Proton Structure Study with CLAS and CLAS12

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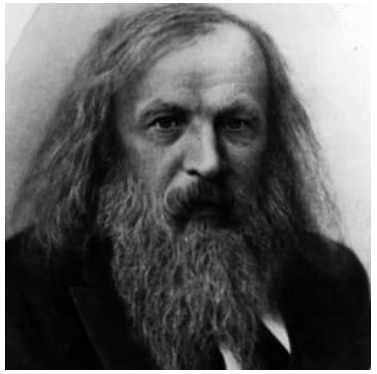
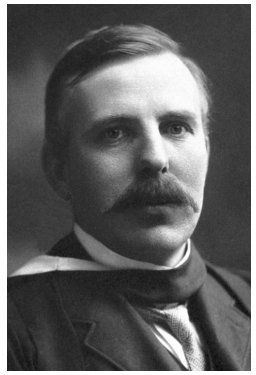
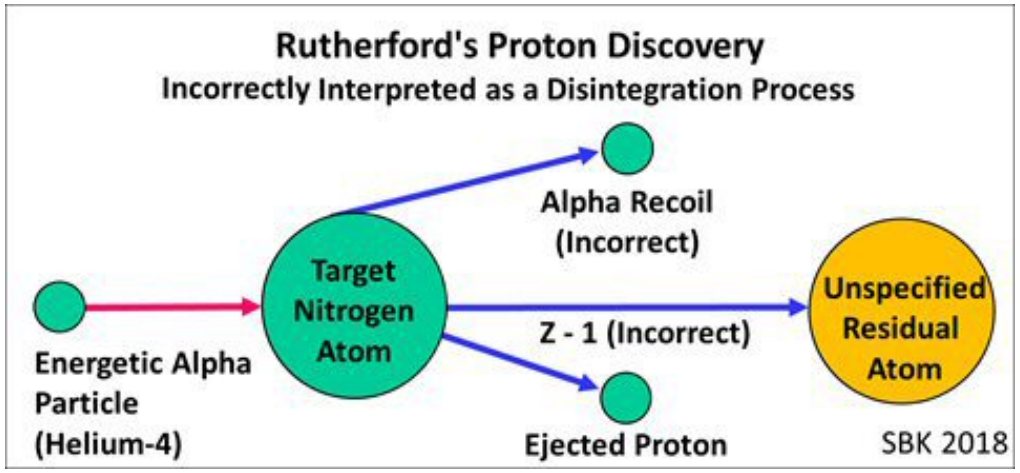
LOMCON2019

150 years of Periodic Table!
100 years of Proton!







1919 – Proton Discovery!

$$\alpha + {}^{14}_{7}N \rightarrow p + {}^{17}_{8}O$$

^{1}H																	^{2}He
^{3}Li	^{4}Be						^{5}B	^{6}C	^{7}N	^{8}O	^{9}F						^{10}Ne
^{11}Na	^{12}Mg						^{13}Al	^{14}Si	^{15}P	^{16}S	^{17}Cl						^{18}Ar
^{19}K	^{20}Ca	^{21}Sc	^{22}Ti	^{23}V	^{24}Cr	^{25}Mn	^{26}Fe	^{27}Co	^{28}Ni	^{29}Cu	^{30}Zn	^{31}Ga	^{32}Ge	^{33}As	^{34}Se	^{35}Br	^{36}Kr
^{37}Rb	^{38}Sr	^{39}Y	^{40}Zr	^{41}Nb	^{42}Mo	^{43}Tc	^{44}Ru	^{45}Rh	^{46}Pd	^{47}Ag	^{48}Cd	^{49}In	^{50}Sn	^{51}Sb	^{52}Te	^{53}I	^{54}Xe
^{55}Cs	^{56}Ba	La-Lu	^{72}Hf	^{73}Ta	^{74}W	^{75}Re	^{76}Os	^{77}Ir	^{78}Pt	^{79}Au	^{80}Hg	^{81}Tl	^{82}Pb	^{83}Bi	^{84}Po	^{85}At	^{86}Rn
^{87}Fr	^{88}Ra	Ac-Lr	^{104}Rf	^{105}Db	^{106}Sg	^{107}Bh	^{108}Hs	^{109}Mt	^{110}Ds	^{111}Rg	^{112}Cn	^{113}Nh	^{114}Fl	^{115}Mc	^{116}Lv	^{117}Ts	^{118}Og

Лантаноиды

^{57}La	^{58}Ce	^{59}Pr	^{60}Nd	^{61}Pm	^{62}Sm	^{63}Eu	^{64}Gd	^{65}Tb	^{66}Dy	^{67}Ho	^{68}Er	^{69}Tm	^{70}Yb	^{71}Lu

Актиноиды

^{89}Ac	^{90}Th	^{91}Pa	^{92}U	^{93}Np	^{94}Pu	^{95}Am	^{96}Cm	^{97}Bk	^{98}Cf	^{99}Es	^{100}Fm	^{101}Md	^{102}No	^{103}Lr

50 years of scaling and parton model!

