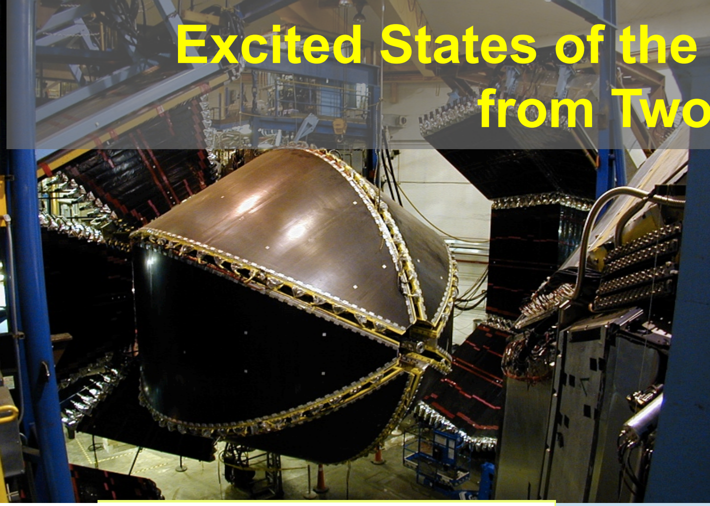
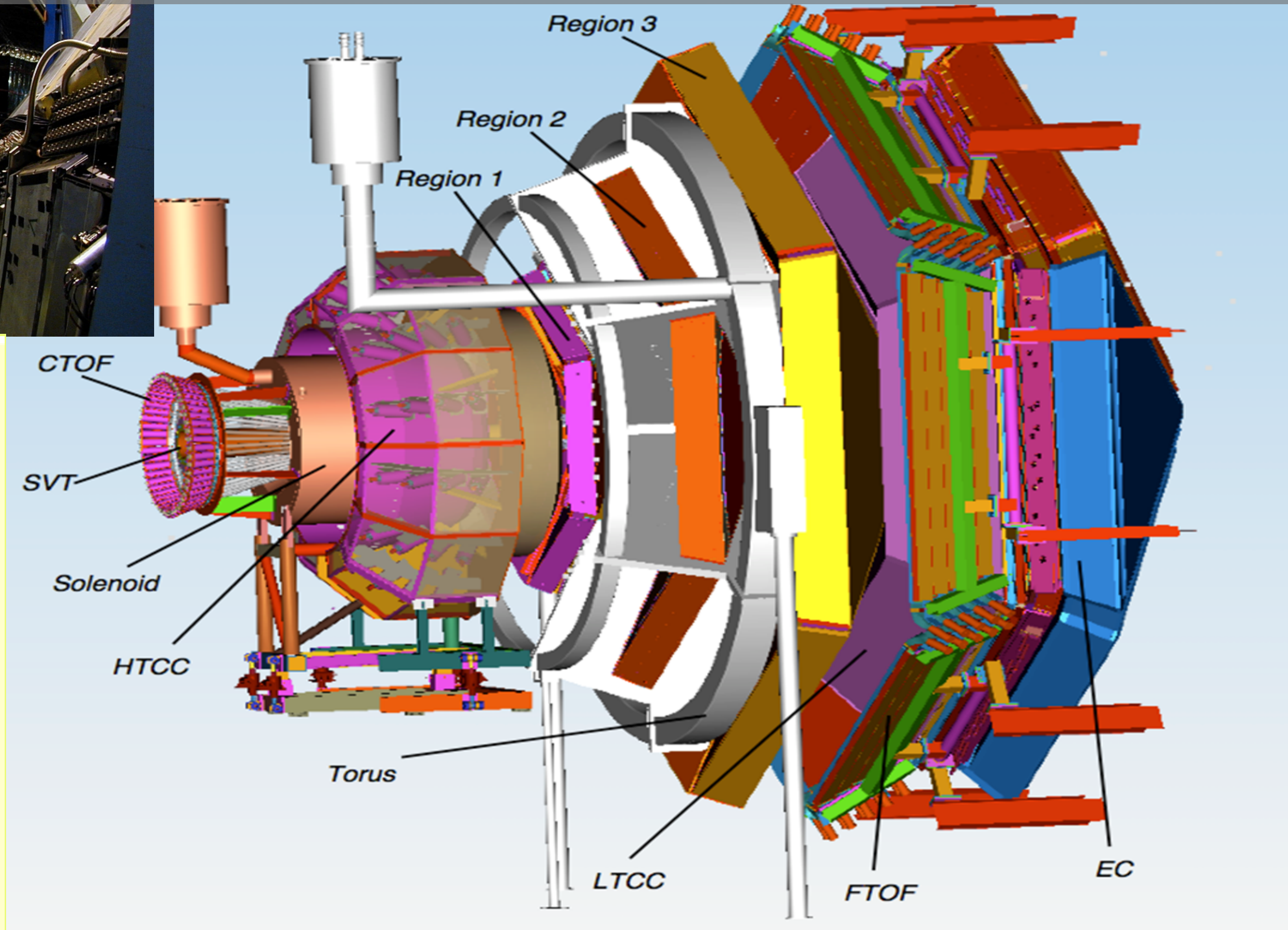
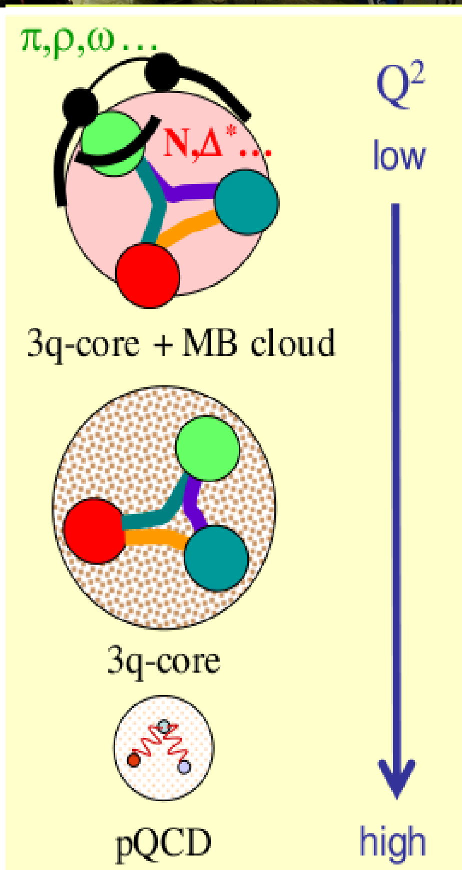
Excited States of the Nucleon and New Resonance Structures from Two-Pion Electroproduction Data







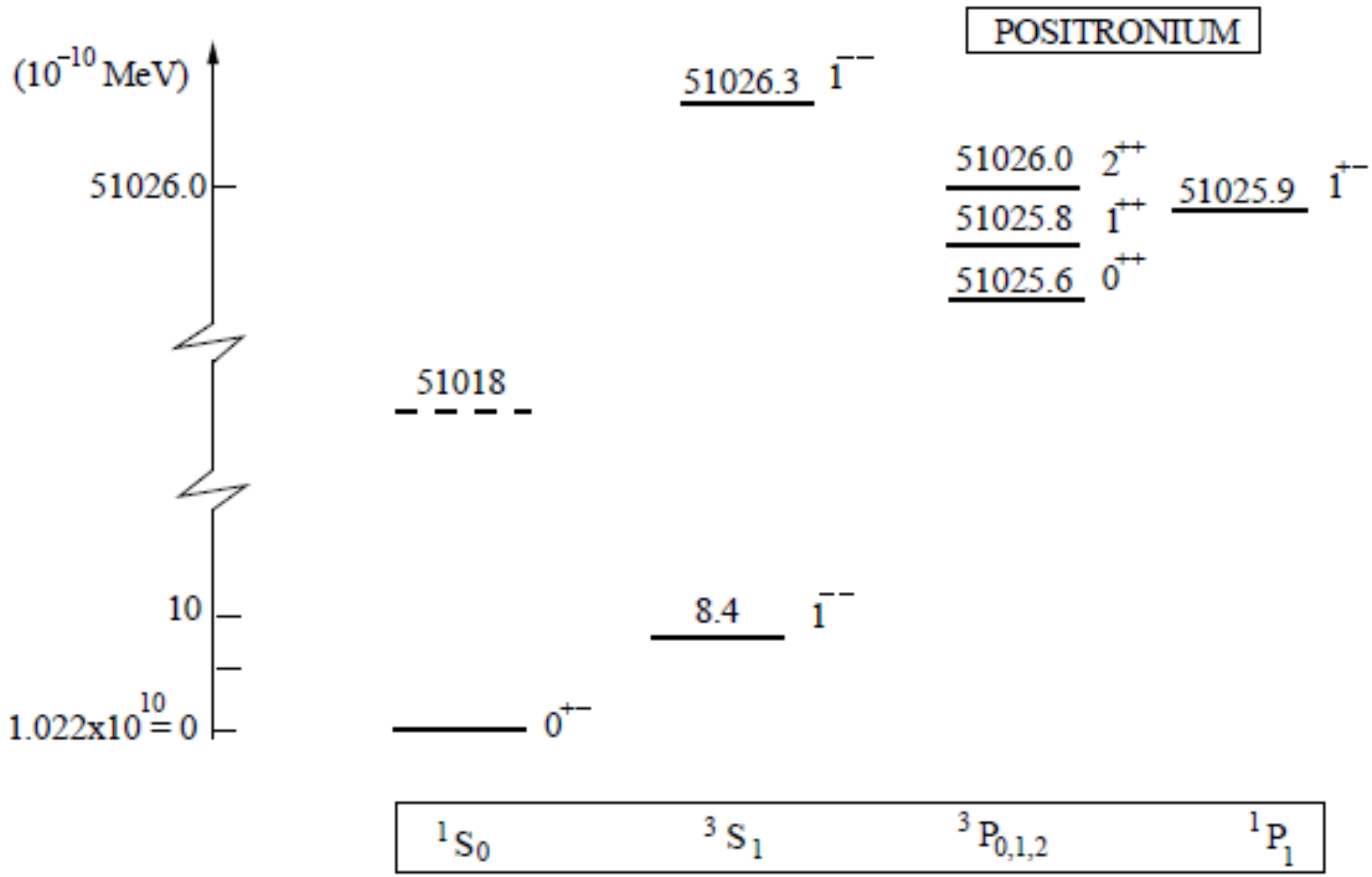
K. Hicks,
JAEA / Ohio University

JAEA Hadron Group Seminar 6/13/2017

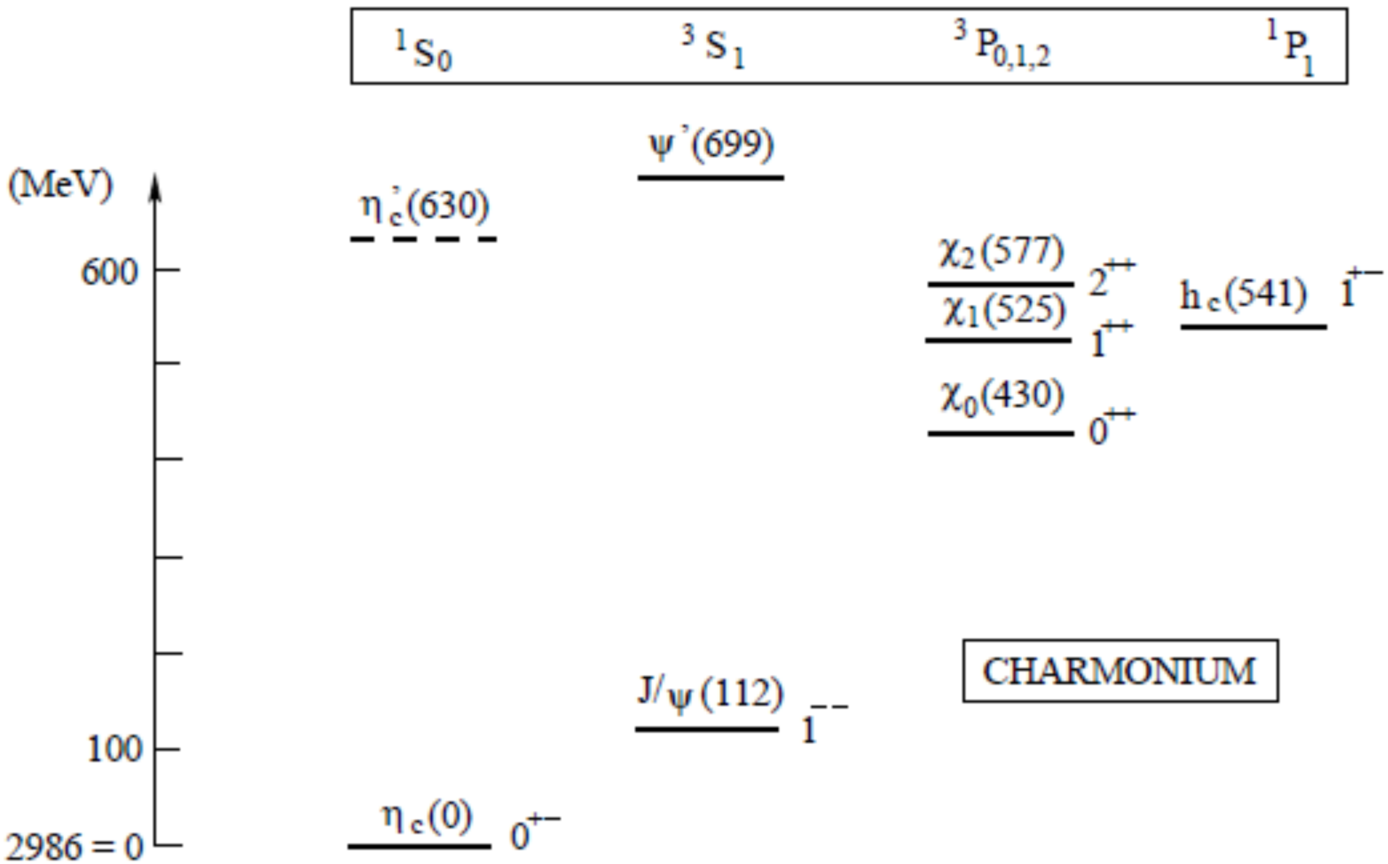
Hadron Physics and QCD

- High-energy physics has evolved to search for physics beyond the standard model
  - But the standard model is still evolving!
- A goal of hadron physics is to study the strong force in the standard model, QCD.
  - Solving QCD at non-perturbative energies is a difficult problem.
  - To test our understanding, we need improved theoretical calculations and better data.

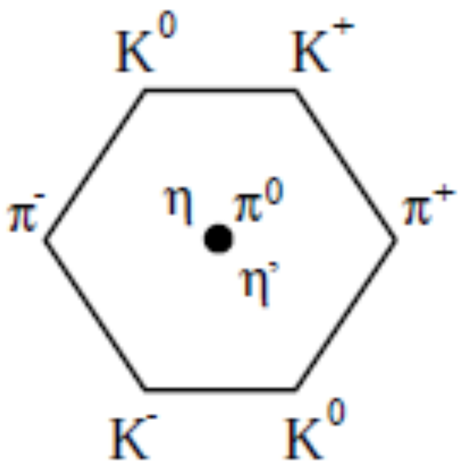
Spectroscopy: positronium

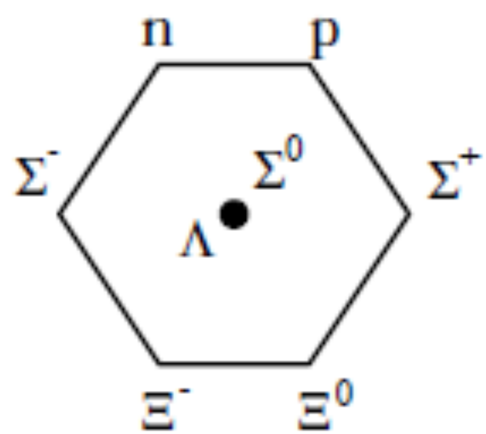


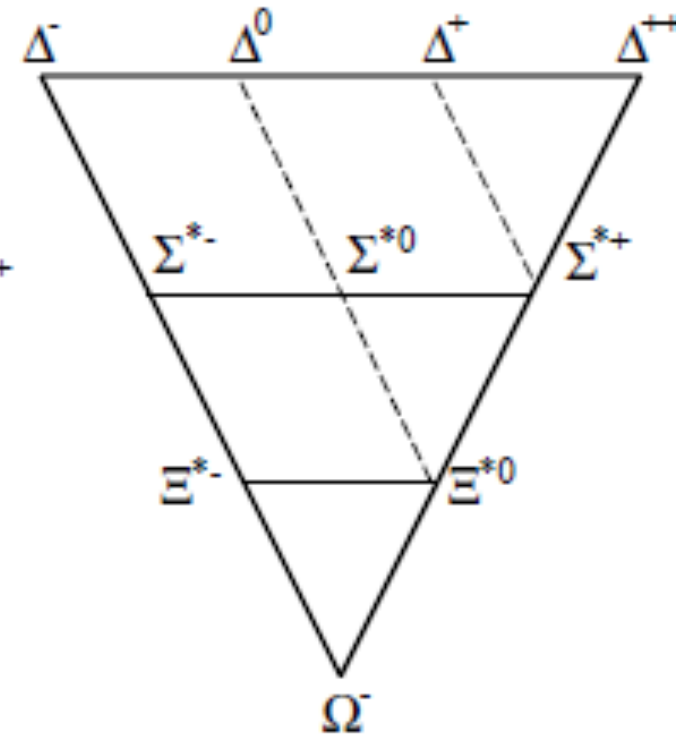
Spectrum of $c\bar{c}$ mesons



Group Theory: Flavor SU(3)







OCTET **DECUPLET**

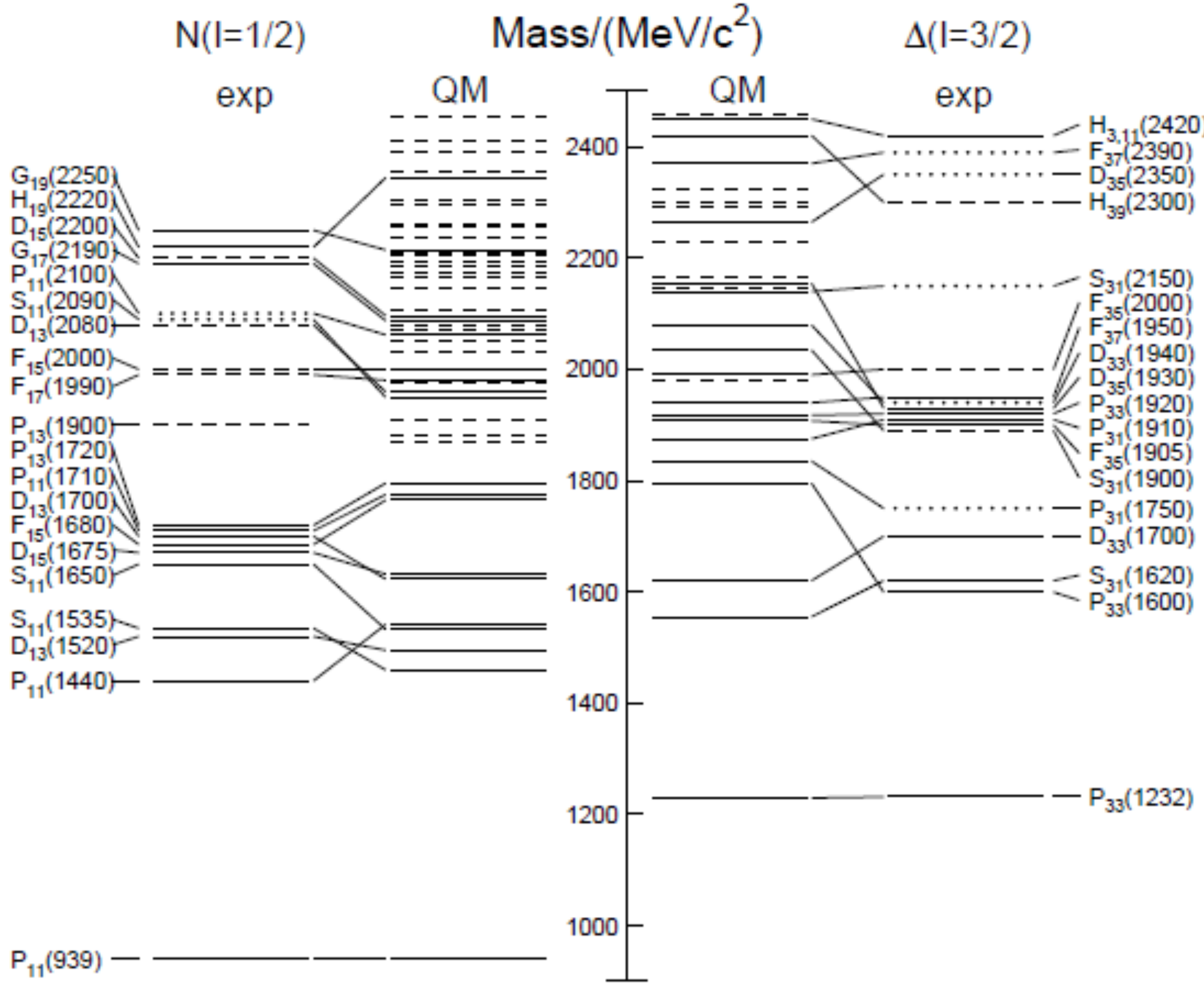
Quark Model: baryons (qqq)

