Hadron structure in soft-wall AdS/QCD at zero and finite temperature

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Plan of the Talk

- Introduction to AdS/QCD = Holographic QCD - novel approach based on correspondence between 5D theories including gravity and gauge 4D theories living on the boundary of AdS space.

- Applications:

  – Mass spectrum of hadrons

  – Electromagnetic structure of nucleon and Roper resonance $N(1440)$

  – Tetraquarks

  – Extension to finite temperature

- Summary

Introduction

- 1993 't Hooft   Holographic Principle
  Information about string theory contained in some region of space can be represented as "Hologram" (theory which lives on the boundary of that region)
- 1997 Maldacena   AdS/CFT correspondence
  Motivated by study of black holes and D-branes in string theories in AdS_5
- AdS/CFT correspondence
  Dynamics of the superstring theory in AdS_{d+1} background is encoded in d conformal field theory living on the AdS boundary.
  - Parameter correspondence (matching partition functions)

  Strings g_s – coupling, l_s – length, R – radius of AdS space

  SU(N) YM g_{YM} – coupling, 't Hooft coupling $\lambda = g^2_{YM} N$

  $$2\pi g_s = g^2_{YM}\,, \qquad \frac{R^4}{l_s^4} = 2\,g^2_{YM}\,N = 2\lambda$$

  - 't Hooft limit (large N at λ fixed) $g^2_{YM} = \lambda/N \ll 1$
  - Strong coupling limit $\lambda \gg 1$ means $l_s \ll R$ small curvature $\mathcal{R} = -20/R^2$

  Supergravity limit (closed strings shrink to point-like particles)
- AdS/CFT $\to$ ADS/QCD — breaking of conformal symmetry and confinement

Introduction

- AdS/QCD $\equiv$ Holographic QCD (HQCD) – approximation to QCD: attempt to model Hadronic Physics in terms of fields living in extra dimensions – anti-de Sitter (AdS) space
- HQCD models reproduce main features of QCD at low and high energies: chiral symmetry, confinement, power scaling of hadron form factors
- Symmetry arguments: Conformal group acting in boundary theory isomorphic to $SO(4,2)$ – the isometry group of AdS$_5$ space

Introduction

- Conformal group contains 15 generators:

  10 Poincaré (4 translations P_μ, 6 Lorentz transformations $M_{\mu\nu}$),
  5 conformal (4 conformal boosts K_μ, 1 dilatation D):

$M_{\mu\nu} = i(x_\mu \partial_\nu - x_\nu \partial_\mu)$	rotational symmetry
$D = i(x\,\partial)$	energy
$P_\mu = i\partial_\mu$	raising energy
$K_\mu = 2ix_\mu(x\,\partial) - ix^2\partial_\mu$	lowering energy

- Isomorphic to $SO(4,2)$ – the isometry group of AdS$_5$ space

- Fields in AdS$_5$ are classified by unitary, irreducible representations of $SO(4,2)$

- $SO(4,2)$ is decomposed with respect to $SO(4) \times SO(2)$
  $SO(4)$ is isomorphic to $SU(2) \times SU(2)$: use spins J_1 and J_2 for classification

- Irreducible representations $D(E_0, J_1, J_2)$ two spins J_1, J_2 and energy E_0
  (corresponds to Δ – conformal dimension of operators in CFT)

Introduction

- Scalar $D(E_0, 0, 0)$

- Vector $D\left(E_0, \frac{1}{2}, \frac{1}{2}\right)$

- Fermions of spin $J = 1/2$

  $D\left(E_0, 0, \frac{1}{2}\right) \oplus D\left(E_0, \frac{1}{2}, 0\right)$

- Fermions of spin $J = 3/2$

  $D\left(E_0, 1, \frac{1}{2}\right) \oplus D\left(E_0, \frac{1}{2}, 1\right)$

- Spin J totally symmetric tensor with $J \geq 2$

  $D\left(E_0, \frac{J}{2}, \frac{J}{2}\right)$

- Spin J totally symmetric spinor-tensor with $J \geq 5/2$

  $D\left(E_0, \frac{J+1/2}{2}, \frac{J-1/2}{2}\right) \oplus D\left(E_0, \frac{J-1/2}{2}, \frac{J+1/2}{2}\right)$

Introduction

- Top-down approaches Low-energy approximation of string theory trying to find a gravitational background with features similar to QCD (e.g. Sakai-Sugimoto model)

- Bottom-up approaches More phenomenological use the features of QCD to construct 5d dual theory including gravity on AdS space

- Towards to QCD:
  – Break conformal invariance and generate mass gap
  – Tower of normalized bulk fields (Kaluza-Klein modes) $\leftrightarrow$ Hadron wave functions
  – Spectrum of Kaluza-Klein modes $\leftrightarrow$ Hadrons spectrum

- Hard-wall:
  AdS geometry is cutted by two branes UV $(z = \epsilon \to 0)$ and IR $(z = z_{\rm IR})$
  Analogue of quark bag model, linear dependence on $J(L)$ of hadron masses

- Soft-wall:
  Soft cuttoff of AdS space by dilaton field $e^{-\varphi(z)}$
  Analytical solution of EOM, Regge behavior of hadron masses $M^2 \sim J(L)$, correct power scaling of hadronic form factors at large Q^2

Introduction

- AdS metric Poincaré form

  $$ds^2 = g_{MN}(z)\, dx^M dx^N = \frac{R^2}{z^2}\left(dx_\mu dx^\mu - dz^2\right)$$ R – AdS radius

- Metric Tensor $g_{MN}(z) = \epsilon^a_M(z)\epsilon^b_N(z)\eta_{ab}$

- Vielbein $\epsilon^a_M(z) = \frac{R}{z}\,\delta^a_M$ (relates AdS and Lorentz metric)

- Manifestly scale-invariant $x \to \lambda x$, $z \to \lambda z$.

- z – extra dimensional (holographic) coordinate;
  $z = 0$ is UV boundary, $z = \infty$ is IR boundary

- Five Dimensions: L = Length, W = Width, H = Height, T = Time, S = Scale

Introduction

- Action for scalar field

$$S_\Phi = \frac{1}{2} \int d^dx dz \, \sqrt{g} \, e^{-\varphi(z)} \left(\partial_M \Phi(x,z) \partial^M \Phi(x,z) - m^2 \, \Phi^2(x,z) \right)$$

- Dilaton field $\varphi(z) = \kappa^2 z^2$
- $g = |\mathrm{det} g_{MN}|$
- m – 5d mass, $m^2 R^2 = \Delta(\Delta - 4)$, $\Delta = 3$ conformal dimension
- Kaluza-Klein (KK) expansion $\Phi(x,z) = \sum\limits_n \phi_n(x) \, \Phi_n(z)$
- Tower of KK modes $\phi_n(x)$ dual to 4-dimensional fields describing hadrons
- Bulk profiles $\Phi_n(z)$ dual to hadronic wave functions

Introduction

- Use $-\partial_\mu \partial^\mu \phi_n(x) = M_n^2 \phi_n(x)$
- Substitute $\Phi_n(z) = \left(\frac{R}{z}\right)^{1-d} \phi_n(z)$
- Identify $\Delta = \tau = N + L$ (here $N = 2$ – number of partons in meson)

  Hete τ is twist = Canonical dimension - Sum of spins

  Examples: mesons $\tau = 2 \times 3/2 - 2 \times 1/2 = 2$
  baryons $\tau = 3 \times 3/2 - 3 \times 1/2 = 3$

$$\left[- \frac{d^2}{dz^2} + \frac{4L^2 - 1}{4z^2} + \kappa^4 z^2 - 2\kappa^2 \right] \phi_n(z) = M_n^2 \phi_n(z)$$

- Solutions:
  $\phi_{nL}(z) = \phi_{n,\tau-2}(z) = \sqrt{\frac{2\Gamma(n+1)}{\Gamma(n+L+1)}} \, \kappa^{L+1} \, z^{L+1/2} \, e^{-\kappa^2 z^2/2} \, L_n^L(\kappa^2 z^2)$
- $M_{nL}^2 = 4\kappa^2 \left(n + \frac{L}{2}\right) = 4\kappa^2 \left(n + \frac{\tau}{2} - 1\right)$
- Massless pion $M_\pi^2 = 0$ for $n = L = 0$ Brodsky, Téramond

Introduction

- "Positive dilaton": Brodsky, Téramond

$$S_\Phi^+ = \frac{1}{2}\int d^d x dz\,\sqrt{g}\,e^{\varphi(z)}\left[\partial_M \Phi_+ \partial^M \Phi_+ - m^2\,\Phi_+^2\right]$$

- "Negative dilaton": Gutsche, Lyubovitskij, Schmidt, Vega PRD 85 (2012) 076003

$$S_\Phi^- = \frac{1}{2}\int d^d x dz\,\sqrt{g}\,e^{-\varphi(z)}\left[\partial_M \Phi_- \partial^M \Phi_- - (m^2 + U(z))\,\Phi_-^2\right]$$

Potential

$$U(z) = \frac{z^2}{R^2}\left(\varphi''(z) + \frac{1-d}{z}\varphi'(z)\right)$$

- "No-wall"

$$S_\Phi = \frac{1}{2}\int d^d x dz\sqrt{g}\left[\partial_M \Phi \partial^M \Phi - (m^2 + V(z))\Phi^2\right]$$

Potential

$$V(z) = \frac{z^2}{R^2}\left(\frac{1}{2}\varphi''(z) + \frac{1}{4}(\varphi'(z))^2 + \frac{1-d}{2z}\varphi'(z)\right)$$

- All 3 actions are equivalent upon field redefintion $\Phi_\pm = e^{\mp\varphi(z)}\Phi_\mp = e^{\mp\varphi(z)/2}\Phi$

Introduction

- Extension to AdS fermions (baryons)

$$S_\psi = \int d^d x dz \sqrt{g}\, \bar\Psi(x,z) \Big(\not{D} - \mu - \varphi(z)/R \Big) \Psi(x,z)$$

- Field decomposition (left/right) and KK expansion

$$\Psi(x,z) = \Psi_L(x,z) + \Psi_R(x,z) \quad \Psi_{L/R} = \frac{1 \mp \gamma^5}{2} \Psi$$

$$\Psi_{L/R}(x,z) = \sum_n \Psi^n_{L/R}(x)\, F^n_{L/R}(z)$$

- EOM

$$\left[-\partial_z^2 + \kappa^4 z^2 + 2\kappa^2 \Big(\mu R \mp \frac{1}{2} \Big) + \frac{\mu R (\mu R \pm 1)}{z^2} \right] F^n_{L/R}(z) = M_n^2\, F^n_{L/R}(z)$$

Solutions (for $d = 4$ and $\mu R = L + 3/2$)

- Bulk profiles

$$F^n_L(z) = \sqrt{\frac{2\Gamma(n+1)}{\Gamma(n+L+3)}}\, \kappa^{L+3}\, z^{L+9/2}\, e^{-\kappa^2 z^2/2}\, L_n^{L+2}(\kappa^2 z^2)$$

$$F^n_R(z) = \sqrt{\frac{2\Gamma(n+1)}{\Gamma(n+L+2)}}\, \kappa^{L+2}\, z^{L+7/2}\, e^{-\kappa^2 z^2/2}\, L_n^{L+1}(\kappa^2 z^2)$$

- Mass spectrum: $M^2_{nL} = 4\kappa^2 \Big(n + L + 2 \Big)$

Introduction

- Extension to higher-spin AdS boson (mesons)

  Vasilev, Buchbinder, Metzaev, Pashnev, ...

  Fields $\Phi \;\rightarrow\; \Phi_{M_1 M_2 \cdots M_J}$

  5d mass $m^2 R^2 \;\rightarrow\; m_J^2 R^2 = (\Delta - J)(\Delta + J - 4)$

  Dilaton potential

$$U_J(z) = \frac{z^2}{R^2}\left(\varphi''(z) + \frac{1 + 2J - d}{z}\varphi'(z)\right)$$

  Solutions

- $\phi_{nL}(z) = \sqrt{\frac{2\Gamma(n+1)}{\Gamma(n+L)}}\; \kappa^{L+1}\; z^{L+1/2}\; e^{-\kappa^2 z^2/2}\; L_n^L(\kappa^2 z^2)$

- $M_{nLJ}^2 = 4\kappa^2\left(n + \frac{L+J}{2}\right) \rightarrow 4\kappa^2\left(n + J\right)$ at large J

Introduction

- Scattering problem for AdS field gives information about propagation of external field from z to the boundary $z = 0$ — bulk-to-boundary propagator $\Phi_{\rm ext}(q,z)$ [Fourier-trasform of AdS field $\Phi_{\rm ext}(x,z)$]:
  $\Phi_{\rm ext}(q,z) = \int d^d x e^{-iqx}\, \Phi_{\rm ext}(x,z)$

- Vector field as example
  $$\partial_z \left(\frac{e^{-\varphi(z)}}{z} \partial_z V(q,z) \right) + q^2\, \frac{e^{-\varphi(z)}}{z} V(q,z) = 0\,.$$
  $$V(Q,z) \;=\; \Gamma\left(1 + \frac{Q^2}{4\kappa^2}\right) U\left(\frac{Q^2}{4\kappa^2}, 0, \kappa^2 z^2\right)$$
  Consistent with GI, fulfills UV and IR boundary conditions :
  $V(Q,0) = 1\,, \;\; V(Q,\infty) = 0$

- Hadron form factors

$$F_\tau(Q^2) = \langle \phi_\tau | \hat{V}(Q) | \phi_\tau \rangle = \int\limits_0^\infty dz\, \phi_\tau^2(z)\, V(Q,z) = \frac{\Gamma(\tau)\,\Gamma(a+1)}{\Gamma(a+\tau)}$$

is implemented by a nontrivial dependence of AdS fields on 5-th coordinate

Introduction

- Power scaling at large Q^2

$$F_\tau(Q^2) \sim \frac{1}{(Q^2)^{\tau-1}}$$

Quark counting rules: Matveev-Muradyan-Tavhelidze-Brodsky-Farrar 1973

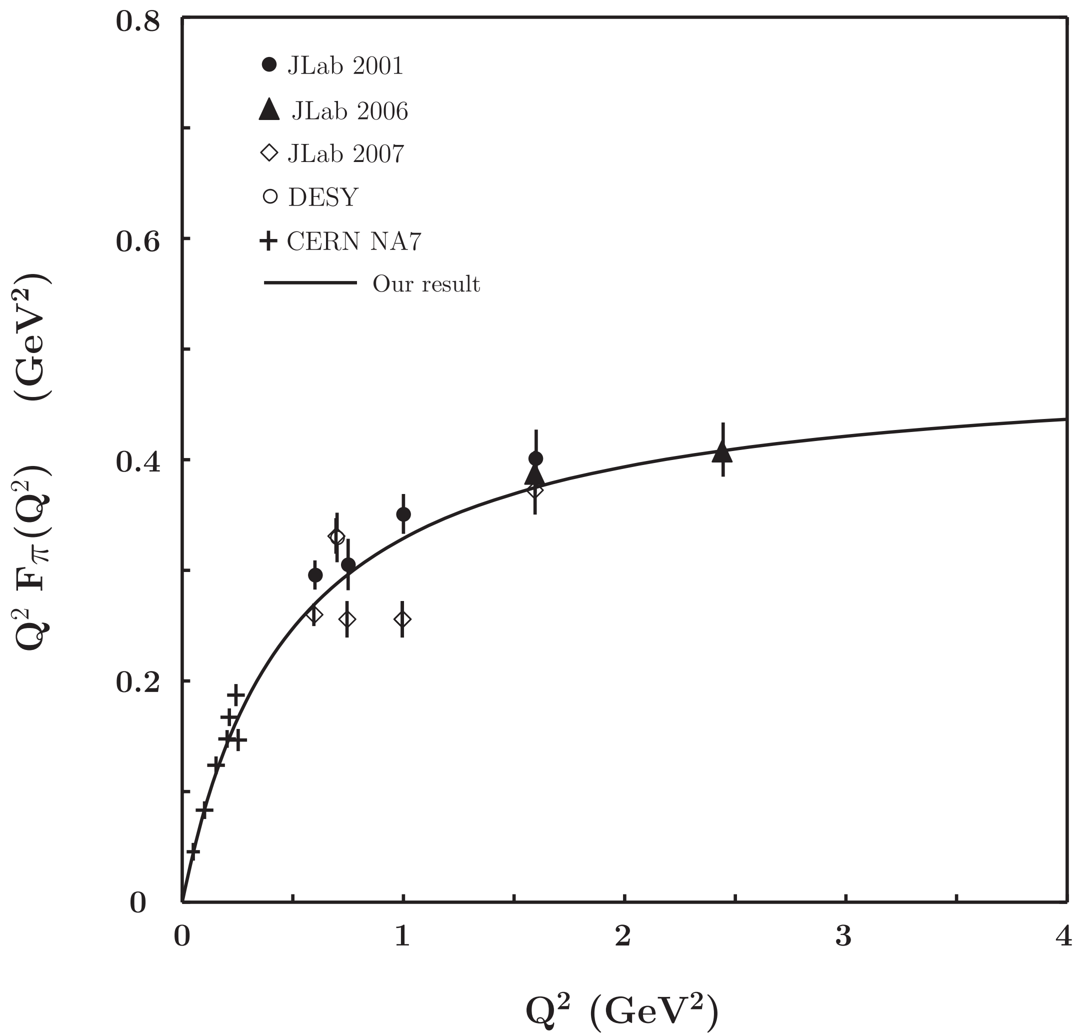
$$\mathrm{Pion}: \quad \frac{1}{Q^2}$$

$$\mathrm{Nucleon(Dirac)}: \quad \frac{1}{Q^4}$$

$$\mathrm{Nucleon(Pauli)}: \quad \frac{1}{Q^6}$$

$$\mathrm{Deuteron(Charge)}: \quad \frac{1}{Q^{10}}$$

Mesons: pion form factor



LFWFs motivated by holographic QCD

- Matching matrix elements (e.g. form factors) in HQCD and LF QCD

- Drell-Yan-West formula

$$F_\tau(Q^2) = \int_0^1 dx \int \frac{d^2\mathbf{k}_\perp}{16\pi^3} \, \psi_\tau^\dagger(x, \mathbf{k}'_\perp) \, \psi_\tau(x, \mathbf{k}_\perp) \,,$$

  where $\psi(x, \mathbf{k}_\perp) \equiv \psi(x, \mathbf{k}_\perp; \mu_0)$, $\mathbf{k}'_\perp = \mathbf{k}_\perp + (1-x)\mathbf{q}_\perp$, and $Q^2 = \mathbf{q}_\perp^2$

