Hadron structure in AdS/QCD

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We perform a detailed analysis of nucleon electromagnetic and axial form factors in a holographic soft-wall model. Our approach is based on an action which describes hadrons with broken conformal invariance and incorporates confinement through the presence of a background dilaton field. For $N_c = 3$ we describe the nucleon structure in a superposition of a three valence quark state with high Fock states including an adjustable number of partons (quarks, antiquarks and gluons) via studying the dynamics of 5D fermion fields of different scaling dimension in anti-de Sitter (ADS) space. According to the gauge/gravity duality the 5D fermion fields of different scaling dimension correspond to the Fock state components with a specific number of partons. In the present application we restrict to the contribution of 3, 4 and 5 parton components in the nucleon Fock state. With a minimal number of free parameters (dilaton scale parameter, mixing parameters of partial contributions of Fock states, coupling constants in the effective Lagrangian) we achieve a reasonable agreement with data for the nucleon form factors.

The 7th International Workshop on Chiral Dynamics,
August 6 -10, 2012
Jefferson Lab, Newport News, Virginia, USA

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1. Introduction

Based on the gauge/gravity duality [1], a class of AdS/QCD approaches which model QCD by using methods of extra-dimensional field theories formulated in anti-de Sitter (AdS) space, was recently successfully developed for describing the phenomenology of hadronic properties. One of the popular formalisms of this kind is the "soft-wall" model [2], which uses a soft infrared (IR) cut-off in the fifth dimension. Here we present a detailed analysis of the nucleon electromagnetic form factors in a holographic soft-wall model [3]-[5] considering the inclusion of higher-dimensional fermion fields. Thus high-Fock state contributions are holographically incorporated in the nucleon. This novel approach is based on an action which describes hadrons with broken conformal invariance and which incorporates confinement through the presence of a background dilaton field. Notice the role of higher Fock components in the pion, in the context of holographic QCD, was considered before in Refs. [6]. In our framework for $N_c = 3$ nucleons are considered as a superposition of three valence quark states and high Fock states including an adjustable number of partons (quarks, antiquarks and gluons) by studying the dynamics of the 5D fermion fields of different scaling dimension in AdS space. According to the gauge/gravity duality the 5D fermion fields of different scaling dimension correspond to Fock state components with a specific number of partons.

2. Approach

We consider the propagation of a fermion field $\Psi(x,z)$ with spin $J = 1/2$ in 5-dimensional AdS space, which contains the contributions of different twist-dimensions. In the language of the AdS/QCD dictionary it corresponds to the inclusion of the three-quark and higher-parton states in the nucleon. For this first time we restrict ourselves to the contribution of $3q$, $3q + g$, $3q + q\bar{q}$ and $3q + 2g$ Fock states, where q, $\bar{q}$ and g denote quark, antiquark and gluon, respectively. The main idea for describing the nucleon in AdS/QCD is based on the correspondence (see detailed discussion in Refs.[7]) between the spinor fields propagating in the bulk space and the QCD interpolating operators creating the nucleons on the boundary of AdS space. The appropriate boundary conditions for the bulk field on the boundary of AdS space ensure that such correspondence is precise due to the equivalence of the functional integrals of both the boundary and bulk theories. In particular, in the boundary theory (QCD) we define the left- and right-handed chiral doublets of nucleons $\mathcal{O}_L$ and $\mathcal{O}_R$. Since the chiral symmetry of the boundary theory is equivalent to the gauge symmetry in the bulk, we need to introduce the pair of bulk fermion fields $\Psi_{\pm}(x,z)$, which are holographic analogues of the $\mathcal{O}_{R/L}$ operators. In particular, the bulk fields $\Psi_{\pm}(x,z)$ contain important information about the baryon structure. On one side, their boundary values (non-normalizable solutions) are analogues of the sources for the QCD interpolating operators, which then via the evaluation of the Euclidean generating functionals produce the correlation functions of QCD operators. On the other side, these fields contain normalizable modes (these are regular and therefore are vanishing on the boundary) - profiles in extra dimension, which correspond to the baryon wave functions or expectation values of QCD operators. In our approach the conformal and chiral symmetries are spontaneously broken via the introduction of the background field (dilaton) $\varphi(z)$ in the effective action. We choose the quadratic dependence of the dilaton on the holographic coordinate z, i.e. $\varphi(z) = \kappa^2 z^2$ with κ being a free scale parameter, which scales as $\mathcal{O}(\sqrt{N_c})$ in the large

