$\gamma N \rightarrow N^*(1535)$ transition in soft-wall AdS/QCDThomas Gutsche,¹ Valery E. Lyubovitskij,^{1,2,3} and Ivan Schmidt²¹*Institut für Theoretische Physik, Universität Tübingen, Kepler Center for Astro and Particle Physics, Auf der Morgenstelle 14, D-72076 Tübingen, Germany*²*Departamento de Física y Centro Científico Tecnológico de Valparaíso-CCTVal, Universidad Técnica Federico Santa María, Casilla 110-V, Valparaíso, Chile*³*Department of Physics, Tomsk State University, 634050 Tomsk, Russia*

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We present a study of the $N^*(1535)$ resonance electroexcitation in a soft-wall AdS/QCD model. Both the transverse $A_{1/2}^p$ and longitudinal $S_{1/2}^p$ helicity amplitudes are calculated resulting in good agreement with data and with the MAID parametrization.

DOI: [10.1103/PhysRevD.101.034026](https://doi.org/10.1103/PhysRevD.101.034026)**I. INTRODUCTION**

The study of electromagnetic transitions between the nucleon and its resonances is an important area of research in hadronic physics, because it can provide essential information about the structure and basic properties of the involved hadrons [1–7]. In fact, right now there are recent experiments at JLab [3–5] and at MAMI [6,7] aiming for a precise determination of the electrocouplings of nucleon resonances and nucleons, which should also be complemented by theoretical studies of these physical properties (for a review see, e.g., Refs. [2,6]).

In the present paper we continue our study of nucleon resonances in soft-wall AdS/QCD. An advantage of this approach is that it contains the correct power scaling description of form factors and helicity amplitudes at large Q^2 [8], but also provides good agreement with data at low and intermediate Q^2 . The preceding study of nucleon resonances in AdS soft-wall approaches focused on the nucleon-Roper transition, see Refs. [9–14]. First, in Ref. [9] the Dirac form factor, which defines the electromagnetic nucleon-Roper transition, was predicted in holographic light-front QCD. In Ref. [10] we proposed and extended the formalism to the description of all nucleon resonances with adjustable quantum numbers in soft-wall AdS/QCD. In a first application we looked at a comprehensive description of Roper-nucleon transition properties, including form factors, helicity amplitudes and charge radii. In Ref. [13] we showed that the description of the electromagnetic form factors of the nucleon and of the Roper

resonance can be sufficiently improved using an extended version of the effective action of soft-wall AdS/QCD. This was achieved by including additional nonminimal terms into the action consistent with gauge invariance, finally resulting in important contributions to the momentum dependence of the form factors and helicity amplitudes. Moreover, in Ref. [14] we presented a description of electromagnetic properties of the nucleon and the Roper at small finite temperatures using the formalism developed in Ref. [15]. In the present manuscript we extend our formalism, previously developed for the study of the Roper resonance, to the negative-parity state $N^*(1535)$.

The electromagnetic nucleon to $N^*(1535)$ transition has been studied in several theoretical approaches. In Ref. [16] the electromagnetic form factors and the helicity amplitudes of the $N^*(1535)$ excitation were calculated in a constituent quark model and formulated in light front dynamics. The electroexcitation of the $N^*(1535)$ resonance has also been studied in Ref. [17], using two methods: dispersion relations and the isobar model. The unitary isobar model MAID has been developed to analyze the world data of pion photoproduction and electroproduction, including the $N^*(1535)$ resonance [18]. The evaluation of the electromagnetic helicity form factors for the electroproduction of the $N^*(1535)$ resonance, considered as a dynamically generated resonance, has been addressed in Ref. [19]. In Ref. [20] the $N^*(1535)$ resonance electroproduction has been studied in the framework of light-cone sum rules, which combine perturbative relations and duality. In Ref. [21] the $\gamma^* N \rightarrow N(1535)$ transition form factors were analyzed in the context of QCD sum rules. In Ref. [22] this resonance was studied using a relativistic constituent quark model. In Refs. [23,24] several methods (semirelativistic approximation, empirical parametrization, a new mechanism for $\gamma \rightarrow q\bar{q}$ coupling, inclusion of the lowest lying pentaquark components $qqqq\bar{q}$) have been

