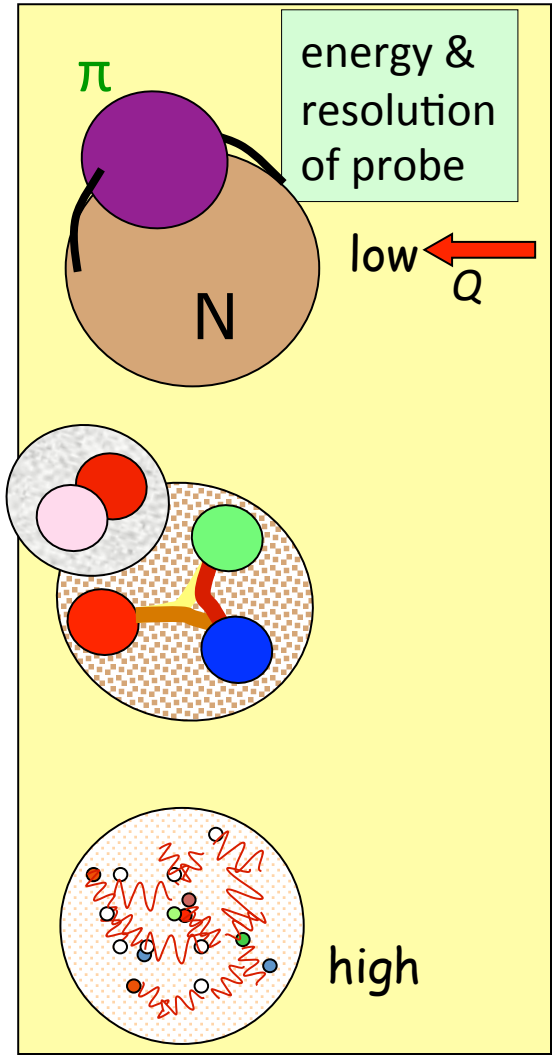
Nucleon resonance transition form factors at JLab

Volker D. Burkert
Jefferson Lab

- Introduction
- Magnetic dipole transition and quadrupole structure of $\gamma p\Delta(1232)$
- Two states in the $[70,1^-]_1$ supermultiplet $N(1520)3/2^-$ & $N(1535)1/2^-$
- The nature of the "Roper" resonance
- LC transition charge densities in transverse space
- Higher mass states and one unique resonance $N(1676)5/2^-$
- Conclusions & Outlook

Why electron beams?



Electron beams have tunable resolution (Q=e-e') and are clean (e.m.) probes of the hadron structure.

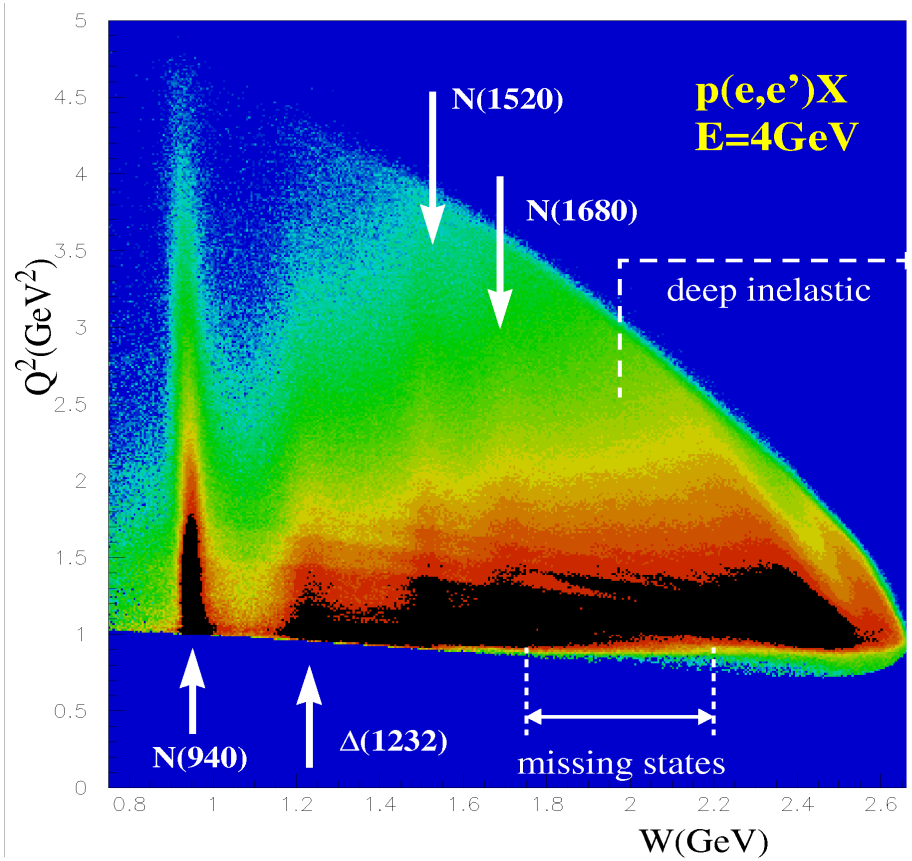
Central question in hadron physics:
"What are the effective degrees of freedom at varying distance scale and what do they reveal about the nucleon structure"?

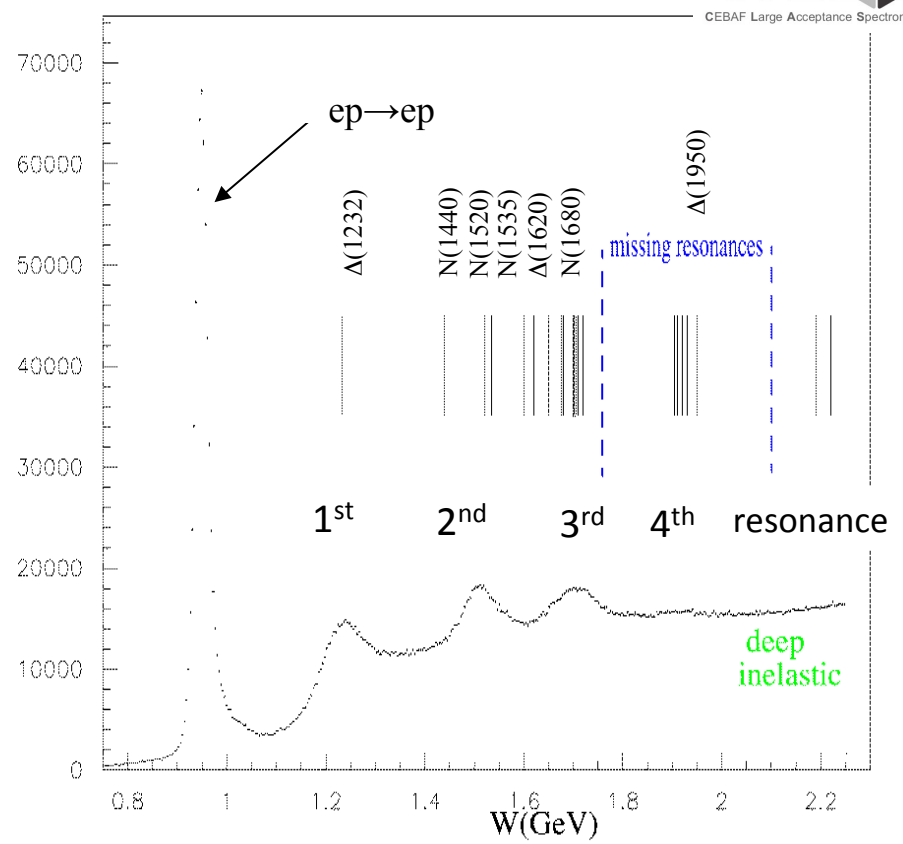
By measuring the resonance excitation strength with virtual photons we probe the contributions to the resonance strength from

- **hadronic degrees-of-freedom (meson-baryons)**
- **the evolution of dressed quarks to bare quarks**
- **hybrid baryons**
- **the running quark mass function**

Inclusive Electron Scattering ep→e'X

$Q^2=-(e-e')^2$; $W^2=(e-e'+p)^2$





- Resonances cannot be uniquely separated in inclusive scattering

→ measure exclusive processes with **Nπ, Nη** and **Nππ** final states to identify specific QN

Tools for N* and Δ* analysis

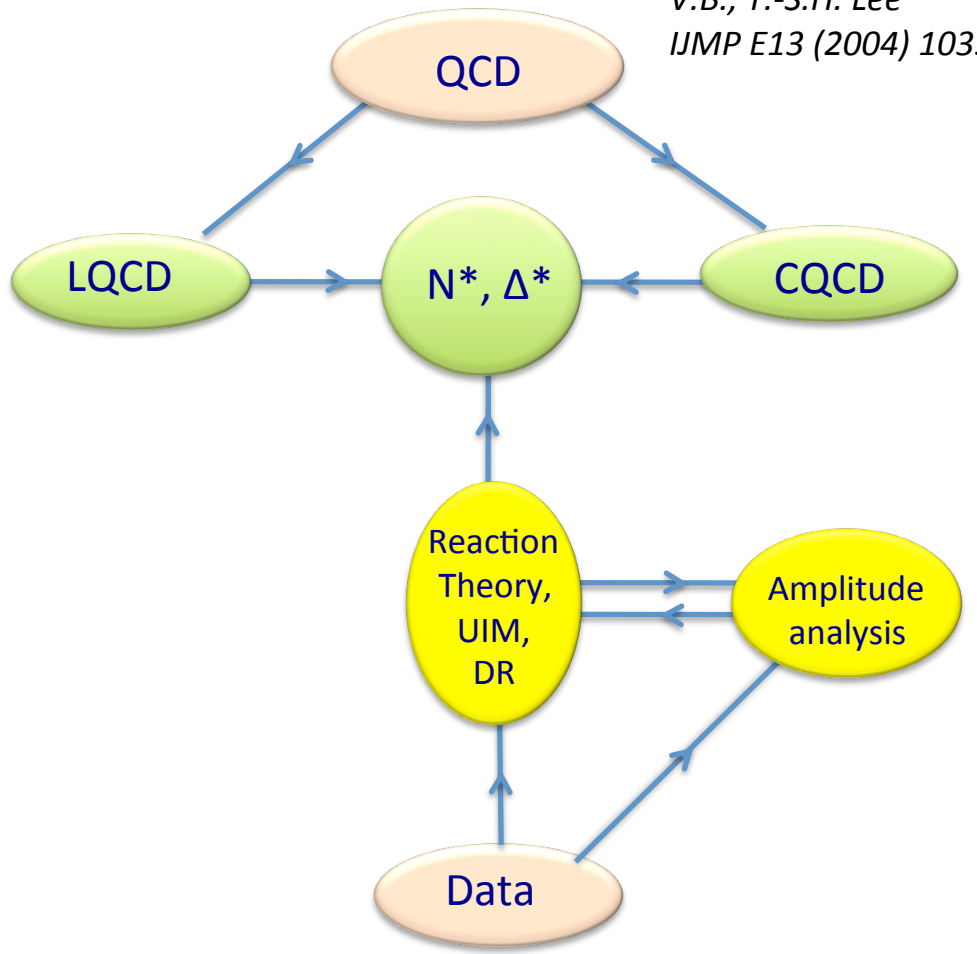
- **UIM** includes π Born terms in s- and u-channel nucleon exchanges and t-channel meson exchanges (π, ρ, ω, b_1, a_2,…).

- In fixed-t **DR** the real part is determined from π Born terms + dispersion integral over imaginary parts of all known resonances.

- The $p\pi^+\pi^-$ analysis uses a data-driven reaction model (JM) **JLAB-MSU.**

I.G. Aznauryan, T.-S. H. Lee, V. Mokeev.

