Электророждение мезонов в резонансной области

НИИЯФ МГУ

Евгений Исупов

Baryon Resonances and SU(6) x O(3)

$|\text{Baryon}\rangle : \ \alpha\,|qqq\rangle + \beta\,|qqq(q\bar{q})| + \gamma\,|qqqG\rangle + ..$

3 Flavors: {u,d,s} $\longrightarrow$ SU(3)

{qqq}: $3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$

Quark spin $s_q = ½$ $\longrightarrow$ SU(2)

{$\vec{q}\vec{q}\vec{q}$ }: $6 \otimes 6 \otimes 6 = 56 \oplus 70 \oplus 70 \oplus 20$

SU(6) multiplets decompose into flavor multiplets:

O(3)

$56 = {}^4 10 \oplus {}^2 8$

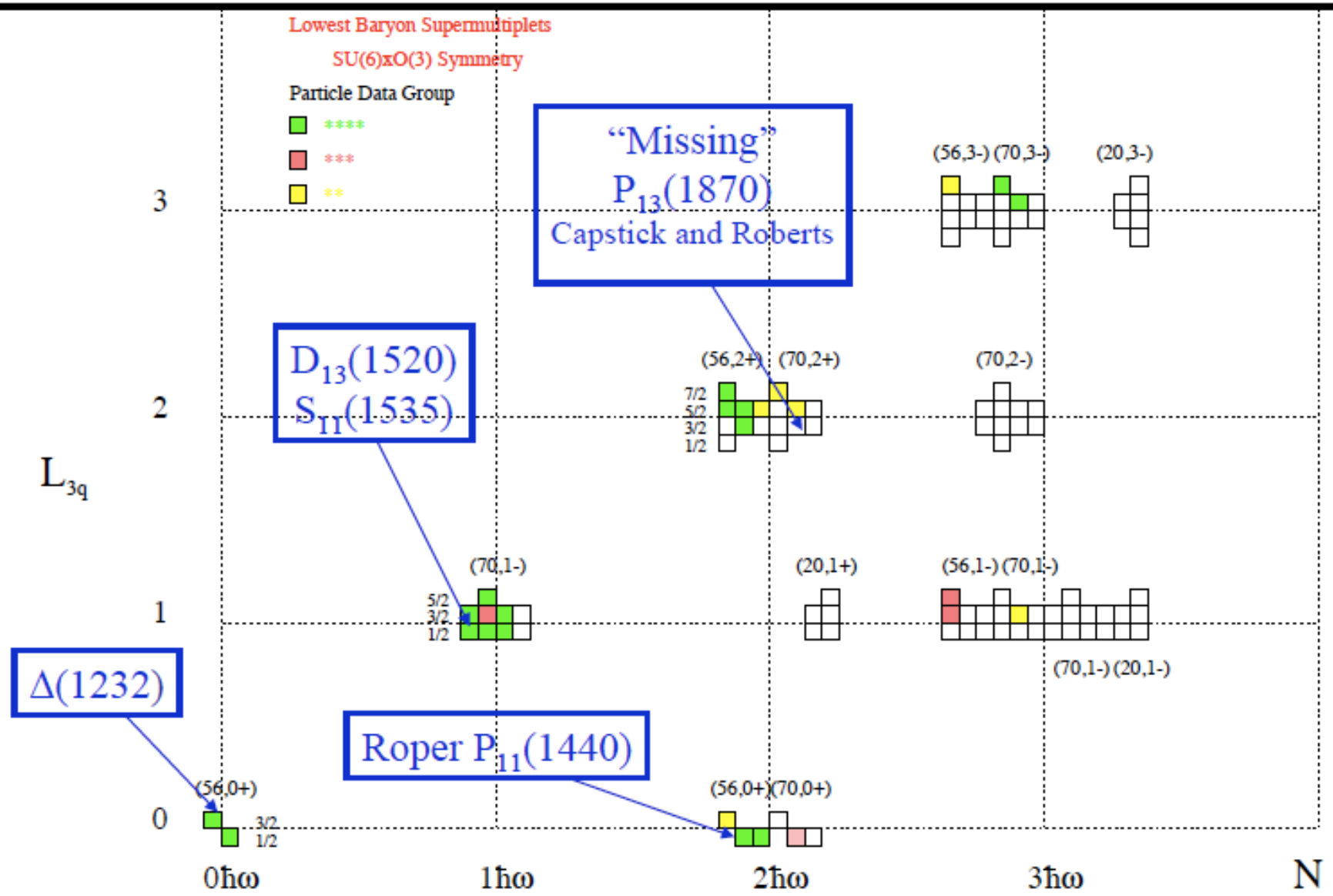
$70 = {}^2 10 \oplus {}^4 8 \oplus {}^2 8 \oplus {}^2 1$

$20 = {}^2 8 \oplus {}^4 1$

Baryon spin: $\vec{J} = \vec{L} + \Sigma \vec{s}_i$

parity: $P = (-1)^L$

SU(6) x O(3) Classification of Baryons



New era in electromagnetic nuclear physics

- Electrons and photons are perfect tools to explore the properties of strongly interacting systems.
- In the past ~ 25 years many facilities with high-quality continuous beam and large acceptance detectors were launched.

MAMI Mainz
ELSA Bonn
GRAAL Grenoble
LEPS Osaka
JLAB Newport News

Insight into the Strong QCD from the Synergy between Experiment, Phenomenology, and Theory

Experiment

Observables from the Experiments with the EM Probes:

- Differential cross sections
- Beam asymmetry
- Target asymmetries
- Recoil asymmetries
- Combinations of 2-fold and 3-fold asymmetries

Phenomenology:

- Amplitude analyses
- Reaction models

⇩

Elastic/Transition form factors
PDFs, PDA,TMD-functions
Compton form factors
Projection of GPD to observables

Strong QCD underlying the hadron generation

⇔

Theory

QCD Lagrangian:

$$\mathcal{L}_{QCD} = \bar{\psi}(i \not{D}_a T_a - m)\psi - \frac{1}{4} F_a^{\mu\nu} F_{\mu\nu,a}$$

- Covariant derivative, gluon field tensor

$$D_a^\mu = \partial^\mu + igA_a^\mu$$
$$F_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A_a^\mu - g f_{abc} A_b^\mu A_c^\nu$$

- Color matrices and structure constants

$$[T_a^{(F)}, T_b^{(F)}] = i f_{abc} T_c^{(F)}, \quad (T_a^{(A)})_{bc} = -i f_{abc}$$

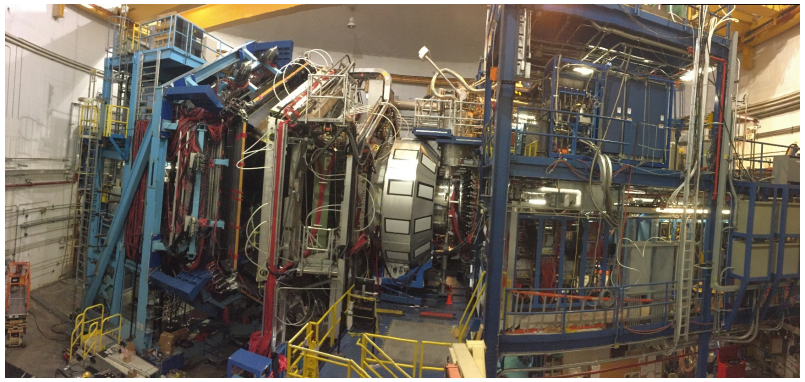
⇕

- Lattice QCD
- Continuum QCD

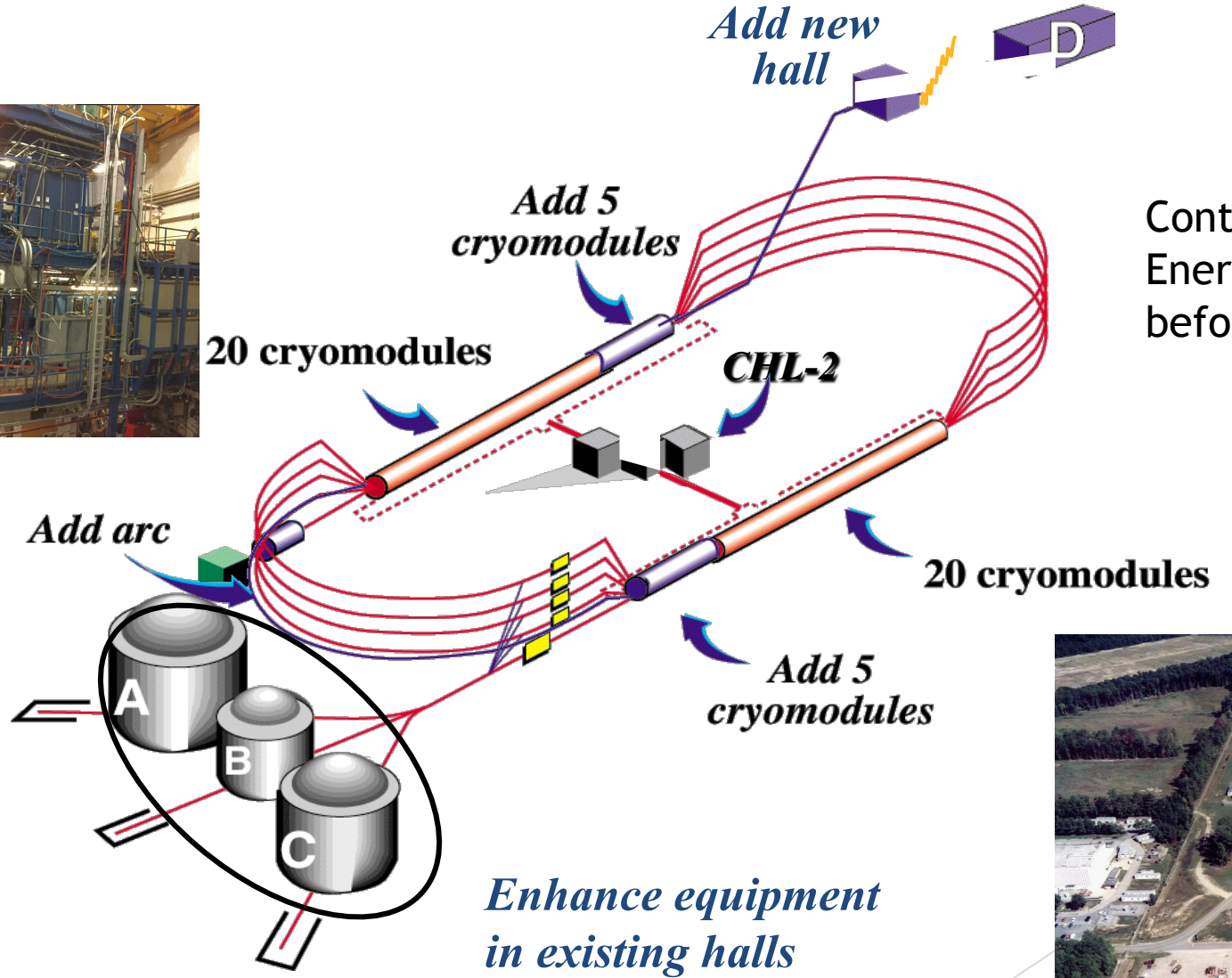
Light front quark models
AdS/CFT approaches
χ Quark-Soliton models
Hypercentral quark model
Covariant quark models
……..

