# Study of Nucleon Resonance Electroexcitations at Jefferson Lab

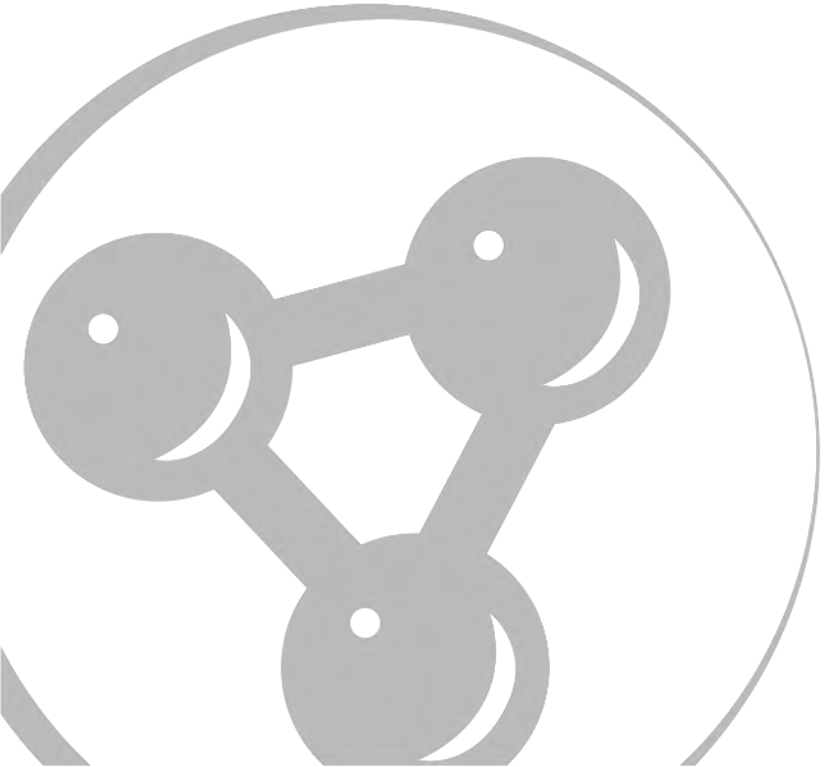
Patrick Achenbach (Jefferson Lab)

*With credits to*
Daniel Carman, Ralf Gothe, and Victor Mokeev

Oct 2o23

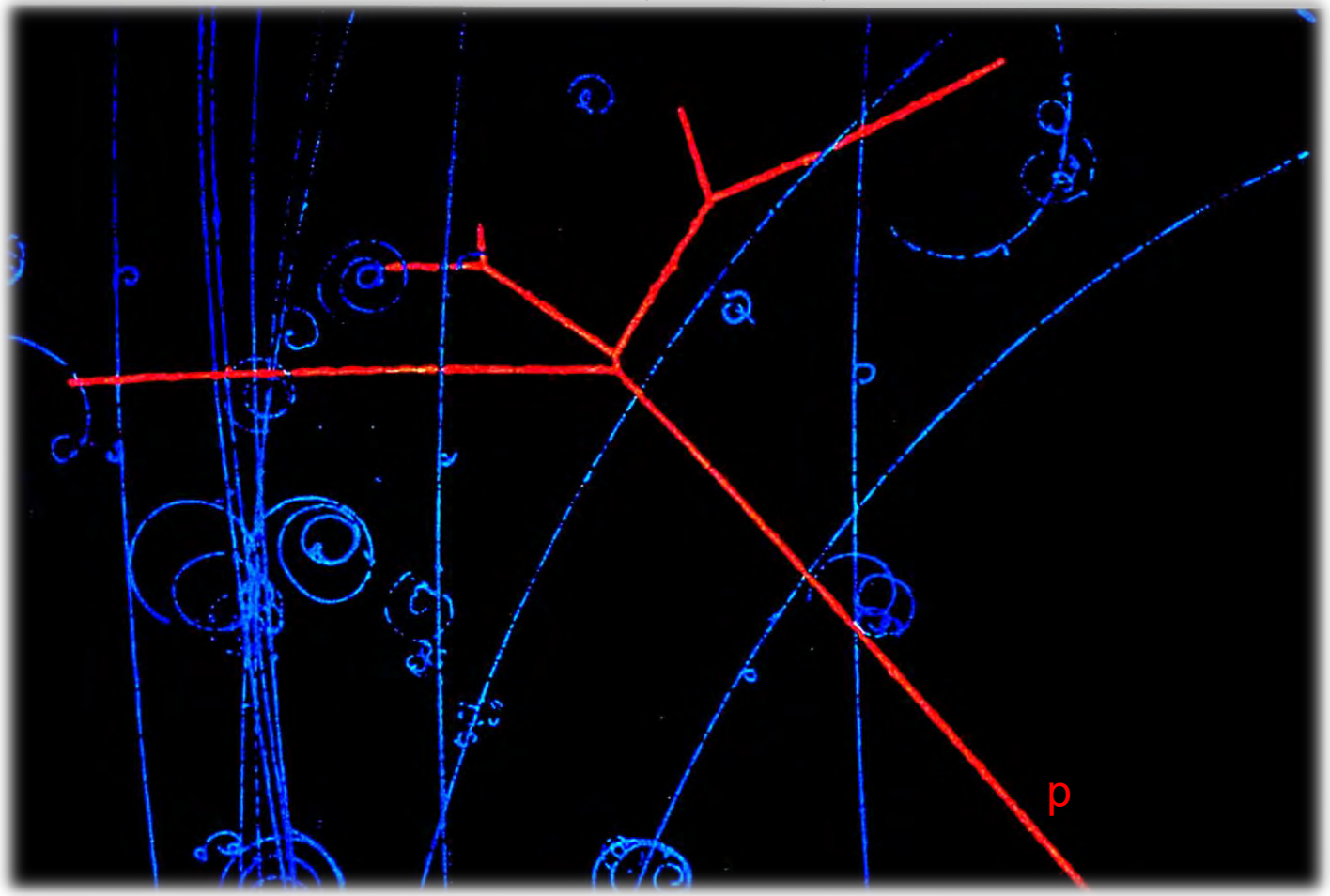
# The Proton and its Excitations

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



# The Proton as a Hard Sphere Scattering Center

[Lawrence Berkeley Laboratory]




In a bubble chamber *elastic proton scattering* on hydrogen resembles “billiards kinematics”

**Proton as an invisible scattering center**

- Billiard balls are **hard spheres of equal masses** colliding with each other
- One important principle of pool: when one ball strikes another *without spin*, the two balls will always separate at 90°
- This principle is a direct result of **energy and momentum conservation**
- Spherical objects have smallest surface-to-volume ratio of any three-dimensional form: a **spherical shape minimizes potential energy**
- Many objects in nature have a spherical shape, for example planets, stars, bubbles, and water drops

# The Proton as Probed By Electrons


Coulomb scattering of *slow & light on heavy* particles …

- … produces a characteristic angular distribution

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{Ru} = \left(\frac{1}{4\pi\varepsilon_0}\frac{Z_1 Z_2 e^2}{4E}\right)^2 \frac{1}{\sin^4\left(\frac{\theta}{2}\right)}\frac{E'}{E}$$

(classical for point-charge, zero-spin)

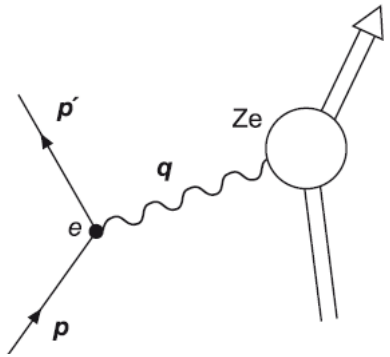
- **Deviations** from above formular provide *information on size and shape*
- The **differential cross section** is a tool to study scattering centers

Inferring the *spatial structure of protons* from the diffraction pattern of **scattered electrons**

- With *de Broglie wavelengths* comparable to size of the proton (about 200 MeV/*c* momentum)
- Observing *deviations* from the point-charge, zero-spin Mott differential cross section:

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^*_{\mathrm{Mott}} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{Rutherford}} \cdot \cos^2\frac{\theta}{2} = \frac{4Z^2\alpha^2(\hbar c)^2 E'^2}{|\boldsymbol{q}c|^4}\cos^2\frac{\theta}{2}$$

# The Proton as a Structured Scattering Center




$$q_\mu = p_{e\mu} - p'_{e\mu} = (\omega, \vec{q})$$

$$Q^2 = -(q_\mu)^2 = 4EE' sin^2 \frac{\theta_e^{lab}}{2}$$

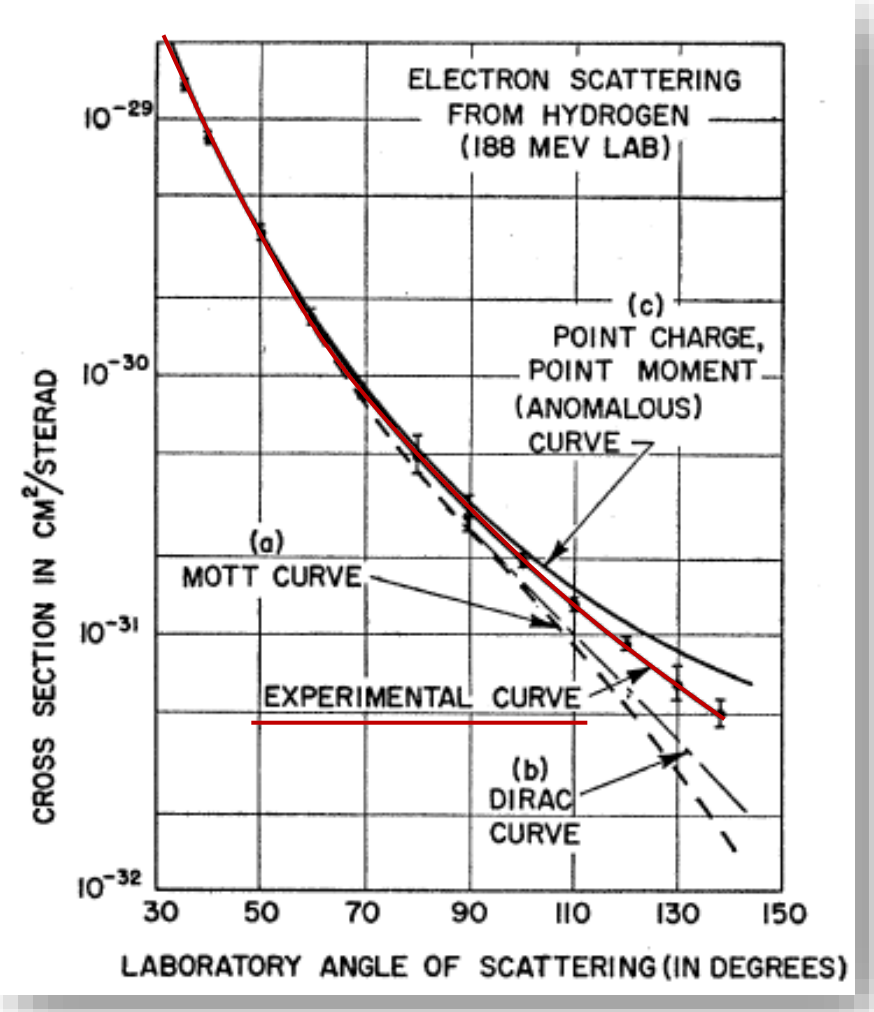
$p_e = (E_e, \vec{p}_e)$ for the incident electron.

$p'_e = (E'_e, \vec{p'}_e)$ for the scattered electron.

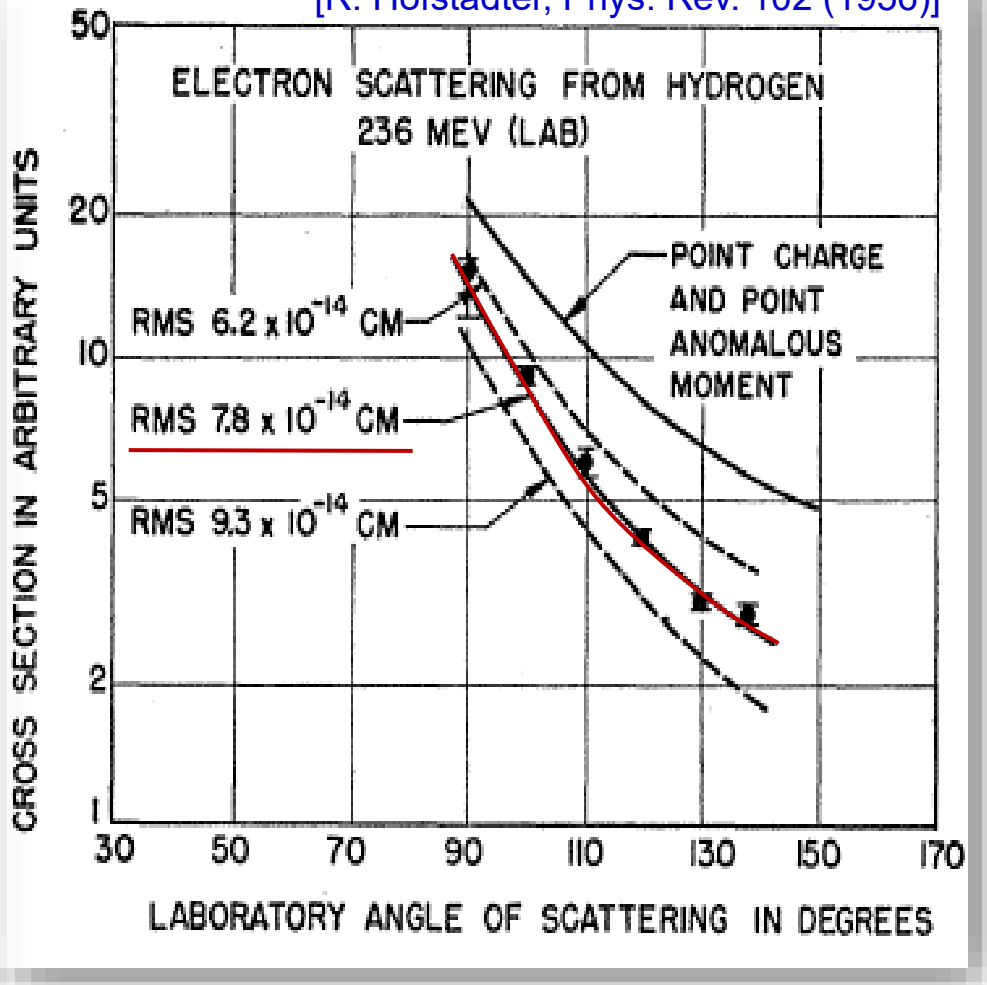
$p_p = (m_p, \vec{0})$ for the proton target.

