Relativistic **approaches** for the $\gamma^* N \to N^*$ transition form factors at intermediate and large momentum transfer

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Many Manifestations of Nonperturbative QCD
Camburi, São Sebastião, SP, Brazil

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Motivation - study of $\gamma^* N \to N^*$ transitions

- Modern facilities [Jefferson Lab, MAMI, MIT-Bates, ...]
  provide very accurate data associated with $\gamma^* N \to N^*$ transitions
  $W=$ 1.4–2.0 GeV; Q^2 =0–8 GeV^2
- Intermediate and large (square) momentum transfer Q^2 =2–12 GeV^2:
  Calls for relativistic models with relativistic kinematics
  – **preferencialy covariant**
- **Challanges:**
  Interpret the present data
  Make predictions for higher Q^2 $\oplus$ Higher W – heavy resonances
  JLab-12 GeV–upgrade
  $N^* = N, \Delta$ – states $J^P = \frac{1}{2}^\pm, = \frac{3}{2}^\pm$,

Plan of the talk – two different approaches

- **Light-Front holography/Holographic QCD**
  Can be used to estimate the **leading order** effects (qqq-states)
  Nucleon and Roper
- **Covariant Spectator Quark Model**
  Constituent Quark Model
  Calibrated by N and lattice data ($\Delta(1232)$)
  $N(1520)\frac{3}{2}^-$, $N(1535)\frac{1}{2}^-$, $N(1440)\frac{1}{2}^+$
  $\Delta(1232)\frac{3}{2}^+$ – Quadrupole form factors

Holographic QCD — Light-Front Holography

- Use connection between LF quantization of QCD and anti-de Sitter conformal field theory (AdS/CFT) — AdS/QCD
- Bottom-up approximation; 5D AdS Lagrangian $x^\mu \to (x^\mu, z)$
  5D generalization of 4D couplings: $\Gamma^A = \frac{R}{z}(\gamma^\mu, -i\gamma^5)$
  $R =$ 5D radius (5D space)
- Confinement implemented using a **soft-wall** potential $\Phi = \kappa^2 z^2$
  Define hadron scale $\kappa \sim m_\rho$
- **Method:**
  - Fix *bare* couplings by large Q^2 data (nucleon)
    Valence quark dominance (qqq Fock state)
    GR and D Melnikov, PRD 97, 034037 (2018); GR, PRD 96, 054021 (2017)
  - Estimate $\gamma^* N \to N(1440)$ form factors $\oplus$
    nucleon axial form factor G_A (including meson cloud effects)
    PRD 97, 073002 (2018)

Light-Front holography – LF – AdS correspondence

Light-Front	$\zeta = \sqrt{\varkappa(1-\varkappa)}\lvert\mathbf{b}_\perp\rvert$	$\psi(\varkappa, \mathbf{b}_\perp)$
AdS$_5$	z	$\phi(z)$

$$\psi(\varkappa, \zeta, \varphi) = e^{iL\varphi}\sqrt{\varkappa(1-\varkappa)}\frac{\phi(\zeta)}{\sqrt{2\pi\zeta}}$$

- Correspondence valid for massless quarks ($m_q = 0$) and for Baryon system ($n = 3$) decomposed into a quark $\oplus$ $(n-1)$ cluster GF Teramond and SJ Brodsky, PRL 102, 081601 (2009); SJ Brodsky at al, Phys. Rep. 584, 1 (2015); T Liu and QM Ma, PRD 92, 096003 (2015)
- Parameter impact space – Light-Front equations $\psi_n(\{\varkappa_j, \mathbf{b}_{\perp j}\})$ = LF wave func.

$$M_B^2 = \sum_n \Pi_{j=1}^{n-1} \int d\varkappa_j \; d^2\mathbf{b}_{\perp j} \psi_n^*(\{\varkappa_j, \mathbf{b}_{\perp j}\}) \sum_q \left(\frac{-\nabla^2_{\mathbf{b}_{\perp q}} + m_q^2}{\varkappa_q} \right) \psi_n(\{\varkappa_j, \mathbf{b}_{\perp j}\}) + (\text{interac. })$$

- Quark-spectator decomp: quark($\varkappa$) $\oplus$ spect($1-\varkappa$): μ_J AM dep.; Φ = eff. conf.

$$M_B^2 = \int d\varkappa \; d^2\mathbf{b}_\perp \psi_B^*(\varkappa, \mathbf{b}_\perp) \underbrace{\left(\frac{-\nabla^2_{\mathbf{b}_\perp}}{\varkappa(1-\varkappa)} + \mu_J + \Phi \right) \psi_B(\varkappa, \mathbf{b}_\perp)}_{= M_B^2 \psi_B(\varkappa, \mathbf{b}_\perp)}$$

- Equivalent to **AdS** equation (variable z) with confinement term

Light-Front holography – AdS$_5$ formalism

- 5D AdS space defined by the metric R =5D radius
[conformal symmetry: invariance $(x,z) \to \lambda(x,z)$]

$$ds^2 = \frac{R^2}{z^2}(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2)$$

- Fermion fields Ψ – F_L/F_R chiral components (Weyl spinors), $n = 0, 1, ...$

$$\Psi(x,z) = \frac{1}{\sqrt{2}} \sum_n z^2 \begin{pmatrix} F_{L,n}(z) \\ F_{R,n}(z) \end{pmatrix} \chi_n(x) e^{ix\cdot P}$$

$$S_N = \int d^4x dz \sqrt{-\det g}\, \bar{\Psi}(\hat{K} - \mu - \Phi)\Psi,$$

$\hat{K}$ = kinetic term, μ = 5D mass, Φ = effective scalar potential

- Interaction V_M = electromagnetic current – 3 couplings (η_p, η_n, g_V) $\eta_N = \frac{1}{8}\kappa_N$

$$\hat{\mathcal{V}}(x,z) = \hat{Q}\Gamma^M V_M(x,z) + \frac{i}{4}\eta_N [\Gamma^M, \Gamma^N] V_{MN}(x,z) + g_V \Gamma^M \gamma^5 V_M(x,z),$$

$$V_\mu(x,z) = \int \frac{d^4q}{(2\pi)^4} \epsilon_\mu(q) e^{-iq\cdot x} V(-q^2,z), \quad V(Q^2,z) = \kappa^2 z^2 \int_0^1 \frac{d\varkappa}{(1-\varkappa)^2} \varkappa^{\frac{Q^2}{4\kappa^2}} e^{-\frac{\kappa^2 z^2 \varkappa}{1-\varkappa}}$$

T Gutsche, VE Lyubovitskij, I Schmidt and A Vega PRD 86, 036007 (2012); HR Grigoryan and AV Radyushkin, PRD 76, 095007 (2007)

Light-Front holography – Nucleon and radial excitations

- Start with AdS equation (equivalent to LF equations) for $\frac{1}{2}^+$ states

  T Gutsche, VE Lyubovitskij, I Schmidt, and A Vega, PRD 86, 036007 (2012); PRD 87, 016017 (2013)

$$\left[\pm\partial_z + \frac{\mu R + \Phi}{z}\right] F_{L/R}(z) = M_N F_{R/L}(z)$$

  Other works: Z Abidin and CE Carlson, PRD 79, 115003 (2009); D Chakrabarti and C Mondal, EPJC 73, 2671 (2013); RS Sufian, GF de Teramond, SJ Brodsky, A Deur, and HG Dosch, PRD 95, 014011 (2017); T Gutsche, VE Lyubovitskij and I Schmidt, PRD 97, 054011 (2018)

- Reduction to second order Schrödinger-like equation $m = \mu R$

$$\left[-\frac{d^2}{dz^2} + \frac{m(m-1)}{z^2} + 2\kappa^2\left(m + \frac{1}{2}\right) F_R + \kappa^4 z^2\right] F_R = M_{N,n}^2 F_R$$

- Solutions and eigenvalues L_n^α = generalized Laguerre polynomials; $n = 0, 1, ..$

$$F_{R,n} \propto z^m e^{-\kappa^2 z^2/2} L_n^{m-1/2}(\kappa^2 z^2), \qquad M_{M,n}^2 = 4\kappa^2\left(n + m + \frac{1}{2}\right),$$

  $m = 3/2$: pQCD form factors falloff – Z Abidin and CE Carlson, PRD 79, 115003 (2009)

- Transition current $S_{\rm int} = \int d^4\, dz \sqrt{-\det g}\,\bar{\Psi}(x,z)\hat{\mathcal{V}}(x,z)\Psi(x,z)$

$$J^\mu = F_1\left(\gamma^\mu - \frac{\not{q} q^\mu}{q^2}\right) + F_2 \frac{i\sigma^{\mu\nu} q_\nu}{M_N + M_{N1}}$$

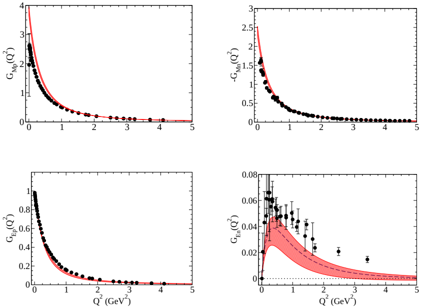
Light-Front holography – Nucleon e.m. form factors