Jefferson Lab (Newport News, VA, USA)

CLAS12 in Hall B

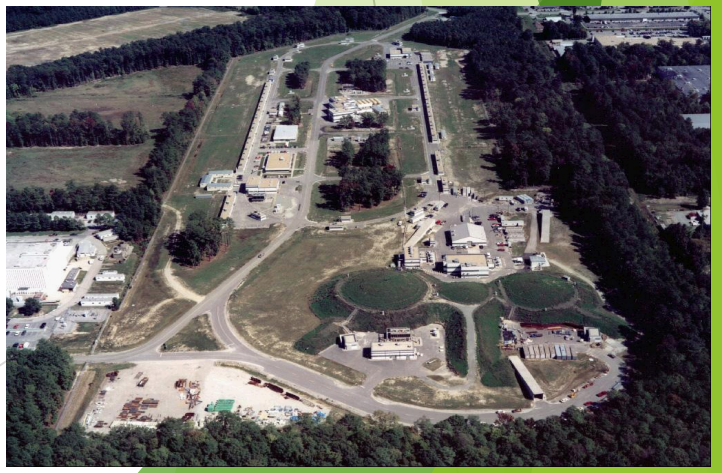


CLAS (1998-2012)



Enhance equipment in existing halls

Continuous electron beam with
Energy = 11 GeV
before upgrade: Energy = 6 GeV



The experimental program on the studies of N* spectrum and structure in exclusive meson photo-/electroproduction with CLAS/CLAS12 seeks to determine:

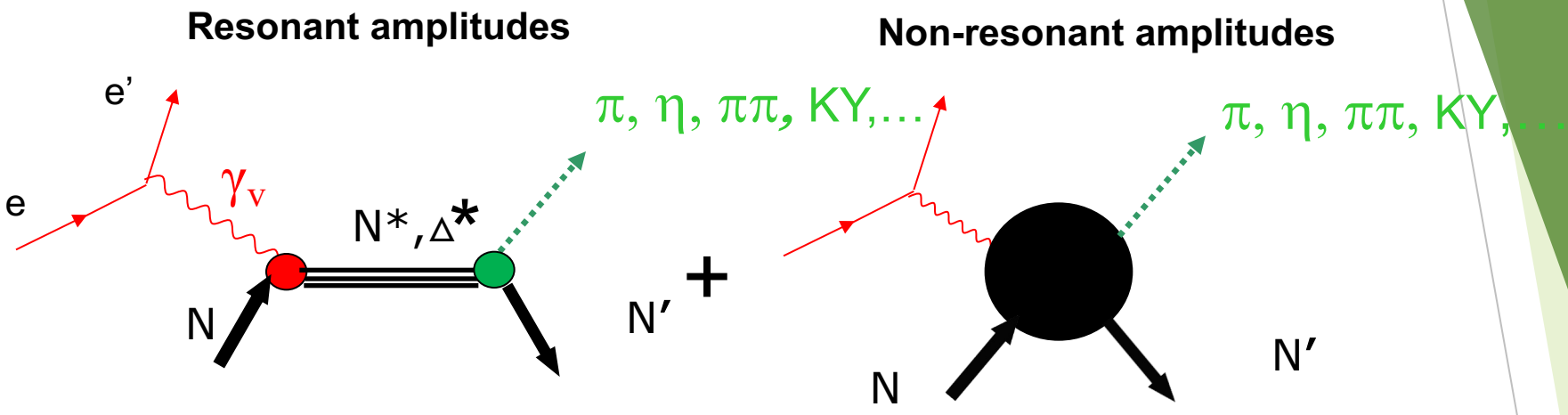
- N* spectrum with a focus on the new, so-called "missing" and hybrid resonance search
- $\gamma_v pN^*$ electrocouplings at photon virtualities up to 5.0 GeV^2 for most of the excited proton states through analyzing major meson electroproduction channels from CLAS data
- extend accessible Q^2 range up to 12 GeV^2 from the CLAS12 data and explore N* structure evolution in the transition from the strong and pQCD regimes
- explore the hadron mass emergence by mapping out dynamical quark mass in the transition from almost massless pQCD quark to fully dressed constituent quark

A unique source of information on many facets of strong QCD in generating excited nucleon states with different structural features

Review papers:

1. I.G. Aznauryan and V.D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012).
2. V.D. Burkert and C.D. Roberts, arXiv:1710.02549 [nucl-ex].
3. C.D. Roberts, Few Body Syst. 59, 72 (2018).
4. V.I. Mokeev, Few Body Syst. 59, 46 (2018).

Extraction of γ_vNN* Electrocouplings from Exclusive Meson Electroproduction off Nucleons



Definition of N* photo-/electrocouplings employed in the CLAS data analyses:

- Real $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$, $S_{1/2}(Q^2)$

I.G. Aznauryan and V.D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012)

$$\Gamma_\gamma = \frac{k^2_{\gamma_{N^*}}}{\pi}\frac{2M_N}{(2J_r+1)M_{N^*}}\left[|A_{1/2}|^2+|A_{3/2}|^2\right]$$

- **Consistent results on γ_vpN* electrocouplings from different meson electroproduction channels are critical in order to validate reliable extraction of these quantities.**

Summary of Published CLAS Data on Exclusive Meson Electroproduction off Protons in N* Excitation Region

Hadronic final state	Covered W-range, GeV	Covered Q^2-range, GeV^2	Measured observables
π^+n	1.1-1.38 1.1-1.55 1.1-1.7 1.6-2.0	0.16-0.36 0.3-0.6 1.7-4.5 1.8-4.5	$d\sigma/d\Omega$ $d\sigma/d\Omega$ $d\sigma/d\Omega$, A_b $d\sigma/d\Omega$
π^0p	1.1-1.38 1.1-1.68 1.1-1.39 1.1-1.8	0.16-0.36 0.4-1.8 3.0-6.0 0.4-1.0	$d\sigma/d\Omega$ $d\sigma/d\Omega$, A_b,A_t,A_{bt} $d\sigma/d\Omega$ $d\sigma/d\Omega$, A_b
ηp	1.5-2.3	0.2-3.1	$d\sigma/d\Omega$
$K^+\Lambda$	thresh-2.6	1.40-3.90 0.70-5.40	$d\sigma/d\Omega$ P^0, P'
$K^+\Sigma^0$	thresh-2.6	1.40-3.90 0.70-5.40	$d\sigma/d\Omega$ P'
$\pi^+\pi^-p$	1.3-1.6 1.4-2.1 1.4-2.0	0.2-0.6 0.5-1.5 2.0-5.0	Nine 1-fold differential cross sections

- $d\sigma/d\Omega$–CM angular distributions
- A_b,A_t,A_{bt}-longitudinal beam, target, and beam-target asymmetries
- P^0, P' -recoil and transferred polarization of strange baryon

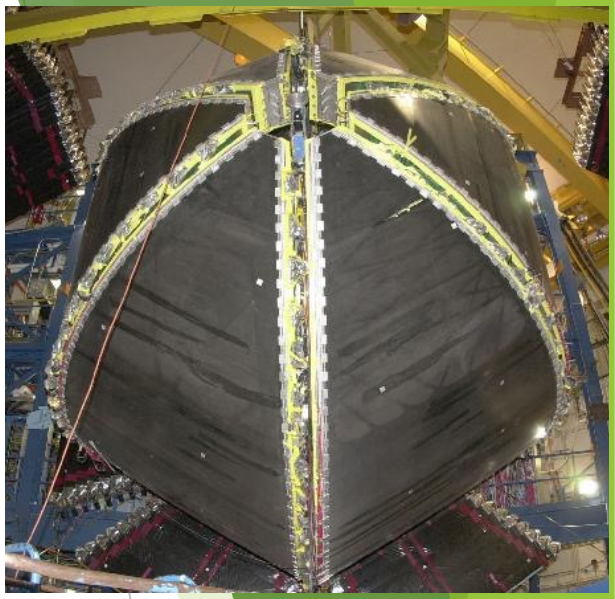
Over 120,000 data points!

Almost full coverage of the final hadron phase space

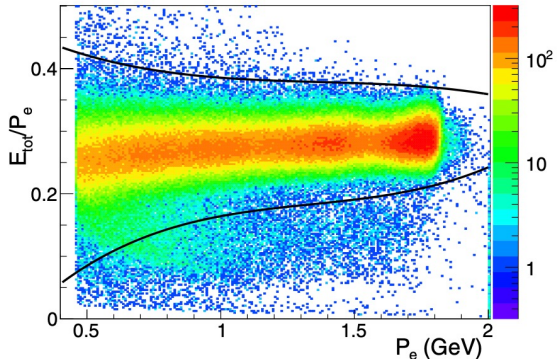
The measured observables from CLAS are stored in the CLAS Physics Data Base http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi

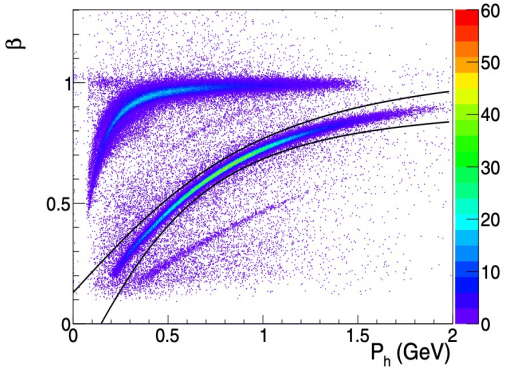
Polarized structure function $\sigma_{LT'}$ from $\pi^0 p$ electroproduction data in the resonance region at $0.4\,\mathrm{GeV}^2 < Q^2 < 1.0\,\mathrm{GeV}^2$

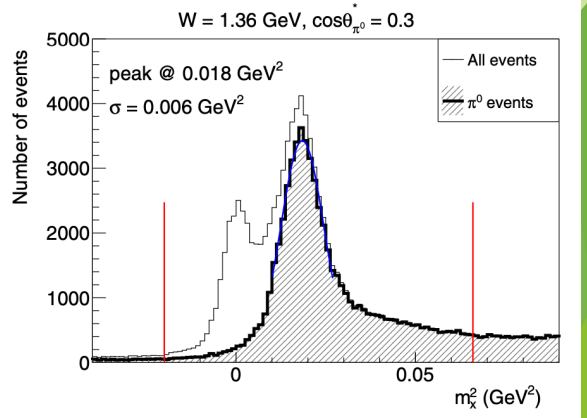
E. L. Isupov *et al.* (CLAS Collaboration)
Phys. Rev. C **105**, L022201 – Published 18 February 2022



- CLAS detector data 12/2002 – 1/2003
- Beam energy: 2.036 GeV
- Beam polarization: ~ 80%
- Target: Liquid Hydrogen, thickness 2 cm
- Number of triggers: ~ 1.5 billion



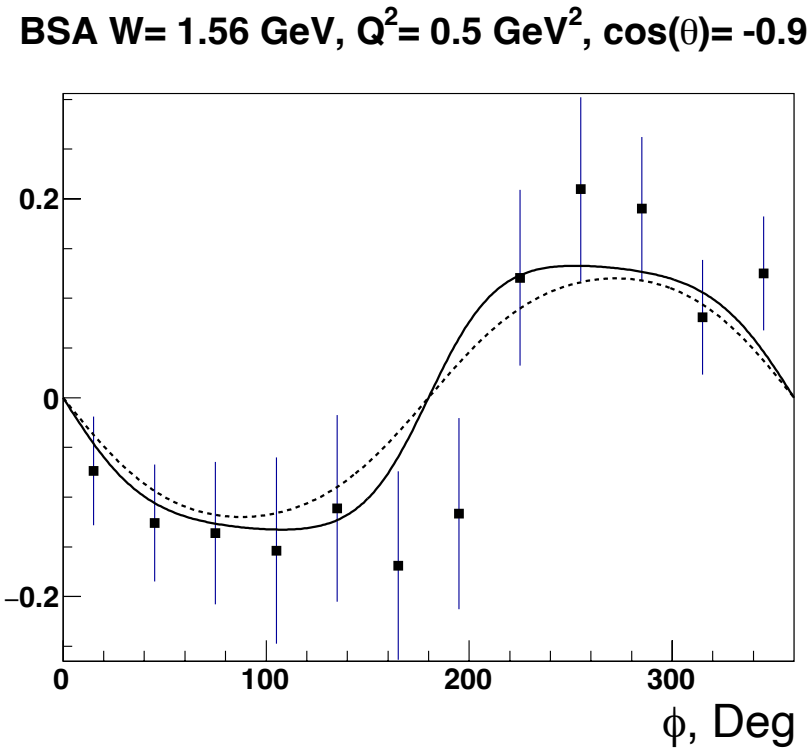


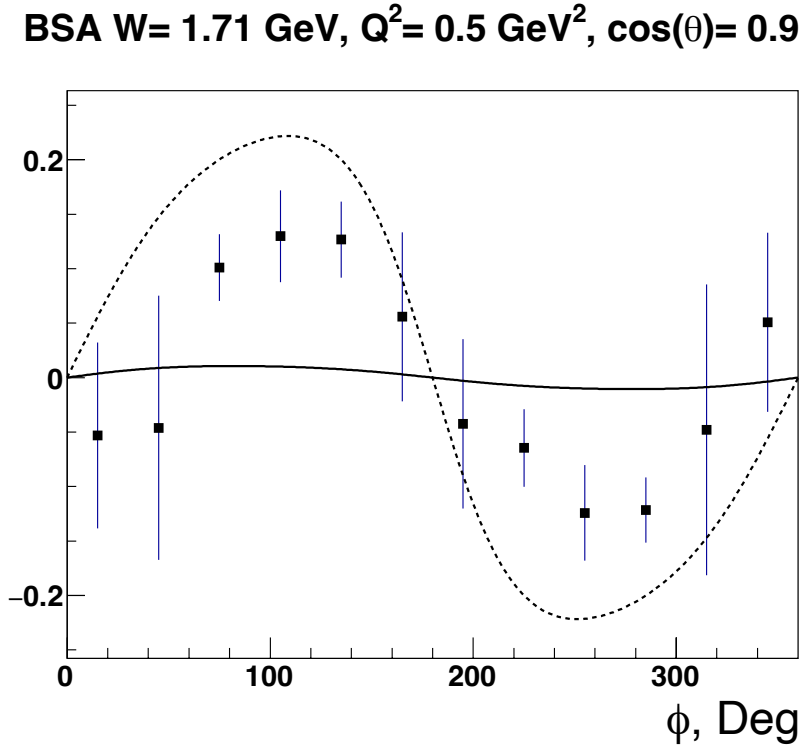


$0.4 < Q^2 < 1\ \mathrm{GeV}^2$

$1.1 < W < 1.8\ \mathrm{GeV}$

Beam spin asymmetries





$$A_{LT'} = \frac{A_m}{P_e},$$

$$A_m = \frac{N_{\pi^+} - N_{\pi^-}}{N_{\pi^+} + N_{\pi^-}}$$

MAID 2007 (solid line)