In electron scattering …

- Electron vertex is well-known from QED
- One-photon exchange is %-level accurate




[R. Hofstadter, Phys. Rev. 102 (1956)]




In a magnetic spectrometer *elastic electron scattering* on hydrogen revealed proton radius in 1954

# Proton Factor Factors

The cross section:

$$\frac{\left(\frac{d\sigma}{d\Omega}\right)}{\left(\frac{d\sigma}{d\Omega}\right)_{Mott}} = \frac{1}{\varepsilon\left(1+\tau\right)}\left[\varepsilon G_E^2\left(Q^2\right) + \tau G_M^2\left(Q^2\right)\right]$$

with:

$$\tau = \frac{Q^2}{4m_p^2}, \quad \varepsilon = \left(1 + 2\left(1+\tau\right)\tan^2\frac{\theta_e}{2}\right)^{-1}$$

Fourier-transform of $G_E$, $G_M$ → spatial distribution (Breit frame)

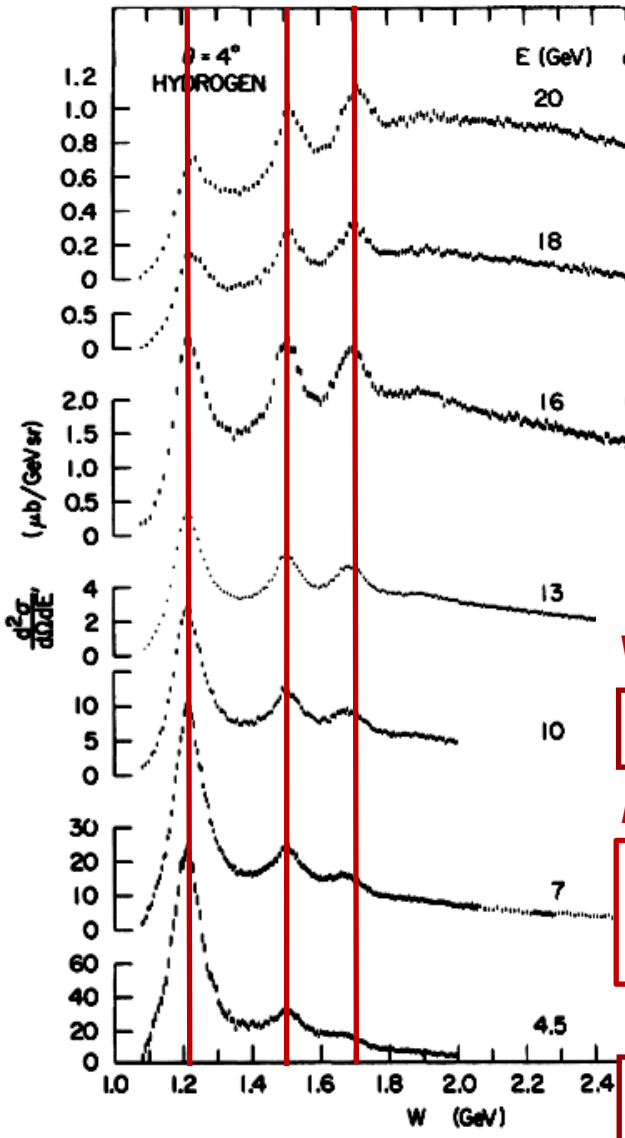
$$\left\langle r_E^2 \right\rangle = -6\hbar^2 \left.\frac{\mathrm{d}G_E}{\mathrm{d}Q^2}\right|_{Q^2=0} \qquad \left\langle r_M^2 \right\rangle = -6\hbar^2 \left.\frac{\mathrm{d}\left(G_M/\mu_p\right)}{\mathrm{d}Q^2}\right|_{Q^2=0}$$

The mean squared radius is determined from the slope of the corresponding form factor at $Q^2 = 0$

# The Proton Radius Puzzle

# Excitation of Proton Resonances

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




*Virtuality of photon:*

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

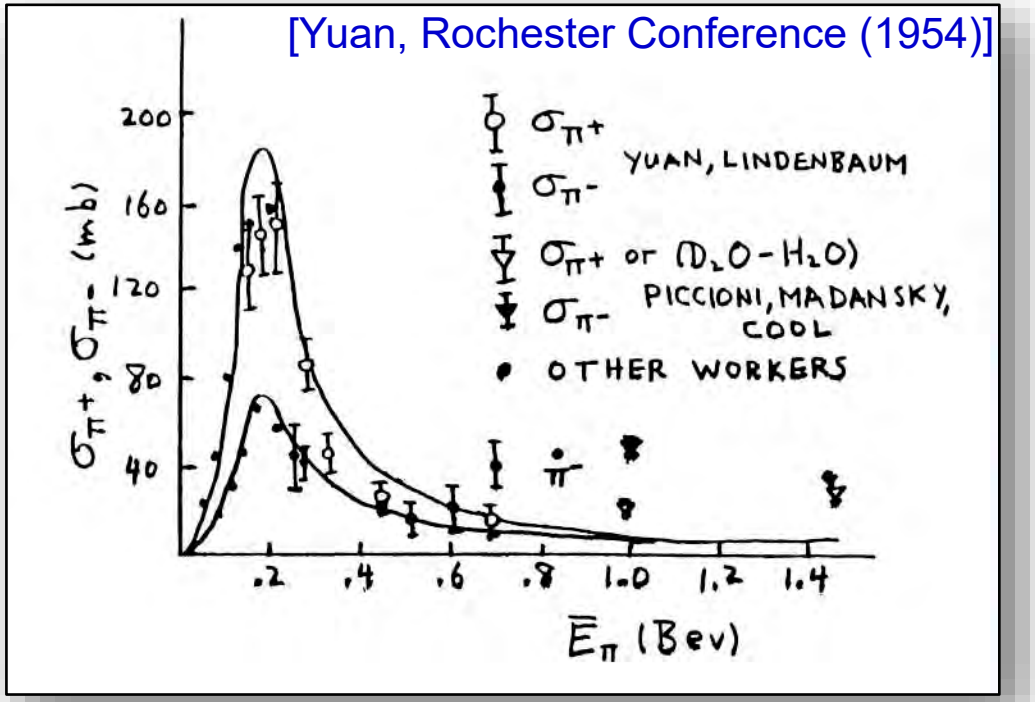
*Inelasticity of process:*

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

*Mass of excited proton:*

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

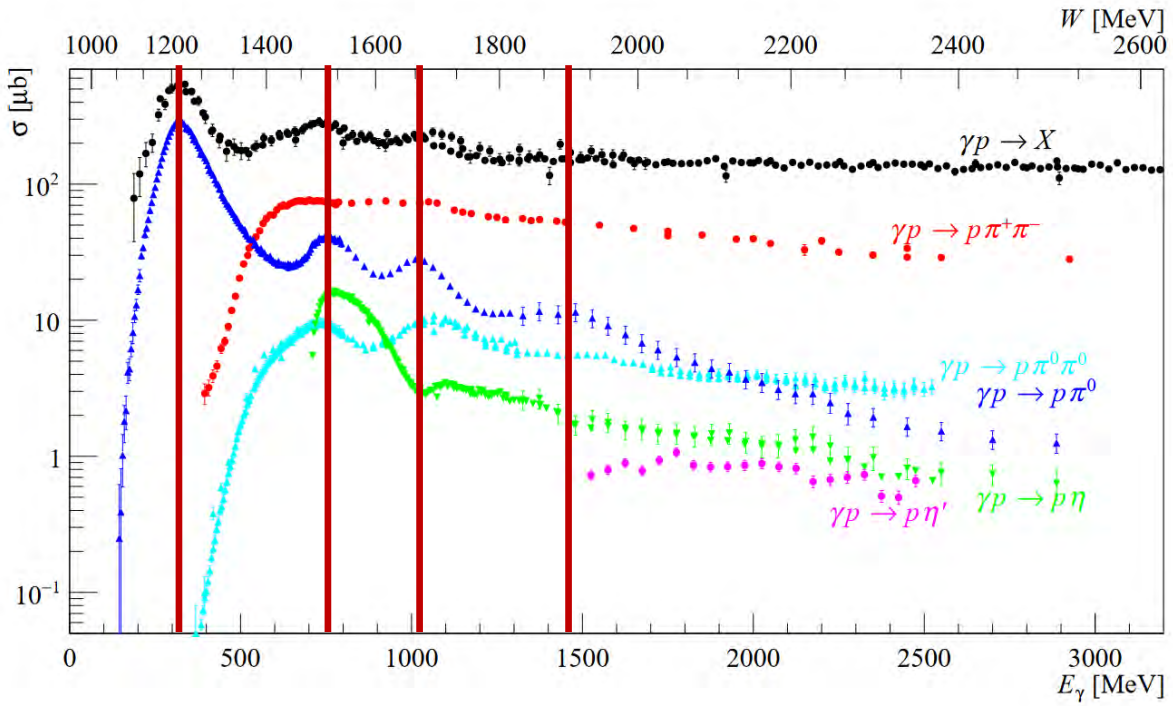
[Yuan, Rochester Conference (1954)]




- Charged *pion beams* revealed a **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)]

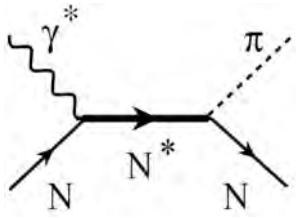
Light baryon spectroscopy by meson-production reactions at electron accelerators

Study of many relevant observables:

– Excitation spectrum / quantum numbers

– Selective and exclusive reactions

Single-pion production as an example:




– Transitions amplitudes and $Q^2$ evolutions

– Polarization observables:

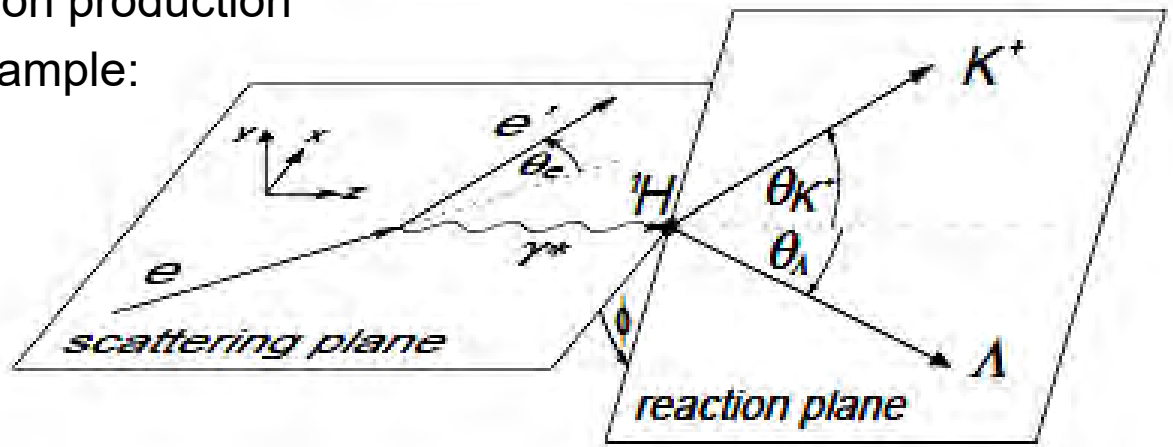
| Beam | | Target | | | Recoil | | | Target + Recoil | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | - | - | - | - | $x'$ | $y'$ | $z'$ | $x'$ | $x'$ | $x'$ | $y'$ | $y'$ | $y'$ | $z'$ | $z'$ | $z'$ |
| | - | $x$ | $y$ | $z$ | - | - | - | $x$ | $y$ | $z$ | $x$ | $y$ | $z$ | $x$ | $y$ | $z$ |
| unpolarized | $\sigma_0$ | | $T$ | | | $P$ | | $T_{x'}$ | | $L_{x'}$ | | $\Sigma$ | | $T_{z'}$ | | $L_{z'}$ |
| linearly pol. | $\Sigma$ | $H$ | $P$ | $G$ | $O_{x'}$ | $T$ | $O_{z'}$ | $L_{z'}$ | $C_{z'}$ | $T_{z'}$ | $E$ | $\sigma_0$ | $F$ | $L_{x'}$ | $C_{x'}$ | $T_{x'}$ |
| 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**

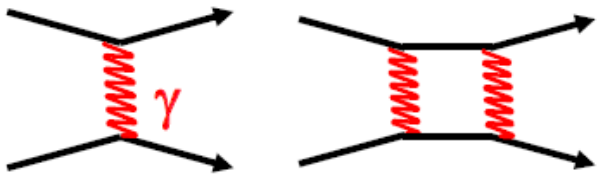
$$\frac{d\sigma}{dE' d\Omega_{e'} d\Omega_K^*} = \Gamma \frac{d\sigma}{d\Omega_K^*}$$

Single-kaon production as an example:




Photon exchange

$O(\alpha) \sim 0.01$




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

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)]

# Connecting to Electrocoupling Amplitudes

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 the following kinematic definitions:

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

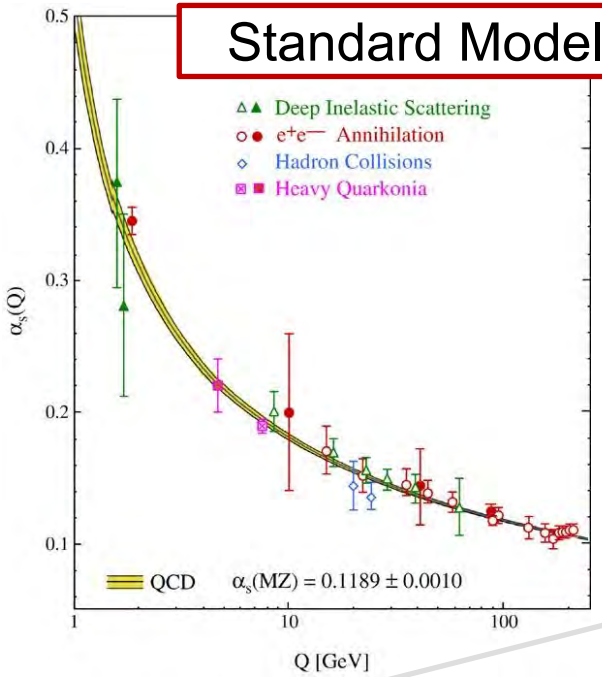
The electromagnetic decay widths at the resonance point $W=M_r$ are given by:

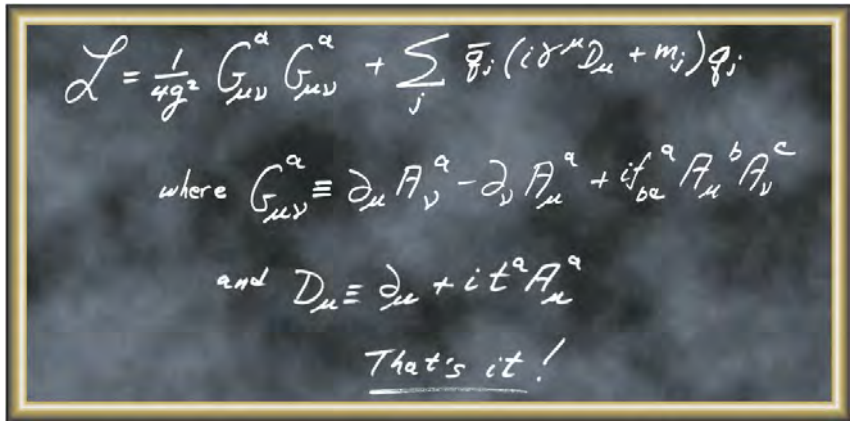
$$\Gamma_\gamma^L(M_r,Q^2) = 2\frac{q_{\gamma,r}^2(Q^2)}{\pi} \frac{2M_N}{(2J_r+1)M_r} |S_{1/2}(Q^2)|^2$$

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

# Connection to Strong QCD Regime

Standard Model $\alpha_s$ diverges as $Q^2$ approaches zero and QCD becomes non-perturbative



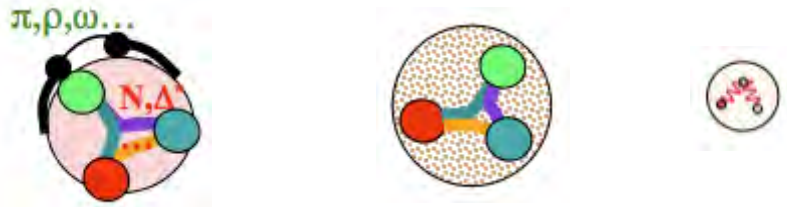




Frank Wilczek, Physics Today, August 2000

- Confinement and meson-baryon (MB) cloud play key role!
- N* degrees of freedom?

