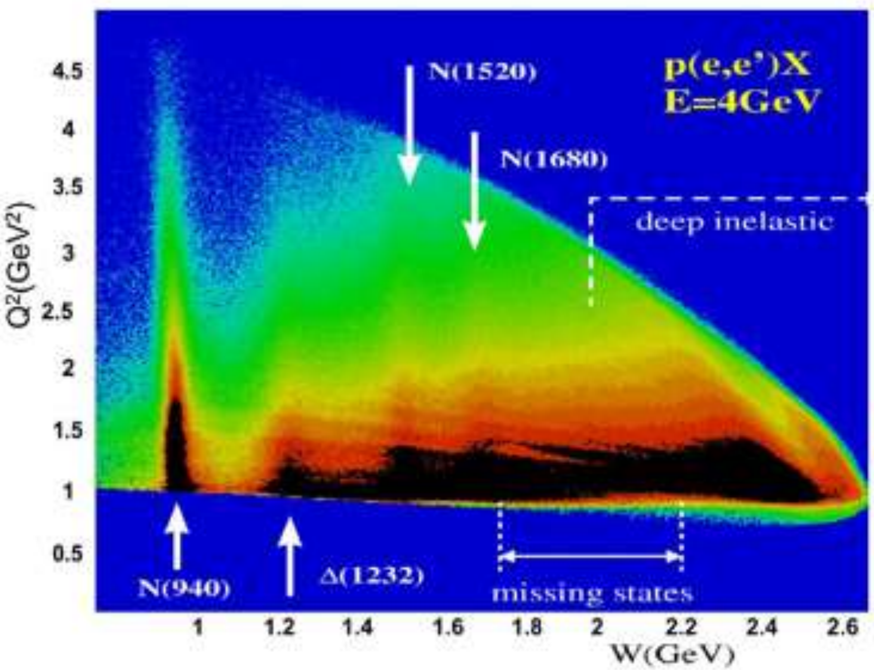
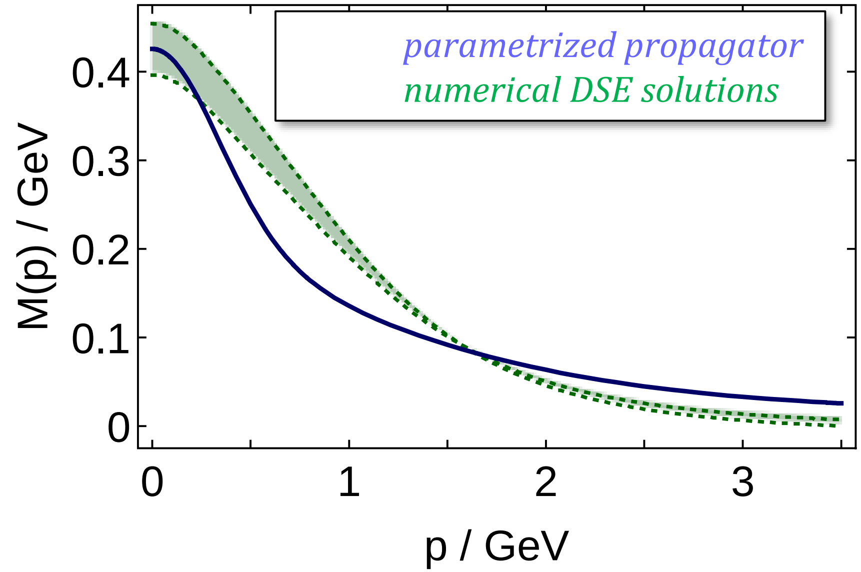
Insight to EHM from the Data on Nucleon Resonance Electroexcitation and the Meson Structure Studies





V.I. Mokeev,
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Talk outline:

- N* structure as a window into hadron mass generation;
- Resonance photo-/electrocouplings from meson electroproduction data;
- Relating resonance electrocouplings to hadron mass generation;
- Mapping dressed quark mass from the data on meson and N* structure;
- Conclusion and outlook

Office of Science

Perceiving the Origin of Hadron Mass through AMBER @ CERN, March 31 – April 3, 2020, Geneva, Switzerland

N* Structure in Experiments with CLAS/CLAS12

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

- $\gamma_v pN^*$ electrocouplings at photon virtualities Q^2 up to 5.0 GeV$^{\mathbf{2}}$ for most of excited proton states through analyzing major meson electroproduction channels from CLAS data
- extend accessible Q^2 range up to 12 GeV^2 and down to 0.05 GeV^2 from CLAS12 data and explore N* structure evolution in the transition from the strong to the pQCD regimes
- explore hadron mass emergence by mapping out running quark mass in the transition from almost massless pQCD quarks to fully dressed constituent quarks

- **A unique source of information on many facets of strong QCD in generating N* states with different structural features**
- **Consistent results on dressed quark mass function from independent studies of different N* electroexcitations validate insight to EHM**

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, Rev. Mod. Phys. 91, 011003 (2019)**
3. **C.D. Roberts, Few Body Syst. 59, 72 (2018)**
4. **V.I. Mokeev, Few Body Syst. 59, 46 (2018)**

Emergence of hadron mass from QCD represents the most challenging and still open problem in the Standard Model (SM) because of distinctive difference between strong interaction underlying the hadron mass generation, and other fundamental processes such as electroweak interactions. The QCD Lagrangian requires that bare current QCD quark should be dressed by gluons and qq-bar pairs coupled to gluon fields. The gauge QCD gluon should be also dressed in the processes shown in the slide. Their dressing is imposed by the QCD Lagrangian expressing the non-Abelian nature of QCD resulting in gluon self-interaction. In regime of large, compareble with unity QCD-rinning coupling, these dressing processes create the effective objects dressed quarks ans dressed gluons. They possess dynamical distance- and momentum-dependent mass. Their structure is complex and related in non-trivial way to elementary current quarks and gauge gluon which enter to the QCD Lagrangian. Thhe continuum QCD approaches computed momentum dependent mass of dressed qurk strating from the QCD Lagrangian with the results shown in the right bottom plot in green.

Dressed quark mass function demonstrateshow almost massless of ~few MeV mass, almopst perturbative QCD quarks at momenta > 1.0 GeV per quark eventually at momenta <0.5 GeV per quark become the fully dressed quaeks of 400 MeV mass. These dressed quarks are employed in constituent quark models (CQM). Higgs mechanisms is responsible for generation of only bare quark mass. It is relevant at momenta p>1.0 GeV woth the contribution to fully dressed quark, and to the hadron mass, <2%. For this reason, Higgs mechanism is almost irrelevant for generation of the mass for hadron consisted of light u and d quarks. A dominant part (>98%) of these hadron masses is created in the dressing processes shown in the left diagrams which are responsible for Dynamical Chiral Symmetry Breaking (DCSB).

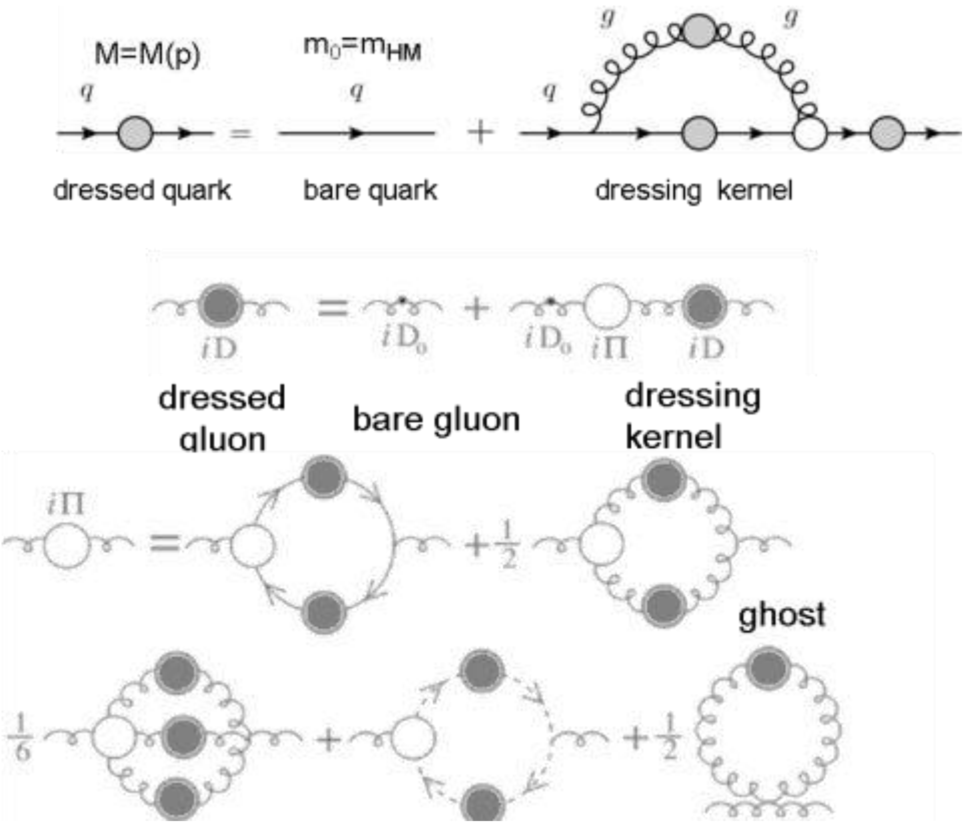
It is a challenge for contemporary experiment to map out the momentum dependence of dressed quark mass. It can not be done directly. Because of quark-gluon confinement, we have no free dressed quarks or free dressed gluons to study. However, dressed quark mass function is a key ingredient of strong QCD. It drives all structural properties of hadrons making it possible to map out the momentum dependence of dressed quark mass in the studies of the hadron structure.

According to continuum QCD approaches, exchange by dressed gluon between two dressed quarks results in qq-correlation (top right plot). Sunsequent exchamge by one of two correlated quarks with third uncorellated quark in baryons result in binding for the three quarks within the baryon. In a such way the ground and excited nucleon states are generated as the bound systems of three dressed quarks. This picture from continuum QCD approaches get a strong support from the experimental results from CLAS on Q^2-evolution on N-→N* electroexcitation amplitudes (gvpN* electrocouplings). In photo-/electroexcitation of the N*, the real/virtual photon interacts to dressed quark probing the dressed quark propagator which is defined by the running mass of dressed quark. By varying the photon virtuality Q^2, it makes possible to map out the momentum dependence of dressed quark mass

For these reasons the study of nucleon elastic electromagnetic form factors and N-→N* electroexcitation amplitudes represents the key direction in a contemporary hadron physics.

