Studies of the Structure of Excited Nucleons at Jefferson Lab

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On behalf of
The CLAS Collaboration

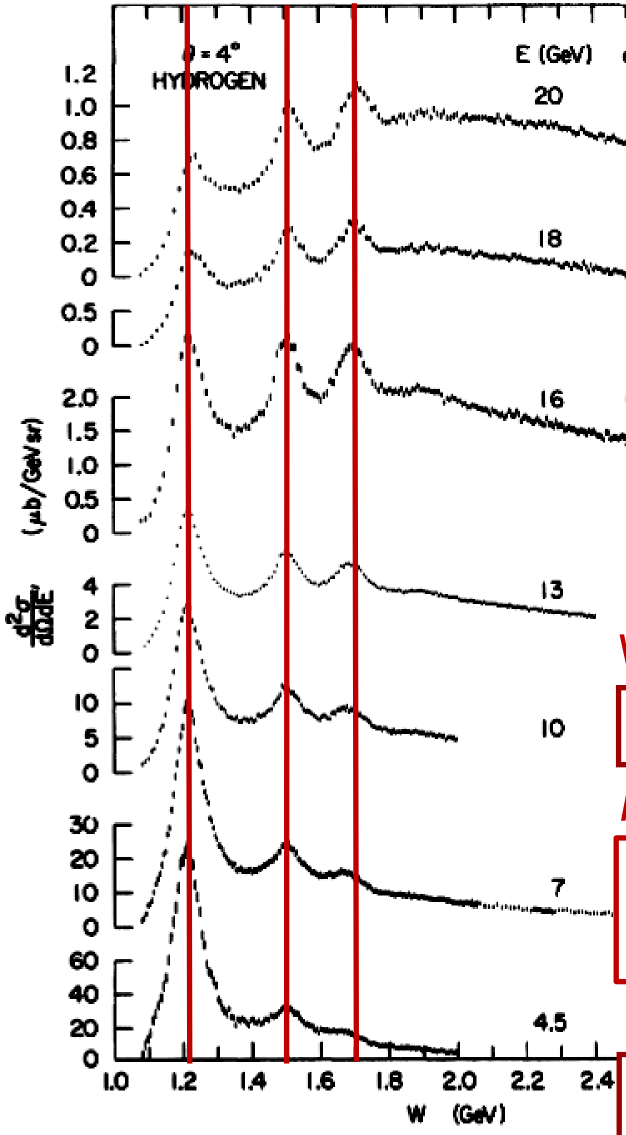
Jan 2o24

The Proton and its Excitations

People have always been fascinated by that are hidden from their view and by what might be found inside objects

Excitation of Proton Resonances

[Stein et al., Phys. Rev. D 12 (1975)]



Virtuality of photon:

$$Q^2 = -q^2 = (q_e^\mu - q_{e'}^\mu)^2$$

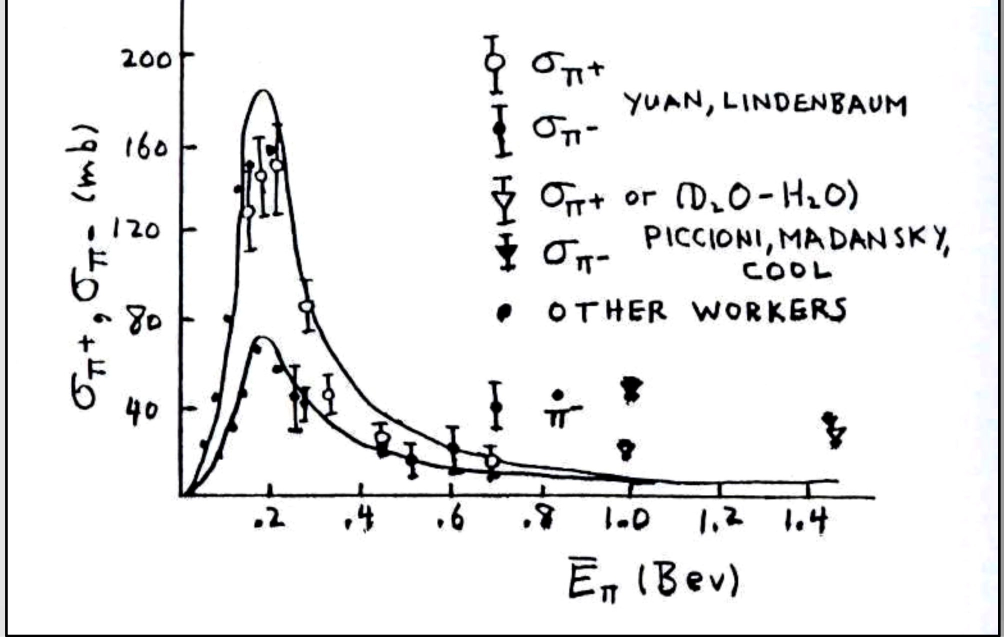
Inelasticity of process:

$$x = \frac{Q^2}{2pq} = Q^2/(2M\nu)$$

Mass of excited proton:

$$W = \sqrt{s} = \sqrt{(q^\mu + p_{\text{target}}^\mu)^2}$$

[Yuan, Rochester Conference (1954)]

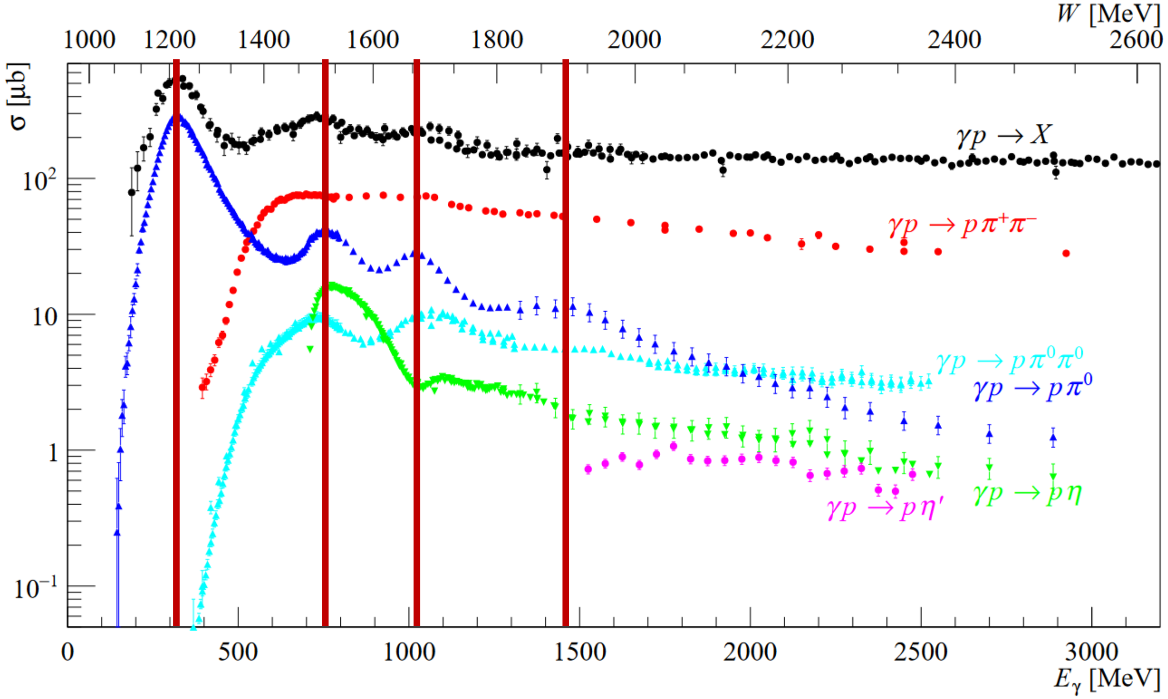


- Charged *pion beams* revealed a clear **proton resonance** as early as 1954 *(and established charge independence)*

- *Electron scattering* on protons revealed **three resonance regions** in the 1970s

The Virtue of Electro- (and Photo-) Excitations

Clean process with electromagnetic vertex well known from QED



[Thiel, Afzal, Wunderlich, Prog. Part. Nucl. Phys. 125, 103949 (2022)]

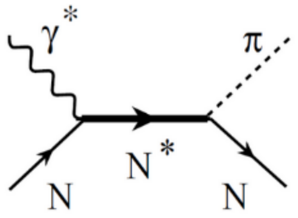
Light baryon spectroscopy by meson-production reactions at electron accelerators

Study of many relevant observables:

– Excitation spectrum / quantum numbers

– Selective and exclusive reactions

Single-pion production as an example:



– ***Q*² evolutions** in electroproduction

– **Polarization** in photoproduction:

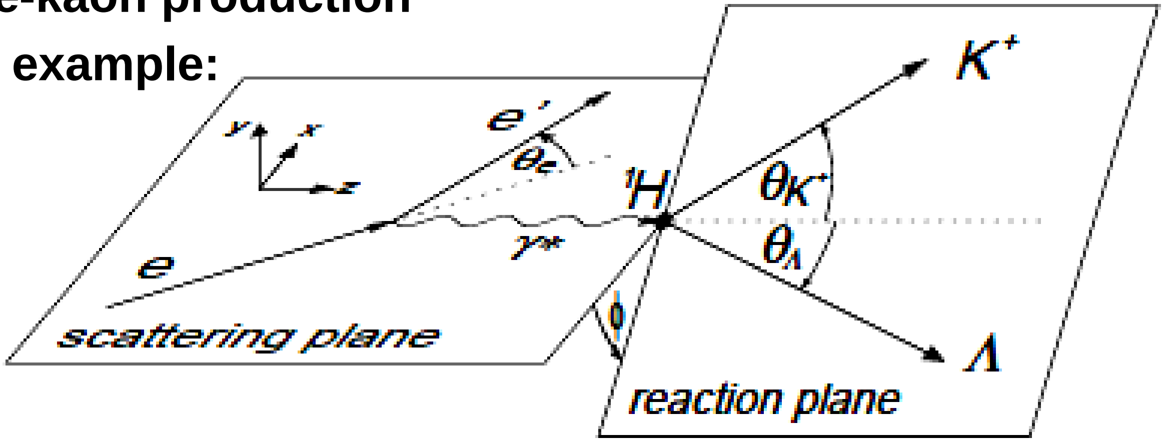
Beam		Target			Recoil			Target + Recoil								
	-	-	-	-	x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
	-	x	y	z	-	-	-	x	y	z	x	y	z	x	y	z
unpolarized	σ_0		T			P		$T_{x'}$		$L_{x'}$		Σ		$T_{z'}$		$L_{z'}$
linearly pol.	Σ	H	P	G	$O_{x'}$	T	$O_{z'}$	$L_{z'}$	$C_{z'}$	$T_{z'}$	E	σ_0	F	$L_{x'}$	$C_{x'}$	$T_{x'}$
circularly pol.		F		E	$C_{x'}$		$C_{z'}$		$O_{z'}$		G		H		$O_{x'}$	

Separation of Cross Sections Into Structure Functions

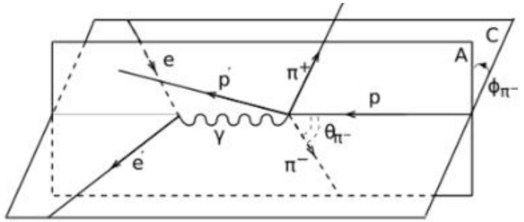
Five-fold differential cross section separates in **virtual photon flux** and **virtual photoproduction**

