We study the helicity-independent generalized parton distributions of nucleons in the zero skewness case, based on a particular light-front quark model derived in a soft-wall AdS/QCD approach.

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I. INTRODUCTION

Generalized parton distributions (GPDs) are important objects containing essential information about the hadronic structure \[1\]–\[15\]. Unfortunately, given the non-perturbative nature of these functions, it is not possible to calculate them directly from Quantum Chromodynamics (QCD), and this situation has motivated the development of other ways to access the GPDs: namely, extraction from the experimental measurements of hard processes, direct calculation using lattice QCD, and different phenomenological models. The last procedure is based on parametrizations of the quark wave function or directly the GPDs, using constraints imposed by sum rules, which relate the parton distribution functions to nucleon electromagnetic form factors \[2\]–\[5\], or including a precise \(x\) behavior to improve the calculations of some hadron properties starting from QPDs. Some examples of this procedure can be found e.g. in \[7\]–\[15\].

Within the phenomenological models used recently some are based on the gauge/gravity duality, and are in general called holographic AdS/QCD models. They suppose the existence of a gravity theory dual to QCD, and this situation has motivated the development of other ways to access the GPDs: namely, extraction from the experimental measurements of hard processes, direct calculation using lattice QCD, and different phenomenological models. The last procedure is based on parametrizations of the quark wave function or directly the GPDs, using constraints imposed by sum rules, which relate the parton distribution functions to nucleon electromagnetic form factors \[2\]–\[5\], or including a precise \(x\) behavior to improve the calculations of some hadron properties starting from QPDs. Some examples of this procedure can be found e.g. in \[7\]–\[15\].

In Refs. \[38\]–\[39\] we applied the AdS/QCD correspondence to the nucleon GPDs and electromagnetic form factors, using both soft-wall and hard-wall holographical models. In particular, the soft-wall version qualitatively reproduced the small and large \(Q^2\) behavior of the GPDs. In the case of related quantities — nucleon form factors — the following results were achieved: i) we analytically reproduced their scaling at large values of Euclidean momentum squared \(Q^2\), consistent with quark counting rules \[44\]; ii) we systematically included the contributions of higher Fock states; iii) a reasonable description of hadronic factors and their ratios at both small and large \(Q^2\) was obtained. In Ref. \[45\] we proposed a light-front quark model based on phenomenological LFWF for the nucleon, which is motivated in a soft-wall AdS/QCD approach. We showed that this model produces the parton distributions and hadronic form factors consistent with quark counting rules and the Drrell-
Yan-West (DYW) duality [10]. We showed that the inclusion of the effects of the longitudinal wave function of nucleons is sufficient to get consistency with model-independent scaling laws. The main objective of this paper is to give an analysis of how to improve the description of quark distributions in the nucleon by including the effect of the longitudinal wave function of nucleons.

The paper is structured as follows. In Sec. II we discuss our approach. In Sec. III we present the numerical analysis of the quark distribution functions, magnetic densities and GPDs. Finally in Sec. IV we present our conclusions.

II. FRAMEWORK

We start by writing down the relations [4] between the nucleon Dirac $F^N_i$ and Pauli $F^N_2$ form factors, the form factors of valence quarks in nucleons ($F^q_i$ and $F^q_2$, $q = u, d$), and the valence quark GPDs ($\mathcal{H}^q$ and $\mathcal{E}^q$):

$$F^q_{i(v)}(Q^2) = \frac{2}{3} F^u(d)(Q^2) - \frac{1}{3} F^d(u)(Q^2) \quad (1)$$

and

$$F^q_i(Q^2) = \int_0^1 dx \mathcal{H}^q(x, Q^2), \quad (2)$$

$$F^q_2(Q^2) = \int_0^1 dx \mathcal{E}^q(x, Q^2). \quad (3)$$

At $Q^2 = 0$ the GPDs $\mathcal{H}^q$ and $\mathcal{E}^q$ reduce to the valence $q_v(x)$ and magnetic $\mathcal{E}^q(x)$ quark densities

$$\mathcal{H}^q(x, 0) = q_v(x), \quad \mathcal{E}^q(x, 0) = \mathcal{E}^q(x), \quad (4)$$

which are normalized to the number of valence $u$ and $d$ quarks in the proton (in the case of $q_v$ distributions) and to the anomalous magnetic moment of the quark (in the case of $\mathcal{E}^q$ distributions), respectively:

$$\int_0^1 dx q_v(x) = 2, \quad \int_0^1 dx d_v(x) = 1, \quad \kappa_q = \int_0^1 dx \mathcal{E}^q(x). \quad (5)$$