Basics for Insight into EHM from Data on N* Electrocouplings

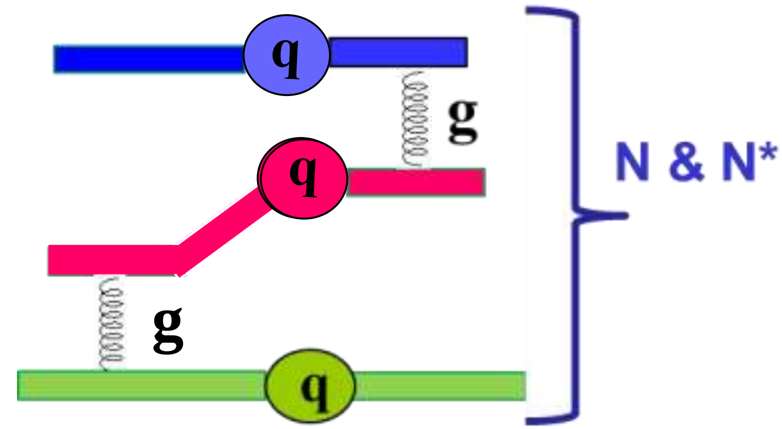
Emergence of Dressed Quarks and Gluons
D. Binosi et al, Phys. Rev. D 95, 031501 (2017)



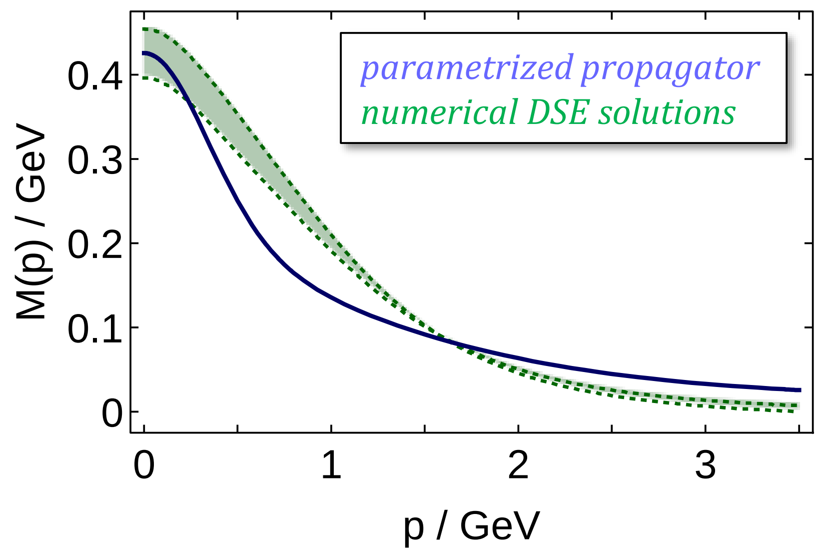
<u>**Data on N* electrocoupling are sensitive to the quark propagators and allow us to:**</u>

- **Map out quark mass function**
- **Constrain the ground nucleon and meson form factors, PDA, & PDF**

Dressed Quark Borromeo Binding in N/N*
J. Segovia et al., arXiv:1908:0572 [nucl-th]



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



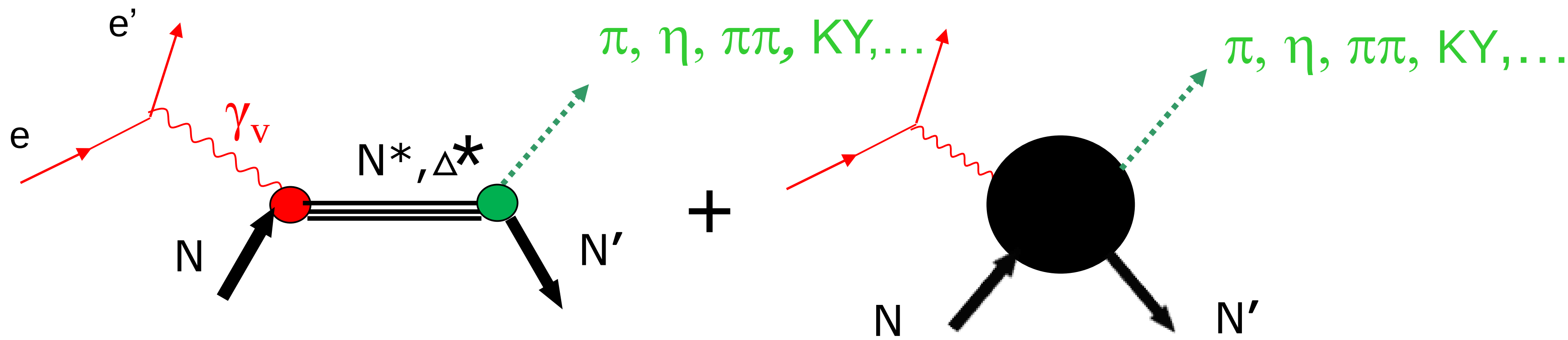
Inferred from QCD Lagrangian with only the Λ_{QCD} parameter

Resonance electroexcitation can be fully described by $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$ and $S_{1/2}(Q^2)$ electrocouplings. They are proportional to helicity amplitudes for the transition between the initial photon-proton and final N*, Delta* states for different helicities of the initial photon and proton in their center of mass frame. They are unambiguously determined by the relation in slide to model independent and measurable N* electromagnetic decay widths

Resonance electrocouplings were determined from the data of exclusive meson electroproduction channels listed in the slide. The full amplitude of any channel is determined by resonance s-channel amplitude and by a complex set of the non-resonant contributions. The non-resonant contributions are different in different channels while resonance electrocouplings should be the same since the N* electroexcitation and hadronic decay amplitudes are independent. Therefore, consistent results on $g_v pN^*$ electrocouplings from different meson electroproduction channels are critical in order to validate reliable extraction of these quantities.

N* Electroexcitation Amplitudes ($\gamma_v NN^*$ Electrocouplings) and their Extraction from Exclusive Electroproduction Data

Resonant amplitudes **Non-resonant amplitudes**



- **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)

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

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

- **Consistent results on $\gamma_v pN^*$ 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** **3.0.0-6.0** **0.4-1.0**	$d\sigma/d\Omega$ $d\sigma/d\Omega$, A_b,A_t,A_{bt} $d\sigma/d\Omega$ $d\sigma/d\Omega$
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** **0.70-5.4**	$d\sigma/d\Omega$ 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 150,000 data points!

Almost full coverage of the final hadron phase space

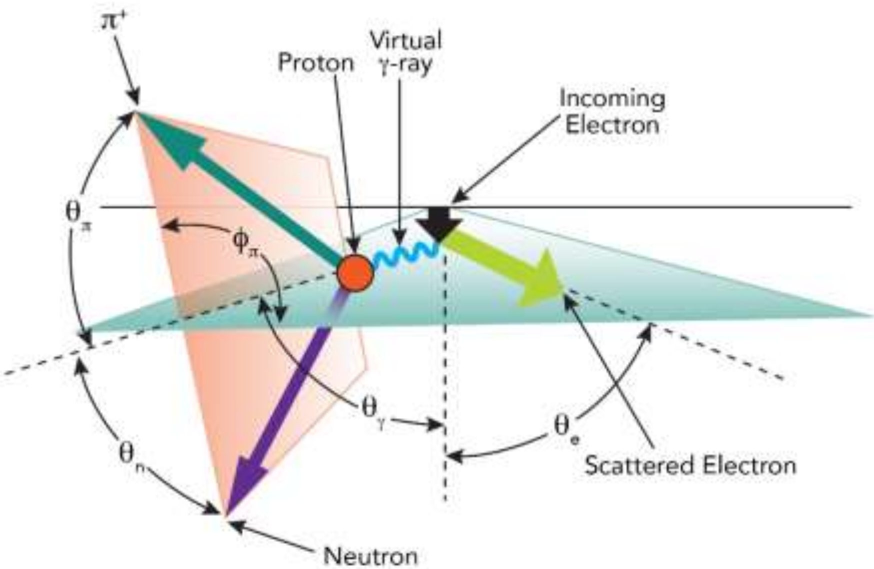
The measured observables from CLAS are stored in the CLAS Physics Database http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi

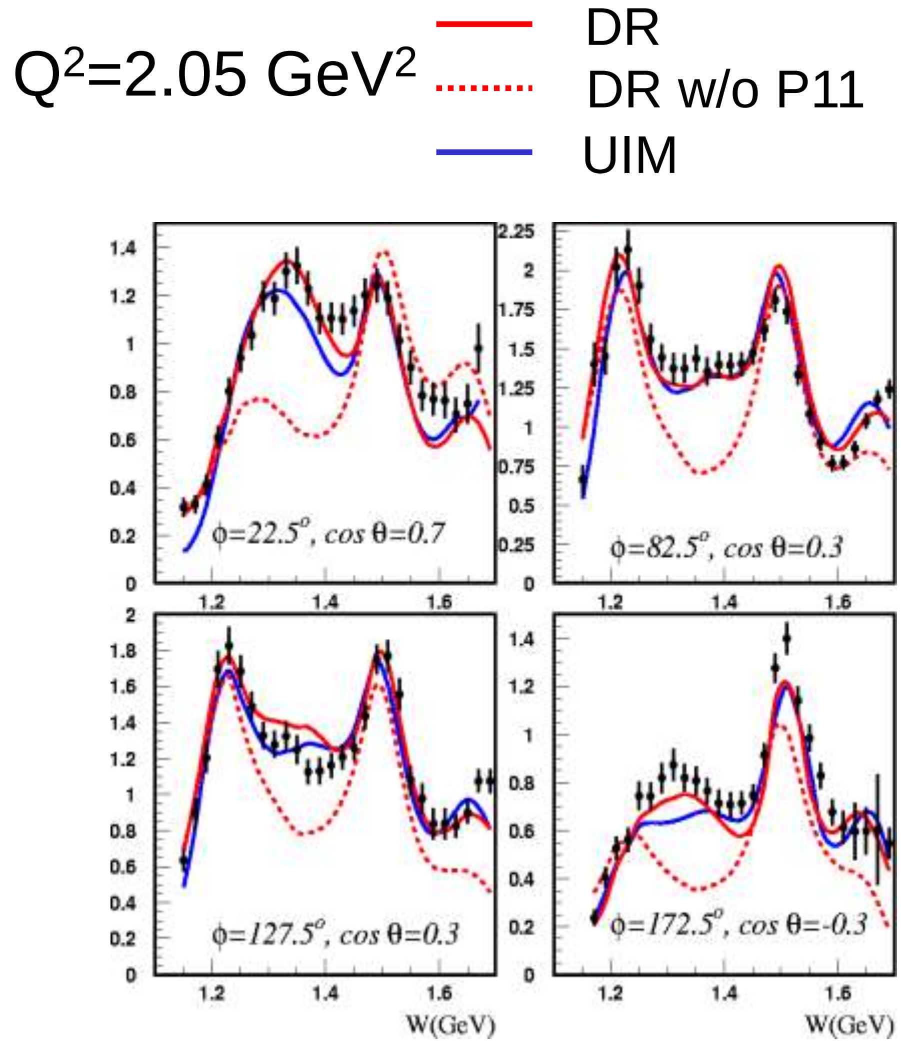
γvpN^* electrocouplings were determined mostly in independent studies of two major electroproduction channels in the resonance region $N\pi$ and $-\pi+\pi p$ electroproduction off protons. Studies of $N\pi$ channels were carried out within two different models: unitary isobar model (UIM) and within dispersion relation (DR) technique. Both approaches provided good description of the $N\pi$ data at $W<1.7$ GeV and $0<Q^2<5$ GeV^2. Representative examples for the data description are shown in the plot.