- HQCD

$$F_\tau(Q^2) = \int_0^\infty dz \, V(Q,z) \, \varphi_\tau^2(z) = \frac{\Gamma(\frac{Q^2}{4\kappa^2} + 1) \, \Gamma(\tau)}{\Gamma(\frac{Q^2}{4\kappa^2} + \tau)} \,.$$

- Result for effective LFWF at the initial scale μ_0

$$\psi_\tau(x, \mathbf{k}_\perp) = \sqrt{\tau - 1} \, \frac{4\pi}{\kappa} \, \sqrt{\log(1/x)} \, (1-x)^{\frac{\tau-4}{2}} \, \exp\left[- \frac{\mathbf{k}_\perp^2}{2\kappa^2} \, \frac{\log(1/x)}{(1-x)^2} \right]$$

Mesons: Light-Front Wave Function

- Mesonic WF longitudinal part and quark masses

  $\phi_{nJ}(z,x,m_1,m_2) = \phi_{nL}(z)\, f(x,m_1,m_2)$

- Modified meson mass formula

$$M^2_{nJ} = 4\kappa^2\Big(n + \frac{L+J}{2}\Big) + \int\limits_0^1 dx\Big(\frac{m_1^2}{x} + \frac{m_2^2}{1-x}\Big) f^2(x,m_1,m_2)$$

- Leptonic decay constants $P^- \to \ell^- \bar{\nu}_\ell$

$$f_M = \kappa\frac{\sqrt{6}}{\pi}\int\limits_0^1 dx\sqrt{x(1-x)}\, f(x,m_1,m_2)$$

- Find $f(x,m_1,m_2)$ to fulfill the following constraints

- In sector of light quarks (consistency with ChPT):

  Gell-Mann-Oakes-Renner (GMOR) $M_\pi^2 = 2\hat{m}\, B$
  Gell-Mann-Okubo (GMO) $4M_K^2 = M_\pi^2 + 3M_\eta^2$

Mesons: Light-Front Wave Function

- In sector of heavy quarks (consistency with HQET)
- Leptonic decay constants

$f_{Q\bar{q}} \sim 1/\sqrt{m_Q}$ heavy–light mesons

$f_{Q\bar{Q}} \sim \sqrt{m_Q}$ heavy quarkonia

$f_{c\bar{b}} \sim m_c/\sqrt{m_b}$ at $m_c \ll m_b$

- Mass spectrum

  Expansion

$$M_{Q\bar{q}} = m_Q + \bar{\Lambda} + \mathcal{O}(1/m_Q)$$

$$M_{Q\bar{Q}} = 2m_Q + E + \mathcal{O}(1/m_Q)$$

Splitting

$$M^V_{Q\bar{q}} - M^P_{Q\bar{q}} \sim \frac{1}{m_Q}$$

Light Mesons

- Following 't Hooft NPB 75 (1974) 461

$$f(x, m_1, m_2) = N\, x^{\alpha_1}\, (1-x)^{\alpha_2}$$

where N is the normalization constant

$$1 = \int_0^1 dx\, f^2(x, m_1, m_2)$$

α_1, α_2 are parameters fixed in order to get consistency with QCD.

- Light quark sector $\alpha_i = m_i/(2B)$

$$B = |\langle 0|\bar{u}u|0\rangle|/F_\pi^2$$

is the quark condensate parameter

- Leptonic decay constants in chiral limit

$$f_\pi = f_K = f_\rho = 3 f_\omega = \frac{3 f_\phi}{\sqrt{2}} = \kappa \frac{\sqrt{6}}{8}\,.$$

Heavy Mesons

- Heavy–light mesons $\alpha_Q = \alpha = \mathcal{O}(1)$

$$\alpha_q = \frac{2\alpha_Q}{m_Q}\left(1 + \frac{\bar{\Lambda}}{2m_Q}\right) - \frac{1}{2}\ .$$

Leds to

$$M_{Qq} = m_Q + \bar{\Lambda} + \mathcal{O}(1/m_Q)$$

$$M^2_{Q\bar{q}} = 4\kappa^2\left(n + \frac{L+J}{2}\right) + (m_Q + \bar{\Lambda})^2$$

$$f_{Q\bar{q}} = \frac{\kappa\sqrt{6}}{\pi}\,\frac{2\sqrt{\alpha}}{\alpha + \frac{3}{2}}\sqrt{\frac{\bar{\Lambda}}{m_Q}} \sim \sqrt{\frac{1}{m_Q}}$$

Heavy Mesons

- Heavy Quarkonia

$$\alpha_{Q_i} = \frac{m_{Q_i}}{4E}\left(1 - \frac{E}{2(m_{Q_1} + m_{Q_2})}\right) + \mathcal{O}\Big(\frac{1}{m_{Q_i}}\Big)$$

$$\kappa = \beta\left(\frac{\mu_{Q_1Q_2}}{E}\right)^{1/4}\left(\frac{m_{Q_1} + m_{Q_2}}{E}\right)^{1/2},$$

where $\beta = \mathcal{O}(1)$ and $\mu_{Q_1Q_2} = m_{Q_1}m_{Q_2}/(m_{Q_1} + m_{Q_2})$.

$$M^2_{Q_1\bar{Q}_2} = 4\kappa^2\left(n + \frac{L+J}{2}\right) + (m_{Q_1} + m_{Q_2} + E)^2$$

and

$$f_{Q\bar{Q}} \sim \sqrt{\frac{m_Q}{E}}\,.$$

Mesons Masses: choice of parameters

- Dilaton parameter $\kappa = 500$ MeV
- Current quark massses

$$m_{u/d} = 7 \text{ MeV}\,, \quad m_s = 24 m_{u/d} = 168 \text{ MeV}$$
$$m_c = 1.275 \text{ GeV}\,, \quad m_b = 4.18 \text{ GeV}$$

Mesons Masses: Results

Masses of light mesons

Meson	n	L	S	Mass [MeV]			
π	0,1,2,3	0	0	140	1010	1421	1738
K	0	0,1,2,3	0	495	1116	1498	1801
η	0,1,2,3	0	0	566	11494	1523	1822
$f_0[\bar{n}n]$	0,1,2,3	1	1	721	1233	1587	1876
$f_0[\bar{s}s]$	0,1,2,3	1	1	985	1404	1723	1993
$\rho(770)$	0,1,2,3	0	1	721	1233	1587	1876
$\omega(782)$	0,1,2,3	0	1	721	1233	1587	1876
$\phi(1020)$	0,1,2,3	0	1	985	1404	1723	1993
$a_1(1260)$	0,1,2,3	1	1	1010	1421	1738	2005

Mesons Masses: Results

Masses of heavy-light mesons and heavy quarkonia

Meson	J^P	n	L	S	Mass [MeV]			
$D(1870)$	0^-	0	0,1,2,3	0	1870	2000	2121	2235
$D^*(2010)$	1^-	0	0,1,2,3	1	2000	2121	2235	2345
$D_s(1969)$	0^-	0	0,1,2,3	0	1970	2093	2209	2320
$D_s^*(2107)$	1^-	0	0,1,2,3	1	2093	2209	2320	2425
$B(5279)$	0^-	0	0,1,2,3	0	5280	5327	5374	5420
$B^*(5325)$	1^-	0	0,1,2,3	1	5336	5374	5420	5466
$B_s(5366)$	0^-	0	0,1,2,3	0	5370	5416	5462	5508
$B_s^*(5413)$	1^-	0	0,1,2,3	1	5416	5462	5508	5553

Mesons Masses: Results

Masses of heavy quarkonia

Meson	J^{P}	n	L	S	Mass [MeV]			
$\eta_c(2980)$	0^-	0,1,2,3	0	0	2975	3477	3729	3938
$\psi(3097)$	1^-	0,1,2,3	0	1	3097	3583	3828	4032
$\chi_{c0}(3415)$	0^+	0,1,2,3	1	1	3369	3628	3843	4038
$\chi_{c1}(3510)$	1^+	0,1,2,3	1	1	3477	3729	3938	4129
$\chi_{c2}(3555)$	2^+	0,1,2,3	1	1	3583	3828	4032	4219
$\eta_b(9390)$	0^-	0,1,2,3	0	0	9337	9931	10224	10471
$\Upsilon(9460)$	1^-	0,1,2,3	0	1	9460	10048	10338	10581
$\chi_{b0}(9860)$	0^+	0,1,2,3	1	1	9813	10110	10359	10591
$\chi_{b1}(9893)$	1^+	0,1,2,3	1	1	9931	10224	10471	10700
$\chi_{b2}(9912)$	2^+	0,1,2,3	1	1	10048	10338	10581	10808
$B_c(6277)$	0^-	0,1,2,3	0	0	6277	6719	6892	7025

Electromagnetic stucture of nucleons

Sachs Nucleon Form Factors in terms of Dirac and Pauli FF

$$
\begin{aligned}
G_E^N(Q^2) &= F_1^N(Q^2) - \frac{Q^2}{4m_N^2} F_2^N(Q^2)\,, \\
G_M^N(Q^2) &= F_1^N(Q^2) + F_2^N(Q^2)\,, \\
\langle r_E^2 \rangle^N &= -6\, \frac{dG_E^N(Q^2)}{dQ^2}\Big|_{Q^2=0}\,, \\
\langle r_M^2 \rangle^N &= -\frac{6}{G_M^N(0)}\, \frac{dG_M^N(Q^2)}{dQ^2}\Big|_{Q^2=0}\,,
\end{aligned}
$$

where $G_M^N(0) \equiv \mu_N$ is the nucleon magnetic moment.
Decomposition of Dirac and Pauli FF in terms quark flavor form factors describing distribution of u and d in nucleons

$$
F_i^{p(n)}(Q^2) = \frac{2}{3} F_i^{u(d)}(Q^2) - \frac{1}{3} F_i^{d(u)}(Q^2)\,, \quad i = 1, 2\,.
$$

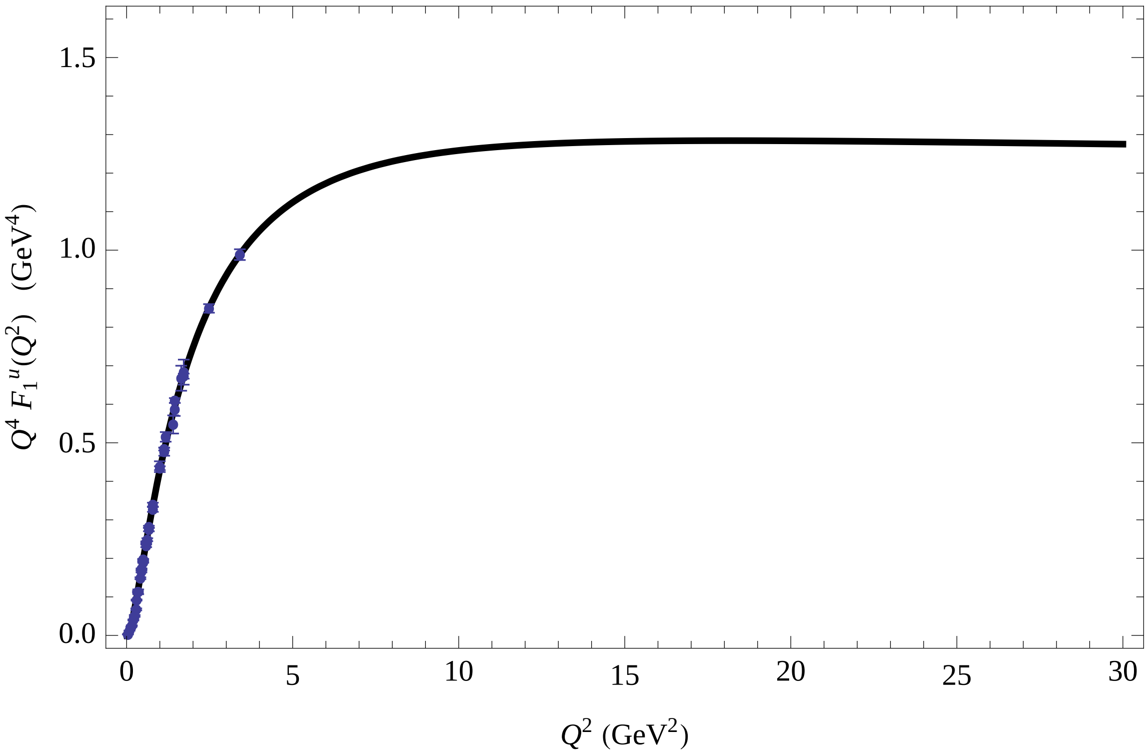
Electromagnetic stucture of nucleons

Mass and electromagnetic properties of nucleons

Quantity	Our results	Data
m_p (GeV)	0.93827	0.93827
μ_p (in n.m.)	2.793	2.793
μ_n (in n.m.)	-1.913	-1.913
r_E^p (fm)	0.840	0.8768 ± 0.0069
$\langle r_E^2 \rangle^n$ (fm^2)	-0.117	-0.1161 ± 0.0022
r_M^p (fm)	0.785	$0.777 \pm 0.013 \pm 0.010$
r_M^n (fm)	0.792	$0.862^{+0.009}_{-0.008}$
r_A (fm)	0.667	0.67 ± 0.01

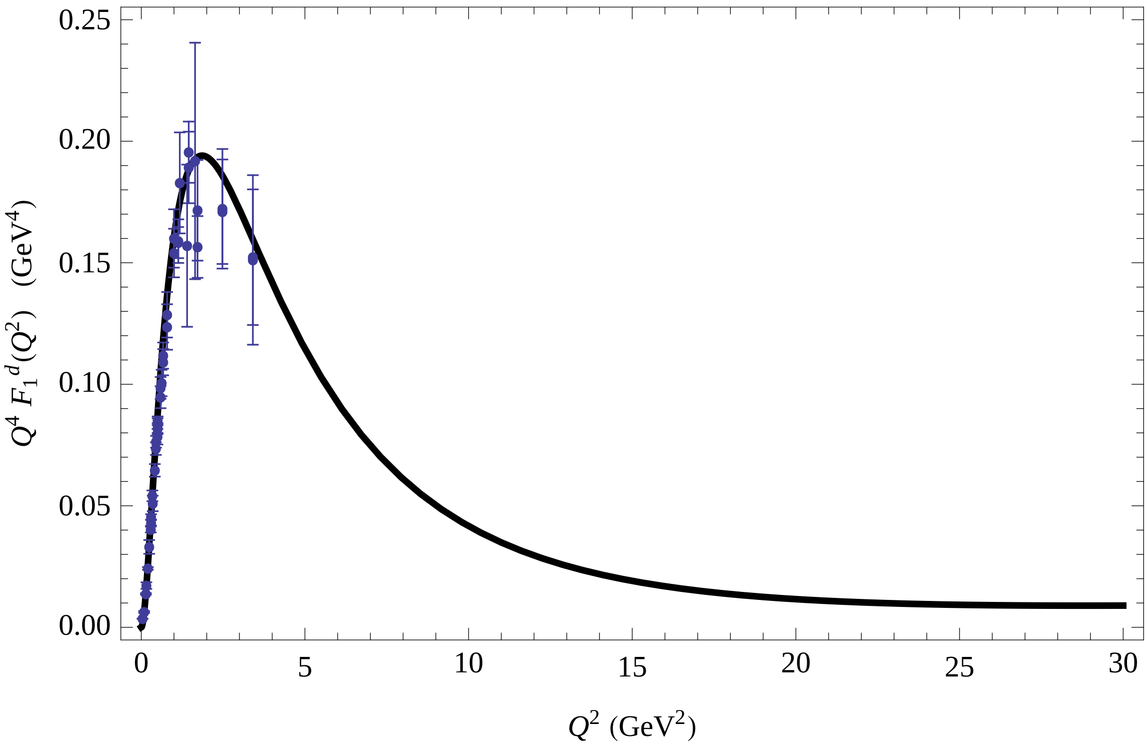
Electromagnetic stucture of nucleons and Roper (1440)