N	sym	L^P	S	$N(I=1/2)$				$\Delta(I=3/2)$			
2	A	1^+	1/2	$1/2^+$	$3/2^+$						
2	M	2^+	3/2	$1/2^+$	$3/2^+$	$5/2^+$	$7/2^+$				
2	M	2^+	1/2		$3/2^+$	$5/2^+$			$3/2^+$	$5/2^+$	
2	M	0^+	3/2		$3/2^+$						
2	M	0^+	1/2	$1/2^+$				$1/2^+$			
				$P_{11}(1710)$				$P_{31}(1750)$			
2	S	2^+	3/2					$1/2^+$	$3/2^+$	$5/2^+$	$7/2^+$
								$P_{31}(1910)$	$P_{33}(1920)$	$F_{35}(1905)$	$F_{37}(1950)$
2	S	2^+	1/2		$3/2^+$	$5/2^+$					
					$P_{13}(1720)$	$F_{15}(1680)$					
2	S	0^+	3/2						$3/2^+$		
									$P_{33}(1600)$		
2	S	0^+	1/2	$1/2^+$							
				$P_{11}(1440)$							
1	M	1^-	3/2	$1/2^-$	$3/2^-$	$5/2^-$					
				$S_{11}(1650)$	$D_{13}(1700)$	$D_{15}(1675)$					
1	M	1^-	1/2	$1/2^-$	$3/2^-$			$1/2^-$	$3/2^-$		
				$S_{11}(1535)$	$D_{13}(1520)$			$S_{31}(1620)$	$D_{33}(1700)$		
0	S	0^+	3/2						$3/2^+$		
									$P_{33}(1232)$		
0	S	0^+	1/2	$1/2^+$							
				$P_{11}(938)$							

PDG: Known Octet States

J^P	$(D, L^P_N)\,S$		Octet members			Singlets
$1/2^+$	$(56,0^+_0)$ $1/2$	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
$1/2^+$	$(56,0^+_2)$ $1/2$	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(1690)^\dagger$	
$1/2^-$	$(70,1^-_1)$ $1/2$	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$	$\Lambda(1405)$
				$\Sigma(1560)^\dagger$		
$3/2^-$	$(70,1^-_1)$ $1/2$	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
$1/2^-$	$(70,1^-_1)$ $3/2$	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$	
				$\Sigma(1620)^\dagger$		
$3/2^-$	$(70,1^-_1)$ $3/2$	$N(1700)$	$\Lambda(?)$	$\Sigma(1940)^\dagger$	$\Xi(?)$	
$5/2^-$	$(70,1^-_1)$ $3/2$	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(1950)^\dagger$	
$1/2^+$	$(70,0^+_2)$ $1/2$	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(1810)^\dagger$
$3/2^+$	$(56,2^+_2)$ $1/2$	$N(1720)$	$\Lambda(1890)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^+$	$(56,2^+_2)$ $1/2$	$N(1680)$	$\Lambda(1820)$	$\Sigma(1915)$	$\Xi(2030)$	
$7/2^-$	$(70,3^-_3)$ $1/2$	$N(2190)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	$\Lambda(2100)$
$9/2^-$	$(70,3^-_3)$ $3/2$	$N(2250)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
$9/2^+$	$(56,4^+_4)$ $1/2$	$N(2220)$	$\Lambda(2350)$	$\Sigma(?)$	$\Xi(?)$	

Compare: Exp. to Quark Model



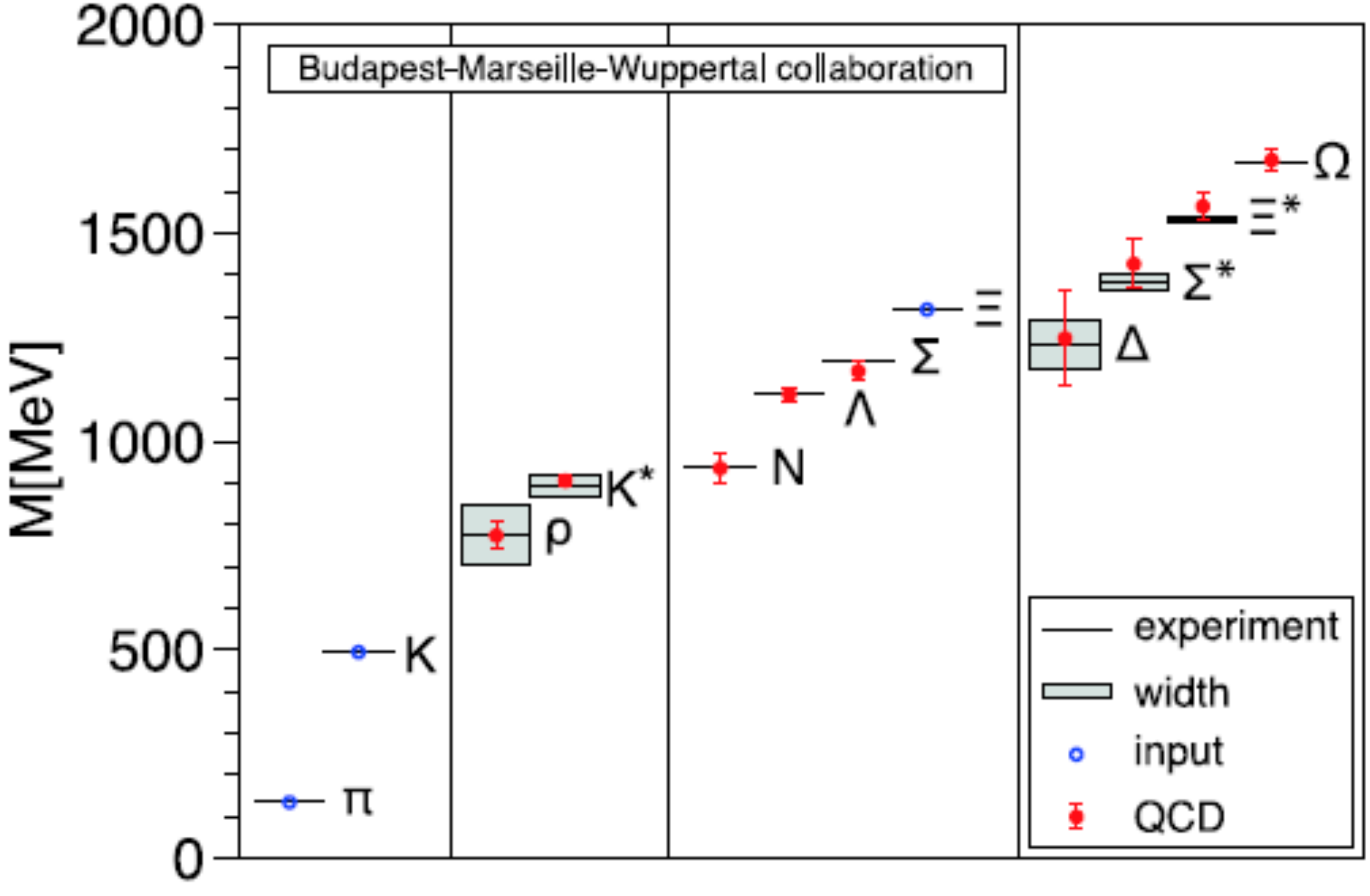
What have we learned?

- The quark model works well for the ground states with L=0.
- When L>0, the predictions of the quark model seem to break down.
- This may be because the energy required to excite a quark into higher orbitals is greater than the pion mass.
  - Is it more efficient to create pions than baryon resonances?

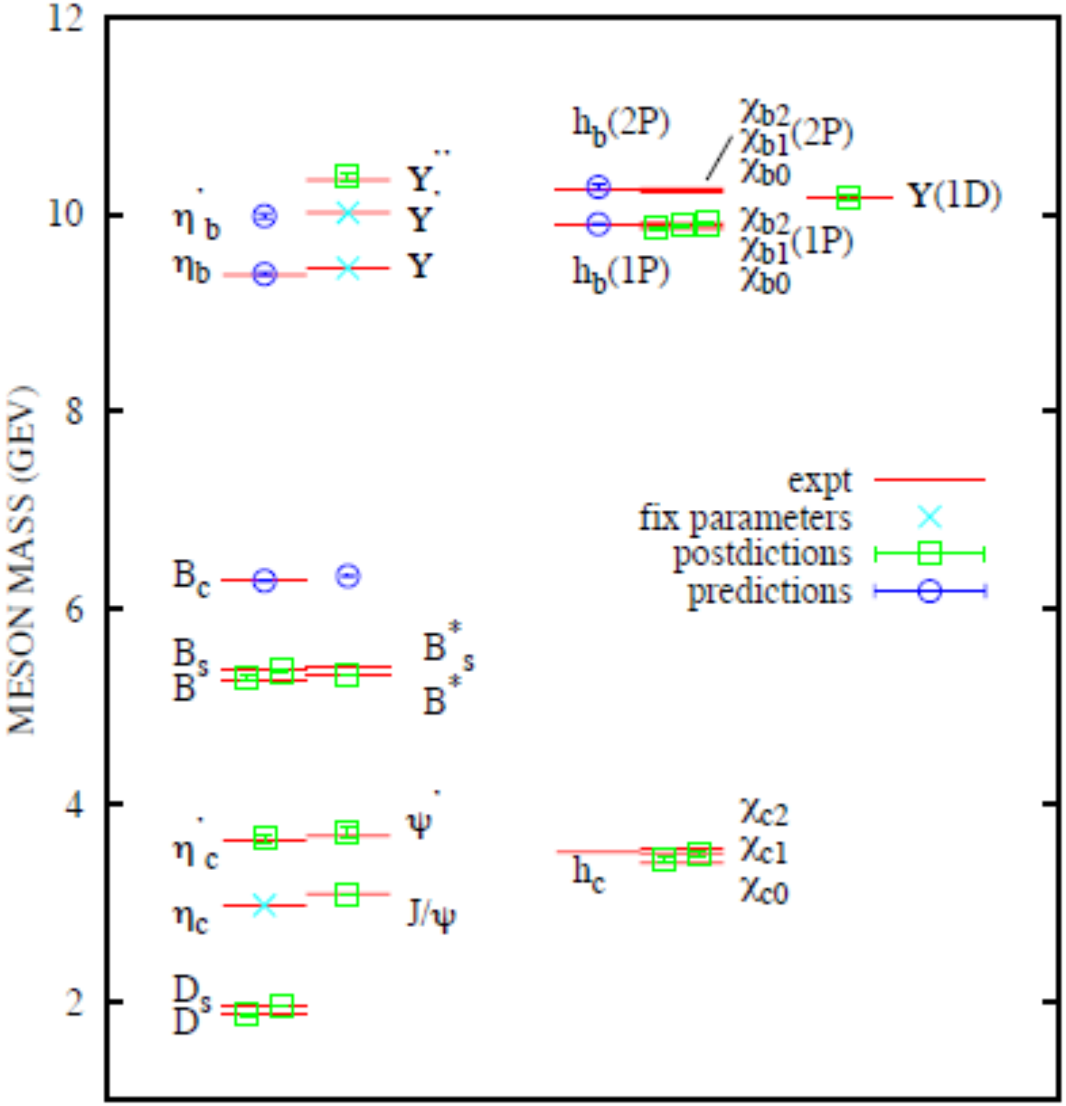
Some Theoretical Tools

- Lattice QCD: direct calculations of QCD using the concept of Feyman path integrals.
  - With advances in computers, these calculations are finally possible to predict hadron resonances
  - One difference from the quark model is that gluon excitations can also form “hybrid” resonances.
- QCD sum rules: fundamental calculations, using the operator product expansion.
  - Oka-san is the expert in this area.

Lattice Gauge Theory

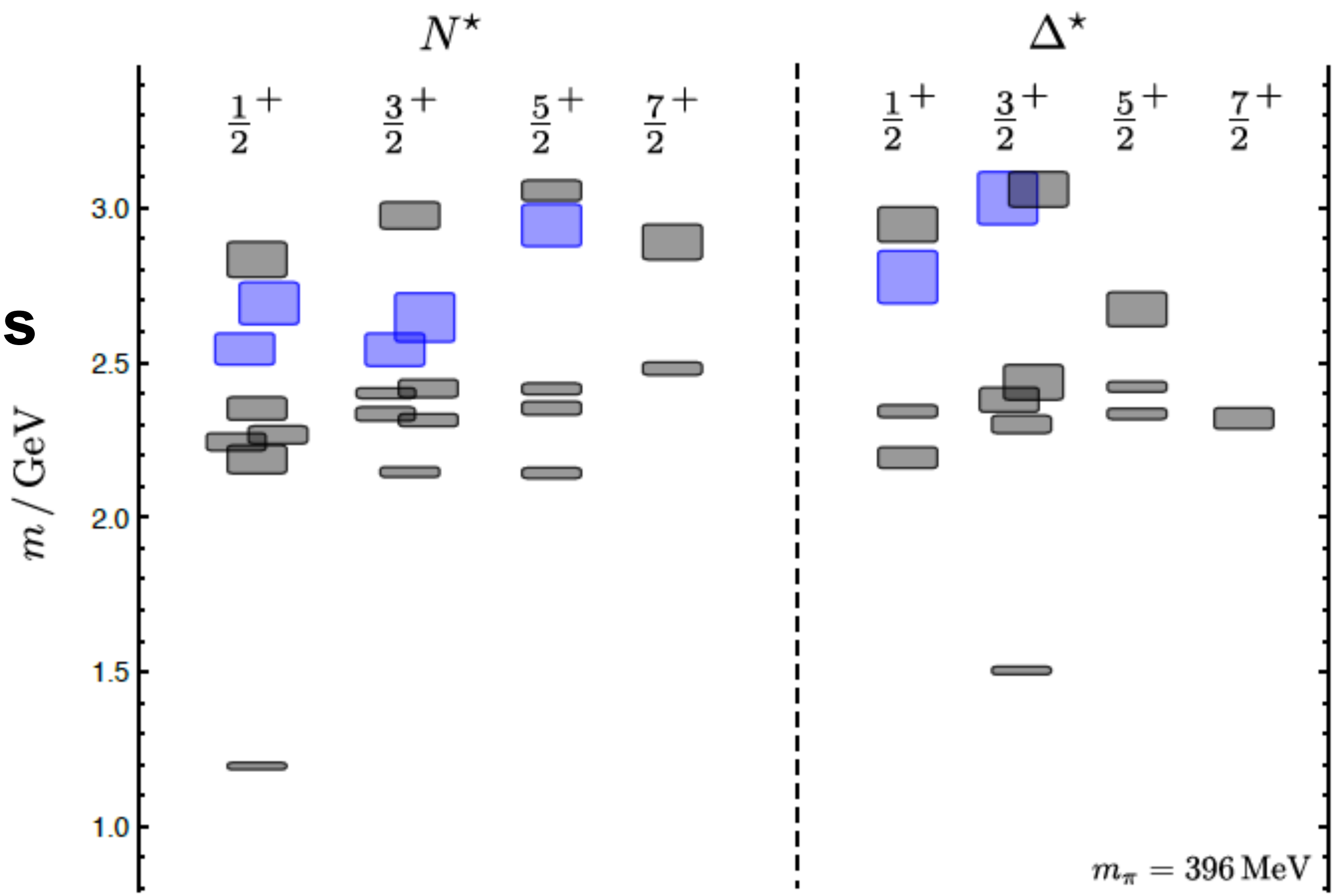


Lattice: heavy meson spectrum

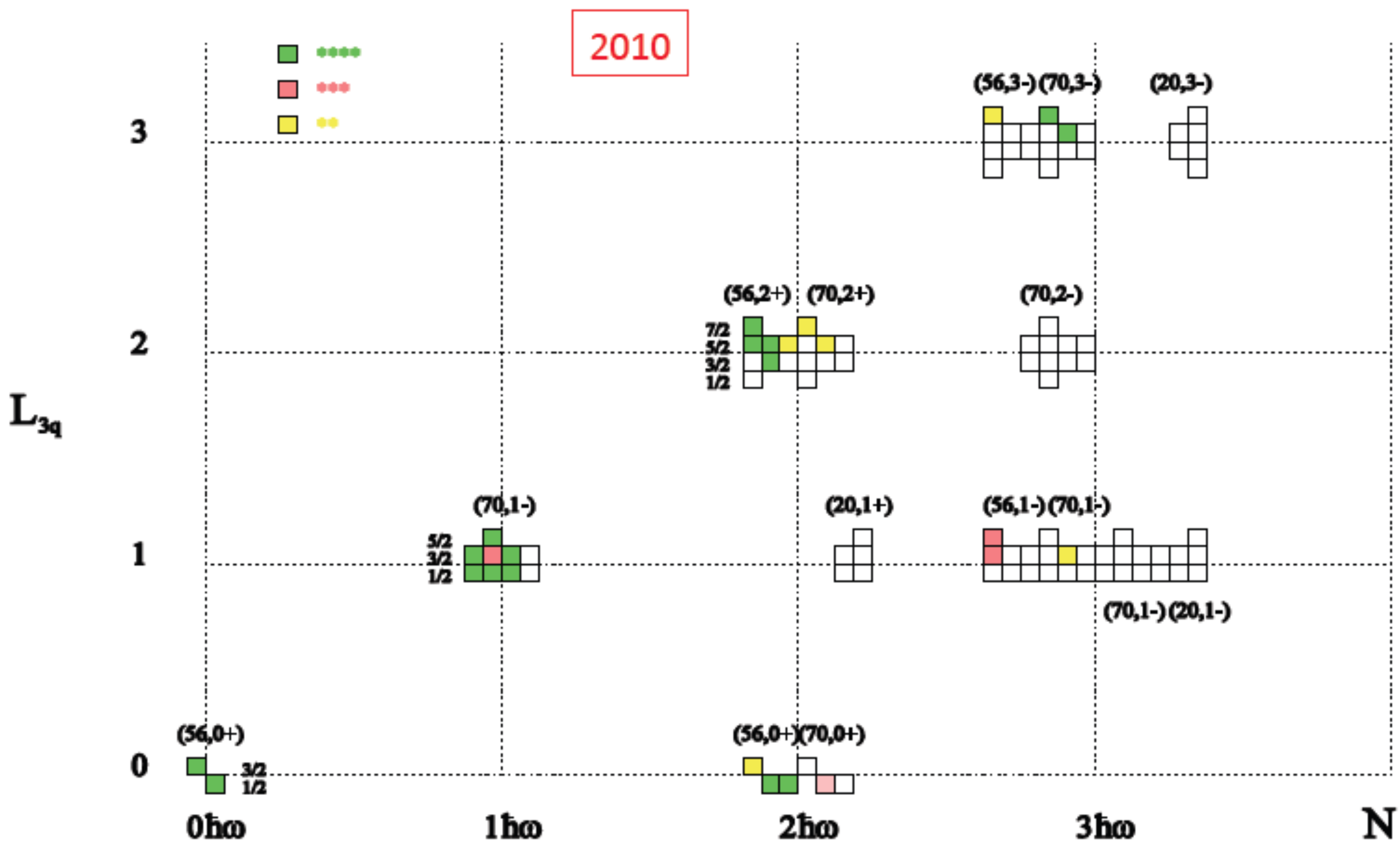


Lattice Predictions: N* and Δ*

Hybrids

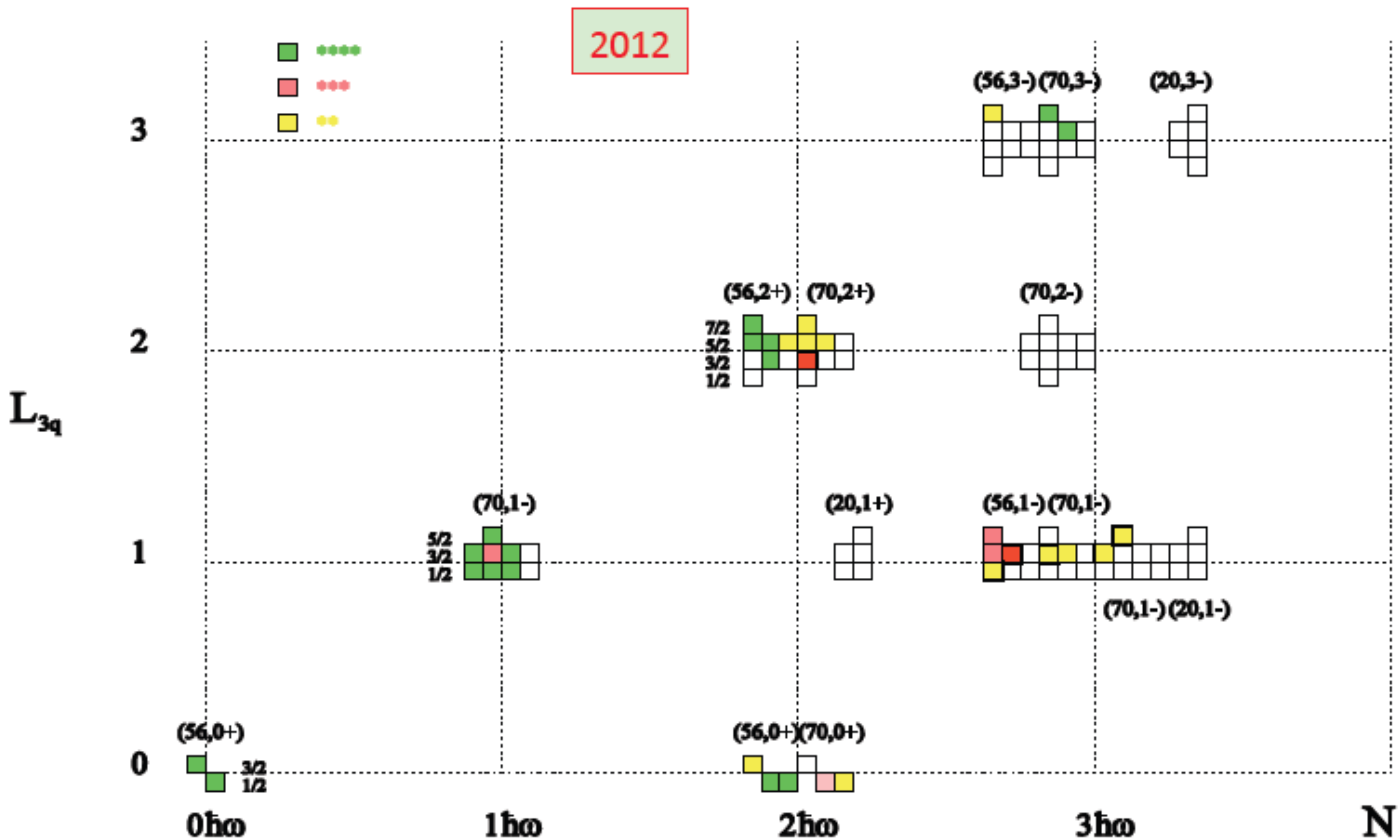


Missing Baryon States (2010)



Empty/Yellow boxes are missing/uncertain baryon states.