Accessing Resonance Electrocouplings from the π^+n Differential Electroproduction Cross Sections off Protons

I.G. Aznauryan et al, PR C67, 015209 (2003), PR C80, 055203 (2009).

Kinematics of exclusive π^+n electroproduction off protons (lab frame)





The final pion angles are in the CM-frame of the final hadrons

The CLAS detector provided the only available in the world data on nine independent 1-fold differential p=p-p photo-/electroproduction off proton cross sections at W<2.0 GeV and 0 <Q^2 < 5.0 GeV^2. Representative examples are shown in the plots. A wealth of these data makes it possible to establish all essential mechanisms contributing to this complex exclusive channels from their manifestation in observables: as peaks in invariant mass, sharp dependencies in angular distributions. The remaining mechanisms without pronounced kinematical dependencies have been established by examining the correlation between the shapes of their contributions to nine 1-fold differential cross sections. Within this strategy, all relevant mechanisms in the resonance region have been established. They a shown in the diagrams of the next slide. A phenomenological, data driven JLAB-MSU (JM) model has been developed with the primary objective of determining resonance electrocouplings and their $\Delta\pi$ and ρp decay widths from the combined fit of all observables in $-\pi+\pi$p photo-/electroproduction. The JM model offers good data description at W<2.0 GeV and 2.0 <Q^2<5. GeV^2. The data fit (right plot) allows good isolation of the resonant contributions. The uncertainties of the extracted in the fit resonance parts are comparable with the data uncertainties. The gvpN* electrocouplings were determined by fitting the resonant contributions within the unitarized Breit-Wigner ansatz explicitly accounting for the restrictions imposed on the resonant amplitudesThe CLAS detector provided the only available ion the world data on nine independent 1-fold differential p=p-p photo-/electroproduction off proton cross sections at W<2.0 GeV and 0 <Q^2 < 5.0 GeV^2. Representative examples are shown in the plots. A wealth of these data makes it possible to establish all essential mechanisms contributing to this complex exclusive channels from their manifestation in observables: as peaks in invariant mass, sharp dependencies in angular distributions. The remaining mechanisms without pronounced kinematical dependencoes have been established by examining the correlation between the shapes of their cintributions to nne 1-fold differential cross sections. Within this strategy all relevant mechaniams in the resonance region have been established. They are shown in the diagrams of the next slide. A phenomenological, data driven JLAB-MSU (JM) model has been developed with the primary objective of determining resonance electrocouplings and their pD and rp decay widths fro the combined fit of all observables in p+p-p pjoto-/electroproduction. The JM model offer good data description at W<2.0 GeV and 2.0 <Q2<5. The data fir (right plot) allows good isolation of the resonant contributions. The uncertainties of the extracted in the fit resonance parts are compareble with the data uncertainties. The gvpN* electrocouplings were determined by fitting the resonant contributions within the unitarized Breit-Wigner ansatz explicitely accounting for the restrictions imposed on the resonant amplitude by a general unitarity condition.

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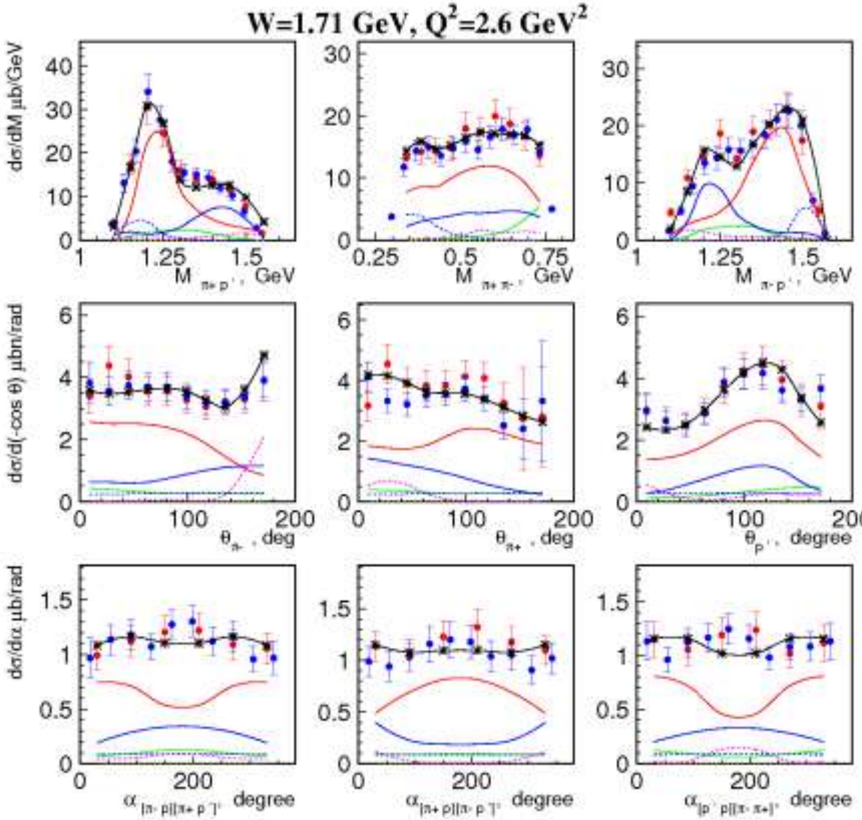
Accessing Resonance Electrocouplings from the $\pi^+\pi^-p$ Differential Electroproduction off Protons Cross Sections

Contributing mechanisms seen in the data

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

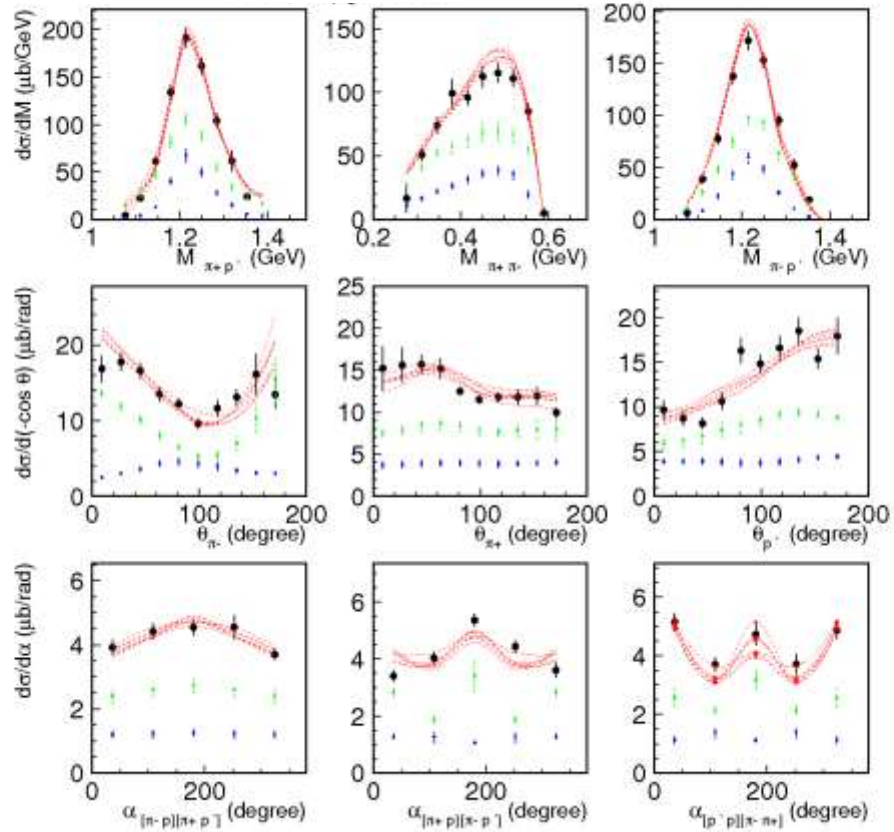
A.Trivedi, Few Body Syst. 60, 5 (2019)



Resonant and non-resonant contributions

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

W=1.51 GeV , Q^2=0.65 GeV^2



full JM — ρp — π^+ N(1520)3/2$^-$

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

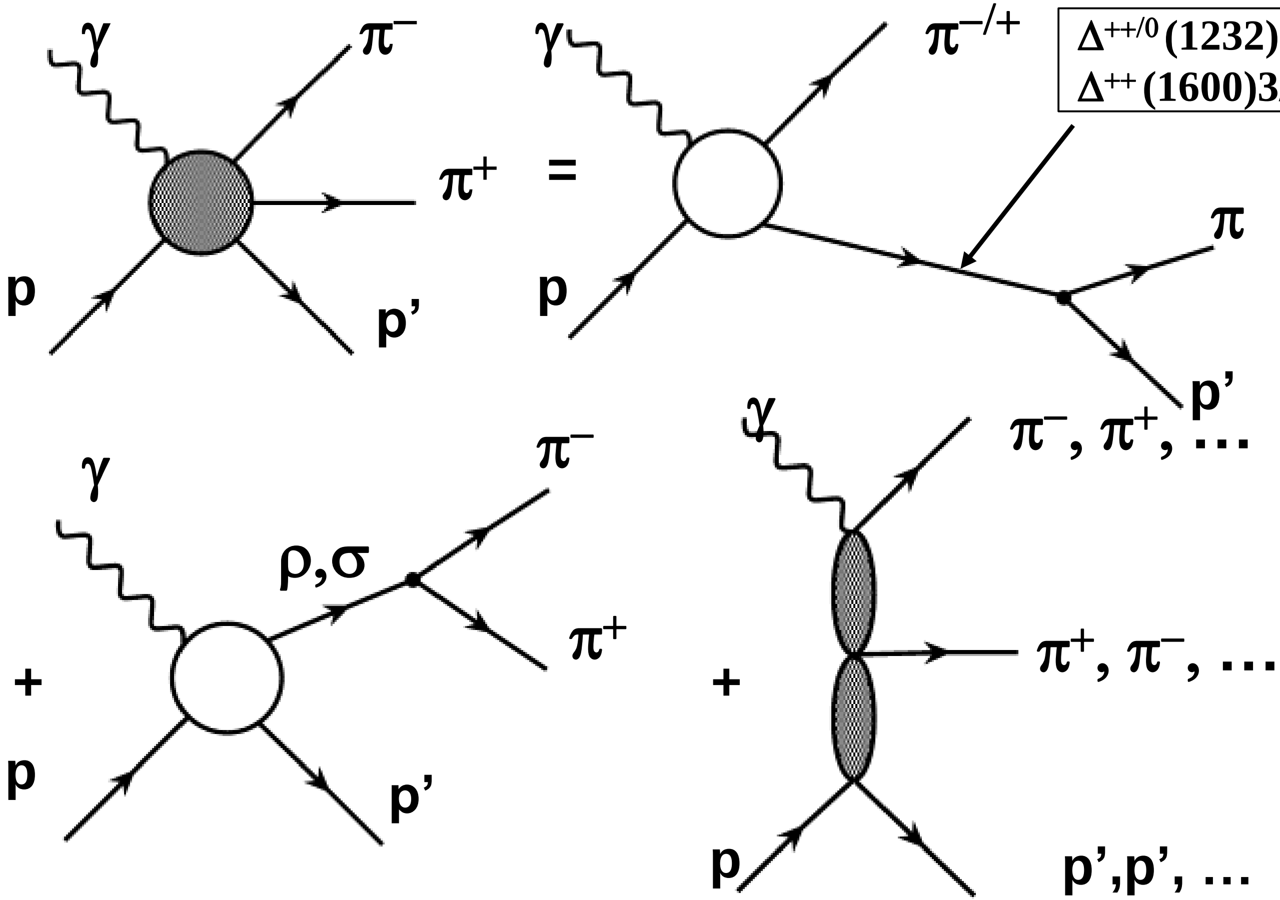
data fit within JM under variations of both resonant and background parameters