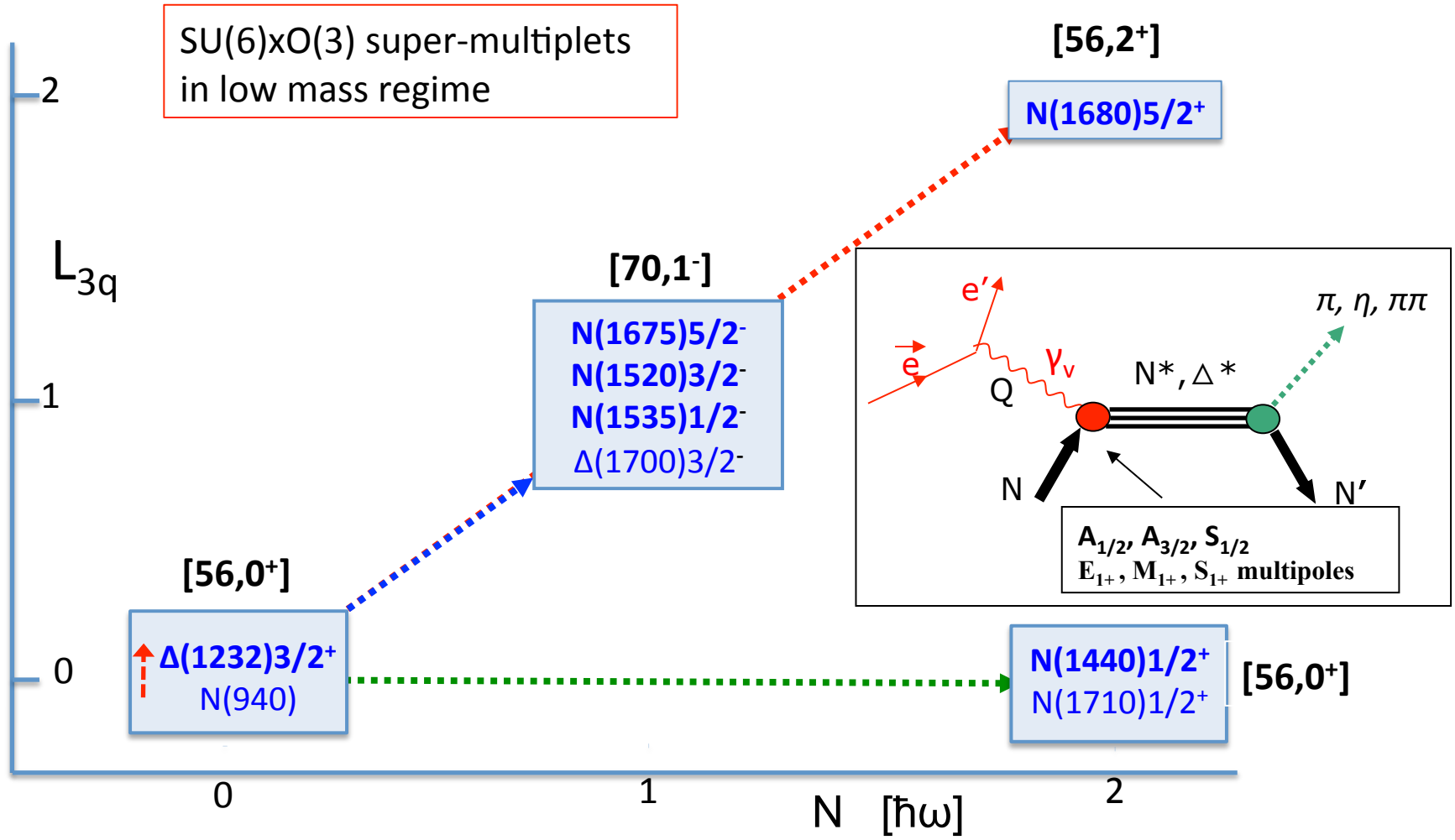
V.B., T.-S.H. Lee
IJMP E13 (2004) 1035



Hadronic production

Electromagnetic production

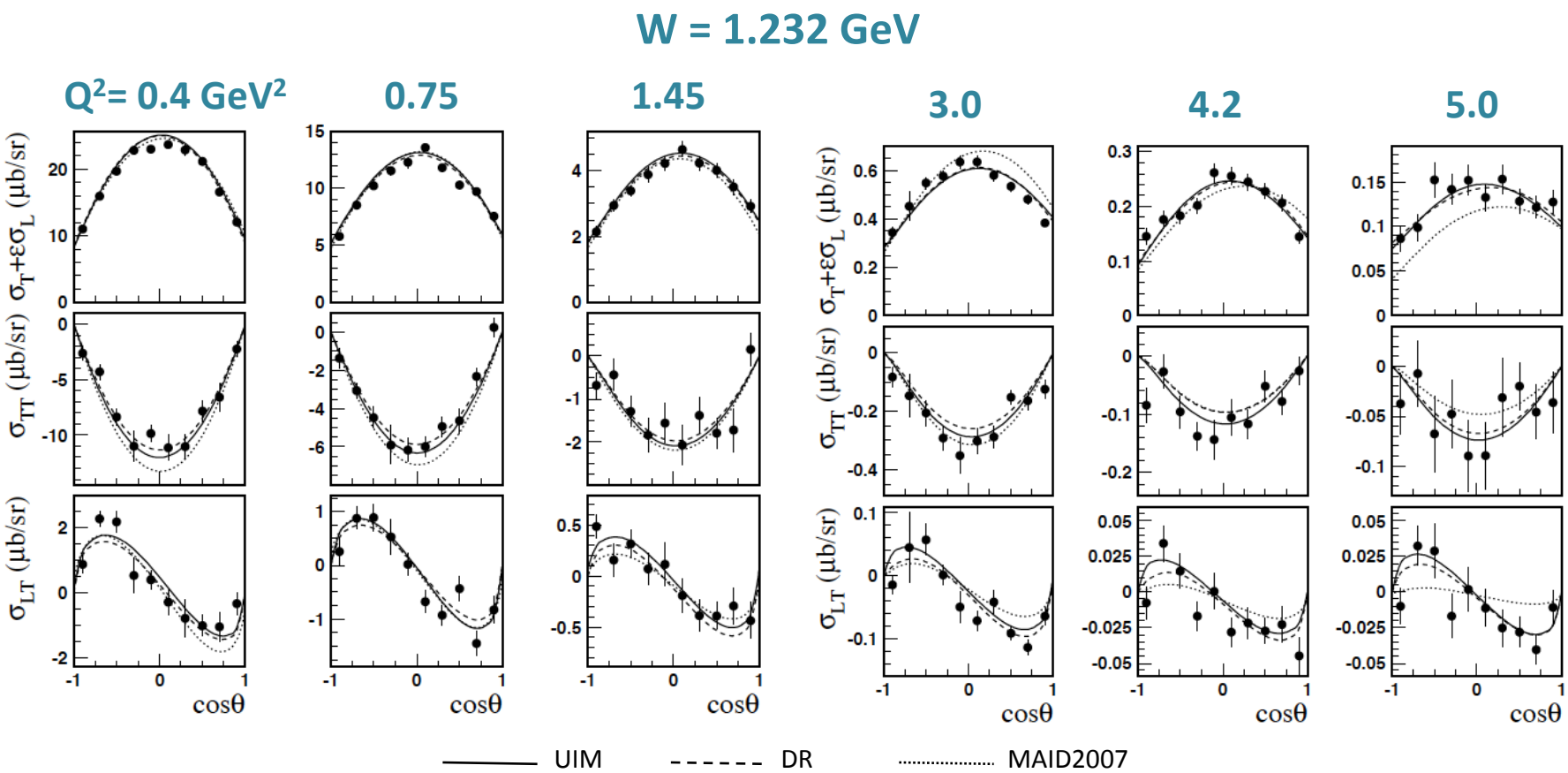
Nucleon resonance transitions



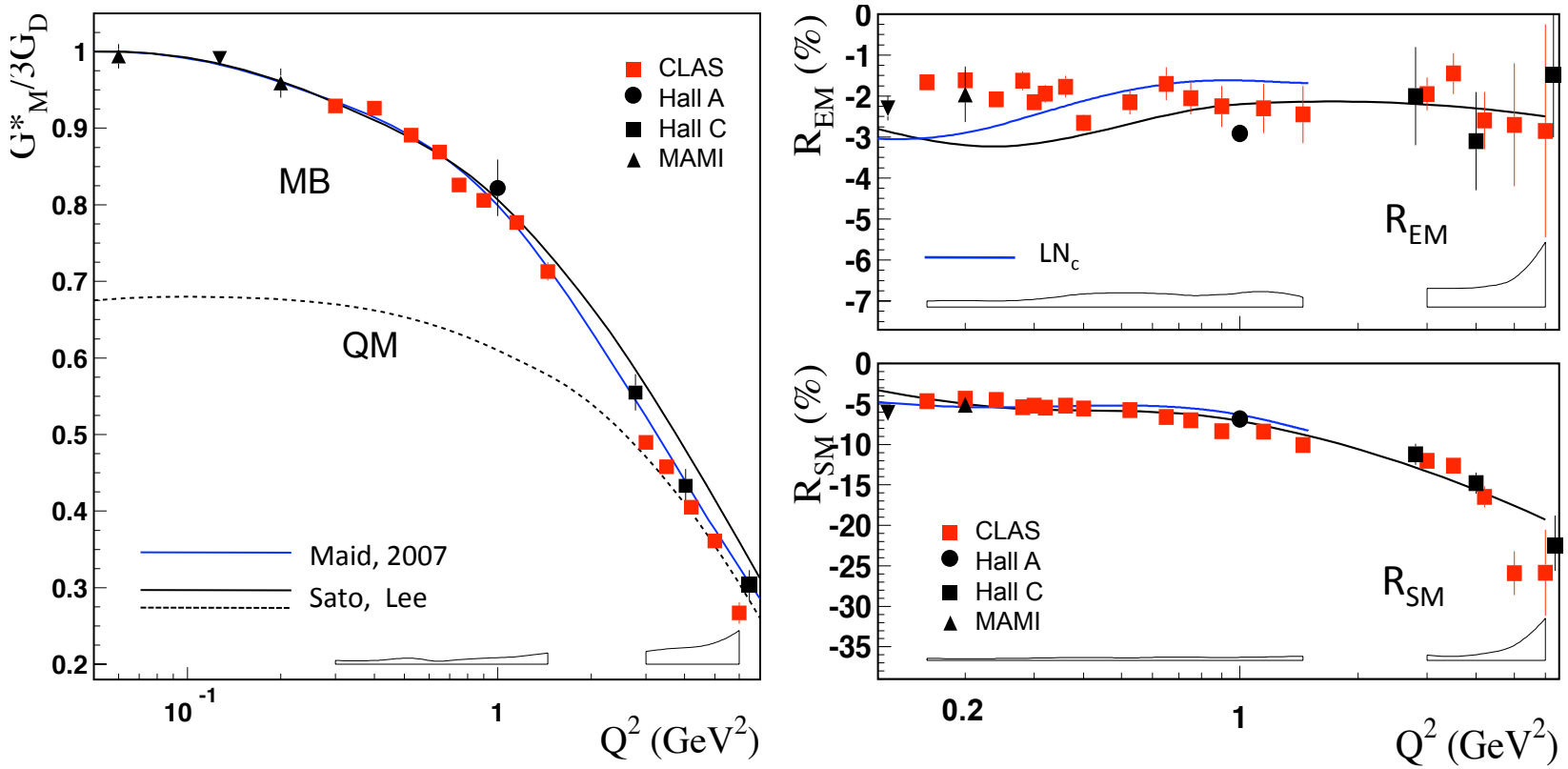
Results based on over 150,000 cross sections and polarization observables in W, Q^2, cosθ, ϕ.

Response functions of $p\pi^0$ in $\Delta(1232)$

Measure azimuth and polar angle dependence of $p(e,e'p)\pi^0$ cross section and polarization observables and extract resonant part with **UIM** and **DR** approach.



