Baryons Spectrum and Structure

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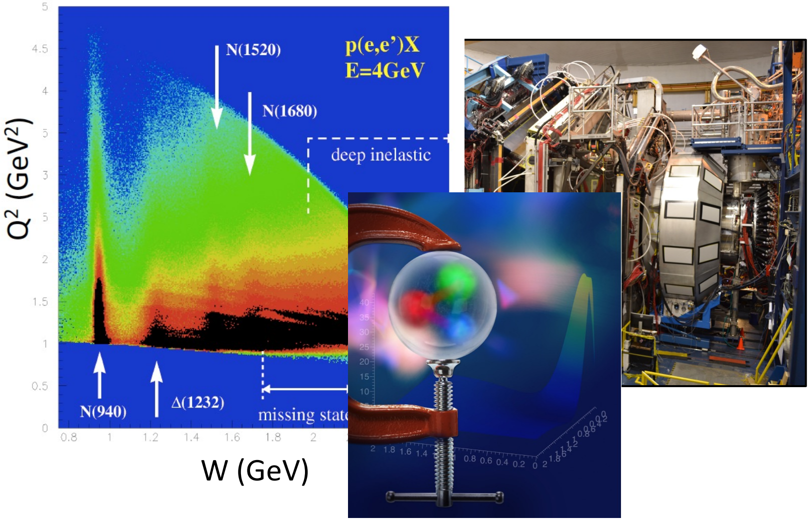
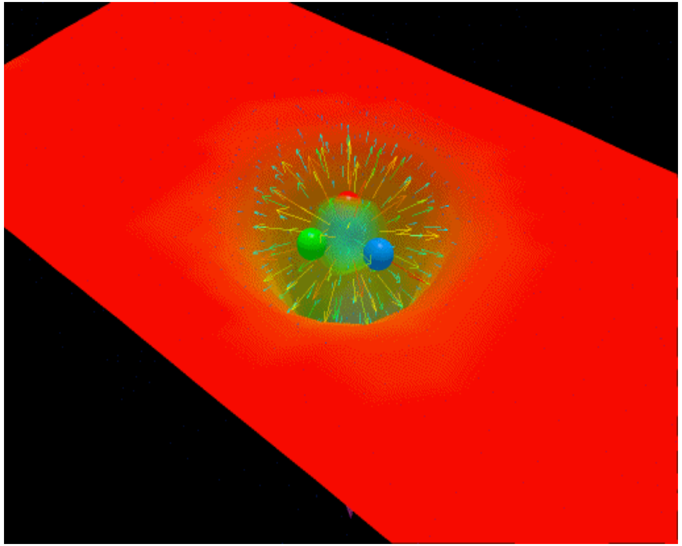


Outline:

- Physics case: color confinement and strong QCD
- Baryons spectrum – polarized photoreactions
- Baryons structure – mesons electro-production
- TMD and DVCS – N spin structure and 3D image
- The future: EIC and the role of the glue

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.

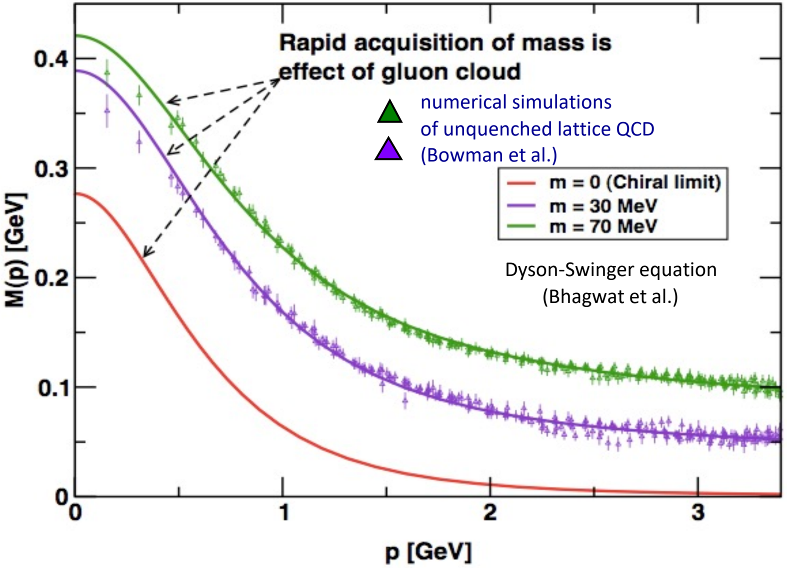
As such they must be ***at the center of any discussion of why the world*** *we actually experience* ***has the character it does.”***

Nathan Isgur, NStar2000, Newport News, Virginia

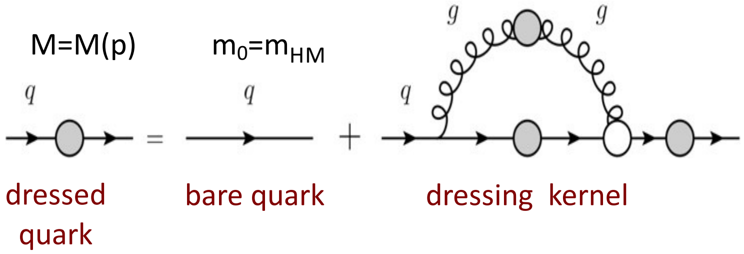
→ **Search for new baryon states**

Critical QCD Questions Addressed

- How do massless quarks acquire mass?



Effective quark mass depends on its momentum



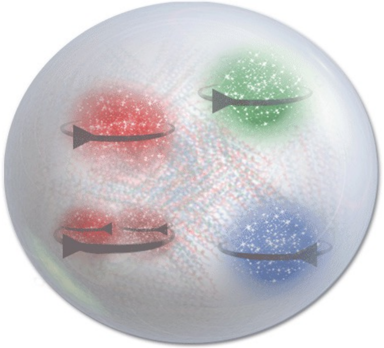
mass composition

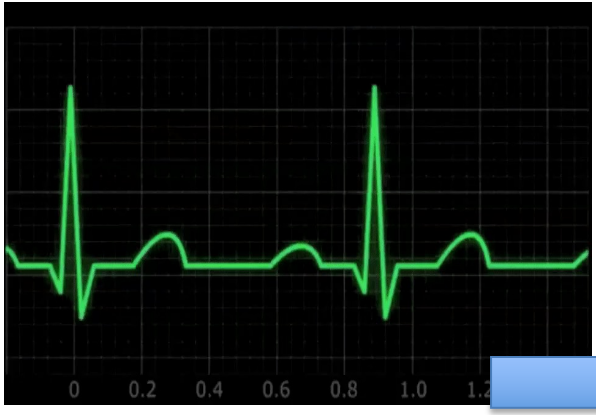
<2%	Higgs mechanism
>98%	non-perturbative strong interaction

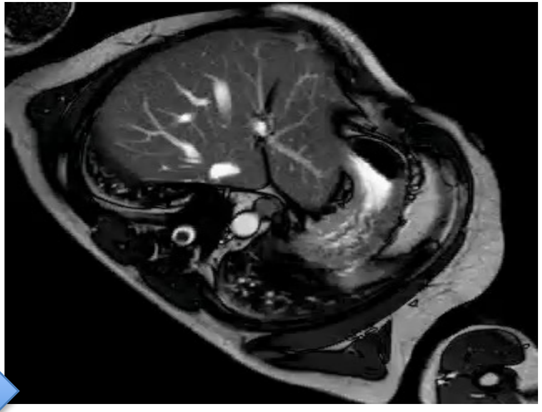
→ **Measure the Q^2 dependence of electrocoupling amplitudes**

Critical QCD Questions Addressed

- How are the quarks and gluons, and their intrinsic spins distributed in space & momentum inside the nucleon? What is the role of the angular momentum ?



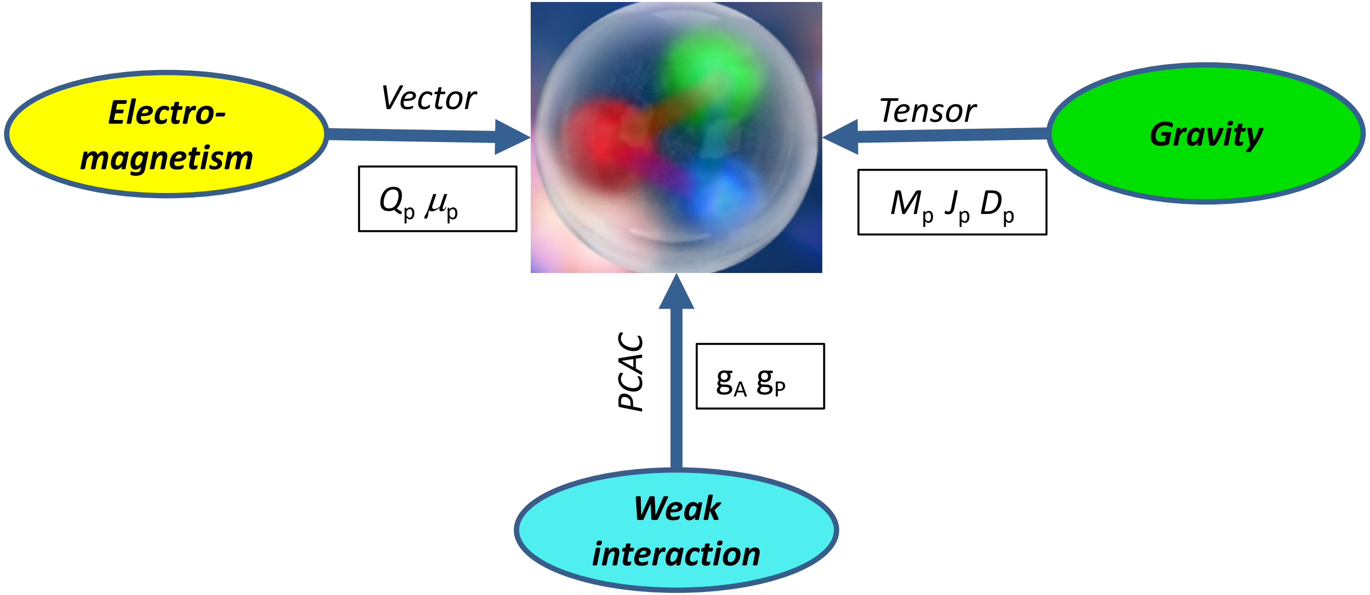




→ **SIDIS and TMDs measurements toward a 3D imaging of the proton**

Critical QCD Questions Addressed

- How is color confinement realized in the force and pressure distributions and stabilize nucleons?



→ **Study GPDs and their moments from DVCS**

Critical QCD Questions Addressed

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

  → **Search for new baryon states**

- How do massless quarks acquire mass?

  → **Measure the Q^2 dependence of electrocoupling amplitudes**

- How are the quarks and gluons, and their intrinsic spins distributed in space & momentum inside the nucleon? What is the role of the angular momentum ?

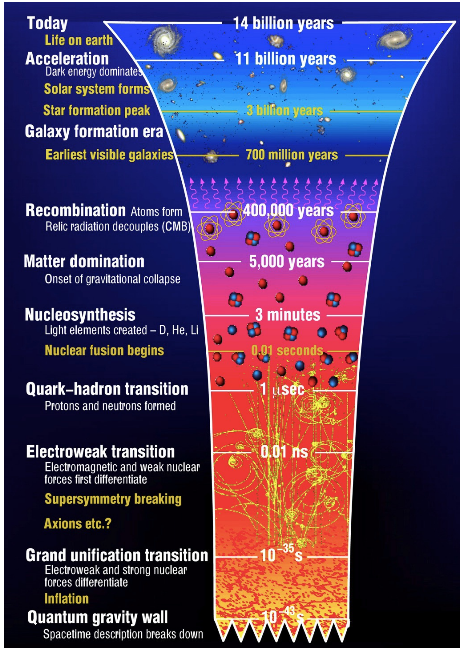
  → **SIDIS and TMDs measurements toward a 3D imaging of the proton**

- How is color confinement realized in the force and pressure distributions and stabilize nucleons?

  → **Study GPDs and their moments from DVCS**

The INFN program at CLAS12 experiment
plays an important role in addressing these questions

Strong QCD is born ~ 1μsec after the Big Bang



T ~ 700, 000, 000 yrs: Galaxies

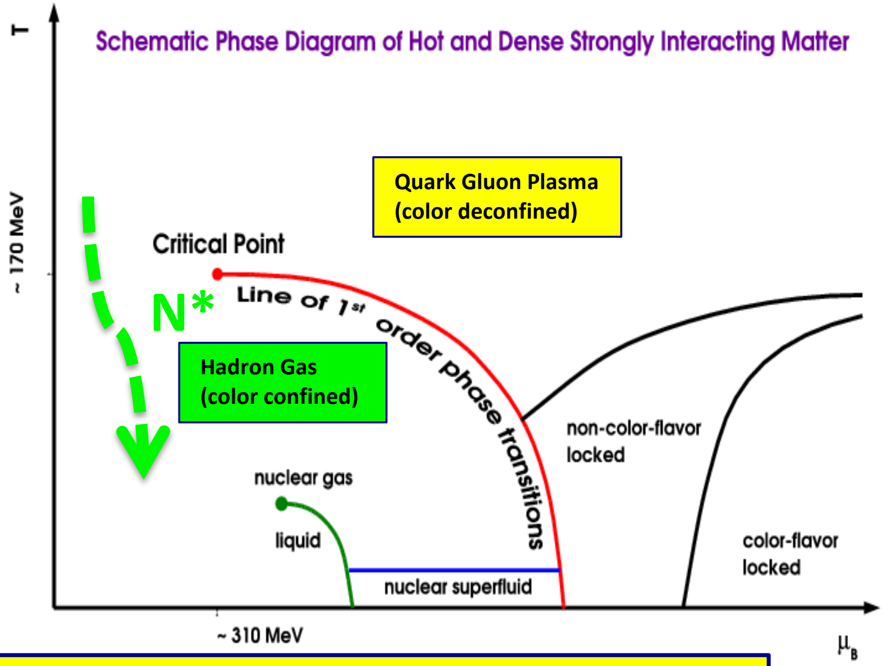
T ~ 400, 000 yrs: Atoms

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

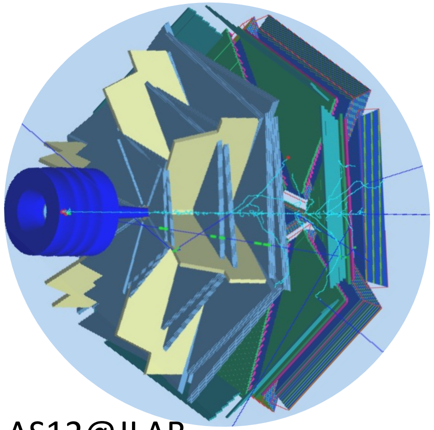


Dramatic events occur in the microsecond old Universe.

- 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 BGOOD@ELSA



CLAS12@JLAB

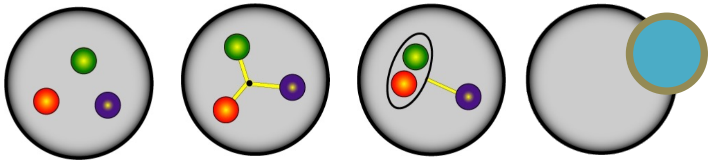
Detectors have been designed to measure cross sections and spin observables over a broad kinematic range for exclusive reaction channels:

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.

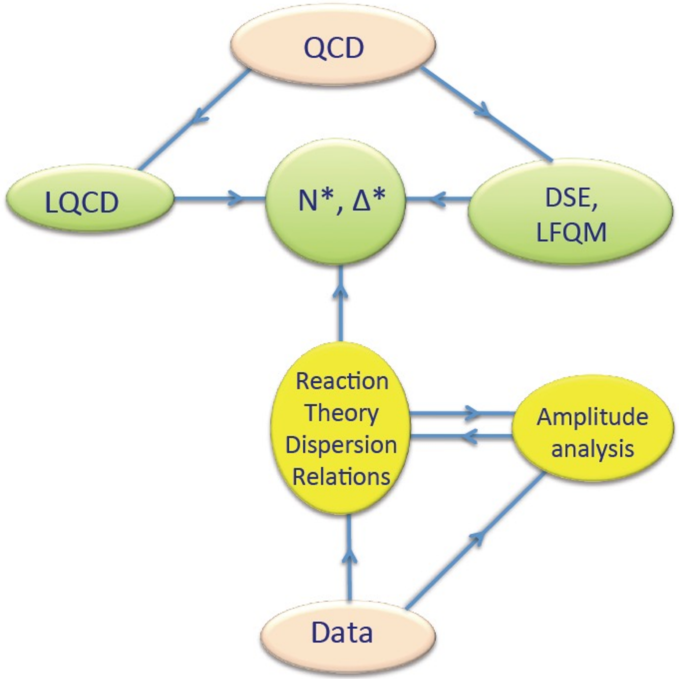
N* degrees of freedom??



