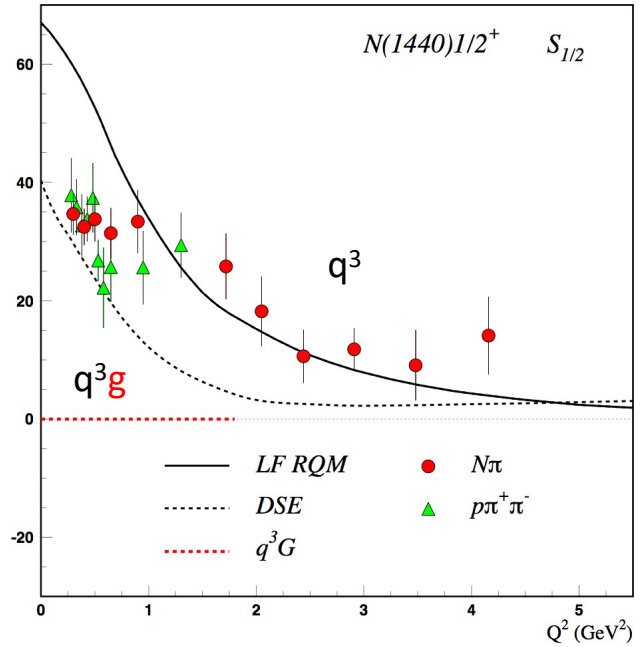
- Overpopulation of N $1/2^+$ and N $3/2^+$ states compared to QM projections.
- **$A_{1/2}$ ($A_{3/2}$) and $S_{1/2}$ show different Q^2 evolution.**

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 ?

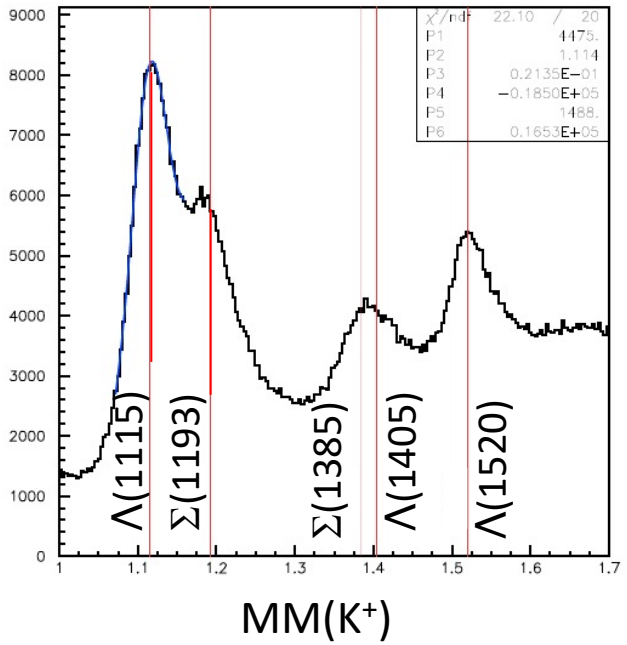


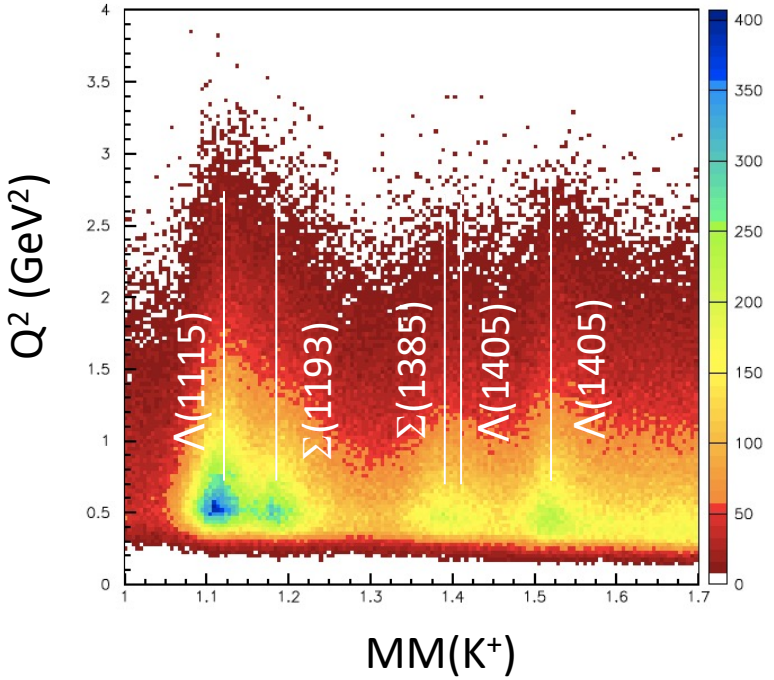


For hybrid "Roper", $A_{1/2}(Q^2)$ drops off faster with Q^2 and $S_{1/2}(Q^2) \sim 0$.