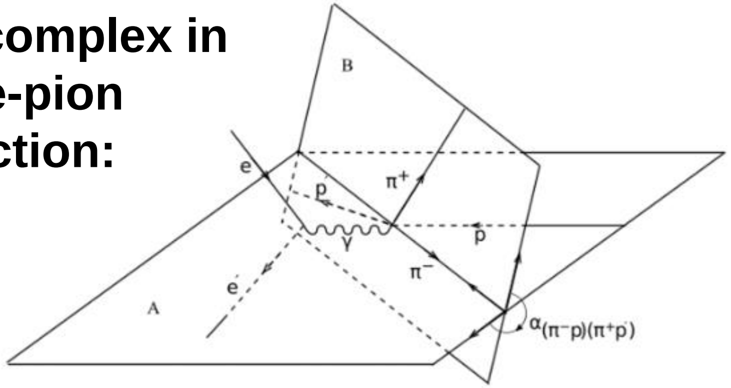
$$\frac{d\sigma}{dE' d\Omega_{e'} d\Omega^*_K} = \Gamma \frac{d\sigma}{d\Omega^*_K}$$

Single-kaon production as an example:



More complex in double-pion production:





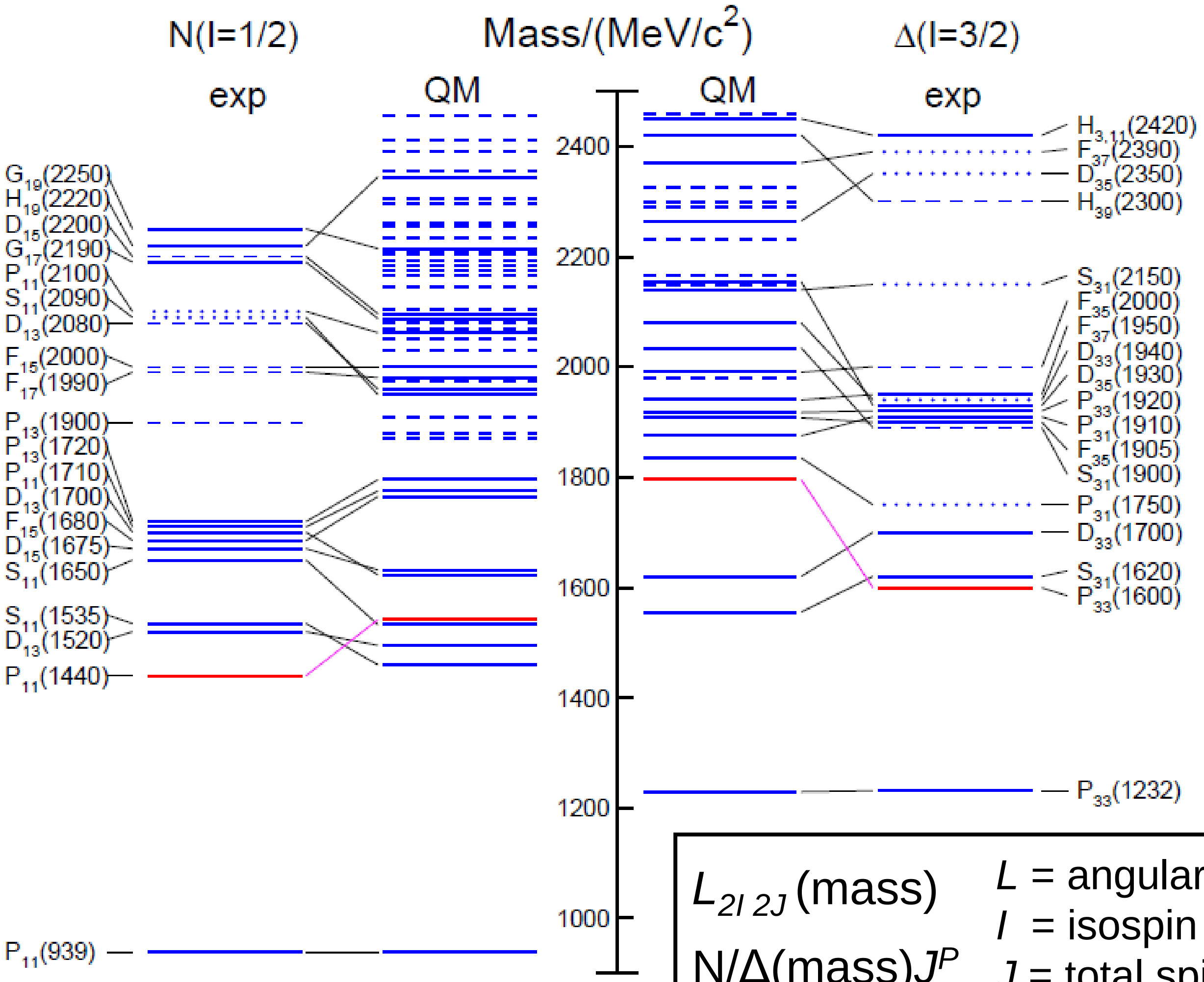
$$\frac{d\sigma}{d\Omega^*_K} = \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}\cos 2\phi + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi + h\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}\sin\phi$$

Degree-of-polarization of photon: $\epsilon = \left(1 + 2\frac{|\vec{q}|^2}{Q^2}\tan^2\theta/2\right)^{-1}$

Helicity of incoming electron: h

[E. Amaldi, S. Fubini, and G. Furlan, Pion-Electroproduction (1979)]
[A. Donnachie & G. Shaw, Electromagnetic Interactions of Hadrons (1978)]

N* Spectrum in Experiments vs. Quark Models



[PDG Review Part. Phys. (2022)]

$L_{2I\,2J}$ (mass)	L = angular momentum state
	I = isospin of resonance
N/Δ(mass)J^P	J = total spin of resonance

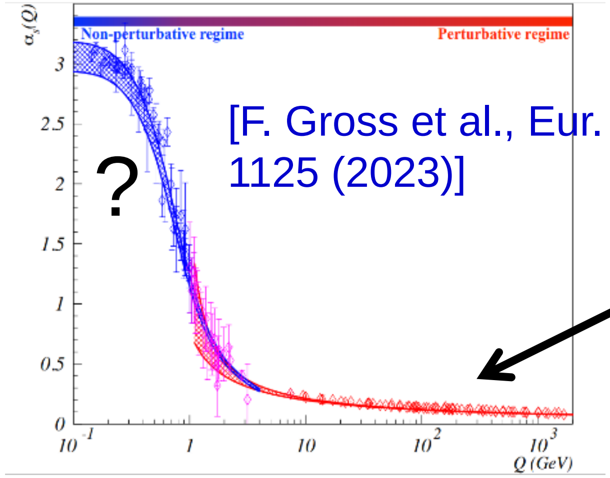
State	2010	2020	πN	KΛ	KΣ	γN
N(1710)$1/2^+$	***	****	****	**	*	****
N(1875)$3/2^-$		***	**	*	*	**
N(1880)$1/2^+$		***	*	**	**	**
N(1895)$1/2^-$		****	*	**	**	****
N(1900)$3/2^+$	**	****	**	**	**	****
N(2000)$5/2^+$	*	**	*			**
N(2060)$5/2^-$		***	**	*	*	***
N(2100)$1/2^+$	*	***	***	*		**
N(2120)$3/2^-$		***	**	**	*	***
Δ(1600)$3/2^+$	***	****	***			****
Δ(1900)$1/2^-$	**	***	***		**	***
Δ(2200)$7/2^-$	*	***	**		**	***

Some problems are evident:
– Ordering and clustering of states
– Missing resonances
– Incomplete/uncertain data (*/**)

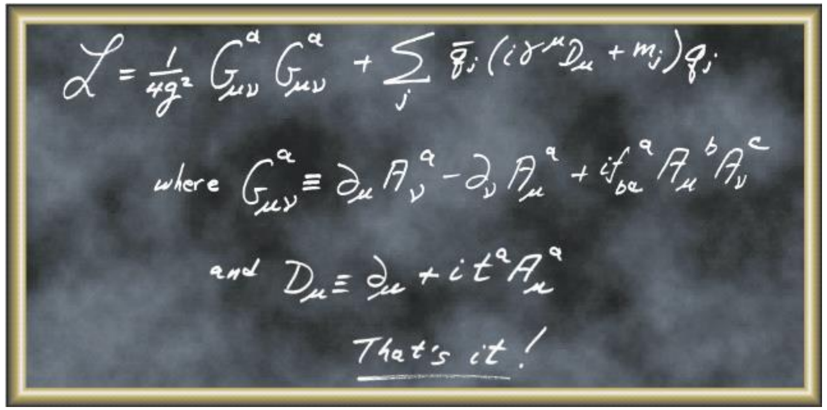
The nucleon's excitation spectrum reflects its complexity where our knowledge is incomplete

Connection to the Strong QCD Regime

Standard Model α_s **diverges** as Q approaches zero and **QCD** becomes **non-perturbative**



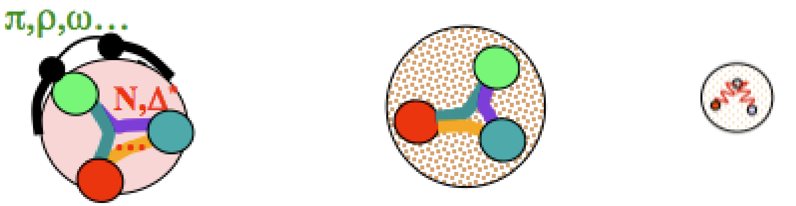
[F. Gross et al., Eur. Phys. J. C 83, 1125 (2023)]



[Frank Wilczek, Physics Today, August 2000]

External meson-baryon cloud in addition to quark core

($Q^2 < 2$ GeV^2)



3q core + cloud | 3q core | pQCD

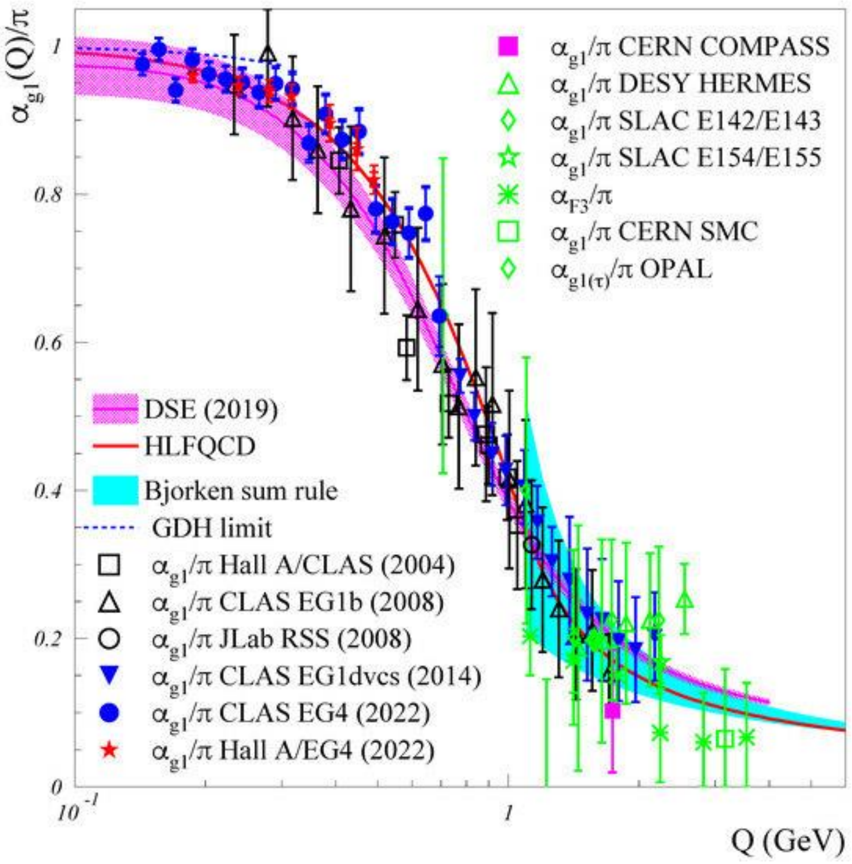
low Q^2 ⟷ high Q^2

Quark core domination: transition from confinement to pQCD regime

($Q^2 > 5$ GeV^2)