Analytic expressions in terms of a ($\kappa \simeq 0.385$ GeV) and g_V, η_p, η_n, $\delta_N = \pm$

T Gutsche, VE Lyubovitskij, I Schmidt, and A Vega, PRD 87, 016017 (2013)

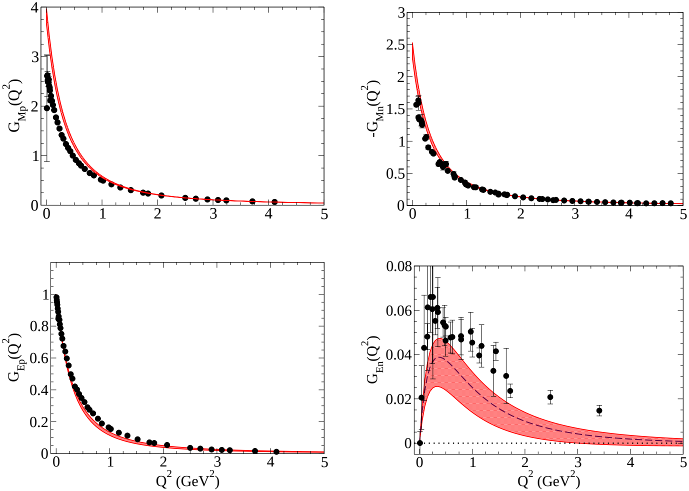
$$a = \frac{Q^2}{4\kappa^2}$$

$$\begin{aligned} F_{1N} &= e_N \frac{a+6}{(a+1)(a+2)(a+3)} + \\ & g_V \delta_N \frac{a}{(a+1)(a+2)(a+3)} + \\ & \eta_N \frac{2a(2a-1)}{(a+1)(a+2)(a+3)(a+4)}, \\ F_{2N} &= \eta_N \frac{M_N}{2\sqrt{2}\kappa} \frac{48}{(a+1)(a+2)(a+3)}, \end{aligned}$$



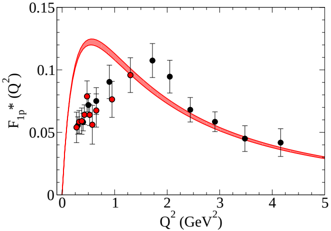
Fit large Q^2 data

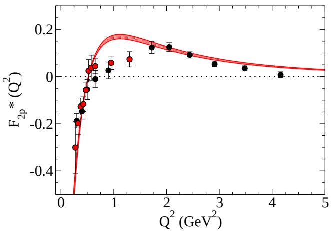
Light-Front holography – Nucleon e.m. form factors



Red bands $g_V = 1.28$–1.57; $\eta_p = 0.38$–0.42; $-\eta_n = 0.32$–0.36

Light-Front holography – $N(1440)$ e.m. form factors





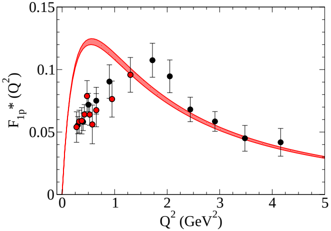
$$F^*_{1p} = \frac{a(\sqrt{2}a + c_1)}{(a+1)(a+2)(a+3)(a+4)} + g_V \frac{a(\sqrt{2}a + c_2)}{(a+1)(a+2)(a+3)(a+4)} \eta_p \frac{2a(2\sqrt{2}a^2 - c_3 a + c_4)}{(a+1)(a+2)(a+3)(a+4)(a+5)}$$

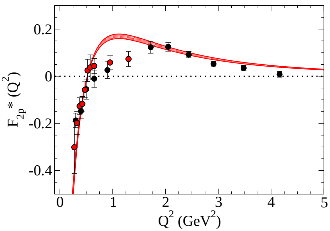
$$F^*_{2p} = \eta_p \left(\frac{M + M_R}{M_R} \right)^2 \frac{M_R}{2\sqrt{3}\kappa} \times \frac{6\sqrt{3}(c_5 a - 4)}{(a+1)(a+2)(a+3)(a+4)}$$

$$a = \frac{Q^2}{4\kappa^2}$$

$$c_1 = 4\sqrt{2} + 3\sqrt{3},\ c_2 = 4\sqrt{2} - 3\sqrt{3},\ c_3 = 9(\sqrt{3} - \sqrt{2}),\ c_4 = 3\sqrt{3} - 5\sqrt{2},\ c_5 = 2 + \sqrt{6}$$

Light-Front holography – $N(1440)$ e.m. form factors (1')



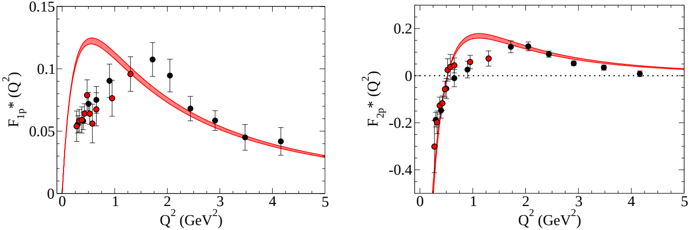


$$
\begin{aligned}
F_{1p}^* &= \frac{a(\sqrt{2}a + c_1)}{(a+1)(a+2)(a+3)(a+4)} \\
&+ g_V \frac{a(\sqrt{2}a + c_2)}{(a+1)(a+2)(a+3)(a+4)} \\
&\eta_p \frac{2a(2\sqrt{2}a^2 - c_3 a + c_4)}{(a+1)(a+2)(a+3)(a+4)(a+5)}
\end{aligned}
$$

$$
\begin{aligned}
F_{2p}^* &= \eta_p \left(\frac{M + M_R}{M_R} \right)^2 \frac{M_R}{2\sqrt{3}\kappa} \\
&\times \frac{6\sqrt{3}(c_5 a - 4)}{(a+1)(a+2)(a+3)(a+4)} \\
& a = \frac{Q^2}{4\kappa^2}
\end{aligned}
$$

Accurate description of $Q^2 > 2$ GeV^2 data (narrow window)
based on the parametrization for the nucleon … good F_{2p}^* at low-Q^2

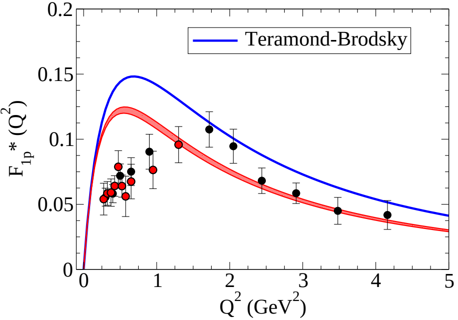
Light-Front holography – $N(1440)$ e.m. form factors (2)



- Light-Front holographic QCD can be used to estimate elastic and transition form factors in leading twist approximation (qqq states, first Fock state)
- Expressions depend on 3 bare couplings: κ_p, κ_n and g_V
- After fixing the couplings (nucleon) $\Longrightarrow$ predictions for large Q^2
- Contrary to previous works, the couplings are fixed by the large Q^2 data
  At low Q^2 we can expect contamination from non valence quark degrees of freedom (mainly $q\bar{q}$ effects)

Light-Front holography – Roper -Analytic expressions (1)

Important result from holography – resonances N^* – Analytic expression
Roper Dirac form factor – GF Teramond and SJ Brodsky AIP Conf. P 1432, 168 (2012)



$$F_{1p}^* = \frac{\sqrt{2}}{3} \times \frac{\frac{Q^2}{m_\rho^2}}{\left(1+\frac{Q^2}{m_\rho^2}\right)\left(1+\frac{Q^2}{m_{\rho 1}^2}\right)\left(1+\frac{Q^2}{m_{\rho 2}^2}\right)}$$

$$m_\rho = 2\kappa, \qquad m_{\rho n} = 2\sqrt{2}\kappa\sqrt{n+\tfrac{1}{2}}\ (n=1,2,...)$$

Light-Front holography – Roper -Analytic expressions (2)

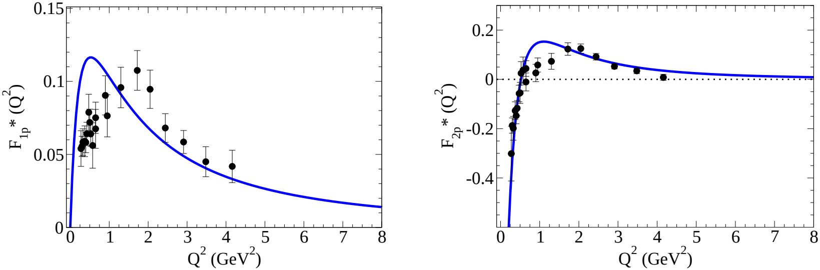
Inspired by the holographic results for F^*_{1p} and F^*_{2p} – $\kappa \simeq 0.385$ GeV
$M_N \simeq 2\sqrt{2}\kappa$, $\quad 4\kappa \simeq 1.520$ GeV $\simeq M_{N1}$ (Roper) – 5% deviation

$$G_2 = \frac{1}{\left(1+\frac{Q^2}{m_\rho^2}\right)\left(1+\frac{Q^2}{m_{\rho 1}^2}\right)\left(1+\frac{Q^2}{M_N^2}\right)\left(1+\frac{Q^2}{M_{N1}^2}\right)}$$

$$G_3 = \frac{1}{\left(1+\frac{Q^2}{m_\rho^2}\right)\left(1+\frac{Q^2}{m_{\rho 1}^2}\right)\left(1+\frac{Q^2}{m_{\rho 2}^2}\right)\left(1+\frac{Q^2}{M_N^2}\right)\left(1+\frac{Q^2}{M_{N1}^2}\right)}$$