background cross sections

resonant cross sections

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 (V.I. Mokeev et al, PR C80, 045212 (2009), PR C86,035203 (2012).

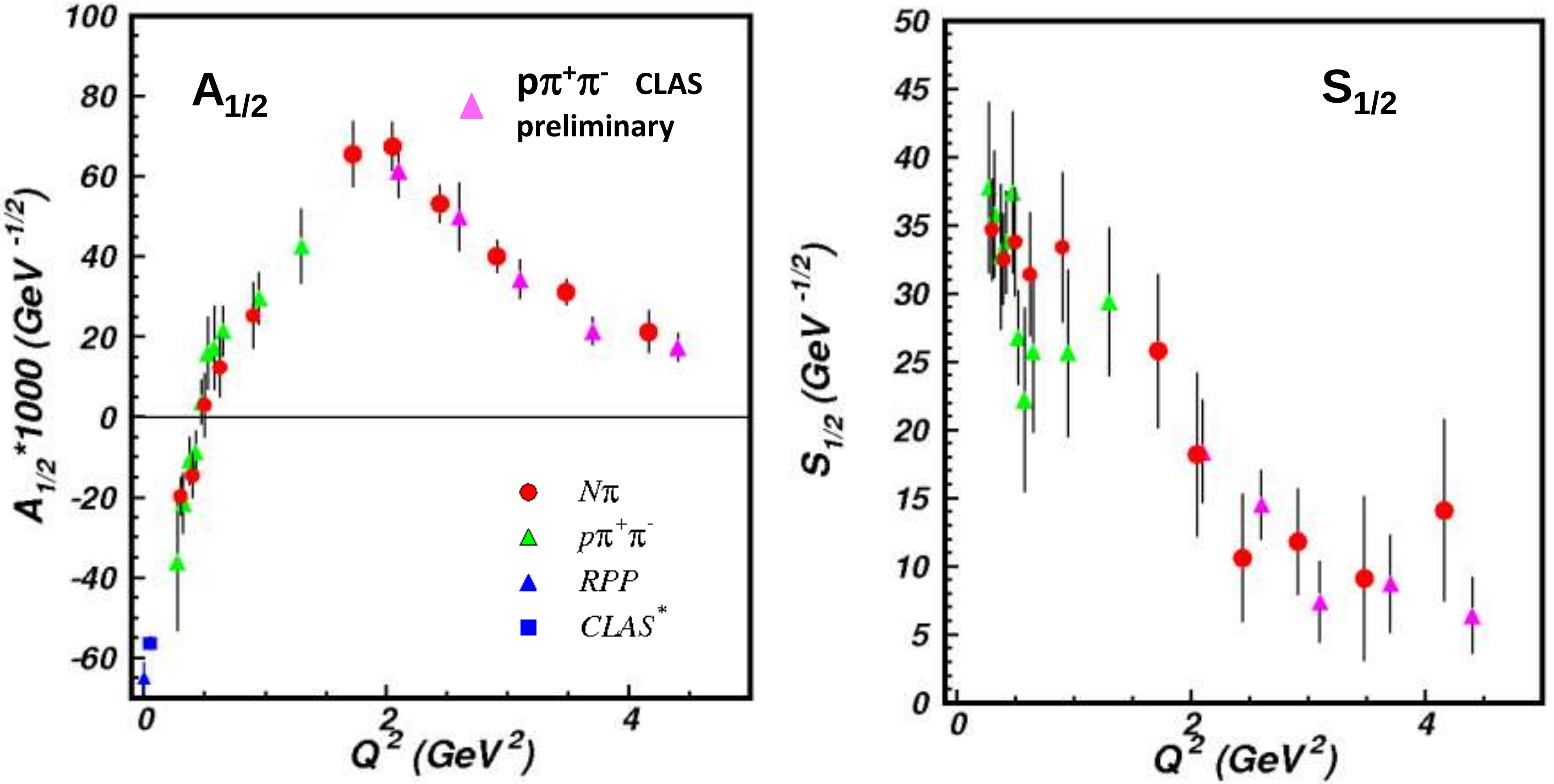


- **five channels with unstable intermediate meson/baryon and direct $\pi^+\pi^-p$ production;**
- **N* contribute to $\pi\Delta$ and ρp channels only;**
- **unitarized Breit-Wigner ansatz for resonant amplitudes;**
- **phenomenological parameterization of the other meson-baryon channel amplitudes**

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

Currently, gvpN* electrocouplings have been determined from the CLAS Nπ and –π+πp electroproduction off proton data in the mass range up to 1.8 GeV and at the photon virtualities up to 5.0 GeV^2. The resonances in the mass range up to 1.6 GeV represent the most explored excited nucleon states. For these resonances electrocouplings have become available from the independent studies of Nπ and –ιπ+πp exclusive channels. In the plots electrocouplinds of Roper resonance are shown. They are available from both the aforementioned exclusive channels in entire Q^2-region up to 5.0 GeV^2. Preliminary results on Roper electrocouplings at $2.0<Q^2<5.0$ GeV^2 were obtained in 2019. The results from both exclusive channels are coincident within their uncertainties.

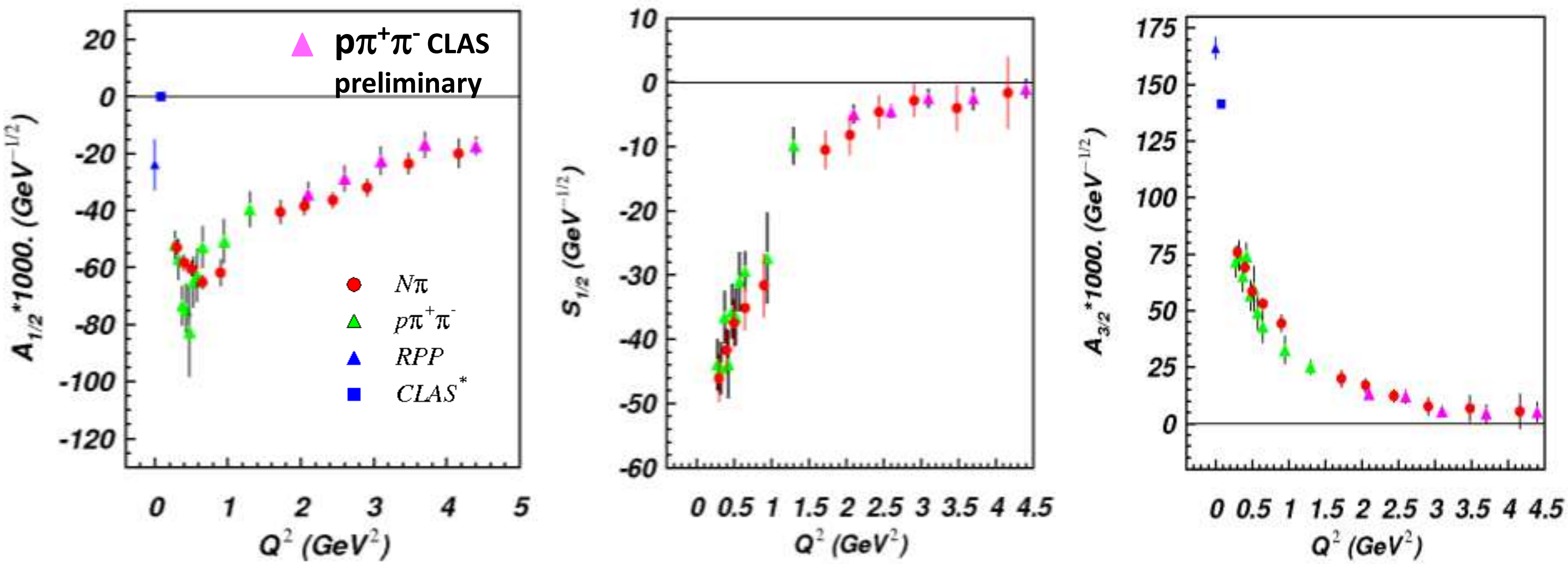
Electrocouplings of N(1440)1/2$^+$ from πN and $\pi^+\pi^-$p Electroproduction off Proton Data



Consistent results on N(1440)1/2$^+$ electrocouplings from independent studies of two major πN 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- resonance are shown in this plot They were determined from independent studies of Nπ and –π+πp electroproduction with coincident from both channels results. The consistent results on electrocouplings of low-lying resonances from independent studies of two major channel in resonance region with entirely different non-resonant contributions strongly support a credible exztraction of these fundamental quantities. This success also demonstrates the capability of the reaction models developed by the CLAS collaboration for a credible extraction of resonance electrocouplings from the independent studies of Nπ and –π+πp electroproduction.

Electrocouplings of N(1520)3/2$^-$ from πN and $\pi^+\pi^-$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.