Confined systems and hadronic degrees-of-freedom play key role for understanding QCD

Non-Perturbative QCD Phenomena



[A. Deur et al., "Experimental Determination of the QCD Effective Charge α_{g1}(Q)", Particles 5, 171 (2022)]

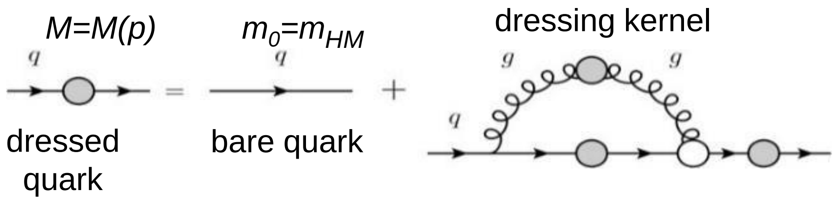
- For $Q \ll 1$ GeV, $\alpha_s(Q) \gtrsim 1$, which is one of the crucial pieces leading to **quark confinement**
- Calculation of non-perturbative QCD phenomena can be performed numerically in **Lattice QCD**
- **Continuum QCD** methods such as Dyson-Schwinger and Bethe-Salpeter equations (DSE/BSE) do not require a discretization of spacetime
- Data show that the QCD effective charge $\alpha_{g1}(Q)$ becomes Q-independent at very low Q
- **Data compare well with two recent predictions** based on DSE and on the AdS/CFT duality
- $\alpha_{g1}(Q)$ approaches QCD running coupling $\alpha_s(Q)$ and characterizes **magnitude of the strong interaction**

Experimental access to QCD observables through spin structure of neutron and proton

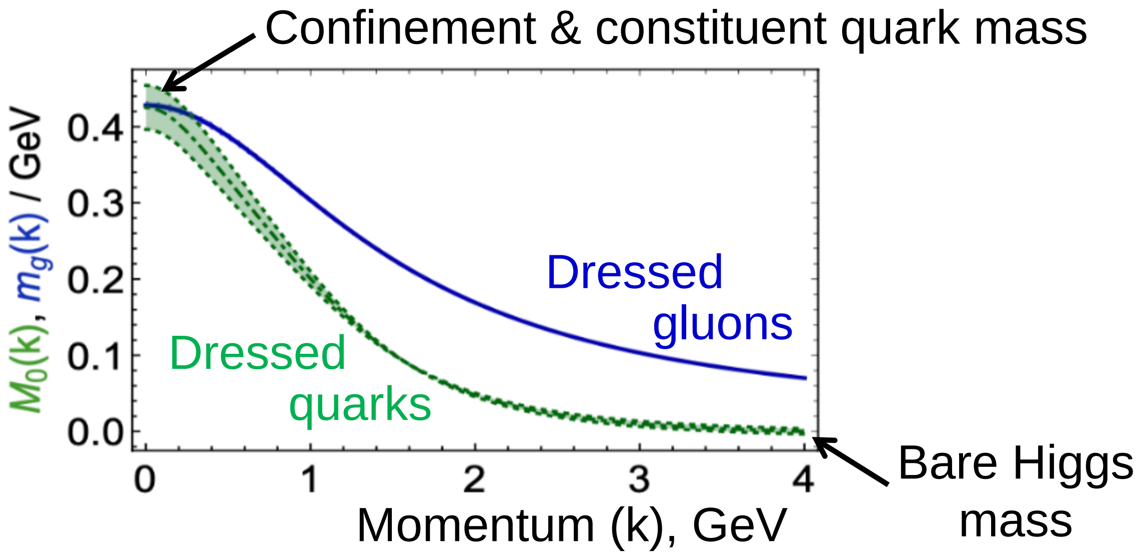
QCD Dynamics with Dressed Quarks

Concepts within Continuum Schwinger Method:

- Dressed quark mass depends on its momentum



- Emergence of hadron mass (EHM) from QCD
- Resonances probe EHM where sum of dressed quark masses is dominant contribution to mass
- Consistency on momentum evolution of dressed quark mass function to validate of insight into EHM

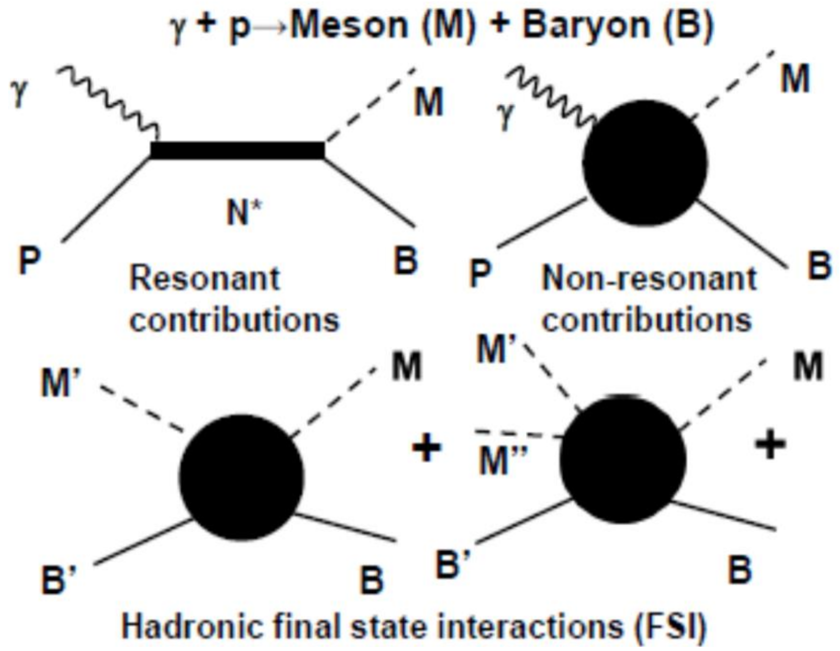


[M. Ding, C.D. Roberts, S.M. Schmidt, Emergence of Hadron Mass and Structure, Particles 6, 57 (2023)]

Hadron masses are an emergent feature of QCD

Program of N* Physics at Electron Accelerators

- Study of exclusive reaction channels over a broad kinematic range: πN, ωN, φN, ηN, η'N, ππN, KY, K*Y, KY*
- Common efforts at Jefferson Lab, ELSA, MAMI, and others:
  - Separation of resonant and non-resonant contributions
- Extraction of electrocouplings from zero to high Q^2:
  - Quark mass momentum dependence shapes N* states and Q^2 evolution of electrocouplings
- Many facets of non-perturbative strong interaction are reflected in N* states and emergence from QCD



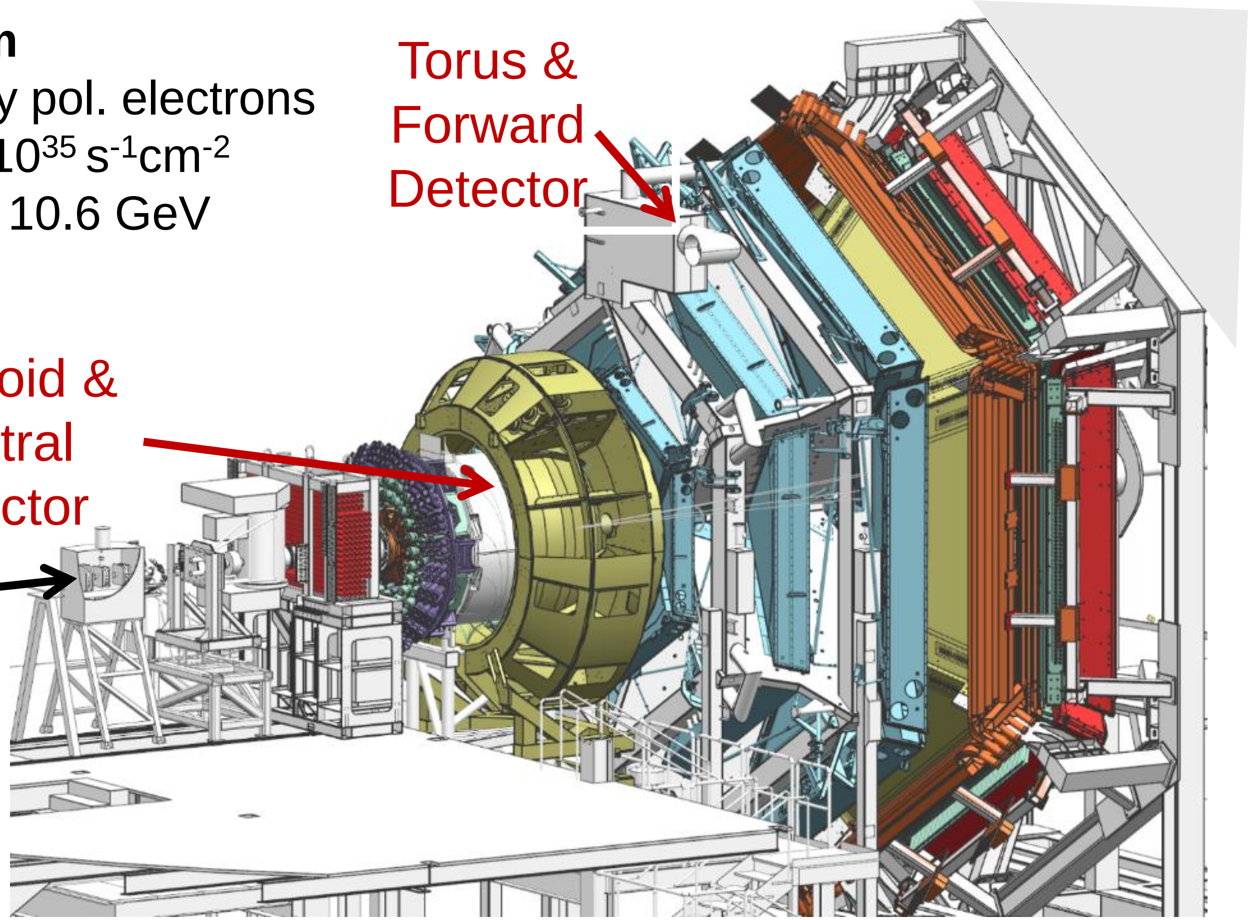
Goal must be to explore the *spectrum* and *structure* of N* states and their connection to QCD dynamics

Good physics needs good tools

Design Model of The CLAS12 Spectrometer

Beam

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

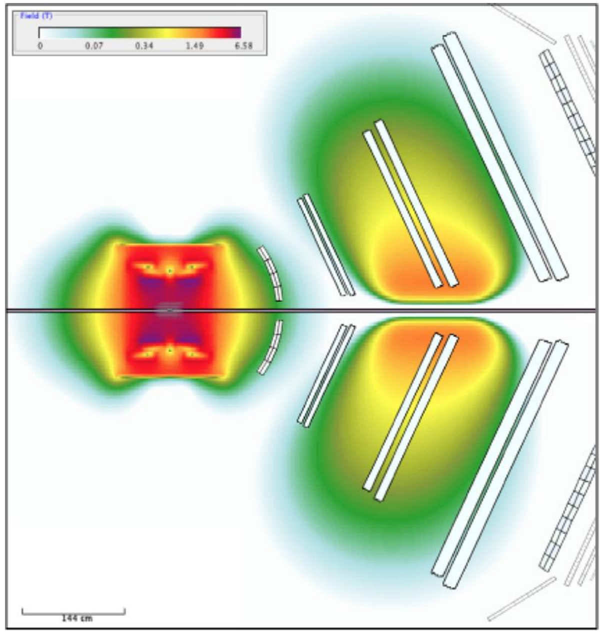


[V.D. Burkert et al., Nucl. Inst. and Meth. A 959, 163419 (2020)]

