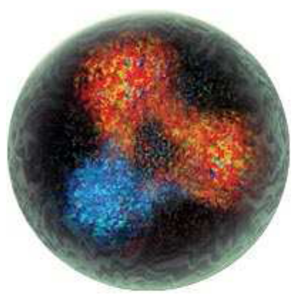
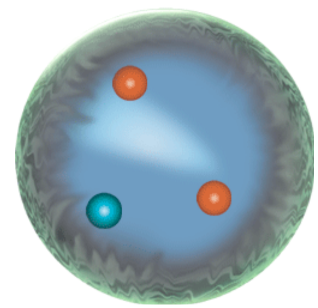
N*-Transition Form Factor Program at JLab

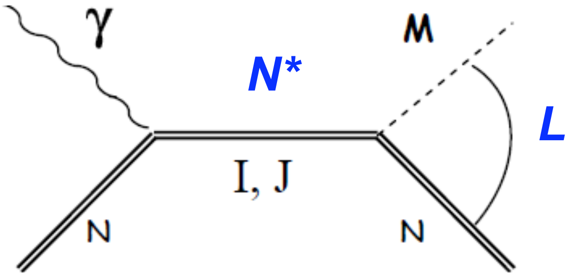
II WORKSHOP ON HADRON PHYSICS IN CHINA AND OPPORTUNITIES WITH 12 GEV JLAB

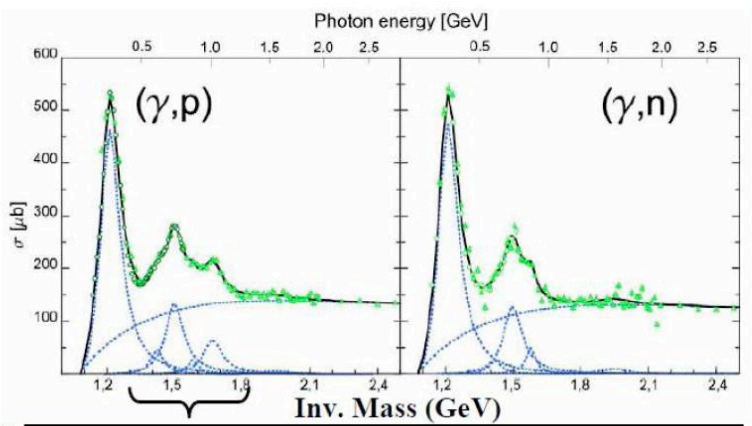




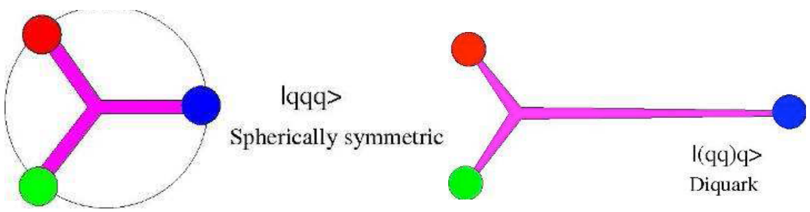
Philip Cole
Idaho State University
July 29, 2010

Motivation





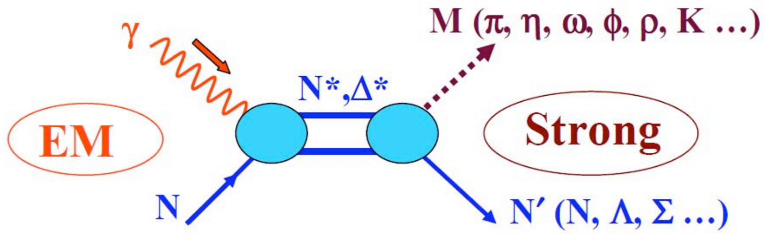
Second resonance region: $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$

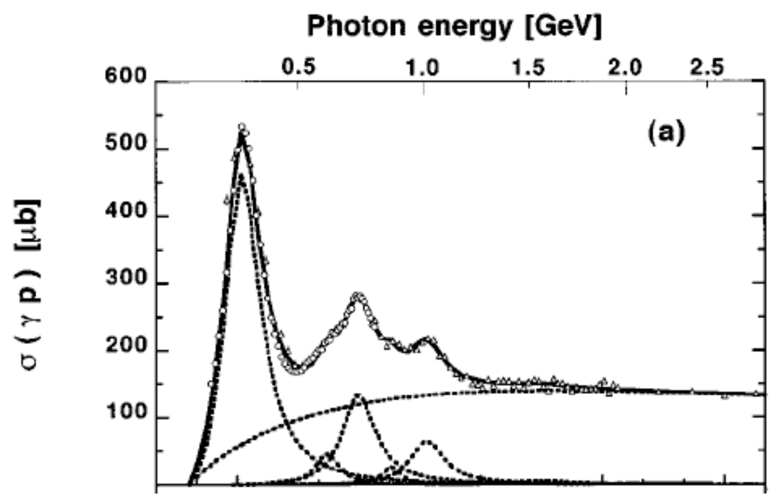


$L_{2I\ 2J}$

N*	Status	SU(6) ⊗ O(3)	Parity	Δ*	Status	SU(6) ⊗ O(3)
P11(938)	****	$(56,0^+)$	+	P33(1232)	****	$(56,0^+)$
S11(1535)[c]	****	$(70,1^-)$				
S11(1650)	****	$(70,1^-)$		S31(1620)	****	$(70,1^-)$
D13(1520)[c,d]	****	$(70,1^-)$	−	D33(1700)	****	$(70,1^-)$
D13(1700)	***	$(70,1^-)$				
D15(1675)	****	$(70,1^-)$				
P11(1520)	****	$(56,0^+)$		P31(1875)	****	$(56,2^+)$
P11(1710)[b]	***	$(70,0^+)$		P31(1835)		$(70,0^+)$
P11(1880)		$(70,2^+)$				
P11(1975)		$(20,1^+)$				
P13(1720)[b,c]	****	$(56,2^+)$		P33(1600)	***	$(56,0^+)$
P13(1870)[b]	**	$(70,0^+)$		P33(1920)	***	$(56,2^+)$
P13(1910)[a]		$(70,2^+)$	+	P33(1985)		$(70,2^+)$
P13(1950)		$(70,2^+)$				
P13(2030)		$(20,1^+)$				
F15(1680)[c,d]	****	$(56,2^+)$		F35(1905)	****	$(56,2^+)$
F15(2000)[a]	**	$(70,2^+)$		F35(2000)	**	$(70,2^+)$
F15(1995)		$(70,2^+)$				
F17(1990)	**	$(70,2^+)$		F37(1950)	****	$(56,2^+)$

Photo & Electroproduction

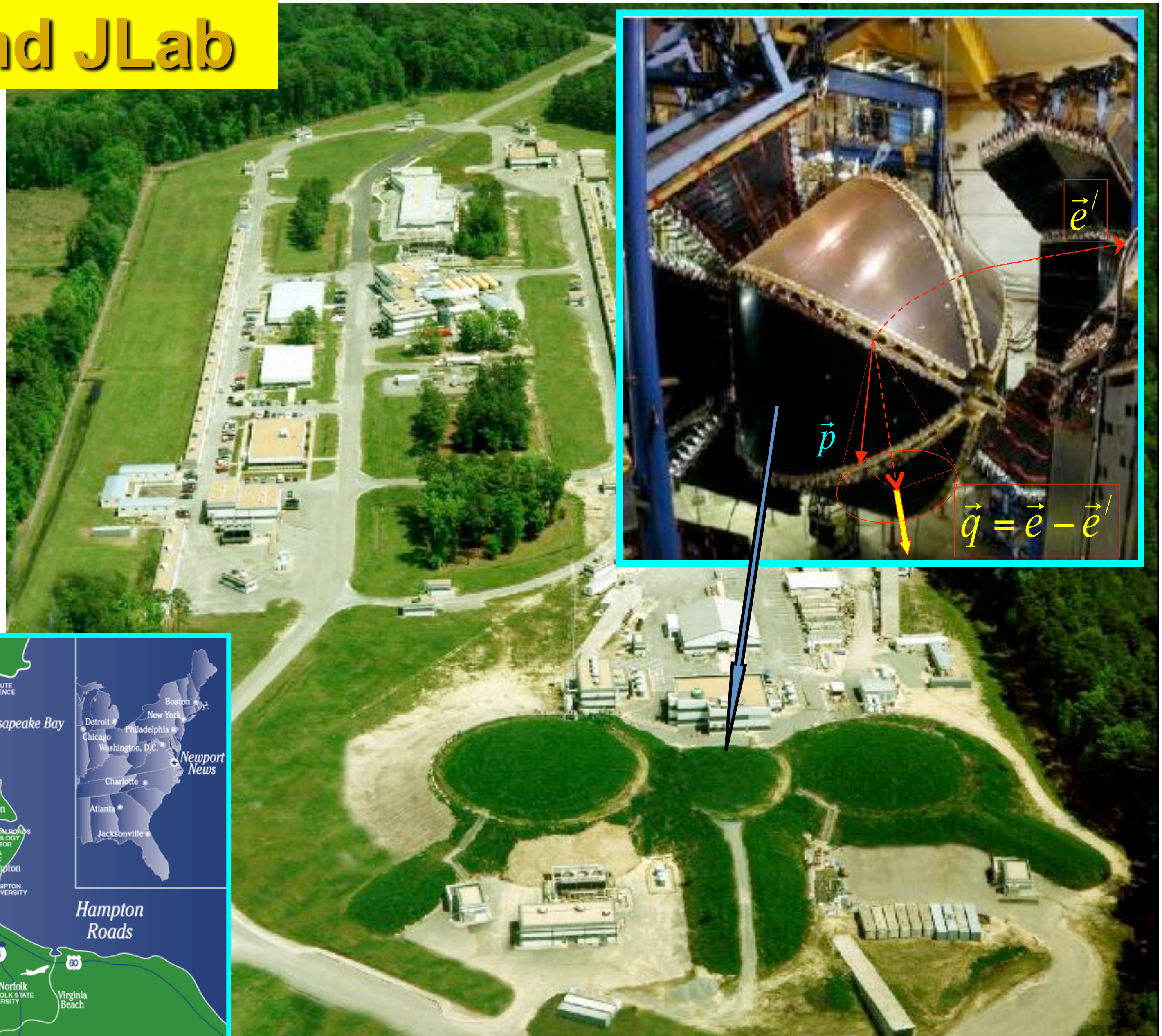




- Difficulties (New Opportunities)
  - Perturbative QCD cannot be applied
  - A lot of resonances could be present in a relatively narrow energy region
  - Nonresonance background is almost equally complicated
- Experiments
  - Jefferson Lab (USA)
  - MAMI (Germany)
  - ELSA (Germany)
  - ESRF (France)
  - SPring-8 (Japan)
  - BES (China) ¶

¶ A unique way of studying the baryon spectrum and N* hadronic decays is via BES: J/ψ → N*,…

CLAS and JLab



Jefferson Lab
Thomas Jefferson National Accelerator Facility

Studying N*s gives insight into structure

- **Active degrees of freedom in baryon structure at various distance scales**

  The 6 GeV Program offers detailed information on the transition in N* structure going from a mixed state of meson-baryon and quark degrees of freedom to the region where the quark core dominates

- **Quark core regime**

  The quark core of the nucleon is especially important since N* properties are determined through interactions between dressed-quarks at distances larger than those most important to the structure of ground states.