$\Rightarrow$ Analytic expressions for F^*_{1p}, F^*_{2p}, functions of $m_{\rho n}$, M_N, M_{N1}
— use empirical masses

Light-Front holography – Roper - Analytic expressions (2')



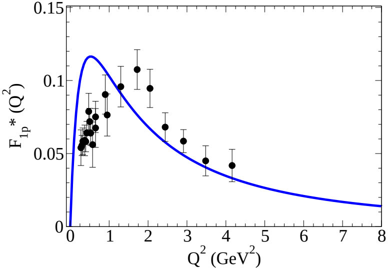
$$F_{1p}^* = \frac{1}{12\sqrt{2}}(1+g_V)\frac{Q^4}{m_\rho^4}G_2 + \frac{1}{24}(c_1+c_2 g_V)\frac{Q^2}{m_\rho^2}G_2 + \frac{1}{60}\eta_p\left(2\sqrt{2}\frac{Q^4}{m_\rho^4} - c_3\frac{Q^2}{m_\rho^2} + c_4\right)\frac{Q^2}{m_\rho^2}G_3$$

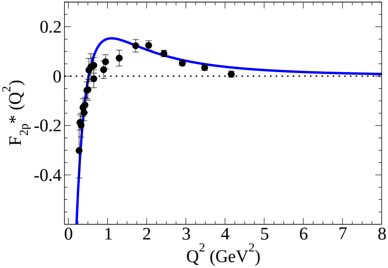
$$F_{2p}^* = \frac{\sqrt{3}}{4}\eta_p\left(\frac{M_{N1}+M_N}{M_{N1}}\right)^2 \times \left(c_5\frac{Q^2}{m_\rho^2} - 4\right)G_2$$

GR, PRD 96, 054021 (2017)

$$c_1 = 4\sqrt{2}+3\sqrt{3},\ c_2 = 4\sqrt{2}-3\sqrt{3},\ c_3 = 9(\sqrt{3}-\sqrt{2}),\ c_4 = 3\sqrt{3}-5\sqrt{2},\ c_5 = 2+\sqrt{6}$$

Light-Front holography – Roper - Analytic expressions (2')





$$
\begin{aligned}
F^*_{1p} &= \frac{1}{12\sqrt{2}}(1+g_V)\frac{Q^4}{m_\rho^4}G_2 \\
&+\frac{1}{24}(c_1+c_2 g_V)\frac{Q^2}{m_\rho^2}G_2 \\
&+\frac{1}{60}\eta_p\left(2\sqrt{2}\frac{Q^4}{m_\rho^4}-c_3\frac{Q^2}{m_\rho^2}+c_4\right)\frac{Q^2}{m_\rho^2}G_3
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$$

$$
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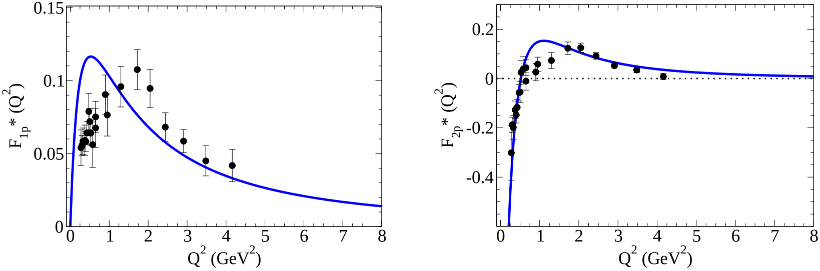
F^*_{2p} &= \frac{\sqrt{3}}{4}\eta_p\left(\frac{M_{N1}+M_N}{M_{N1}}\right)^2 \\
&\times\left(c_5\frac{Q^2}{m_\rho^2}-4\right)G_2
\end{aligned}
$$

GR, PRD 96, 054021 (2017)

Good analytic representation of the F^*_{1p} and F^*_{2p} data for $Q^2 > 2.5$ GeV^2

Light-Front holography – Roper - Analytic expressions (2')



$$
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&\times\left(c_5\frac{Q^2}{m_\rho^2}-4\right)G_2
\end{aligned}
$$

GR, PRD 96, 054021 (2017)

First analytic representation of F_{2p}^*

Light-Front holography – Nucleon Axial form factor (1)

Holographic estimate of the meson cloud contribution to nucleon axial form factor

GR PRD 97, 073002 (2018)

- Nucleon wave function: sum of Fock states: (no $(qqq)g$ states)
  qqq – leading order $\oplus$ $qqq(\bar{q}q)$ – 3rd Fock state
- Following T Gutsche, VE Lyubovitskij, I Schmidt and A Vega PRD 86, 036007 (2012)

$$\mathcal{L}_A = [g_A^0 \Gamma^M \gamma_5 \pm \Gamma^M] \mathcal{A}_M(x,z) \frac{\tau_3}{2} + \eta_A [\Gamma^M, \Gamma^N] \gamma_5 \mathcal{A}_{MN}(x,z) \frac{\tau_3}{2}$$

g_A^0, η_A coupling constants; $\mathcal{A}_M$ = axial field, $\mathcal{A}_{MN} = \partial_M A_N - \partial_N A_M$

- Axial form factor: c_3: qqq state; c_5: $qqq(\bar{q}q)$; $c_3 + c_5 = 1$

$$G_A(Q^2) = c_3 \, G_A^B(Q^2) + c_5 \, G_A^{\rm MC}(Q^2)$$

- Compare with Quark Model: $|N\rangle = Z_N \left[|qqq\rangle + b_N \, |{\rm MC}\rangle \right], Z_N = 1/(1+b_N^2)$

$$G_A(Q^2) = Z_N \, G_A^B(Q^2) + (1 - Z_N) \, G_A^{\rm MC}(Q^2)$$

Physical N: Z_N = probability of qqq state; $1 - Z_N$ = probability of MC st.

- $c_3 \equiv Z_N \oplus c_3 \leq 1$ – **Important constraint** for holographic models

Light-Front holography – Nucleon Axial form factor (2)

Independent parameters: c_3, g_A^0 (bare axial coupling),
η_A (bare induced pseudoscalar coupling) PRD 86, 036007 (2012)
$a = \frac{Q^2}{4\kappa^2}$, $\kappa = \frac{m_\rho}{2} = 0.385$ GeV – holographic mass scale

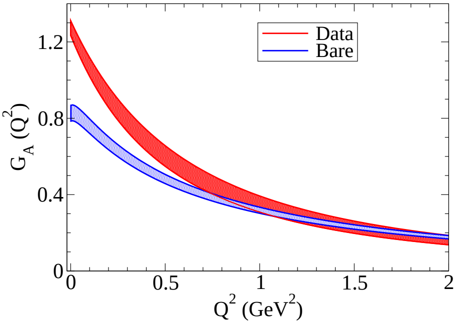
$$G_A^B = \left[g_A^0 + \frac{a}{6}(g_A^0 - 1)\right] G_1 + \frac{1}{12}\eta_A a(2a+18)G_2$$

$$G_A^{\rm MC} = \left[g_A^0 + \frac{a}{10}(g_A^0 - 1)\right] G_3 + \frac{1}{30}\eta_A a(4a+49)G_4$$

$$G_1 = \frac{1}{(1+a)(1+\frac{a}{2})(1+\frac{a}{3})}, \quad G_2 = \frac{G_1}{1+\frac{a}{4}}, \quad G_3 = \frac{G_2}{1+\frac{a}{5}}, \quad G_4 = \frac{G_3}{1+\frac{a}{6}}$$

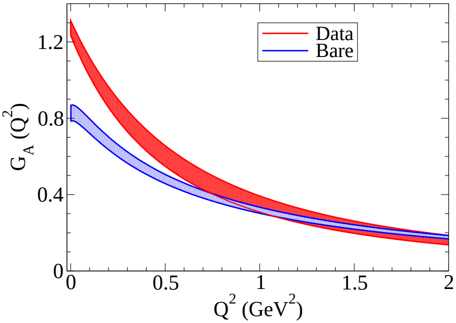
- Bare and MC depend both on g_A^0 and η_A
- $G_A^B(0) = g_A^0$, $G_A^{\rm MC}(0) = g_A^0$; Thus $G_A(0) = c_3 g_A^0 + c_5 g_A^0 \equiv g_A^0$
  All holographic models give $G_A(0) = g_A^0$
- How to fix the parameters c_3 and η_A ?
- A free fit to the $G_A^{\rm exp}$ data provides different equivalent solutions
  $(\eta_A, c_5) = (0.45, -0.41)$ – unphysical solution; $Z_N = 1.41 > 1$;
  $(\eta_A, c_5) = (0.68, 0.00)$ – no meson cloud
- The data does not fix c_3 unless we provide a estimate for G_A^B
  Use information from lattice QCD