CLAS12 K^+ electroproduction data

1.6 GeV < W < 3 GeV





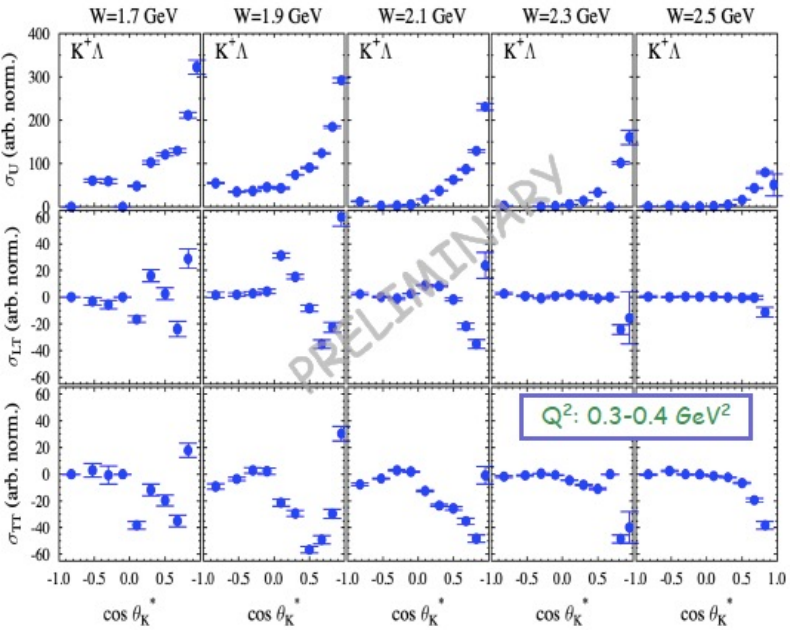
4 M total $K\Lambda$ events already collected

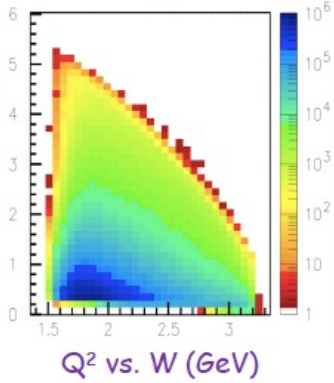
CLAS12 KY electro-production Cross Section Measurements