- **γ_vNN* electrocouplings at the higher Q^2**

  Is dynamical chiral symmetry breaking in QCD the root cause for generating the vast bulk of the mass of observable matter in the universe?

Indeed, in the words of the theorist, Craig Roberts:

"there is no greater challenge in the Standard Model, and few in physics, than learning to understand the truly non-perturbative long-range behavior of the strong interaction."

Electromagnetic Excitation of N*s

The experimental N* Program has two major components:

1) Transition form factors of known resonances to study their internal structure and the interactions among constituents, which are responsible for resonance formation.

2) Spectroscopy of excited baryon states, search for new states.

- Both parts of the program are being pursued in various meson photo and electroproduction channels, e.g. $N\pi$, $p\eta$, $p\pi^+\pi^-$, $K\Lambda$, $K\Sigma$, $p\omega$, $p\rho^0$ using cross sections and polarization observables.

- Global analysis of ALL meson photo- and electroproduction channels – within the framework of an advanced coupled-channel approach developed by EBAC (Excited Baryon Analysis Center – JLab).

Physics Goals for CLAS6

- Measure differential cross sections and polarization observables in single and double pseudo-scalar meson production: π^+n, π^0p, ηp, KY, and $\pi^+\pi^-p$ over the full polar and azimuthal angle range.

- Determine the electrocouplings of prominent excited nucleon states (N^*, Δ^*) and the evolution of the transition form factors in the range $Q^2 < 5$ GeV^2.

- Measure N* structure and its evolution with distance through the transition regime. Going from the "constituent quark region" of combined contributions of meson-baryon dressing and quark core at $Q^2 < 1.0$ GeV^2 to quark-core dominance at $Q^2 > 5.0$ GeV^2.

Announcement of Firsts from CLAS

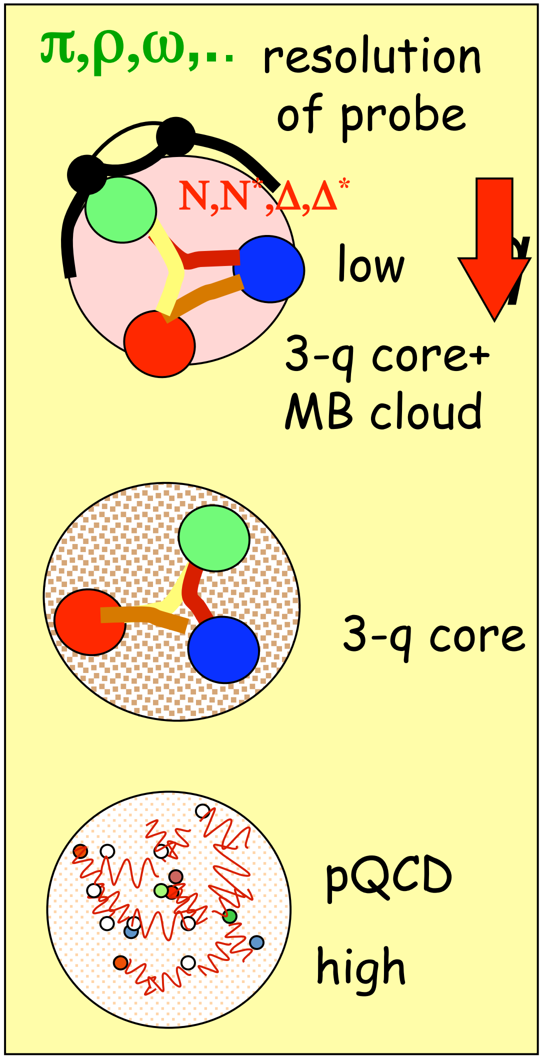
- First electroproduction data:
    - channels: π^+n, π^0p, and ηp
    - Q^2 evolution information on the $\gamma_v NN^*$ electrocouplings for the states: $P_{33}(1232)$, $P_{11}(1440)$, $D_{13}(1520)$, and $S_{11}(1535)$ for $Q^2 < 5.0$ GeV.

I.G. Aznauryan *et al.*, (CLAS Collaboration) Phys. Rev. **C80,** 055203 (2009).

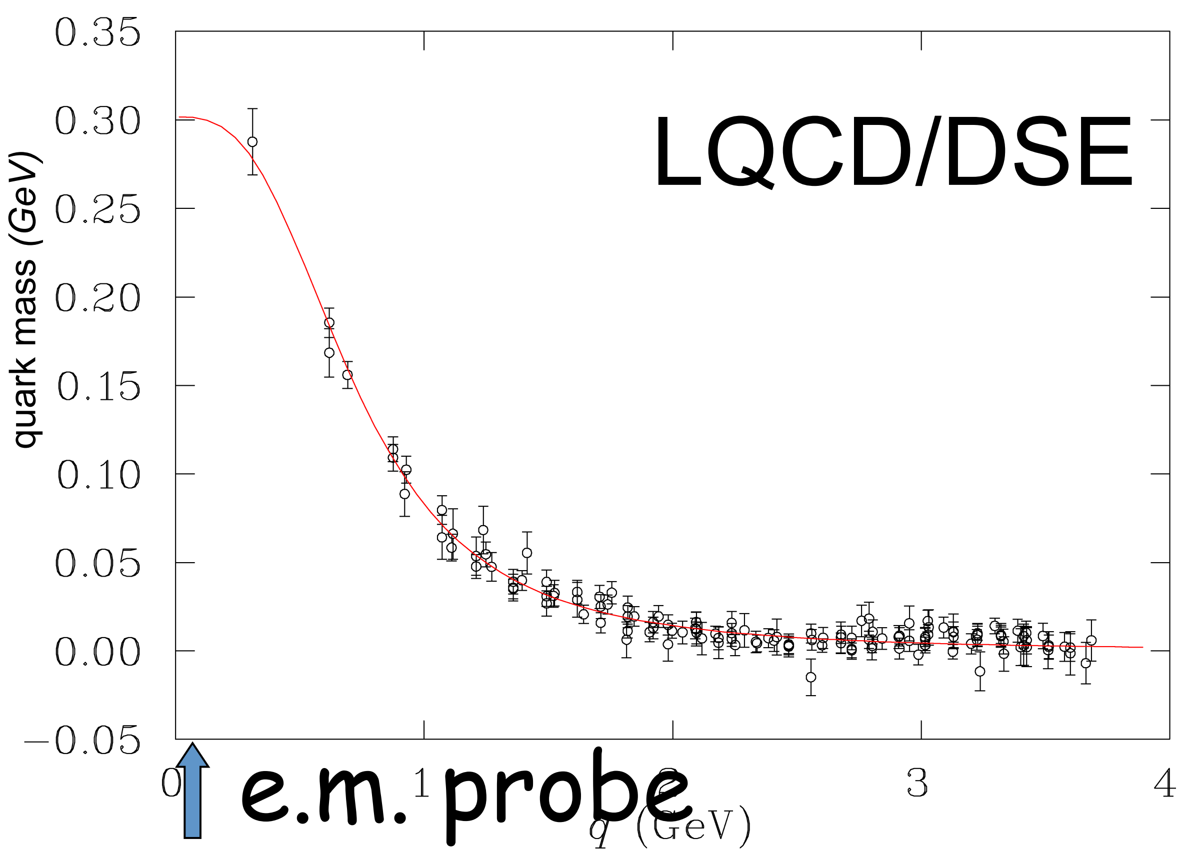
- We recently published the preliminary (first) results on the electrocouplings of the states $P_{11}(1440)$ and $D_{13}(1520)$ at $Q^2 < 0.6$ GeV^2 in $N\pi\pi$ electroproduction from protons.

V.I. Mokeev *et al.*, (CLAS Collaboration) arXiv:0906.4081[hep-ex] **+**
Workshop on the Physics of Excited Nucleon: NSTAR2009, Beijing, China, April 19-22, 2009, Chinese Phys. **C33**, 1210 (2009).

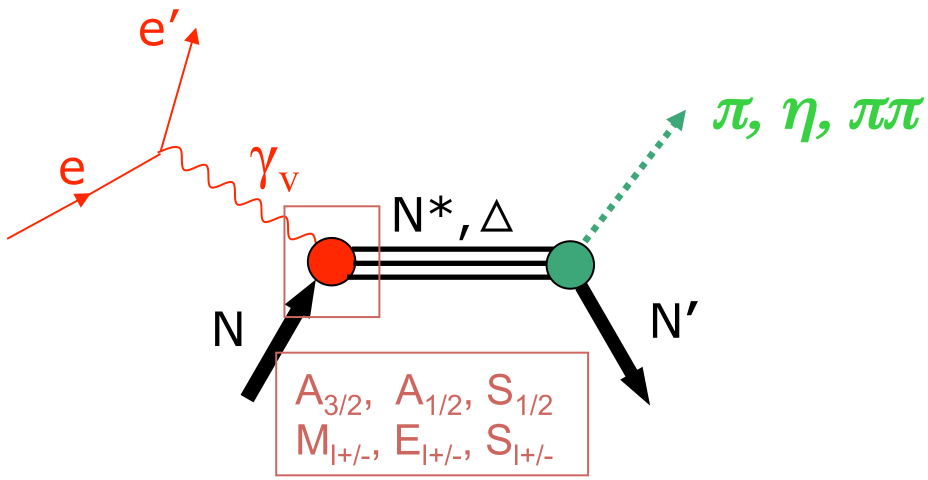
Hadron Structure with Electromagnetic Probes

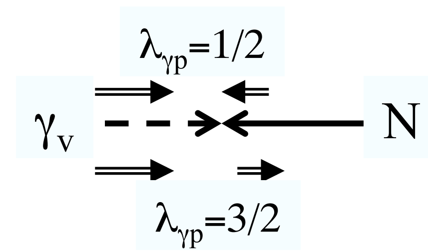


Allows to address central question:
What are the relevant degrees-of-freedom at varying distance scale?