The NΔ(1232) Transition

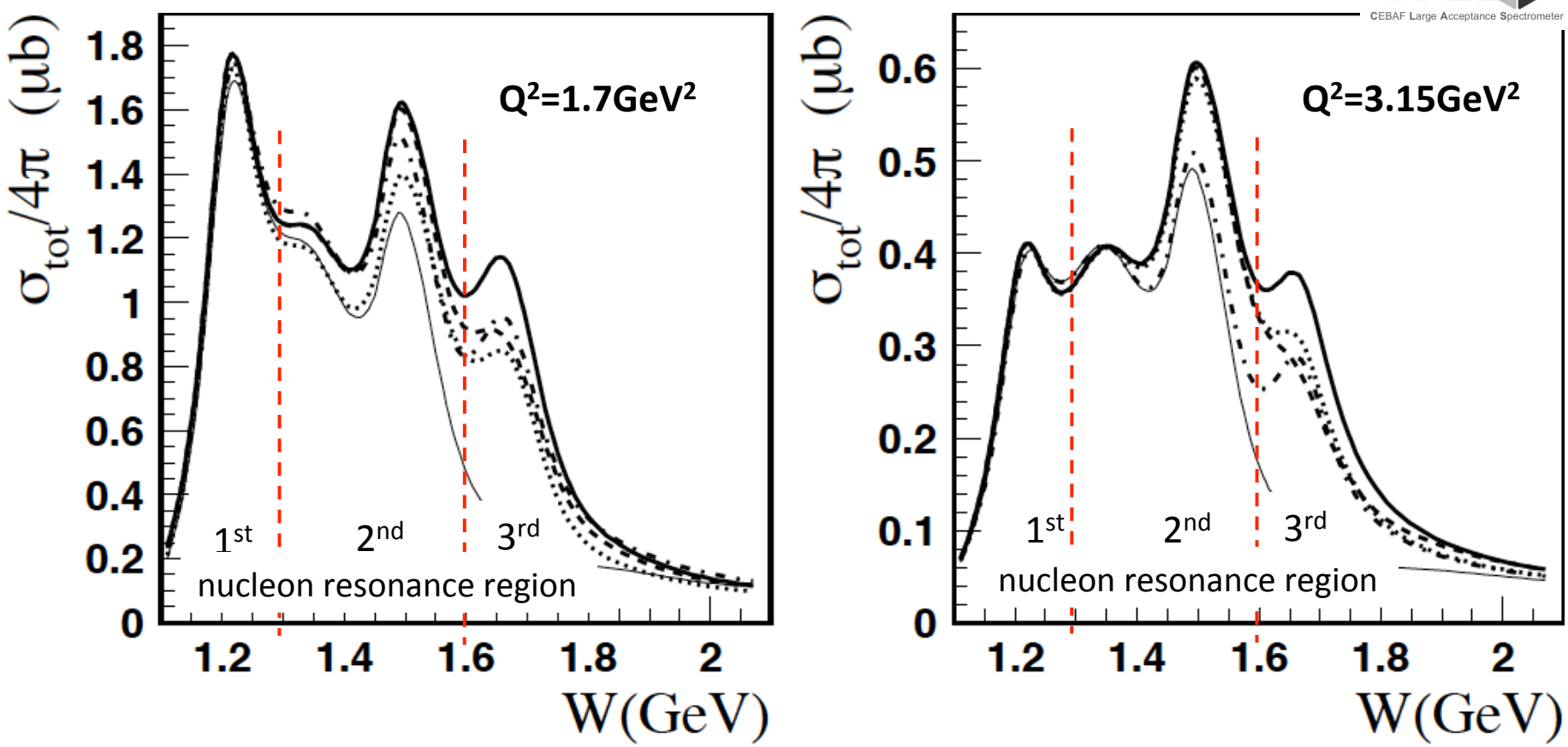


LN_c: Pascalutsa, Vanderhaeghen 2007

- Large MB contributions (1/3) needed to describe magnetic dipole transition at Q^2=0
- For G^*_M the MB contribution are decreasing with increasing Q^2
- R_{EM} and R_{SM} described with MB contributions only
- No approach to asymptotic behavior R_{EM} => +100%

Total cross section at W < 2.1 GeV

$\gamma^* p \rightarrow \pi^+ n$

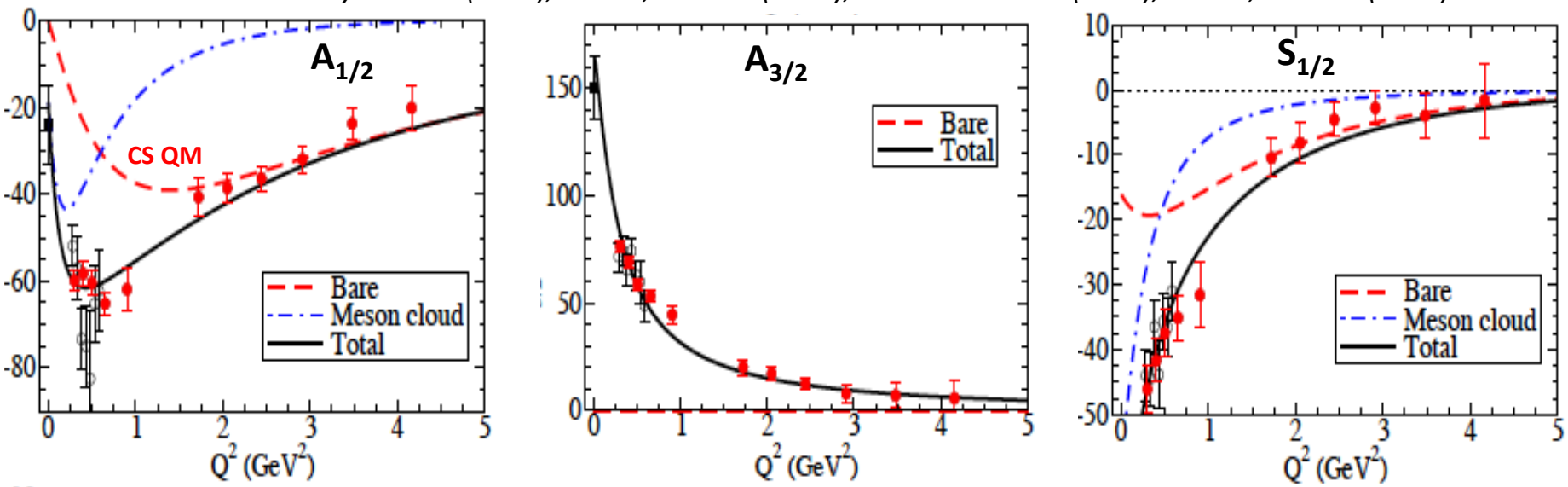


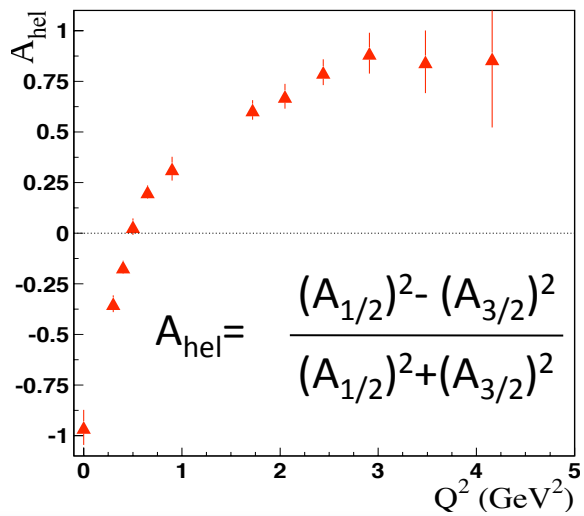
Access "Roper" N(1440)1/2$^+$, N(1520)3/2$^-$, and N(1535)1/2$^-$

K. Park et al., PR C77 (2008) 015208; PR C91 (2015) 045203

Electrocouplings of $\gamma_v pN(1520)3/2^-$

Aznauryan et al. (CLAS), PRC80, 055203 (2009), V. Mokeev et al. (CLAS), PRC86, 035203 (2012)





$$A_{hel} = \frac{(A_{1/2})^2 - (A_{3/2})^2}{(A_{1/2})^2 + (A_{3/2})^2}$$

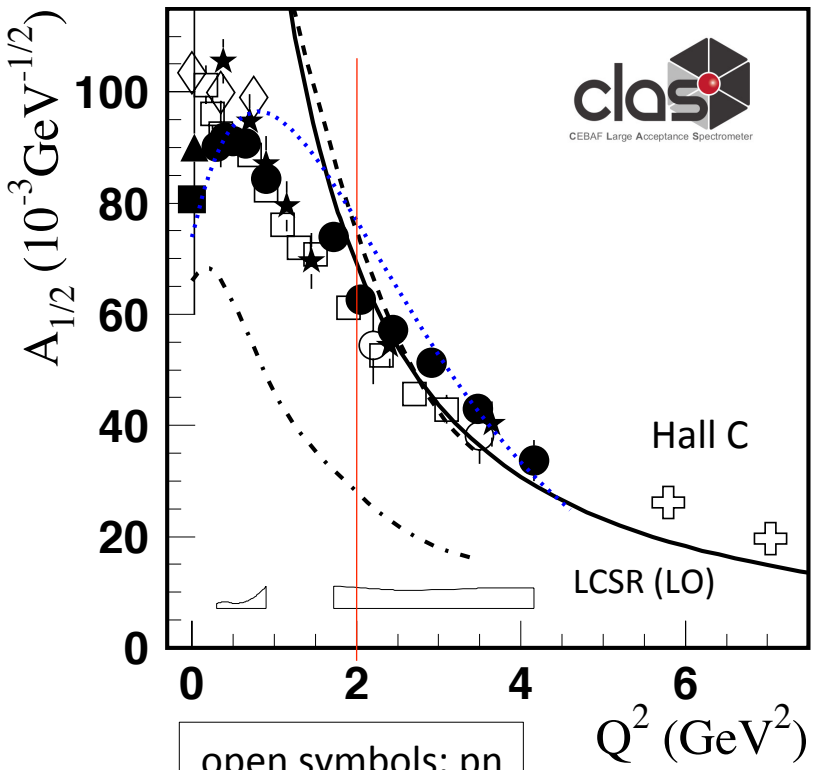
- Lowest negative parity spin 3/2 state => 3 amplitudes
- Firmly established switch from $A_{3/2}$ dominance at $Q^2=0$ to $A_{1/2}$ dominance at $Q^2 > 1$ GeV^2.
  - $A_{1/2}$ strength at high Q^2 from bare quarks
  - MB dominate amplitudes at low Q^2
  - $A_{3/2} = 0$, not computed in this model

CS QM: *G. Ramalho and M. T. Peña, PR D89 (2014) 094016*

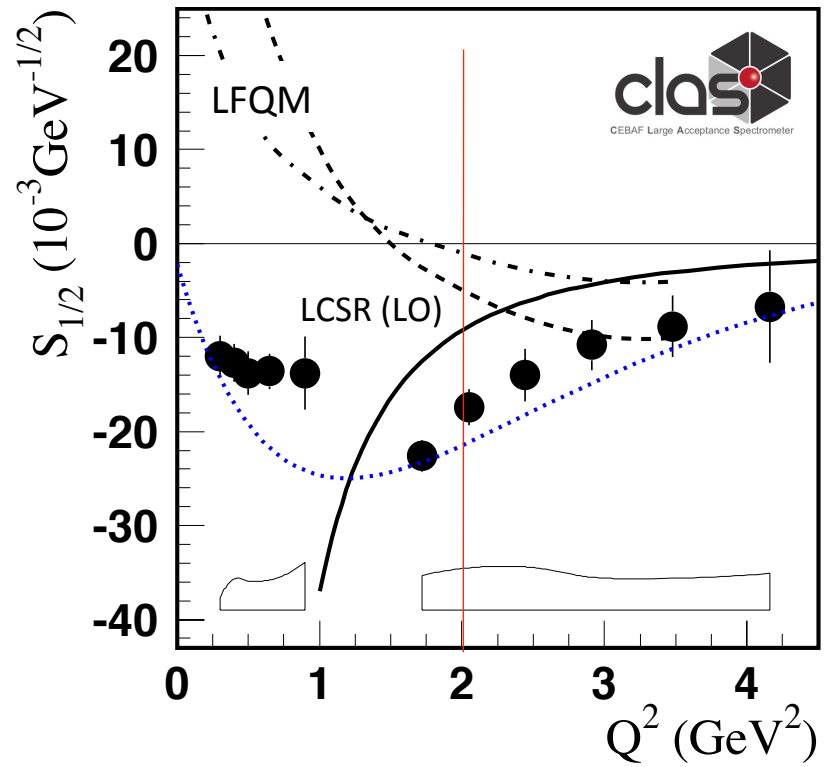
Electrocouplings of $\gamma_v pN(1535)1/2^-$

Is it a 3-quark state or a hadronic molecule?