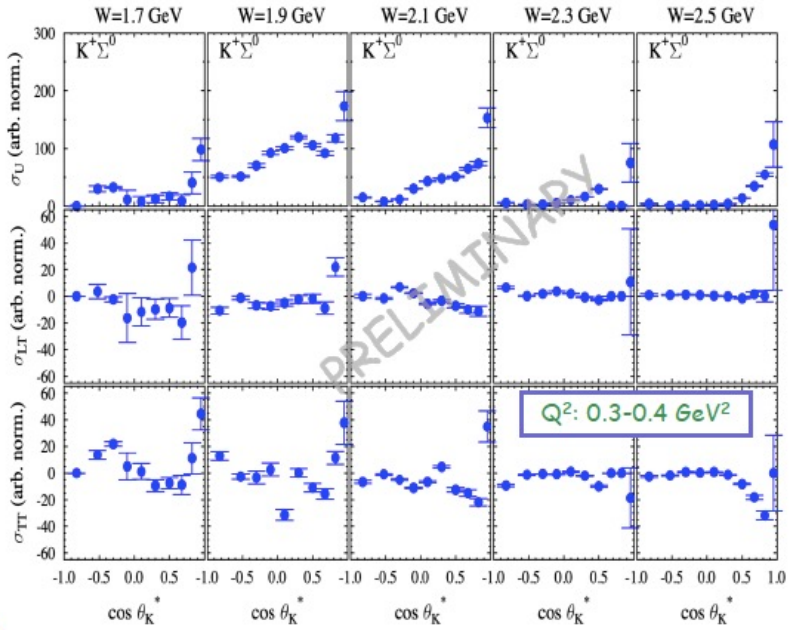
$ep \rightarrow e'K^+\Lambda$

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

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







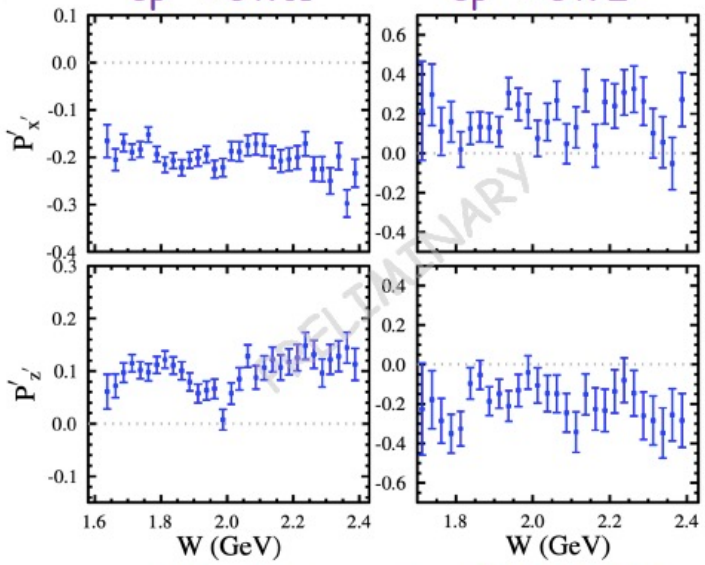
$\sigma_{T,L,LT,TT} = f(Q^2, W, \cos\theta_K^*)$

6.535 GeV RG-K

Courtesy of Dan Carman

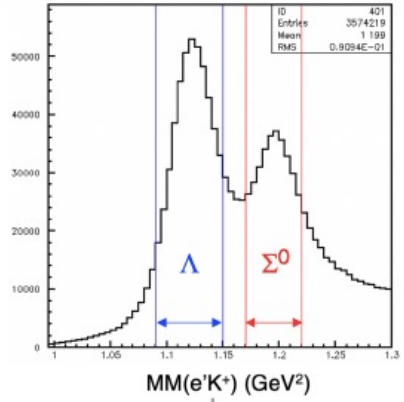
CLAS12 KY electro-production Cross Section Measurements

