Study of Nucleon Resonance Electroexcitations at Jefferson Lab

Patrick Achenbach (Jefferson Lab)

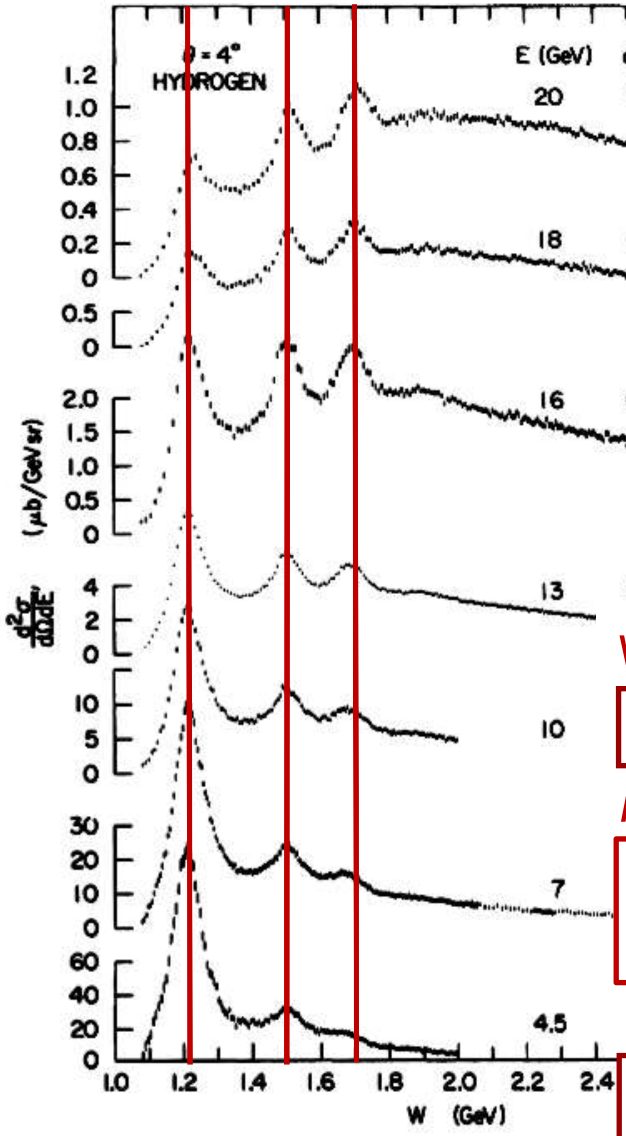
With special credits to
Adnan Bashir, Daniel Carman, Ralf Gothe, and Victor Mokeev
and The CLAS Collaboration

Nov 2o23

Nucleon Resonances

Excitation of Proton Resonances

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



Virtuality of photon:

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

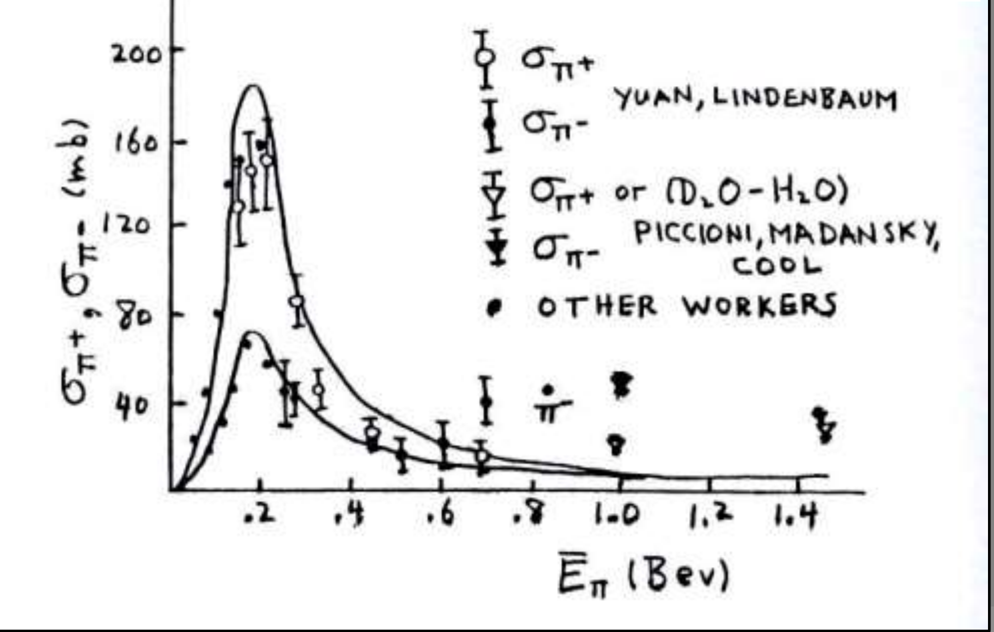
Inelasticity of process:

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

Mass of excited proton:

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

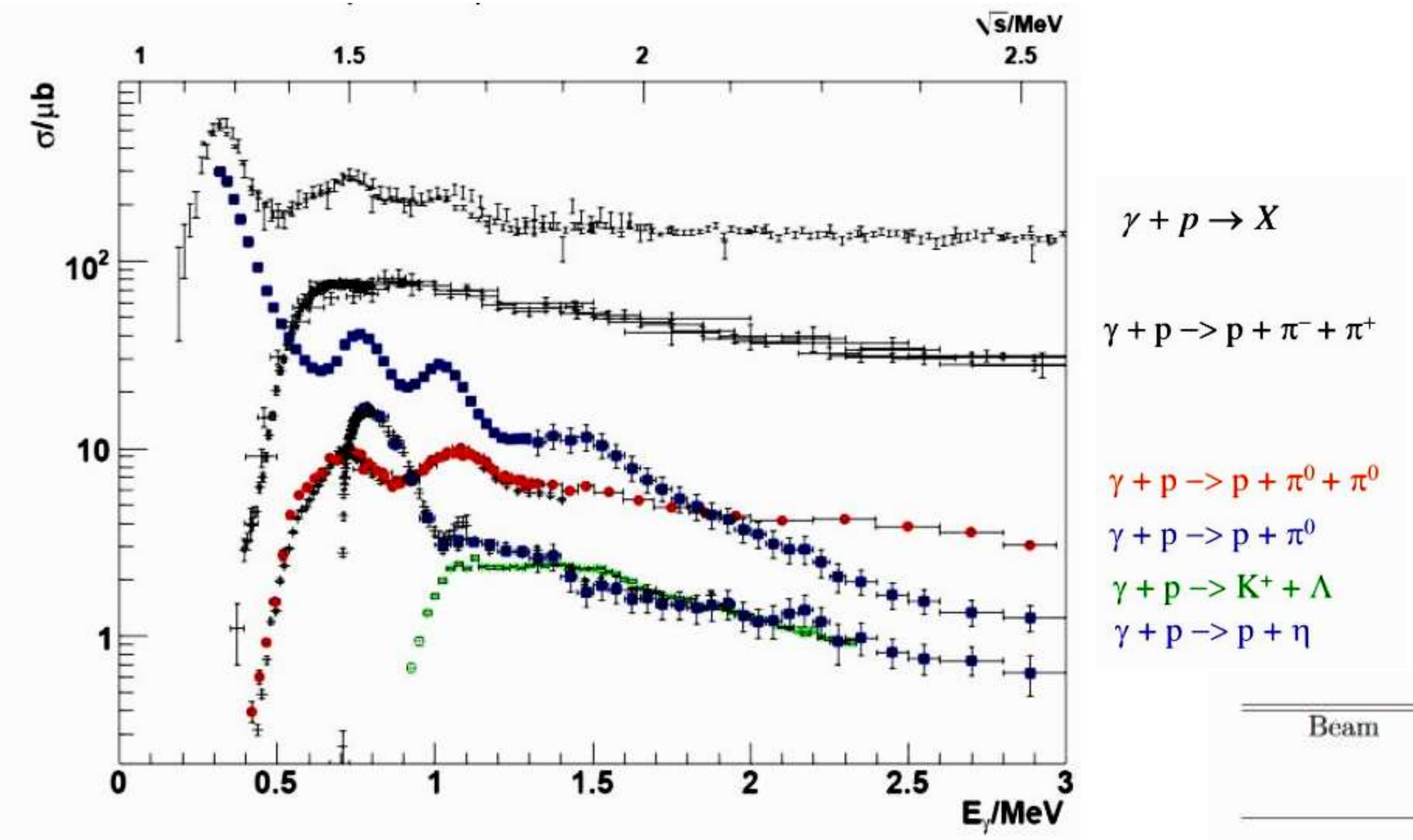
[Yuan, Rochester Conference (1954)]



- 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

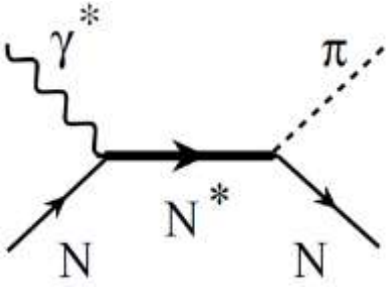


Light baryon spectroscopy has well advanced during the last few decades by meson-production reactions at electron accelerators

– Excitation spectrum / quantum numbers

– Selective and exclusive reactions

Single-pion production as an example

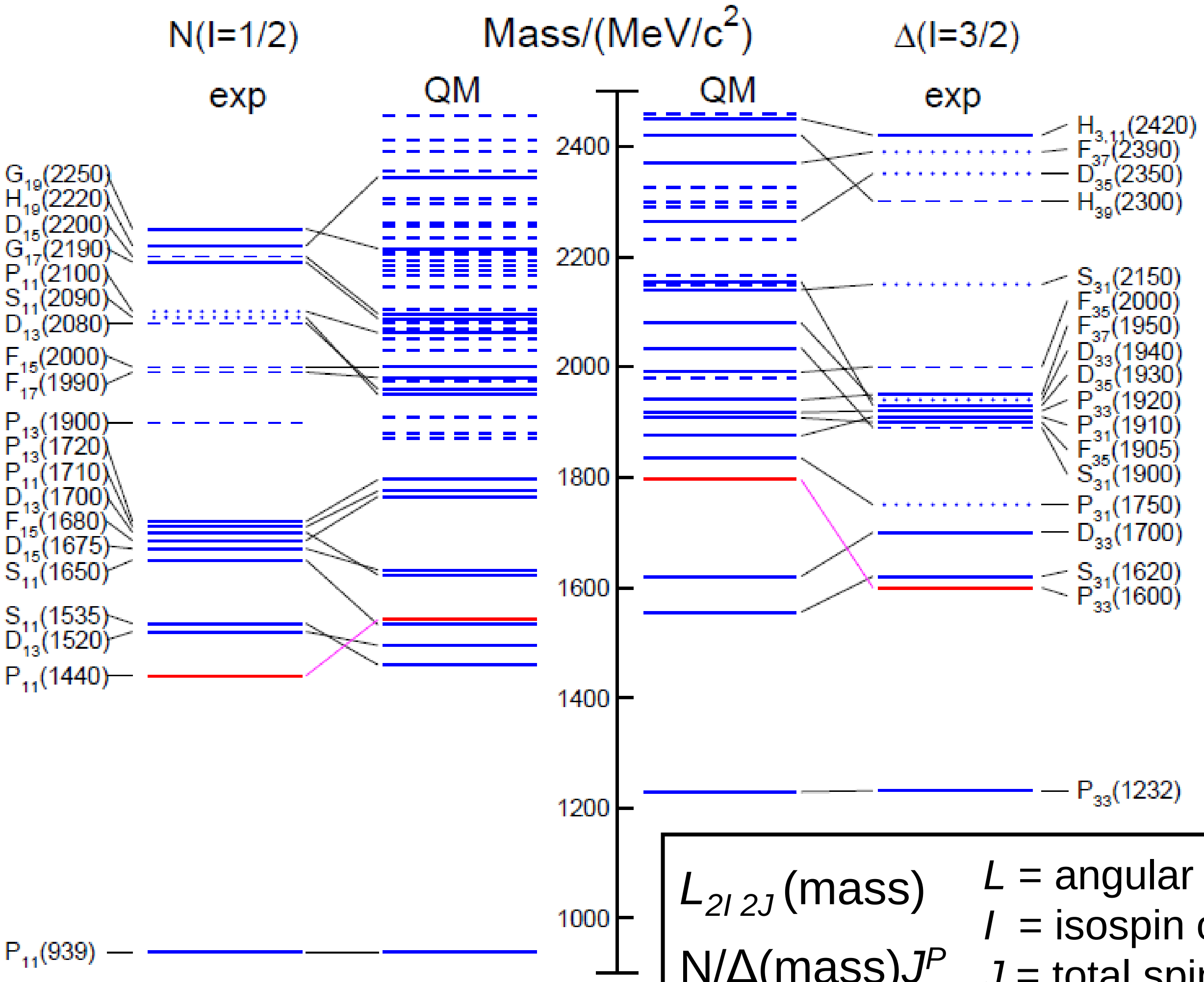


– Transitions amplitudes and Q^2 evolutions

– 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	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		$O_{x'}$	