The constants $\kappa_q$ are related to the anomalous magnetic moments of nucleons $k_N = F^N_2(0)$ [5]:

$$\kappa_u = 2\kappa_p + \kappa_n = 1.673, \quad \kappa_d = \kappa_p + 2\kappa_n = -2.033. \quad (6)$$

In Ref. [45] we proposed a light-front quark model for nucleons which is motivated by the soft-wall AdS/QCD approach developed in Refs. [25, 30] and is consistent with quark counting rules and DYW duality [10]. In particular, we showed that the quark GPDs in the nucleon are given in the form [45]:

$$\mathcal{H}^q(x, Q^2) = q_v(x) f(x, Q^2), \quad (7)$$

$$\mathcal{E}^q(x, Q^2) = \mathcal{E}^q(x) f(x, Q^2), \quad (8)$$

where the quark densities at large $x \to 1$ behave in accordance with the scaling laws

$$q_v(x) \sim (1 - x)^3, \quad \mathcal{E}^q(x) \sim (1 - x)^5. \quad (9)$$

The function $f(x, Q^2)$ is universal for both types of quark densities and as in [7]-[14] it contains both the form factors, the $Q^2$-dependence and to implement the DYW duality by taking [45]:

$$f(x, Q^2) = \exp \left[ -\frac{Q^2}{4\kappa^2} \log(1/x)(1 - x) \right], \quad (10)$$

where $\kappa$ is the scale parameter.

As in Ref. [11], our function $f(x, Q^2)$ has a clear interpretation in the framework of the light-front formalism [17], since it corresponds to the modified Regge ansatz proposed in Ref. [7]. The Dirac and Pauli quark form factors are obtained in terms of LFWFs by

$$F^q_i(Q^2) = \int_0^1 dx \int \frac{d^2 k_\perp}{16\pi^3} \left[ \psi^+_{i+q}(x, k_\perp) \psi^+_{i+q}(x, k_\perp) \right. \right.$$  

$$+ \left. \psi^+_{i+q}(x, k_\perp^\prime) \psi^+_{i+q}(x, k_\perp) \right], \quad (11)$$

$$F^q_2(Q^2) = -\frac{2M_N}{q^2 - i\epsilon^2} \int_0^1 dx \int \frac{d^2 k_\perp}{16\pi^3} \left[ \psi^+_{i+q}(x, k_\perp^\prime) \psi^+_{i+q}(x, k_\perp) \right. \right.$$  

$$+ \left. \psi^+_{i+q}(x, k_\perp^\prime) \psi^+_{i+q}(x, k_\perp) \right], \quad (11)$$

where $k_\perp^\prime = k_\perp + (1 - x)q_\perp$. In these equations $M_N$ is the nucleon mass, $\psi^N_{\lambda q}(x, k_\perp)$ are the LFWFs with specific helicities of the nucleon $\lambda_N = \pm$ and struck quark $\lambda_q = \pm$, where plus and minus correspond to $+\frac{1}{2}$ and $-\frac{1}{2}$, respectively. Working in the frame $q = (0, 0, q_\perp)$ we have that $-q^2 = Q^2 = q_\perp^2$.

The LFWFs $\psi^N_{\lambda q}(x, k_\perp)$ are defined as [45].
\[ \psi_{\pm q}(x, \mathbf{k}_\perp) = \begin{cases} \frac{m_{1q} + xM_N}{x} \varphi_q(x, \mathbf{k}_\perp), & \text{for } \psi^+_{\pm q}(x, \mathbf{k}_\perp) \\ -\frac{k^1 + i k^2}{x} (1 - x) \mu_q \varphi_q(x, \mathbf{k}_\perp), & \text{for } \psi^-_{\pm q}(x, \mathbf{k}_\perp) \end{cases} \]

(12)

where \( m_{1q} \) is the mass of the struck quark. The wave function \( \varphi_q(x, \mathbf{k}_\perp) \) can be taken from recent AdS / QCD work, and is given by the product of transverse and longitudinal wave functions \[\psi\] [33, 45].