external M-B cloud in addition to quark core

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




3q core + M-B cloud | 3q core | pQCD

low $Q^2$ → high $Q^2$

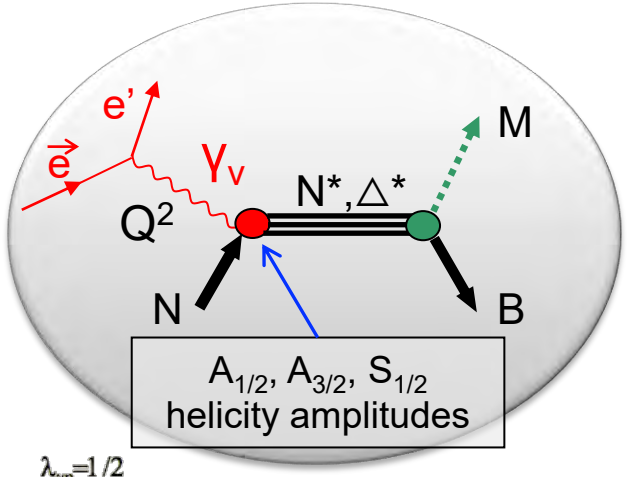
quark core dominates; transition from confinement to pQCD regimes

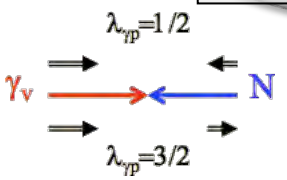
($Q^2 > 5$ GeV$^2$)

# The Excited Nucleon Structure

N* structure is more complex than what can be described accounting for quarks only

- Study of exclusive reaction channels over a broad kinematic range:
  πN, ωN, φN, ηN, η'N, ππN, KY, K*Y, KY*
- Studies of electrocouplings from low to high $Q^2$ probe N* structure
- Momentum dependence of underlying degrees of freedom shapes structure of N* states and $Q^2$ evolution of electrocouplings
- Only source of information on many facets of non-perturbative strong interaction in generation of N* states and emergence from QCD




*$A_{1/2}$ , $A_{3/2}$ – transverse*
*$S_{1/2}$ - longitudinal*

Goal is to explore the *spectrum* and *structure* of N* states

$L_{IJ}$ (mass)

*L* = angular momentum state
*I* = isospin of resonance x 2
*J* = total spin of resonance x 2

# Emergence of Hadron Mass

Mass scale for 3 dressed quarks inside proton is consistent with observed N/N* masses

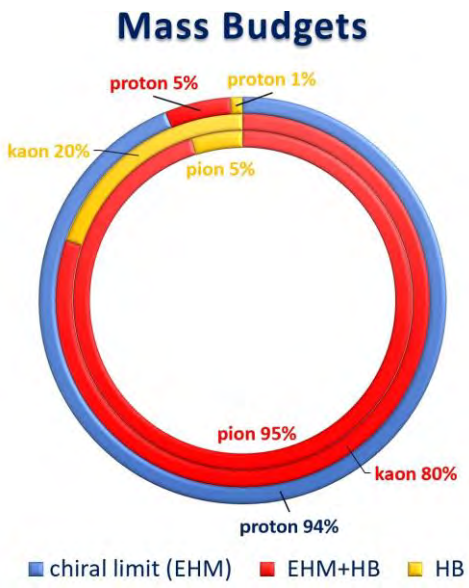
The pion as q-q system should have 2/3 $M_N$

Why is 1 GeV proton mass paired with 1/7 GeV pion mass in the same theory of Nature?

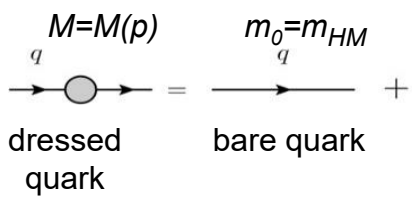
The lightest hyperon ≈ 20% above nucleon mass

Why is $m_s/m_{u,d}$ current quark mass ≈ 30?

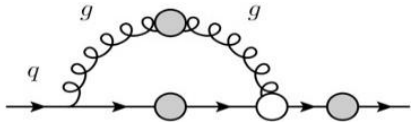
- Probing EHM in a regime where sum of dressed quark masses is dominant contribution to physical resonance mass
- Studies of different π vs. K structure are critical to test separation of emergent and Higgs mechanisms
- Consistency on momentum evolution of dressed quark mass function of importance for validation of insight into EHM

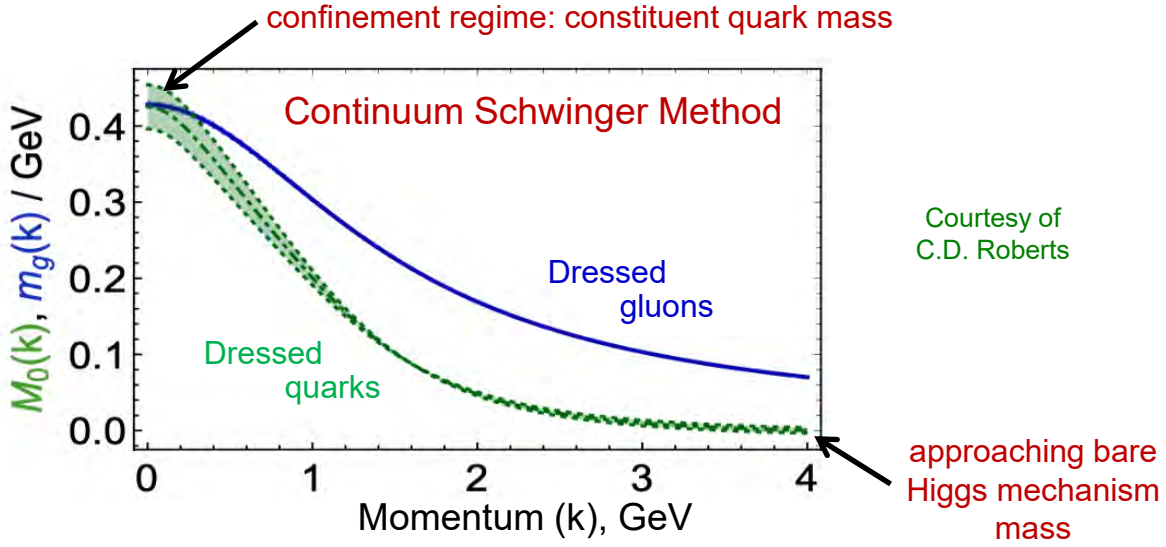



Dressed quark mass depends on its momentum



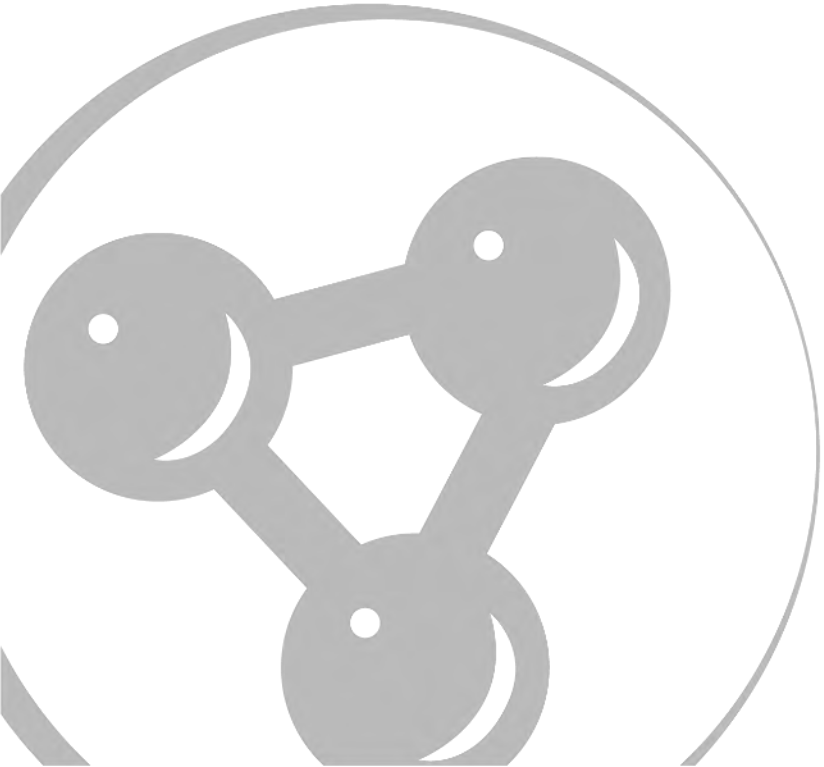

dressing kernel




Courtesy of C.D. Roberts

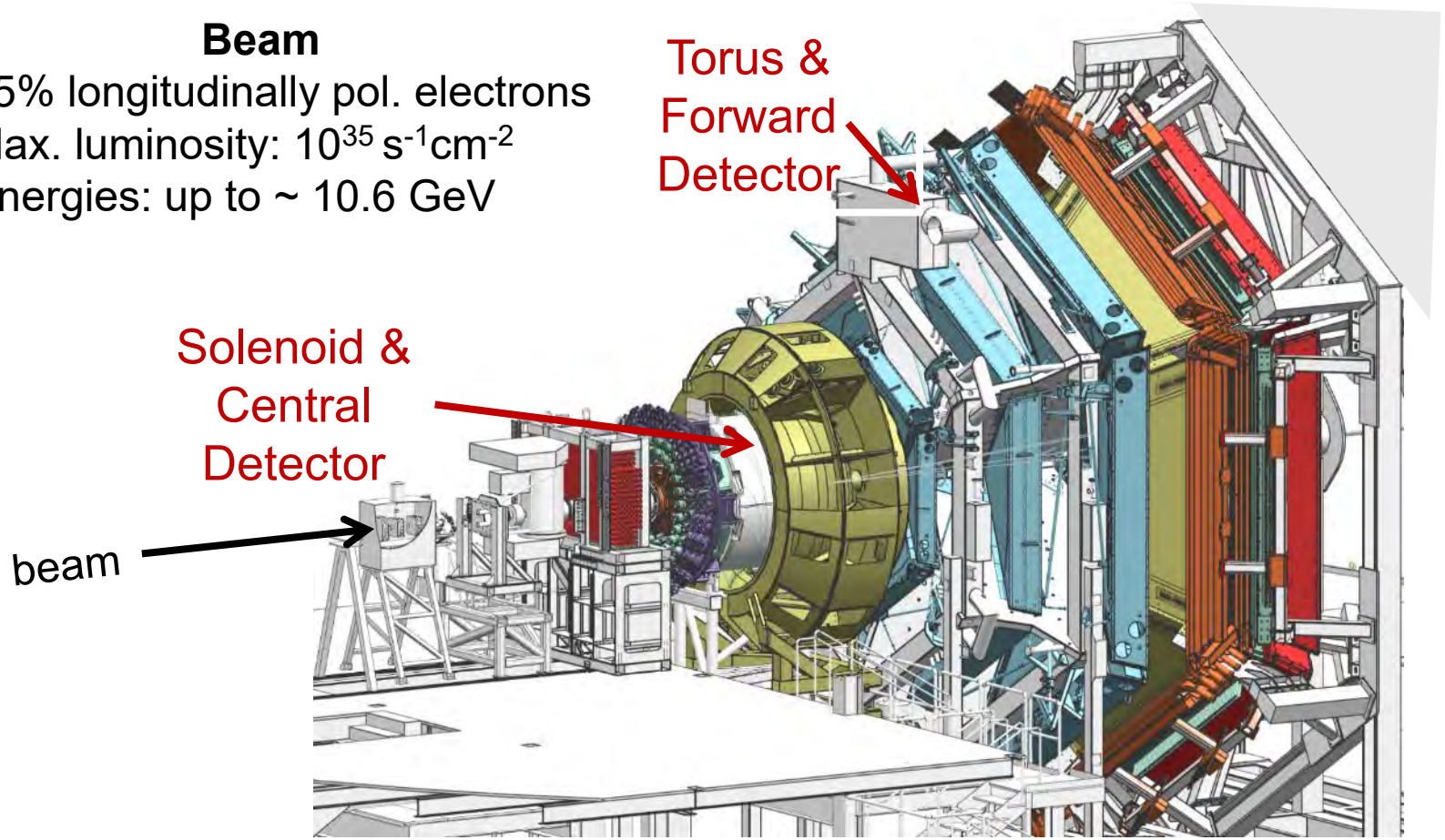
*Good Physics Needs Good Tools*



# 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

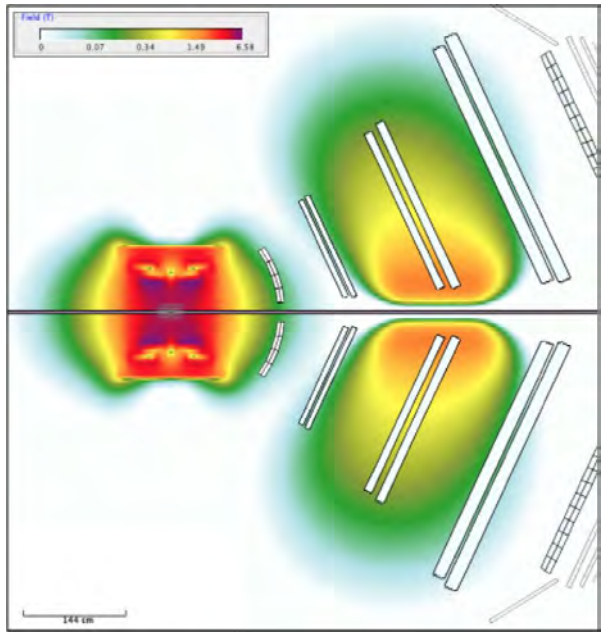



[V.D. Burkert et al., Nucl. Inst. and Meth. A 959, 163419 (2020)]

**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**

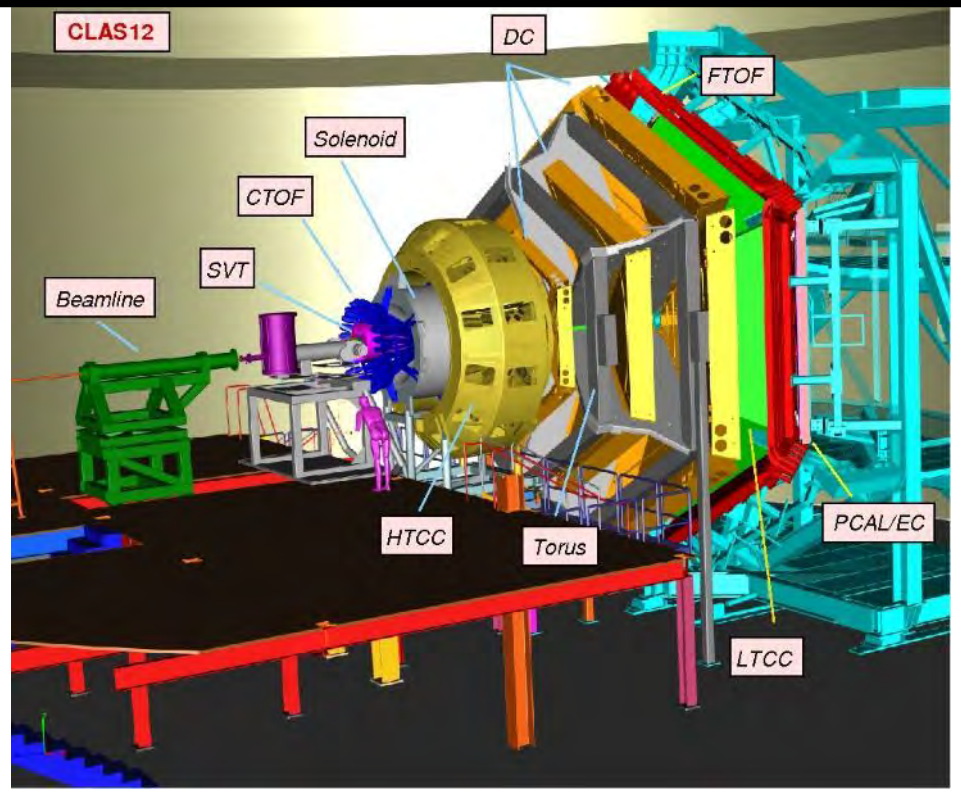


Ideal instrument to study exclusive meson electroproduction in the nucleon resonance region

# Subsystems of the CLAS12 Spectrometer

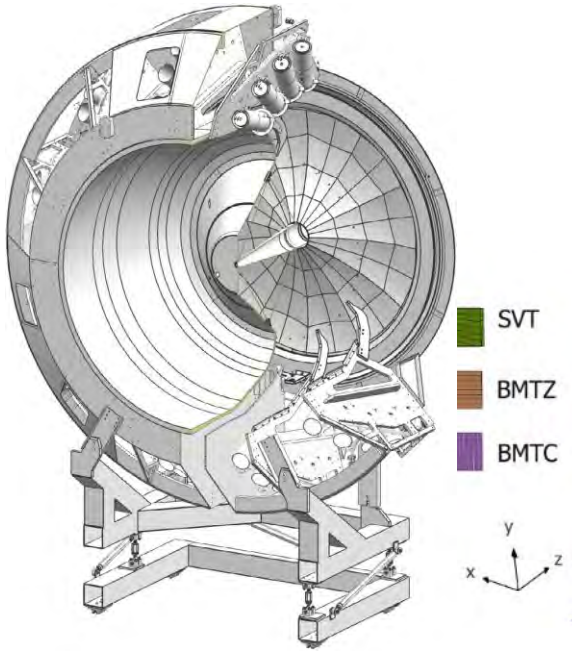
**CENTRAL**

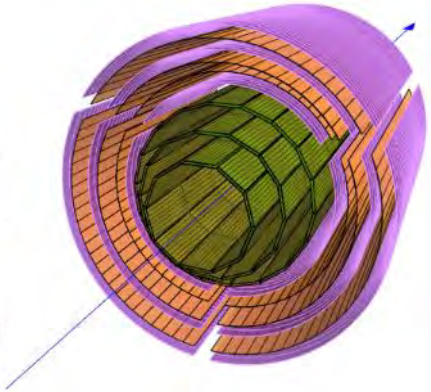
- Beamline
- Target
- Central Vertex Tracker
- Central Time of Flight
- Central Neutron Det.
- Back-Angle Neutron Det.

