N* Transition form factors in a light-cone relativistic quark model.

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Outline:

- Motivation
- The model: q^3 + meson cloud
- Description of elastic form factors
- N* transition form factors at $Q^2 \leq 5$ GeV^2
- Predictions for $Q^2 > 5$ GeV^2
- Conclusions/Outlook

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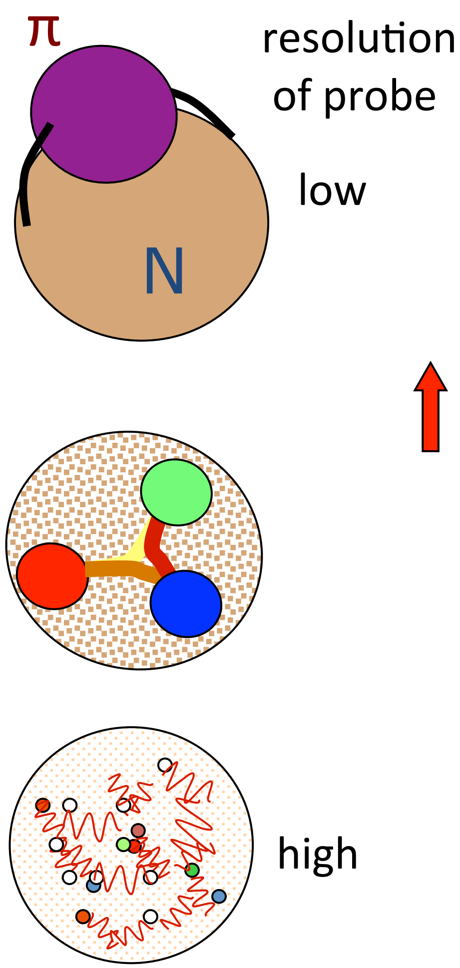
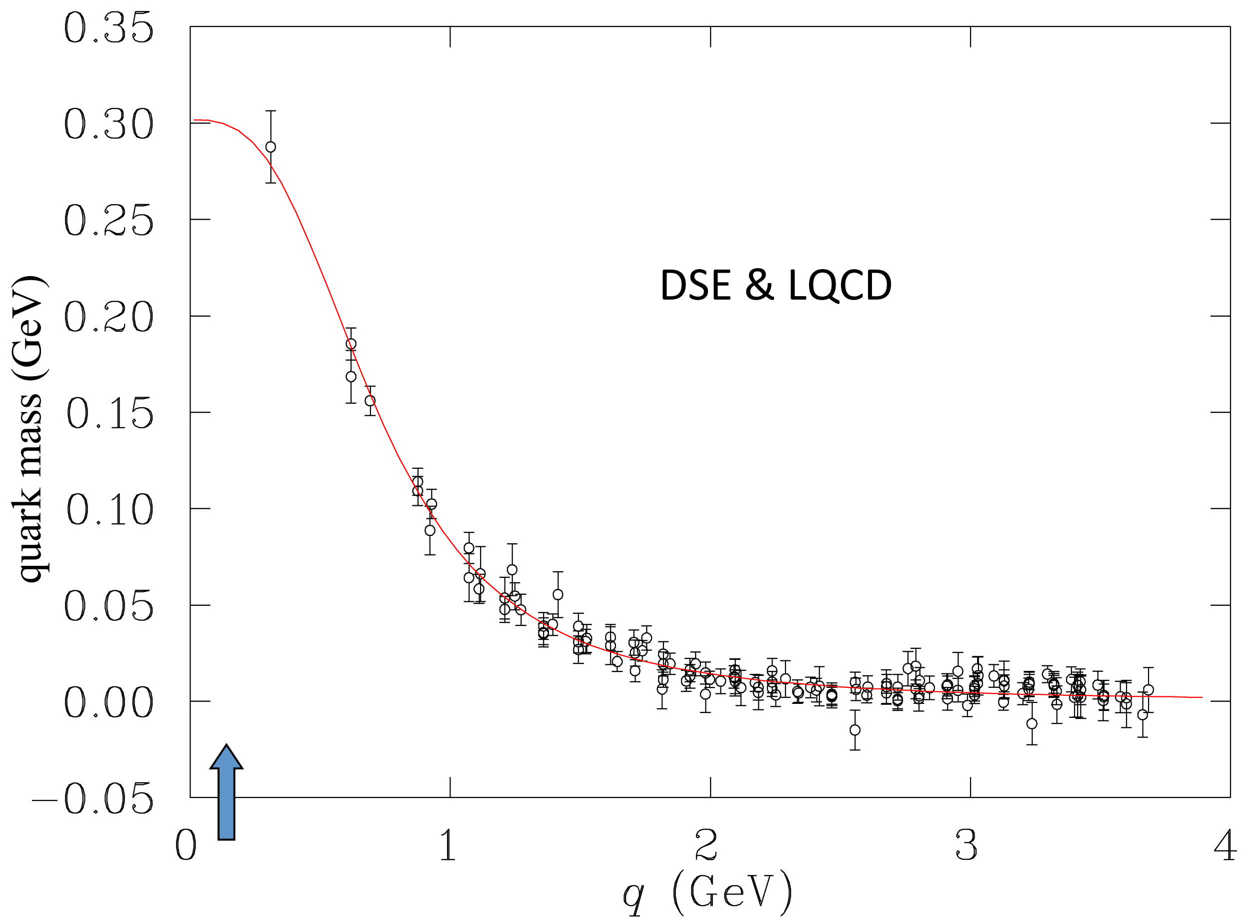
Motivation

What are the relevant degrees of freedom at varying distance scales?