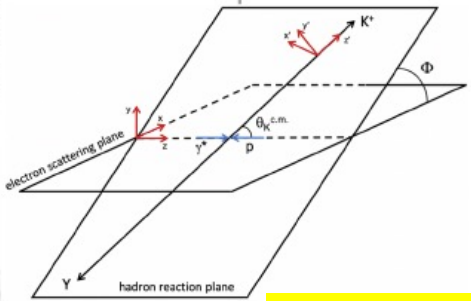
CLAS12 RG-K @ 6.535 GeV



Publication in preparation

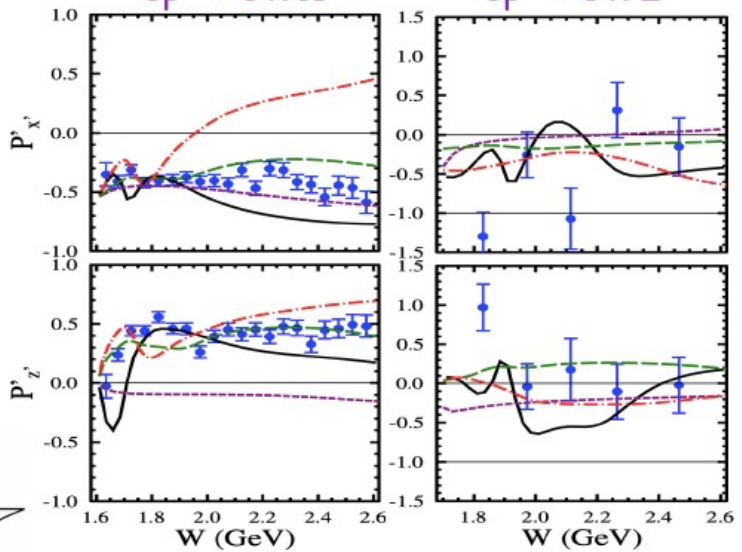
Raw uncorrected polarization





Courtesy of Dan Carman

CLAS e1-6 @ 5.754 GeV



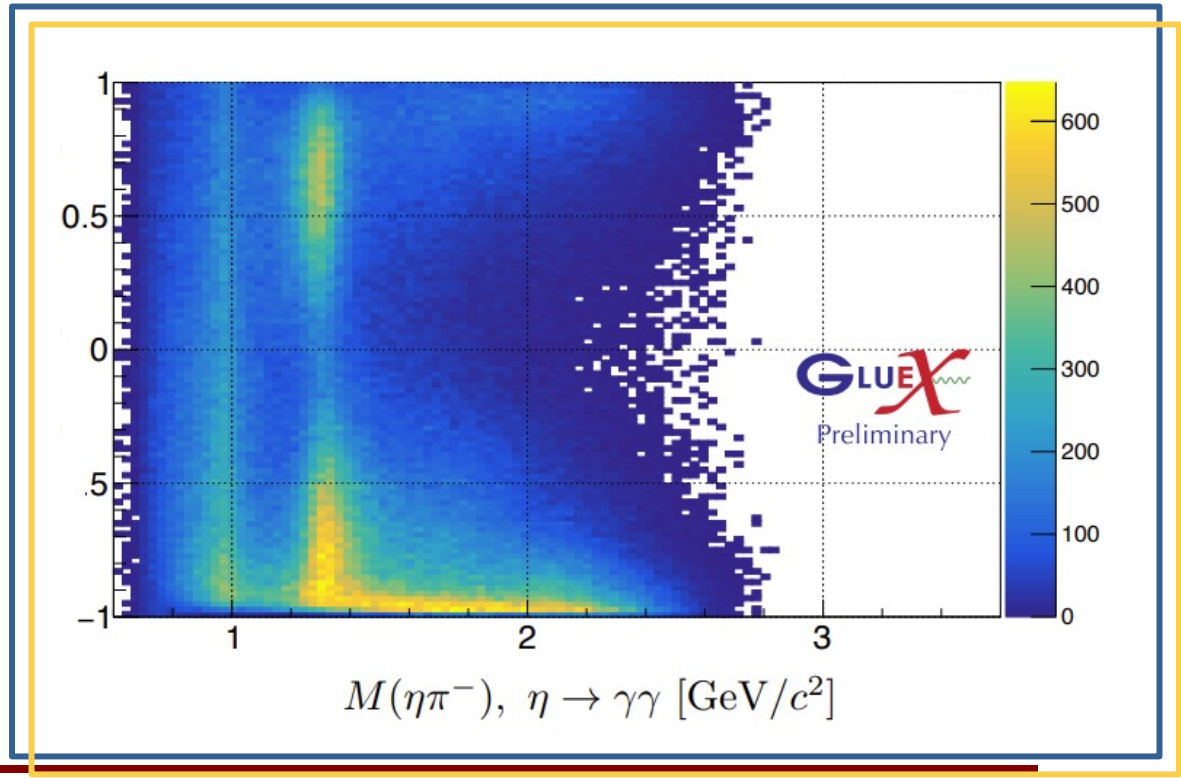
D.S. Carman et al., PRC79, 065205 (2009)

