Изучение структуры нуклонных резонансов на детекторах CLAS/CLAS12

Е. Исупов

Эксперименты Ферми по рассеянию пионов на протонах. Дельта-резонансы.

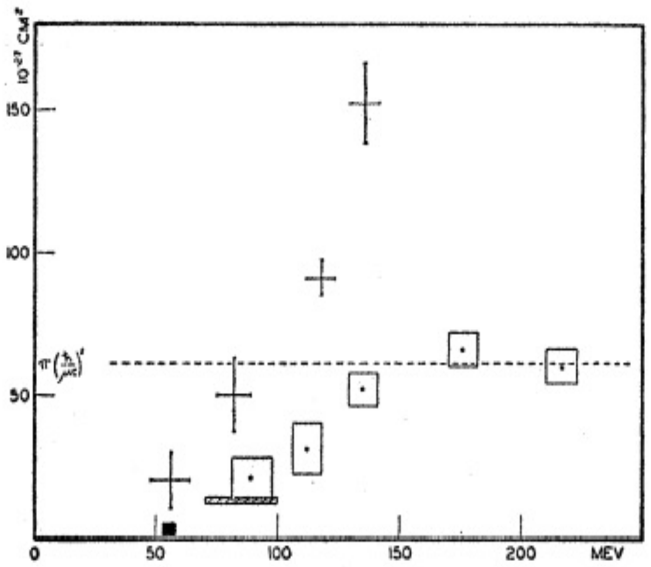
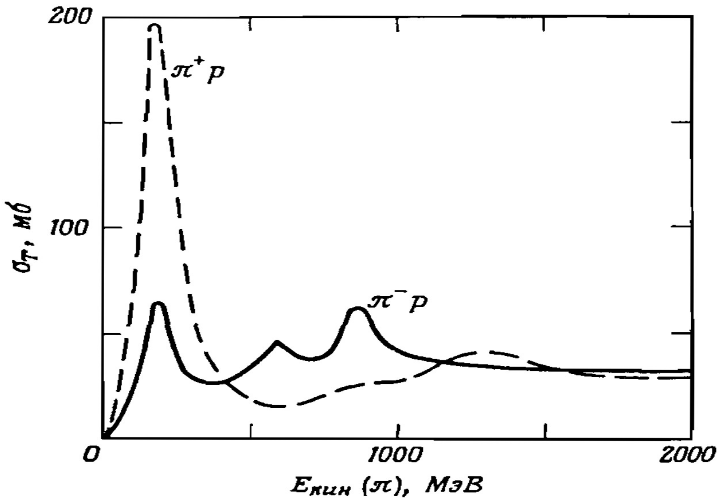


FIG. 1. Total cross sections of negative pions in hydrogen (sides of the rectangle represent the error) and positive pions in hydrogen (arms of the

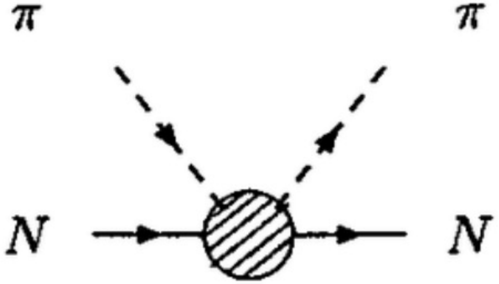


$$\pi^+ p \to \pi^+ p$$
$$\pi^- p \to \pi^- p$$

$$L_{2I,2J}$$

$\Delta(1232)P_{33}$ $N(1680)F_{15}$

$\Delta(1232)3/2^+$ $N(1680)5/2^+$



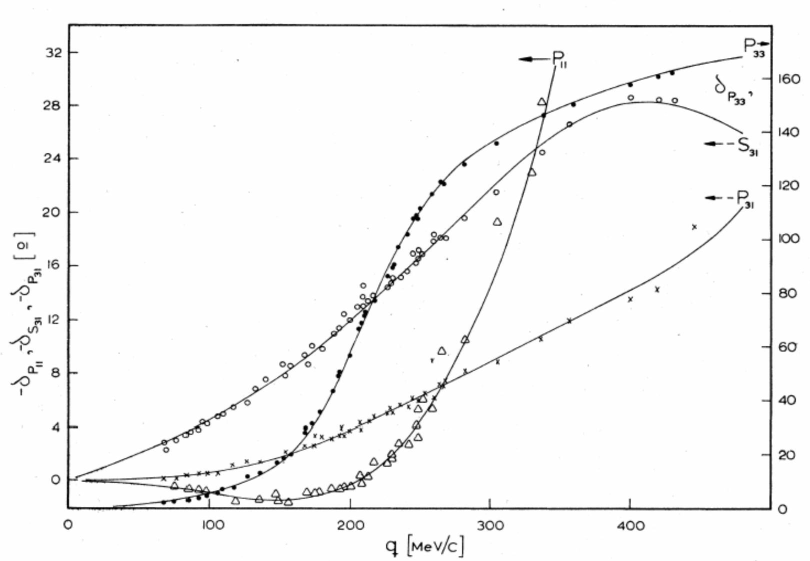


FIG. 1. Phase shifts in degrees for S_{31}, P_{11}, P_{31}, and P_{33} waves. The points have been taken from Refs. 11–17.

Фазовый анализ

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

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

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

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

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

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

SU(6) multiplets decompose into flavor multiplets:

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

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

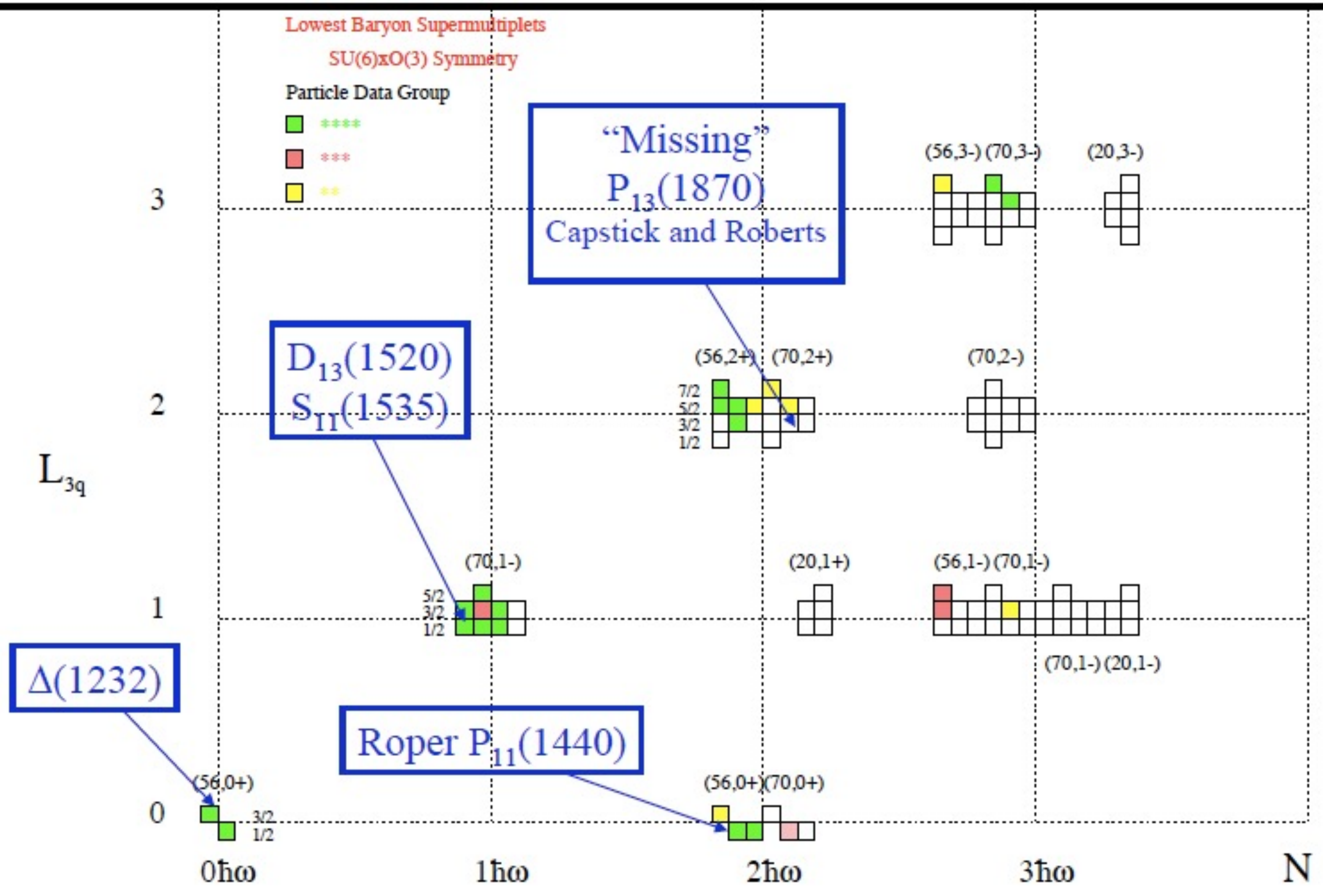
$20 = {}^2 8 \oplus {}^4 1$

O(3)

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

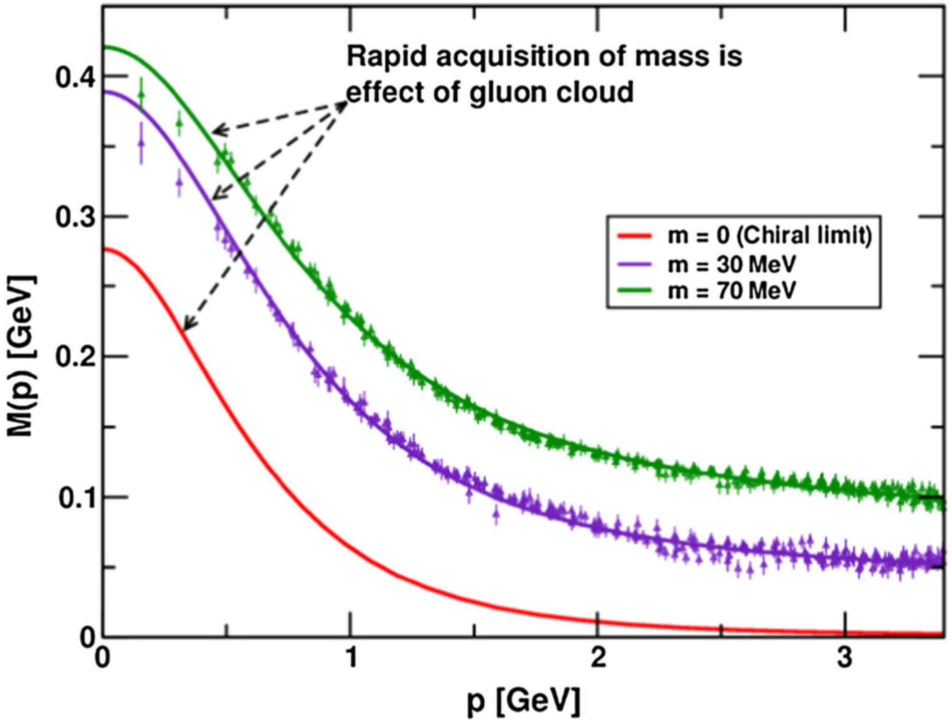
parity: $P = (-1)^L$

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



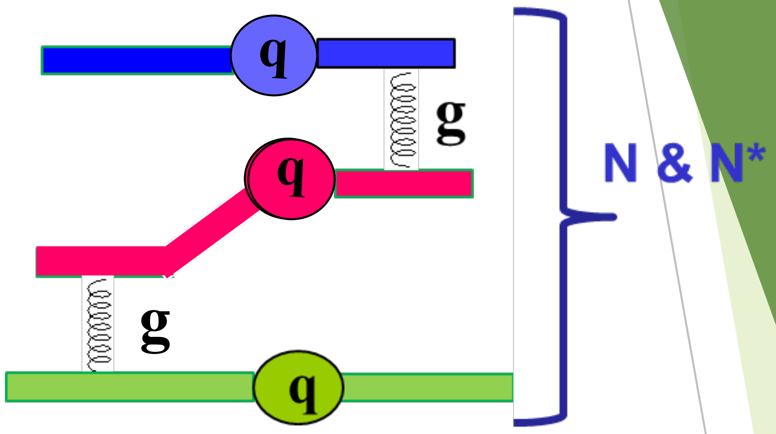
Excited Nucleon States and Insight into Strong QCD Dynamics