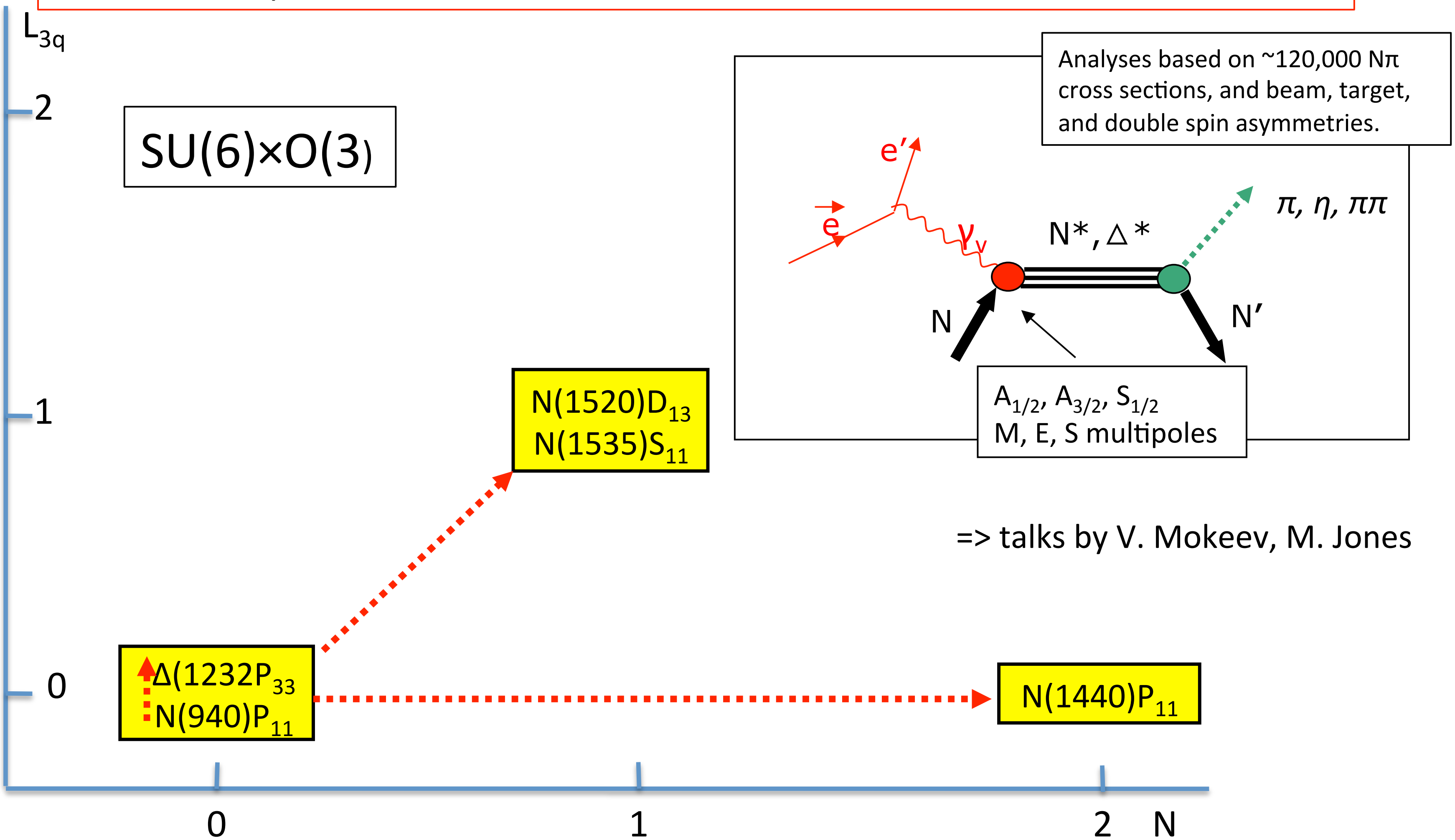




Do measurements of N* transition form factors probe $m_q(q)$?

