ARE ALL HADRONS ALIKE? ELECTROPRODUCTION of RESONANCES at LARGE MOMENTUM TRANSFERS

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- T.-S.H. Lee *et al.* Research Proposal: Nucleon Resonance Studies with CLAS12
  1. why we need large Q^2?
  2. which resonances to study?
  3. physics goals?
  4. theory perspectives?

- In this talk I argue:
  1. $\Rightarrow$ to select well-defined parton (valence) configurations
  2. $\Rightarrow$ concentrate on parity partners
  3. $\Rightarrow$ momentum fraction distributions of valence quarks and effects of orbital angular momentum
  4. $\Rightarrow$ combination of lattice calculations and light-cone sum rules

Spontaneous chiral symmetry breaking lifts degeneracy between

$N(940)$, $J^P = \frac{1}{2}^+$ $N^*(1535)$, $J^P = \frac{1}{2}^-$

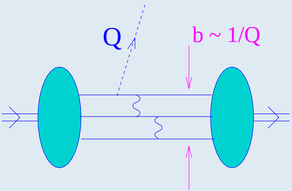
How is this reflected in their parton distributions?

QCD factorization

In theory

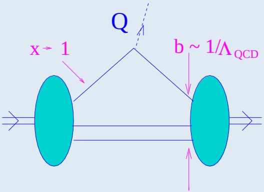
Efremov, Radyushkin, Brodsky, Lepage, Chernyak

- quarks can acquire large transverse momenta when they exchange gluons
- “hard” gluon exchanges can be separated from “soft” nonperturbative wave functions
- hard gluons can only be exchanged at small transverse separations



Hard rescattering:

Small b
Average $0 < x < 1$



Soft (Feynman):

Average b
Large $x \to 1$

In practice three-quark states indeed seem to dominate, however

- “Squeesing” to small transverse separations occurs very slowly
- Helicity selections rules do not work. Orbital angular momentum?
- $\Rightarrow$ More complicated nonperturbative input needed

Wave functions and Distribution amplitudes

- **Nucleon light-cone wave function** — Brodsky, Lepage

$$|P\uparrow\rangle^{\ell_z=0} = \int \frac{[dx][d^2\vec{k}]}{12\sqrt{x_1x_2x_3}}\,\psi^{L=0}(x_i,\vec{k}_i)\times$$
$$\times\Big\{\big|u^\uparrow(x_1,\vec{k}_1)u^\downarrow(x_2,\vec{k}_2)d^\uparrow(x_3,\vec{k}_3)\big\rangle - \big|u^\uparrow(x_1,\vec{k}_1)d^\downarrow(x_2,\vec{k}_2)u^\uparrow(x_3,\vec{k}_3)\big\rangle\Big\}$$

- **Leading-twist-three distribution amplitude**

Brodsky, Lepage, Peskin, Chernyak, Zhitnitsky

$$\Phi_3(x_1,x_2,x_3;\mu) = 2\int^{\mu}[d^2\vec{k}]\,\psi^{L=0}(x_1,x_2,x_3;\vec{k}_1,\vec{k}_2,\vec{k}_3)$$

can be studied using the OPE

$$\begin{aligned}\Phi_3(x_i;\mu) = 120 f_N x_1x_2x_3\Big\{&1 + c_{10}(x_1-2x_2+x_3)L^{\frac{8}{3\beta_0}}\\ &+ c_{11}(x_1-x_3)L^{\frac{20}{9\beta_0}} + c_{20}\left[1+7(x_2-2x_1x_3-2x_2^2)\right]L^{\frac{14}{3\beta_0}}\\ &+ c_{21}\,(1-4x_2)\,(x_1-x_3)\,L^{\frac{40}{9\beta_0}} + c_{22}\left[3-9x_2+8x_2^2-12x_1x_3\right]L^{\frac{32}{9\beta_0}} + \ldots\Big\}\end{aligned}$$

- $f_N(\mu_0)$: **wave function at the origin**
- $c_{nk}(\mu_0)$: **shape parameters**

$L \equiv \alpha_s(\mu)/\alpha_s(\mu_0)$

Braun, Manashov, Rohwild

Wave functions and Distribution amplitudes (II)