Establishing the N* and Δ Spectrum

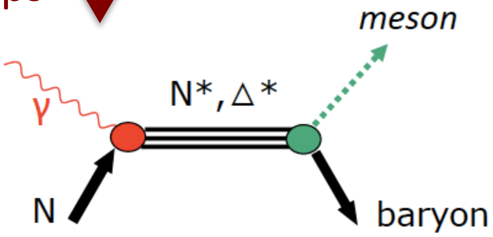
Experimental requirements:

- Precision measurements of photo-induced processes in wide kinematics, e.g.
  γp→πN, ηp, KY, .., γn→πN, K^0Y^0, ..
- More complex reactions, e.g. γp → ωp, ρϕ, ππp, ηπN, K*Y, .. may be sensitive to high mass states through direct transition to ground state or through cascade decays
- Polarization observables are essential



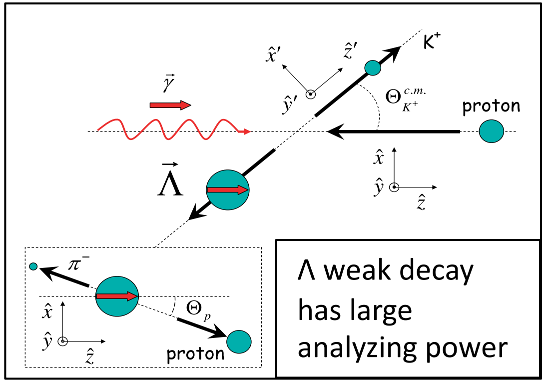
Engaging theoretical groups

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

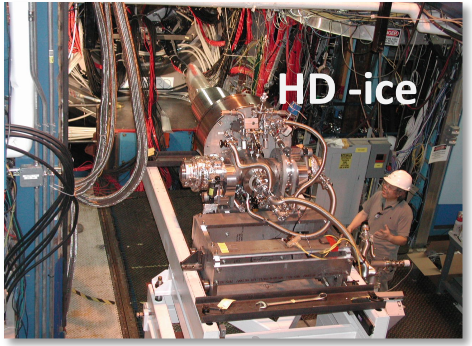
Beam (P^γ)		Target (P^T)			Recoil (P^R)			Target (P^T) + Recoil (P^R)								
					x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
		x	y	z				x	y	z	x	y	z	x	y	z
unpolarized	$d\sigma_0$		$\hat{T}$			$\hat{P}$		$\hat{T}_{x'}$		$\hat{L}_{x'}$		$\hat{\Sigma}$		$\hat{T}_{z'}$		$\hat{L}_{z'}$
$P_L^\gamma \sin(2\phi_\gamma)$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

Experimental set-up

Polarized Frozen-spin Targets & **C**EBAF **L**arge **A**cceptance **S**pectrometer

or



+

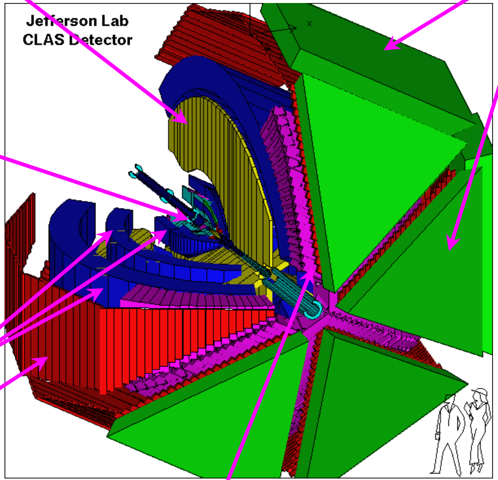
start counter

Torus magnet

6 superconducting coils

Electromagnetic calorimeters

Lead/scintillator, 1296 photomultipliers



Drift chambers

35,000 cells

Time-of-flight counters

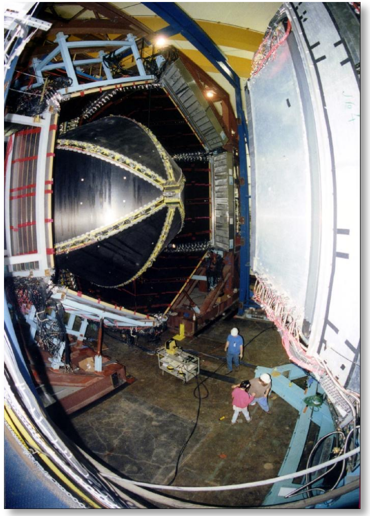
plastic scintillators,

684 photomultipliers

Gas Cherenkov counters

e/π separation, 256 PMTs

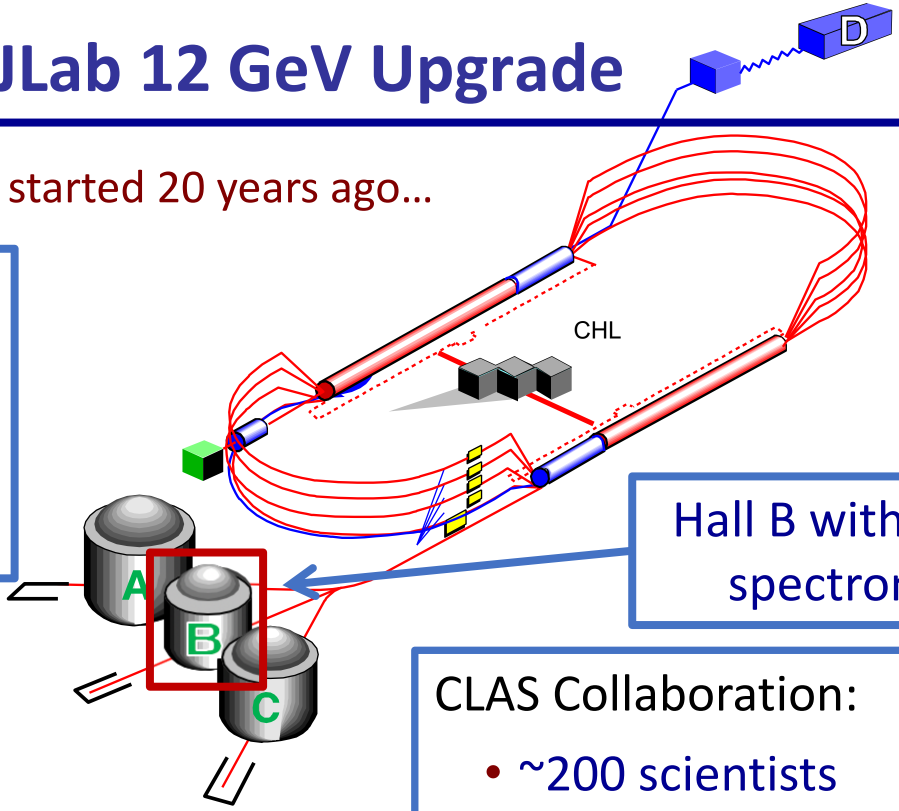
Open CLAS detector



CLAS12 and the JLab 12 GeV Upgrade

The JLab 12 GeV upgrade project started 20 years ago…

- 2000-2004: Science case
- 2004-2008: R&D
- 2006-2009: Design and Engineering
- 2009-2015: Construction
- 2012-2017: Installation



Hall B with CLAS12 spectrometer

Scope of the 12 GeV upgrade project:

- Double the accelerator beam energy
- New Hall D
- Upgrades to existing Halls A, B, C

CLAS Collaboration:

- ~200 scientists
- 55 institutions
- 12 countries

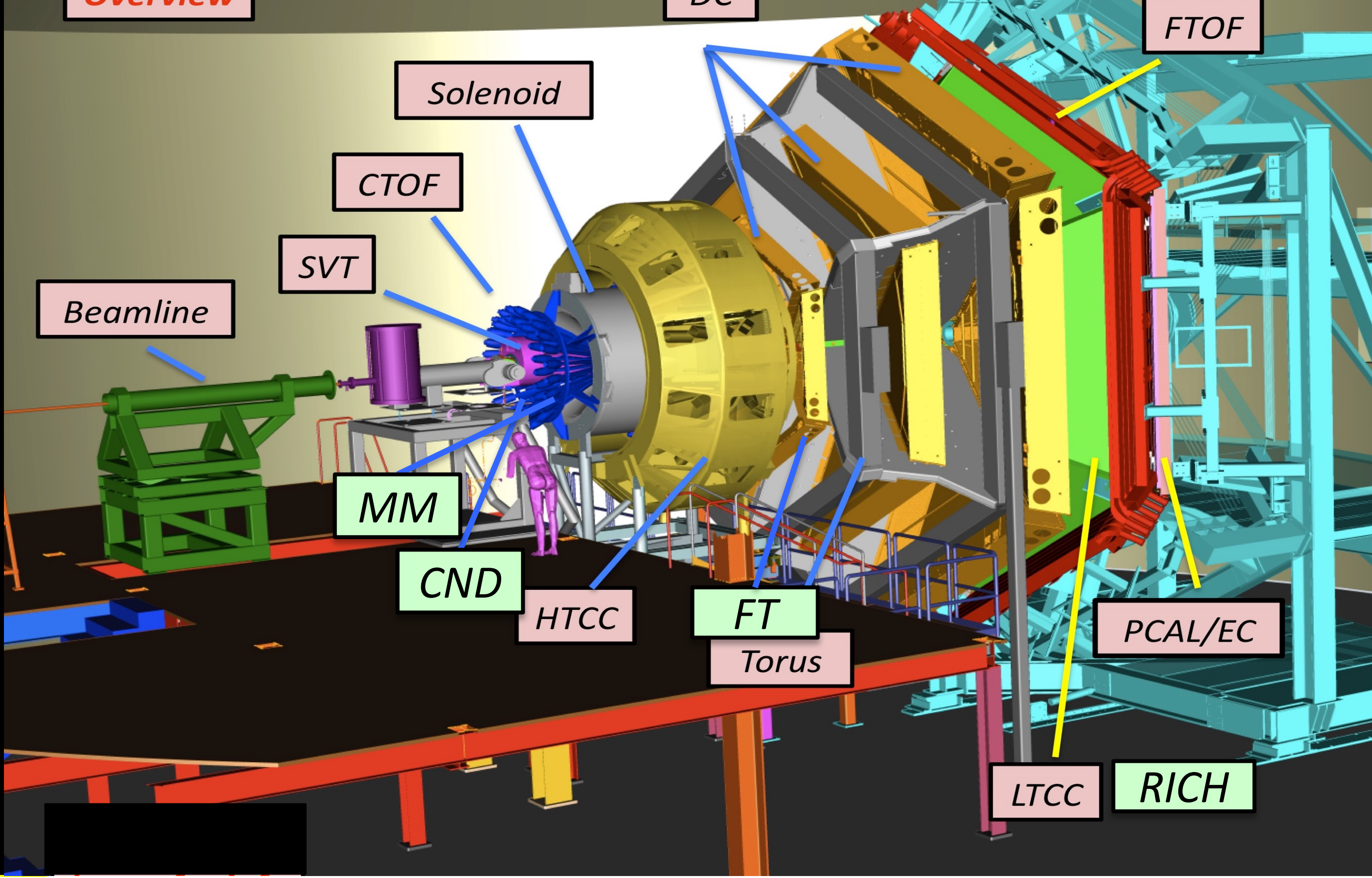
CLAS12

<u>Forward Detector (FD)</u>
- TORUS magnet
- HT Cherenkov Counter
- Drift chamber system
- LT Cherenkov Counter
- Forward TOF System
- Pre-shower calorimeter
- E.M. calorimeter

<u>Central Detector (CD)</u>
- SOLENOID magnet
- Silicon Vertex Tracker
- Central Time-of-Flight

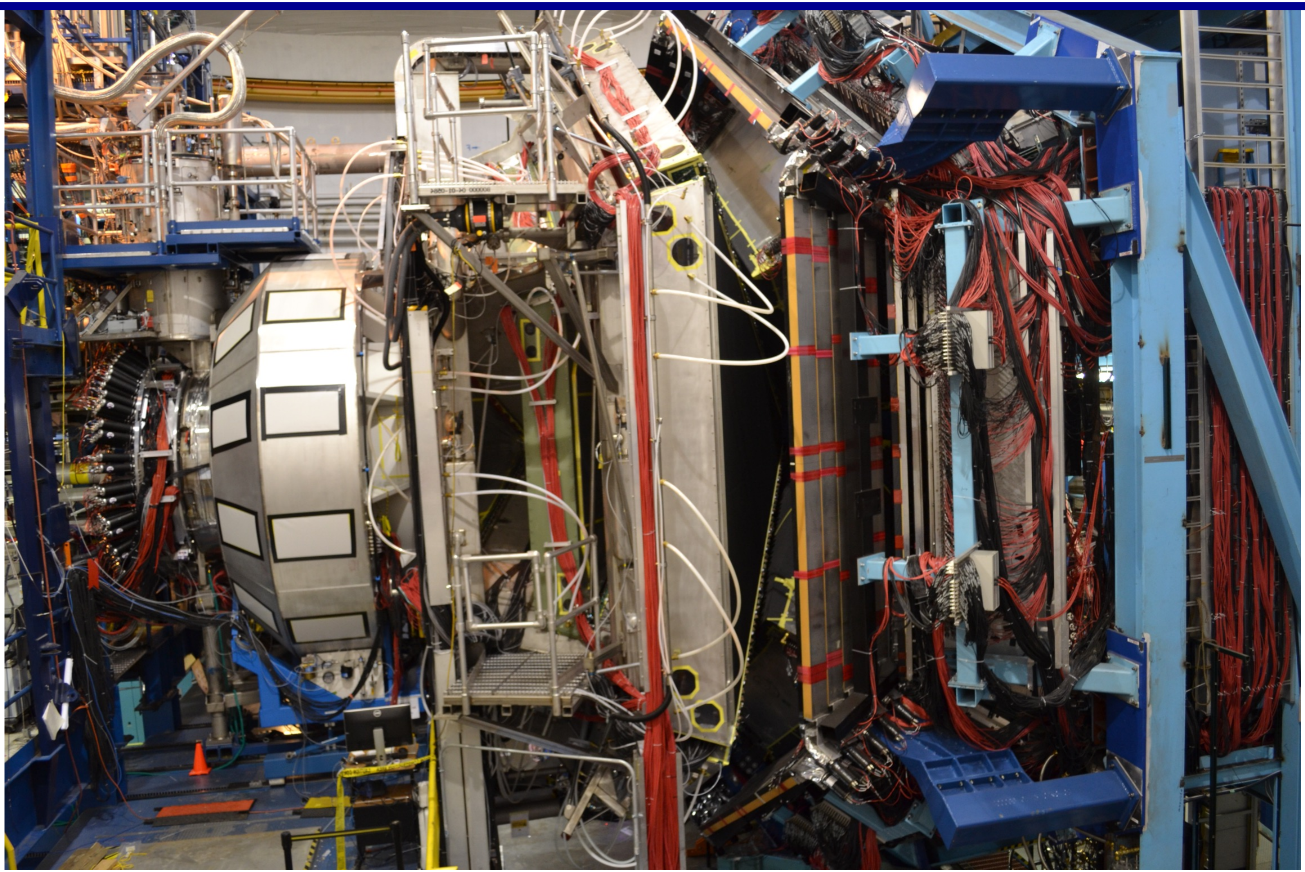
<u>Beamline</u>
- Cryo Target
- Moller polarimeter
- Shielding
- Photon Tagger

<u>Upgrade to the baseline</u>
- Central Neutron Detector
- MicroMegas
- Forward Tagger
- RICH detector
- Polarized target

