SLAC–PUB–16806

Analysis of Nucleon Electromagnetic Form Factors from Light-Front Holographic QCD : The Space-Like Region

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Abstract

We present a comprehensive analysis of the nucleon electromagnetic form factors and their flavor decomposition within the framework of light-front holographic QCD. We show that the inclusion of the higher Fock components $|qqqq\bar{q}\rangle$ has a significant effect on the spin-flip elastic Pauli form factor and almost zero effect on the spin-conserving Dirac form factor. We present light-front holographic QCD predictions of proton and neutron form factors in the momentum transfer range of $0 \leq Q^2 \leq 20\,\mathrm{GeV}^2$ and show that these predictions agree with the available experimental data with high accuracy. In order to correctly describe the Pauli form factor we need an admixture of a five quark state of about 30% in the proton and about 40% in the neutron. We also extract the nucleon charge and magnetic radii and perform a flavor decomposition of the nucleon electromagnetic form factors. The number of free parameters needed to describe the experimental nucleon form factors in the space-like domain is minimal: two parameters for the probabilities of higher Fock states for the spin-flip form factor and a phenomenological parameter R, required to account for the lack of a non-zero constraint of the neutron Dirac form factor at momentum transfer $Q^2 = 0$ as well as possible SU(6) spin-flavor symmetry breaking effects.

INTRODUCTION

The space-like electromagnetic form factors of the proton and neutron measured in lepton-nucleon elastic scattering are key measures of the fundamental structure of hadrons. The helicity-conserving and helicity-flip current matrix elements required to compute the Dirac $F_1(Q^2)$ and Pauli $F_2(Q^2)$ form factors, respectively, have an exact representation in terms of the overlap of the nonperturbative hadronic light-front wave functions (LFWFs) [1], the eigensolutions of the QCD light-front Hamiltonian –the Drell-Yan-West formulae [2, 3]. The squares of the same hadronic LFWFs, summed over all Fock states, underly the structure functions measured in deep inelastic lepton-nucleon scattering. A central goal of hadron physics is to not only successfully predict these dynamical observables but to also accurately account for the spectroscopy of hadrons.

The quest for a detailed quantitative understanding of the nucleon form factors is an active field in hadronic physics. A wide variety of models has been proposed to describe the nucleon form factors. However, in most of these approaches there has been no attempt to understand the observed hadron spectroscopy. Furthermore, a consensus among different phenomenological models and parameterizations which describe the nucleon form factors has not yet been achieved, especially for the neutron Dirac and Pauli electromagnetic form factors, nor the nucleon time-like form factors.

Detailed reviews of the experimental results and models can be found in Refs. [4, 5]. It should be noted that inconsistencies in the extraction of the data appear in the proton electric to magnetic Sachs form factor (FF) ratio $R_p(Q^2) = \mu_p G_E^p(Q^2)/G_M^p(Q^2)$, when one compares double polarization experiments [6–9], in which the ratio R_p decreases almost linearly for momentum transfer $Q^2 > 0.5\,\mathrm{GeV}^2$, with the results obtained from the Rosenbluth separation method [10–21] in which R_p remains constant in the space-like (SL) region. Predictions for different combinations of the neutron FFs are even more puzzling to explain using phenomenological models. A further limitation is that experimental data for the neutron FFs is not available in the large $Q^2 = -q^2$ regime. Another challenge is to describe the modulus of the electric to magnetic Sachs FF ratio $|G_E^p/G_M^p|$ measured by the PS170 experiment at LEAR [22] and by the BABAR Collaboration in the time-like (TL) domain [23] above the physical threshold $q^2_{phys} = 4m_N^2$, where m_N is the proton mass, at which proton-antiproton pairs are produced at rest in their center of mass system, and where strong threshold effects are also important.

The recent 12 GeV energy upgrade of Jefferson Lab will bring a wealth of high precision measurements at larger Q^2. A measurement of G_M^p in Jefferson Lab's Hall A is currently ongoing in the 7 to 17 GeV^2 range, with a precision aimed at less than 2 % [24]. Future experiments approved for running in Hall A include measurements of $R_p(Q^2)$ up to 15 GeV^2 using recoil polarization [25], of $R_n(Q^2) = \mu_n G_E^n(Q^2)/G_M^n(Q^2)$ up to 10.2 GeV^2 using a polarized ^{3}He target [26], and of G_M^n up to $Q^2 = 18$ GeV^2 using a deuteron target [27]. A similar experiment up to $Q^2 = 14$ GeV^2 will run in Jefferson Lab's Hall B [28] and a G_E^n measurement up to $Q^2 = 7$ GeV^2 using a deuteron target and recoil polarization will run in Jefferson Lab's Hall C [29]. Finally, in order to provide an unambiguous value of the proton electric radius from electron scattering, an experiment was recently completed (April 2016) which measured G_E^p down to $Q^2 = 10^{-4}$ GeV^2, with a statistical precision better than 2×10^{-3} and a systematic accuracy of 5×10^{-3} [30].

The spectra of hadrons and their FFs can both be calculated using a novel nonperturbative approach to hadron physics called light-front (LF) holographic QCD (LFHQCD) [31–34], which provides new analytical tools for hadron dynamics within a relativistic frame-independent first-approximation to the LF QCD Hamiltonian. This new approach to hadronic physics follows from the precise mapping of the Hamiltonian equations in Anti-de Sitter (AdS) space to the relativistic semiclassical light-front bound-state equations in the usual Minkowsky space [32, 33], which is the boundary space of AdS$_5$. This connection gives an exact relation between the holographic variable z of AdS space and the invariant impact LF variable ζ in physical space-time [31]. This connection also implies that the light-front effective potential U in the LF Hamiltonian equations, corresponds to the modification of the infrared region of AdS space –usually described in terms of a dilaton profile: its specific form is given by superconformal quantum mechanics [35–39], which captures the relevant aspects of color confinement based on a universal emerging single mass scale $\kappa = \sqrt{\lambda}$ [40].