The invariant mass is

\[ M^2 = M_0^2 + \frac{k_{\perp}^2}{x(1 - x)} + \frac{k_{\perp}^2 + m_{1q}^2}{1 - x} \]

(14)

and

\[ N_q = \frac{4\pi \sqrt{n_q}}{\kappa M_N} \int_0^1 dx x^{2\beta_{1q}} (1 - x)^{3 + 2\beta_{2q}} \times \left[ R_q(x) e^{-\frac{M_q^2}{x^2} x \log(1/x)} \right]^{-1/2}, \]

\[ R_q(x) = \left( 1 + \frac{m_{1q}}{xM_N} \right)^2 + \frac{\kappa^2 \mu_q^2}{M_N^2} \frac{(1 - x)^3}{x^2 \log(1/x)} \]

(15)

is the normalization constant and \( \beta_{1q} \) and \( \beta_{2q} \) are the flavor dependent parameters (quark masses). The parameters \( \mu_q \ (q = u, d) \) are fixed through the nucleon magnetic moments.

In the LFWF \( \psi_{\pm q}(x, \mathbf{k}_\perp) \) we included the extra factor \( (1 - x) \) in order to generate an extra power \( (1 - x)^2 \) in the helicity-flip parton density \( \mathcal{E}^q(x) \sim (1 - x)^5 \) in comparison to the helicity non-flip density \( q_v(x) \sim (1 - x)^3 \).

III. PARTON DISTRIBUTIONS IN NUCLEONS

Our results for the quark Dirac and Pauli form factors are \[\phi\] [45].

\[ F_1^q(Q^2) = C_q \int_0^1 dx x^{2\beta_{1q}} (1 - x)^{3 + 2\beta_{2q}} \times \left[ \exp\left[-\frac{Q^2}{4\kappa^2} \log(1/x) (1 - x) \right] \right] \times \exp\left[-\frac{M_q^2}{\kappa^2} x \log(1/x) \right], \]

(16)

\[ F_2^q(Q^2) = C_q \int_0^1 2dx x \mu_q \left( 1 + \frac{m_{1q}}{xM_N} \right)^2 x^{2\beta_{1q}} (1 - x)^{5 + 2\beta_{2q}} \times \left[ \exp\left[-\frac{Q^2}{4\kappa^2} \log(1/x) (1 - x) \right] \right] \times \exp\left[-\frac{M_q^2}{\kappa^2} x \log(1/x) \right], \]

where

\[ C_q = N_q^2 \left( \frac{\kappa M_N}{4\pi} \right)^2 \]

\[ = n_q \left[ \int_0^1 dx x^{2\beta_{1q}} (1 - x)^{3 + 2\beta_{2q}} \times \left[ \exp\left[-\frac{M_q^2}{x^2} x \log(1/x) \right] \right]^{-1} \right], \]

\[ R_q(x, Q^2) = R_q(x) - \frac{Q^2}{4M_N^2} \frac{\mu_q^2}{x^2} (1 - x)^4. \]

(17)

TABLE I: Parameters used for three different fits in the parton distributions \( q_v(x) \). In all cases we consider \( \kappa = 350 \text{ MeV} \).

| Model | \( m_q \) [MeV] | \( m_D \) [MeV] | \( A \) | \( \rho_1 \) | \( \rho_2 \) |
|-------|----------------|----------------|------|--------|--------|
| I     | 0              | 0              | 4.76 | -0.18  | 2.56   |
| II    | 7              | 100            | 105.14 | 1.41    | 5.93   |
| III   | 300            | 600            | 63.67 | 1.15   | 2.74   |

TABLE II: Parameters used for three different fits in the parton distributions \( q_d(x) \). In all cases we consider \( \kappa = 350 \text{ MeV} \).