- Chiral unitary model analyses: state may have large KΛ and pϕ components



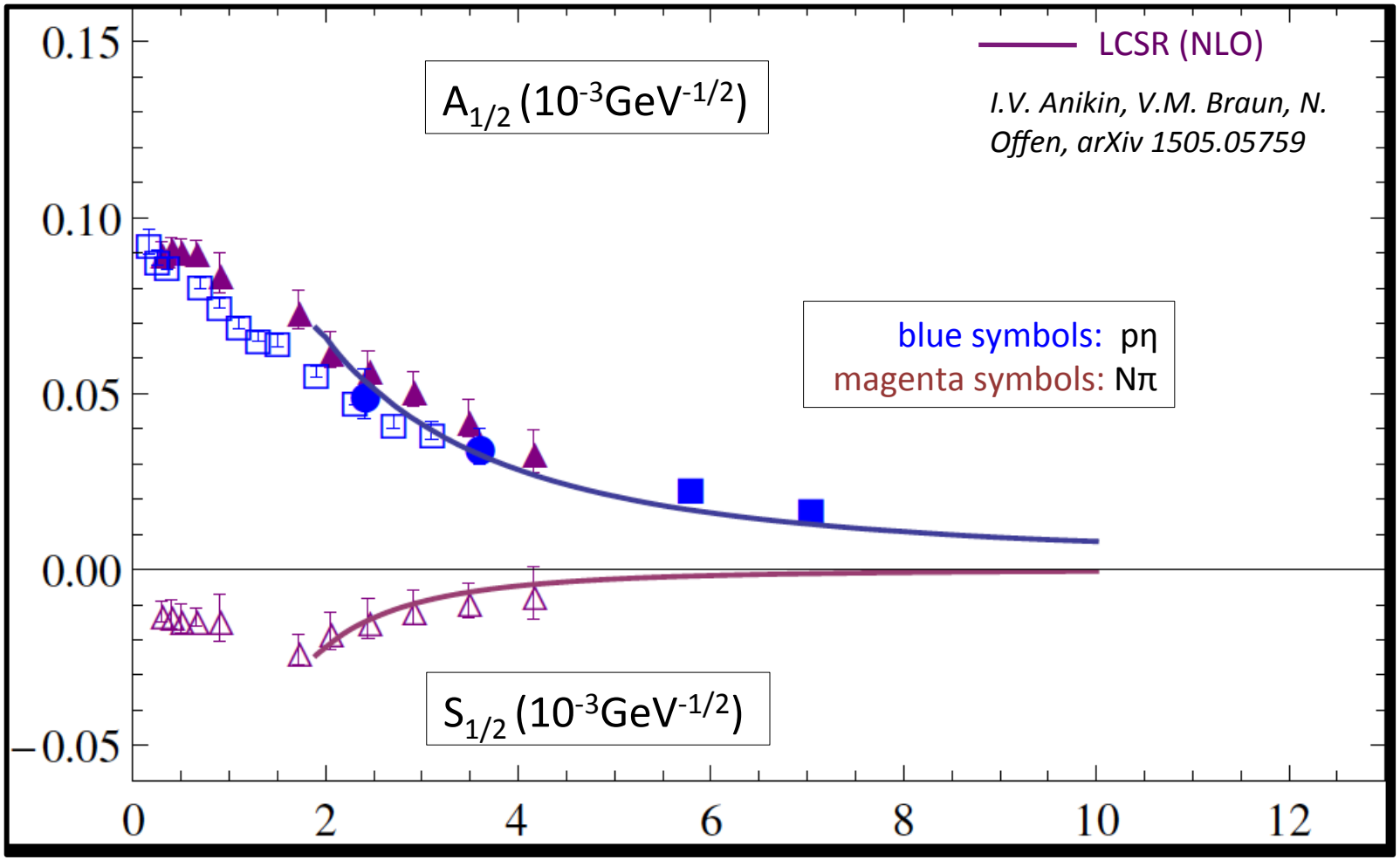
open symbols: pη
full symbols: **Nπ**



LCSR: V.M. Braun et al., PRL 103 (2009)

KΛ or pϕ could explain low Q^2 behavior that contrasts LFQM predictions.

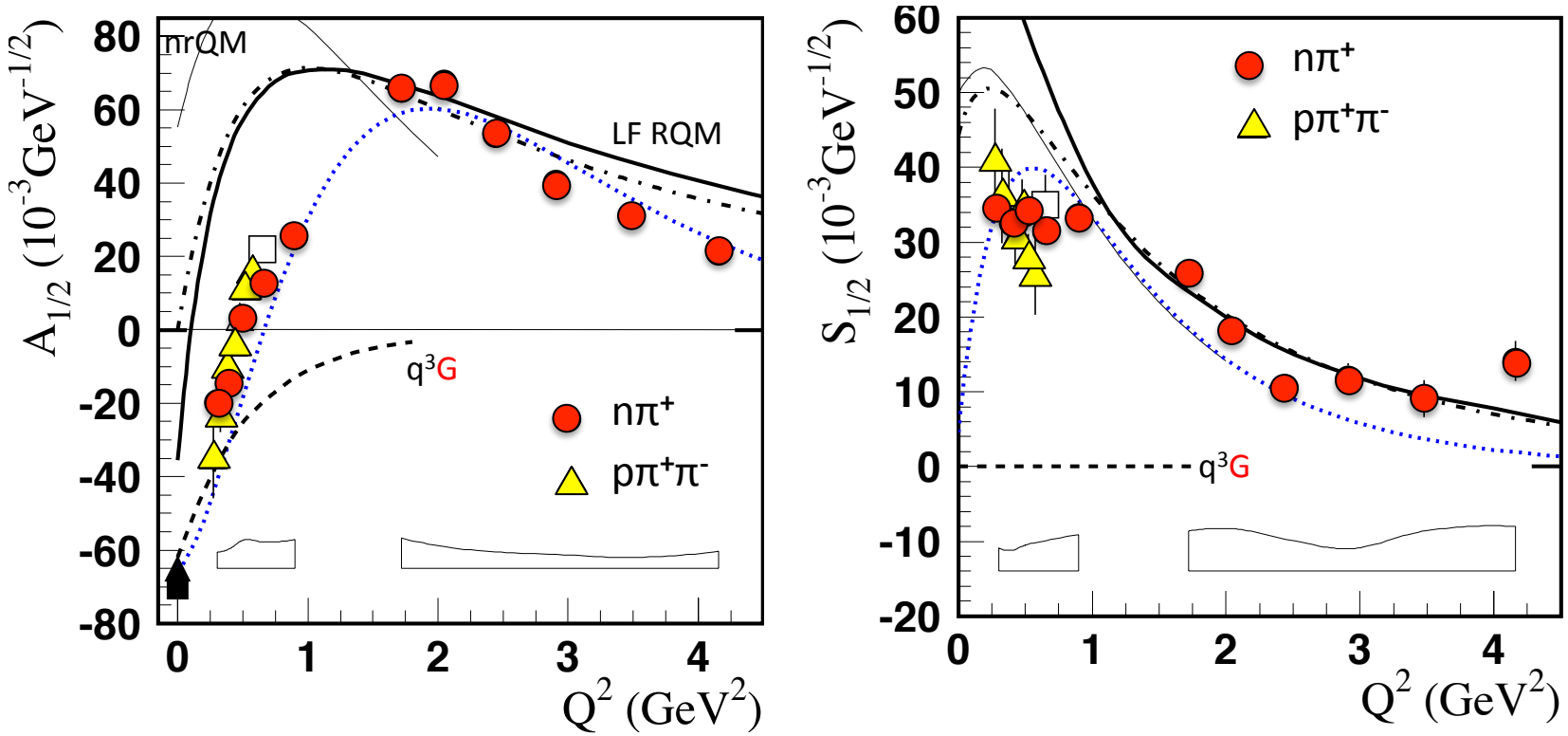
Electrocouplings of $\gamma_v pN(1535)1/2^-$ in QCD



Quantitative description at $Q^2 \geq 2$ GeV^2.

Electrocouplings of 'Roper' $\gamma_v pN(1440)1/2^+$

Aznauryan et al. (CLAS), PRC80, 055203 (2009), V. Mokeev et al. (CLAS), PRC86, 035203 (2012)

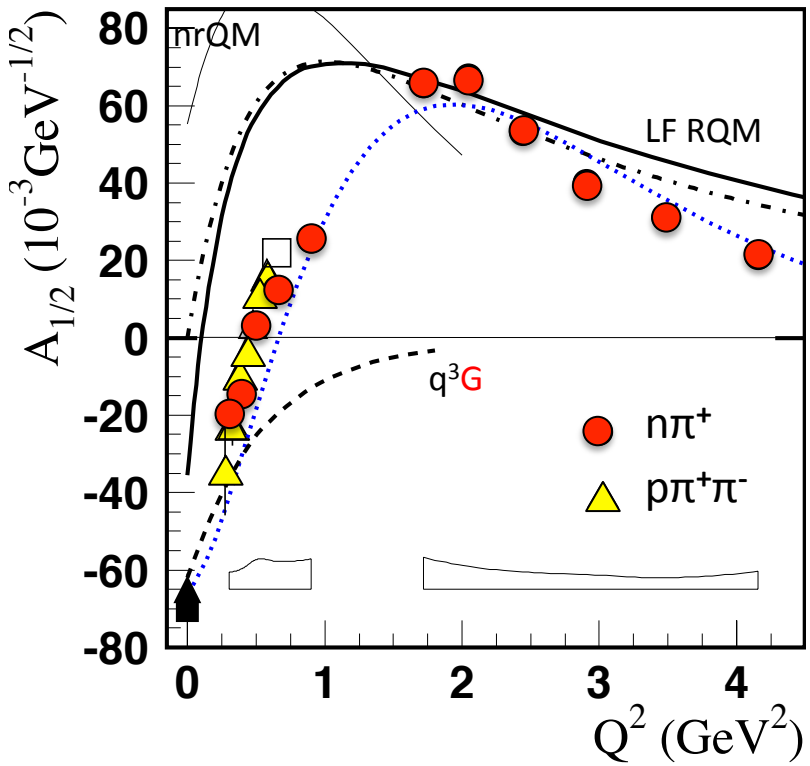


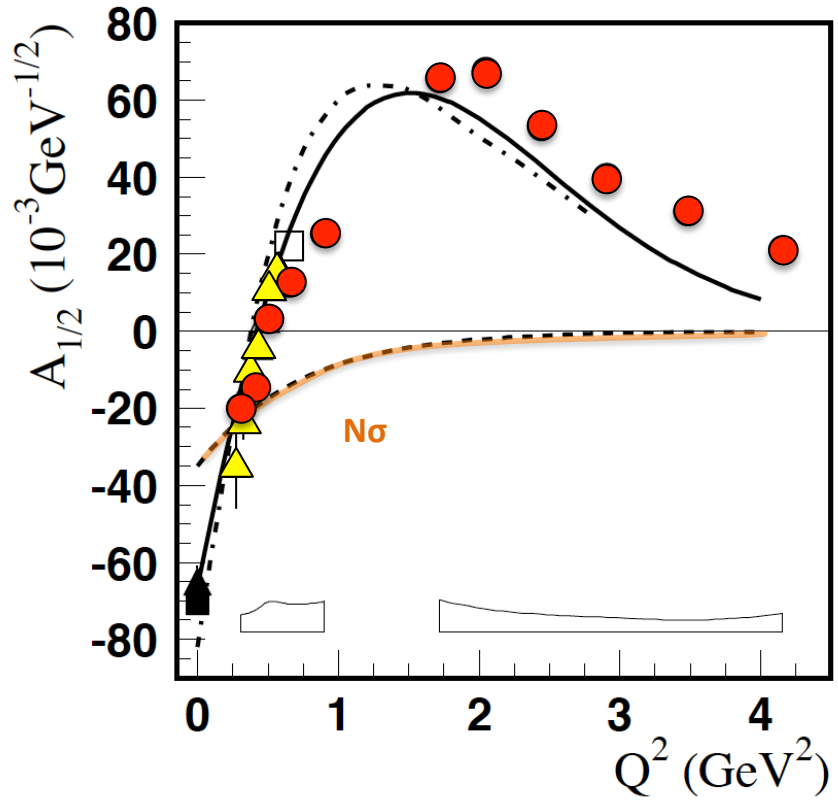
LF-RQM: I.G. Aznauryan, 2007
G. Ramalho, K. Tsushima, 2010

- $A_{1/2}$ changes sign and has large magnitude at high Q^2
- $N\pi$ and $N\pi\pi$ give consistent results
- QM assign state to the 1st radial excitation - fails to reproduce low Q^2 behavior, LCQM better at large Q^2
- Both $A_{1/2}(Q^2)$ and $S_{1/2}(Q^2)$ are inconsistent with hybrid baryon model prediction

Electrocouplings of 'Roper' $\gamma_v pN(1440)1/2^+$

Aznauryan et al. (CLAS), PRC80, 055203 (2009), V. Mokeev et al. (CLAS), PRC86, 035203 (2012)





- $A_{1/2}$ changes sign and has large magnitude at high Q^2
- Nπ and Nππ give consistent results
- QM assign state to the 1st radial excitation - fails to reproduce low Q^2 behavior, LCQM better at large Q^2
- Both $A_{1/2}(Q^2)$ and $S_{1/2}(Q^2)$ are inconsistent with hybrid model prediction
- Significant Nσ coupling needed to describe small Q^2 behavior