This new approach to hadron physics predicts universal linear Regge trajectories and slopes in both orbital angular momentum and radial excitation quantum numbers, the appearance of a massless pion in the limit of zero-mass quarks, and gives remarkable connections between the light meson and nucleon spectra [39, 40]. The superconformal approach has thus the advantage that mesons and nucleons are treated on the same footing, and the confinement potential is uniquely determined by the formalism. Remarkably, the meson spectrum and baryon spectrum are related by a simple shift of the orbital angular momentum $L_M = L_B + 1$. The QCD running coupling is also consistently described at both small and large Q^2 [41–43].

In this paper we will calculate the space-like nucleon electromagnetic (EM) form factors within the framework of LFHQCD [34]. In the gravity theory, FFs are computed from the overlap integral of normalizable modes, which represent the incoming and outgoing hadrons, convoluted with a non-normalizable mode which represents an electromagnetic current [44]. The EM current propagates into the infrared modified AdS space and generates an infinite number of poles. Thus, the FF in the gravity theory has the advantage that it generates the nonperturbative pole structure in the time-like region of the FF [34]. It is also possible to find a precise mapping between a "dressed" EM current propagating in a modified AdS space, and the LF QCD Drell-Yan-West expression for the form factor. In this case the resulting LFWF incorporates non-valence higher Fock states generated by the confined current [45]. The gauge/gravity duality also incorporates the connection between the twist-scaling dimension τ of the QCD boundary interpolating operators with the fall-off of the normalizable modes in AdS near its conformal boundary [46], consistent with leading-twist scaling; *i.e.*, in agreement with the power-law fall-off of the counting rules for hard scattering dynamics at large Q^2 [47, 48]. Here, the twist is defined as $\tau = N + L$, where N is the number of constituents and L is the relative angular momentum between the constituents.

When computing nucleon FFs one has to constrain the asymptotic boundary conditions of the leading fall-off of the form factors to match the twist of the nucleon's interpolating operator, *i.e.* $\tau = 3$, to represent the fact that at high virtualities the nucleon is essentially a system of 3 weakly interacting partons. For a multi-quark bound state, the LF invariant impact variable ζ corresponds to a system composed of an active quark plus a spectator "cluster". For example, for a three-quark nucleon state, the three-body problem is reduced to an effective two-body problem where two of the constituents form a diquark cluster [34]. This follows from the holographic approach, where one has only one variable to describe the internal structure of the nucleon. This means, for example, that for a proton the bound state behaves as a quark-diquark system, *i.e.*, like a twist-2 system. However, at large momentum transfer, or at small distances, where the cluster is resolved into its individual constituents, the nucleon is governed by twist-3, in contrast to the nonperturbative region where it is approximated by twist-2. A similar feature appears in the study of sequential decay chains in baryons [49], which are sensitive to the short distance behavior of the wave function. The eigenfunctions which follows from computing the spectrum of the nucleon are leading twist-2, since essentially the nonperturbative eigenvalue equation describes the dynamics of a quark-diquark cluster. At very short distances, the bound state is a twist-3 as the two constituents particles in the diquark are resolved. This different scaling behavior of the structure functions at low and high virtualities can be properly addressed from the LF cluster decomposition for bound states [50–52] and will be discussed below.

In contrast to the prototypical example of the gauge/gravity duality, the AdS/CFT correspondence [53], where the baryon is identified as an $SU(N_C)$ singlet bound state of N_C quarks in the large-N_C limit, in the LFHQCD formalism, baryons are computed for $N_C = 3$, not $N_C \to \infty$. The nucleon AdS solutions have both a $L = 0$ and a $L = 1$ components with equal weight. Therefore we use both twist $\tau = 3$ and $\tau = 3 + L = 4$ to compute the valence contribution to the nucleon form factors. The space-like Pauli FF of the nucleons arises from the overlap of $L = 0$ and $L = 1$ AdS wavefunctions [1]. It is important to recall that the spin-flavor symmetry is not contained in the holographic principles, which essentially describes the Q^2 scale dependence for a given twist, and has to be imposed from the symmetries of the quark model under consideration. In the present work we use the SU(6) spin-flavor symmetry and examine possible breaking effects of this symmetry.

In holographic QCD gluonic degrees of freedom only arise at high virtuality, whereas gluons with small virtuality are sublimated in the effective confining potential [54]. Thus, Fock states of hadrons can have any number of extra $q\bar{q}$ pairs created by the confining potential. One can extend the formalism in order to examine the contribution of higher-Fock states using the holographic framework described here. Indeed, it was shown in Refs. [34, 55] that higher Fock components are essential to describe the rather complex time-like structure of the pion FF. Contribution from the higher-twist components ($q\bar{q}$ and $q\bar{q}q\bar{q}$) has also been considered to describe the pion transition FF in $\gamma\gamma* \to \pi^0$ [45]. Contributions from three, four, and five parton components in the nucleon Fock expansion have been considered in the holographic QCD framework in Ref. [56], but the experimental data of a different combination of Sachs FFs, such as $\mu_p G_E^p / G_M^p$, could not be successfully described. More recent work [57] by the same group can describe the experimental data of nucleon FFs well, but the number of parameters required to describe the experimental data is large, typically about 8 free parameters and, additionally, an explicit scale dependence of a given process is introduced. Other attempts to describe the flavor nucleon FFs in AdS/QCD also require a large number of parameters [58]. On the other hand, simple holographic models –which essentially include only the valence contribution, fail to systematically account for all the properties of the nucleon FFs and their flavor decomposition [34, 59]. As we will show below, higher-twist components in the Fock expansion are in general needed for an accurate description of the nucleon FFs, and, in fact, this can be achieved with a minimal number of parameters in the LF holographic framework.