N_c-expansion. In particular, later we show that the nucleon (baryon) mass is proportional to the parameter κ, which is consistent with large N_c QCD: $M_N \sim \kappa\sqrt{N_c} \sim N_c$. The main advantage of the dilaton with quadratic profile is the possibility to produce linear Regge-like trajectories for hadron masses. The relevant AdS/QCD action for the description of the nucleon electromagnetic and axial form factors is constructed in terms of the fermion fields $\Psi_{\pm,\tau}(x,z)$ with spin $J = 1/2$ and scaling dimension τ, the vector field $V_M(x,z)$ with spin $J = 1$ (holographic analogue of the electromagnetic field) and the axial field $A_M(x,z)$ (holographic analogue of the axial isovector field) [5]

$$S = \int d^4x dz \sqrt{g}\, e^{-\varphi(z)} \left\{ \mathscr{L}_\Psi(x,z) + \mathscr{L}_{V+A}(x,z) + \mathscr{L}_{\text{int}}(x,z) \right\},$$

$$\mathscr{L}_\Psi(x,z) = \sum_{i=+,-} \sum_\tau c_\tau \bar{\Psi}_{i,\tau}(x,z)\, \hat{\mathscr{D}}_i(z)\, \Psi_{i,\tau}(x,z),$$

$$\mathscr{L}_{V+A}(x,z) = -\frac{1}{4} V_{MN}(x,z) V^{MN}(x,z) - \frac{1}{4} A_{MN}(x,z) A^{MN}(x,z),$$

$$\mathscr{L}_{\text{int}}(x,z) = \sum_{i=+,-} \sum_\tau c_\tau \bar{\Psi}_{i,\tau}(x,z) \left\{ \hat{\mathscr{V}}_i(x,z) + \hat{\mathscr{A}}_i(x,z) \right\} \Psi_{i,\tau}(x,z),$$

$$\hat{\mathscr{D}}_\pm(z) = \frac{i}{2} \Gamma^M \overleftrightarrow{\partial}_M \mp (\mu + U_F(z)), \quad A \overleftrightarrow{\partial} B \equiv A\,(\partial B) - (\partial A) B,$$

$$\hat{\mathscr{V}}_\pm(x,z) = Q_N \Gamma^M V_M(x,z) \pm \frac{i}{4} \eta_V [\Gamma^M, \Gamma^N] V_{MN}(x,z) \pm g_V \tau_3 \Gamma^M i\Gamma^z V_M(x,z),$$

$$\hat{\mathscr{A}}_\pm(x,z) = \frac{\tau_3}{2} \left(\mp \Gamma^M A_M(x,z) + \frac{i}{4} \eta_A [\Gamma^M, \Gamma^N] A_{MN}(x,z) + g_A \Gamma^M i\Gamma^z A_M(x,z) \right). \quad (2.1)$$

Here $V(A)_{MN}$ is the stress tensor of the vector (axial) field, Q_N and τ_3 are nucleon charge and isospin matrices, Γ^M are the five-dimensional Dirac matrices. μ is the bulk fermion mass related to the scaling dimension τ as $m = \mu R = \tau - 3/2$. Notice that the scaling dimension of the AdS fermion field is holographically identified with the scaling dimension of the baryon interpolating operator $\tau = N + L$, where N is the number of partons in the baryon and $L = \max|L_z|$ is the maximal value of the z-component of the quark orbital angular momentum in the light-front wavefunction [8]. $U_F(z) = \varphi(z)/R$ is the dilaton field dependent effective potential providing the correct asymptotics of the nucleon electromagnetic form factors at large Q^2 [9, 10]. In this paper we restrict to the three leading contributions $\tau = 3, 4$ and 5. The coefficients c_τ are a set of parameters which take into account the mixing of AdS fermion fields with different scaling dimension τ, which are constrained by the correct normalization of the kinetic term of the four-dimensional spinor field and by charge conservation as $\sum_\tau c_\tau = 1$ [5]. The five free parameters κ, c_3, c_4, g_V and η_A are fixed to the values $\kappa = 383$ MeV, $c_3 = 1.25$, $c_4 = 0.16$, $g_V = 0.3$, $\eta_A = 0.5$ [5].