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proposed for a better understanding of the $\gamma N \rightarrow N^*(1535)$ transition. Most of the approaches (except in the MAID [18] analysis) fail in the description of the longitudinal $S_{1/2}$ amplitude in the low Q^2 domain. In Refs. [25,26] a unified description of the electroexcitation of the Roper and $N(1535)$ resonances has been done in the light-front quark model. A reasonable description of the helicity amplitudes at intermediate and high Q^2 has been obtained.

The main aspect of the present paper is that we can indicate a mechanism which leads to reasonable results for the helicity amplitudes also in the low- Q^2 regime: inclusion of the minimal coupling of the nucleon and the $N^*(1535)$ Fock components with the same twist dimension. The nucleon has orbital momentum $L = 0$, while the negative-parity resonance $N^*(1535)$ has $L = 1$. Therefore, the leading twists for the nucleon and the $N^*(1535)$ are $\tau = 3$ and $\tau = 4$, respectively. Then the only possibility is that the leading twists of the nucleon and $N^*(1535)$ couple with the photon via a nonminimal coupling, since the minimal one is forbidden by current conservation. But we find that the minimal coupling between the nucleon and the $N^*(1535)$ is possible for equal twists, which means that the leading minimal electromagnetic coupling between nucleon and $N^*(1535)$ occurs for $\tau_N = \tau_{N^*(1535)} = 4$. Inclusion of this particular coupling helps to improve the description of both helicity amplitudes $A_{1/2}$ and $S_{1/2}$ at low Q^2 .

The paper is organized as follows. In Sec. II we briefly discuss our formalism. In Sec. III we present the analytical calculation and the numerical analysis of electromagnetic form factors and helicity amplitudes of the nucleon- $N(1535)$ transition. Finally, Sec. IV contains our summary and conclusions.

II. FORMALISM

In this section we briefly review our approach [10,13,27,28]. We start with the definition of the conformal Poincaré metric,

$$g_{MN}x^Mx^N = \epsilon_M^a \epsilon_N^b \eta_{ab} x^M x^N = \frac{1}{z^2} (dx_\mu dx^\mu - dz^2), \quad (1)$$

where $\epsilon_M^a = \delta_M^a/z$ is the vielbein, and we define $g = |\det(g_{MN})| = 1/z^{10}$ as the magnitude of the determinant of g_{MN} .

The soft-wall AdS/QCD action S for the nucleon $N = (p, n)$ and the $N^*(1535)$ resonance [in the following we use the notation $N^* = (N_p^*, N_n^*)$] including photons is constructed in terms of the dual spin-1/2 fermion and vector fields. These fields have constrained (confined) dynamics in AdS space due to the presence of a background field—dilaton field $\varphi(z) = \kappa^2 z^2$, where κ is its scale parameter.

The action S contains a free part S_0 , describing the confined dynamics of AdS fields, and an interaction part

S_{int} , describing the interactions of fermions with the vector field [below, for simplicity, we only display the coupling of N and $N^*(1535)$ to the vector field]

$$\begin{aligned} S &= S_0 + S_{\text{int}}, \\ S_0 &= \int d^4x dz \sqrt{g} e^{-\varphi(z)} \{ \mathcal{L}_N(x, z) + \mathcal{L}_{N^*}(x, z) + \mathcal{L}_V(x, z) \}, \\ S_{\text{int}} &= \int d^4x dz \sqrt{g} e^{-\varphi(z)} \mathcal{L}_{VNN^*}(x, z). \end{aligned} \quad (2)$$