Two conceptually different approaches for description of nucleon/N* structure from first QCD principles:
- Lattice QCD (LQCD)
- Dyson-Schwinger Equation of QCD (DSEQCD)



Dressed Quark Mass Function
C.D. Roberts, Few Body Syst. 58, 5 (2017)

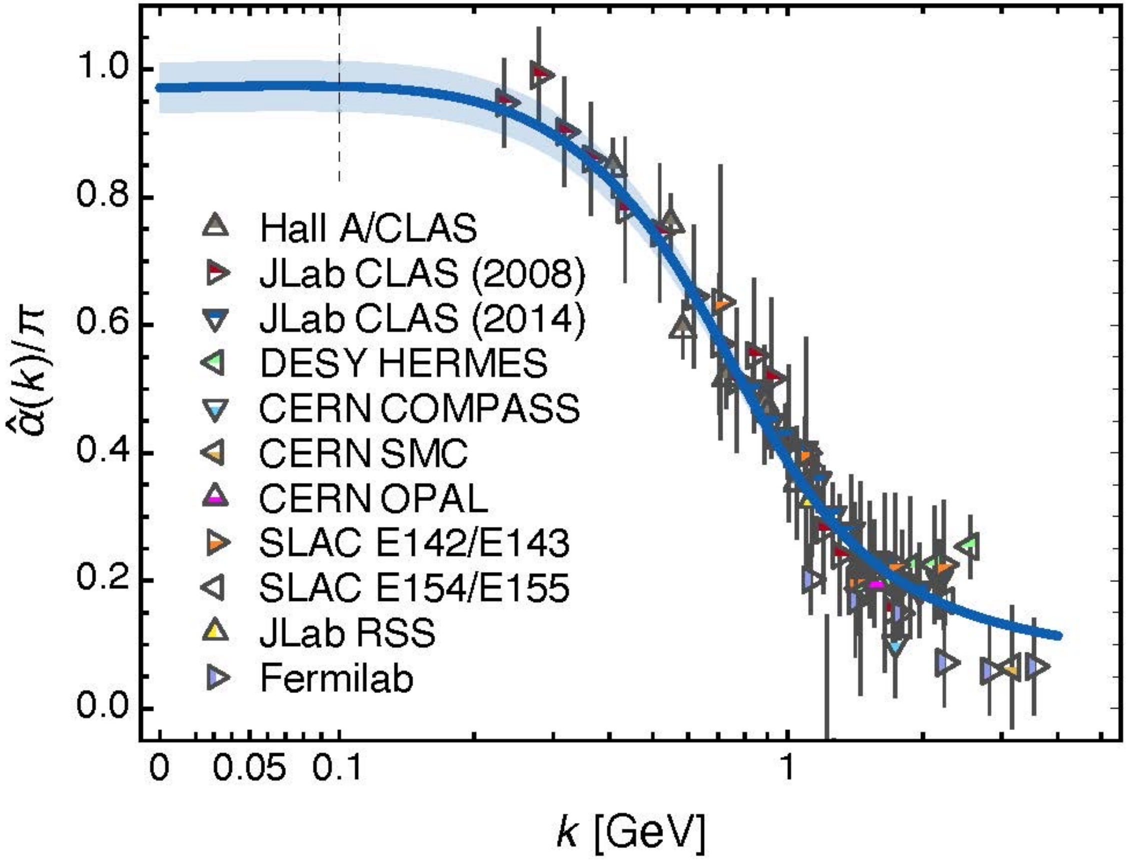
quark-quark correlations in baryons
Ch. Chen et al, Phys. Rev. D97, 034016 (2018)



N* structure studies address:

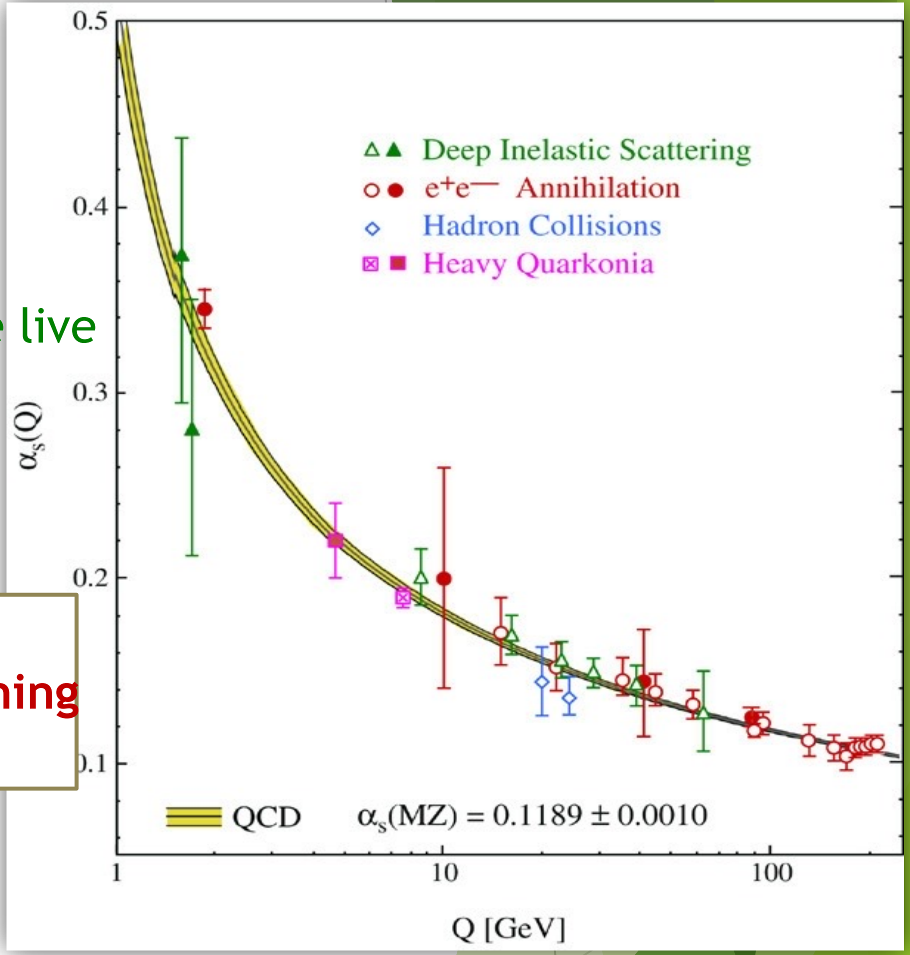
- Nature of > 98% of hadron mass
- Emergence of the ground nucleon parton distributions in 1D and 3D

QCD's Running Coupling



Daniele Binosi et al., Phys. Rev. D 96, 054026 (2017)

This is where we live



⇐
What's happening out here?!

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

Experiment

Theory

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 $\alpha_s \sim 1$

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

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

- 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
…………………………….

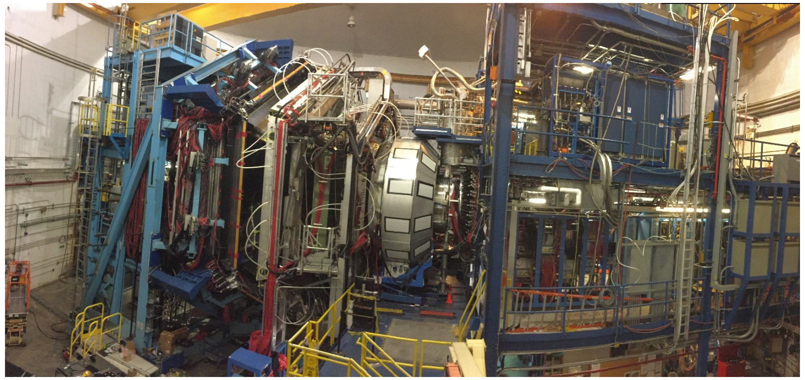
New era in electromagnetic nuclear physics

- 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.

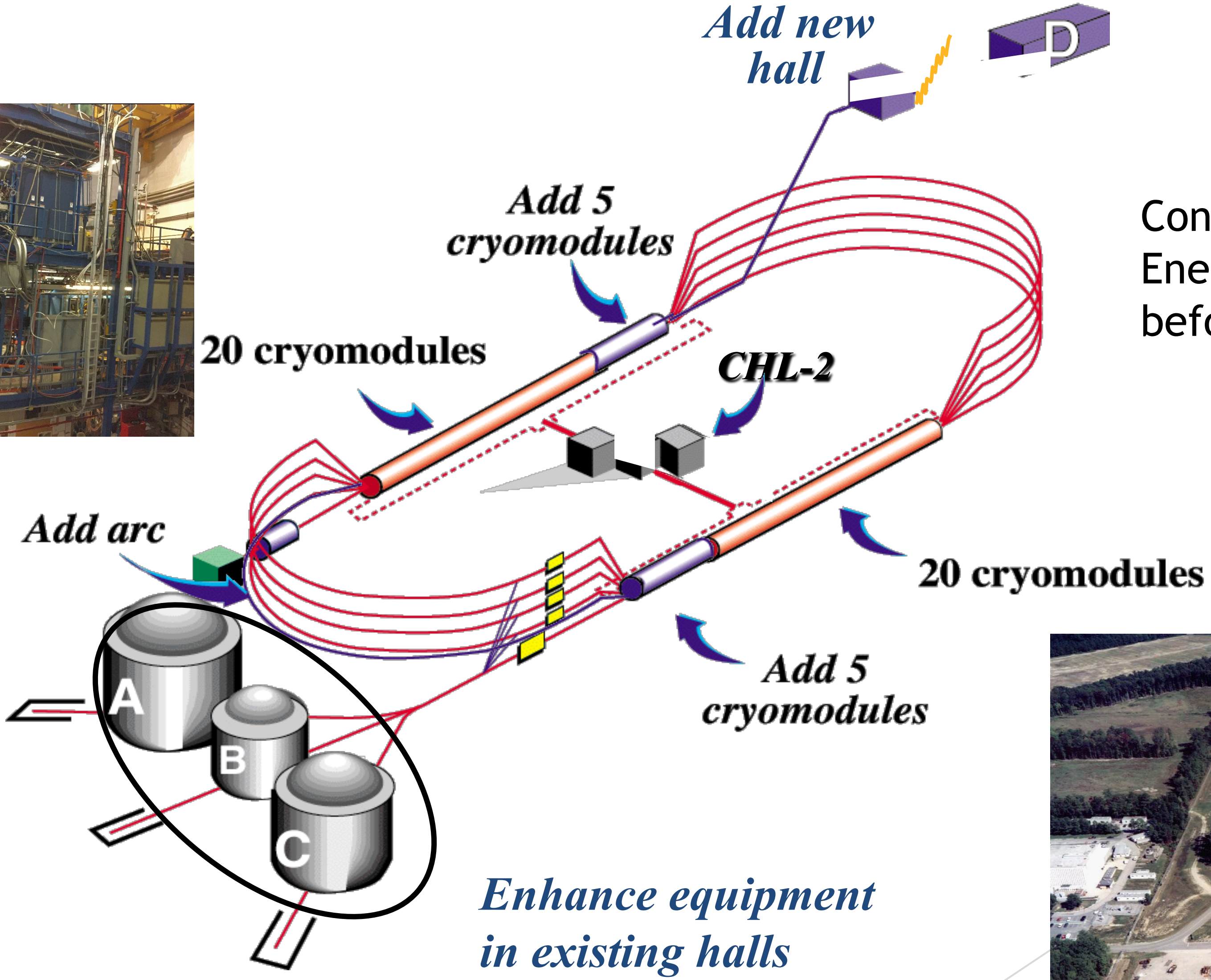
MAMI Mainz
ELSA Bonn
GRAAL Grenoble
LEPS Osaka
JLAB Newport News