Mart/Bennhold RPR-2
RPR-1 Regge

GlueX & CLAS

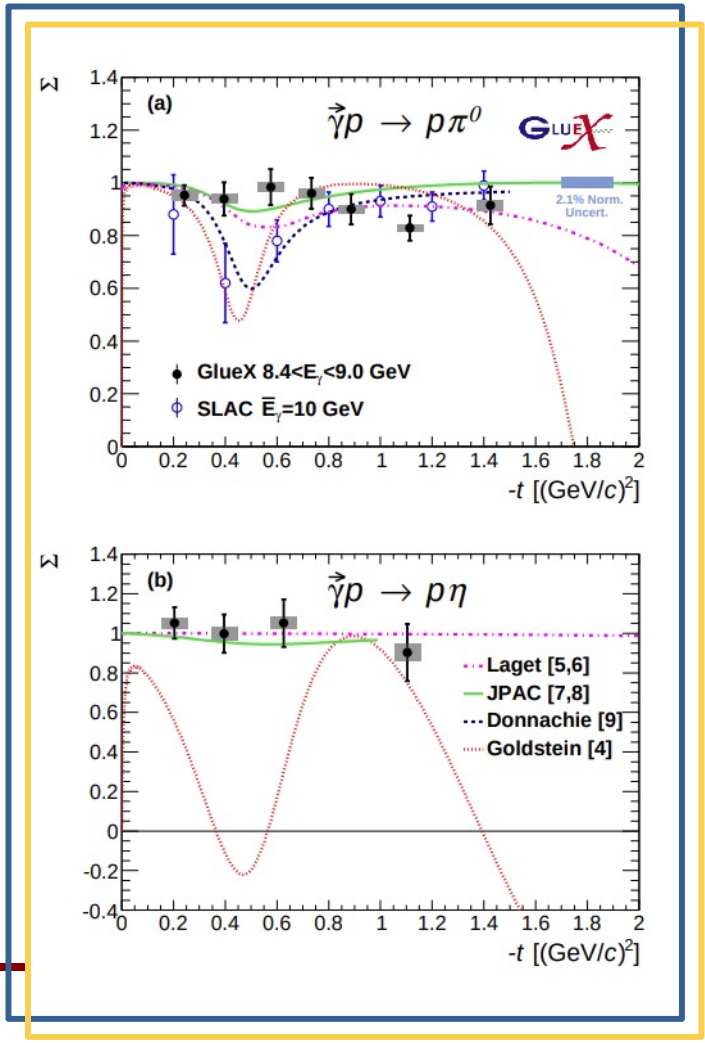
Courtesy of L. Biondo

- Searching for $\eta\pi^-$ **channel** in order to investigate **exotic mesons production**
- Seen at **GlueX**; ongoing partial wave analysis



GlueX & CLAS

- Searched for $\gamma + p \rightarrow \pi_0 + p$ reaction at **Gluex**
- **Discrepancies in beam asymmetry** were found between **GlueX & SLAC** results



Courtesy of L. Biondo

GlueX & CLAS

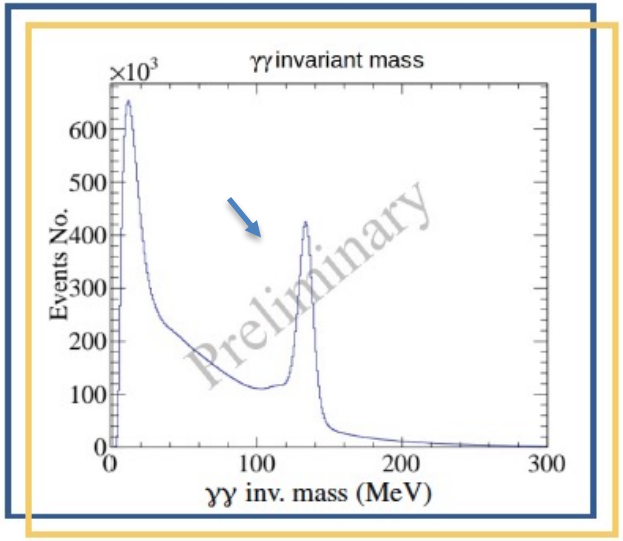
- Searched for $e + p \rightarrow e + \pi^0 + p$ reaction in CLAS, using RG-A Fall 2018 dataset.
- 2γ system invariant mass and proton missing mass are shown, respectively.

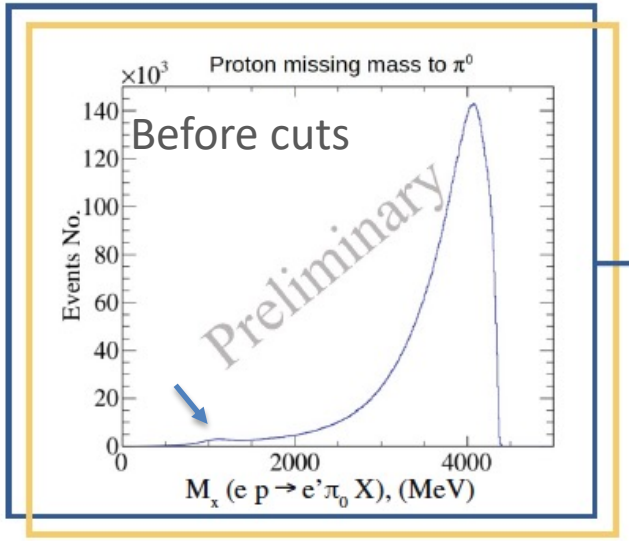
Objective: Differential cross section $d\sigma/dt$ measurement