MAID 2007 with modified electrocouplings, taken from CLAS analyses (dotted line)

EC fits https://userweb.jlab.org/~isupov/couplings/

Polarized Structure Function $\sigma_{LT'}$

$$\frac{d^2\sigma^h}{d\Omega_\pi^*} = \frac{p_\pi^*}{k_\gamma^*}[\sigma_0 + h\sqrt{2\epsilon_L(1-\epsilon)}\ \sigma_{LT'}\ \sin\theta_\pi^*\ \sin\phi_\pi^*]$$

$$A_{LT'} = \frac{\sqrt{2\epsilon_L(1-\epsilon)}\ \sigma_{LT'}\ \sin\theta_\pi^*\ \sin\phi_\pi^*}{\sigma_0}$$

$$A_{LT'} = \frac{A_m}{P_e},$$

We have unpolarized cross sections from the same data.

$$A_m = \frac{N_\pi^+ - N_\pi^-}{N_\pi^+ + N_\pi^-}$$

Extraction Of Polarized Structure Function $\sigma_{LT'}$

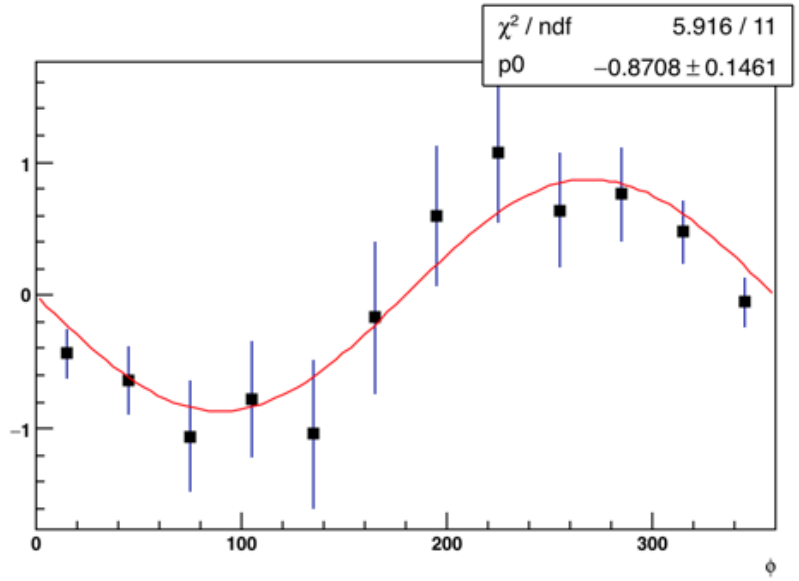
Binning:

28 W-bins from 1.1 to 1.8 GeV, width = 25 MeV
2 Q^2-bins [0.4-0.6] and [0.6-1.0] GeV^2
10 Cos(θ)-bins [-1,1] width = 0.2
12 Φ-bins [0,360] width = 30°

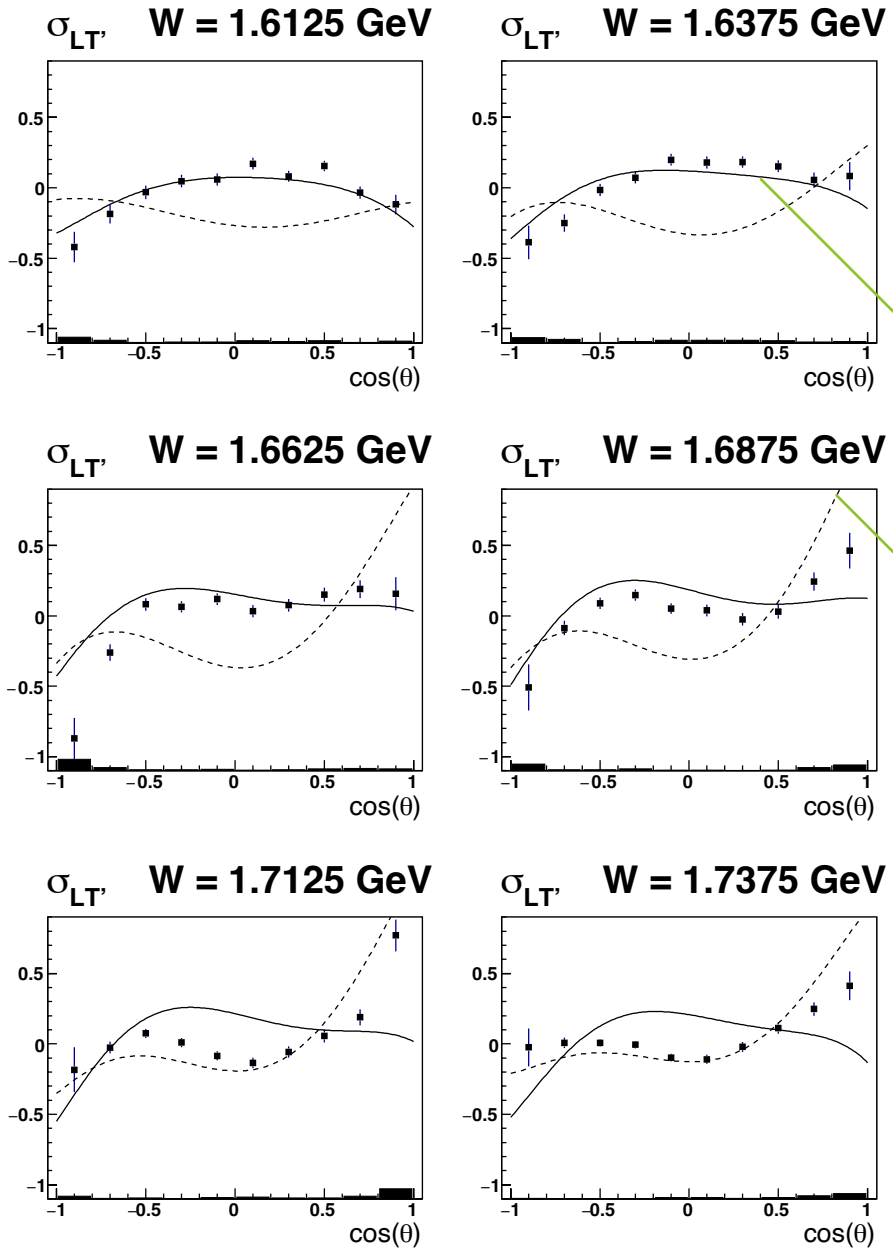
W = 1.66 GeV

$0.4<Q^2<0.6$ GeV^2

Cos(θ)=-0.9



Polarized Structure Function $\sigma_{LT'}$, $0.4 < Q^2 < 0.6$ GeV^2



MAID 2007 (solid line)

MAID 2007 with modified electrocouplings, taken from CLAS analyses (dashed line)

Legendre Polynomials of $\sigma_{LT'}$

l=0,1,2,3 $\sigma_{LT'}$=D0+D1*x+D2*0.5*(3*x^2 -1)+D3*0.5*(5*x^3 -3*x)

x = cos(θ)

sensitivity to P13(1720)

D1 ~ -Im(… 6*S1p*conj(E1p) - 6*S1p*conj(M1p) …)

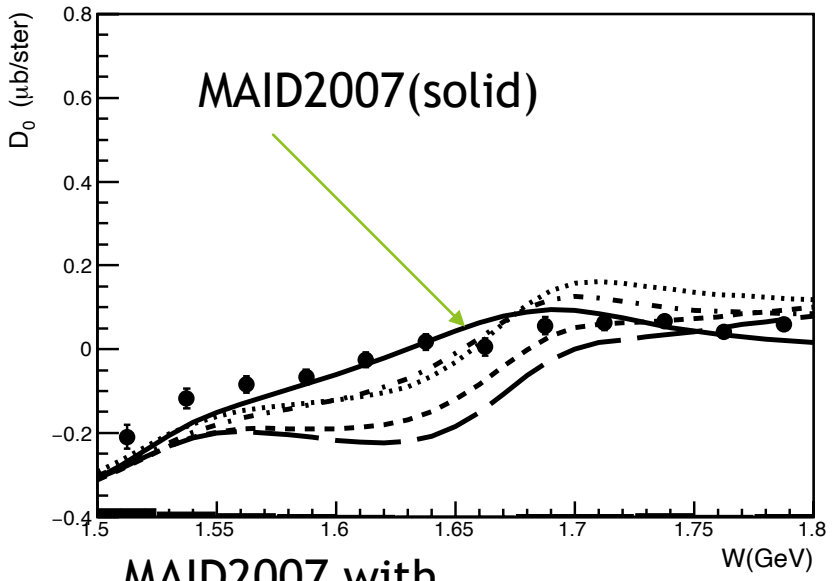
sensitivity to D33(1700)

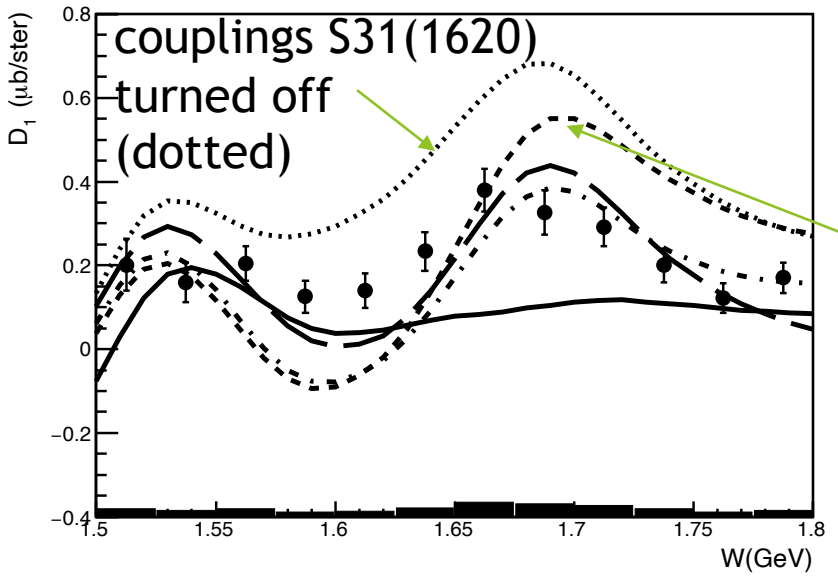
D1 ~ -Im(… - 6*S2m*conj(E2m) - 6*S2m*conj(M2m)…)

LP – effective way to present our data and to demonstrate sensitivity to different excited states of the nucleon

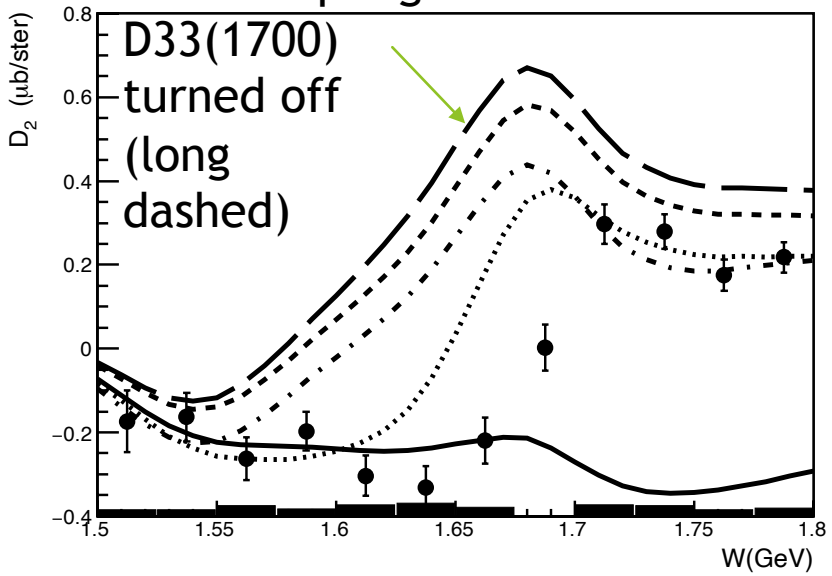
P_{11}	P_{31}	$\frac{1}{2}^+$	1^+	L_{1-}
S_{11}	S_{31}	$\frac{1}{2}^+$	0^-	L_{0+}, E_{0+}
D_{13}	D_{33}	$\frac{1}{2}^+$	2^-	L_{2-}, E_{2-}
P_{11}	P_{31}	$\frac{1}{2}^+$	1^+	M_{1-}
P_{13}	P_{33}	$\frac{1}{2}^+$	1^+	M_{1+}
P_{13}	P_{33}	$\frac{1}{2}^+$	1^+	L_{1+}, E_{1+}
F_{15}	F_{35}	$\frac{1}{2}^+$	3^+	L_{3-}, E_{3-}
D_{13}	D_{33}	$\frac{1}{2}^+$	2^-	M_{2-}
D_{15}	D_{35}	$\frac{1}{2}^+$	2^-	M_{2+}