Jefferson Lab (Newport News, VA, USA)

CLAS12 in Hall B



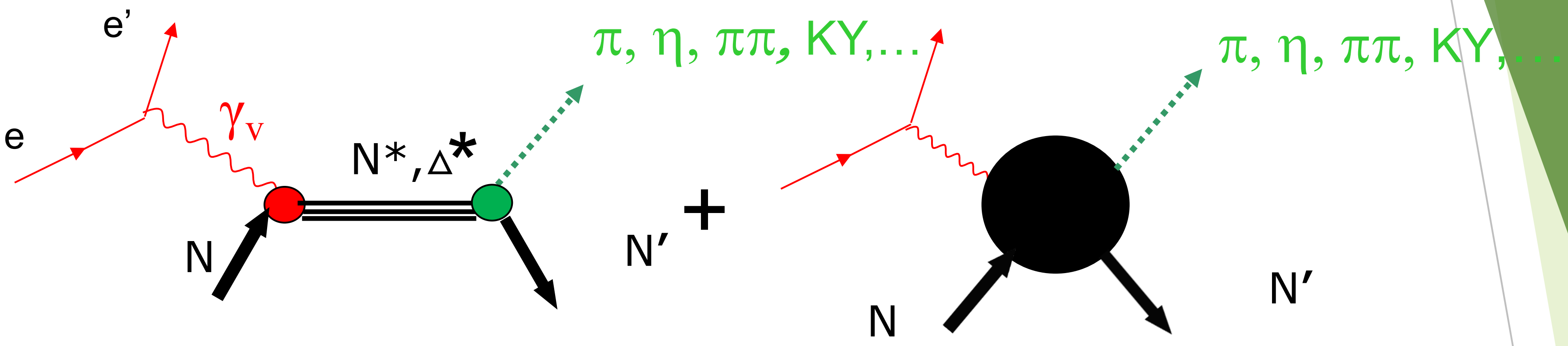
CLAS (1998-2012)



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

Extraction of $\gamma_v NN^*$ Electrocouplings from Exclusive Meson Electroproduction off Nucleons

Resonant amplitudes **Non-resonant amplitudes**



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)

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

- **Consistent results on $\gamma_v pN^*$ 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

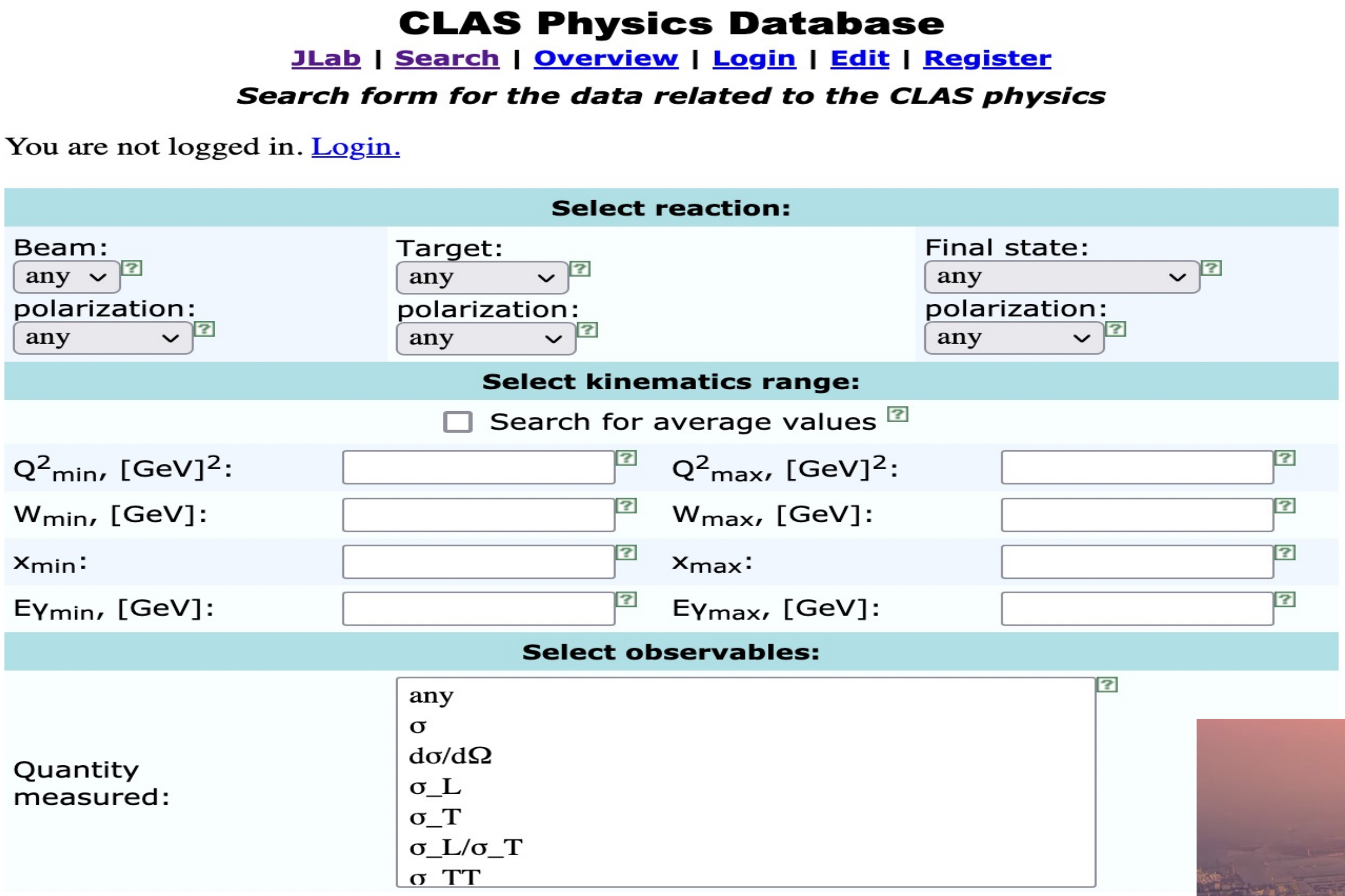
Hadronic final state	Covered W-range, GeV	Covered Q^2-range, GeV^2	Measured observables
$\pi^+ n$	1.1-1.38 1.1-1.55 1.1-1.7 1.6-2.0	0.16-0.36 0.3-0.6 1.7-4.5 1.8-4.5	$d\sigma/d\Omega$ $d\sigma/d\Omega$ $d\sigma/d\Omega$, A_b $d\sigma/d\Omega$
$\pi^0 p$	1.1-1.38 1.1-1.68 1.1-1.39 1.1-1.8	0.16-0.36 0.4-1.8 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

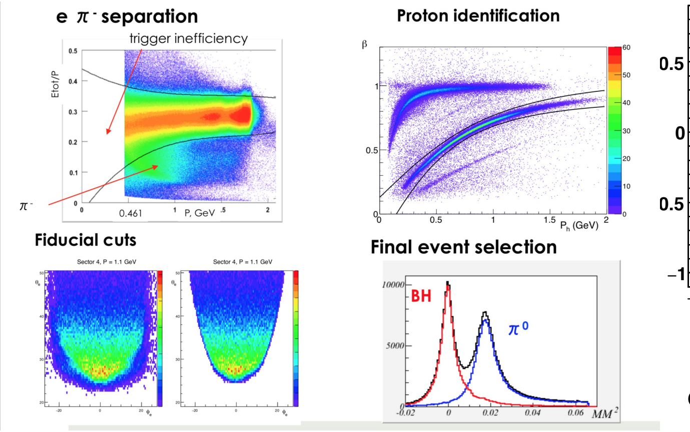
The measured observables from CLAS are stored in the CLAS Physics Data Base http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi

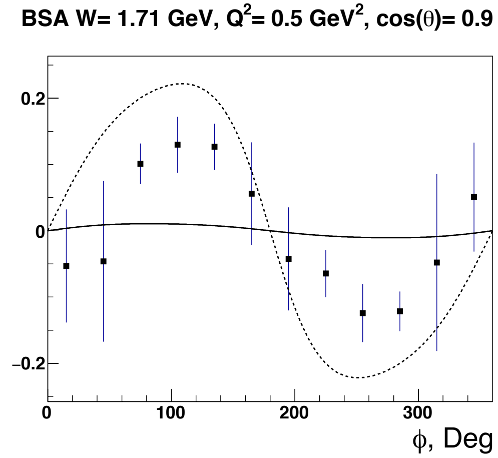


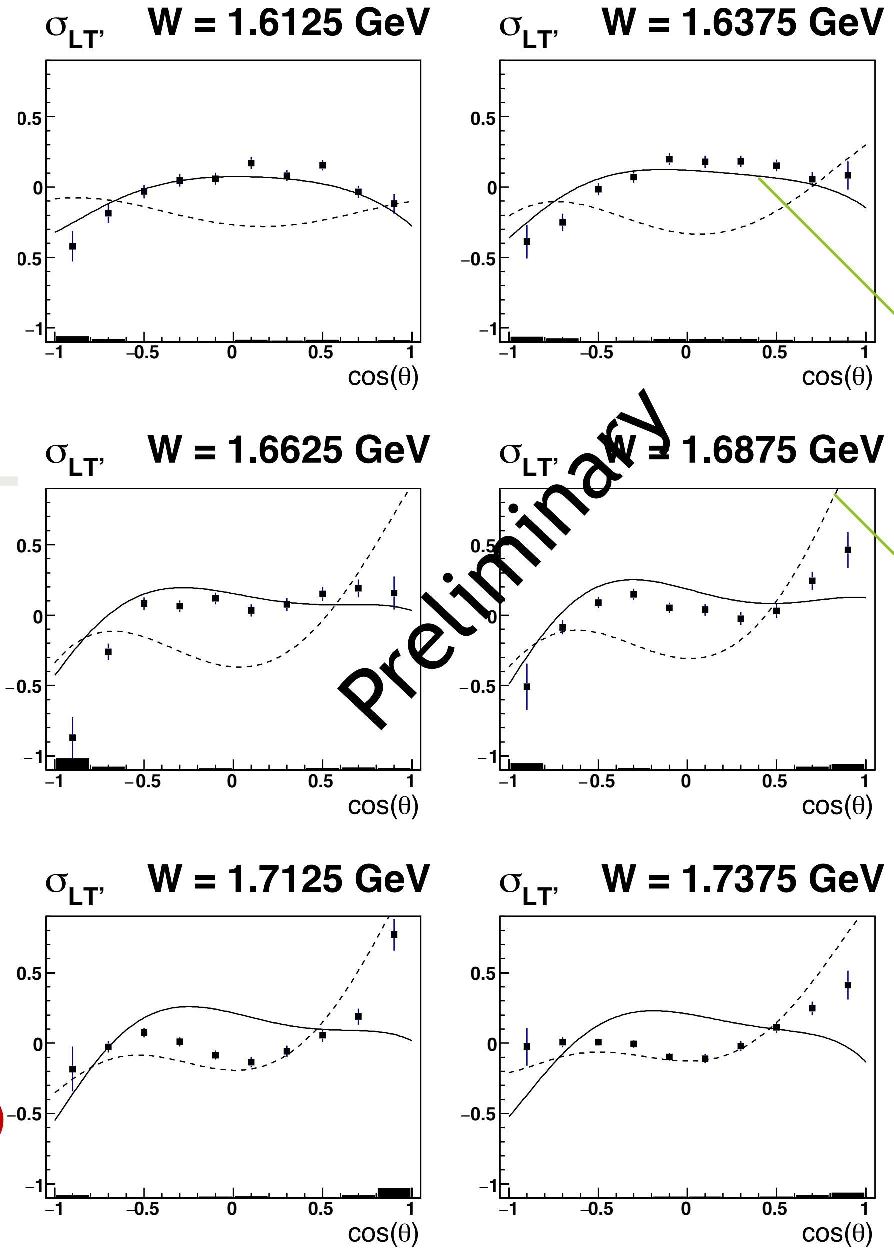
В.Чесноков – База данных экспериментов CLAS