Electromagnetic Excitation of N*s





DOE Milestone 2012

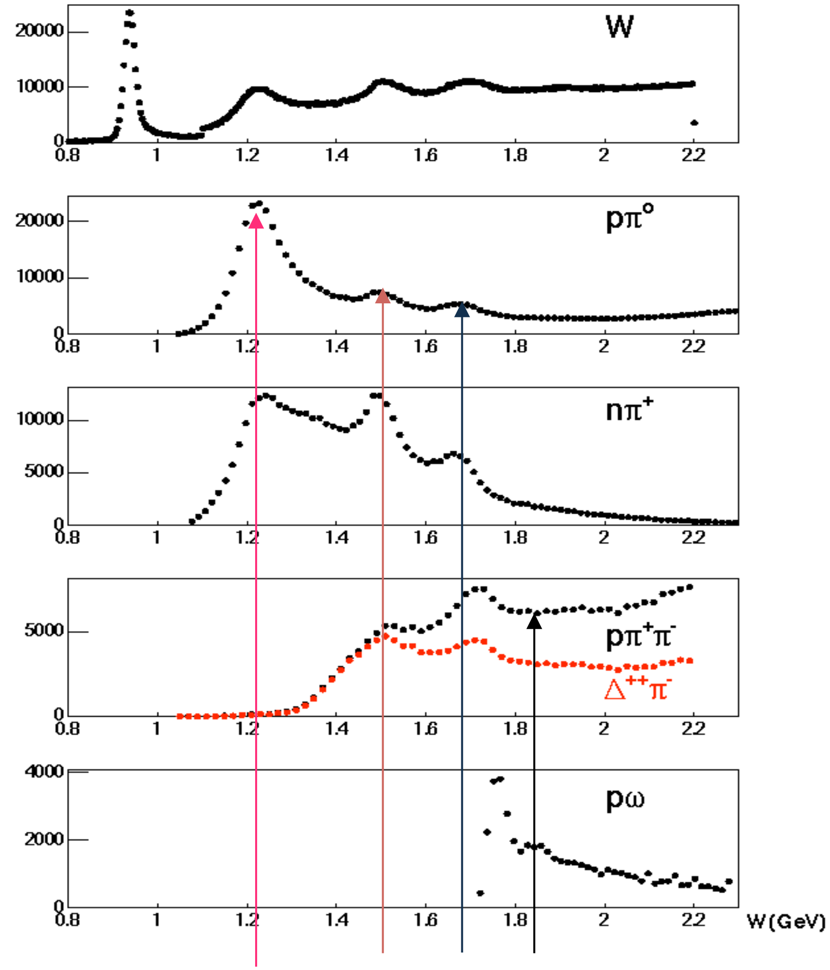
Measure the electromagnetic excitations of low-lying baryon states (<2 GeV) and their transition form factors over the range Q^2 = 0.1 – 7 GeV^2 and measure the electro- and photo-production of final states with one and two pseudo-scalar mesons.

Why Nπ/Nππ electroproduction channels are important

- Nπ/Nππ channels are the two major contributors in N* excitation region;
- these two channels combined are sensitive to almost all excited proton states;
- they are strongly coupled by πN→ππN final state interaction;
- may substantially affect exclusive channels having smaller cross sections, such as ηp, KΛ, and KΣ.

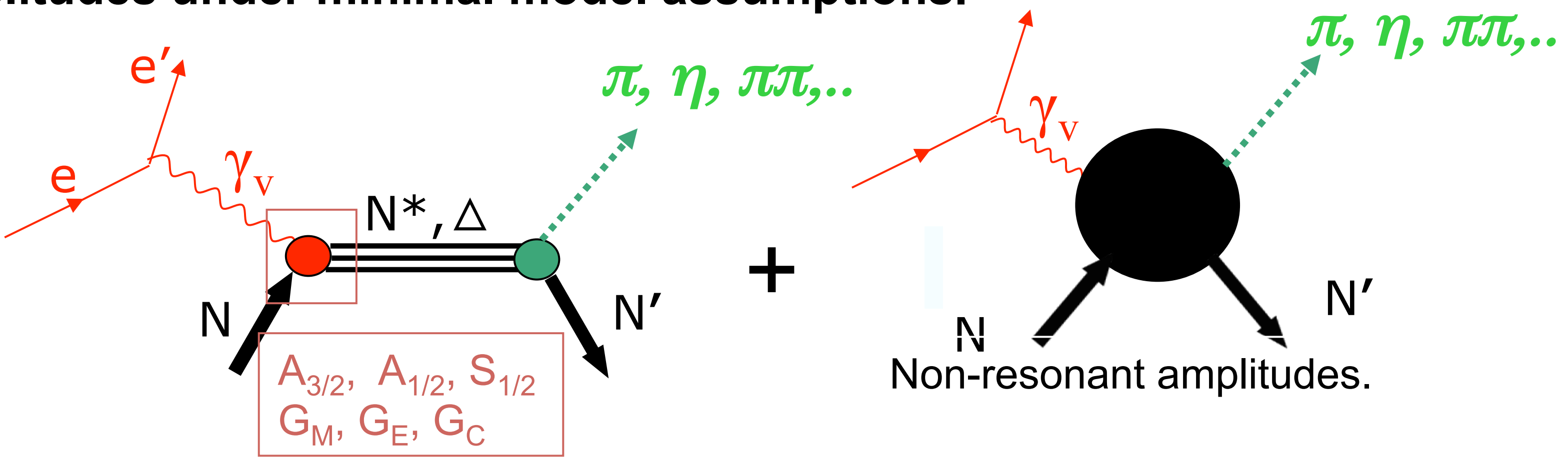
Therefore knowledge on Nπ/Nππ electroproduction mechanisms is key for the entire N* Program

CLAS data on meson electroproduction at $Q^2 < 4.0$ GeV²



How N* electrocouplings can be accessed

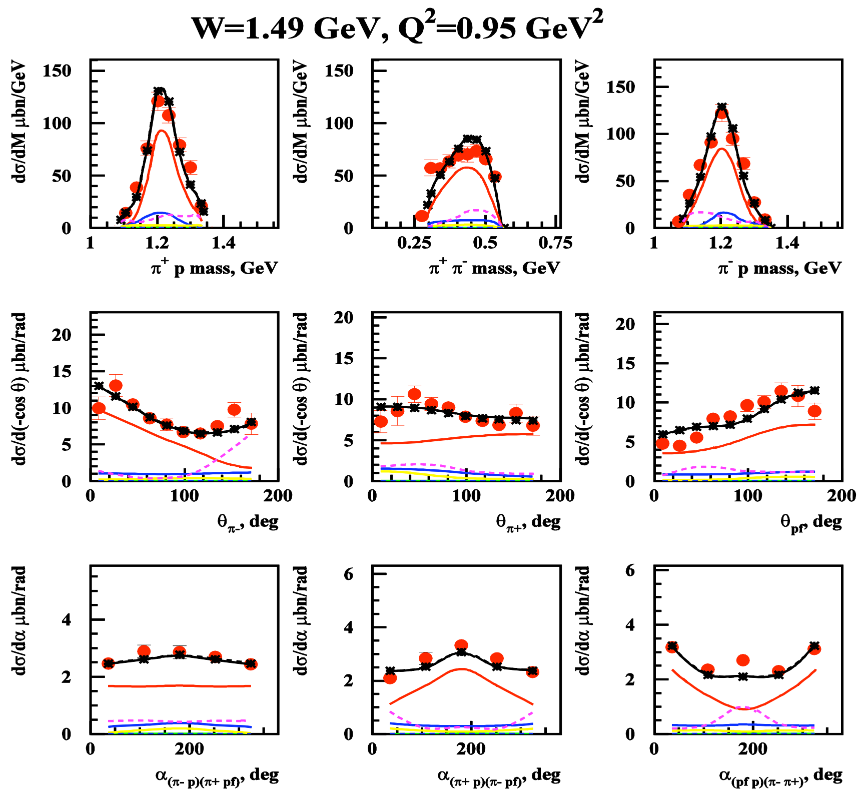
- **Isolate the resonant part of production amplitudes by fitting the measured observables within the framework of reaction models, which are rigorously tested against data.**
- **These N* electrocouplings can then be determined from resonant amplitudes under minimal model assumptions.**

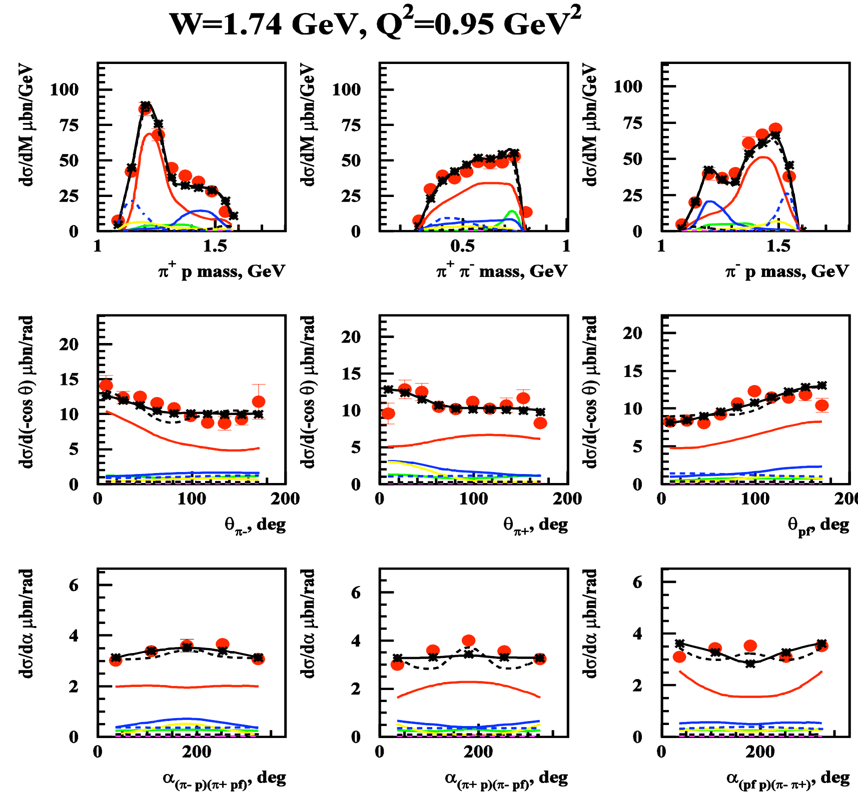


Consistent results on N* electrocouplings obtained in analyses of various meson channels (e.g. *πN, ηp, $\pi\pi N$) with entirely different non-resonant amplitudes* will show that they are determined reliably

Advanced coupled-channel analysis methods are being developing at EBAC: B.Julia-Diaz, T-S.H.Lee *et al.,* PRC76, 065201 (2007);T.Sato and T-S.H.Lee arXiv:0902.353[nucl-th]