$\mathcal{L}_N$, $\mathcal{L}_{N^*}$, $\mathcal{L}_V$ and $\mathcal{L}_{VNN^*}$ are the free and interaction Lagrangians, respectively, and are written as

$$\begin{aligned} \mathcal{L}_N(x, z) &= \sum_{i=+, -; \tau} c_\tau^N \bar{\psi}_{i, \tau}^N(x, z) \hat{\mathcal{D}}_i(z) \psi_{i, \tau}^N(x, z), \\ \mathcal{L}_{N^*}(x, z) &= \sum_{i=+, -; \tau} c_{\tau+1}^{N^*} \bar{\psi}_{i, \tau+1}^{N^*}(x, z) \hat{\mathcal{D}}_i(z) \psi_{i, \tau+1}^{N^*}(x, z), \\ \mathcal{L}_V(x, z) &= -\frac{1}{4} V_{MN}(x, z) V^{MN}(x, z), \\ \mathcal{L}_{VNN^*}(x, z) &= \sum_{i=+, -; \tau} [c_{\tau+1}^{N^*} \bar{\psi}_{i, \tau+1}^{N^*}(x, z) \hat{\mathcal{V}}_{i, m}^{N^*}(x, z) \psi_{i, \tau+1}^N(x, z) \\ &\quad + d_\tau^{N^*} \bar{\psi}_{i, \tau+1}^{N^*}(x, z) \hat{\mathcal{V}}_{i, nm}^{N^*}(x, z) \psi_{i, \tau}^N(x, z)] + \text{H.c.} \end{aligned} \quad (3)$$

Here τ runs from 3. We thereby introduce the shortened notation

$$\begin{aligned} \hat{\mathcal{D}}_\pm(z) &= \frac{i}{2} \Gamma^M \overset{\leftrightarrow}{\partial}_M - \frac{i}{8} \Gamma^M \omega_M^{ab} [\Gamma_a, \Gamma_b] \mp (\mu + U_F(z)), \\ \hat{\mathcal{V}}_{\pm, m}^{N^*N}(x, z) &= Q \Gamma^M V_M(x, z), \\ \hat{\mathcal{V}}_{\pm, nm}^{N^*N}(x, z) &= \pm \frac{i}{4} \eta_V^H [\Gamma^M, \Gamma^N] V_{MN}(x, z) \\ &\quad + \zeta_V^{N^*N} z \Gamma^M \partial^N V_{MN}(x, z), \end{aligned} \quad (4)$$

where μ is the five-dimensional mass of the spin- $\frac{1}{2}$ AdS fermion with $\mu = 3/2 + L$ (L is the orbital angular momentum); $U_F(z) = \varphi(z)$ is the dilaton potential; $Q = \text{diag}(1, 0)$ is the nucleon (N^*) charge matrix; $V_{MN} = \partial_M V_N - \partial_N V_M$ is the stress tensor for the vector field; $\omega_M^{ab} = (\delta_M^a \delta_z^b - \delta_M^b \delta_z^a)/z$ is the spin connection term; $\sigma^{MN} = [\Gamma^M, \Gamma^N]$ is the commutator of the Dirac matrices in AdS space, which are defined as $\Gamma^M = \epsilon_a^M \Gamma^a$ and $\Gamma^a = (\gamma^\mu, -i\gamma^5)$. The subscripts m and nm in the vector matrix $\hat{\mathcal{V}}_{\pm, m/nm}^{N^*N}(x, z)$ refer to minimal (m) or nonminimal (nm) couplings, respectively. As was pointed out in the Introduction, due to gauge invariance the minimal coupling between the nucleon and the N^* is only possible for the same twist, while for the nonminimal coupling it is not constrained and we include the coupling between nucleon with twist $\tau_N = 3, 4, 5$ and the $N^*(1535)$ resonance with the twist $\tau_{N^*} = \tau_N + 1 = 4, 5, 6$.