HADRON FORM FACTORS IN LIGHT-FRONT HOLOGRAPHIC QCD

In the five-dimensional gravity theory the EMFF of a hadronic bound state with twist-τ has the form [44]

$$F(Q^2) = \int \frac{dz}{z^3} \, V(Q^2, z) \, \Phi_\tau^2(z), \tag{1}$$

where z is the fifth-dimensional holographic variable. At small values of $z \sim 1/Q$, where the EM current $V(Q^2, z)$ has its important support, the hadron modes scale as $\Phi_\tau \sim z^\tau$, and the hard-scattering power-scaling behavior [47, 48] is recovered [46]

$$F(Q^2) \to \left[\frac{1}{Q^2}\right]^{\tau-1}. \tag{2}$$

In our approach the twist-τ hadronic wave functions are

$$\Phi_\tau(z) = \sqrt{\frac{2}{\Gamma(\tau-1)}} \, \kappa^{\tau-1} z^\tau e^{-\kappa^2 z^2/2}, \tag{3}$$

and the EM current $V(Q^2, z)$ is the solution of the wave-equation of a vector current in AdS_5, with modifications determined by the superconformal algebra, which are the same as used in spectroscopy. It has the integral representation [60]

$$V(Q^2, z) = \kappa^2 z^2 \int_0^1 \frac{dx}{(1-x)^2} \, x^{Q^2/4\kappa^2} e^{-\kappa^2 z^2 x/(1-x)}. \tag{4}$$

Since the integrand in (4) contains the generating function of the associated Laguerre polynomials L_n^k, it can also be expressed as a sum of poles [60]

$$V(Q^2, z) = 4\kappa^4 z^2 \sum_{n=0}^{\infty} \frac{L_n^1(\kappa^2 z^2)}{M_n^2 + Q^2}, \tag{5}$$

with the poles located at $-Q^2 = M_n^2 = 4\kappa^2(n+1)$. To compare with the data, one has, however, to shift the poles in Eq. (5) to their physical location at the vector meson masses [34]

$$-Q^2 = M_{\rho_n}^2 = 4\kappa^2\left(n + \frac{1}{2}\right), \; n = 0, 1, 2, ... \quad . \tag{6}$$

The ground-state mass of the ρ meson, $M_{\rho_{n=0}} \equiv M_\rho = 0.775\,\mathrm{GeV}$ gives the value of $\kappa = M_\rho/\sqrt{2} = 0.548\,\mathrm{GeV}$, where $\kappa = \sqrt{\lambda}$ is the emerging confinement scale [37].

Substituting (3) and (4) in Eq. (1), we find for integer twist the result [34, 61, 62]

$$F_\tau(Q^2) = \frac{1}{\left(1 + \frac{Q^2}{M^2_{\rho_{n=0}}}\right)\left(1 + \frac{Q^2}{M^2_{\rho_{n=1}}}\right)\cdots\left(1 + \frac{Q^2}{M^2_{\rho_{n=\tau-2}}}\right)}, \tag{7}$$

expressed as a product of $\tau - 1$ poles along the vector meson Regge radial trajectory in terms of the ρ vector meson mass M_ρ and its radial excitations. For a pion, for example, the leading twist is two, and thus the corresponding FF has a monopole form [62]. It is interesting to notice that even if an infinite number of poles appears in the "dressed" EM current (5), for a twist τ-bound state the corresponding form factor is given by a product of $\tau - 1$ poles, thus establishing a precise relation between the twist of each Fock state in a hadron and the number of poles in the hadron FF. As expected from this construction, the analytical form (7) incorporates the correct hard scattering twist scaling behavior at high virtuality and also vector meson dominance (VMD) at low energy [63].

In LF quantization [64], a hadron state $|H\rangle$ is a superposition of an infinite number of Fock components $|N\rangle$, $|H\rangle = \sum_N \psi_{N/H}|N\rangle$, where $\psi_{N/H}$ represents the N-component LFWF with normalization $\sum_N |\psi_{N/H}|^2 = 1$. Thus the FF is given by the sum over an infinite number of terms

$$F_H(Q^2) = \sum_\tau P_\tau F_\tau(Q^2), \tag{8}$$

where F_τ is given by Eq. (7). Since the charge is a diagonal operator, only amplitudes with an identical number of components in the initial and final states contribute to the sum in Eq. (8). Normalization at $Q^2 = 0$, $F_H(0) = 1$, $F_\tau(0) = 1$ (Eq. (7)) implies that $\sum_\tau P_\tau = 1$ if all possible states are included. (In general $\tau = N + L$.)

Conventionally, the analysis of FFs is based on the generalized vector meson dominance model where the EMFF is written as a single-pole expansion

$$F_H(Q^2) = \sum_\lambda C_\lambda \frac{M_\lambda^2}{M_\lambda^2 - Q^2}, \tag{9}$$

with a dominant contribution from the ρ vector meson plus contributions from the higher resonances ρ', ρ'', ρ''', ..., etc. [65]. Comparison of Eqs. (8) and (9) allow us to determine the coefficients C_λ in terms of the probabilities P_τ for each Fock state and the vector meson masses $M^2_{\rho_n}$. The advantage, however, of the holographic approach is that no fine tuning of the coefficients C_λ is necessary since the correct scaling is incorporated from the onset, the expansion coefficients P_λ then have a clear physical meaning in terms of the probability of each Fock component.

The expression for the form factor (7) contains a cluster decomposition: the hadronic FF factorizes into a product of twist-two FFs evaluated at different scales [52]:

$$F_{\tau=N+L}(Q^2) = F_{\tau=2}\left(Q^2\right)\, F_{\tau=2}\left(\tfrac{1}{3}Q^2\right) \cdots F_{\tau=2}\left(\tfrac{1}{2N-3}Q^2\right). \tag{10}$$

In the case of a baryon, for example, the Dirac FF of the twist-3 valence quark-diquark state $F_1(Q^2) = F_{\tau=2}\left(Q^2\right)\, F_{\tau=2}\left(\frac{1}{3}Q^2\right)$ corresponds to the factorization of the proton FF as a product of a point-like quark and composite diquark FFs. The identical twist-3 expression from Eq. (7) is described by the product of two poles consistent with leading-twist scaling, $Q^4 F_1(Q^2) \sim$ const, at high momentum transfer.