The experimental results from CLAS on electrocouplings of low-lying resonances have a profound impact on the development of the continuum QCD approaches which are capable to relate the phenomenological information on Q^{2-}evolution of the resonance electrocouplings to the momentum dependence of dressed quark mass M(p). For the first time, elecrocouplings of (Δ1323)3/2+ and N(1440)1/2+ resonances were successfully described at Q^2>2.0 GeV^2 within continuum QCD approaches under a traceable connection to the QCD Lagrangian. Studies of the nucleon resonances with CLAS demonstrated that their structure is coming from a complex interplay between inner core of three constituent quarks and the external meson-baryon cloud. Currently, the continuum QCD approaches account for the contributions from quark core only. Therefore, these approaches can be directly confronted to the data only at higher enough Q^2 where the contributions from quark core become the biggest.

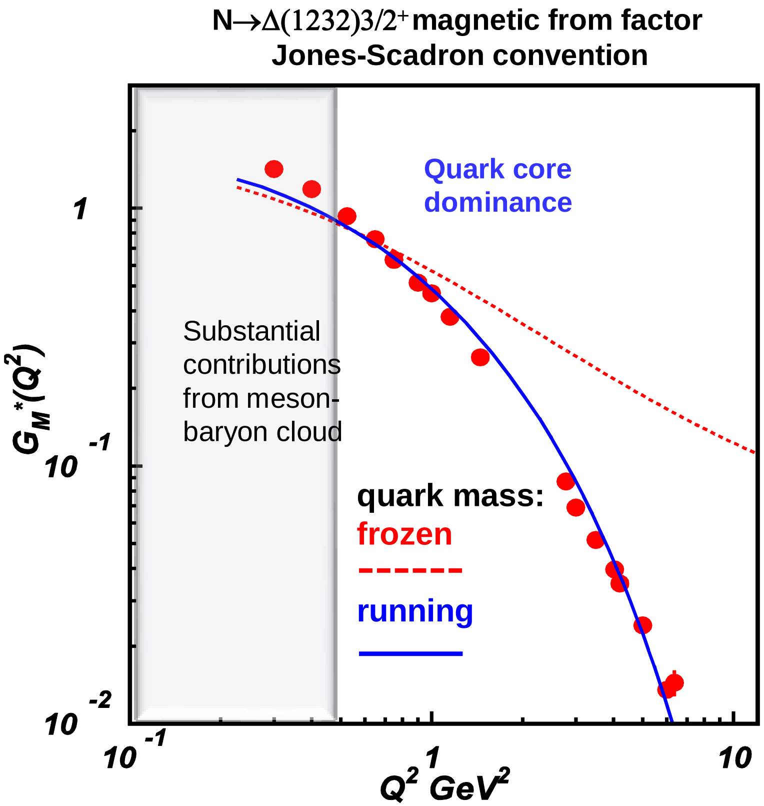
The leading p→Δ magnetic transition form factor (left plot) was computed within continuum QCD by employing the two ansatzs for qq-interaction. In the first exploratory evaluations the simplified contact qq-interaction was used. This interaction results in frozen momentum independent dressed quark mass, however, accounts for the generation of 360 MeV quark mass in the dressing processes. The transition N-→Δ magnetic form factor computed with frozen quark mass is shown in magenta in the left plot. The computation overestimates the data at Q^2>1.0 GeV^2. The discrepancy between the data and computations increases with Q^2. Eventually, contact ansatz for qq interaction has been replaced by the most advances ansatz inferred from the QCD Lagrangian within the continuum QCD approach. This advanced ansatz results in the momentum dependent mass of dressed quark. The N-→Δ magnetic transition form factor computed with running quark mass is shown in the left plot in blue. Use of running quark mass allow us to reproduce the CLAS data in entire range of Q^2>0.8 GeV^2. Analysis of the CLAS results within the continuum QCD approaches conclusively demonstrated that dressed quark mass function is in fact running.

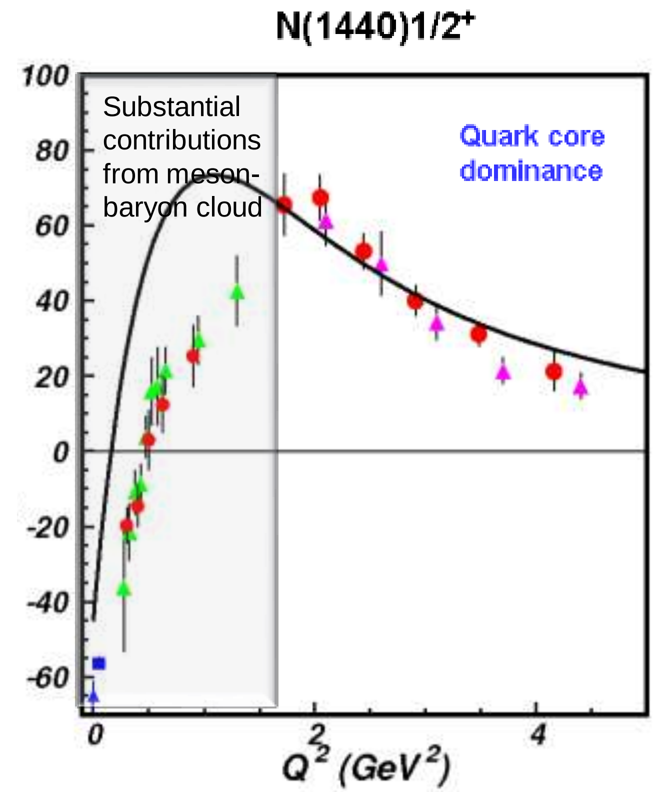
Remarkably, a successful description of Roper resonance electrocouplings (right part) has been achieved with exactly the same dressed quark mass function M(p) as used previously for a successful description of the pion, nucleon elastic form factor and Δ(1322)3/2+ electroexcitation amplitude. The structure of Δ(1323)3/2+ and N(1440)1/2+ resonances are completely different. The Δ(1232)3/2+ state represents the spin-isospin flip of three quarks in the ground nucleons, while N(1440)1/2+ state is the first radial excitation of three dressed quarks. Consistent results on the dressed quark mass function from independent studies of pion/nucleon elastic amplitudes and from the electroexcitation amplitudes of the resonances of distinctively different structure strongly suggests the relevance of dressed quark with running mass computed within continuous QCD approaches as active degrees of freedom in the structure of pion, ground, and excited nucleon states. This success also demonstrated the capability to map out the momentum dependence of dressed quark mass from the experimental results on nucleon elastic form factors and the nucleon resonance electroexcitation amplitudes.

Insight to EHM From Resonance Electrocouplings

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 CLAS data on $\Delta(1232)3/2^+$ electroexcitation demonstrate that dressed quark mass is running with momentum.

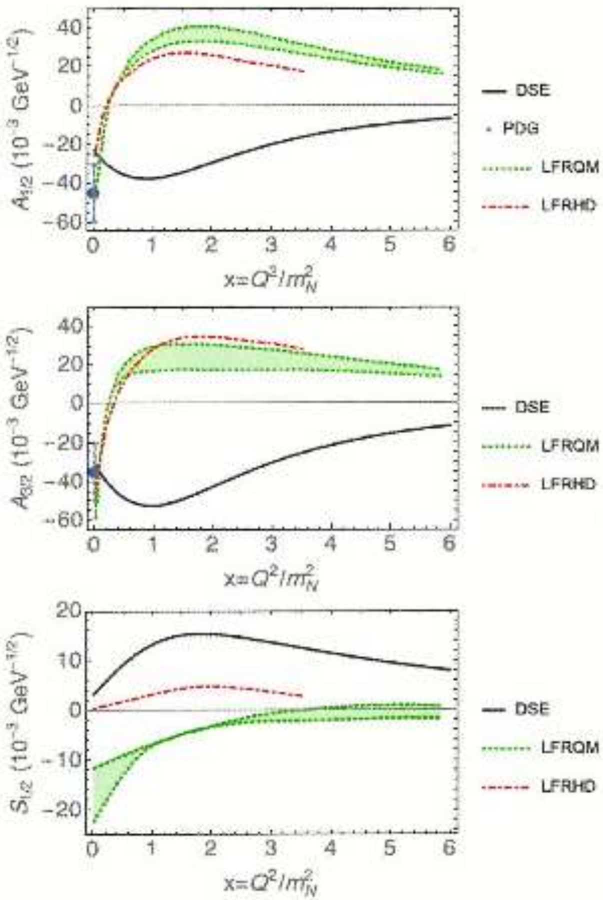
Good data description at Q^2>2.0 GeV^2 achieved with <u>the same dressed quark mass function</u> for the ground and two excited nucleon states of distinctively different structure validate the DSE results on momentum dependence of dressed quark mass. $\gamma_v pN^*$ electrocoupling data offer access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

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

Continnum QCD approaches provided parameter free prediction on (Δ1600)3/2+ electrocopuplings. The CLAS π+π-p electroproduction data at 2.0 < Q^2 < 5.0 GeV^2 (current and next slides) are consistent with the contribution of Δ(1600)3/2+ resonance with electrocouplings predicted within continuum QCD approach. The extraction of these electrocouplings from the data without any model bias is in progress. If expectations from continuum QCD on electrocouplings of this state will be confirmed, the access to dressed quark mass function from the data on resonance electrocouplings will be fully validated.