Plot $Q^4 F_1^u(Q^2)$



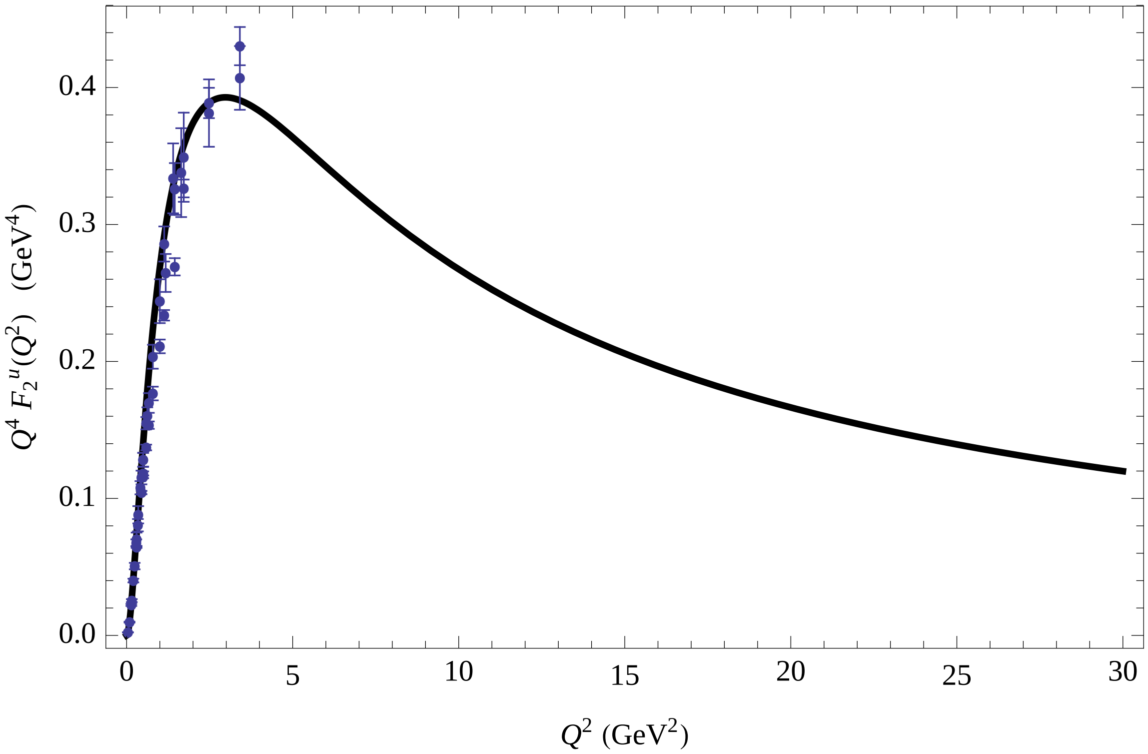
Electromagnetic stucture of nucleons and Roper (1440)

Plot $Q^4 F_1^d(Q^2)$



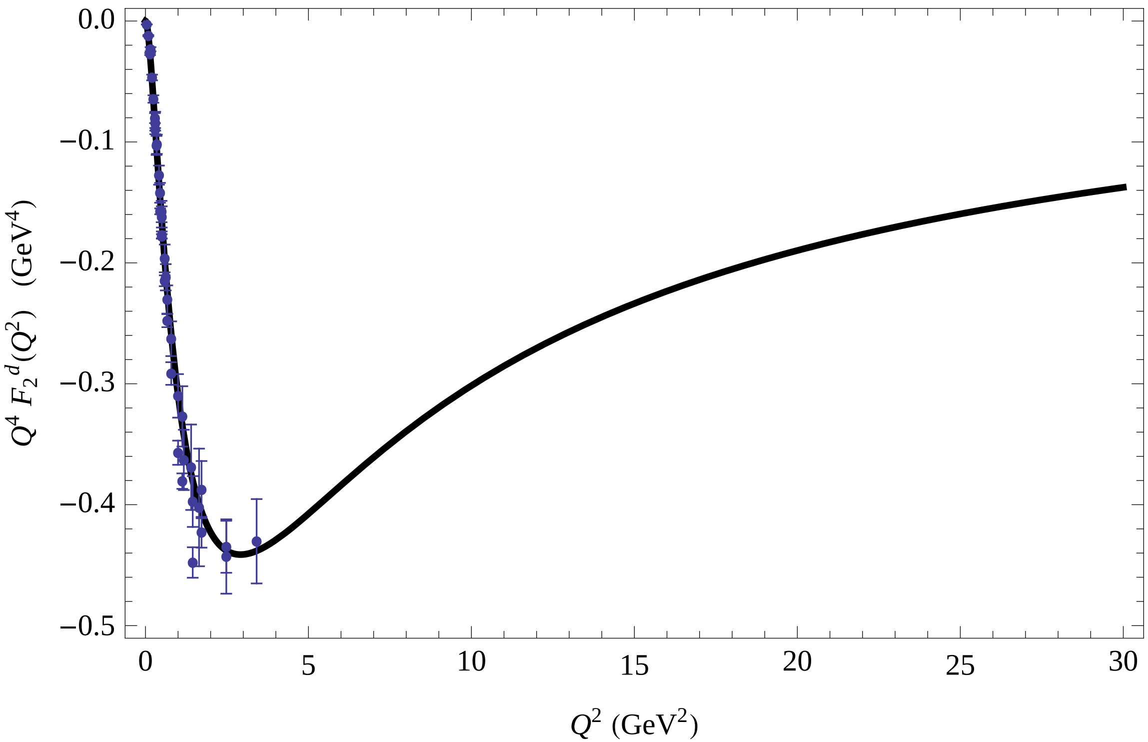
Electromagnetic stucture of nucleons and Roper (1440)

Plot $Q^4 F_2^u(Q^2)$



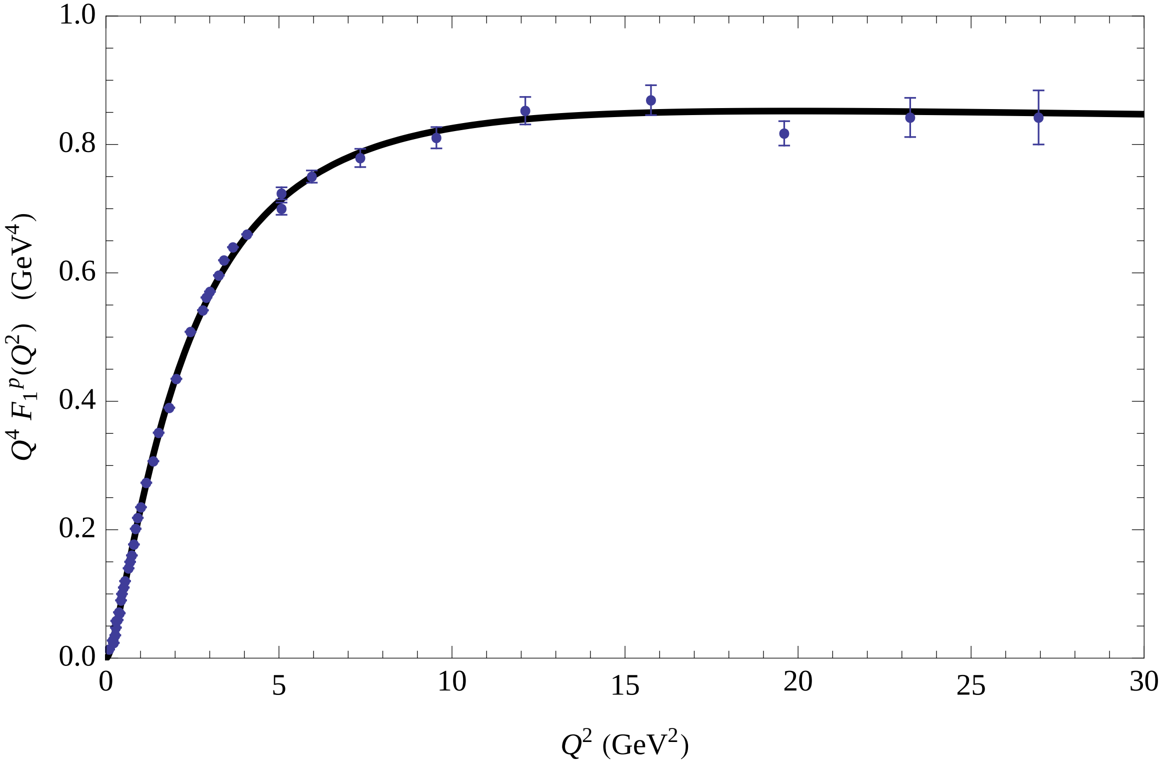
Electromagnetic stucture of nucleons and Roper (1440)

Plot $Q^4 F_2^d(Q^2)$

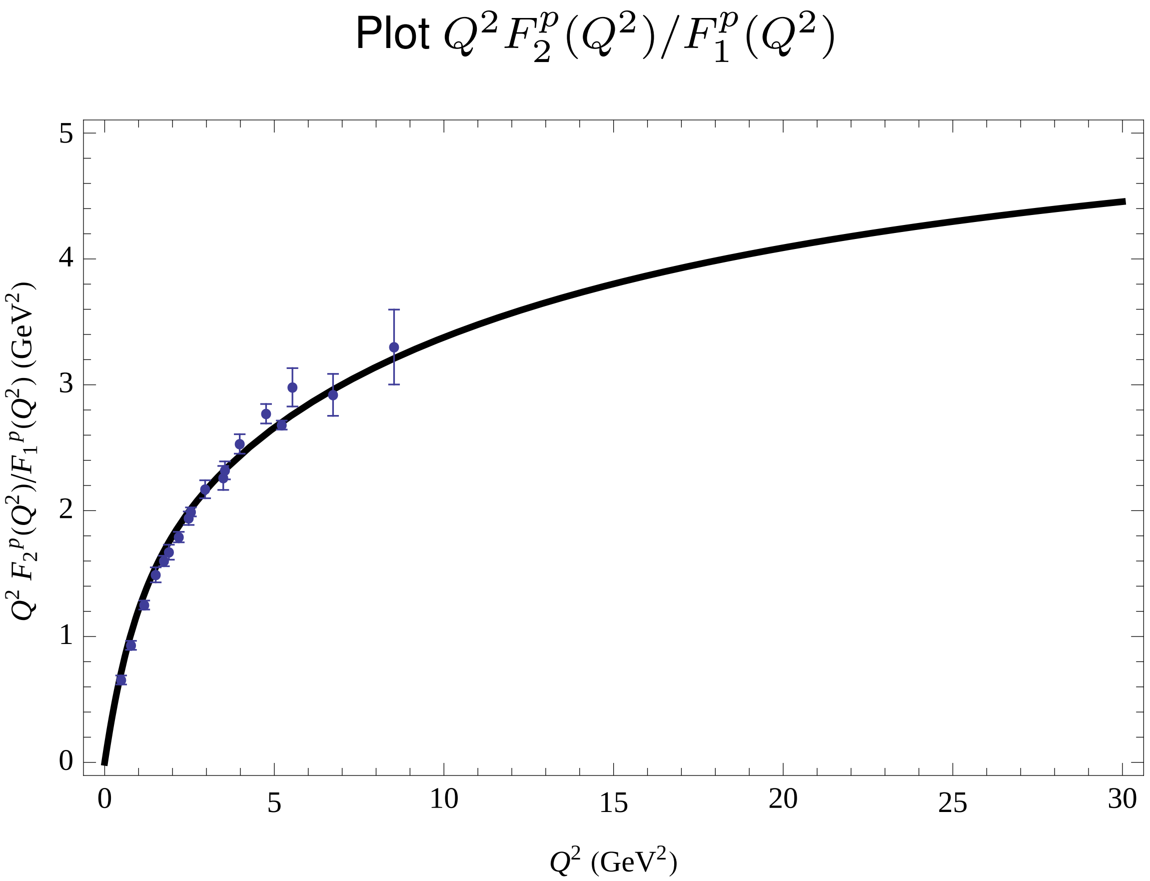


Electromagnetic stucture of nucleons and Roper (1440)

Plot $Q^4 F_1^p(Q^2)$

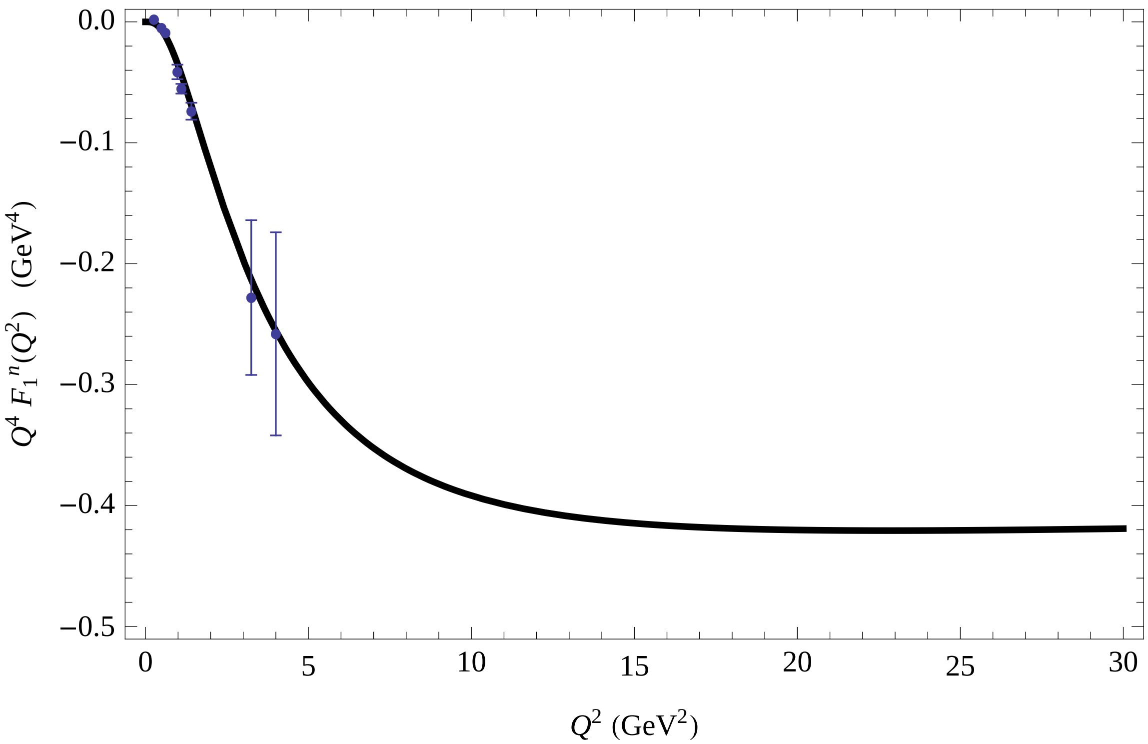


Electromagnetic stucture of nucleons and Roper (1440)



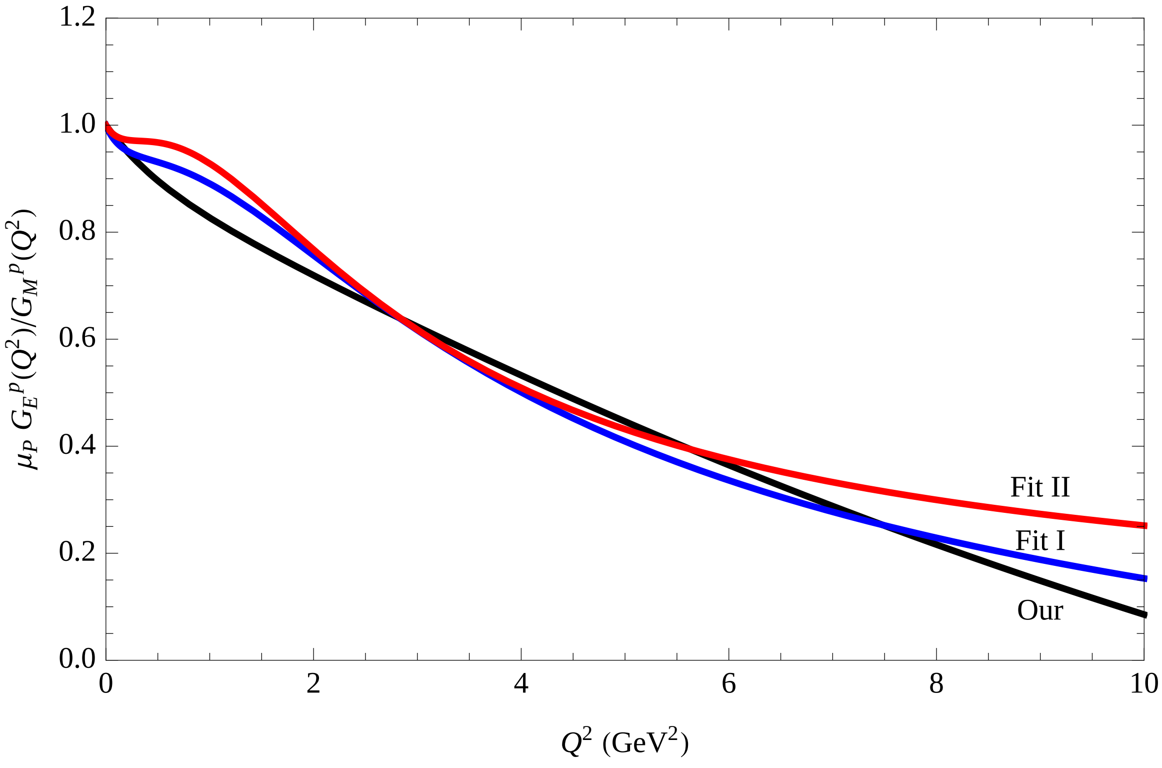
Electromagnetic stucture of nucleons and Roper (1440)