Missing Baryon States (2012)

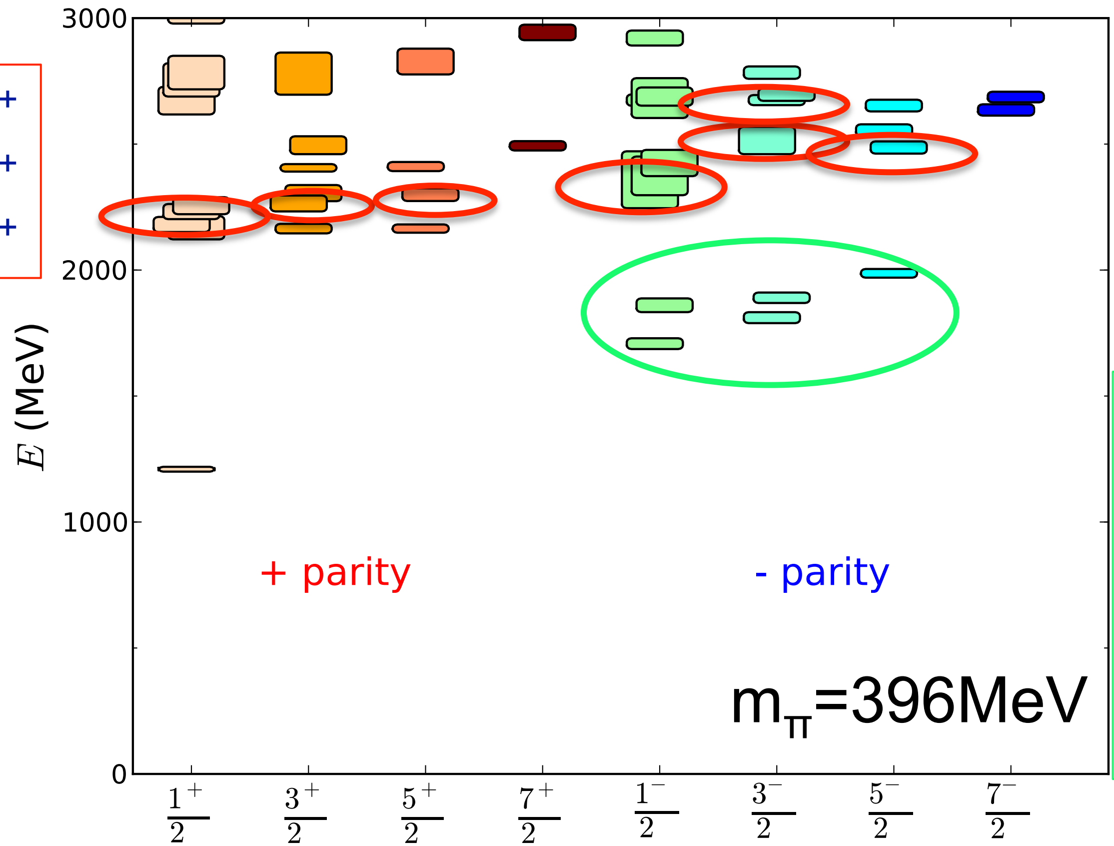


Empty/Yellow boxes are missing/uncertain baryon states.

Do the new states fit into LQCD ?

R. Edwards et al., Phys.Rev. D84 (2011) 074508

N(1860)5/2+
N(1900)3/2+
N(1880)1/2+



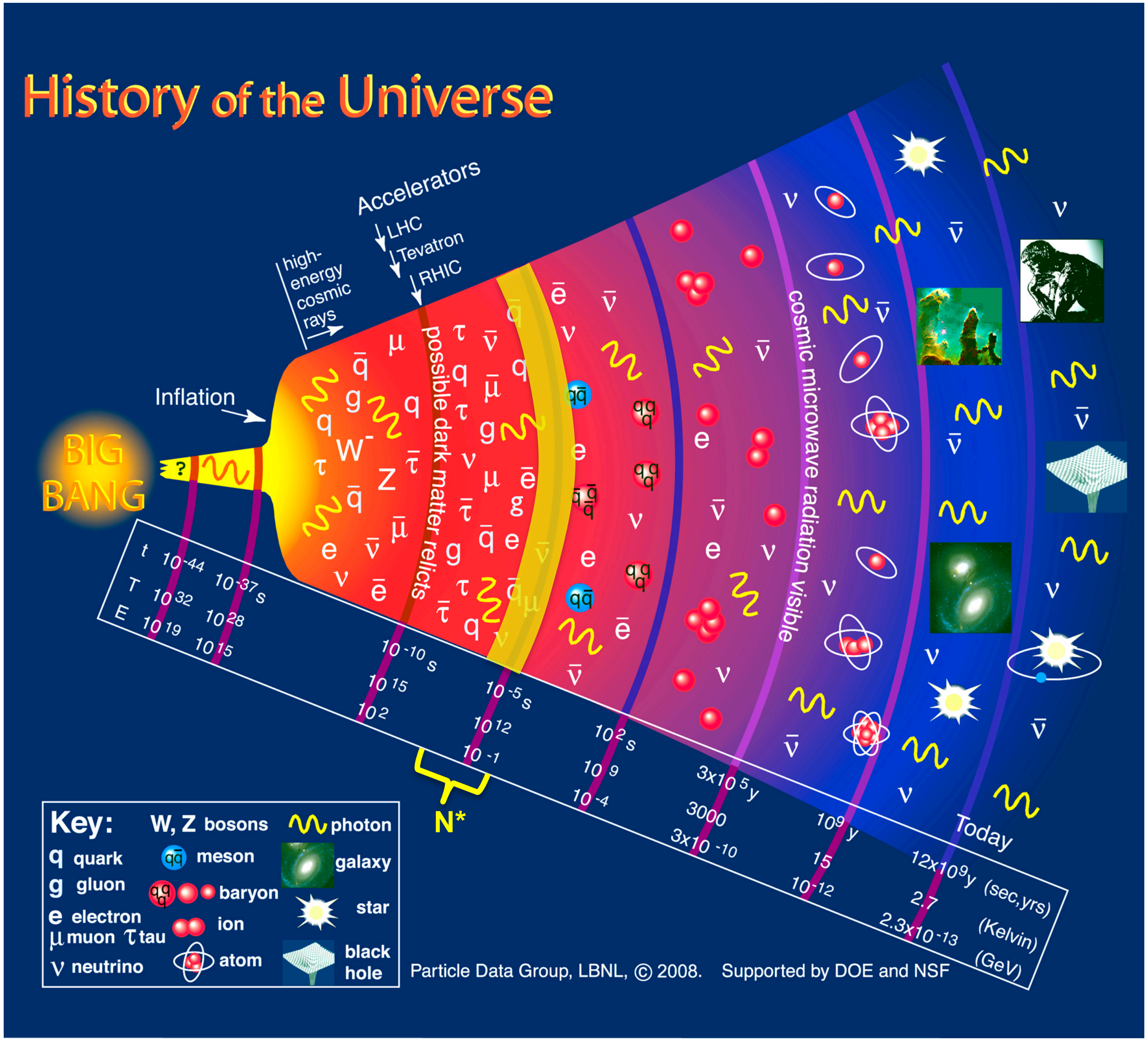
N(2060)5/2-
N(2120)3/2-
N(1875)3/2-
N(1895)1/2-

Known states:
N(1675)$_{5/2}$-
N(1700)$_{3/2}$-
N(1520)$_{3/2}$-
N(1650)$_{1/2}$-
N(1535)$_{1/2}$-

Ignoring the mass scale, new candidate states fit with the J^P values predicted from LQCD.

Slide borrowed from V. Burkert.

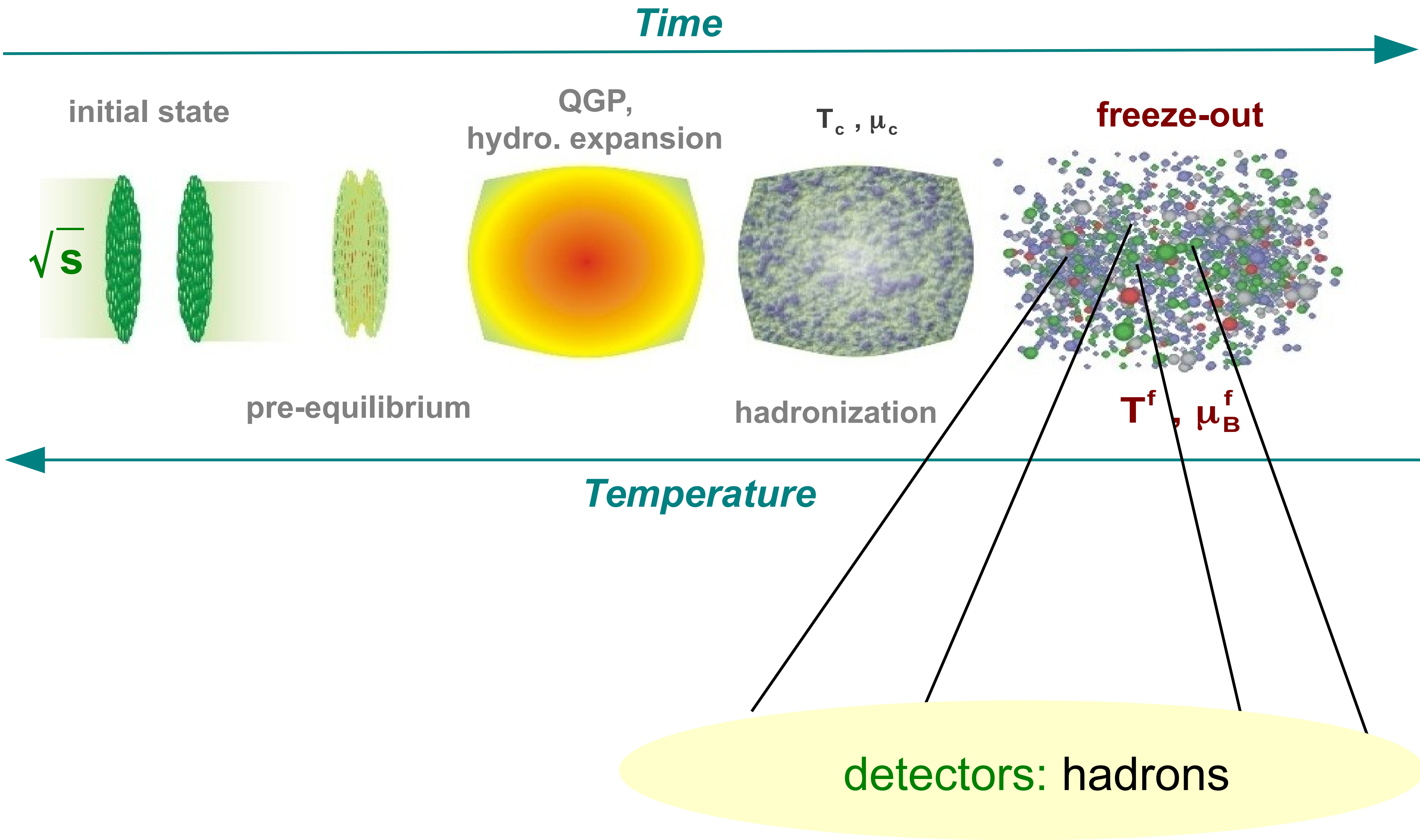
Excited Baryons in the history of the Universe



Excited baryons are at the transition between the quark-gluon liquid, described in **hot QCD**, and the confinement of quarks and gluons in nucleons, described in **strong QCD**. This period lasted ~ 10^{-6} seconds.

Do we understand this transition?

Slide borrowed from V. Burkert.



freeze-out stage

"observed" in HIC

Slide borrowed from S. Mukherjee.

Studies of N*-Spectrum and Structure with CLAS

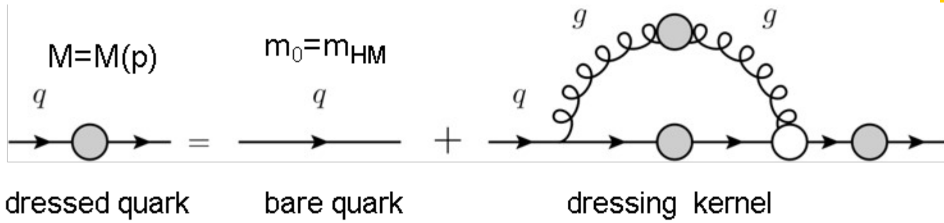
The experimental program on the studies of N* structure in exclusive meson photo-/electroproduction with CLAS seeks to determine:

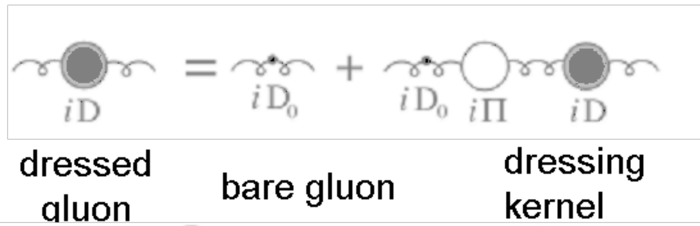
- $\gamma_v NN^*$ electrocouplings at photon virtualities up to 5.0 GeV^2 for most of the excited proton states from meson electroproduction.
- extend knowledge on the N*-spectrum and from the data for photo- and electroproduction reactions.

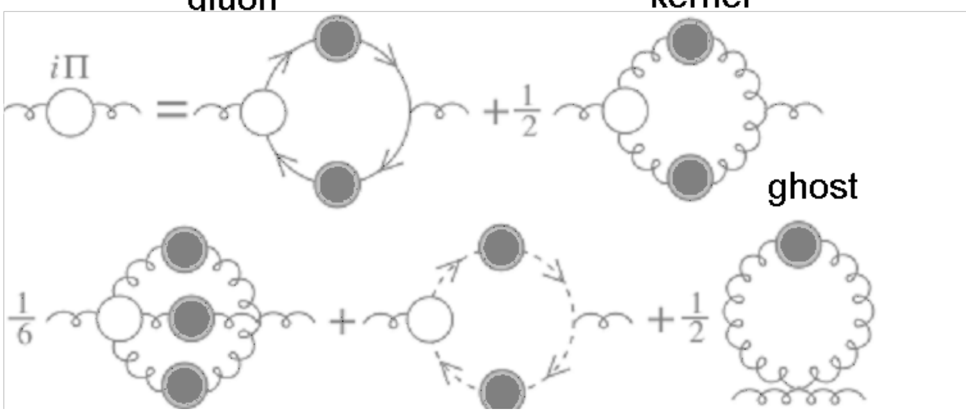
This provides a unique source of information on non-perturbative QCD that generates excited nucleon states (N*'s).

Excited Nucleon States and Insight to Strong QCD Dynamics

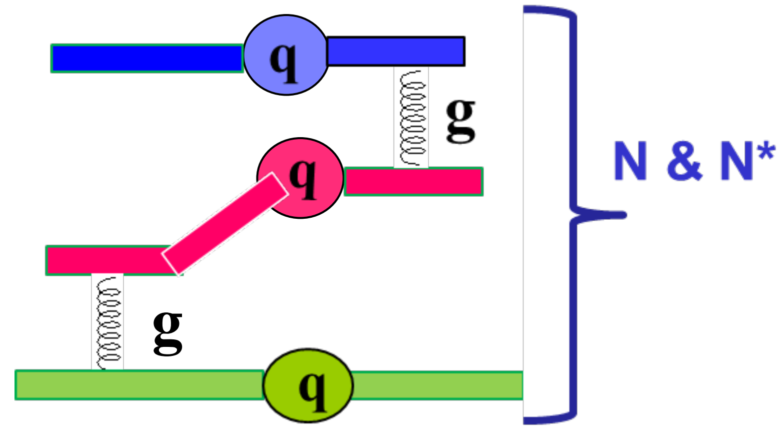
Emergence of Dressed Quarks and Gluons
C.D. Roberts, J.Phys. Conf. Ser. 706, 022003 (2016).



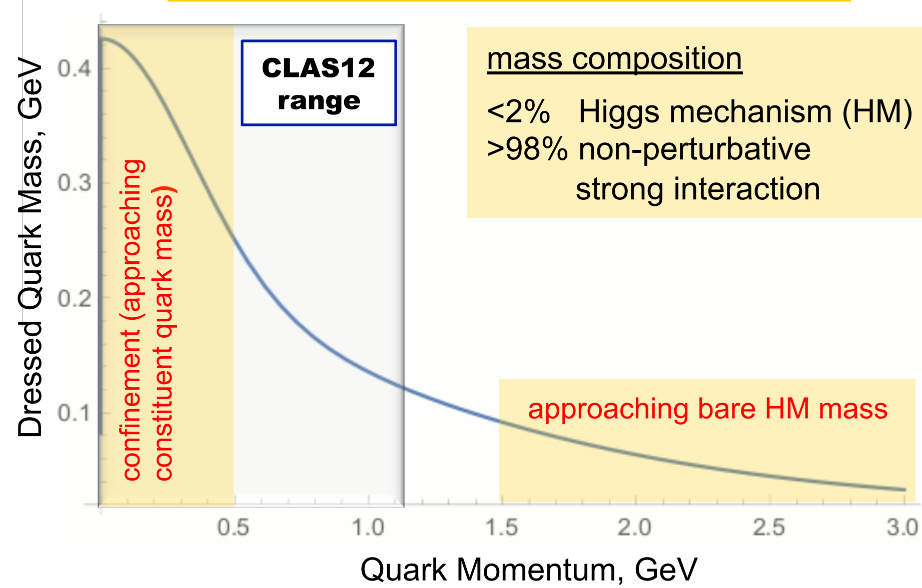




Dressed Quark Borromeo Binding in Baryons
C.D. Roberts, J.Segovia, Few Body Syst. 57 1067 (2016)

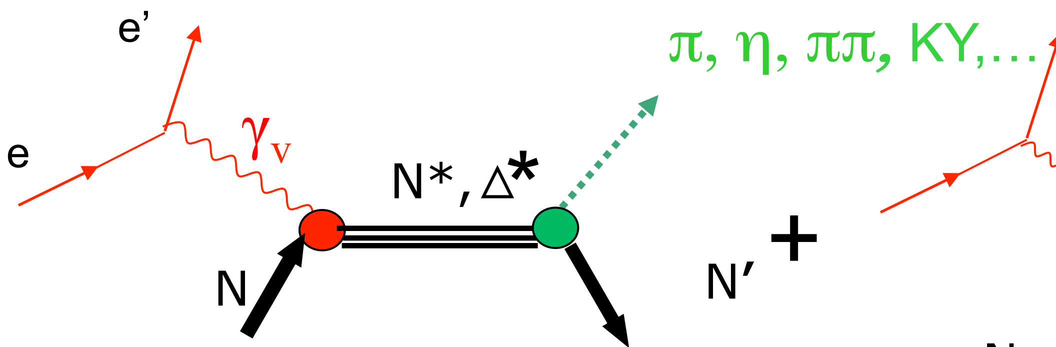


Dressed Quark Mass Function
C.D.Roberts, Few Body Syst. 58, 5 (2017).



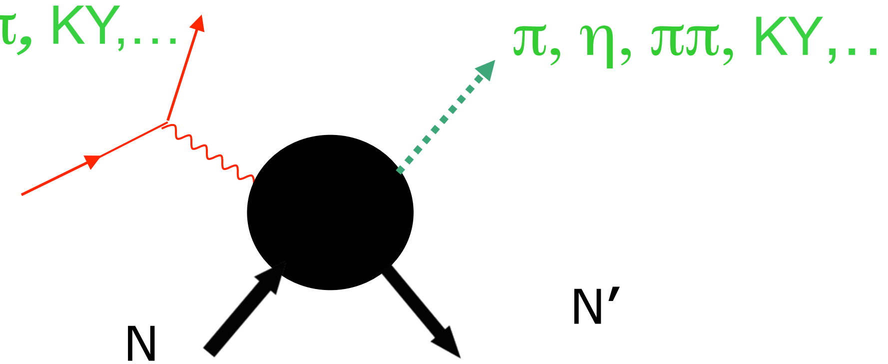
Extraction of $\gamma_v NN^*$ Electrocouplings from the Exclusive Meson Electroproduction off Nucleons

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 the CLAS data analyses:

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

Γ_γ stands for N* electro-magnetic decay widths and $W=M_{N^*}$ on the real energy axis.

- **Consistent results on $\gamma_v NN^*$ electrocouplings from different meson electroproduction channels and different analysis approaches demonstrate the reliable extraction of these quantities.**

Summary of the 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	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	0.2-0.6 0.5-1.5	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

Almost full coverage of the final hadron phase space in πN, $\pi^+\pi^-$p, ηp, KY electroproduction

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

- **Analyses of different pion 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 Coll., Phys Rev. C80, 055203 (2009).