- Observed Behavior of Highly Inelastic Electron-Proton Scattering

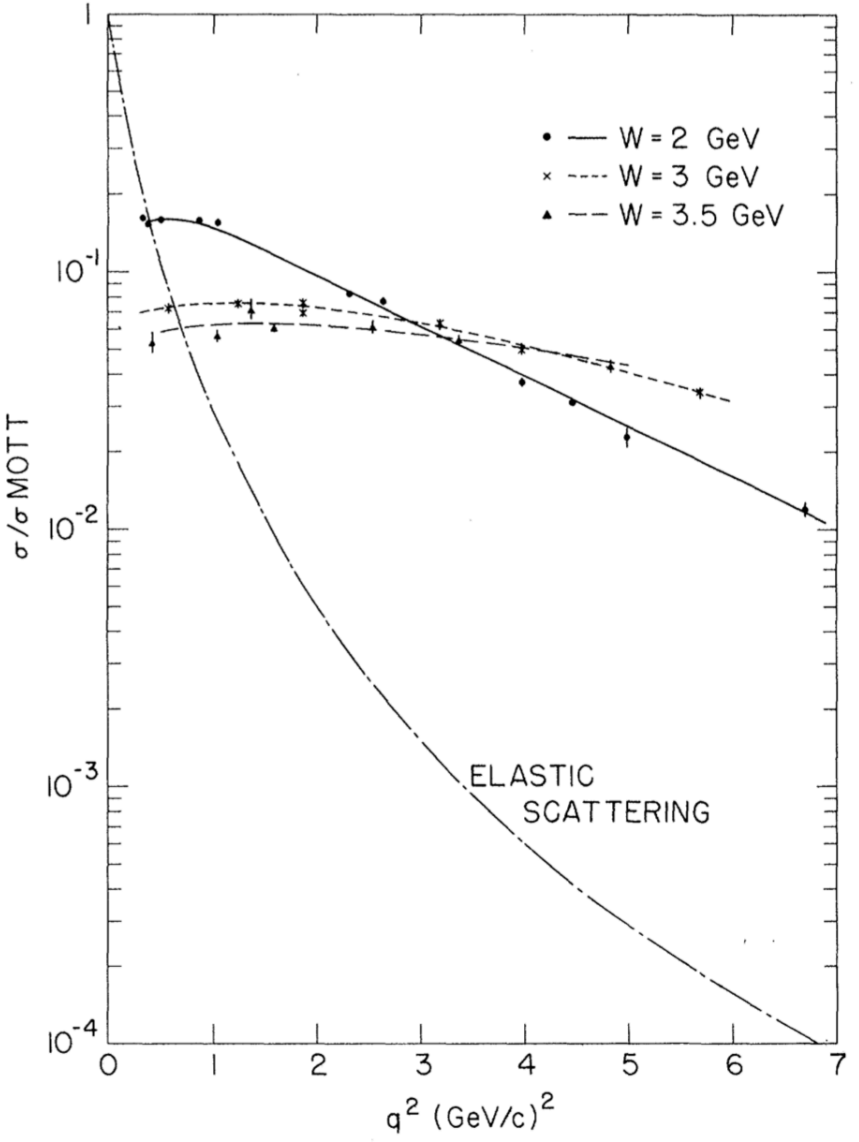
M. Breidenbach, J. I. Friedman, H. W. Kendall, E. D. Bloom, D. H. Coward, H. DeStaebler, J. Drees, L. W. Mo, and R. E. Taylor

Phys. Rev. Lett. **23**, 935 – Published 20 October 1969

- Inelastic Electron-Proton and γ-Proton Scattering and the Structure of the Nucleon