Light-Front holography – Nucleon Axial form factor (3)



- Red band parametrization of the G_A data
- Blue band estimate of G_A^B based on lattice QCD data
- Extrapolation based QM in the range m_π =0.35–0.5 GeV^2
GR and K Tsushima,
PRD 94, 014001 (2016)

Light-Front holography – Nucleon Axial form factor (3)



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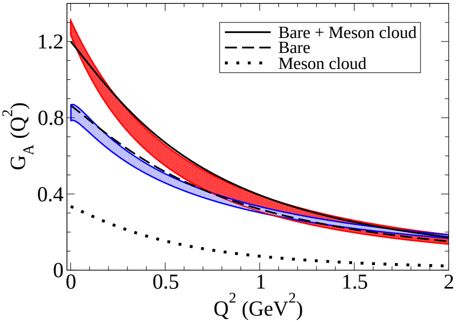
- Best fit: $\mathbf{g_A^0} = 1.2$, $\eta_A = 1.08$ $c_3 = 0.72$ (MC $\sim$ 30%)

Light-Front holography – Nucleon Axial form factor (3')



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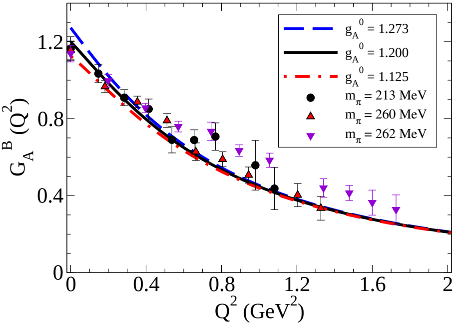
  GR and K Tsushima,
  PRD 94, 014001 (2016)
- Best fit: $\mathbf{g_A^0} = 1.2$, $\eta_A = 1.08$
  $c_3 = 0.72$ (MC $\sim$ 30%)
- Very slow falloff for MC $(\cdots)$
  Slower than in most QM

Light-Front holography – Nucleon Axial FF – Lattice

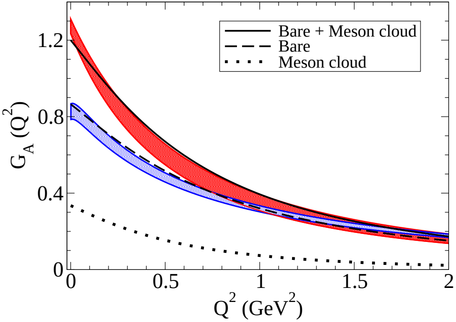


Compare with lattice

$g_A^0 = 1.12$; **1.20**, 1.27

$$G_A = G_A^B + (1 - c_3)[G_A^{\rm MC} - G_A^B]$$

- Lattice QCD underestimates $G_A^{\rm exp}(0) \simeq 1.27$ in general
  T Yamazaki et al, PRD 79, 114505 (2009)
- Best model (**1.20**) compares well with lattice ($m_\pi \approx 230$ MeV)
- **Conclusions:**
  – good estimate of bare comp.
  – still small MC effects for $m_\pi \approx 230$ MeV



Holographic model

- 3 parameters
  $G_A = G_A(c_3, g_A^0, \eta_A)$
- Estimate of G_A^B is necessary to calibrate the model ($c_3 < 1$)
- $g_A^0 = 1.2$ – Good estimate of $G_A(\text{lattice}) \simeq G_A^B$
- **No dependence** on microscopic scales (dimension of bare core); pointlike quarks/mesons
- Very slow falloff of MC components ($\cdots$)

Light-Front holography – Summary and outlook

GR and D Melnikov, PRD 97, 034037 (2018); GR, PRD 96, 054021 (2017); PRD 97, 073002 (2018)

- Light-Front holography can be used to estimate elastic and transition form factors in leading twist approximation
  (qqq states, first Fock state)
- At small Q^2 we expect contamination of next to leading order corrections (higher Fock states, $q\bar{q}$, ...)
  Low Q^2 should not be used to fix the bare couplings
- Formalism can be used to derive analytic expressions for the transition form factors at large Q^2 (F_1^* and F_2^*)
- Higher order corrections depend on the mixing coefficients (c_3, c_5, ...) and from the bare couplings
  $\Rightarrow$ No reference to microscopic baryon-meson couplings
  & size of baryon bare core — slow falloff of the meson cloud
- Very promising method to estimate $\gamma^* N \to N^*$ transition form factors at large Q^2 – leading twist

- **Introduction**
- $N(1520)\frac{3}{2}^-$, $N(1535)\frac{1}{2}^-$ SR approximation; $N(1440)\frac{1}{2}^+$
- $\Delta(1232)\frac{3}{2}^+$ – recent results for the quadrupole form factors

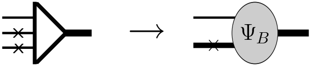
In collaboration with:

F. Gross (JLab/USA), M.T. Peña (Lisbon/Portugal),
and K. Tsushima (UCS/Brasil)

Covariant Spectator Quark Model – Introduction (1)

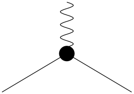
- Baryons are three constituent quark systems
- Wave functions based on the $SU(6)$ spin-flavor quark states
- Covariant Spectator Theory: quark$\oplus$(quark-pair) separation
  Integration into the quark-pair degrees of freedom – eff. diquark mass m_s

$$\int_{k_1}\int_{k_2} = \int_{4m_q^2}^{+\infty} ds \sqrt{\frac{s-4m_q^2}{s}} \int \frac{d^3\mathbf{k}}{2\sqrt{s+\mathbf{k}^2}}$$



Stadler, Gross and Frank PRC 56, 2396 (1998); Gross and Agbakpe PRC 73, 015203 (2006); Gross, GR and Peña PRC 77, 015202 (2008); PRD **85**, 093005 (2012)

- Radial wave function $\psi_B(P_B,k)$ determined phenomelogically
  $\psi_B(P_B,k) = \psi_B\left(\frac{(M_B-m_s)^2-(P_B-k)^2}{m_s M_B}\right)$
  $M_B =$ baryon mass; $m_s =$ diquark mass



- Quarks with electromagnetic structure
  (**impulse approximation**)

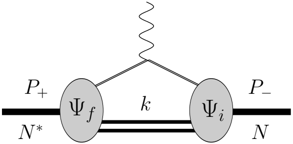
$$j_q^\mu = \left(\frac{1}{6}f_{1+} + \frac{1}{2}f_{1-}\tau_3\right)\gamma^\mu + \left(\frac{1}{6}f_{2+} + \frac{1}{2}f_{2-}\tau_3\right)\frac{i\sigma^{\mu\nu}q_\nu}{2M_N}$$

quark form factors $f_{i\pm}$ parametrize dressing of quarks (gluons and $q\bar{q}$)

- Vector Meson Dominance: $f_{i\pm} = f_{i\pm}(Q^2; m_\rho, M_N)$ PRD 80, 033004 (2009)

- Transition current –relativistic impulse approximation

$$J^\mu = 3 \sum_\lambda \int_k \bar{\Psi}_f(P_+, k) j_q^\mu \Psi_i(P_-, k)$$



diquark on-shell

- Quark current j_q^μ and nucleon radial wave function $\psi_N(P_N, k)$ callibrated by **nucleon elastic form factor data**

  Gross, GR, Peña, PRC 77, 015202 (2008)

- **Generalization to lattice QCD:**
  - $f_{i\pm}(Q^2; m_\rho, M_N) \to f_{i\pm}(Q^2; m_\rho^{\rm latt}, M_N^{\rm latt})$ – VMD
  - $\psi_B(M_B) \to \psi_B(M_B^{\rm latt})$

  GR, MT Peña, JPG 36, 115011 (2009); PRD 80, 013008 (2009); GR, K Tsushima, F Gross, PRD 80, 033004 (2009); GR, K Tsushima, AW Thomas, JPG 40, 015102 (2013)

Semirelativistic approximation - Introduction

$\mathbf{q} =$ photon three-momentum at the R rest frame

- **Non relativistic regime:**
  Othogonality between states is defined when $|\mathbf{q}| = 0$.
  Both particles at rest
  Transition form factors independent of the mass (M_N or M_R)
- **Relativistic regime:**
  There are ambiguties related with the **relativistic generalization**
  Dificulties in defining **othogonality** between states defined
  in different rest-frames when $M_R \neq M_N$
- **SemiRelativistic approximation**: GR, PRD 95, 054008 (2017)
  - Calculate elementary form factors ($F_1^*, F_2^*/G_1, G_2, G_3$)
    in the limit $M_R = M_N$
  - Use definition of multipole form factors and helicity amplitudes
    ($M_R \neq M_N$) to compare with **measured data**.