Plot $Q^4 F_1^n(Q^2)$



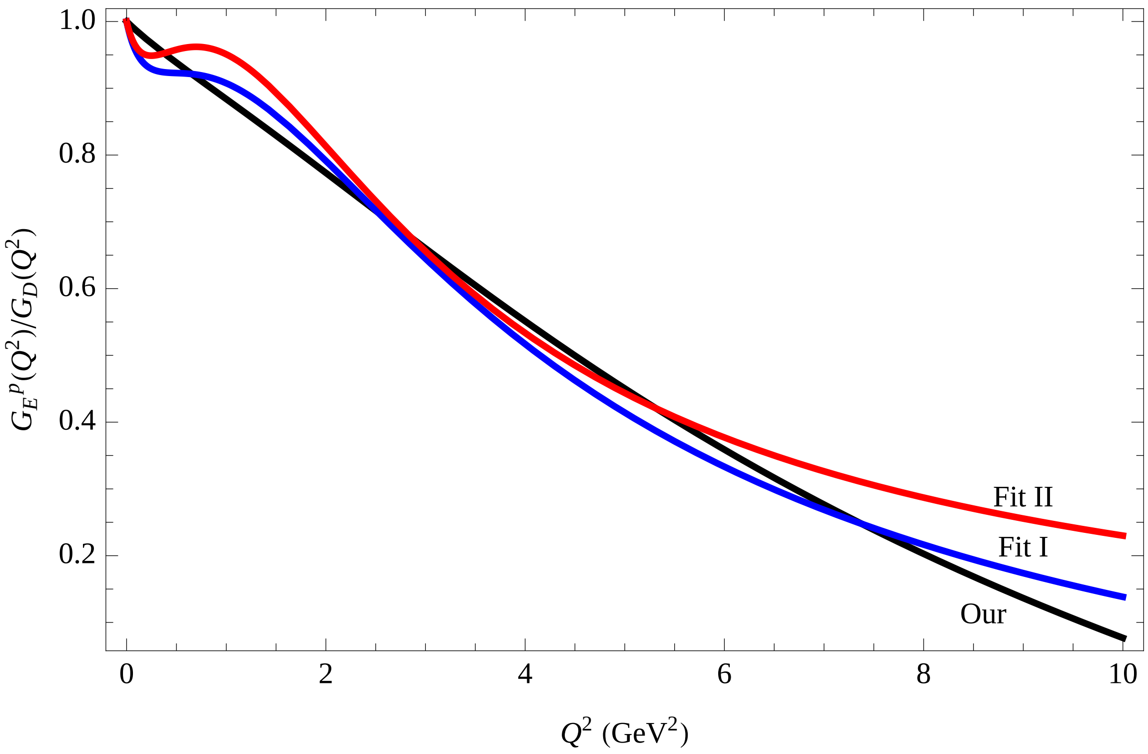
Electromagnetic stucture of nucleons and Roper (1440)

Plot $\mu G_E^p(Q^2)/G_M^p(Q^2)$



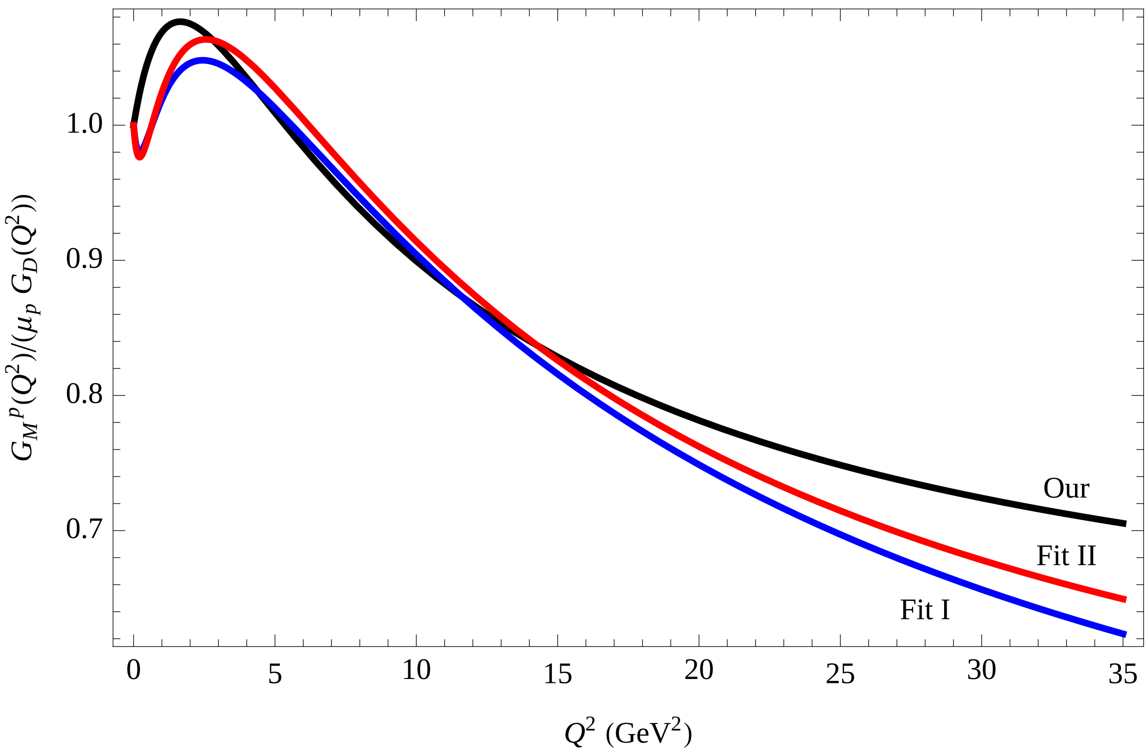
Electromagnetic stucture of nucleons and Roper (1440)

Plot $G_E^p(Q^2)/G_D(Q^2)$, where $G_D(Q^2) = 1/(1+Q^2/\Lambda^2)^2$, $\Lambda = 0.84$ GeV.

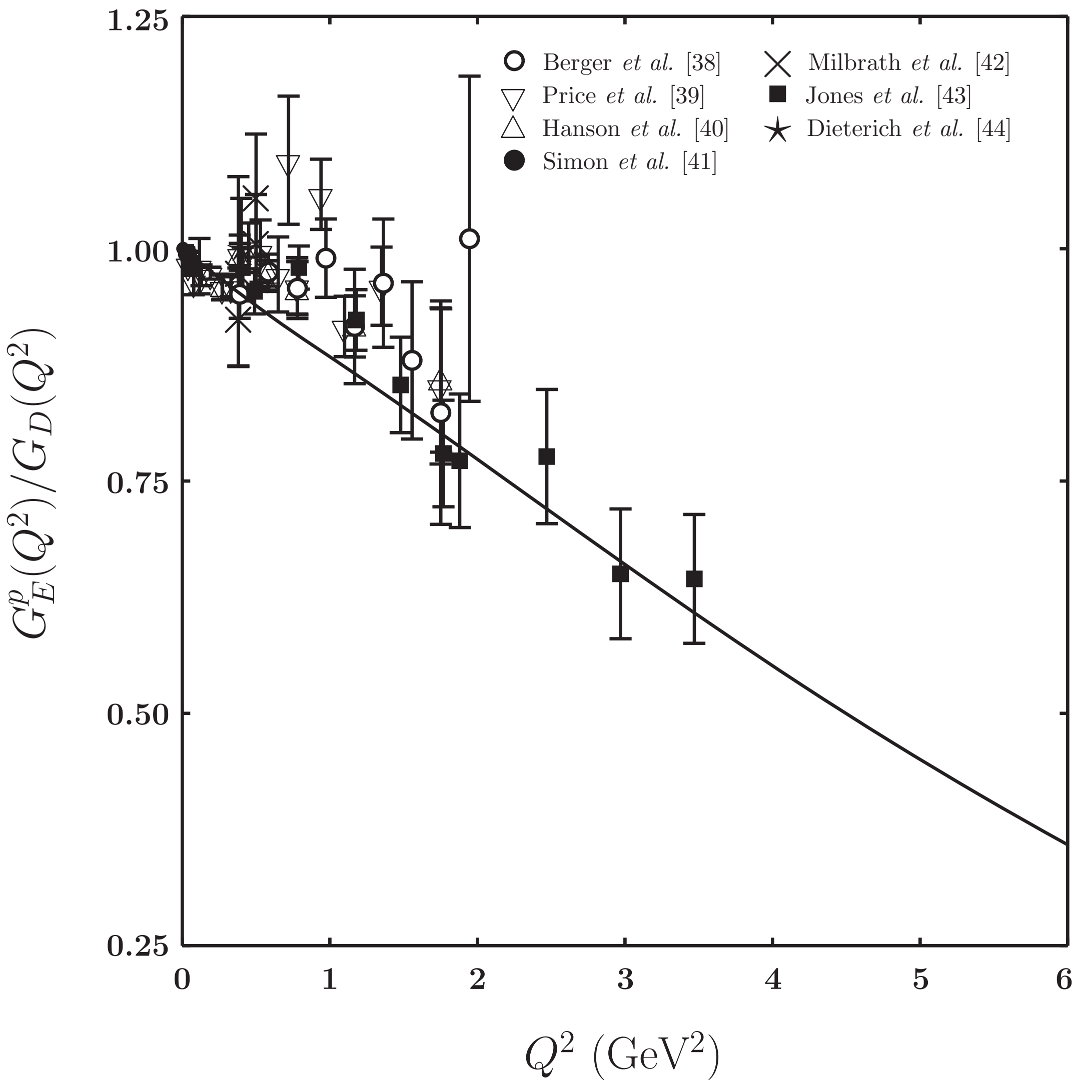


Electromagnetic stucture of nucleons and Roper (1440)

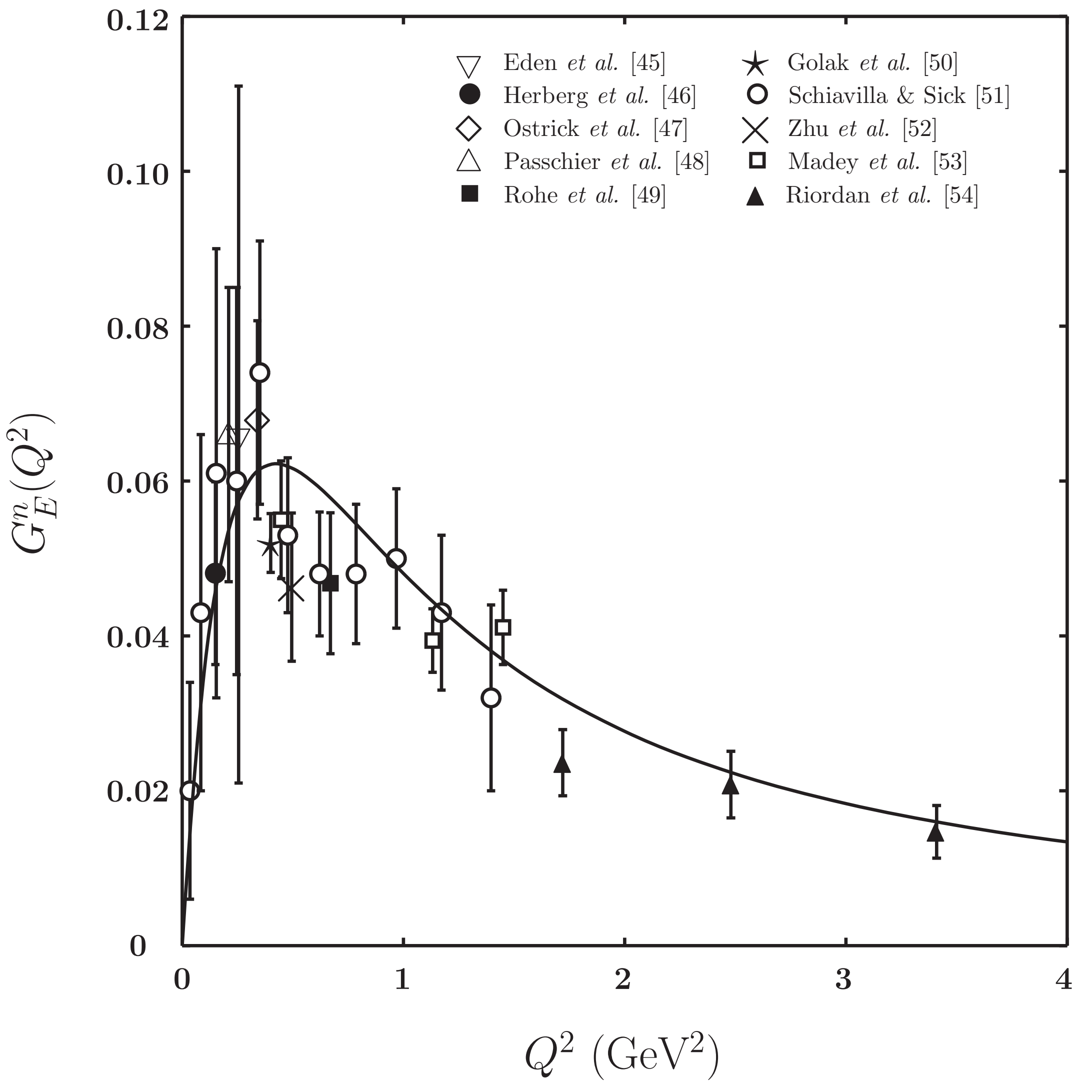
Plot $G_M^p(Q^2)/G_D(Q^2)$, where $G_D(Q^2) = 1/(1 + Q^2/\Lambda^2)^2$, $\Lambda = 0.84$ GeV.



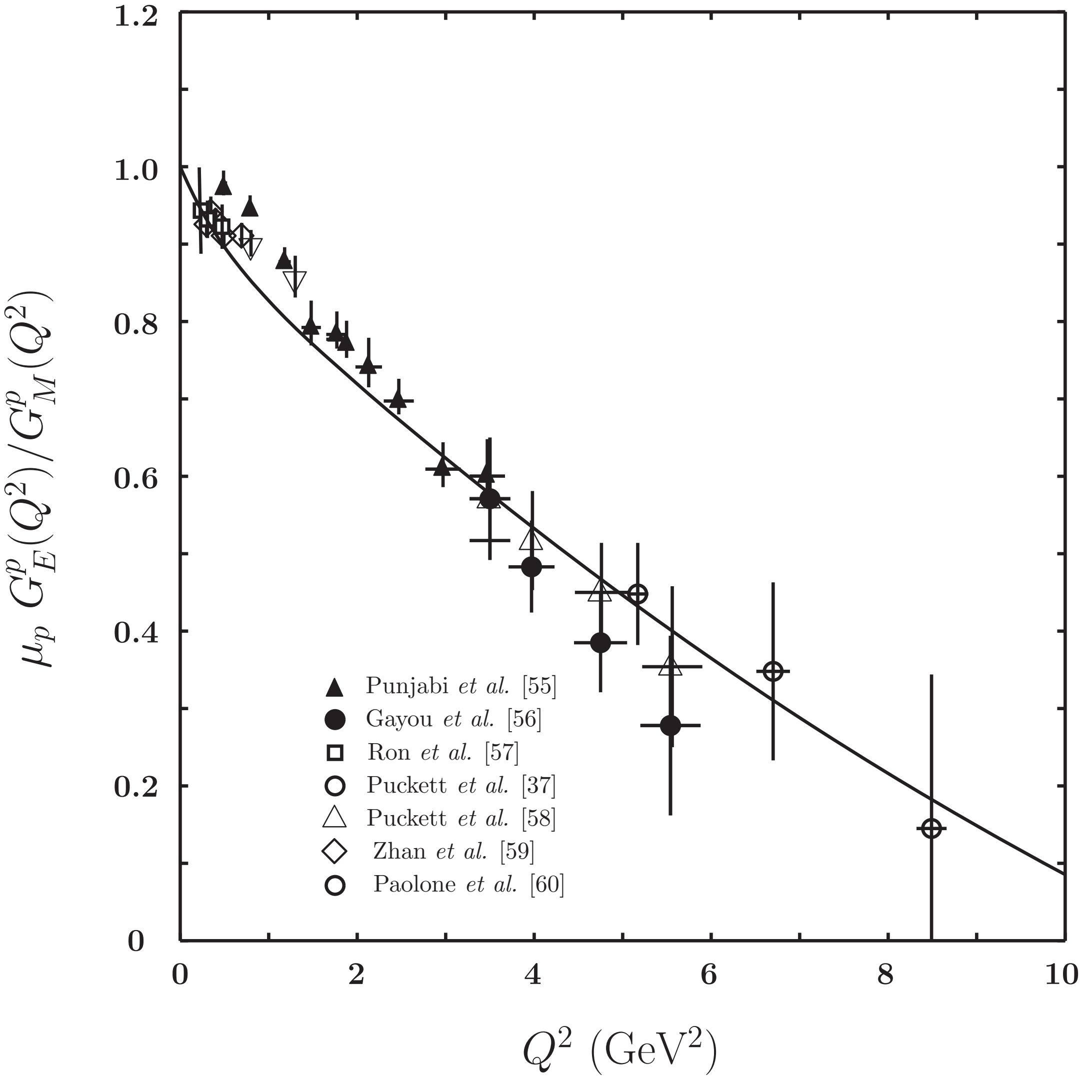
Electromagnetic stucture of nucleons and Roper (1440)