A SIMPLE LIGHT-FRONT HOLOGRAPHIC MODEL FOR NUCLEON FORM FACTORS

In the higher dimensional gravity theory nucleons are described by plus and minus wave functions Ψ_+ and Ψ_- corresponding to the positive and negative chirality of the nucleon [33, 34]

$$\Psi_+(z) \sim z^{\tau+1/2} e^{-\kappa^2 z^2/2}, \quad \Psi_-(z) \sim z^{\tau+3/2} e^{-\kappa^2 z^2/2}, \tag{11}$$

which represent orbital angular momentum $L = 0$ and $L = 1$ respectively and have identical normalization. The spin non-flip and spin flip nucleon elastic form factors F_1 and F_2 are then given in terms of Ψ_+ and Ψ_- [34],

$$F_\pm(Q^2) \sim \int \frac{dz}{z^4}\, V(Q^2, z)\, \Psi^2_\pm(z), \quad F_\pm(Q^2) \sim \int \frac{dz}{z^3}\, \Psi_+(z)\, V(Q^2, z)\, \Psi_-(z), \tag{12}$$

but their specific spin-flavor structure is not determined by holographic principles. As a simple procedure we will determine the spin-flavor structure of the Dirac form factors $F_1^{p,n}$ from SU(6) and normalize the Pauli Form factors $F_2^{p,n}$ to their static values χ_p and χ_n [34, 66].

Following Ref. [55] we will consider a simplified model where we only include the first two components in a Fock expansion of the nucleon LF function with no constituent dynamical gluons [54]

$$|N\rangle_{L=0} = \psi^{L=0}_{qqq/N}|qqq\rangle_{\tau=3} + \psi^{L=0}_{qqqq\bar{q}/N}|qqqq\bar{q}\rangle_{\tau=5} + \cdots , \tag{13}$$

$$|N\rangle_{L=1} = \psi^{L=1}_{qqq/N}|qqq\rangle_{\tau=4} + \psi^{L=1}_{qqqq\bar{q}/N}|qqqq\bar{q}\rangle_{\tau=6} + \cdots , \tag{14}$$

where $N = p, n$. The additional $q\bar{q}$ contribution to the nucleon wave function from higher Fock components is relevant at larger distances and is usually interpreted as a pion cloud.

We have performed a systematic evaluation of the relevance of higher Fock components in the nucleon FFs by extending the previous results in Ref. [34] for the Dirac and Pauli FFs. For example, for the proton Dirac FF we have determined the relevance of higher Fock components by writing $F_1^p(Q^2) = (1 - \alpha_p)\, F_{\tau=3}(Q^2) + \alpha_p\, F_{\tau=5}(Q^2)$, where α_p is the twist-5 probability $\alpha_p = P_{qqqq\bar{q}/p}$. It is found that $P_{qqqq\bar{q}/p}$ is very small, of the order of 1 %. Likewise, the contribution of higher Fock components to the Dirac neutron FF is of the order of 2 % and does not change significantly our previous results [34]. We thus drop the contribution of the higher Fock components to the spin non-flip nucleon FFs in the rest of our analysis, which gives us a considerable simplification. Within this approximation, thus considering only the effect of higher $q\bar{q}$ Fock components to the spin-flip nucleon FFs, we write

$$F_1^p(Q^2) = F_{\tau=3}(Q^2), \tag{15}$$

$$F_2^p(Q^2) = \chi_p[(1 - \gamma_p)F_{\tau=4}(Q^2) + \gamma_p F_{\tau=6}(Q^2)] \tag{16}$$

for the proton, where $\chi_p = 1.793$ is the proton anomalous moment, and

$$F_1^n(Q^2) = -\frac{1}{3}\left[F_{\tau=3}(Q^2) - F_{\tau=4}(Q^2)\right], \tag{17}$$

$$F_2^n(Q^2) = \chi_n\left[(1 - \gamma_n)F_{\tau=4}(Q^2) + \gamma_n F_{\tau=6}(Q^2)\right] \tag{18}$$

for the neutron, with $\chi_n = -1.913$. Eqs. (15) and (17) are the exact SU(6) results for the spin non-flip nucleon FFs in the valence configuration [34, 61], whereas (16) and (18) correspond to the extension of the phenomenological spin-flip nucleon FFs described in Refs. [34, 61] to incorporate the effect of twist-6 Fock components.

The inclusion of higher Fock states does not describe all of the available data for the neutron Dirac form factor. However, we shall show that the inclusion of one additional parameter R, which is required phenomenologically to compensate for the lack of a non-zero constraint at zero momentum transfer for F_1^n, does describe the data well. Indeed, the neutron Dirac FF is calculated from the difference of two normalizable wave functions, which vanishes at $Q^2 = 0$, and therefore, contrary to the other three FFs, namely F_1^p, F_2^p and F_2^n, the neutron Dirac FF does not have a non-zero constraint at $Q^2 = 0$. With this free parameter R we modify the expression for the neutron Dirac FF as,

$$F_1^n(Q^2) = -\frac{1}{3} R[F_{\tau=3}(Q^2) - F_{\tau=4}(Q^2)]. \tag{19}$$

The value $R = 2.08$ is required to give a proper matching to the available experimental data as shown in Fig. 1. Also, keeping in mind that the gauge-gravity duality does not determine the spin-flavor structure of the nucleons, which is conventionally included in the nucleon wave function using SU(6) spin-flavor symmetry, the departure of this free parameter R from unity may be interpreted as a SU(6) symmetry-breaking effects in the neutron Dirac FF. Indeed, the breaking of SU(6) flavor-spin symmetry has also been observed in a meson cloud model where mixed symmetry in the nucleon wave function was included to reproduce the experimental data [69]. The effect of SU(6) symmetry breaking on the neutron FFs was also investigated within a LF constituent quark model in Ref. [70].

