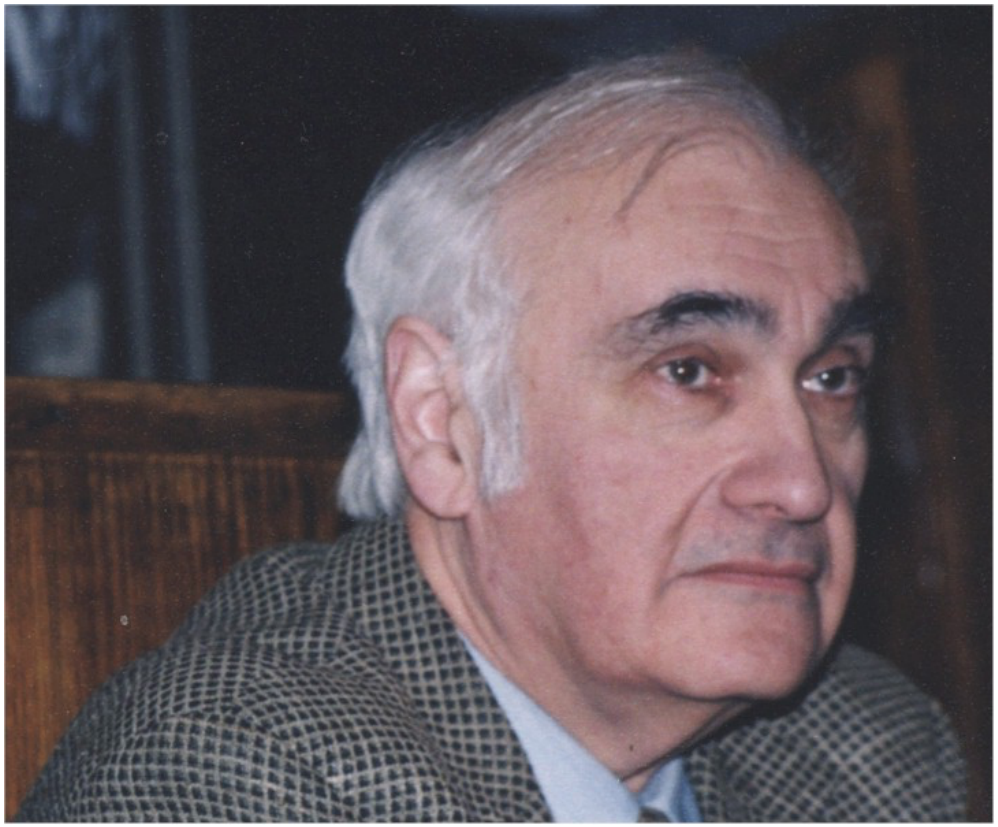
Studies of Nucleon Resonances with Electromagnetic Probes at MSU Under Prof. B.S. Ishkhanov Leadership



Talk outline:

- The scope of collaborative efforts between MSU and Hall B at Jlab.
- New nucleon resonances.
- The N* structure from exclusive meson photo-/ electroproduction.
- Shedding light on the emergence of hadron mass.
- New era in the N* studies with the CLAS12.

V.I. Mokeev, Jefferson Laboratory, for the CLAS Collaboration

Office of Science

Seminar at Skobeltsyn Institute of Nuclear Physics at MSU, December 15, 2020, Moscow

MSU/Hall-B Collaboration: Research Scope

Collaboration Leaders:

Outstanding Scientist of Virginia,
Dr. V.D. Burkert (Jlab)

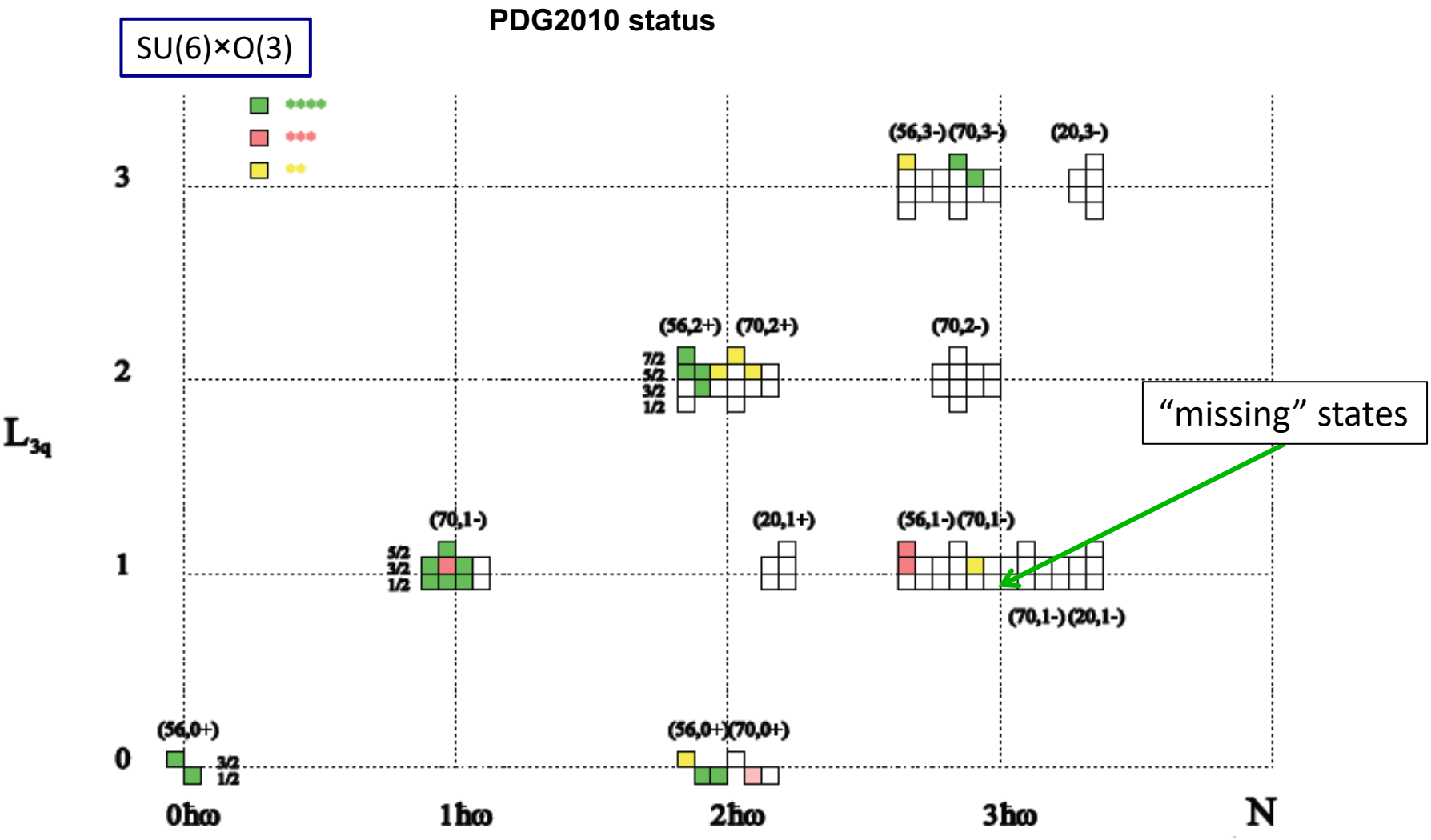
Prof. B.S. Ishkhanov (MSU)

The initial scope:
Studies of the N* spectrum/structure from $\pi^+\pi^-$p photo-/electroproduction with CLAS

Selected achievements

- $\pi^+\pi^-$p photo-/electroproduction cross sections from the CLAS data at W<2.0 GeV and Q^2<5.0 GeV^2 (G.V. Fedotov, E.N. Golovatch, E.L. Isupov, Yu.A. Skorodumina)
- Only available tool for extraction of γ_vpN* electrocouplings from π+π-p photo-/electroproduction data, the JM model was developed (V.D. Burkert, E.N. Golovatch, V.I. Mokeev)
- Discovery of new baryon state N'(1720)3/2$^+$ (V.D. Burkert, E.N. Golovatch, B.S. Ishkhanov, V.I. Mokeev)
- First results on γ_vpN* electrocouplings published, in part, in PDG (V.D.Burkert, B.S. Ishkhanov, V.I.Mokeev)
- Extension of π^0p electroproduction data (E.L. Isupov, N. Markov)
- CLAS Physics Data Base (V. Chesnokov, B.S. Ishkhanov, M.E. Stepanov)
- Predictions on Nπ cross sections from the CLAS data (A. Bulgakov, M. Davydov, A. Nasrtdinov)
- The very first steps in the N* studies with the CLAS12 (A.Bulgakov, A.Golubenko, A.Frolova, E.L. Isupov)