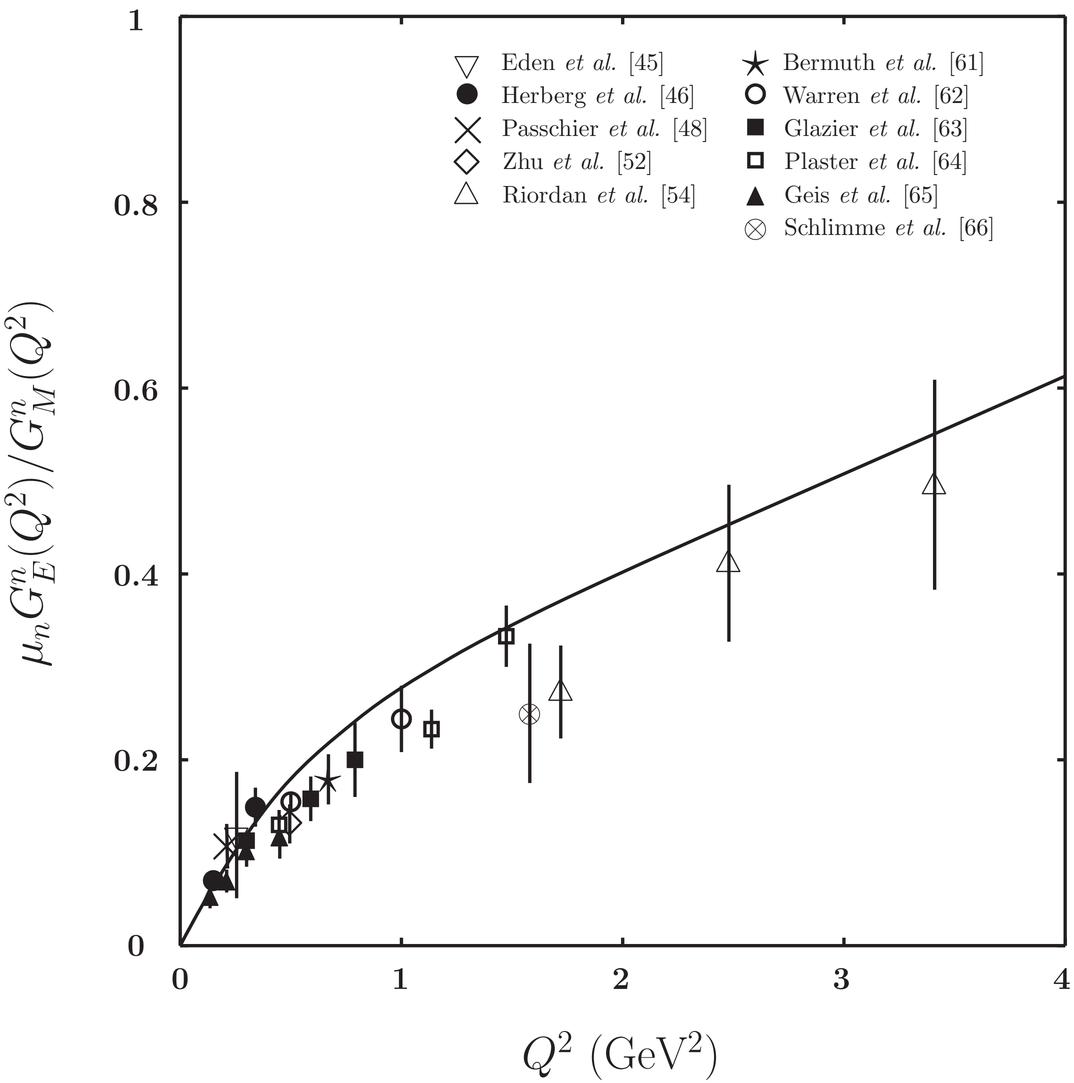
Electromagnetic stucture of nucleons and Roper (1440)



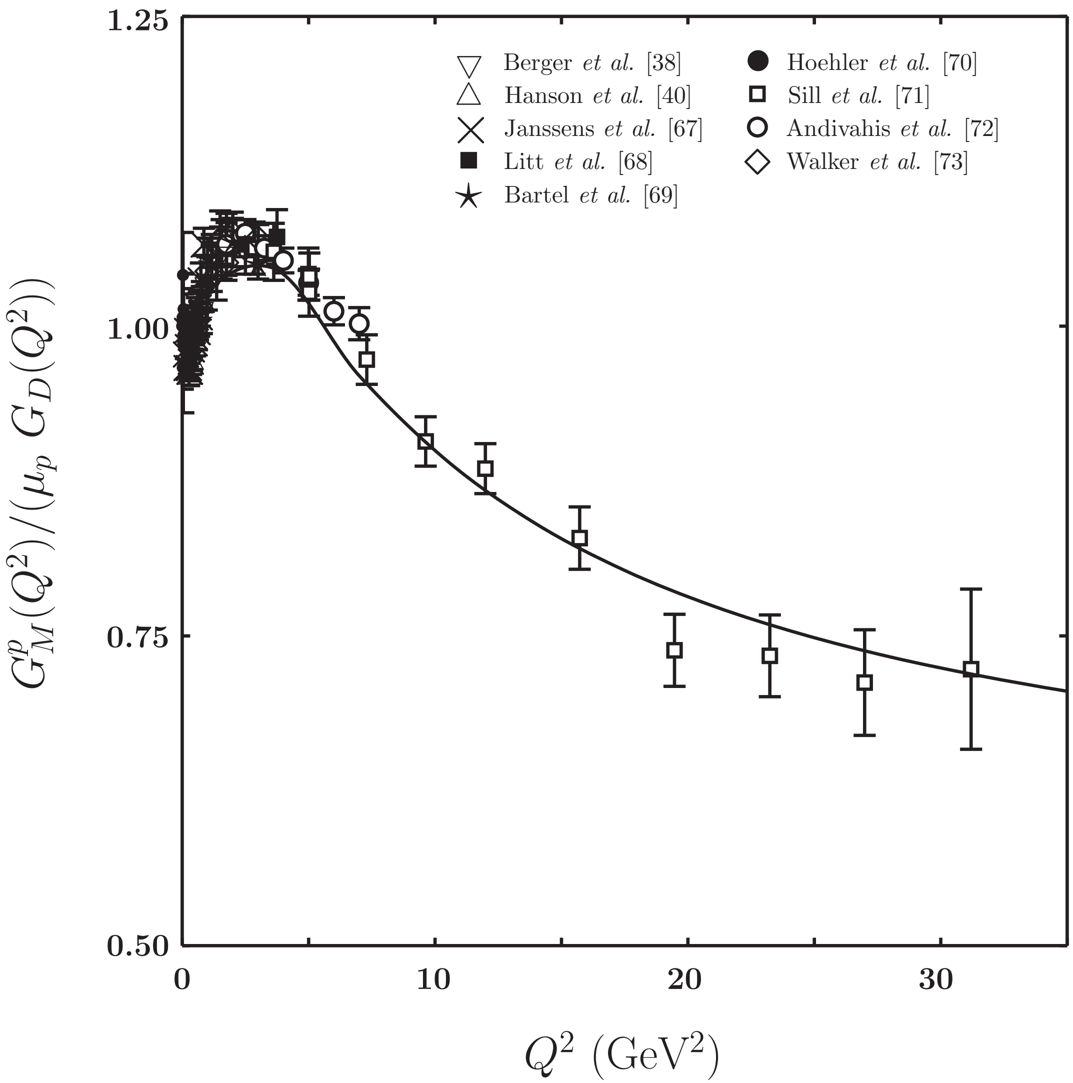
Electromagnetic stucture of nucleons and Roper (1440)



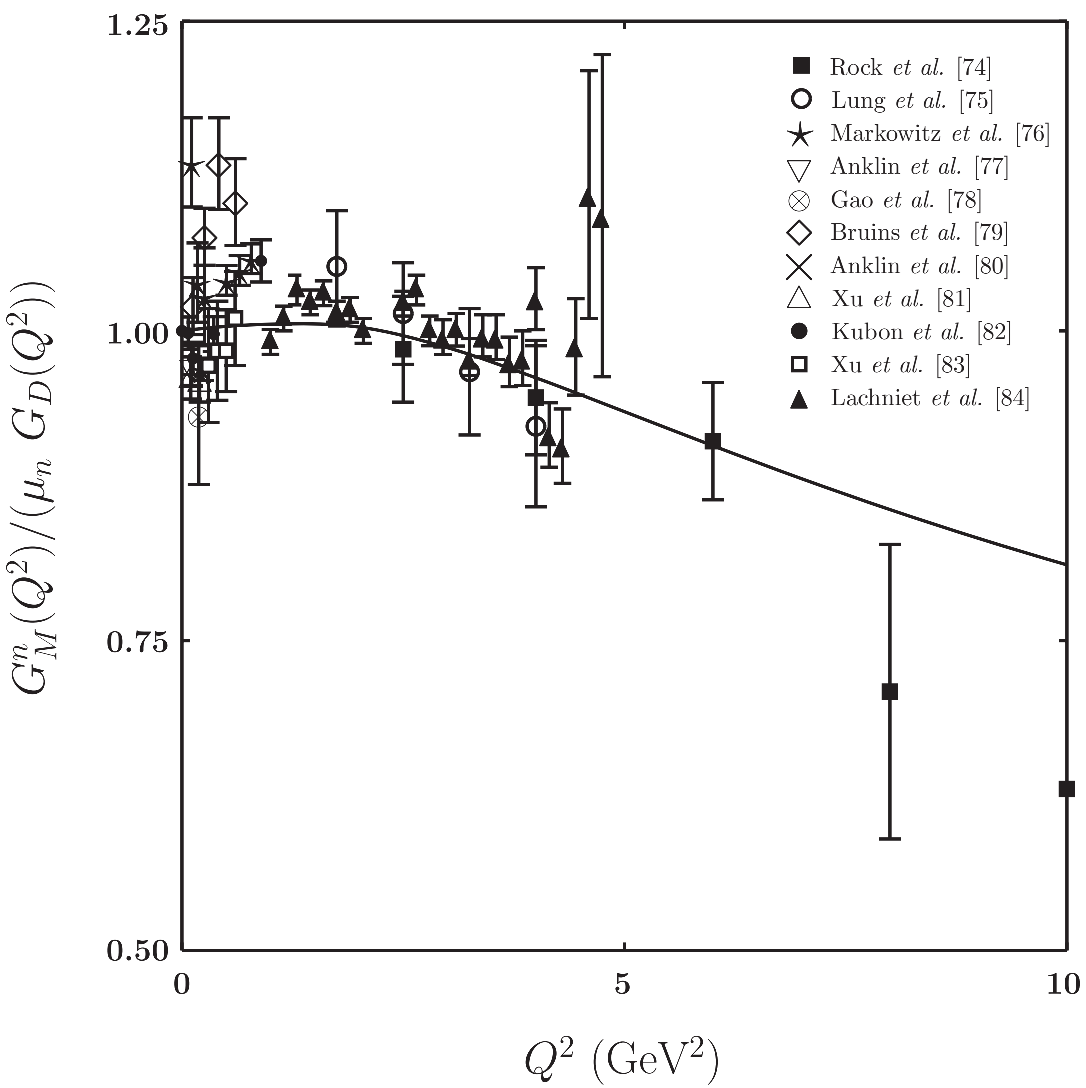
Electromagnetic stucture of nucleons and Roper (1440)



Electromagnetic stucture of nucleons and Roper (1440)



Electromagnetic stucture of nucleons and Roper (1440)



Electromagnetic stucture of nucleons and Roper (1440)

- Put $n = 1$ and get solutions dual to Roper:
- $N \to R + \gamma$ transition

$$M^\mu = \bar{u}_{\mathcal{R}} \left[\gamma_\perp^\mu \, F_1(q^2) \, + \, i\sigma^{\mu\nu} \frac{q_\nu}{M_{\mathcal{R}}} \, F_2(q^2) \right] u_N \, , \quad \gamma_\perp^\mu = \gamma^\mu - q^\mu \frac{\not{q}}{q^2}$$

- Helicity amplitudes

$$H_{\pm\frac{1}{2}0} = \sqrt{\frac{Q_-}{Q^2}} \left(F_1 M_+ - F_2 \frac{Q^2}{M_{\mathcal{R}}} \right)$$

$$H_{\pm\frac{1}{2}\pm 1} = -\sqrt{2Q_-} \left(F_1 + F_2 \frac{M_+}{M_{\mathcal{R}}} \right)$$

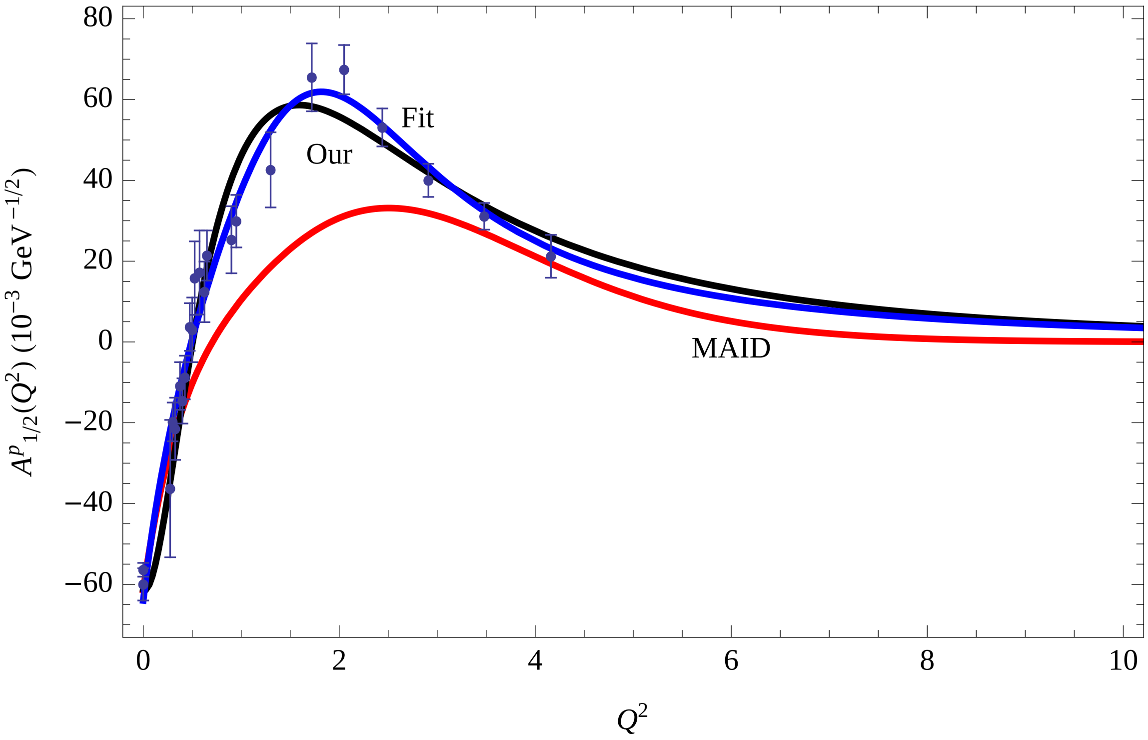
- Alternative set

$$A_{1/2} = -b \, H_{\frac{1}{2}1} \, , \quad S_{1/2} = b \, \frac{|\mathbf{p}|}{\sqrt{Q^2}} \, H_{\frac{1}{2}0} \, ,$$

$$Q_\pm = M_\pm^2 + Q^2 \, , \quad M_\pm = M_{\mathcal{R}} \pm M_N \, , \quad b = \sqrt{\frac{\pi\alpha}{2EM_{\mathcal{R}}M_N}}$$

Electromagnetic stucture of nucleons and Roper (1440)

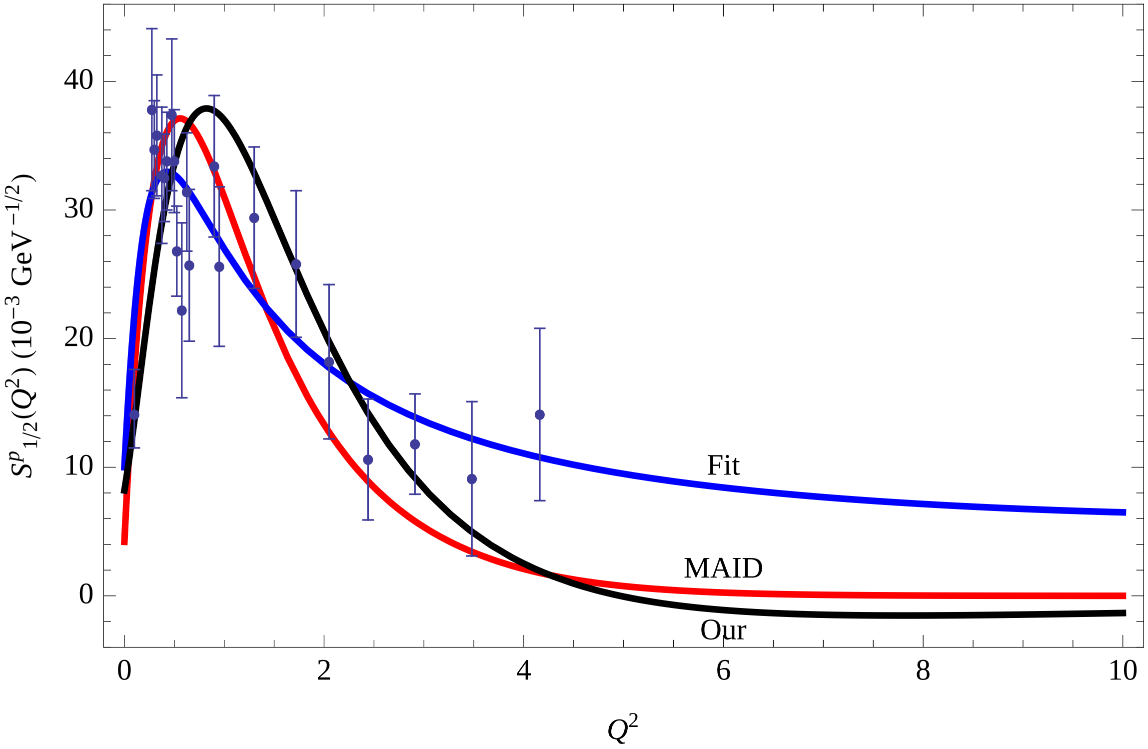
Helicity amplitude $A^p_{1/2}(Q^2)$



Data: CLAS Coll at JLab, Mokeev et al, PRC86 (2012) 035203

Electromagnetic stucture of nucleons and Roper (1440)