Targets (org. by Run Groups)

- Proton (RG-A/K)
- Deuteron (RG-B)
- Nuclei (RG-M/D/E)
- Long. pol. NH_3/ND_3 (RG-C)

Magnetic Field

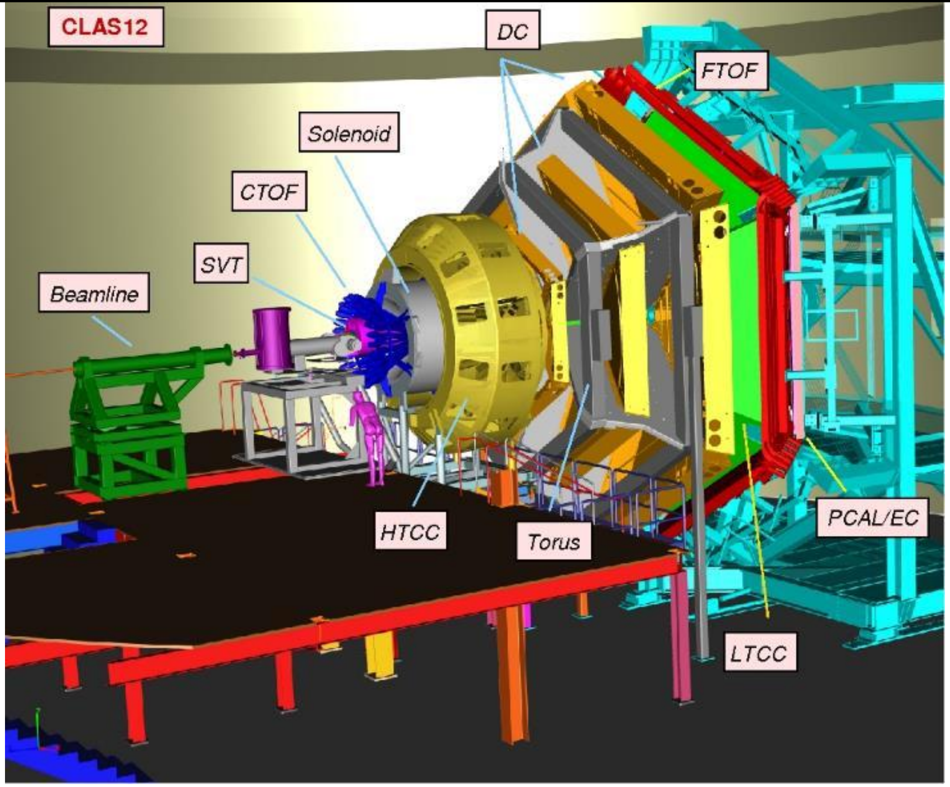


Ideal instrument to study exclusive meson electroproduction in the nucleon resonance region

Subsystems of the CLAS12 Spectrometer

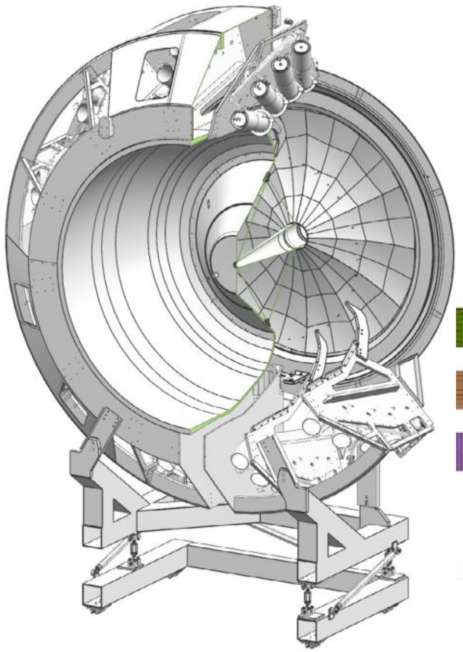
C E N T R A L

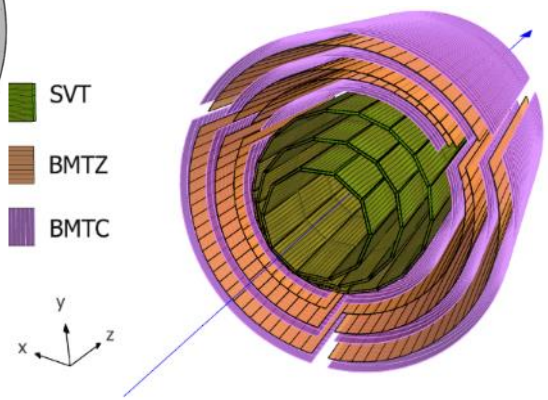
- Beamline
- Target
- Central Vertex Tracker
- Central Time of Flight
- Central Neutron Det.
- Back-Angle Neutron Det.

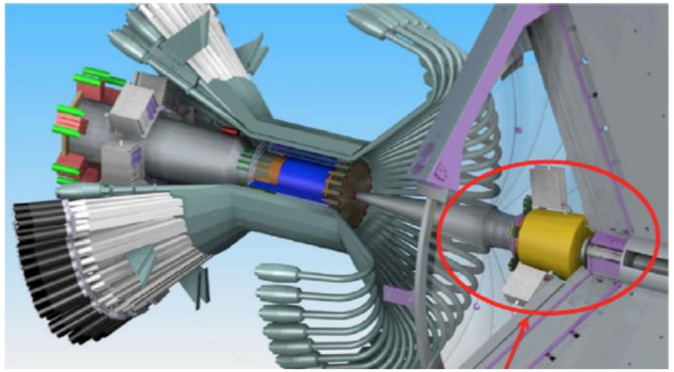


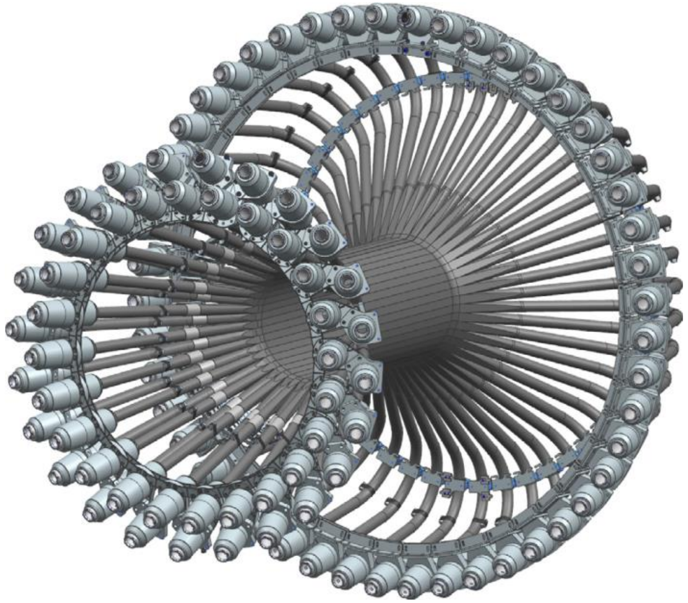
F O R W A R D

- High Threshold Cherenkov
- Forward Tagger
- Drift Chambers
- Low Threshold Cherenkov
- Ring Imaging Cherenkov
- Forward Time of Flight
- EM Calorimeter