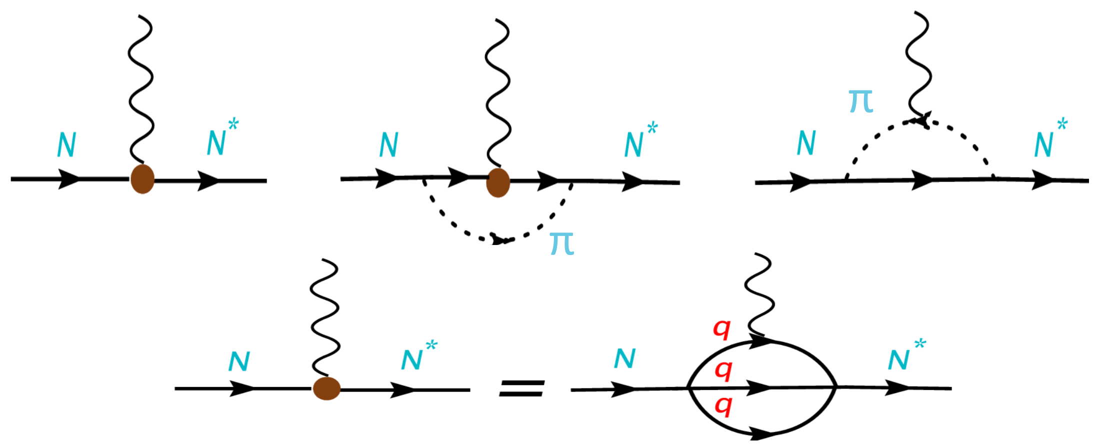
Electroexcitation of Nucleon Resonances

We have now precise experimental information on the Q^2 dependence of transition amplitudes for several lower mass excited states for $Q^2 < 4.5\text{-}7\ GeV^2$



Model ingredients

- Nearly massless Goldstone bosons (pions) create loop contributions to electromagnetic form factors at relatively small Q^2. They are crucial for the description of $G_{En}(Q^2)$ and the magnetic dipole form factor $G^*_M(Q^2)$ of the $\Delta(1232)$.
- Electromagnetic NN* transition form factors must include contributions from the **quark core** and from the **pion loops** (pion cloud).



- Light-front dynamics realizes Poincare invariance and allows for the description of the vertices N,N* -> q^3, Nπ through wave functions.

Model ingredients, cont'd

- Prior work on light-front relativistic model for bound states:

  Berestetski, Terentiev, Yad.Fiz. 24,1044 (1976); Yad.Fiz. 25,653 (1977)

  Aznauryan et al., Phys.Lett. B112, 393(1982); Aznauryan, Phys.Lett. B316, 391 (1993)

- G. Miller computed pion-loop contributions for the nucleon e.m. form factor in LF model.

  G. Miller, Phys.Rev. C66, 032201 (2002)

Model ingredients, cont'd

- To study sensitivity to the form of the quark wave function, we employ two widely used forms for the 3-quark radial wave function,

$$\Phi_{\rm rad} \sim \exp(-M_0^2/\alpha_1^2), \qquad (I)$$
$$M_0^2 = \Sigma \frac{k_{i\perp}^2 + m_q^2}{x_i}$$

and

$$\Phi_{\rm rad} \sim \exp\left[-(k_1^2 + k_2^2 + k_3^2)/\alpha_2^2\right], \qquad (II)$$
$$k_{iz} = \frac{1}{2}\left(x_i M_0 - \frac{k_{i\perp}^2 + m_q^2}{x_i M_0}\right)$$

S. Capstick and B. Keister, PRD51, 3598, 1995

M_0 – invariant 3-quark mass

- m_q and $\mathbf{k}_{i\perp}$ – quark mass and transverse momentum in light-front frame
  => $\Phi_{\rm rad}$ increases as m_q decreases
- Oscillator parameters α_1 and α_2 are chosen to give the same wave function in non-relativistic approximation.

Running quark mass $m_q(Q^2)$

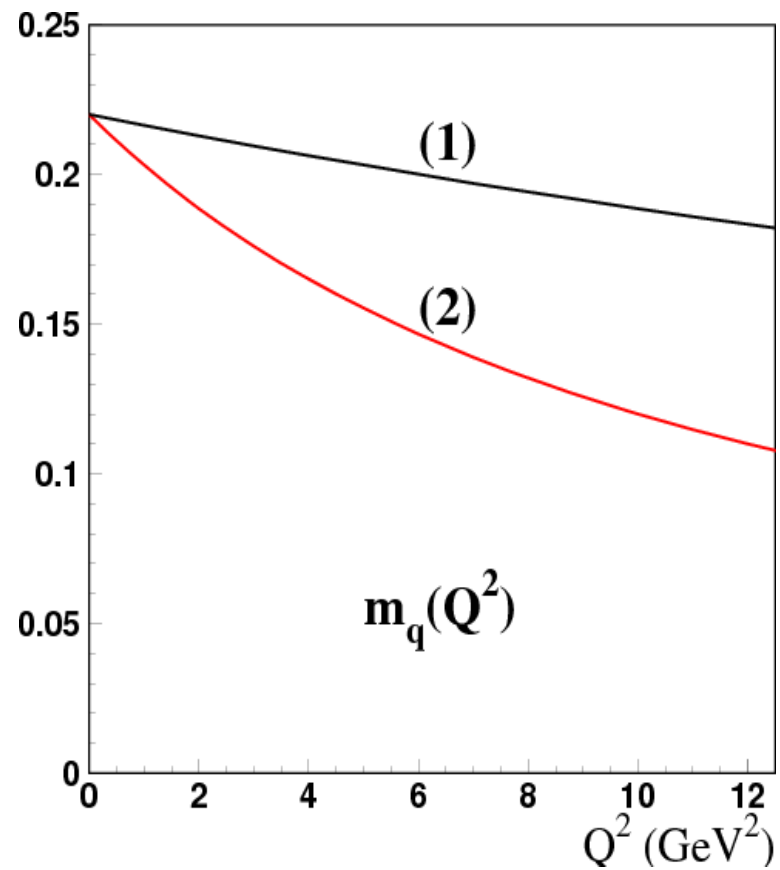
The quark mass value of $m_q(0)=0.22$GeV is taken from the description of baryon and meson masses (S. Capstick, N. Isgur).