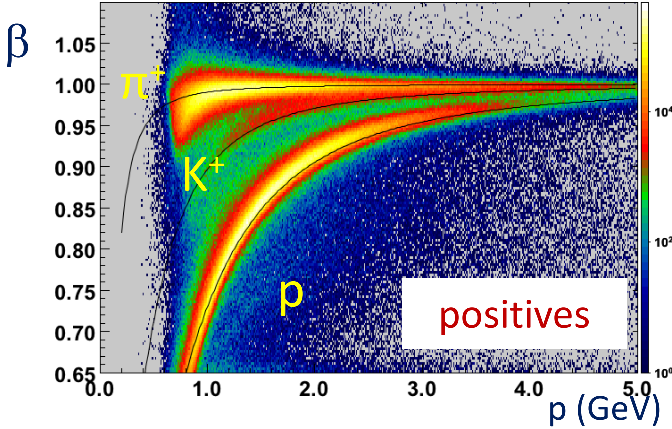


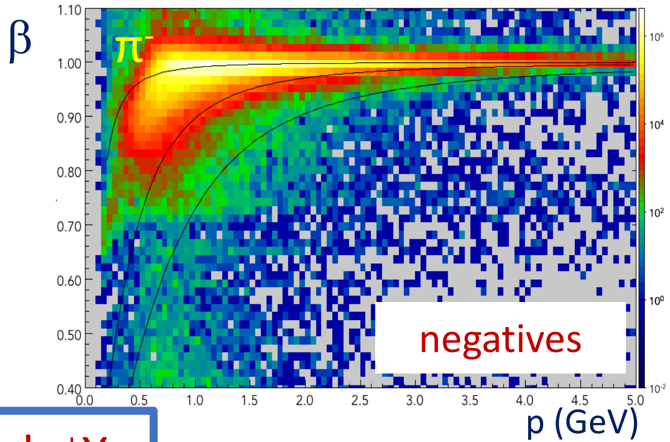
CLAS12 Spectrometer

beam

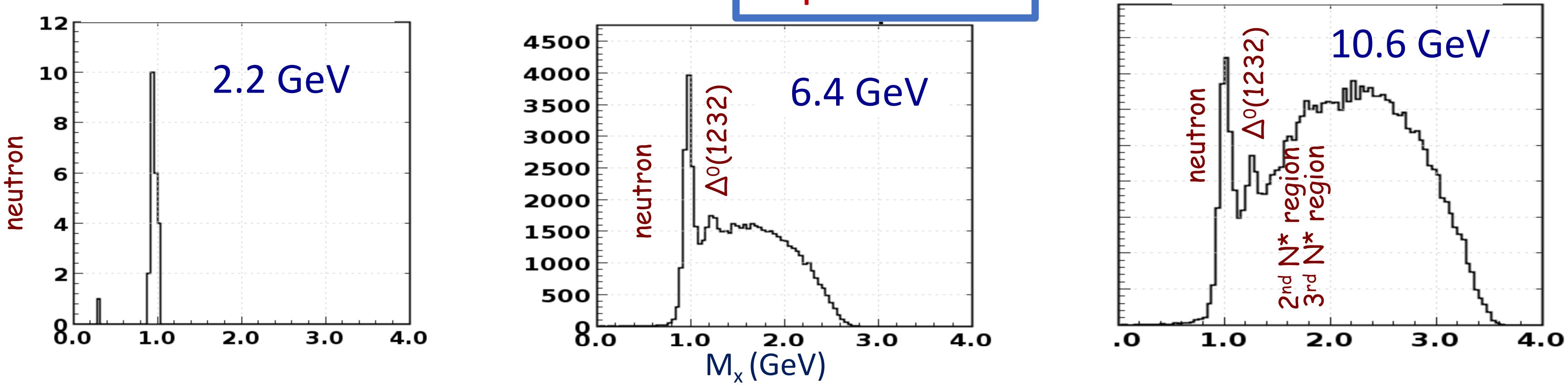


Event Reconstruction





ep → e'π^+X



CLAS N* Experimental Program

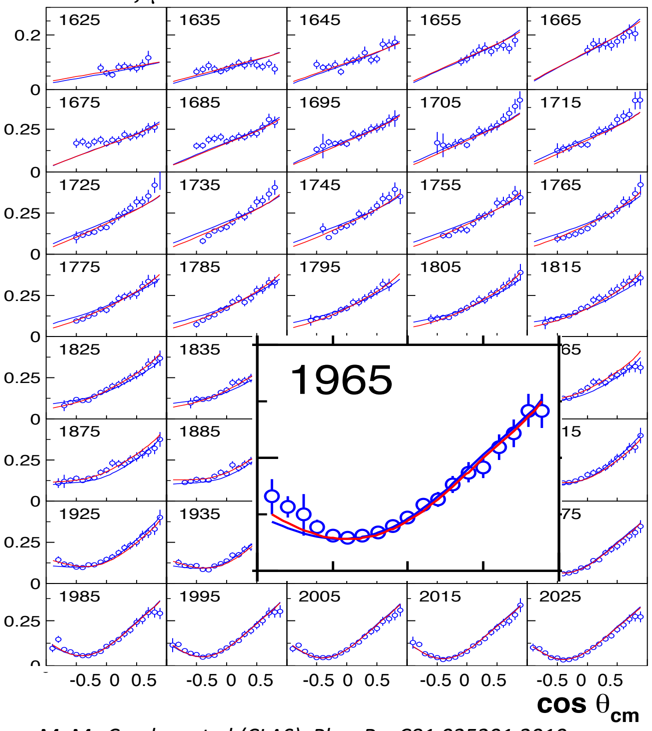
✓ (red) -published, ✓-acquired

	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
Proton targets																
$p\pi^0$	✓ (red)	✓ (red)	✓		✓ (red)	✓	✓ (red)	✓								
$n\pi^+$	✓ (red)	✓	✓		✓ (red)	✓	✓ (red)	✓								
$p\eta$	✓ (red)	✓ (red)	✓		✓ (red)	✓	✓	✓								
$p\eta'$	✓	✓ (red)	✓		✓	✓	✓	✓								
$N\pi\pi$	✓ (red)	✓ (green)	✓		✓	✓	✓ (green)	✓								
$p\ \omega/\phi$	✓ (red)	✓ (red)	✓ (red)	✓ (red)	✓ (red)	✓ (red)		✓ (red)	✓ (red) SDME							
$K^+\Lambda$	✓ (red)	✓ (red)	✓ (red)	✓ (red)	✓	✓	✓	✓	✓	✓	✓	✓	✓ (red)	✓ (red)	✓ (red)	✓ (red)
$K^+\Sigma^0$	✓ (red)	✓ (red)	✓ (red)	✓ (red)	✓	✓	✓	✓	✓	✓	✓	✓	✓ (red)	✓ (red)	✓ (red)	✓ (red)
$K^{0*}\Sigma^+$	✓ (red)	✓									✓	✓				
$K^{+*}\Lambda$	✓ (red)	✓		✓ (red)					✓ (red) SDME							
Neutron targets																
$p\pi^-$	✓ (red)	✓			✓ (red)	✓	✓									
$p\rho^-$	✓ (red)	✓			✓	✓	✓									
$K^+\Sigma^-$	✓	✓ (red)			✓ (red)	✓	✓									
$K^0\Lambda$	✓ (red)	✓		✓	✓ (red)	✓	✓				✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓		✓	✓ (red)	✓	✓				✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓														

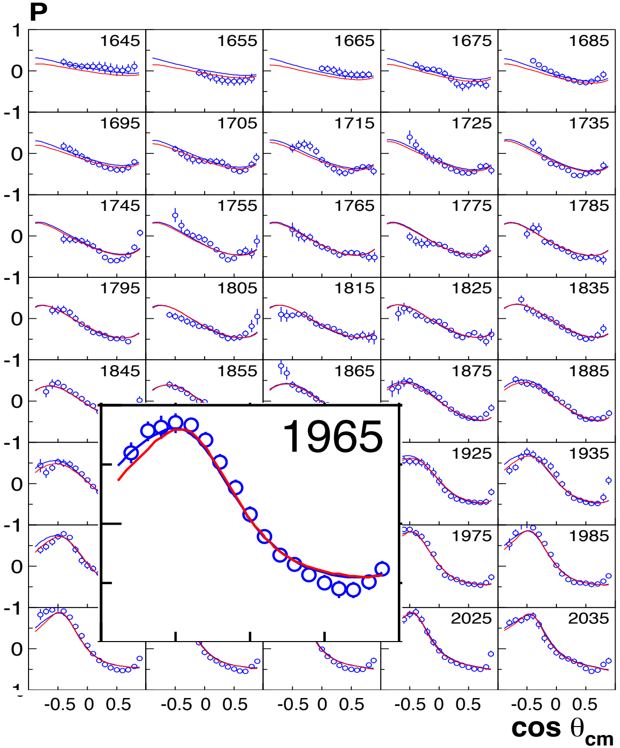
Establishing the N* spectrum – Precision & Polarization are essential

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

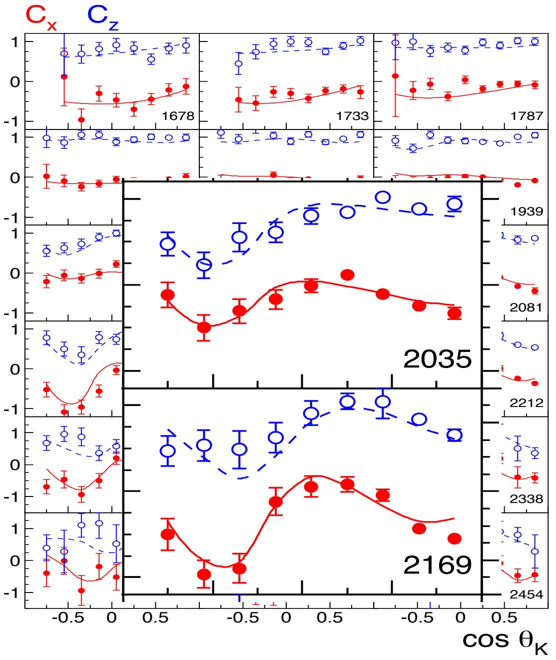
Fit by BnGa group *A.V. Anisovich et al, EPJ A48, 15 (2012)*



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

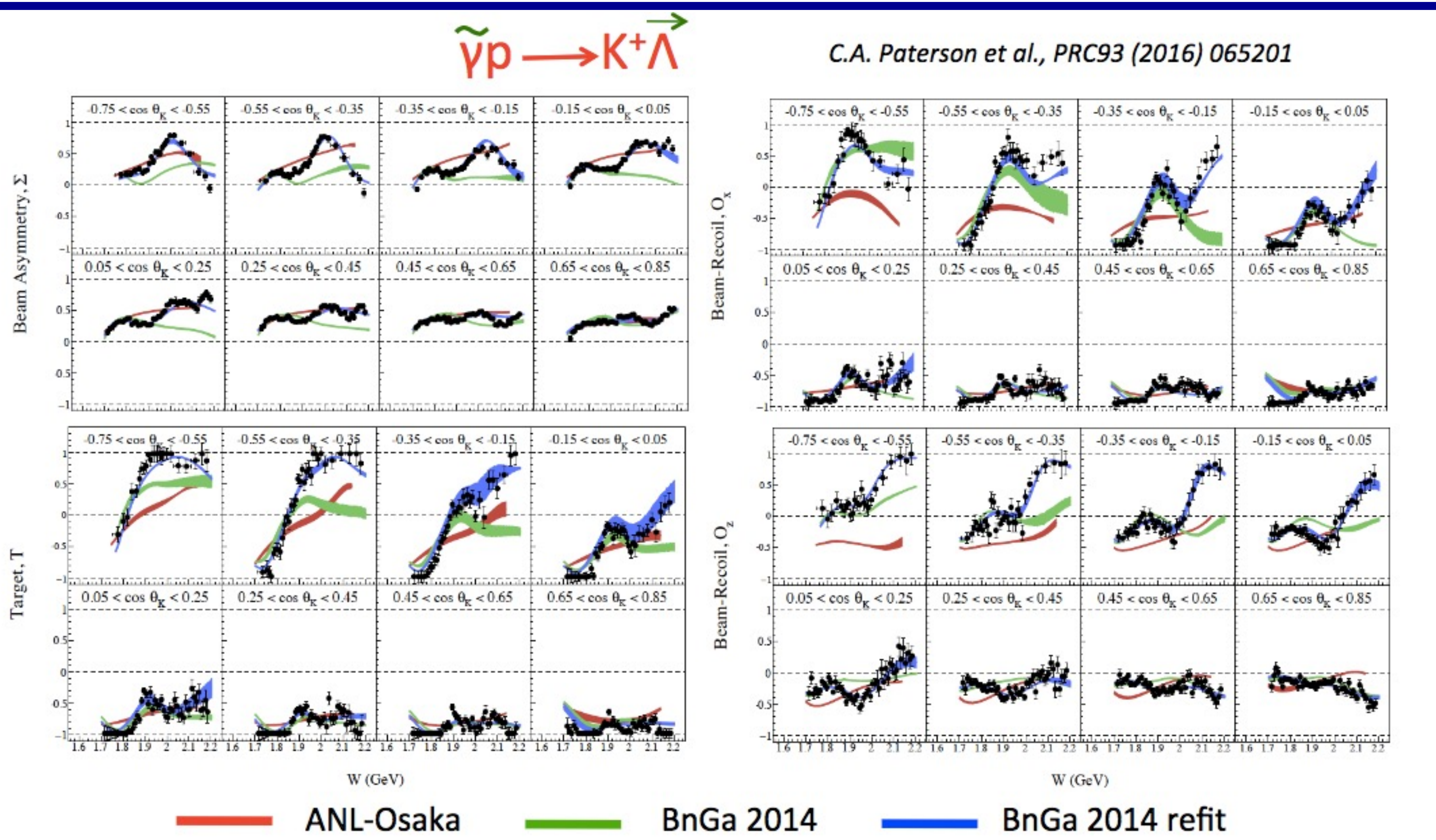


γ->Λ **Polarization** transfer



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

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



New Multipole Extraction

PRC96,055202 (2017)

Updated Spectrum of Baryon Resonances

- From 2000 to 2010 no new Baryon resonances in PDG. πN- scattering data and π-photoproduction only.
- Multi-channel models now include many photoproduction data. e.g. Bonn-Gatchina PWA analysis

State N(mass)J^P	PDG pre 2010	PDG 2012	PDG 2021
N(1710)$1/2^+$	***	***	****
N(1880)$1/2^+$		**	***
N(1895)$1/2^-$		**	****
N(1900)$3/2^+$	**	***	****
N(1875)$3/2^-$		***	***
N(2120)$3/2^-$		**	***
N(2000)$5/2^+$	*		**
N(2060)$5/2^-$		**	***

A. Anisovich et al. EPJ A 48, 15 (2012)

PRL 119, 062004, 2017)

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

- Results from photoproduction now add to the PDG tables and determine properties of baryon resonances

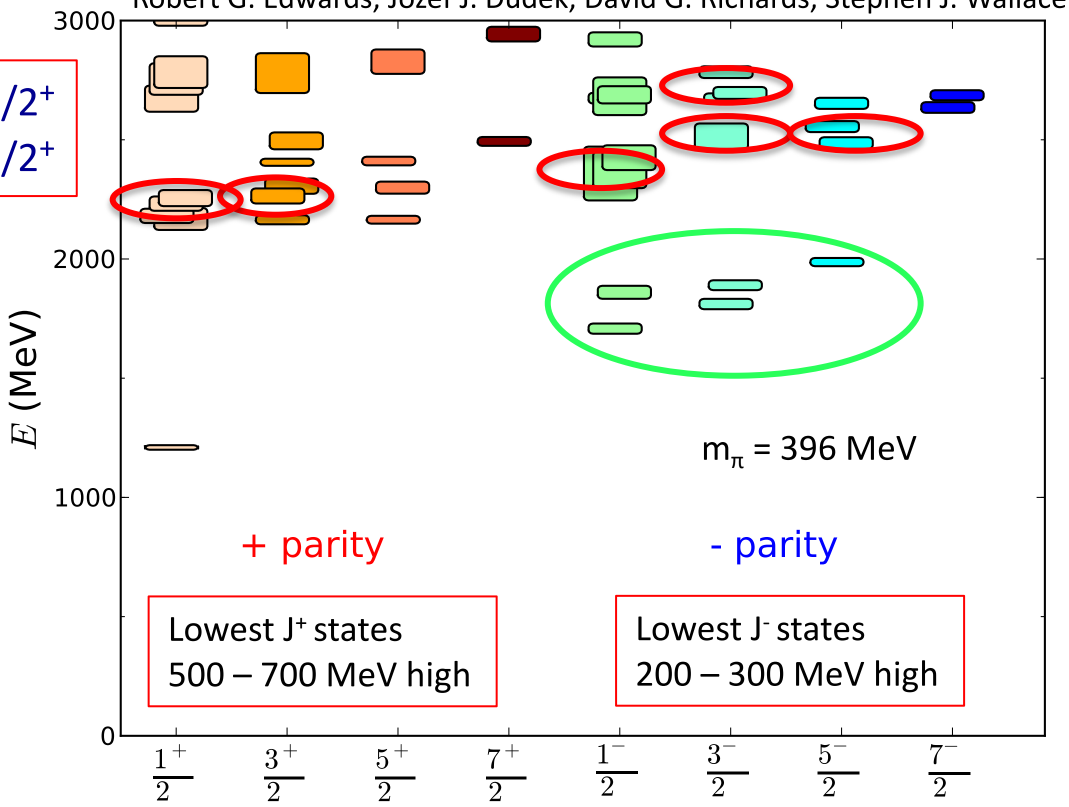
Do New States Fit into LQCD Projections ?

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+

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

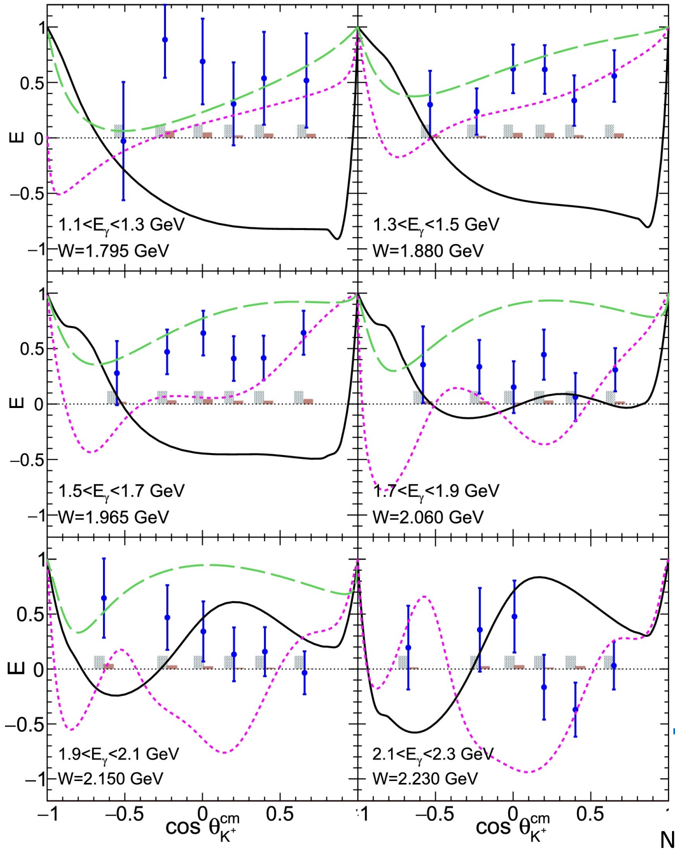
The field would really benefit from more realistic Lattice masses for N* states.