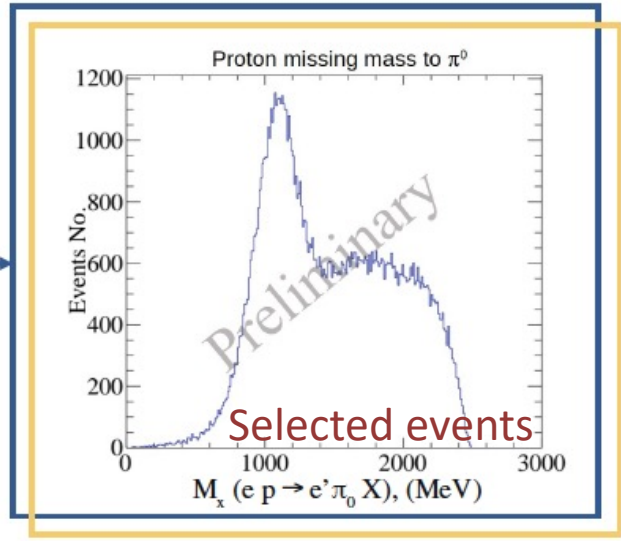
Reaction Identification:

1 electron and 2γ ($E\gamma$= 500-8500 MeV) detected in Forward Tagger, with 2ns coincidence in detection time. π^0 reconstructed via 2γ system invariant mass. Proton reconstructed via missing mass to π^0.

Courtesy of L. Biondo







Measurement of Spin Density Matrix Elements in Λ(1520) Photoproduction at 8.2 - 8.8 GeV

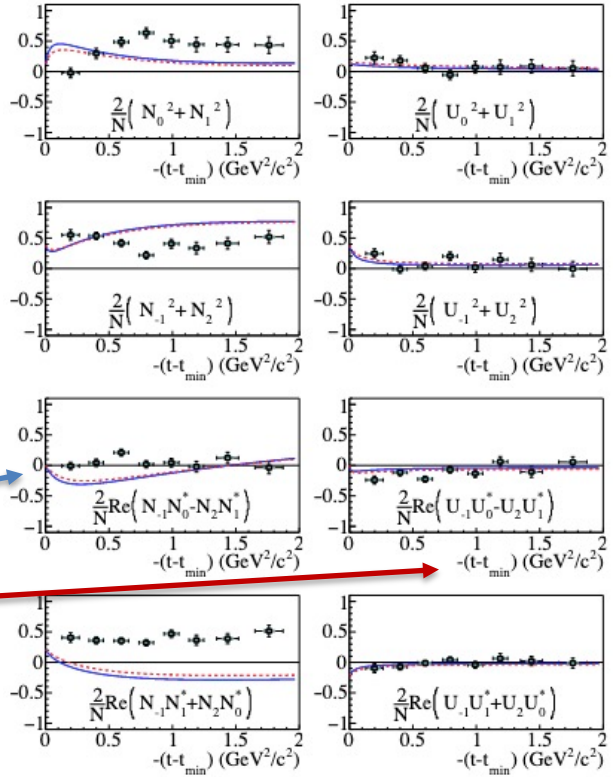
- GlueX has extracted the Lambda(1520) SDME
- Combinations of SDME may single out specific production mechanisms.

In particular the (experimentally extracted) SDME linear combinations corresponding to:

- natural parity meson exchange production dominate

- **unnatural parity meson exchange** production are compatible with a Kaon exchange

Courtesy of V. Mathieu



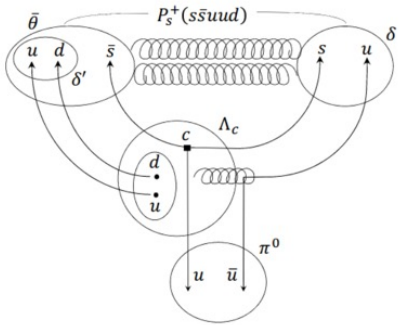
Search for hidden-strangeness pentaquark in Λc decay at BESIII