To describe electromagnetic form factors and N* transitions, we use functional forms **(1)** and **(2)** of $m_q(Q^2)$ to test N* transition FF sensitivity to $m_q(Q^2)$.

$$m_q(Q^2) = m_q(0)/(1+Q^2/\Lambda)$$

(1) $\Lambda = 60\text{GeV}^2$

(2) $\Lambda = 10\text{GeV}^2$



Nucleon – q^3 + pion cloud

form (I)

form (II)

$N=q^3+\pi;\ m_q(Q^2)$

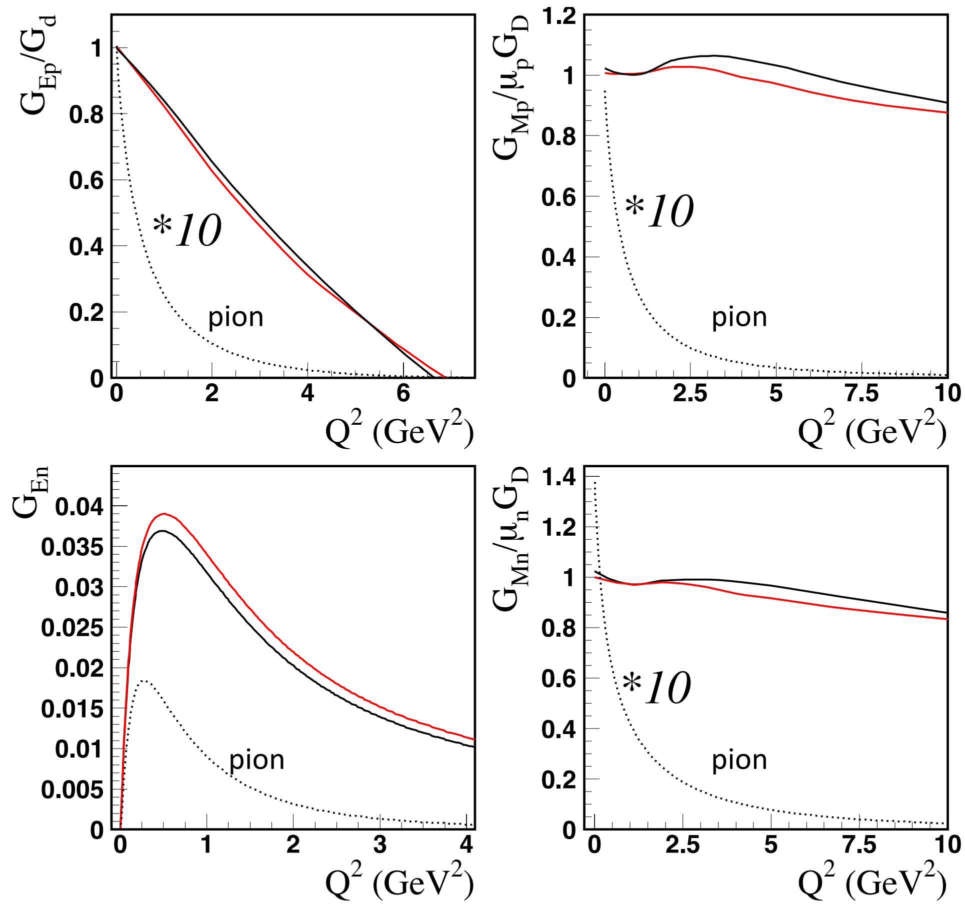
<u>Pion cloud contributions:</u>

Significant for G_{en} at Q^2<2-3GeV^2

Negligible for other F.F. at Q^2>2GeV^2

From $G_{Ep}(0)=1$ follows that

$|N\rangle = 0.95|q^3\rangle + 0.313\ |N\pi\rangle$



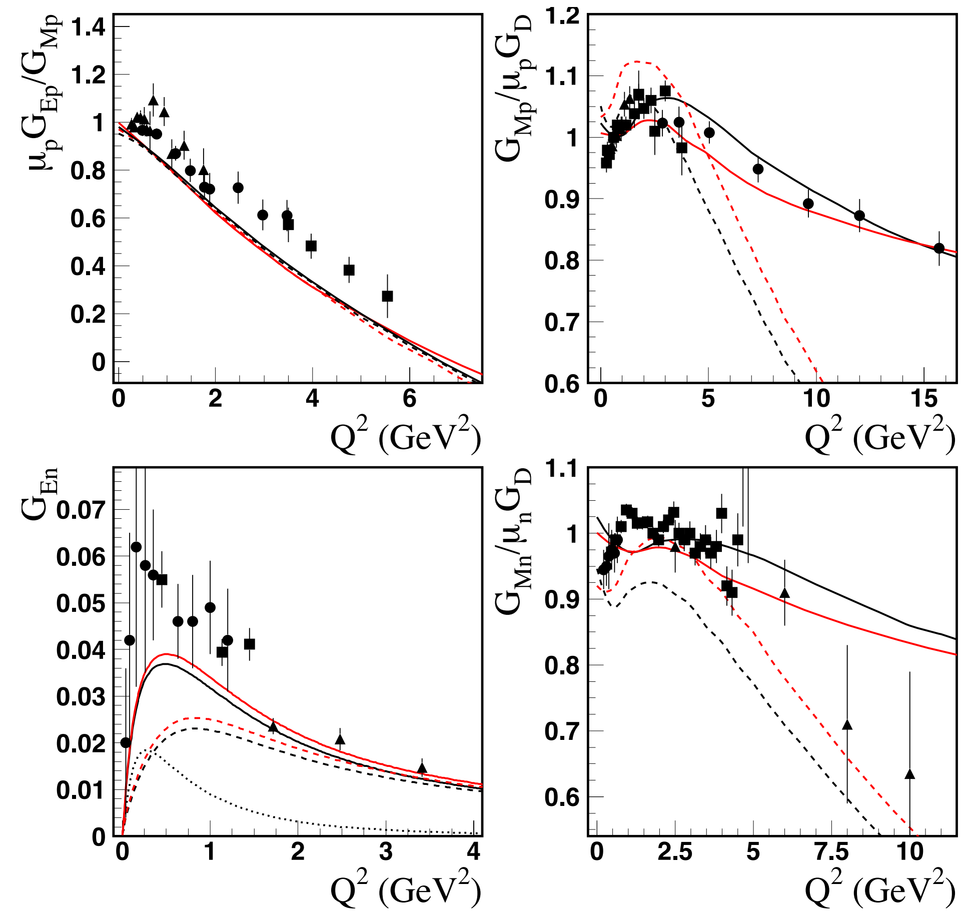
Nucleon electromagnetic form factors

form (I)

form (II)

$N = q^3; m_q(0)$

$N = q^3+\pi; m_q(Q^2)$



Combining **(1)** with form (I) gives results that are comparable to results when combining **(2)** with form (II)

The running of $m_q(Q^2)$ allows for the description of G_{Mp} at $Q^2 < 16$ GeV^2 within the LC rel. quark model.