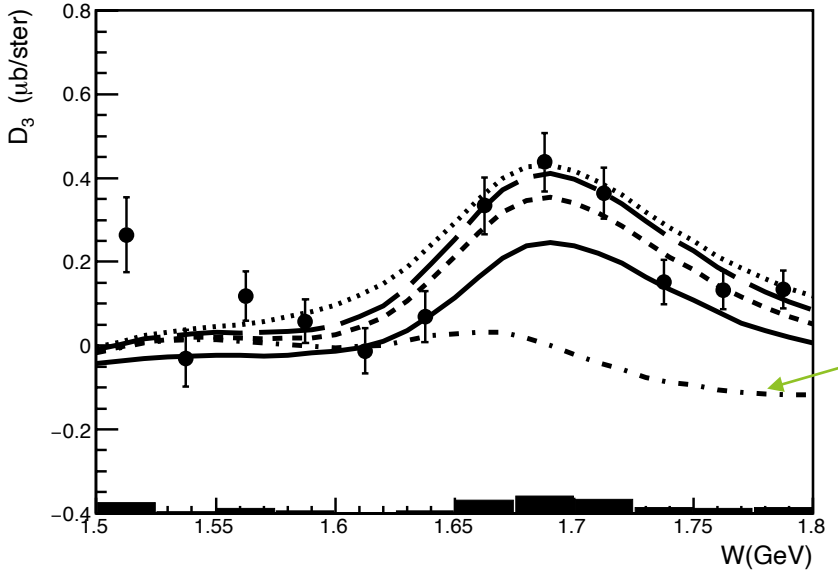
Legendre Moments of Polarized Structure Function σ_{LT}, $0.4 < Q^2 < 0.6$ GeV^2





MAID2007 with CLAS couplings (dashed)

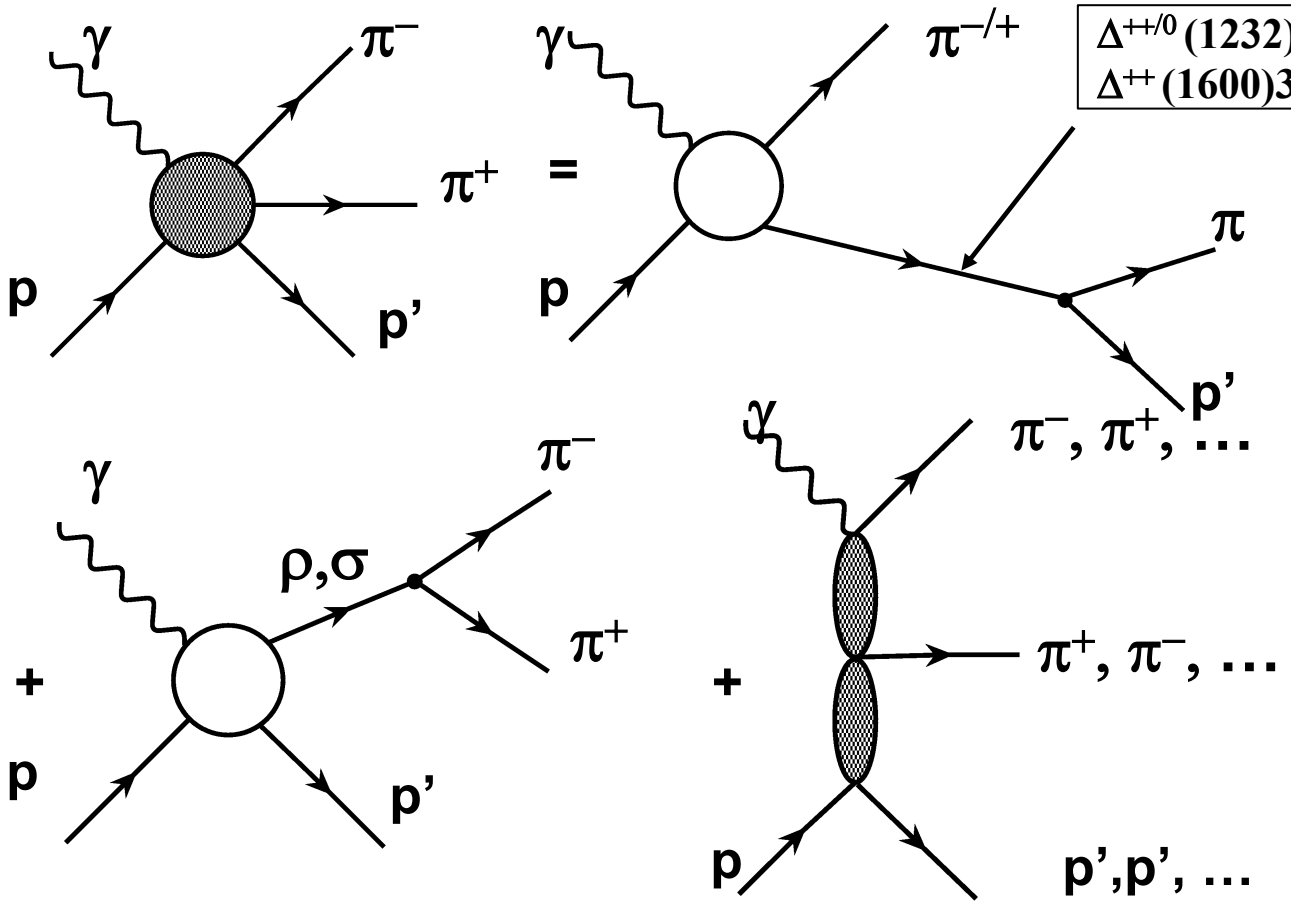




MAID2007 with CLAS couplings P13(1720) turned off (dotted dashed)

JM Model for Analysis of $\pi^+\pi^-$p Photo-/Electroproduction

Major objectives: extraction of $\gamma_{r,v}$pN* photo-/electrocouplings and $\pi\Delta$, ρp decay widths



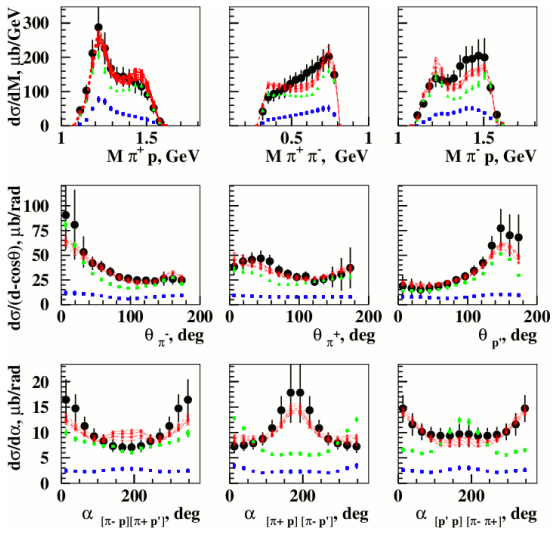
$\Delta^{++/0}(1232)3/2^+$, $N^0(1520)3/2^-$,
$\Delta^{++}(1600)3/2^+$, $N^0(1680)5/2^+$

- five channels with unstable intermediate meson/baryon and direct $\pi^+\pi^-$p production;
- N* contribute to $\pi\Delta$ and ρp channels only;
- unitarized Breit-Wigner ansatz for resonant amplitudes;
- phenomenological parameterization of the other meson-baryon channel amplitudes (see Ref. 2)

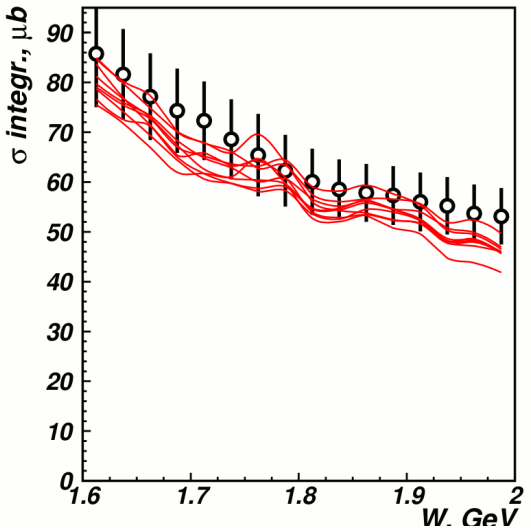
Good description of $\pi^+\pi^-$p photo-/electroproduction off protons cross sections at 1.4 GeV<W<2.0 GeV and 0 GeV^2<Q^2<5.0 GeV^2

Resonance Photocouplings from the CLAS $\pi^+\pi^-p$ Photoproduction Cross Sections

W=1.74 GeV



Fully integrated cross section



E.N. Golovach et al, CLAS Collaboration, Phys. Lett. B788, 371 (2019).

JM18 reaction model fit:

- Full
- Resonant contributions
- Non-resonant contributions

1.15 χ^2/d.p.<1.30

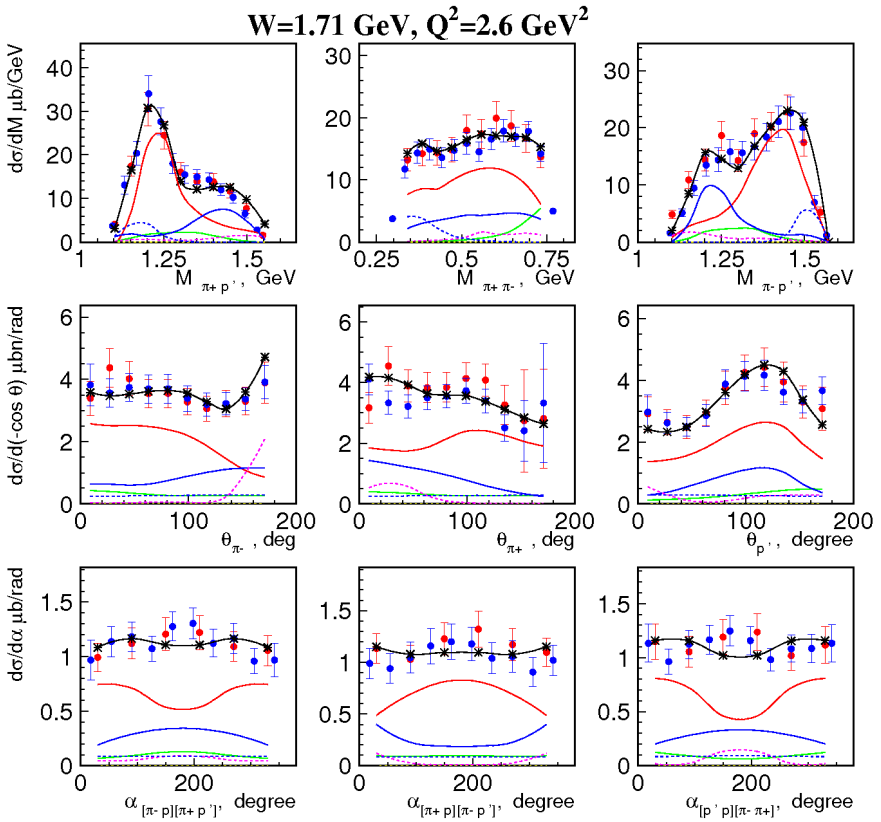
Resonances	$A_{1/2}\times10^3$ from $\pi^+\pi^-p$ $GeV^{-1/2}$	$A_{1/2}\times10^3$ PDG ranges $GeV^{-1/2}$	$A_{1/2}\times10^3$ multichannel analysis [7] $GeV^{-1/2}$	$A_{3/2}\times10^3$ from $\pi^+\pi^-p$ $GeV^{-1/2}$	$A_{3/2}\times10^3$ PDG ranges $GeV^{-1/2}$	$A_{3/2}\times10^3$ multichannel analysis [7] $GeV^{-1/2}$
$\Delta(1620)1/2^-$	29.0±6.2	30 – 60	55±7			
$N(1650)1/2^-$	60.5±7.7	35 – 55	32±6			
$N(1680)5/2^+$	−27.8±3.6	−18 – −5	−15±2	128±11	130 – 140	136±5
$N(1720)3/2^+$	80.9±11.5	80 – 120	115±45	−34.0±7.6	−48 – 135	135±40
$\Delta(1700)3/2^-$	87.2±18.9	100 – 160	165±20	87.2±16.4	90 – 170	170±25
$\Delta(1905)5/2^+$	19.0±7.6	17 – 27	25±5	−43.2±17.3	−55 – −35	−50±5
$\Delta(1950)7/2^+$	−69.8±14.1	−75 – −65	−67±5	−118.1±19.3	−100 – −80	−94±4

In 2019 partial update of the Review of Particle Physics the entries on photocouplings and Nππ decay widths for many resonances with masses >1.6 GeV were revised based on the studies of $\pi^+\pi^-p$ photoproduction with CLAS.