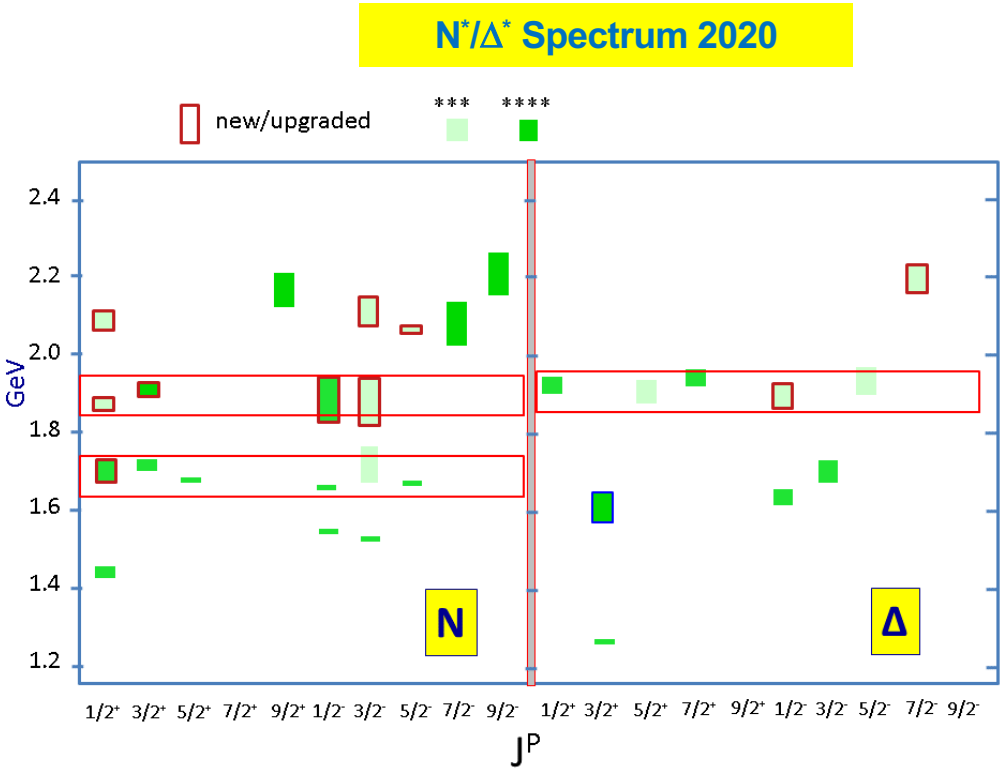
SU(6)xO(3) Spin-Flavor Symmetry and ``Missing" Resonances



Studies of the N*-spectrum were driven by a guess for the ``missing" baryon states expected from underlying SU(6) xO(3) symmetry and supported by LQCD exploratory results on the N*-spectrum.

Advances in Exploration of the N* Spectrum

Several new nucleon resonances were established in a global multi-channel analysis of exclusive photoproduction data



Nucleon resonances listed in Particle Data Group (PDG) tables

State N(mass)J^P	PDG pre 2012	PDG 2020*
N(1710)1/2+	***	****
N(1880)1/2+		***
N(1895)1/2-		****
N(1900)3/2+	**	****
N(1875)3/2-		***
N(2100)1/2+	*	***
N(2120)3/2-		***
N(2000)5/2+	*	**
N(2060)5/2-		***
Δ(1600)3/2+	***	****
Δ(1900)1/2-	**	***
Δ(2200)7/2-	*	***

Description of the exclusive electroproduction data off the proton with the same masses and hadronic decay widths as in photoproduction will validate the existence of new baryon states.

Combined studies of the CLAS $\pi^+\pi^-$p photo-/electroproduction off proton data allow us to observe a new N'(1720)3/2+ baryon state in addition to those listed above.

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

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

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

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

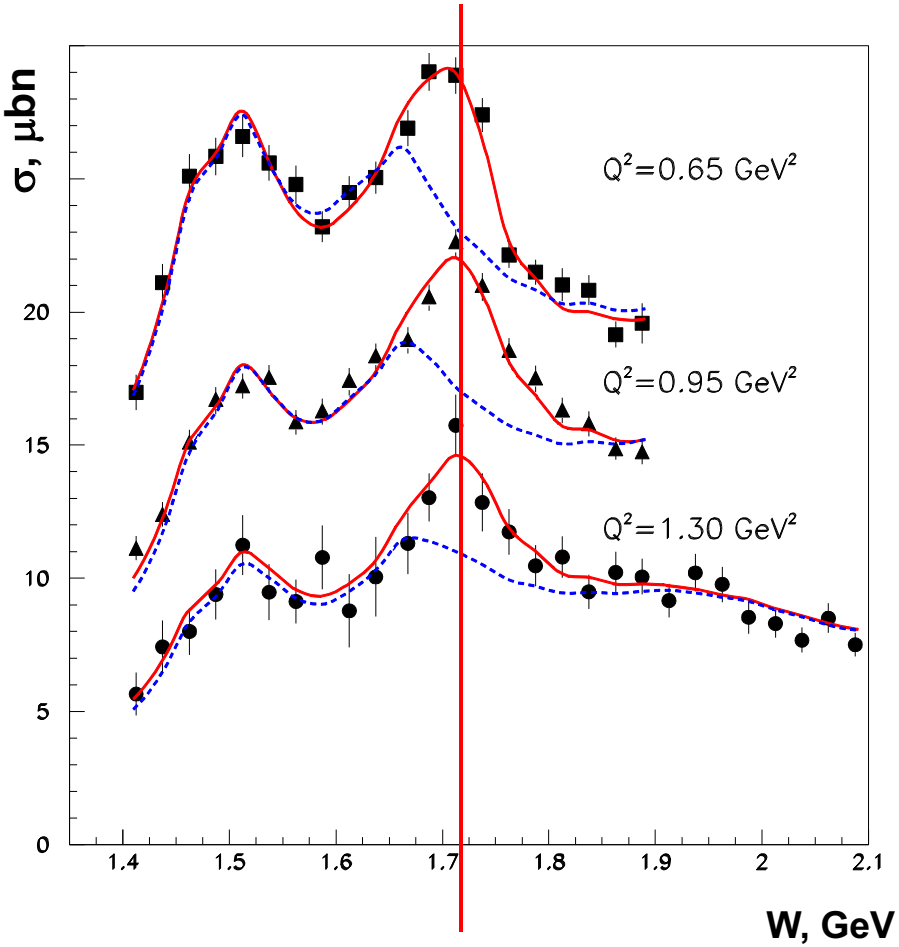
Two equally successful ways for the data description:

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

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

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

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

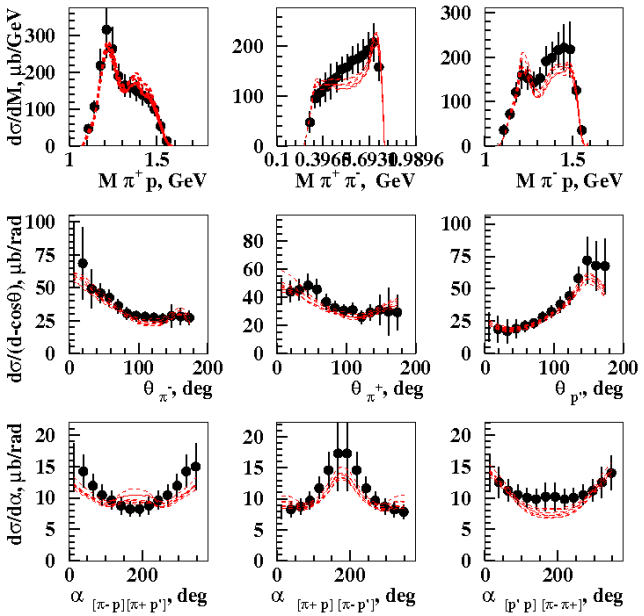


Description of the CLAS $\pi^+\pi^-p$ Photoproduction off Protons Data with/without the New State N'(1720)3/2$^+$