М.Давыдов, А.Насртдинов
Структурные функции
однопионного рождения

Polarized Structure Function $\sigma_{LT'}$ from ep->epπ^0 at 0.4 < Q^2 < 0.6 GeV^2







$$\frac{d^2\sigma^h}{d\Omega^*_\pi} = \frac{p^*_\pi}{k^*_\gamma}[\sigma_0 + h\sqrt{2\epsilon_L(1-\epsilon)}\ \sigma_{LT'} \sin\theta^*_\pi \sin\phi^*_\pi]$$

$$A_{LT'} = \frac{d^2\sigma^+ - d^2\sigma^-}{d^2\sigma^+ + d^2\sigma^-} = \frac{\sqrt{2\epsilon_L(1-\epsilon)}\ \sigma_{LT'} \sin\theta^*_\pi \sin\phi^*_\pi}{\sigma_0}$$

MAID 2007 (solid line)

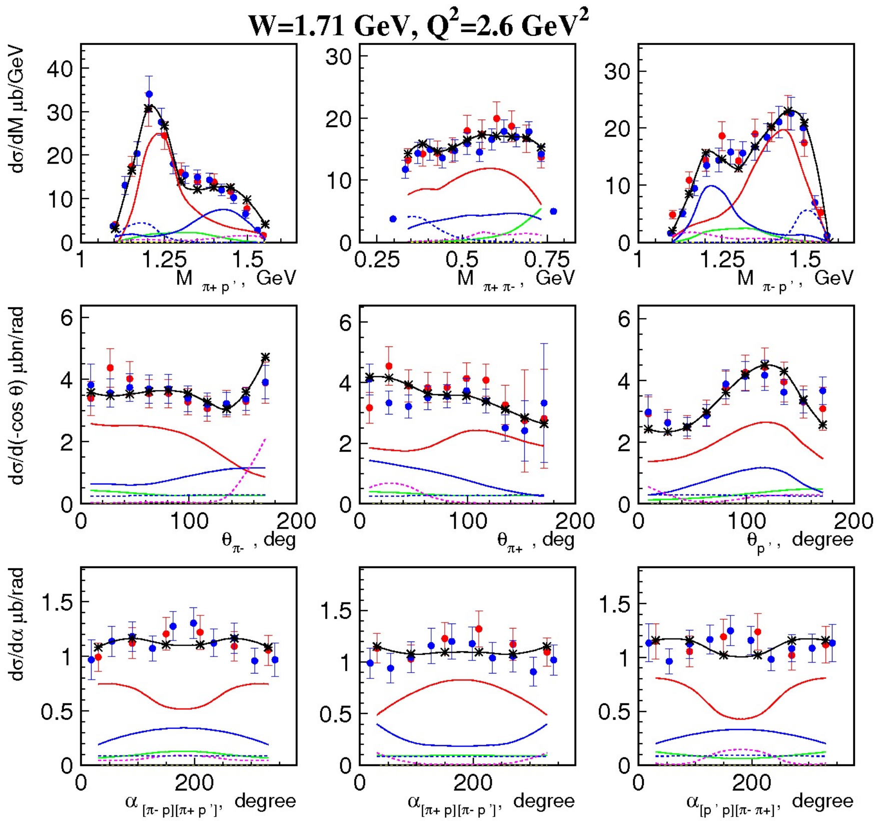
MAID 2007 with modified electrocouplings, taken from CLAS analyses (dashed line)

A.Golubenko, E.Isupov
et al. (under coll. review)

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

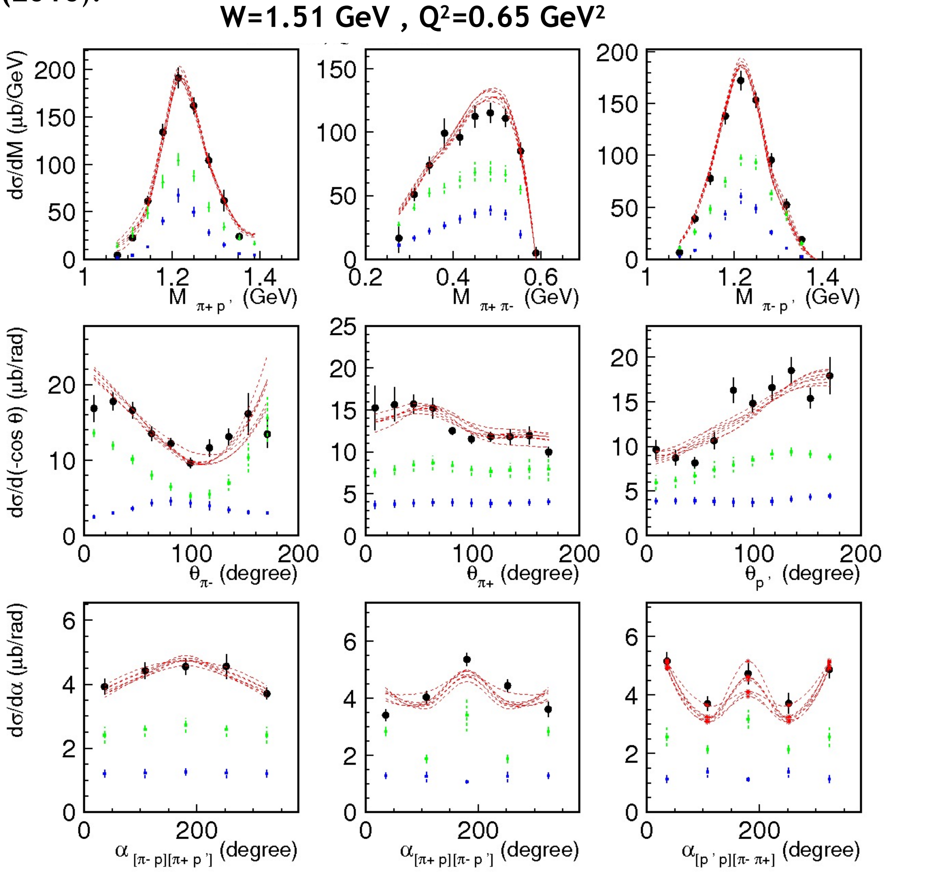
Contributing mechanisms seen in the data

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).

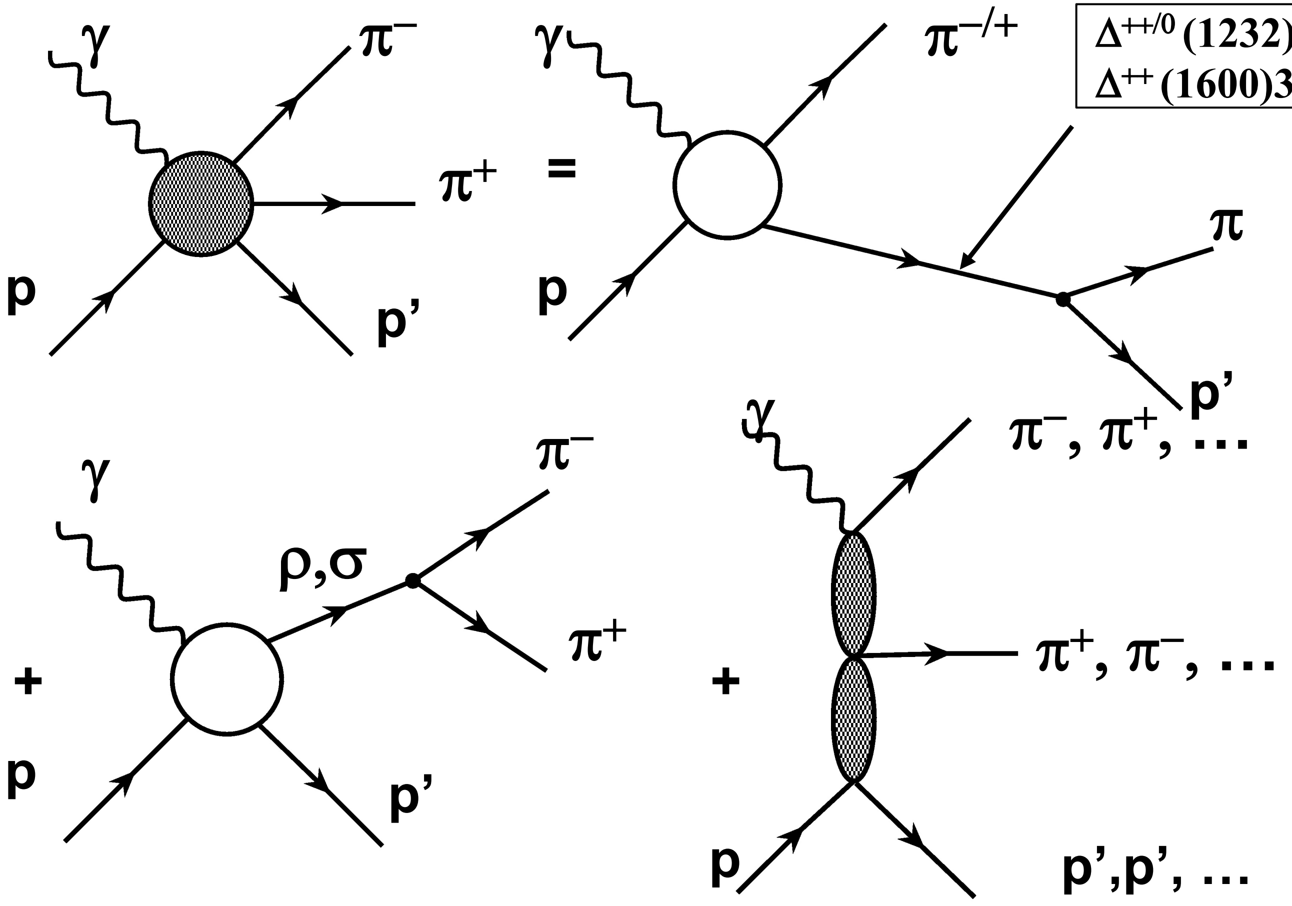


full JM
$\pi^-\Delta^{++}$
ρp
$\pi^+\Delta^0$
π^+ N(1520)3/2$^-$
π^+ N(1680)5/2$^+$

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

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

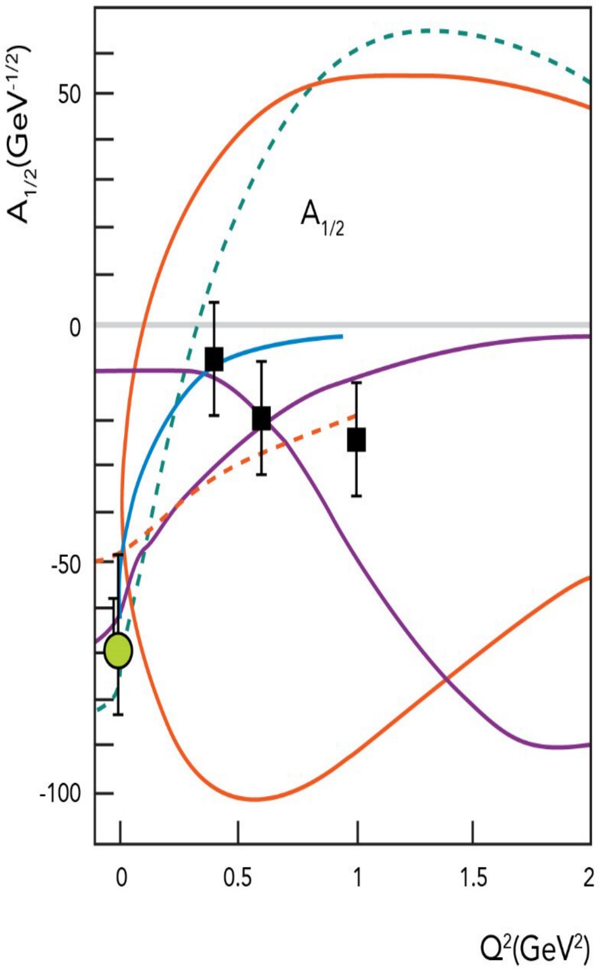


- five channels with unstable intermediate meson/baryon and direct $\pi^+\pi^-p$ production;
- N* contribute to $\pi\Delta$ and ρp channels only;
- unitarized Breit-Wigner ansatz for resonant amplitudes;
- phenomenological parameterization of the other meson-baryon channel amplitudes (see Ref. 2)