- **Contributions of orbital angular momentum** Ji, Ma, Yuan, '03

$$|P\uparrow\rangle^{\ell_z=1} = \int \frac{[dx][d^2\vec{k}]}{12\sqrt{x_1x_2x_3}}\left[k_1^+\psi_1^{L=1}(x_i,\vec{k}_i)+k_2^+\psi_2^{L=1}(x_i,\vec{k}_i)\right]\times$$
$$\times\left\{\left|u^\uparrow(x_1,\vec{k}_1)u^\downarrow(x_2,\vec{k}_2)d^\downarrow(x_3,\vec{k}_3)\right\rangle - \left|d^\uparrow(x_1,\vec{k}_1)u^\downarrow(x_2,\vec{k}_2)u^\downarrow(x_3,\vec{k}_3)\right\rangle\right\}$$

are related to higher-twist-four distribution amplitudes

Belitsky, Ji, Yuan, '03

$$\Phi_4(x_2,x_1,x_3;\mu) = 2\int^\mu \frac{[d^2\vec{k}]}{m_N x_3}\, k_3^-\left[k_1^+\psi_1^{L=1}+k_2^+\psi_2^{L=1}\right](x_i,\vec{k}_i)$$

$$k^\pm = k_x \pm ik_y$$

$$\Psi_4(x_1,x_2,x_3;\mu) = 2\int^\mu \frac{[d^2\vec{k}]}{m_N x_2}\, k_2^-\left[k_1^+\psi_1^{L=1}+k_2^+\psi_2^{L=1}\right](x_i,\vec{k}_i)$$

and, again, can be studied using OPE Braun, Fries, Mahnke, Stein '00

$$\Phi_4(x_i;\mu) = 12\lambda_1 x_1x_2 + 12f_N x_1x_2\left[1+\frac{2}{3}(1-5x_3)\right]+\ldots$$
$$\Psi_4(x_i;\mu) = 12\lambda_1 x_1x_3 + 12f_N x_1x_3\left[1+\frac{2}{3}(1-5x_2)\right]+\ldots$$

- **to this accuracy only one new nonperturbative constant** $\lambda_1(\mu)$

What is to be done?

Braun *et al.* Phys.Rev.Lett.103:072001,2009

- Calculate moments of distribution amplitudes (DAs)
  $\Leftarrow$ **lattice QCD**
  - expensive
  - many technical problems still need to be solved
  - only limited information
  - studies of parity partners look most promising, e.g.

$$\langle 0|qqq|N(p)\rangle = f_N N(p) \qquad \langle 0|qqq|N^*(p)\rangle = f_{N^*}\gamma_5 N(p)$$

- Calculate electroproduction cross sections (transition form factors) in terms of DAs
  $\Leftarrow$ **light-cone sum rules (LCSRs)**
  - based on analyticity and quark-hadron duality
  - well-known and tested technique for mesons, less so for baryons
  - irredicible uncertainty of 20%(?) – need confirmation
  - NLO calculations so far not available

Parity separation

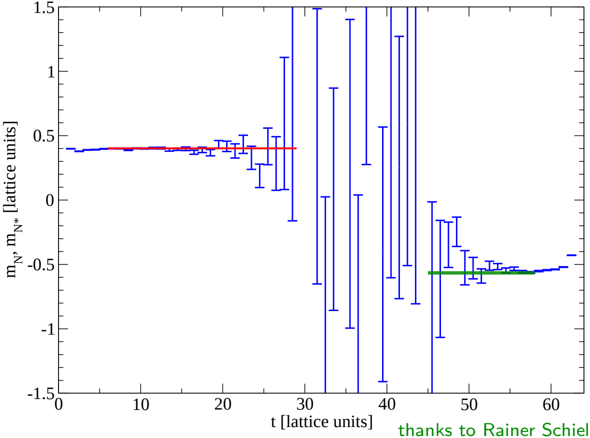
$32^3 \times 64$

$a = 0.0753$ fm
$a^{-1} = 2.620$ GeV

$m_\pi = 282(2)$ MeV

$m_\pi L = 3.44$

$$m_N = 1051(5) \text{ MeV}$$
$$m_{N^*} = 1482(17) \text{ MeV}$$



thanks to Rainer Schiel

- **New:** Generalized Lee-Leinweber parity projectors implemented

Overview of lattices

$N_f = 2$ **clover Wilson fermions**

κ	m_π/ MeV	Size	# Configurations
$\beta = 5.29$, $a = 0.0753$ fm			
0.13590	627	$24^3 \times 48$	901
0.13620	407	$24^3 \times 48$	850
0.13632	282	$32^3 \times 64$	578 + more in progress
0.13632	271	$40^3 \times 64$	in progress
0.13640	170	$40^3 \times 64$	coming soon
$\beta = 5.40$, $a = 0.0672$ fm			
0.13610	648	$24^3 \times 48$	687
0.13625	558	$24^3 \times 48$	1180
0.13640	451	$24^3 \times 48$	1037
0.13660	233	$48^3 \times 64$	coming soon