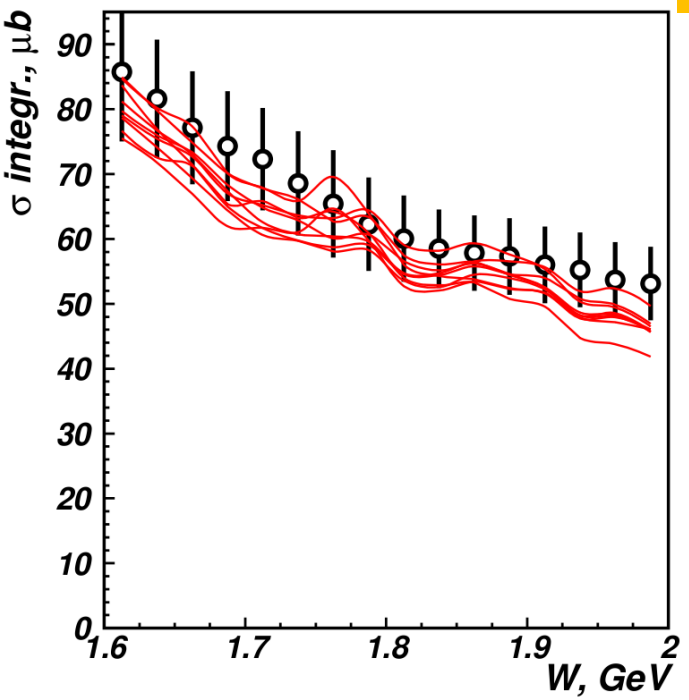
E.N. Golovach et al., CLAS Collaboration, Phys. Lett. B 788, 371 (2019).

One-fold differential cross sections

W=1.71 GeV



Fully integrated cross sections



Almost the same quality of the photoproduction data description was achieved with and without the new N'(1720)3/2$^+$ state:

N(1720)3/2$^+$ and N'(1720)3/2$^+$ ⟶ $1.19 < \chi^2/d.p. < 1.28$

N(1720)3/2$^+$ only ⟶ $1.08 < \chi^2/d.p. < 1.26$

Would it be possible to describe photo- and electroproduction data with Q^2-independent resonance masses and total and partial hadron decay widths?

Evidence for the Existence of the New State N'(1720)3/2$^+$ from Combined $\pi^+\pi^-$p Analyses in both Photo- and Electroproduction

V.I. Mokeev et al., Phys. Lett. B 805, 135457 (2020)

N(1720)3/2$^+$ hadronic decays from the CLAS data fit with conventional resonances only

	BF($\pi\Delta$), %	BF(ρp), %
electroproduction	64-100	<5
photoproduction	14-60	19-69

The contradictory BF values for N(1720)3/2$^+$ decays to the $\pi\Delta$ and ρp final states deduced from photo- and electroproduction data make it impossible to describe the data with conventional states only.

N* hadronic decays from the data fit that incorporates the new N'(1720)3/2$^+$ state

Resonance	BF($\pi\Delta$), %	BF(ρp), %
N'(1720)3/2$^+$ electroproduction photoproduction	 47-64 46-62	 3-10 4-13
N(1720)3/2$^+$ electroproduction photoproduction	 39-55 38-53	 23-49 31-46
Δ(1700)3/2$^-$ electroproduction photoproduction	 77-95 78-93	 3-5 3-6

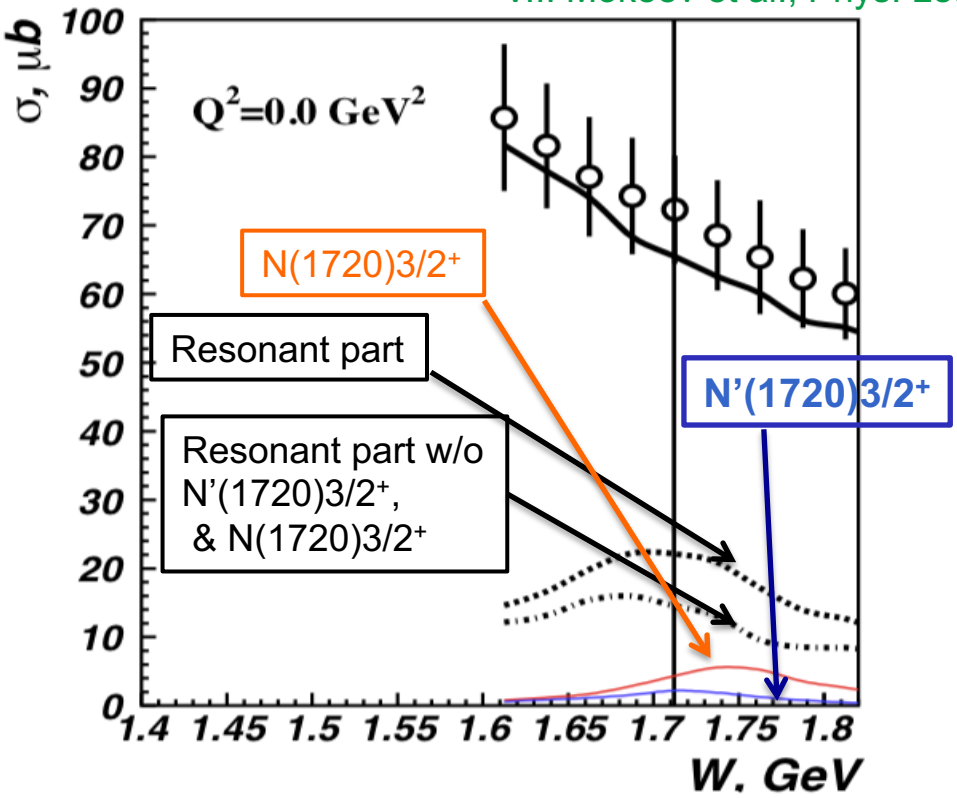
The successful description of the $\pi^+\pi^-$p photo- and electroproduction data achieved by implementing new N'(1720)3/2$^+$ state with Q^2-independent hadronic decay widths of all resonances contributing at W~1.7 GeV provides strong evidence for the existence of the new N'(1720)3/2$^+$ state.

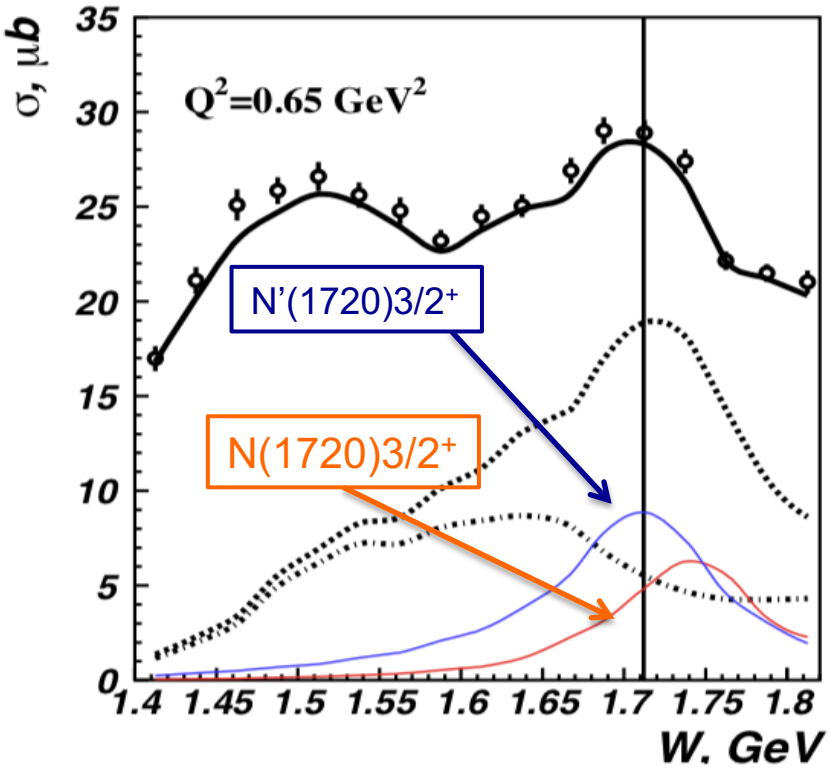
Newly Discovered N'(1720) 3/2$^+$

$\pi^+\pi^-$p photoproduction

$\pi^+\pi^-$p electroproduction

V.I. Mokeev et al., Phys. Lett. B 805, 135457 (2020)