JM Mechanisms as Determined by the CLAS 2π Data





Full JM calc

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

$\pi^+\Delta^0$

2π direct

$\pi^+D_{13}(1520)$

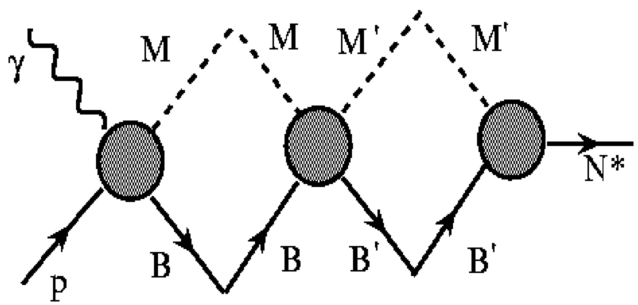
ρp

$\pi^+F_{15}(1685)$

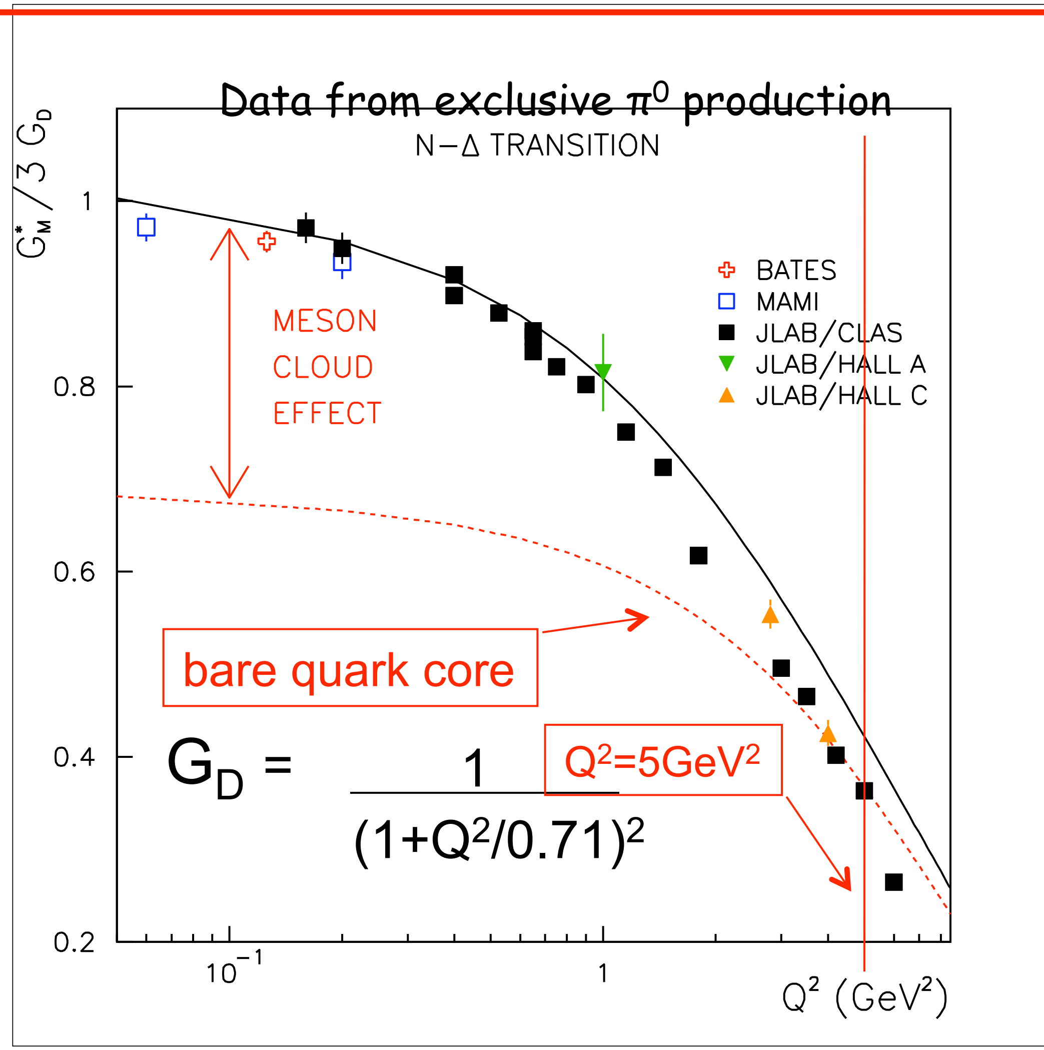
Any contributing mechanism has considerably different shapes of cross sections in various observables defined by the particular behavior of their amplitudes. A successful description of all observables allows us to check and to establish the dynamics of all essential contributing mechanisms.

Effects of Meson-Baryon Dressing

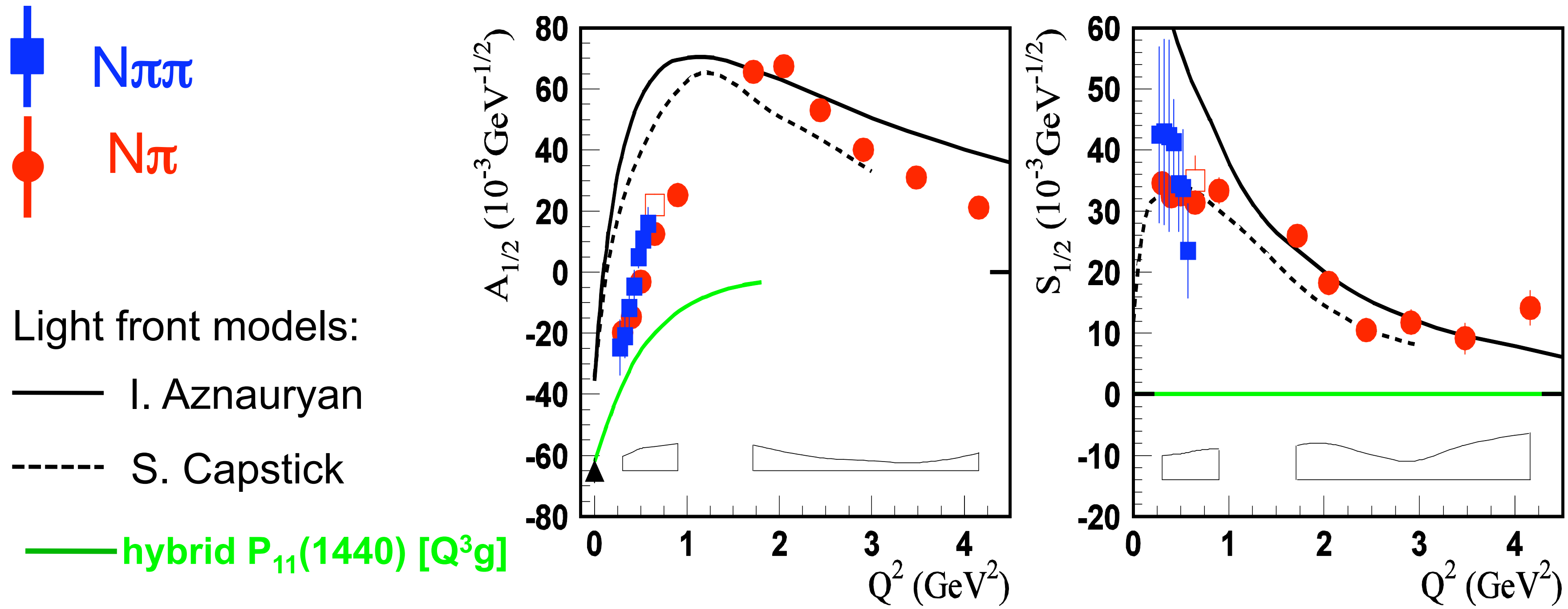
- One third of G^*_M at low Q^2 is due to contributions from meson-baryon (MB) dressing:



Within the framework of relativistic QM (rQM) [B.Julia-Diaz *et al.*, PRC 69, 035212 (2004)], the bare-core contribution is reasonably described by the three-quark component of the wavefunction



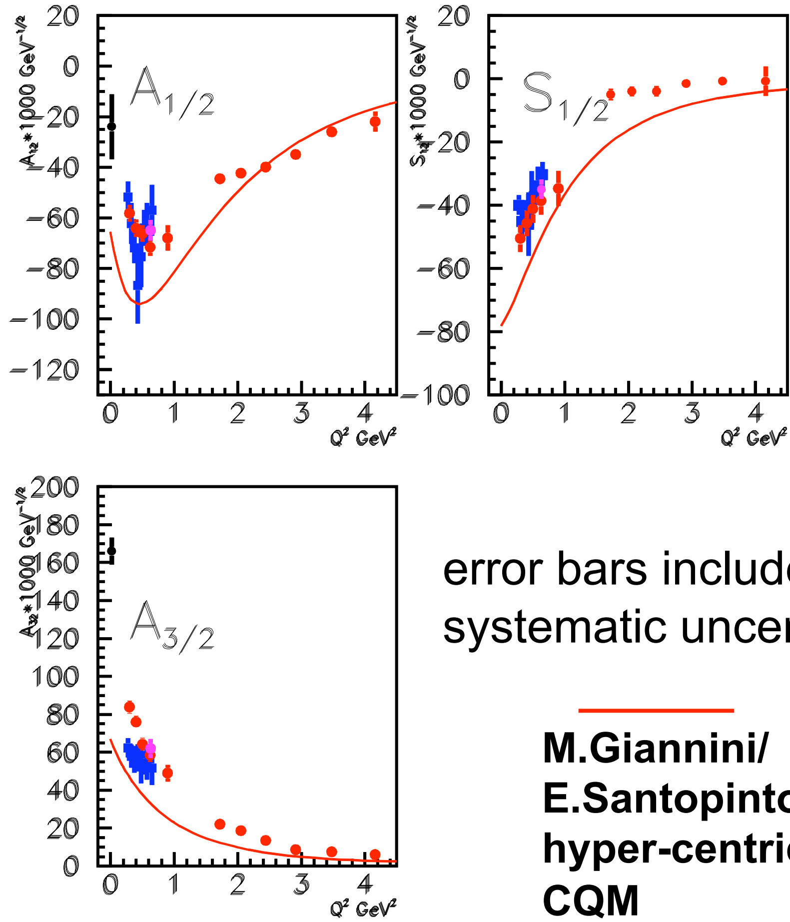
P_{11}(1440) electrocouplings from the CLAS data on Nπ/Nππ electroproduction



- **Good *agreement* between the electrocouplings obtained from the *Nπ and Nππ channels*: Reliable measure of the electrocouplings.**
- **The electrocouplings for $Q^2 > 2.0$ GeV^2 are consistent with *P_{11}(1440)* structure as a *3-quark radial excitation*.**
- ***Zero crossing for the $A_{1/2}$* amplitude has been observed for the first time, indicating an importance of light-front dynamics.**
- **Hypothesis on the hybrid origin of P_{11}(1440) has been ruled out.**