Cases: $N(1535)\frac{1}{2}^-$, $N(1520)\frac{3}{2}^-$

SR approximation – Notation

Use R rest frame, for simplicity, to define invariant integrals

$$\mathcal{I}_R(Q^2) = \int_k \frac{k_z}{|\mathbf{k}|} \psi_R(P_R, k) \psi_N(P_N, k)$$

We assume that $\psi_R \equiv \psi_N$; In the limit $M_R \to M_N$:

$$\mathcal{I}_R \propto |\mathbf{q}|$$

$\mathcal{I}_R(0) = 0$: orthogonality between N (mass M_N) and R (mass M_R) states
Equal mass limit: $M_N, M_R \to M \equiv \frac{1}{2}(M_N + M_R)$

$$\begin{aligned} j_i^S &\equiv \frac{1}{6} f_{i+} + \frac{1}{2} f_{i-} \tau_3 \\ j_i^A &\equiv \frac{1}{6} f_{i+} - \frac{1}{6} f_{i-} \tau_3 \end{aligned}$$

SR approximation – $N(1535)$

$$J^\mu = \bar{u}_R \left[F_1^* \left(\gamma^\mu - \frac{\not{q} q^\mu}{q^2} \right) + F_2^* \frac{i\sigma^{\mu\nu} q_\nu}{M_N + M_R} \right] \gamma_5 u_N$$

GR, MT Peña, PRD 84, 033007 (2011); GR, PRD 95, 054008 (2017)

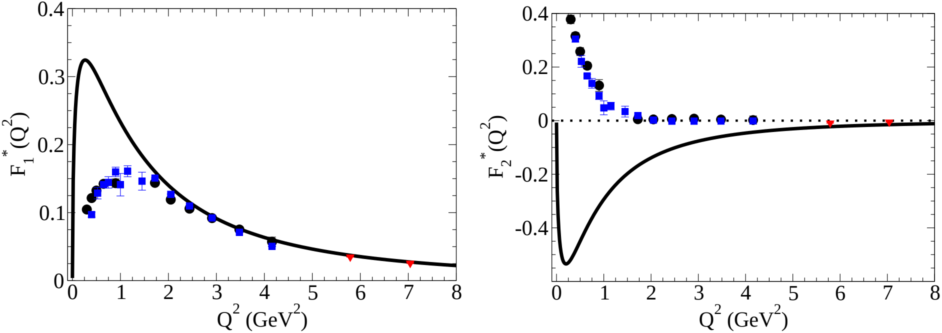
$$\begin{aligned} F_1^* &= \frac{1}{2}(3j_1^S + j_1^A)\mathcal{I}_R \\ F_2^* &= -\frac{1}{2}(3j_2^S - j_2^A)\frac{M_N + M_R}{2M_N}\mathcal{I}_R \end{aligned}$$

SR approach: **No parameters adjusted**

$$\frac{M_N + M_R}{2M_N} \to 1, \qquad |\mathbf{q}| \to Q\sqrt{1+\tau}$$

where $\tau = \frac{Q^2}{(M_N+M_R)^2}$

SR approximation – $N(1535)$ – Results



- Data from **CLAS**, MAID and Jlab/Hall C
- $F_i^*(Q^2) \propto |\mathbf{q}|$, implying that $F_i^*(0) = 0$
- Good results for F_1^* ($Q^2 > 2$ GeV^2), F_2^* wrong sign; $(F_2^*)_{\rm exp} \approx 0$ more latter

$$J^\mu = \bar{u}_\alpha \left[G_1 q^\alpha \gamma^\mu + G_2 q^\alpha P^\mu + G_3 q^\alpha q^\mu + ... \right] \gamma_5 u_N$$

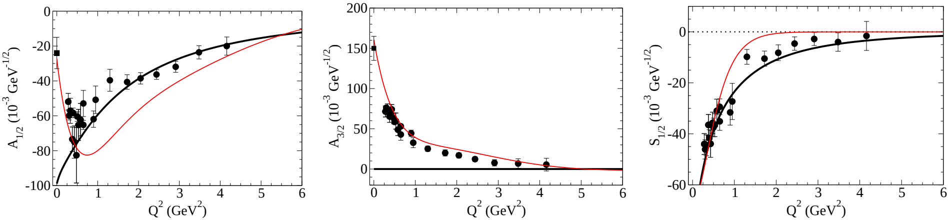
GR, MT Peña, PRD 89, 094016 (2014); PRD 95, 014003 (2017) $G_M = -G_E$

$$\begin{aligned}
G_1 &= -\frac{3}{2\sqrt{2}} \left[\left(j_1^A + \frac{1}{3} j_1^S \right) + \frac{M_R + M_N}{2M_N} \left(j_2^A + \frac{1}{3} j_2^S \right) \right] \frac{\mathcal{I}_R}{|\mathbf{q}|} \\
G_2 &= \frac{3}{2\sqrt{2}M_N} \left[j_2^A + \frac{1}{3} \frac{1-3\tau}{1+\tau} j_2^S + \frac{4}{3} \frac{2M_N}{M_R + M_N} \frac{1}{1+\tau} j_1^S \right] \frac{\mathcal{I}_R}{|\mathbf{q}|} \\
G_3 &= \frac{3}{2\sqrt{2}} \frac{M_R - M_N}{Q^2} \left[j_1^A + \frac{1}{3} \frac{\tau - 3}{1+\tau} j_1^S + \frac{4}{3} \frac{M_R + M_N}{2M_N} \frac{\tau}{1+\tau} j_2^S \right] \frac{\mathcal{I}_R}{|\mathbf{q}|}
\end{aligned}$$

SR approach: $|\mathbf{q}| \to Q\sqrt{1+\tau}$ **No parameters adjusted**

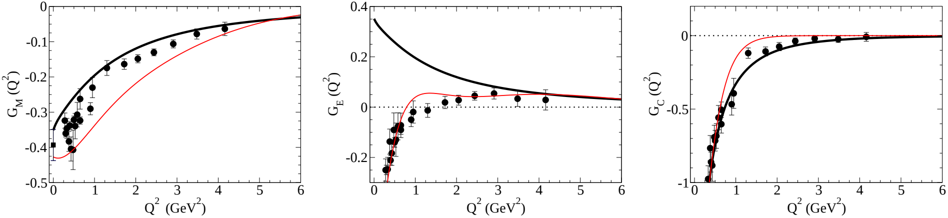
$$\frac{\mathcal{I}_R}{|\mathbf{q}|} \to \text{const } (M_R \to M_N), \qquad Q^2 G_3 \to 0$$

SR approximation – $N(1520)$ – Results (1)



- SemiRelativistic approach (**SR**); data from **CLAS**, include MAID fit
- **SR** very good description of the $Q^2 > 1.5$ GeV^2 data
  Except for $A_{3/2}$ (CSQM: $A_{3/2} \equiv 0$) – $A_{3/2} \leftarrow$ dominated by meson cloud ?
- **Describe well valence quark degress of freedom** ($(A_{3/2})_{\text{bare}} \approx 0$)

SR approximation – $N(1520)$ – Results (2)



- SemiRelativistic approach (**SR**); data from **CLAS**, include MAID fit
- **SR** very good description of the $Q^2 > 1.5$ GeV^2 data
  Except for G_E (CSQM: $G_E \equiv -G_M$, $A_{3/2} \equiv 0$)
- **Describe well valence quark degress of freedom** ($(A_{3/2})_{\text{bare}} \approx 0$)

SR approximation – Summary

- In general **SR approach** gives a good description of the form factors
  No parameters adjusted ($\psi_R \equiv \psi_N$)
- Good description of region $Q^2 > 1.5$ GeV^2
  Exceptions:
  - $N(1520)$: $A_{3/2}$ and G_E
    Quark models: $A_{3/2}$ is *usually* very small
    Interpretation: $A_{3/2}$ dominated by meson cloud effects $A_{3/2} \simeq A_{3/2}^{\rm mc}$
    [Using $|A_{3/2}^{\rm mc}| \gg |A_{1/2}^{\rm mc}|$: $\Rightarrow G_M^{\rm mc} \simeq \frac{1}{3} G_E^{\rm mc}$]
  - $N(1535)$: F_2^* –discussed in next slide

GR, PRD 95, 054008 (2017)

Implications of $F_2^* = 0$?

$\tau = \frac{Q^2}{(M_R+M_N)^2}$ $Q^2 > 1.5$ GeV^2

$$S_{1/2} \simeq -\frac{\sqrt{1+\tau}}{\sqrt{2}} \frac{M_R^2 - M_N^2}{2 M_R Q} A_{1/2}$$

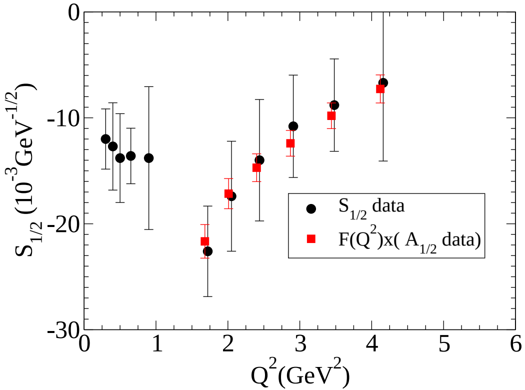
GR, K Tsushima
PRD 84, 051301 (2011)

GR, D Jido, K Tsushima
PRD 85, 093014 (2012)

Cancellation between valence and meson cloud

Consistent with meson cloud calculations – χ Unitary Model

D Jido, M Doring and E Oset,
PRC 77, 065207 (2008)



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GR, K Tsushima
PRD 84, 051301 (2011)

GR, D Jido, K Tsushima
PRD 85, 093014 (2012)