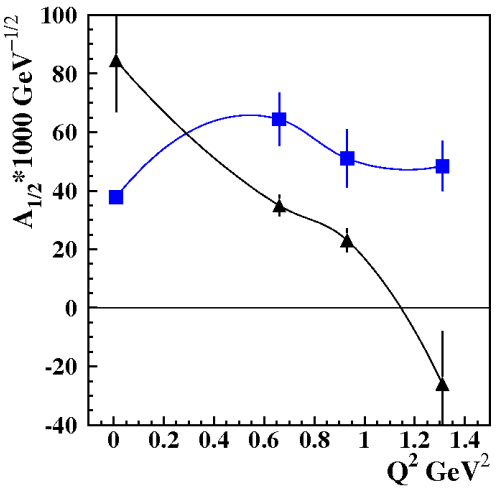


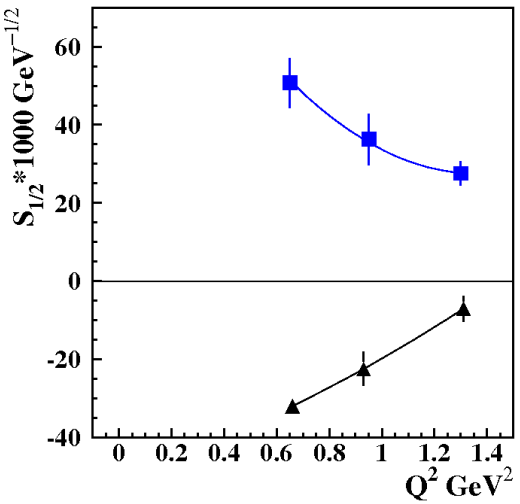


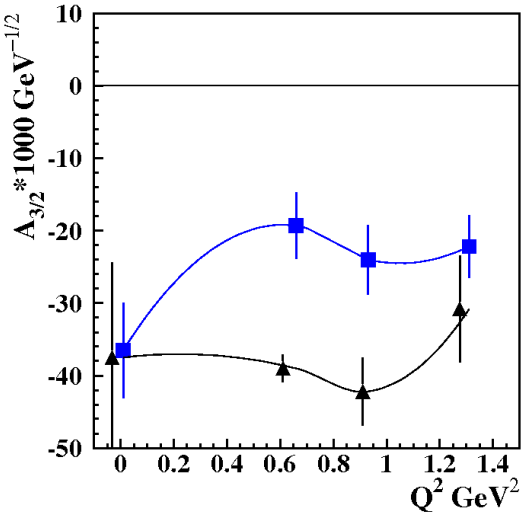
- Evidence of a new N'(1720) 3/2$^+$ resonance from the combined analysis of CLAS photo- and electroproduction of the $\pi^+\pi^-$p channel

The Parameters of the New N'(1720)3/2$^+$ State from the CLAS Data Fit

The photo-/electrocouplings of the N'(1720)3/2$^+$ and conventional N(1720)3/2$^+$ states







N'(1720)3/2$^+$

N(1720)3/2$^+$

Resonance	Mass, GeV	Total width, MeV
N'(1720)3/2$^+$	1.715-1.735	120±6
N(1720)3/2$^+$	1.743-1.753	112±8

- N'(1720)3/2$^+$ is the only new resonance for which data on electroexcitation amplitudes have become available.
- Gaining insight into the ``missing" resonance structure will shed light on their peculiar structural features that have made them so elusive, as well as on the emergence of new resonances from QCD.

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^2 for most excited proton states through analyzing major meson electroproduction channels from CLAS data
- extend accessible Q^2 range within 5.0 $GeV^2 < Q^2 < 12$ GeV^2 and down to 0.05 GeV^2 from CLAS12 data
- 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**
- **Allow evaluation of the resonant contributions to inclusive F_1, F_2, and F_L structure functions from experimental results on $\gamma_v pN^*$ electrocouplings**

References:

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. D.S. Carman, K. Joo, and V.I. Mokeev, Few Body Syst. 61, 29 (2020)
4. A.N. Hiller Blin et al., Phys. Rev. C100, 035201 (2019)

EHM from Studies of the Nucleon and N* Structure

Composition of the Nucleon Mass:

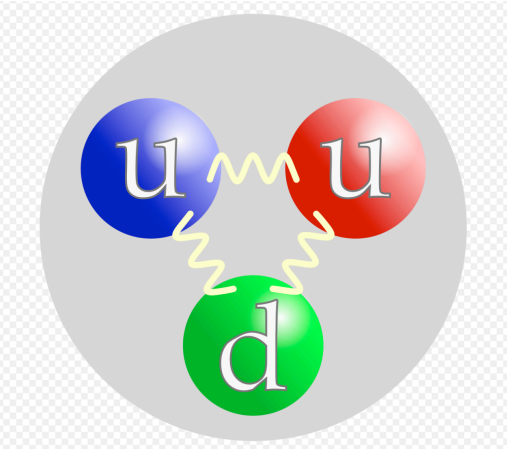
M_p, MeV (PDG20)

938.2720813
±0.0000058

Sum of bare quark masses, MeV

2.16+2.16+4.67
=8.99 or < 1.0%

proton



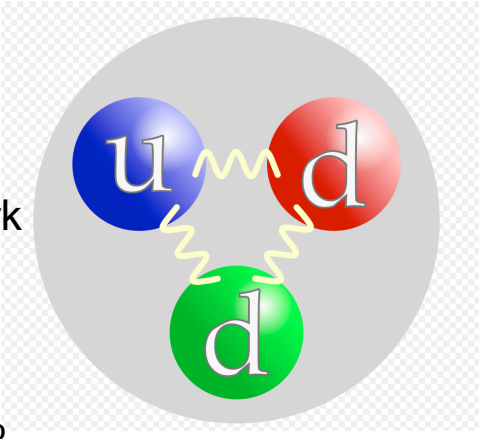
M_n, MeV (PDG20)

939.5654133
±0.0000058

Sum of bare quark masses, MeV

4.67+4.67+2.16
=11.50 or < 1.1%

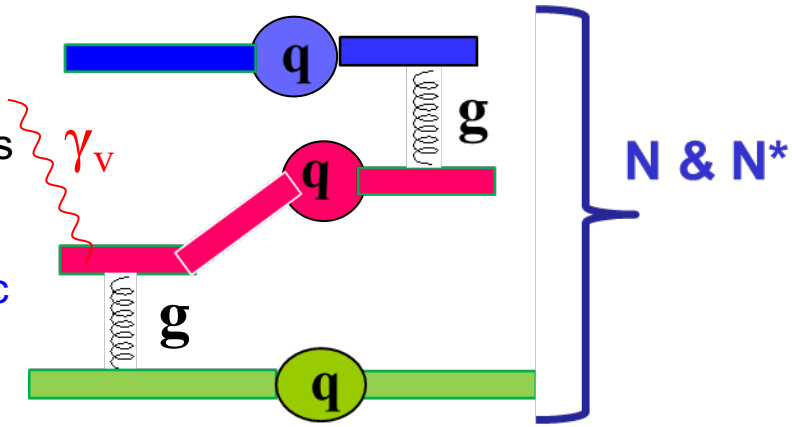
neutron



Dominant part of nucleon mass emerges from strong interaction in the regime when the QCD's process-independent running-coupling becomes comparable with unity.