D_{13}(1520) electrocouplings from the CLAS data on $N\pi/N\pi\pi$ electroproduction

- **electrocouplings as determined from the $N\pi$ & $N\pi\pi$ channels are in good agreement overall**
- **but the apparent discrepancies for the $A_{3/2}$ amplitude at $Q^2 < 0.4$ GeV^2 will be further investigated in a combined $N\pi/N\pi\pi$ analysis**
- **hypercentric Consituent Quark Model calculations reasonably describe electrocouplings at Q^2>2.5 GeV^2, suggesting that the 3-quark component is the primary contribution to the structure of this state at high Q^2.**

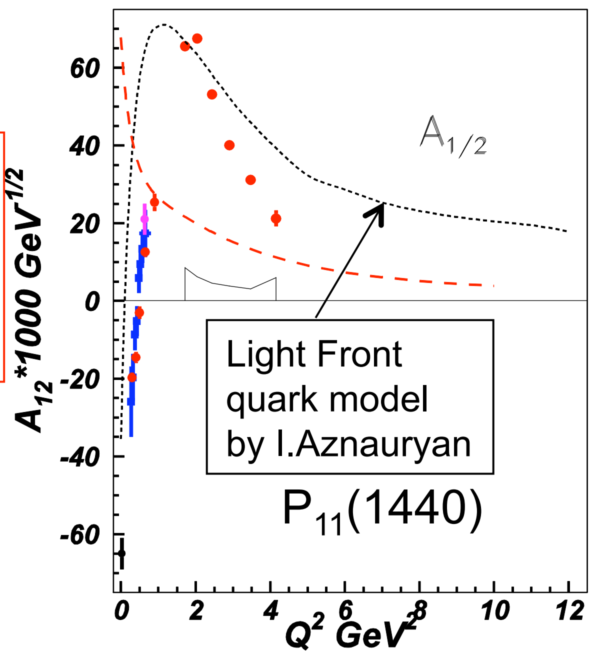


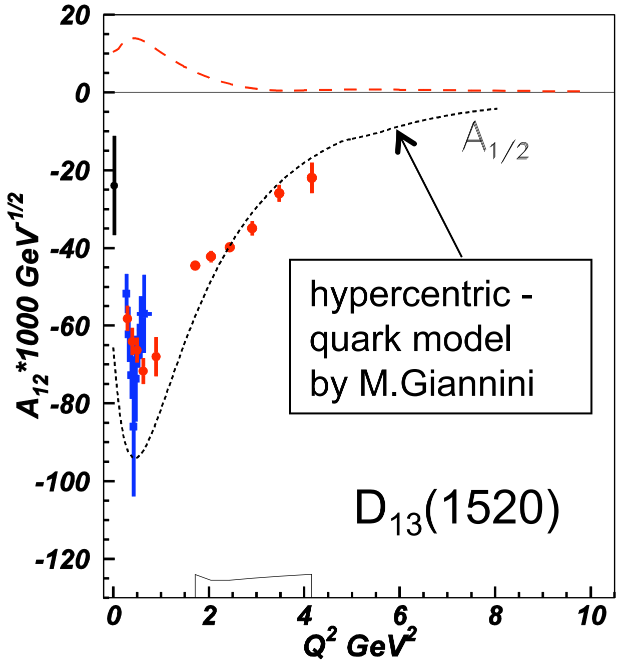
error bars include systematic uncertainties

M.Giannini/
E.Santopinto
hyper-centric
CQM

Meson-baryon dressing / Quark core contributions in the $A_{1/2}$ electrocouplings of the $P_{11}(1440)$ & $D_{13}(1520)$ states.

Estimates from EBAC for the MB dressing: B.Julia-Diaz *et al*., PRC 76, 5201 (2007).





- MB dressing effects have substantial contribution to low lying N* electrouplings at $Q^2<1.0$ GeV^2 and gradually decrease with Q^2;
- Contribution from dressed quarks increases with Q^2 and are expected to be dominant at $Q^2>5.0$ GeV^2.

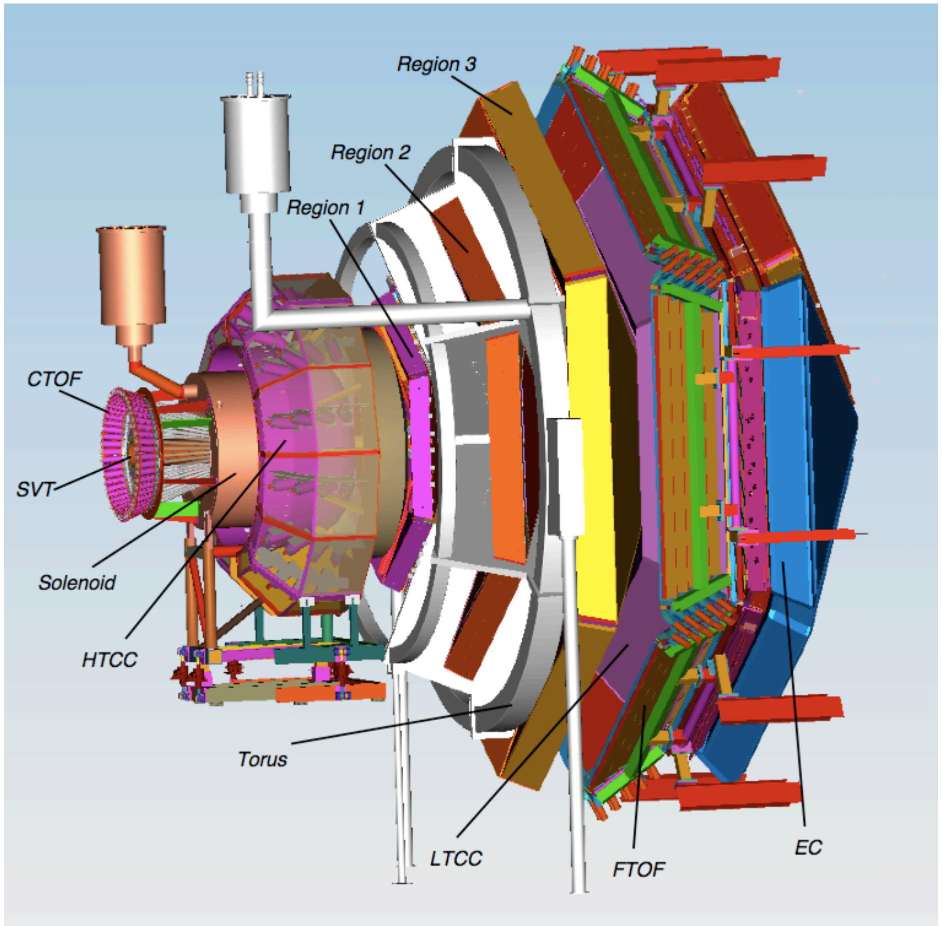
CLAS12 JLab Upgrade to 12 GeV

Luminosity > $10^{35} cm^{-2} s^{-1}$

- General Parton Distributions
- Transverse parton distributions
- Longitudinal Spin Structure
- N* Transition Form Factors
- Heavy Baryon Spectroscopy
- Hadron Formation in Nuclei

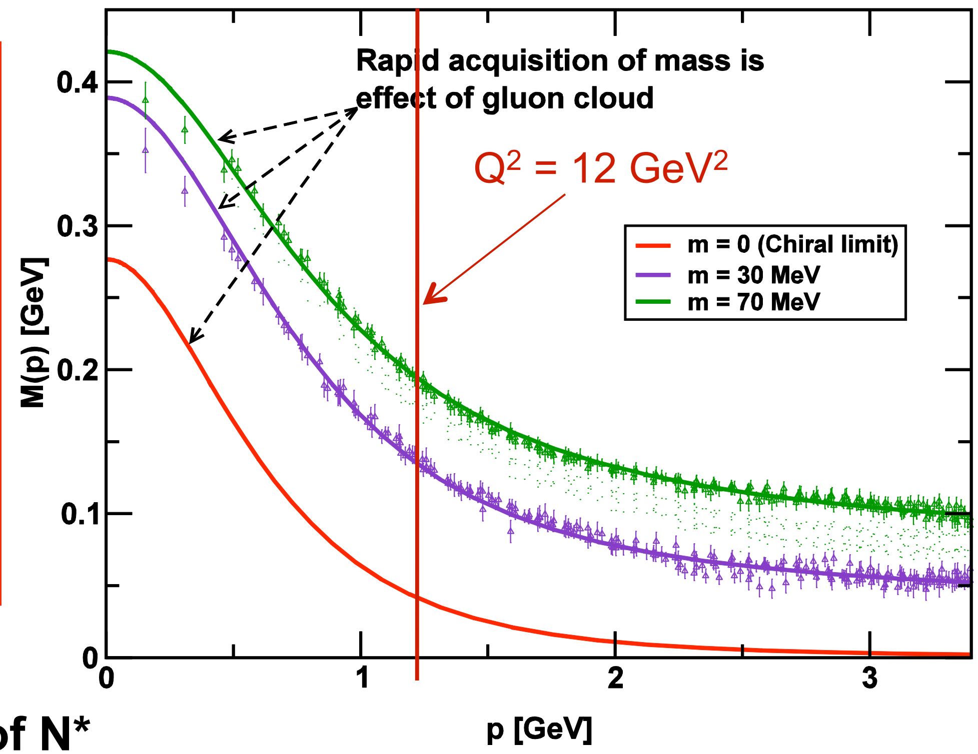
Forward Tracker, Calorimeter, Particle ID

Solenoid, ToF, Central Tracker



Physics Objectives in the N* Studies with CLAS12

- **explore the interactions between the dressed quarks, which are responsible for the formation for both ground and excited nucleon states.**
- **probe the mechanisms of light current quark dressing, which is responsible for >97% of nucleon mass.**



