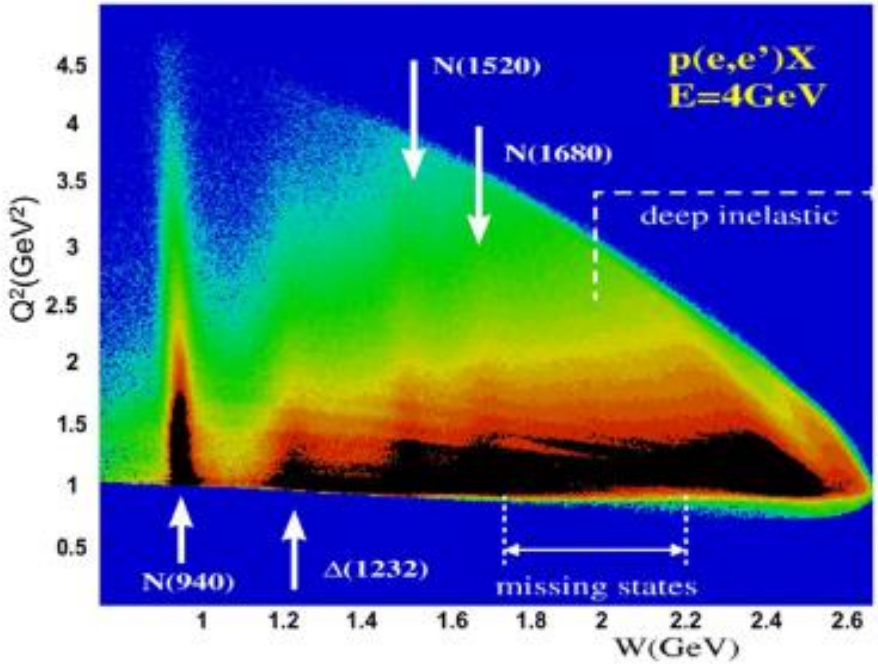
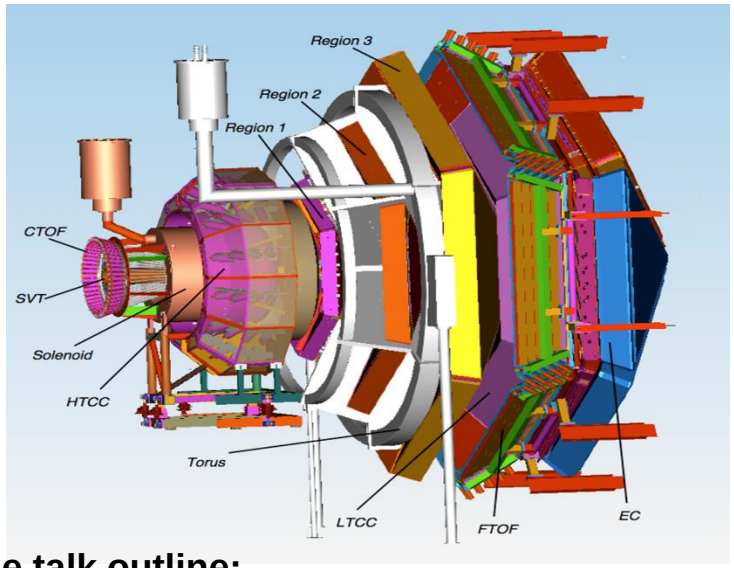
Results form two-pion production in electron scattering experiments

From CLAS legacy to the new era with the CLAS12





The talk outline:

- **N* electrocouplings as a window into the strong QCD;**
- **N* electrocouplings from $\pi^+\pi^-p$ electroproduction off protons ;**
- **accessing active degree of freedom in the N* structure**
- **future prospects in experiments with the CLAS12 detector.**

V.I. Mokeev,
Jefferson Laboratory

Office of Science

Workshop on two-pion and e+e- production in hadronic reactions,
May 22 — 24, 2018; Columbus, Ohio

Major Directions in the Studies of N*-Structure with CLAS

The experimental program on the studies of N* structure in exclusive meson electroproduction with CLAS seeks to determine:

- $\gamma_v pN^*$ electrocouplings at photon virtualities up to 5.0 GeV^2 for most of the excited proton states through analyzing major meson electroproduction channels.
- explore manifestation of ``missing" resonances seen in photoproduction in exclusive electrproduction data with Q^2-independent masses and hadron decay widths.

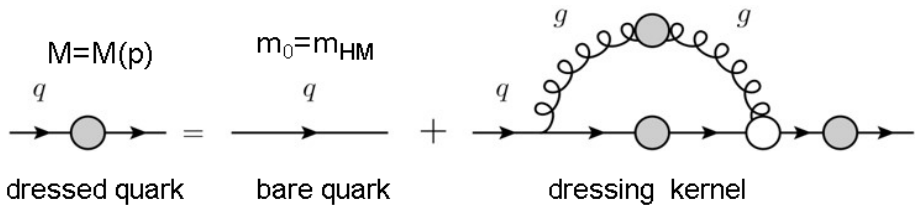
A unique source of information on many facets of strong QCD in generating different excited nucleon states

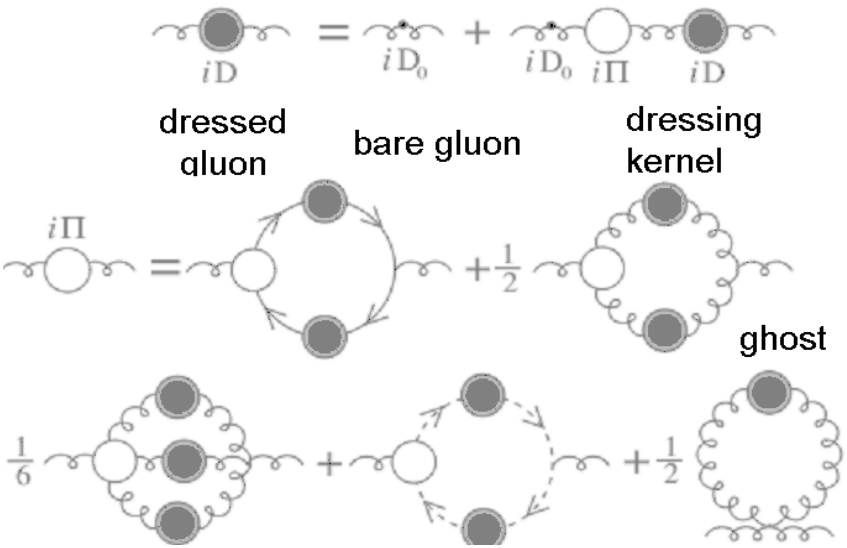
Review papers:

1. **I.G. Aznauryan and V.D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012).**
2. **I.G. Aznauryan et al., Int. J. Mod. Phys. E22,1330015 (2013).**
3. **V.D. Burkert, Few Body Syst. 59, 57 (2018).**
4. **C.D. Roberts, Few Body Syst. 59, 72 (2018).**

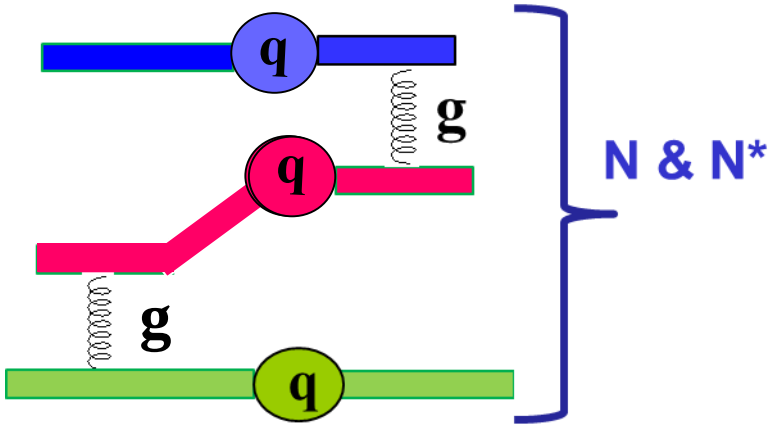
Excited Nucleon States and Insight into Strong QCD Dynamics

Emergence of Dressed Quarks and Gluons
D. Binosi, et al, Phys. Rev. D95, 031501 (2017)

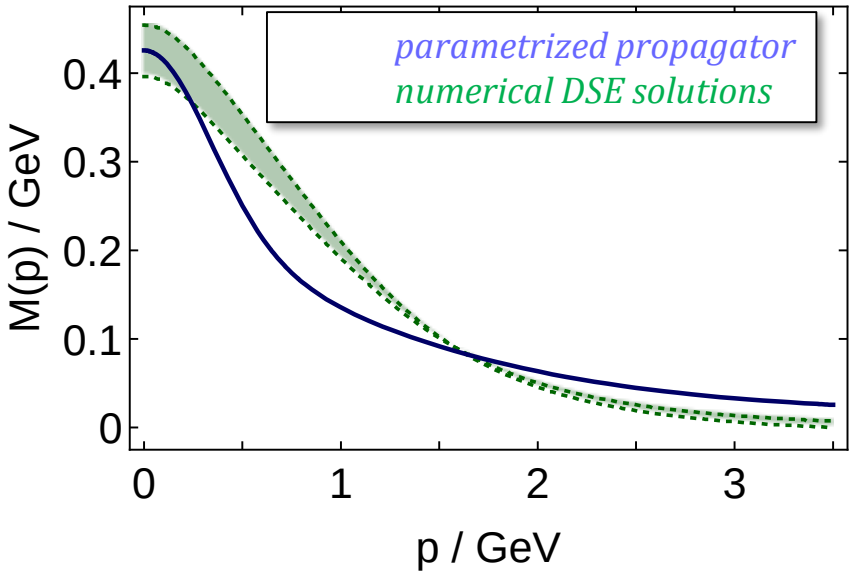




Dressed Quark Borromeo Binding in Baryons
Ch. Chen, et al, Phys. Rev. D97, 034016 (2018)