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

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

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

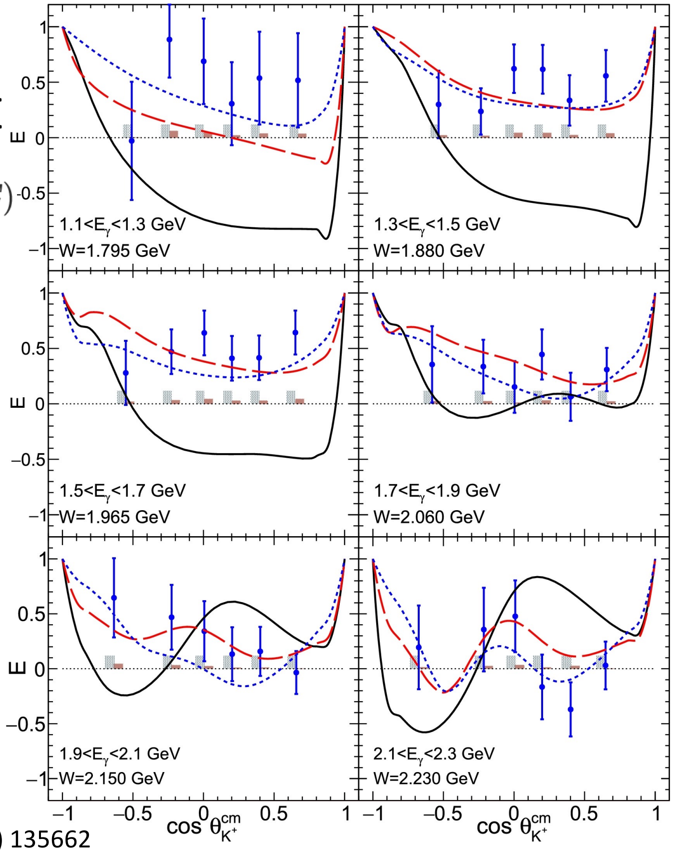
Kaon-Maid2017

Bonn-Gatchina 2017

↓

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

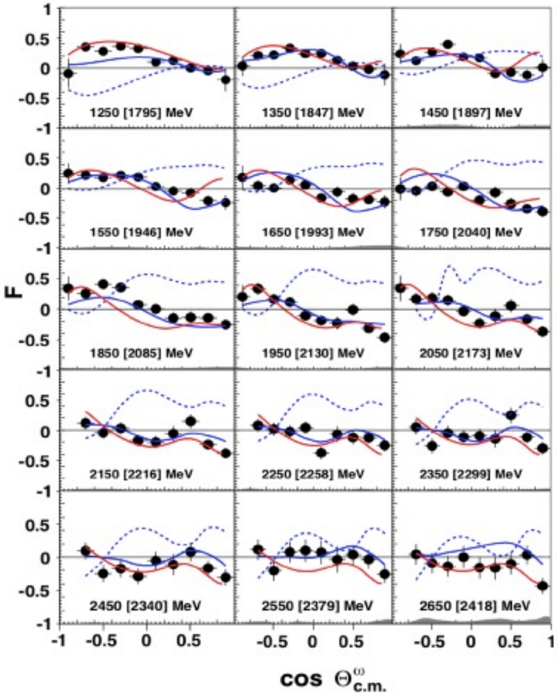
Bonn-Gatchina 2019
+ N(2170) 3/2$^+$

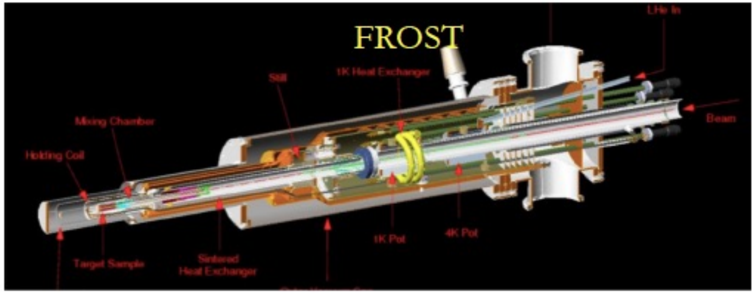


N. Zachariou et al Phys lett B 808 (2020) 135662

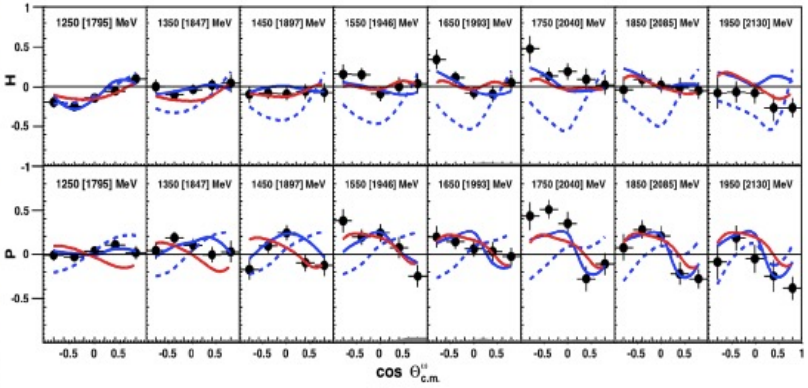
Beam-target asymmetries $\vec{\gamma}\,\vec{p} \to p\,\omega$

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





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

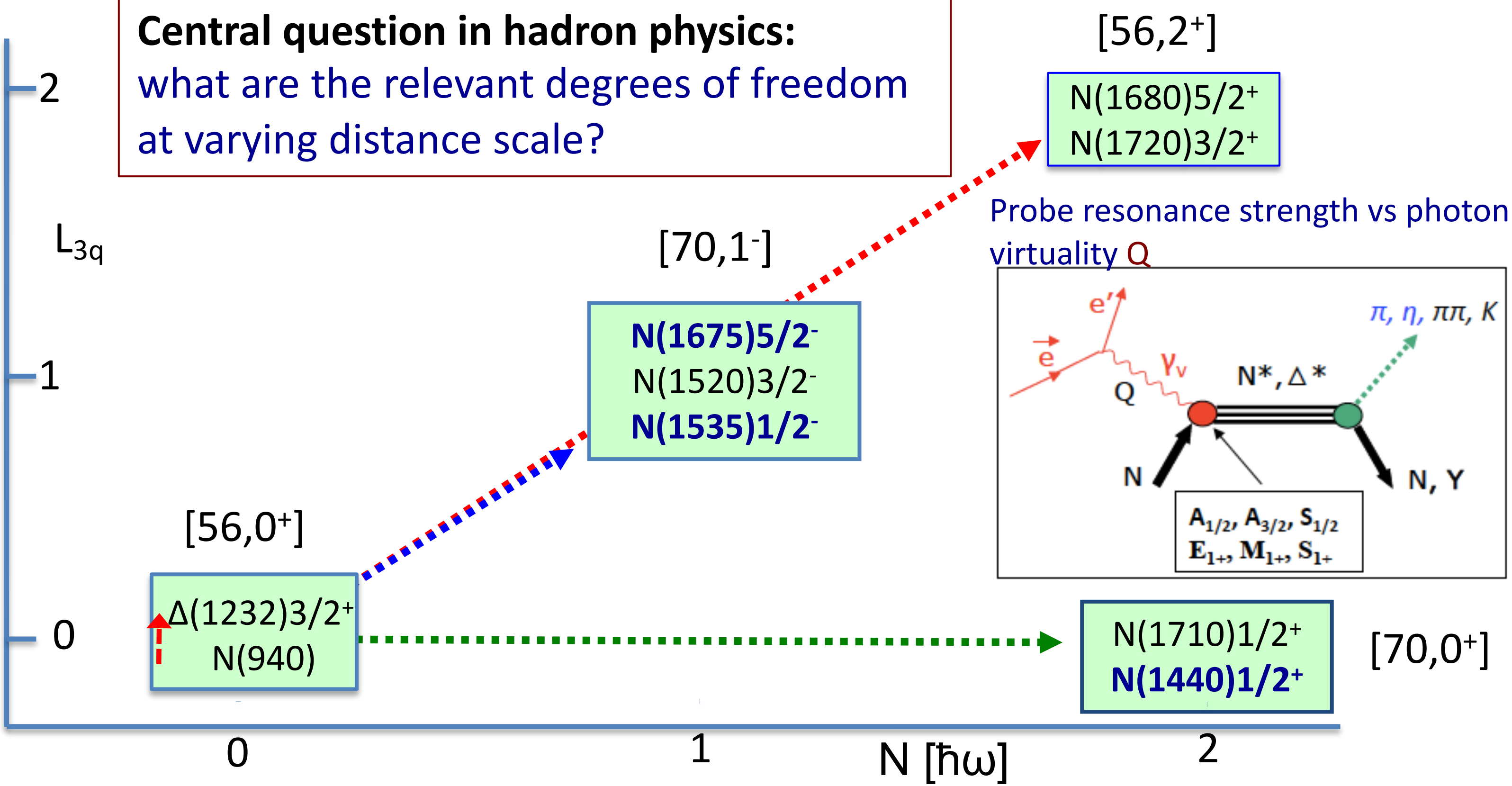


PWA: BnGa, Wei

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)

Electroexcitation of N*/Δ resonances

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

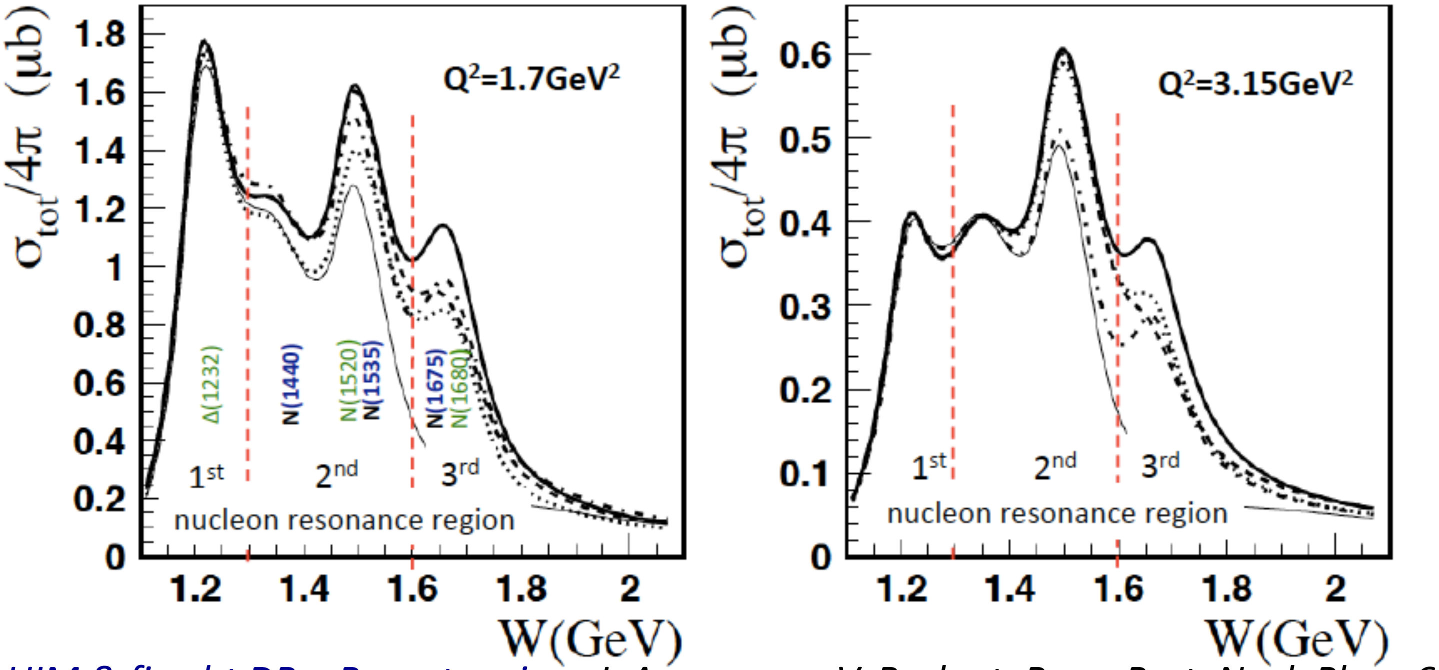


Total cross section at W < 2.1 GeV

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

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*



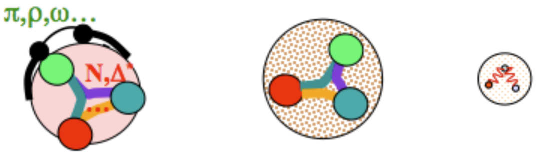
Analysis with UIM & fixed-t DR; *Recent review:* *I. Aznauryan, V. Burkert, Prog. Part. Nucl. Phys. 67 (2012) 1.*

Excited Nucleon Structure

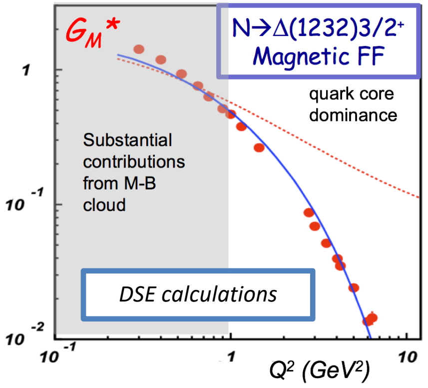
- Nucleon structure is more complex than what can be described accounting for quark degrees of freedom only

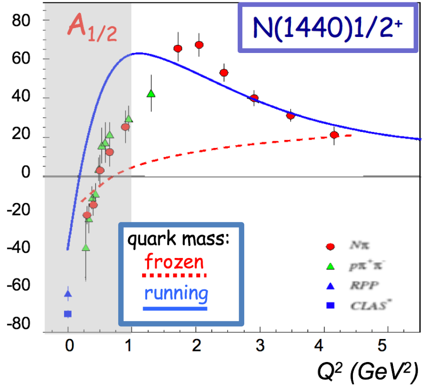
  - Low Q^2: *($Q^2 < 5$ GeV^2)* — structure well described by adding an external meson cloud to inner quark core

  - High Q^2: *($Q^2 > 5$ GeV^2)* — quark core dominates; transition from confinement to pQCD regime

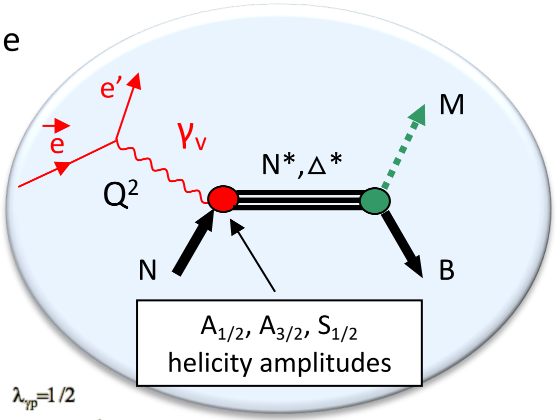


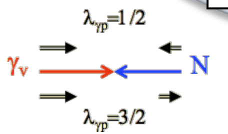
- Calculations of form factors and electrocoupling amplitudes are sensitive to the underlying quark mass distribution





CLAS results vs. QCD expectations with running quark mass

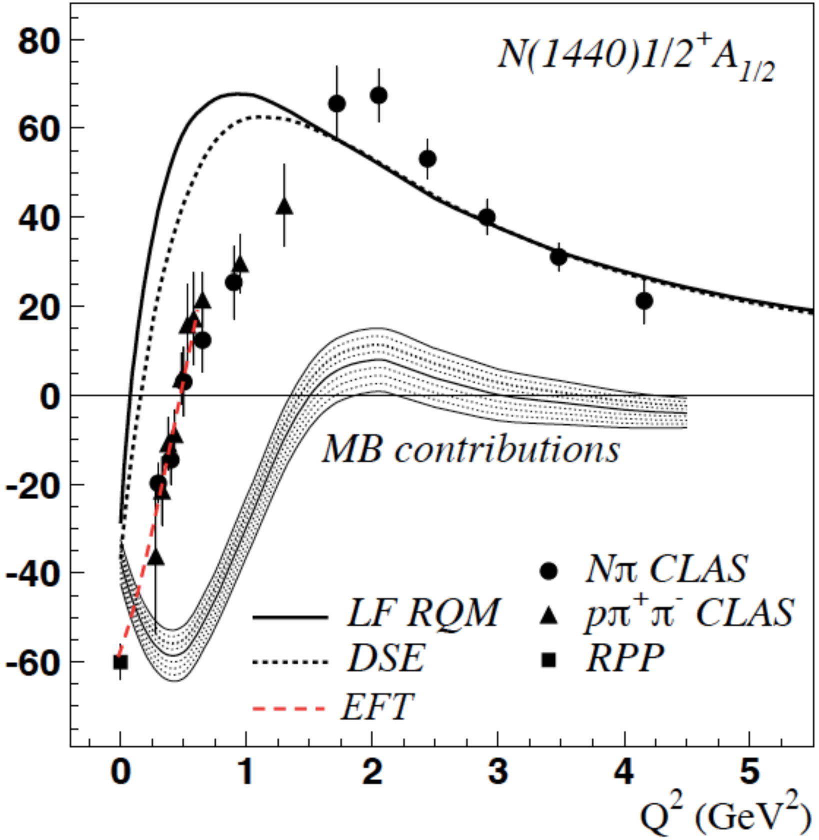




$A_{1/2}$, $A_{3/2}$ – transverse

$S_{1/2}$ - longitudinal

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*

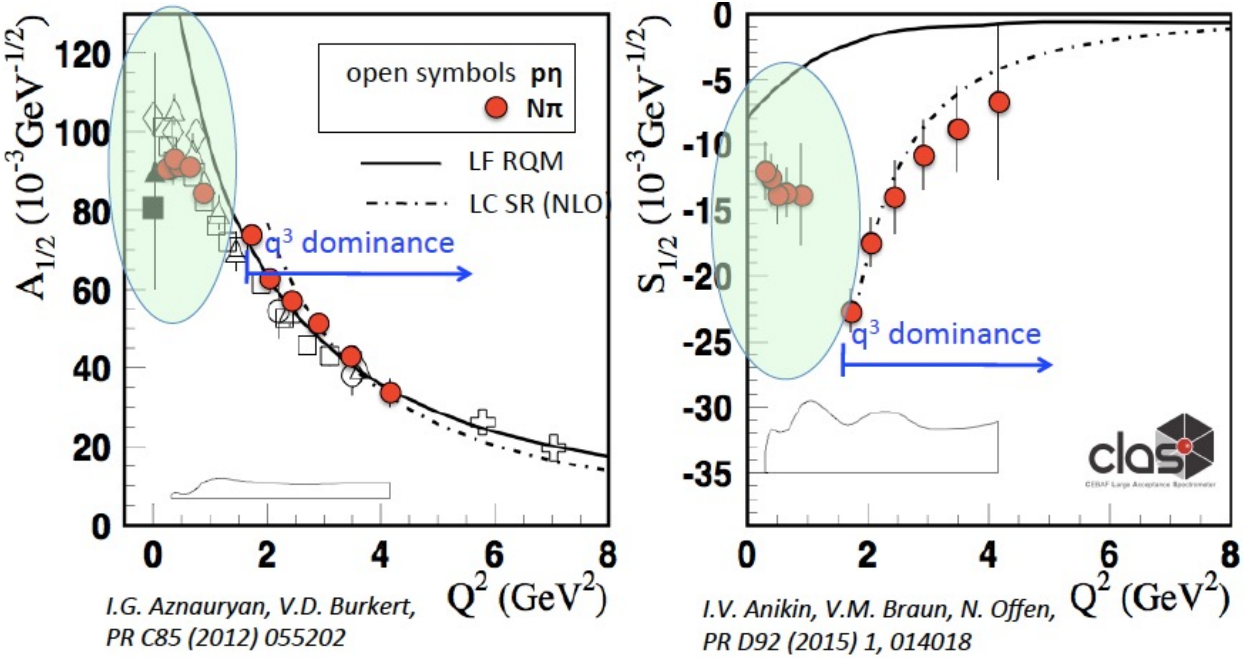
➔ Non-quark contributions are significant at $Q^2 < 2.0$ GeV^2. The behavior at $Q^2 < 0.5$ can be modeled in EFT.