Excited nucleon states

- No calculations available that allow separation of $|q^3>$ and $|N\pi>$ ($|Nm>$) contributions to nucleon resonances.
  - Coefficient c^* in $|N^*> = c^*|q^3>+...$, $c^* <1$, is unknown.
  - Weight of $c_N c^* <N^*=q^3|J_{em}|N=q^3>$ in $<N^*|J_{em}|N>$ is not known.

- Determine weight factor by fitting to the experimental amplitudes at $Q^2 \approx 2\text{-}3 GeV^2$ assuming that the transitions amplitudes are dominated by the q^3 core, as is the case for the nucleon e.m. form factors.

- All other parameters of the model are taken from the description of the nucleon form factors.

Delta resonance $P_{33}(1232)$

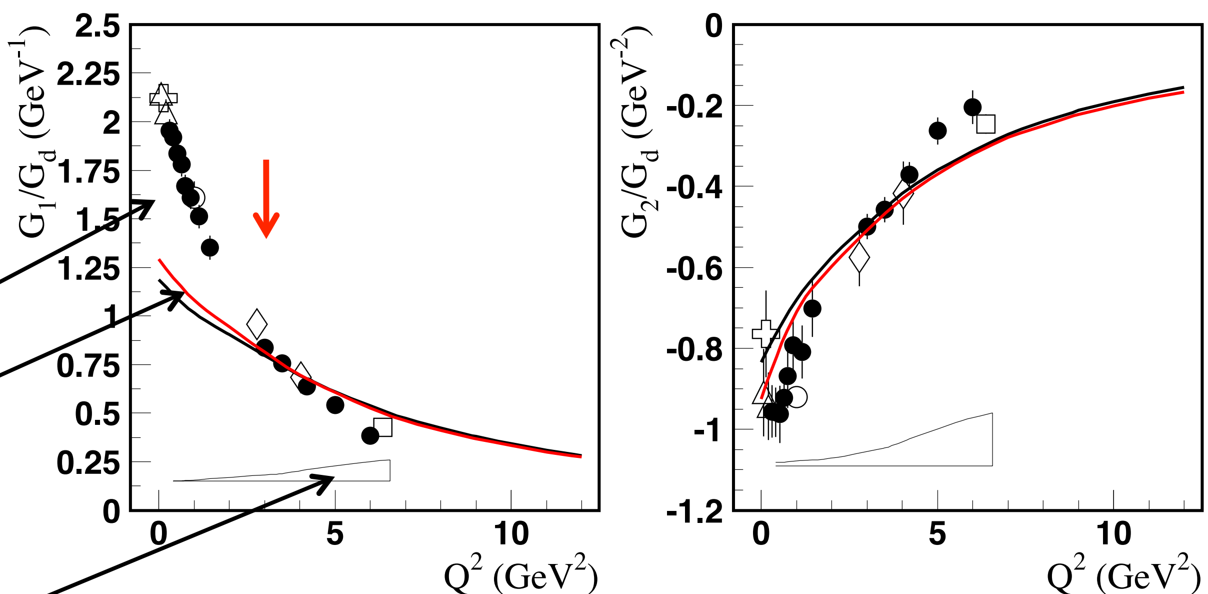
q^3 weight factors:

$$c_{N^*}^{(1)} = 0.67 \pm 0.04$$

$$c_{N^*}^{(2)} = 0.72 \pm 0.04$$

Pion cloud effects

$G_1(Q^2) \sim (G_M - G_E)$



Model uncertainties of amplitudes extracted from CLAS data by Jlab group.