Helicity amplitude $S^p_{1/2}(Q^2)$



Data: CLAS Coll at JLab, Mokeev et al, PRC86 (2012) 035203

Nonperturbative hadron properties: GPDs/PDFs

Hadronic form factor is given by

$$F_\tau(Q^2) = \int_0^\infty dz\, \varphi_\tau^2(z)\, V(Q^2, z^2) = \int_0^1 dx\, \mathcal{H}_\tau(x, Q^2)\,,$$

$$\mathcal{H}_\tau(x, Q^2) = q_\tau(x)\, f_\tau(x, Q^2)$$

Here

$$f_\tau(x, Q^2) = \frac{1}{(\tau+1)\,\Gamma(\tau-1)} \int_0^\infty dt t^{\tau-2}\, e^{-t}(2+t)\, V(Q^2, t(1-x))$$

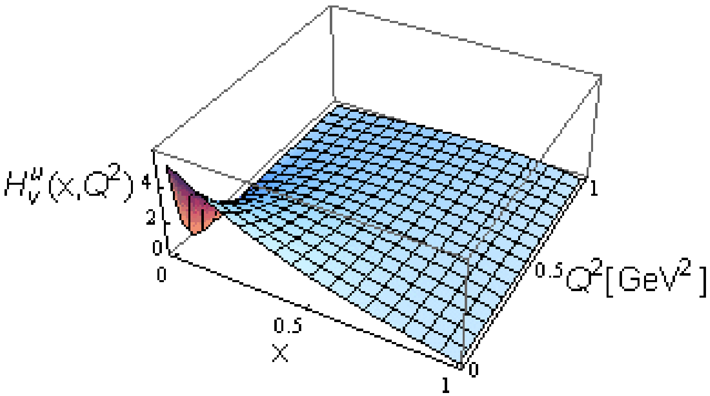
$$V(Q^2, t(1-x)) \to V(Q^2, 0) \equiv 1$$

as required by model-independent result and $f_\tau(x, Q^2) \to 1$

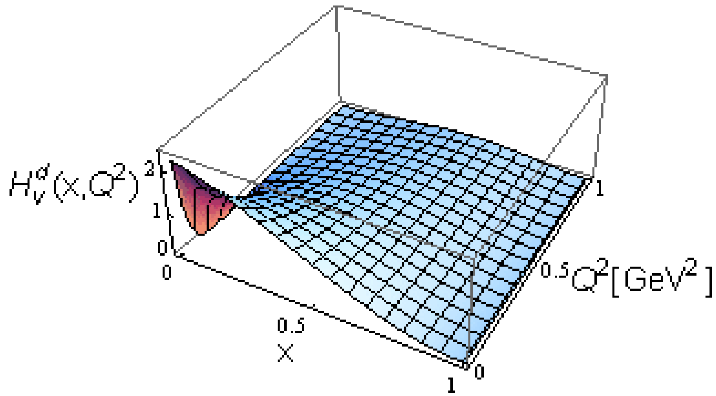
The GPD $H_\tau(x, Q^2)$ and PDF $q_\tau(x)$ have correct behavior at $x \to 1$

$$H_\tau(x, Q^2) \sim q_\tau(x) \sim (1-x)^\tau$$

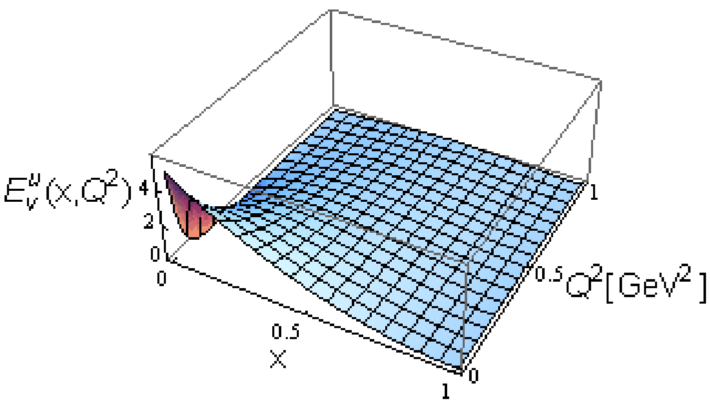
Nucleon GPDs



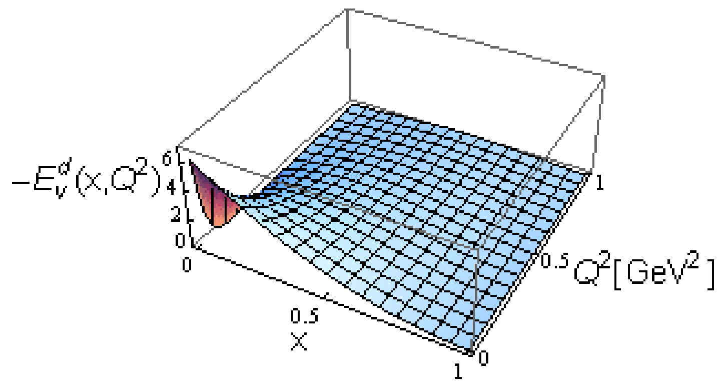
$H_v^u(x, Q^2)$



$H_v^d(x, Q^2)$

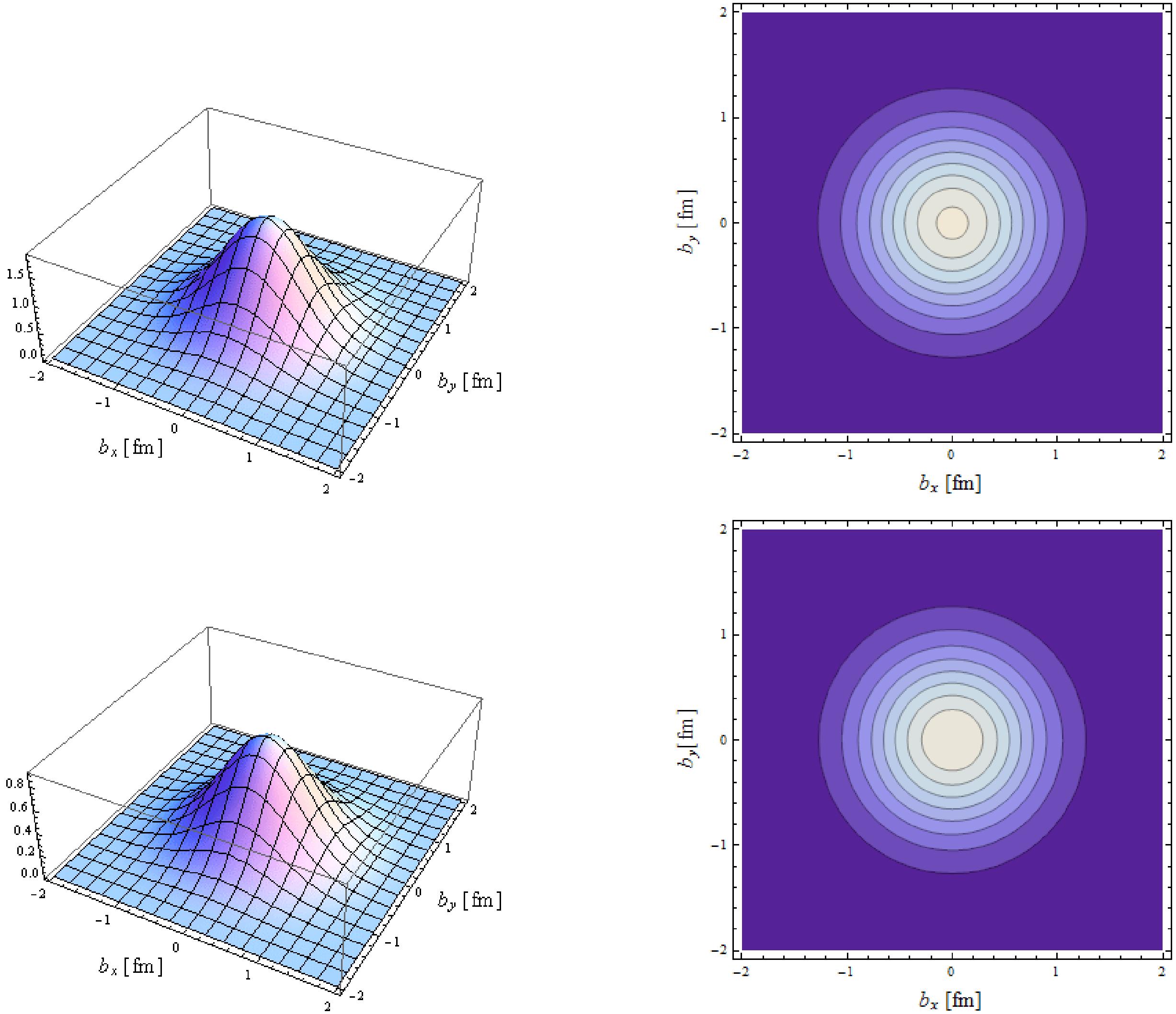


$E_v^u(x, Q^2)$



$E_v^d(x, Q^2)$

Nucleon PDFs



Plots for $q(x, \mathbf{b}_\perp)$ for $x = 0.1$: $u(x, \mathbf{b}_\perp)$ - upper pannels, $d(x, \mathbf{b}_\perp)$ - lower pannels

Deuteron

- Effective action in terms of AdS fields $d^M(x,z)$ and $V^M(x,z)$
- $d^M(x,z)$ – dual to Fock component contributing to deuteron with twist $\tau = 6$
- $V^M(x,z)$ – dual to the electromagnetic field

$$\begin{aligned} S &= \int d^4x dz \, e^{-\varphi(z)} \Big[-\frac{1}{4} F_{MN}(x,z) F^{MN}(x,z) - D^M d_N^\dagger(x,z) D_M d^N(x,z) \\ &- i c_2(z) F^{MN}(x,z) d_M^\dagger(x,z) d_N(x,z) \\ &+ \frac{c_3(z)}{4M_d^2} \partial^M F^{NK}(x,z) \Big(-d_M^\dagger(x,z) \overleftrightarrow{D}_K \, d_N(x,z) + \mathrm{H.c.} \Big) \\ &+ d_M^\dagger(x,z) \Big(\mu^2 + U(z) \Big) d^M(x,z) \Big] \end{aligned}$$

Deuteron

- Three EM form factors $G_{1,2,3}$ of the deuteron are related to the charge G_C, quadrupole G_Q and magnetic G_M form factors by
- Expressions for the form factors

$$G_C = G_1 + \frac{2}{3}\tau_d G_Q\,, \quad G_M \;=\; G_2\,, \quad G_Q = G_1 - G_2 + (1+\tau_d)G_3, \quad \tau_d = \frac{Q^2}{4M_d^2}$$

These form factors are normalized at zero recoil as

$$G_C(0) = 1\,, \quad G_Q(0) = M_d^2 \mathcal{Q}_d = 25.83\,, \quad G_M(0) = \frac{M_d}{M_N}\mu_d = 1.714$$

- $\mathcal{Q}_d = 7.3424$ GeV^{-2} and $\mu_d = 0.8574$ – quadrupole and magnetic moments of the deuteron.

Deuteron

- Differential cross section for the elastic e-D scattering (Rosenbluth formula)
$d\sigma/d\Omega \sim \left[A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2}\right]$
- Structure functions

$$\begin{aligned} A(Q^2) &= G_C^2(Q^2) + \frac{2}{3}\tau_d G_M^2(Q^2) + \frac{8}{9}\tau_d^2 G_Q^2(Q^2)\,, \\ B(Q^2) &= \frac{4}{3}\tau_d(1+\tau_d)G_M^2(Q^2)\,. \end{aligned}$$

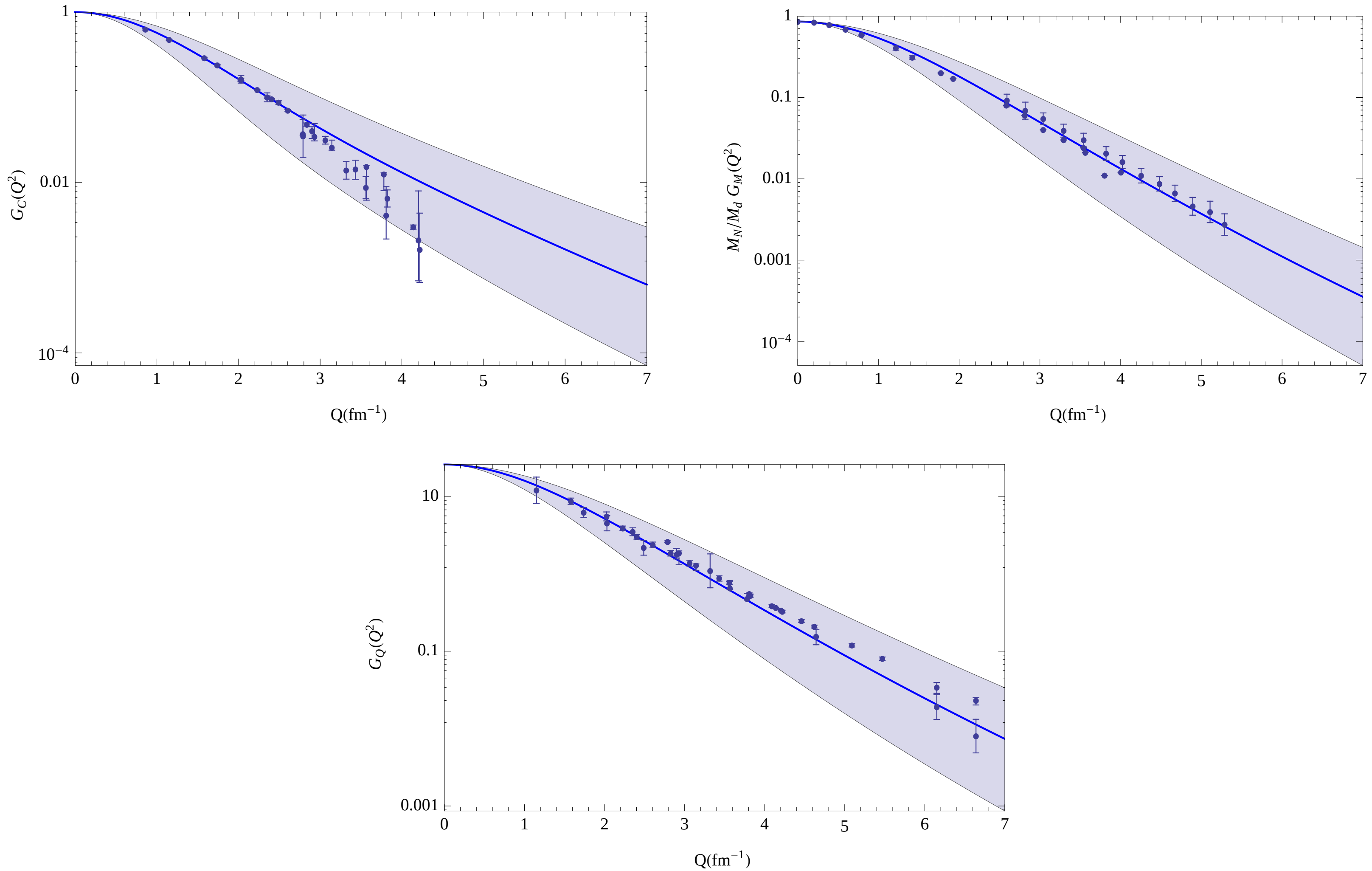
- Scaling at large Q^2 (Brodsky et al., Carlson et al.)

$$\begin{aligned} \text{Leading}: &\quad \sqrt{A(Q^2)} \sim \sqrt{B(Q^2)} \sim G_C(Q^2) \sim 1/Q^{10} \\ \text{Subleading}: &\quad G_M(Q^2) \sim G_Q(Q^2) \sim 1/Q^{12} \end{aligned}$$

It fixes the z dependence of $c_2(z)$ and $c_3(z)$

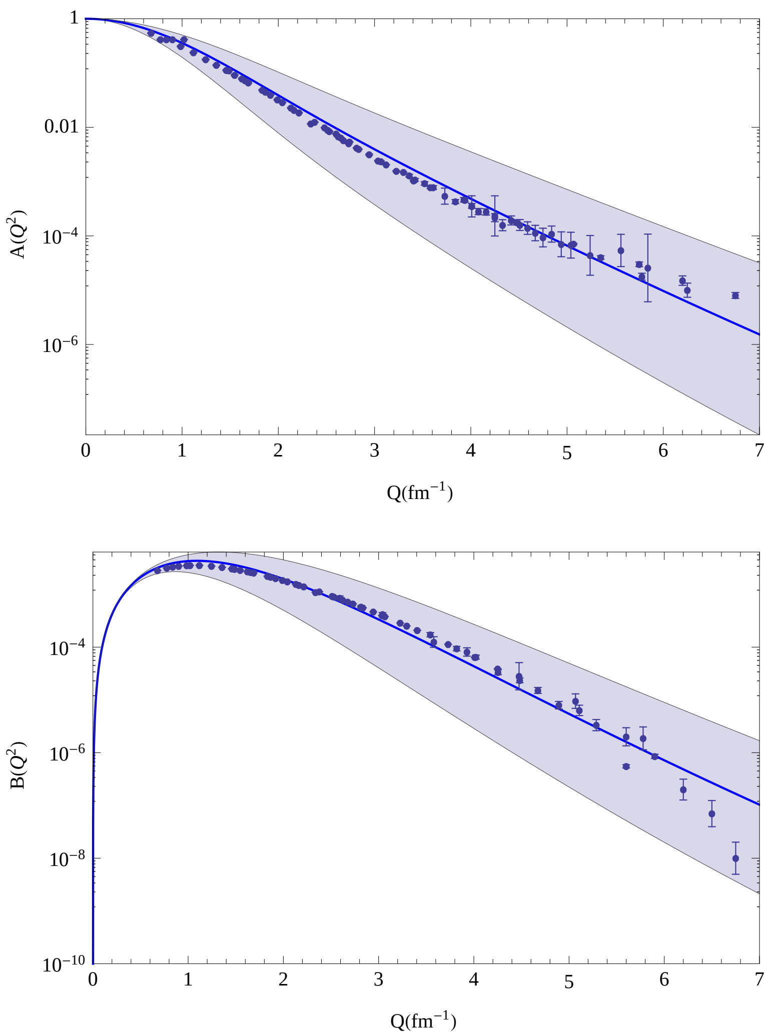
$$c_2(z) = \frac{M_d}{30M_N}\mu_d\,\kappa^2 z^2\,, \quad c_3(z) = \left(M_d^2\mathcal{Q}_d - 1 + \frac{M_d}{30M_N}\mu_d\right)\kappa^2 z^2$$

Deuteron



Deuteron form factors

Deuteron



Structure Functions $A(Q^2)$ and $B(Q^2)$

Deuteron

Charge radius
$r_C = (-6G'_C(0))^{1/2} = 1.92$ fm
Data: $r_C = 2.13 \pm 0.01$ fm

Magnetic radius $r_M = (-6G'_M(0)/G_M(0))^{1/2} = 2.24$ fm
Data $r_M = 1.90 \pm 0.14$ fm.