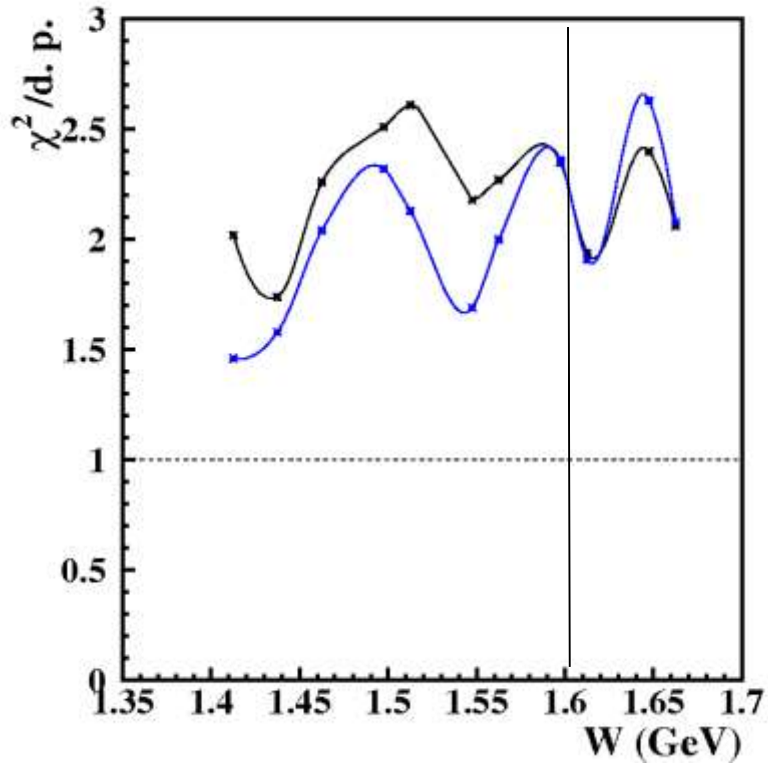
Dressed Quark Mass Function from Electrocouplings of Radial Δ-Excitation

Δ(1600)3/2⁺



Parameter free predictions for Δ(1600)3/2+ electrocouplings Ya Lu et al, Phys. Rev. D100, 034001 (2019)

χ^2/d.p. in all W bin covered by the data at Q^2=3.6 GeV^2



No Δ(1600)3/2⁺

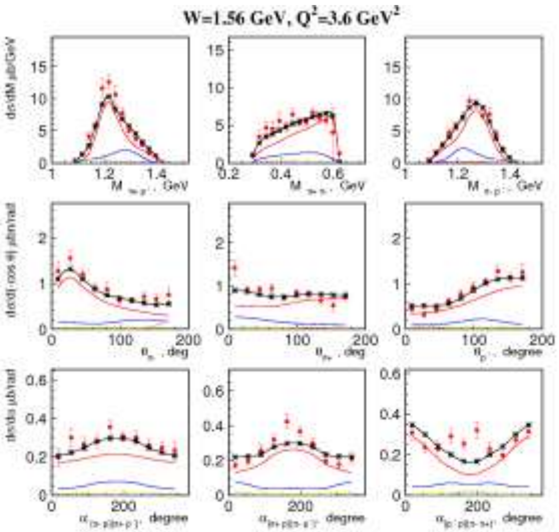
Δ(1600)3/2⁺ included

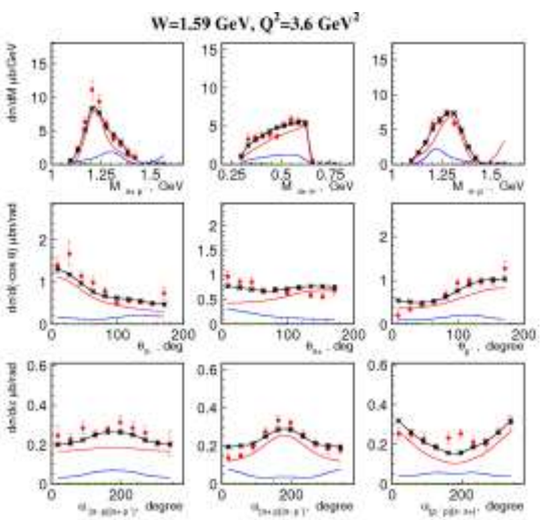
- **CLAS $\pi^+\pi^-p$ electroproduction off protons data at 1.4 GeV < W < 2.0 GeV and 2.0 GeV^2 < Q^2 < 5.0 GeV^2 are consistent with the D(1600)3/2⁺ contribution with electrocouplings predicted by DSE**
- **Δ(1600)3/2⁺ electrocouplings will be extracted soon**
- **Confirmation of the DSE expectations will prove the reliable access to the dressed quark mass function**
- **Studies of [70.1-] orbital excitations is the next step**

Description of the CLAS $\pi^+\pi^-p$ Electroproduction Data at W Near Mass of $\Delta(1600)3/2^+$

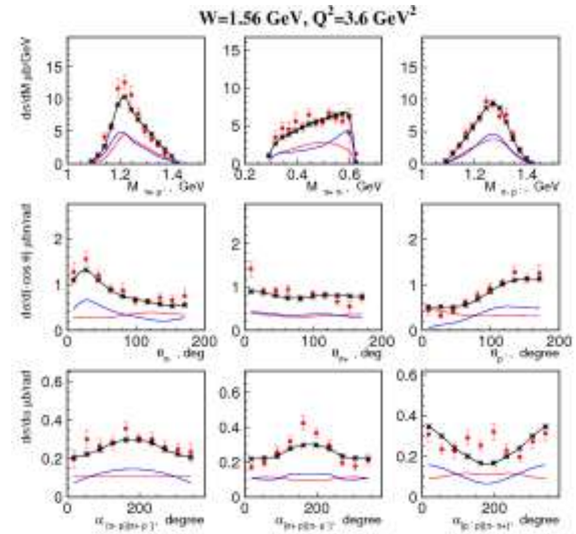
Preliminary CLAS $\pi^+\pi^-p$ electroproduction data,
A.Trivedi, Few Body Syst. 60, 1 (2019)

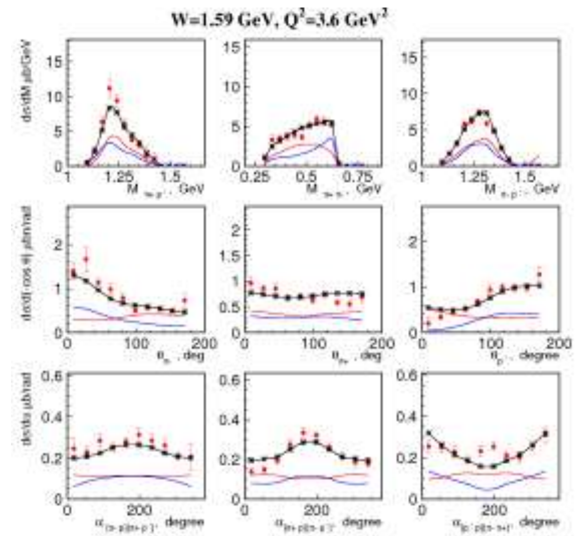
PDG18 parameters of of $\Delta(1600)3/2^+$: M=1.50-1.64 GeV (1.57 GeV central); Γ = 200-300 MeV (250 MeV central); BF($N\pi\pi$)= 73-83 %





full
$\pi^-\Delta^{++}$
$\pi^+\Delta^0$
2π direct
$\pi^+D_{13}(1520)$
π^+F_{15}
ρp





Full.
Resonances
background

Model, gauge and renormalization scheme independent GT relation between a scalar part of dressed quark propagator $B(p^2)$ and the biggest part of the pion BS amplitude $E_\pi(p^2)$ in chiral limit:

$$f_\pi E_\pi(p^2) = B(p^2)$$

- **Consistency between $B(p^2)$ from the dressed quark mass function mapped out from the results on $\gamma_v pN^*$ electrocouplings and the $E_\pi(p^2)$ part of pion BS amplitudes available from the data on pion structure (e.m. form factor & PDF) are critical in order to validate reliable insight into EHM.**

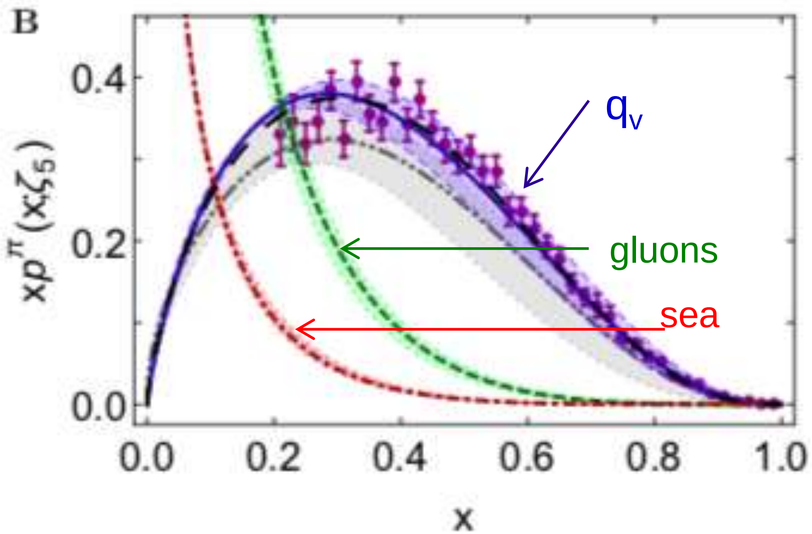
- **Comparison between the data kaon e.m. form factor with the continuum QCD evaluation with light quark mass function from the results on N* electrocouplings will enhance capability to map out strange quark mass function shedding light on the EHM evolution with quark flavor and on the interplay between DCSB and Higgs mechanisms in hadron mass generation.**

With the dressed quark mass function mapped out to nucleon resonance electrocouplings, continuum QCD approaches are able to compute pion/kaon PDFs and elastic form factors. The results are shown in the plot. They can be confronted to the experimental results on the meson structure observables. A successful description of these data will demonstrate relevance of dressed quark with running mass in the structure of both mesons and baryons. Furthermore, the result on kaon structure open up a new avenue on getting insight into the evolution of the hadron mass generation dynamics with the quark flavor

Hadron Mass Generation from the Combined Studies of Pion and N* Structure

A.C. Aguliar et al., Eur. Phys. J A55, 190 (2019)

PDF



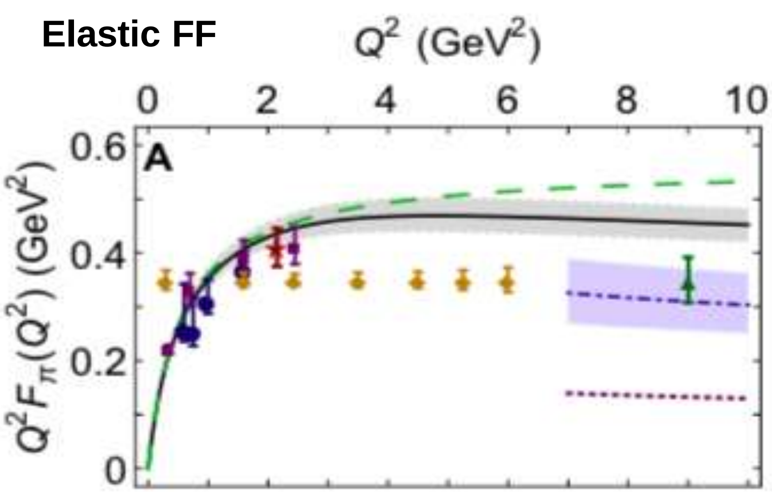
Pion elastic FF and PDF can be computed with exactly the same quark mass function as established from $\gamma_v pN^*$ electrocoupling results and confronted to the data

Strong sensitivity to momentum dependence of dressed quark mass

Pion PDF would be x-independent for frozen quark mass

Essential difference for computed pion elastic form factor with frozen/running quark mass

Elastic FF



DSEQCD:
Full

Hard*soft part factorization with PDF:
for pQCD frozen quark mass

for running quark mass

Conclusions and Outlook

- **High quality meson 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.**

- **<u>Profound impact on the exploration of the hadron mass generation:</u>**
  a) first continuum QCD evaluations of $\Delta(1232)3/2^+$, $N(1440)1/2^{+,}$ and $\Delta(1600)3/2^+$ electroexcitation amplitudes with the same dressed quark mass function computed starting from the QCD Lagrangian;
  b) good description of CLAS results on $\Delta(1232)3/2^+$ and $N(1440)1/2^+$ electroexcitation amplitudes *<u>achieved with the same dressed quark mass function</u>* as used previously in successful evaluations of the elastic ground nucleon and pion form factors, validate insight to the dressed quark mass function in a nearly model independent way.