The action (2) is constructed in terms of the 5D AdS fermion fields $\psi_{\pm,\tau}^N(x, z)$, $\psi_{\pm,\tau}^{N^*}(x, z)$ and the vector field $V_M(x, z)$. Fermion fields are duals to the left- and right-handed chiral doublets of the nucleon and the $N^*(1535)$ resonance with $\mathcal{O}^L = (B_1^L, B_2^L)^T$ and $\mathcal{O}^R = (B_1^R, B_2^R)^T$, where $B_1 = p, N_p^*$ and $B_2 = n, N_n^*$. These fields are in the fundamental representations of the chiral $SU_L(2)$ and $SU_R(2)$ subgroups and are holographic analogs of the nucleon N and $N^*(1535)$ resonance, respectively.

The 5D AdS fields $\psi_{\pm,\tau}^B(x, z)$ are products of the left/right 4D spinor fields

$$\psi_N^{L/R}(x) = \frac{1 \mp \gamma^5}{2} \psi(x) \quad (5)$$

for the nucleon, and

$$\psi_{N^*}^{L/R}(x) = \gamma^5 \frac{1 \mp \gamma^5}{2} \psi(x) = \mp \frac{1 \mp \gamma^5}{2} \psi(x) \quad (6)$$

for the $N^*(1535)$ resonance with spin 1/2, and the bulk profiles

$$F_\tau^{L/R}(z) = z^2 f_\tau^{L/R}(z), \quad (7)$$

with twist τ , which depend on the holographic (scale) variable z :

$$\begin{aligned} \psi_{\pm,\tau}^N(x, z) &= \frac{1}{\sqrt{2}} [\pm \psi_N^L(x) F_\tau^{L/R}(z) + \psi_N^R(x) F_\tau^{R/L}(z)], \\ \psi_{\pm,\tau}^{N^*}(x, z) &= \frac{1}{\sqrt{2}} [\mp \psi_N^L(x) F_\tau^{L/R}(z) + \psi_N^R(x) F_\tau^{R/L}(z)], \end{aligned} \quad (8)$$

where

$$\begin{aligned} f_\tau^L(z) &= \sqrt{\frac{2}{\Gamma(\tau)}} \kappa^\tau z^{\tau-1/2} e^{-\kappa^2 z^2/2}, \\ f_\tau^R(z) &= \sqrt{\frac{2}{\Gamma(\tau-1)}} \kappa^{\tau-1} z^{\tau-3/2} e^{-\kappa^2 z^2/2}. \end{aligned} \quad (9)$$

The nucleon is identified as the ground state with $n = L = 0$ while the $N^*(1535)$ resonance as the first orbitally excited state with $n = 0$ and $L = 1$. In the case of the vector field we work in the axial gauge $V_z = 0$ and perform a Fourier transformation of the vector field $V_\mu(x, z)$ with respect to the Minkowski coordinate

$$V_\mu(x, z) = \int \frac{d^4 q}{(2\pi)^4} e^{iqx} V_\mu(q) V(q, z). \quad (10)$$

We can then derive an equation of motion for the vector bulk-to-boundary propagator $V(q, z)$ dual to the q^2 -dependent electromagnetic current

$$\partial_z \left(\frac{e^{-\varphi(z)}}{z} \partial_z V(q, z) \right) + q^2 \frac{e^{-\varphi(z)}}{z} V(q, z) = 0. \quad (11)$$

The solution of this equation in terms of the gamma $\Gamma(n)$ and Tricomi $U(a, b, z)$ functions reads

$$V(q, z) = \Gamma \left(1 - \frac{q^2}{4\kappa^2} \right) U \left(-\frac{q^2}{4\kappa^2}, 0, \kappa^2 z^2 \right). \quad (12)$$

In the Euclidean region ($Q^2 = -q^2 > 0$) it is convenient to use the integral representation for $V(Q, z)$ [29]:

$$V(Q, z) = \kappa^2 z^2 \int_0^1 \frac{dx}{(1-x)^2} x^a e^{-\kappa^2 z^2 \frac{x}{1-x}}, \quad (13)$$

where x is the light-cone momentum fraction and $a = Q^2/(4\kappa^2)$.