J. D. Bjorken and E. A. Paschos

Phys. Rev. **185**, 1975 – Published 25 September 1969



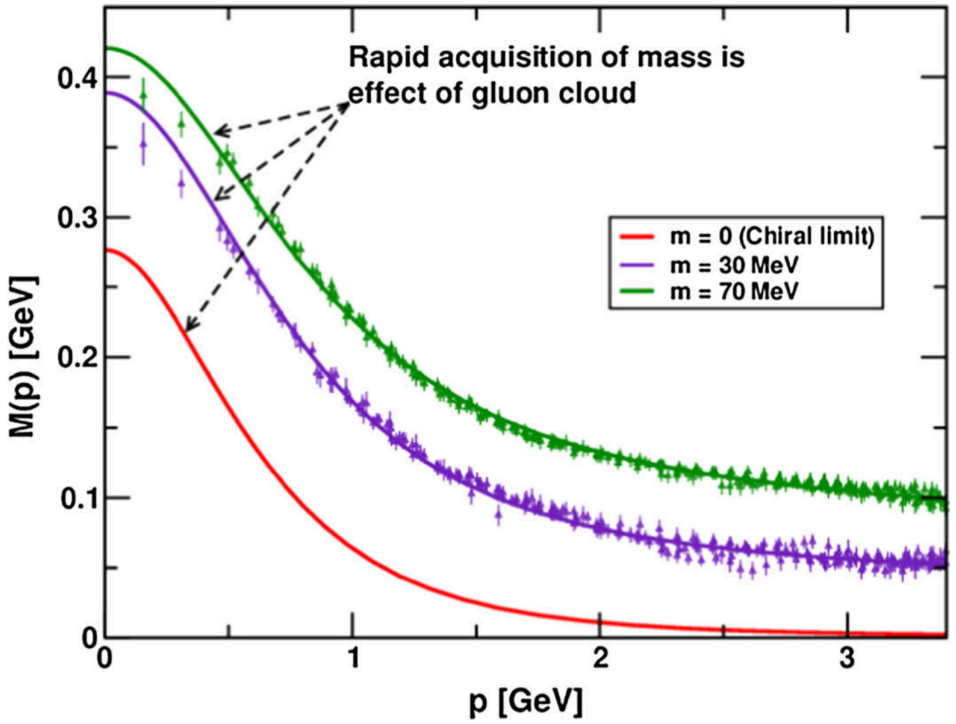
New era in electromagnetic nuclear physics

- 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

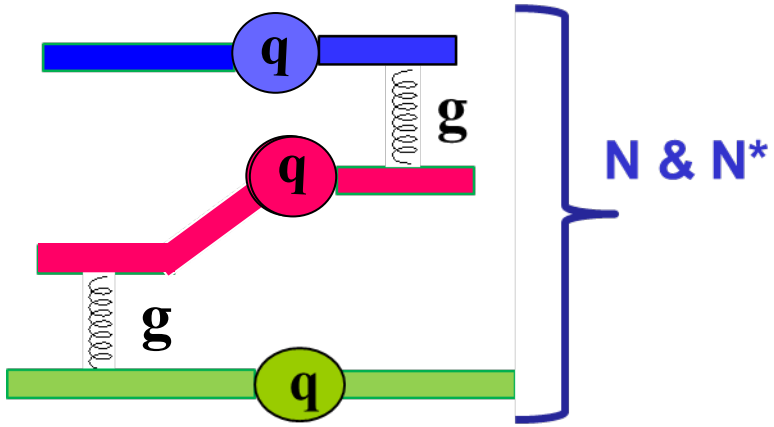
Excited Nucleon States and Insight into Strong QCD Dynamics

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)

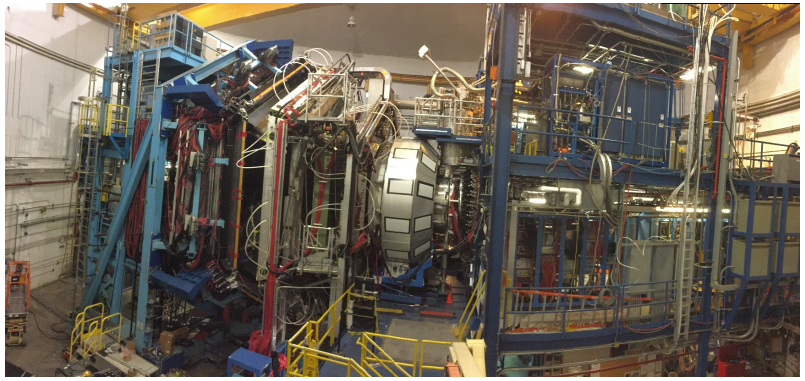


N* structure studies address:

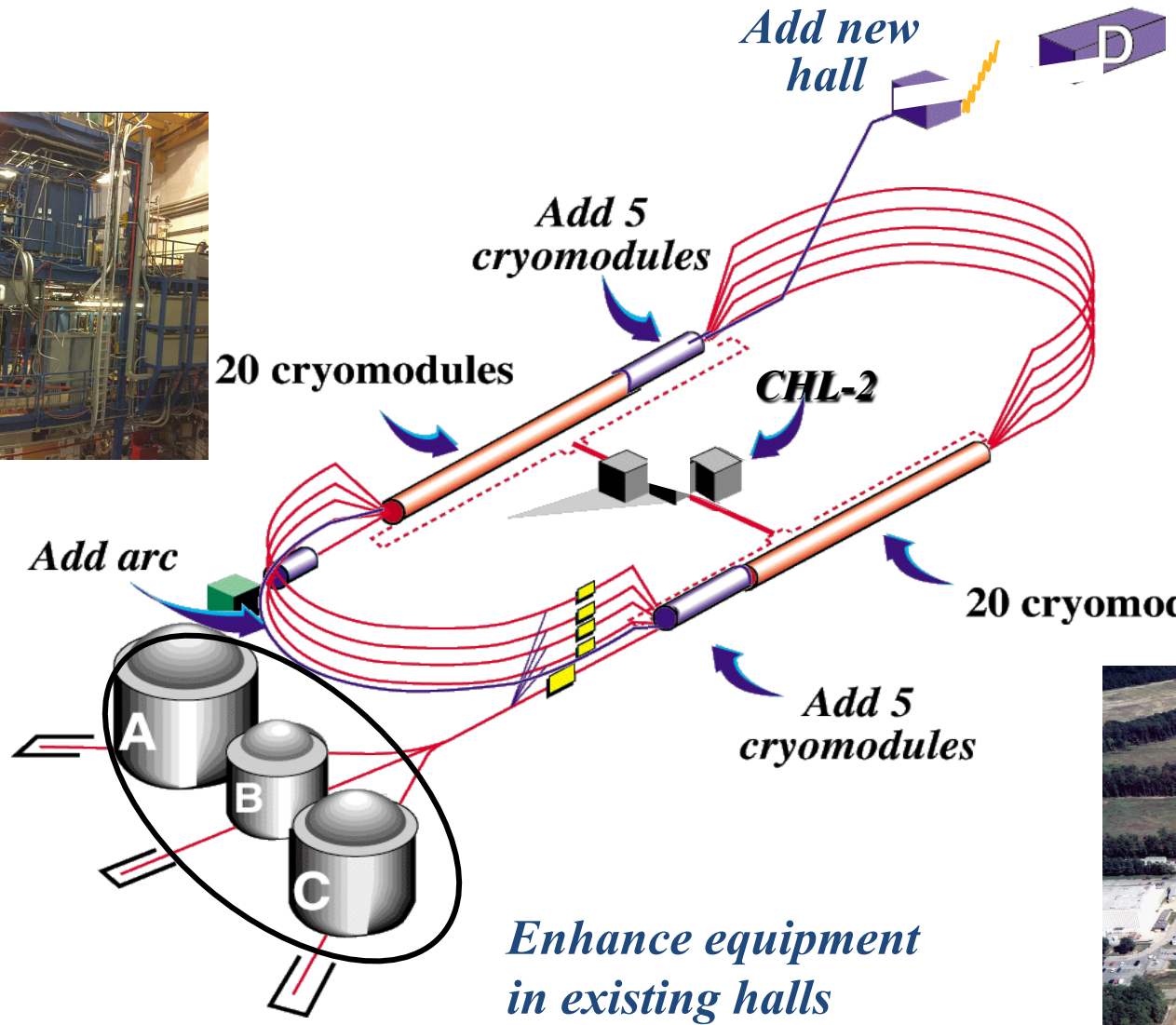
- **Nature of > 98% of hadron mass**
- **Emergence of the ground nucleon parton distributions in 1D and 3D**

Jefferson Lab (Newport News, VA, USA)

CLAS12 in Hall B

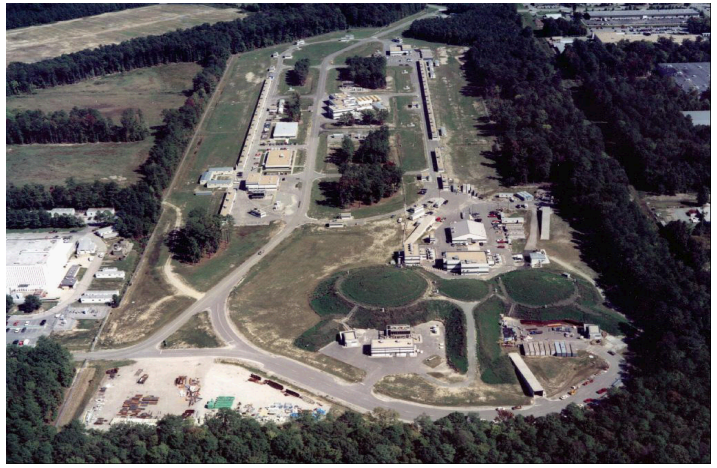


CLAS (1998-2012)



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:

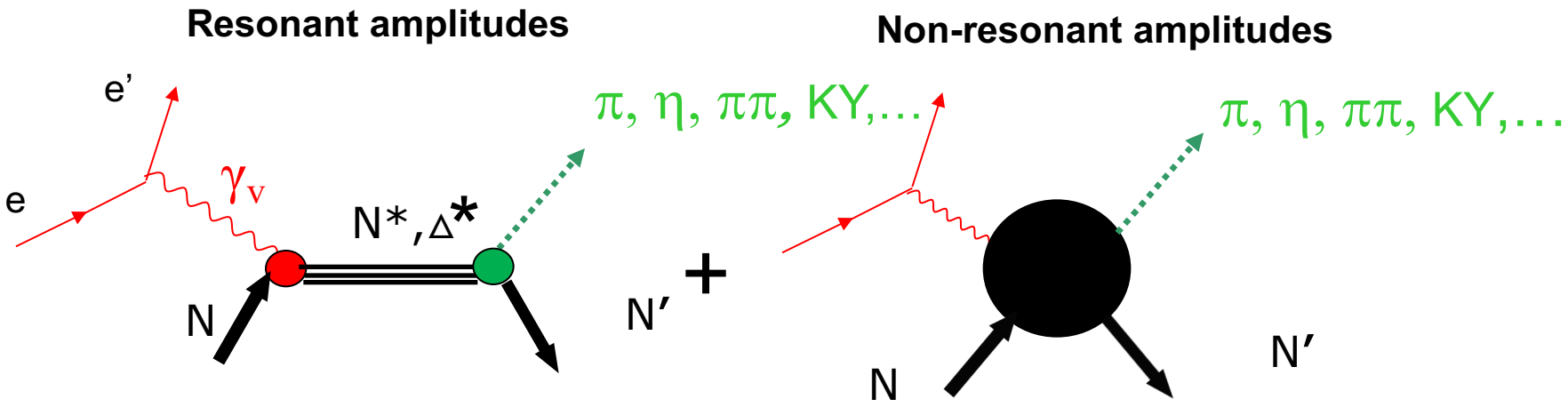
- N* spectrum with a focus on the new, so-called ``missing'' and hybrid resonance search
- $\gamma_v pN^*$ electrocouplings at photon virtualities up to 5.0 GeV^2 for most of the excited proton states through analyzing major meson electroproduction channels from CLAS data
- extend accessible Q^2 range 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**	**0.16-0.36** **0.4-1.8** **3.0-6.0**	**$d\sigma/d\Omega$** **$d\sigma/d\Omega$, A_b,A_t,A_{bt}** **$d\sigma/d\Omega$**
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

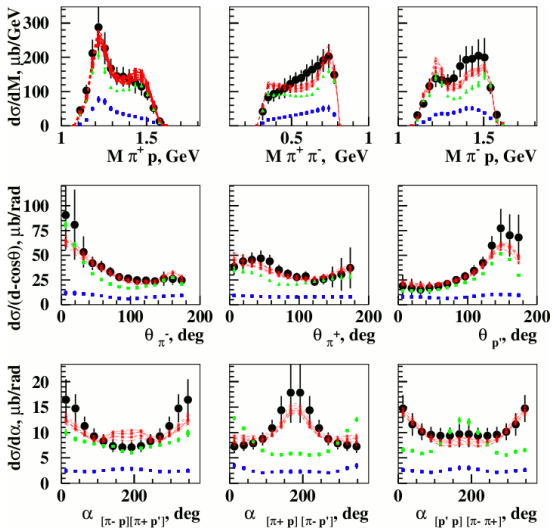
Over 120,000 data points!

Almost full coverage of the final hadron phase space

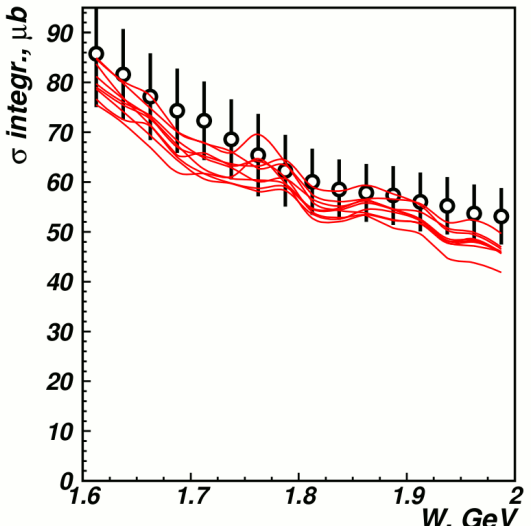
The measured observables from CLAS are stored in the CLAS Physics Data Base http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi

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 $\pi^+\pi^-p$ $\mathrm{GeV}^{-1/2}$	$A_{1/2}\times10^3$ PDG ranges $\mathrm{GeV}^{-1/2}$	$A_{1/2}\times10^3$ multichannel analysis [7] $\mathrm{GeV}^{-1/2}$	$A_{3/2}\times10^3$ from $\pi^+\pi^-p$ $\mathrm{GeV}^{-1/2}$	$A_{3/2}\times10^3$ PDG ranges $\mathrm{GeV}^{-1/2}$	$A_{3/2}\times10^3$ multichannel analysis [7] $\mathrm{GeV}^{-1/2}$
$\Delta(1620)1/2^-$	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