The "Roper" resonance in 2015

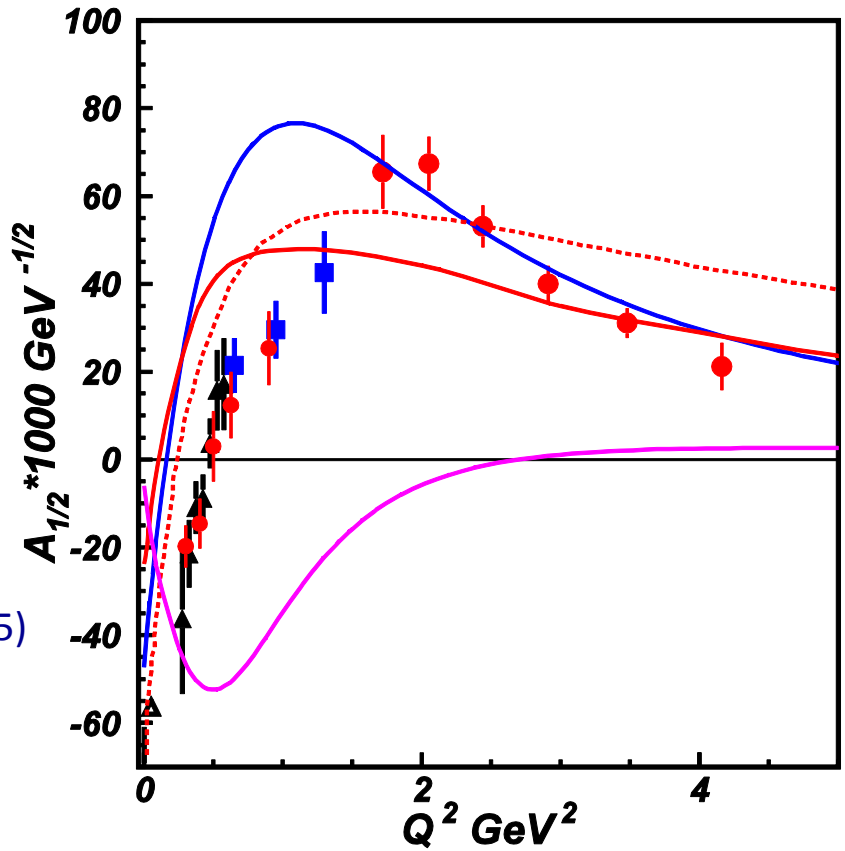
Description of the N(1440)1/2$^+$ $A_{1/2}$ electro-coupling in LF QM that incorporate the inner core of three dressed quarks in the first radial excitation and outer meson-baryon (MB) cloud:

Nπ loops to model MB cloud; **running quark mass**, in LF RQM. I.G. Aznauryan, V.B., Phys. Rev. C85, 055202 (2012).

Nσ loops to model MB cloud**; frozen constituent quark mass**. I.T. Obukhovsky, et al., Phys. Rev. D89, 014032 (2014).

Quark core contributions from DSE/QCD (2015) J. Segovia et al., arXiv:1504.04386

MB cloud **inferred from the CLAS data** as the difference between the data and quark core evaluated in DSE/QCD.



The structure of N(1440)1/2$^+$ resonance is determined by the interplay between a core of three dressed quarks in the 1st radial excitation and the external meson-baryon cloud.

Light-cone N* transition charge densities

$$A_{1/2} = e\frac{Q_-}{\sqrt{K}\,(4M_N M^*)^{1/2}}\left\{F_1^{NN^*} + F_2^{NN^*}\right\},$$

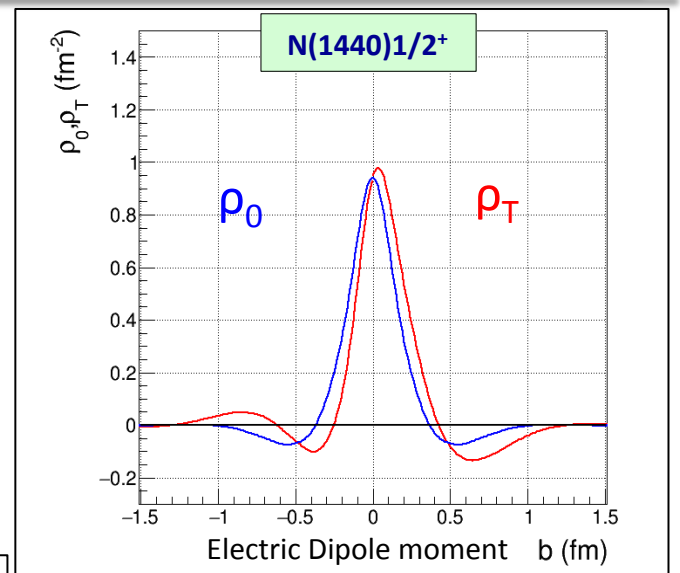
$$S_{1/2} = e\frac{Q_-}{\sqrt{2K}\,(4M_N M^*)^{1/2}}\left(\frac{Q_+Q_-}{2M^*}\right)\frac{(M^*+M_N)}{Q^2}\left\{F_1^{NN^*} - \frac{Q^2}{(M^*+M_N)^2}F_2^{NN^*}\right\}$$

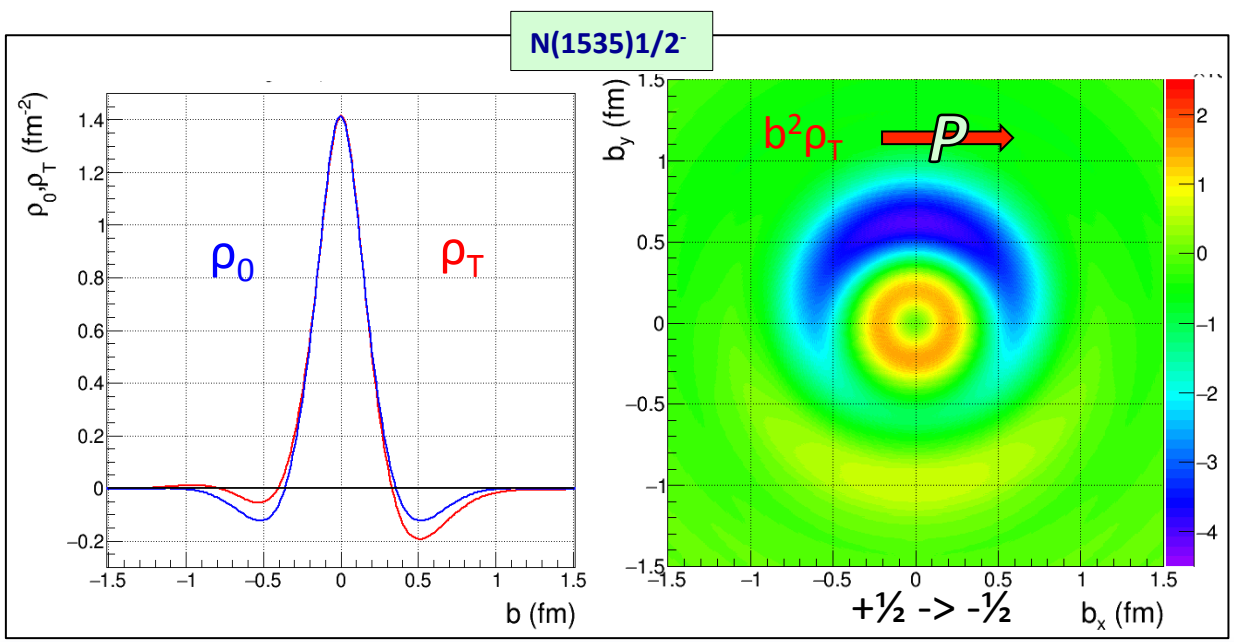
L. Tiator, M. Vanderhaeghen, PLB 672 (2009) 344

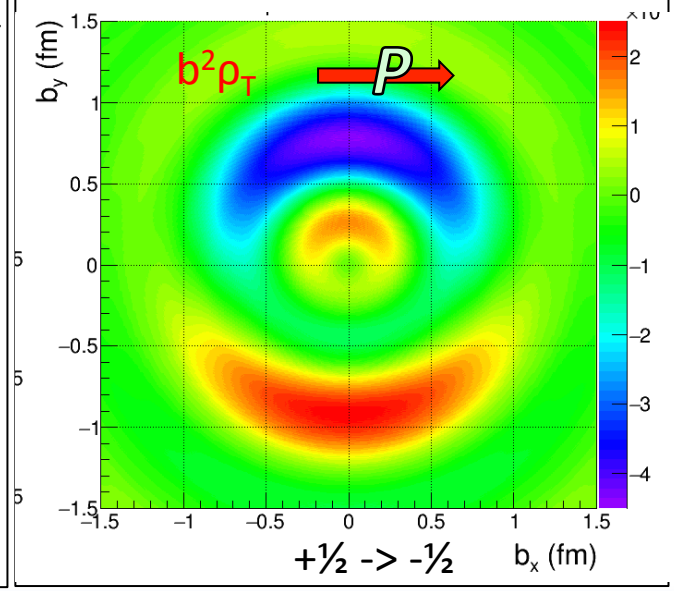
$$\rho_0^{NN^*}(\vec{b}) = \int_0^\infty \frac{dQ}{2\pi} Q\, J_0(b\,Q) F_1^{NN^*}(Q^2)$$

Exp: $0 < Q^2 < 4.5\text{-}7\ \mathrm{GeV}^2$

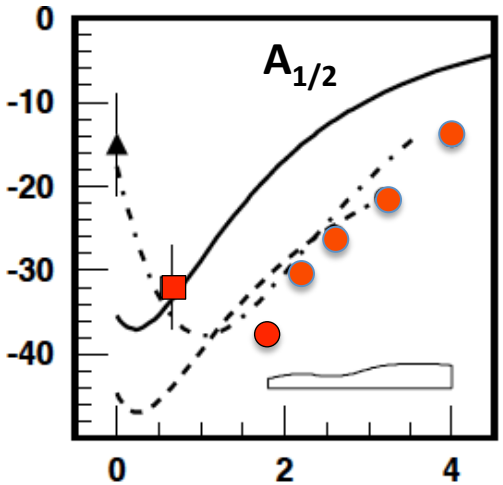
$$\rho_T^{NN^*}(\vec{b}) = \rho_0^{NN^*}(b) + \sin(\phi_b - \phi_S)\int_0^\infty \frac{dQ}{2\pi}\frac{Q^2}{(M^*+M_N)} J_1(b\,Q) F_2^{NN^*}(Q^2)$$

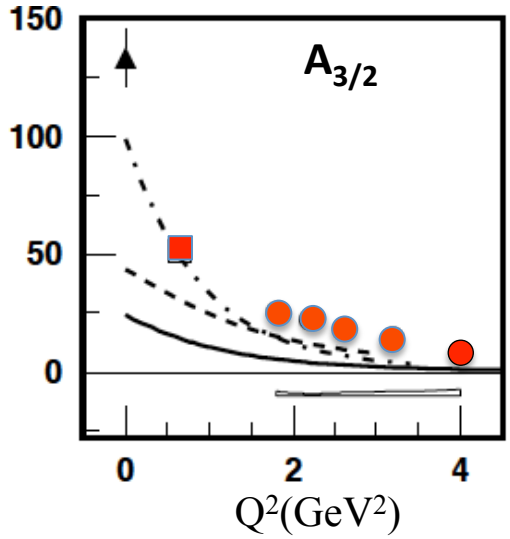


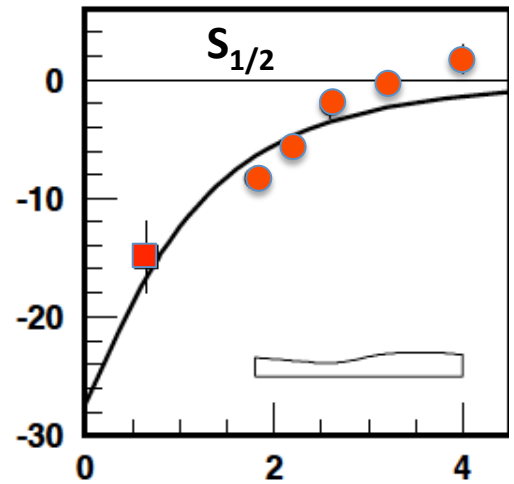




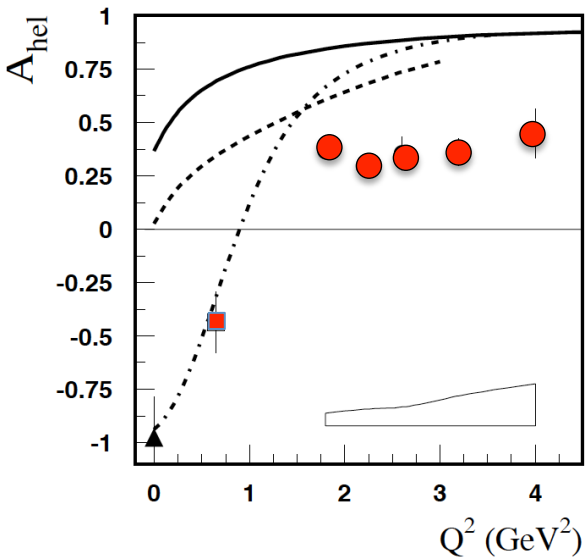
Electrocouplings of $\gamma_v pN(1680)5/2^+$