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



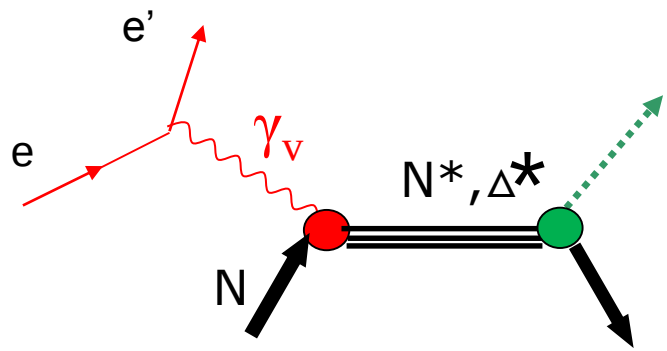
Inferred from QCD Lagrangian with the only Λ_{QCD} parameter

N* structure studies address:

- **Nature of > 98% of hadron mass**
- **Confinement and color charge emergence from QCD**

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

Resonant amplitudes



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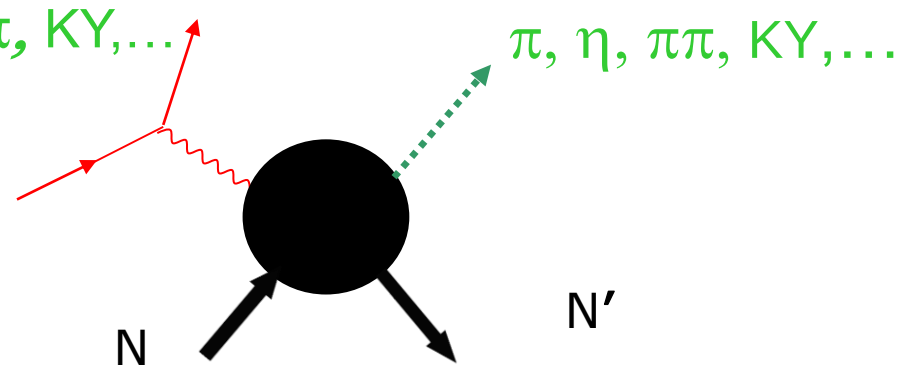
Non-resonant amplitudes



- **Real $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$, $S_{1/2}(Q^2)$**
  or
- **$G_1(Q^2)$, $G_2(Q^2)$, $G_3(Q^2)$**
  or
- **$G_M(Q^2)$, $G_E(Q^2)$, $G_C(Q^2)$**

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

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

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

Γ_γ: N* electromagnetic decay widths;
$W=M_{N^*}$ on the real energy axis.

- **Consistent results on $\gamma_v NN^*$ electrocouplings from different meson electroproduction channels and different analysis approaches demonstrate reliable extraction of these quantities.**
- **$N\pi$ and $\pi^+\pi^-p$ electroproduction off proton channels are the two major contributors in the resonance region offering cross check for the values of extracted electrocouplings.**

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 asym-metries
- P^0, P' –recoil and transferred polarization of strange baryon

Over 120,000 data points!

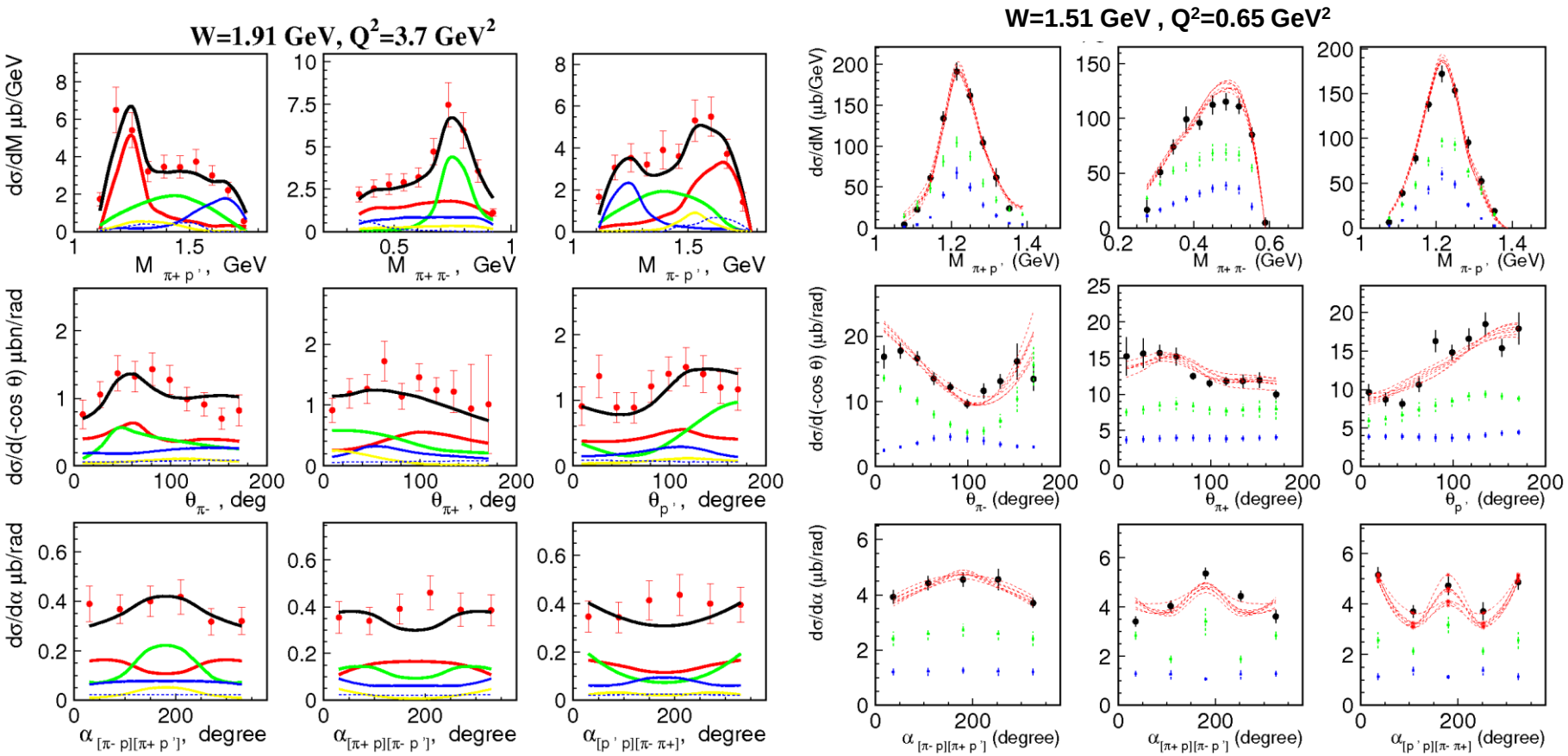
Only available results on nine independent $\pi^+\pi^-p$ electroproduction off protons cross sections

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

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

Contributing mechanisms seen in the data

Resonant and non-resonant contributions



full JM — ρp — π^+ N(1520)3/2$^-$ — data fit within JM under variations of both resonant and background parameters

$\pi^-\Delta^{++}$ — $\pi^+\Delta^0$ — π^+ N(1680)5/2$^+$ — background cross sections

resonant cross sections

Approaches for Extraction of $\gamma_v NN^*$ Electrocouplings from the CLAS Exclusive Meson Electroproduction Data

Analyses of different meson electroproduction channels independently:

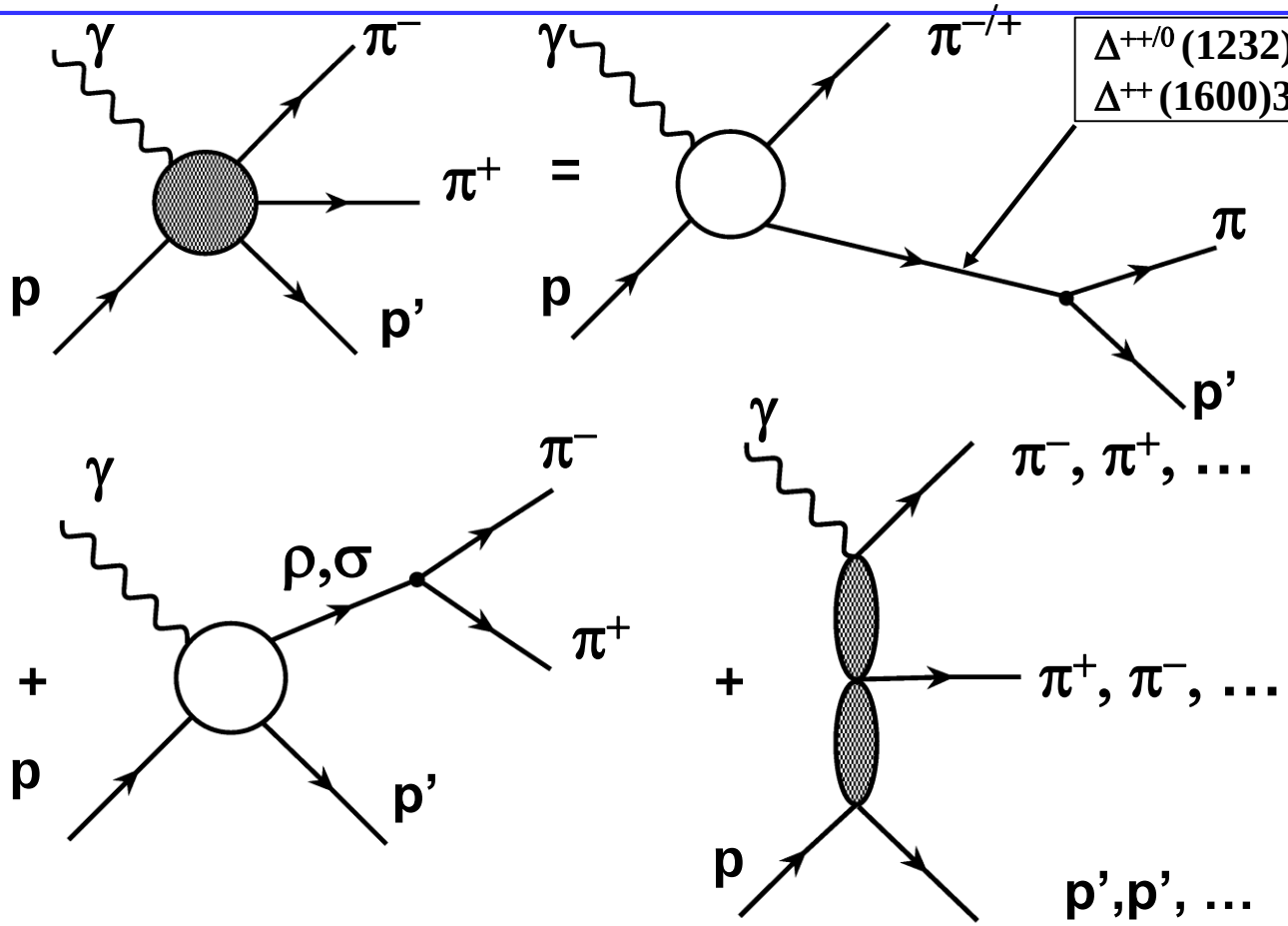
- **π^+n and π^0p channels:**
  Unitary Isobar Model (UIM) and Fixed-t Dispersion Relations (DR)
  I.G. Aznauryan, Phys. Rev. C67, 015209 (2003)
  I.G. Aznauryan et al. (CLAS), Phys. Rev. C80, 055203 (2009)
  I.G. Aznauryan et al. (CLAS), Phys. Rev. C91, 045203 (2015)
- **ηp channel:**
  Extension of UIM and DR
  I.G. Aznauryan, Phys. Rev. C68, 065204 (2003)
  Data fit at W<1.6 GeV, assuming N(1535)1/2$^-$ dominance
  H. Denizli et al. (CLAS), Phys. Rev. C76, 015204 (2007)
- **$\pi^+\pi^-p$ channel:**
  Data driven JLab-MSU meson-baryon model (JM)
  V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C80, 045212 (2009)
  V.I. Mokeev et al. (CLAS), Phys. Rev. C86, 035203 (2012)
  V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C93, 054016 (2016)

Global coupled-channel analysis of $\gamma_{r,v}N$, πN, ηN, $\pi\pi N$, $K\Lambda$, $K\Sigma$ exclusive channels:

H. Kamano, Few Body Syst. 59, 24 (2018)
H. Kamano, JPS Conf. Proc. 13, 010012 (2017)

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

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

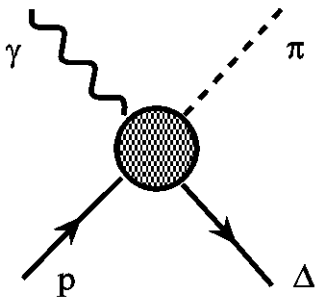


- five channels with unstable intermediate meson/baryon and direct $\pi^+\pi^-p$ production;
- N* contribute to $\pi\Delta$ and ρp channels only;
- unitarized Breit-Wigner ansatz for resonant amplitudes;
- phenomenologocal parameterization of the others meson-baryon channel amplitudes (see Ref. 2)

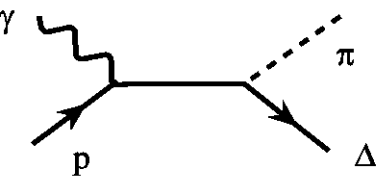
1. V.I. Mokeev, V.D. Burkert et al., (CLAS Collaboration) Phys. Rev. C86, 035203 (2012).
2. V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C80, 045212 (2009).

Non-Resonant Contributions to $\pi\Delta$ Channels

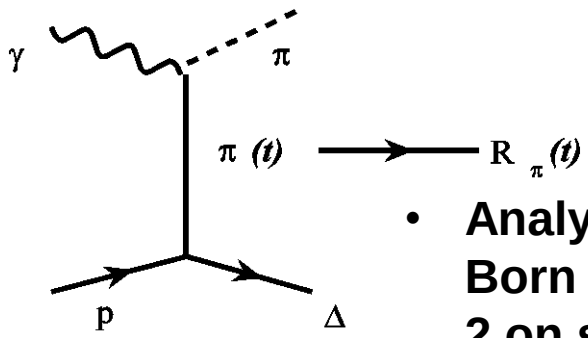
Minimal set of current conserving Born terms:



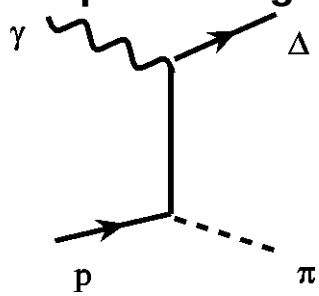
contact



nucleon term



pion in flight



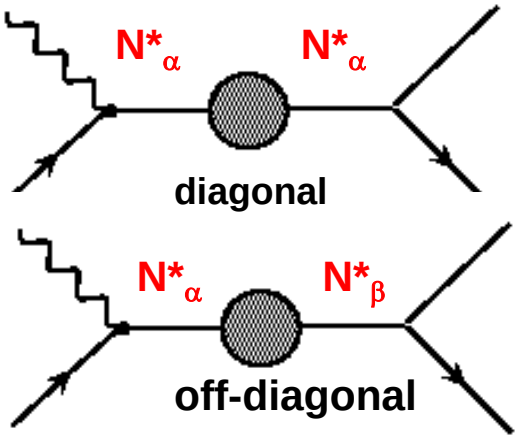
delta in flight

- **Analytical expressions for the Born terms can be found in Ref. 2 on slide #8.**
- **Born terms were reggeized, current conservation was kept, and extra contact term was added to account for other contributions (See Ref. 2 on slide # 8).**

Effective FSI treatment in $\pi\Delta$ channels within the framework of the absorptive ansatz (M.Ripani et al., Nucl Phys. A672, 220 (2000)).

Unitarized Breit-Wigner Ansatz for Resonant Amplitudes

Resonant amplitude : $$T^{res}_{\gamma p \to MB} = f_{\beta MB} S_{\alpha\beta} f_{\alpha\gamma p}$$



Inverse of the JM unitarized N* propagator:

$$S^{-1}_{\alpha\beta} = M^2_{N^*}\delta_{\alpha\beta} - i\left(\sum_i \sqrt{\Gamma_{\alpha i}}\sqrt{\Gamma_{\beta i}}\right)\sqrt{M_{N^*\alpha}}\sqrt{M_{N^*\beta}} - W^2\delta_{\alpha\beta}$$

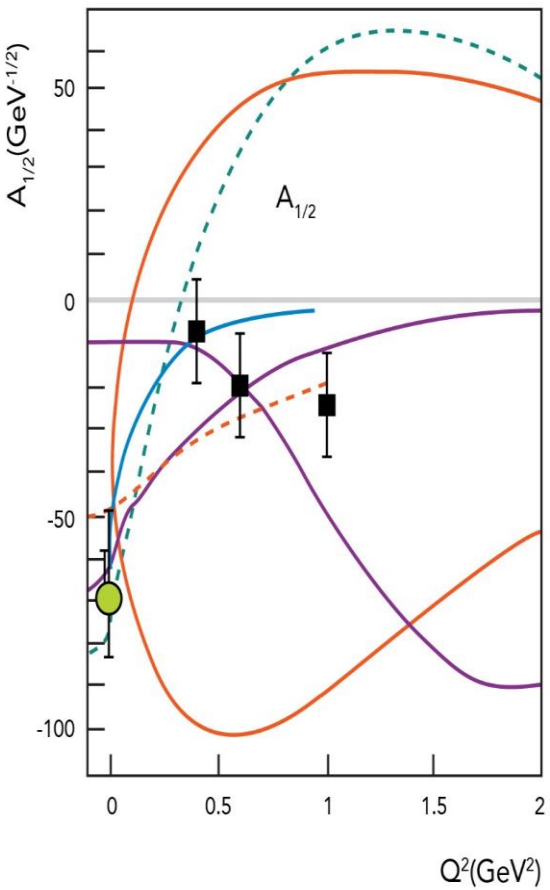
Off-diagonal transitions incorporated into the full resonant amplitudes of the JM model:

N(1535)1/2$^-$ ↔ N(1650)1/2$^-$
N(1520)3/2$^-$ ↔ N(1700)3/2$^-$
3/2$^+$(1720) candidate ↔ N(1720)3/2$^+$

Full resonant amplitude of unitarized Breit-Wigner ansatz is consistent with restrictions imposed by a general unitarity condition. See details in Ref. 1 in slide # 8

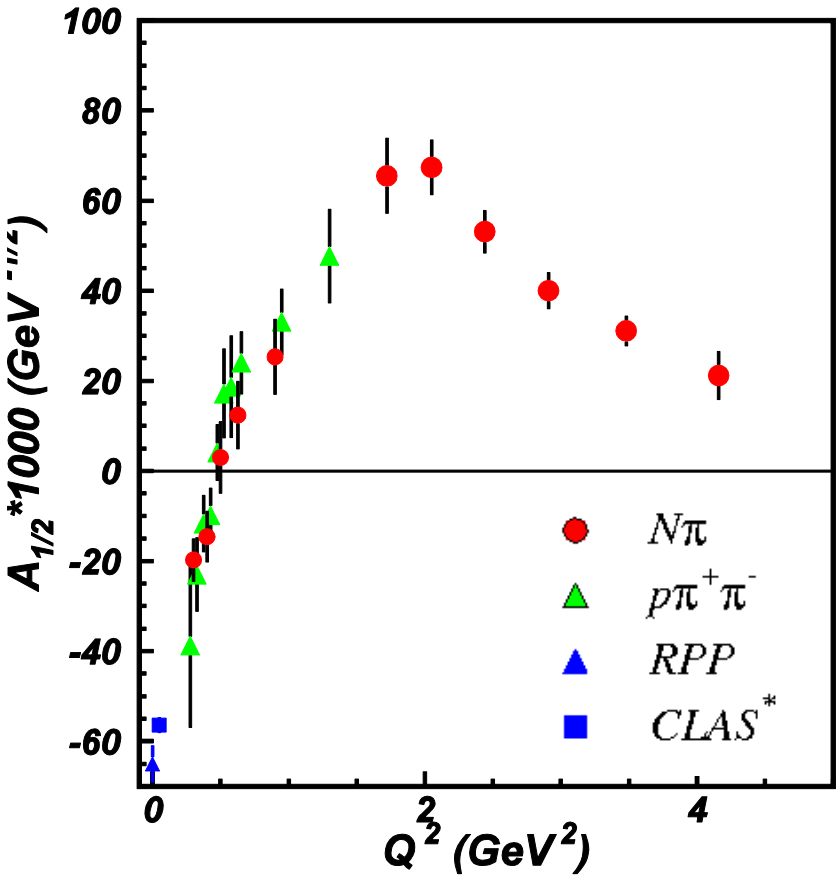
Roper Resonance in 2002 & 2018

2002



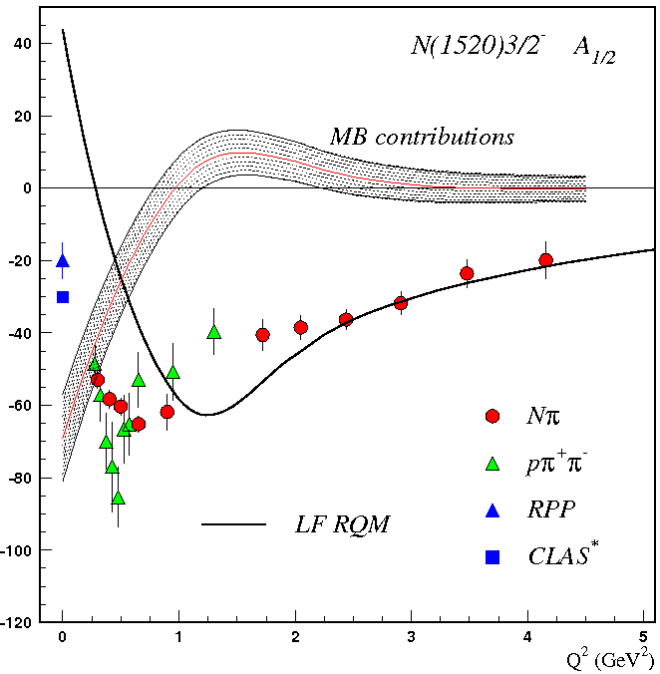
V. Burkert, Baryons 2002

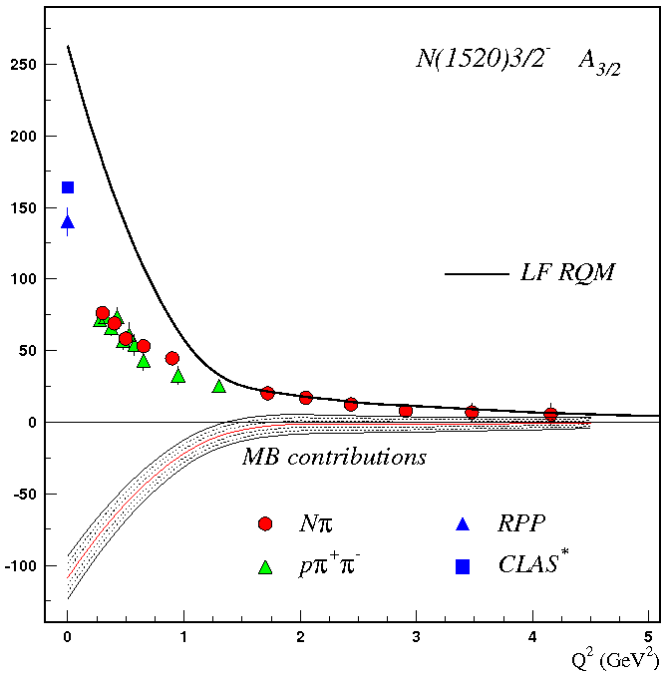
2018



V. D. Burkert, Baryons 2016

$\gamma_v pN^*$ Electrocouplings from $N\pi$ and $\pi^+\pi^- p$ Electroproduction





CLAS data points from:
I.G. Aznauryan et al., Phys. Rev. C80, 055203 (2009).
K. Park et al., Phys. Rev. C91, 045203 (2015).
V.I. Mokeev et al., Phys. Rev . C86, 035203 (2012).
V.I. Mokeev et al., Phys. Rev.. C93, 025206 (2016).

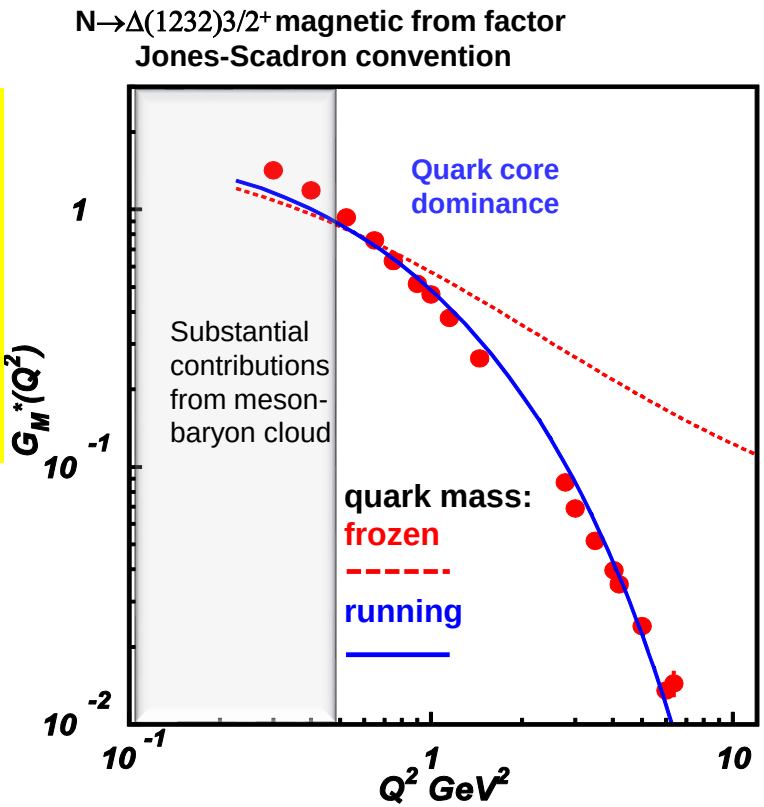
Consistent values of resonance electrocouplings from $N\pi$ and $\pi^+\pi^- p$ electroproduction strongly support their reliable extraction.