N* Spectrum in Experiments vs. Quark Models



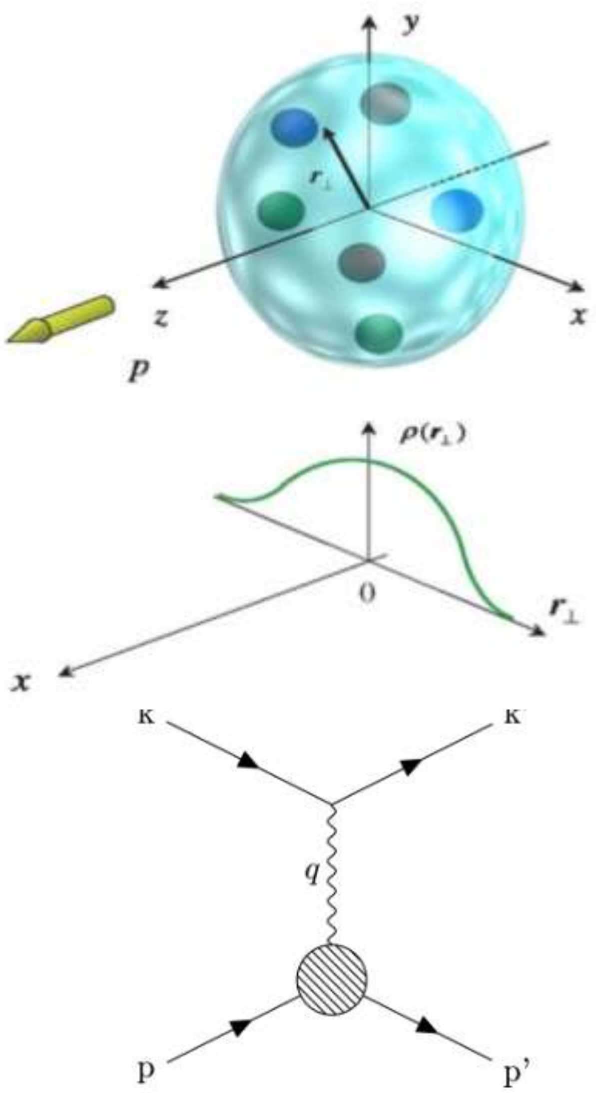
$L_{2I\,2J}$ (mass)	L = angular momentum state
N/Δ(mass)J^P	I = isospin of resonance
	J = total spin of resonance

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$^-$	*	***	**		**	***

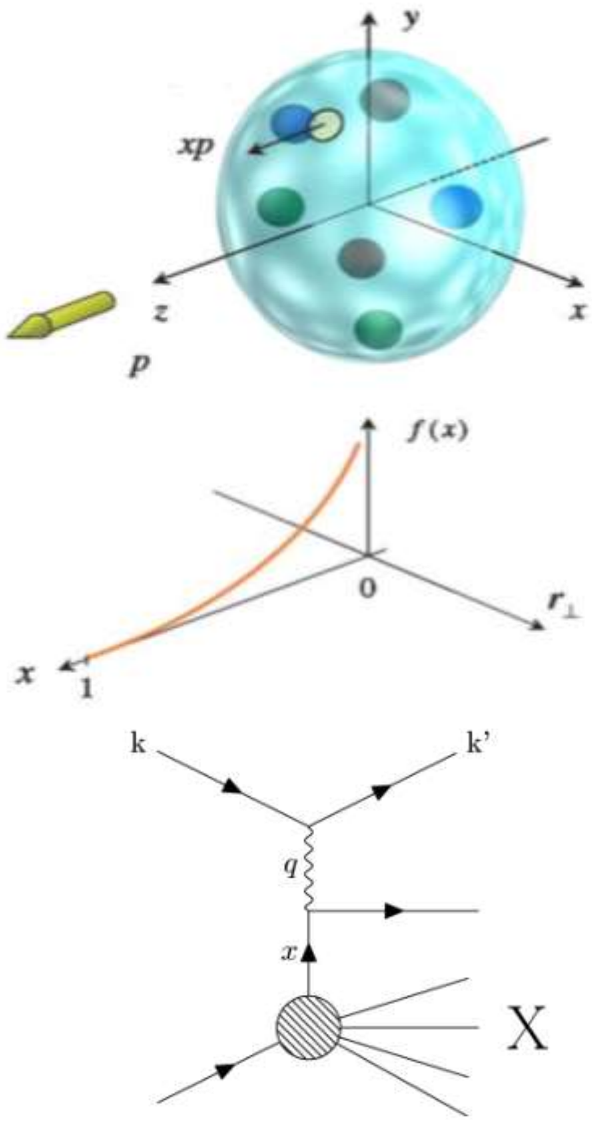
Some problems are evident:
- Ordering and clustering of states
- Missing resonances
- Incomplete/uncertain data (*/**)

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

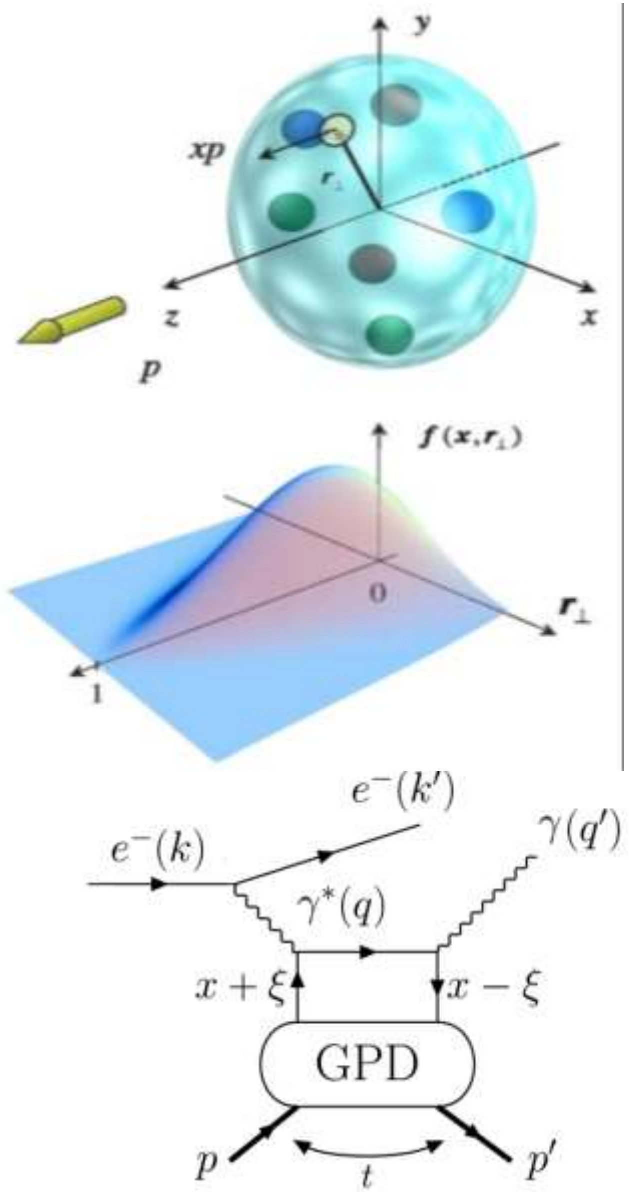
N* Structure in Three Dimensions



[Hofstadter et. al., Phys. Rev. 91, 422 (1953)]
[Hofstadter, Rev. Mod. Phys. 28, 214 (1956)]



[Feynman, Phys. Rev. Lett. 23, 1415 (1969)]



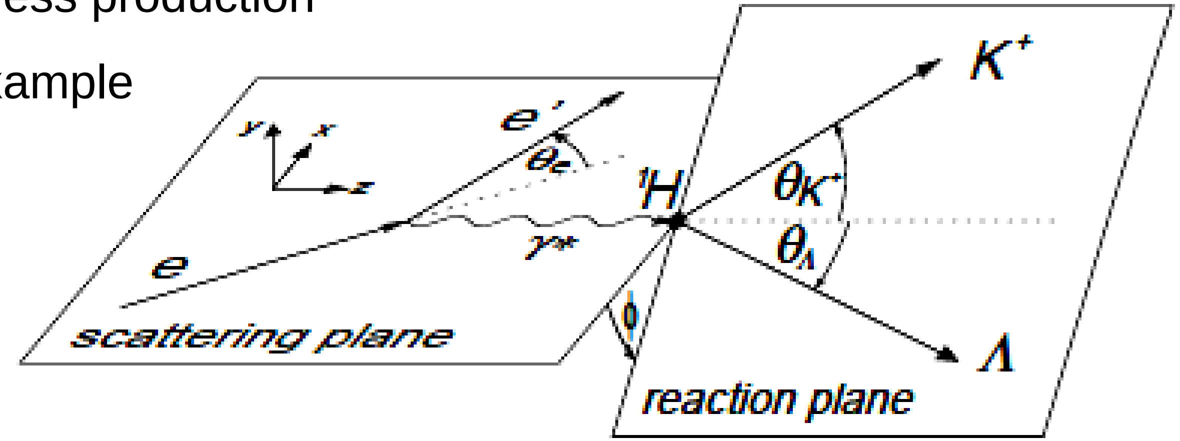
Separation of Cross Sections Into Structure Functions

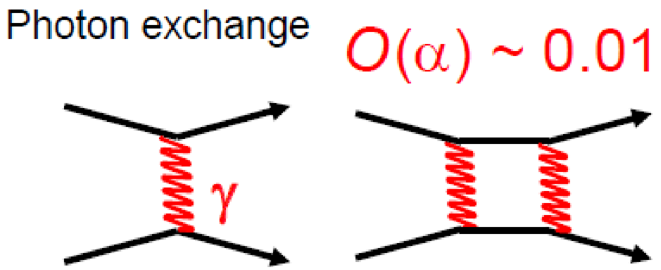
Five-fold differential cross section separates in **virtual photon flux** and **virtual photoproduction**

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

Strangeness production

as an example





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

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

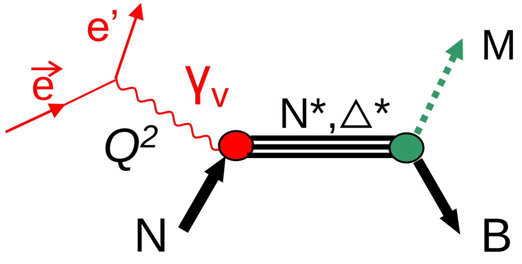
Note: Electron is always detected to define kinematics

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

Extraction of Electroproduction Amplitudes

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

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



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:

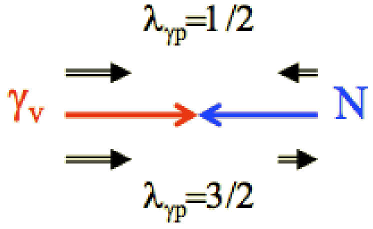
$$\boxed{\Gamma_\gamma^L(M_r,Q^2)} = 2\frac{q^2_{\gamma,r}(Q^2)}{\pi}\frac{2M_N}{(2J_r+1)M_r}|S_{1/2}(Q^2)|^2$$

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

Helicity amplitudes:

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

$S_{1/2}$: longitudinal

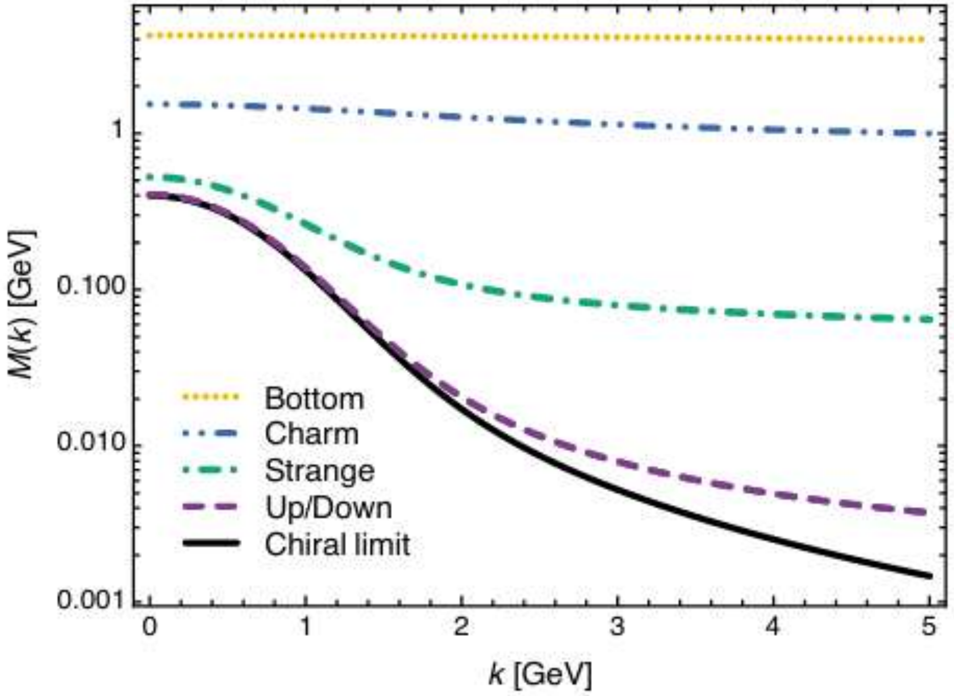


[Mokeev et al., PRC 86 035203 (2012)]