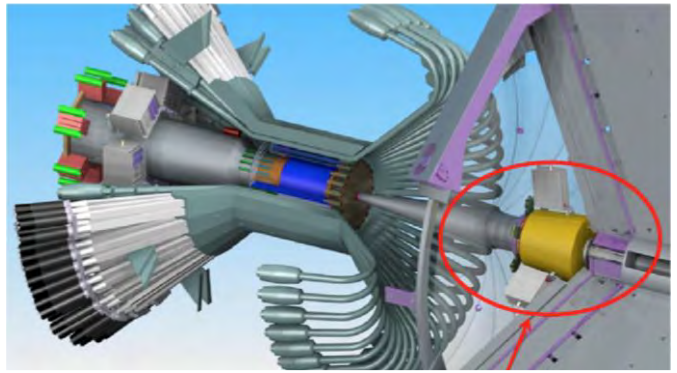


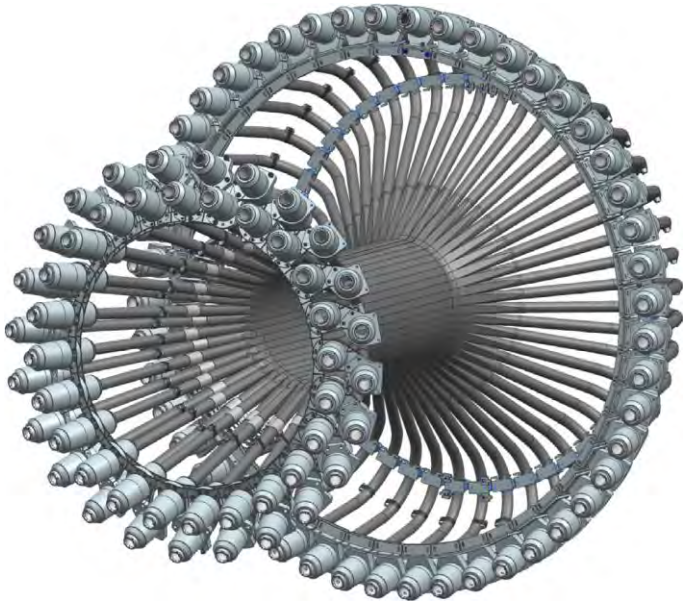

**FORWARD**

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



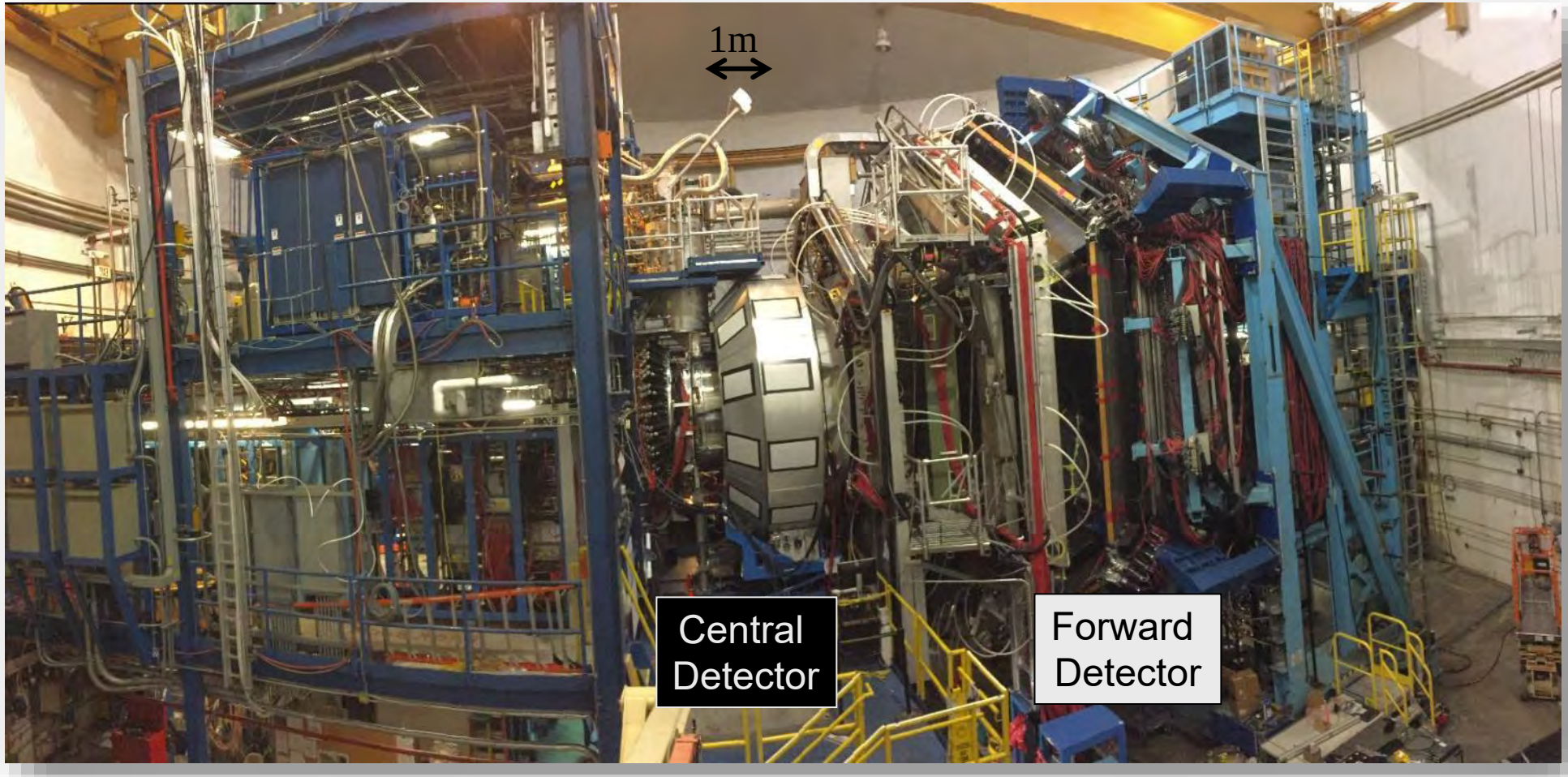





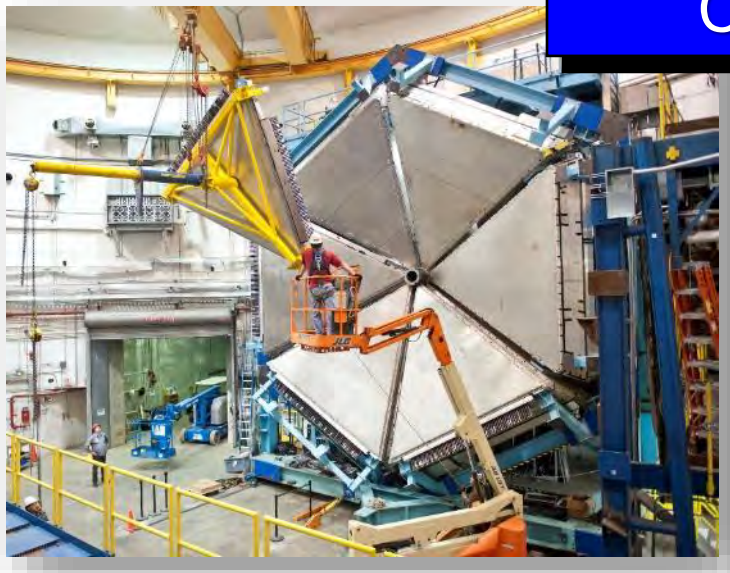


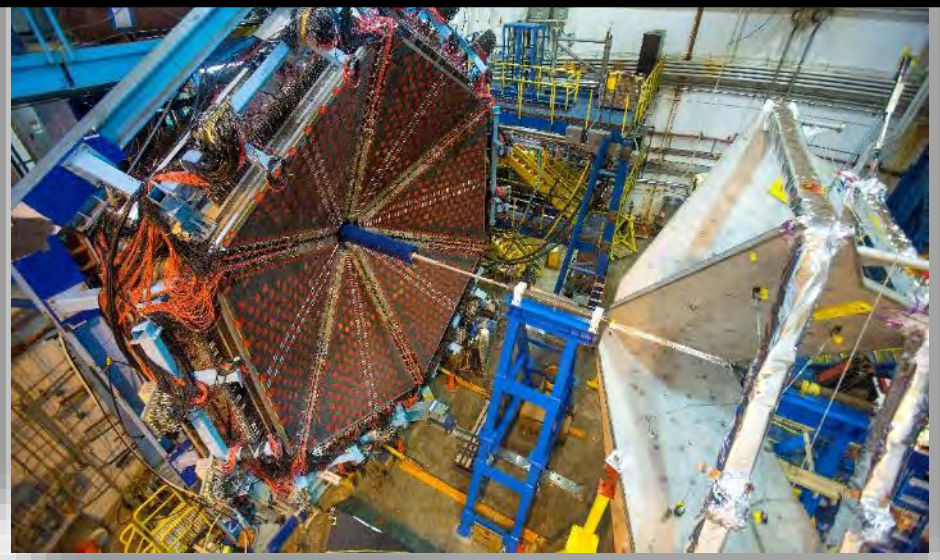
# Side View Photograph of CLAS12 Spectrometer

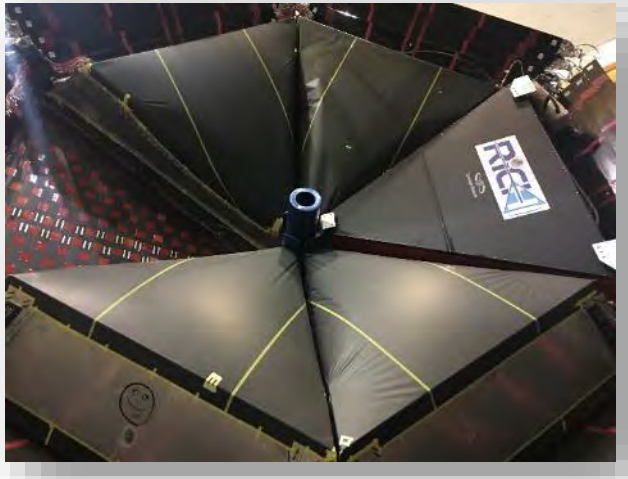
Electron beam →

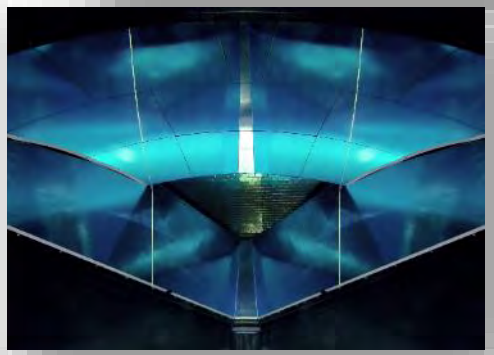


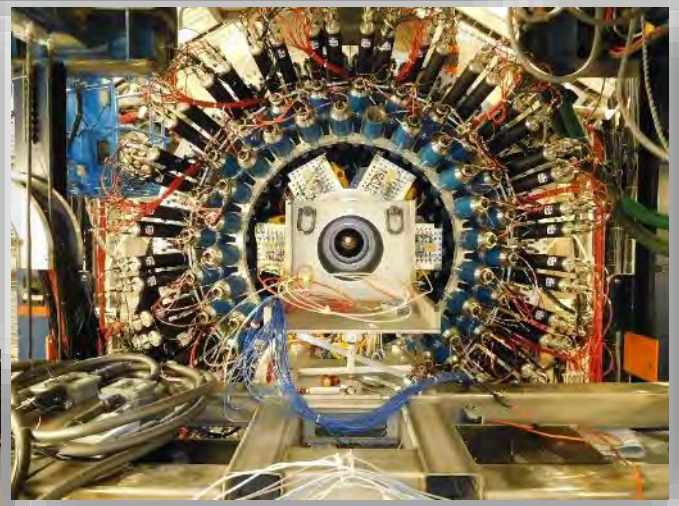
# CLAS12 Subsystems During Installation











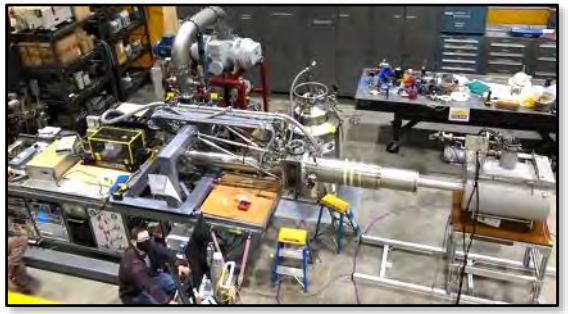
# Hall B Experimental Setup 2022–23

**Longitudinally polarized cryo-target** inside solenoid

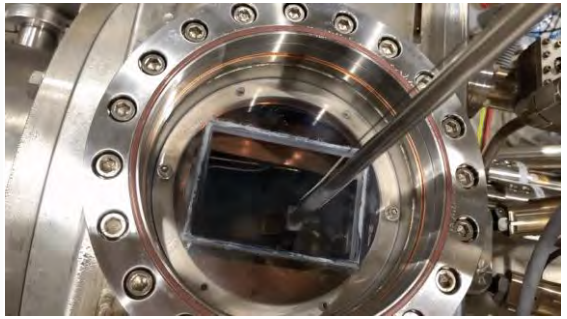
Multiple configurations: $NH_3$, $ND_3$, C, $CH_2$, $CD_2$, …

Thermoluminescence of target material

Installation in Hall B, June 2022



Testing in Target Lab, March 2022



Rapid exchange of target samples

| Proton | Deuteron |
|---|---|
| Polarization 78.87% | Polarization 47.17% |
| Signal Area -0.485024 | Signal Area -0.300473 |