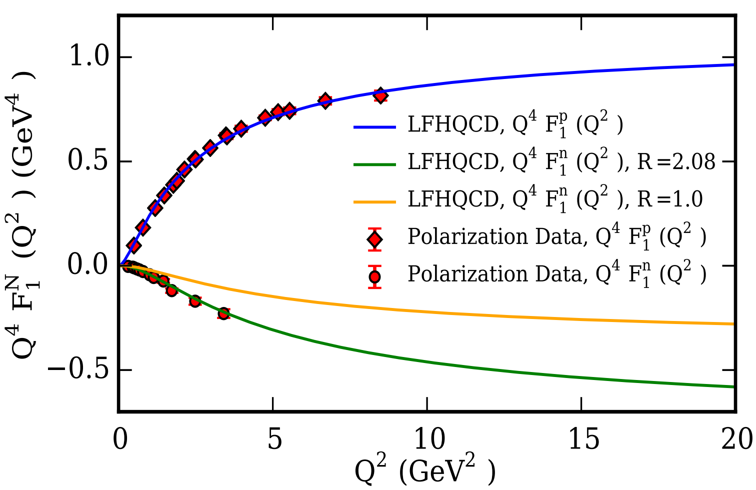

FIG. 1. Polarization measurements of F_1 for the proton and neutron [67, 68]. The blue line is the prediction of the proton Dirac FF from LFHQCD, Eq. (15) multiplied by Q^4. The orange and the green lines are predictions for the neutron Dirac FF, $Q^4 F_1^n(Q^2)$, from Eq. (17) and from Eq. (19) with the phenomenological factor $R = 2.08$, respectively.

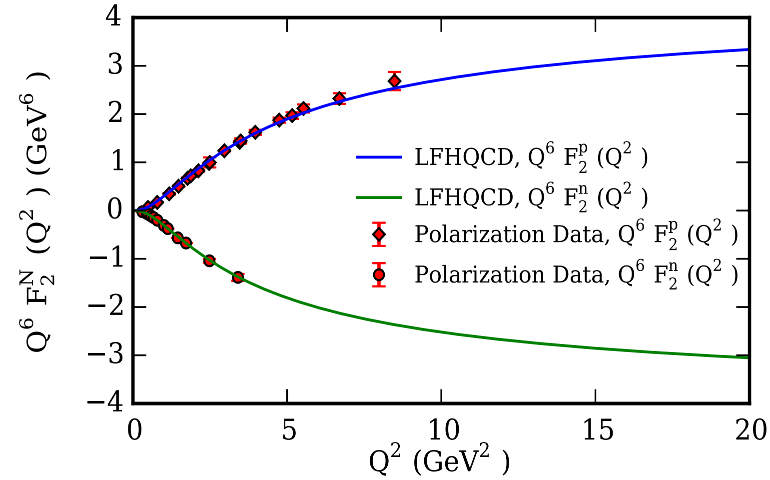

FIG. 2. Polarization measurements of F_2 for the proton and neutron [67, 68]. The blue line is the proton Pauli FF, $Q^6 F_2^p(Q^2)$ prediction, with $\gamma_p = 0.27$ in Eq. (16). The green line is the prediction for the neutron Pauli FF, $Q^6 F_2^n(Q^2)$, with $\gamma_n = 0.38$ in Eq. (18) from LFHQCD.

For the extended LFHQCD model of the nucleon FFs described here we estimate the errors from the uncertainty of the universal confinement scale κ. From the meson trajectories we obtain the value $\kappa_M = 0.524$ GeV, from the baryon trajectories $\kappa_B = 0.509$ GeV [40]. We show in Fig. 3 the band which represents the resulting estimated uncertainty of the model.

From Figs. 1 and 2, it is evident that the contribution of an additional $q\bar{q}$ pair, which embodies the pion cloud in the nucleon, only plays an important role in reproducing the experimental data for the spin-flip Pauli FFs. Such an effect of the pion cloud has been addressed in various calculations, for example in Ref. [71], to show that the same light-front model fails to reproduce the neutron electric Sachs FF G_E^n, unless the effect of the pion cloud is included. An estimate reported in Ref. [72] is that the pion loop effect results in a 6% and 12% increase in proton charge and magnetic radii, respectively. For the neutron, the effects are a 65% and a 19% increase in charge and magnetic radii, respectively. From the values of γ_p and γ_n in our LFHQCD calculation, it is also obvious that the effect of pion cloud on the Pauli FF is larger for the neutron.

Another pair of FFs, called the electric and the magnetic Sachs FFs can be defined using a combination of Dirac and Pauli FFs as the following:

$$G_E^{\gamma,N}(Q^2) = F_1^{\gamma,N}(Q^2) - \frac{Q^2}{4m_N^2} F_2^{\gamma,N}(Q^2), \tag{20}$$

$$G_M^{\gamma,N}(Q^2) = F_1^{\gamma,N}(Q^2) + F_2^{\gamma,N}(Q^2). \tag{21}$$

The results of the ratio $R_p = \mu_p G_E^p / G_M^p$ from the polarization experiments have triggered a revision of various nucleon models, and for $Q^2 > 10\,\mathrm{GeV}^2$, R_p may vanish or become negative. We present in Fig. 3 the LFHQCD prediction of R_p up to $Q^2 = 25\,\mathrm{GeV}^2$ and compare our result with selected world data of unpolarized cross section and polarization measurement experiments. It is clearly seen from Fig. 3 that LFHQCD predicts G_E^p to decrease more rapidly than G_M^p for $Q^2 > 1\,\mathrm{GeV}^2$, in agreement with the polarization measurements of R_p. The monotonic decrease of R_p with Q^2 demonstrates that the FFs are not simply the sum of dipole-like contributions from the up and down quarks.