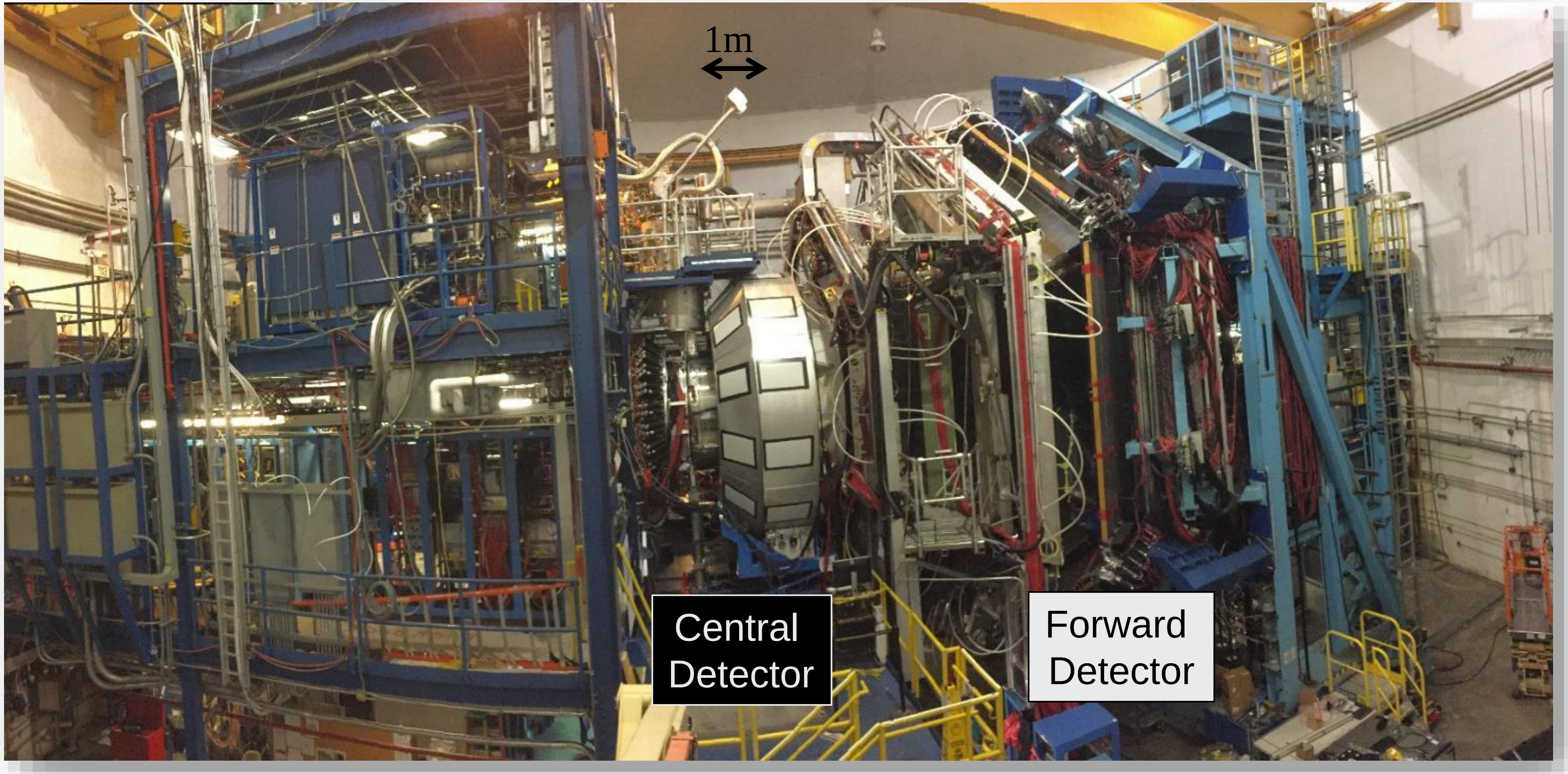




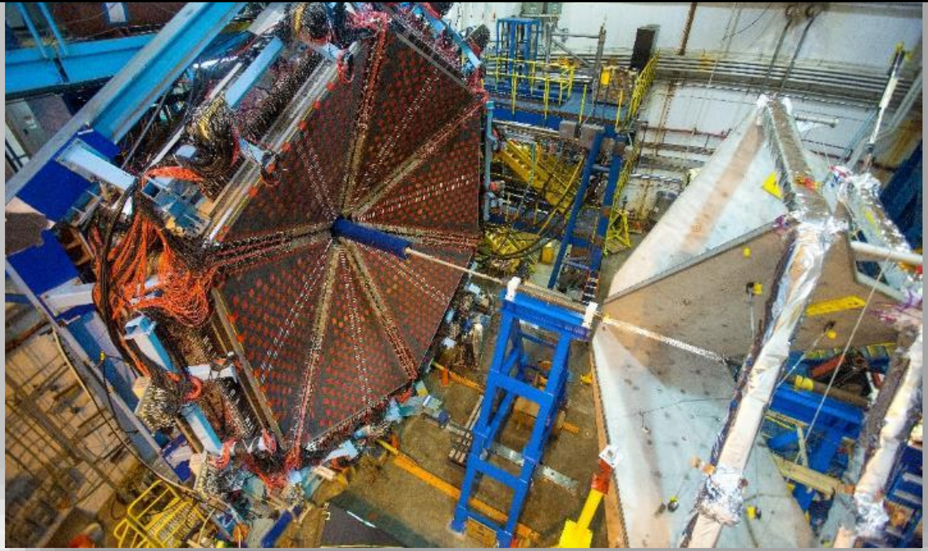


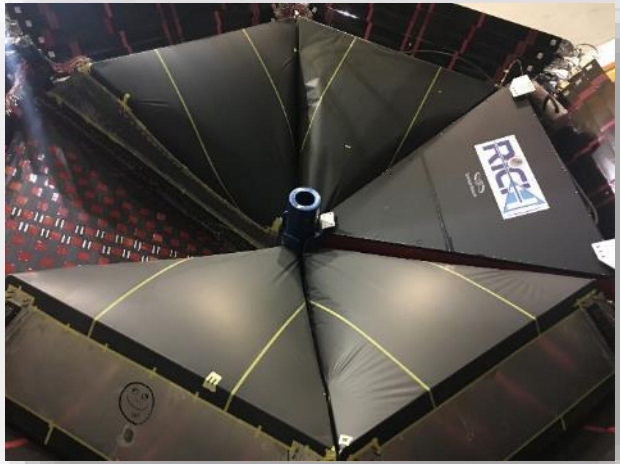
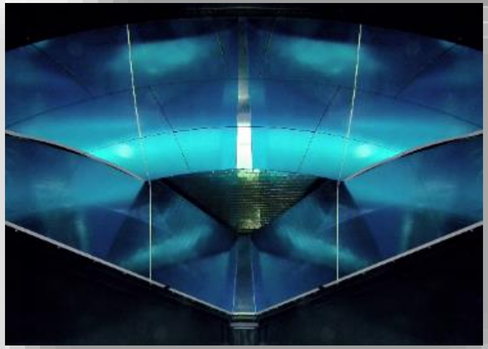
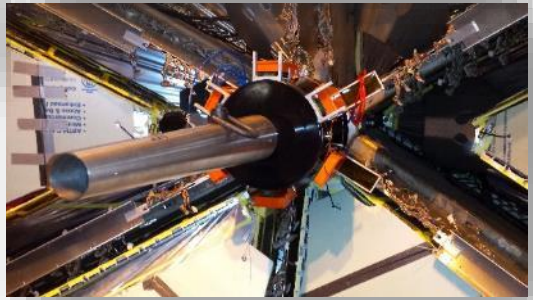
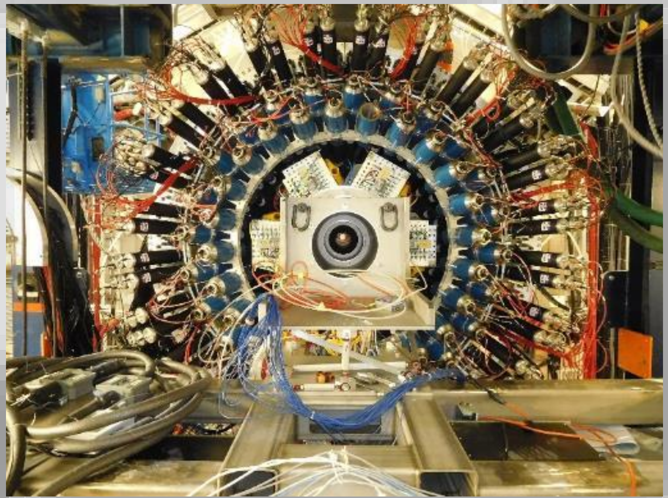
Side View Photograph of CLAS12 Spectrometer