I.G. Aznauryan et al., CLAS Coll., 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 Coll., 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 Coll., Phys. Rev. C86, 035203 (2012).

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

- **Global coupled-channel analyses of the CLAS/world data of $\gamma_{r,v}N$, πN, ηN, $\pi\pi N$, $K\Lambda$, $K\Sigma$ exclusive channels:**

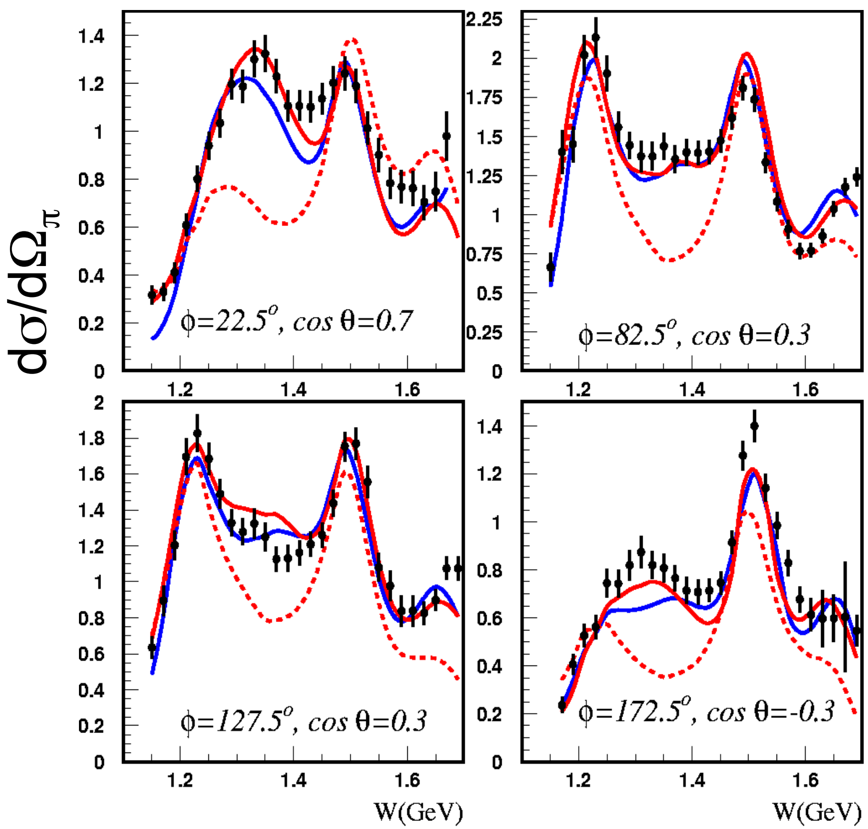
T.-S. H. Lee , AIP Conf. Proc. 1560, 413 (2013).

H. Kamano et al., Phys. Rev. C88, 035209 (2013).

Fits to $\gamma p \rightarrow \pi^+ n$ Differential Cross Sections and Structure Functions

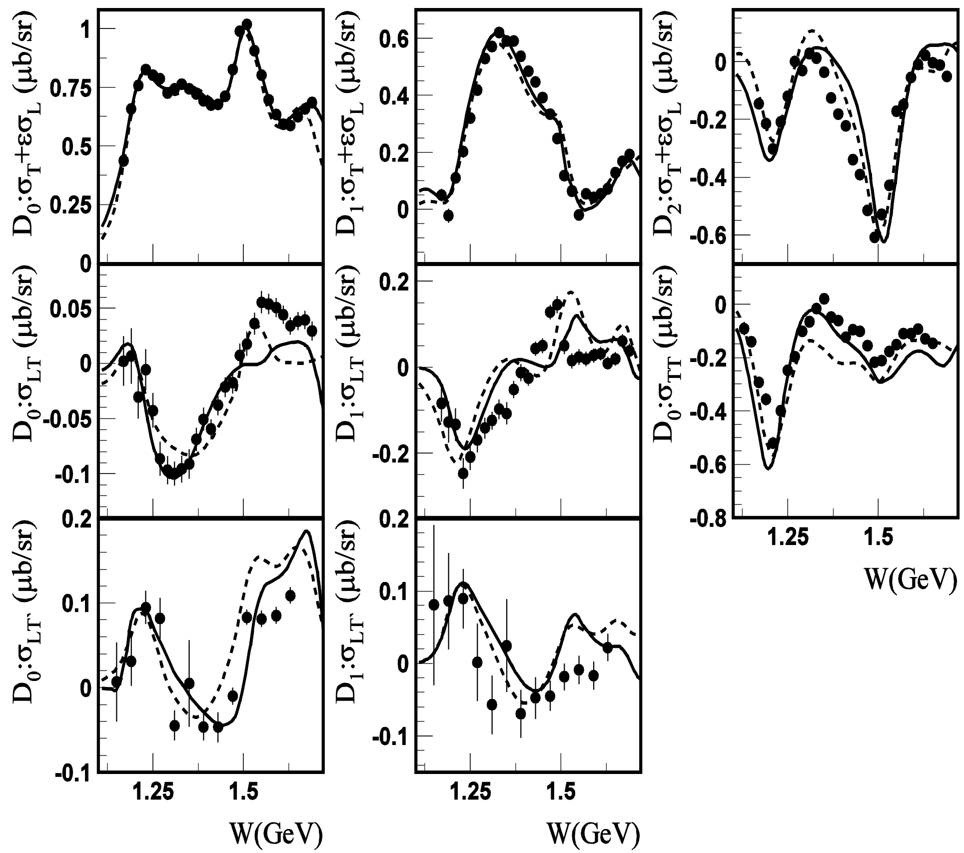
Q^2=2.05 GeV^2

DR
DR w/o P11
UIM



Q^2=2.44 GeV^2

DR
UIM

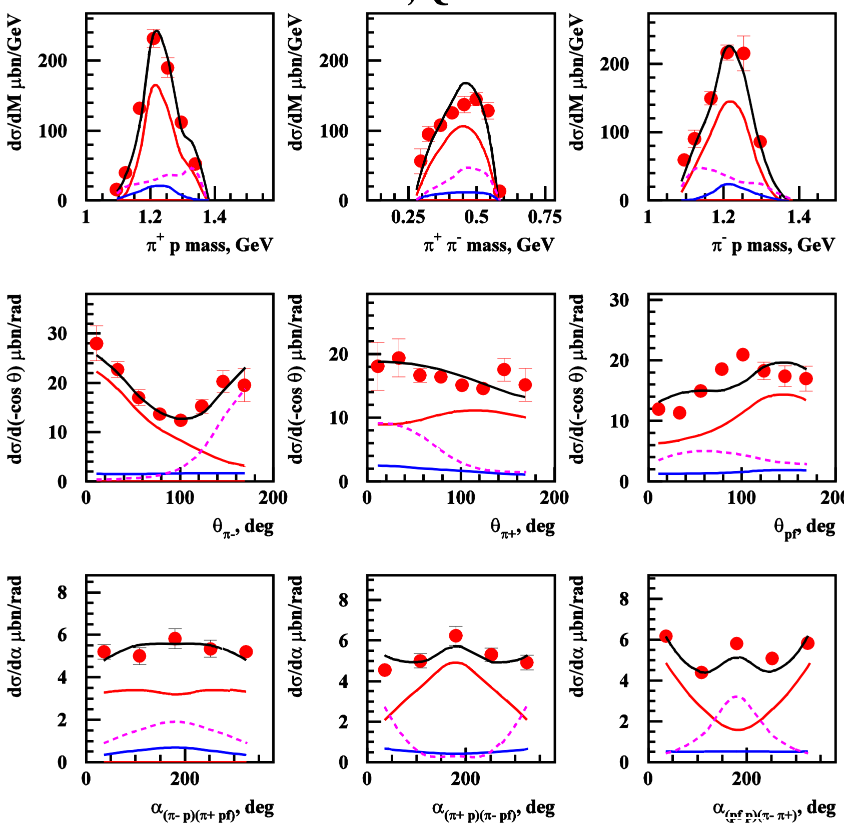


Legendre moments D_l (l=0,1,2) from various structure functions

The CLAS Data on $\pi^+\pi^-p$ Differential Cross Sections and their Fit within the Framework of Meson-Baryon Reaction Model JM

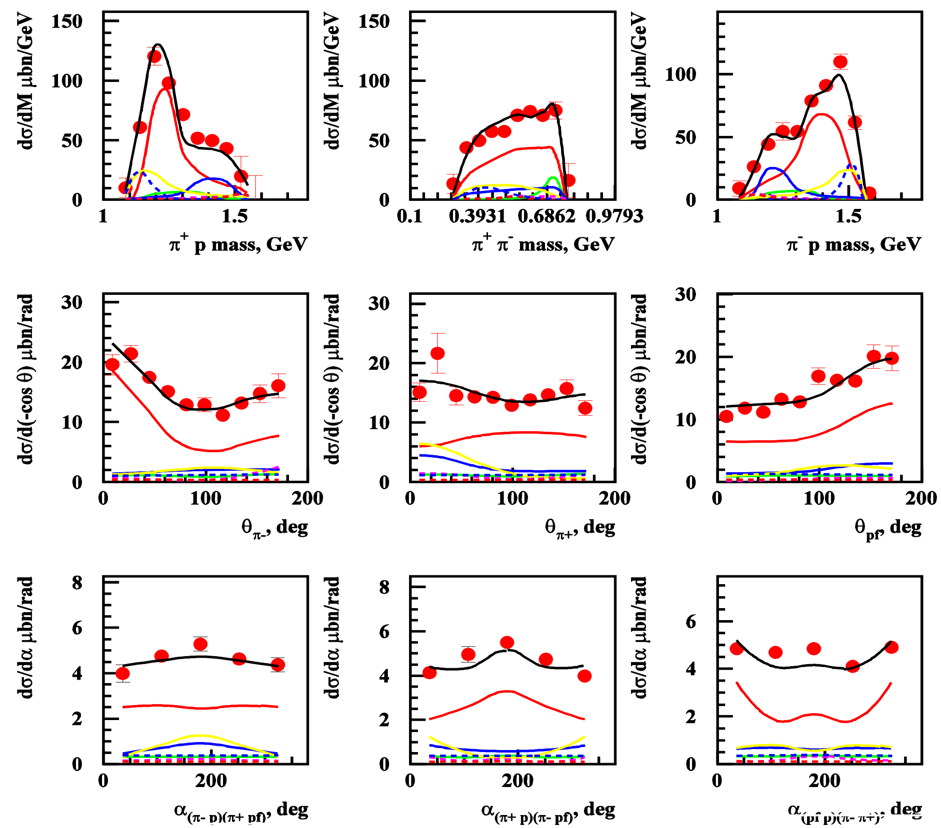
G.V.Fedotov et al, PRC 79 (2009), 015204
1.30<W<1.56 GeV; 0.2<Q^2<0.6 GeV^2

W=1.5125 GeV, Q^2=0.375 GeV^2



M.Ripani et al, PRL 91 (2003), 022002
1.40<W<2.30 GeV; 0.5<Q^2<1.5 GeV^2

W=1.71 GeV, Q^2=0.65 GeV^2



full JM calc. — $\pi^+\Delta^0$ — ρp — $\pi^+F^0_{15}(1680)$

$\pi^-\Delta^{++}$ — 2π direct — $\pi^+D^0_{13}(1520)$

Summary of the Results on $\gamma_v pN^*$ Electrocouplings from CLAS

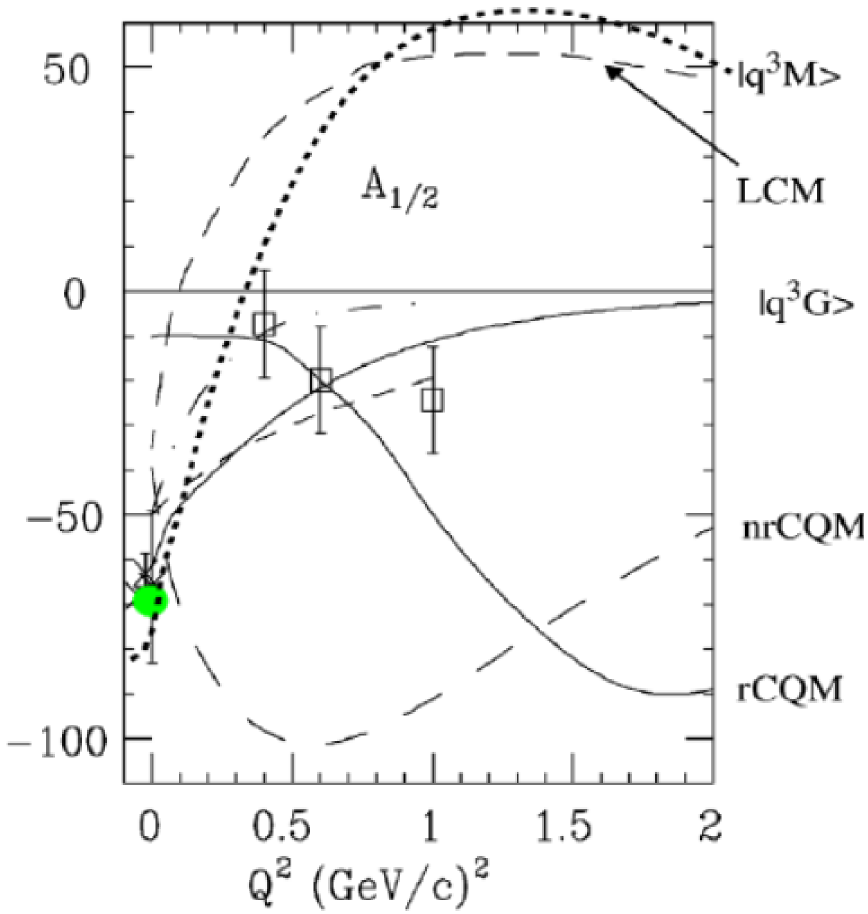
Exclusive meson electroproduction channels	Excited proton states	Q^2-ranges for extracted $\gamma_v NN^*$ electrocouplings, GeV^2
$\pi^0 p$, $\pi^+ n$	$\Delta(1232)3/2^+$ $N(1440)1/2^+$,$N(1520)3/2^-$, $N(1535)1/2^-$	0.16-6.0 0.30-4.16
$\pi^+ n$	$N(1675)5/2^-$, $N(1680)5/2^+$ $N(1710)1/2^+$	1.6-4.5
ηp	$N(1535)1/2^-$	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 0.5-1.5

The values of resonance electrocouplings can be found in:
https://userweb.jlab.org/~mokeev/resonance_electrocouplings/

The CLAS results on $\gamma_v pN^*$ electrocouplings for the excited states in mass range up to 1.8 GeV were interpolated/extrapolated in Q^2-range up to 5.0 GeV^2.

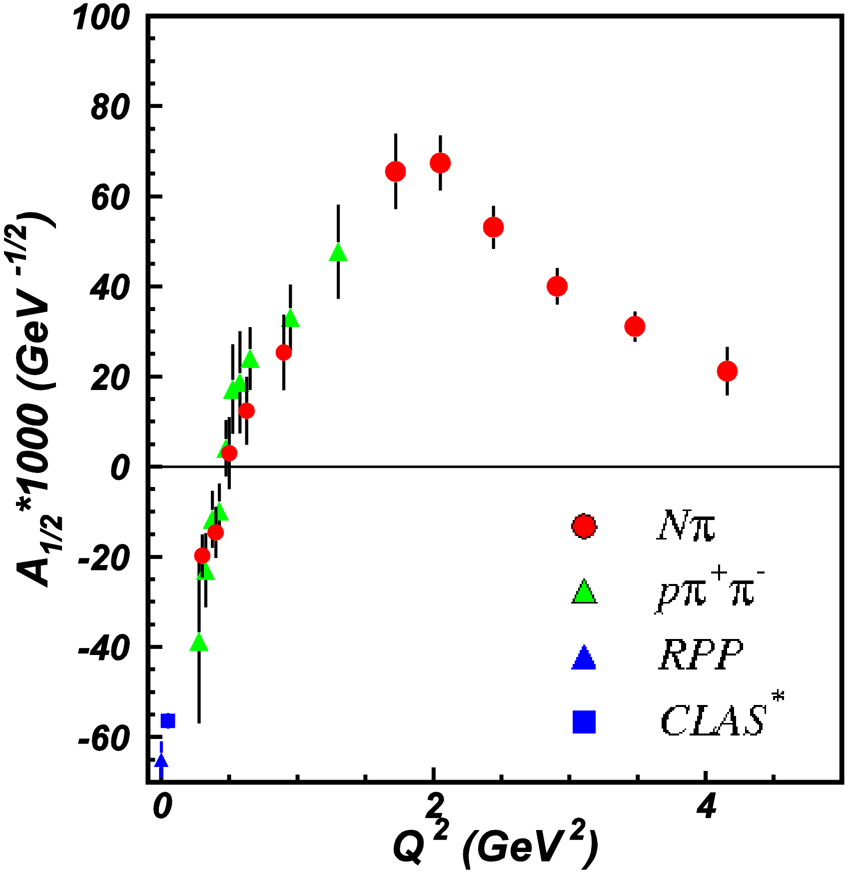
Roper resonance in 2002 & 2016

2002



V. Burkert, Baryons 2002

2016

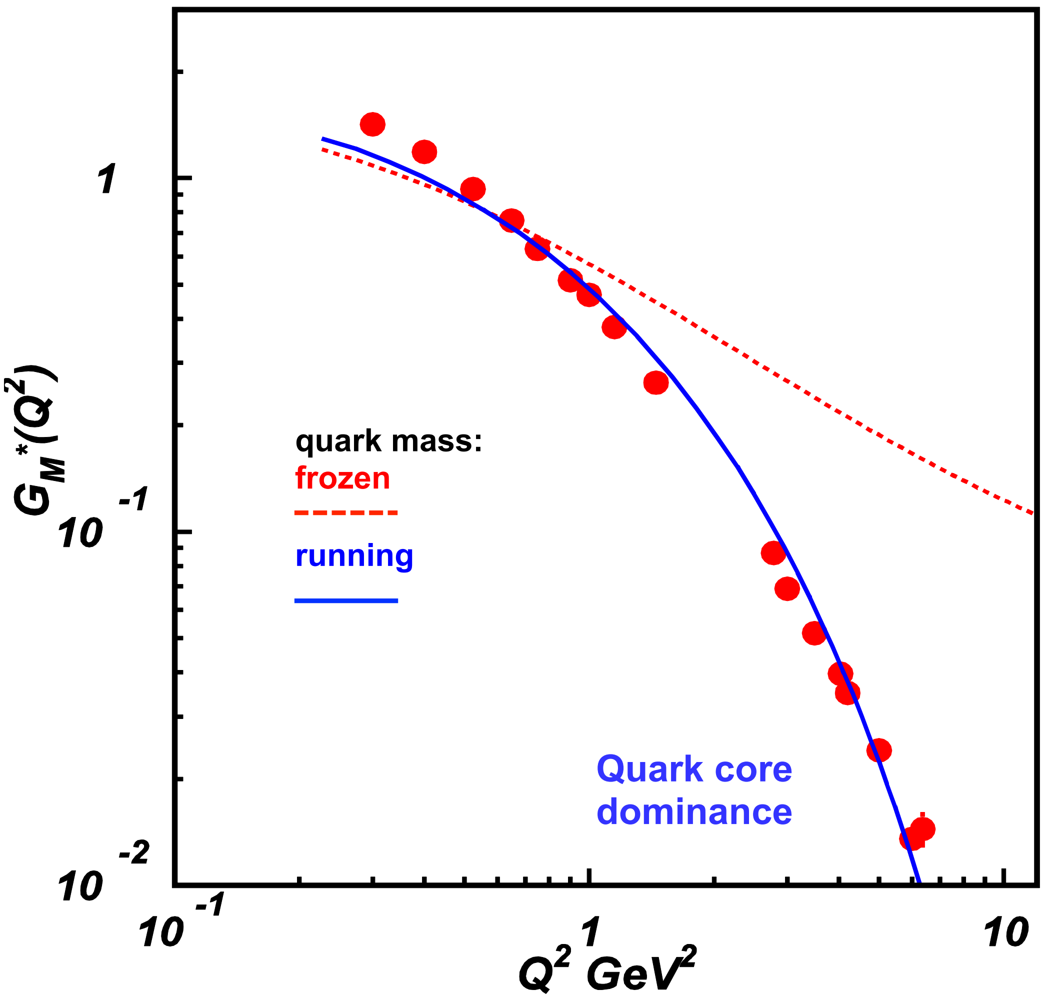


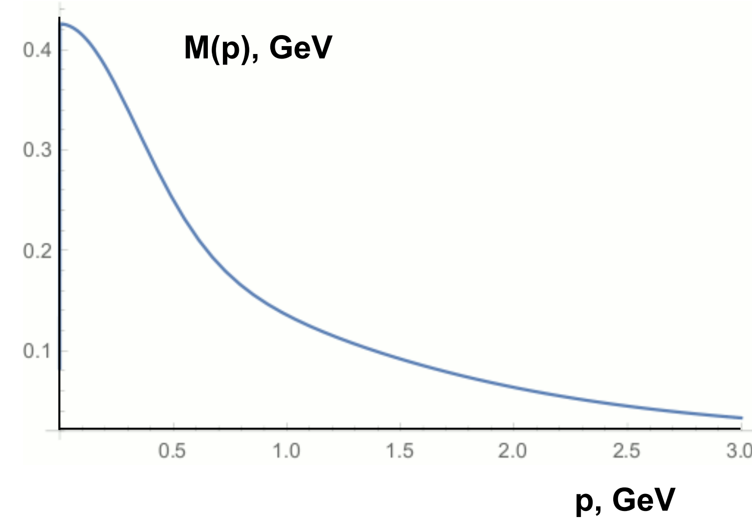
V. D. Burkert, Baryons 2016

Electrocouplings of $\Delta(1232)3/2^+$, $N(1440)1/2^+$, $N(1520)3/2^-$, $N(1535)1/2^-$, $N(1675)5/2^-$, $N(1680)5/2^+$, $N(1710)1/2^+$ were published in the recent edition of the PDG , Chin. Phys. C40, 100001 (2016).