Accessing resonance electrocouplings from the $\pi^+\pi^-p$ differential electroproduction off protons cross sections

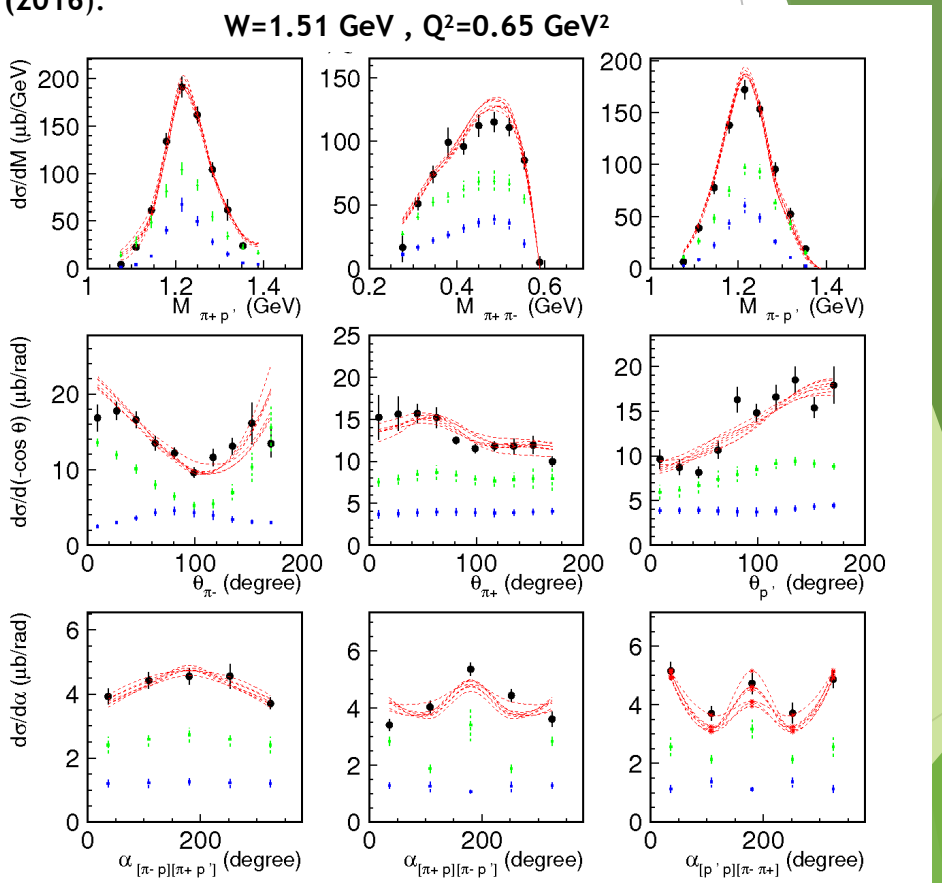
Contributing mechanisms seen in the data

E. Isupov et al., CLAS Coll., Phys. Rev. C96, 025209 (2017)
A.Trivedi, Few Body Syst. 60, 5 (2019)



Resonant and non-resonant contributions

V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C93, 054016 (2016).



full JM
ρp
$\pi^+ N(1520)3/2^-$
$\pi^-\Delta^{++}$
$\pi^+\Delta^0$
$\pi^+ N(1680)5/2^+$

data fit within JM under variations of both resonant and background parameters
background cross sections
resonant cross sections

Interpretation of the Structure at W~1.7 GeV in $\pi^+\pi^-$p Electroproduction

M. Ripani et al., CLAS Collaboration
Phys. Rev. Lett. 91, 022002 (2003)

..... *conventional states only, consistent with PDG 02*

——— *implementing N'(1720)3/2⁺ candidate or only conventional states with different N(1720)3/2⁺ Nππ decays than in PDG 02*

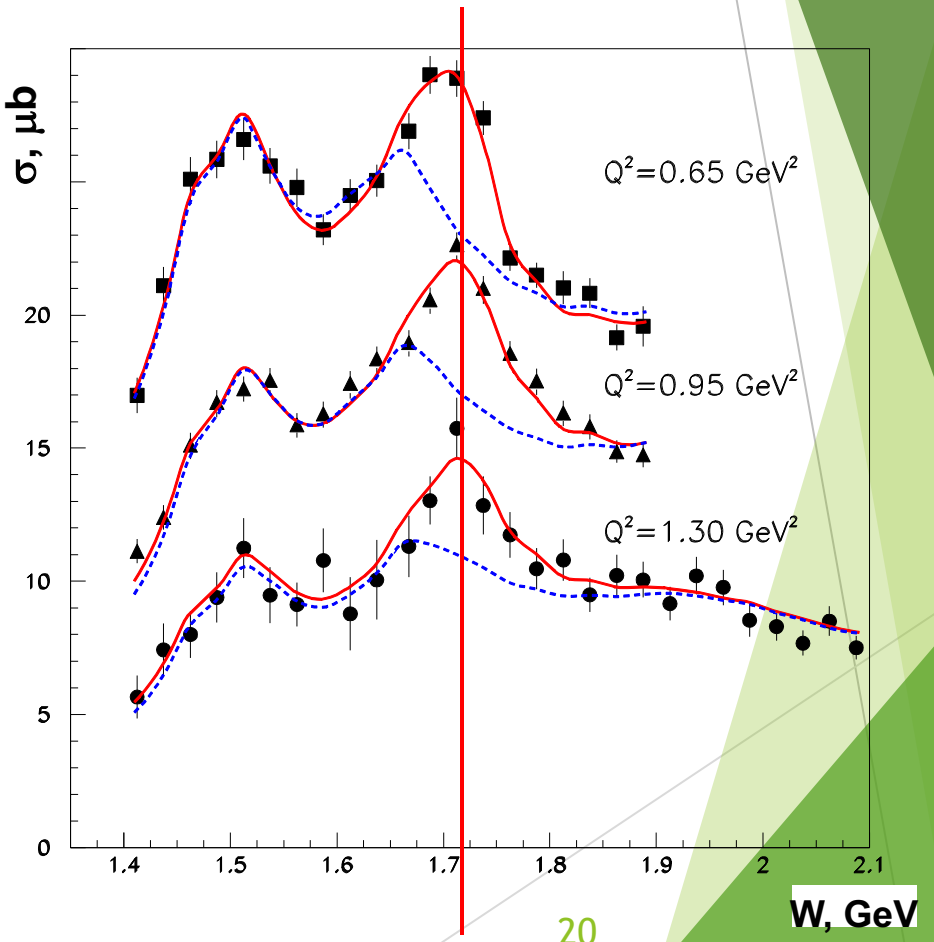
Two equally successful ways for the data description:

No new states, different than in PDG 02'
N(1720)3/2⁺ Nππ hadronic decay widths:

	Γ_{tot}, MeV	BF(πΔ) %	BF(ρp) %
N(1720)3/2⁺ decays fit to the CLAS Nππ data	126±14	64-100	<5
N(1720)3/2⁺ PDG 02'	150-300	<20	70-85

new N'(1720)3/2⁺ and regular N(1720)3/2⁺:

	Γ_{tot}, MeV	BF(πΔ) %	BF(ρp) %
N'(1720)3/2⁺ New	119±6	47-64	3-10.
N(1720)3/2⁺ Conventional	112±8	39-55	23-49



Evidence for the New $N'(1720)3/2^+$ Nucleon Resonance from Combined Studies of CLAS $\pi^+\pi^- p$ Photo- and Electroproduction Data

V.I. Mokeev[a,*], V.D. Burkert[a], D.S. Carman[a], L. Elouadrhiri[a], E. Golovatch[b], R.W. Gothe[c], K. Hicks[d], B.S. Ishkhanov[b], E.L. Isupov[b], K. Joo[e], N. Markov[a,e], E. Pasyuk[a], A. Trivedi[c]

[a] *Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*
[b] *Skobeltsyn Institute of Nuclear Physics and Physics Department, Lomonosov Moscow State University, 119234 Moscow, Russia*
[c] *University of South Carolina, Columbia, South Carolina 29208, USA*
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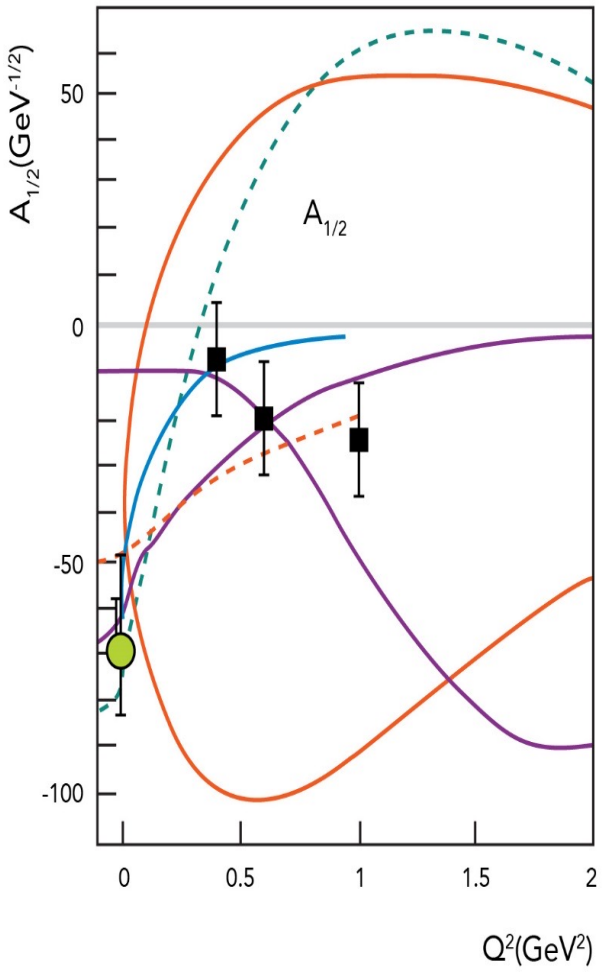
Published in Physics Letters B
Volume 805, 10 June 2020, 135457