The set of parameters c_τ^N , $c_{\tau+1}^{N^*}$, $c_{\tau+1}^{N^*N}$, and $d_\tau^{N^*N}$ induces mixing of the contributions of AdS fields with different twist dimensions. In Refs. [10,28] we showed that the parameters c_τ^N and $c_{\tau+1}^{N^*}$ are constrained by the conditions $\sum_\tau c_\tau^N = 1$ and $\sum_\tau c_{\tau+1}^{N^*} = 1$ in order to get the correct normalization of the kinetic term $\bar{\psi}(x) i \not{\partial} \psi(x)$ of the four-dimensional spinor field. This condition is also consistent with electromagnetic gauge invariance. Therefore, the nucleon and $N^*(1535)$ masses can be identified with the following expressions [10,28]:

$$M_N = 2\kappa \sum_\tau c_\tau^N \sqrt{\tau-1}, \quad M_{N^*} = 2\kappa \sum_\tau c_{\tau+1}^{N^*} \sqrt{\tau}. \quad (14)$$

As in the previous case of the nucleon and the Roper resonance we restrict our calculation to the three leading twist contributions to the $N^*(1535)$ mass ($\tau_{N^*} = 4, 5, 6$). With the condition $\sum_\tau c_{\tau+1}^{N^*} = 1$ only two parameters are linearly independent. One of the possible solutions fixing the central value of the $N^*(1535)$ mass of 1510 MeV [30] reads $c_4^{N^*} = 0.82$, $c_5^{N^*} = -0.63$, and $c_6^{N^*} = 1 - c_4^{N^*} - c_5^{N^*} = 0.81$.

The baryon form factors are determined analytically using the bulk profiles of fermion fields and the bulk-to-boundary propagator $V(Q, z)$ of the vector field (for exact expressions see the next section). The calculational technique was already described in detail in Refs. [10,13,28]. The parameter $\kappa = 383$ MeV is universal and was fixed in previous studies (see, e.g., Refs. [10,28]). The other parameters are fixed from a fit to the helicity amplitudes of the $\gamma N \rightarrow N^*(1535)$ transition:

$$\begin{aligned}
c_4^{N^*N} &= 25.52, & c_5^{N^*N} &= -26.90, \\
d_3^{N^*N} &= -1.89, & d_4^{N^*N} &= 5.64, & d_5^{N^*N} &= -3.58, \\
\eta_V^{N^*N} &= 4.28, & \zeta_V^{N^*N} &= -0.47.
\end{aligned} \tag{15}$$

III. ELECTROMAGNETIC FORM FACTORS AND HELICITY AMPLITUDES OF THE $\gamma N \rightarrow N^*(1535)$ TRANSITION

The electromagnetic form factors of the $\gamma N \rightarrow N^*(1535)$ transition are defined, due to Lorentz and gauge invariance, by the following matrix element:

$$\begin{aligned}
M^\mu(p_1\lambda_1, p_2\lambda_2) \\
= \bar{u}_{N^*}(p_1\lambda_1) \left[\gamma_\perp^\mu F_1^{N^*N}(-q^2) + i\sigma^{\mu\nu} \frac{q_\nu}{M_+} F_2^{N^*N}(-q^2) \right] \\
\times \gamma^5 u_N(p_2\lambda_2).
\end{aligned} \tag{16}$$