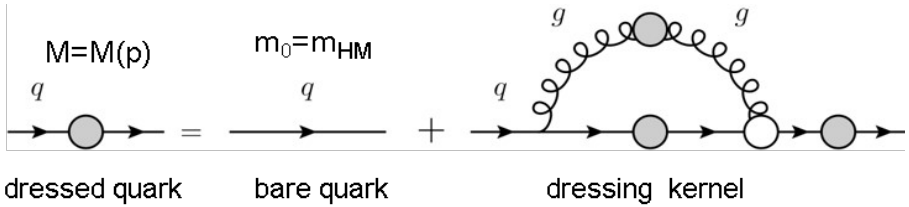
- Elastic/Resonance electroexcitation amplitudes are sensitive to dressed quark propagator allowing us to map-out momentum dependence of dressed quark mass

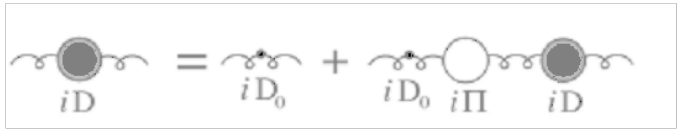
- Consistent results on momentum dependence of dressed quark mass from independent studies of elastic and transition N→N* ff validate credible insight into the hadron mass generation dynamics

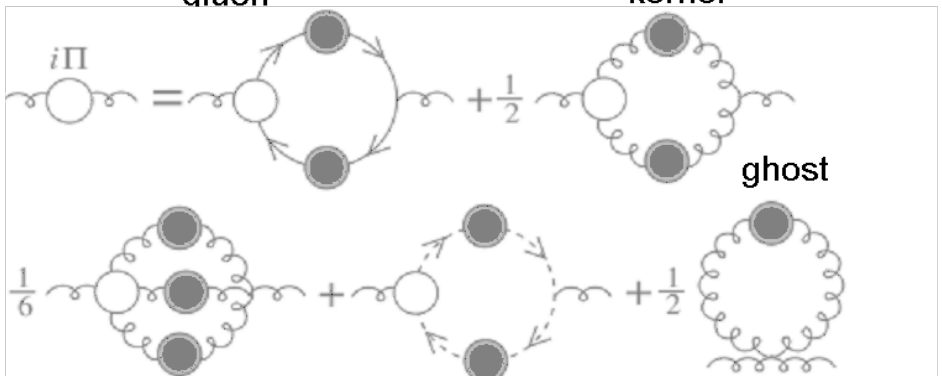


Basics for Insight into EHM

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



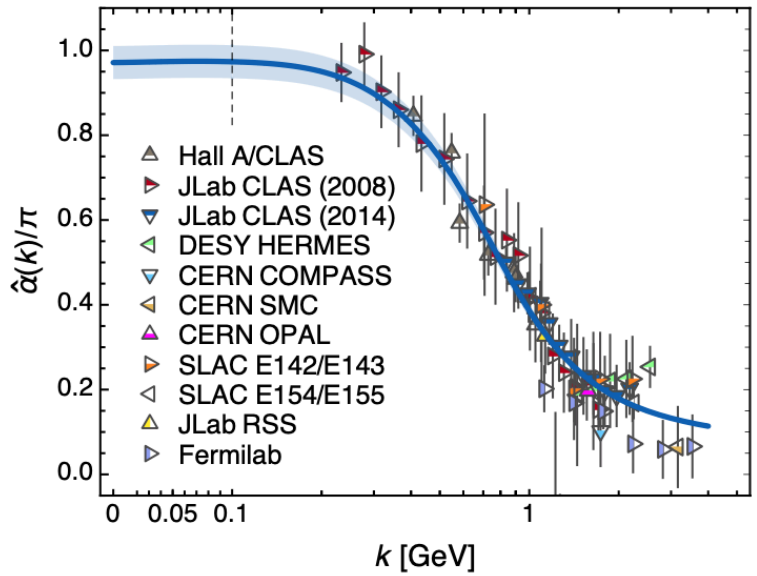


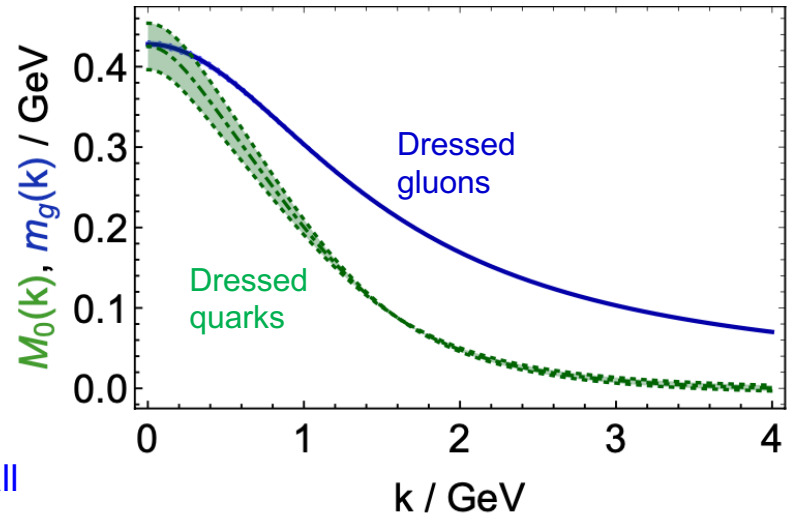


- Dressed quark/gluon masses converge at the complete QCD mass scale of 0.43(1) GeV.

- Momentum-dependent quark/gluon masses shape the ground/ excited hadron structure and constrain the behavior of $\alpha(k)$, making QCD well-defined theory at all distance scales.

QCD running coupling $\alpha(k)$ & dressed quark/gluon masses
C.D. Roberts, NJU-INP 029/20





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

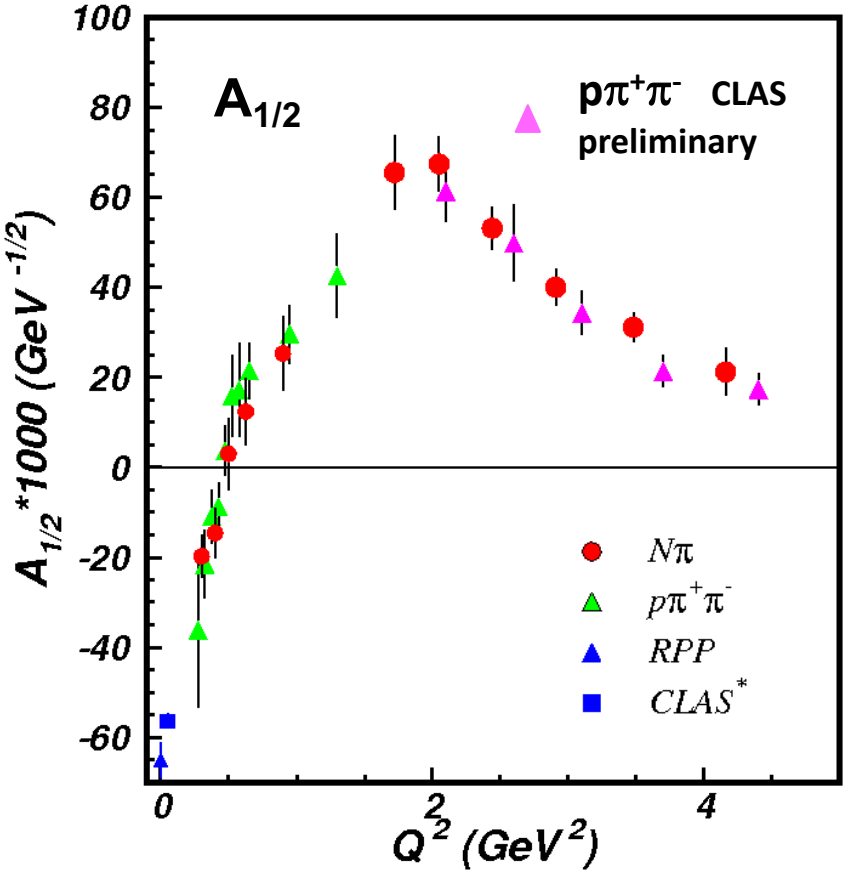
Nucleon Resonance Electrocouplings from Data On Exclusive Meson Electroproduction with CLAS