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 more
- Extraction of electrocouplings from low to high Q^2
- Momentum dependence of underlying degrees of freedom shapes N* states and Q^2 evolution of electrocouplings
- Many facets of non-perturbative strong interaction in generation of N* states and emergence from QCD

Emergence of hadron masses from QCD dynamics:

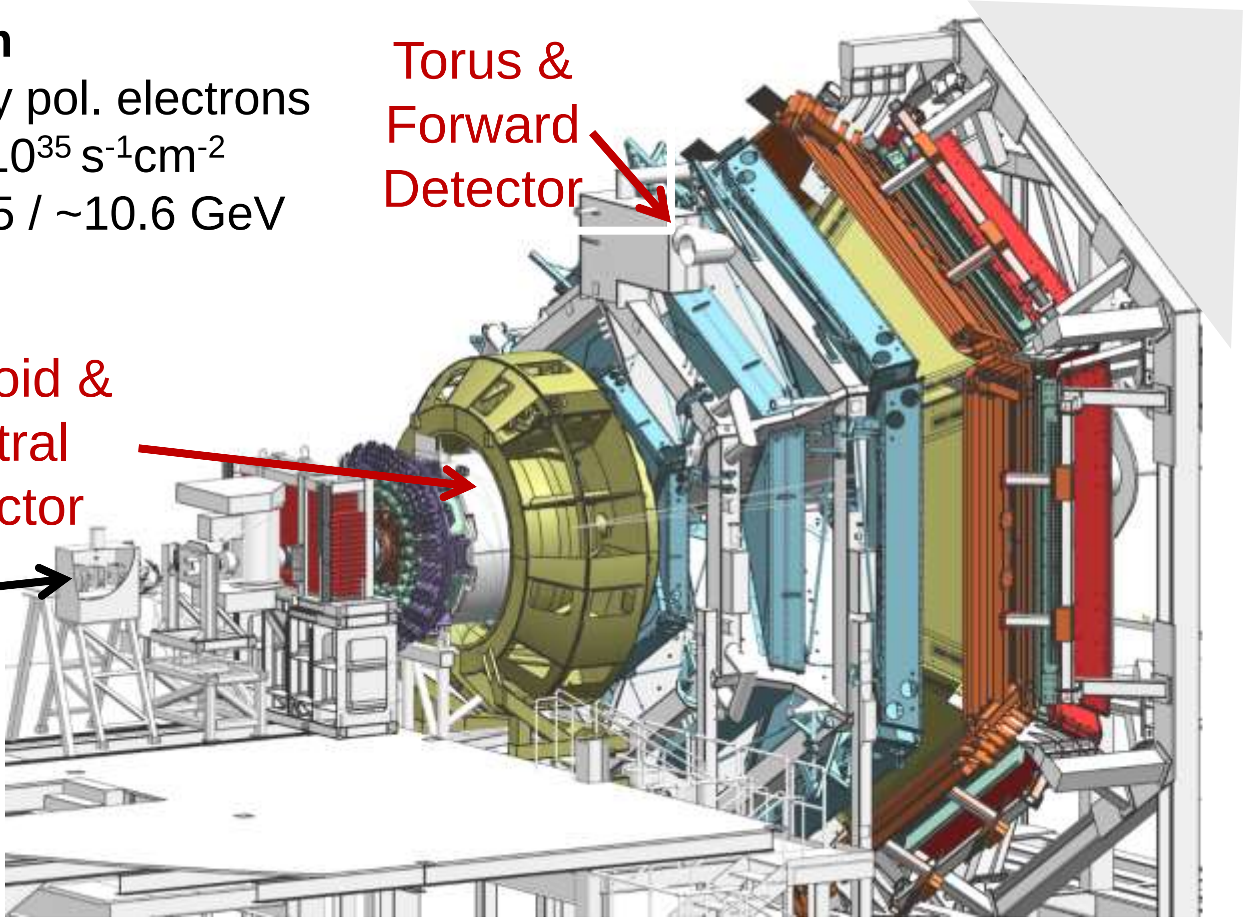


Continuum Schwinger Method
[See talk by C. Roberts]

Goal must be to explore the *spectrum* and *structure* of N* states

The CLAS12 Spectrometer for 12-GeV Beam

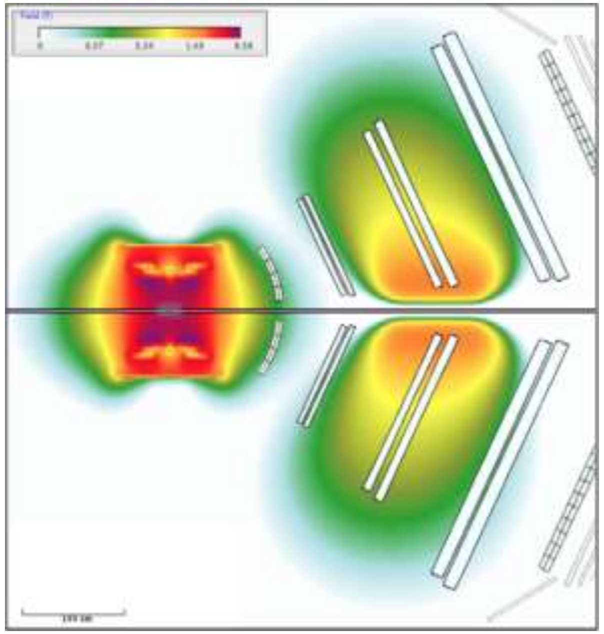
Beam
- 85% longitudinally pol. electrons
- Max. luminosity: $10^{35}\ s^{-1}cm^{-2}$
- Energies: 6.5 / 7.5 / ~10.6 GeV



[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

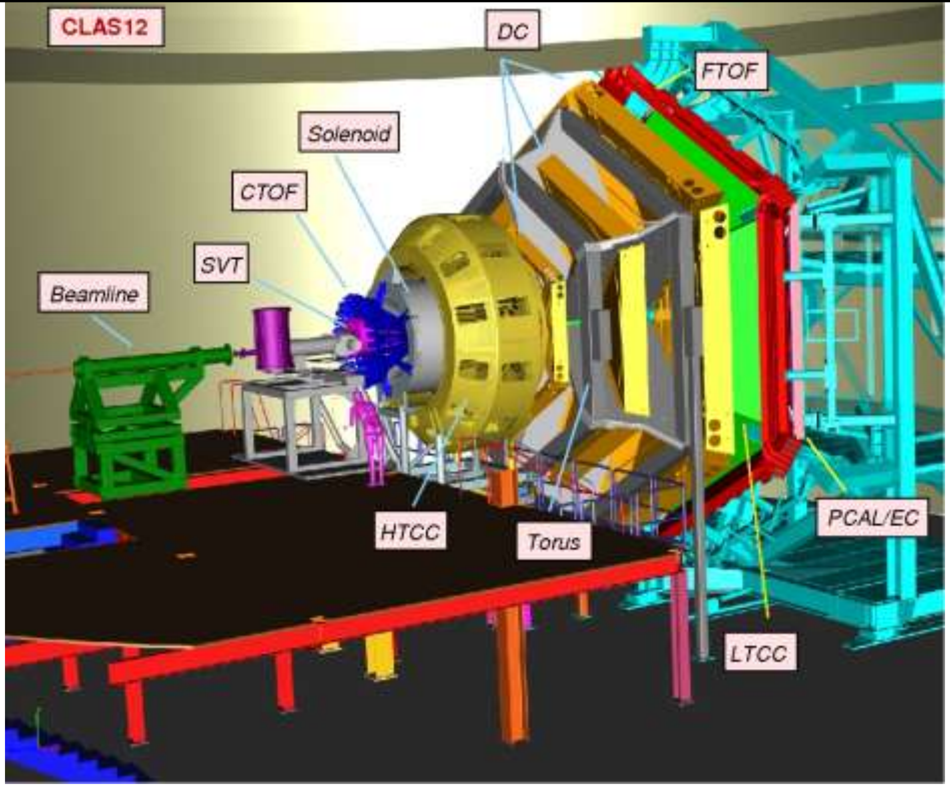


Ideal instrument to study exclusive meson electroproduction in the nucleon resonance region

Subsystems of the CLAS12 Spectrometer

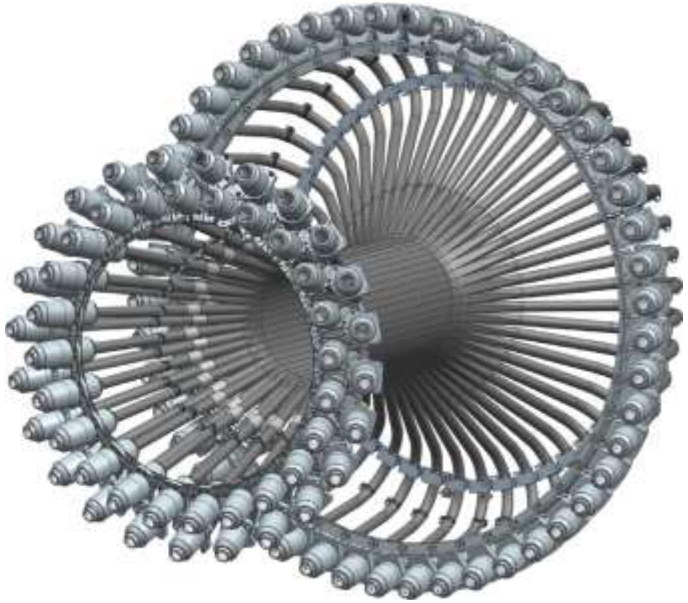
C E N T R A L

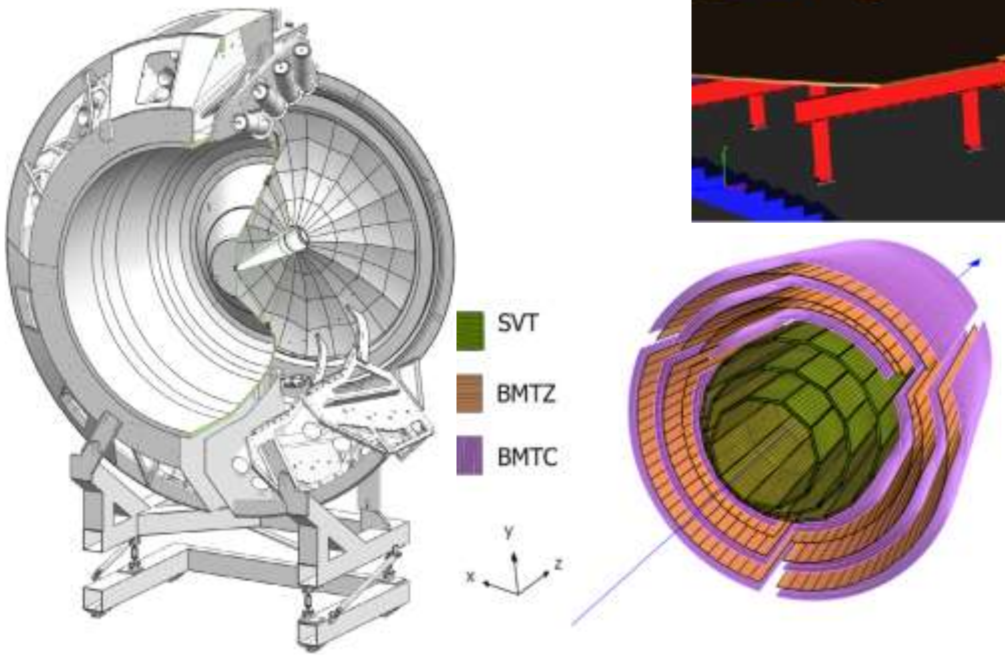
- Beamline
- Target
- Central Vertex Tracker
- Central Time of Flight
- Central Neutron Det.
- Back-Angle Neutron Det.