Cancellation between valence and meson cloud

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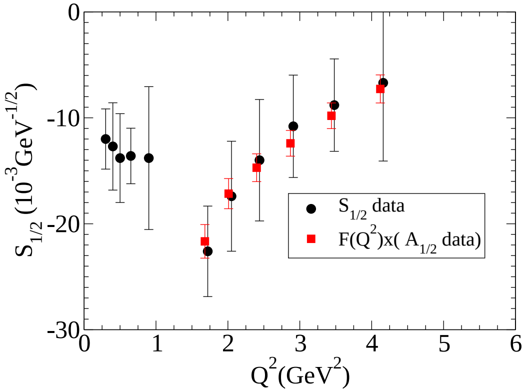
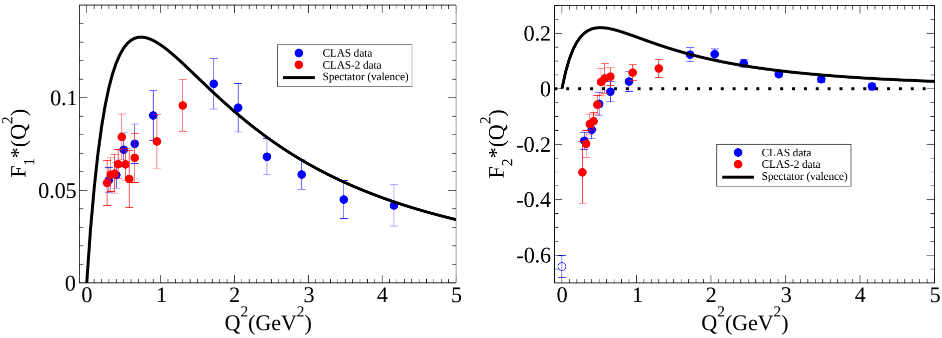
D Jido, M Doring and E Oset,
PRC 77, 065207 (2008)

More data are welcome

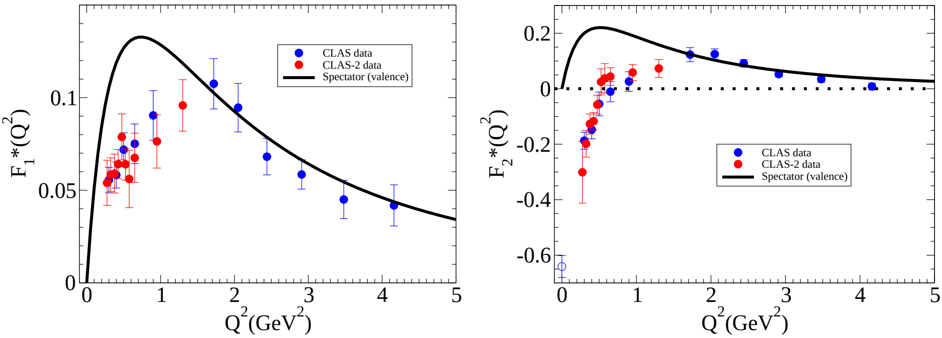


$\gamma^* N \to N(1440)$ – Introduction



- **CSQM:** Roper defined as the **1st radial** excitation of the nucleon
  Same spin/flavor structure as the nucleon
  Radial wave function defined by the orthogonality with nucleon state
  GR and K Tsushima, PRD 81, 074020 (2010); PRD 89, 073010 (2014)
- No adjustable parameters; **No** meson cloud components included
- **CLAS data:** IG Aznauryan et al., PRC 80, 055203 (2009);
  VI Mokeev et al., PRC 86, 035203 (2012); PRC 93, 025206 (2016)

$\gamma^* N \to N(1440)$ – Results



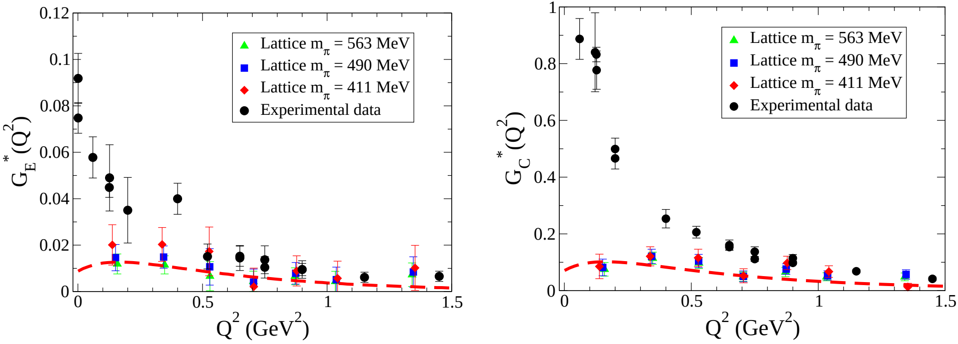
- **Good results** for $Q^2 > 1.5$ GeV^2 – valence quark dominance
  Support **Roper** as **1st radial** excitation of the nucleon – IG Aznauryan PRC 76, 025212 (2007)
- Failure for $Q^2 < 1.5$ GeV^2 – meson cloud ?
  Used to estimate meson cloud from CLAS data
  GR and K Tsushima, AIP Conf.Proc. 1374, 353 (2011)

$\gamma^* N \to \Delta(1232)$ – Form Factors – Status

- **Magnetic form factors G_M^*:** (not discussed here)
  - Dominated by valence quark effects ($\approx 70\%$):
    The gap between QM and the explained as **pion cloud effects**
  - There is today a convergence of results based on different frameworks;
    Dynamical Models, Dyson-Schwinger, Quark Models; Lattice QCD, ...
- **Quadrupole form factors G_E^*, G_C^* (smaller magnitude)** (next)
  - Quarks models (mostly NR) predict only a fraction (≈10–20%)
  - Pion cloud estimates
    $SU(6)$ Constituent Quark Models $\oplus$ Large N_c models
    $\Longrightarrow$ G_E^*, G_C^* are dominated by pion cloud effects
    V Pascalutsa and M Vanderhaeghen, PRD 76, 111501 (2007);
    P Grabmayr and AJ Buchmann, PLB 86 (2001)
  - Exceptions: Dyson-Schwinger equations:
    – larger contributions from the bare core
    G Eichmann and D Nicmorus, PRD 85, 093004 (2012);
    J Segovia, and CD Roberts, PRC 94, 042201 (2016)

$\gamma N \to \Delta$: $G_E^*(Q^2)$, $G_C^*(Q^2)$ (bare) (D1 $S_q = 1/2$; D3 $S_q = 3/2$)

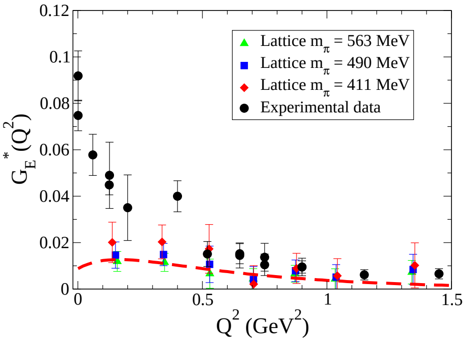
Small valence quark contributions

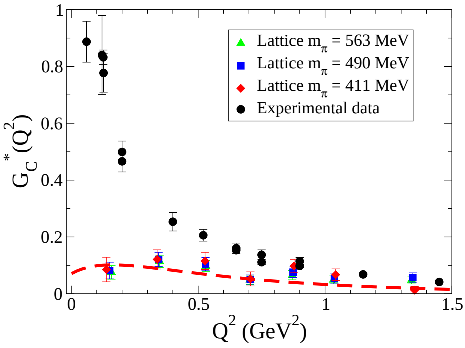


- *D*-state parameters adjusted to lattice QCD data (D1, D3 $\approx 0.7\%$)
- − − − Result extrapolated to the **physical limit**

$\gamma N \to \Delta$: $G_E^*(Q^2)$, $G_C^*(Q^2)$ (bare) (D1 $S_q = 1/2$; D3 $S_q = 3/2$)

Small valence quark contributions

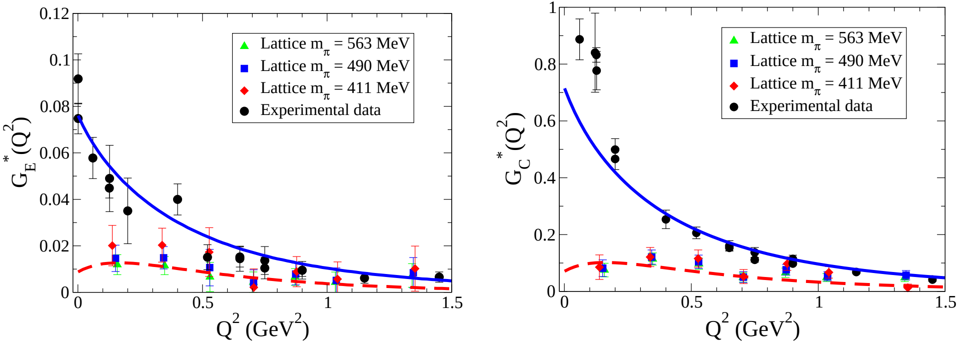




- D-state parameters adjusted to lattice QCD data (D1, D3 $\approx 0.7\%$)
- Lattice data: Alexandrou et al, PRD 77, 085012 (2008)