K. Park et al., PRC91 (2015) 045203



$$A_{hel} = \frac{(A_{1/2})^2 - (A_{3/2})^2}{(A_{1/2})^2 + (A_{3/2})^2}$$

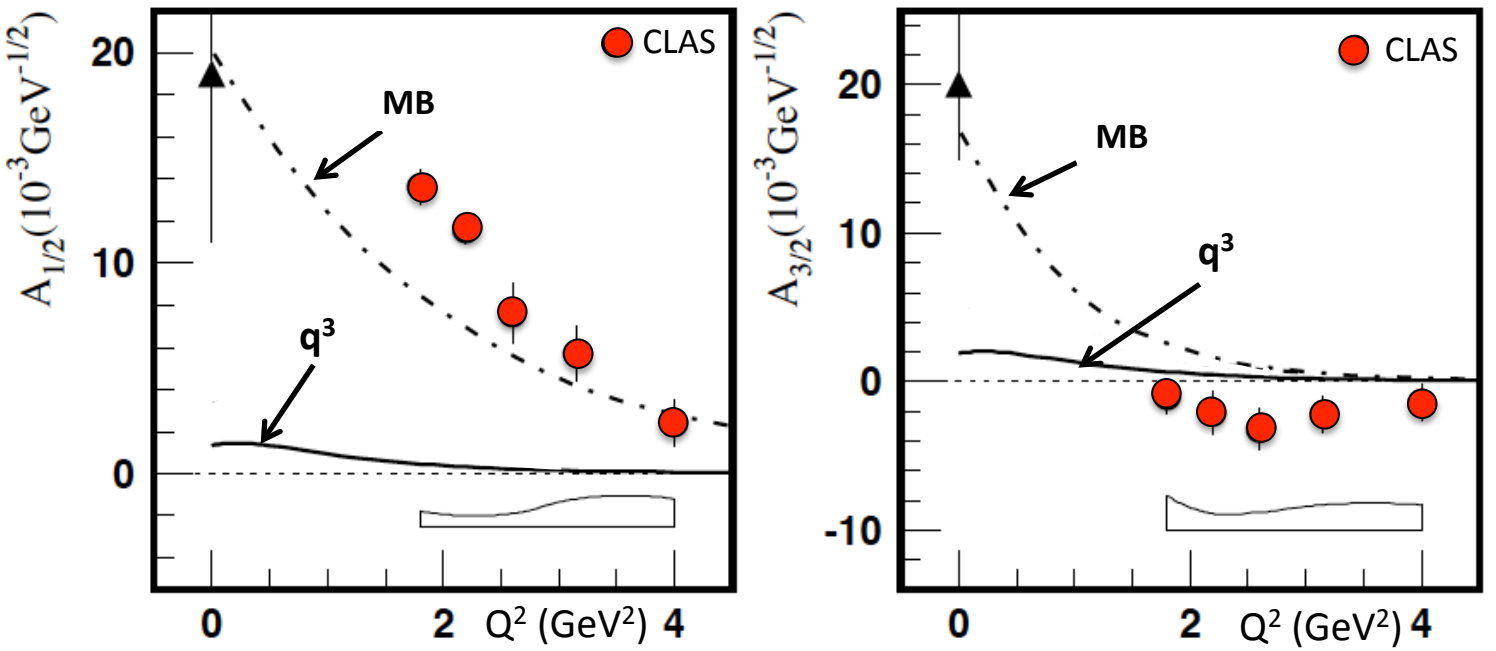
- Switch from $A_{3/2}$ dominance at $Q^2 = 0$ to $A_{1/2}$ at high Q^2 dominance slower than predicted from CQM.
- Are there large MB contributions in $A_{3/2}$ at high Q^2?

MB contribution to $\gamma_v pN(1675)5/2^-$

Quark components to the helicity amplitudes of the $N(1675)5/2^-$ are strongly suppressed for proton target.

Single Quark Transition:
$A^p_{1/2} = A^p_{3/2} = 0$

I. Aznauryan, V.B., arXiv:1412.1296

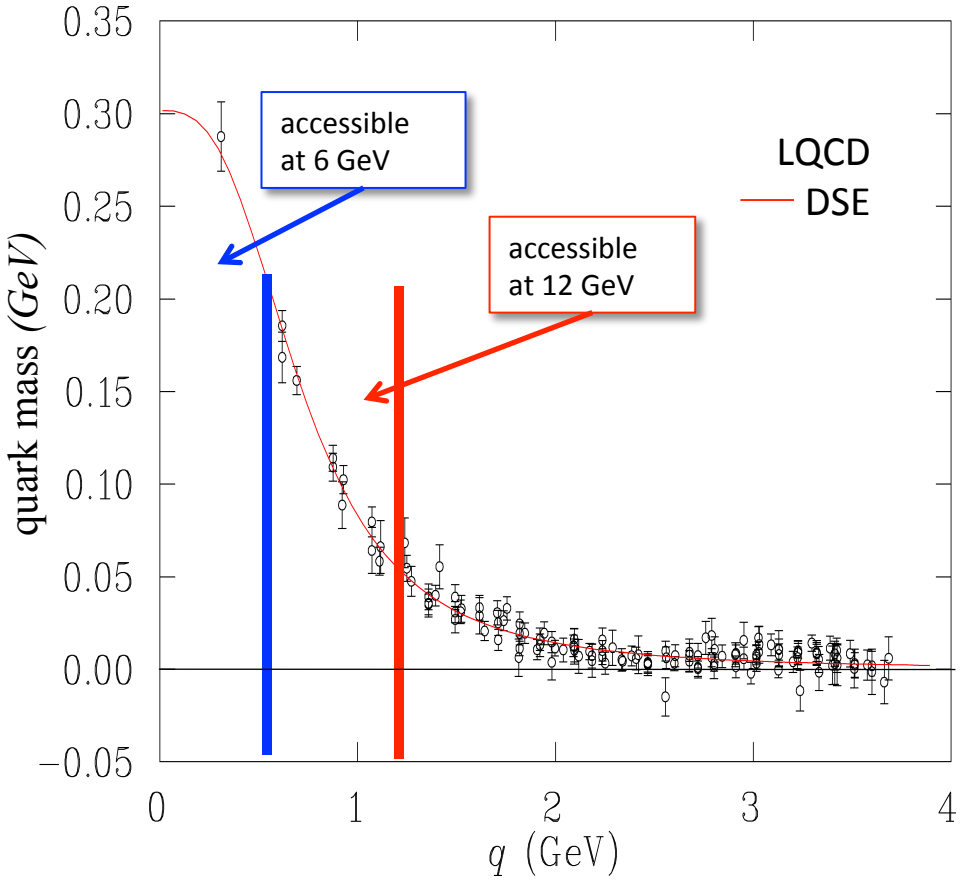


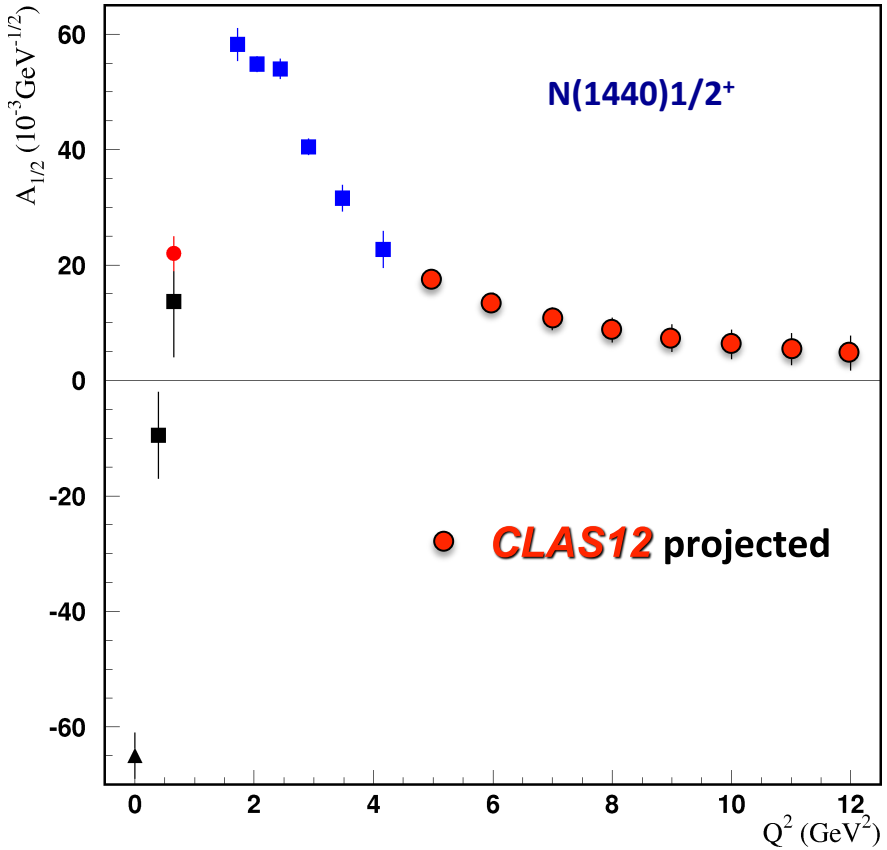
- Measures the meson-baryon contribution to $\gamma^* pN(1675)5/2^-$ directly
- Calibrate the dynamical coupled-channel model input

——— *E. Santopinto and M. M. Giannini, PRC 86, 065202 (2012)*

– · – · *B. Juliá-Díaz, T.-S.H. Lee, et al., PR C 77, 045205 (2008)*

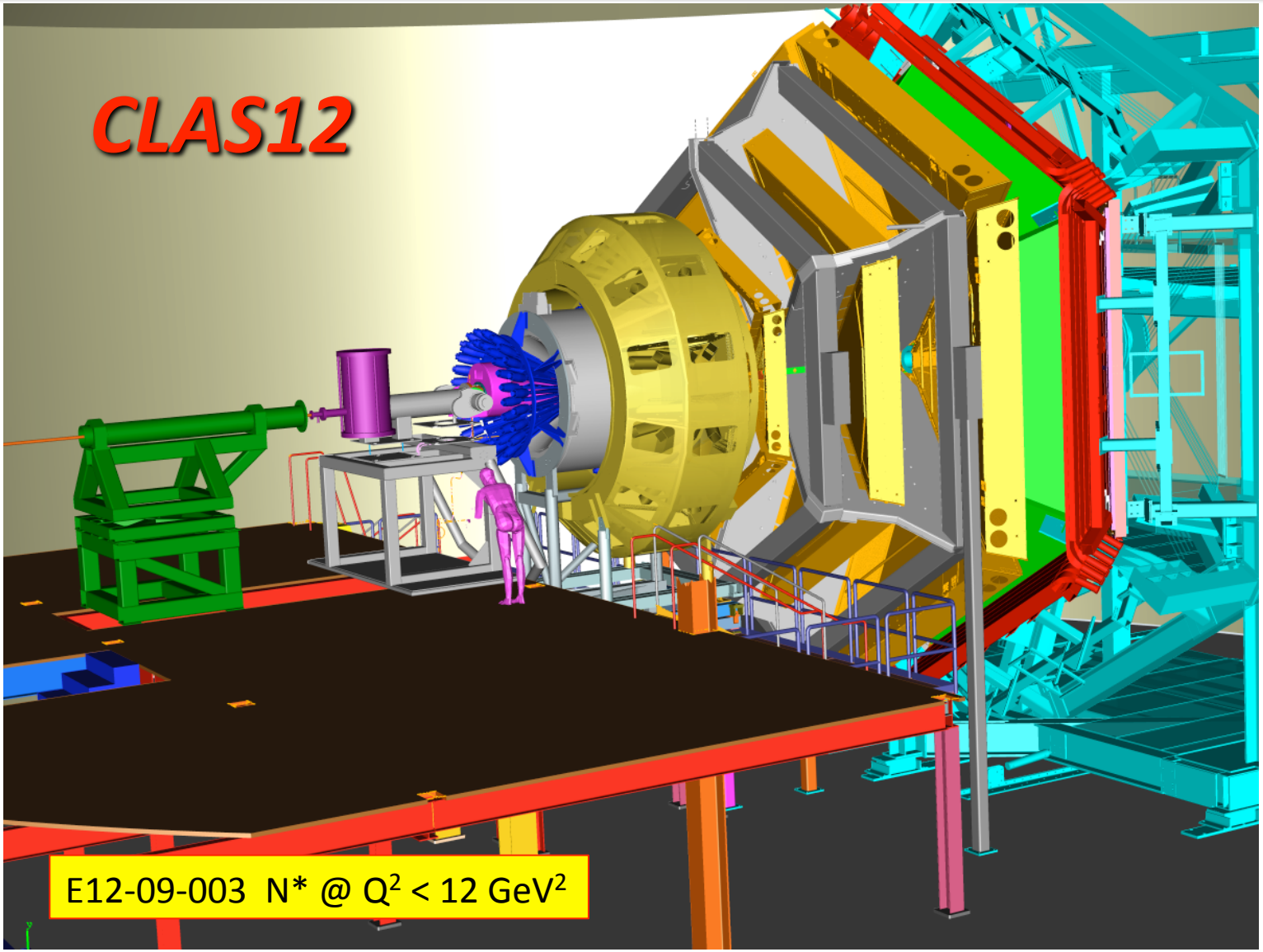
Probing the running quark mass at JLab12





Nucleon resonance transitions amplitudes probe the quark mass function from constituent quarks to dressed quarks and elementary quarks.