➔ 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$^-$

Is it a 3-quark state or a hadronic molecule?



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.

Hybrid Hadrons: Hadrons 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).

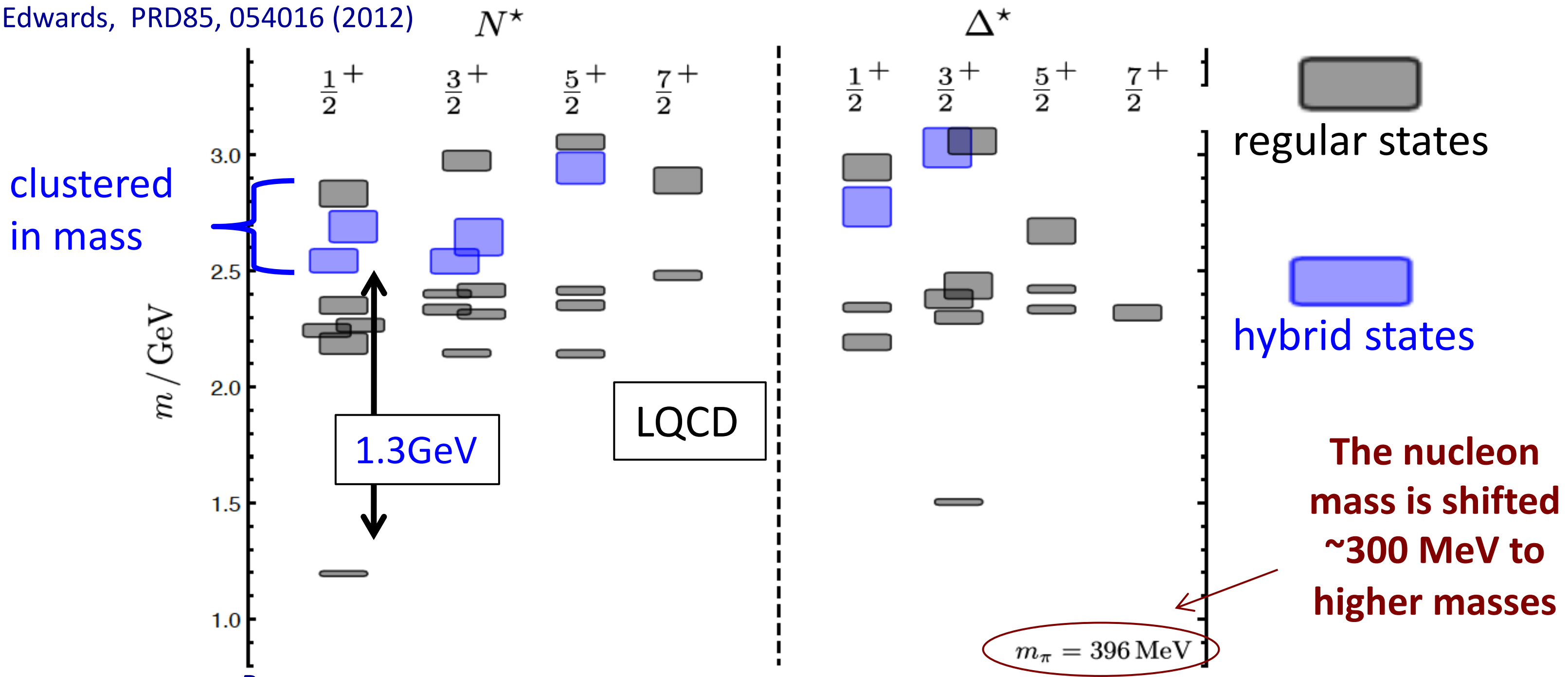
✧ QCD Sum Rule - L. Kisslinger and Z. Li, Phys. Rev. D 51, R5986 (1995).

✧ 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)



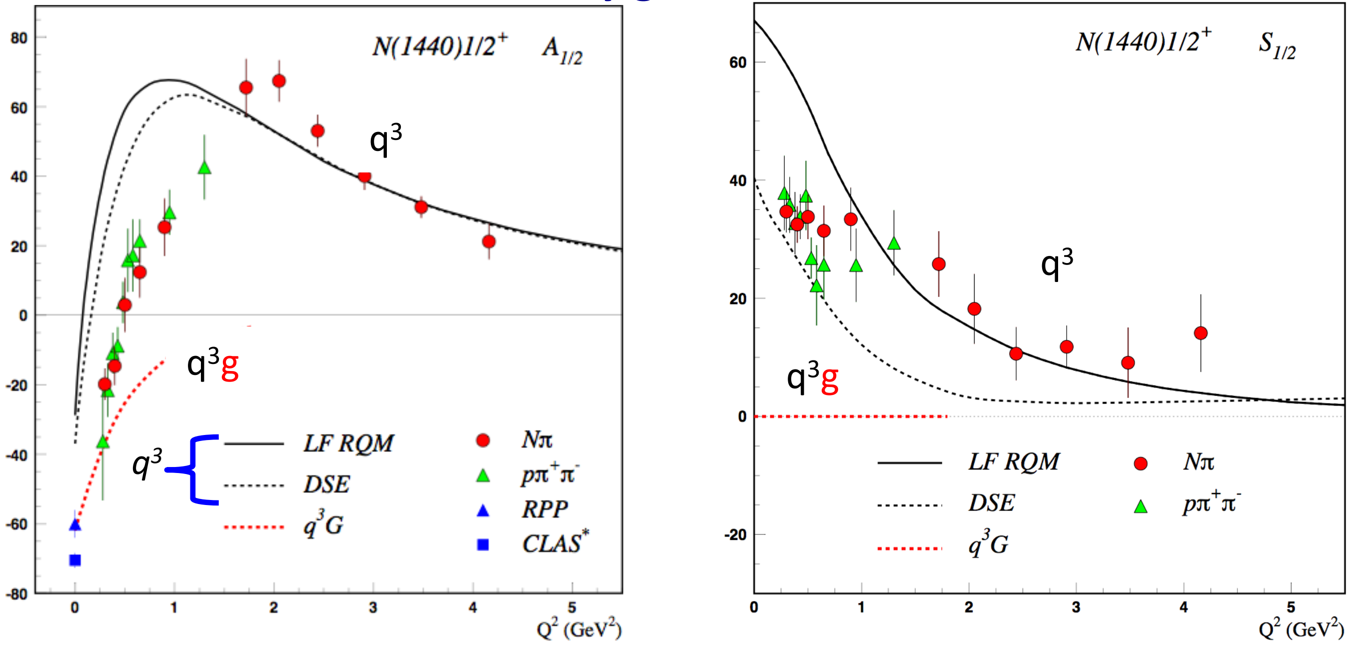
Hybrid states have same J^P values as qqq baryons. How to identify them?

- 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.

History of Nucleon Structure Studies

1950-1960: Does the proton have finite size and structure?

- Elastic electron-proton scattering
  - ✦ the proton is not a point-like particle but has finite size – seen through charge and current distribution in the proton G_E/G_M

Nobel prize 1961- R. Hofstadter

1960-1990: What are the internal constituents of the nucleon?

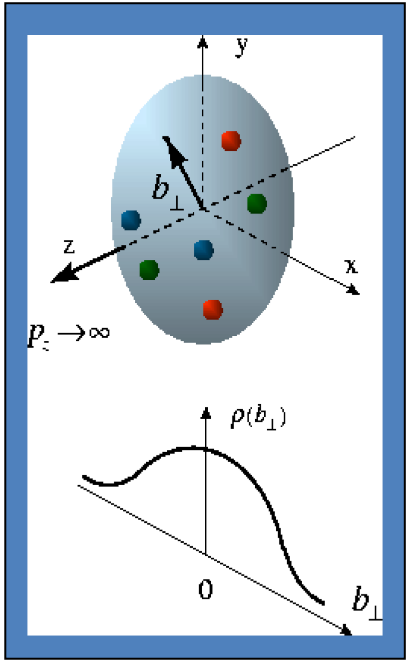
- Deeply inelastic scattering
  - ✦ discover quarks in ‘scaling’ of structure function - measure their momentum and spin distributions

Nobel prize 1990 - J. Friedman, H. Kendall, R. Taylor

Today: Unraveling a 3-D image of the quark and gluon distributions, including mass, spin, and pressure distributions

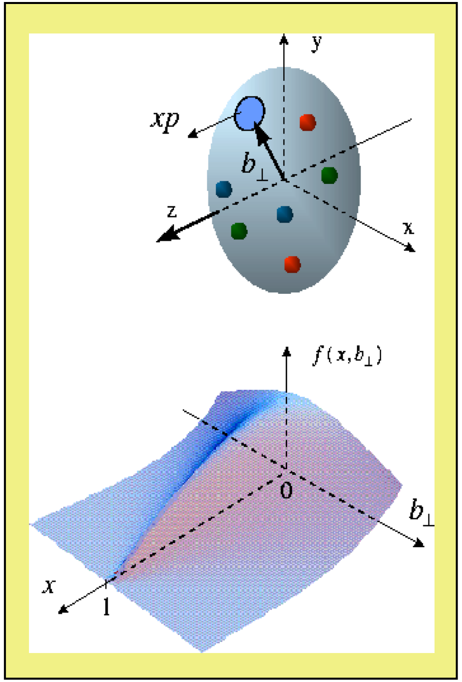
Nucleon Structure Evolution

elastic scattering



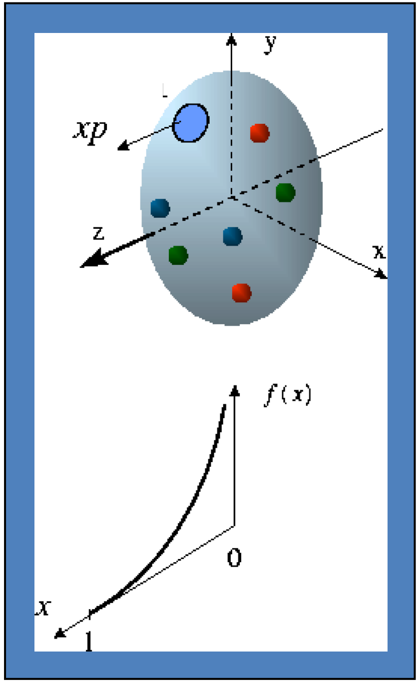
Transverse quark distribution in coordinate space

deep-exclusive scattering



Correlated quark space and momentum distributions – GPD

deep-inelastic scattering

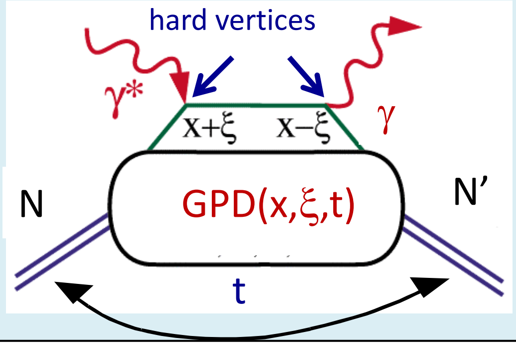


Longitudinal quark distribution in momentum space

DVCS – The Quintessential Process

GPDs are *universal* and can be determined in any suitable reaction

Deeply Virtual Compton Scattering



x – longitudinal quark momentum fraction

2ξ – longitudinal momentum transfer

t – four momentum transfer to final N

"handbag" mechanism

H, E : spin-independent GPDs

$$\int_{-1}^{1} dx\, H^q(x,\xi,t) = F_1^q(t), \qquad \int_{-1}^{1} dx\, E^q(x,\xi,t) = F_2^q(t)$$

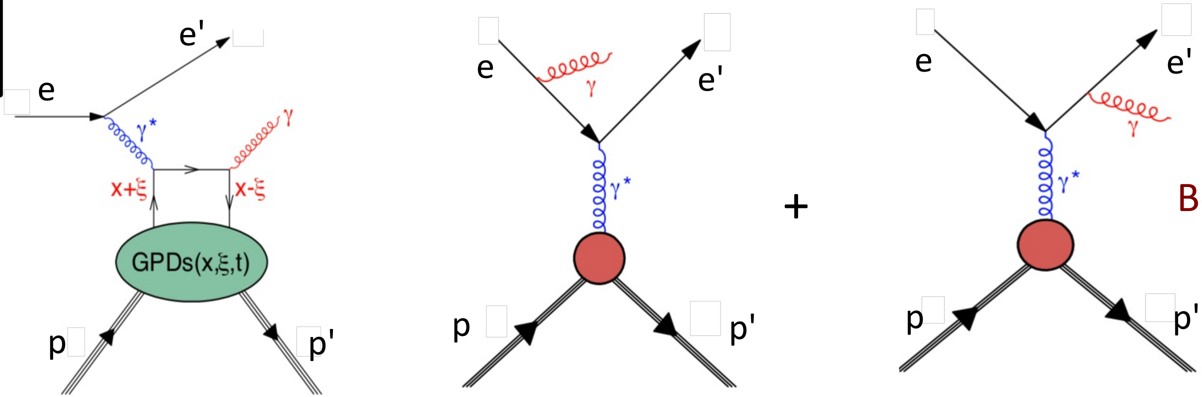
$\tilde{H}$, $\tilde{E}$: spin-dependent GPDs

$$\int_{-1}^{1} dx\, \tilde{H}^q(x,\xi,t) = g_A^q(t), \qquad \int_{-1}^{1} dx\, \tilde{E}^q(x,\xi,t) = g_P^q(t)$$

Accessing GPDs

ep → e'p'γ

DVCS



Bethe-Heitler (BH)

$$\frac{d^4\sigma}{dQ^2 dx dt d\Phi} \sim |\tau_{DVCS} + \tau_{BH}|^2$$

τ_{DVCS} : derived from GPDs

τ_{BH} : derived from Form Factors

Measure one of various spin asymmetries:

e.g. polarized beam + unpolarized target:

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma} \sim \mathrm{Im}(\tau_{DVCS})\tau_{BH}$$

X. Ji, Phys. Rev. D 55, 7114 (1997)

$$\Delta\sigma_{LU} \sim \sin\phi \; \mathrm{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\} \, d\phi$$

⇨ $H(\xi,t)$ *(other terms kinematically suppressed)*

Accessing GPDs

Different spin asymmetries are sensitive to different GPDs

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

- Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi \; \mathrm{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\} \, d\phi$$

kinematically suppressed

⇒ $H(\xi,t)$

- Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi \; \mathrm{Im}\{F_1 \tilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi)E) - \ldots\} \, d\phi$$

kinematically suppressed

⇒ $H(\xi,t), \tilde{H}(\xi,t)$

- Unpolarized beam, transverse target:

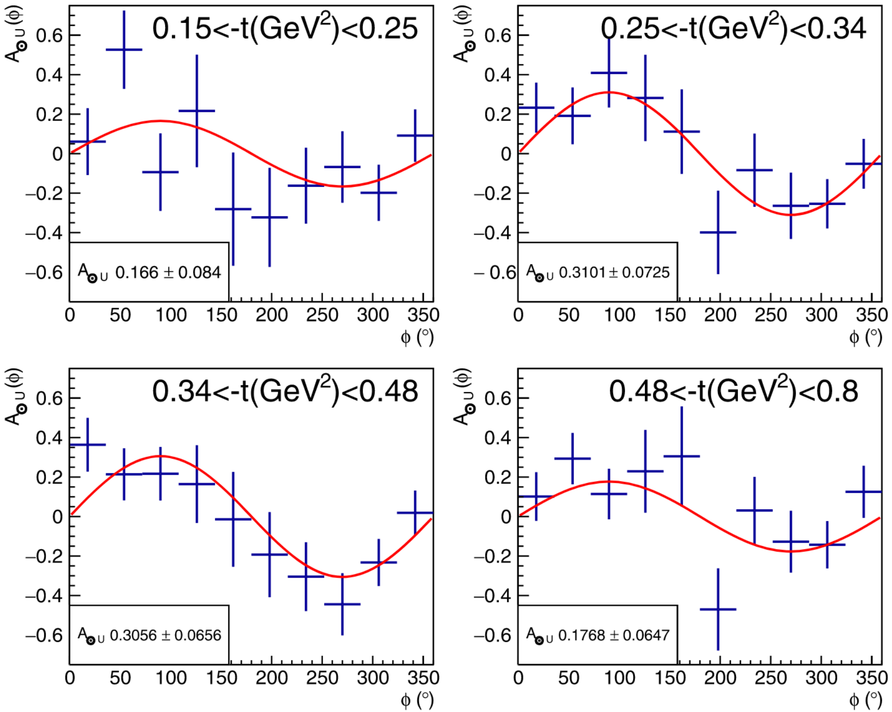
$$\Delta\sigma_{UT} \sim \sin\phi \; \mathrm{Im}\{k(F_2 H - F_1 E) + \ldots\} \, d\phi$$

kinematically suppressed

⇒ $H(\xi,t), E(\xi,t)$

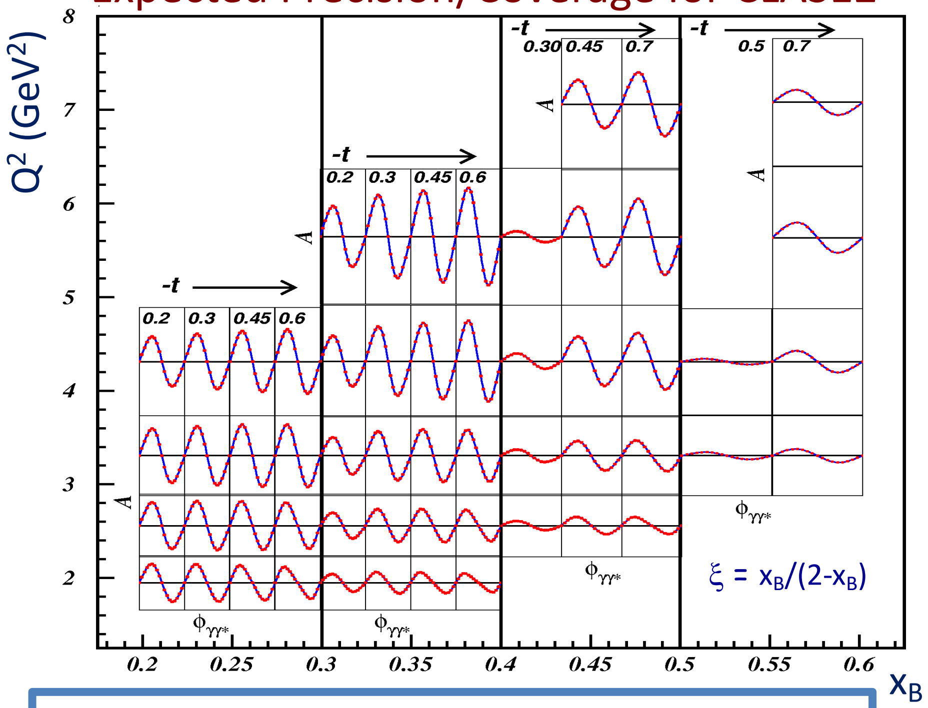
DVCS Beam Spin Asymmetry

P_e=85% $\vec{e}\,p \rightarrow e'p'\gamma$ CLAS12



P. Chatagnon et al. Phys. Rev Lett 127, 262501 (2021)

Expected Precision/Coverage for CLAS12



Extraction of GPDs is a major goal of the CLAS12 program

Accessing the Forces & Pressure on Quarks

Nucleon matrix element of EMT contains:

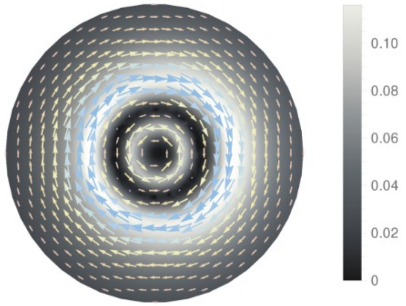
$M_2(t)$: Mass distribution inside the nucleon
$J(t)$: Angular momentum distribution
$d_1(t)$: **Shear forces and pressure distribution**

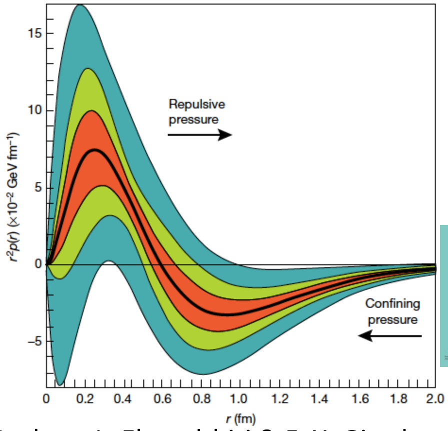
$$\int dx\, x\, [H(x,\xi,t) + E(x,\xi,t)] = 2\, J(t)$$
$$\int dx\, x\, H(x,\xi,t) = M_2(t) + 4/5\, \xi^2\, d_1(t)$$

Separate $M_2(t)$ and $d_1(t)$ through measurements at small/large ξ.

Measuring these form factors, we learn about confinement forces.

Shear forces inside the nucleon

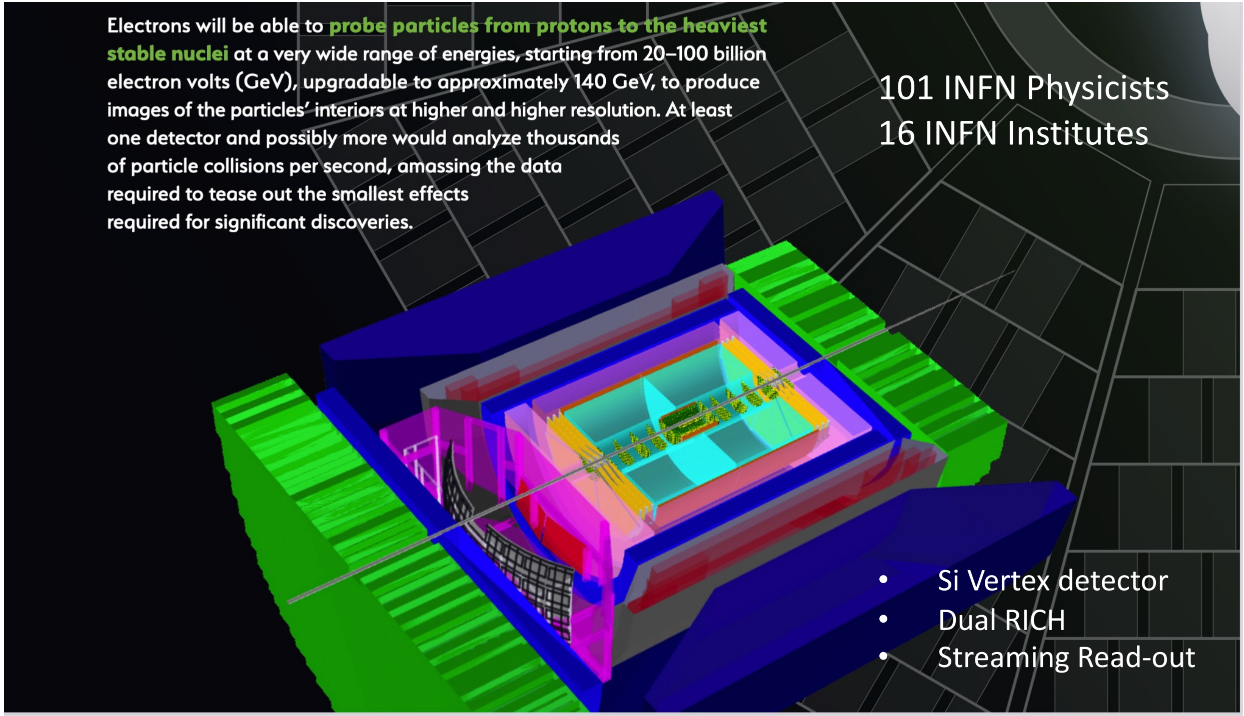




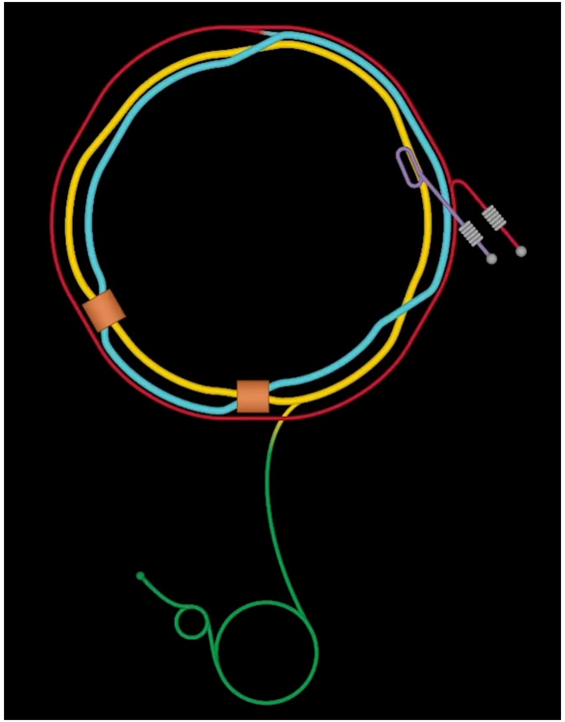
V. D. Burkert, L. Elouadrhiri & F. X. Girod
Nature, 557 396-399 (2018)

THE FUTURE: EIC @ BNL

E_e =100-140 GeV

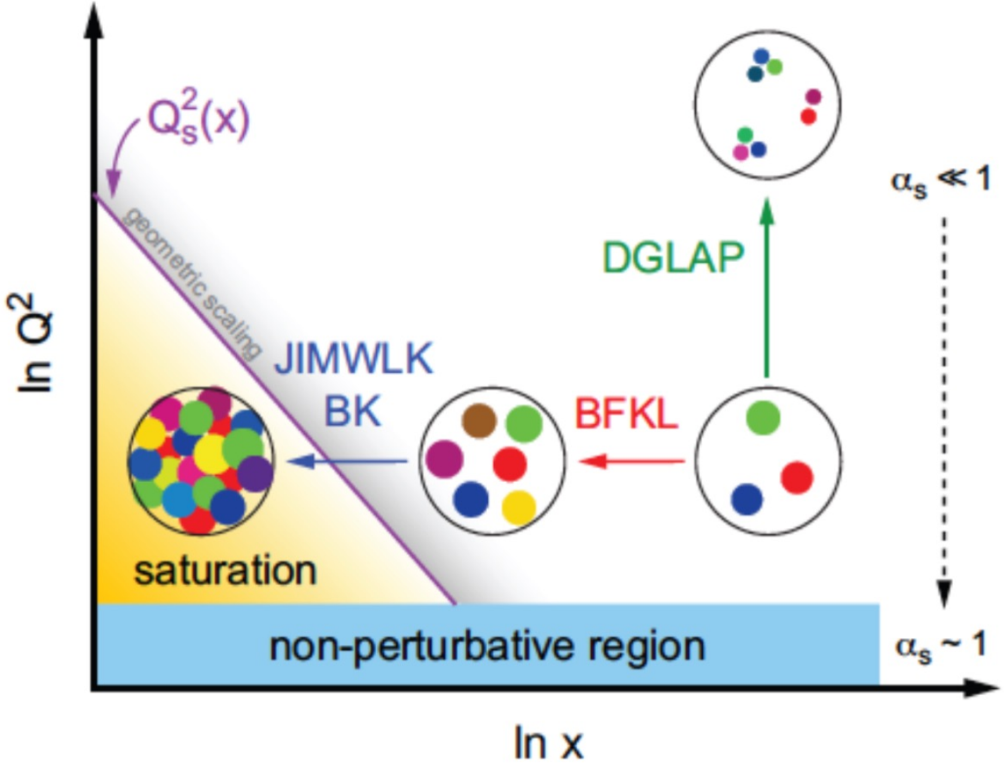


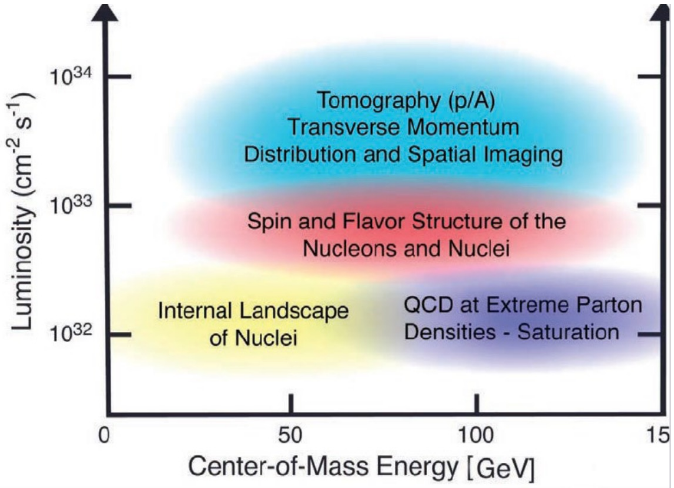
Electron-Ion Collider



THE FUTURE: EIC @ BNL

E_e =100-140 GeV Electron-Ion Collider





Color Glass Condensate

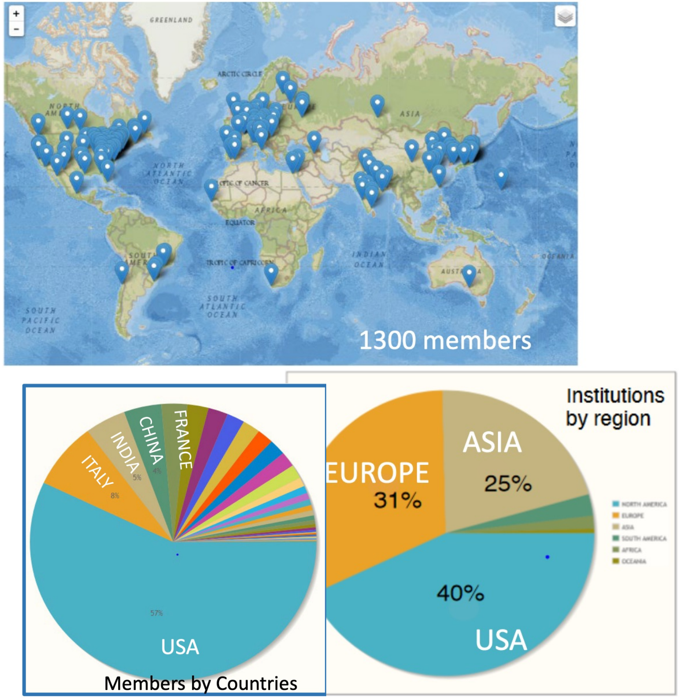
In QCD, the large soft-gluon density drives the non-linear gluon-gluon recombination. This gives rise to a saturation scale Qs, at which gluon splitting and recombination reach a balance.

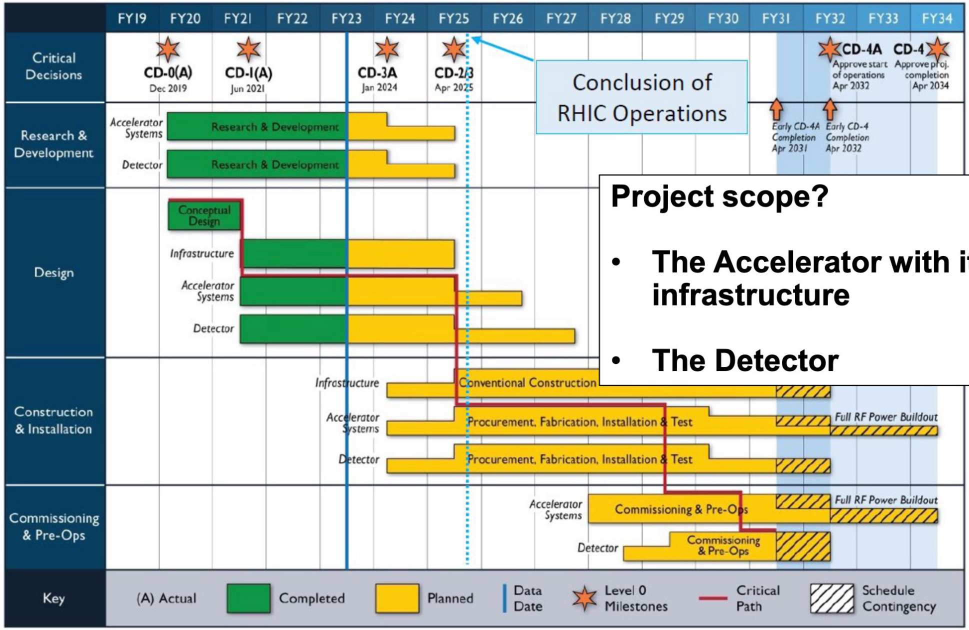
At this scale, the density of gluons is expected to saturate, and may produce new and universal forms of hadronic matter.