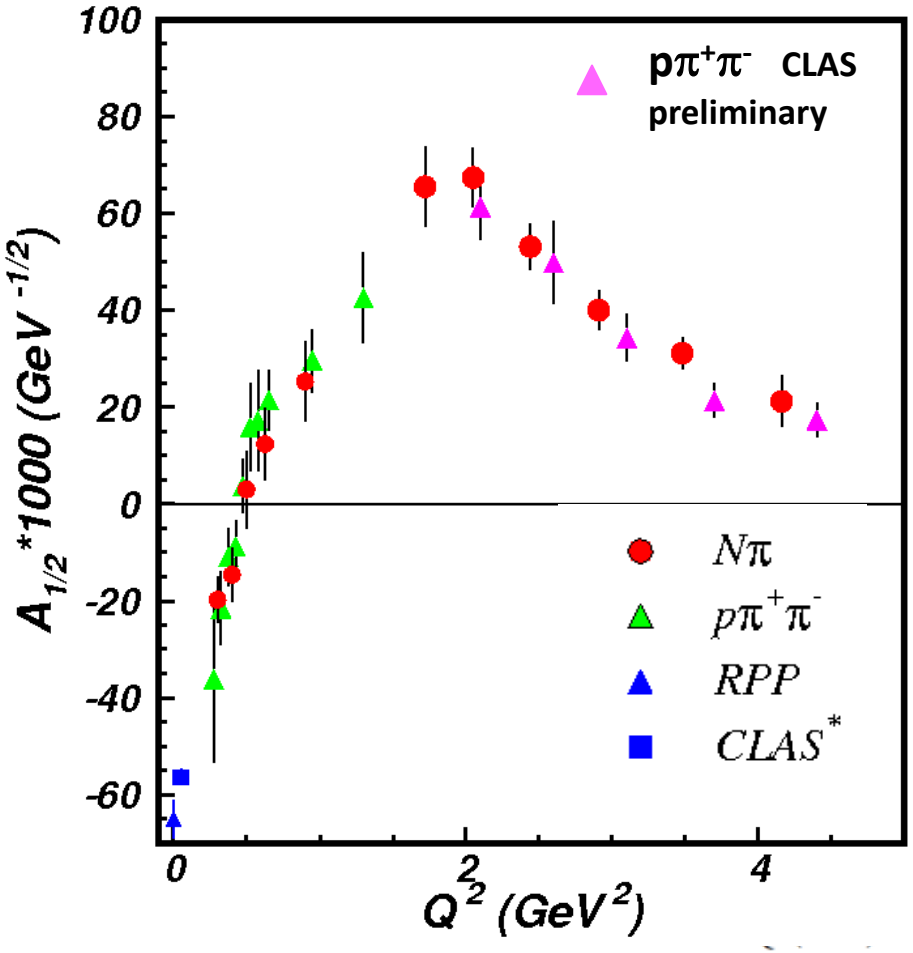
Roper Resonance in 2002 & 2019

2002



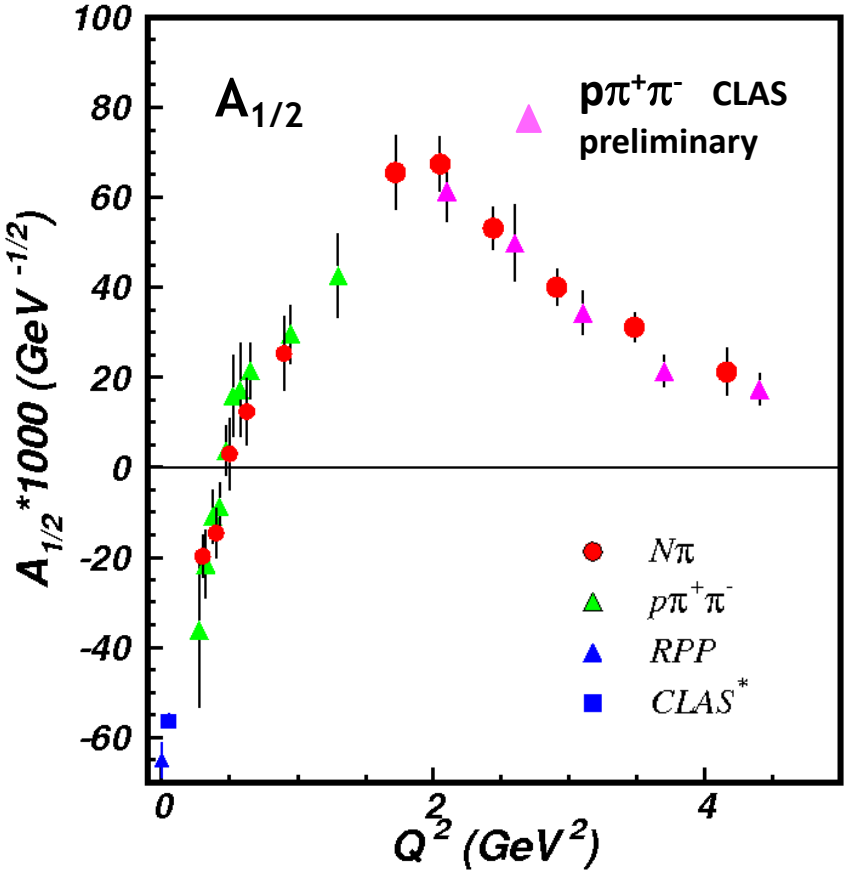
V. Burkert, Baryons 2002

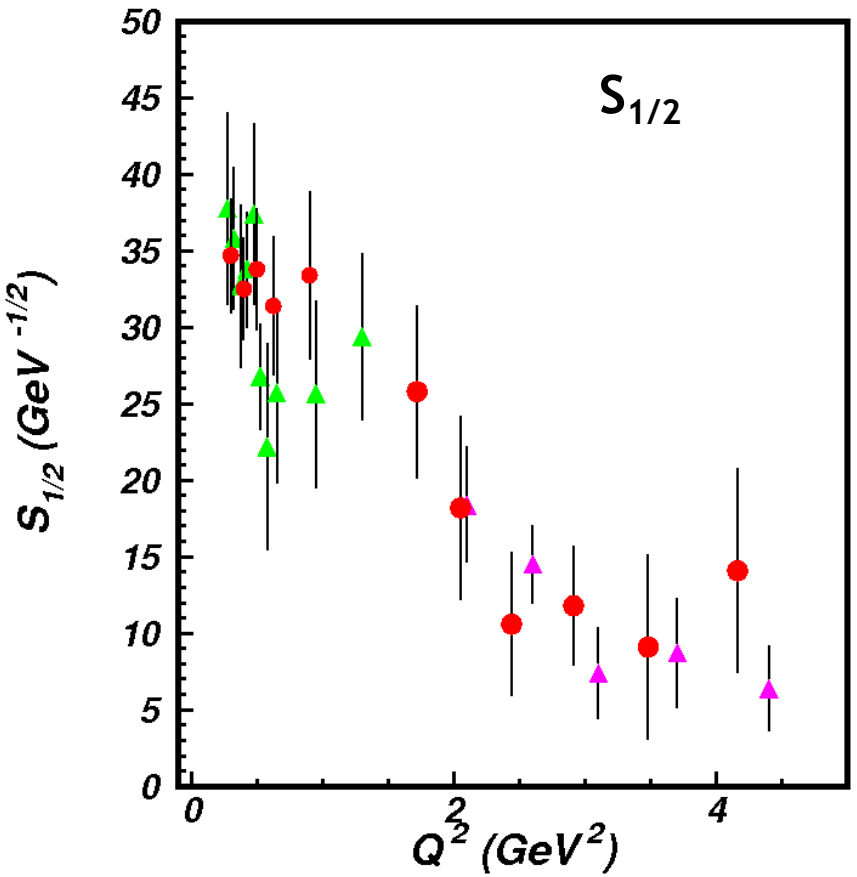
2019



V. D. Burkert, Baryons 2016 and the recent update from the CLAS $\pi^+\pi^-$p electroproduction off protons data

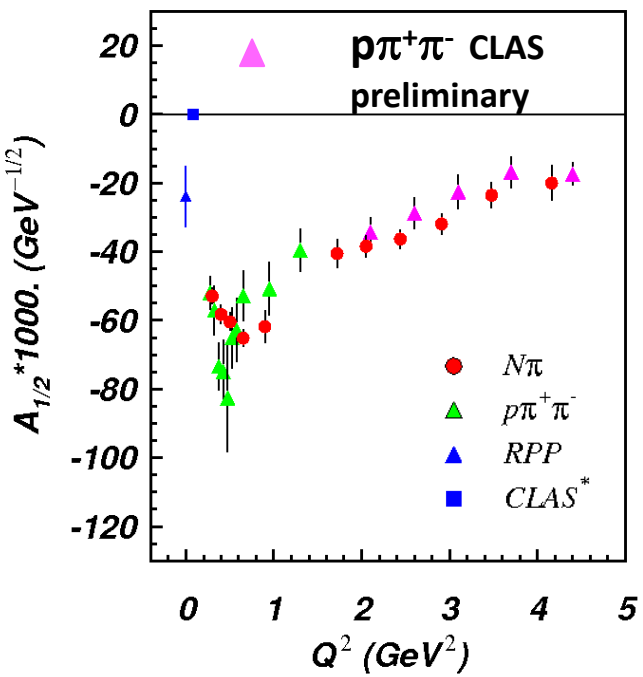
Electrocouplings of N(1440)1/2$^+$ from Nπ and $\pi^+\pi^-$p Electroproduction off Proton Data

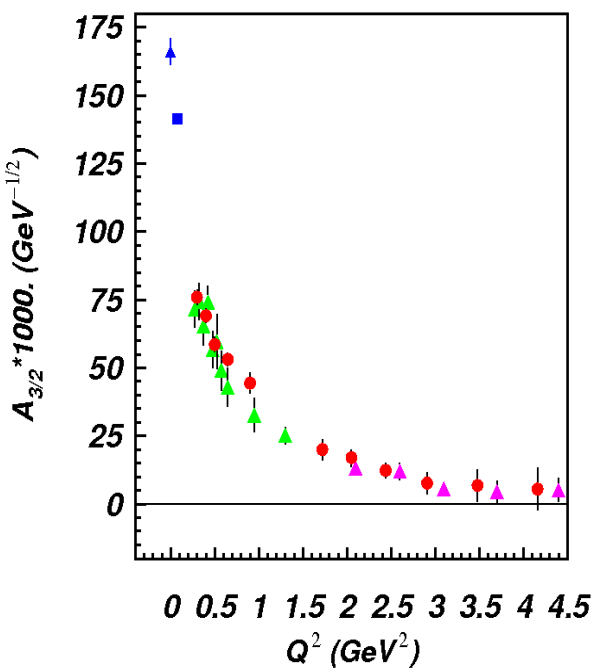


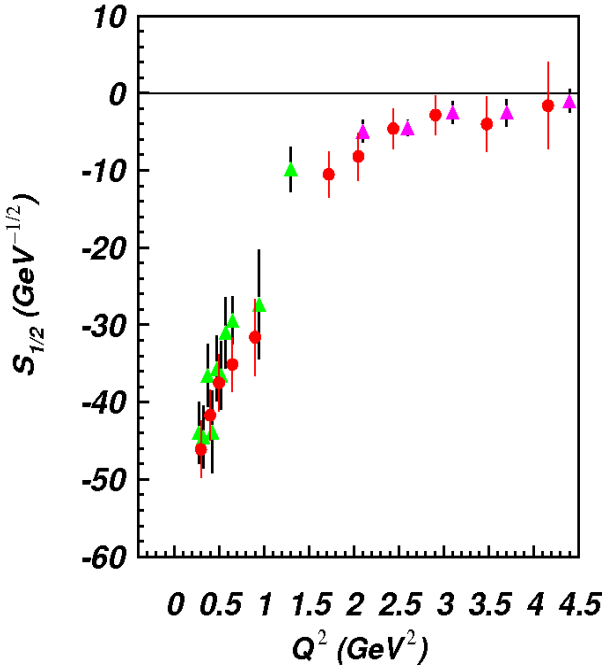


Consistent results on N(1440)1/2$^+$ electrocouplings from the independent studies of two major Nπ and $\pi^+\pi^-$p electroproduction off proton channels with different non-resonant contributions strongly support credible extraction of these quantities in a nearly model-independent way.

Electrocouplings of N(1520)3/2⁻ from Nπ and π⁺π⁻p Electroproduction off Proton Data







Consistent results from Nπ and $\pi^+\pi^-$p electroproduction off proton data on electrocouplings of N(1440)1/2⁺ and N(1520)3/2⁻ resonances with the biggest combined contribution into the resonant parts of both channels at W<1.55 GeV strongly support the capabilities of the developed reaction models for credible extraction of resonance electrocouplings from independent analyses of both Nπ and $\pi^+\pi^-$p electroproduction.

CLAS Physics Database

JLab | Search | Overview | Login | Edit | Register

Search form for the data related to the CLAS physics

You are not logged in. Login.