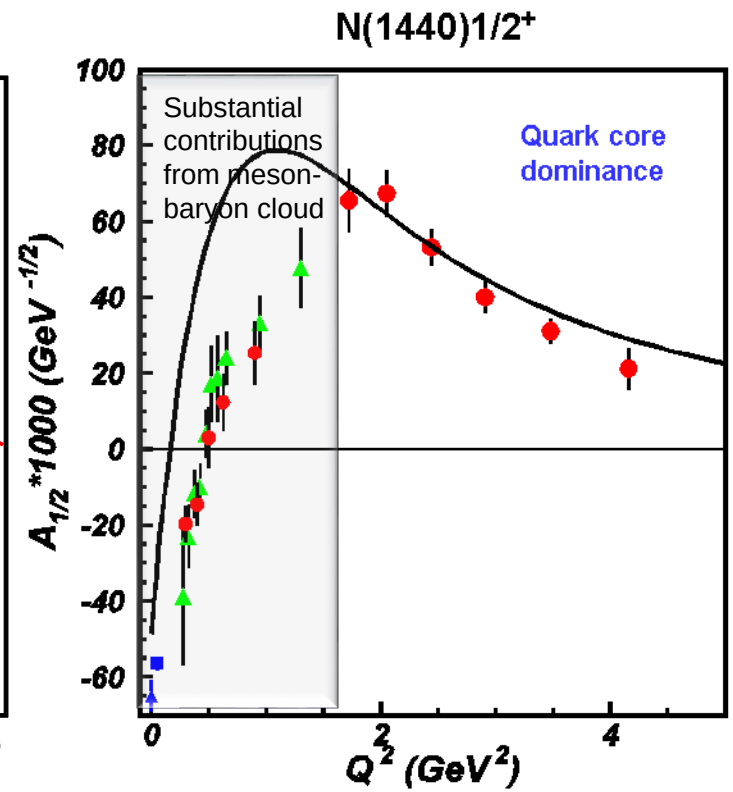
The structure of all resonances studied with CLAS represents a complex interplay between inner quark core and external meson-baryon cloud.

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).**



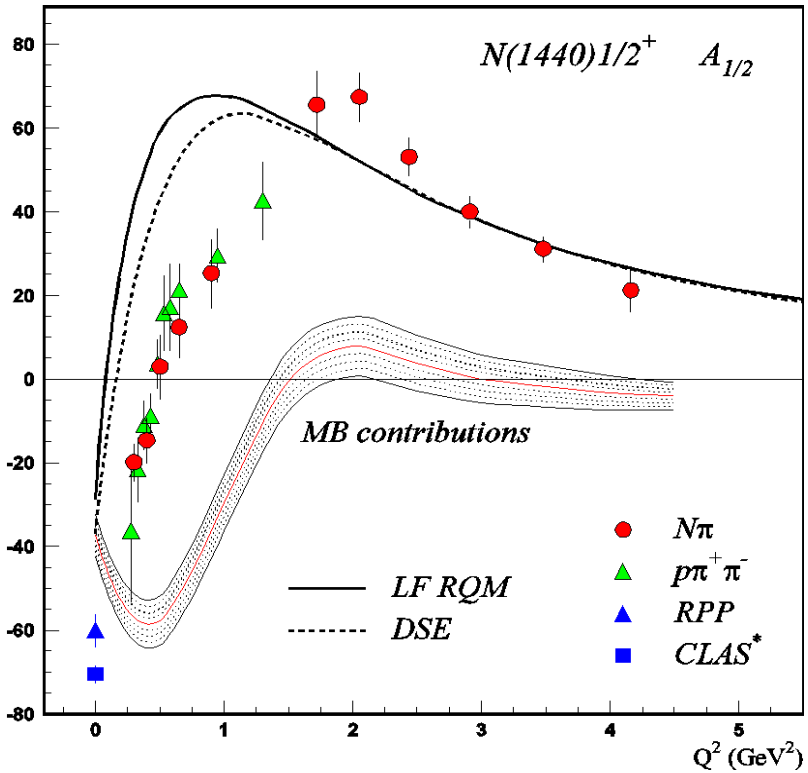


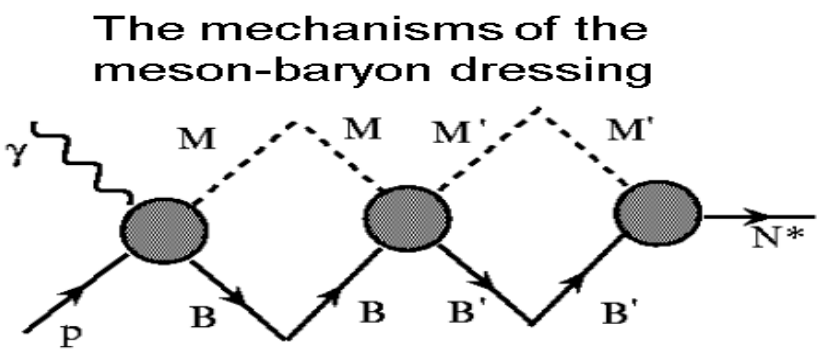
DSE analyses of the CLAS data on Δ(1232)3/2+ electroexcitation demonstrated that dressed quark mass is running with momentum.

Good data description at Q^2>2.0 GeV^2 achieved with <u>the same dressed quark mass function</u> 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 and theorists.

Resolving Roper Puzzle





CLAS data in the range of Q^2<5.0 GeV^2 revealed the structure of N(1440)1/2$^+$ as a complex interplay between inner core of three dressed quarks in the first radial excitation and external meson-baron (MB) cloud

LF RQM-Light Front relativistic quark model: V.D. Burkert, I.G. Aznauryan, Phys . Rev. C85, 055202 (2012); Phys. Rev. C95, 065207 (2017).

Quark core description within LF RQM and DSE is consistent

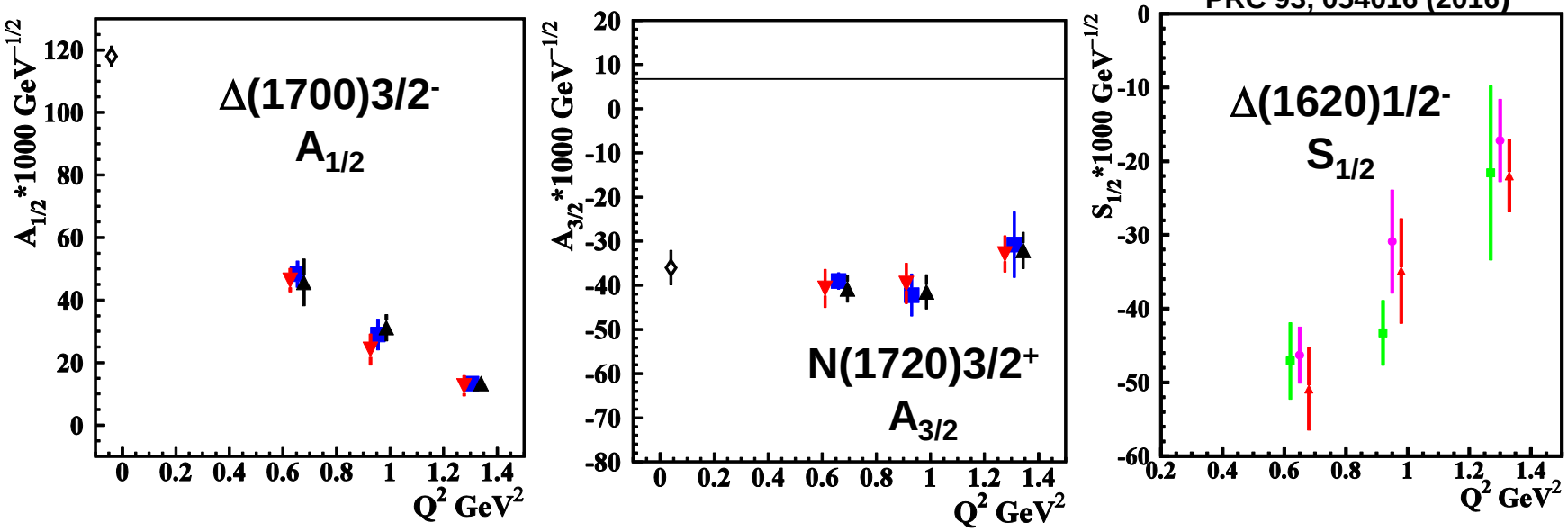
For more details on resolving Roper puzzle see:

V. D. Burkert and C.D. Roberts ``Roper resonance-solution to the fifty year puzzle", arXiv:1710.02549 [nucl-ex] .

Electrocouplings of the Orbital Excited Resonances from the CLAS $\pi^+\pi^-p$ Electroproduction Data

V.I. Mokeev and I.G. Aznauryan., Int. J. Mod. Phys. Conf. Ser. 26. 146080 (2014)

V.I. Mokeev et al., PRC 93, 054016 (2016)