< ~ 80% H polarization

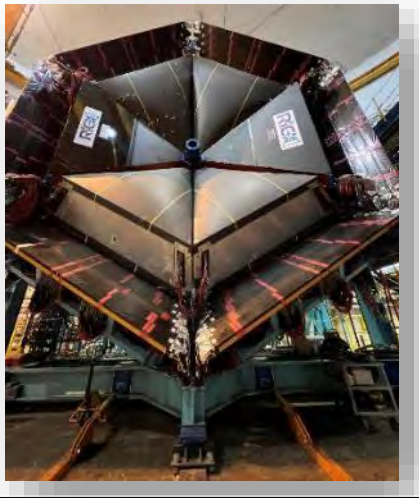
< ~ 45% D polarization

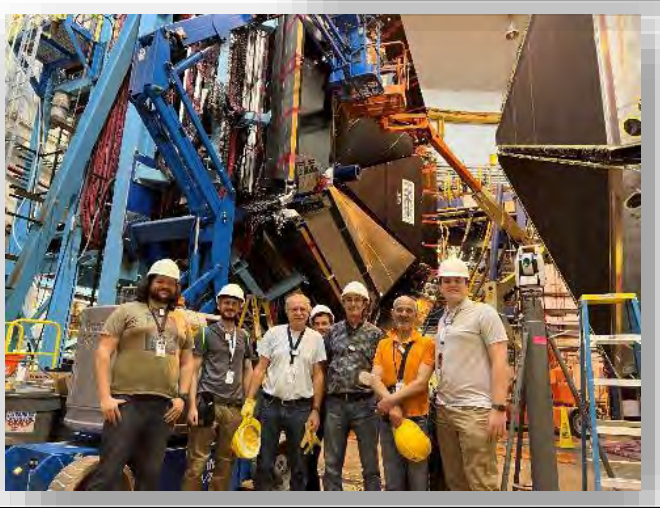
DNP by 140 GHz μwaves

1 K with ℓHe refrigerator

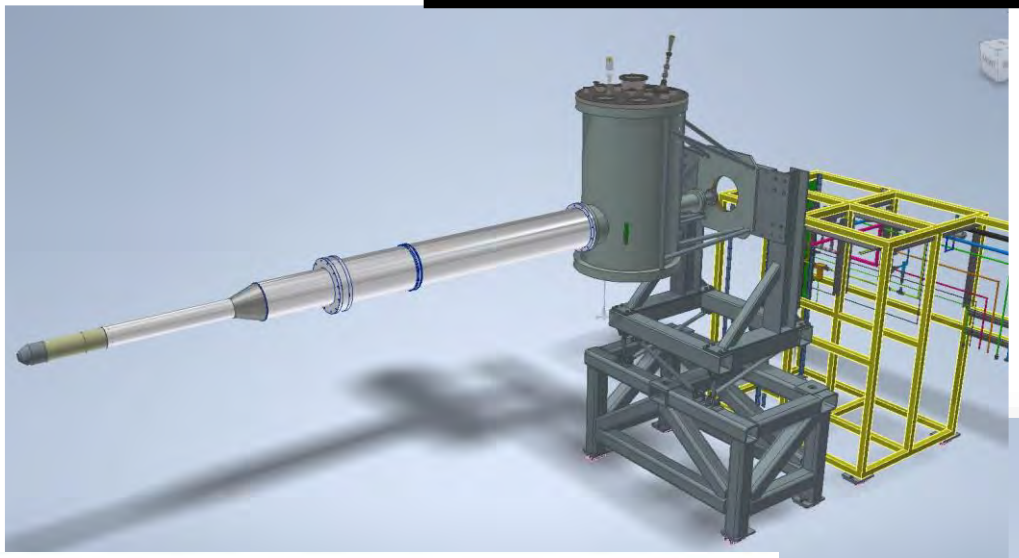
Forward Tagger and Møller shield

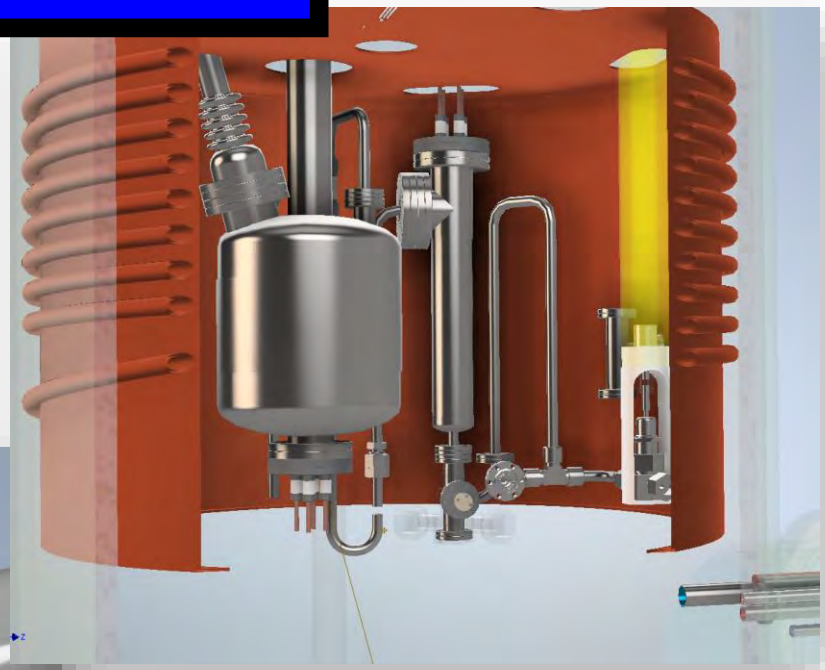
Additional 2nd sector **RICH** coverage with 50,048 channels

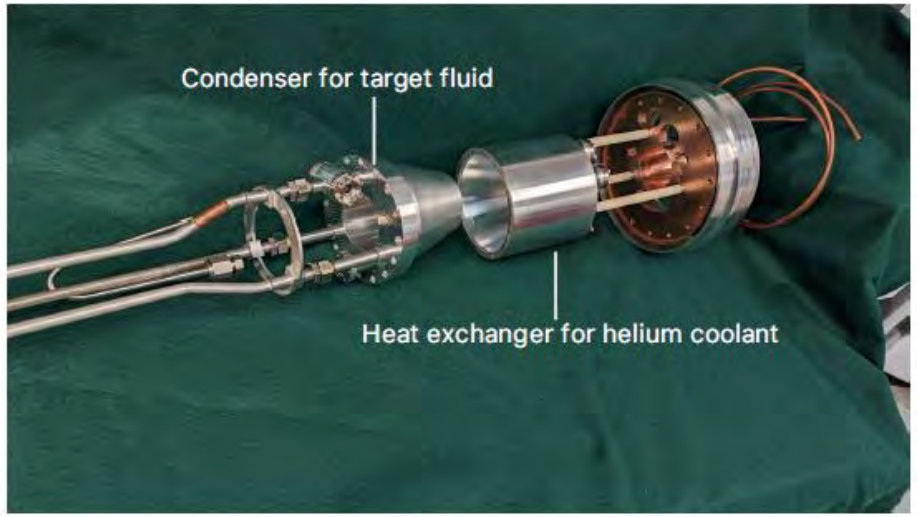


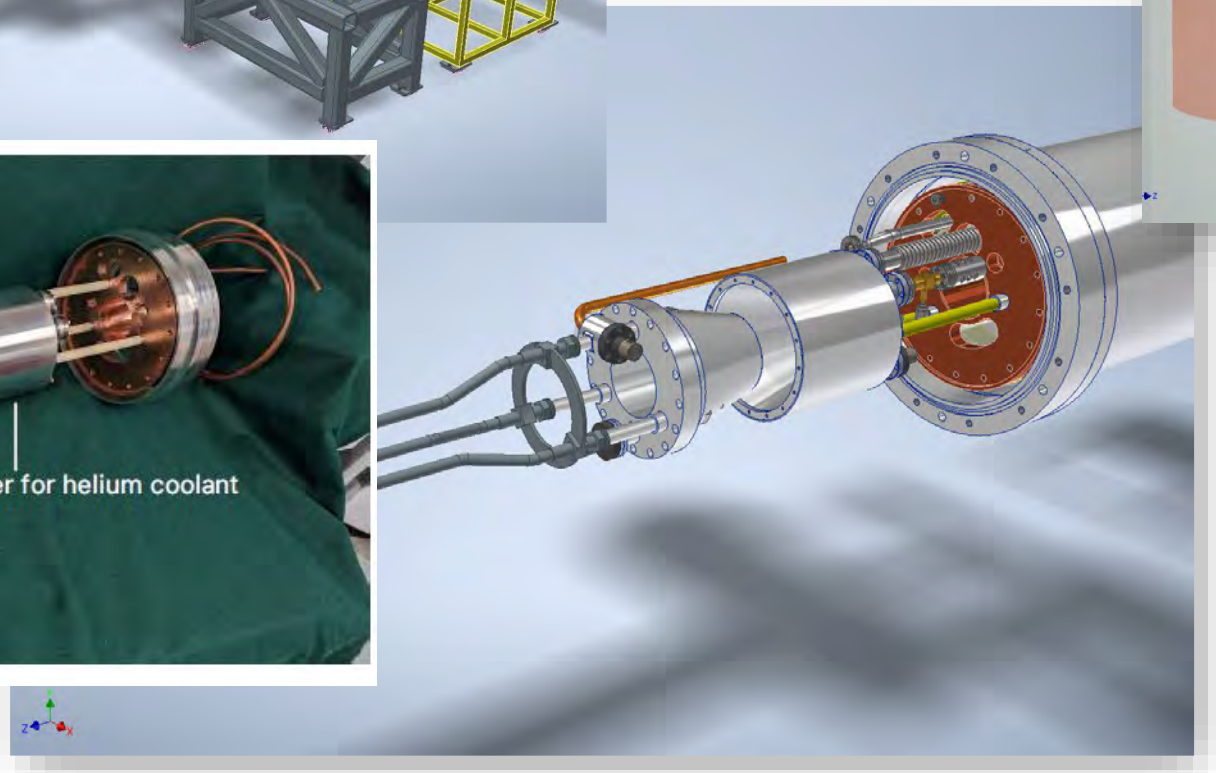


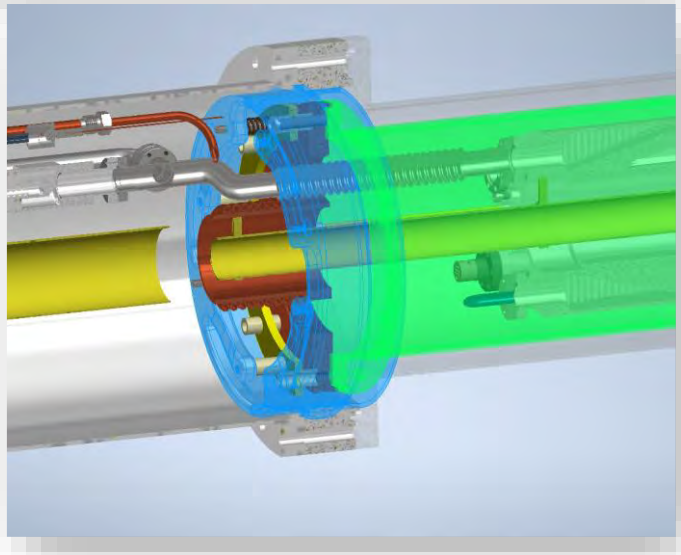
# Unpolarized Cryo-Target for Runs in 2023+



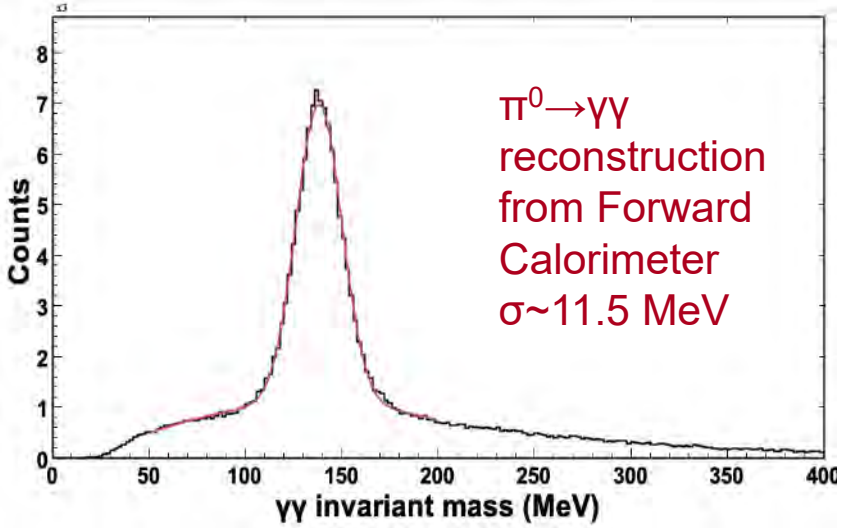




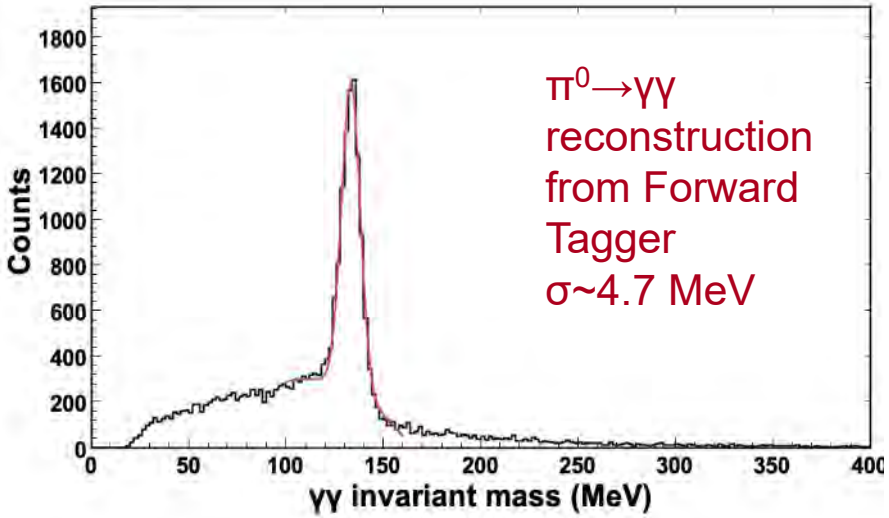





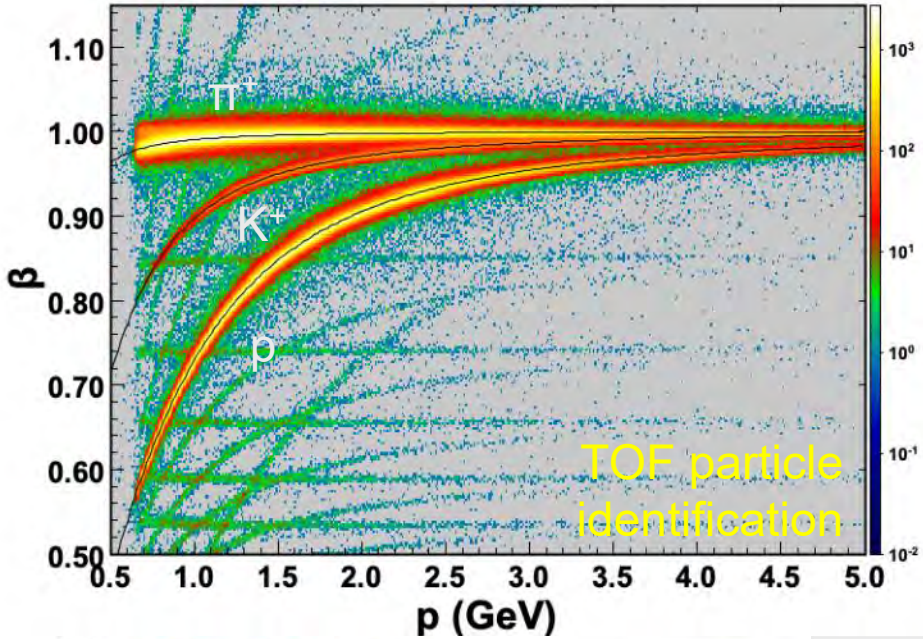
# Event Reconstruction in CLAS12



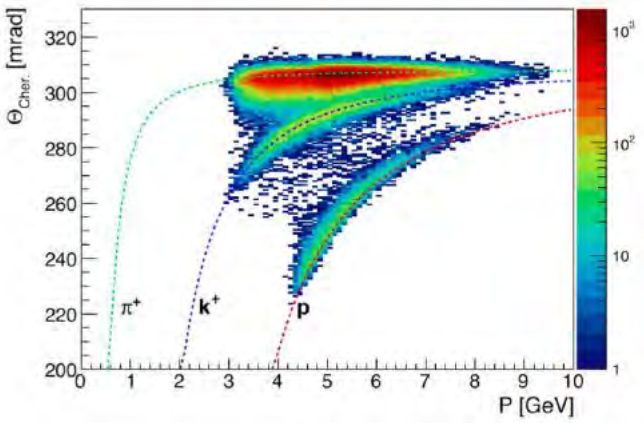

$\pi^0 \rightarrow \gamma\gamma$ reconstruction from Forward Calorimeter $\sigma \sim 11.5$ MeV