We have $u_{N^*}(p_1\lambda_1)$ and $u_N(p_2\lambda_2)$ which are the usual spin- $\frac{1}{2}$ Dirac spinors describing the $N^*(1535)$ resonance and nucleon, $M_\pm = M_{N^*} \pm M_N$, $\gamma_\perp^\mu = \gamma^\mu - q^\mu \not{q}/q^2$, $q = p_1 - p_2$, and λ_1, λ_2 , and λ are the helicities of the final, initial baryon and photon, respectively, with the relation $\lambda_2 = \lambda_1 - \lambda$. In the rest frame of the $N^*(1535)$ the four momenta of N^* , N , photon and the polarization vector of photon are specified as

$$\begin{aligned}
p_1 &= (M_1, \vec{0}), & p_2 &= (E_2, 0, 0, -|\mathbf{p}|), \\
q &= (q^0, 0, 0, |\mathbf{p}|), \\
\epsilon^\mu(\pm) &= (0, -\vec{e}^\pm), & \vec{e}(\pm) &= \frac{1}{\sqrt{2}}(\pm 1, i, 0), \\
\epsilon^\mu(0) &= \frac{1}{\sqrt{Q^2}}(|\mathbf{p}|, 0, 0, q^0),
\end{aligned} \tag{17}$$

where $|\mathbf{p}| = \frac{\sqrt{Q_+ Q_-}}{2M_{N^*}}$ is the absolute value of the three-momentum of the nucleon or the photon.

It is important to point out that the matrix element (16) is manifestly gauge invariant. The form factor $F_1^{N^*N}(Q^2)$ vanishes at $Q^2 = 0$. In more detail the contribution to $F_1^{N^*N}(Q^2)$ from nonminimal terms of the action (2) includes the z -derivative acting on the vector bulk-to-boundary propagator $\partial_z V(Q, z)$, which is zero at $Q^2 = 0$ because of $V(0, z) \equiv 1$. In the case of the minimal term its contribution to the $F_1^{N^*N}(Q^2)$ reads

$$F_{1,m}^{N^*N}(Q^2) = \frac{a}{2} \sum_\tau c_{\tau+1}^{N^*N} B(a+1, \tau+1), \tag{18}$$

where $a = Q^2/(4\kappa^2)$, $B(x, y) = \Gamma(x)\Gamma(y)/\Gamma(x+y)$ and $\Gamma(x)$ are the beta and gamma functions. It should be clear that $F_{1,m}^{N^*N}(0) = 0$ at $Q^2 = 0$.

Next we introduce the helicity amplitudes $H_{\lambda_1\lambda}$ which are related to the invariant form factors F_i^{RN} as (see details in Refs. [31,32])

$$H_{\lambda_1\lambda} = M_\mu(p_1\lambda_1, p_2\lambda_2) \epsilon^\mu(\lambda). \tag{19}$$

A straightforward evaluation gives [1,2,4,31,32]

$$\begin{aligned}
H_{\pm\frac{1}{2}0} &= \mp \sqrt{\frac{Q_+}{Q^2}} \left(F_1^{N^*N} M_- - F_2^{N^*N} \frac{Q^2}{M_+} \right), \\
H_{\pm\frac{1}{2}\pm 1} &= \pm \sqrt{2Q_+} \left(F_1^{N^*N} + F_2^{N^*N} \frac{M_-}{M_+} \right),
\end{aligned} \tag{20}$$

where $Q_\pm = M_\pm^2 + Q^2$. In the case of the Roper-nucleon transition we also have an additional set of helicity amplitudes $(A_{1/2}, S_{1/2})$ related to the $(H_{\frac{1}{2}0}, H_{\frac{1}{2}\pm 1})$ by

FIG. 1. Helicity amplitude $A_{1/2}^p(Q^2)$ up to $Q^2 = 10 \text{ GeV}^2$ with data taken from CLAS. Left panel: Displayed are our results (Our), the MAID parametrization (MAID), and (Fit)—the parametrization of Eq. (25). Right panel: Our results are shown for the case of variation of parameters of our approach (shaded band) in comparison with data.

