ELECTROPRODUCTION of the $N^*(1535)$ RESONANCE at LARGE MOMENTUM TRANSFERS

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Electroproduction of $N^*(1535)$

Vereshkov and Volchanskiy, PRD **76** (2007) 073007

electromagnetic transition matrix element

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

The helicity amplitudes

$$A_{1/2}(Q^2) = \sqrt{2\pi\alpha_{\rm em}\frac{Q^2+(m_{N*}+m_N)^2}{m_N^5(m_{N^*}^2-m_N^2)}}\left[Q^2 G_1(Q^2) + m_N(m_{N^*}-m_N)G_2(Q^2)\right]$$

$$\tilde{S}_{12}(Q^2) = \sqrt{\pi\alpha_{\rm em}\frac{Q^2+(m_{N*}+m_N)^2}{m_N^5(m_{N^*}^2-m_N^2)}}\,Q\left[(m_{N^*}-m_N)G_1(Q^2) - m_N G_2(Q^2)\right]$$

The differential cross section

$$\frac{d\sigma}{dQ^2}(eN\to eN^*) = \frac{\alpha_{\rm em}M_N(M_{N^*}^2-m_N^2)}{2Q^2(s-m_N^2)^2(1-\varepsilon)}\left[2\varepsilon|\tilde{S}_{12}(Q^2)|^2 + |A_{1/2}(Q^2)|^2\right]$$

QCD theory

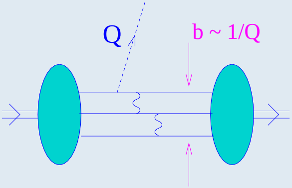
- Direct lattice calculations of form factors
  - restricted to $Q \ll 1/a$, currently $a = 0.06 - 0.08$ fm $\sim 1/(2 - 3$ GeV); unlikely to go beyond $Q^2 \sim 3$ GeV^2
  - black box

- Light-cone sum rules
  - need N^* light-cone distribution amplitudes (DAs) or at least good interpolating current
  - in approaches based on duality, separation of states of different parity is very difficult:

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

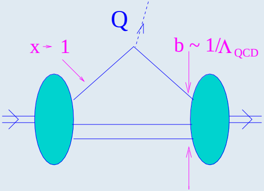
- In this work
  - calculate moments of N^* light-cone distribution amplitudes on the lattice
  - use them as input in LCSRs to calculate form factors

- why light-cone sum rules?



Hard rescattering:

Small b
Average $0 < x < 1$



Soft (Feynman):

Average b
Large $x \to 1$

♡ pQCD 'hard' contributions are included

♡ 'soft' contribution is built as a sum of contributions of DAs of increasing twist: expansion parameter $(\Lambda^2_{\rm QCD}/s_0)^{\rm twist}$ where s_0 is interval of duality

♡ there is no double counting but separation of 'soft' and 'hard' is scheme- and scale-dependent

This technique provides one with the most direct relation between form factors and parton structure that is available at present, with no other parameters

Lattice Calculation

- QCDSF/DIK configurations generated with $N_f = 2$ flavors of clover fermions

β	κ	m_π[GeV]	volume	a[fm]	L[fm]
5.29	0.1340, 0.1350, 0.1359	1.411, 1.029, 0.587	$16^3 \times 32$	0.08	1.28
5.29	0.1355, 0.1359, 0.1362	0.800, 0.587, 0.383	$24^3 \times 48$	0.08	1.92
5.40	0.135, 1356, 0.1361, 0.13625, 13640	1.183, 0.856, 0.648, 0.559, 0.421	$24^3 \times 48$	0.07	1.68