3. Results

One of advantages of the soft-wall AdS/QCD model is that most of the calculations can be done analytically. E.g., the nucleon mass is given by the expression $M_n = 2\kappa \sum_\tau c_\tau \sqrt{n + \tau - 1}$. As we stressed before, the nucleon (baryon) mass is proportional to the parameter κ and this is consistent with large N_c QCD: $M_N \sim \kappa\sqrt{\tau} \sim N_c$, where $\tau \sim N_c$. Next we present the numerical analysis of nucleon properties [5]. All analytical expressions are given in [5]. In Table I we present the results for the nucleon mass and the electroweak properties of nucleons. Selected results for the

nucleon form factors in comparison to known data are shown in Figs. 1 and 2. We demonstrated that the soft-wall holographic model reproduces the main features of the electromagnetic structure of the nucleon. In particular, we achieved the following results: the analytical power scaling of the elastic nucleon form factors at large momentum transfers in accordance with quark-counting rules; reproduction of experimental data for magnetic moments and electromagnetic radii. One can see that with a minimal number of free parameters (five parameters) we obtain a reasonable description of the nucleon electromagnetic form factors including the correct power scaling at large Q^2. It demonstrates that the soft-wall model successfully describes nucleon structure at any resolution scale. In a next step, one can include effects of quark masses and extend the approach to nucleon resonances, light baryons with higher spins, strange and heavy baryons.
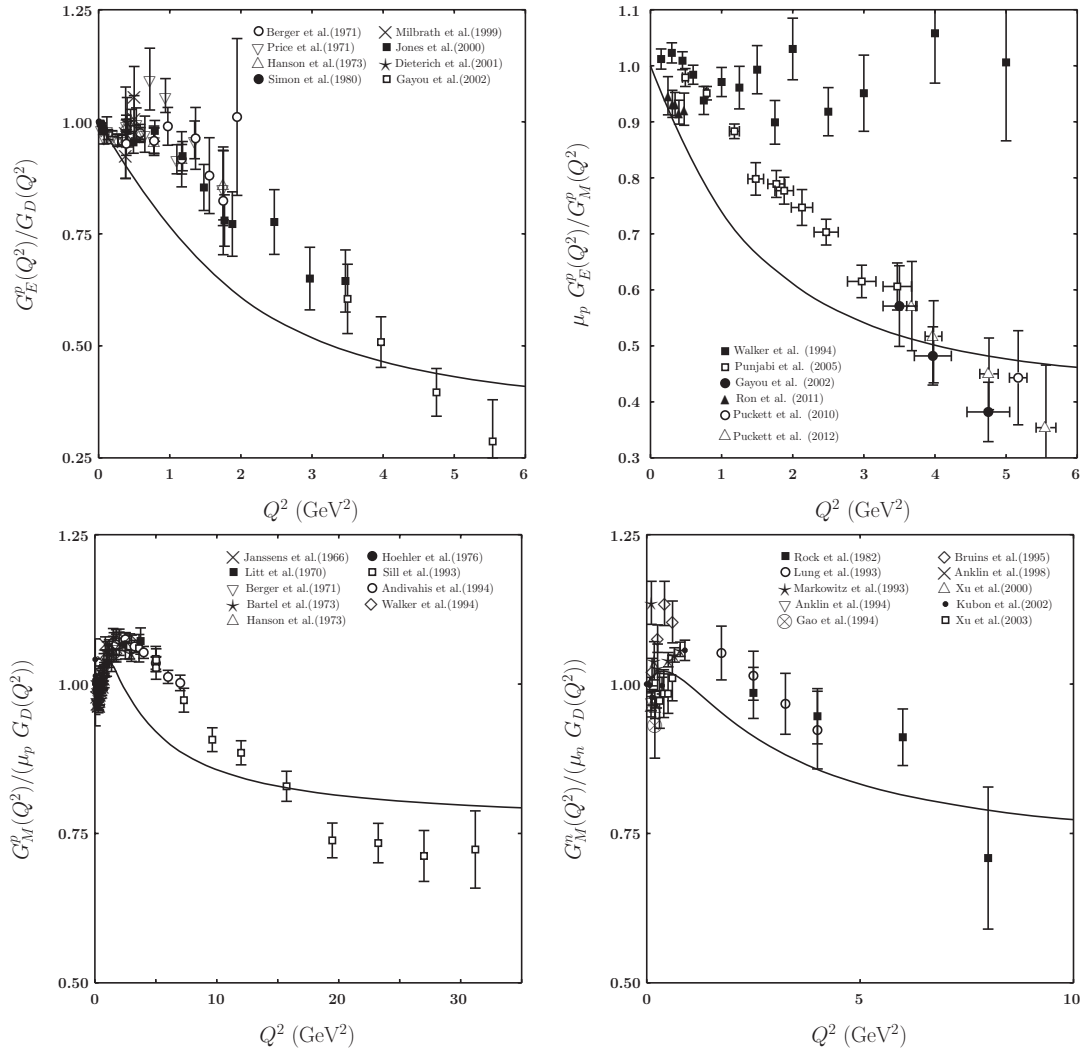
Acknowledgments

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Table 1: 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
g_A	1.270	1.2701
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