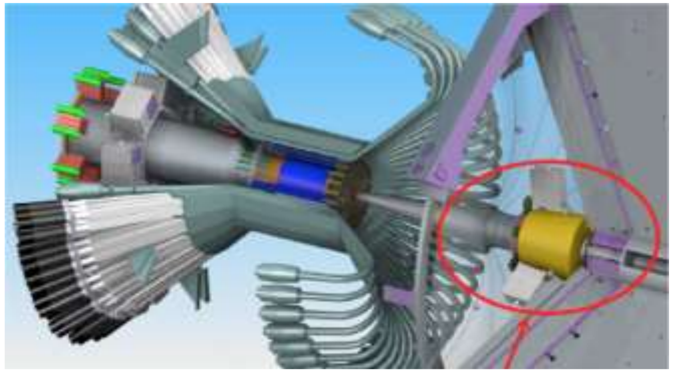


F O R W A R D

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

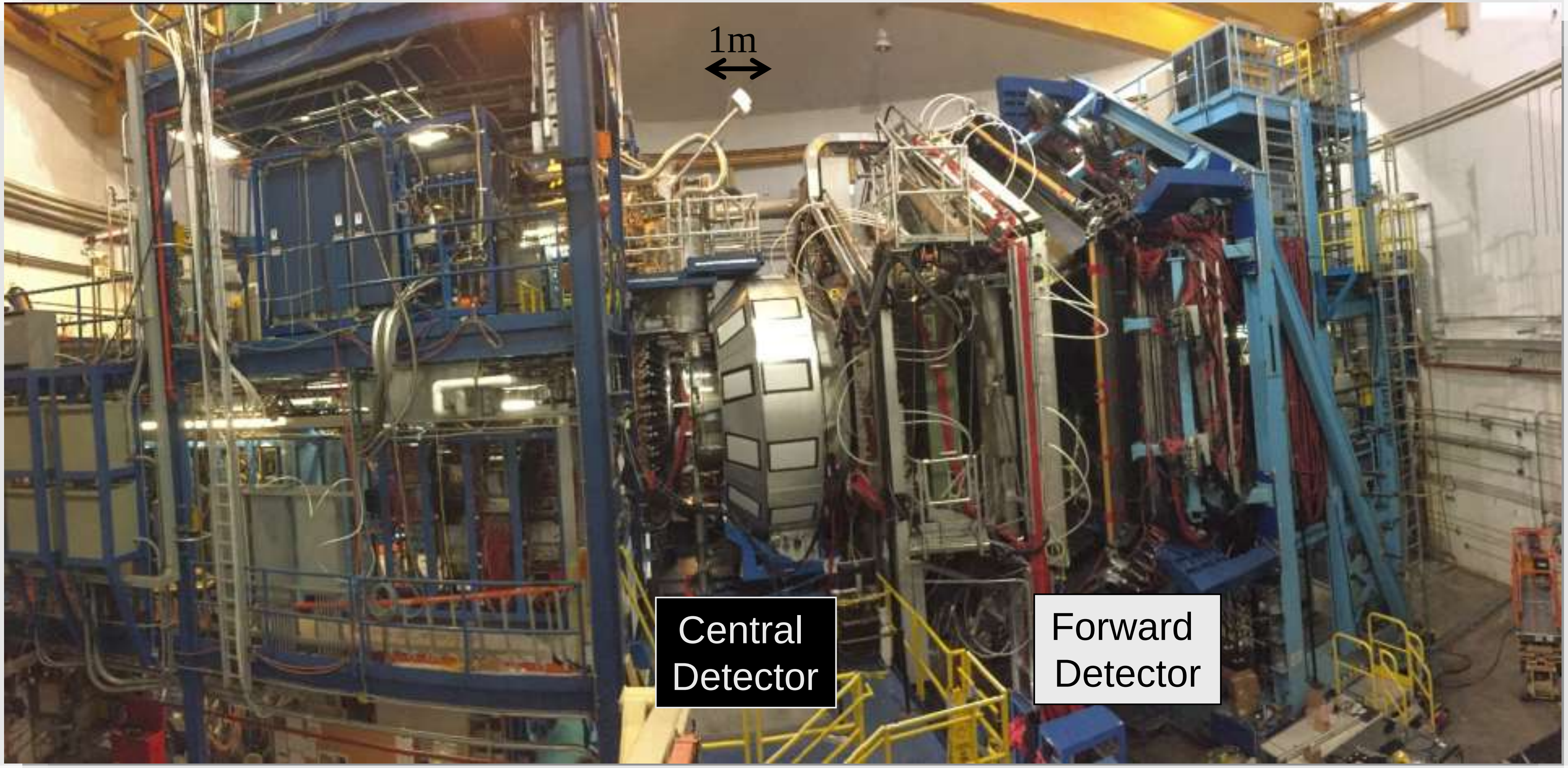




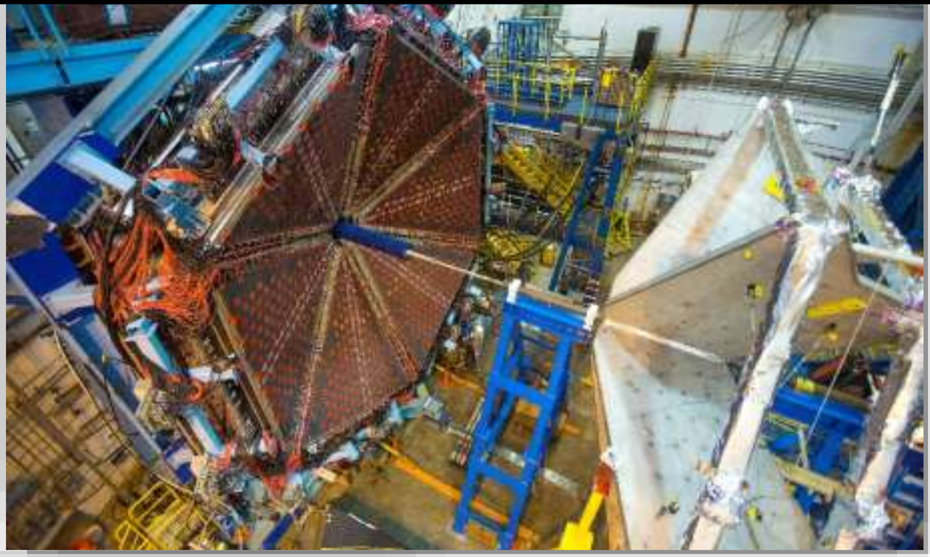


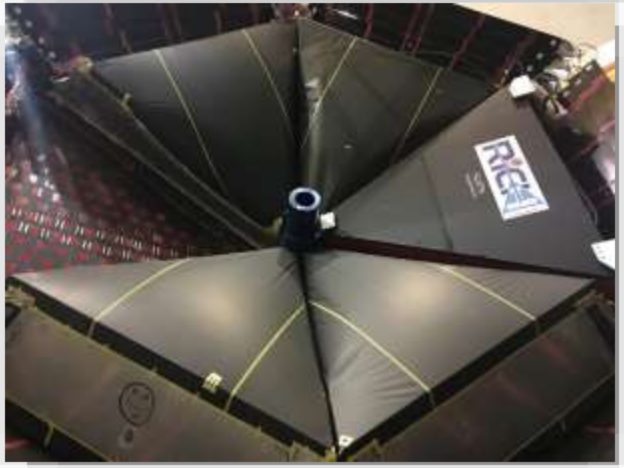
Side View of The Real CLAS12 Spectrometer