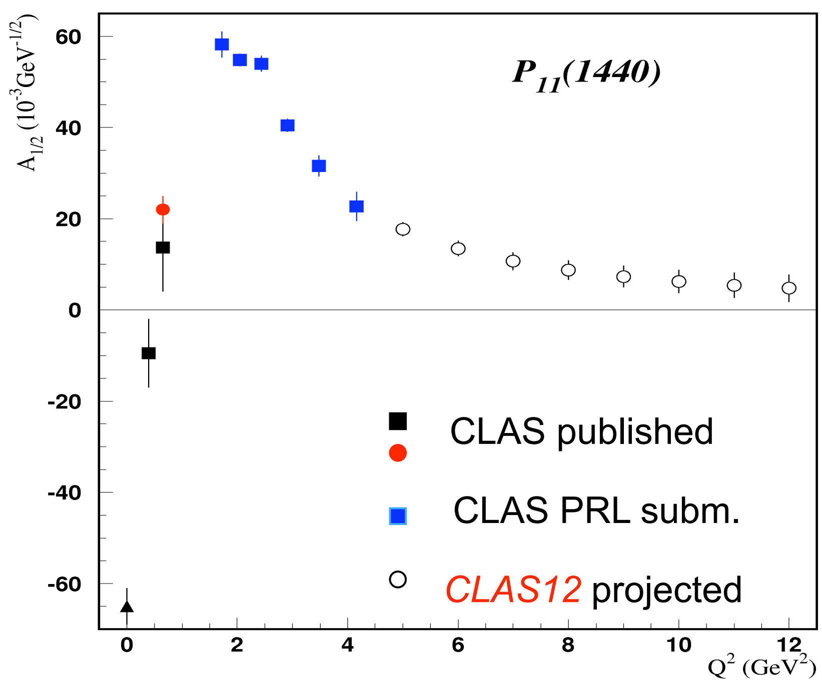
Approaches for theoretical analysis of N* electrocouplings: LQCD, DSE, relativistic quark models. See details in the 62-page White Paper of EmNN* JLAB Workshop, October 13-15, 2008: http://www.jlab.org/~mokeev/white_paper/
I. Aznauryan *et al.,* arXiv:0907.1901[nucl-th]

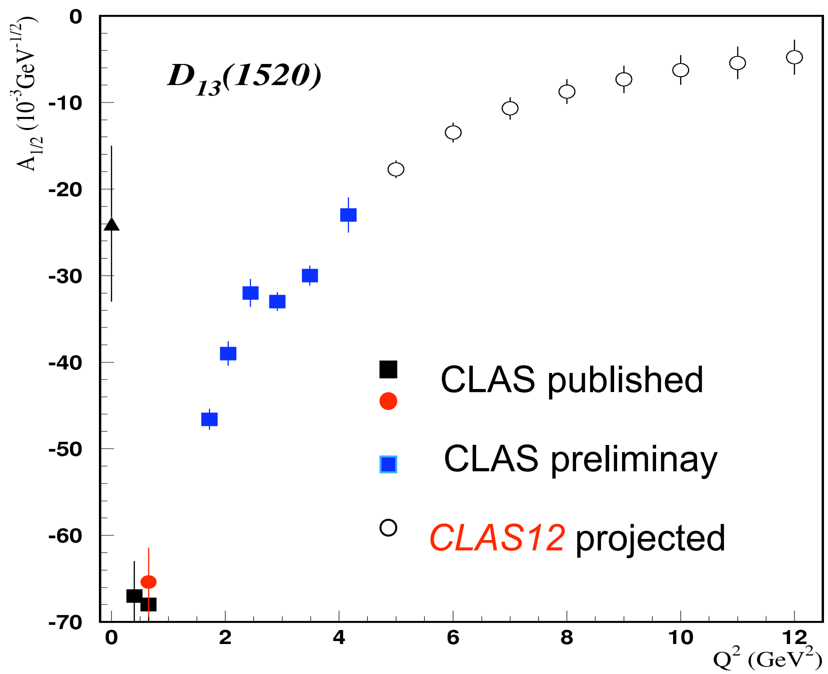
Independent QCD Analyses
Line Fit: DSE Points: LQCD

Need to multiply by $3p^2$ to get the Q^2 per quark

CLAS12 Projections for N* Transitions

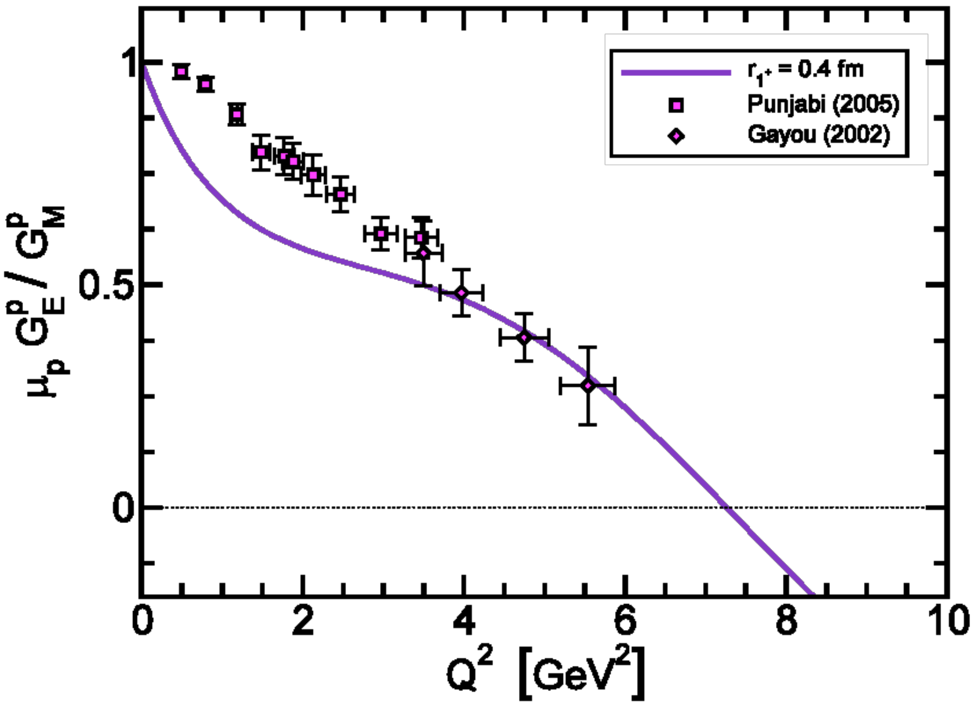
For the foreseeable future, CLAS12 will be the only facility worldwide, which will be able to access the N* electrocouplings in the Q^2 regime of 5 GeV^2 to 10 GeV^2, where the quark degrees of freedom are expected to dominate. Our experimental proposal "*Nucleon Resonance Studies with CLAS12*" was approved by PAC34 for the full 60-day beamtime request. http://www.physics.sc.edu/~gothe/research/pub/nstar12-12-08.pdf.





Dyson-Schwinger Equation (DSE) Approach

DSE provides an avenue to relate N* electrocouplings at high Q^2 to QCD and to test the theory's capability to describe the N* formation based on QCD.



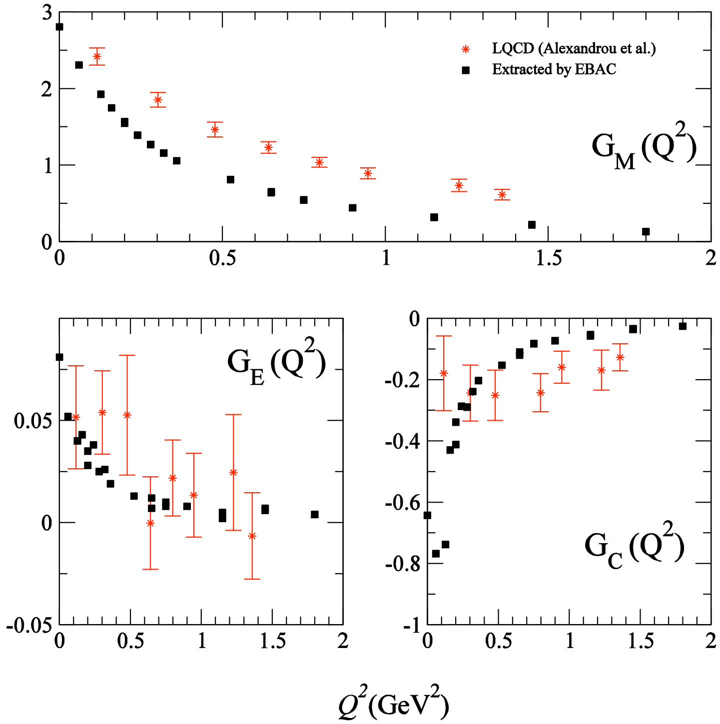
DSE approaches provide a link between dressed quark propagators, form factors, and scattering amplitudes and QCD.

N* electrocouplings can be determined by applying Bethe-Salpeter /Fadeev equations to 3 dressed quarks while the properties and interactions are derived from QCD.

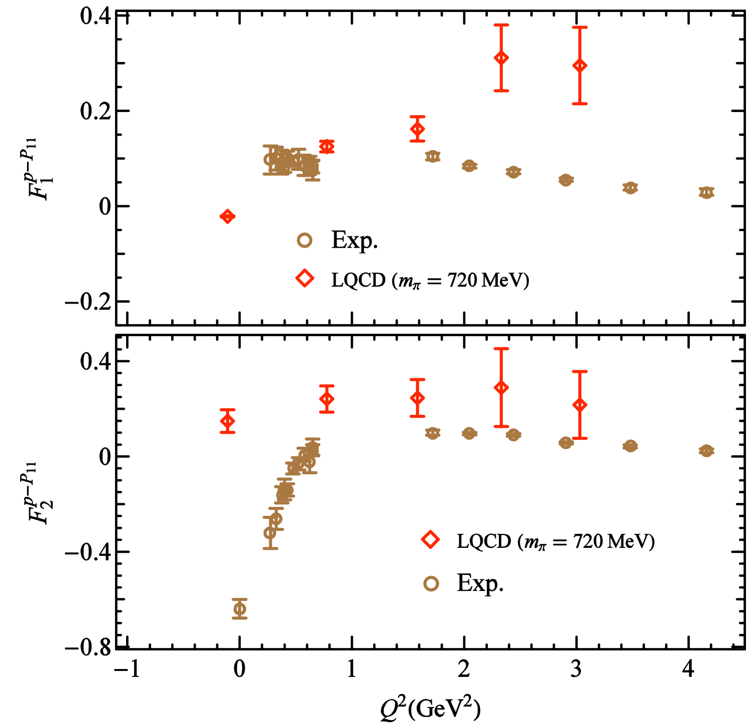
By the time of the upgrade DSE electrocouplings of several excited nucleon states will be available as part of the commitment of the Argonne NL and the University of Washington.

Current Status of Lattice QCD

$\Delta(1232)P_{33}$



$N(1440)P_{11}$



LQCD calculations of the $\Delta(1232)P_{33}$ and $N(1440)P_{11}$ transitions have been carried out with large π-masses.

By the time of the upgrade LQCD calculations of N* electrocouplings will be extended to Q^2 = 10 GeV^2 near the physical π-mass as part of the commitment of the JLAB LQCD and EBAC groups in support of this proposal.