Tetraquarks

- Under study at CERN, KEK, Fermilab, etc.

- N_c QCD:
  Mesons $q^a \bar{q}^a$ and under $SU(N_c)$ the $\bar{q}^a$ transforms similar to
  $\epsilon^{a a_1 \dots a_{N_c - 1}} \underbrace{q_{a_1} \dots q_{N_c - 1}}_{N_c - 1}$

- Baryons $\epsilon^{a_1 \dots a_{N_c}} \underbrace{q_{a_1} \dots q_{N_c}}_{N_c}$

- q^a transforms similar to $\epsilon^{a a_1 \dots a_{N_c - 1}} \underbrace{\bar{q}_{a_1} \dots \bar{q}_{N_c - 1}}_{N_c - 1}$

- Multiquarks $\epsilon_{a a_1 \dots a_{N_c - 1}} \; \epsilon_{a b_1 \dots b_{N_c - 1}} \underbrace{q^{a_1} \dots q^{a_{N_c - 1}}}_{N_c - 1} \underbrace{\bar{q}^{b_1} \dots \bar{q}^{b_{N_c - 1}}}_{N_c - 1}$

- Limit to real QCD: $N_c = 3$

  Tetraquark $T = D^a \, \bar{D}^a = \left(\epsilon^{a a_1 a_2} \; q_{a_1} q_{a_2} \right) \left(\epsilon^{a b_1 b_2} \; \bar{q}_{b_1} \bar{q}_{b_2} \right)$
  is color diquark-antidiquark bound state

Tetraquarks

- Equation of motion from mesons case by rescaling $\tau \to \tau + 2$
- Solutions: $\phi_{nL}(z) = \sqrt{\frac{2\Gamma(n+1)}{\Gamma(n+L+3)}}\, \kappa^{L+3}\, z^{L+7/2}\, e^{-\kappa^2 z^2/2}\, L_n^{L+2}(\kappa^2 z^2)$
- $M^2_{nJL} = 4\kappa^2\left(n + \frac{L+J}{2} + 1\right)$
- Agreement with COMPASS Coll. at SPS (CERN)
  for $a_1(1414)$ with spin-parity $J^{PC} = 1^{++}$ discovered in 2015
- Put $n = 0, L = 1, J = 1$ and get $M^2_{a_1} = 8\kappa^2$ or $M_{a_1} = 2\kappa\sqrt{2}$
- Using $\kappa = 0.5$ GeV get $M_{a_1} = \sqrt{2} \simeq 1.414$ GeV
- Brodsky-Teramond (superconformal case) $M^2_{nLS} = 4\kappa^2\left(n + L + \frac{S}{2} + 1\right)$
- Our $M^2_{nJL} = 4\kappa^2\left(n + \frac{L+J}{2} + 1\right)$
- Degenerate at $J = L + S$, when all three decouple
- Specifically for $a_1(1414)$ with $J^{PC} = 1^{++}$ we have $J = L = S = 1$

QCD Compositeness and Quark Counting Rules

QCD compositeness vs. VMD (Vector Meson Dominance model)

Brodsky, Lebed, Lyubovitskij: Phys.Lett.B764 (2017) 174; Phys.Rev.D97 (2018) 034009

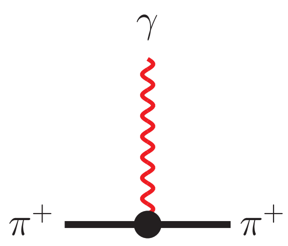
- Novel idea relevant for electrocouplings of baryon resonances
- QCD compositenens (vector mesons are bound states of quarks) leads to a nontrivial Q^2 dependence of vector meson - photon transition

$$\mathbf{V^0} = \rho^{\mathbf{0}}, \omega, \phi, \mathbf{J}/\psi, \boldsymbol{\Upsilon}$$

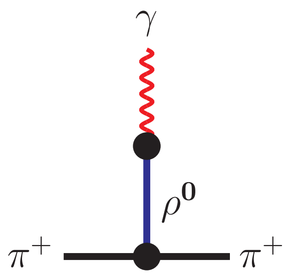
- Structure of matrix element $G_V(g^{\mu\nu}Q^2 - Q^\mu Q^\nu)$, where Q is Euclidean momentum of V^0 and γ
- In VMD G_V is constant
- $G_V(Q^2)$ must have $G_V(Q^2) \sim 1/\sqrt{Q^2}$ behavior at large Q^2

QCD Compositeness and Quark Counting Rules

- Consider the pion



(a) Direct



(b) ρ^0 exchange

- In VMD: contact diagram 1, vector meson diagram gives $-Q^2/(M_V^2 + Q^2)$
- The sum is $M_V^2/(M_V^2 + Q^2)$ scales as M_V^2/Q^2
- Contact diagram is 1, resonance is $-1 + M_V^2/Q^2$
- In pQCD: contact diagram $1/Q^2$, vector meson diagram is subleading $1/Q^3$ because of falloff of the vector meson-photon form factor

QCD Compositeness and Quark Counting Rules

- New formula for electrocouplings of two hadrons with ajustable constituent content n_1 and n_2

$$F_{H_{n_1} H_{n_2}}(Q^2) = \frac{\Gamma(\frac{n_1+n_2}{2})\,\Gamma(\frac{n_1+n_2}{2}-1)}{\sqrt{\Gamma(n_1-1)\Gamma(n_2-1)}}\,\frac{\Gamma(a+1)}{\Gamma(a+1+\frac{n_1+n_2}{2}-1)}$$
$$\sim \frac{1}{a^{(n_1+n_2)/2-1}},$$

where $a = Q^2/(4\kappa^2)$ and $\Gamma(n) = \int\limits_0^\infty dx x^{n-1} e^{-x}$ is gamma function.

For $n_1 = n_2 = n$ we get

$$F_{H_n} \sim \left(\frac{1}{Q^2}\right)^{n-1}$$

For $n_1 = n, \;\; n_2 = 0$ we get

$$F_{H_n} \sim \left(\frac{1}{Q^2}\right)^{(n-1)/2}$$

QCD Compositeness and Quark Counting Rules

- In particular, the scaling of the form factor corresponding to $\gamma^* \to Z_c^+ + \pi^-$ is

$$F_{Z_c^+ \pi^-} \sim \frac{1}{Q^4}$$

in case of tetraquark structure of Z_c state, and

$$F_{Z_c^+ \pi^-} \sim \frac{1}{Q^2}$$

in the case when Z_c^+ is a system of two tightly bound diquarks (Brodsky-Lebed)
For $\gamma^* \to Z_c^+ + Z_c^-$,

$$F_{Z_c^+ Z_c^-} \sim \frac{1}{Q^6}$$

in case of a Z_c state with tetraquark structure, and

$$F_{Z_c^+ Z_c^-} \sim \frac{1}{Q^2}$$

in case when Z_c^+ is a system of two tightly bound diquarks (Brodsky-Lebed)

AdS/QCD at finite temperature

- Study of hadron properties at finite temperature is a promising task, since it allows for a deeper understanding of the evolution of the early Universe, the formation of hadronic matter and its phase transitions.

- Application of soft-wal AdS/QCD:

  1. Herzog, PRL 98 (2007) 0916011:
  Deconfinement occurs via 1st -order Hawking-Page phase transition between low T AdS and high temperature black hole

  Model-dependent predictions (difficult to compare to QCD):
  $T_c^{\rm HW} = 122$ MeV and $T_c^{\rm SW} = 191$ MeV
  Lattice: $T_c^{\rm Lattice} = 192 \pm 7 \pm 4$ MeV

  2. Other prediction for the T_c and more detailed/improved description:
  in Grigoryan et al, PRD 82 (2010) 026005; Colangelo et al, PRD 83 (2011) 035015; Braga et al, PLB 774 (2017) 476; Bartz et al, PRD 94 (2016) 075022; Vega et al, EPJA 53 (2017) 217.

AdS/QCD at finite temperature

- Popular way to introduce the T to consider the specific metric (geometry)
- AdS-Schwarzschild geometry

$$ds^2 = e^{2A(z)} \left[f_T(z) dt^2 - (d\vec{x})^2 - \frac{dz^2}{f_T(z)} \right]$$

Here $f_T(z) = 1 - z^4/z_H^4$, where z_H is the position of the event horizon, which is related to the black-hole Hawking temperature $T = 1/(\pi z_H)$.

- The latter also represents (holography correspondence) the temperature of the boundary field theory.

AdS/QCD at finite temperature

- In addition of T-dependence of metric we propose the T dependence of dilaton parameter

$$\kappa^2(T) = \kappa^2 \, \frac{\Sigma(T)}{\Sigma} \, .$$

using its relation to the quark condensate parameter Σ

$$\Sigma = \langle 0|\bar{q}q|0\rangle = -N_f \, B \, F^2 == -\frac{3N_f \, B}{64} \, \kappa^2 \, .$$

Here N_f is the number of quark flavors, B is the quark condensate parameter, and F is the pseudoscalar meson decay constant in the chiral limit at zero temperature.

AdS/QCD at finite temperature

- T-dependence of quark condensate $\Sigma(T)$ was derived by Gasser and Leutwyler in two-loop ChTP [PLB184 (1987) 83]

$$\Sigma(T) \quad = \quad \Sigma\left[1 - \frac{N_f^2-1}{N_f}\,\frac{T^2}{12F^2} - \frac{N_f^2-1}{2N_f^2}\left(\frac{T^2}{12F^2}\right)^2 + \mathcal{O}(T^6)\right]$$

This result is valid for an adjustable number of quark flavors with $N_f \geq 2$ and is given as an expansion in T^2.
For three-loop result see Gerber and Leutwyler, NPB321 (1989) 387.

- Critical temperature in ChPT (vanishing of condensate):

$$\frac{\left(T_c^{\rm QCD}\right)^2}{12F^2} = N_f\left[\sqrt{\frac{N_f^2+1}{N_f^2-1}} - 1\right].$$

$T_c^{\rm QCD} = 230$ MeV for $N_f = 2$.
Power scaling behavior at large N_f:
$T_c^{\rm QCD} \sim F/\sqrt{N_f}$

AdS/QCD at finite temperature

- In the rest frame of the AdS field with $\vec{p} = 0$ we get EOM

$$\Big[- \frac{d^2}{dz^2} + U_J(z,T) \Big] \phi_{nJ}(z,T) = M^2_{nJ}(T) \phi_{nJ}(z,T) \,,$$

where $U_J(z,T)$ is the effective potential at finite temperature, which can be decomposed into a zero temperature term $U_J(z) \equiv U_J(z,0)$ and a temperature dependent term $\Delta U_J(z,T)$

$$\begin{aligned} U_J(z,T) &= U_J(z) + \Delta U_J(z,T) \,, \\ U_J(z) &= \kappa^4 z^2 + 2\kappa^2 (J-1) + \frac{4m^2 - 1}{4z^2} \,, \\ \Delta U_J(z,T) &= 2\rho(T)\kappa^2 \left(\kappa^2 z^2 + J - 1\right) + \frac{4z^2}{5z_H^4} J(J-1)(\kappa^2 z^2 - J) \,, \end{aligned}$$

where $m = N + L - 2$ and ρ_T parametrizes T dependence of the dilaton: $\kappa^2(T) = \kappa^2[1 + \rho(T)]$, where

$$\begin{aligned} \rho(T) &= \delta_{T_1} \frac{T^2}{12F^2} + \delta_{T_2} \left(\frac{T^2}{12F^2} \right)^2 + \mathcal{O}(T^6) \,, \\ \delta_{T_1} &= -\frac{N_f^2 - 1}{N_f} \,, \quad \delta_{T_2} = -\frac{N_f^2 - 1}{2N_f^2} \,. \end{aligned}$$

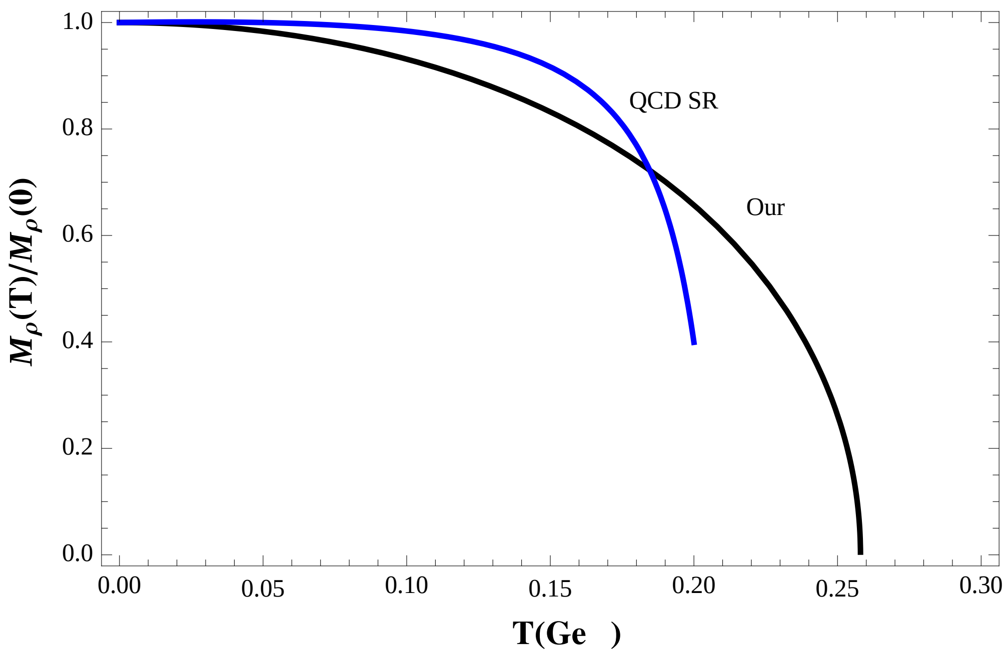
AdS/QCD at finite temperature

- Meson mass spectrum at finite T reads:

$$
\begin{aligned}
M^2_{nJ}(T) &= M^2_{nJ}(0) \, + \, \Delta M^2_{nJ}(T) \, , \\
\Delta M^2_{nJ}(T) &= \rho_T \, M^2_{nJ}(0) + R_{nJ} \, \frac{\pi^4 T^4}{\kappa^2} \, , \\
R_{nJ} &= \frac{4}{5} J(J-1) \Big[(m+1)(m+2) + (6n-J)(n+m+1) - nJ \Big] \, .
\end{aligned}
$$

AdS/QCD at finite temperature

- Comparison of $M_\rho(T)/M_\rho(0)$ with result of QCD sum rules (Lowe et al)



AdS/QCD at finite temperature

- Use pure Poincare metric with thermal dilaton

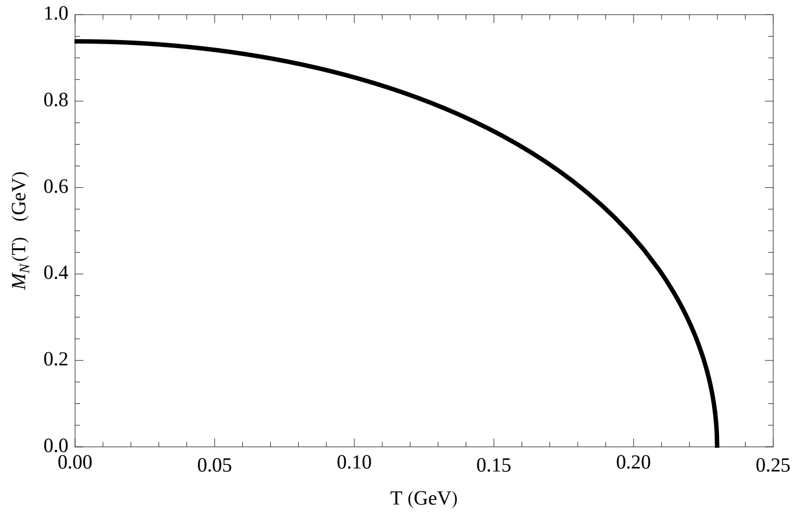
$$g_{MN}\, x^M x^N = \epsilon^a_M\, \epsilon^b_N\, \eta_{ab}\, x^M x^N = \frac{1}{z^2}\,(dx_\mu dx^\mu - dz^2)$$

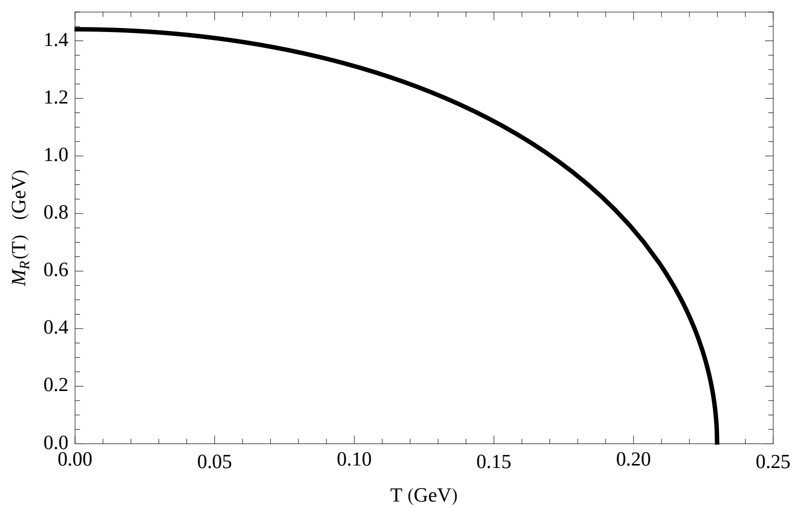
$$\begin{aligned}
\kappa^2(T) &= \kappa^2\left[1 + \delta_{T_1}\frac{T^2}{12F^2} + \delta_{T_2}\left(\frac{T^2}{12F^2}\right)^2 + \mathcal{O}(T^6)\right], \\
\delta_{T_1} &= -\frac{N_f^2 - 1}{N_f}, \quad \delta_{T_2} = -\frac{N_f^2 - 1}{2N_f^2}.
\end{aligned}$$

F is the pseudoscalar coupling constant in the chiral limit, N_f is the number of quark flavors.