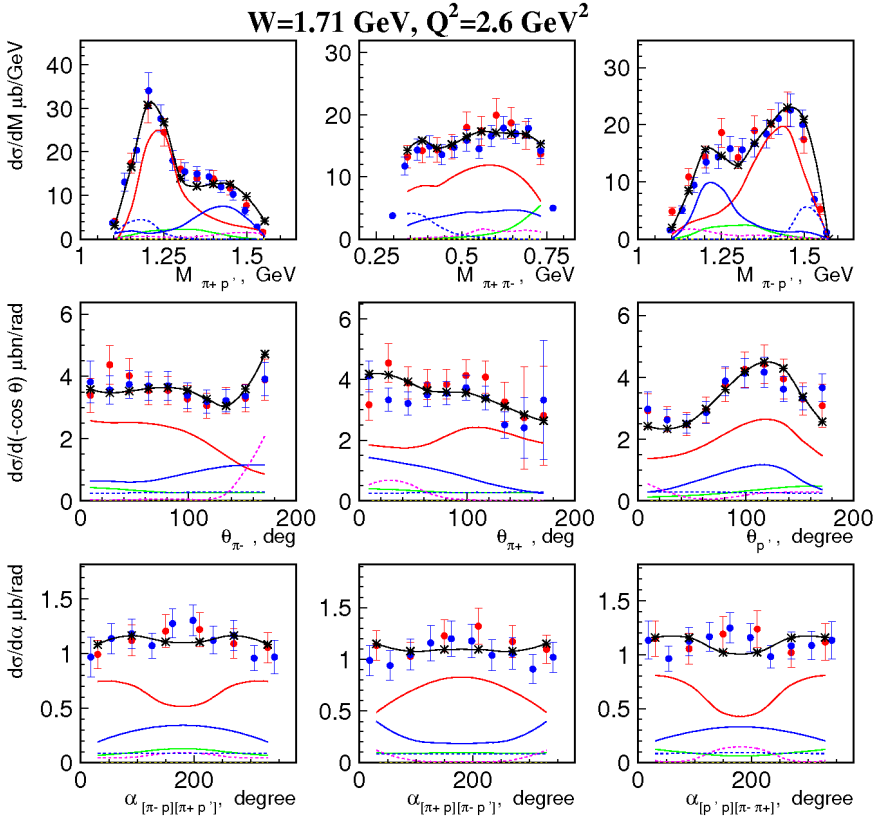
In 2019 partial update of the Review of Particle Physics the entries on photocouplings and N$\pi\pi$ decay widths for many resonances with masses >1.6 GeV were revised based on the studies of $\pi^+\pi^-$p photoproduction with CLAS.

Accessing Resonance Electrocouplings from the $\pi^+\pi^-$p Differential Electroproduction off Protons Cross Sections

Contributing mechanisms seen in the data

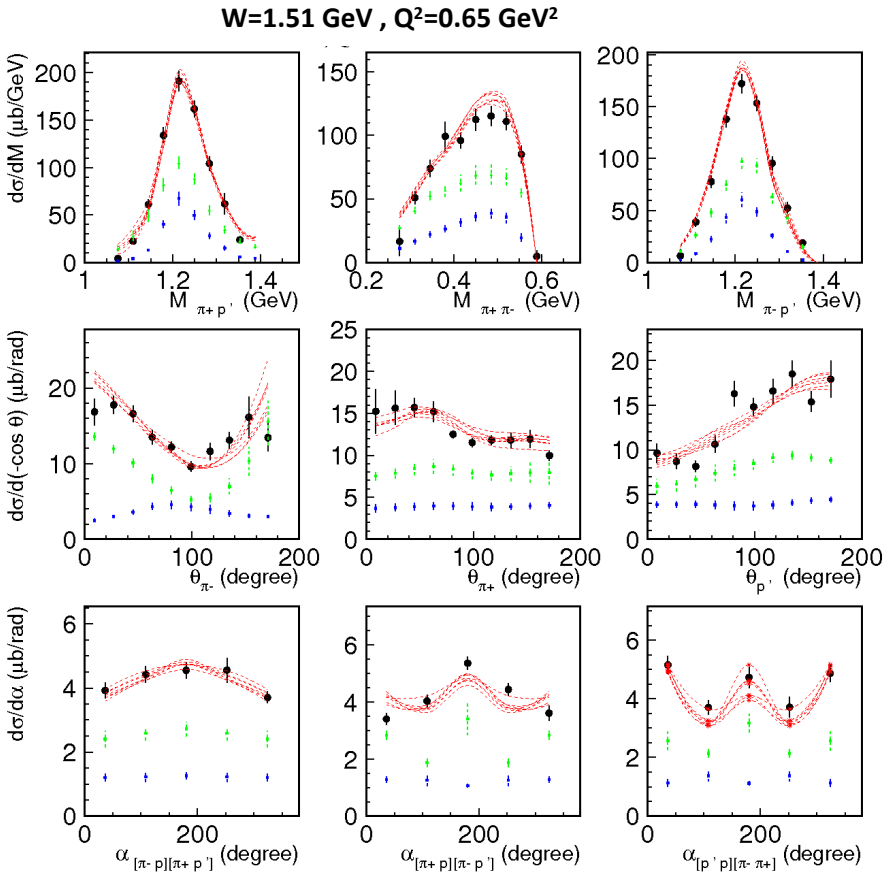
E. Isupov et al., CLAS Coll., Phys. Rev. C96, 025209 (2017)