FIG. 2. Helicity amplitude $S_{1/2}^p(Q^2)$ up to $Q^2 = 10 \text{ GeV}^2$ with data taken from CLAS. Left panel: Displayed are our results (Our), the MAID parametrization (MAID), and (Fit)—the parametrization of Eq. (25). Right panel: Our results are shown for the case of variation of parameters of our approach (shaded band) in comparison with data.

$$A_{1/2} = b H_{\frac{1}{2}1}, \quad S_{1/2} = b \frac{|\mathbf{p}|}{\sqrt{Q^2}} H_{\frac{1}{2}0}, \quad (21)$$

where

$$b = \sqrt{\frac{\pi\alpha}{M_+ M_- M_N}} \quad (22)$$

and $\alpha = 1/137.036$ is the fine-structure constant.

At $Q^2 = 0$ our predictions for the last set of helicity amplitudes (proton channel) in the $N - N^*(1535)$ transition are

$$A_{1/2}^p(0) = 0.09 \text{ GeV}^{-1/2}, \quad S_{1/2}^p(0) = -0.002 \text{ GeV}^{-1/2}. \quad (23)$$

Our results for the Q^2 dependence of the helicity amplitudes in the $N - N^*(1535)$ transition (proton channel) are fully displayed in the left panels in Figs. 1 and 2. We compare them to experimental results of the CLAS collaboration (JLab) [3–5] and to the MAID parametrization [18]

$$\begin{aligned} A_{1/2}^p(Q^2) &= 0.066 \text{ GeV}^{-1/2} (1 + 1.61 \text{ GeV}^{-2} Q^2) \\ &\quad \times \exp[-0.70 \text{ GeV}^{-2} Q^2], \\ S_{1/2}^p(Q^2) &= -0.002 \text{ GeV}^{-1/2} (1 + 23.9 \text{ GeV}^{-2} Q^2) \\ &\quad \times \exp[-0.81 \text{ GeV}^{-2} Q^2]. \end{aligned} \quad (24)$$

We further display a parametrization proposed by us:

$$\begin{aligned} A_{1/2}^p(Q^2) &= A_{1/2}^p(0) \frac{1 + a_1 Q^2}{1 + a_2 Q^2 + a_3 Q^4 + a_4 Q^6}, \\ S_{1/2}^p(Q^2) &= S_{1/2}^p(0) \frac{1 + s_1 Q^2}{1 + s_2 Q^2 + s_3 Q^4 + s_4 Q^6}, \end{aligned} \quad (25)$$

where

$$A_{1/2}^p(0) = 0.090 \text{ GeV}^{-1/2}, \quad S_{1/2}^p(0) = -0.002 \text{ GeV}^{-1/2}, \quad (26)$$

and

$$\begin{aligned} a_1 &= 3.066 \text{ GeV}^{-2}, & a_2 &= 2.965 \text{ GeV}^{-2}, \\ a_3 &= 0.889 \text{ GeV}^{-4}, & a_4 &= 0.127 \text{ GeV}^{-6}, \\ s_1 &= 20.460 \text{ GeV}^{-2}, & s_2 &= 1.325 \text{ GeV}^{-2}, \\ s_3 &= -0.900 \text{ GeV}^{-4}, & s_4 &= 0.550 \text{ GeV}^{-6}. \end{aligned} \quad (27)$$

We also present an analysis of the error of our approach due to a variation of the parameters (up to 15%) for both helicity amplitudes in the right panels of Figs. 1 and 2.

IV. SUMMARY

We extended our formalism based on a soft-wall AdS/QCD approach to the description of the $\gamma N \rightarrow N^*(1535)$ transition. We showed that inclusion of the minimal electromagnetic coupling of the nucleon and the $N^*(1535)$ resonance, based on the coupling of two fermion AdS fields with the same twist-dimension, is manifestly gauge invariant. It then results in a satisfactory description of data on the helicity amplitudes even at small Q^2 . The failure to reproduce the low- Q^2 behavior of these helicity amplitudes was a long-standing problem of most theory descriptions, the present soft-wall AdS/QCD approach can offer a solution. In the future we plan to apply our formalism to the calculation of electromagnetic transitions between the nucleon and further high-spin resonances.

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