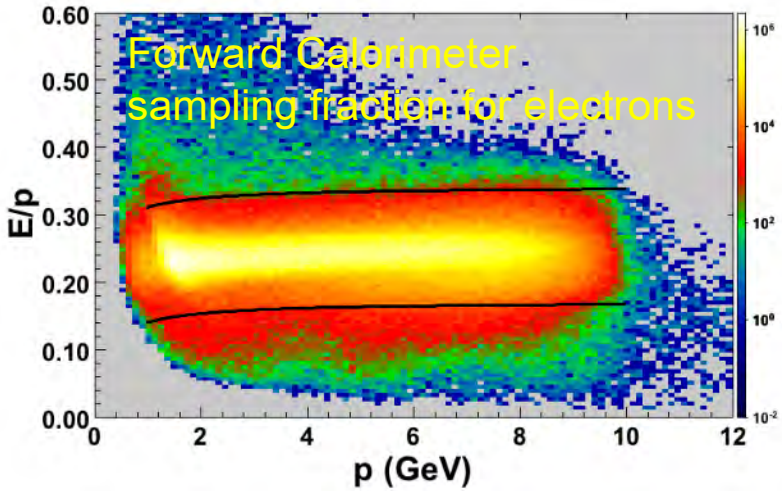



$\pi^0 \rightarrow \gamma\gamma$ reconstruction from Forward Tagger $\sigma \sim 4.7$ MeV




RICH particle identification

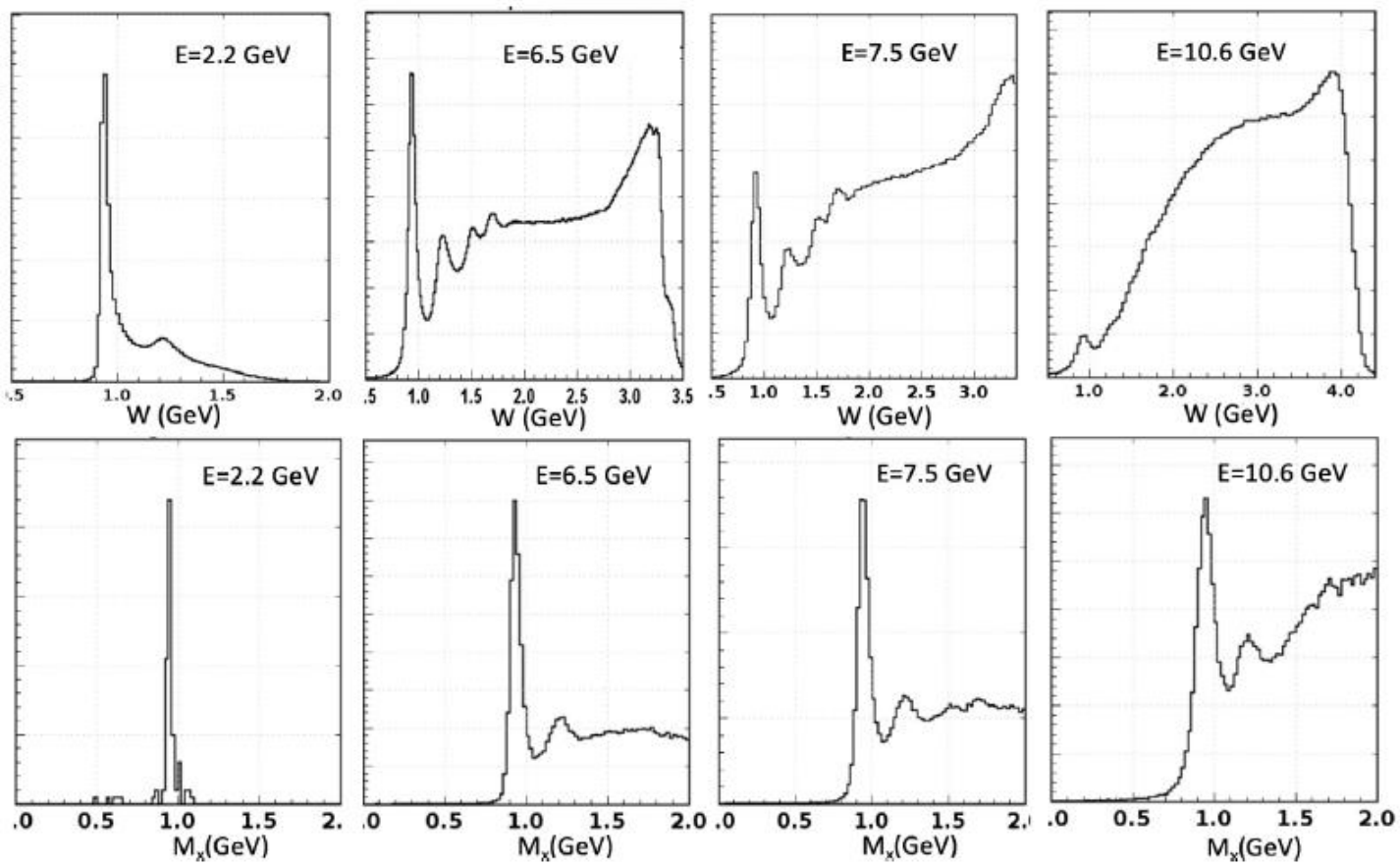



| | Forward | Central |
|---|---|---|
| Angular coverage | 5° – 35° | 35° – 135° |
| Momentum resolution | dp/p < 1% | dp/p < 5% |
| θ resolution | 1 mrad | 5 – 10 mrad |
| φ resolution | 1 mrad/sinθ | 5 mrad/sinθ |

# Exclusive and Inclusive Processes

*Note: Inclusive ep → e'X spectrum is 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

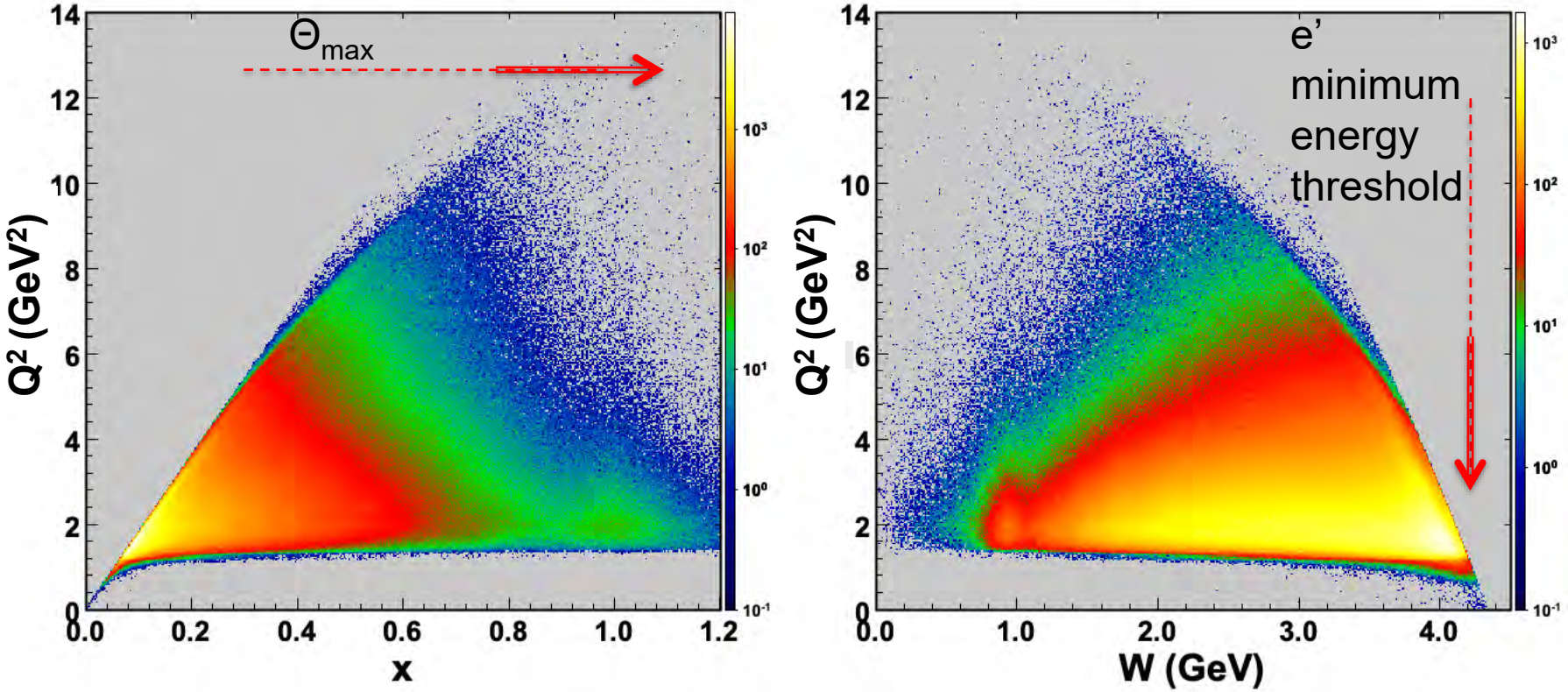
Examples of missing mass spectra
in $ep \rightarrow e'\pi^+X$ at the same energies

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

# CLAS12 Kinematic Reach

Beam energy at 10.6 GeV, Torus current 3770 A, electrons in-bending, Solenoid magnet at 2416 A

p(e,e')X




Electron ID

HTCC hit
+
ECAL cluster
+
DC track
+
TOF hit

Plots based on 200 min. of data taking

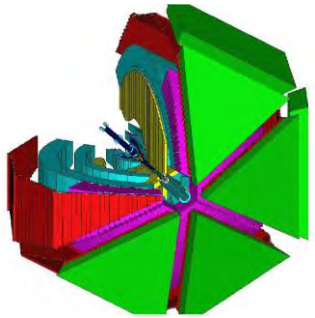
# CLAS (But not CLAS12) Results

# CLAS N* Program Measurement Overview

| Reaction | Observable | $Q^2$ ($GeV^2$) | W (GeV) | Reference |
|---|---|---|---|---|
| $ep \to ep\pi^+\pi^-$ | $d\sigma/dM$, $d\sigma/\cos\theta$, $d\sigma/d\alpha$ | 0.4 - 1.0 | 1.3 - 1.825 | PRC 98, 025203 (2018) |
| | | 2.0 - 5.0 | 1.4 - 2.0 | PRC 96, 025209 (2017) |
| | | 0.25 - 0.60 | 1.34 - 1.56 | PRC 86, 035203 (2012) |
| | | 0.2 - 0.6 | 1.3 - 1.57 | PRC 79, 015204 (2009) |
| | | 0.5 - 1.5 | 1.4 - 2.1 | PRL 91, 022002 (2003) |
| $ep \to ep\pi^0$ | $\sigma_{LT'}$ | 0.4- 1.0 | 1.5 - 1.8 | PRC 105, L022201 (2022) |
| | $d\sigma/d\Omega$ | 0.4- 1.0 | 1.0 - 1.8 | PRL 101, 015208 (2020) |
| | $A_t$, $A_{et}$ | 1.0 - 6.0 | 1.1 - 3.0 | PRC 95, 035207 (2017) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$ | 1.0 - 4.6 | 2.0 - 3.0 | PRC 90, 025205 (2014) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$ | 2.0 - 4.5 | 1.08 - 1.16 | PRC 87, 045205 (2013) |
| | $d\sigma/dt$ | 1.0 - 4.6 | | PRL 109, 112001 (2012) |
| | $d\sigma/d\Omega$ | 3.0 - 6.0 | 1.1 - 1.4 | PRL 97, 112003 (2006) |
| | $A_t$, $A_{et}$ | 0.187 - 0.77 | 1.1 - 1.7 | PRC 78, 045204 (2008) |
| | $\sigma_{LT'}$ | 0.4 - 0.65 | 1.34 - 1.46 | PRC 72, 058202 (2005) |
| | $A_t$, $A_{et}$ | 0.5 - 1.5 | 1.1 - 1.3 | PRC 68, 035202 (2003) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$ | 0.4 - 1.8 | 1.1 - 1.4 | PRL 88, 122001 (2002) |
| $ep \to en\pi^+$ | $A_t$, $A_{et}$ | 1.0 - 6.0 | 1.1 - 3.0 | PRC 95, 035206 (2017) |
| | $A_t$, $A_{et}$ | 0.05 - 5.0 | 1.1 - 2.6 | PRC 94, 05520 (2016) |
| | $A_t$, $A_{et}$ | 0.0065 - 0.35 | 1.1 - 2.0 | PRC 94, 045207 (2016) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$ | 1.8 - 4.5 | 1.6 - 2.0 | PRC 91, 045203 (2015) |
| | $d\sigma/dt$ | 1.6 - 4.5 | 2.0 - 3.0 | EPJA 49, 16 (2013) |
| | $\sigma_{LT'}$ | 0.4 - 0.65 | 1.1 - 1.3 | PRC 85, 035208 (2012) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$, $\sigma_{LT'}$ | 1.7 - 4.5 | 1.15 - 1.7 | PRC 77, 015208 (2008) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$ | 0.25 - 0.65 | 1.1 - 1.6 | PRC 73, 025204 (2006) |
| | $\sigma_{LT'}$ | 0.4 - 0.65 | 1.34 - 1.46 | PRC 72, 058202 (2005) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$ | 2.12 - 4.16 | 1.11 - 1.15 | PRC 70, 042201 (2004) |
| | $A_{et}$ | 0.35 - 1.5 | 1.12 - 1.72 | PRL 88, 082001 (2002) |