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

π^+ N(1520)3/2$^-$

$\pi^-\Delta^{++}$

$\pi^+\Delta^0$

π^+ N(1680)5/2$^+$

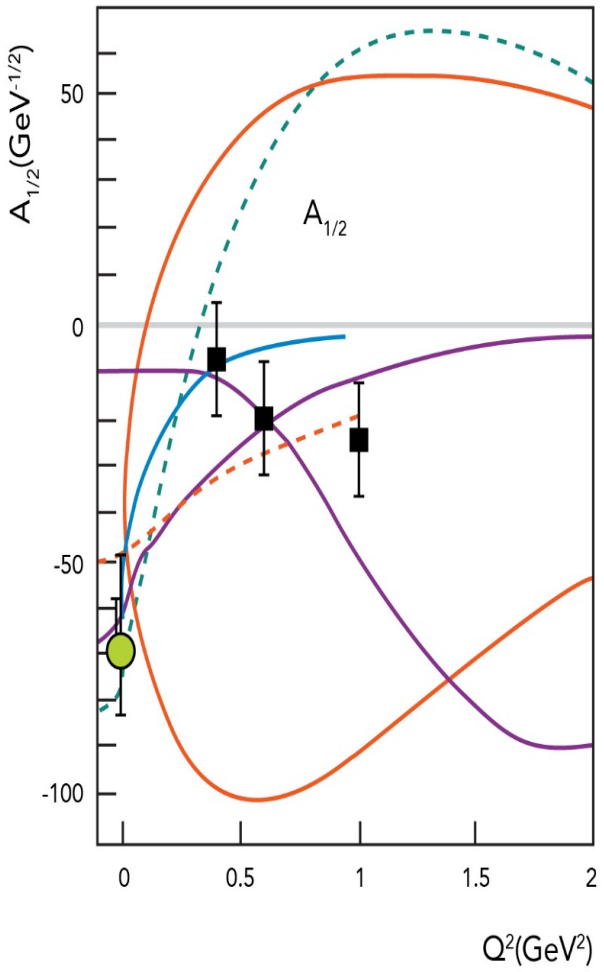
data fit within JM under variations of both resonant and background parameters