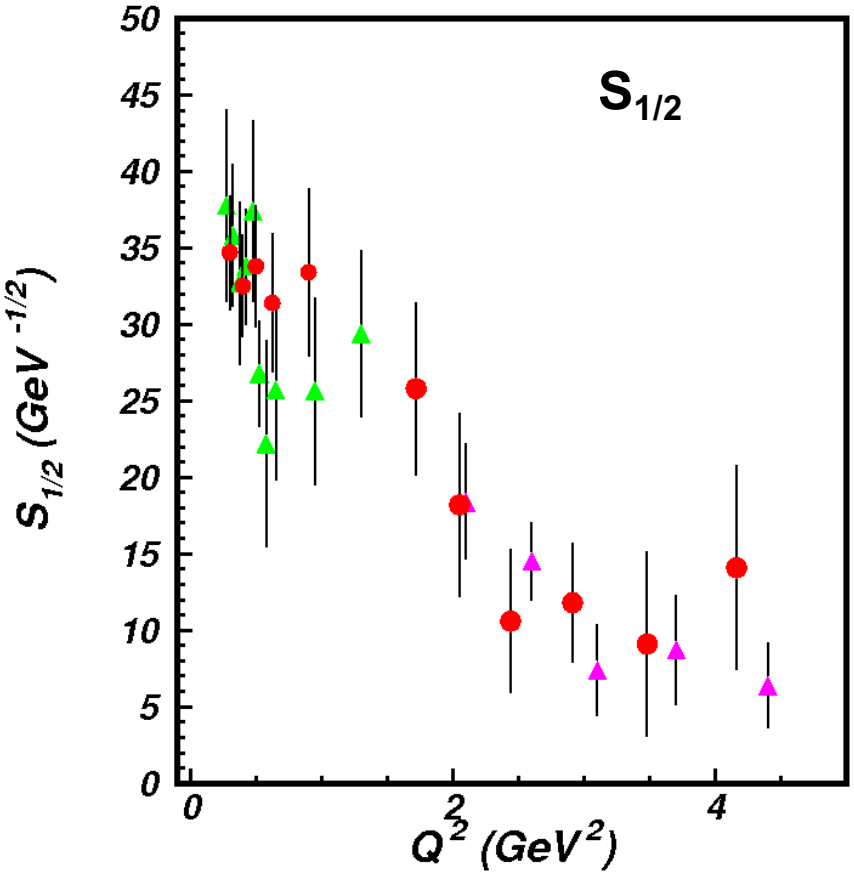
Exclusive meson electroproduction channels	Excited proton states	Q^2-ranges for extracted $\gamma_v pN^*$ electrocouplings, GeV^2
$\pi^0 p$, $\pi^+ n$	$\Delta(1232)3/2^+$ $N(1440)1/2^+$,$N(1520)3/2^-$, $N(1535)1/2^-$	0.16-6.0 0.30-4.16
$\pi^+ n$	$N(1675)5/2^-$, $N(1680)5/2^+$ $N(1710)1/2^+$	1.6-4.5
ηp	$N(1535)1/2^-$	0.2-2.9
$\pi^+\pi^- p$	$N(1440)1/2^+$, $N(1520)3/2^-$ $\Delta(1620)1/2^-$, $N(1650)1/2^-$, $N(1680)5/2^+$, $\Delta(1700)3/2^-$, $N(1720)3/2^+$, $N'(1720)3/2^+$	0.25-1.50 2.0-5.0 (preliminary) 0.5-1.5

The website with numerical results and references:
https://userweb.jlab.org/~mokeev/resonance_electrocouplings/

Interpolation at $0.5\ GeV^2<Q^2<7.0\ GeV^2$ for resonances in the mass range of $W<1.8$ GeV is available in: A.N. Hiller Blin et al., Phys. Rev. C 100, 035201 (2019)

Electrocouplings of N(1440)1/2⁺ from πN and π⁺π⁻p Electroproduction off Proton Data



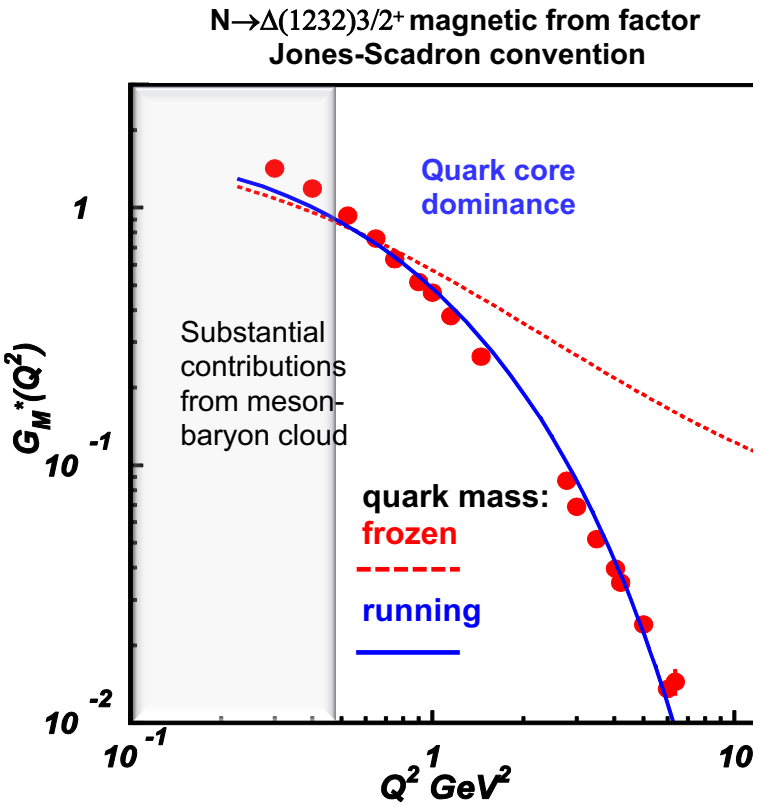


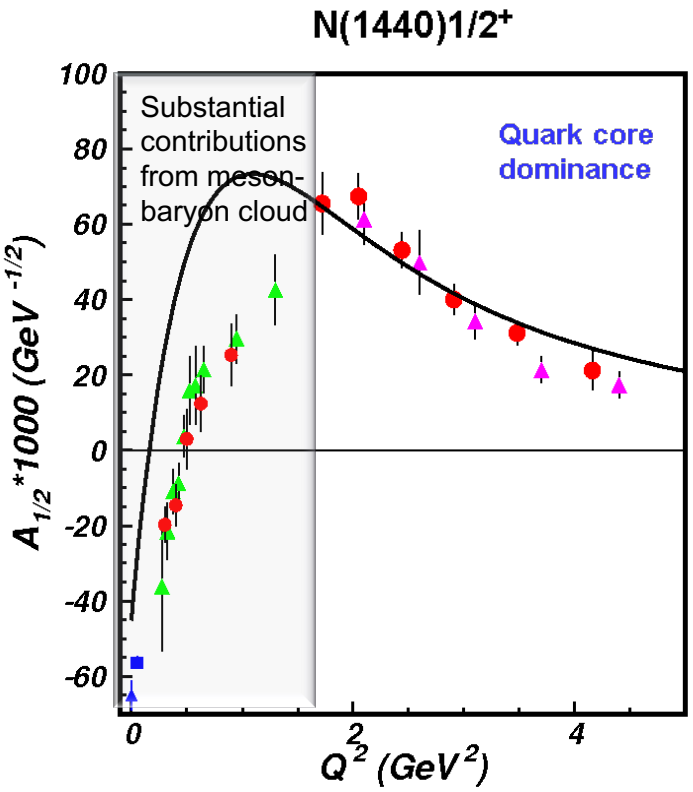
Consistent results on N(1440)1/2⁺ electrocouplings from independent studies of two major πN and π⁺π⁻p electroproduction channels with different non-resonant contributions allow us to evaluate the systematic uncertainties of these quantities in a nearly model-independent way

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)





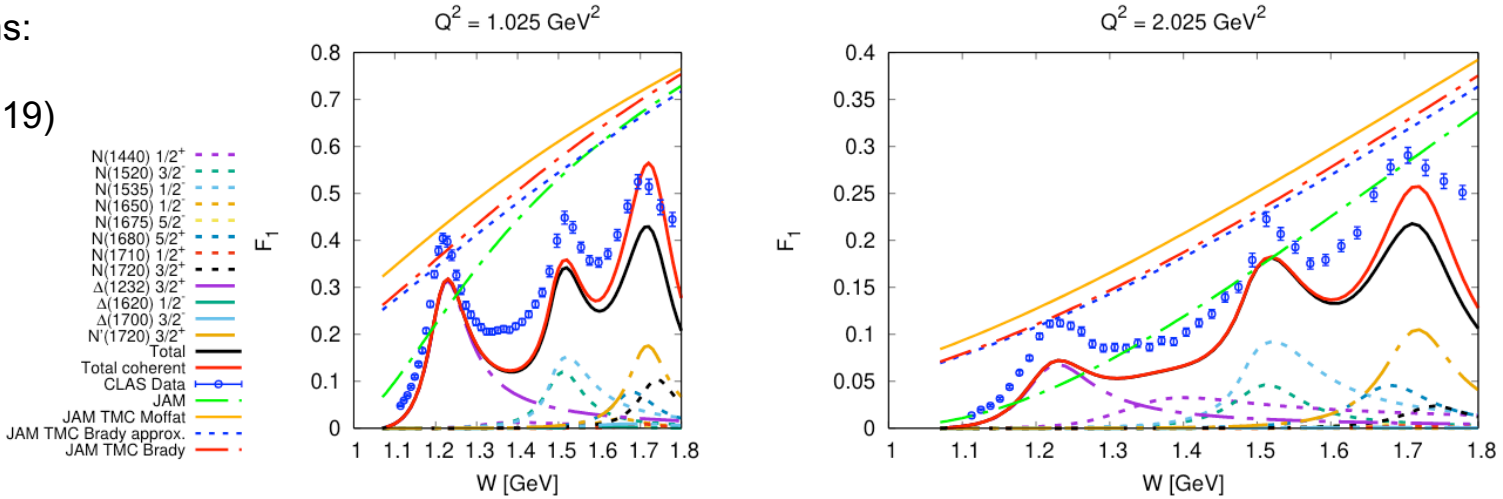
DSE analyses of CLAS data on Δ(1232)3/2⁺ electroexcitation demonstrate that dressed quark mass runs with momentum