R.G. Milner

THE FUTURE: EIC @ BNL

The EICUG (User Group)

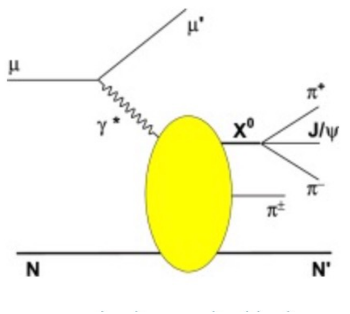


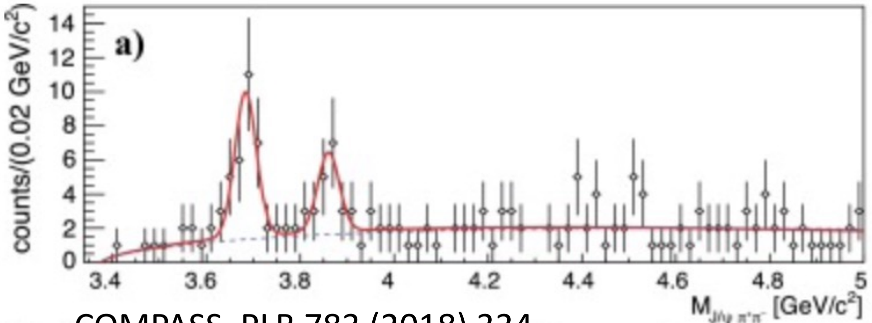


Project scope?

- **The Accelerator with its infrastructure**
- **The Detector**

Exotic hadrons via photoproduction at EIC





COMPASS, PLB 783 (2018) 334

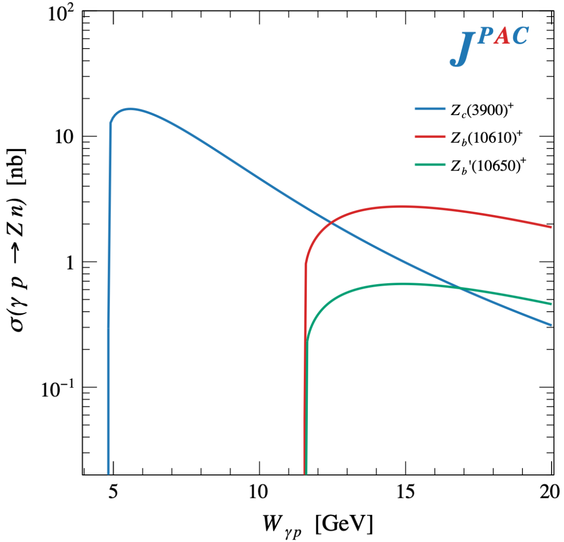
COMPASS proved that photo-production of exotic states is possible

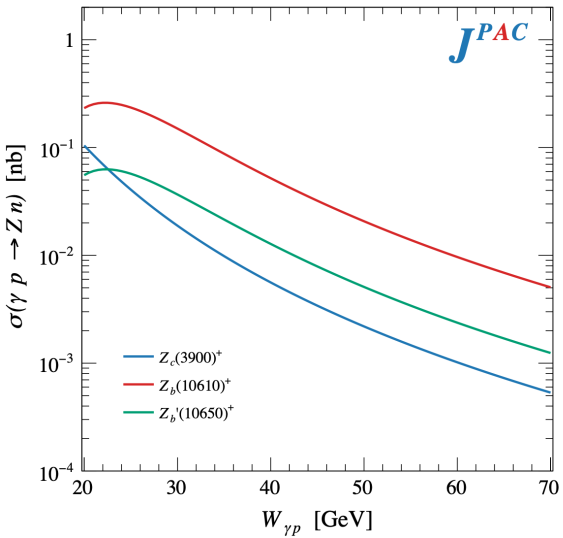
O (10^5) XYZ events in six months at 10^{33} cm-^{2} s^{-1} luminosity @EIC
Z $\rightarrow$J/ψ π^+ (and J J/ψ $\rightarrow$ e^+e^-)

It has been studied by the JPAC group

Z photoproduction

- The Zs are charged charmonium-like 1^{+-} states close to open flavor thresholds
- Focus on $Z_c(3900)^+ \to J/\psi\,\pi^+, Z_b(10610)^+, Z_b'(10650)^+ \to \Upsilon(nS)\,\pi^+$
- The pion is exchanged in the t-channel
- Sizeable cross sections especially at Low Energies

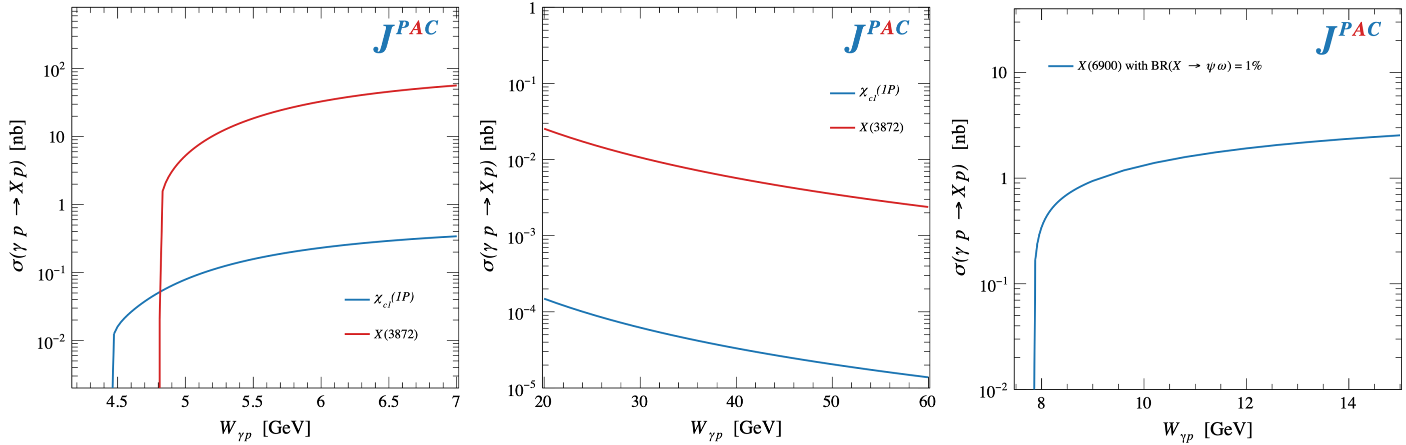




A. Pilloni – Exotic hadron spectroscopy

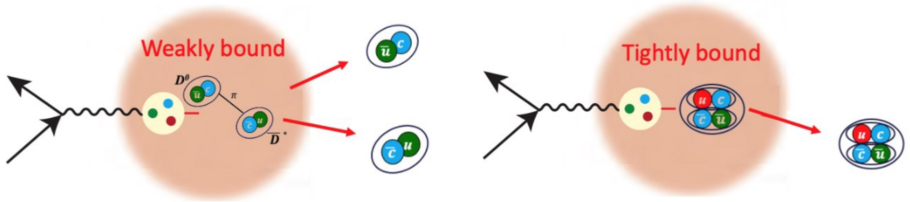
X photoproduction

- Focus on the famous 1^{++} $X(3872) \to J/\psi\ \rho, \omega$
- Studying also $X(6900) \to J/\psi\ J/\psi$ (assumed 0^{++})
- **ω** and **ρ** exchanges give main contributions:
  need to assume the existence of a OZI-suppressed $X(6900) \to J/\psi\ \omega$
- Extremely suppressed cross sections at HE: LE most promising



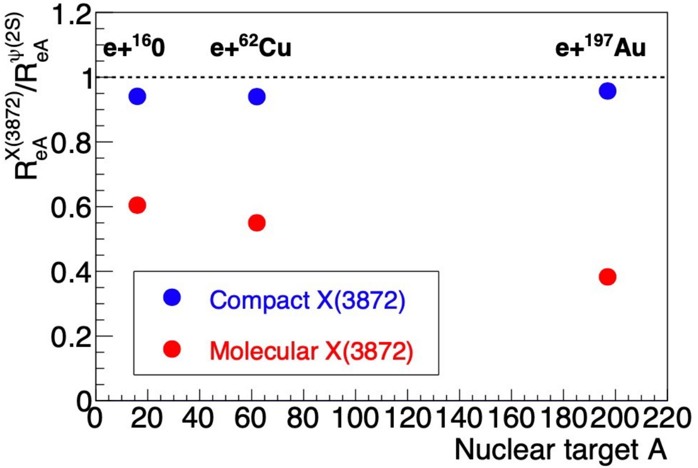
A. Pilloni – Exotic hadron spectroscopy

Studying exotic hadrons nature via eA



$3\ 10^4 – 1.5\ 10^5$ events assuming
300 fb-1intergrated luminosity

Pan-Pan Shi et al., arXiv:2208.02639



Summary

- Major progress made in the last years in the search for N* and Δ states.
  - Polarization observables in photo-production have provided crucial constraints

- Knowledge of Q^2-dependence of electro-couplings is necessary to understand the nature (the internal structure) of the excited states.
  - Leading electrocoupling amplitudes of prominent low-mass states 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) electro-couplings.

- Generalized momentum distributions will provide the spin structure and 3D-imaging of the nucleon:
  - First results from CLAS12 have been published.

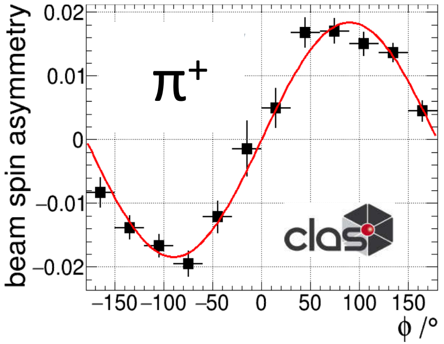
- The future EIC will allow to study the gluonic content of the nucleon and eventually to study the nature of exotics in eA scattering.

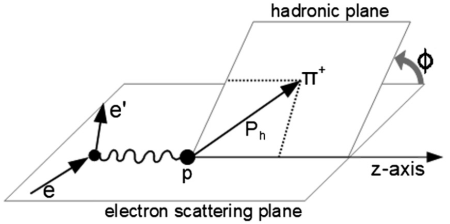
Thank you !

BACKUP SLIDES

Semi-Inclusive-Deep-Inelastic-Scattering (SIDIS)

p(e,e'π⁺)X

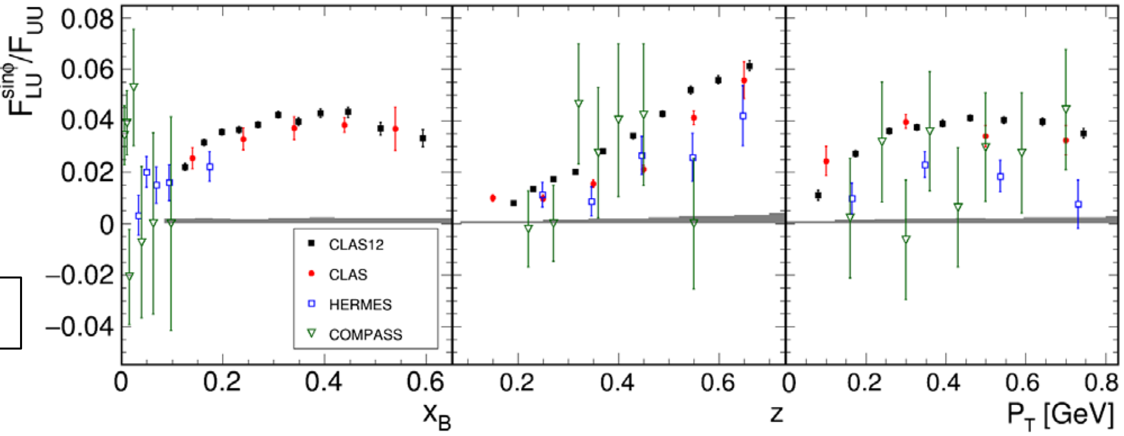




$$A_{LU}^{\sin\phi} = \frac{\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi}}{F_{UU,T}+\epsilon F_{UU,L}}$$

S. Diehl et al Phys Rev Lett 128, 062005 (2022)

Input to TMD program to extract 3D images in quark momentum space.



$0.13 < x_B < 0.52$

$z = \frac{E_\pi}{\nu}$ $0.3 < z < 0.7$

High statistics enabled binning in several kinematical quantities for a total of 344 bins

The unresolved nature

Elementary particles

Quarks & gluons

Nature

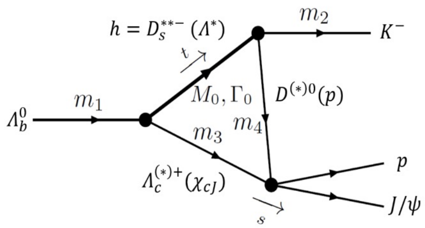
Color-singlet mesons and baryons

strong interaction
(long-distance effects)

States could also be mimic by

Rescattering effects

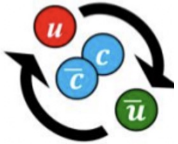
PRD 92 (2015) 071502
PLB 757 (2016) 231
PLB 757 (2016) 61
and others



Compact tetra/pentaquark

Color Forces

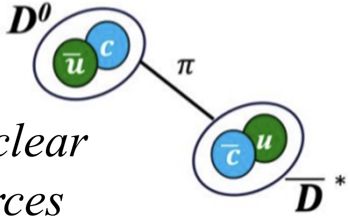
Diquark-antidiquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



Hadrocharmonium/ adjoint charmonium
PLB 666 344 (2008)
PLB 671 82 (2009)

Hadronic molecules

PRL 105 (2010) 232001,
PRL 115 (2015) 122001
PRD 100 (2019) 011502 (R)
and others

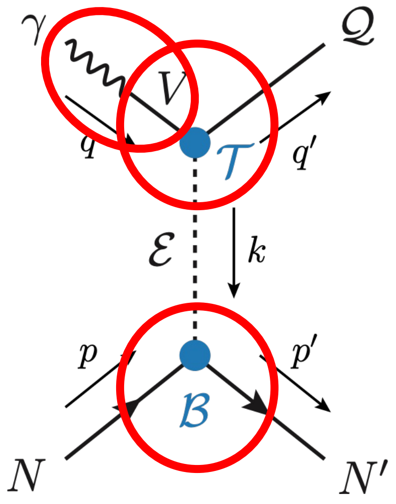


Nuclear Forces

+ qq̄g hybrid, glueball or mixture

Exclusive (quasi-real) photoproduction

- XYZ have so far not been seen in photoproduction: independent confirmation
- Not affected by 3-body dynamics: determination of resonant nature
- Experiments with high luminosity in the appropriate energy range are promising
- We study near-threshold (LE) and high energies (HE)
- Couplings extracted from data as much as possible, not relying on the nature of XYZ



M. Albaladejo et al. [JPAC], PRD

$$< \lambda_{\mathcal{Q}}\lambda'_N | T | \lambda_\gamma \lambda_N >= \sum_{V,\mathcal{E}} \frac{e f_V}{m_V} \mathcal{T}^{\alpha_1\cdots\alpha_j}_{\lambda_V=\lambda_\gamma,\lambda_{\mathcal{Q}}} \mathcal{P}_{\alpha_1\cdots\alpha_j;\beta_1\cdots\beta_j} \mathcal{B}^{\beta_1\cdots\beta_j}_{\lambda_N\lambda'_N}$$

Bottom vertex from standard photoproduction pheno, exponential form factors to further suppress large t

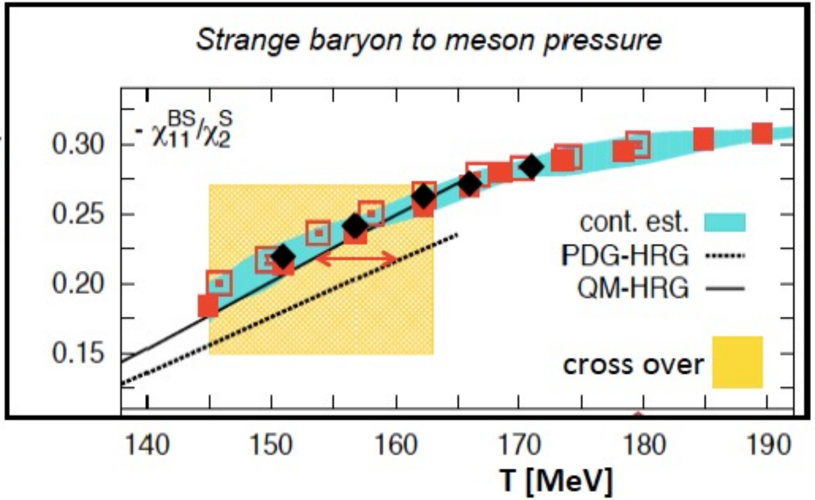
Top vertex from $\mathcal{Q} \to V\mathcal{E}$ decay width

VMD is used to couple the incoming photon to a vector quarkonium V

A. Pilloni – Exotic hadron spectroscopy

Missing Baryons in QCD Phase Transition

From Hot QCD:
Fluctuation Ratio of Baryon Number to Strangeness at hadron freeze-out



A. Bazavov et al., Phys.Rev.Lett. 113 (2014) 7, 072001

Transition shifted by about 8 MeV to lower temperature (later times) due to missing excited strange baryons

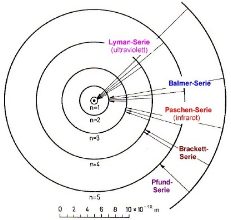
➔ The number of known excited strange baryon states (PDG) is insufficient to account for the QCD phase cross-over from the QGP phase to the baryon phase.