Select reaction:

Beam:	Target:	Final state:
any	any	any
polarization: any	polarization: any	polarization: any

Select kinematics range:

Search for average values

Q^2_{min}, [GeV]^2:		Q^2_{max}, [GeV]^2:	
W_{min}, [GeV]:		W_{max}, [GeV]:	
x_{min}:		x_{max}:	
$E_{\gamma min}$, [GeV]:		$E_{\gamma max}$, [GeV]:	

Select observables:

Quantity measured:

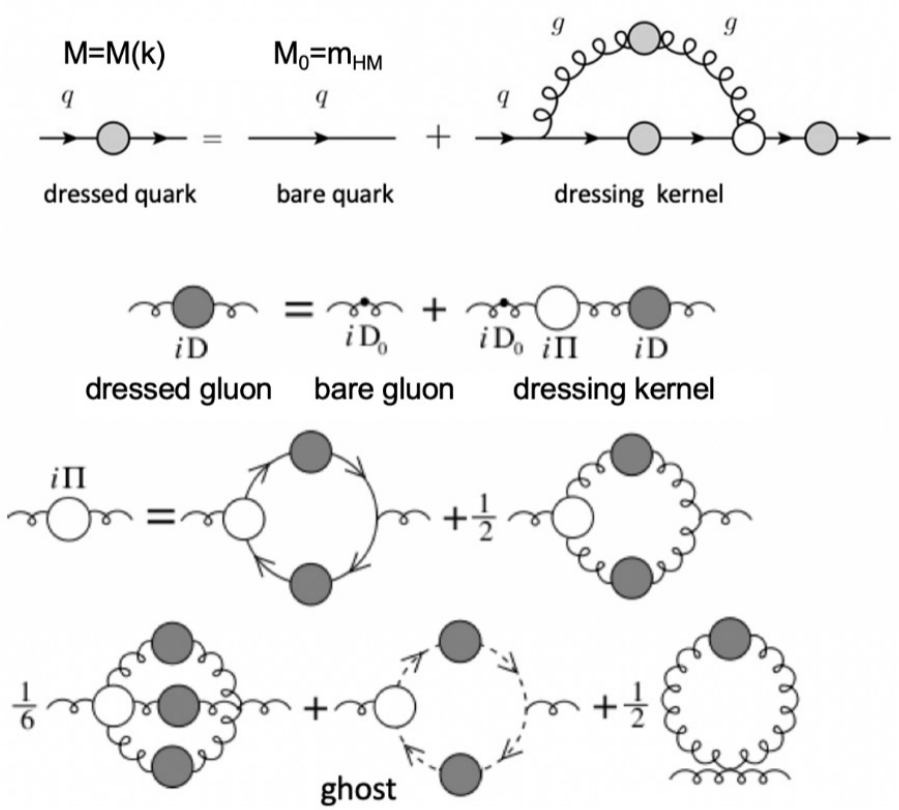
any
σ
dσ/dΩ
σ_L
σ_T
σ_L/σ_T
σ_TT

М.Давыдов, А.Насртдинов
Структурные функции однопионного рождения

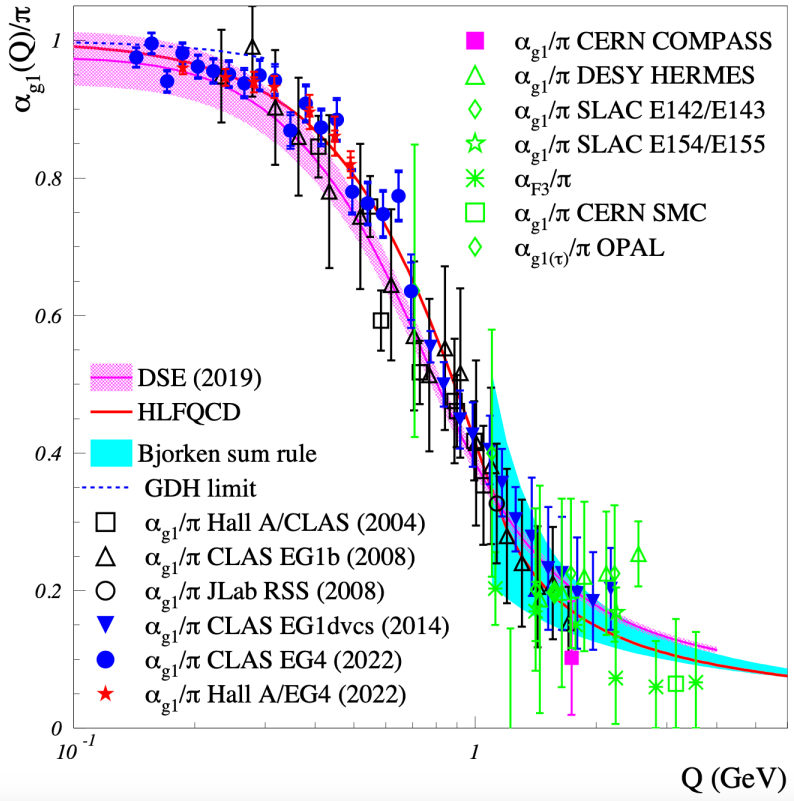
База данных экспериментов CLAS/CLAS12

Basics for Insight into EHM: Continuum and Lattice QCD Synergy

Emergence of Dressed Quarks and Gluons
D. Binosi et al., Phys. Rev. D 95, 031501 (2017)



QCD Running Coupling α(k)
Zh-F. Cui et al., Chin. Phys. C44, 083102 (2020)
A. Deur et al., Particles 5, 171 (2022)

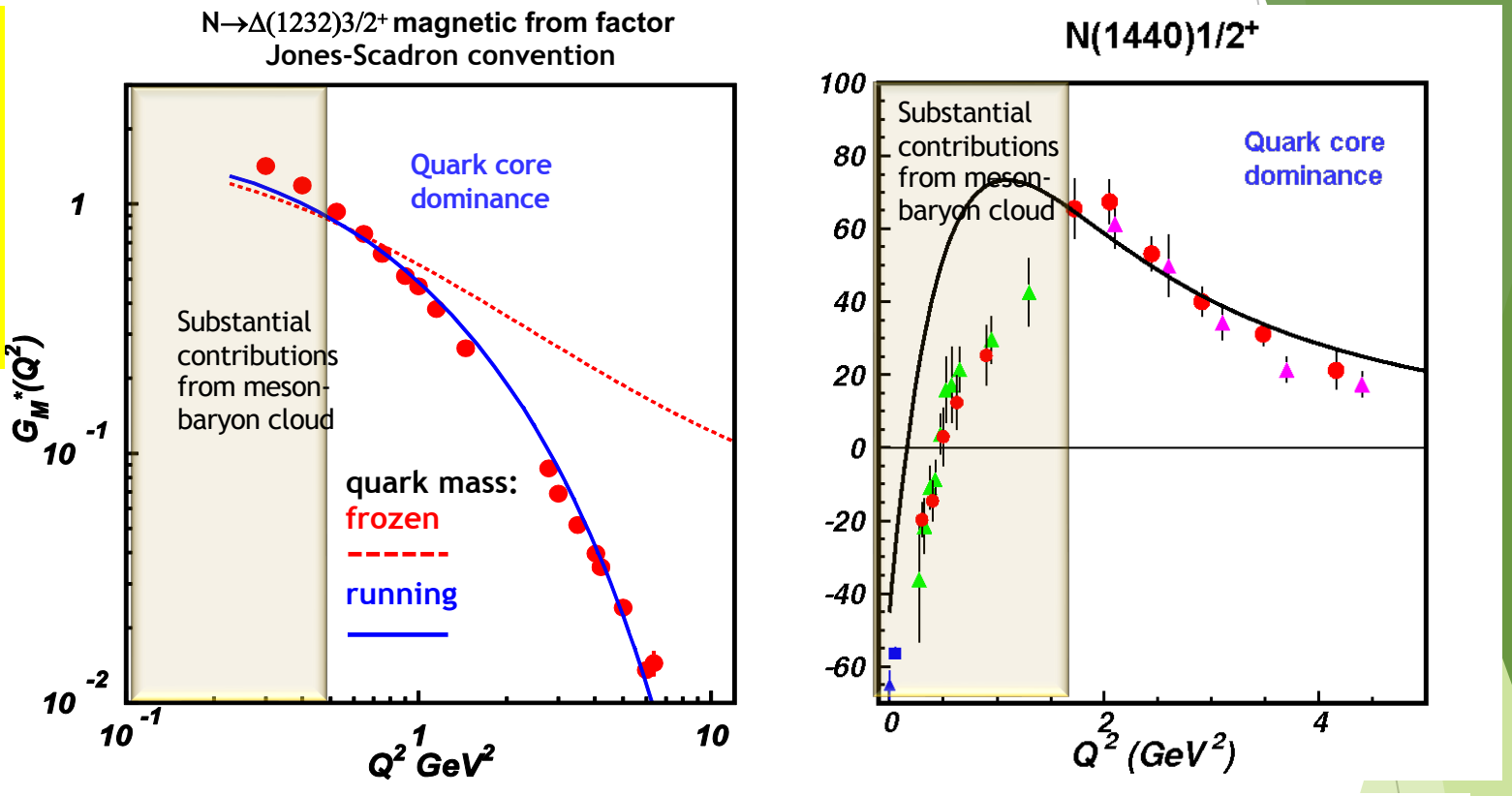


In the regime of the QCD running coupling comparable with unity, dressed quarks and gluons with distance (momentum) dependent masses emerge from QCD, as follows from the equations of the motion for the QCD fields depicted above

From Resonance Electrocouplings to Hadron Mass Generation

Dyson-Schwinger Equations (DSE):

- J. Segovia et al., Phys .Rev. Lett. 115, 171801 (2015).
- J. Segovia et al., Few Body Syst. 55, 1185 (2014).

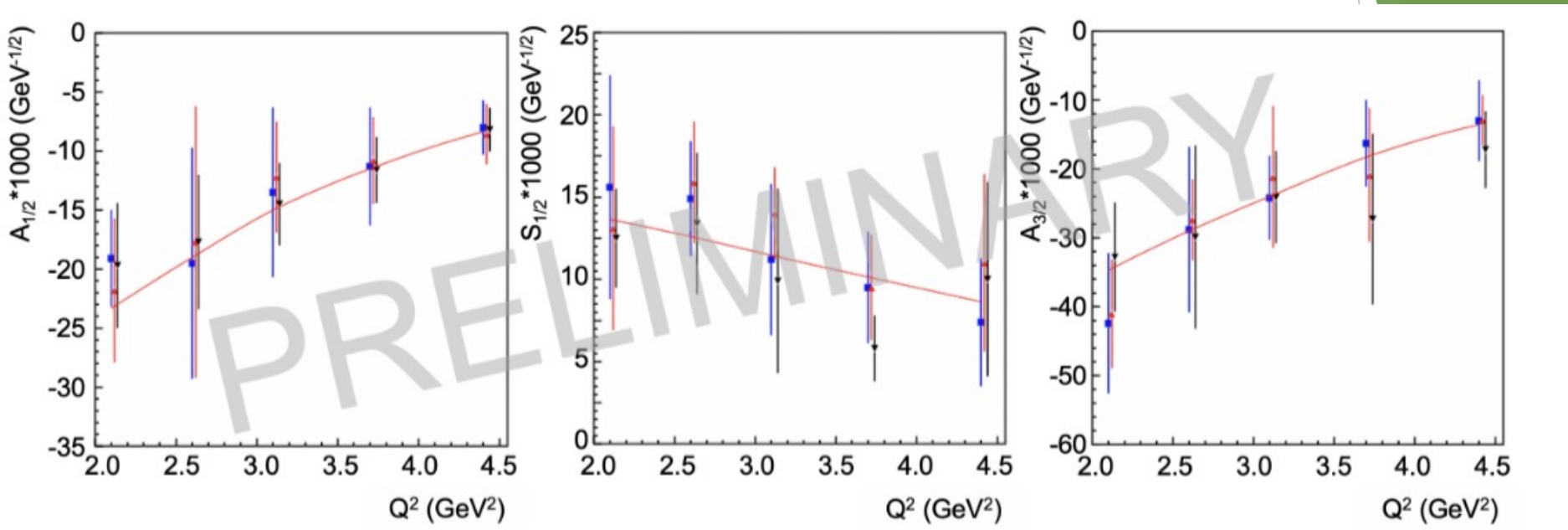


DSE analyses of the CLAS data on Δ(1232)3/2⁺ electroexcitation demonstrated that dressed quark mass is running with momentum.

Good data description at Q^2>2.0 GeV^2 achieved with the same dressed quark mass function for the ground and excited nucleon states of distinctively different structure validate the DSE results on momentum dependence of dressed quark mass. $\gamma_v pN^*$ electrocoupling data offer access to the strong QCD dynamics underlying the hadron mass generation.

One of the most important achievements in hadron physics of the last decade in synergistic efforts between experimentalists, phenomenologists and theorists.