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

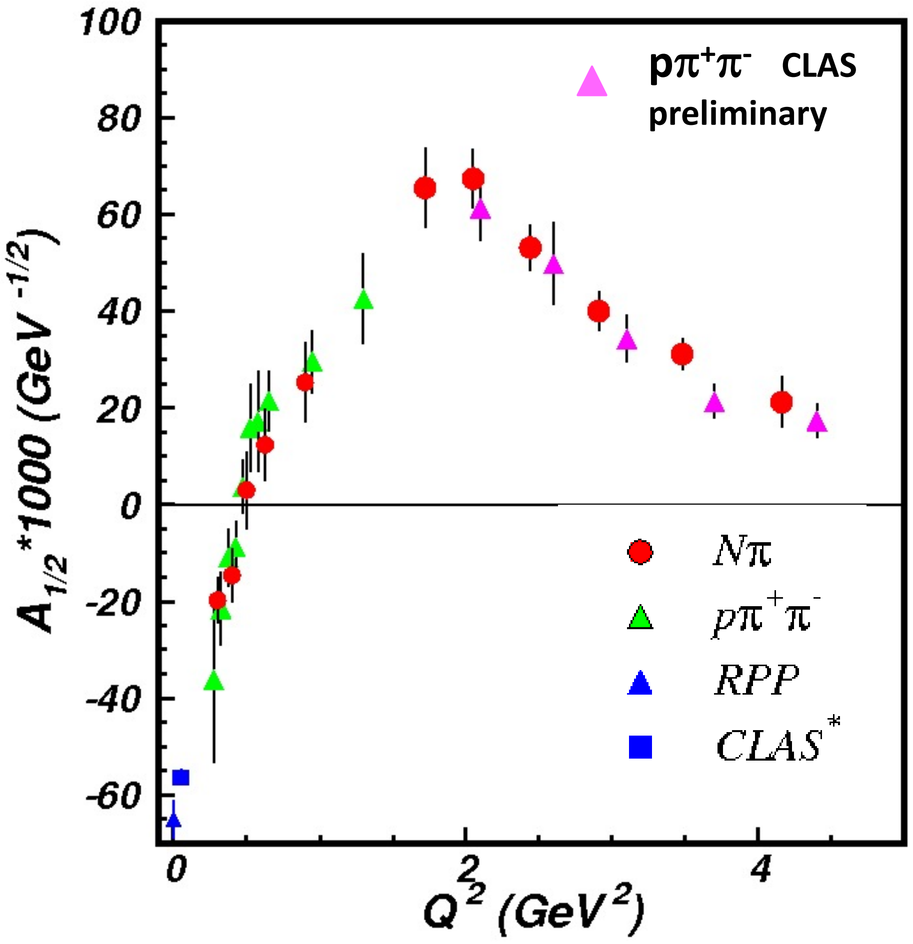
Roper Resonance in 2002 & 2019

2002



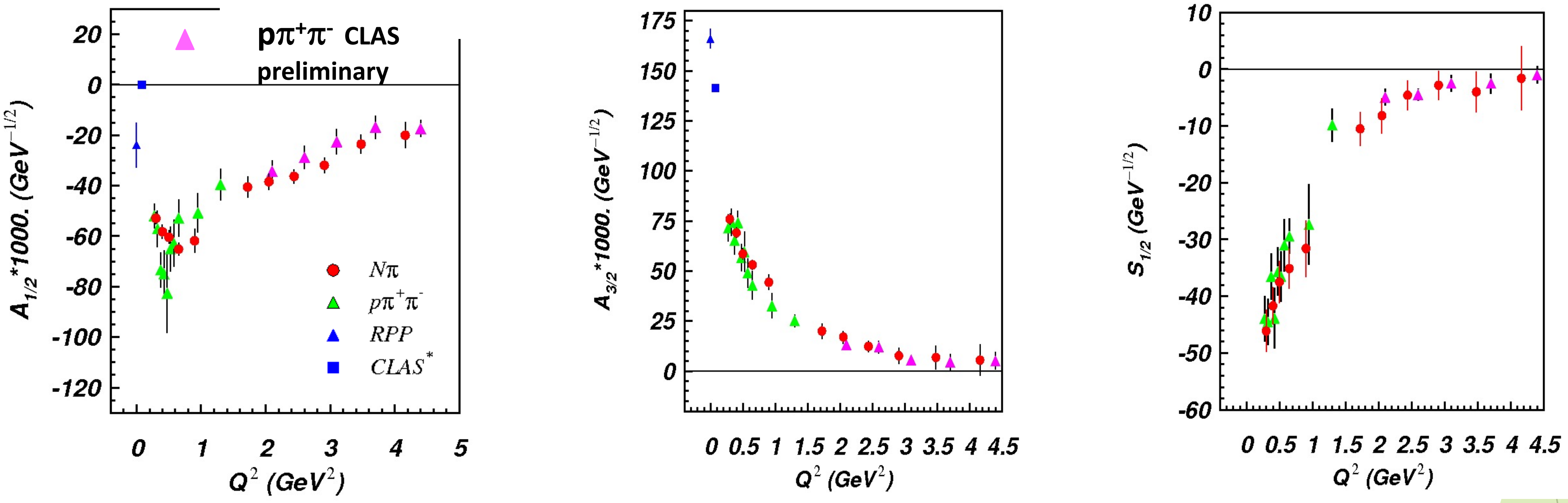
V. Burkert, Baryons 2002

2019



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

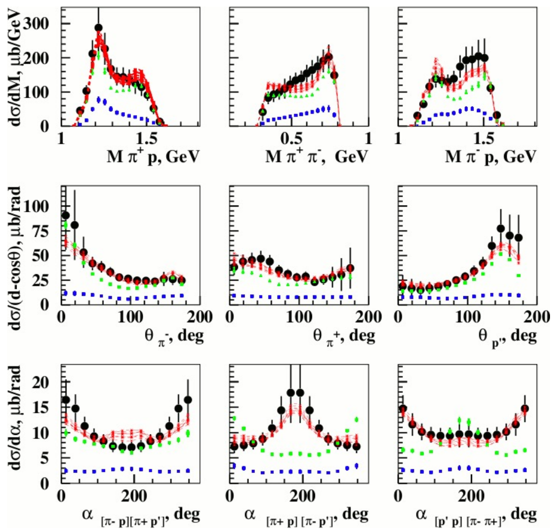
Electrocouplings of N(1520)3/2⁻ from Nπ and $p\pi^-\pi^+$ Electroproduction off Proton Data



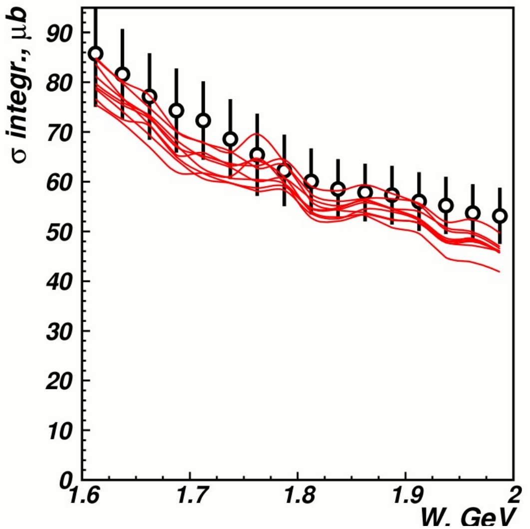
Consistent results from Nπ and $\pi^+\pi^-p$ electroproduction off proton data on electrocouplings of $N(1440)1/2^+$ and $N(1520)3/2^-$ resonances with the biggest combined contribution into the resonant parts of both channels at W<1.55 GeV strongly support the capabilities of the developed reaction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

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

$1.15 < \chi^2/\text{d.p.} < 1.30$

Resonances	$A_{1/2} \times 10^3$ from $\pi^+\pi^-p$ $\text{GeV}^{-1/2}$	$A_{1/2} \times 10^3$ PDG ranges $\text{GeV}^{-1/2}$	$A_{1/2} \times 10^3$ multichannel analysis [7] $\text{GeV}^{-1/2}$	$A_{3/2} \times 10^3$ from $\pi^+\pi^-p$ $\text{GeV}^{-1/2}$	$A_{3/2} \times 10^3$ PDG ranges $\text{GeV}^{-1/2}$	$A_{3/2} \times 10^3$ multichannel analysis [7] $\text{GeV}^{-1/2}$
$\Delta(1620)1/2^-$	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 $N\pi\pi$ decay widths for many resonances with masses >1.6 GeV were revised based on the studies of $\pi^+\pi^-p$ photoproduction with CLAS.

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⁺ $N\pi\pi$ decays than in PDG 02

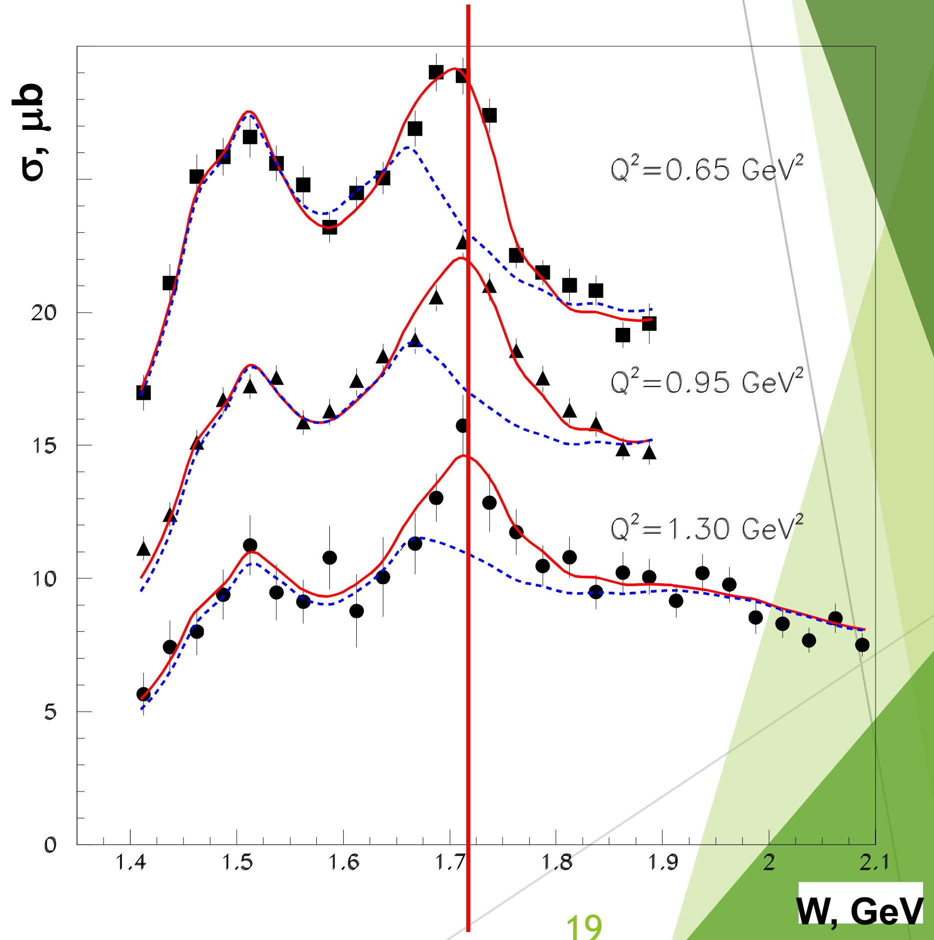
<u>Two equally successful ways for the data description:</u>