- Irreducible spinor representations of $H(4)$

	$d = 9/2$ (0 derivatives)	$d = 11/2$ (1 derivative)	$d = 13/2$ (2 derivatives)
$\tau_1^{\underline{4}}$	$\mathcal{B}^{(0)}_{1,i}, \mathcal{B}^{(0)}_{2,i}, \mathcal{B}^{(0)}_{3,i}, \mathcal{B}^{(0)}_{4,i}, \mathcal{B}^{(0)}_{5,i}$		$\mathcal{B}^{(2)}_{1,i}, \mathcal{B}^{(2)}_{2,i}, \mathcal{B}^{(2)}_{3,i}$
$\tau_2^{\underline{4}}$			$\mathcal{B}^{(2)}_{4,i}, \mathcal{B}^{(2)}_{5,i}, \mathcal{B}^{(2)}_{6,i}$
$\tau^{\underline{8}}$	$\mathcal{B}^{(0)}_{6,i}$	$\mathcal{B}^{(1)}_{1,i}$	$\mathcal{B}^{(2)}_{7,i}, \mathcal{B}^{(2)}_{8,i}, \mathcal{B}^{(2)}_{9,i}$
$\tau_1^{\underline{12}}$	$\mathcal{B}^{(0)}_{7,i}, \mathcal{B}^{(0)}_{8,i}, \mathcal{B}^{(0)}_{9,i}$	$\mathcal{B}^{(1)}_{2,i}, \mathcal{B}^{(1)}_{3,i}, \mathcal{B}^{(1)}_{4,i}$	$\mathcal{B}^{(2)}_{10,i}, \mathcal{B}^{(2)}_{11,i}, \mathcal{B}^{(2)}_{12,i}, \mathcal{B}^{(2)}_{13,i}$
$\tau_2^{\underline{12}}$		$\mathcal{B}^{(1)}_{5,i}, \mathcal{B}^{(1)}_{6,i}, \mathcal{B}^{(1)}_{7,i}, \mathcal{B}^{(1)}_{8,i}$	$\mathcal{B}^{(2)}_{14,i}, \mathcal{B}^{(2)}_{15,i}, \mathcal{B}^{(2)}_{16,i}, \mathcal{B}^{(2)}_{17,i}, \mathcal{B}^{(2)}_{18,i}$

Kaltenbrunner, Göckeler, Schäfer, Eur.Phys.J.C55(2008)387

- Nonperturbative renormalization of three-quark operators

Göckeler et al., [QCDSF Collaboration], paper in preparation

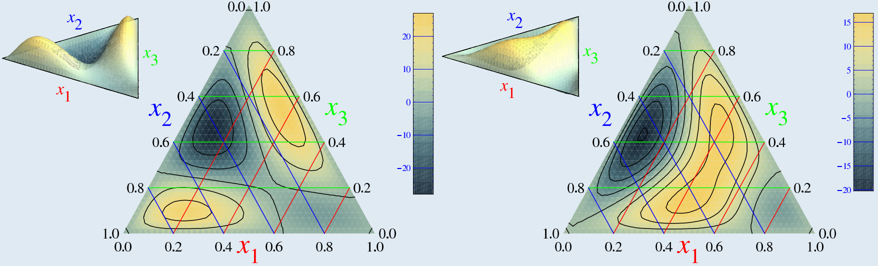
Moments of Distribution Amplitudes

	Asympt.	N	$N^\star(1535)$
$f_N \cdot 10^3 [\mathrm{GeV}^2]$		3.234(63)(86)	4.544(117)(223)
$-\lambda_1 \cdot 10^3 [\mathrm{GeV}^2]$		35.57(65)(136)	37.55(101)(768)
$\lambda_2 \cdot 10^3 [\mathrm{GeV}^2]$		70.02(128)(268)	191.9(44)(391)
φ^{100}	$\frac{1}{3} \simeq 0.333$	0.3999(37)(139)	0.4765(33)(155)
φ^{010}	$\frac{1}{3} \simeq 0.333$	0.2986(11)(52)	0.2523(20)(32)
φ^{001}	$\frac{1}{3} \simeq 0.333$	0.3015(32)(106)	0.2712(41)(136)
φ^{200}	$\frac{1}{7} \simeq 0.143$	0.1816(64)(212)	0.2274(89)(307)
φ^{020}	$\frac{1}{7} \simeq 0.143$	0.1281(32)(106)	0.0915(45)(224)
φ^{002}	$\frac{1}{7} \simeq 0.143$	0.1311(113)(382)	0.1034(160)(584)
φ^{011}	$\frac{2}{21} \simeq 0.095$	0.0613(89)(319)	0.0398(132)(497)
φ^{101}	$\frac{2}{21} \simeq 0.095$	0.1091(41)(152)	0.1281(56)(131)
φ^{110}	$\frac{2}{21} \simeq 0.095$	0.1092(67)(219)	0.1210(101)(304)

Table: Comparison of the lattice results as obtained from QCDSF/DIK configurations at $\beta = 5.40$ for the nucleon (N) and $N^\star(1535)$ at $\mu^2_{\overline{MS}} = 1\,\mathrm{GeV}^2$. The first error is statistical, the second error represents the uncertainty due to the chiral extrapolation and renormalization. The systematic error should be considered with caution.