Figure 1: Ratios $G_E^p(Q^2)/G_D(Q^2)$, $\mu_p G_E^p(Q^2)/G_M^p(Q^2)$, $G_M^p(Q^2)/(\mu_p G_D(Q^2))$ and $G_M^n(Q^2)/(\mu_n G_D(Q^2))$.
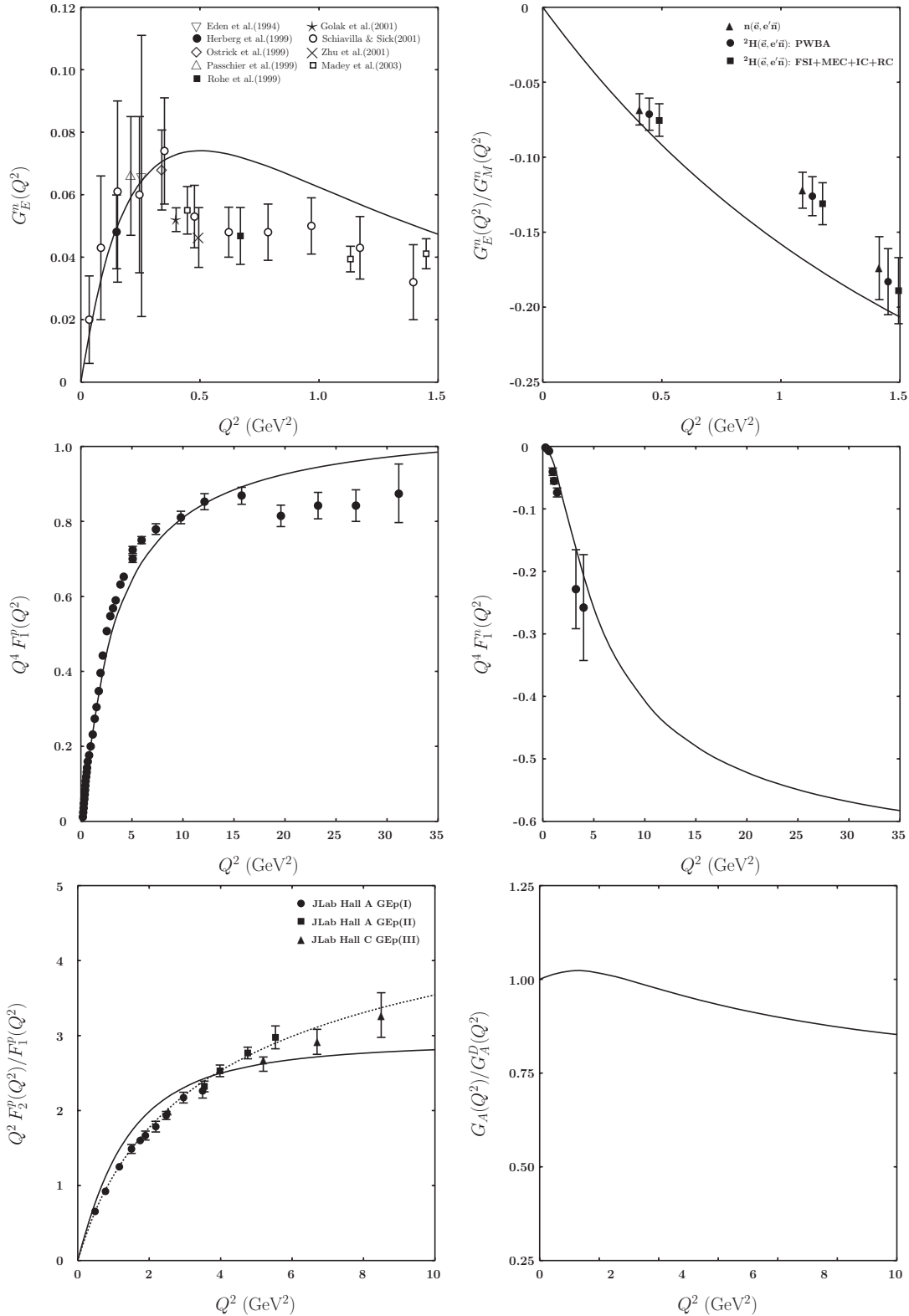
Figure 2: The charge neutron form factor, ratio $G_E^n(Q^2)/G_M^n(Q^2)$, proton and neutron Dirac form factor multiplied with Q^4, ratios $Q^2 F_2^p(Q^2)/F_1^p(Q^2)$ (the dashed line is the approximation of data suggested in Ref. [11]) and $G_A(Q^2)/G_A^D(Q^2)$.