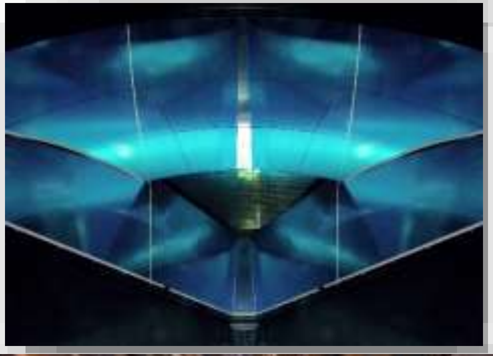
Electron beam

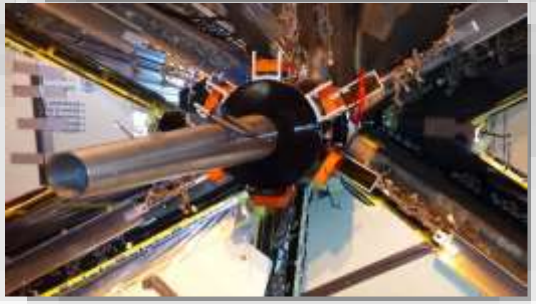


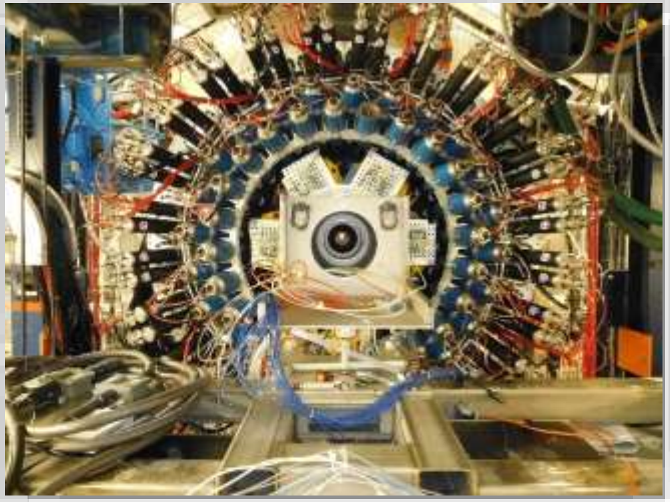
CLAS12 Subsystems During Installation

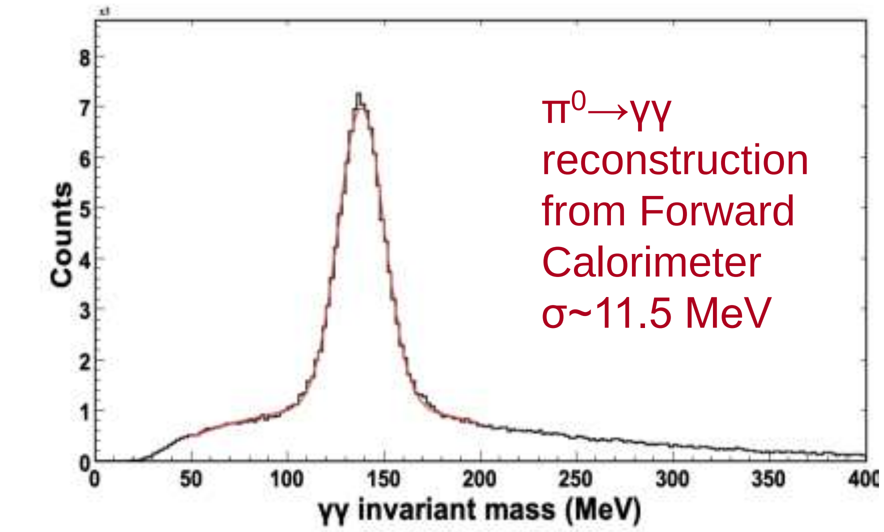


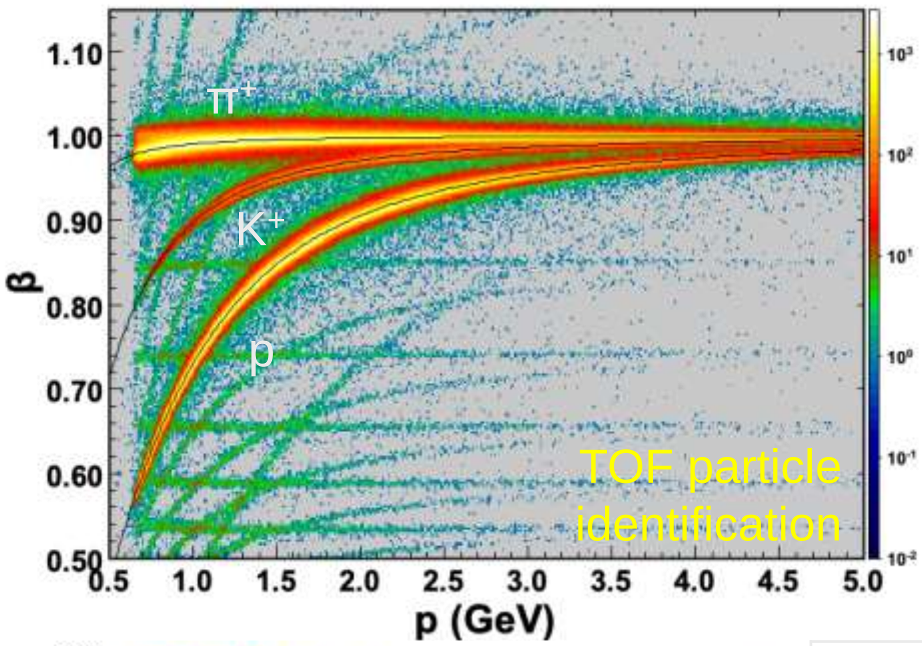




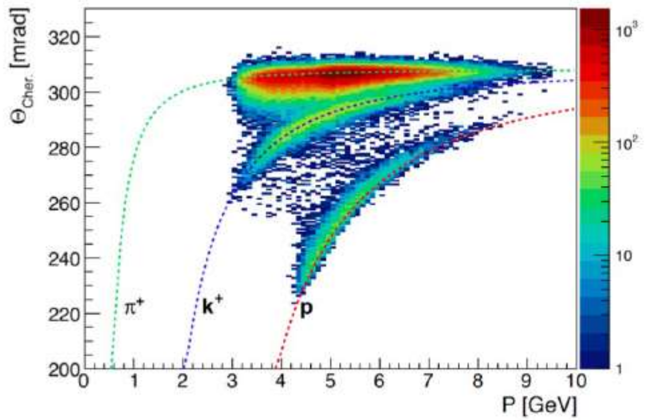


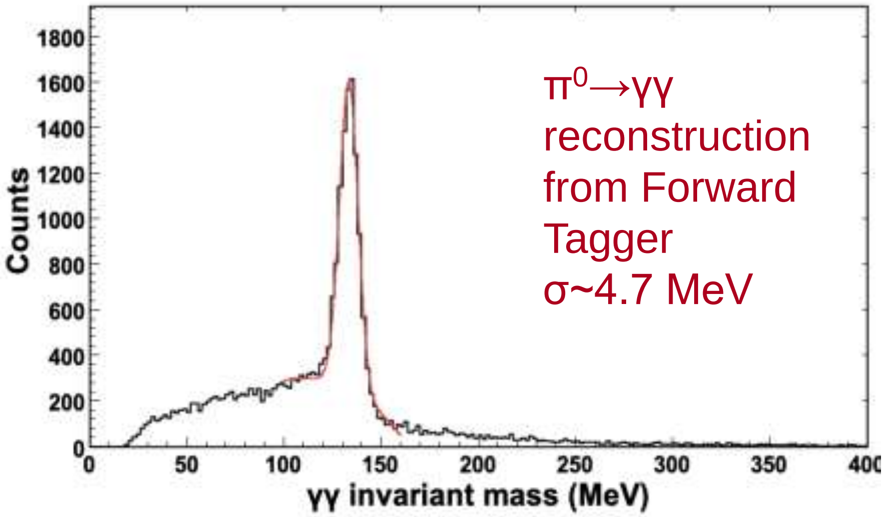


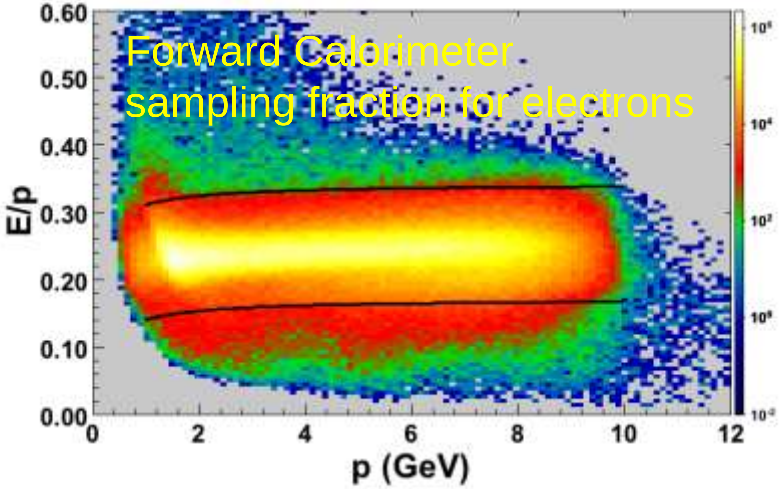




RICH particle
identification





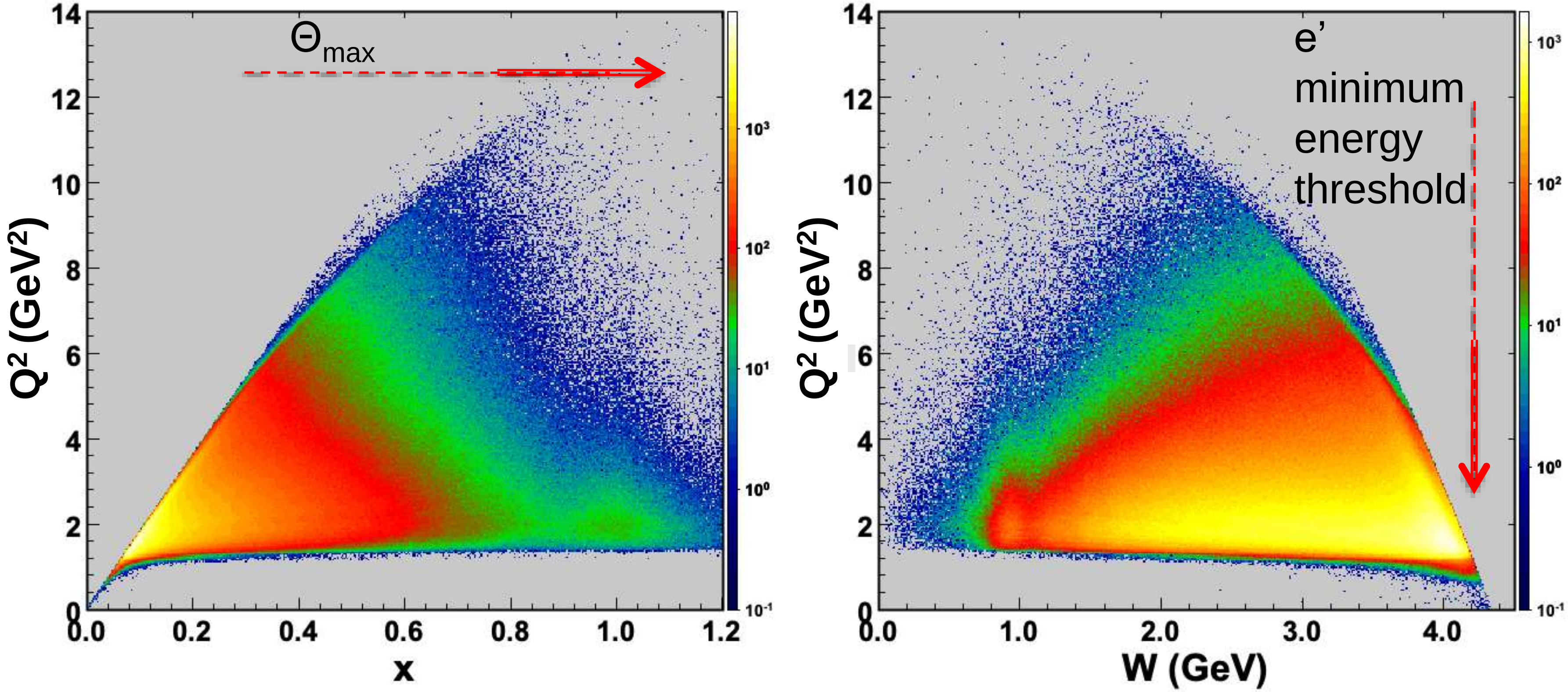


	Forward	Central
Angular coverage	5º – 35º	35º – 135º
Momentum resolution	dp/p < 1%	dp/p < 5%
θ resolution	1 mrad	5 – 10 mrad
φ resolution	1 mrad/sinθ	5 mrad/sinθ

CLAS12 Kinematic Reach

p(e,e')X

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



Electron ID

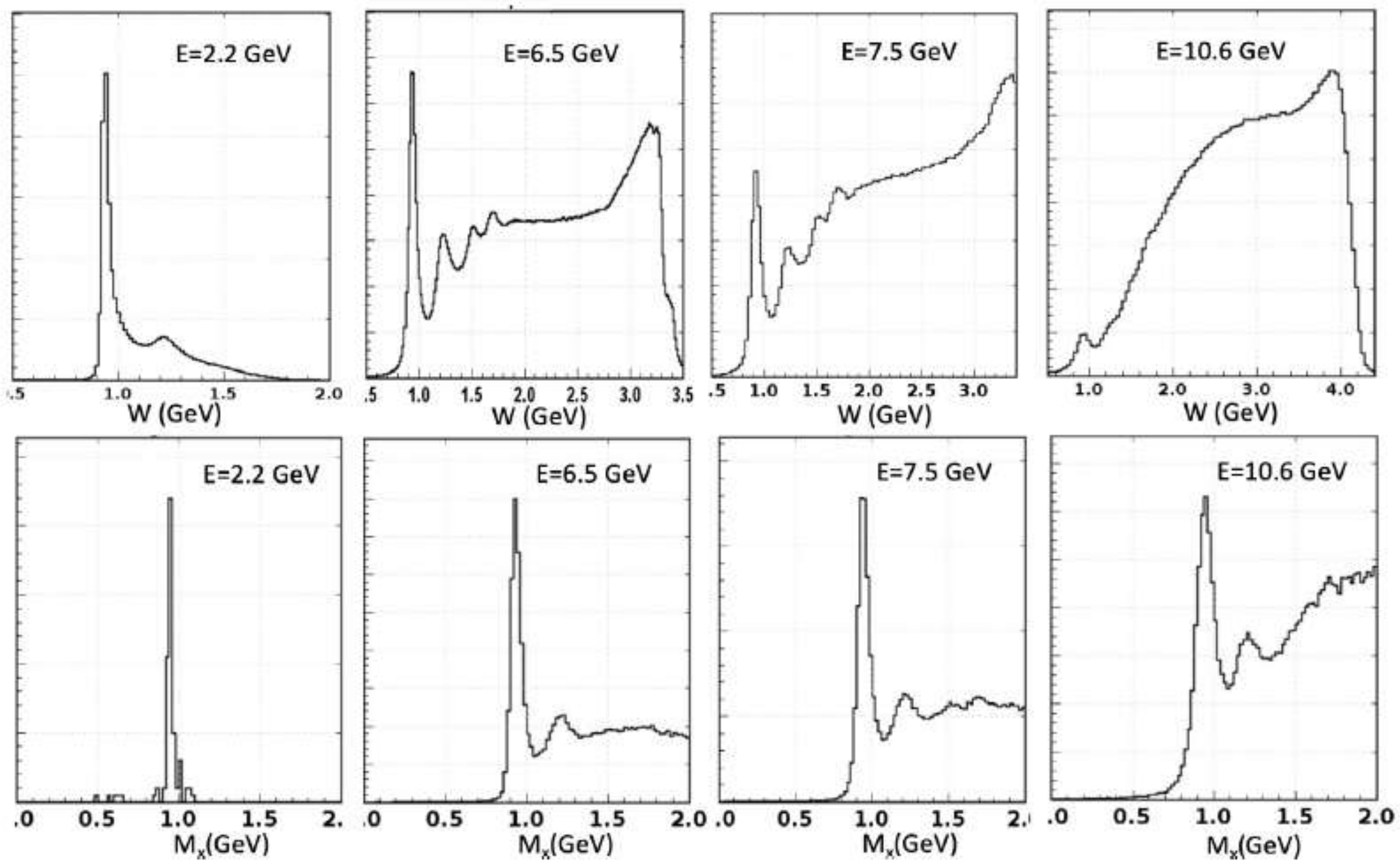
HTCC hit
+
ECAL cluster
+
DC track
+
TOF hit

200 min. of DAQ

Coverage in kinematical quantities Q^2 and x and W of the scattered electrons detected in the FD demonstrates capabilities for nucleon structure studies

Exclusive and Inclusive Processes

Note: Inclusive ep → e'X spectrum is sum over all exclusive channels



Examples of mass
at four different beam energies

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

Examples of missing mass
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

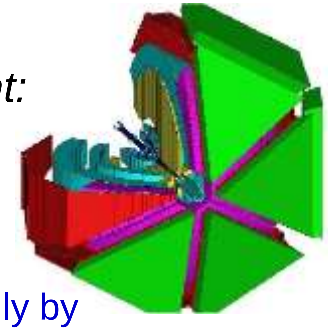
CLAS (CLAS12) N* Results

CLAS N* Program Overview

Reaction	Observable	Q^2 (GeV^2)	W (GeV)	Reference
ep --> ep$\pi^+\pi^-$	dσ/dM, dσ/cosθ, dσ/dα	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 --> epπ^0	$\sigma_{LT'}$	0.4- 1.0	1.5 - 1.8	PRC 105, L022201 (2022)
	dσ/dΩ	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)
	σ_U, σ_{LT}, σ_{TT}	1.0 - 4.6	2.0 - 3.0	PRC 90, 025205 (2014)
	σ_U, σ_{LT}, σ_{TT}	2.0 - 4.5	1.08 - 1.16	PRC 87, 045205 (2013)
	dσ/dt	1.0 - 4.6		PRL 109, 112001 (2012)
	dσ/dΩ	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)
	σ_U, σ_{LT}, σ_{TT}	0.4 - 1.8	1.1 - 1.4	PRL 88, 122001 (2002)
ep --> enπ^+	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)
	σ_U, σ_{LT}, σ_{TT}	1.8 - 4.5	1.6 - 2.0	PRC 91, 045203 (2015)
	dσ/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)
	σ_U, σ_{LT}, σ_{TT}, $\sigma_{LT'}$	1.7 - 4.5	1.15 - 1.7	PRC 77, 015208 (2008)
	σ_U, σ_{LT}, σ_{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)
	σ_U, σ_{LT}, σ_{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 --> epπ^-	A_t, A_{et}	0.05 - 5.0	1.1 - 2.6	PRC 94, 05520 (2016)
ep --> epη	σ_U, σ_{LT}, σ_{TT}	1.6 - 4.6	2.0 - 3.0	PRC 95, 035202 (2017)
	σ_U, σ_{LT}, σ_{TT}	0.13 - 3.3	1.5 - 2.3	PRC 76, 015204 (2007)
	dσ/dΩ	0.25 -1.50	1.5 - 1.86	PRL 86, 1702 (2001)
ep --> eK$^+$Y	P^0	0.8 - 3.2	1.6 - 2.7	PRC 90, 035202 (2014)
	σ_U, σ_{LT}, σ_{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)
	σ_U, σ_{LT}, σ_{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 --> epω	σ_U, σ_{LT}, σ_{TT}	1.725 - 4.85	1.85 - 2.77	EPJA 24, 445 (2005)
ep --> epρ^0	σ_U	1.6 - 5.6	1.8 - 2.8	EPJA 39, 5 (2009)
	σ_L/σ_T	1.5 - 3.0	1.85 - 2.2	PLB 605, 256 (2005)
ep --> epϕ	dσ/dt	1.4 - 3.8	2.0 - 3.0	PRC 78, 025210 (2008)
	dσ/dt'	0.7 - 2.2	2.0 - 2.6	PRC 63, 059901 (2001)