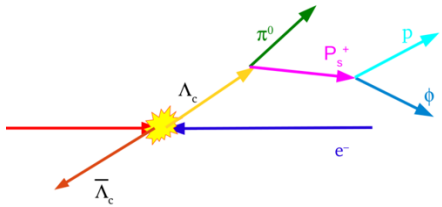
In 2014, BESIII has collected 567 pb^{-1} close to $\Lambda_c\bar{\Lambda}_c$ production threshold (4.6 GeV)

- The pentaquark is searched in the pϕ invariant mass
- The result is limited by statistic
- No evidence of signal is found
- **PLANS: BESIII has collected new data between 4.6 to 4.9 GeV in 2020/2021**

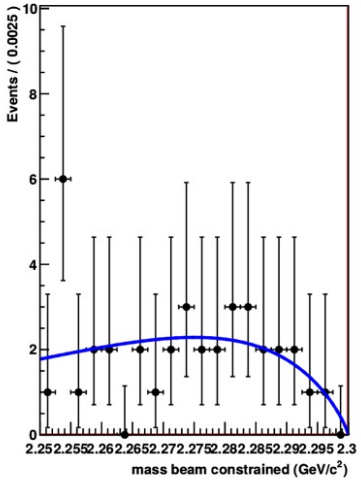
—> this analysis will be updated (the idea is to start to have a look from the beginning of the next year)

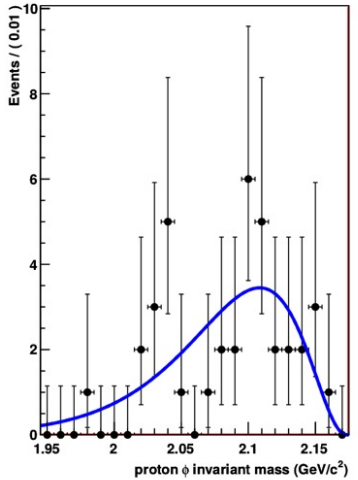
Stimulated by LHCb and Belle observation, in BESIII we peached for a hidden-strangeness pentaquark in Λc decay





Courtesy of I. Garzia





Ω (2012) production at LHC energies

$\Omega\,(2012)^{\pm}$ is the newly excited baryon recently observed by Belle collaboration

J. Yelton et al., Phys. Rev. Lett., 121 (2018)052003

- The large colliding energies, the high luminosity reached at the **Large Hadron Collider** and the unique characteristic of tracking and Particle Identification of the **ALICE** detector should permit to identify $\Omega(2012)$ never seen at the LHC energies.

- INFN-Catania team is testing different machine learning techniques to improve $\Omega(2012)^{\pm}$ reconstruction efficiency and signal significance.
- The $\Omega(2012)^{\pm}$ resonance is reconstructed via its decay in $K^0_s\ \Xi^{\pm}$.

Courtesy of A. Badalà

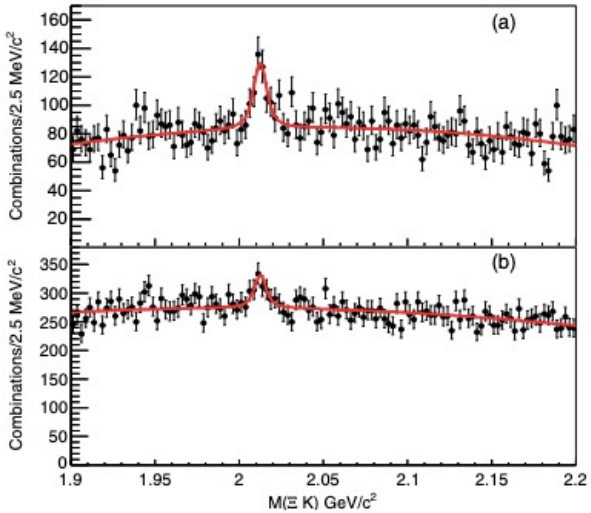


FIG. 2. The (a) $\Xi^0 K^-$ and (b) $\Xi^- K^0_S$ invariant mass distributions in data taken at the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ resonance energies. The curves show a simultaneous fit to the two distributions with a common mass and width.

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 at CLAS on $\pi, \pi\pi$, and KY photoproduction (and electroproduction) which 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 at by JPAC for the $\Lambda\,(1520)$ **SDME measurements** at GlueX.
- **New BESIII results in pentaquark** production have been obtained.
- Search for the $\Omega\,(2012)$ observed at BELLE is foreseen **at ALICE.**