$\gamma N \to \Delta$: $G_E^*(Q^2)$, $G_C^*(Q^2)$ (bare + pion cloud)

Add pion cloud contribution



- G_E^*: Pascalutsa and Vanderhaeghen, PRD 76 (2007) – Large N_c
- G_C^*: Buchmann PRD 66 (2002) – $G_{E,C}^* \propto G_{En}/Q^2$

$\gamma N \to \Delta$: $G_E^*(Q^2)$, $G_C^*(Q^2)$ – Pion cloud effects

- Constituent Quark Models with two-body exchange currents (diagrams with pion and $q\bar{q}$ states) & Large N_c limit
  – processes interpreted as pion cloud effects
  V Pascalutsa and M Vanderhaeghen, PRD 76, 111501 (2007);
  P Grabmayr and AJ Buchmann, PLB 86 (2001)
  - Exact $SU(6)$ (symmetric N and Δ)

$$G_E^*(0) = 0, \qquad G_C^*(0) = 0, \qquad G_{En} \equiv 0,$$

  - Broken $SU(6)$ (deformed Δ, assymetric neutron)

$$G_E^*(0) \propto r_n^2, \quad G_C^*(0) \propto r_n^2, \quad G_{En} \simeq -\frac{1}{6} r_n^2 Q^2,$$

  $G_{En} \neq 0$ also interpreted as consequence deformation of $q\bar{q}$ cloud
  AJ Buchmann and EM Henley, PRC 63, 015202 (2000)

Siegert's theorem ($E_{1+}/|\mathbf{q}| \propto S_{1+}/|\mathbf{q}|^2$)

At the pseudo-threshold (nucleon and Δ at rest): $Q_{pt}^2 = -(M_\Delta - M)^2$

$$G_E^*(Q_{pt}^2) = \frac{\overbrace{M_\Delta - M}^{=\kappa}}{2M_\Delta} G_C^*(Q_{pt}^2)$$

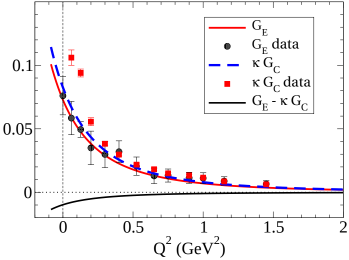
HF Jones and MD Scadron, Ann Phys 81, 1 (1973); AJ Buchmann, E Hernandez, U Meyer, and A Faessler, PRC 58, 2478 (1998); D Drechsel, L Tiator, JPG 18, 449 (1992); GR, PRD 94, 114001 (2016); arXiv:1709.07412 [hep-ph]

Pascalutsa-Vanderhaeghen-Buchmann parametrization **violate** Siegert's theorem

Large-N_c: $\tilde{G}_{En} = G_{En}/Q^2$

$$G_E^\pi = \left(\frac{M}{M_\Delta}\right)^{3/2} \frac{M_\Delta^2 - M^2}{2\sqrt{2}} \tilde{G}_{En}$$

$$G_C^\pi = \left(\frac{M}{M_\Delta}\right)^{1/2} \sqrt{2} M M_\Delta \tilde{G}_{En},$$



No quark effects

GR, PRD 94, 114001 (2016)

Breaking of Siegert's theorem

$$\mathcal{R}_{pt} = G_E(Q^2_{pt}) - \kappa G_C(Q^2_{pt}) \simeq -\left(\frac{M}{M_\Delta}\right)^{3/2} \frac{r_n^2}{12\sqrt{2}} Q^2_{pt} = \mathcal{O}\left(\frac{1}{N_c^2}\right)$$

M, $M_\Delta = \mathcal{O}(N_c)$; $M_\Delta - M = \mathcal{O}(1/N_c)$

$\gamma^* N \to \Delta$: quadrupoles – Siegert's theorem (2)

Imposing Siegert's theorem

Corrected Large-N_c: $\alpha = \frac{Q^2}{2M_\Delta(M_\Delta - M)}$

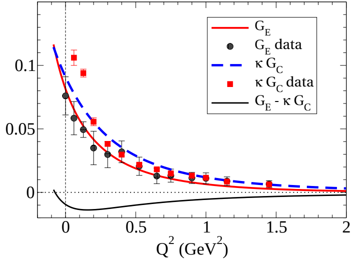
Relative correction $\mathcal{O}(1/N_c^2)$ in G_E^π at PT

$$G_E^\pi = \left(\frac{M}{M_\Delta}\right)^{3/2} \frac{M_\Delta^2 - M^2}{2\sqrt{2}} \tilde{G}_{En} \frac{\tilde{G}_{En}}{1+\alpha}$$

$$G_C^\pi = \left(\frac{M}{M_\Delta}\right)^{1/2} \sqrt{2} M M_\Delta \tilde{G}_{En},$$

$\frac{1}{1+\alpha}$ – preserve result at $Q^2 = 0$

Siegert's theorem: $\mathcal{R}_{pt} = 0$



Valence quark effects included

GR arXiv:1709.07412 [hep-ph]/EPJA

Imposing Siegert's theorem

Corrected Large-N_c: $\alpha = \frac{Q^2}{2M_\Delta(M_\Delta - M)}$

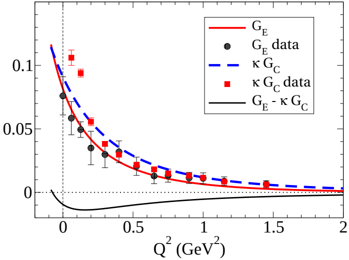
Relative correction $\mathcal{O}(1/N_c^2)$ in G_E^π at PT

$$G_E^\pi = \left(\frac{M}{M_\Delta}\right)^{3/2} \frac{M_\Delta^2 - M^2}{2\sqrt{2}} \tilde{G}_{En} \frac{\tilde{G}_{En}}{1+\alpha}$$

$$G_C^\pi = \left(\frac{M}{M_\Delta}\right)^{1/2} \sqrt{2} M M_\Delta \tilde{G}_{En},$$

$\frac{1}{1+\alpha}$ – preserve result at $Q^2 = 0$

Siegert's theorem: $\mathcal{R}_{pt} = 0$



Valence quark effects included

GR arXiv:1709.07412 [hep-ph]/EPJA

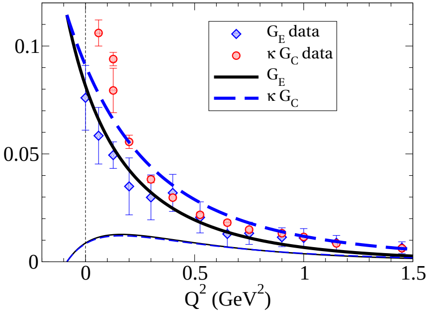
G_C **data underestimated**

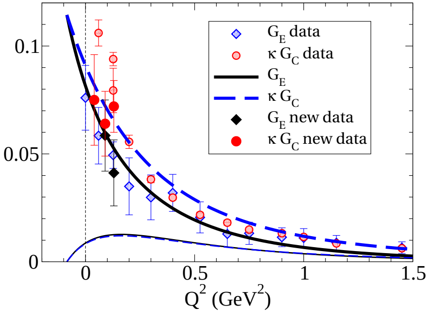
$\gamma^* N \to \Delta$: quadrupoles – Siegert's theorem – new results

Electroexcitation of the $\Delta^+(1232)$ at low momentum transfer
A Blomberg, PLB 760, 267 (2016), JLab/Hall A

- New results at **low momentum transfer region**, where the mesonic cloud dynamics is predicted to be dominant ...
- The new data explore the Q^2 dependence of the resonant quadrupole amplitudes and **for the first time indicate that the Electric and the Coulomb quadrupole amplitudes converge as** $Q^2 \to 0$
  [$\Rightarrow$ **reduction of values for** G_C]
- The **source of disagreement** (compared with previous measuments) has been identified in the **extraction procedure of the resonant amplitudes** from the measured MAMI cross sections.