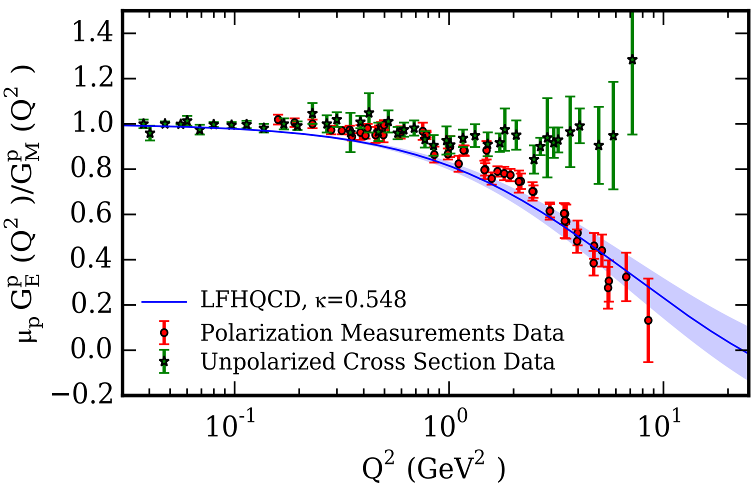

FIG. 3. LFHQCD prediction and comparison with selected world data of the ratio $R_p = \mu_p G_E^p / G_M^p$ from unpolarized cross section measurements from [12, 15, 16, 73] and polarization measurements from [7, 8, 74–78]. The LFHQCD prediction (blue line) from Eqs. (15) and (16) corresponds to the range $0 \leq Q^2 \leq 25\,\mathrm{GeV}^2$. The band represents an estimated theoretical uncertainty of the model. Our theoretical results agree well with the polarization data and are incompatible with the experimental results obtained from Rosenbluth separation.

In contrast to the proton FFs, the neutron FFs are more difficult to measure because there is no free neutron target. Experimental data of neutron FFs are available only up to relatively small values of Q^2. Since most nucleon form factor models such as [70, 79–81] cannot reproduce the experimental data for the ratio $R_n = \mu_n G_E^n / G_M^n$ for $Q^2 \geq 2\,\mathrm{GeV}^2$, it is desirable that one can parameterize the ratio R_n according to the available experimental data and predict its behavior at large Q^2. To this end, we compare in Figs. 4 and 5 the Sachs electric FF and the ratio R_n computed in LFHQCD with selected experimental data. From these results, one can see that LFHQCD can properly reproduce G_E^n and R_n in the whole range of available experimental data. We have also extended our results for the neutron FFs to higher Q^2 in order to compare with upcoming JLab experiments [26–29].

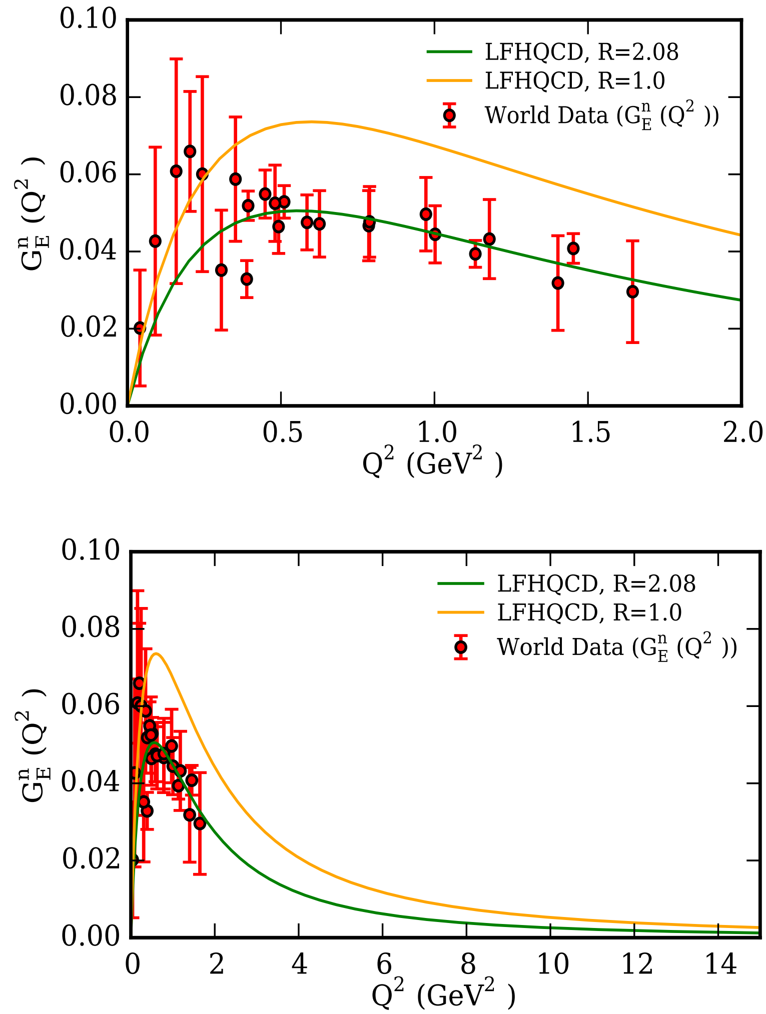

FIG. 4. Comparison of the neutron electric FF $G_E^n(Q^2)$ world data [82–92] with the LFHQCD prediction from Eqs. (17), (18) and (19).