Taking into account the systematic uncertainties in the data, the Q^2 -dependence of the form factors is described well at $Q^2 > 3$ GeV^2.

The Roper resonance $P_{11}(1440)$

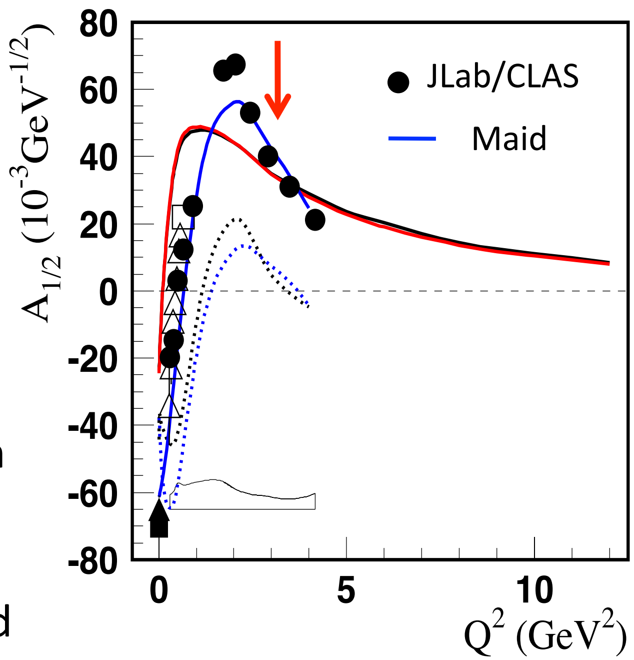
q^3 weight factors:

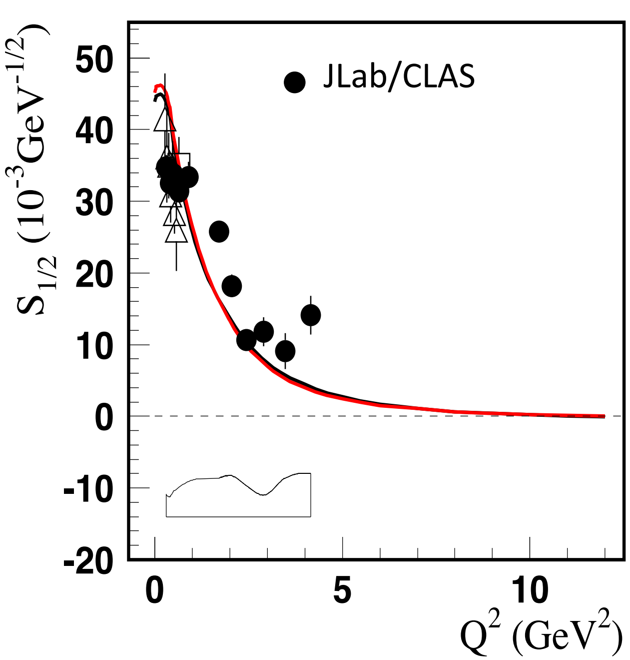
$$c_{N^*}^{(1)} = 0.73 \pm 0.05$$

$$c_{N^*}^{(2)} = 0.77 \pm 0.05$$

For $A_{1/2}$ the model predicts slower fall off with Q^2 than observed in the data.

The estimated meson cloud contribution for $A_{1/2}$ ············ shows a non-trivial Q^2 – dependence