[QCDSF collaboration]

Wave functions at the origin

$32^3 \times 64$

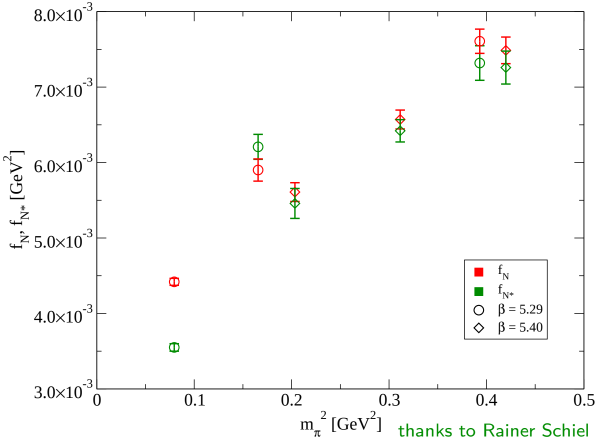
$a = 0.0753$ fm

$m_\pi = 282(2)$ MeV

$m_\pi L = 3.44$

$$f_N = 4.42(5) \cdot 10^{-3}\text{GeV}^2$$

$$f_{N^*} = 3.55(5) \cdot 10^{-3}\text{GeV}^2$$



thanks to Rainer Schiel

- **All results preliminary, statistical errors only, no chiral extrapolation**

Shape parameters

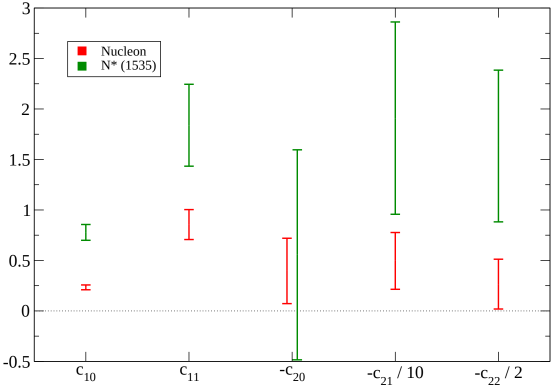
$32^3 \times 64$

$a = 0.0753$ fm

$m_\pi = 282(2)$ MeV

$m_\pi L = 3.44$

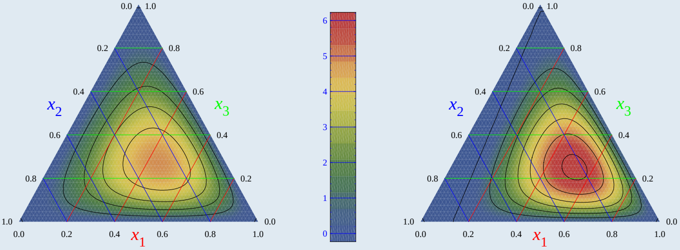
578×4
configurations



thanks to Rainer Schiel

- **All results preliminary, statistical errors only, no chiral extrapolation**

Shape parameters (II)



thanks to Rainer Schiel

NUCLEON	$N^*(1535)$
$c_{10}^N = 0.233 \pm 0.024\,,$	$c_{10}^{N^*} = 0.778 \pm 0.078$
$c_{11}^N = 0.855 \pm 0.145\,,$	$c_{11}^{N^*} = 1.84 \pm 0.41$

- **Momentum fraction distribution of valence quarks in $N^*(1535)$ is much more asymmetric as compared to the nucleon**
- **All results preliminary, statistical errors only, no chiral extrapolation**

Open problems

- **Energy conservation on a lattice**

$$\partial(A\cdot B) = (\partial A)\cdot B + A\cdot(\partial B) + \mathcal{O}(a)$$

In our latest data

$$x_1 + x_2 + x_3 \simeq 0.94$$

Becomes a serious issue for second moments

- **Calculations of third, fourth etc. moments not feasible**

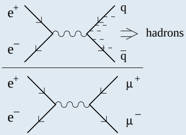
(nonperturbative operator renormalization needed)