We now compute magnetic root-mean-square (rms) radii of the nucleons from the definition $\langle r_M^2 \rangle = -\frac{6}{G_M(0)} \frac{dG_M(Q^2)}{dQ^2}|_{Q^2=0}$ and use $\langle r_E^2 \rangle = -6 \frac{dG_E(Q^2)}{dQ^2}|_{Q^2=0}$ to compute the charge mean-square radii of the nucleons. The LFHQCD predictions of different radii are compared with the experimental values in Table. I. In determining the charge and magnetic radii, we include the experimental uncertainty by fitting the experimental data and also the systematic uncertainties coming from the LFHQCD model itself. The statistical uncertainties

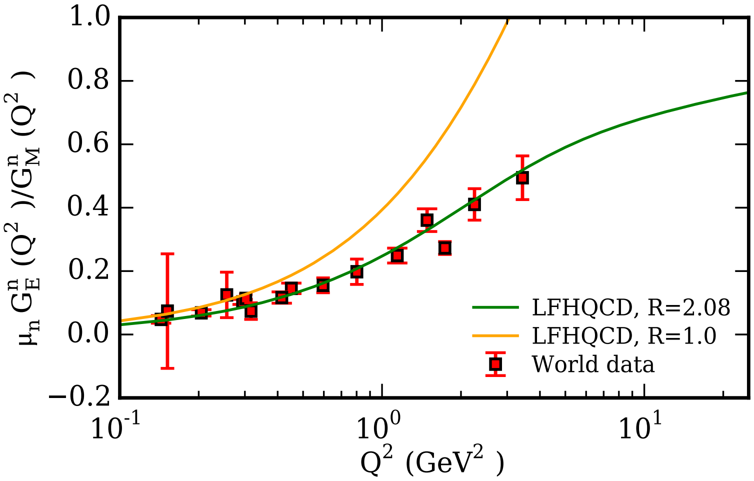

FIG. 5. Selected world data of the ratio $R_n = \mu_n G_E^n / G_M^n$ from double polarization experiments; recoil polarization with deuterium target, asymmetry with polarized deuterium target, and asymmetry with polarized ^{3}He target. The data points are taken from Refs. [67, 82, 83, 85, 89, 98–100]. For more data points and other theoretical predictions, see Ref. [5].

are related to the the uncertainties in the probabilities $\gamma_{p,n}$ in the fits of the experimental data with $\chi^2/d.o.f. \sim 0.9$ for different fits. We calculate the systematic uncertainties coming from the inclusion of higher Fock components and the parameter R (only for the neutron Dirac FF) in the FF expressions and also the uncertainty coming from the value of $\kappa_M = 0.524\,\text{GeV}$ and $\kappa_B = 0.509\,\text{GeV}$ obtained from the best fit to the Regge trajectories of mesons and baryons, respectively, including all the radial and orbital excitations [40]. In all, the radii computed from the LFHQCD model described here are in good agreement with the experimental measurements. It would be interesting to examine the effects of including quark masses in the FF expressions, which is a non-trivial task for the nucleon and higher Fock components, as well as a proper treatment of SU(6) flavor symmetry breaking.

We compare in Figs. 6 and 7 the flavor decomposition of various FFs obtained by using the LFHQCD results discussed here with the experimental results from Ref. [68]. In Fig. 7 the results are scaled by κ_q^{-1}, the limiting values of F_2^q at $Q^2 = 0$, *i.e.*, $\kappa_u = \mu_u - 2 = 1.67$ and $\kappa_d = \mu_d - 1 = -2.03$. A faster fall-off of the down quark contribution with Q^2 has been interpreted as a possible large contribution from the strange quark in the nucleon FFs in Ref. [93], and as a possible axial-vector diquark contribution in Refs. [94–96]. However, a recent high precision lattice QCD calculation [97] indicates that the strange

TABLE I. Comparison between the experimental values of the nucleon charge and magnetic radii and LFHQCD predictions from this work. The radii agree with the experimental values [101]. They also agree the predictions without contributions of higher Fock states made in [34].

Nucleon radii	Experimental values [101]	LFHQCD [This work]
$\sqrt{\langle r_E^p \rangle^2}$	0.8775(51) fm (ep CODATA)	0.801(38) fm
$\sqrt{\langle r_E^p \rangle^2}$	0.84087(39) fm (μp Lamb shift)	0.801(38) fm
$\sqrt{\langle r_M^p \rangle^2}$	0.777(16) fm	0.789(51) fm
$\langle (r_E^n)^2 \rangle$	-0.1161(22) fm^2	-0.073(29) fm^2
$\sqrt{\langle r_M^n \rangle^2}$	0.862(9) fm	0.796(54) fm

quark contribution to the proton EMFFs is quite small. The flavor FF data is also well described by Eqs. (15), (16), (18) and (19).

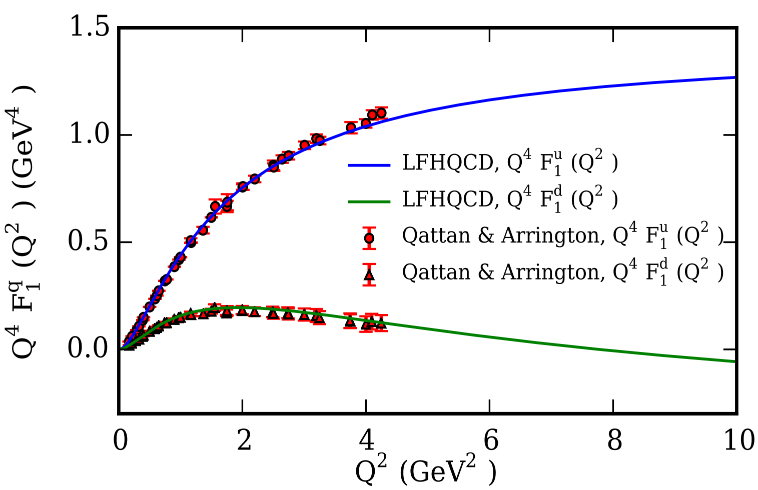

FIG. 6. LFHQCD prediction of the up and the down-quark contributions to the Dirac FF multiplied by Q^4. The data is from Ref. [68].