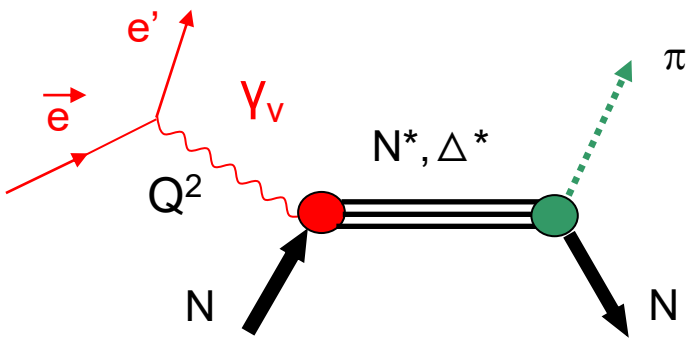
| Reaction | Observable | $Q^2$ ($GeV^2$) | W (GeV) | Reference |
|---|---|---|---|---|
| $en \to ep\pi^-$ | $A_t$, $A_{et}$ | 0.05 - 5.0 | 1.1 - 2.6 | PRC 94, 05520 (2016) |
| $ep \to ep\eta$ | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$ | 1.6 - 4.6 | 2.0 - 3.0 | PRC 95, 035202 (2017) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$ | 0.13 - 3.3 | 1.5 - 2.3 | PRC 76, 015204 (2007) |
| | $d\sigma/d\Omega$ | 0.25 -1.50 | 1.5 - 1.86 | PRL 86, 1702 (2001) |
| $ep \to eK^+Y$ | $P^0$ | 0.8 - 3.2 | 1.6 - 2.7 | PRC 90, 035202 (2014) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$, $\sigma_{LT'}$ | 1.4 - 3.9 | 1.6 - 2.6 | PRC 87, 025204 (2013) |
| | $P'_x$, $P'_z$ | 0.7 - 5.4 | 1.6 - 2.6 | PRC 79, 065205 (2009) |
| | $\sigma_{LT'}$ | 0.65, 1.0 | 1.6 - 2.05 | PRC 77, 065208 (2008) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$, $\sigma_{LT'}$ | 0.5 - 2.8 | 1.6 - 2.4 | PRC 75, 045203 (2007) |
| | $P'_x$, $P'_z$ | 0.3 - 1.5 | 1.6 - 2.15 | PRL 90, 131804 (2003) |
| $ep \to ep\omega$ | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$ | 1.725 - 4.85 | 1.85 - 2.77 | EPJA 24, 445 (2005) |
| $ep \to ep\rho^0$ | $\sigma_U$ | 1.6 - 5.6 | 1.8 - 2.8 | EPJA 39, 5 (2009) |
| | $\sigma_L/\sigma_T$ | 1.5 - 3.0 | 1.85 - 2.2 | PLB 605, 256 (2005) |
| $ep \to ep\phi$ | $d\sigma/dt$ | 1.4 - 3.8 | 2.0 - 3.0 | PRC 78, 025210 (2008) |
| | $d\sigma/dt'$ | 0.7 - 2.2 | 2.0 - 2.6 | PRC 63, 059901 (2001) |

*CLAS: 1997 - 2012*



# Overview of Extractions of Electrocouplings

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




Analysis codes employed for extractions:

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

} for πN and ηN

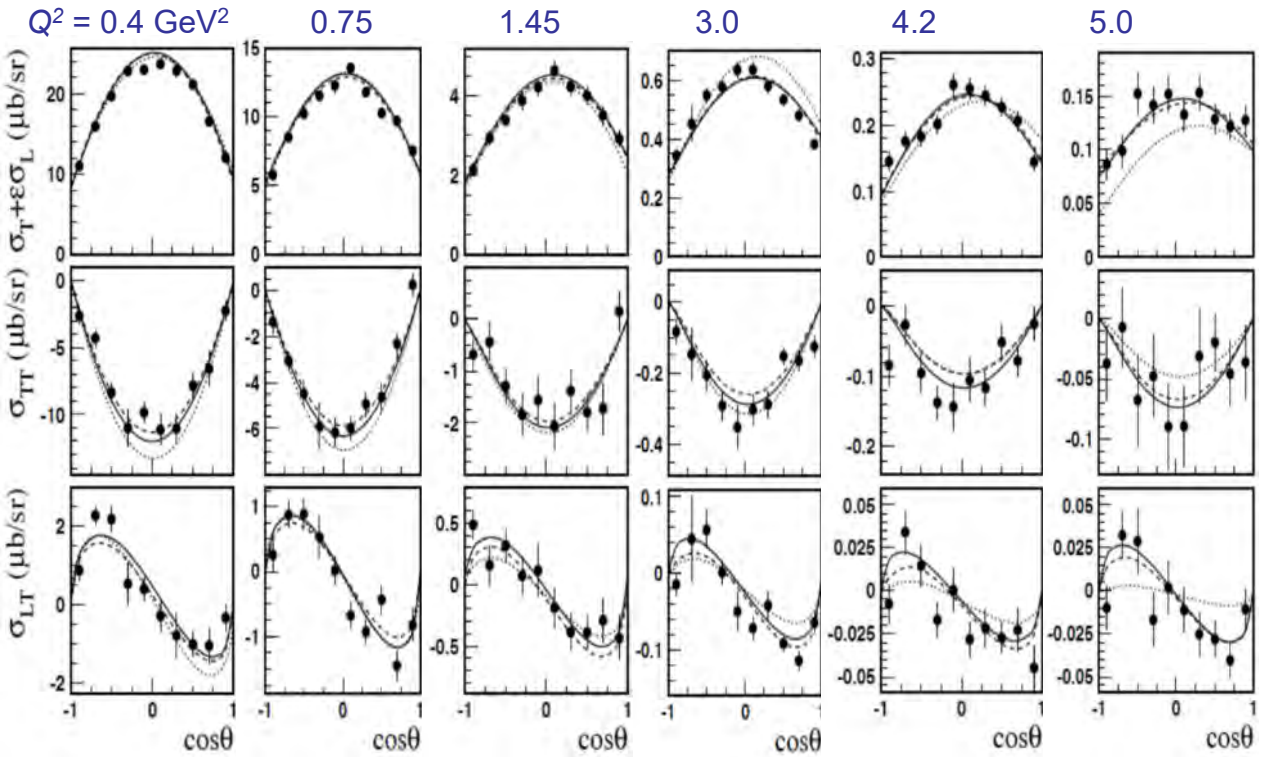
- Data-driven reaction model for $\pi^+\pi^- N$ (JM09, JM16, JM19)

*Aznauryan et al., Int. J. Mod. Phys. E 22, 1330015 (2013)*
*Mokeev, FBS 57, 909 (2016); Mokeev and Carman, FBS 63, 59 (2022)*

# CLAS N* Electrocouplings – First Resonance Region

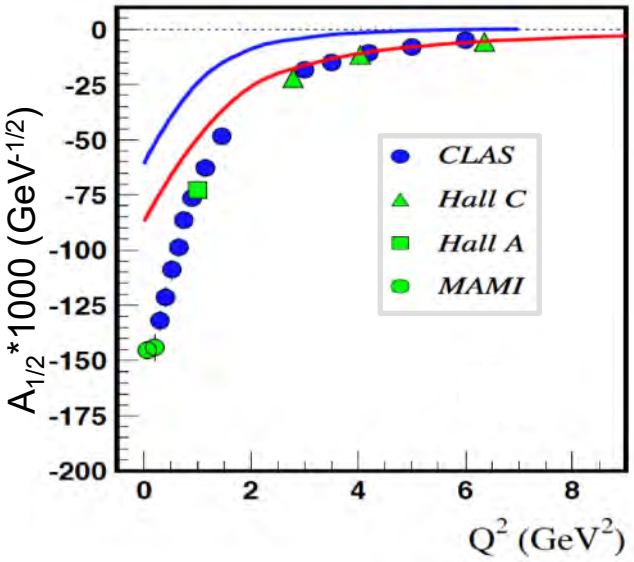
$\gamma^* p \rightarrow \pi^0 p$

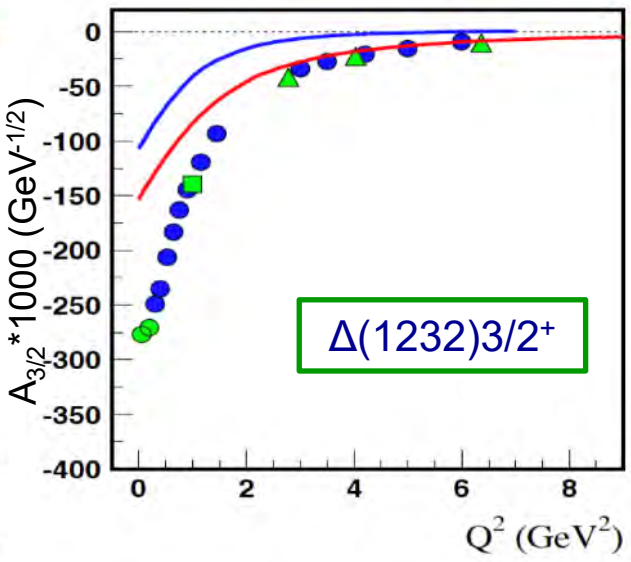
W = 1.232 GeV

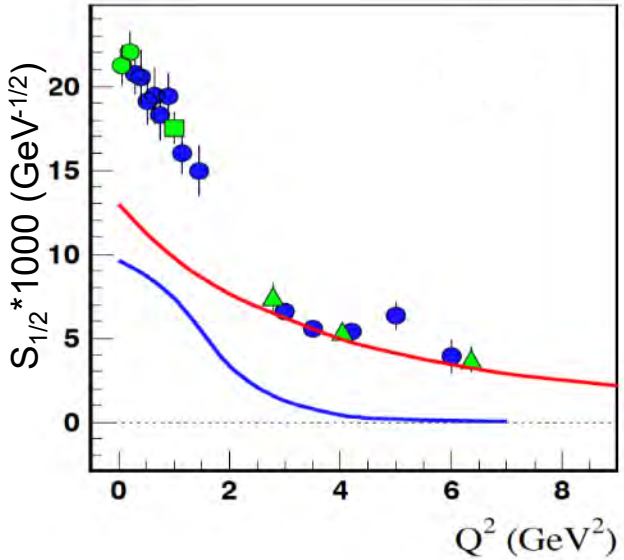



Good agreement between UIM and DR approaches

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

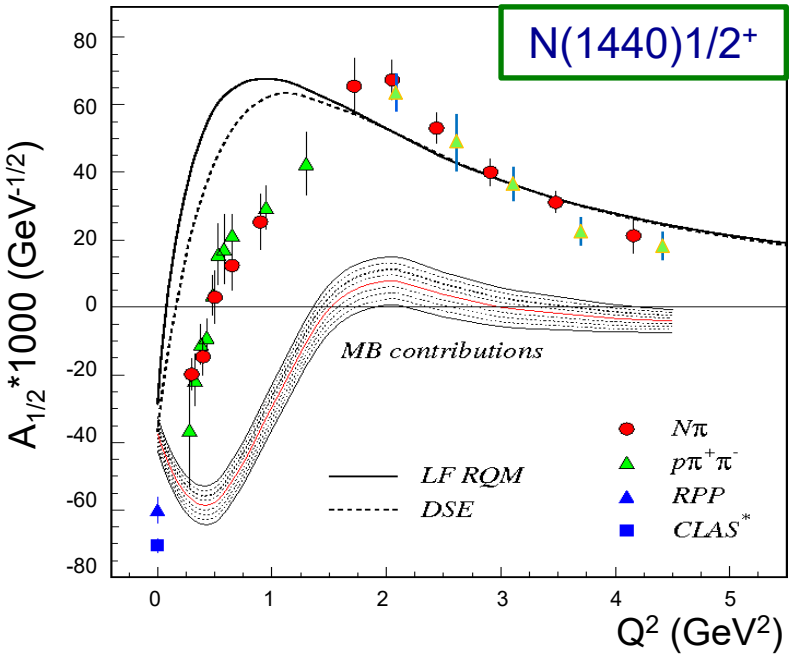


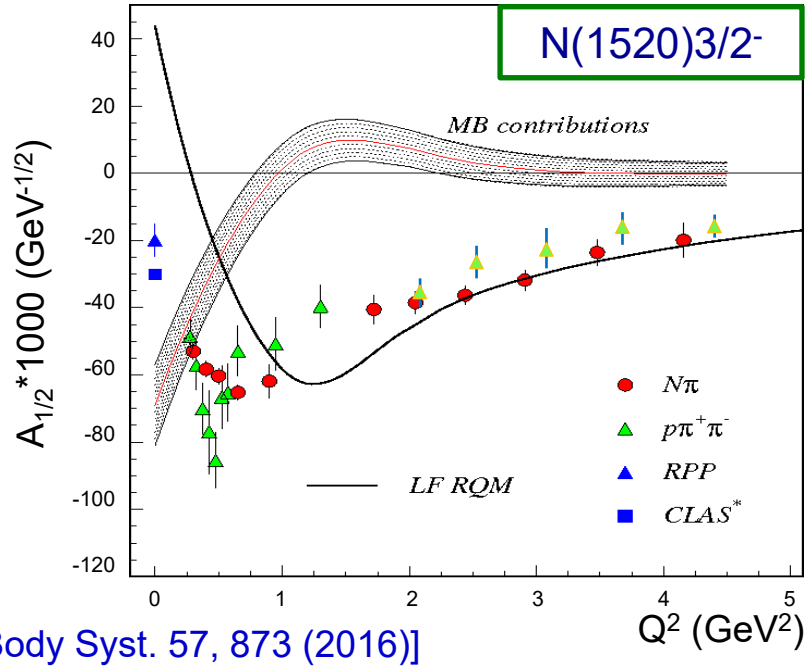




QCD calculations compatible with data where meson cloud does not contaminate evolution $Q^2 \leq 2$ GeV$^2$

# CLAS N* Electrocouplings – Second Resonance Region




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




[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

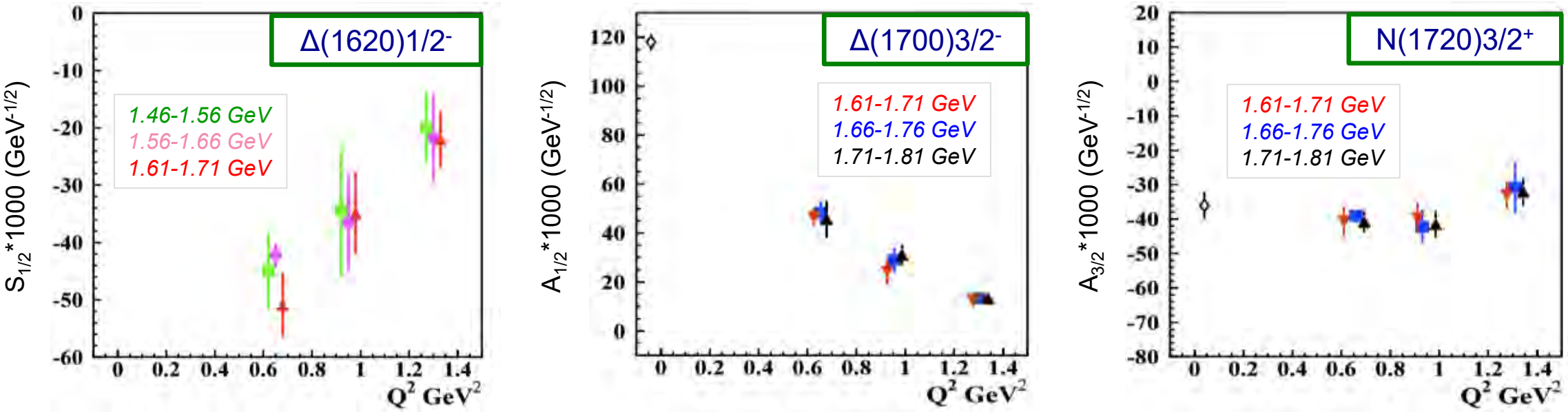
- Different channels have very different mechanisms for non-resonant background