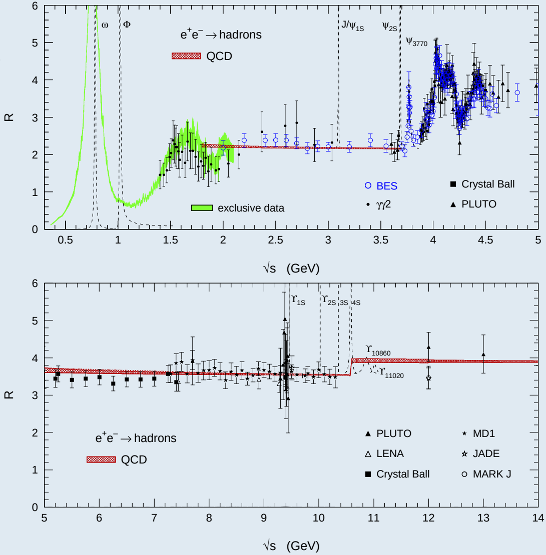
- **Decay width** $\Gamma \sim 150$ **MeV,** $N^*(1535) \to N\pi, N\eta$

- **Contamination by** $N^*(1650)$

From distribution amplitides to form factors: Duality

$R(s = E_{\rm cm}^2) =$





observe

$$R^{\rm QCD}(s) \neq R^{\rm exp}(s)$$

in the resonance region $\sqrt{s} < 1.5 GeV$, but

$$\int_0^{s_0} ds\, R^{\rm QCD}(s) = \int_0^{s_0} ds\, R^{\rm exp}(s)$$

s_0 is called interval of duality

Davier et al., Eur.Phys.J.C27:497-521,2003

a consequence of two major principles:

- **unitarity** $\leftarrow$ probability interpretation of wave functions

$$R(s) \quad = \quad \frac{1}{\pi}\text{Im}\,\Pi(s=q^2)$$

where

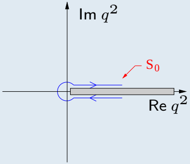
$$i\int d^4x\, e^{iqx}\langle 0|\,T\{j_\mu^{\rm em}(x)j_\nu^{\rm em}(0)\}|0\rangle \;=\; (q_\mu q_\nu - g_{\mu\nu}q^2)\Pi(q^2)$$

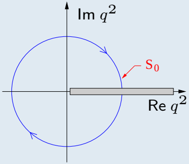
- **analyticity** $\leftarrow$ causality

$$R(s) \;=\; \frac{1}{2\pi i}[\Pi(q^2+i\epsilon)-\Pi(q^2-i\epsilon)]$$

$$\int_0^{s_0} ds\, R(s) \;=\; \frac{1}{2\pi i}\oint dq^2\, R(q^2)$$

$$\simeq\; \frac{1}{2i}\oint dq^2\, R^{\rm pQCD}(q^2)$$





because the region of $q^2 \sim \Lambda^2_{\rm QCD}$ is avoided

can be used to estimate hadron properties

example: pion decay constant

$$\langle 0|A_\mu(0)|\pi^+(p)\rangle = ip_\mu f_\pi, \qquad A_\mu = \bar{u}\gamma_\mu\gamma_5 d$$

consider

$$i\int d^4x\, e^{iqx}\langle 0|T\{A_\mu(x)A^\dagger_\nu(0)\}|0\rangle = (q_\mu q_\nu - g_{\mu\nu}q^2)\Pi_A(q^2)$$

- physical spectral density: $R_A^{\rm phys}(s) = f_\pi^2\delta(s-m_\pi^2) +$ resonances $+$ continuum
- QCD spectral density: $R_A^{\rm QCD}(s) = \frac{1}{4\pi^2} +$ corrections

equating $\int_0^{s_0} ds\, R_A^{\rm phys}(s) = \int_0^{s_0} ds\, R_A^{\rm QCD}(s)$ obtain a duality relation:

$$s_0 = 4\pi^2 f_\pi^2, \qquad s_0 \sim 0.7 \text{ GeV}^2$$

IMPORTANT: $s_0 \gg \Lambda^2_{\rm QCD} \sim (0.2\,\textbf{GeV})^2; \qquad \alpha_s(s_0)/\pi \ll 1$