- *Evidence for experimentally-missing strange baryons*
- *Evidence observed also for missing charm and light quark baryons*
- *Motivates an excited baryon program of all quark flavors.*

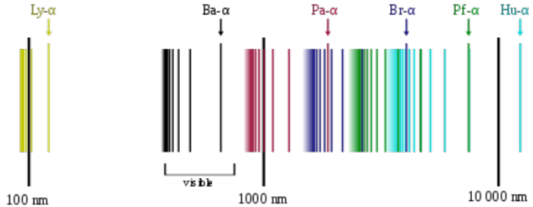
The RHIC operation plan for 2016 includes an energy scan to map out this behavior.

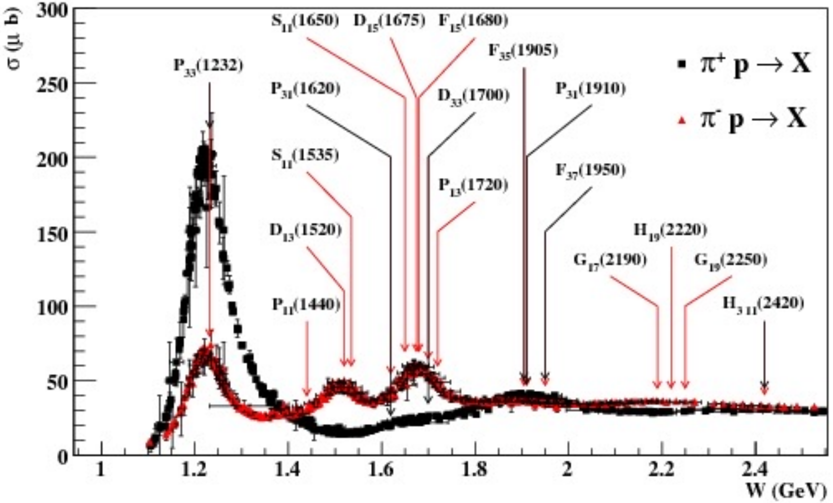
Why N* ? From the Hydrogen Spectrum to QCD

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.

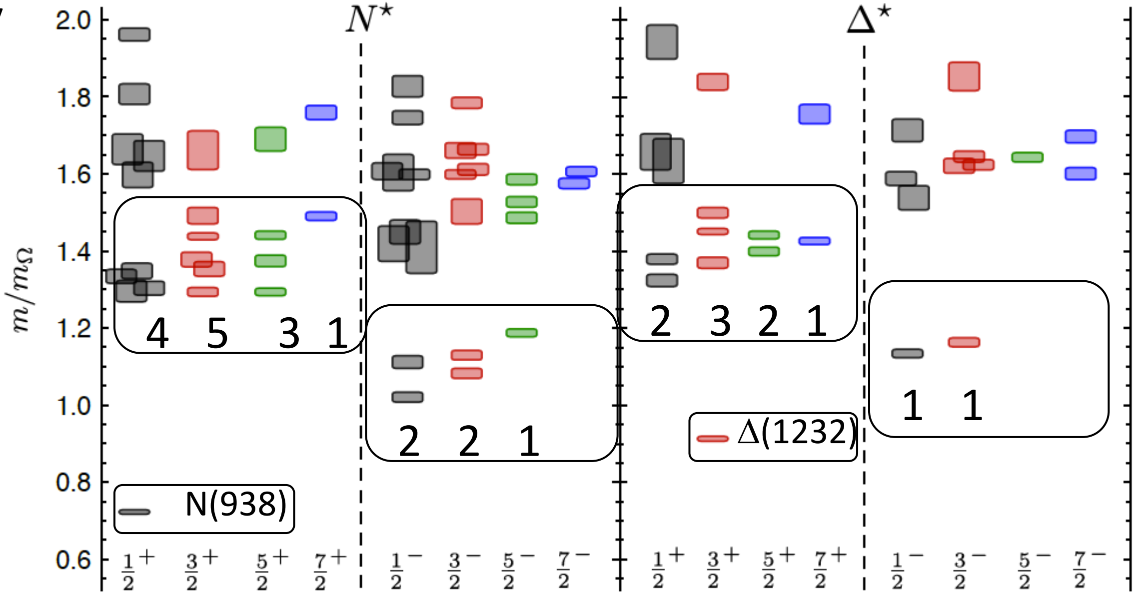
- Understanding the proton's ground state requires understanding its excitation spectrum.

→ From the Constituent Quark model to QCD.

LQCD N* & Δ Spectra

- Exhibit the SU(6)×O(3)-symmetry features
- Counting of levels consistent with non-rel. quark model
- Striking similarity with quark model
- No parity doubling

Problems are not solved!

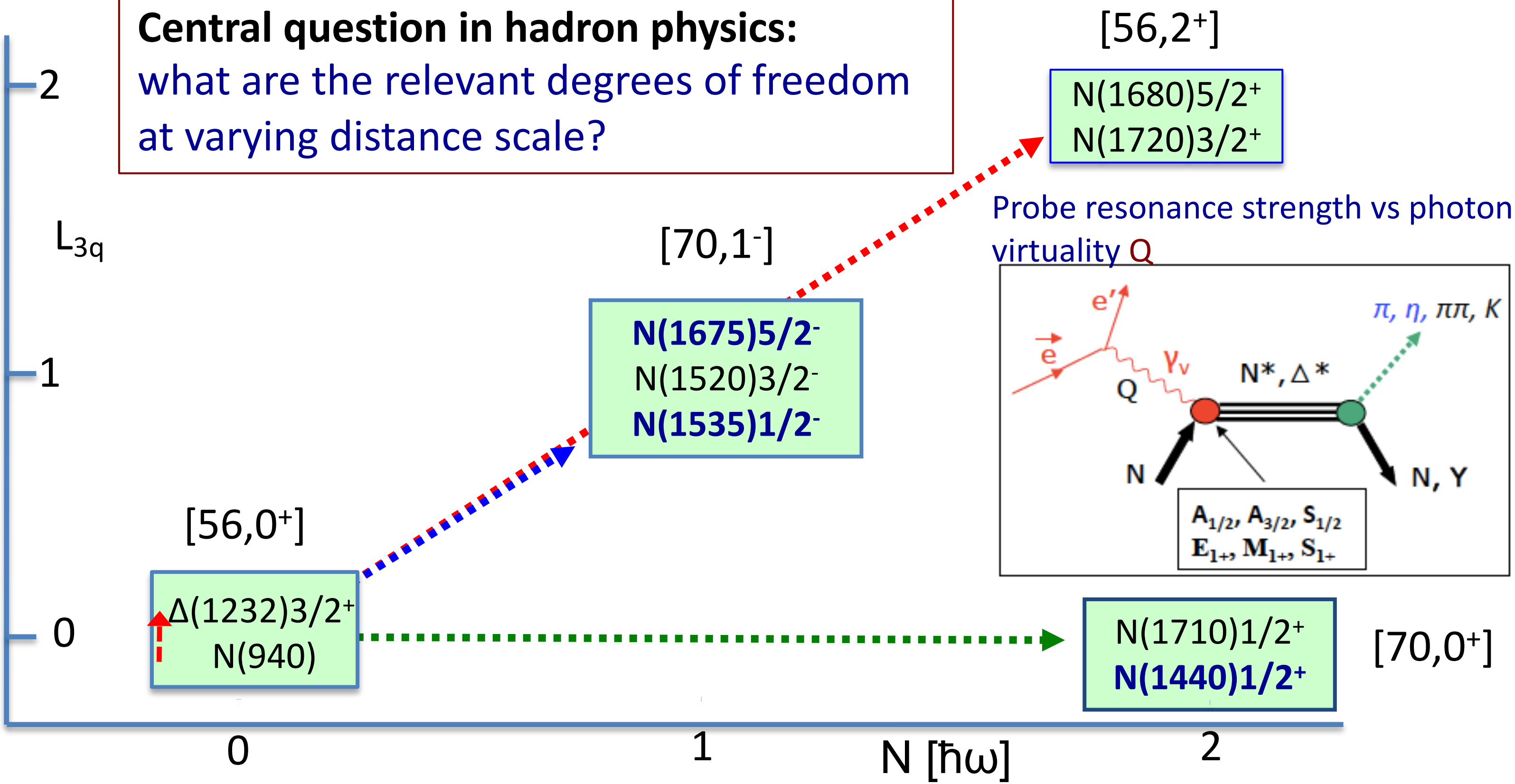


Robert G. Edwards, Jozef J. Dudek, David G. Richards, Stephen J. Wallace
Phys.Rev. D84 (2011) 074508

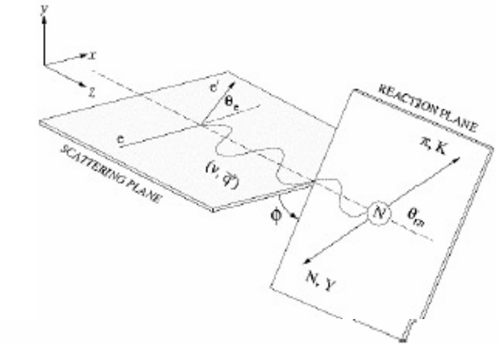
Electroexcitation of N*/Δ resonances

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

Probe resonance strength vs photon virtuality Q



Electroexcitation kinematics



$$\frac{d^4\sigma}{dQ^2 dW\, d\Omega_K} = \Gamma(Q^2, W) \times \frac{d\sigma}{d\Omega_K}\left(Q^2, W, \Theta_K, \varepsilon, \phi\right)$$

Virtual photon flux

Electroproduction cross section

$$\frac{d\sigma}{d\Omega_K} = \sigma_T + \varepsilon_L \sigma_L + \varepsilon \sigma_{TT} \cos(2\phi) + \sqrt{2\varepsilon_L(\varepsilon+1)}\,\sigma_{LT} \cos(\phi) + h\sqrt{2\varepsilon_L(1-\varepsilon)}\,\sigma_{LT'}$$

Transverse

Transverse-transverse interference

Helicity structure

σ_u "Unseparated"

Longitudinal (sensitive to J=0$^{\pm}$ exchange in t-channel: mesons, diquarks)

Transverse-longitudinal interference

Measured σ are decomposed using UIM or fixed-t DR to extract N* & Δ helicity amplitudes.

Electrocouplings of the 'Roper' in 2016

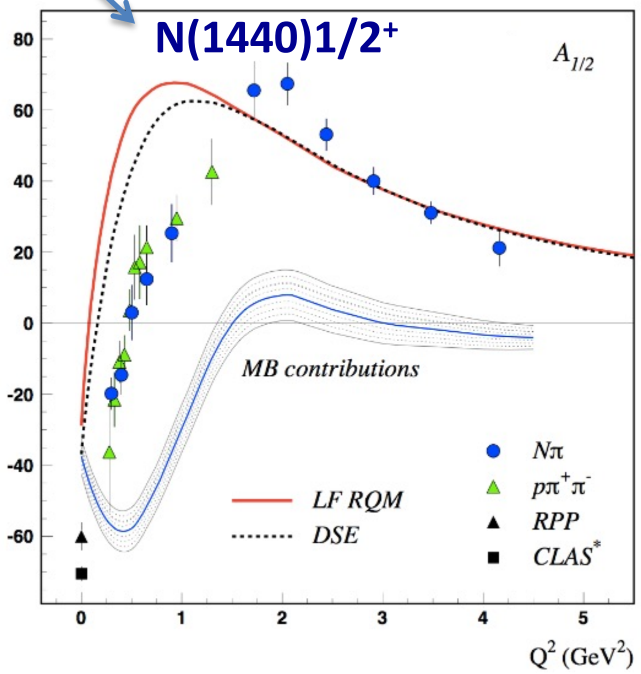
LF RQM: I. Aznauryan, V.B. arXiv:1603.06692

Quark-core contributions from DSE/QCD
J. Segovia et al. PRL 115 (2015) 171801.

***Meson Baryon cloud** inferred from CLAS data as the difference between data and the quark-core evaluation in DSE/QCD.*
V. Mokeev et al., PR C 93 (2016) 025206.

Non-quark contributions are significant at $Q^2 < 2.0$ GeV^2.

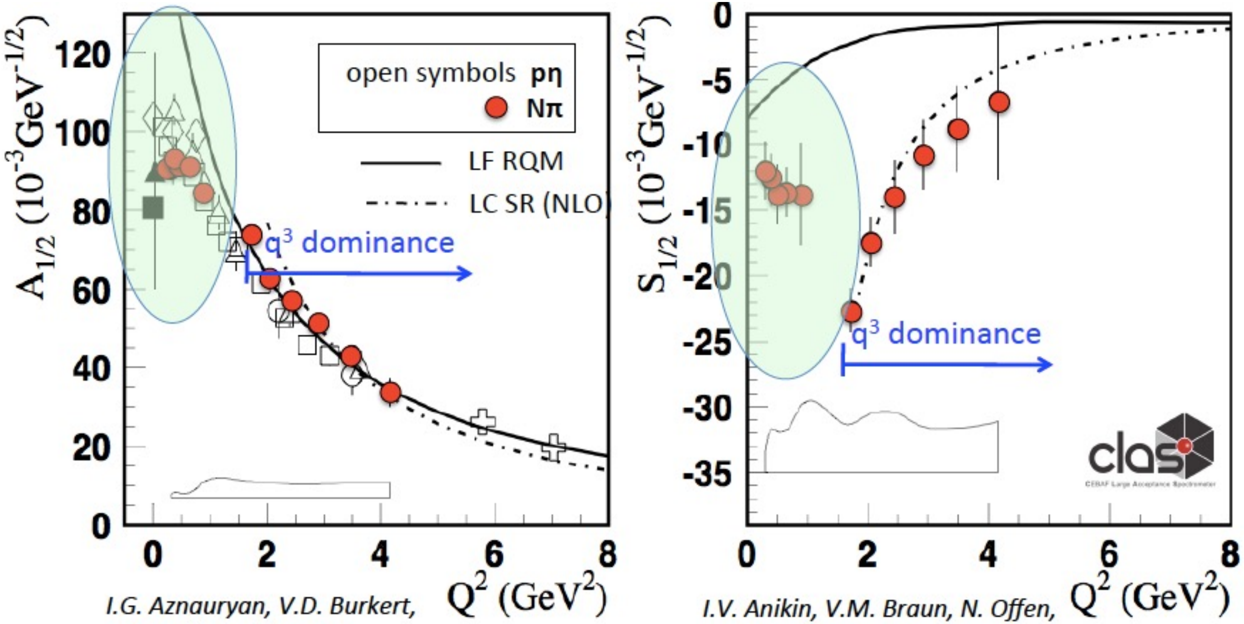
The 1st radial excitation of the q3 core emerges as the probe penetrates the MB cloud.



The structure of the Roper is driven by the interplay of the core of three dressed quarks in the 1st radial excitation and the external meson-baryon cloud.

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

Is it a 3-quark state or a hadronic molecule?



I.G. Aznauryan, V.D. Burkert, PR C85 (2012) 055202

I.V. Anikin, V.M. Braun, N. Offen, PR D92 (2015) 1, 014018

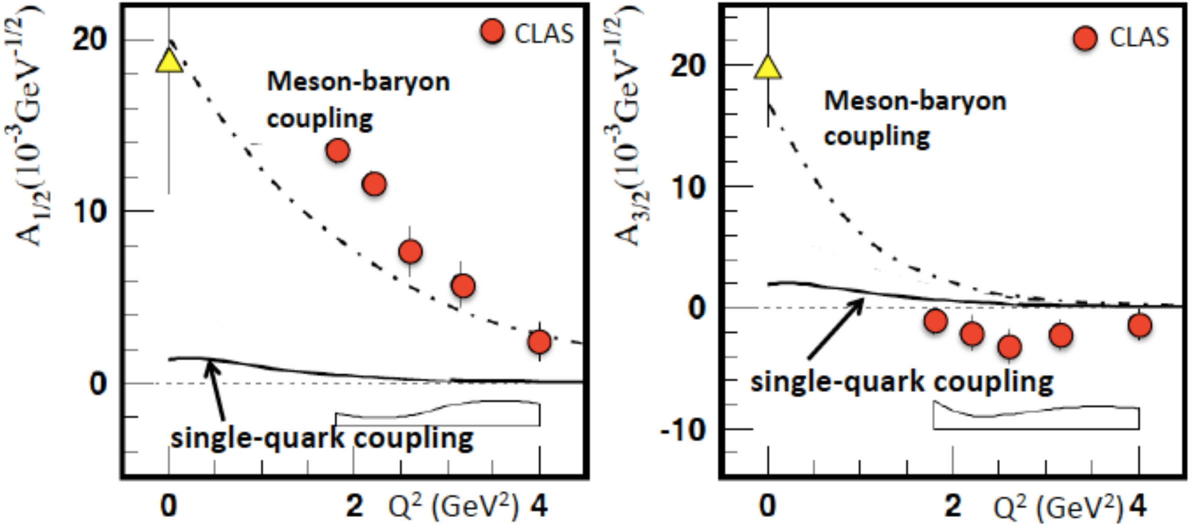
N(1535)1/2$^-$ is consistent with the 1st orbital excitation of the nucleon.

- 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)