| Model | \( m_q \) [MeV] | \( m_D \) [MeV] | \( A \) | \( \rho_1 \) | \( \rho_2 \) |
|-------|----------------|----------------|------|--------|--------|
| I     | 0              | 0              | 2.87  | -0.21  | 3.76   |
| II    | 7              | 100            | 33.06 | 1.63   | 5.71   |
| III   | 300            | 600            | 27.30 | 1.10   | 3.42   |
It means that the quark densities are given by

\[ q_v(x) = C_q x^{2\beta_{1q} + \beta_{2q}} R_q(x) e^{-\frac{\mu_q^2}{x} \log(1/x)}, \] (18)

\[ E_q(x) = C_q x^{2\beta_{1q} + \beta_{2q}} P_q(x) e^{-\frac{\mu_q^2}{x} \log(1/x)}, \] (19)

where

\[ P_q(x) = \frac{2\mu_q}{x} \left( 1 + \frac{m_{1q}}{x M_N} \right). \] (20)

We remind again that the parameters \( \beta_{1q} \) and \( \beta_{2q} \) define the flavor structure of the longitudinal part of the hadronic LFWF. In Ref. [33] we showed that the longitudinal part of the hadronic LFWF is an essential ingredient for generating the mechanism of explicit breaking of chiral symmetry in the sector of light quarks and imposing the constraints required by the heavy quark symmetry. See also other recent papers [48, 49] discussing the role of the longitudinal LFWF. Therefore, it is interesting to study the sensitivity of the quark densities to the choice of the parameters \( \beta_{1q} \) and compare them with global fits.

We consider three models with usually assigned values for the quark \( m_q \) and diquark \( m_D \) masses. In model I we consider the case without massive quarks, in model II we consider a current quark and in model III we use a constituent quark mass.

We start with the analysis of the fit I

\[ q_v(x) = A_q x^{\rho_{1q}} (1 - x)^{\rho_{2q}}, \] (21)

\[ E_q(x) = D_q x^{\rho_{1q}} (1 - x)^{2 + \rho_{2q}}, \] (22)

where \( A_q \) and \( D_q \) are the normalization constants fixed from the conditions [5].

The sets of free parameters \( \rho_{1q} \) are fixed by comparison with the parton densities that consider the global fit of MRST2002 [50]. Notice that in the literature there
exist several alternative parametrizations for the quark distribution functions, see e.g. Refs. [11][14].

For models II and III we use

\[ q_u(x) = A_q x^{\rho_1} (1-x)^{\rho_2} R_q(x) e^{-\frac{x^2}{2} \frac{e}{x} \log(1/x)} , \]

\[ E_q(x) = D_q x^{\rho_1} (1-x)^{2+\rho_2} P_q(x) e^{-\frac{x^2}{2} \frac{e}{x} \log(1/x)} . \]

The parameters for each fit are summarized in Tables I and II. In Figs. 1 and 2 we show the parton distributions calculated with these values. For all cases we use \( \kappa = 350 \text{ MeV} \) as in [39].

As for example in [11][14] a standard representation of \( E_q(x) \) is

\[ E_u(x) = \frac{k_u}{N_u} (1-x)^{\kappa_1} u(x) \]

\[ E_d(x) = \frac{k_d}{N_d} (1-x)^{\kappa_2} d(x) , \]

where \( \kappa_1 = 1.53 \) and \( \kappa_2 = 0.31 \), and according to the normalization

\[ k_u = 1.673, \quad k_d = -2.033, \quad N_u = 1.53, \quad N_d = 0.946. \]

We compare our results to these expressions for \( E_q(x) \). Fig. 2 summarizes our results and the comparison for the magnetic densities.

IV. CONCLUSIONS

Starting from a light-front quark model we derived nucleon PDFs and GPDs consistent with scaling rules. Then we gave a numerical analysis of quark PDFs for three parameter sets. In version I we considered the holographical model without including massive quarks. In models II and III quark masses, current or constituent ones, are included.

In our expressions for \( q(x) \) we obtain a good representation in each parameter version, as evident from Fig. 1. For the \( E_q(x) \) of Fig. 2 the situation is different, we get agreement with the standard representations of Eqs. [25] and [26] just in model III.

If we consider in the expression of [24] an arbitrary index \( \sigma_2 \) (instead of \( 2+\rho_2 \)) the agreement with \( E_q(x) \) can be improved but at the cost of a new parameter.

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