Elucidating the Running Dressed Quark Mass

N→Δ(1232)3/2+ magnetic from factor
Jones-Scadron convention





Dyson-Schwinger Equations (DSE):

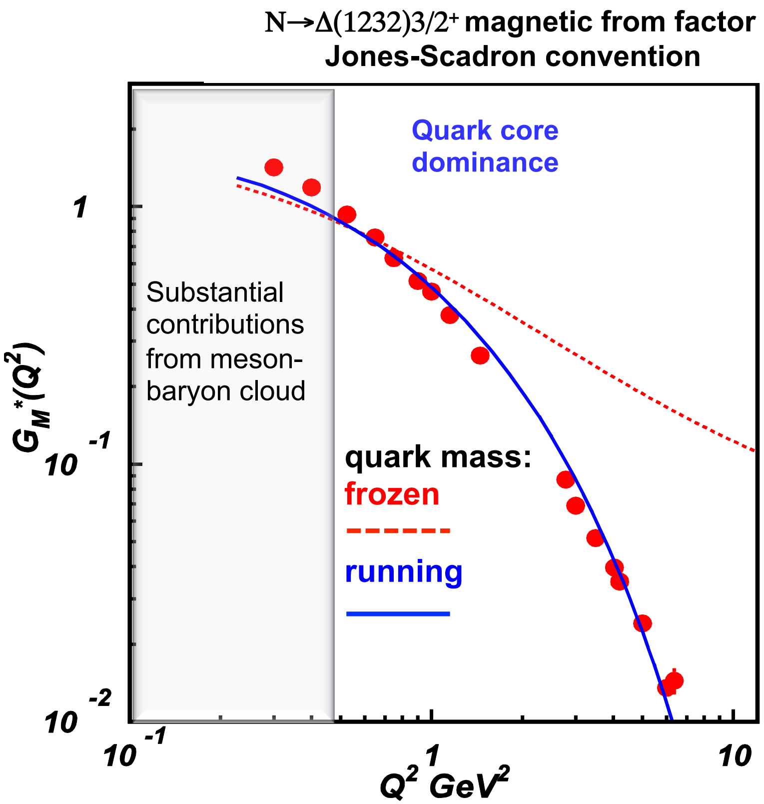
- J. Segovia et al., Phys .Rev. Lett. 115, 171801 (2015).
- J. Segovia et al., Few Body Syst. 55, 1185 (2014).

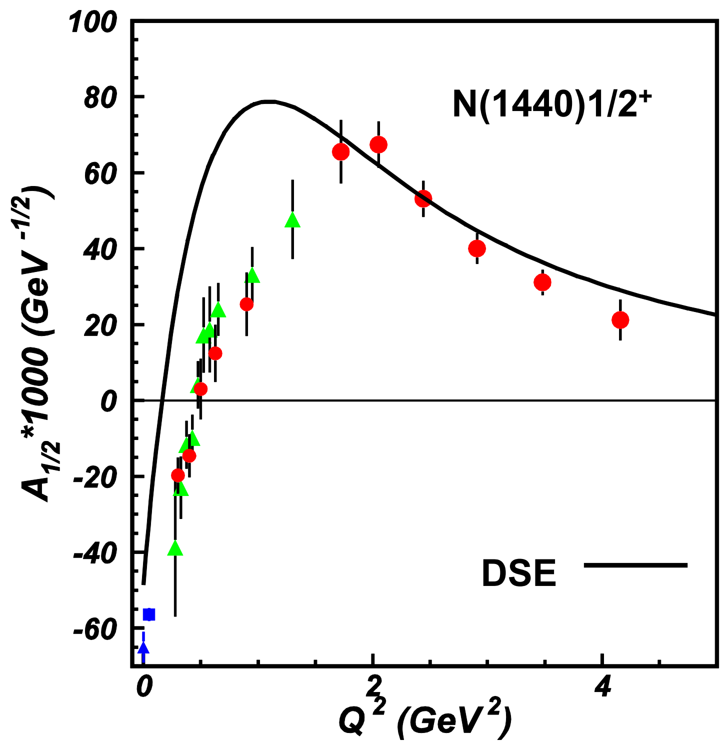
Data on Δ(1232)3/2+ electroexcitation from CLAS for the first time demonstrated that dressed quark mass is running with momentum.

Validating the Access to the Quark Mass Function

<u>Dyson-Schwinger Equations (DSE):</u>

- J. Segovia et al., Phys .Rev. Lett. 115, 171801 (2015).
- J. Segovia et al., Few Body Syst. 55, 1185 (2014).

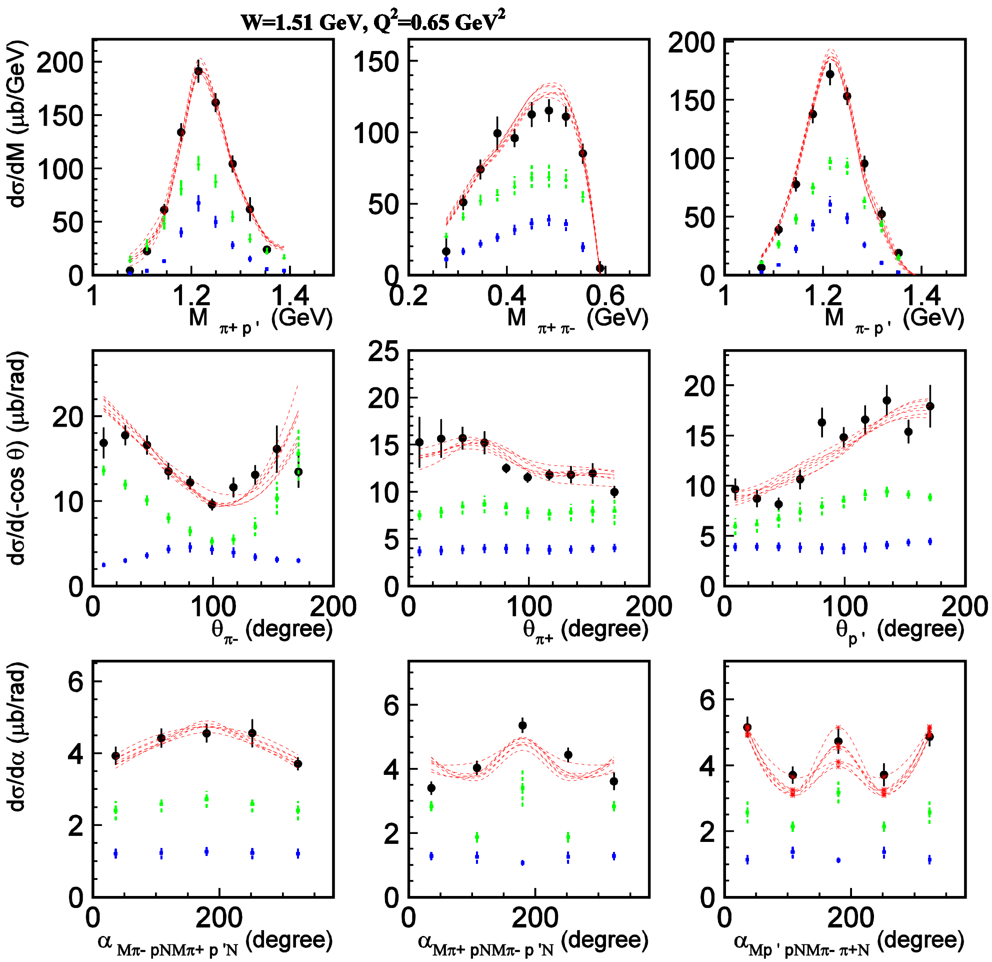




Good data description at $Q^2>2.0$ GeV^2 achieved with <u>the same dressed quark mass function</u> for the ground and excited nucleon states of distinctively different structure.

One of the most important achievement in hadron physics of the last decade obtained in synergistic efforts between experimentalists and theorists.

Accessing Quark Mass Function from the $N\pi/\pi^+\pi^-p$ Electroproduction off Protons Data



Resonant/Non-resonant contributions from the fit of the CLAS $\pi^+\pi^-p$ electroproduction off protons cross sections (V.I.Mokeev, et al., PRC 93 025206 (2016))

CLAS data

JM model analysis:

fit to the data computed cross sections

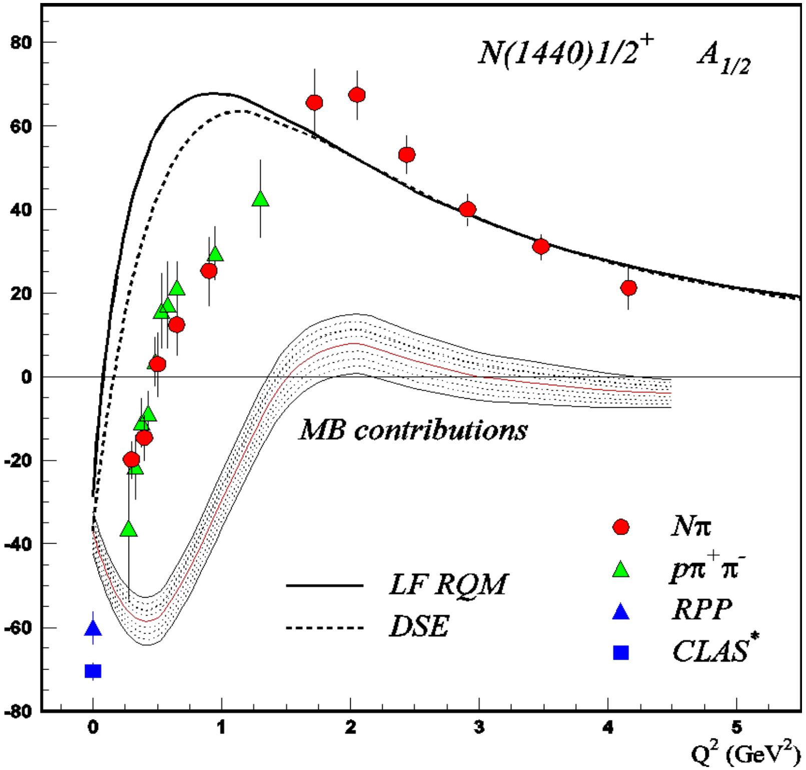
resonant part of the computed cross sections

non-resonant part of the computed cross sections

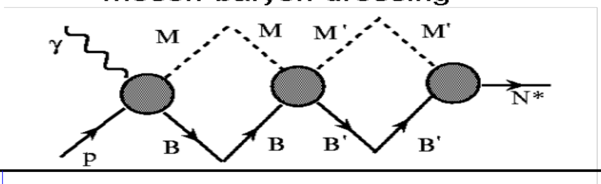
- **non-resonant contributions are determined from the data fit**

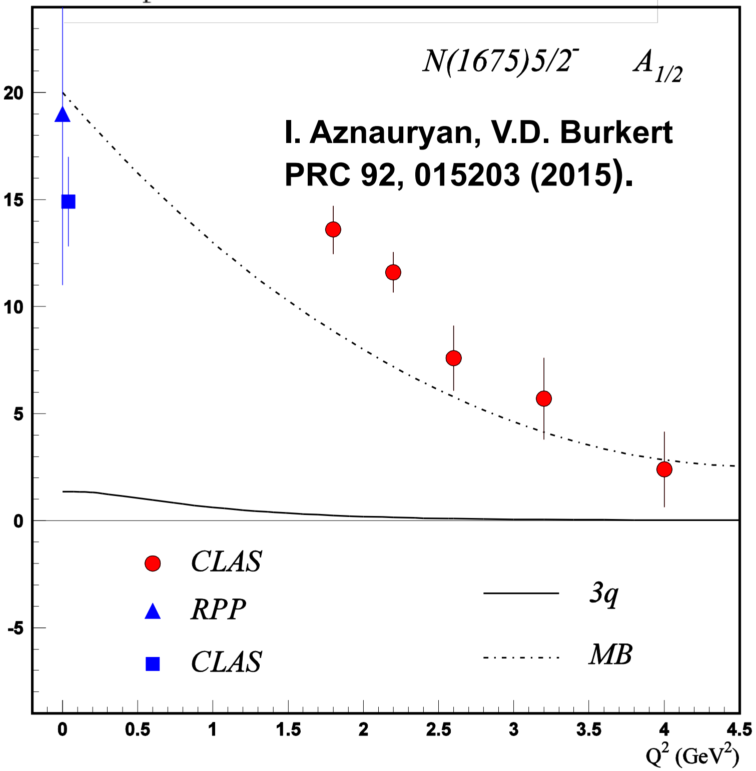
Meson-Baryon Cloud and Quark Core in the N* Structure

First estimates for meson-baryon cloud amplitudes from the CLAS data on resonance electrocouplings and DSE/LF RQM evaluations for the quark core



The mechanisms of the meson-baryon dressing





MB cloud is relevant at Q^2<1.5 GeV^2

MB cloud dominates at Q^2<4.5 GeV^2

- **The structure of all studied resonances is determined by a complex interplay between inner core of dressed quarks and external meson-baryon cloud.**

Peculiarities in the Structure of $\Delta(1620)1/2^-$

- Only known resonance with dominant longitudinal electroexcitation at $Q^2>0.5$ GeV^2 .
- QM with three quarks only failed in describing the resonance electropcouplings

<u>Hadron decays from the CLAS $\pi^+\pi^-p$ electroproduction data</u>

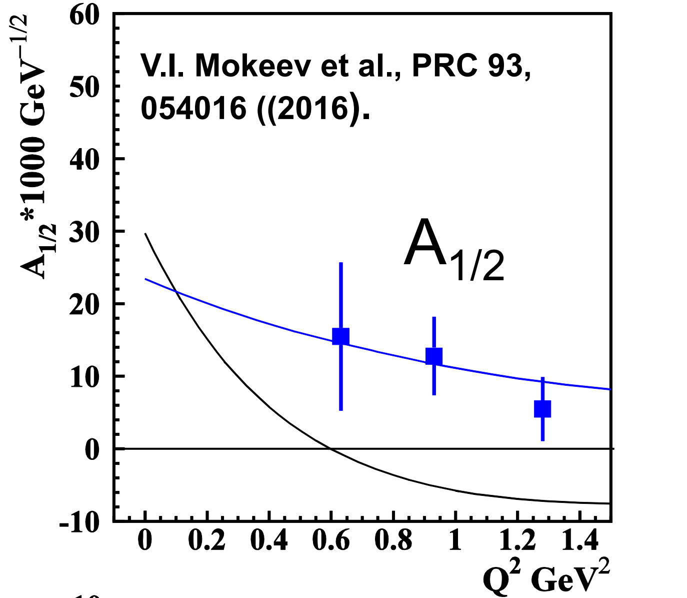
Channel	Branching Fraction, %
$\pi\Delta$	27-64
ρp	31-63

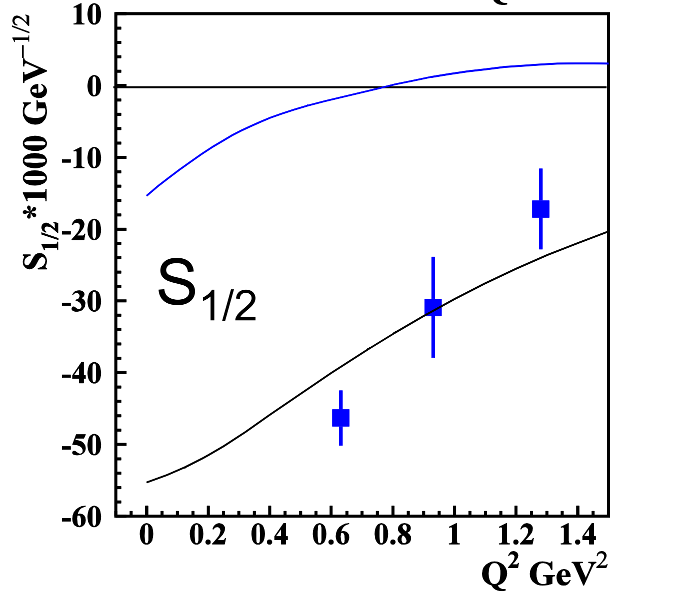
Large ρp decay in the sub-threshold region

↓

Suggestive for a substantial contribution from ρp loops :
- either to the MB-cloud or as
- penta-quark admixture in the quark core

Evaluation of $\Delta(1620)1/2^-$ electrocouplings at $Q^2>2.0$ GeV^2 (in progress).





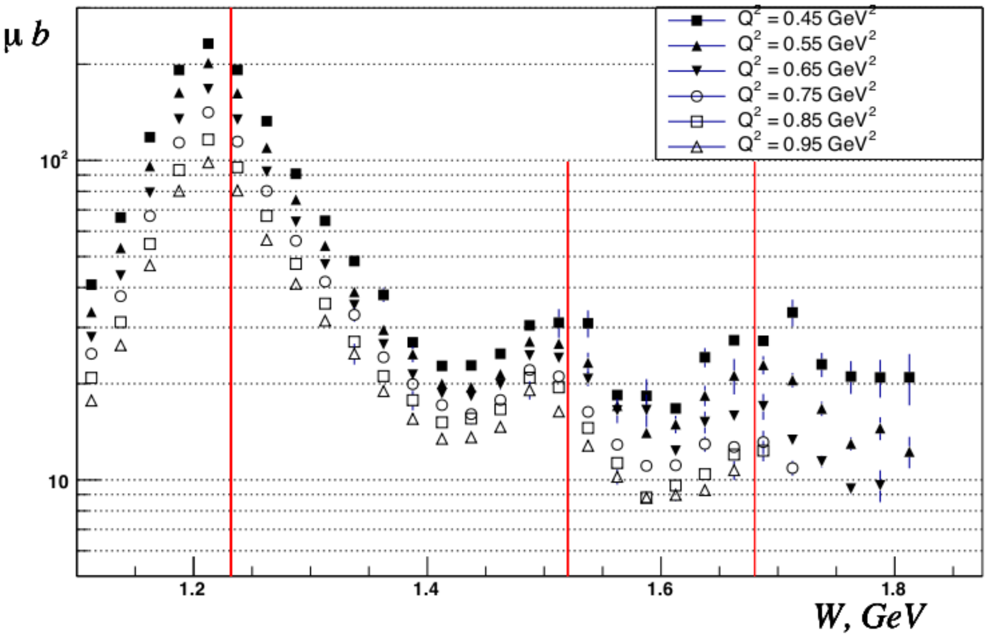
Hypercentral CQM: E.Santopinto, M.Giannini, PRC 86, 065202 (2012).

Bethe-Salpeter CQM M.Ronninger, B.Ch.Metsch,EPJ, A49, 8 (2013).

New CLAS Results on $\pi^0 p$ electroproduction

N. Markov, K.Joo, UCONN

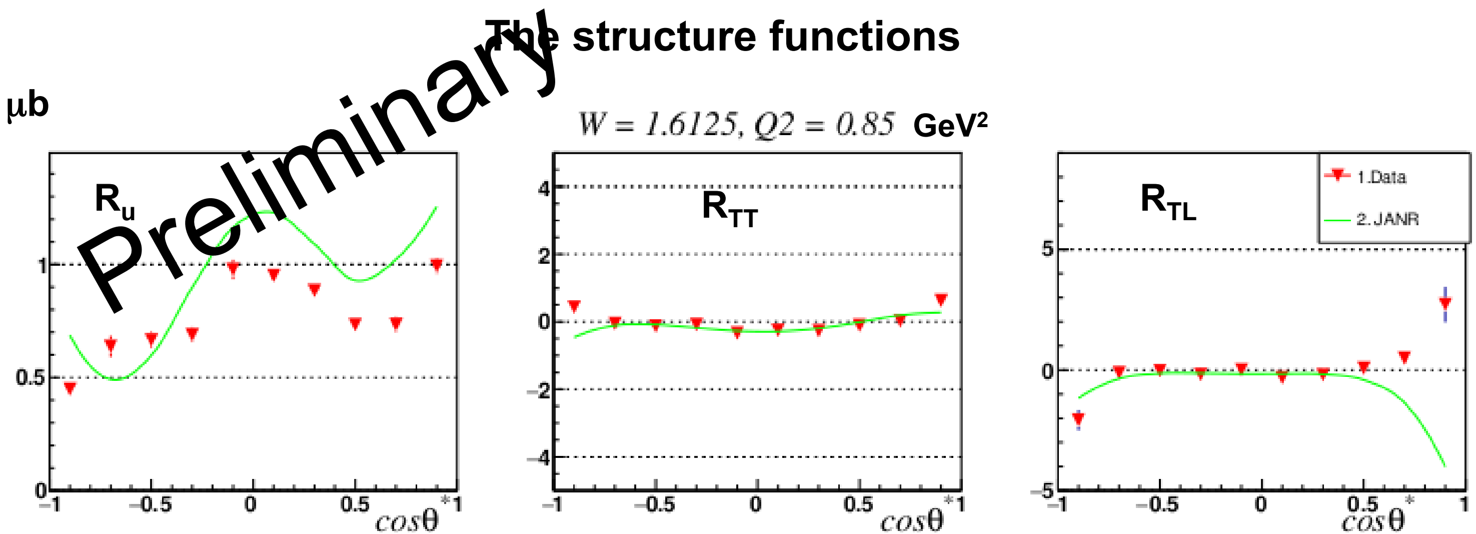
Fully integrated cross sections



1.10GeV<W<1.80 GeV, 0.3 GeV^2<Q^2<1.0 GeV^2

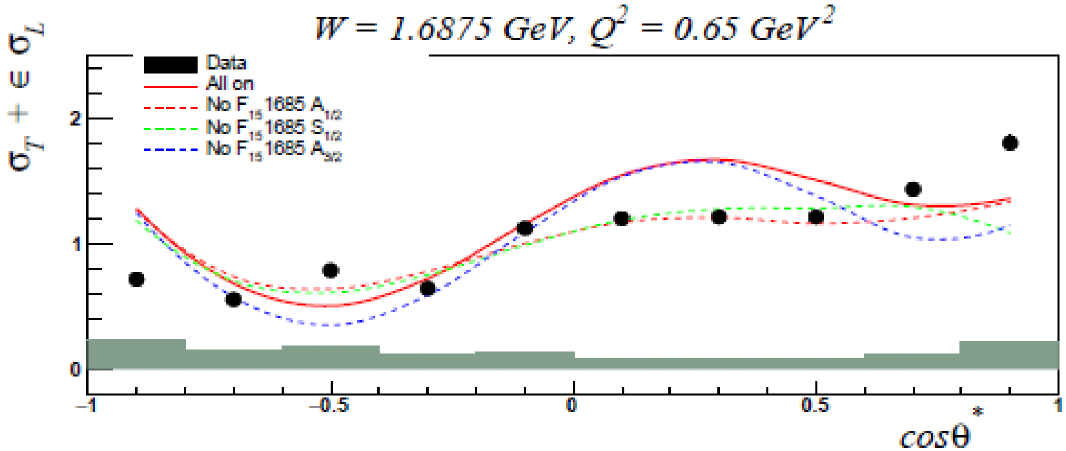
Fit of the structure functions within the framework of UIM/DR (slide#6,7) will provide electrocouplings of the resonances in mass range up to 1.8 GeV with substantial decays to the $N\pi$ final state.