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

	Γ_{tot}, MeV	BF($\pi\Delta$) %	BF(ρp) %
N(1720)3/2⁺ decays fit to the CLAS $N\pi\pi$ 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($\pi\Delta$) %	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]

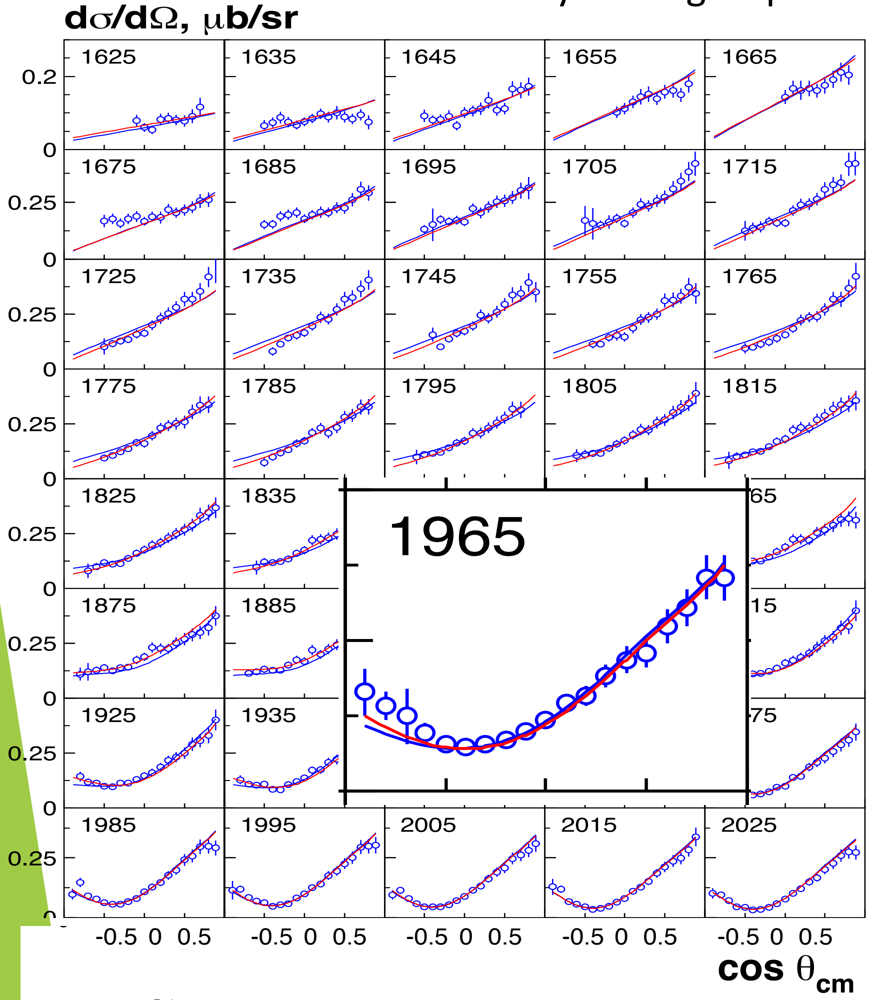
[a] *Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*
[b] *Skobeltsyn Institute of Nuclear Physics and Physics Department, Lomonosov Moscow State University, 119234 Moscow, Russia*
[c] *University of South Carolina, Columbia, South Carolina 29208, USA*
[d] *Ohio University, Athens, Ohio 45701, USA*
[e] *University of Connecticut, Storrs, Connecticut 06269, USA*

Published in Physics Letters B
Volume 805, 10 June 2020, 135457

Establishing the N* spectrum – Precision & Polarization are essential

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

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



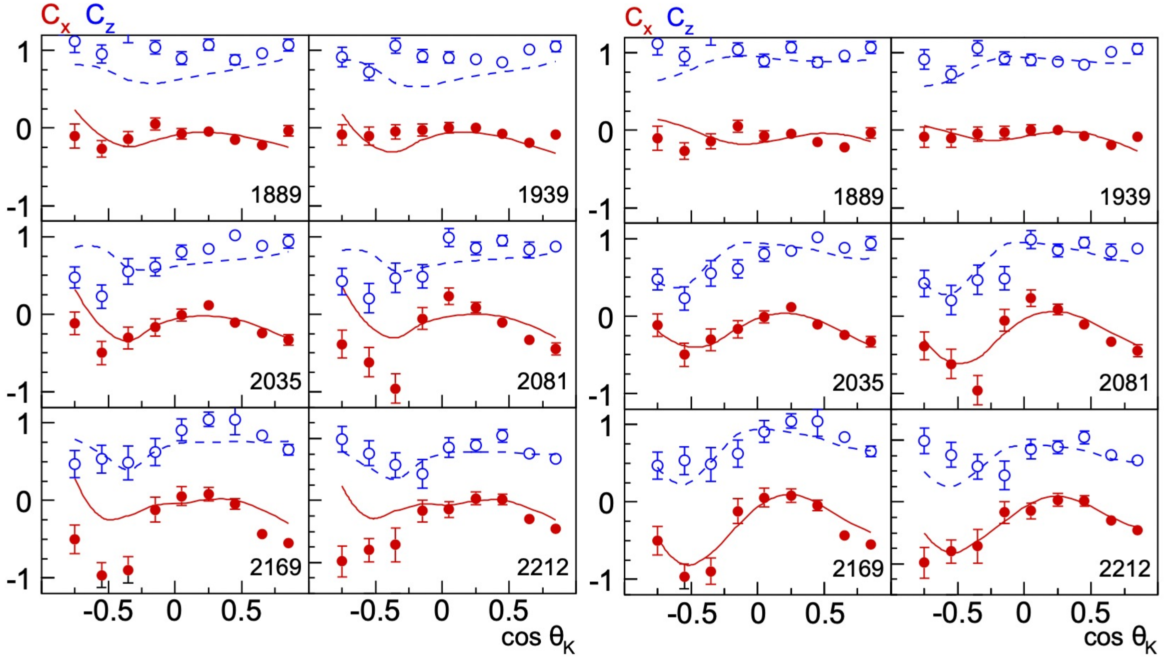


Figure 2. Double polarization observables C_x (red points) C_z (open blue circles) for $\gamma p \to K^+\Lambda$ [72]. The solid (C_x) dashed (C_z) curves are our result obtained without (left pa and with the $N(1900)3/2^+$ state (right panel) included in the

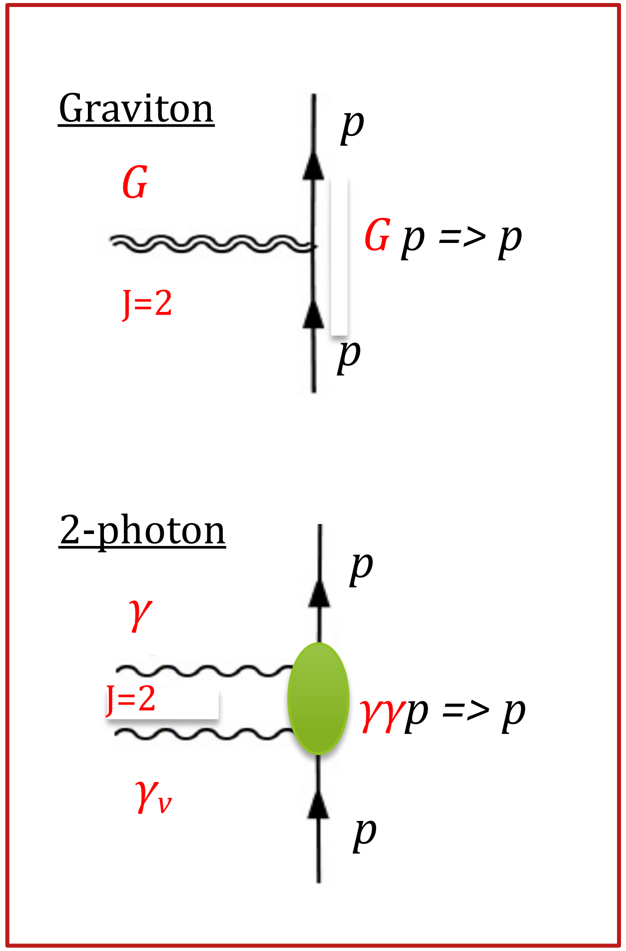
	RPP 2010	our analyses	RPP 2012
$N(1860)5/2^+$		*	**
$N(1875)3/2^-$		***	***
$N(1880)1/2^+$		**	**
$N(1895)1/2^-$		**	**
$N(1900)3/2^+$	**	***	***
$N(2060)5/2^-$		***	**
$N(2150)3/2^-$		**	**
$\Delta(1940)3/2^-$	*	**	**

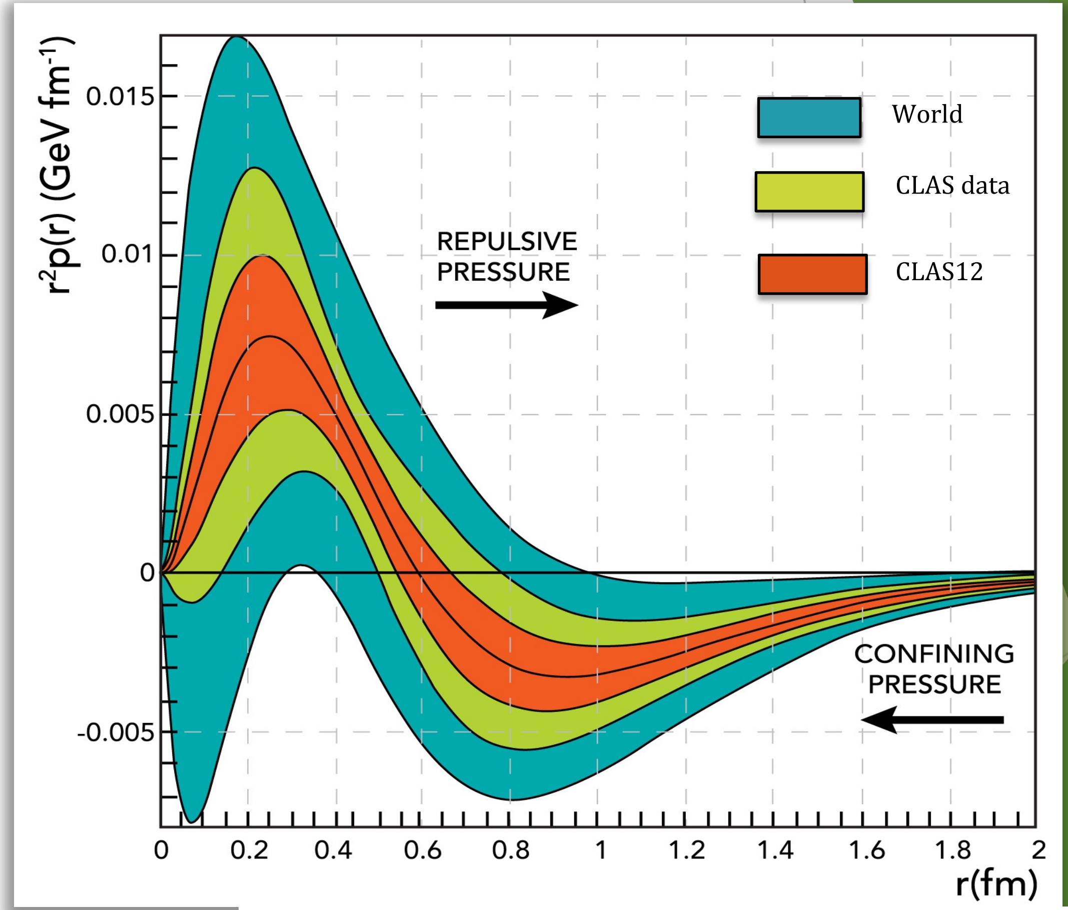
M. Mc Cracken et al.(CLAS), Phys.RevC81,025201,2010