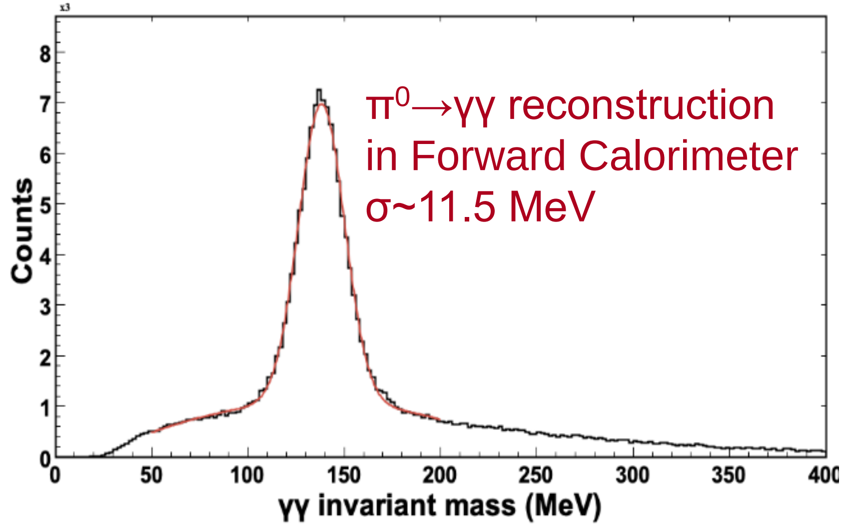
Electron
beam

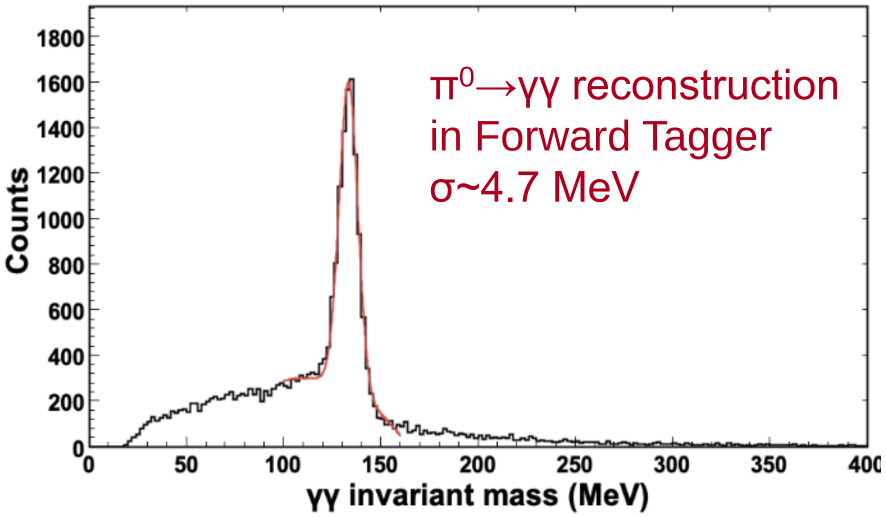


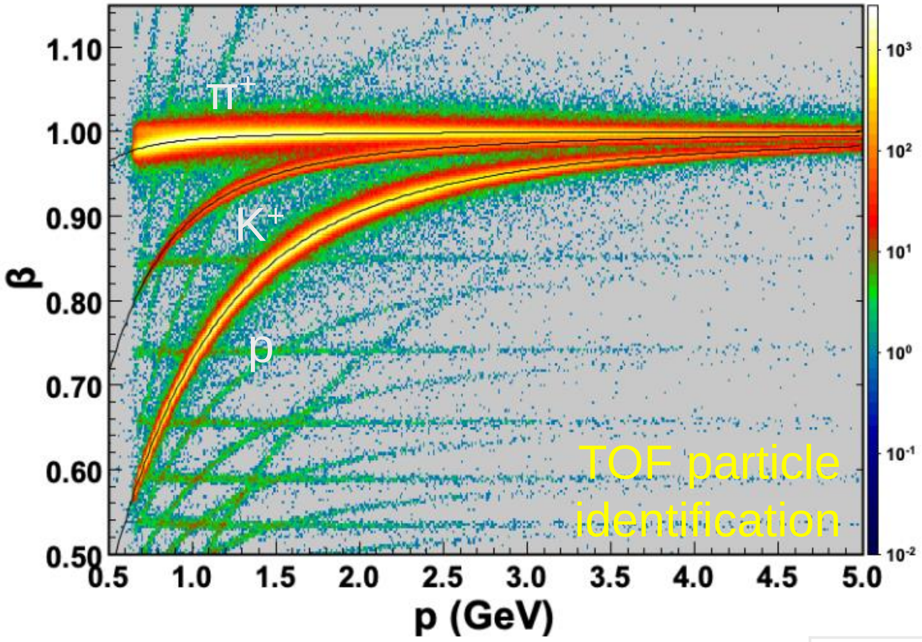
CLAS12 Subsystems During Installation

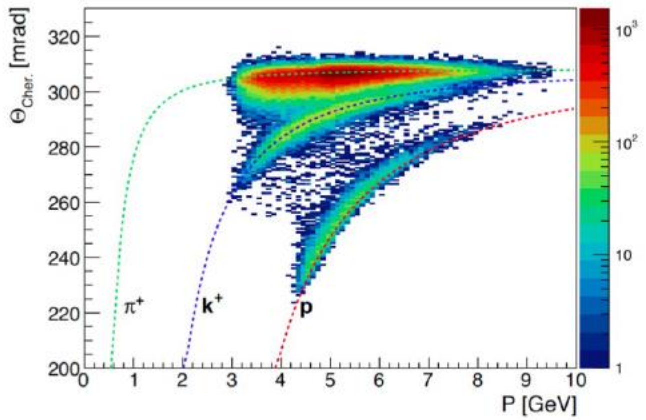






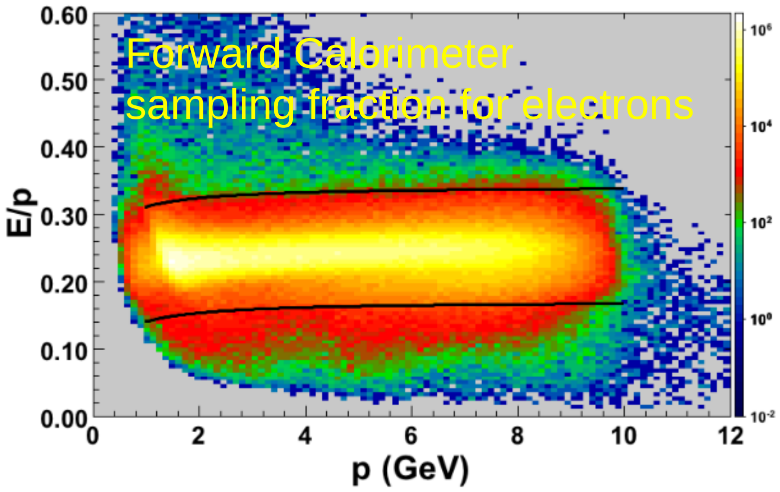







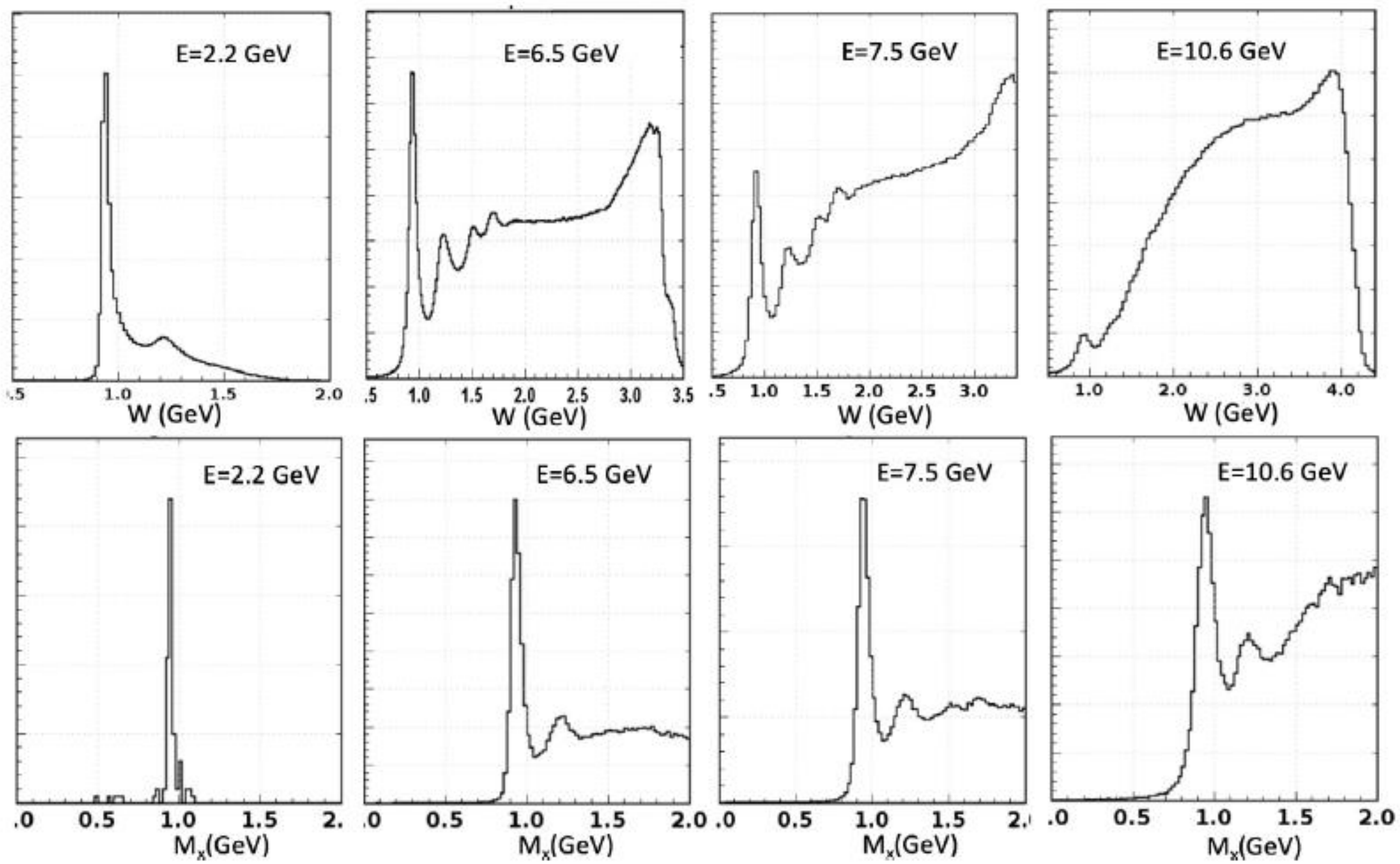
RICH particle identification





	Forward	Central
Angular coverage	5º – 35º	35º – 135º
Momentum resolution	dp/p < 1%	dp/p < 5%
θ resolution	1 mrad	5 – 10 mrad
φ resolution	1 mrad/sinθ	5 mrad/sinθ

Inclusive ep → e'X spectra as sum over all exclusive channels



Examples of mass spectra
at four different beam energies

Elastic peak and first 3 N* states, $\Delta(1232)$, $N(1520)$, and $N(1680)$, visible

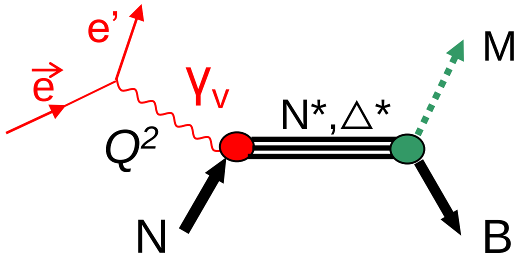
Examples of missing mass spectra
in $ep \to e'\pi^+X$ at the same energies

Sharp peak of undetected neutron, peak of $\Delta^0(1232)$, and indications of higher excitations visible

Not all bumps are resonances, not every resonance generates a bump in all observables

Overview of Extractions of Electrocouplings

Reaction Channel	N*, Δ* States	Q^2 ranges of $\gamma_v pN^*$ Electrocouplings (GeV^2)
$\pi^0 p$, $\pi^+ n$	Δ(1232)3/2$^+$ N(1440)1/2$^+$, N(1520)3/2$^-$, N(1535)1/2$^-$	0.16 – 6.0 0.30 – 4.16
$\pi^+ n$	N(1675)5/2, N(1680)5/2$^+$, N(1710)1/2$^+$	1.6 – 4.5
ηp	N(1535)1/2$^-$	0.2 – 2.9
$\pi^+\pi^- p$	N(1440)1/2$^+$, N(1520)3/2$^-$ Δ(1620)1/2$^-$, N(1650)1/2$^-$, N(1680)5/2$^+$, Δ(1700)3/2$^-$, N(1720)3/2$^+$, N'(1720)3/2$^+$	0.25 – 1.5 0.5 – 1.5



Analysis codes employed for extractions:

- Unitary Isobar Model (UIM)
- Fixed-t dispersion relations (DR)

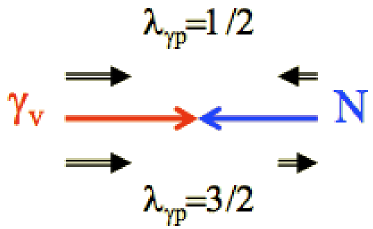
} for πN and ηN

- Data-driven reaction model for $\pi^+\pi^- N$ (JM09, JM16, JM19)
  [I.G. Aznauryan et al., Int. J. Mod. Phys. E 22, 1330015 (2013)]
  [V. Mokeev, Few-Body Syst. 57, 909 (2016)]
  [V. Mokeev and D. Carman, Few-Body Syst. 63, 59 (2022)]

Helicity amplitudes:

$A_{1/2}$, $A_{3/2}$: *transverse*

$S_{1/2}$: *longitudinal*



Amplitude Extraction using Breit-Wigner Parametrization

Cross sections of resonance *r* of mass M_r and width $\Gamma_{tot}(M_r) = \Gamma_r$ and spin J_r:

$$\sigma^r_{L,T}(W,Q^2) = \frac{\pi}{q_\gamma^2} \sum_{N^*,\Delta^*} (2J_r+1) \frac{M_r^2 \Gamma_{tot}(W) \Gamma_\gamma^{L,T}(M_r)}{(M_r^2 - W^2)^2 + M_r^2 \Gamma_{tot}^2(W)} \frac{q_\gamma}{K}$$

with following kinematic definitions:

$$q_\gamma = \sqrt{Q^2 + E_\gamma^2}, \quad E_\gamma = \frac{W^2 - Q^2 - M_N^2}{2W}, \quad K = \frac{W^2 - M_N^2}{2W}$$

Electromagnetic decay widths at the resonance point $W = M_r$ given by:

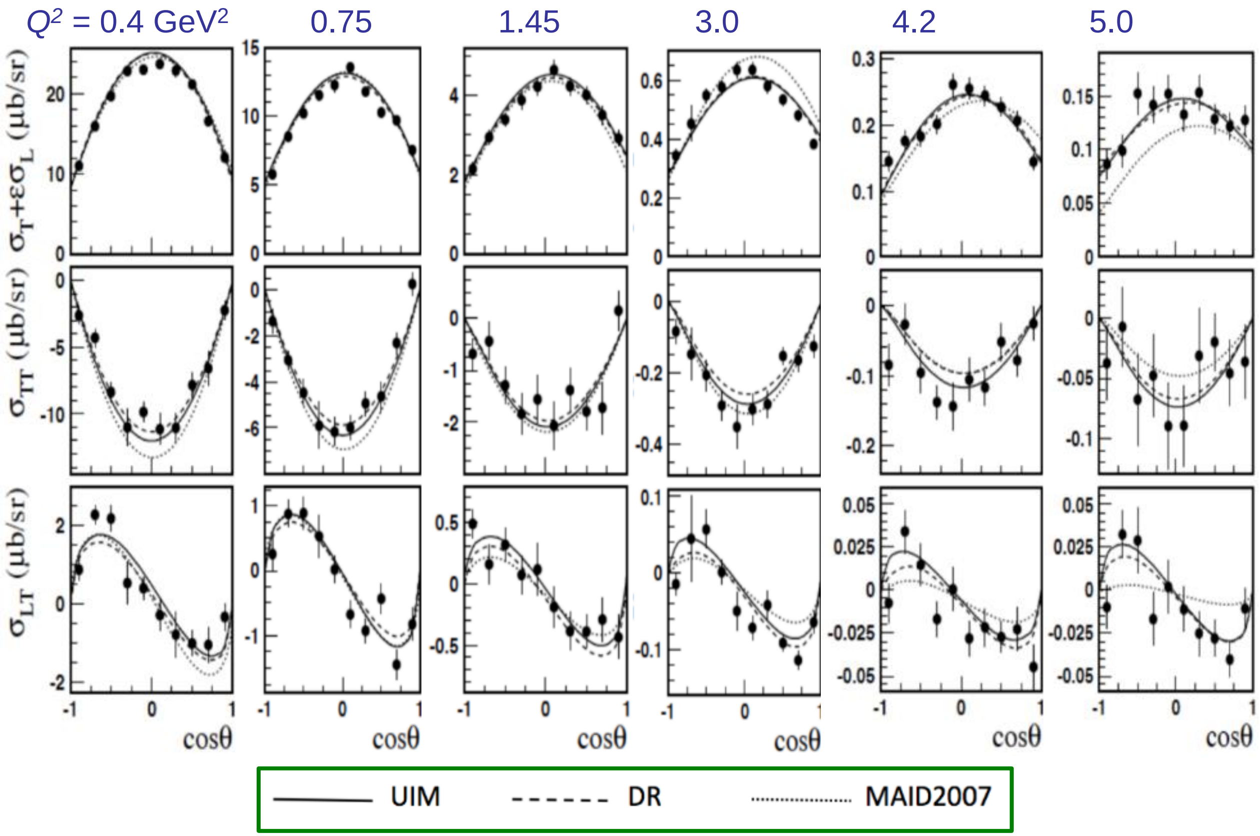
$$\Gamma_\gamma^L(M_r, Q^2) = 2 \frac{q^2_{\gamma,r}(Q^2)}{\pi} \frac{2M_N}{(2J_r+1)M_r} |S_{1/2}(Q^2)|^2$$