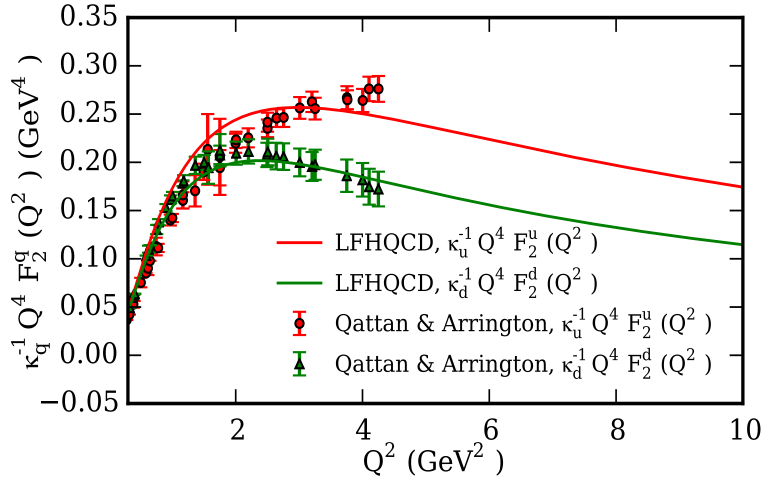

FIG. 7. LFHQCD prediction of the up and the down-quark contributions to the Pauli FF multiplied by $\kappa_q^{-1} Q^4$. The data is from Ref. [68].

Finally, it is important to recall that we have used a universal value for the confinement scale κ in deriving Eq. (7), but in fact the value of κ for the nucleon wave function, which is obtained from the nucleon slope, is slightly smaller than the value of κ in the EM current which is obtained from the rho mass [40]; it determines the slope of the vector meson trajectory of radial excitations –the poles in the EM current. Indeed, as described above, we have used the difference in the value of the scale κ, obtained from the average of all meson and all baryon trajectories to evaluate the theoretical uncertainty of our holographic model. Since the wave function determines the low energy bound state dynamics, we expect that observables which depend on the nucleon wave function, such as radii, are more sensitive to the lower value of κ, whereas at higher energies, where the amplitudes depend on the structure of the vector meson poles, we would expect that the data is better described by the slightly higher value of κ from the rho trajectory of radial excitations. A simple analysis of the data shows that this is indeed the case.

CONCLUSIONS

We have performed a complete analysis of the nucleon electromagnetic form factors in the space-like region in the framework of light-front holographic QCD. The essential dynamical element in our approach is the embedding of superconformal quantum mechanics in AdS, which fixes its deformation [38, 39]. The essential parameter in the model is the confinement scale $\kappa = \sqrt{\lambda}$ which is universal for the light hadrons and is determined by hadron spectroscopy. This universality holds to better than 10% accuracy [40], and has been used to describe a variety of fairly disconnected measurements, such as mass spectra of mesons and nucleons [34], form factors [34] and the infrared behavior of the strong QCD coupling α_{g1} [43]. This 10% departure from universality stems from the approximations used –such as neglecting quark masses– necessary to construct a calculable semiclassical model based on light front holographic QCD.

In the present article, we have considered the effects of the pion cloud, the contribution of which depends on the process, giving information on the relevance of higher Fock states. For the spin-flip Pauli form factors, we find an admixture of a five quark state of about 30% in the proton and about 40% in the neutron, and essentially no contribution of the higher Fock components to the spin-non-flip Dirac form factors. This relatively important contribution of the higher Fock components to the Pauli form factor of the nucleons is rather startling, and may be related to the fact that the spin-flip form factor corresponds to a change of light-front orbital angular momentum $L = 0 \to L = 1$. Likewise, the spin-conserving transition form factor of the proton to a Roper resonance, which can be interpreted as a radial transition from $n = 0 \to n = 1$, also requires higher Fock components to describe the low energy data [52].

Since the holographic model does not include spin-flavor structure, we have used the SU(6) symmetry to determine the effective electromagnetic couplings to the quarks for the spin non-flip form factors. This choice, however, is not accurate enough if cancellations are required, as in the case of the neutron Dirac form factor. In this case an additional parameter R has to be introduced (see Eq. (19)) which accounts for the lack of non-zero constraint of the neutron Dirac form factor at $Q^2 = 0$, possible SU(6) spin-flavor symmetry breaking effects and leading order cancellation between the squares of the wave functions at low Q^2 in the neutron. For the spin-flip form factors we use the experimental values of the anomalous magnetic moments as an effective coupling. Note that in order to obtain agreement with data, one has to apply a constant shift of the poles predicted by AdS/QCD in the expression for the dressed current to their physical locations. These shifted locations are then obtained from the bound state equations of the hadrons in this model.

The simple holographic model described here reproduces quite well the main features of the nucleon form factor data. Indeed, with the confinement scale fixed by hadron spectroscopy and the anomalous magnetic moments of proton and neutron fixed by experiment, we have introduced only 3 free parameters to describe an extensive set of data of the nucleon electromagnetic form factors. Our results for the nucleon form factors and their flavor decomposition, agree very well with existing data and provide predictions for the various nucleon form factors in the large momentum transfer regions, which have not been explored by the experiments yet. The charge and magnetic radii of the proton and neutron were extracted and found to agree, within the estimated uncertainty, with their experimental determinations. Our value of the proton charge radius favors the muon Lamb shift determination. In general, the approximations from LFHQCD lead to uncertainties of about 10%. Our results should be considered within this typical accuracy. The new JLab experiments will provide a valuable test for our light-front holographic framework which explores the nucleon structure with a minimal number of free parameters.

Since the analytic expression for the form factors (7) contains the time-like poles, it is especially suited to describe the nucleon form factors also in the time-like region, as has been done already for the pion form factor in Refs. [34, 55]. The formalism can also be applied to the nucleon transition form factors to other baryons. These points will be addressed separately.

Acknowledgments: R. S. S. thanks Keh-Fei Liu who provided insight and expertise that greatly assisted the research. S.J.B is supported by the Department of Energy, contract DE–AC02–76SF00515. SLAC-PUB-16806. A. D. is supported by the U.S. Department of Energy, office of Science, Office of Nuclear Physics under contract DE–AC05–06OR23177.

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