AdS/QCD at finite temperature

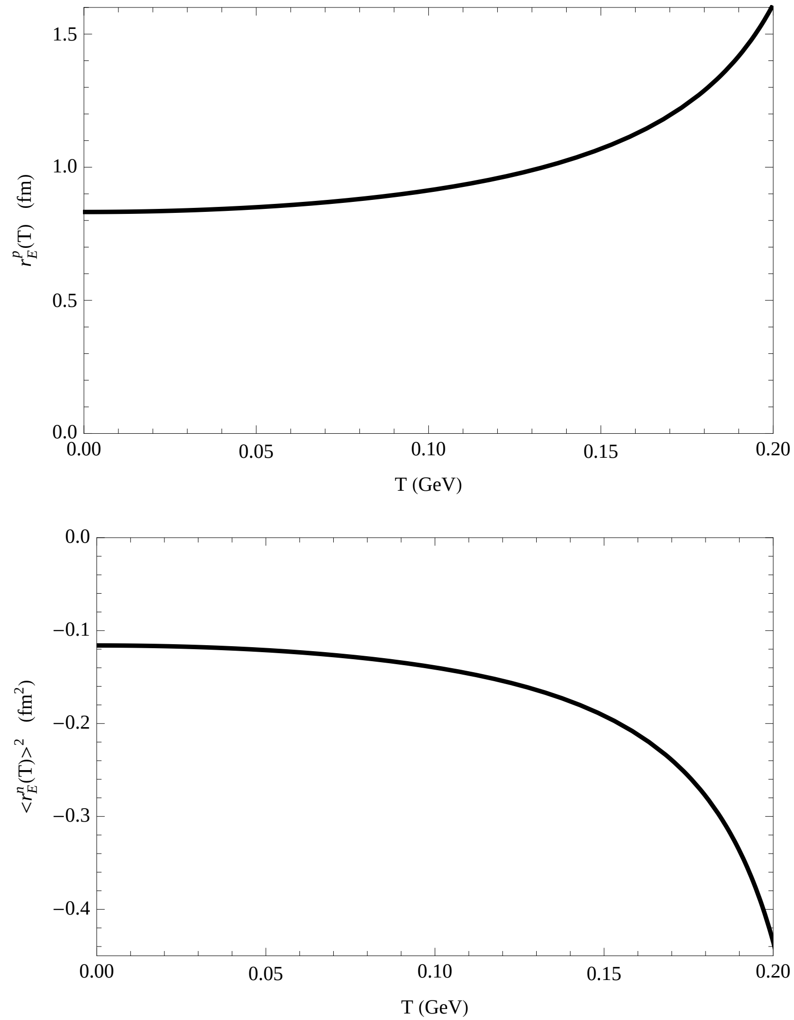
- Nucleon and Roper masses up to $T_c = 230$ MeV.





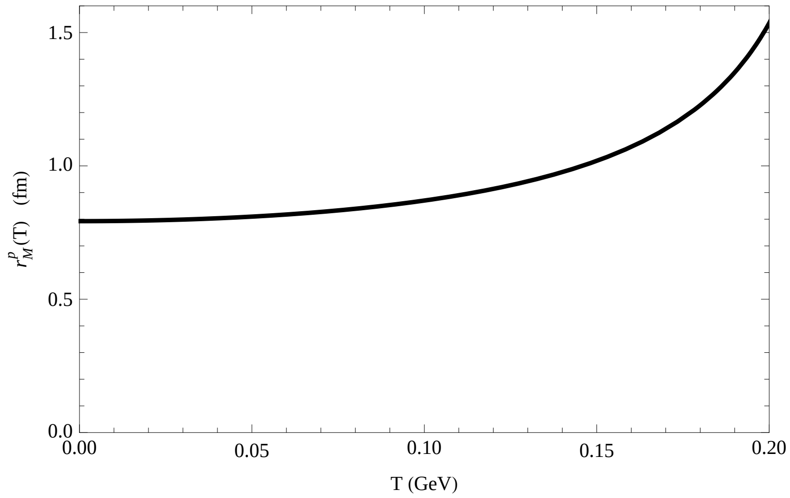
AdS/QCD at finite temperature

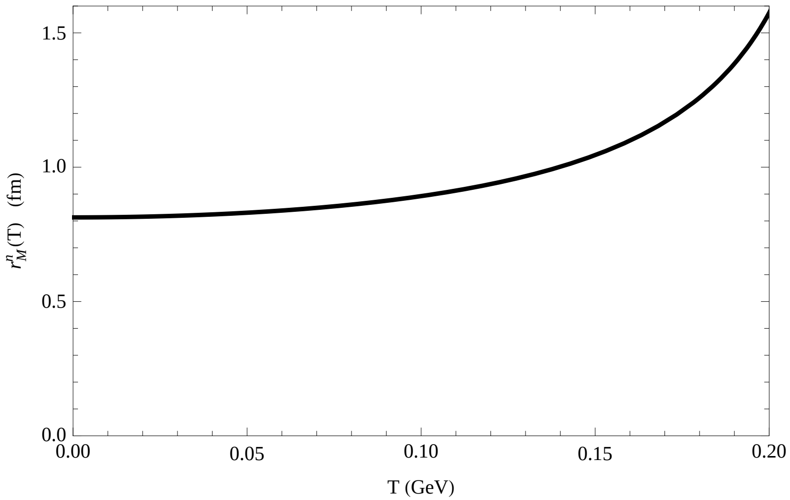
- Temperature dependence of nucleon charge radii r_E^p and $\langle r_E^2 \rangle^n$



AdS/QCD at finite temperature

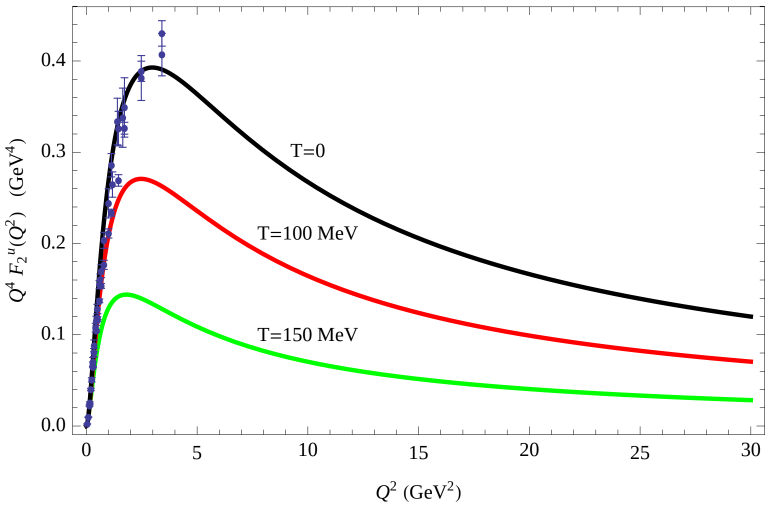
- Temperature dependence of nucleon magnetic radii r_M^p and r_M^n

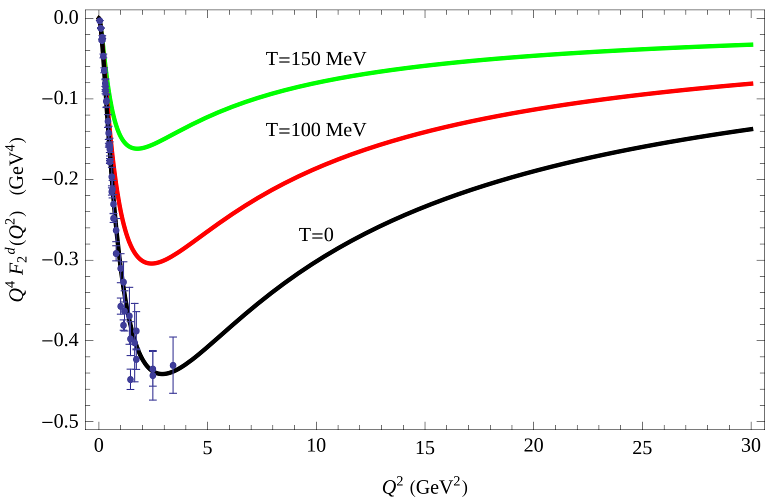




AdS/QCD at finite temperature

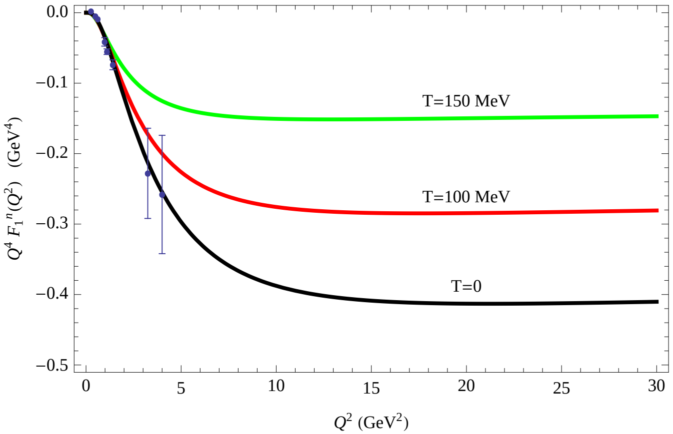
- Temperature dependence of Pauli u and d quark form factors multiplied by Q^4.

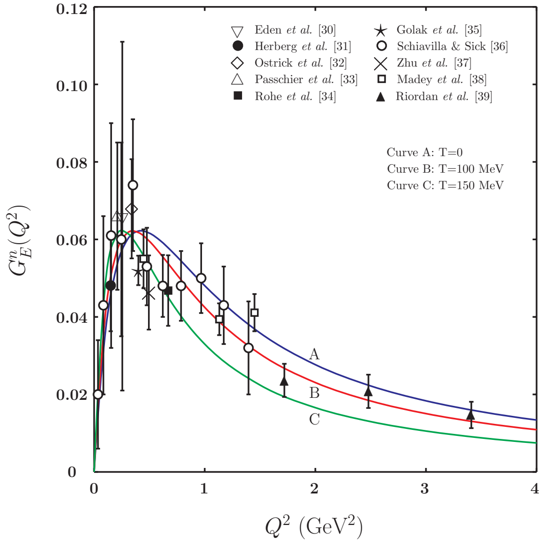




AdS/QCD at finite temperature

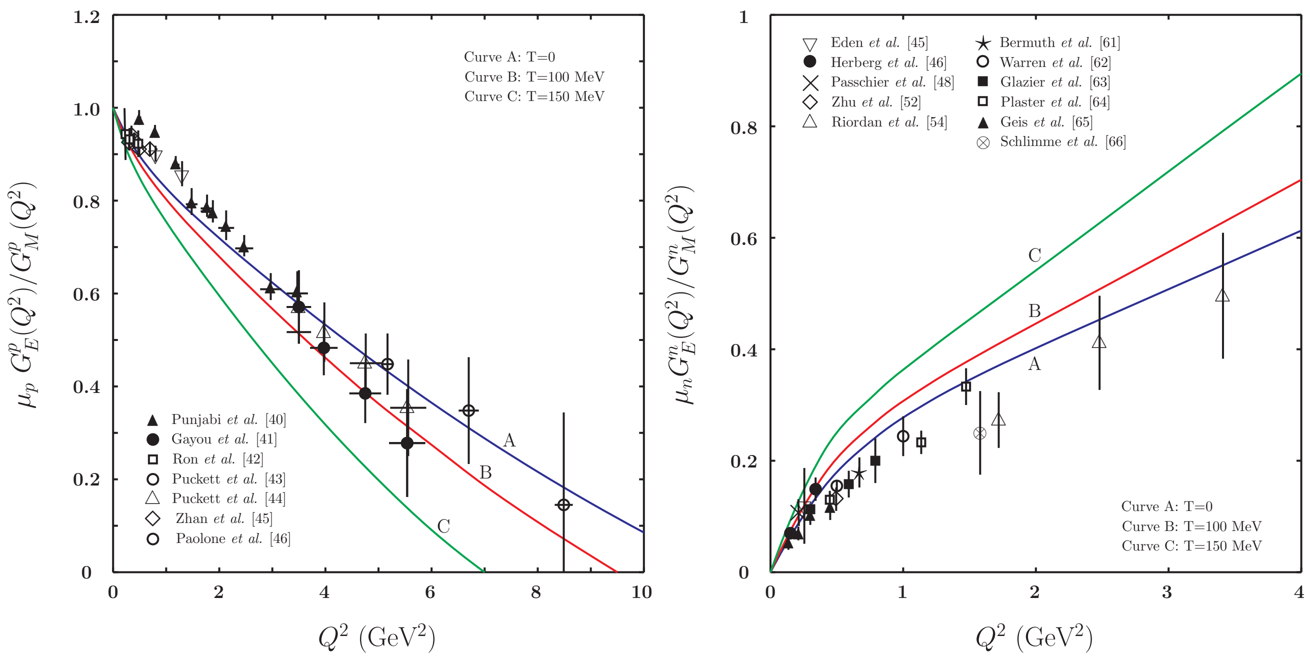
- T-dependence of the Dirac and charge Sachs neutron form factor





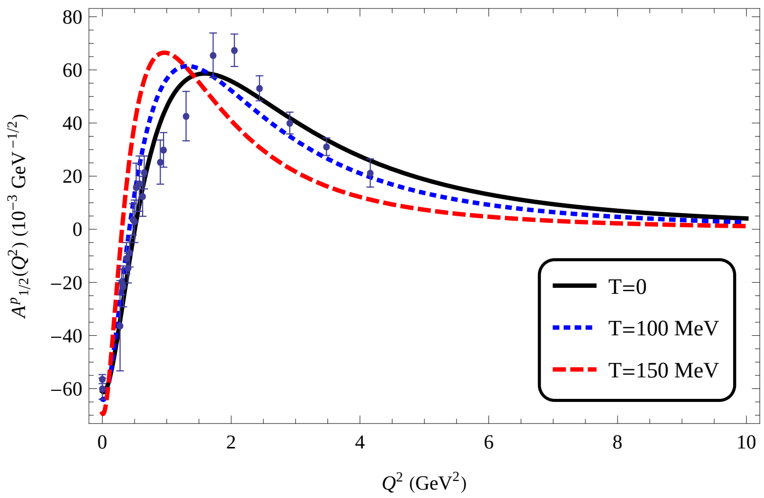
AdS/QCD at finite temperature

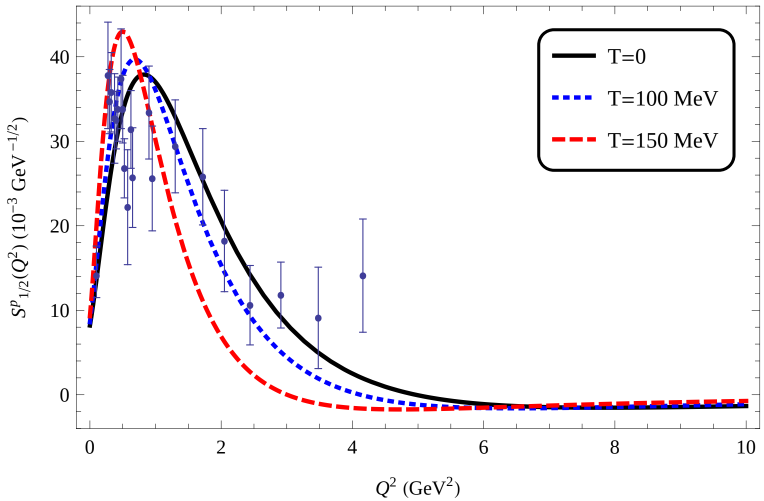
- T dependence of the ratios $\mu_p G_E^p(Q^2)/G_M^p(Q^2)$ and $\mu_n G_E^n(Q^2)/G_M^n(Q^2)$



AdS/QCD at finite temperature

- T dependence of the the helicity amplitudes $A^p_{1/2}(Q^2)$ and $S^p_{1/2}(Q^2)$





Summary

- AdS/QCD: Effective actions using correspondence between 5D theories on AdS manifolds including gravity and 4D gauge theory living on the boundary of AdS space
- AdS fields are dual to hadrons and exotic states
- Bulk profiles of AdS fields in 5th (holographic direction) dual to hadronic wave functions
- Applications: Regge behavior of hadron masses, correct power scaling of hadron form factors at large Q^2, extension for multiquark states (straightforward)
- Gives more realistic Light-Front Wave Fuctions underlying Light-Front QCD
- Extension to finite temperature