N* Transition FF Physics @ JLAB12



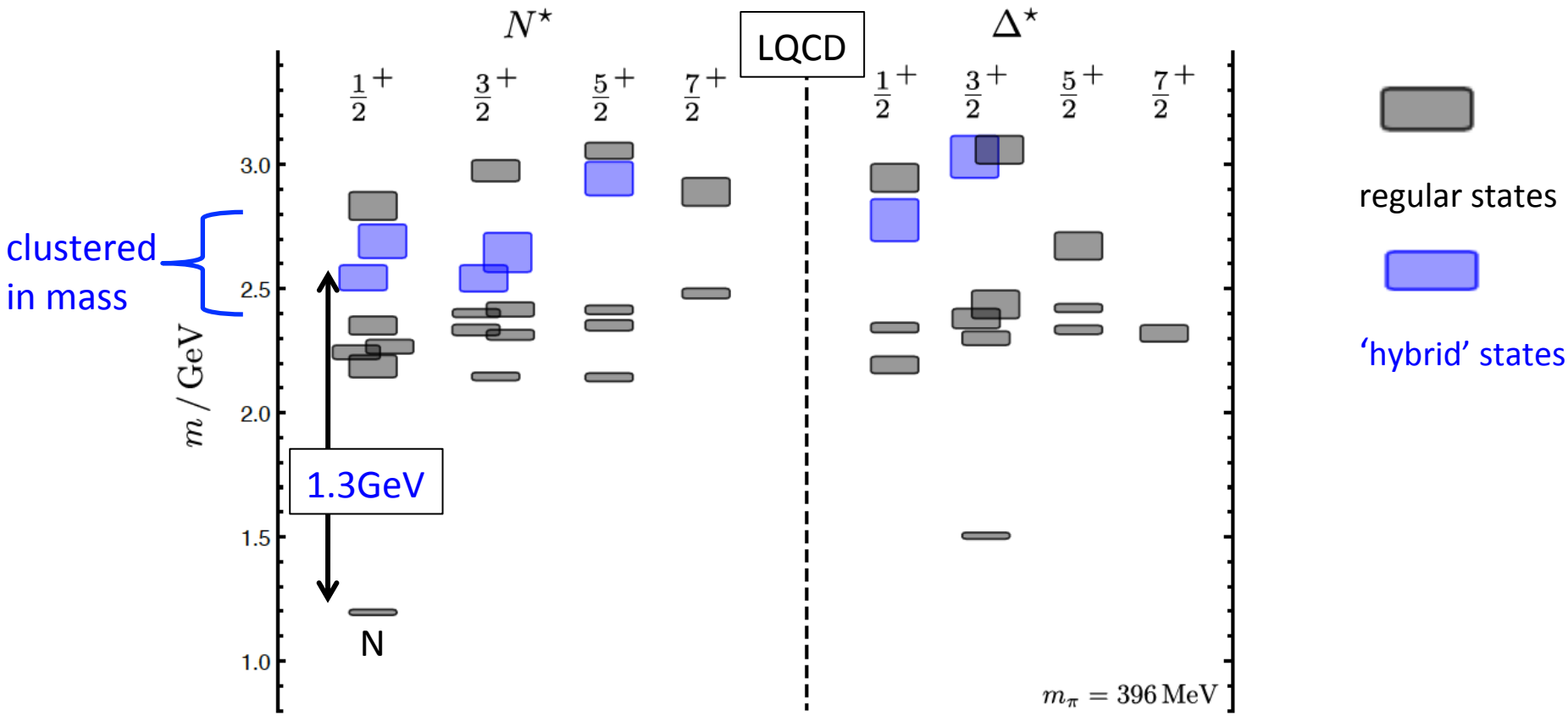
Conclusions & Outlook

- The 3-quark core becomes dominant to MB contributions in electroexcitation with $Q^2 > 2\text{-}4\ GeV^2$ in all studied excited states.
- The structure of the Roper resonance is determined by the interplay between the core of 3 dressed quarks in the 1st radial excitation and the external meson-baryon cloud.
- Transverse charge transition densities reveal significant differences for different excited states.
- Precise computation of electromagnetic transition form factors has become a topic of strong QCD.
- Planned experiment with CLAS12 at JLab@12GeV will measure resonances at highest Q^2 as a probe of the running quark mass.
- Electroexcitation of resonances may be an essential tool to isolate gluonic baryon excitations that can be explored with CLAS12.

Additional slides

Gluonic Baryons q^3G

J.J. Dudek and R.G. Edwards, PRD85 (2012) 054016 *T. Barnes and F.E. Close, PLB128, 277 (1983)*

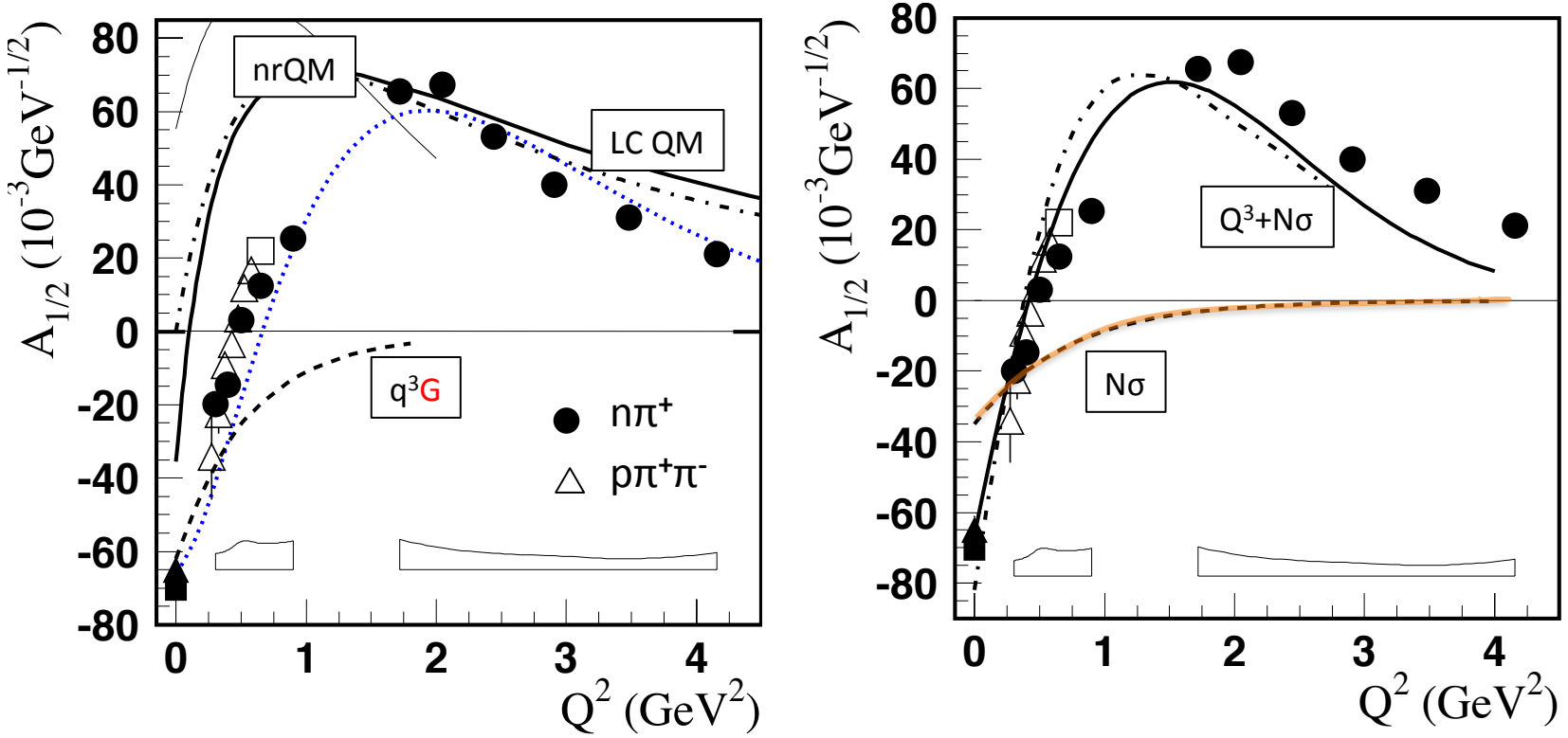


Hybrid states have same J^P values as q^3 baryons. How to identify them?

- Overpopulation of $N1/2^+$ and $N3/2^+$ states compared to QM projections?
- Transition form factors in electroproduction?

Electrocouplings of 'Roper' N(1440)1/2$^+$

Aznauryan et al. (CLAS), PRC80, 055203 (2009), V. Mokeev et al. (CLAS), PRC86, 035203 (2012)



- nrQM assign it to the 1st radial excitation of the nucleon, but fails in $A_{1/2}$
- $A_{1/2}$ dominant amplitude at high Q^2 indicates radial q^3 excitation but fails at low Q^2
- Significant meson-baryon coupling needed to describe small Q^2 behavior

- $A_{1/2}(Q^2)$ and $S_{1/2}(Q^2)$ are inconsistent with gluonic excitation

Unitary Isobar Model (UIM)

MAID Model: D. Drechsel, O. Hanstein, S. Kamalov, L. Tiator, Nucl.Phys. A 645 (1999) 145

$$L_{\pi NN} = \frac{\Lambda^2}{\Lambda^2 + |\mathbf{q}|^2} L^{PV}_{\pi NN} + \frac{|\mathbf{q}|^2}{\Lambda^2 + |\mathbf{q}|^2} L^{PS}_{\pi NN}.$$

$$Unitarized(M_{l\pm}, E_{l\pm}, S_{l\pm})_{background} = (M_{l\pm}, E_{l\pm}, S_{l\pm})_{background}(1 + ih_{l\pm}).$$

$$aA^R_{l\pm}(B^R_{l\pm}, S^R_{l\pm}) = \hat{A}_{l\pm}(\hat{B}_{l\pm}, \hat{S}_{l\pm}) \frac{M\Gamma_{tot} e^{i\phi}}{M^2 - W^2 - iM\Gamma_{tot}} f_{\gamma N}(W) \qquad f_{\gamma N}(W) = \left(\frac{|\mathbf{k}|}{|\mathbf{k}_r|}\right)^n \left(\frac{X^2 + |\mathbf{k}_r|^2}{X^2 + |\mathbf{k}|^2}\right)$$

$$\Gamma_{\pi N} = \beta_{\pi N} \Gamma \left(\frac{|\mathbf{q}|}{|\mathbf{q}_r|}\right)^{2l+1} \left(\frac{X^2 + |\mathbf{q}_r|^2}{X^2 + |\mathbf{q}|^2}\right)^l \frac{M}{W} \qquad \Gamma_{inel} = (1 - \beta_{\pi N}) \Gamma \left(\frac{|\mathbf{q}_{2\pi}|}{|\mathbf{q}_{2\pi,r}|}\right)^{2l+4} \left(\frac{X^2 + |\mathbf{q}_{2\pi,r}|^2}{X^2 + |\mathbf{q}_{2\pi}|^2}\right)^{l+2}$$

Include Regge exchanges at high s, I. Aznauryan,

$$Background = [N + \pi + \rho + \omega]_{UIM} \ at \ s < s_0,$$
$$= [N + \pi + \rho + \omega]_{UIM} \frac{1}{1 + (s - s_0)^2} + Re[\pi + \rho + \omega + b_1 + a_2]_{Regge} \frac{(s - s_0)^2}{1 + (s - s_0)^2} \ at \ s > s_0.$$

Fixed-t DRs for invariant Ball amplitudes

$\gamma^* N \to N\pi$

Dispersion relations for 6 invariant Ball amplitudes:

17 Unsubtracted Dispersion Relations

$$ReB_i^{(\pm,0)}(s,t,Q^2)\left[ReB_3^{(+,0)}(s,t,Q^2)\right] = R_i^{(v,s)}(Q^2)\left(\frac{1}{s-m_N^2}+\frac{\eta_i\eta^{(+,-,0)}}{u-m_N^2}\right) + \frac{P}{\pi}\int_{s_{thr}}^{\infty} ImB_i^{(\pm,0)}(s',t,Q^2)\left(\frac{1}{s'-s}+\frac{\eta_i\eta^{(+,-,0)}}{s'-u}\right)ds'$$

(i=1,2,4,5,6)

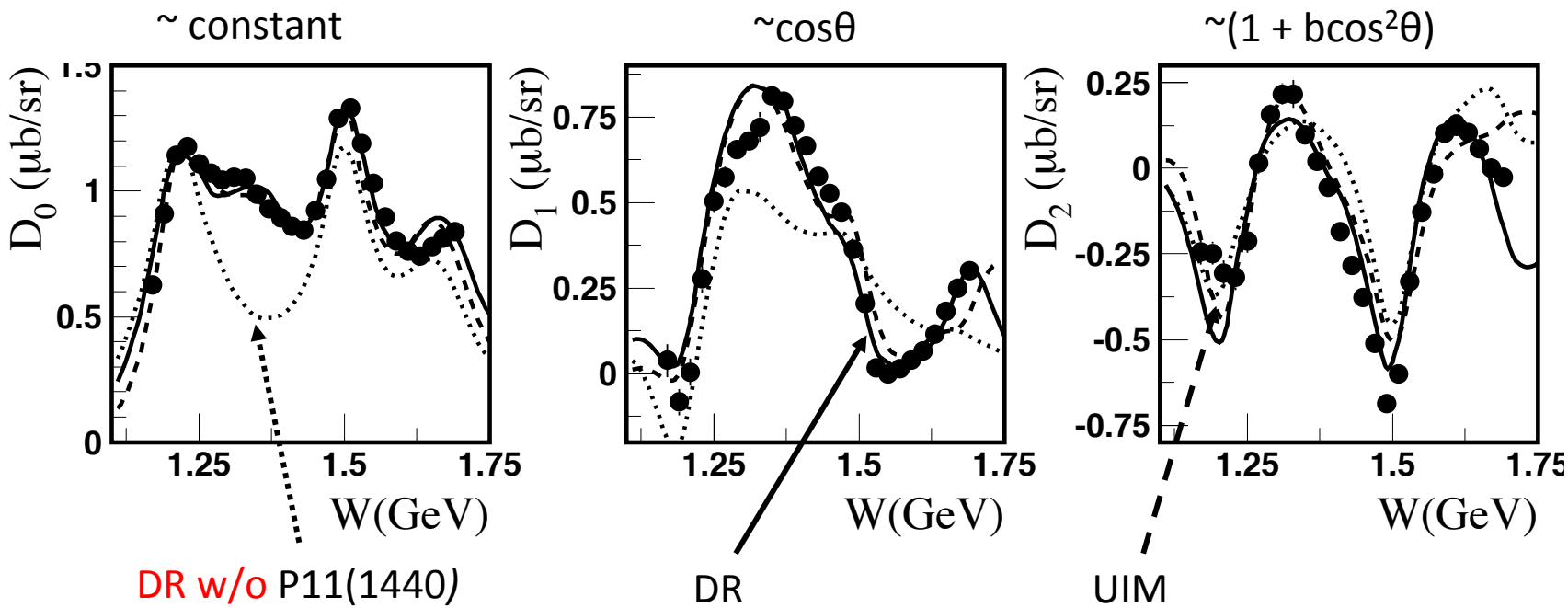
1 Subtracted Dispersion Relation

$$ReB_3^{(-)}(s,t,Q^2) = R_3^{(v)}(Q^2)\left(\frac{1}{s-m_N^2}+\frac{1}{u-m_N^2}\right) - eg\frac{F_\pi(Q^2)}{t-m_\pi^2} + f_{sub}(t,Q^2) + \frac{P}{\pi}\int_{s_{thr}}^{\infty} Im\ B_3^{(-)}(s',t,Q^2)\left(\frac{1}{s'-s}+\frac{1}{s'-u}\right)ds'$$

From fit to high Q^2 data: $f_{sub}(t, Q^2) = -(1.62 + 0.5*t) + Q^2(0.32 + 0.11*t)$

Legendre moments reveal large N(1440)1/2$^+$

$n\pi^+$ Q^2=2.05 GeV^2



Peaks in P33, D13/S11 region, broad enhancement from P11 partial wave (Roper).

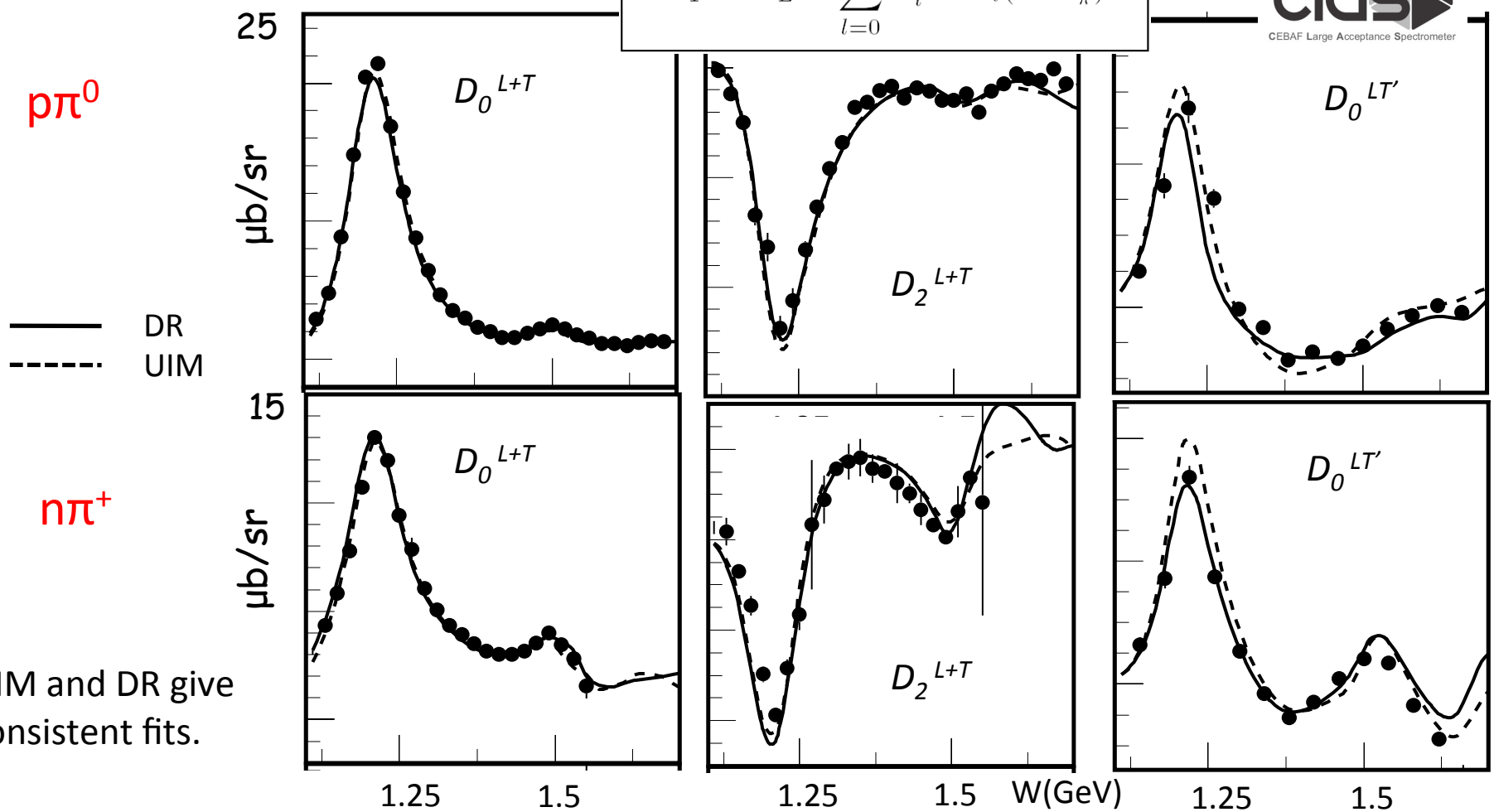
Broad structure from 1.2 to 1.5GeV due to s-p interference terms.

Dip in Δ region S11-D13 interference

Legendre Moments for ep→eNπ

Q^2=0.4 GeV^2

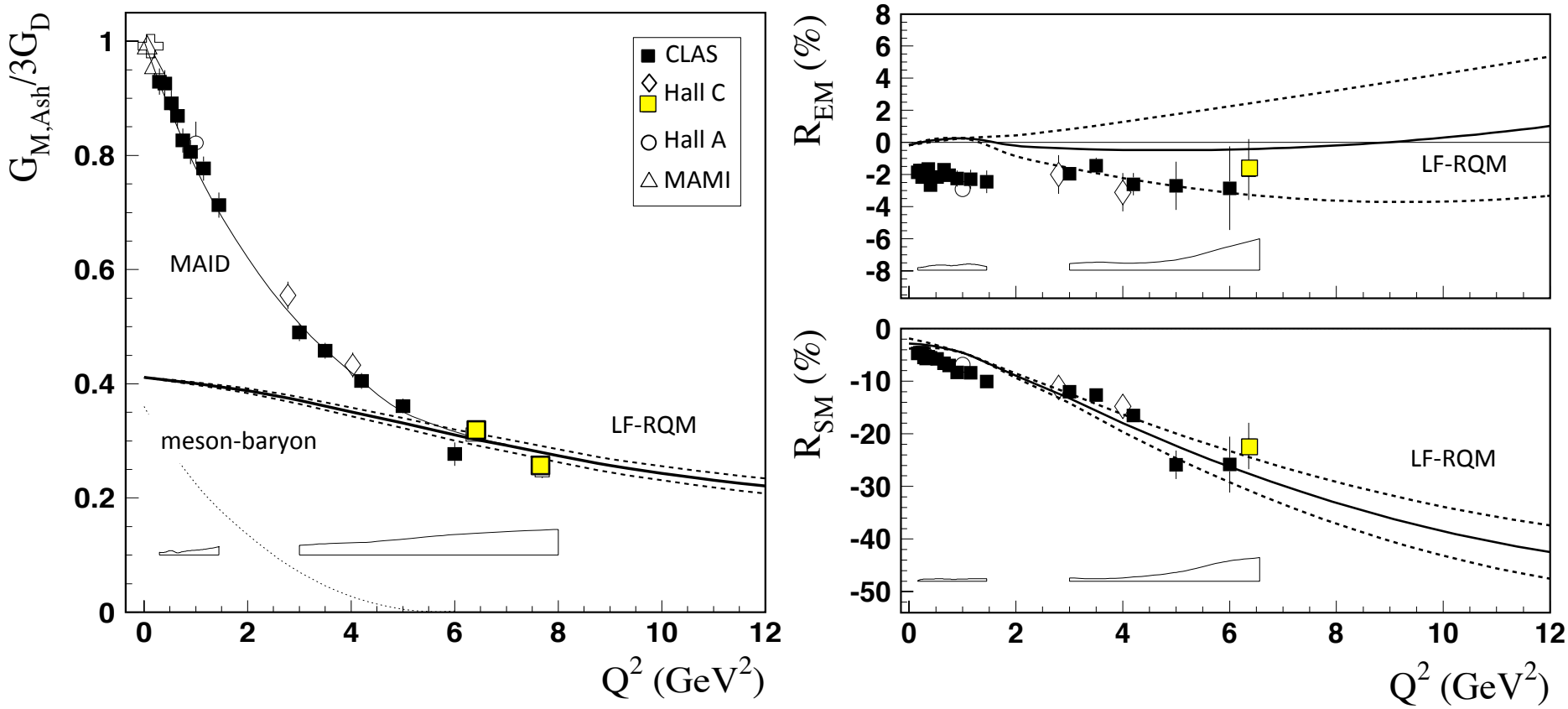
$$\sigma_T + \epsilon\sigma_L = \sum_{l=0}^{n} D_l^{T+L} P_l(\cos\theta_\pi^*)$$



UIM and DR give consistent fits.

Different channels sensitive to resonances of different isospin

The NΔ(1232) Transition in $\gamma^* p \rightarrow p\pi^0$



- LF-RQM quark core and MB of similar magnitude at Q^2=0.
- Describes G_M at $Q^2 \geq 5$ GeV^2.
- Transition to asymptotic behavior $R_{EM} \longrightarrow$ +100% not in sight. Described with MB.
- Predicts R_{SM} to continue to grow in magnitude at large Q^2. (AdS/QCD => -100%)

LF-RQM: I. Aznauryan, VB; prel. (2015)