The structure functions

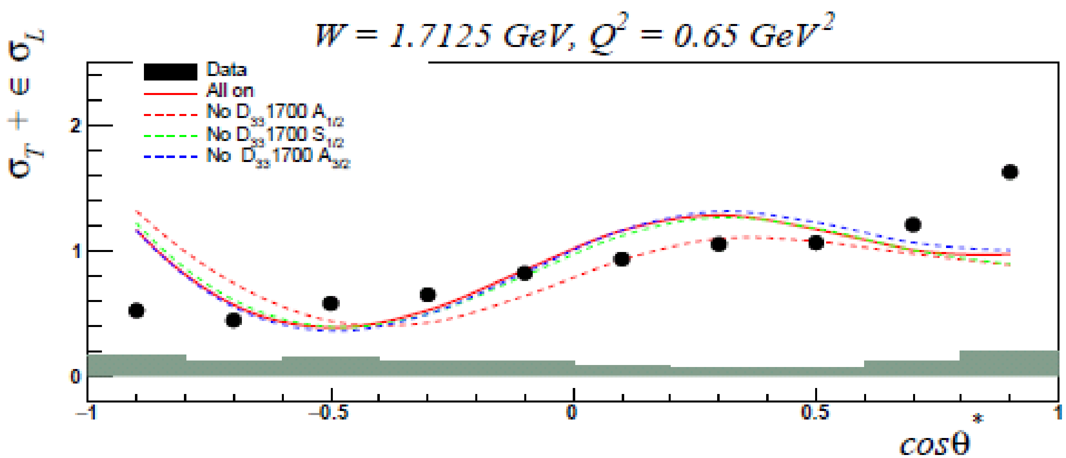


Sensitivity of the $\pi^0 p$ Electroproduction off Protons Data to Electrocouplings of the Excited Nucleon States in the 3-rd Resonance Region

- Structure functions were evaluated within the UIM (see slide # 7)
- $\gamma_v pN^*$ electrocouplings and hadronic decay widths were taken from previous analyses of the CLAS $N\pi$ and $\pi^+\pi^- p$ electroproduction off protons data.
- The data on unpolarised structure functions are compared with the UIM expectations accounting for all relevant resonances and when particular $\gamma_v pN^*$ amplitudes were switched off .



Sensitivity to electrocouplings of N(1680)5/2$^-$



Sensitivity to electrocouplings of Δ(1700)3/2$^-$

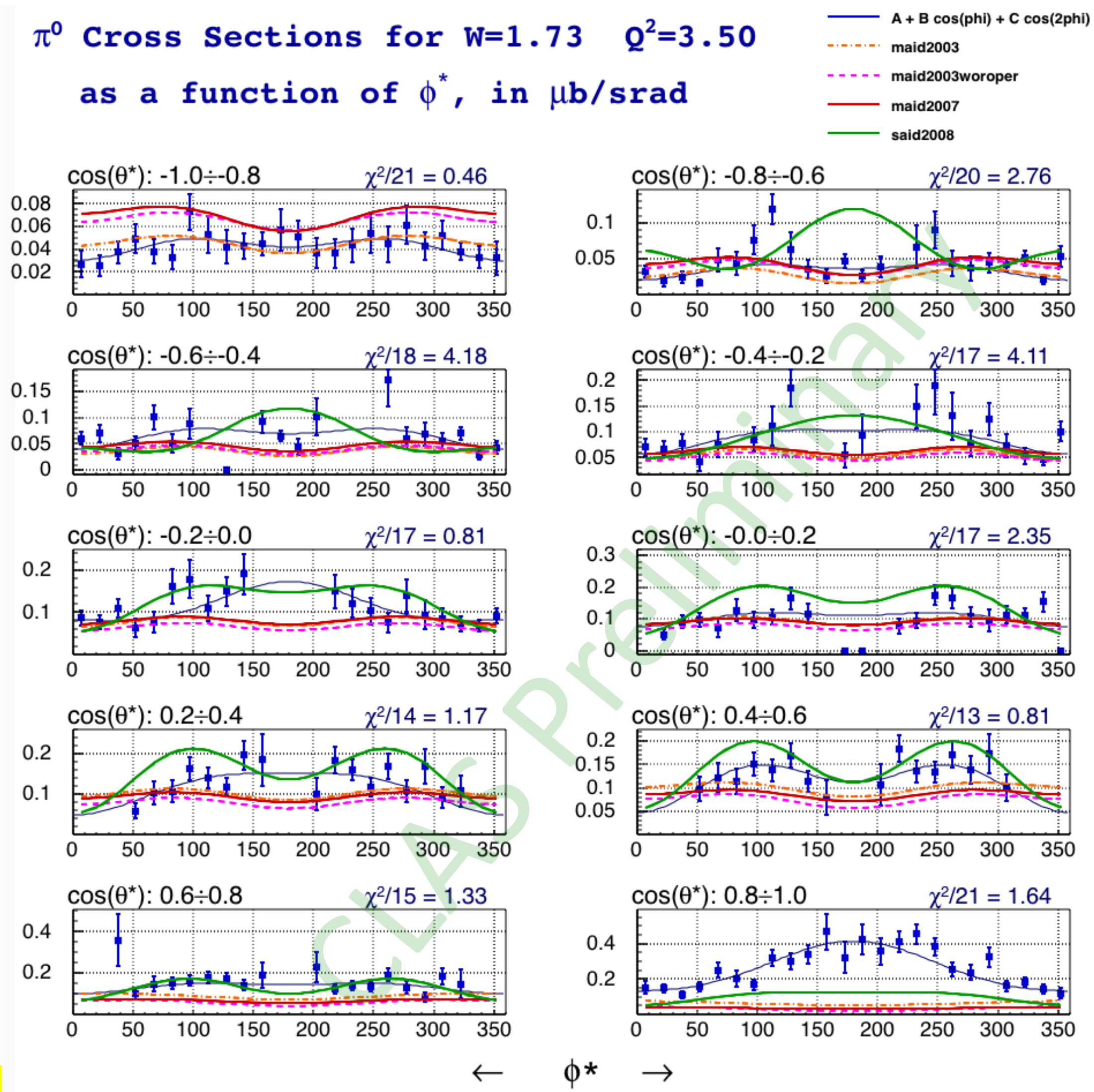
Preliminary Results – very high W

$d\sigma/d\Omega^* = \sigma_T + \varepsilon\sigma_L + \varepsilon\sigma_{TT}\cos 2\phi + \sqrt{2\varepsilon(\varepsilon+1)}\sigma_{LT}\cos\phi$

$$\sigma_L + \varepsilon\sigma_T = a$$

$$\sigma_{LT} = \frac{b}{\sin\theta\sqrt{2\varepsilon(\varepsilon+1)}}$$

$$\sigma_{TT} = \frac{c}{\sin^2\theta\,\varepsilon_T}$$

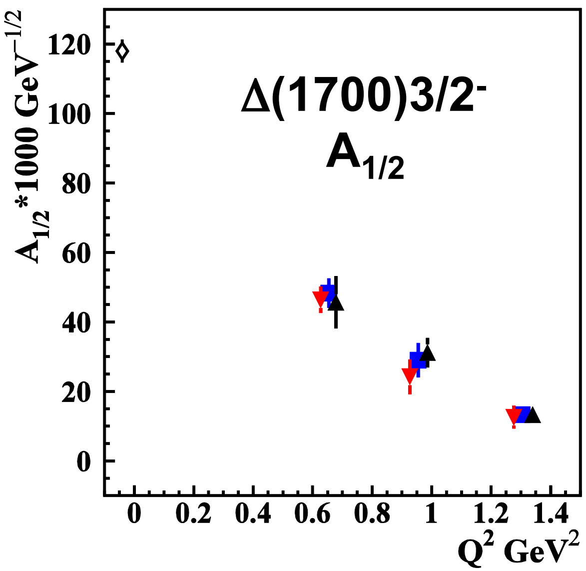


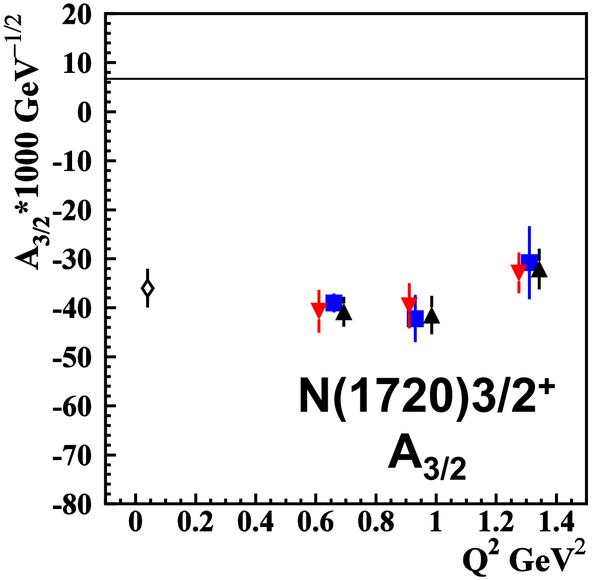
M.Ungaro, talk at INT N* Workshop 2016

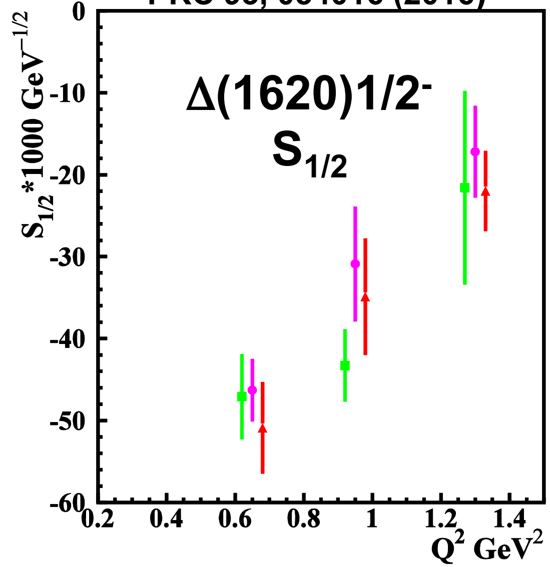
Electrocouplings of the Orbital Excited Resonances from the CLAS $\pi^+\pi^-p$ Electroproduction Data

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)







<u>Independent fits in different W-intervals:</u>

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**

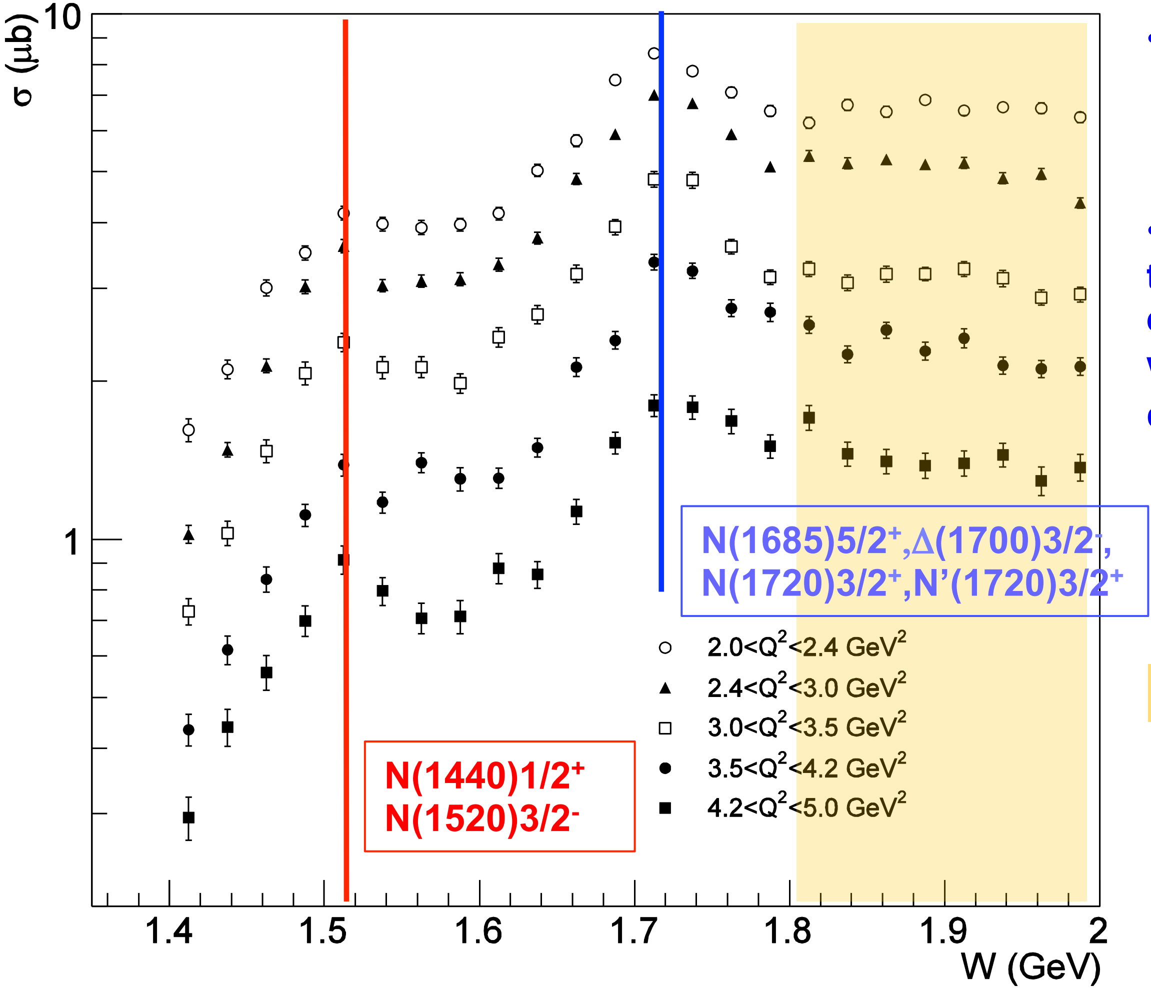
The $\pi^+\pi^-p$ electroproduction data are the major source of the information on electrocouplings of the Δ(1620)1/2⁻, Δ(1700)3/2⁻, and N(1720)3/2⁺ resonances <u>which decay preferentially to the Nππ final states</u>.

The CLAS $\pi^+\pi^-p$ Electroproduction Data at High Photon Virtualities

Fully integrated $\pi^+\pi^-p$ electroproduction cross sections off protons

E.L. Isupov, K. Hicks, MSU/Ohio Univ.

1.40 GeV<W<2.00 GeV, 2.00 GeV^2<Q^2<5.0 GeV^2

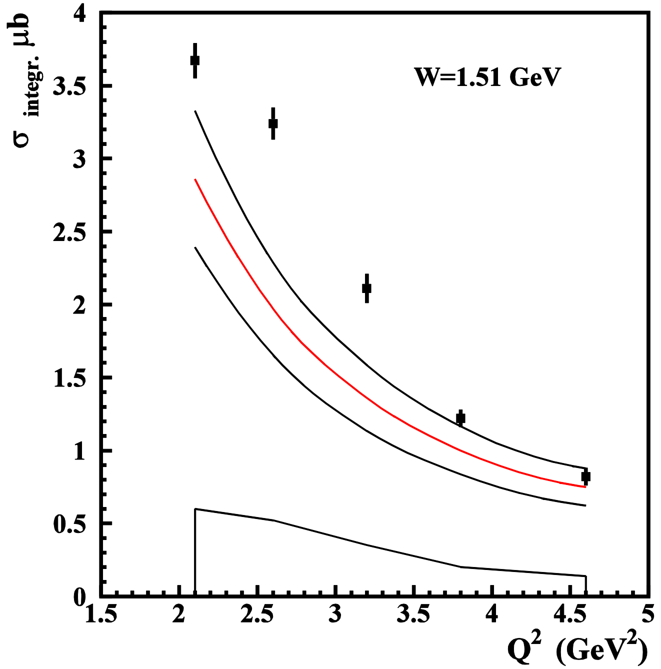


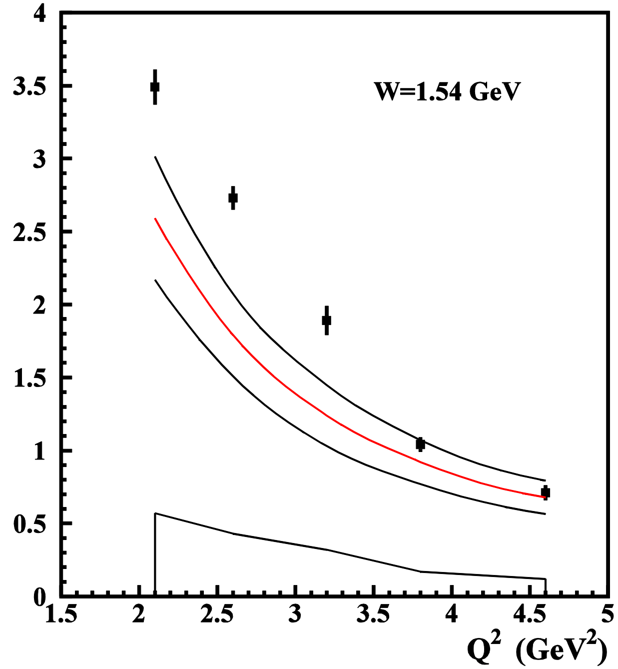
Analysis objectives:

- **Extraction of $\gamma_v pN^*$ electrocouplings for most N*s in mass range up to 2.0 GeV and 2.0< Q^2< 5.0 GeV^2 .**
- **Search for new baryon states through their manifestations in exclusive $\pi^+\pi^-p$ electroproduction with Q^2-independent masses and decay widths.**

Mass range where the signals from new baryon states were reported, A.V. Anisovich et al., Eur. Phys. J. A48, 15 (2012).