- refinement $\Rightarrow$ QCD sum rule approach

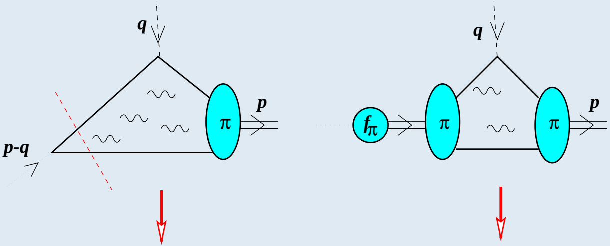
Shifman, Vainstein, Zakharov, Nucl.Phys.B147:385-447,1979
3646 citations in SLAC SPIRES, as of 13.05.10

Light-Cone Sum Rules Example: pion form factor

- another refinement ⇒ Light-Cone Sum Rules:

$$T_{\mu\nu}(p,q) = i\int dx\, e^{-iqx}\langle 0|T\{A_\nu(0)j^{\rm em}_\mu(x)\}|\pi(p)\rangle = 2p_\mu p_\nu\, T(p,q) + \ldots$$

duality:

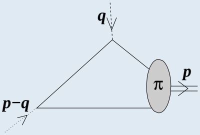


$$\frac{1}{\pi}\int_0^{s_0} ds\, \text{Im}\, T(p,q) \quad \stackrel{duality}{=} \quad f_\pi F_\pi(Q^2)$$

- $T(p,q)$ is calculated in terms of distribution amplitudes of increasing twist

Balitsky, Braun, Kolesnichenko, Nucl.Phys.B312:509-550,1989
Braun, Halperin, Phys.Lett.B328:457-465,1994

- ## Leading–order calculation



$$T(p,q) = \int_0^1 dx\, \frac{x f_\pi \phi_\pi(x)}{(1-x)Q^2 - xs - i\epsilon}, \qquad s = (p-q)^2$$

$$\frac{1}{\pi}\text{Im}\, T(s) = f_\pi \int_0^1 dx\, x\phi_\pi(x)\, \delta((1-x)Q^2 - xs) = \frac{f_\pi Q^2}{(Q^2+s)^2}\phi_\pi\Big(x = Q^2/(Q^2+s)\Big)$$

leading to

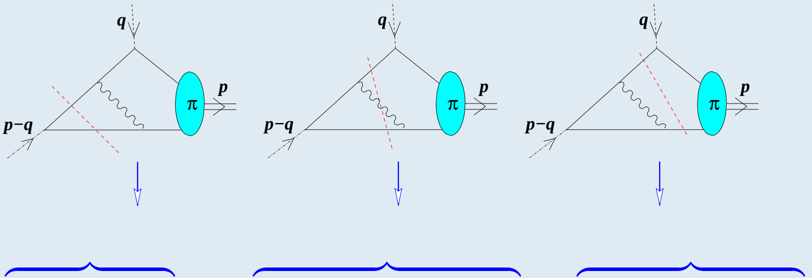
$$F_\pi(Q^2) = \frac{1}{\pi f_\pi}\int_0^{s_0} ds\, \text{Im}\, T(s) = \int_{Q^2/(Q^2+s_0)}^{1} dx\, \phi_\pi(x)$$

- integral over the end-point region $\hookrightarrow$ purely soft contribution
- $\phi_\pi(x) \sim (1-x)$ for $x \to 1$ $\hookrightarrow$ suppression
- for asymptotic DA $\phi_\pi(x) = 6x(1-x)$ (example)

$$F_\pi^{\rm soft}(Q^2) = \frac{s_0^2}{(Q^2+s_0)^2}\Big[1 + 2Q^2/(Q^2+s_0)\Big], \qquad F_\pi^{\rm hard}(Q^2) = \frac{8\pi f_\pi^2 \alpha_s(Q^2)}{Q^2} = \frac{\alpha_s}{\pi}\frac{2s_0}{Q^2}$$

- **loose s_0/Q^2 but win α_s/π**
- note $s_0/Q^2 \gg \Lambda^2_{\rm QCD}/Q^2$ (factor 10)

different dispersion parts: **radiative corrections**



hard rescattering | qGq component in the WF | initial state interaction

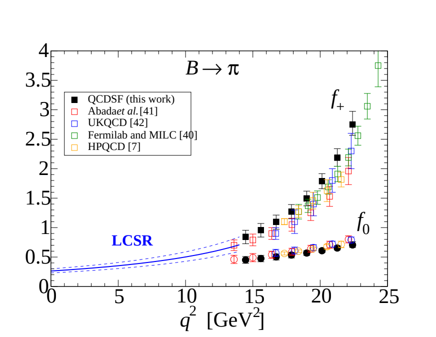
♡ **LCSR are fully consistent with pQCD**