- **The structure of mesons in terms of elastic/transition form factors, PDF, and PDA can be predicted within continuum QCD approaches by employing the dressed quark mass function available from the studies of the ground nucleon/N* structure. These predictions can tested in experiments on meson structure studies, bridging the efforts between meson and baryon sectors in addressing the EHM problem.**

Back Up

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

Independent analyses of different meson electroproduction channels:

- **$\pi^+ n$ and $\pi^0 p$ 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:**

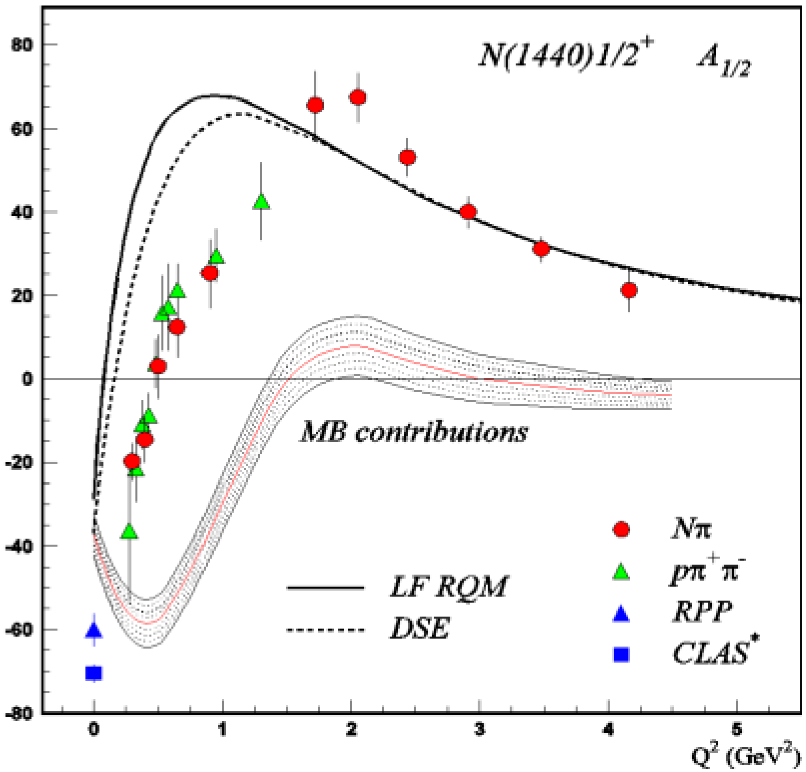
  Data driven JLab-MSU meson-baryon model (JM)

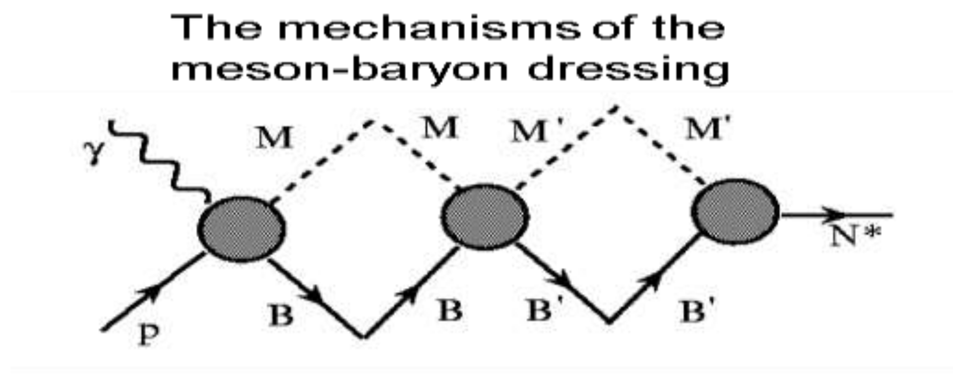
  V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C80, 045212 (2009)
  V.I. Mokeev et al. (CLAS), Phys. Rev. C86, 035203 (2012)
  V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C93, 054016 (2016)

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)

Resolving Puzzle of the Roper Structure





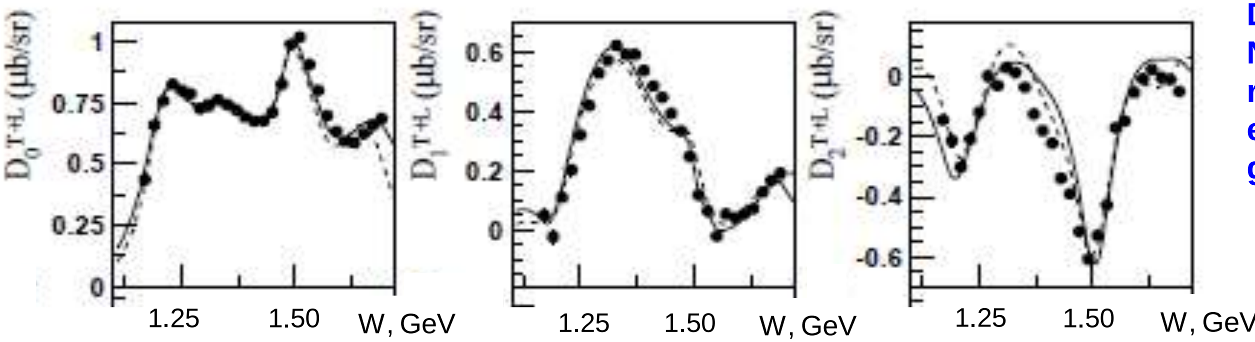
CLAS data in the range of $Q^2<5.0$ GeV^2 reveal the structure of N(1440)1/2$^+$ as a complex interplay between inner core of three dressed quarks in the first radial excitation and external meson-baron (MB) cloud

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

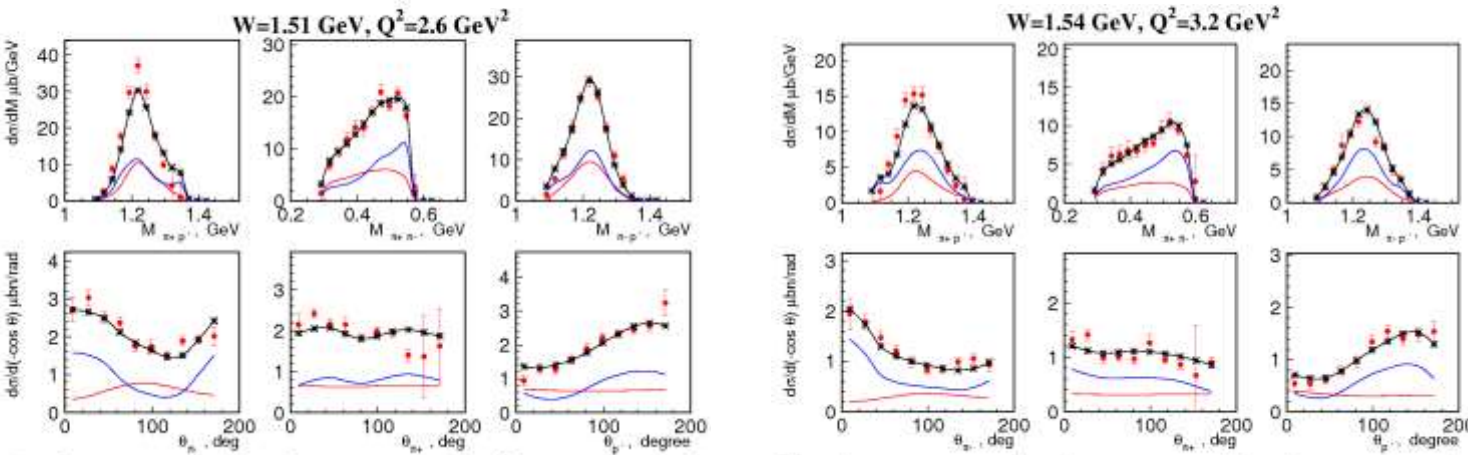
For more details on resolving Roper puzzle see:
V. D. Burkert and C.D. Roberts, Rev. Mod. Phys. 91, 011003 (2019)

Dressed Quark Mass Function from Exclusive Meson Electroproduction off Protons Data



DSE evaluations of N(1520)3/2$^-$ and N(1535)1/2$^-$ electrocouplings represent the next step needed for exploration of hadron mass generation

Legendre moments of unpolarized $\gamma_v p \to \pi^+ n$ cross sections at Q^2=2.44 GeV^2



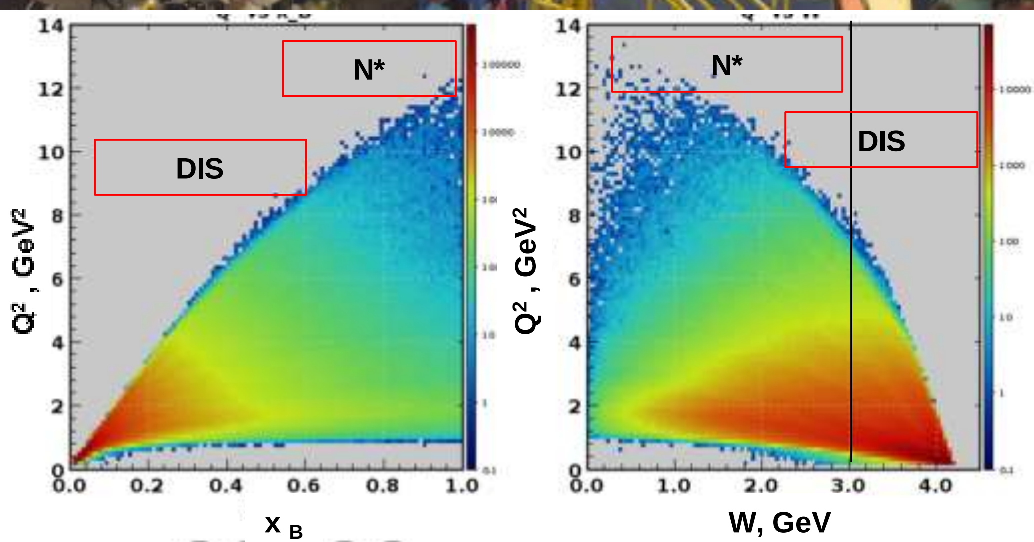
$\gamma_v p \to \pi^+ \pi^- p$

Resonant contributions

Non-resonant contributions

- **The observables of Nπ and $\pi^+\pi^-$p exclusive channels at W<1.55 GeV and 2.0 GeV^2<Q^2< 5.0 GeV^2 will be computed with electrocouplings of four relevant Δ(1232)3/2$^+$, N(1440)1/2$^+$, N(1520)3/2$^-$, and N(1535)1/2$^-$ resonances obtained within DSE by employing a common dressed quark mass function. Mass function parameters will be fit to the data.**