The $D_{13}(1520)$ resonance

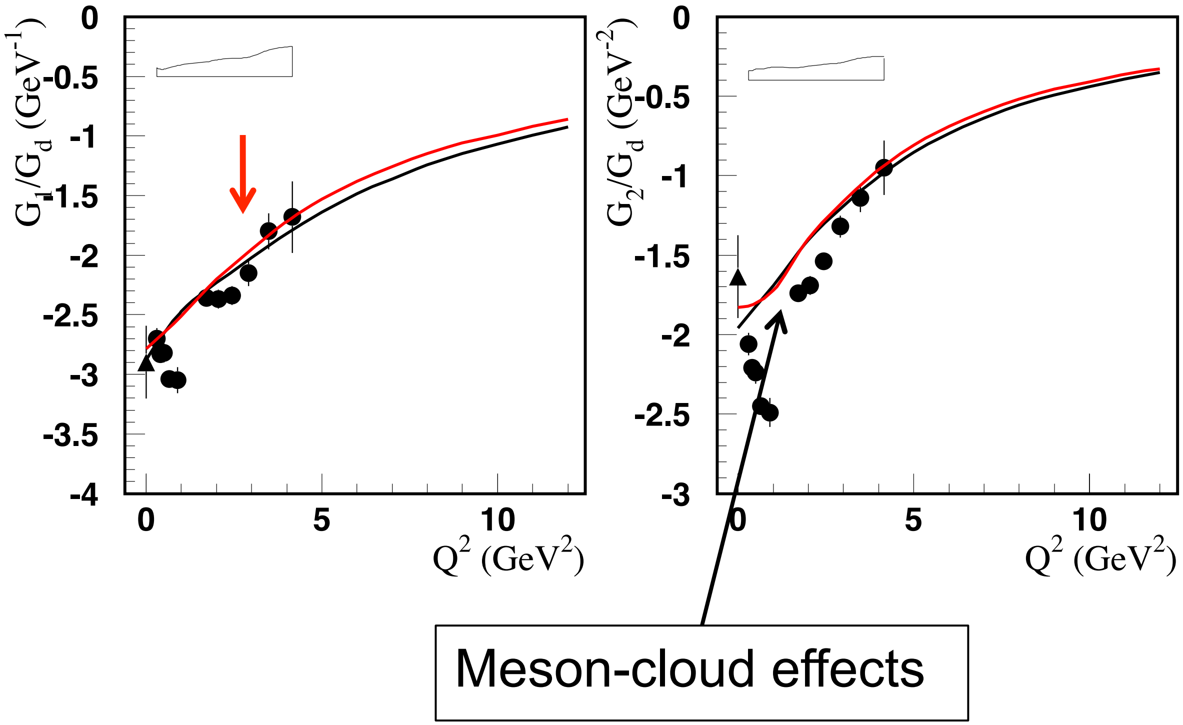
q^3 weight factors:

$$c_{N^*}^{(1)} = 0.78 \pm 0.06$$

$$c_{N^*}^{(2)} = 0.82 \pm 0.06$$

$G_1(Q^2) \sim (A_{1/2} - A_{3/2}/\sqrt{3})$

$G_2(Q^2) = f(A_{1/2}, A_{3/2}, S_{1/2})$



Q^2 -dependence of the form factors is described by the model at $Q^2 > 2.5$ GeV^2.

The S_{11}(1535) resonance

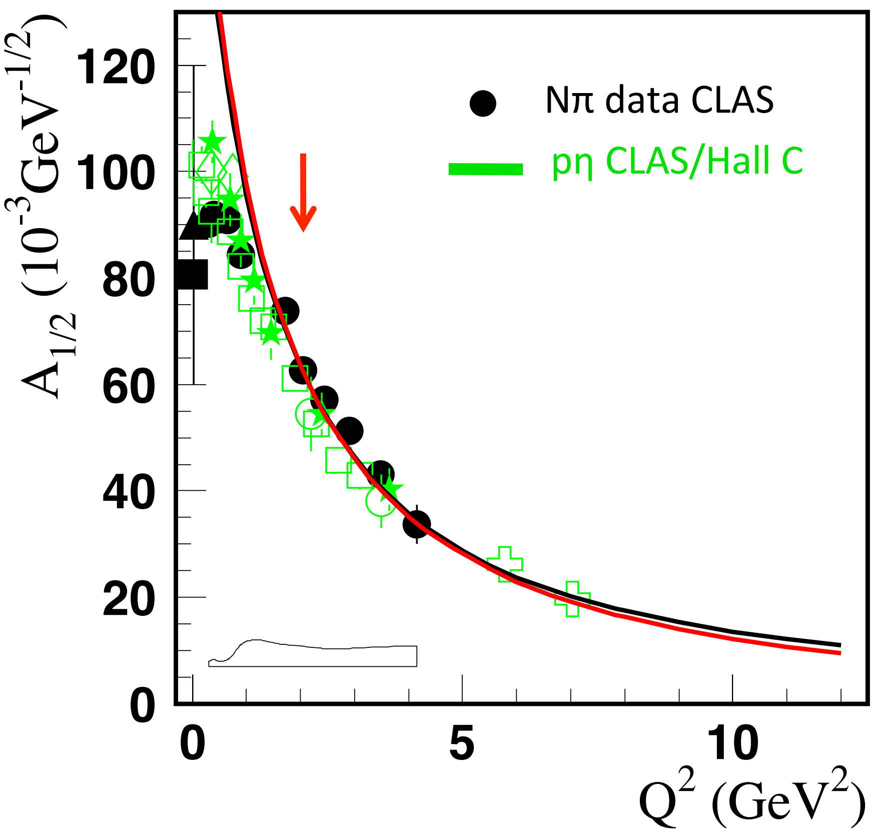
q^3 weight factors:

$$c_{N^*}^{(1)} = 0.88 \pm 0.03$$

$$c_{N^*}^{(2)} = 0.94 \pm 0.03$$

- The weight of the q^3-core contribution is found from the transverse amplitude at Q^2=2GeV^2. Predictions for $Q^2 \leq 7$GeV^2 agree well with the data.