- **a complicated interplay of soft and hard contributions;**

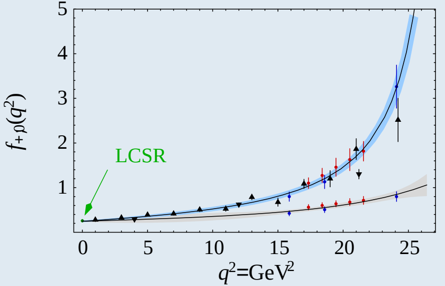
explicit calculation suggests significant cancellations
between soft and hard higher-twist corrections

Braun, Khodjamirian, Maul, Phys.Rev.D61:073004,2000

Light-Cone Sum Rules: $B \to \pi \ell \nu_\ell$, state-of-the-art



Ball, Zwicky, Phys.Rev.D71:014015,2005
Duplancic, et al., JHEP 0804:014,2008



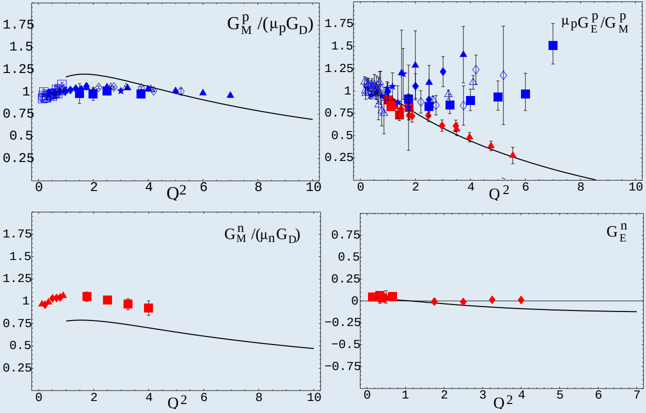
Flynn, Nieves, Phys.Rev.D76:031302,2007

$$|V_{ub}| \quad = \quad (3.5 \pm 0.4 \pm 0.2 \pm 0.1) \times 10^{-3}$$

Light-Cone Sum Rules: Nucleon Electromagnetic Formfactors

proton

neutron



Braun, Lenz, Wittmann; PRD73:094019,2006

- **Nucleon DAs fitted to the G_E^p/G_M^p ratio**

Electroproduction $\gamma^* N \to N^*(1535)$

electromagnetic transition matrix element

$$\langle N^*(P')|j_\nu^{\rm em}|N(P)\rangle = \bar N^*(P')\left(\frac{G_1(q^2)}{m_N^2}(\not q q_\nu - q^2\gamma_\nu) - i\frac{G_2(q^2)}{m_N}\sigma_{\nu\rho}q^\rho\right)\gamma_5 N(P)$$

Aznauryan, Burkert, Lee, arXiv:0810.0997

helicity amplitudes

$$A_{1/2}(Q^2) = -e\,B\left[Q^2 G_1(Q^2) - m_N(m_{N^*} - m_N)G_2(Q^2)\right]$$

$$S_{1/2}(Q^2) = \frac{e}{\sqrt{2}}B\,C\left[(m_{N^*} - m_N)G_1(Q^2) + m_N G_2(Q^2)\right]$$

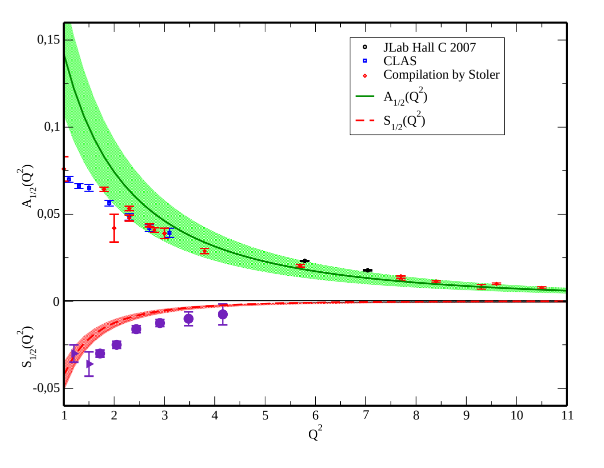
with

$$B = \sqrt{\frac{Q^2 + (m_{N*} + m_N)^2}{2m_N^5(m_{N^*}^2 - m_N^2)}} \qquad C = \sqrt{1 + \frac{(Q^2 - m_{N^*}^2 + m_N^2)^2}{4Q^2 m_{N^*}^2}}$$