Nucleon Resonance Studies with CLAS12

R. Arndt[4], H. Avakian[6], I. Aznauryan[11], A. Biselli[3], W.J. Briscoe[4], **V. Burkert[6]**, V.V. Chesnokov[7], **P.L. Cole[5]**, D.S. Dale[5], C. Djalali[10], L. Elouadrhiri[6], G.V. Fedotov[7], T.A. Forest[5], E.N. Golovach[7], **R.W. Gothe*[10]**, Y. Ilieva[10], B.S. Ishkhanov[7], E.L. Isupov[7], **K. Joo[9]**, T.-S.H. Lee[1,2], **V. Mokeev*[6]**, M. Paris[4], K. Park[10], N.V. Shvedunov[7], S. Stepanyan[6], **P. Stoler[8]**, I. Strakovsky[4], S. Strauch[10], D. Tedeschi[10], M. Ungaro[9], R. Workman[4], and the CLAS Collaboration

JLab PAC 34, January 26-30, 2009
Approved for 40 days beamtime

Argonne National Laboratory (IL,USA)[1], Excited Baryon Analysis Center (VA,USA)[2], Fairfield University (CT, USA)[3], George Washington University (DC, USA)[4], Idaho State University (ID, USA)[5], Jefferson Lab (VA, USA)[6], Moscow State University (Russia)[7], Rensselaer Polytechnic Institute (NY, USA)[8], University of Connecticut (CT, USA)[9], University of South Carolina (SC, USA)[10], and Yerevan Physics Institute (Armenia) [11]

Spokesperson
Contact Person*

Theory Support Group

V.M. Braun[7], I. Cloët[8], R. Edwards[5], M.M. Giannini[4,6], B. Julia-Diaz[2], H. Kamano[2], T.-S.H. Lee[1,2], A. Lenz[8], H.W. Lin[5], A. Matsuyama[2], C.D. Roberts[1], E. Santopinto[4,6], T. Sato[2], G. Schierholz[7], N. Suzuki[2], Q. Zhao[3], and B.-S. Zou[3]

JLab PAC 34, January 26-30, 2009

Argonne National Laboratory (IL,USA)[1],
Excited Baryon Analysis Center (VA,USA)[2],
Institute of High Energy Physics (China)[3],
Istituto Nazionale di Fisica Nucleare (Italy)[4],
Jefferson Lab (VA, USA)[5],
University of Genova (Italy)[6],
University of Regensburg (Germany)[7],
and University of Washington (WA, USA)[8]

Open invitation.

List is open to any and all who wish to participate!

Our CLAS12 experiment will give access to

The electroproduction cross sections and beam-spin asymmetries of $p\pi$, $n\pi$, $p\eta$ for W =1.1 – 2.0 GeV, $Q^2 < 12$ GeV^2 with full coverage in $\cos\theta^*_{\pi,\eta}$ and $\phi^*_{\pi,\eta}$;

9 single differential cross sections of the $p\pi^+\pi^-$ channels in the energy range W =1.3 – 2.0 GeV, $Q^2 < 8$ GeV^2 with full angle coverage

Thus armed, we can extract the electrocouplings for the helicity amplitudes $A_{1/2}$, $A_{3/2}$, and $S_{1/2}$ as a function of Q^2 for prominent nucleon and Δ states.

The results from our experiment will be used by EBAC and the Theory Support Group for our proposal to provide

- access to the dynamics of non-perturbative strong interactions among dressed quarks and their emergence from QCD and the subsequent formation into baryon resonances;
- information on how the constituent quark mass arises from a cloud of low-momentum gluons, which constitute the dressing to the current quarks.

[This process of dynamical chiral symmetry breaking accounts for over 97% of the nucleon mass]

- enhanced capabilities for exploring the behavior of the universal QCD β-function in the infrared regime.

Now a few words on the possibility for a US-Chinese collaboration on N* studies

龍

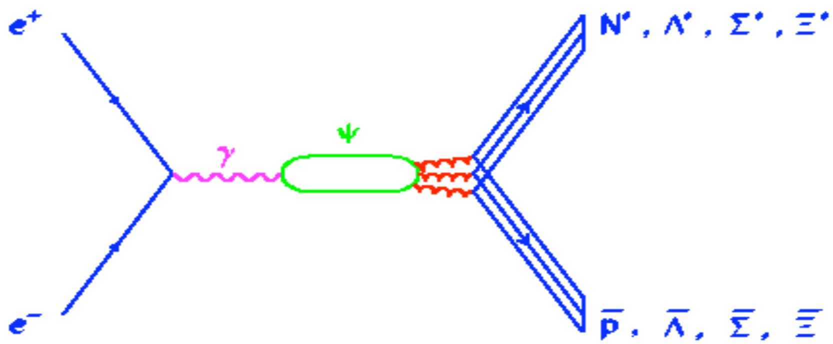
龙

Baryon spectroscopy from J/ψ decays:

Beijing Electron Spectrometer / Beijing Electron-Positron Collider

(BES/BEPC)

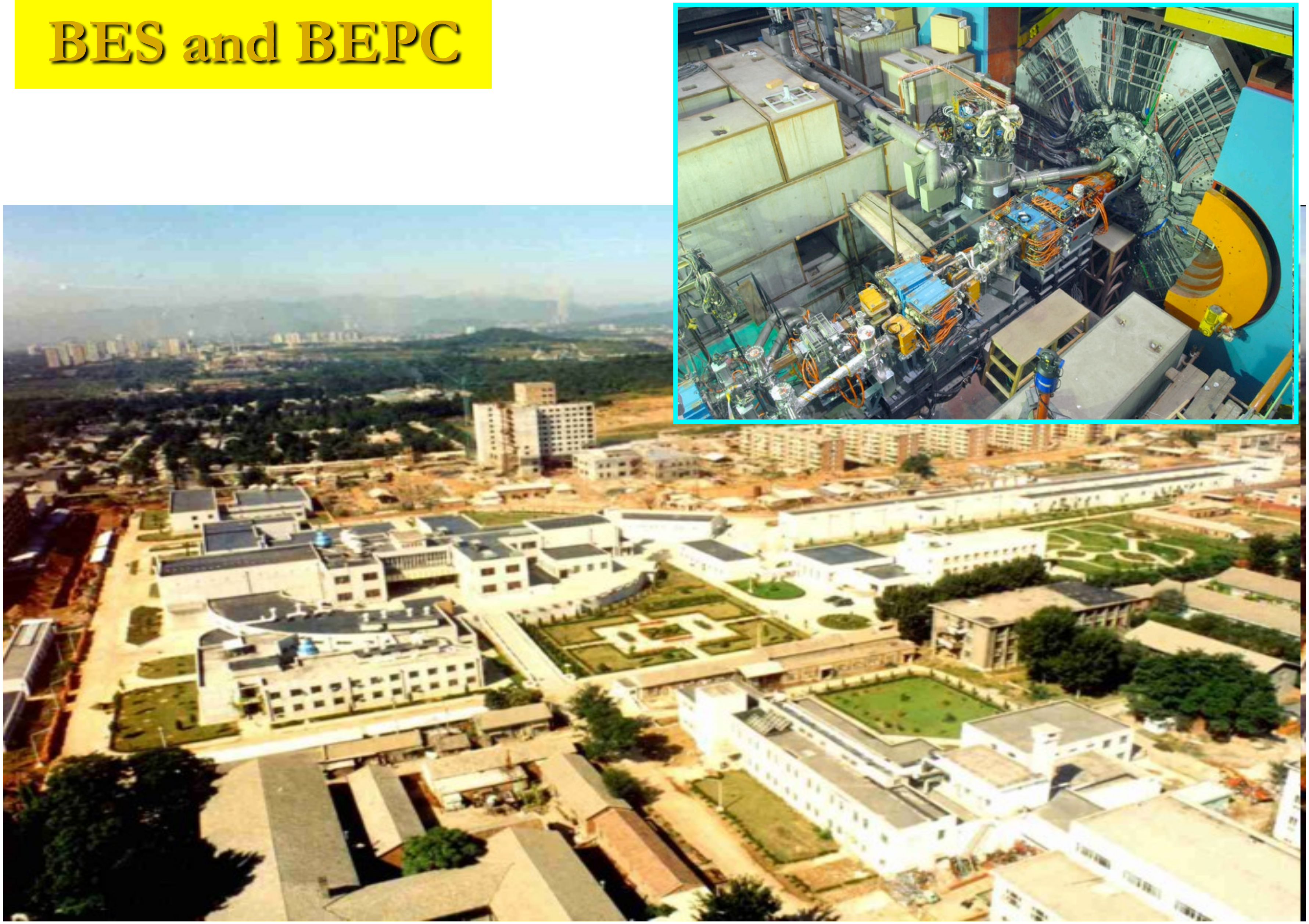
$$J/\Psi \rightarrow \overline{B}BM \;\Rightarrow\; N^*, \Lambda^*, \Sigma^*, \Xi^*$$