N. Warkentin for the QCDSF collaboration, LATTICE-2008

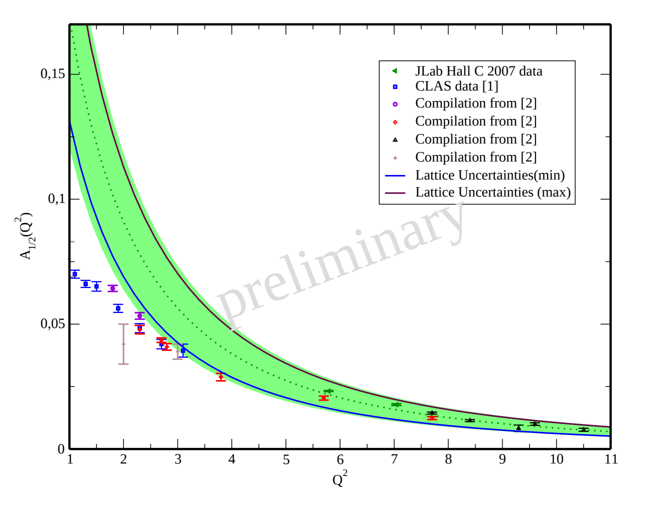
Leading–Twist Distribution Amplitudes of the Nucleon and $N^*(1535)$



(a) (b)

Figure: Barycentric plot of the distribution amplitudes for nucleon (left) and $N^\star(1535)$ (right) at $\mu_{\overline{MS}} = 1\mathrm{GeV}$ using the central values of the lattice results. The lines of constant x_1, x_2 and x_3 are parallel to the sides of the triangle labelled by x_2, x_3 and x_1, respectively.

Results: $\gamma^* N \to N^*(1535)$



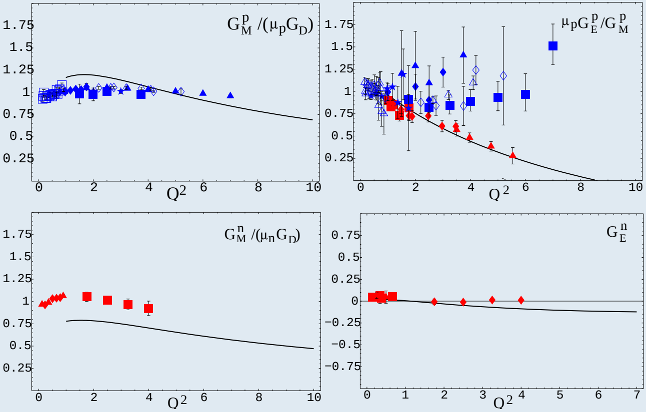
[1] H. Denizli et al., Phys. Rev. C **76** (2007) 015204

[2] P. Stoler, Phys. Rept. **226** (1993) 103

Comparison: Electromagnetic Formfactors

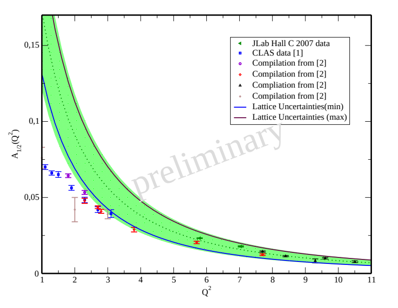
proton

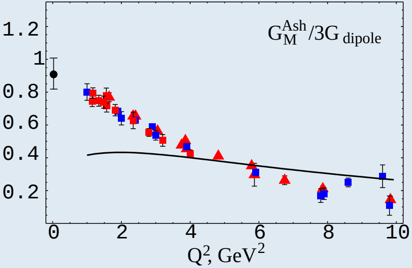
neutron



Braun, Lenz, Wittmann; PRD73:094019,2006

Comparison: $\gamma^* N \to N^*(1535)$ vs. $\gamma^* N \to \Delta(1232)$





Braun, Lenz, Peters, Radyushkin; PRD73:034020,2006

●: *J. Rohrwild; PRD75:074025,2007*

- ‘kinematic’ mass corrections $\sim m_R^2/Q^2$?
- or ‘macroscopic’ structure of the resonances?

Outlook

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

- All results preliminary
- Lattice results will improve significantly within 2-5 years
- NLO light-cone sum rules necessary, a large project
- Resummation of $\sim m_R^2/Q^2$ corrections open problem

Request: please present experimental results for form factors, not (not only) helicity amplitudes