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

Mapping DVCS to Gravity

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





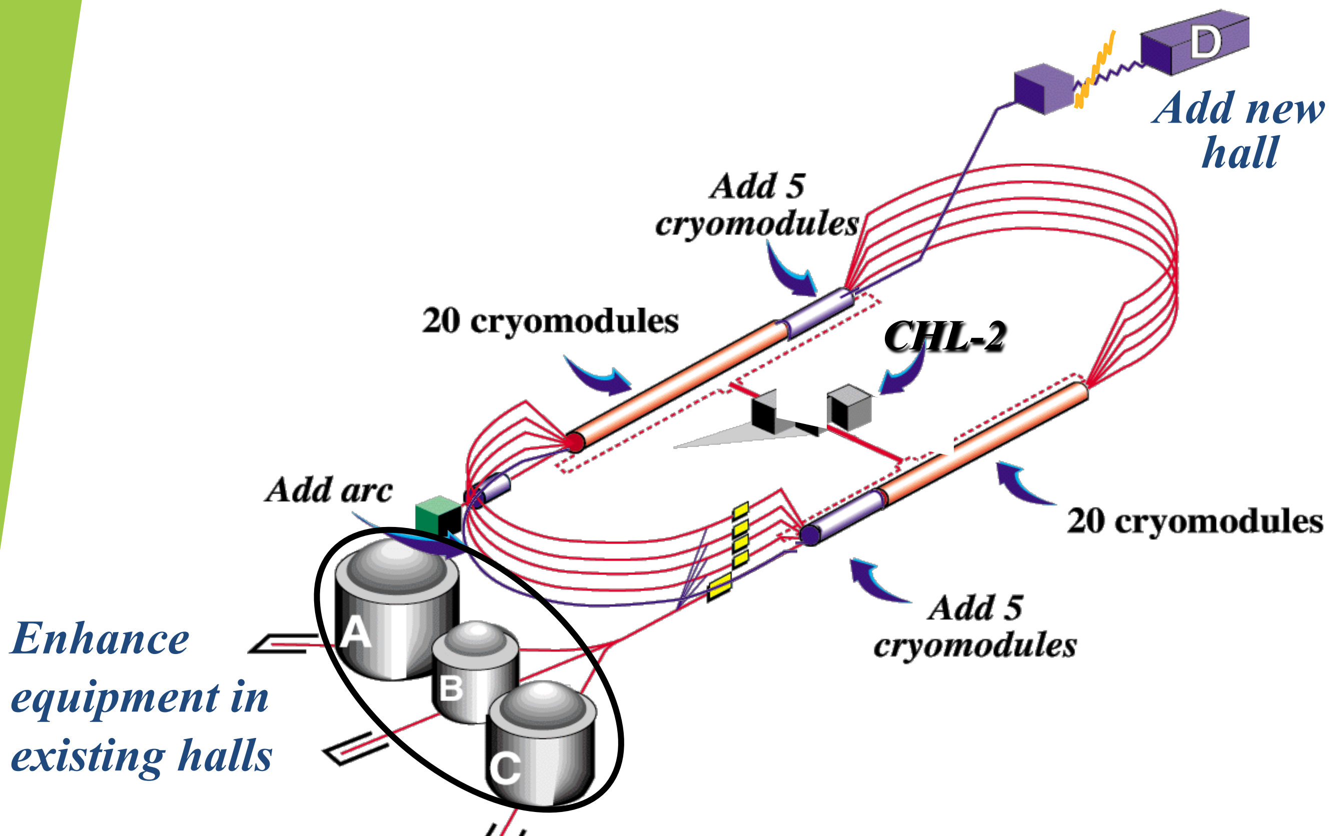
The pressure distribution inside the proton

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



Hadron Structure Experiments (E12-09-003, E12-06-108A)

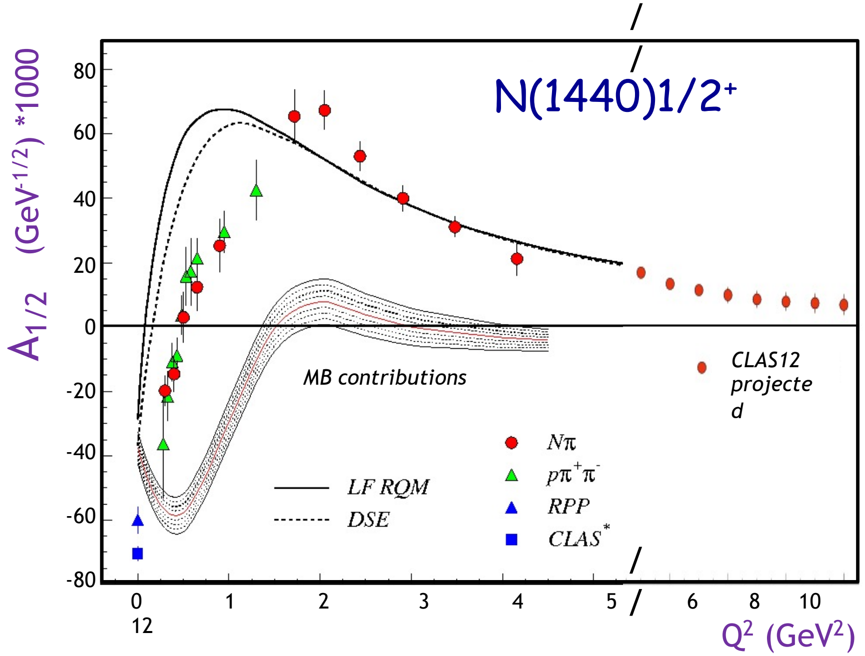
N* electroexcitation studies with CLAS12 will address the critical open questions:

How is >98% of hadron mass generated and how is it related to Dynamical Chiral Symmetry Breaking?

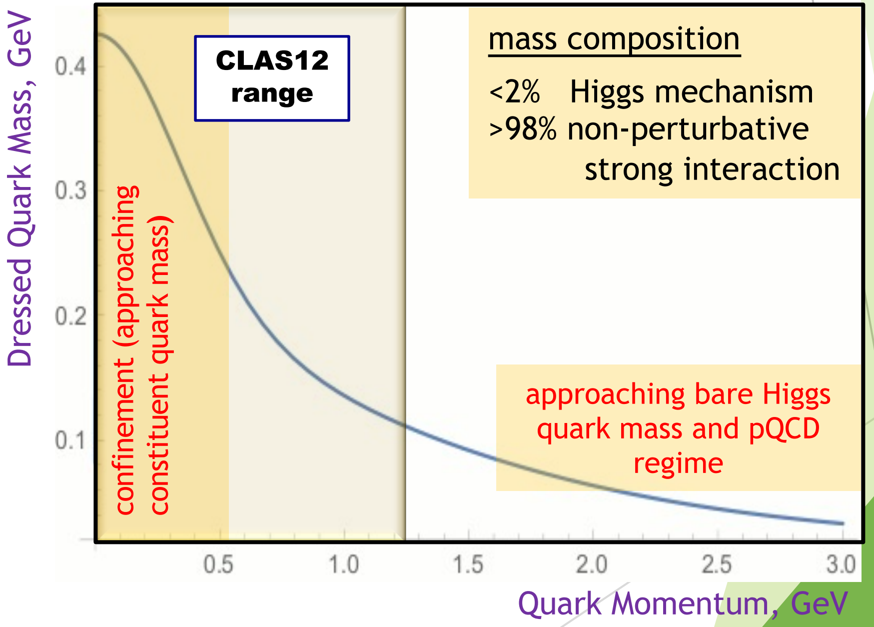
What is the behavior of QCD's running coupling at infrared momenta?

Mapping out the quark mass function from CLAS12 data on the $\gamma_v pN^*$ electrocouplings of spin-isospin flip, radial, and orbital excited nucleon resonances for Q^2:[5:12] GeV^2 will allow us to explore how the dominant part of hadron mass is generated in the transition from the strong QCD to pQCD regimes

Chart the QCD running coupling from the results on the electrocouplings of orbital excited resonances

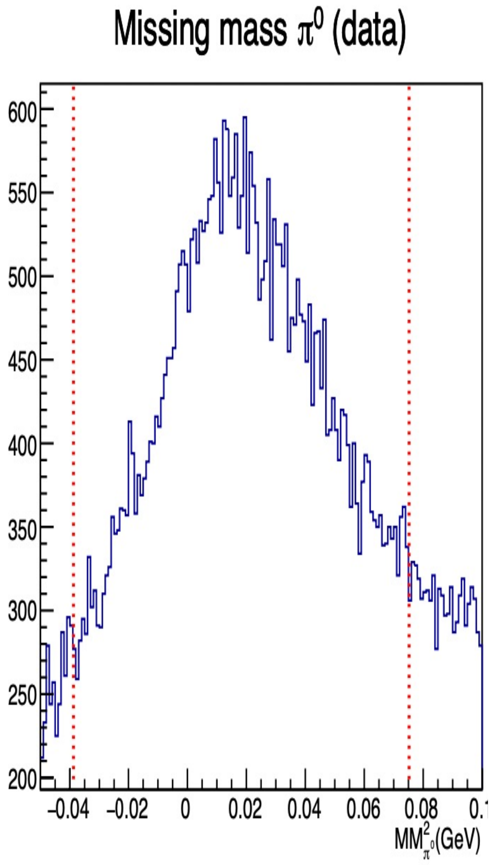


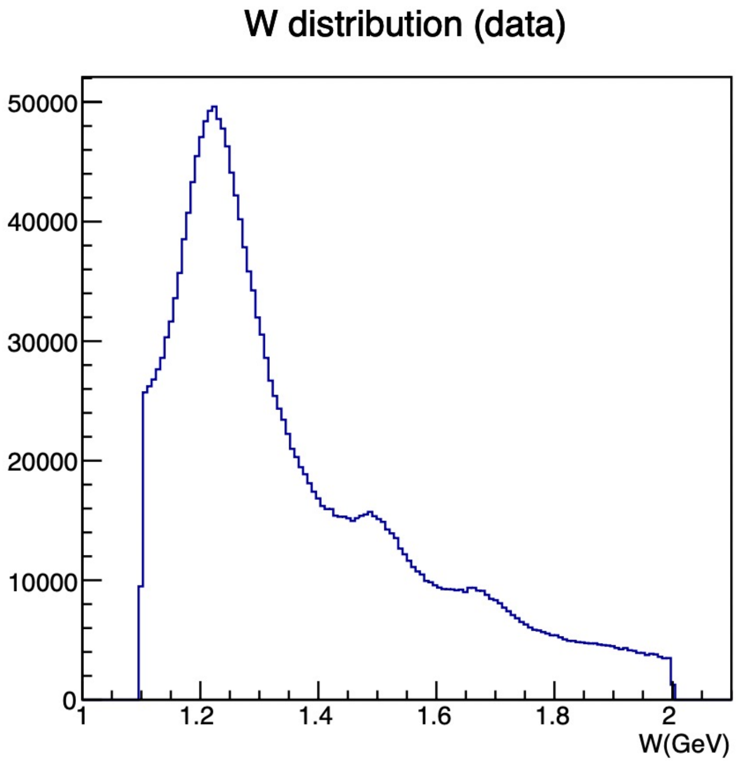
CLAS results vs. theory expectations with running quark mass