- **Insight to the dressed quark mass function from the Nπ and and $\pi^+\pi^-$p electroproduction observables. The correlations between different resonance electrocouplings imposed by the common quark mass function will be checked against the data for the first time. Successful data description will unambiguously validate credible access to the quark mass function.**



Physics run started successfully in February 2018

CLAS12 N* Program at High Q^2

E12-09-003

Nucleon Resonance Studies with CLAS12

Gothe, Mokeev, Burkert, Cole, Joo, Stoler

E12-06-108A

KY Electroproduction with CLAS12

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, $Q^2 = 3 \rightarrow 12$ GeV^2, $W \rightarrow 3.0$ 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:

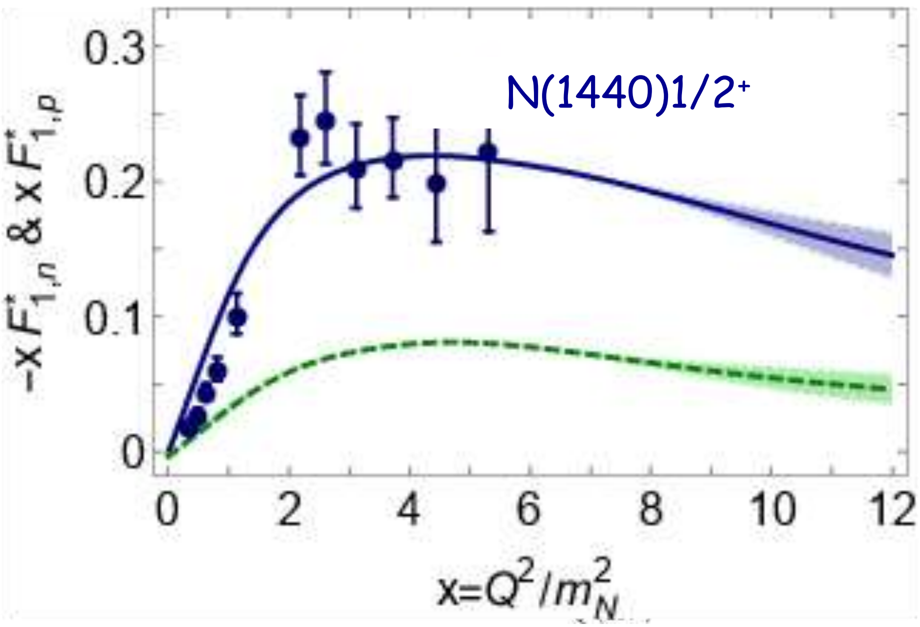
How is >98% of visible mass generated?

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?

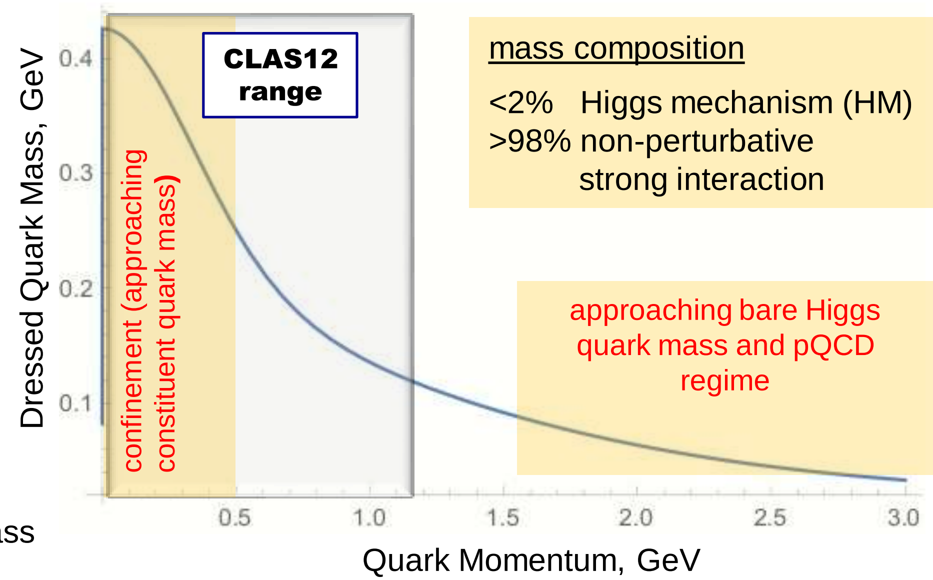
Mapping-out quark mass function from the CLAS12 results on $\gamma_v pN^*$ electrocouplings of spin-isospin flip, radial, and orbital excited nucleon resonances at $5<Q^2<12$ GeV^2 will allow us to explore the transition from strong QCD to pQCD regimes

Ch. Chen et al, Phys.Rev. D99, 034013 (2019)



CLAS results versus theory expectations with running quark mass

Access to the dressed quark/hadron mass generation



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

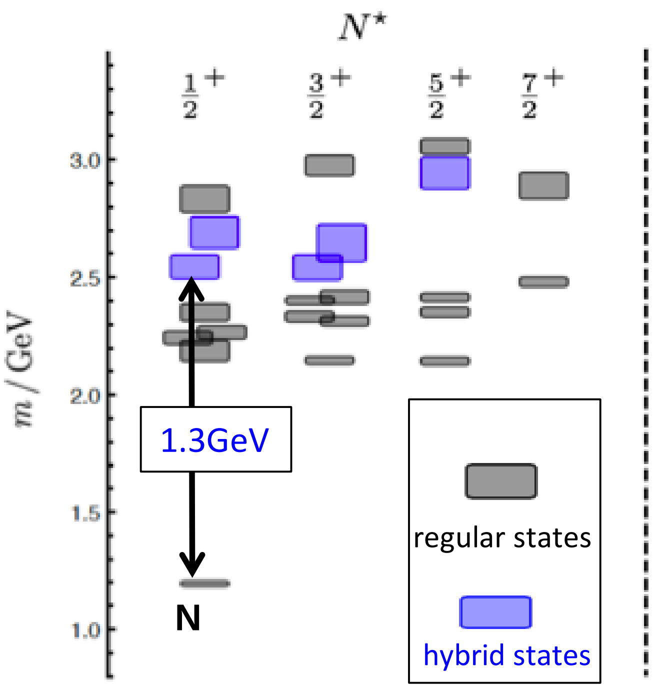
Run Group conditions:
E_b = 6.6 GeV, 50 days
E_b = 8.8 GeV, 50 days

- Polarized electrons, unpolarized LH_2 target
- L = 1×10^{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?

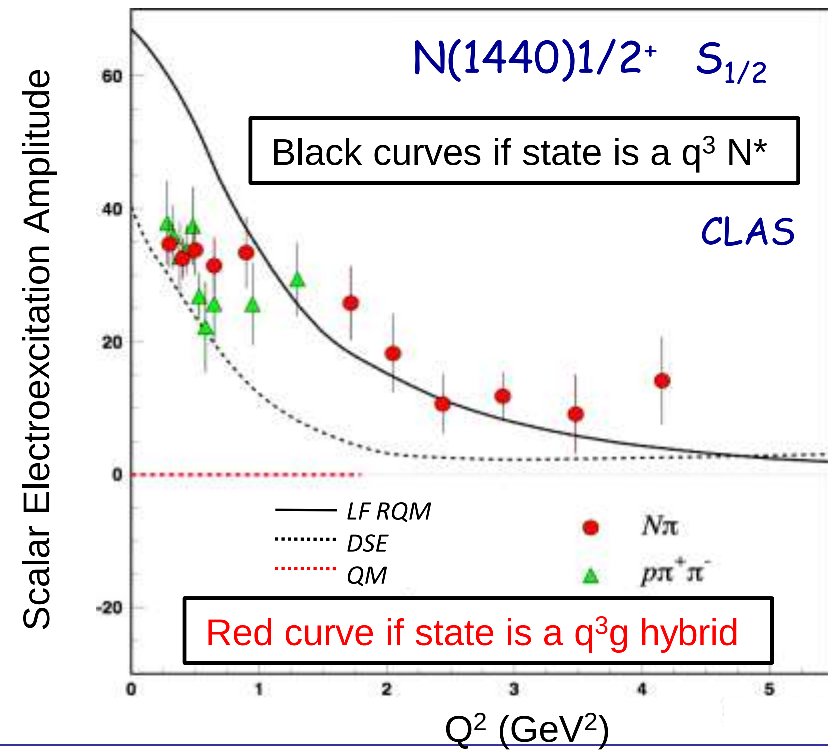
Predictions of the N* spectrum from QCD show both regular q^3 *and* hybrid q^3g states



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



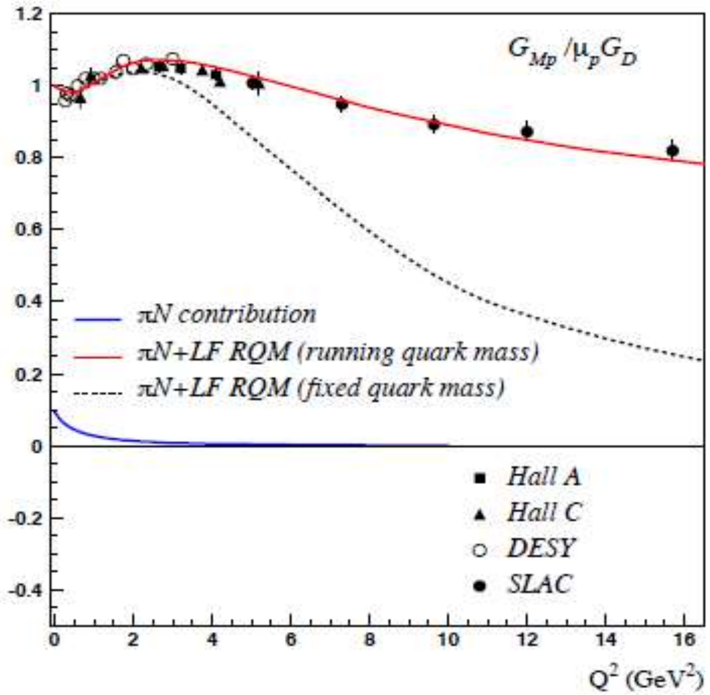
Quark Model with Input from QCD-based Approaches

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