$\Delta(1600)3/2^+$ Electrocouplings : CSM Prediction vs. Data Determination



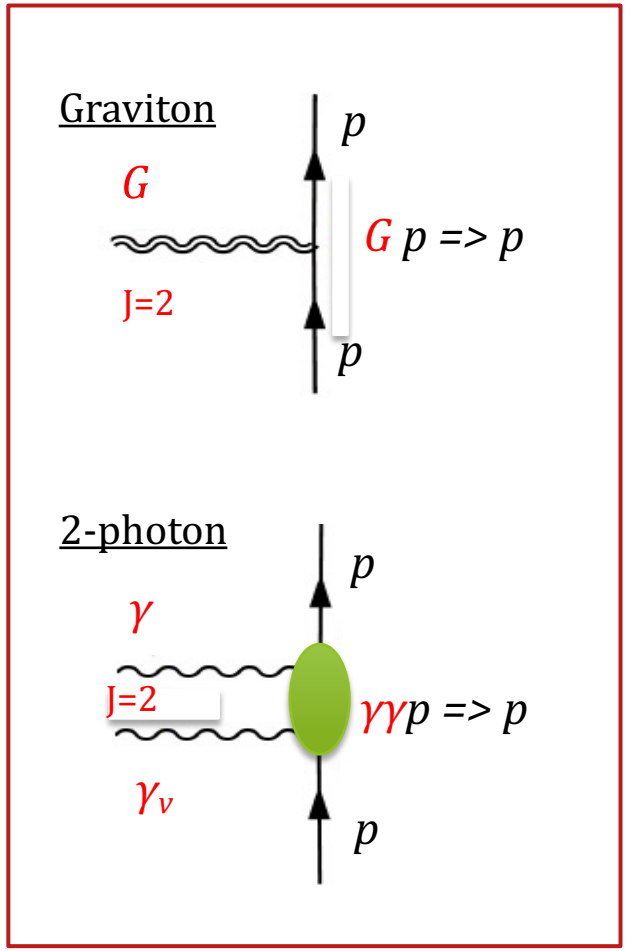
CSM predictions, Ya Lu et al., Phys. Rev. D 100, 034001 (2019)

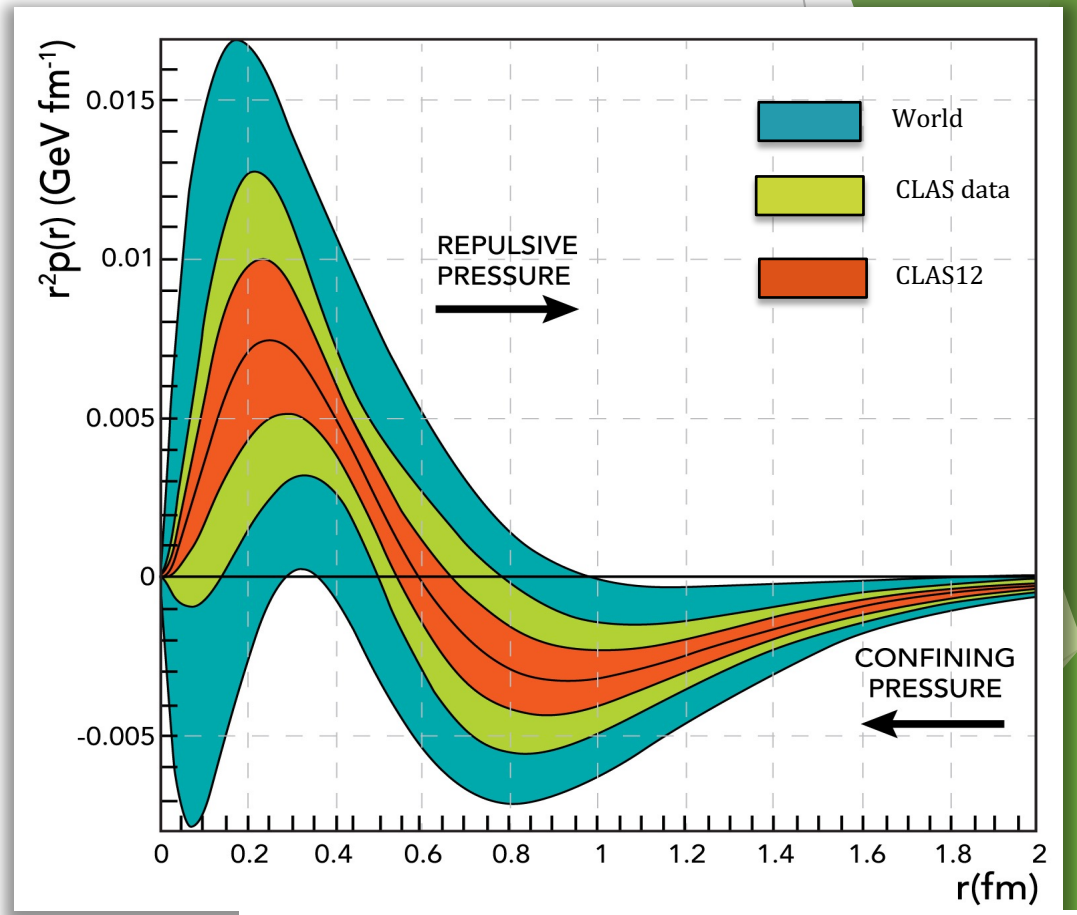
Electrocouplings from independent analyses of $\pi^+\pi^-p$ differential cross sections within three W-intervals, 1.46<W<1.56 GeV, 1.51<W<1.61 GeV, and 1.56<W<1.66 GeV for $2.0<Q^2<5.0$ GeV^2

CLAS results on $\Delta(1600)3/2^+$ electrocouplings confirmed the CSM prediction, solidifying evidence for gaining insight into dressed quark mass function and, consequently, into EHM from the studies of $\gamma_v pN^*$ electrocouplings

Mapping DVCS to Gravity

The 2-γ field couples to the EMT the same way gravity does.





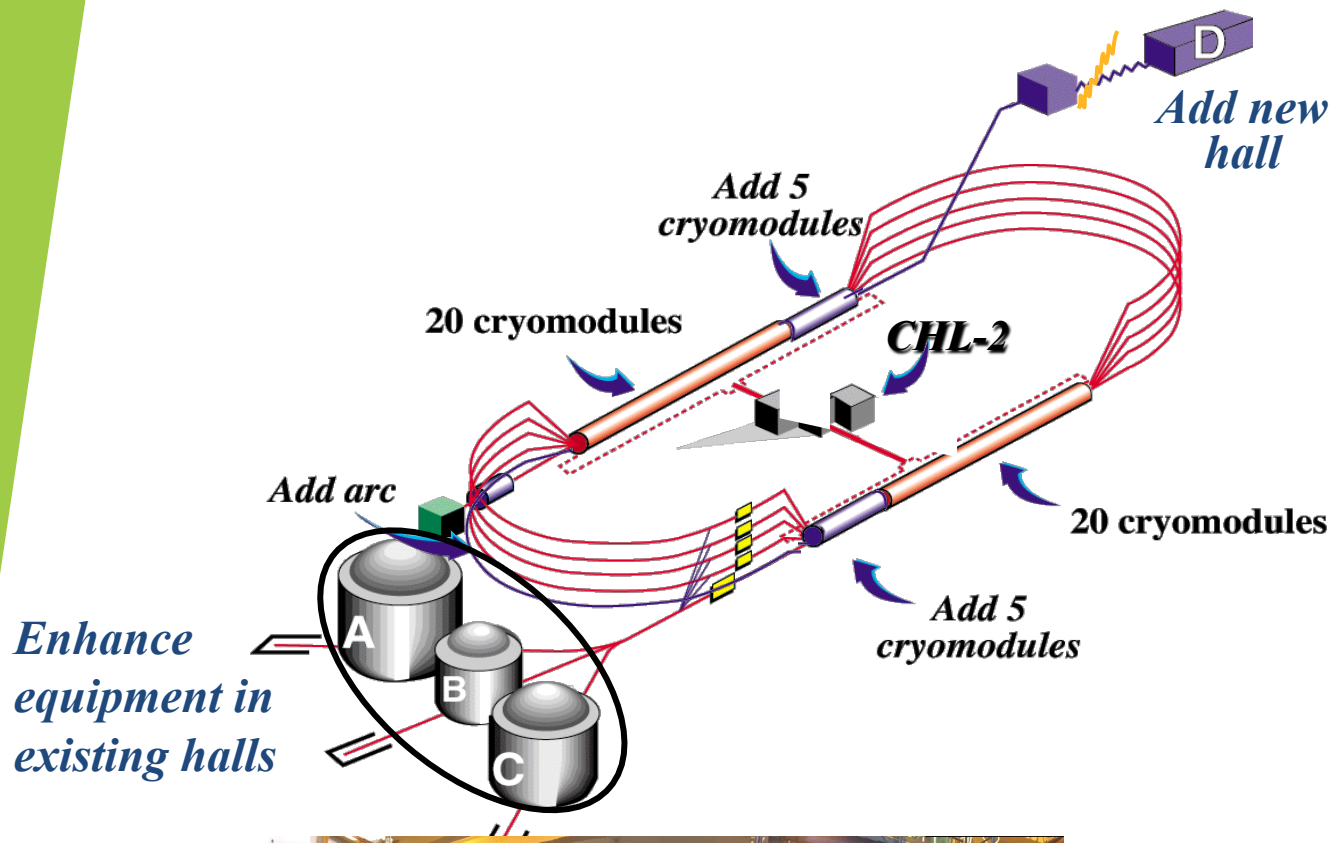
The pressure distribution inside the proton

V. D. Burkert ✉, L. Elouadrhiri & F. X. Girod

Nature **557**, 396–399 (2018) | Cite this article

DVCS makes mechanical properties accessible to experiment

JLab @ 12 GeV Project



CLAS12 N* Program at High Q^2

E12-09-003	E12-06-108A
Nucleon Resonance Studies with CLAS12	KY Electroproduction with CLAS12
Gothe, Mokeev, Burkert, Cole, Joo, Stoler	*Carman, Gothe, Mokeev*

- Measure exclusive electroproduction cross sections from an unpolarized proton target with polarized electron beam for $N\pi$, $N\eta$, $N\pi\pi$, KY:

  E_b = 11 GeV, Q^2 = 3 → 12 GeV^2, W → 3.0 GeV with nearly complete coverage of the final state phase space

- Key Motivation

  Study the structure of all prominent N states in the mass range up to 2.0 GeV vs. Q^2 up to 12 GeV^2.*

  CLAS12 is the only facility to map-out the N quark with minimal meson-baryon cloud contributions.*

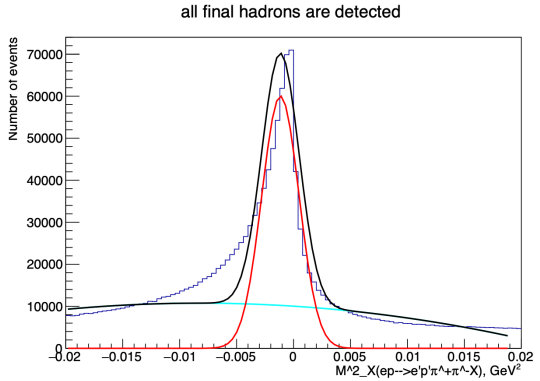
The experiments already started in February 2018!

by Anna Frolova and Alexander Bulgakov

$\pi^+\pi^-$p CLAS12 data analysis

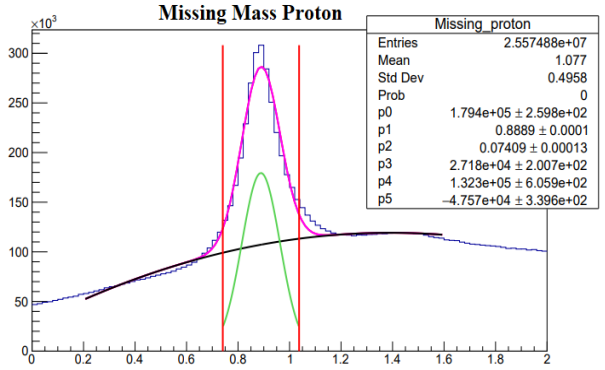
RG-K @ 6.5 GeV

ep→ ep'$\pi^+\pi^-$X



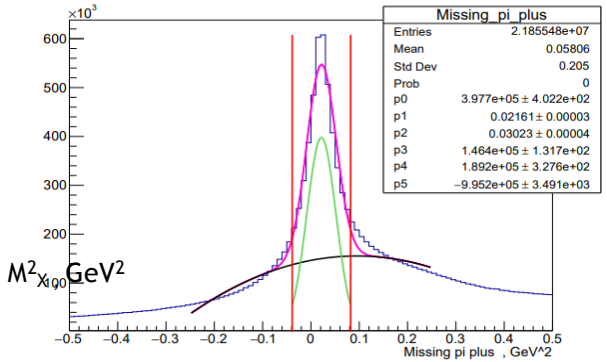
M^2_X , GeV^2

ep→ e$\pi^+\pi^-$X



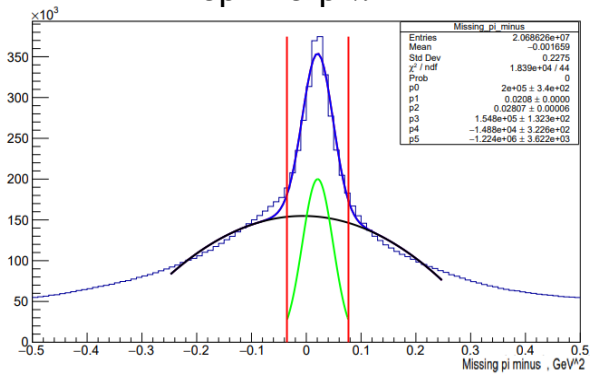
M^2_X , GeV^2

ep → e'p'π^-X



M^2_X , GeV^2

ep → e'p'π^{-+}X



M^2_X , GeV^2

Available data-set: Data on nine independent one-fold differential cross sections →nucleon resonance electroexcitation

Full statistics for RG-K will allow:

- to obtain $\pi^+\pi^-$p electroproduction cross section within Q^2-bins of 0.1 GeV^2 size

Спасибо за внимание!