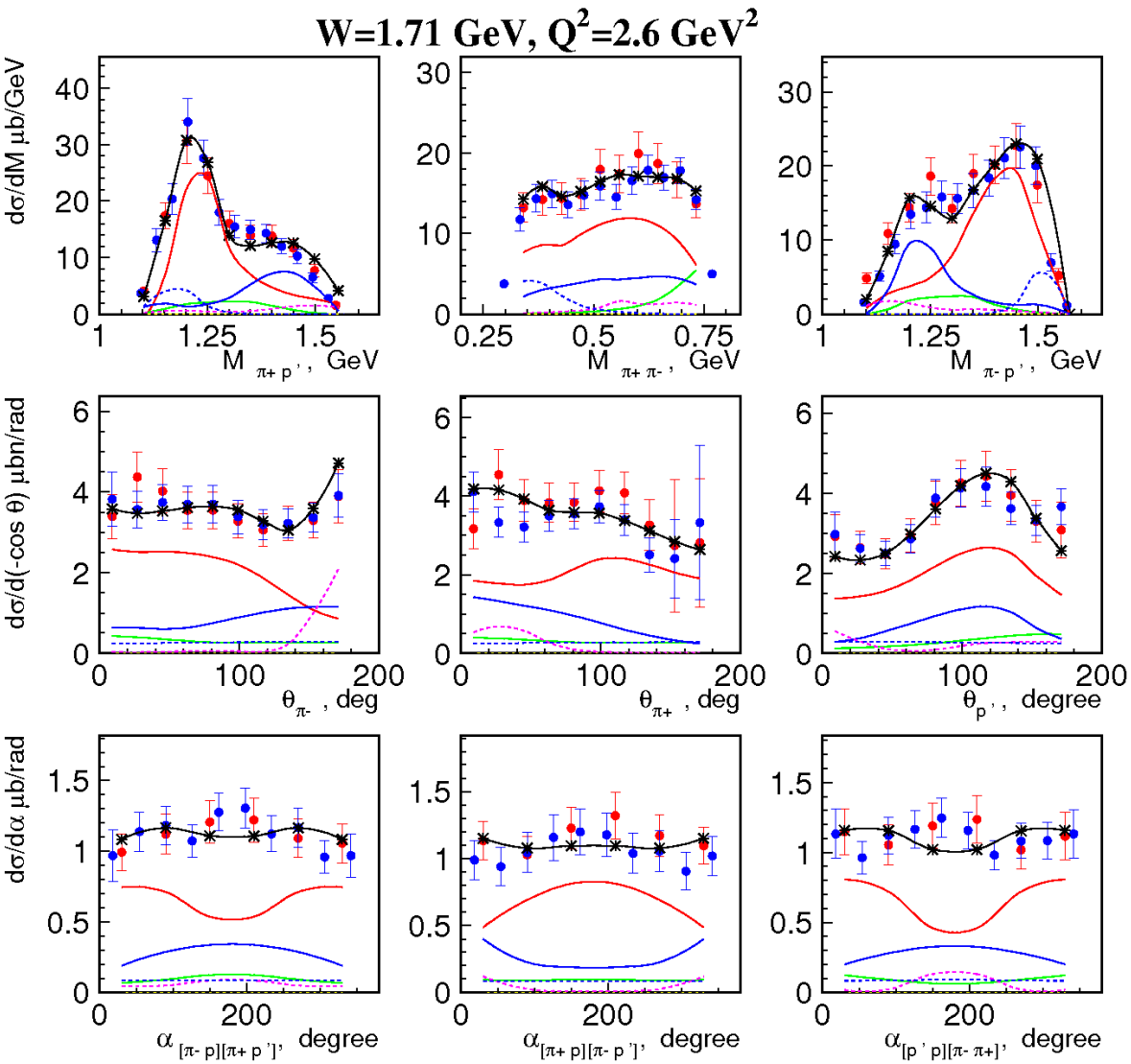


Independent fits in different W-intervals:

green: 1.51<W<1.61 GeV red: 1.61<W<1.71 GeV black: 1.71<W<1.81 GeV
magenta: 1.56<W<1.66 GeV blue: 1.66<W<1.76 GeV

The $\pi^+\pi^-p$ electroproduction is the major source of information on electrocouplings of the $\Delta(1620)1/2^-$, $\Delta(1700)3/2^-$, and $N(1720)3/2^+$ resonances that decay preferentially to the $N\pi\pi$ final states.

Extending the Kinematical Coverage of $\pi^+\pi^-p$ Electroproduction off Proton Data



Two data sets have recently become available at 1.40 GeV <W<2.0 GeV and 2.0 GeV² < Q² < 5.0 GeV² :

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

blue - preliminary, A.Triverdi, R.W. Gothe, USC.

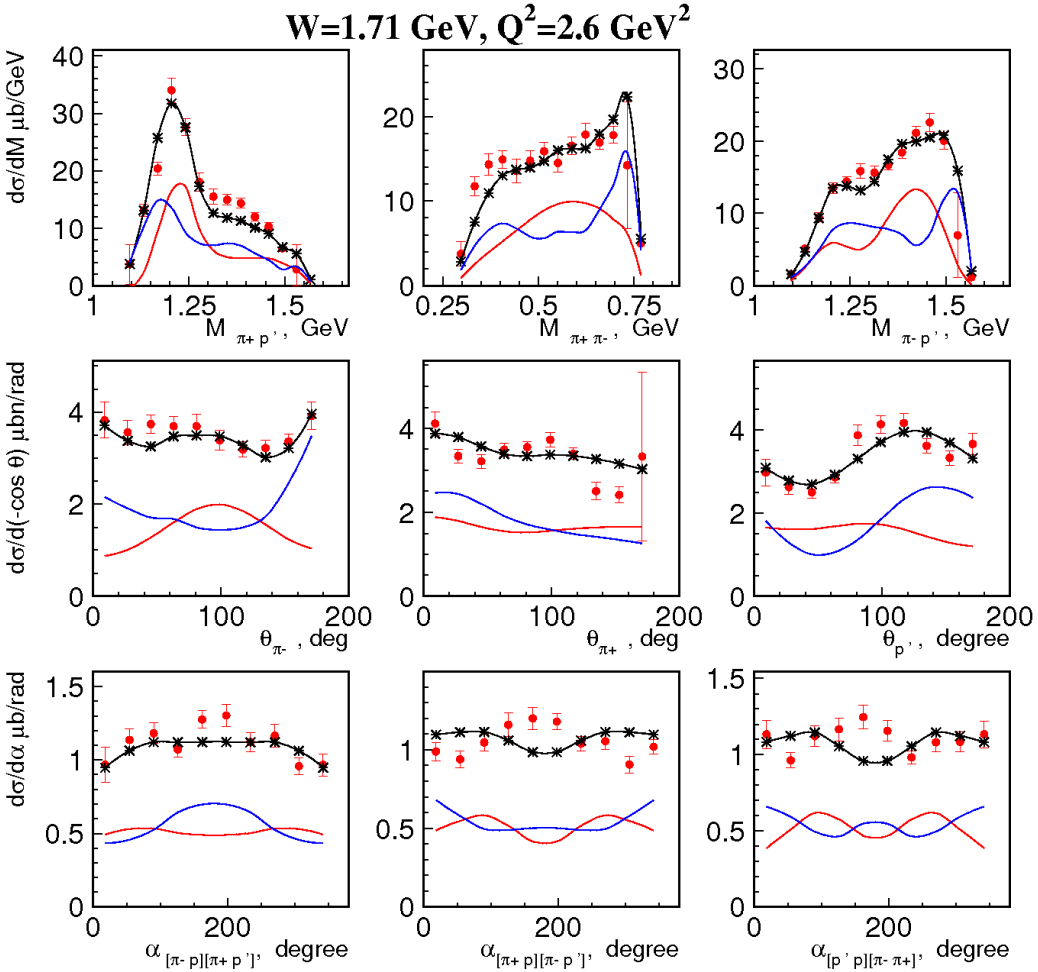
black – JM16 adjusted to the published data (in red)

Two data sets are consistent validating reliable evaluation of 9 differential $\pi^+\pi^-p$ cross sections

Good data description of both data sets was achieved within the updated JM 17 model

The JM17 model offers a good description of all available $\pi^+\pi^-p$ electroproduction off protons data at 1.4 GeV < W < 2.0 GeV and 0.25 GeV² < Q² < 5.0 GeV²

Future Extension of the Results on $\gamma_v pN^*$ Electrocouplings



JM18 model version adjusted to the preliminary A.Trivertdi & R.W. Gothe data (only statistical errors were used in evaluation of χ^2/d/.p.)

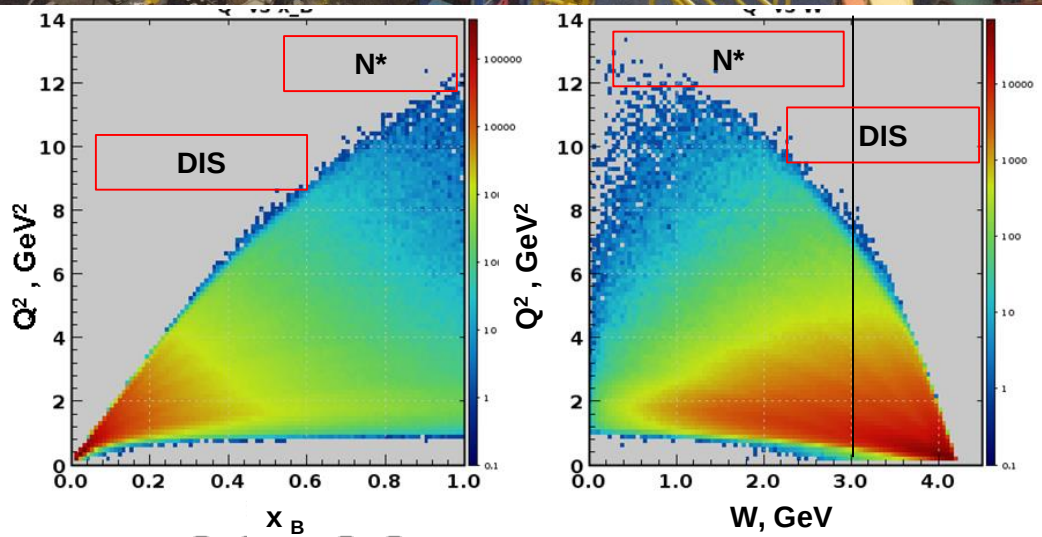
Resonant contributions

Non-resonant contributions

Significant resonant contributions and pronounced differences in behavior of the resonant /non-resonant contributions seen in all nine one-fold differential cross sections suggest the good prospects for extraction of $\gamma_v pN^*$ electrocouplings.