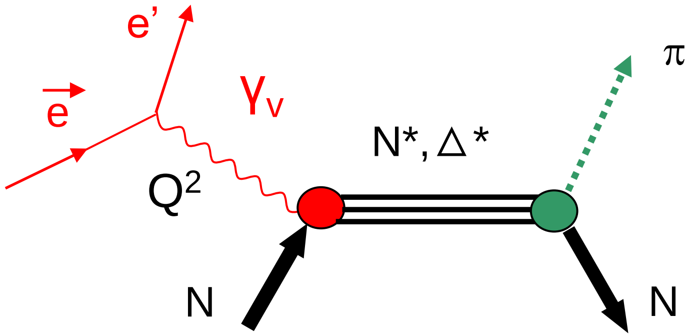
From CLAS Experiment:
1997 - 2012



[This and following slides originally by
Daniel Carman, NSTAR2022 (Oct. 2022)]

Overview of Extractions of Electrocouplings

Reaction Channel	N^*, Δ^* States	Q^2 ranges of $\gamma_v pN^*$ Electrocouplings (GeV^2)
$\pi^0 p$, $\pi^+ n$	$\Delta(1232)3/2^+$ $N(1440)1/2^+$, $N(1520)3/2^-$, $N(1535)1/2^-$	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
$\pi^+ \pi^- p$	$N(1440)1/2^+$, $N(1520)3/2^-$ $\Delta(1620)1/2^-$, $N(1650)1/2^-$, $N(1680)5/2^+$, $\Delta(1700)3/2^-$, $N(1720)3/2^+$, $N'(1720)3/2^+$	0.25 – 1.5 0.5 – 1.5



Analysis codes employed for extractions:

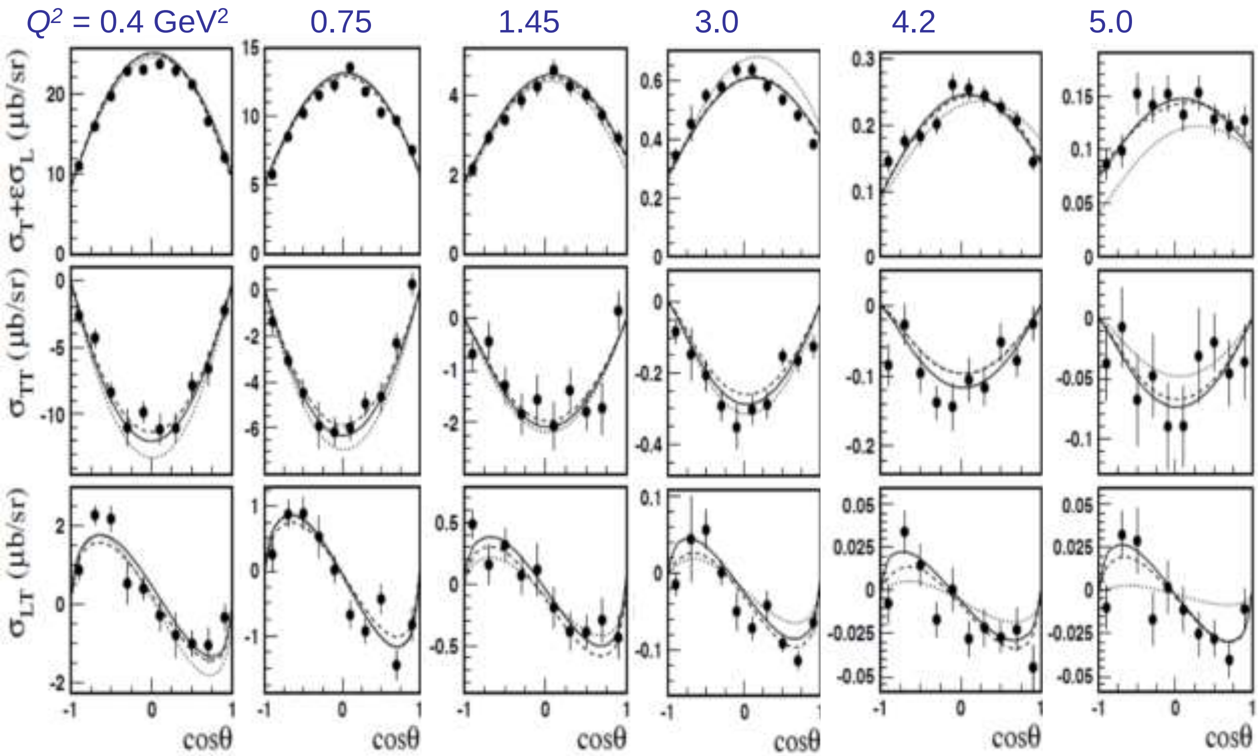
- Unitary Isobar Model (UIM) } for πN and ηN
- Fixed-t dispersion relations (DR) } for πN and ηN
- Data-driven reaction model for $\pi^+\pi^- N$ (JM09, JM16, JM19)

[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

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

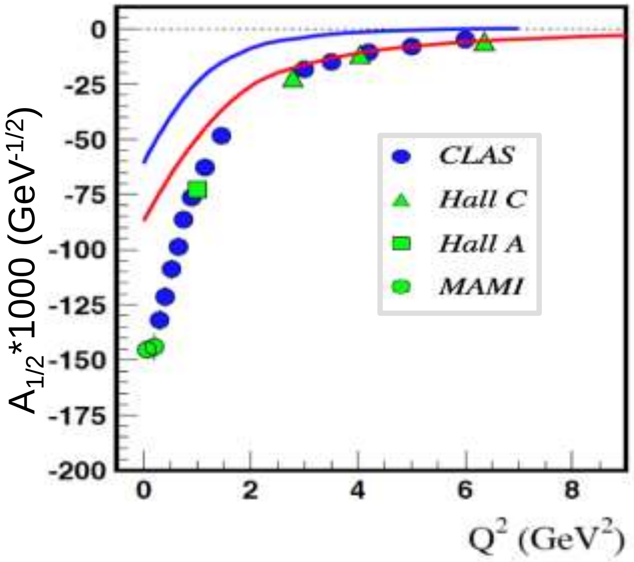
W = 1.232 GeV

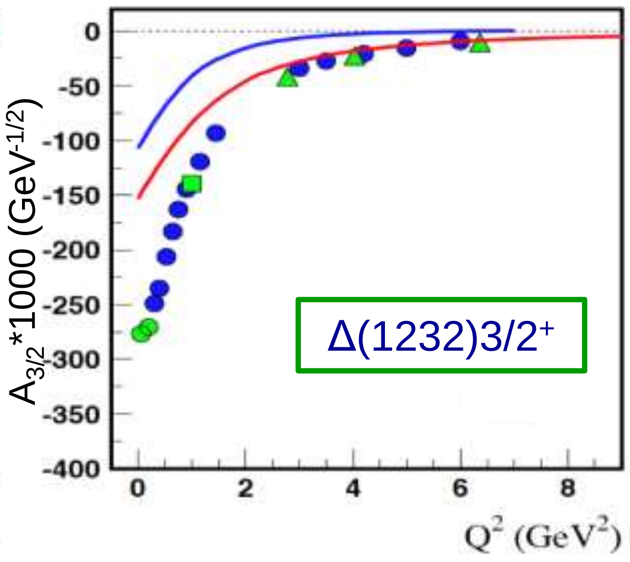


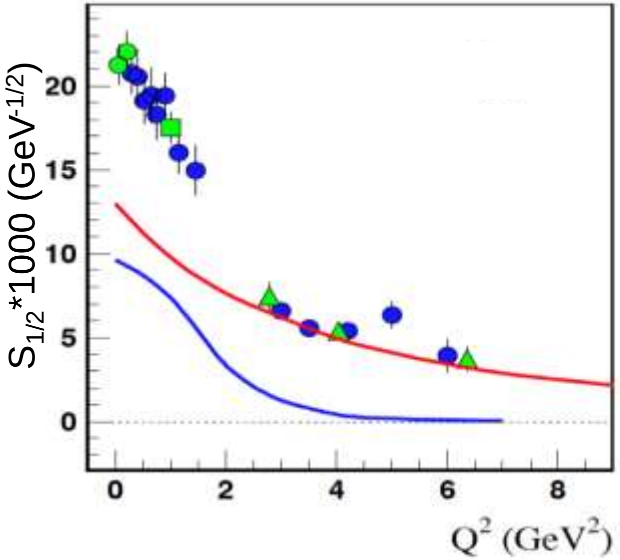
UIM DR MAID2007

Good agreement between UIM and DR approaches

[Aznauryan et al., PRC 80, 055203 (2009)]

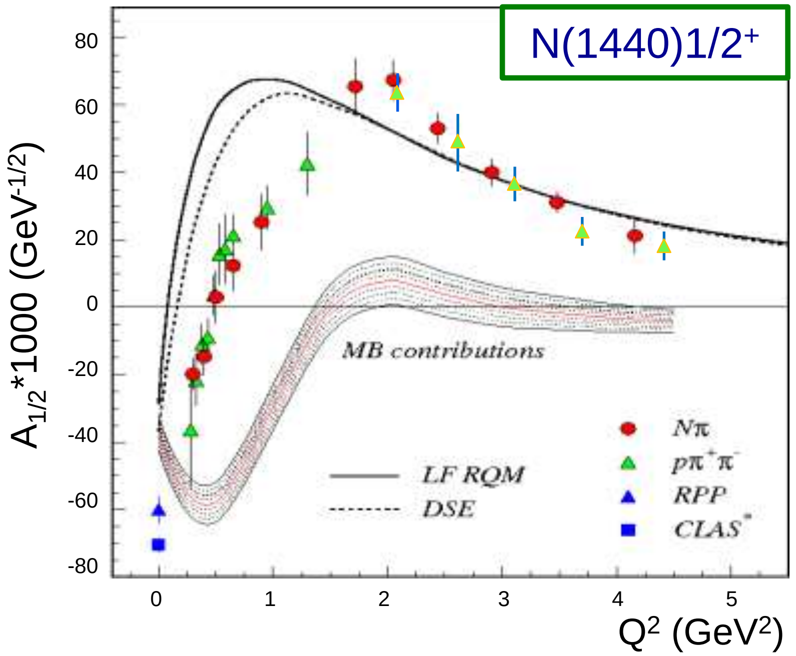




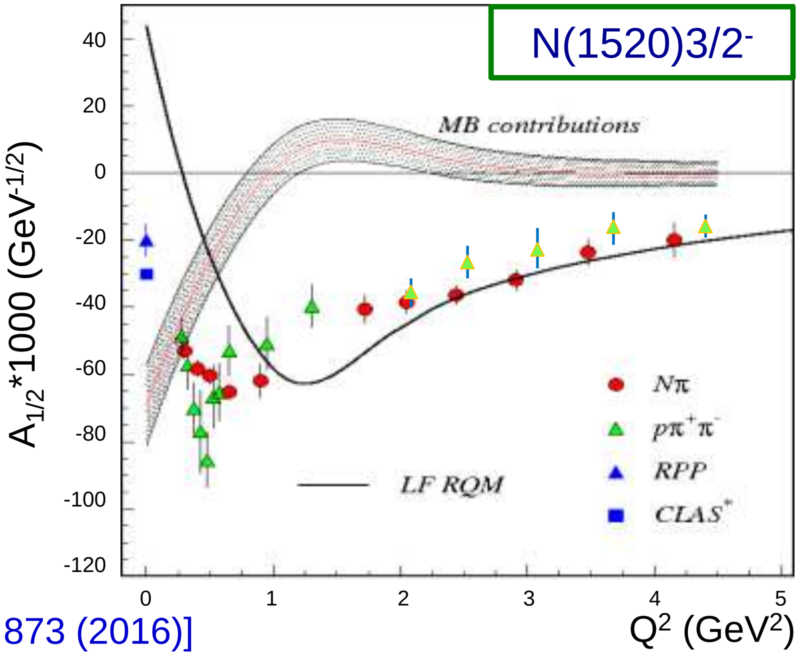


QCD calculations compatible with data where meson cloud does not contaminate evolution $Q^2 \leq 2$ GeV^2