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

# CLAS N* Electrocouplings – Third Resonance Region

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

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

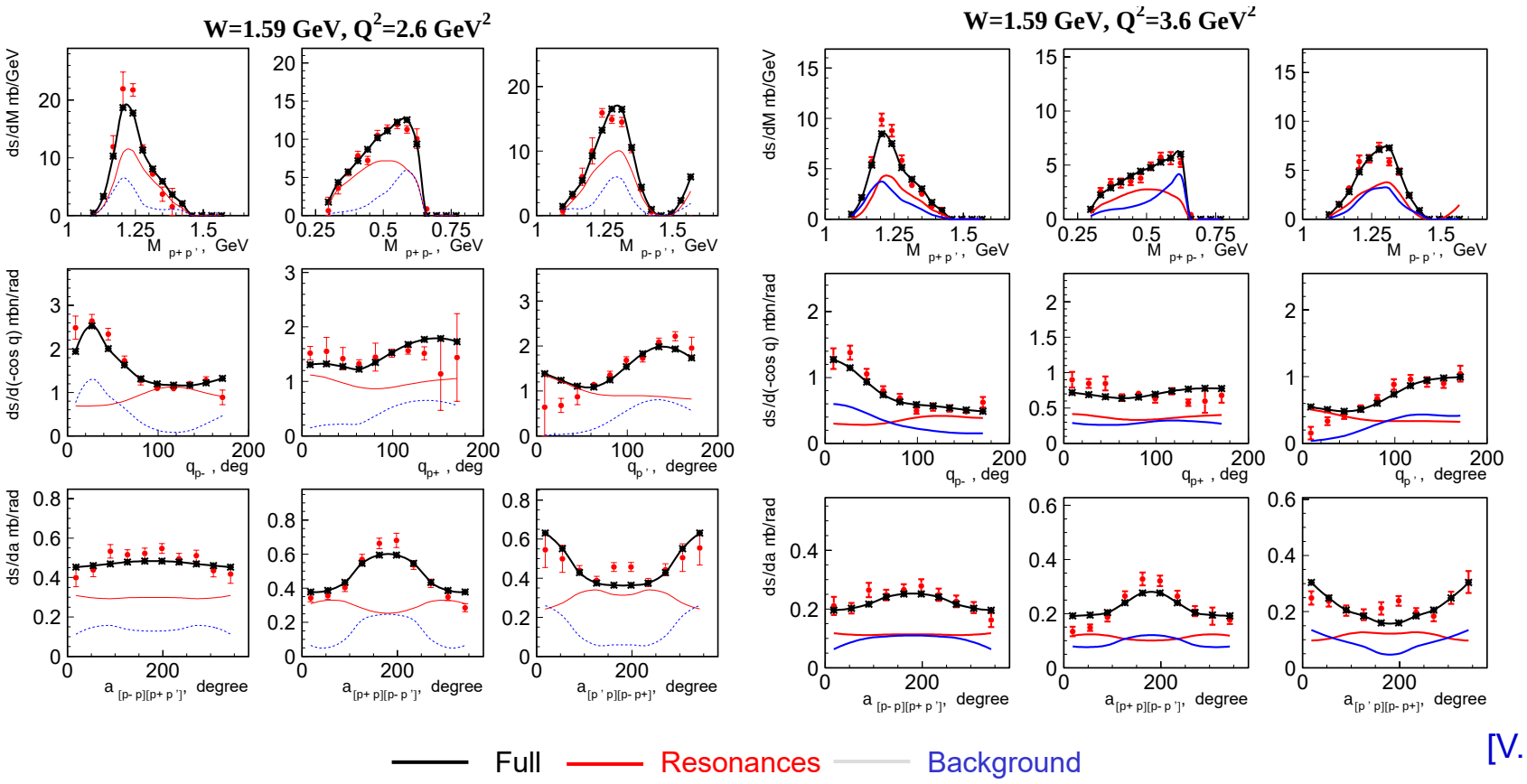



[Mokeev, Aznauryan, IJMPC 26, 1460080 (2014); Mokeev et al., PRC 93, 025206 (2016); Carman, Joo, Mokeev, FBS 61, 29 (2020)]

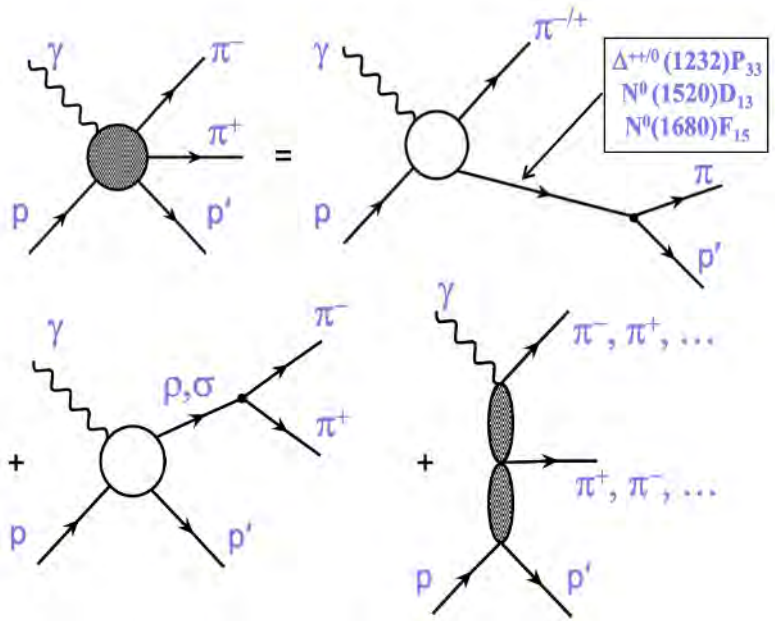
Nππ channel gave first electrocoupling results on higher-lying states up to 1.8 GeV

# Description of $p\pi^+\pi^-$ 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




JLab-Moscow Reaction Model (JM)




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

JM model provides reasonable description of data for extraction of resonance electrocouplings

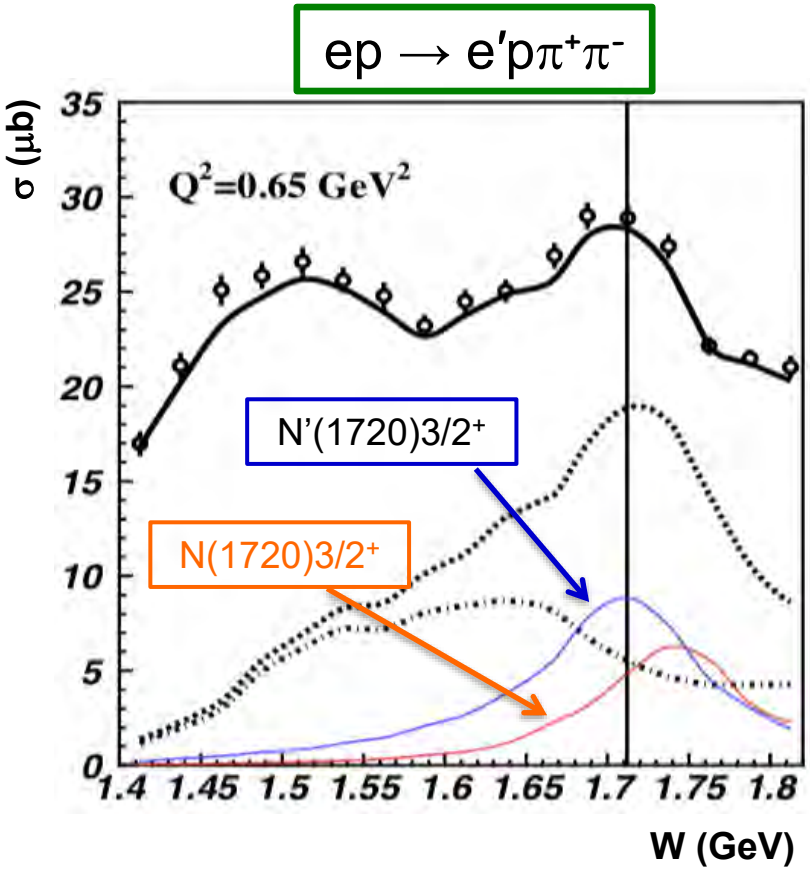
# A New N′(1720) State from Nππ Analysis

| N(1720)3/2⁺ hadronic decays from CLAS data fit with only conventional N* states | | |
|---|---|---|
| | BR(πΔ), % | BR(ρp), % |
| electroproduction | 64-100 | <5 |
| photoproduction | 14-60 | 19-69 |

- N(1720)3/2⁺ **decays** to πΔ and ρp deduced **from γp and $\gamma_v$p** data were **contradictory**
- Impossible to describe data with conventional N* states

| N* hadronic decays from CLAS data fit that incorporates new N'(1720)3/2⁺ state | | |
|---|---|---|
| Resonance | BR(πΔ), % | BR(ρp), % |
| N'(1720)3/2⁺ electroproduction | 47-64 | 3-10 |
| photoproduction | 46-62 | 4-13 |
| N(1720)3/2⁺ electroproduction | 39-55 | 23-49 |
| photoproduction | 38-53 | 31-46 |
| Δ(1700)3/2⁻ electroproduction | 77-95 | 3-5 |
| photoproduction | 78-93 | 3-6 |

- Good description of both γp and $\gamma_v$p data achieved by including **new N'(1720)3/2⁺**

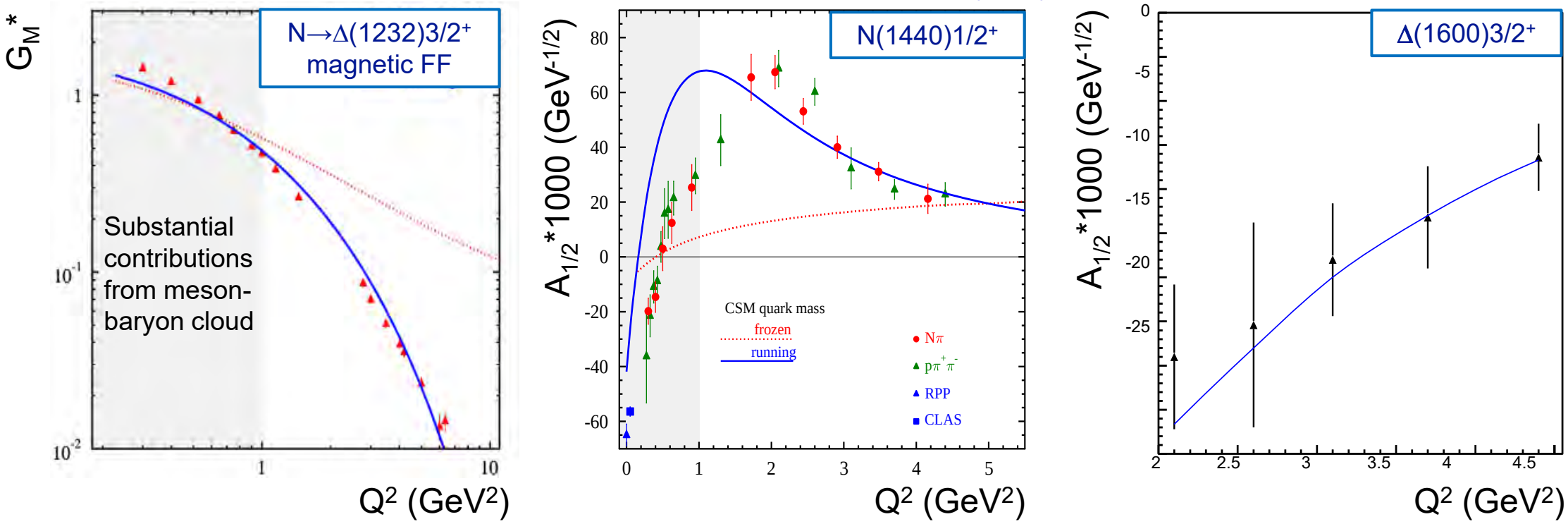



[V.I. Mokeev et al., Phys. Lett. B 805, 135457 (2020)]

⇒ Both, photo- and electroproduction data are essential for a full understanding of the N* spectrum

# 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

# CLAS12 N* Program

- Measure exclusive electroproduction of Nπ, Nη, Nππ, KY final states from unpolarized proton target with longitudinally polarized electron beam

E = 6.6, 8.8, 11 GeV, $Q^2$ = 0.05 → 12 GeV$^2$, $W$ → 3.0 GeV, cos θ = [-1:1]

| | |
|---|---|
| E12-09-003 | Nucleon Resonance Studies with CLAS12 |
| E12-06-108A | KY Electroproduction with CLAS12 |
| E12-16-010A | N* Studies Via KY Electroproduction at 6.6 and 8.8 GeV |
| E12-16-010 | A Search for Hybrid Baryons in Hall B with CLAS12 |

| | | |
|---|---|---|
| RG-A | Spr. 18<br>126 mC | 10.2 GeV,<br>10.6 GeV<br>50% of total |
| | Fall 18<br>99 mC | |
| | Spr. 19<br>58 mC | |
| RG-K | Fall 18<br>28 mC | 6.5 GeV,<br>7.5 GeV<br>10% of total |

continuing in Winter 23

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

# 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 $Q^2 \sim 5$ GeV$^2$
- Electrocouplings of most N* states < 1.8 GeV have been extracted for the first time

**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

# Where Do We Stand in Deciphering Nature?

One-photon approximation,
Effective models …

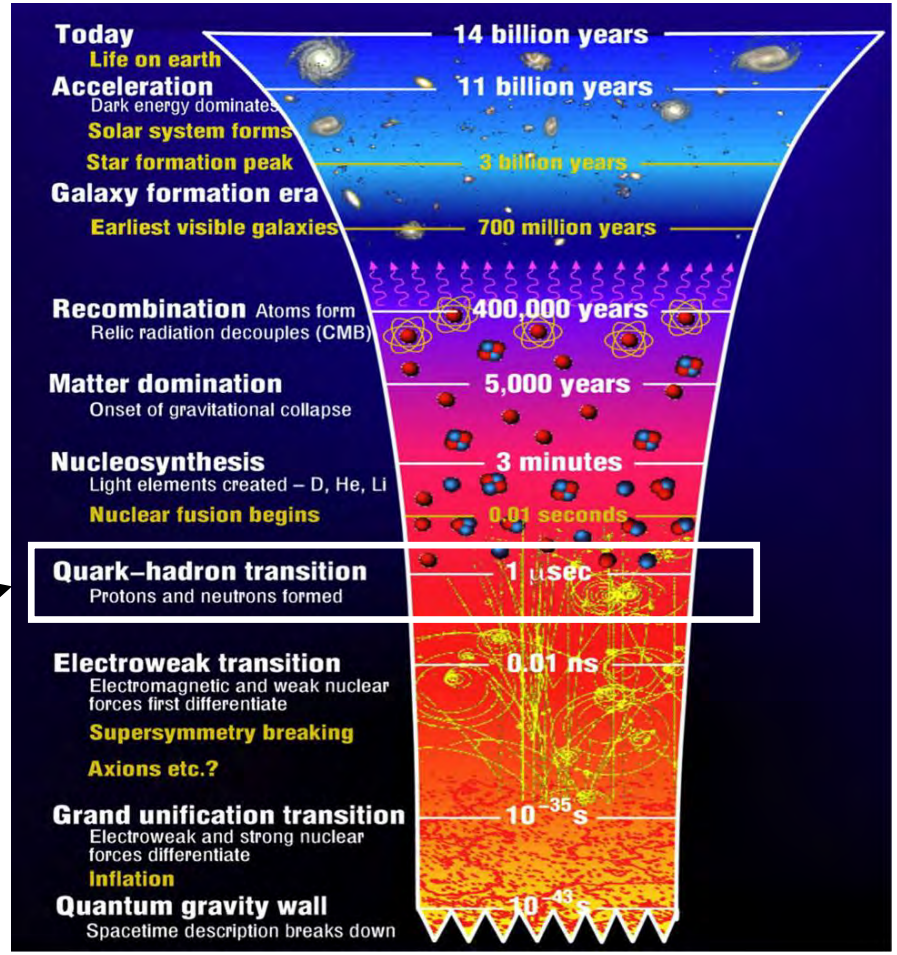
Simplificati…

Complexity

Emergence of mass, Gluon & quark dressing, Running couplings …

Hot QCD, Age of …verse ~10 μs …

Time/Energy




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

Resonances are sufficiently complex to reveal hidden QCD and early Universe phenomena, but not so complex that fundamental theories are bound to fail