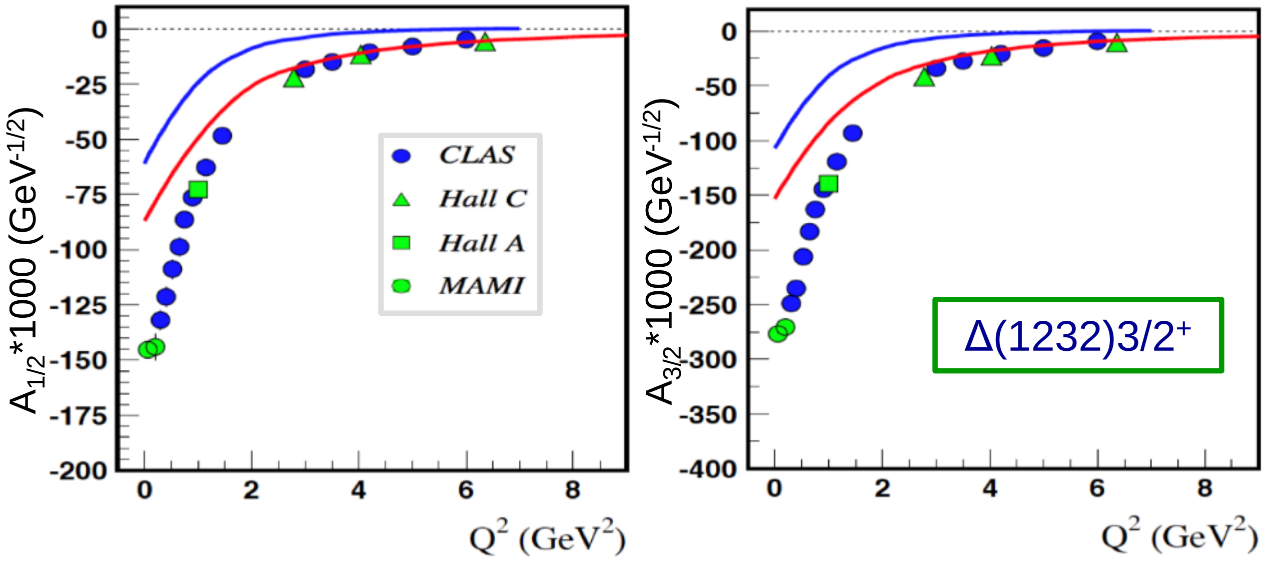
$$\Gamma_\gamma^T(M_r, Q^2) = \frac{q^2_{\gamma,r}(Q^2)}{\pi} \frac{2M_N}{(2J_r+1)M_r} (|A_{1/2}(Q^2)|^2 + |A_{3/2}(Q^2)|^2)$$

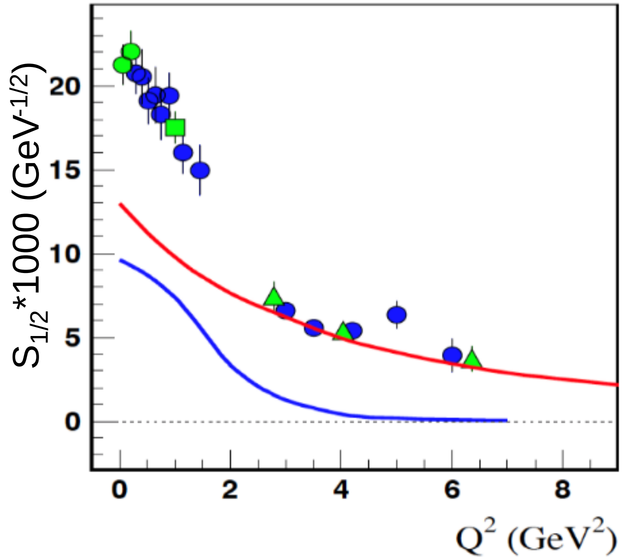
CLAS N* Electrocouplings – First Resonance Region

$\gamma^* p \to \pi^0 p$

W = 1.232 GeV





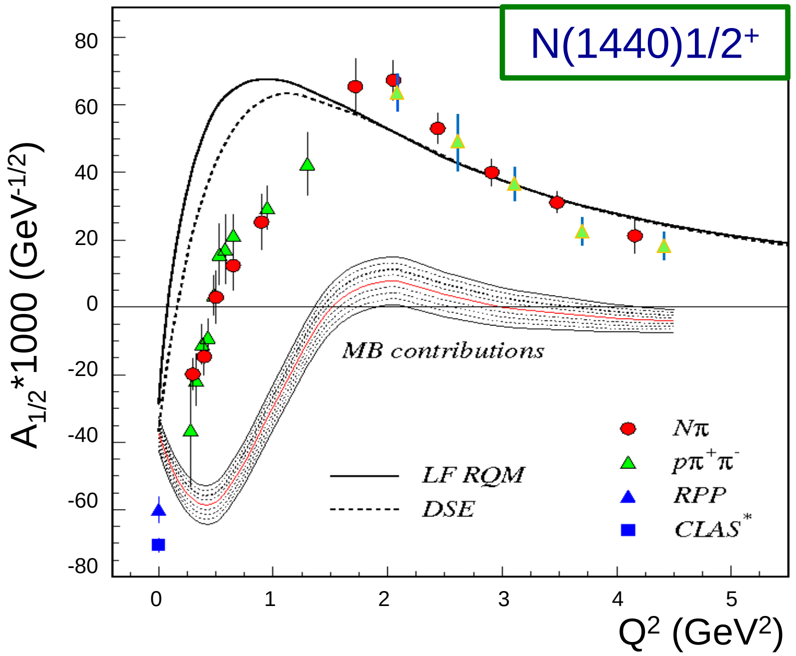


QCD calculations compatible with data where meson cloud does not contaminate evolution $Q^2 \leq 2$ GeV^2

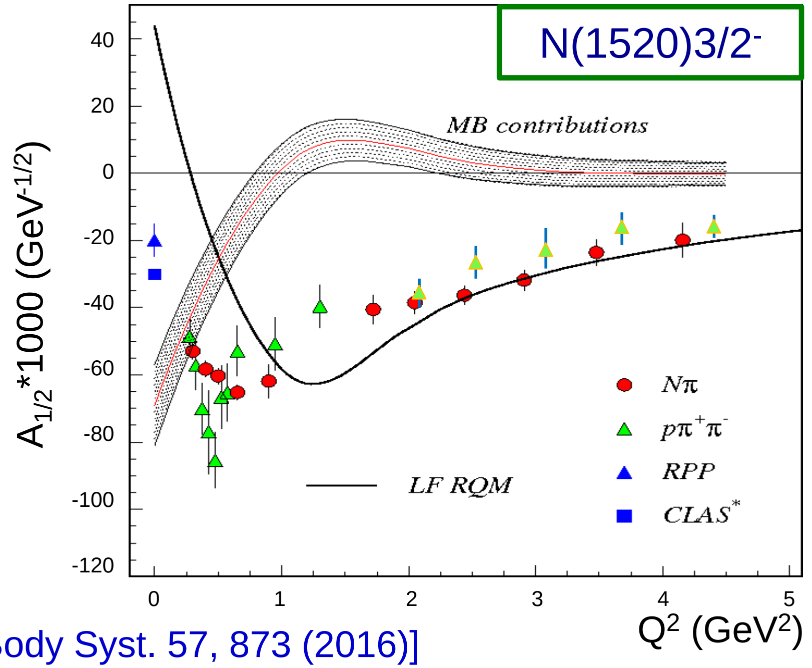
Good agreement between UIM and DR approaches

[I.G. Aznauryan et al., Phys. Rev. C 80, 055203 (2009)]

CLAS N* Electrocouplings – Second Resonance Region



γ*p → pπ
γ*p → pππ



[V.D. Burkert, Few-Body Syst. 57, 873 (2016)]

Electrocouplings reveal different interplay between meson-baryon cloud and quark core

Good agreement of the extracted N* electrocouplings from Nπ and Nππ:

- Compelling evidence for reliability of results

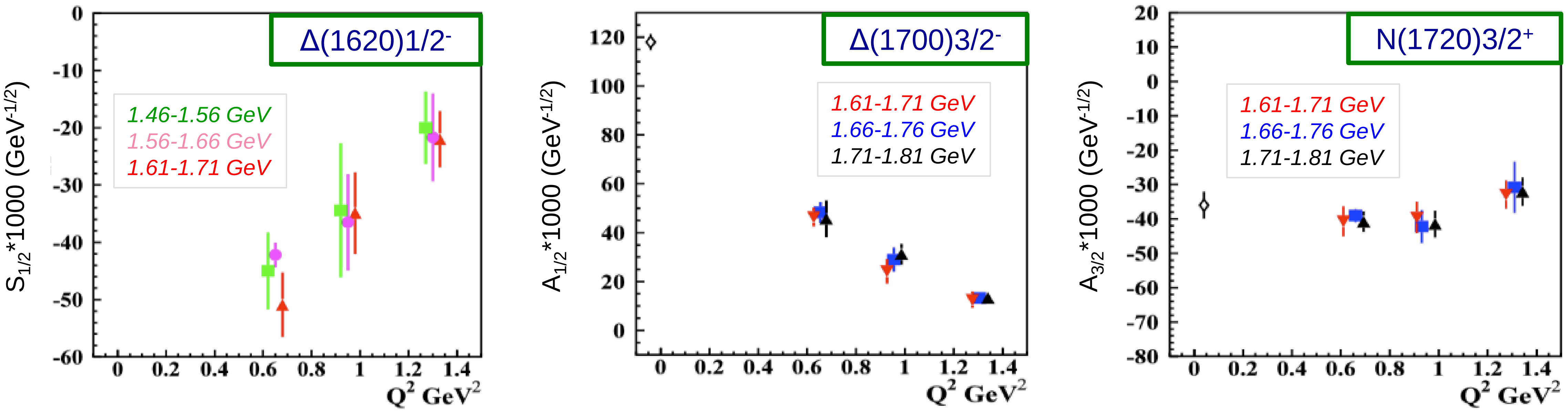
- Different channels have very different mechanisms for non-resonant background