New mechanism for baryon production & an ideal isospin filter

BingSong Zou MENU 07

BES and BEPC



$J/\psi \rightarrow N^*$ Production in e^-e^+ collisions at BES

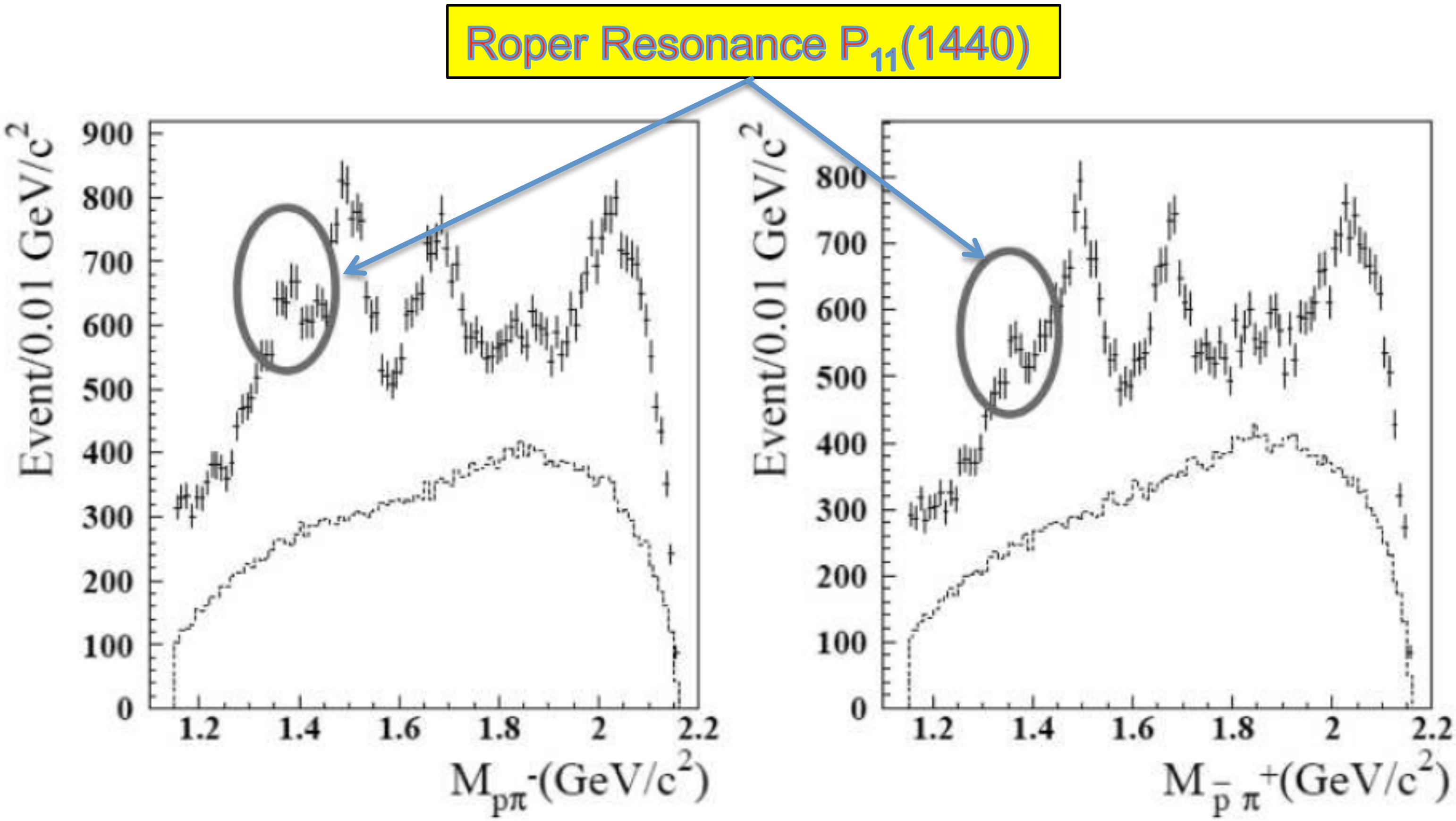


Fig. 3. The above plots come from Fig. 5 in the BES collaboration paper: Observation of Two New N* Peaks in $J/\psi \rightarrow p\pi^-\bar{n}$ and $\bar{p}\pi^+n$ Decays.[65] The $p\pi^-$ and $\bar{p}\pi^+$ invariant mass spectra for $J/\psi \rightarrow p\pi^-\bar{n}$ (left) and $\bar{p}\pi^+n$ (right), compared with phase space. The circled peak around 1360 MeV/c^2 marks the first direct observation of the Roper Resonance, i.e. the $N(1440)P_{11}$. From the IHEP partial wave analysis (in units of MeV): $M = 1358 \pm 17$ and $\Gamma = 179 \pm 56$.

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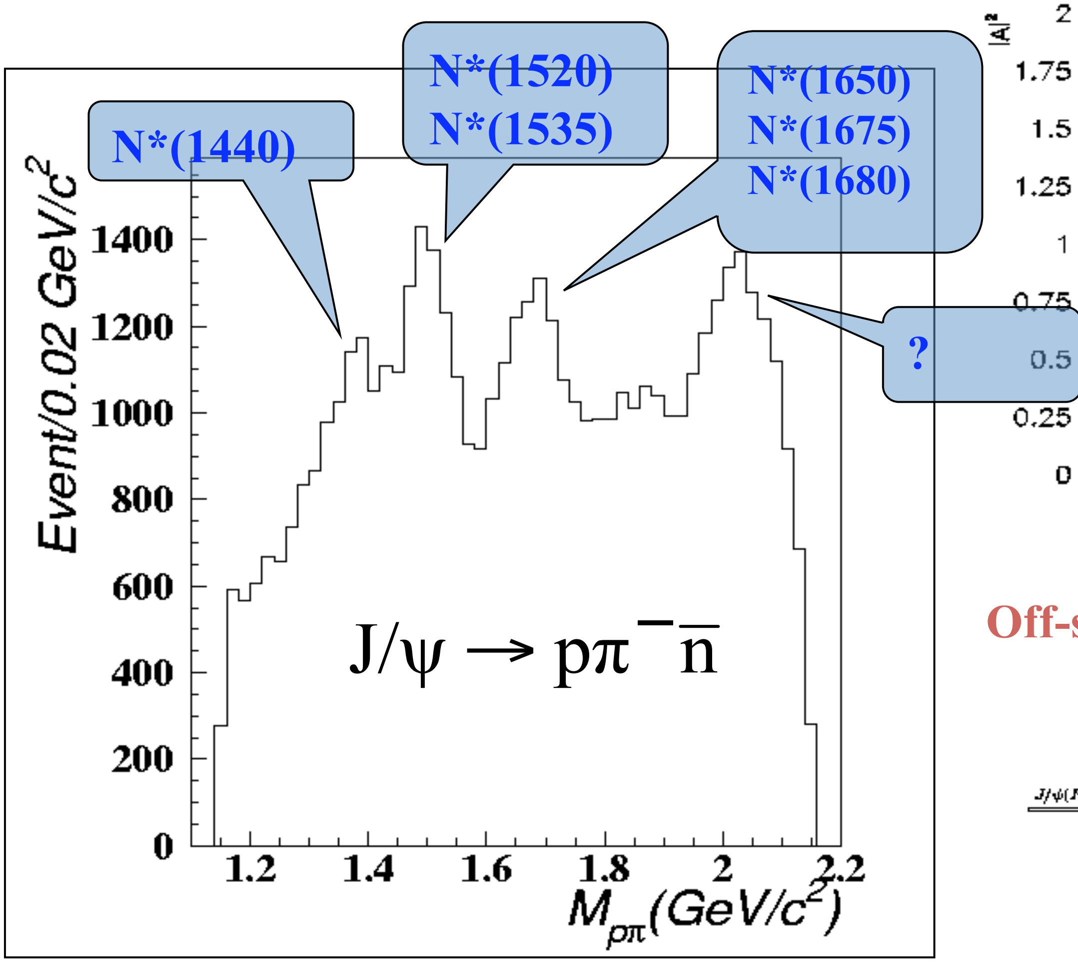
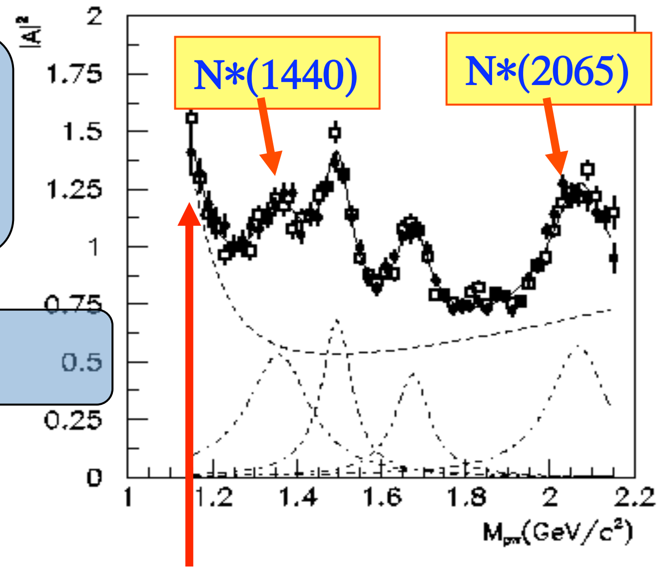
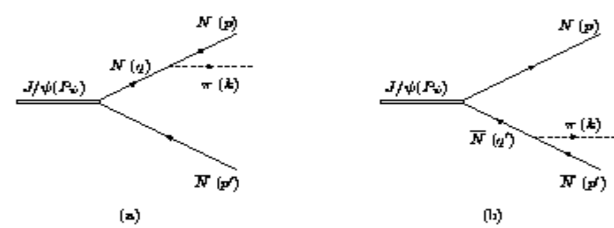
Observation of Two New N^* Peaks in $J/\psi \to p\pi^- \bar{n}$ and $\bar{p}\pi^+ n$ Decays





Off-shell nucleon contribution



Nucleon-pole diagrams for $J/\psi \to \pi N \bar{N}$ decay.

BingSong Zou MENU 07

$J/\psi \rightarrow N^*$ Production in e^-e^+ collisions at BES

Table 1. Measured J/ψ decay branching ratios ($BR\times10^3$) for channels involving baryon/antibaryon/meson(s). (From Table 10.2 of Ref. [7]).

$J/\psi \rightarrow N^*\bar{N} \rightarrow$	$BR\times10^3$	500 M J/ψs
$p\bar{n}\pi^-$	2.4 ± 0.2	1,200,000
$p\bar{p}\pi^0$	1.1 ± 0.1	500,000
$p\bar{p}\pi^+\pi^-$	6.0 ± 0.5	3,000,000
$p\bar{p}\eta$	2.1 ± 0.2	1,000,000
$p\bar{p}\omega$	1.3 ± 0.3	650,000
$p\bar{\Lambda}K^-$	0.9 ± 0.2	450,000
$\Lambda\bar{\Sigma}^-\pi^+$	1.1 ± 0.1	550,000
$p\bar{\Sigma}^0K^-$	0.3 ± 0.1	150,000
$p\bar{p}\phi$	0.045 ± 0.015	22,500

Issues (1)

BES and CLAS datasets

- **They have very different contributions to the production background.**
  - electron (photon) beam onto fixed target

- **They separately have unique N* signatures**
  - BES: $J/\psi \rightarrow \bar{B}N^* \rightarrow \bar{B}BM$ (e.g. $\bar{N}N\pi$, $\bar{N}N\eta$)
  - CLAS: $N^* \rightarrow BM/BMM$ (e.g. $N\pi/N\pi\pi$)
  - electron-positron collider

CLAS : study N* structure through measuring electrocouplings as a function of Q^2

Issues (2)

BES tells where to dig and CLAS has the steam shovel

- **BES** at **BEPC** has collected high statistics data on J/ψ production. Its decay into baryon-antibaryon channels offers a unique and complementary way of probing nucleon resonances (N*).
- **CLAS** at **JLab** has access to N* form factors at high Q^2, which is advantageous for the study of structure of nucleon resonances,
- Several N* states have been seen at **BES** in the mass region of 2 GeV.

M. Ablikim *et al.*, (BES Collaboration), Phys. Rev. Lett. **97**, 062001 (2006).

Coordination of efforts between BES and CLAS is timely

Issues (2+)

BES tells where to dig and CLAS has the steam shovel

- The low-background **BES** results will be able to provide guidance for the search for less-dominant excited states at JLab.

- **BES**'s capability to study multiparticle hadronic decays of N*s is important for the search of new baryon states as well as for the reliable treatment of FSI in electro-production processes.

- With the precision electron and photon beams afforded by **JLab**, not only would the existence of these new N* states be confirmed, but it would further allow for their properties to be precisely mapped out at various distances or Q^2.

Coordination of efforts between BES and CLAS is timely