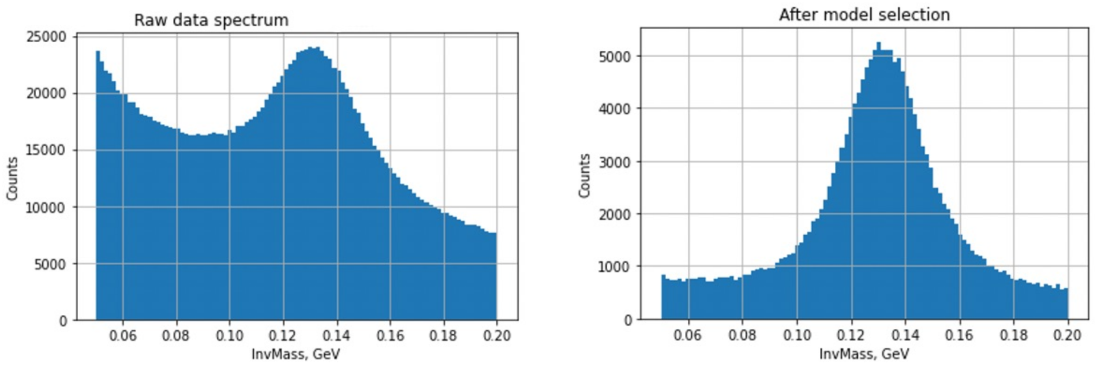


V.D. Burkert, C.D. Roberts, Rev. Mod. Phys. 91, 011003 (2019)
D.S. Carman, K. Joo, V.I. Mokeev, FBS 61, 29 (2020)

CLAS12 current analyses - ep->epπ^0



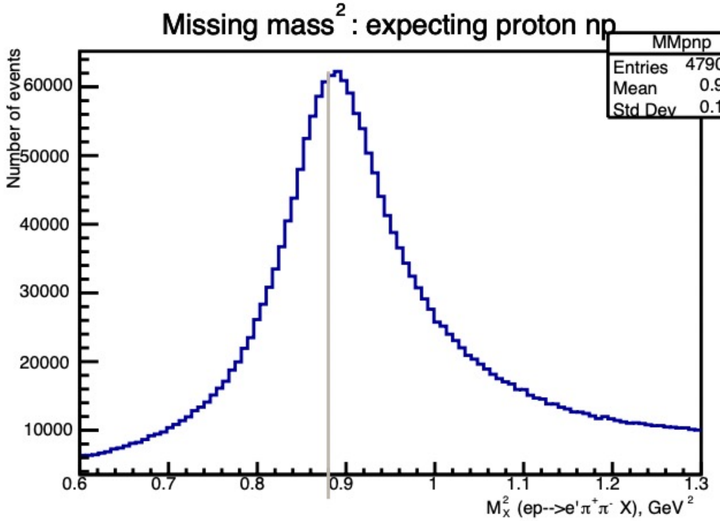


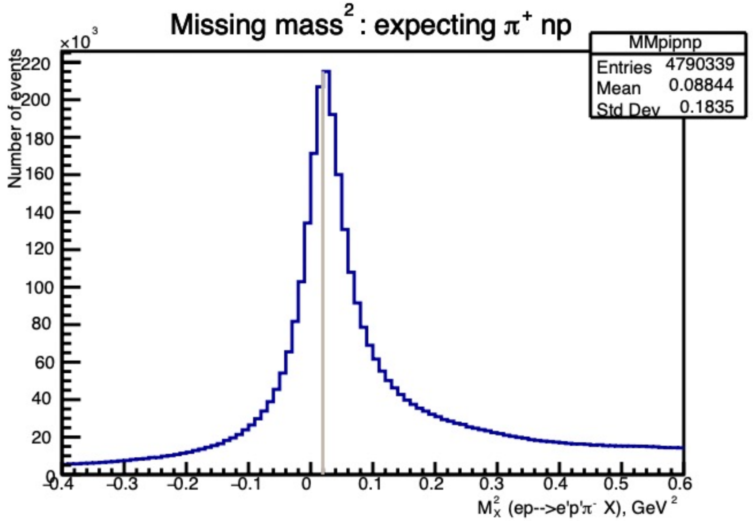


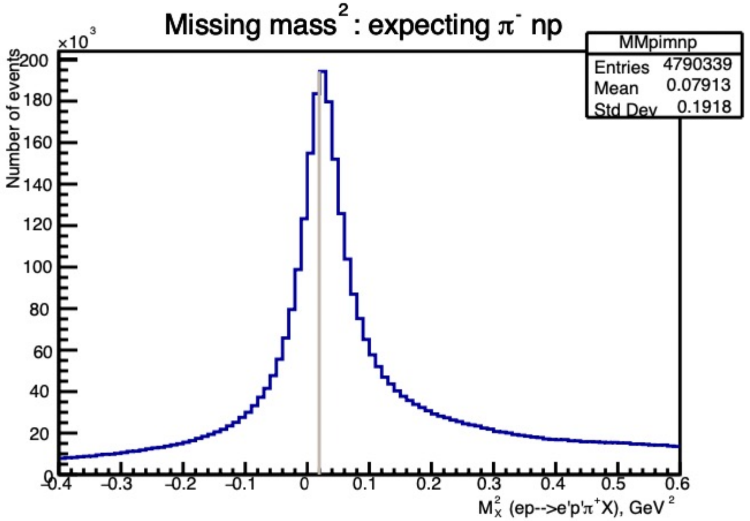
А.Голда - Гистограммы для инвариантной массы нейтрального пиона. Слева без применения отборов, справа после работы алгоритма, отсеивающего фоновые гамма-кванты.

А.Голубенко - Гистограммы для квадрата недостающей массы нейтрального пиона и энергии в системе центра масс виртуальный фотон – протон.

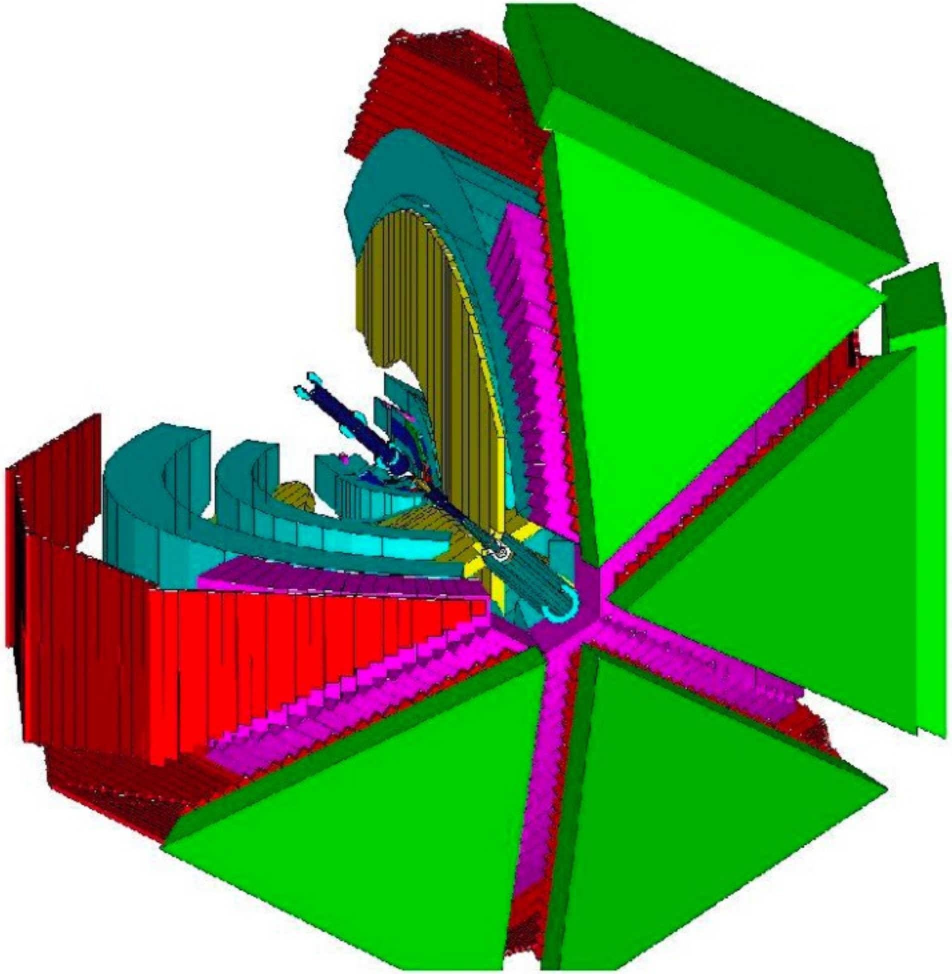
CLAS12 current analyses - ep->epπ⁺π⁻

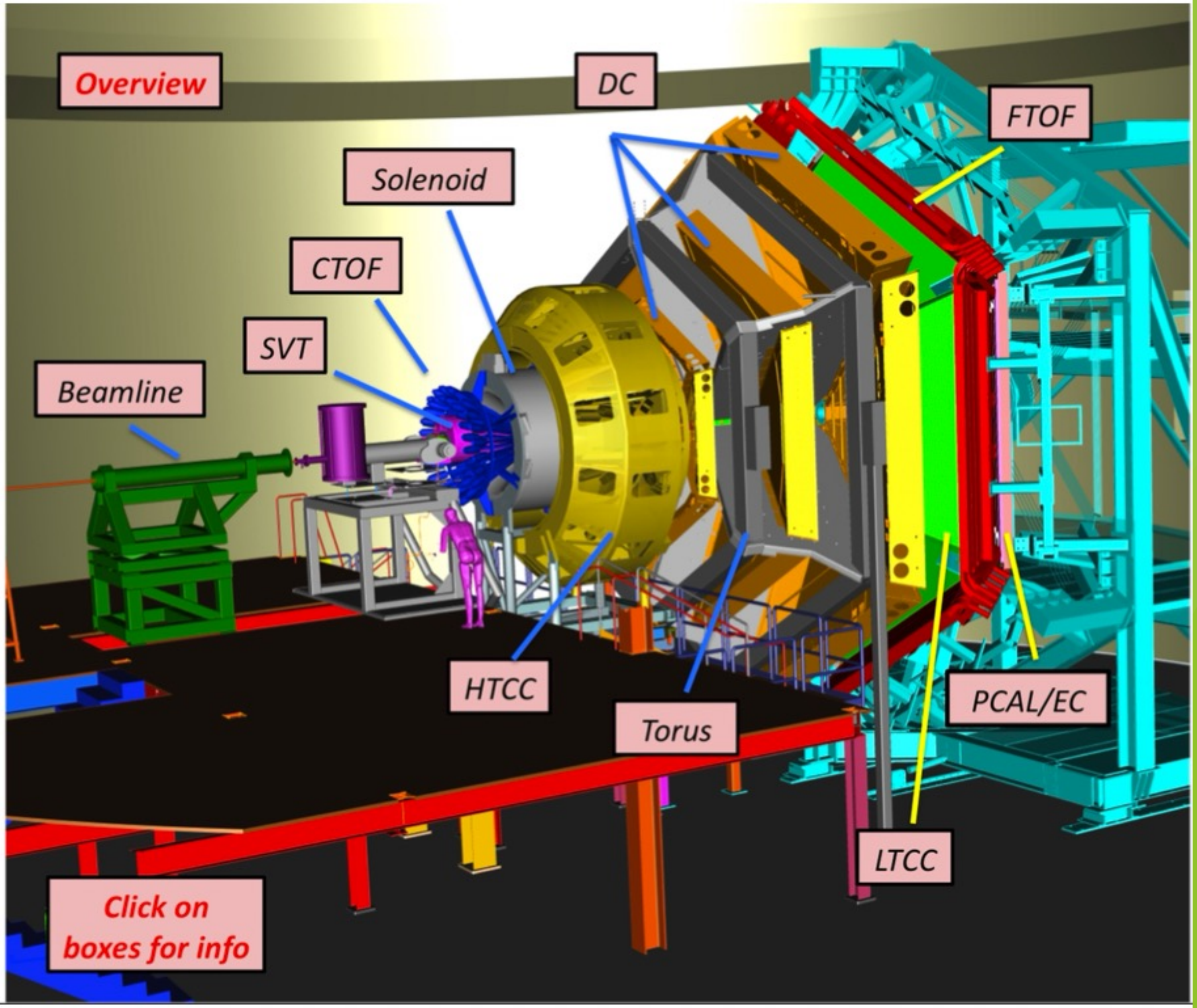






А.Булгаков, А.Фролова - Гистограммы для квадрата недостающей массы протона, положительного и отрицательного пиона.





Overview
DC
FTOF
Solenoid
CTOF
SVT
Beamline
HTCC
Torus
PCAL/EC
LTCC
Click on boxes for info