Good data description at Q^2>2.0 GeV^2 achieved with the same dressed quark mass function for the ground and two excited nucleon states of distinctively different structure validates 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.

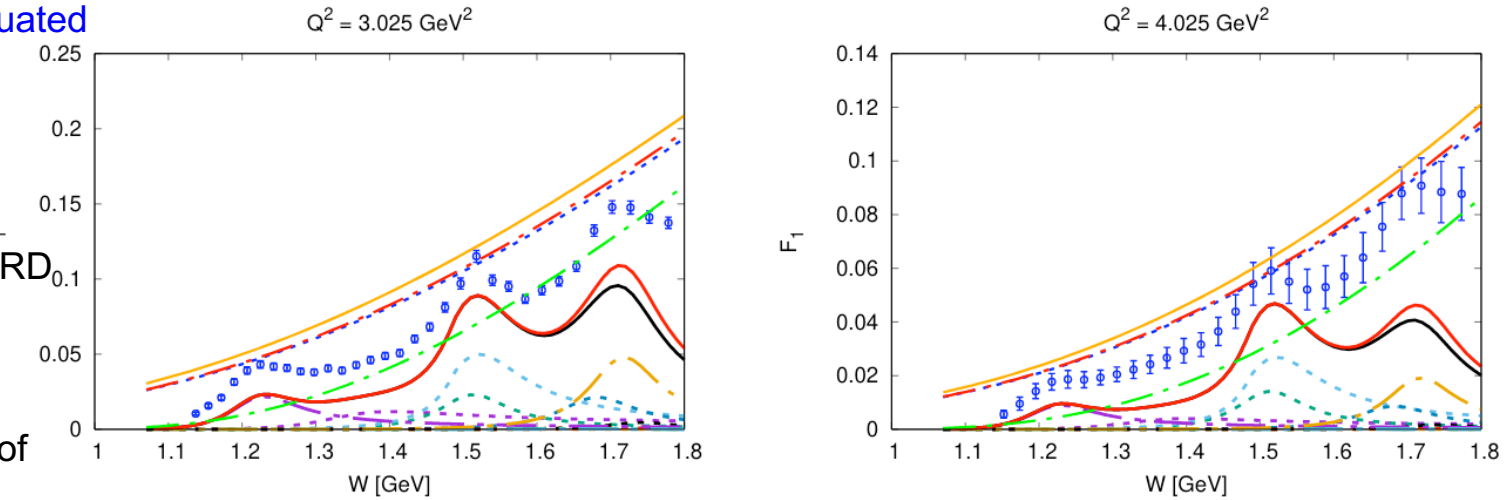
One of the most important achievements in hadron physics of the last decade in synergistic efforts between experimentalists, phenomenologists, and theorists

Resonant Contributions into Inclusive $F_1(W,Q^2)$ Structure Functions & the Contributions from the PDF in the Ground State of the Nucleon Evaluated from the Data in DIS Region

Resonant contributions:
A.N. Hiller Blin et al.,
PRC 100, 035201 (2019)



Data points are from interpolation of the CLAS results re-evaluated with the σ_L/σ_T ratio from Hall C data

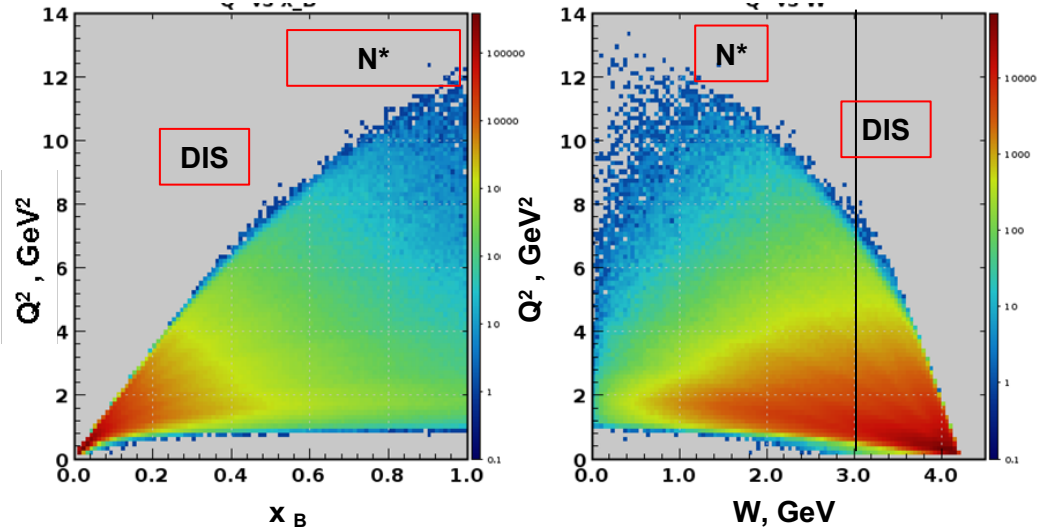


CLAS data:
M. Osipenko et al., PRD 67, 092001 (2003)

Hall C data:
Y. Liang, PhD thesis of American University (2003)

Green dot-dashed lines: F_1 from JAM PDF
Other smooth curves: F_1 from JAM PDF after target mass corrections within different prescriptions

12 GeV Era with the CLAS12 Detector

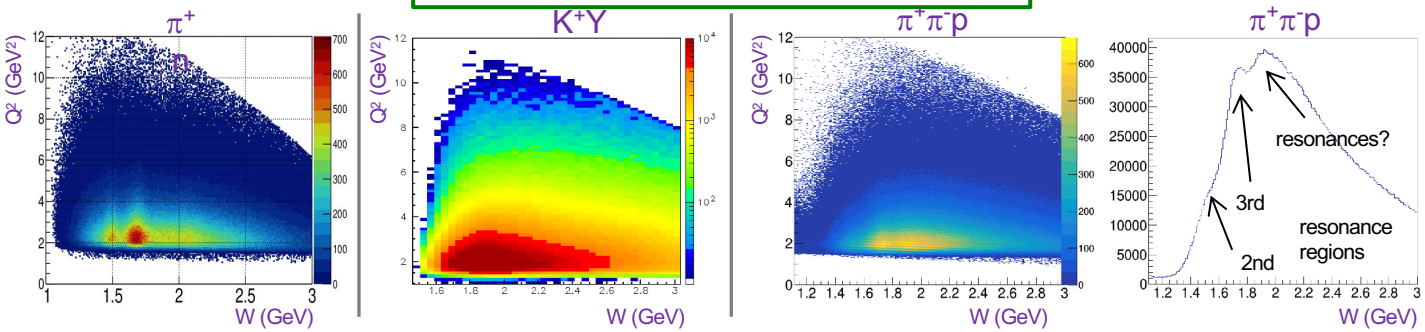


Physics run started successfully in February 2018

N* Electroexcitation to high Q^2 with CLAS12

Expected outcome: The first results on the $\gamma_v pN^*$ electrocouplings of most N* states from data in the range W < 3.0 GeV and Q^2 > 5.0 GeV^2 for exclusive reaction channels: πN, $\pi\pi N$, KY, K*Y, KY*