$\gamma^* N \to N^*(1535)$: helicity amplitudes

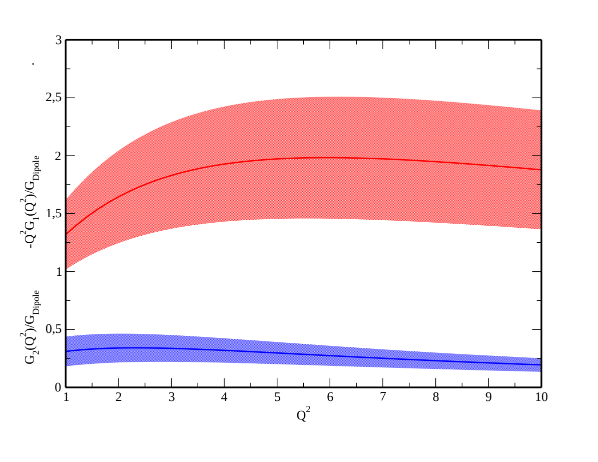
- **A pilot project:** Braun *et al.* Phys.Rev.Lett.103:072001,2009

Electroproduction of $N^*(1535)$ with lattice-constrained N^* distribution amplitides



CLAS $S_{1/2}$ data: *I.G. Aznauryan et al., Phys.Rev.C80:055203,2009*

$\gamma^* N \to N^*(1535)$: helicity amplitudes



- Both form factors show a dipole behavior
- Negative $S_{1/2}$ implies smallness of $G_2(Q^2)$

Open problems

- **Next-to-leading-order (NLO) corrections needed**

  general structure of the $Q^2 \to \infty$ expansion

$$\underbrace{1 \cdot \frac{1}{Q^6} + \frac{\alpha_s(s_0)}{\pi} \cdot \frac{1}{Q^6}}_{} + \left(\frac{\alpha_s(Q^2)}{\pi}\right)^2 \cdot \frac{1}{Q^4}$$

$\Uparrow$ LCSR $\Uparrow$ pQCD

  this is not a straightforward calculation

- **Kinematic power corrections proportonal to powers of m_{N^*}**

$$1 + \frac{m_{N^*}^2}{s_0} + \ldots\,, \qquad s_0 \sim 2.5\ \text{GeV}^2$$

  resummation ?

First baryon LCSRs with NLO corrections

Passek-Kumericki, Peters, Phys.Rev.D78:033009,2008

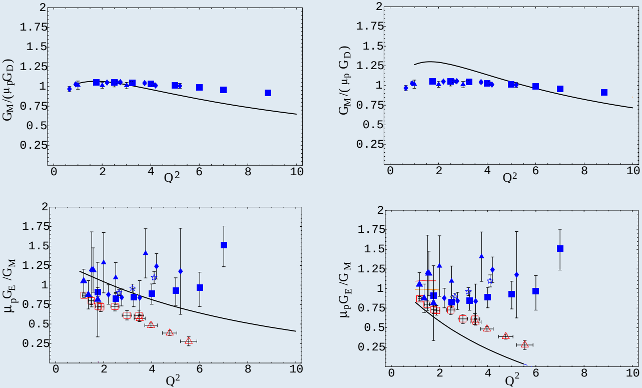


Figure: LCSR results for the electromagnetic proton form factors for a realistic model of nucleon distribution amplitudes. Left panel: Leading order (LO); right panel: next-to-leading order (NLO) for twist-three contributions. Figure adapted from [PassekKumericki:2008sj].

- **Combination of lattice QCD and light-cone sum rules offers one a powerful method to study transition region to perturbative QCD**

Goal

Valence quark distributions in nucleon resonances

- **Pilot project:** $\gamma^* N \to N^*(1535)$
- **Lattice:**
  - new lattices, $m_\pi \sim 280 MeV$
  - new code
  - improved parity separation implemented
- **LCSR:**
  - first results on NLO corrections
  - new DFG project 9209475

Disclaimer

From Wikipedia:

Pilot project is a short and/or incomplete realization of a certain method or idea(s) to demonstrate its feasibility, or a demonstration in principle, whose purpose is to verify that

some concept or theory is probably capable of being useful

We have a long way to go!