Need for data on the electrocouplings over broad range of Q^2

CLAS N* Electrocouplings – Third Resonance Region

γ*p → pππ

Most high-lying N* states decay mainly to Nππ with much smaller strength to Nπ

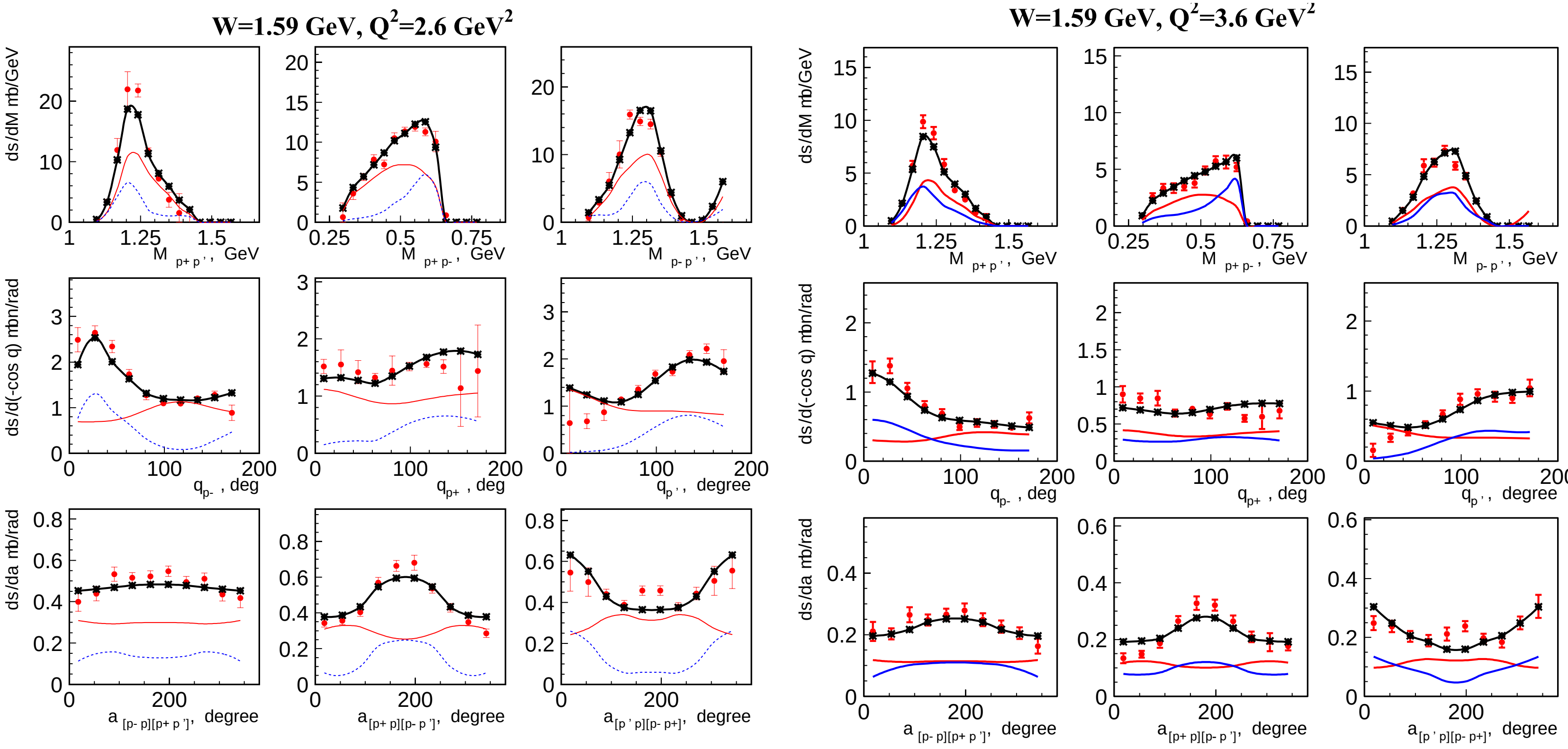


[Mokeev, Aznauryan, IJMPC 26, 1460080 (2014); Mokeev et al., PRC 93, 025206 (2016); Carman, Joo, Mokeev, FBS 61, 29 (2020)]

Nππ channel gave first electrocoupling results on higher-lying states up to 1.8 GeV

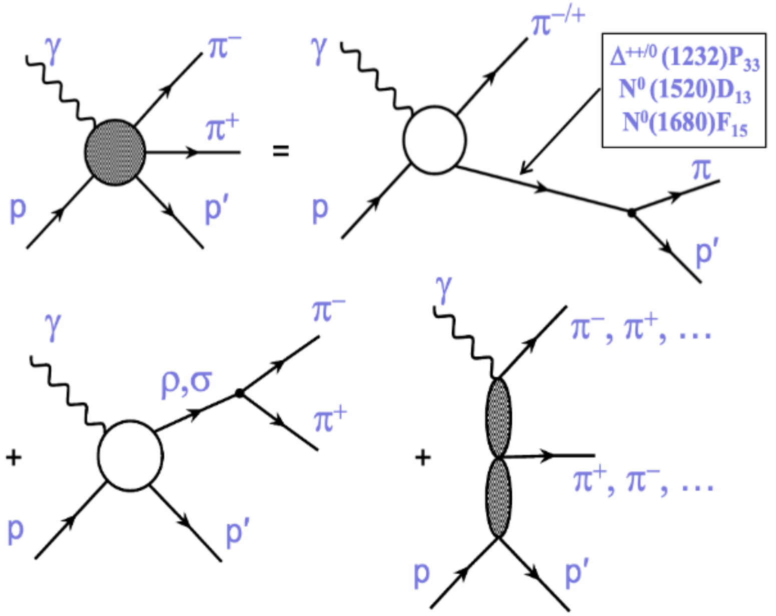
Description of pπ⁺π⁻ Data by a Reaction Model

5-fold differential cross section $\frac{d^5\sigma}{d^5\tau}$, where the denominator consists of differentials for the five variables that define the final state kinematics



Full Resonances Background

JLab-Moscow Reaction Model (JM)

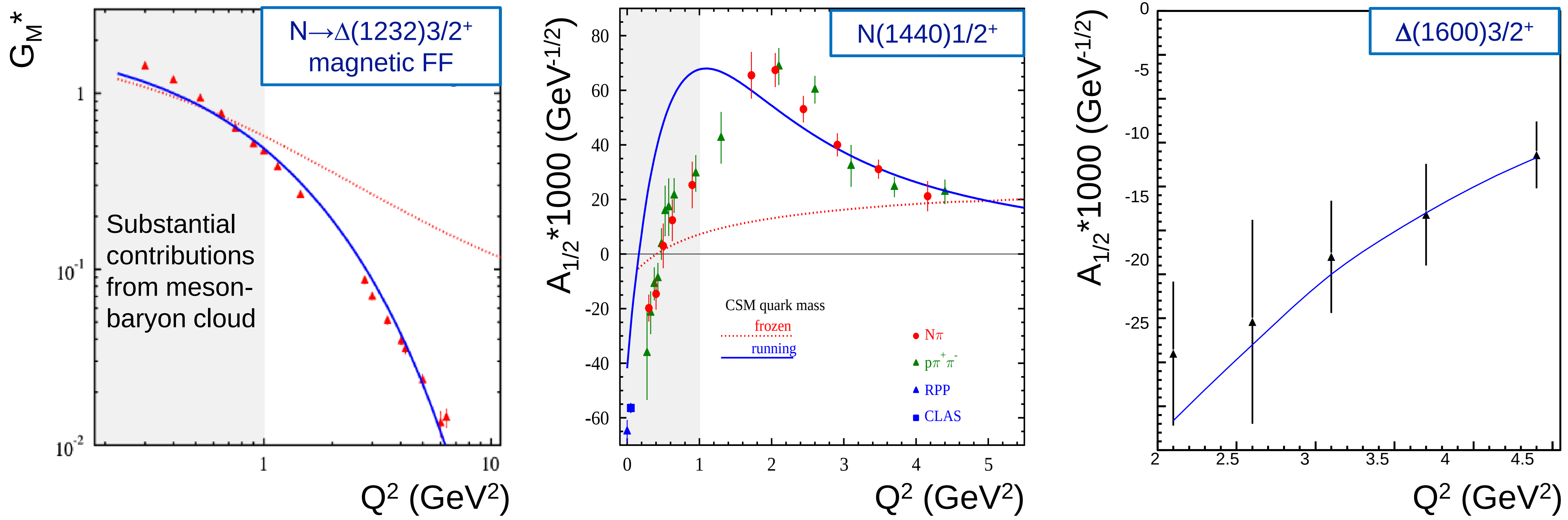


[V.I. Mokeev et al., Phys. Rev. C 86, 035203 (2012)]

Model provides reasonable description of data for extraction of resonance electrocouplings

Nucleon Resonance Electroexcitation Amplitudes

[D.S. Carman, R.W. Gothe, V.I. Mokeev, and C.D. Roberts, Particles 6, 416 (2023)]



Satisfactory description for Δ(1232)3/2+, N(1440)1/2+, Δ(1600)3/2+

Continuum QCD predictions:
[Y. Lu et al., Phys. Rev. D 100, 034001 (2019)]

- Important evidence for the **different internal structures** of nucleon resonances
- Insight into **strong interaction dynamics underlying Emergence of Hadron Mass**
- Data compared to **Continuum Schwinger Method** with momentum-dependent quark masses

Concluding Remarks on the CLAS N* Program

Study of N* states is one of the key foundations of the CLAS physics program

- CLAS has provided a huge amount of data up to Q^2 ~ 5 GeV^2
- Electrocouplings of most N* states < 1.8 GeV have been extracted for the first time

Probed N* structure is very complex and relates to fundamental QCD phenomena

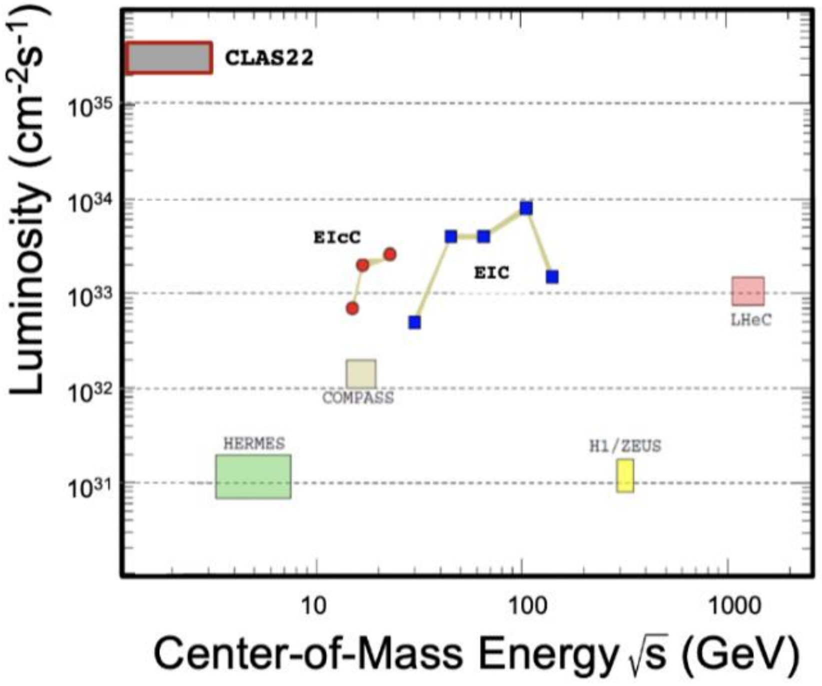
CLAS12 will extend these studies to 0.05 < Q^2 < 12 GeV^2 and W < 2.4 GeV

- Exclusive electroproduction of Nπ, Nη, Nππ, KY reactions from unpolarized proton target with longitudinally polarized electron beam
- Data will provide access to higher-lying N* states
- Goal is the understanding of active degrees of freedom that account for N* structure *vs*. distance scale

RG-A	Spr. 18 126 mC	10.2 GeV, 10.6 GeV 50% of total
	Fall 18 99 mC	
	Spr. 19 58 mC	
RG-K	Fall 18 28 mC	6.3 GeV, 7.4 GeV 10% of total

Running since last week

Electrocouplings for πN, KY, and $\pi^+\pi^-$p reaction with 22 GeV beam
can be determined up to **Q^2 ~ 30 GeV^2** for **$\mathcal{L}$ ~ 2 - 5 × 10^{35} cm^{-2}s^{-1}**



A. Accardi et al., e-print:2306.09360 [nucl-ex]

The high luminosity frontier provides JLab a special advantage in comparison with EIC or EIcC.

It offers a unique opportunity to study Nature's simplest 3-body bound state and its electrocouplings with its resonances in a large domain of momentum transfer.

CLAS22 will map out the working of QCD from its non-perturbative behavior at low Q^2 to its asymptotic regime where perturbative QCD can provide predictions, charting out the pattern of dynamical chiral symmetry breaking.