Q^2-Evolution of the Resonant Contributions to the $\pi^+\pi^-p$ Electro-production off Protons Cross sections at 2.0 GeV^2 < Q^2 < 5.0 GeV^2





Resonant cross sections:

Central values

Uncertainty range

Data point error bars show the stat. uncertainty

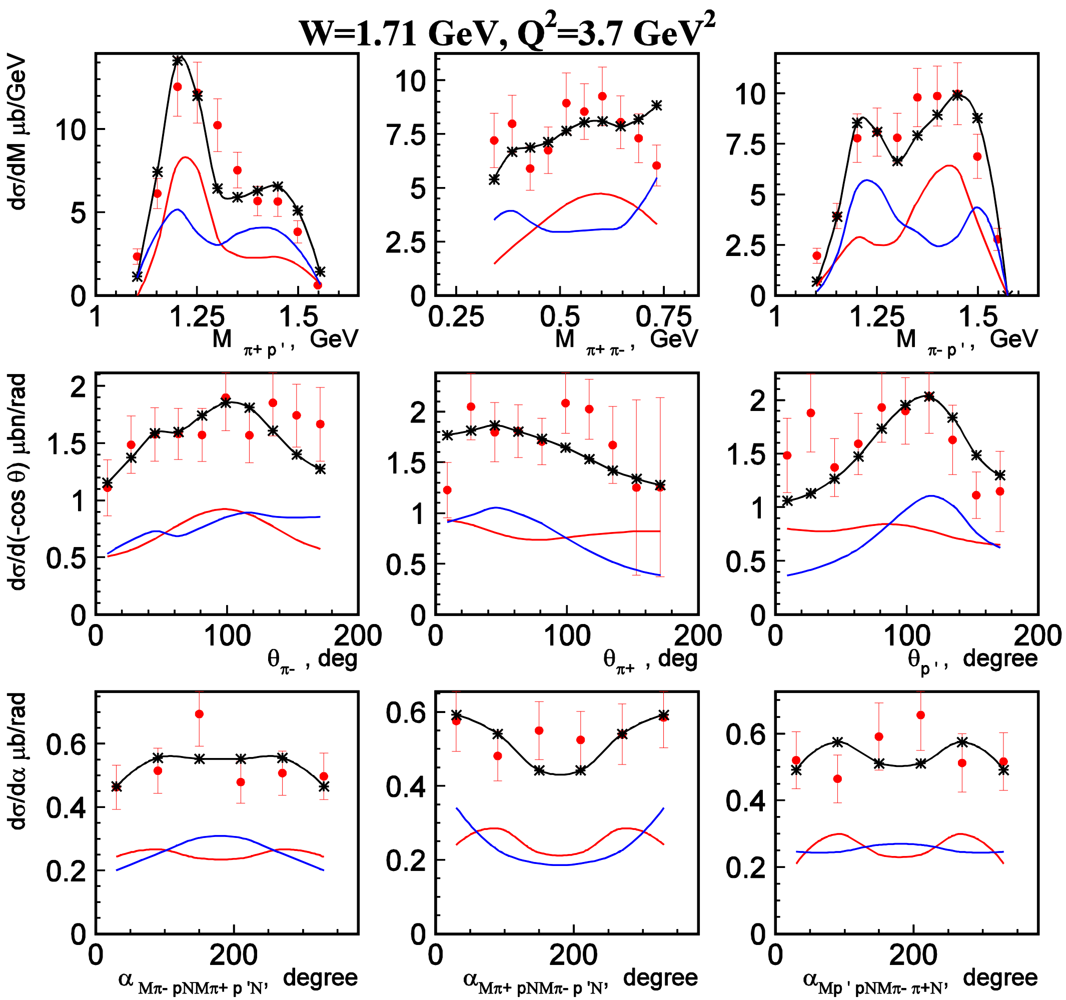
Bands on the bottom are the data syst. uncertainties

- **Resonant contributions were computed within the framework of unitarized Breit-Wigner ansatz successfully used for extraction of the resonance electrocouplings.**

- **$\gamma_v pN^*$ electrocouplings and $\pi\Delta$/ ρp decay widths were taken from the CLAS results**

Growth of the relative resonant contributions with Q^2 suggests good prospects for extraction of $\gamma_v pN^*$ electrocouplings in the entire range of 2.0 GeV^2<Q^2<5.0 GeV^2 .

Description of the Differential $\gamma_v p \rightarrow \pi^+\pi^- p$ Cross Sections at 2.0 GeV^2<Q^2 <5.0 GeV^2 within the Updated JM17 model



JM17 model;

- **no new mechanisms in comparison with JM15 (slide #6).**
- **modifications for the non-resonant amplitudes of the $\pi\Delta$, ρp, and $\pi^+N(1680)5/2^+$ meson-baryon channels.**

<u>Resonant & non-resonant contributions from JM17 model:</u>

Full

Resonant contribution

Non-resonant contribution

- **A good description of data at 1.4 GeV < W < 2.0 GeV and 2.0 GeV^2 < Q^2 < 4.2 GeV^2 was achieved with χ^2/d.f. < 1.4.**

Extension of the Experimental Results on $\gamma_v pN^*$ Electrocouplings and the Need for the Theory Support

- $\gamma_v pN^*$ electrocouplings of all prominent nucleon resonances in mass range M_{N^*}<2.0 GeV and at $0.3<Q^2<5.0$ GeV^2 will be determined from independent analyses of $N\pi$, $N\pi\pi$, channels measured with the CLAS .

- The information on the structure of orbital excited N* with total orbital momenta of dressed quarks L=1 and L=2 will become available for the first time.

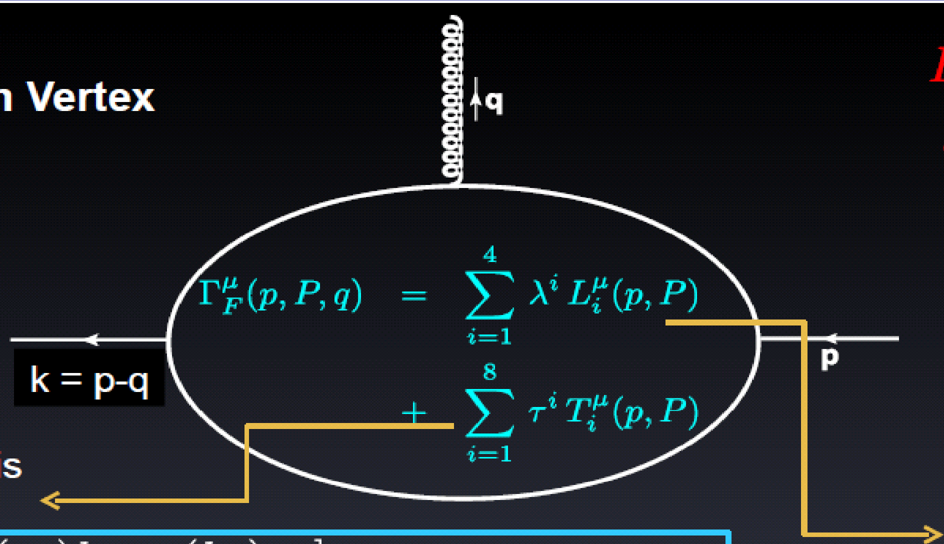
- DSE evaluations of the $[70,1^-]$, $[56,2^+]$ $SU_{sf}(6)$-multiplet electrocouplings will extend the access to the strong QCD dynamics allowing us to address:
  - a) environmental sensitivity of the quark mass function to orbital excitations of three dressed quarks;
  - b) complexity of quark-gluon vertex dressing beyond rainbow-ladder truncation;
  - c) first studies of pseudoscalar and vector di-quark correlations.

- New data on $\gamma_v pN^*$ electrocouplings will shed light on dymaical Chiral Symmetry Breaking (DCSB) and its evolution with distance from studies of the chiral partners $\Delta(1232)3/2^+/\Delta(1700)3/2^-$ as the first step.

Orbital Excited N* and Quark-Gluon Vertex

Quark Gluon Vertex

$$P = k + p$$
$$q = k - p$$



$$\Gamma_F^\mu(p,P,q) = \sum_{i=1}^{4} \lambda^i L_i^\mu(p,P) + \sum_{i=1}^{8} \tau^i T_i^\mu(p,P)$$

$$\begin{aligned}
T_{1_\mu} &= -i\,[(pq)k_\mu - (kq)p_\mu] \\
T_{2_\mu} &= -\,\not{P}\,[(pq)k_\mu - (kq)p_\mu] \\
T_{3_\mu} &= \not{q}\,q_\mu - q^2\gamma_\mu \\
T_{4_\mu} &= -i\left[q^2\sigma_{\mu\nu}P_\nu + 2q_\mu\sigma_{\nu\lambda}p_\nu k_\lambda\right] \\
T_{5_\mu} &= -i\,\sigma_{\mu\nu}q_\nu \\
T_{6_\mu} &= (qP)\gamma_\mu - \not{q}\,P_\mu \\
T_{7_\mu} &= -\frac{i}{2}(qP)\sigma_{\mu\nu}P_\nu - i\,P_\mu\,\sigma_{\nu\lambda}\,p_\nu\,k_\lambda \\
T_{8_\mu} &= -\gamma_\mu\,\sigma_{\nu\lambda}\,p_\nu\,k_\lambda - \not{p}\,k_\mu + \not{k}\,p_\mu
\end{aligned}$$

$$\begin{aligned}
L_{1_\mu} &= \gamma_\mu \\
L_{2_\mu} &= -\,\not{P}P_\mu \\
L_{3_\mu} &= -i\,P_\mu \\
L_{4_\mu} &= -i\,\sigma_{\mu\nu}P_\nu
\end{aligned}$$

<u>Simplest rainbow-ladder (RL) truncation</u>: All structures $L_{i\mu}$ are equal to zero except $L_{1\mu}$.

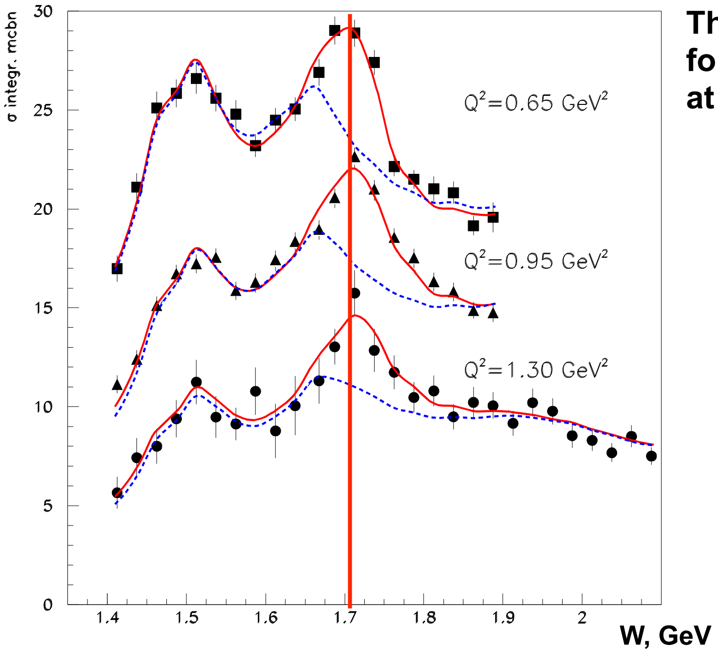
Far from reality, but a reasonable approximation for the states with orbital momentum of quarks L=0.

Dressing of quark-gluon vertex beyond RL-truncation produces nonzero quark orbital angular momenta.

Talks by: D.Binosi, A.Kizilerzu, J. Papavassiliou , G.Eichmann at NPQCD16 Workshop: www.uhu.es gem/meeting/QCDNP201 program-LP.php

Electrocouplings of N* states with nonzero quark orbital angular momentum extend the capabilities for access to the complexity of quark-gluon vertex dressing beyond the simplest rainbow-ladder truncation.

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



The structure at W~1.7 GeV represents the major feature for W-dependencies of fully integrated cross sections at 0.5 GeV^2 < Q^2 < 5.0 GeV^2 (see also slide # 20).

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 Branching Fraction (BF) 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.

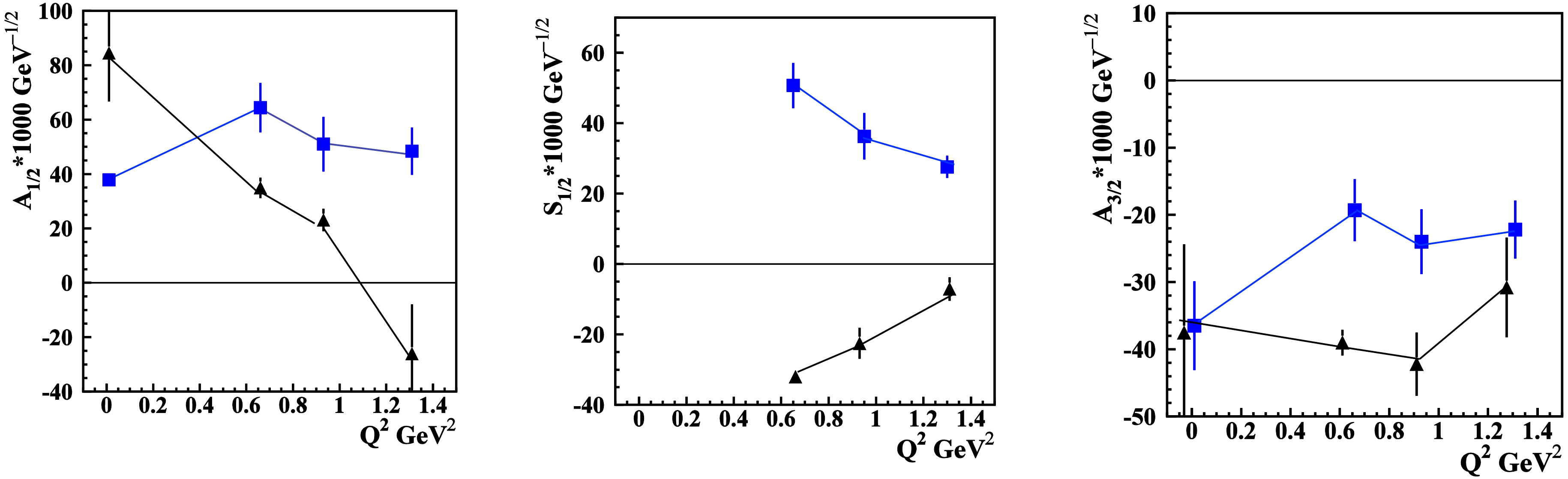
N* hadronic decays from the data fit that incorporates the new N'(1720)3/2$^+$ state

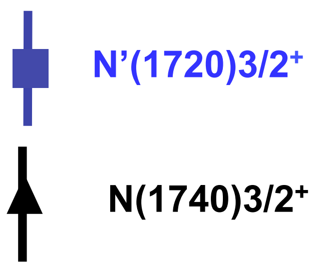
Resonance	BF($\pi\Delta$), %	BF(ρp), %
N'(1720)3/2$^+$ electroproduction photoproduction	 47-64 46-62	 3-10 4-13
N(1720)3/2$^+$ electroproduction photoproduction	 39-55 38-53	 23-49 31-46
Δ(1700)3/2$^-$ electroproduction photoproduction	 77-95 78-93	 3-5 3-6

Successful description of $\pi^+\pi^-p$ 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 new N'(1720)3/2$^+$ state.

The Parameters of N’(1720)3/2$^+$ and N(1740)3/2$^+$ from the CLAS Data Fit

The photo-/electrocouplings of N’(1720)3/2$^+$ and conventional N(1740)3/2$^+$ states:





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* at 0.05 GeV^2 < Q^2 < 7.0 GeV^2 with the CLAS12

Hybrid Baryons PR12-16-010	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 PR12-16-010A	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

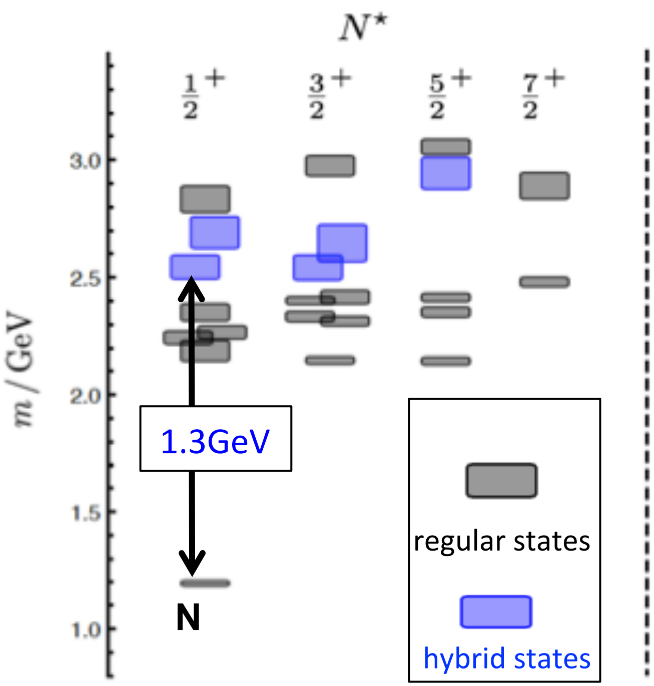
Run Group conditions:
E_b = 6.6 GeV, 50 days
E_b = 8.8 GeV, 50 days

- 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?

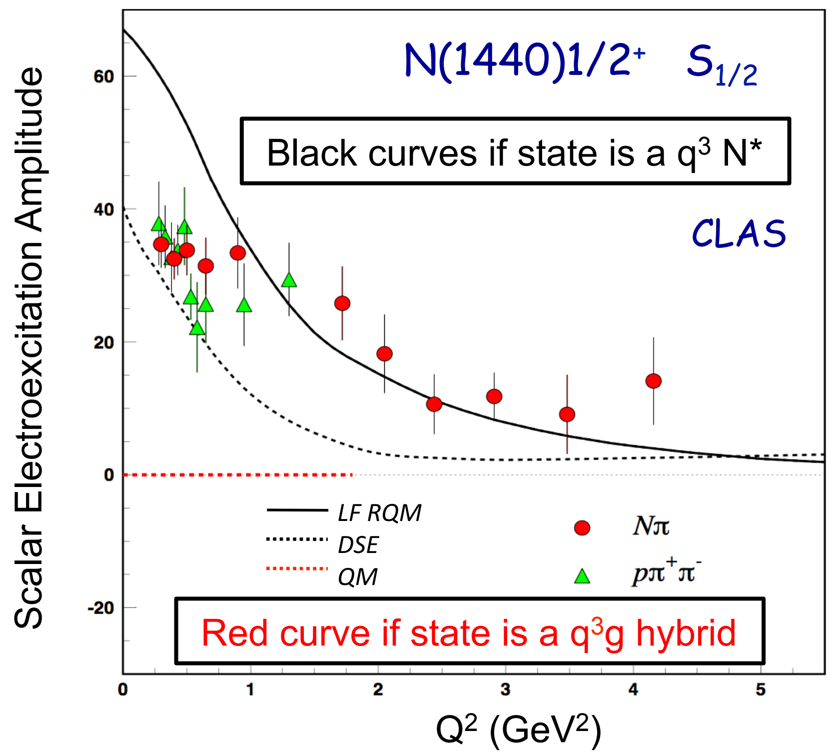
Predictions of the N* spectrum from QCD show both regular q^3 *and* hybrid q^3g states



JLab LQCD group results

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

The only way to establish the nature of a baryon state as q^3 or q^3g is from the Q^2 evolution of its electroexcitation amplitudes



CLAS12 N* Program at High Q^2

E12-09-003	E12-06-108A
Nucleon Resonance Studies with CLAS12	KY Electroproduction with CLAS12
Burkert, Mokeev, Stoler, Joo, Gothe, Cole	*Carman, Mokeev, Gothe*

- 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 the almost 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 foreseen in the world capable to map-out N quark core under almost negligible contributions from meson-baryon cloud*

The experiments will start at the end of 2017!

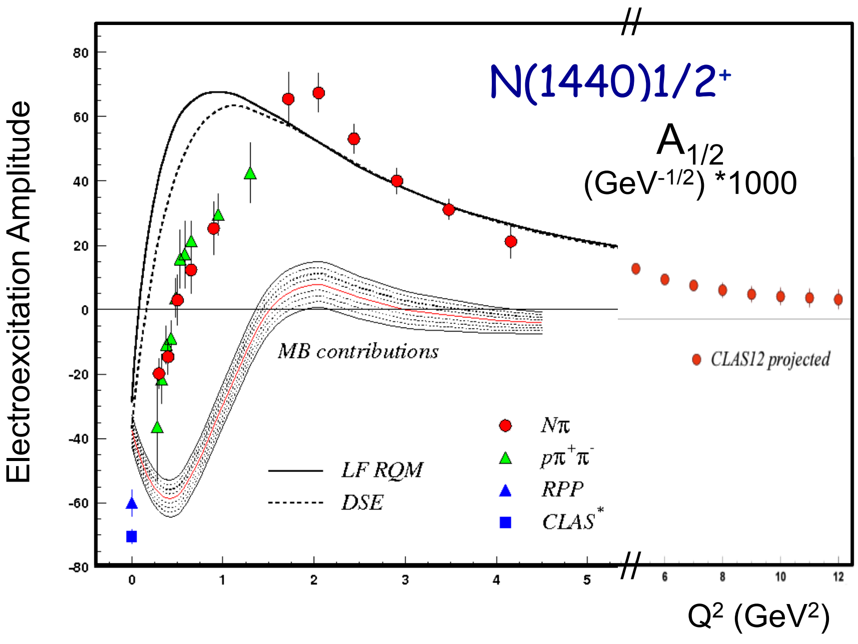
Emergence of Hadron Mass and Quark-Gluon Confinement

N* electroexcitation studies with CLAS12 in Hall B at JLab will address the critical open questions:

How is >98% of visible mass generated,?

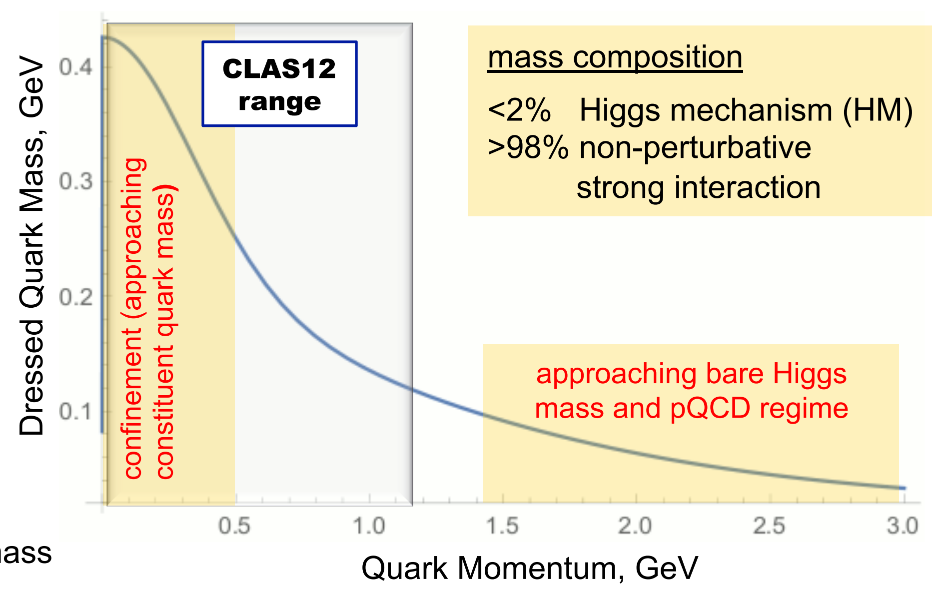
How confinement emerges from QCD and how it is related to DCSB?