CLAS N* Electrocouplings – Second Resonance Region



γ*p → pπ
γ*p → pππ



[V.D. Burkert, FBS 57, 873 (2016)]

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

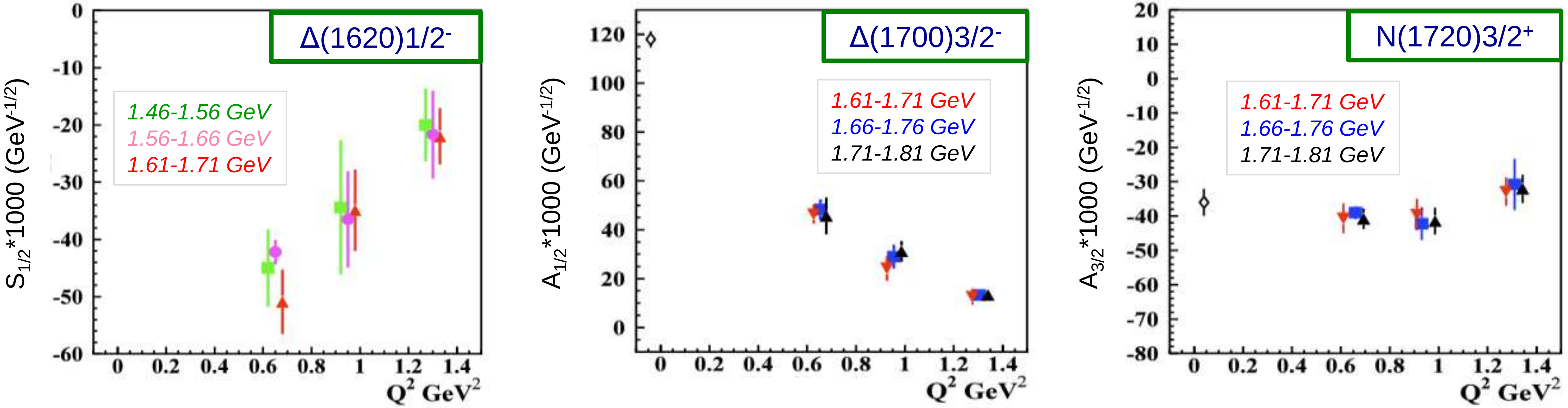
  Good agreement of the extracted N* electrocouplings from Nπ and Nππ:
  - Compelling evidence for reliability of results
  - Channels have very different mechanisms for non-resonant background

- Data on the electrocouplings over broad range of Q^2 needed to:
  - Map out the transition from meson-baryon to confined quark degrees of freedom
  - Gain fundamental insight into the strong QCD dynamics that underlies hadron mass generation

CLAS N* Electrocouplings – Third Resonance Region

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

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

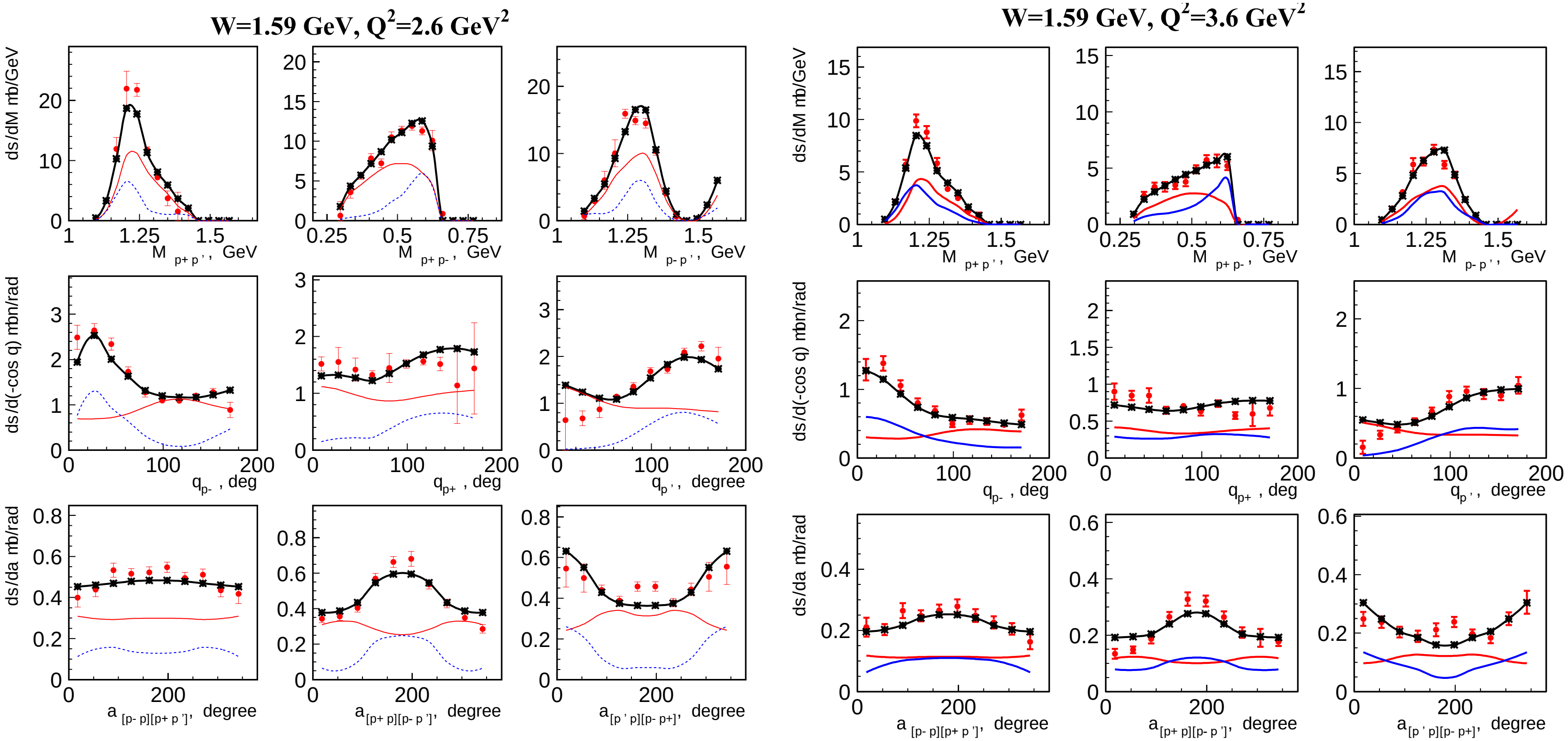


[Mokeev, Aznauryan, IJMPC 26, 1460080 (2014); Mokeev et al., PRC 93, 025206 (2016); Carman, Joo, Mokeev, FBS 61, 29 (2020)]

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

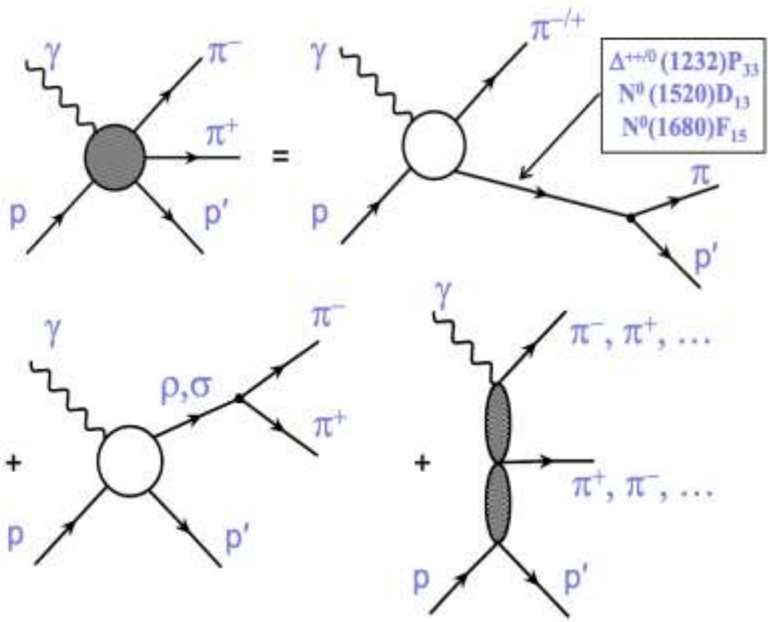
Description of $p\pi^+\pi^-$ Data by JM Model

χ^2/d.p. = 2.71 χ^2/d.p. = 2.59



Full Resonances Background

JLab-Moscow Reaction Model (JM)



[V.I. Mokeev et al., PRC 86, 035203 (2012)]

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

New N′(1720) State from Nππ Analysis

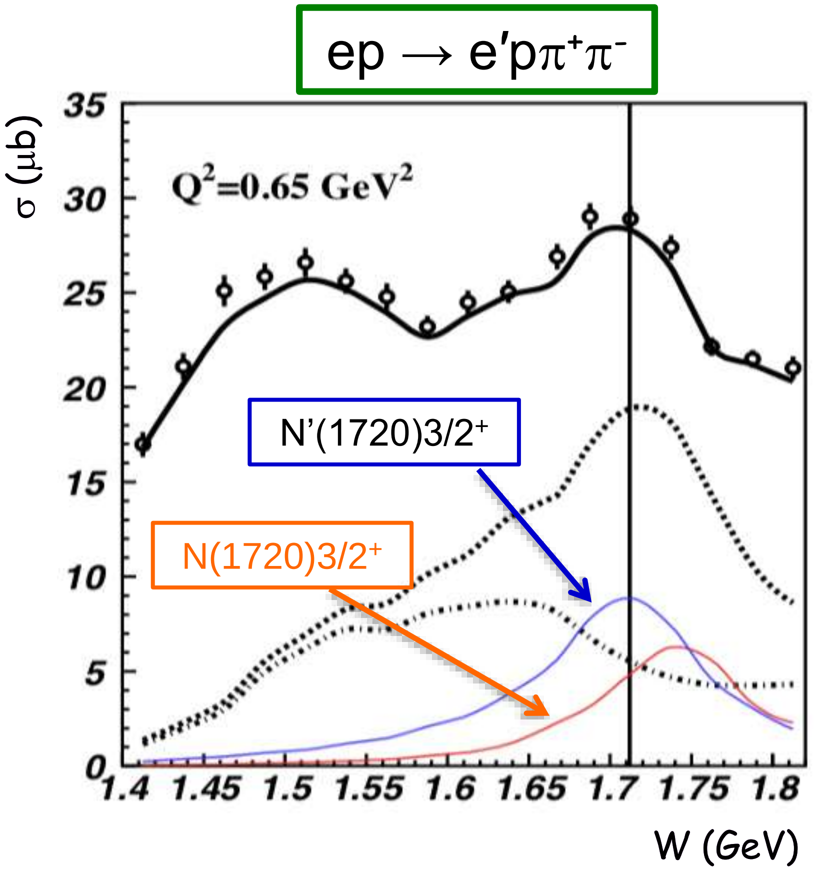
N(1720)3/2+ hadronic decays from CLAS data fit with only conventional N* states		
	BR(πΔ), %	BR(ρp), %
electroproduction	64-100	<5
photoproduction	14-60	19-69

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

- N(1720)3/2+ decays to πΔ and ρp deduced from γp and γ_vp data contradictory

- Impossible to describe data with conventional N* states

- Good description of both Nππ γp and γ_vp data achieved only by including new N'(1720)3/2+

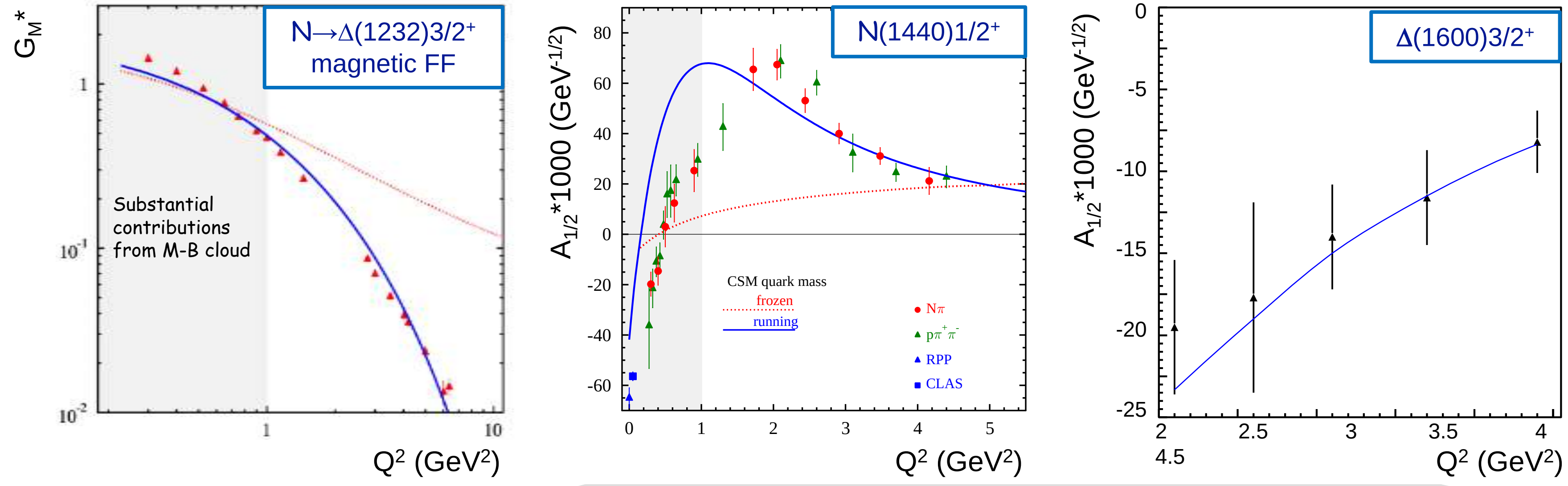


[V.I. Mokeev et al., PLB 805, 135457 (2020)]