In the near term future electrocouplings of most excited nucleon states in the mass range up to 2.0 GeV will become available from the CLAS $\pi^+\pi^-p$ electroproduction off protons data at 2.0 GeV^2<Q^2<5.0 GeV^2

12 GeV Era with the CLAS12 Detector



Physics run started successfully in February 2018.

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!

Emergence of Hadron Mass and Quark-Gluon Confinement

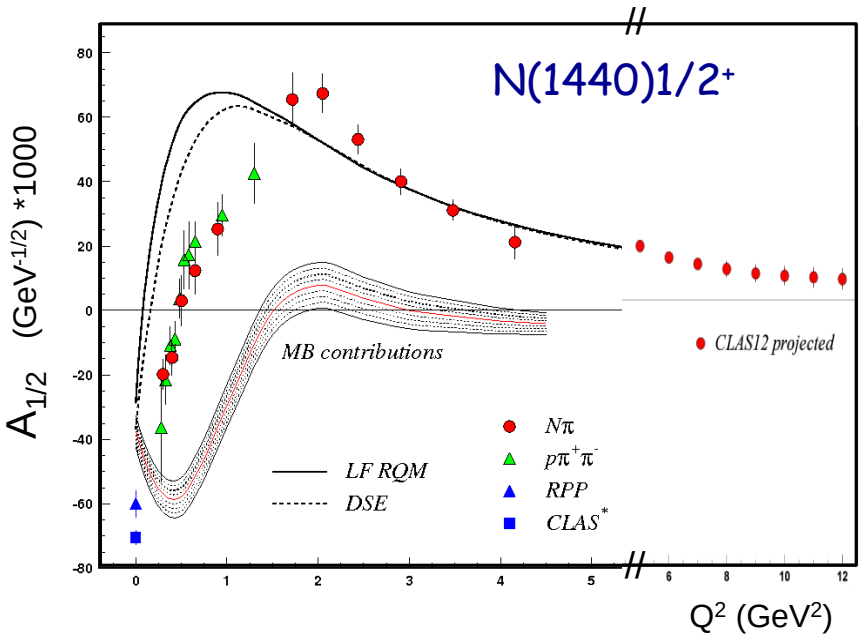
N* electroexcitation studies at JLab will address the critical open questions:

How is >98% of visible mass generated?

How does confinement emerge from QCD and how is it related to Dynamical Chiral Symmetry Breaking?

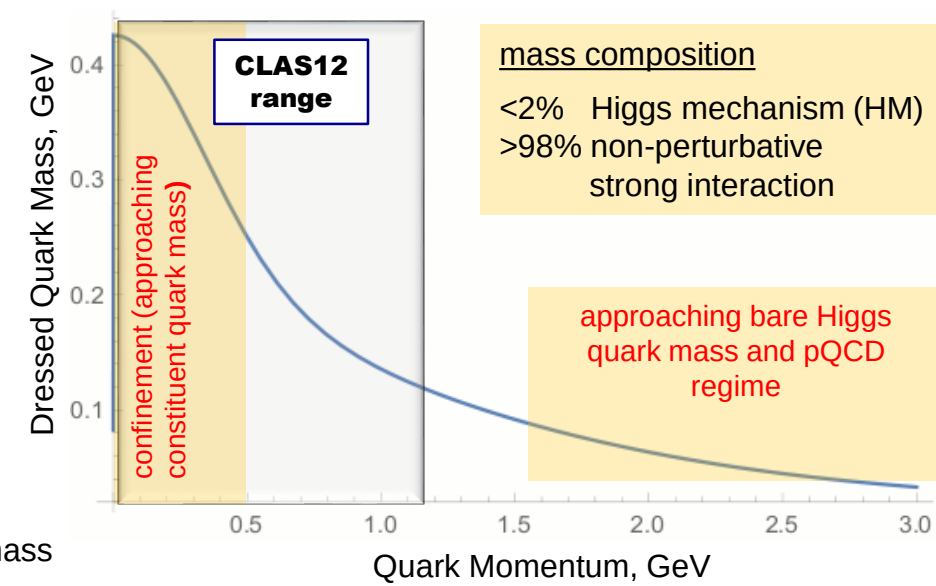
What is the behavior of QCD's running coupling at infrared momenta?

Mapping-out quark mass function from the CLAS12 results on $\gamma_v pN^*$ electrocouplings of spin-isospin flip, radial, and orbital excited nucleon resonances at $5<Q^2<12$ GeV^2 will allow us to explore the transition from strong QCD to pQCD regimes.



CLAS results versus theory expectations with running quark mass

Access to the dressed quark/hadron mass generation



mass composition

<2% Higgs mechanism (HM)
>98% non-perturbative strong interaction

approaching bare Higgs quark mass and pQCD regime

Conclusions and Outlook

- **High quality $\pi^+\pi^-p$ electroproduction data from CLAS have allowed us to determine the electrocouplings of most resonances in the mass range up to 1.8 GeV with consistent results from analyses of π^+n, π^0p, ηp, and $\pi^+\pi^-p$ electroproduction channels.**

- **Physics analyses of the $\gamma_v pN^*$ electroexcitation amplitudes from CLAS revealed the structure of excited nucleons as a complex interplay between the inner core of three dressed quarks and external meson-baryon cloud.**

- **<u>Profound impact on the exploration of strong QCD dynamics:</u>**
  a) first DSE evaluations of $\Delta(1232)3/2^+$ and $N(1440)1/2^+$ electroexcitation amplitudes with a traceable connection to the QCD Lagrangian;
  b) synergistic efforts involving experimental studies of $\gamma_v pN^*$ electrocouplings in Hall B at JLab and their continuum QCD analyses have demonstrated the capacity for reliable access to the mechanisms responsible for hadron mass generation.

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

Conclusions and Outlook

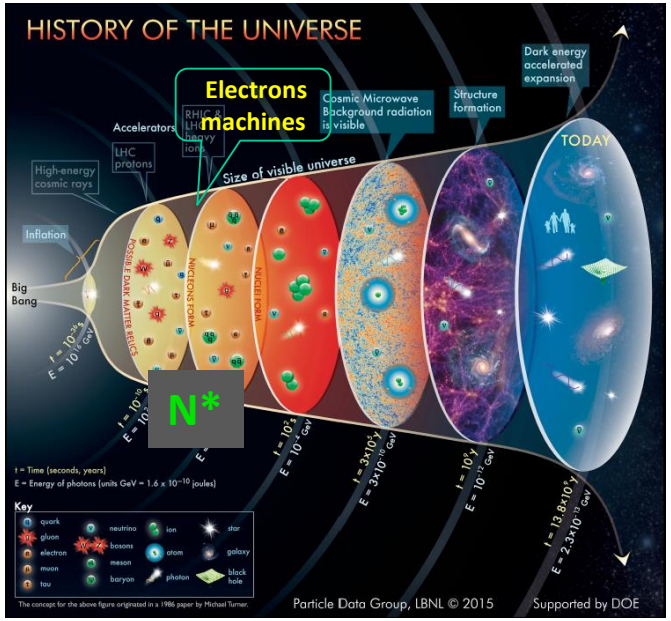
- **CLAS12 is the only facility in the world capable to obtain electrocouplings of all prominent N* states at still unexplored ranges of low photon virtualities down to 0.05 GeV^2 and highest photon virtualities for exclusive reactions from 5.0 GeV^2 to 12 GeV^2 from measurements of $N\pi$, $\pi^+\pi^-p$, and KY electroproduction.**

- **The expected results will allow us:**
  a) to search for hybrid-baryons and complete the N*-spectrum exploration;
  b) to map out the dressed quark mass function at the distances where the transition from quark-gluon confinement to pQCD regime is expected, <u>addressing the most challenging problems of the Standard Model on the nature of >98% of hadron mass and of quark-gluon confinement.</u>

- **Success of the N* Program will be very beneficial for the hadron physics community. It requires close collaborative efforts between *<u>experiment and phenomenology</u>* for resonance parameter extraction from the data, and *<u>the QCD-based hadron structure theory</u>* capable of relating resonance parameters to strong QCD dynamics.**