$\gamma^* N \to \Delta$: quadrupoles – Siegert's theorem – new results





Before 2016 **After 2016**

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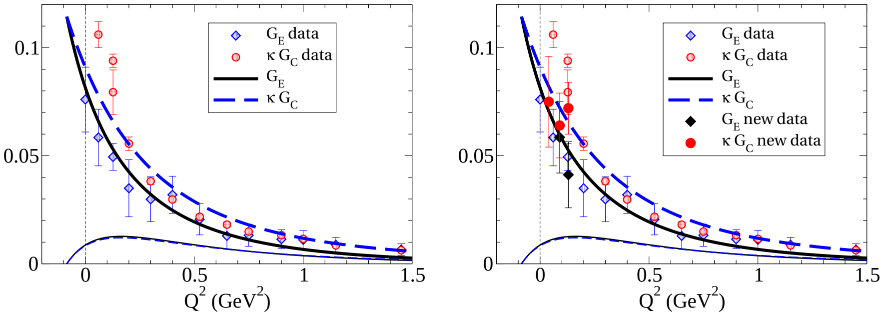

Before 2016 **After 2016**

- The combination of valence quark component (fixed by lattice QCD)

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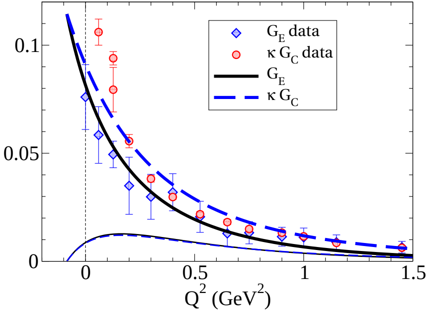
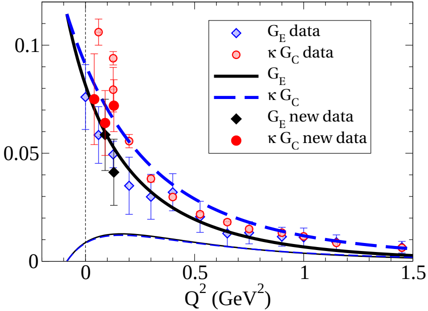


Before 2016



After 2016

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- ... with well known pion cloud parametrizations (parameter-free)

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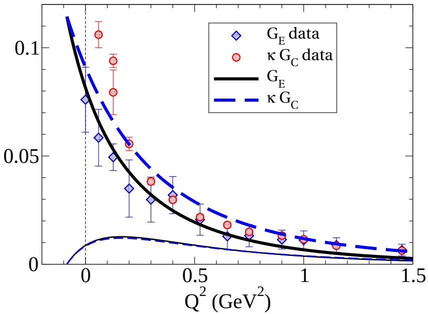

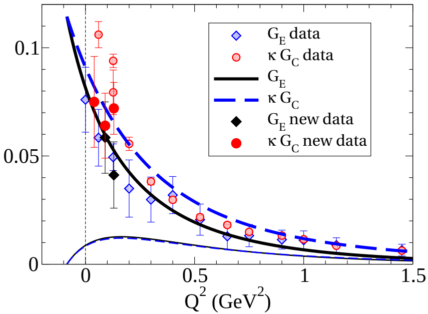

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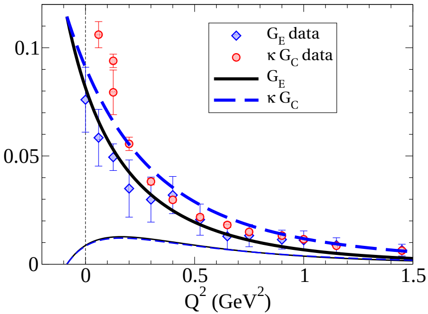
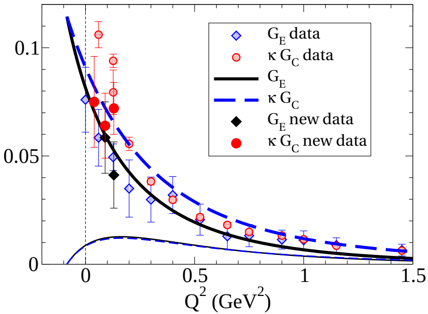
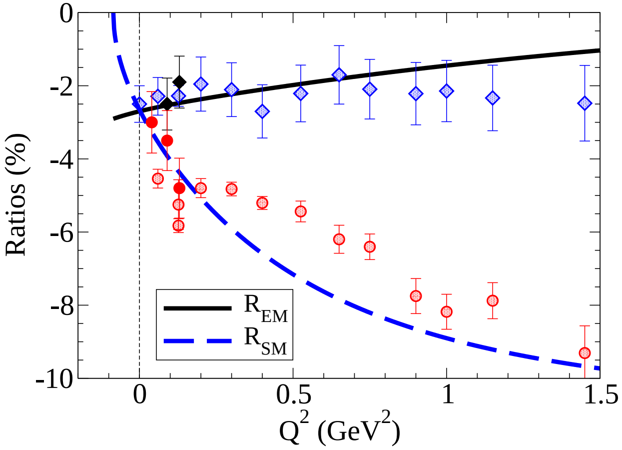




Before 2016 **After 2016**

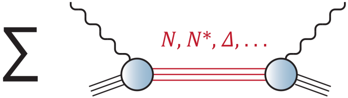
- The combination of valence quark component (fixed by lattice QCD)
- ... with well known pion cloud parametrizations (parameter-free)
- $\Rightarrow$ **good description** of the new data ... and consistence with **ST**

$\gamma^* N \to \Delta$: quadrupoles – new results – EM ratios †



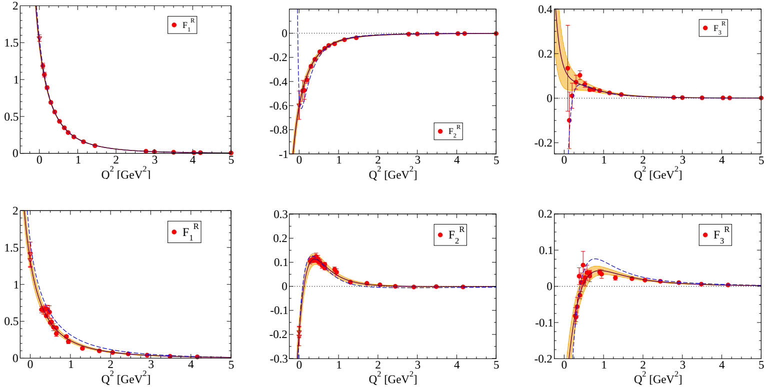
Other applications

Compton Scattering – parametrization of N^* form factors



G Eichmann and GR, in preparation

Results dominated by $\Delta(1232)$ (top) and $N(1520)$ (bottom)



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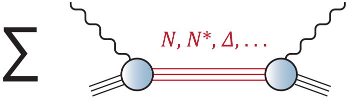
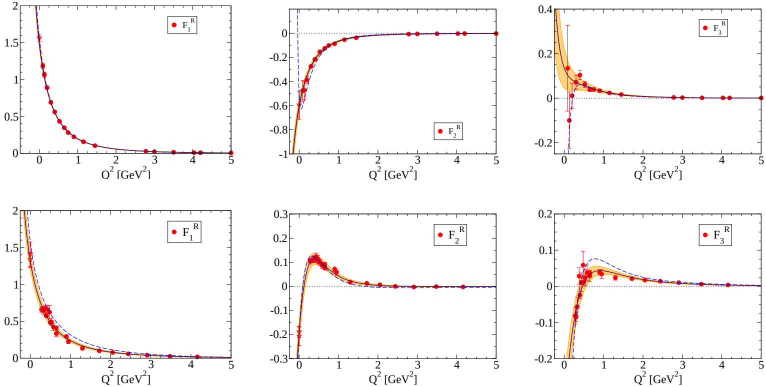


G Eichmann and GR, in preparation

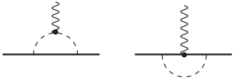
More accurate **low-Q^2 data** is necessary to determine the trend of the form factors



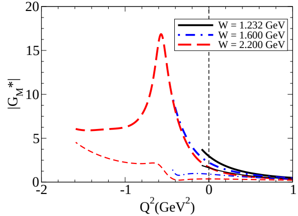
$\gamma^* N \to \Delta$ timelike FF ($Q^2 < 0$): Dalitz decay ($\Delta \to e^+e^- N$) – $\frac{d\sigma}{dm_{ee}}(pp)$

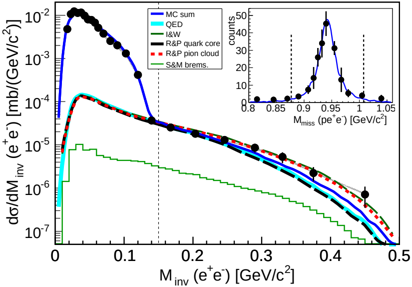
Form factor $G_M^*(Q^2, W)$ - timelike regime $Q^2 \le -(W-M)^2$ **HADES**

Relation between the $N - \Delta$ pion cloud and pion form factor $F_\pi(Q^2) \propto 1/(m_\rho^2 + Q^2)$

$F_\pi(Q^2) \leftarrow$ 

$G_M^*(Q^2) \to G_M^*(Q^2, W)$:





GR and MT Peña, PRD 85113014 (2012) **Data**: HADES collaboration, PRC 95, 065205 (2017)

GR, MT Peña J Weil, H van Hees and U Mosel, PRD 93, 033004 (2016) – W-dependence

Covariant Spectator QM – Summary and conclusions

- Provide covariant estimates for the form factors (helicity amplitudes) for several N^* states – $\Delta(1232)$, $N(1440)$, and $N(1535)$, $N(1520)$ – SR approach
- In general we have a good agreement with the (large Q^2) data ... with a few exceptions
  Role of quark degrees of freedom seems to be under control
- $\Delta(1232)$– quadrupole transition form factors: large pion cloud
  Pion cloud parametrizations consistent with
  Siegert's theorem $\oplus$ valence quark component
  $\Rightarrow$ very good description of new low-Q^2 data (G_C, G_E)
- The model can be extended to higher Q^2 and higher resonances
  Predictions can be tested in the JLab in a near future (JLab-12)
  Also $N(1650)\frac{1}{2}^-$, $N(1700)\frac{3}{2}^-$, $\Delta(1620)\frac{1}{2}^-$, $\Delta(1700)\frac{3}{2}^-$– PRD 90, 033010 (2014)

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Thank you