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

Nucleon Resonance Electroexcitation Amplitudes and Emergent Hadron Mass

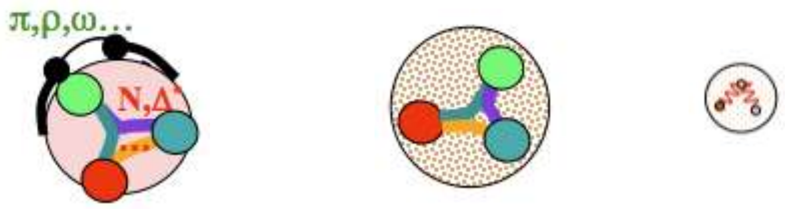
[D.S. Carman, R.W. Gothe, V.I. Mokeev, and C.D. Roberts, Particles 6, 416 (2023)]



Electroexcitation amplitudes of N*s of different structure reproduced by QCD-based Continuum-Schwinger Method with momentum-dependent dressed quark mass *offer important evidence for insight into strong interaction dynamics underlying EHM*

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)

Satisfactory description of transition to Δ(1232)3/2+, N(1440)1/2+, Δ(1600)3/2+ in QCD models

Status of CLAS12 N* Program

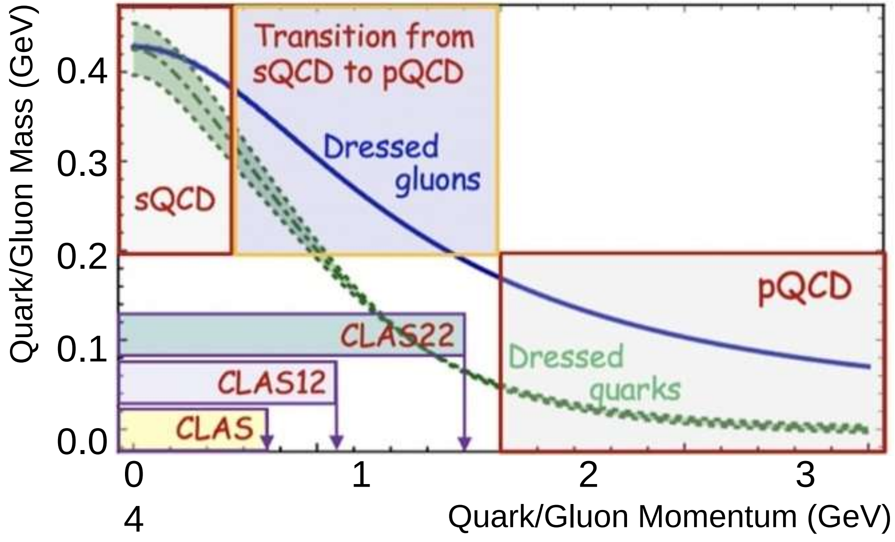
- Measure exclusive electroproduction of Nπ, Nη, Nππ, KY final states from unpolarized proton target with longitudinally polarized electron beam

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

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

continuing in Winter 23



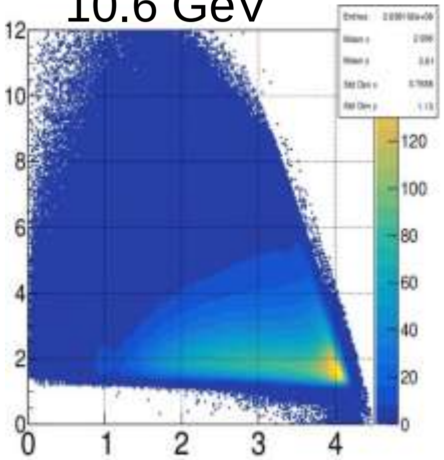
Extension to Q^2 ~ 5-10 GeV^2 :

- Exploring range of quark momenta in transition *from strong to perturbative QCD*

- Dominant part of hadron mass is emerging

Continuum Schwinger Method
[See talk by C. Roberts]

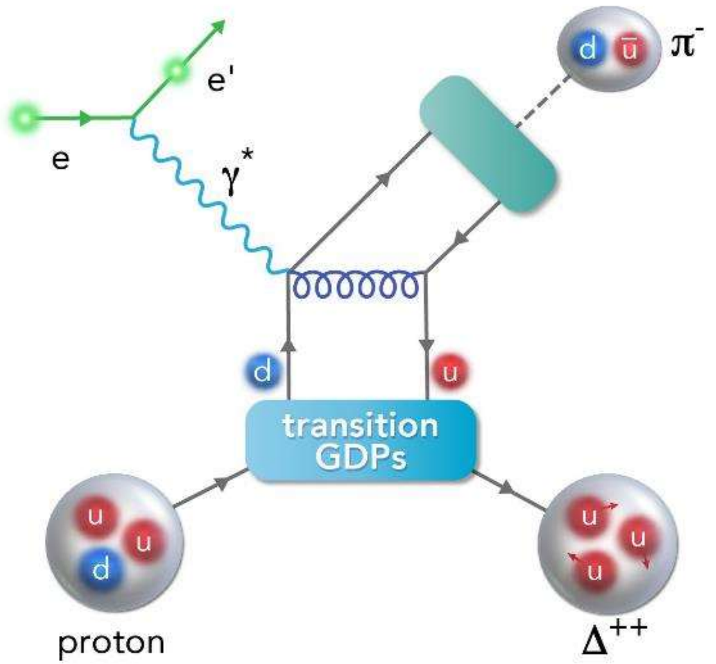
RG-A data
10.6 GeV



First Access to Transition GPDs in $\pi^-\Delta^{++}$ Electroproduction

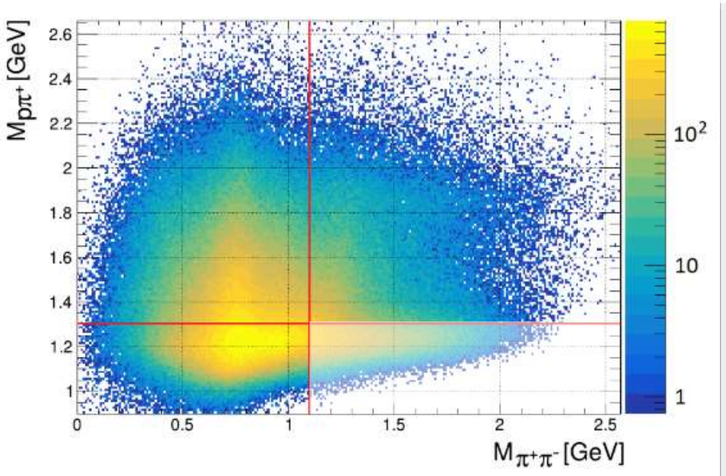
Transition GPDs as a generalization of GPDs to N → Δ processes

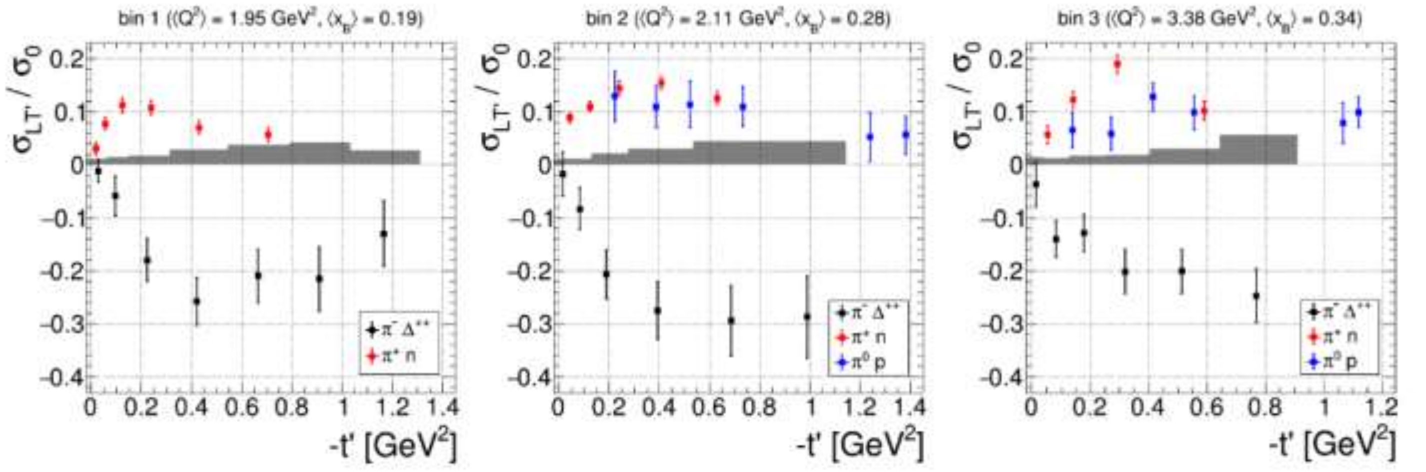
$ep \rightarrow e' p \pi^-(\pi^+)$



$$BSA = \frac{\sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi}{1+\sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}\cos\phi+\epsilon\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi}$$

- Exploratory measurement
- 3D structure on resonances
- Access to *d*-quark content





[S. Diehl et al. (CLAS Collab.), Phys. Rev. Lett. 131, 021901,11 July 2023]

Concluding Remarks

The study of N* states is one of the key foundations of the CLAS physics program:

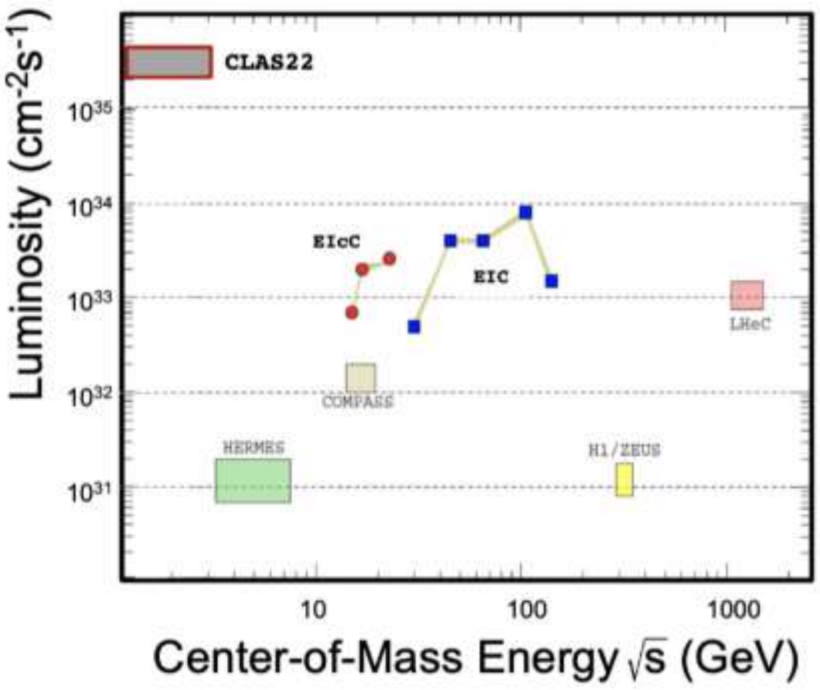
- CLAS has provided a huge amount of data up to $Q^2 \sim 5$ GeV^2
- Electrocouplings of most N* states < 1.8 GeV have been extracted for the first time

The CLAS12 N* program will extend these studies for $0.05 < Q^2 < 12$ GeV^2:

- Study higher-lying N* states
- Understand active degrees of freedom that account for N* structure vs. distance scale
- Probe quark dressing effects and di-quark correlations in N* structure

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

Simulations of πN, KY, and $\pi^+\pi^-$p electroproduction for 22 GeV show that $\gamma_v pN^*$ electrocouplings can be determined up to $Q^2 \sim 30$ GeV^2 for $\mathcal{L} \sim 2 - 5 \times 10^{35}$ 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.