Back up

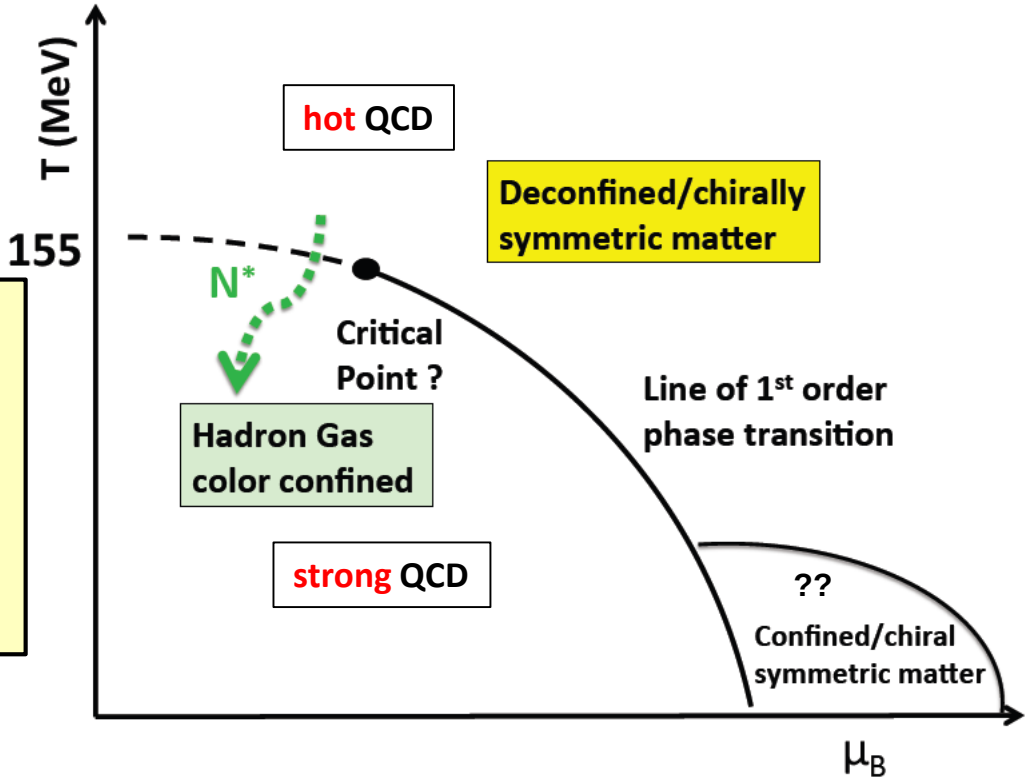
Nucleon Resonances in the History of the Universe



Dramatic events occur in the micro-second old universe during the transition from the QGP phase to hadron phase.

- Chiral symmetry is broken
- Quarks acquire mass
- Baryon resonances occur
- Quark-gluon confinement emerges

Full baryon spectrum shaped this transition



N* studies at 0.05 GeV^2 < Q^2 < 7.0 GeV^2 with CLAS12

Hybrid Baryons E12-16-010	Search for hybrid baryons (qqqg) focusing on 0.05 GeV^2 < Q^2 < 2.0 GeV^2 in mass range from 1.8 to 3 GeV in KΛ, Nππ, Nπ *(A. D'Angelo, et al.)*
KY Electroproduction E12-16-010A	Study N* structure for states that couple to KY through measurements of cross sections and polarization observables that will yield Q^2 evolution of electrocoupling amplitudes at Q^2<7.0 GeV^2 *(D. Carman, et al.)*

Approved by PAC44

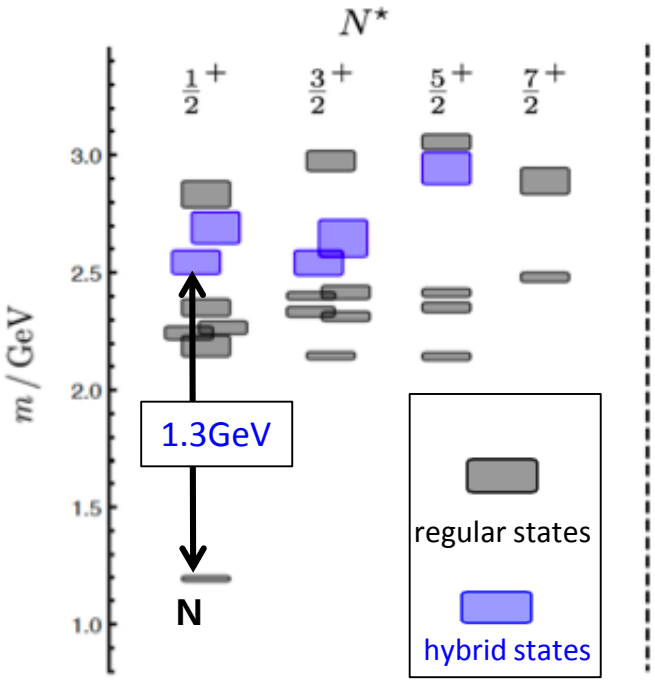
Run Group conditions:
E_b = 6.6 GeV, 50 days
E_b = 8.8 GeV, 50 days

- Polarized electrons, unpolarized LH_2 target
- L = 1x10^{35} cm^{-2}s^{-1}

Hunting for Glue in Excited Baryons with CLAS12

Can glue be a structural component to generate hybrid q^3g baryon states?

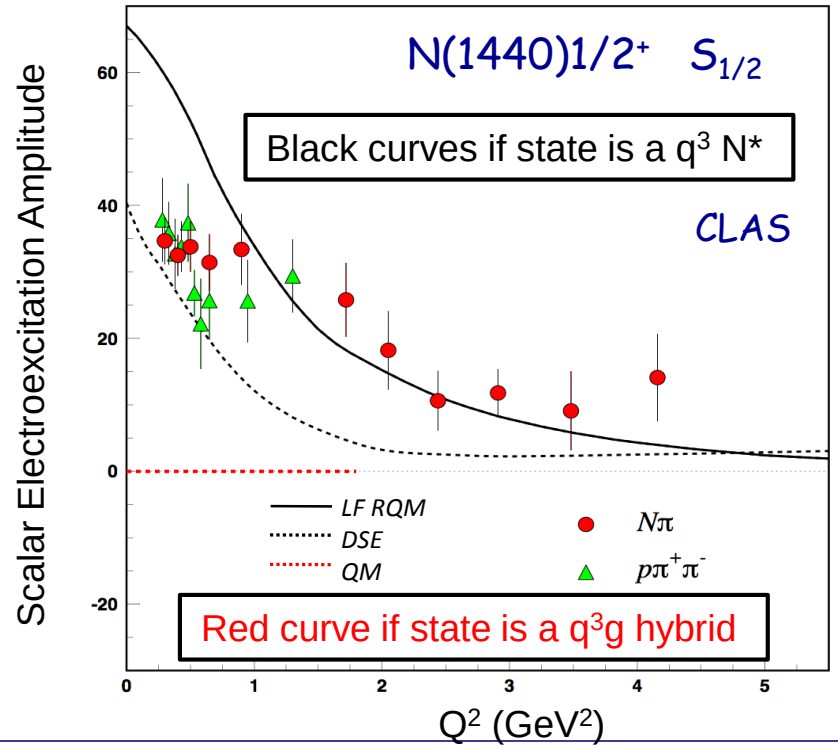
Predictions of the N* spectrum from QCD show both regular q^3 *and* hybrid q^3g states



JLab LQCD group results

Search for hybrid baryons with CLAS12 in exclusive KY and $\pi^+\pi^-p$ electroproduction

LQCD and/or QM predictions on Q^2 evolution of the hybrid-baryon electroexcitation amplitudes are critical in order to establish the nature of a baryon state



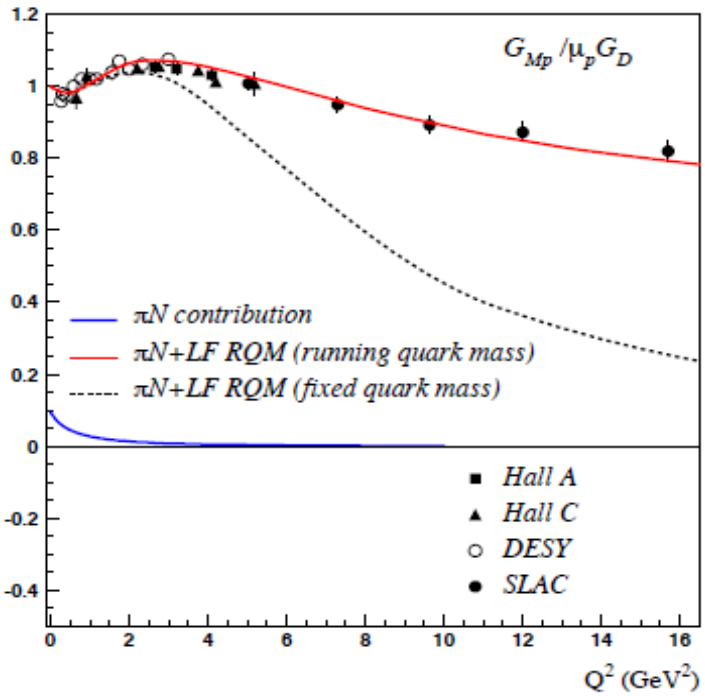
Quark Model with Input from QCD-based Approaches

Light Front QM by I.G. Aznauryan and V.D. Burkert: PRC 85, 055202 (2012).

The approach discussed here is purely phenomenological, and addresses a few topics that have some importance for the direction of the field, in particular:

- obtain a better understanding of the expected meson-baryon contributions
- study the sensitivity of the resonance transition amplitudes to the running quark mass, which is a result of the DSE approach and of LQCD calculations.

Proton Magnetic Form Factor



- Nucleon electromagnetic form factors
  → $q^3 + \pi N$ loops contributions in light-front dynamics
  → running quark mass
- Electroexcitation of $\Delta(1232)\frac{3}{2}^+$, $N(1440)\frac{1}{2}^+$, $N(1520)\frac{3}{2}^-$, and $N(1535)\frac{1}{2}^-$
  → q^3 contribution in a LF RQM with running quark mass
  → inferred MB contributions

Implementation of momentum-dependent quark mass is needed in order to reproduce elastic magnetic form factor of proton at Q^2>3.0 GeV^2