Mapping-out quark mass function from the CLAS12 results on $\gamma_v pN^*$ electrocouplings of spin-flavor 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 with a traceable connection to the QCD Lagrangian.



CLAS results versus theory expectations with running quark mass

Access to the dressed quark mass function



Conclusions and Outlook

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

- **<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 between the DSE theory and the experimental studies of $\gamma_v pN^*$ electrpocouplings at JLAB revealed access to quark mass function for the first time.
  c) reaction model developments pave a way to relating quark mass function to the measured observables of $N\pi$ and $\pi^+\pi^-p$ electroproduction channels based on DSE input for the low-mass N* electrocouplings.

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

- **Future analyses the CLAS results on electrocouplings of N* resonances within the QCD-based framework will extend insight to the strong QCD dynamics addressing:**
  a) the environmental sensitivity/universality of dressed quark mass function,
  b) complexity of the dressed quark-gluon vertex and qq-interaction kernel ,
  c) shed light on the DCSB manifestation in the structure of chiral partners $\Delta(1232)\ 3/2^+$ and $\Delta(1700)3/2^-$.

Conclusions and Outlook

- **After 12 GeV Upgrade, CLAS12 will be only available worldwide facility 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 photo virtialities ever achieved for exclusive reactions from 5.0 GeV^2 to 12 GeV^2 from the measurements of exclusive Nπ, $\pi^+\pi^-$p, and KY electroproduction.**

- **The expected results will allow us:**
  a) search for hybrid-baryons and other new states of baryon matter;
  b) to map out the dressed quark mass function at the distance scales where the transition from quark-gluon confinement to pQCD regime is expected, addressing the most challenging problems of the Standard Model on the nature of >98% of hadron mass and quark-gluon confinement.

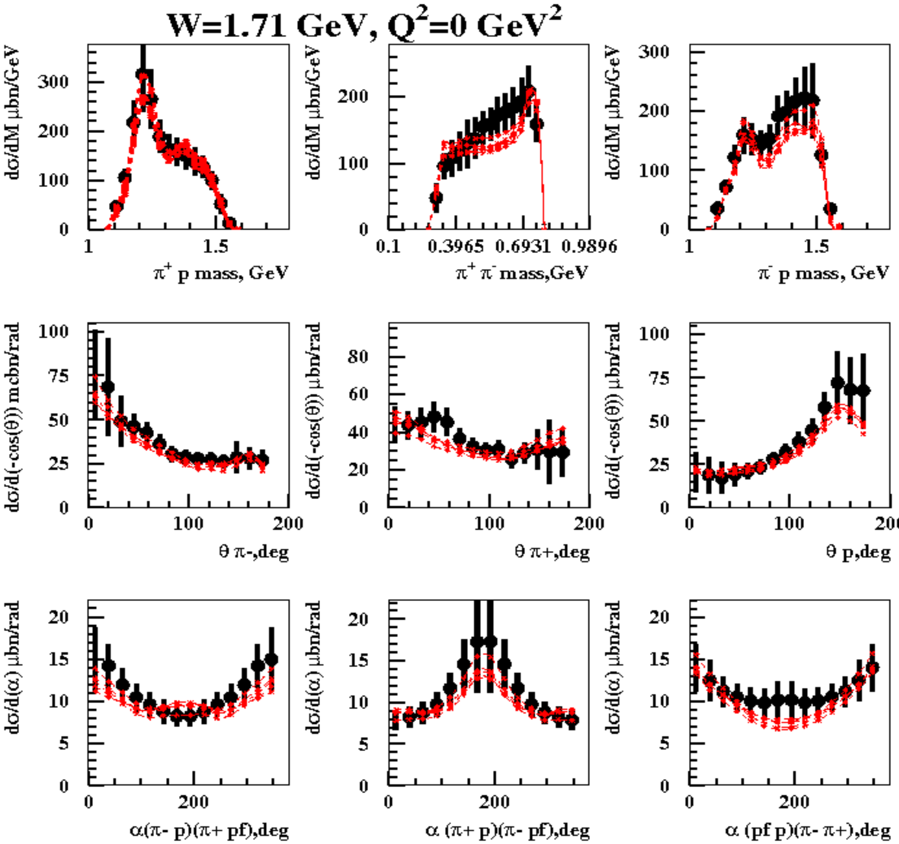
- **Success of N* Program with the CLAS12 detector at Jefferson Lab will be very beneficial for hadron physics community . It requires close collaborative efforts between experiment, phenomenology and the QCD-based hadron structure theory.**

Back up

Analysis of the $\gamma p/ep \rightarrow \pi^+\pi^- p$ CLAS data at W~1.7 GeV in the JM15 model

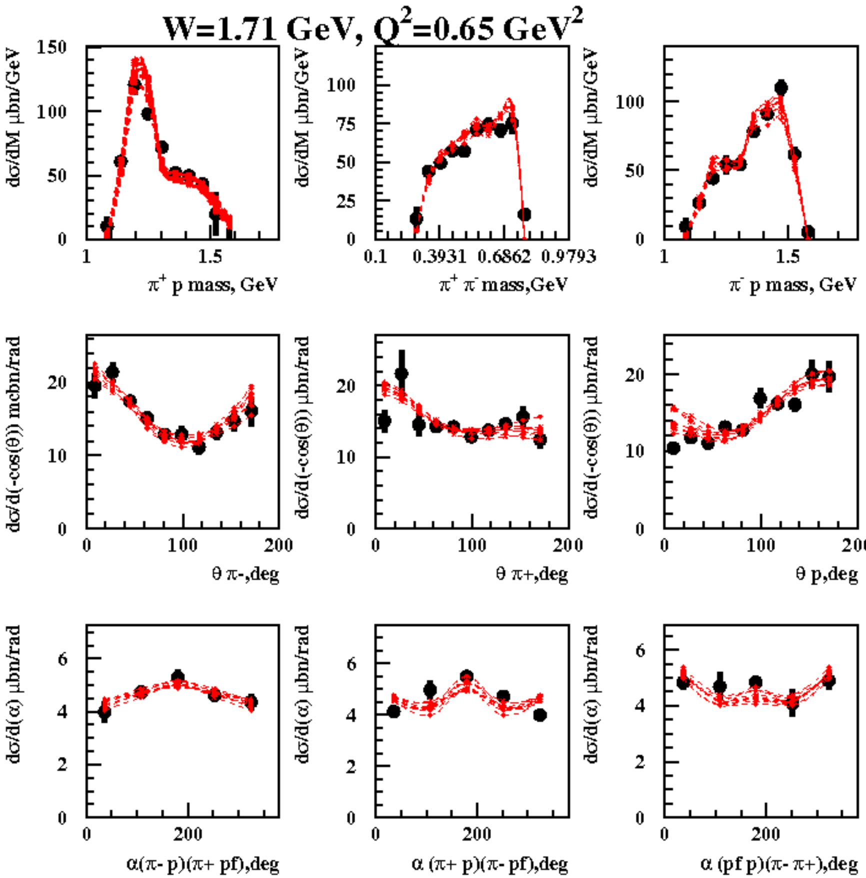
Photoproduction

$1.17<\chi^2$/d.p.<1.31 (1.66 GeV<W<1.76 GeV)



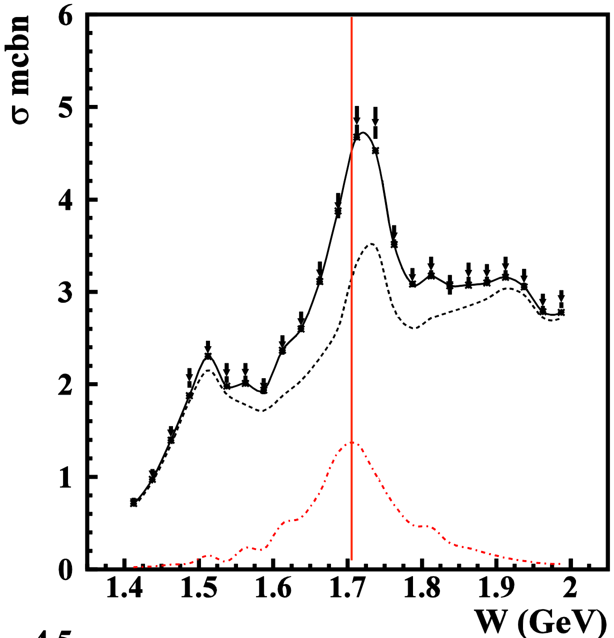
Electroproduction

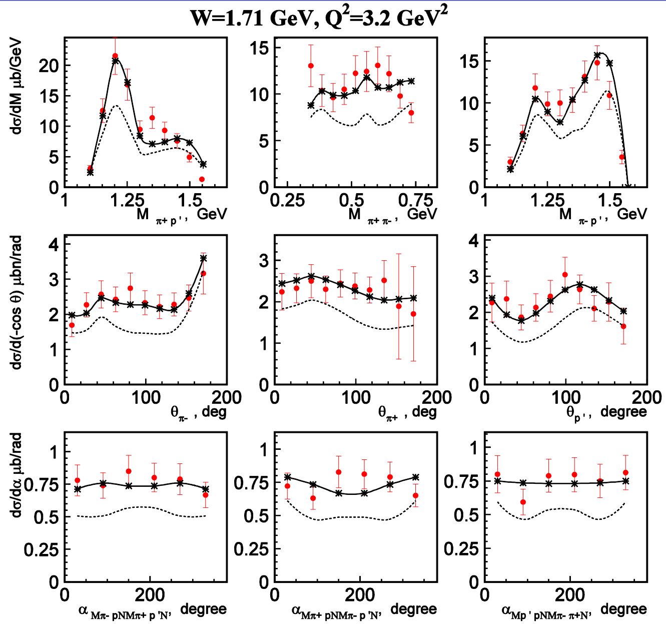
$2.56<\chi^2$/d.p.<2.80 (1.66 GeV<W<1.76 GeV)



- Fit of $\theta_{\pi-}$, $\theta_{\pi+}$, θ_p angular distributions requires essential contribution(s) from $J^\pi=3/2^+$ resonances
- Accounting for the known resonances only results in <u>contradictory values</u> for the N(1720)$3/2^+$ BF to the ρp final state inferred from the photo- and the electroproduction data

N'(1720)3/2$^+$ New State at 2.0 GeV^2 < Q^2 < 5.0 GeV^2



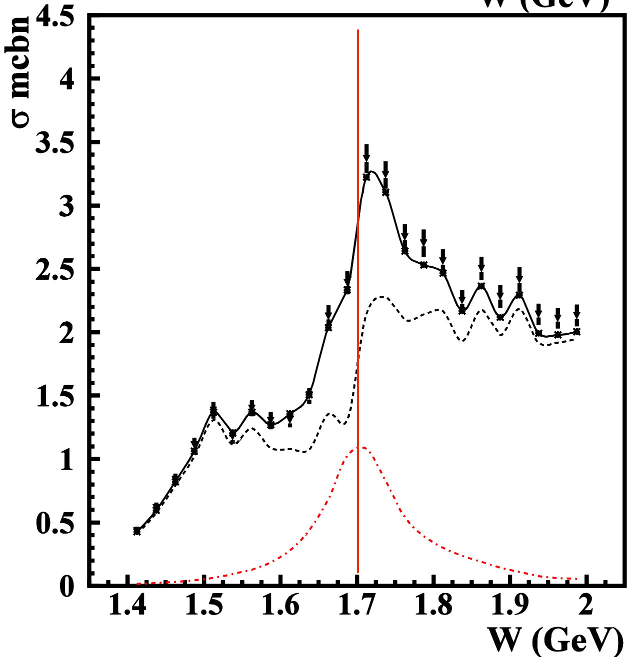


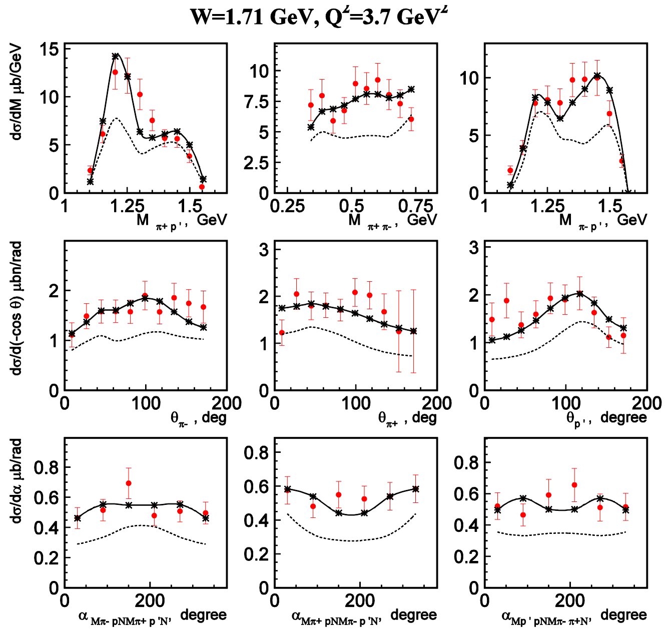
<u>Data description in the JM17 model:</u>

full

no N'(1720)3/2$^+$

difference with/without N'(1720)3/2$^+$

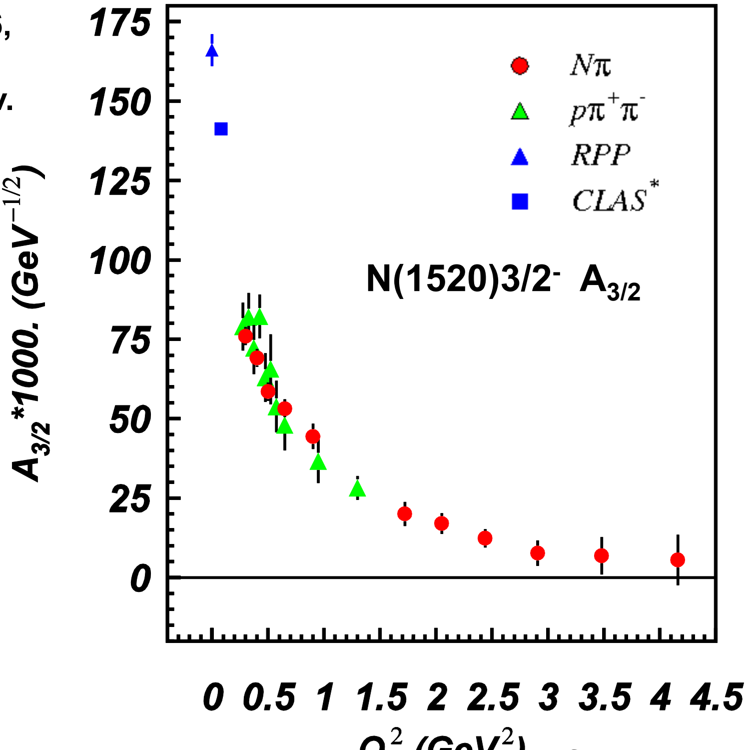


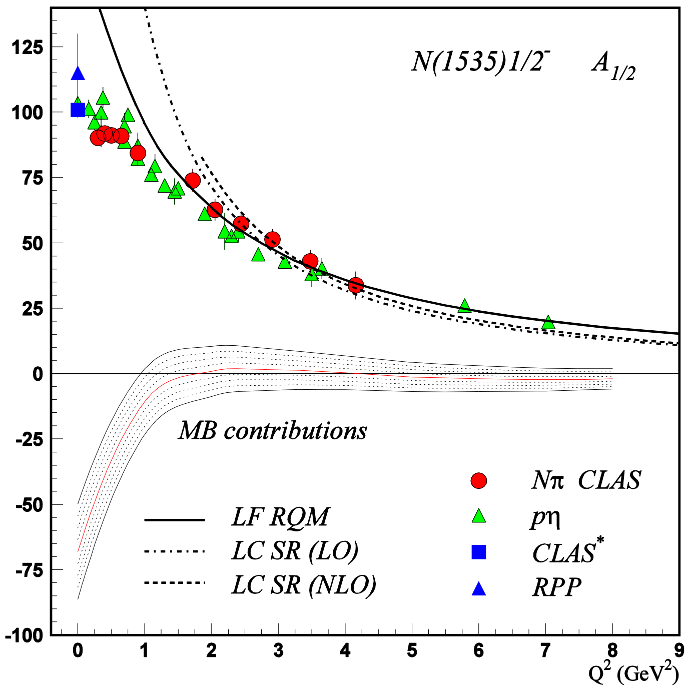


CLAS data will elucidate the N'(1720)3/2$^+$ structure at 0.0<Q^2<5.0 GeV^2 for the first time.

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

H Denizli et al., Phys. Rev. C76, 015204 (2007).
I.G. Aznauryan et al., Phys. Rev. C80, 055203 (2009).
V.I. Mokeev et al., Phys. Rev . C86, 035203 (2012).
K. Park et al., Phys. Rev. C91, 052014 (2015).
V.I. Mokeev et al., Phys. Rev . C93, 054016 (2016).





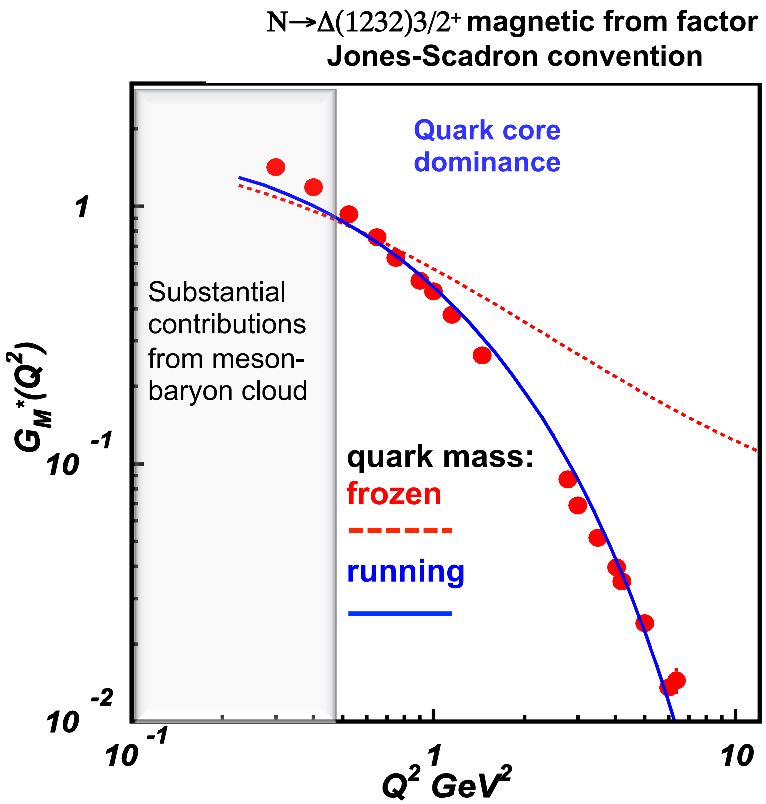
Consistent values of resonance electrocouplings from analyses of $N\pi$/ $\pi^+\pi^-p$ and $N\pi/N\eta$ electroproduction off protons demonstrate the capabilities of the developed reaction models to obtain resonance electrocouplings in independent analyses of these exclusive channels.

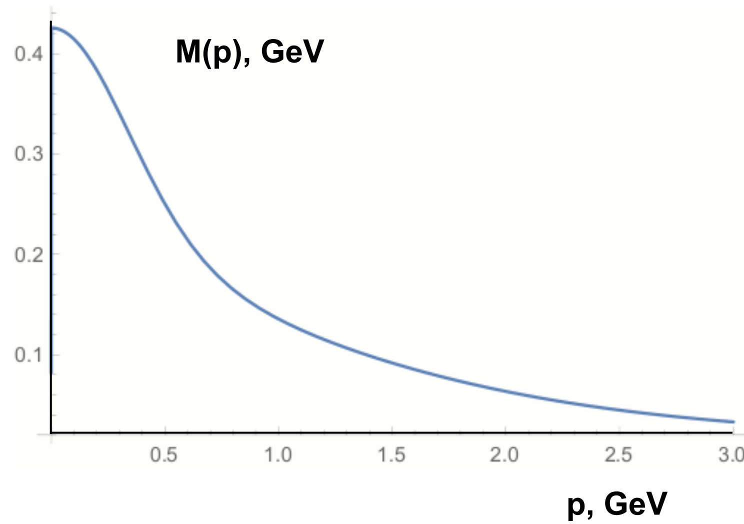
Electrocouplings of $\Delta(1232)3/2^+$, $N(1440)1/2^+$, $N(1520)3/2^-$, $N(1535)1/2^-$, $N(1675)5/2^-$, $N(1680)5/2^+$, $N(1710)1/2^+$ were published in the recent edition of the PDG , Chin. Phys. C40, 100001 (2016).

Nature of the Hadron Mass from N* Electroexcitation

Dyson-Schwinger Equations (DSE):

- **J. Segovia et al., Phys .Rev. Lett. 115, 171801 (2015).**
- **J. Segovia et al., Few Body Syst. 55, 1185 (2014).**





Common dressed quark mass function employed for description of elastic, N→Δ G_M form factors and N(1440)1/2⁺ electrocouplings/form factors

- **Good CLAS data description at the distances where quark core is the biggest contributor (Q^2>0.8 GeV^2), was achieved with realistic qq-interaction that generates momentum dependent quark mass.**
- **Data on Δ(1232)3/2⁺ electroexcitation from CLAS for the first time demonstrated that dressed quark mass which is running with momentum.**