- Quark model results for $S_{1/2}(Q^2)$ amplitude depend strongly on the model parameters. Large meson contribution, and possibly additional contributions are needed.



Conclusions

- We obtain good description of the nucleon electromagnetic form factors at $Q^2 < 16 GeV^2$ in light-front dynamics that includes q^3 and π-cloud contributions.
  - close results are obtained for two widely used **$N=q^3$** wave functions
- Running of the constituent quark mass **$m_q(Q^2)$** is essential to achieve good description in a wide Q^2 range.
- Qualitative agreement with QCD lattice calculations and Dyson-Schwinger equations.

Conclusions cont'd

- At $Q^2 > 3$ GeV^2 the model describes several electro-excitation amplitudes for major low mass states Δ(1232), D_{13}(1520), S_{11}(1535).
- Predicts quark-core contributions for Q^2 = 5-12 GeV^2.
- The models predicts flatter than observed $A_{1/2}$ amplitude for the Roper P_{11} (1440). There is a need for data at higher Q^2 to check the Q^2 evolution.
- At $Q^2 < 3$ GeV^2, we expect significant meson-cloud effects for
  - P_{33}(1232) - $G_M^*(Q^2)$
  - P_{11}(1440) - $A_{1/2}(Q^2)$
  - S_{11}(1535) - $S_{1/2}(Q^2)$
  - D_{13}(1520) - $G_2(Q^2)$ transition form factor
- S_{11}(1535) – $A_{1/2}(Q^2)$ indicates meson cloud effects only at $Q^2 < 1$ GeV^2.

- Measurements of N* transition form factors **do** probe the running of $m_q(q)$!

Outlook

- Data for resonances at masses > 1.6 GeV, and Q^2> 2 GeV^2 are expected from the analysis of CLAS runs in $n\pi^+$, $p\pi^0$, and $p\pi^+\pi^-$ channels (talks by K. Park, M. Ungaro in session I-A)

- N* transition form factors at $Q^2 \leq 12$ GeV^2 will be measured after the JLab 12 GeV energy upgrade with the CLAS12 spectrometer.

- In a scheme where the quark mass is generated dynamically, quarks may have their own anomalous magnetic moments, and their own form factors. These should be incorporated in model predictions.

- Introducing quark form factors will cause a faster Q^2 fall-off of the transition amplitudes in the quark model. This will force $m_q(q)$ to drop faster with Q^2 to describe the data, bringing it in closer agreement with DSE and LQCD.

Additional slide

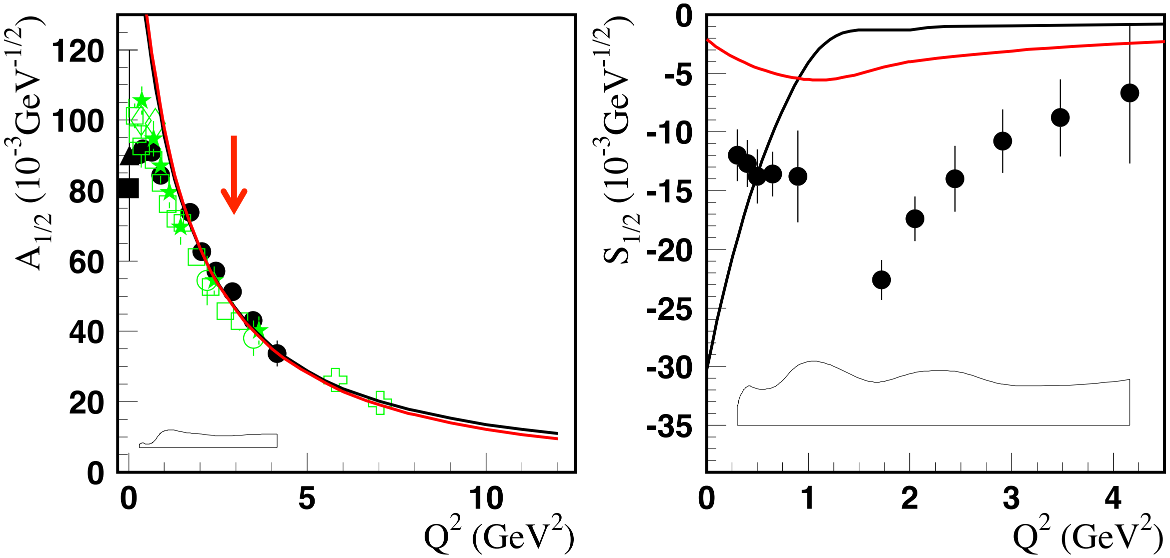
The $S_{11}(1535)$ resonance

$$\mathbf{c}_{\mathbf{N}^*}^{(1)} = \mathbf{0.88 \pm 0.03}$$

$$\mathbf{c}_{\mathbf{N}^*}^{(2)} = \mathbf{0.94 \pm 0.03}$$

- The weight of the q^3-core contribution is found from the transverse amplitude at Q^2=3-4GeV^2. Higher Q^2 ranges are predictions, and agree well with the data.

- Quark model results for longitudinal amplitudes depend strongly on the model parameters.



Large meson cloud or other contributions are needed to describe the longitudinal amplitude.