kinematic coverage for RG-A data @ 10.6 GeV



Expected events per Q^2/W bin for full RG-A dataset

π^+n			$K^+\Lambda$ & $K^+\Sigma^0$					$\pi^+\pi^-p$		
Q^2 [GeV^2]	W [GeV] 1.5-1.55	W [GeV] 1.7-1.75	Q^2 [GeV^2]	W_Λ [GeV] 1.7-1.75	W_Σ [GeV] 1.7-1.75	W_Λ [GeV] 1.9-1.95	W_Σ [GeV] 1.9-1.95	Q^2 [GeV^2]	W [GeV] 1.7-1.75	W [GeV] 1.9-1.95
			1.4-2.2	63417	6012	66564	33170			
			2.2-3.0	72144	5364	77443	28720			
5.2-5.8	15272	4175	3.0-4.0	52358	3945	51991	18936	5.2-5.8	2813	2808
5.8-6.5	10737	2637	4.0-5.0	24833	3103	26690	5925	5.8-6.5	1822	1969
6.5-7.2	7367	1684	5.0-6.0	11203	1598	11160	2642	6.5-7.2	1159	1294
7.2-8.1	4567	1290	6.0-7.0	5566	648	6300	943	7.2-8.1	661	924
8.1-9.1	2742	540	7.0-8.0	2606	338	3276	633	8.1-9.1	364	414
9.1-10.5	1453	194	8.0-9.0	1440	244	936	86	9.1-10.5	118	179

Collecting the remainder of the approved RG-A beam time will give a factor of two more statistics

This will extend the Q^2 range of the $\gamma_v pN^*$ electrocouplings to 8-10 GeV^2 for each of these channels – *the data collected so far will limit us to 6-8 GeV^2*

Emergence of Hadron Mass and Quark-Gluon Confinement

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

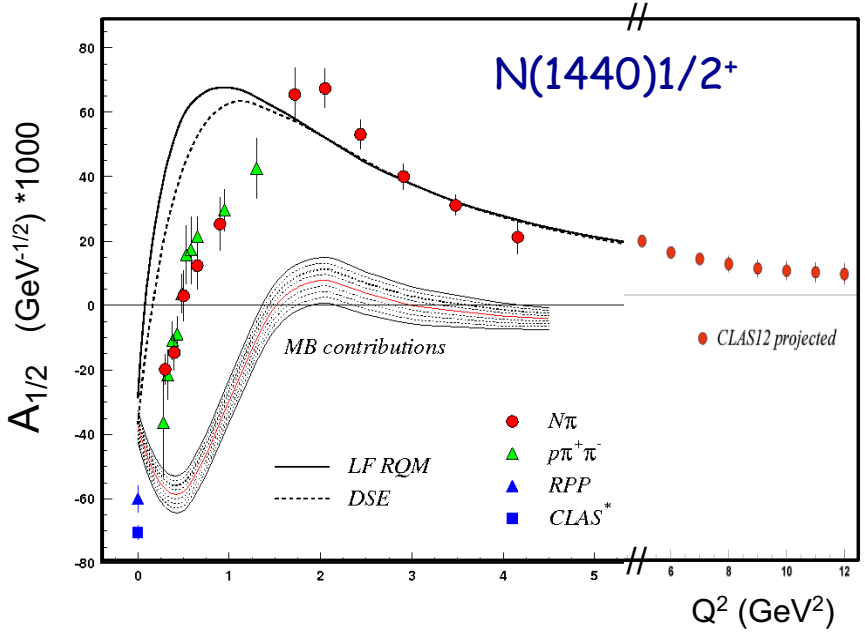
How is >98% of visible mass generated?

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?

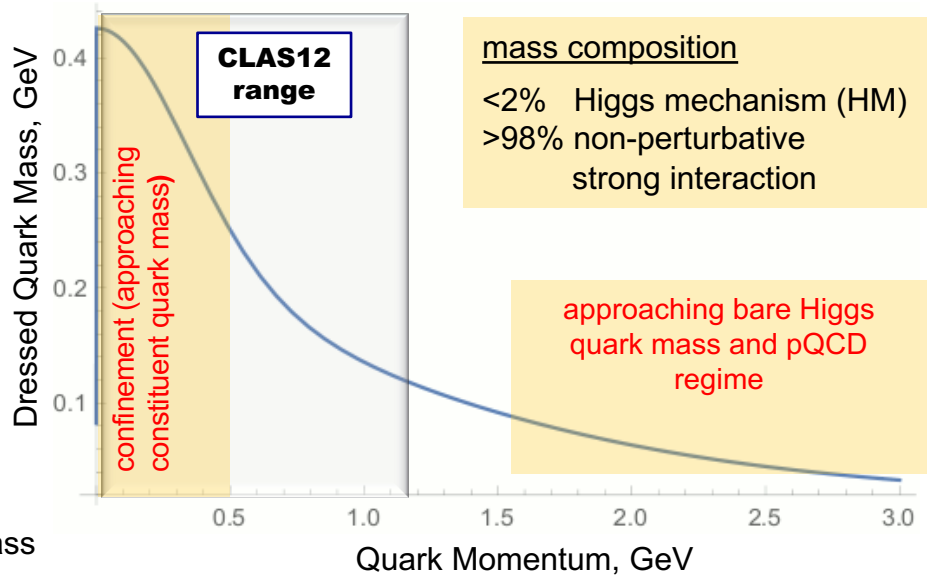
(S.J, Brodsky et al., Int. J. Mod. Phys. Rev. E29, 2030006 (2020))

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



Conclusions and Outlook

- **New scientific direction on exploration of nucleon resonances in experiments with electromagnetic probes has been established at MSU under Prof. B.S. Ishkhanov leadership in collaboration with the Hall B at Jefferson Lab.**

- **New resonance N'(1720)3/2$^+$ has been observed in combined studies of $\pi^+\pi^-$p photo- and electroproduction data with CLAS. N'(1720)3/2$^+$ new state is the only ``missing" resonance for which the results on Q^2-evolution of γ_vpN* electrocouplings have become available. They pave a way for the hybrid baryon search in experiments with the CLAS12.**

- **High quality $\pi^+\pi^-$p electroproduction data by MSU group 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.**

- **A good description of CLAS results on Δ(1232)3/2$^+$ and N(1440)1/2$^+$ electroexcitation amplitudes *achieved with the same dressed quark mass function* as used previously in successful evaluations of the elastic ground nucleon and pion form factors, validate insight to the dynamics which underlie the emergence of hadron mass.**

- **The expected results from CLAS12 will allow us to map out the dressed quark mass function at the distances where the transition from quark-gluon confinement to pQCD regime is expected, addressing the most challenging problems of the Standard Model on the nature hadron mass and of quark-gluon confinement.**

Back Up

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

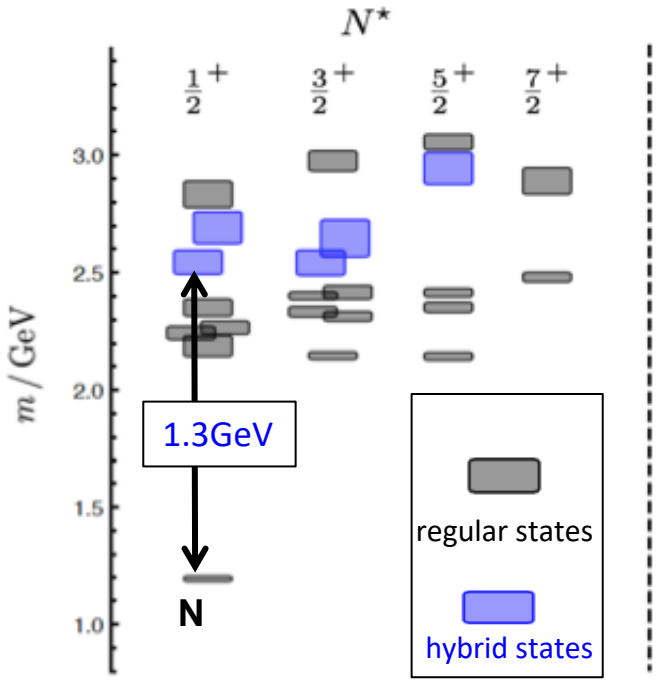
Run Group conditions:
E_b = 6.6 GeV, 50 days
E_b = 8.8 GeV, 50 days

- 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