background cross sections

resonant cross sections

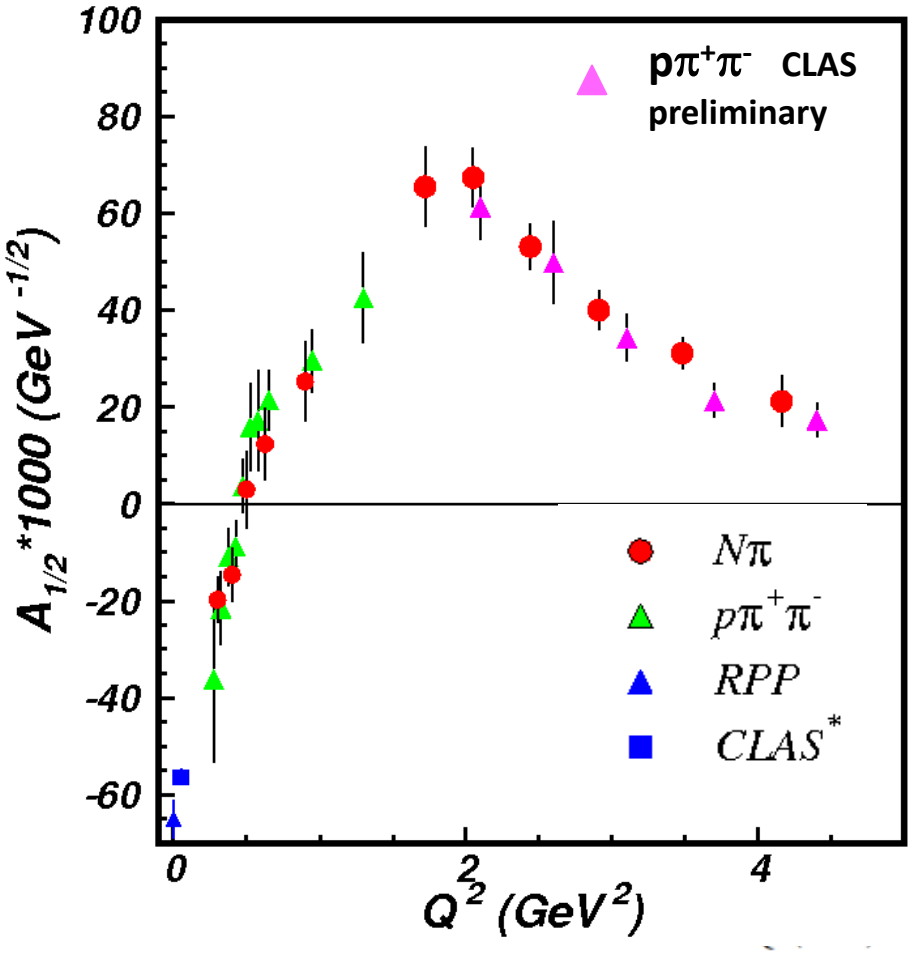
Roper Resonance in 2002 & 2019

2002



V. Burkert, Baryons 2002

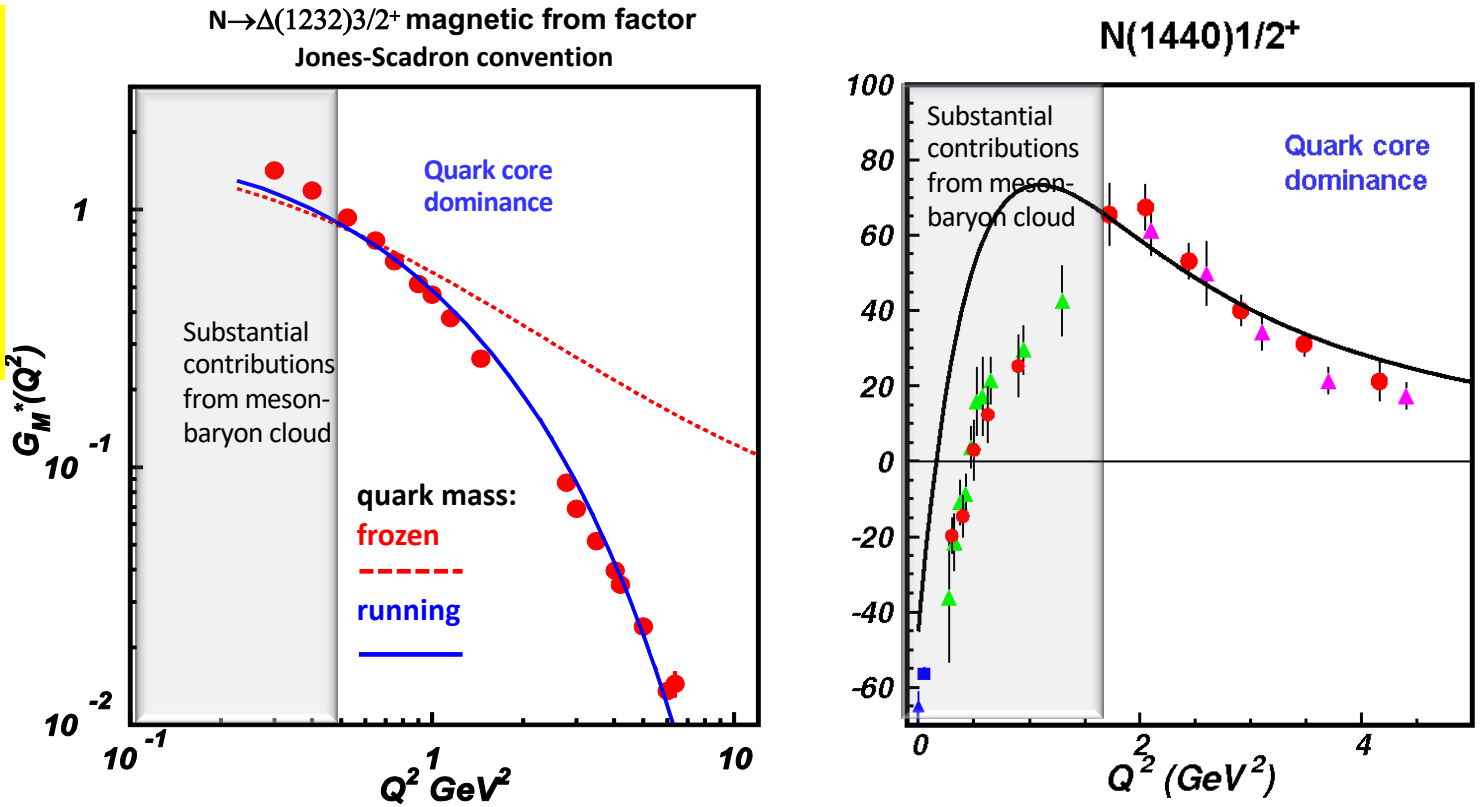
2019



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

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.

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!

Summary

- **Electrocouplings of most resonances in the mass range up to 2.0 GeV will be obtained at 2.0 GeV^2<Q^2<5.0 GeV^2 from the new CLAS data on $\pi^+\pi^-$p electroproduction in the near term future.**

- **CLAS12 is the only facility in the world capable of obtaining electrocouplings of all prominent N* states at still unexplored ranges of low photon virtualities down to 0.05 GeV^2 and highest photon virtualities for exclusive reactions from 5.0 GeV^2 to 12 GeV^2 from measurements of Nπ, $\pi^+\pi^-$p, and KY electroproduction and to address the most challenging problems in hadron physics on the nature of hadron mass and quark-gluon confinement**

Thank you for your attention!