Isovector and isoscalar tensor form factors of $N(1535) \to N$ transition in light-cone QCD

Ulaş Özdem$^{1,*}$

$^1$Health Services Vocational School of Higher Education, Istanbul Aydin University, Sefakoy-Kucukcekmece, 34295 Istanbul, Turkey

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We have applied isovector and isoscalar tensor current to evaluate the tensor form factors of the $N(1535) \to N$ transition with the help of light-cone QCD sum rule method. In numerical computations, have used the most general forms of the interpolating current for the nucleon and the tensor current together with two different sets of the input parameters in the DAs of the $N(1535)$ state. We have obtained that the values of $N(1535) \to N$ transition tensor form factors very sensitive to the input parameters of the DAs of the $N(1535)$ state. We have acquired that the $Q^2$ dependence of $N(1535) \to N$ transition tensor form factors are well defined by a p-pole fit function.

Keywords: Tensor form factors, nucleon, $N(1535)$, Light-cone QCD sum rule

I. INTRODUCTION

The essential subject of QCD is to understanding the internal structure of hadrons and their features in terms of degrees of freedom of quark-gluons. Hadron charges described as matrix elements of tensor, axial and vector currents between hadron states include complete knowledge about internal structure of the hadron. At the twist-two level, the corresponding charges are characterized by the helicity distribution $g_1(x)$, transversity distribution $h_1(x)$ and unpolarized distribution $f_1(x)$ function of the quark. Moreover, at the leading twist, eight generalized parton distributions (GPDs) encompass full knowledge on the internal structure of hadrons: Four chiral-odd spin-dependent GPDs $H_T(x,\xi, t)$, $E_T(x,\xi, t)$, $H_T(x,\xi, t)$, and $\tilde{E}_T(x,\xi, t)$; two chiral-even spin-dependent GPDs $\tilde{H}(x,\xi, t)$, and $\tilde{E}(x,\xi, t)$ and; two chiral-even spin-independent GPDs $H(x,\xi, t)$, $E(x,\xi, t)$, where $\xi$ is the skewness and $t = -Q^2$ is the squared momentum transfer [14]. These observables include important knowledge about the internal structure of the hadron. They characterize, e.g., how partons are distributed in the transverse plane according to motion of the hadron or the contribution of quark orbital angular momentum to total angular momentum of the hadron. The helicity and unpolarized distribution functions can be extracted from inclusive deep-inelastic scattering data because of their chiral-even nature. However, the transversity distribution function has chiral-odd nature so, there is a big experimental problem to measure it. It can be acquired Drell-Yan processes and semi-inclusive deep inelastic scattering, as distributions of transversity do appear at leading twist in the cross-section. Photo- and electro-production of mesons off the polarized nucleons and the transversely polarized Drell-Yan process are recommended as suitable ways to measure transversity distribution. In Ref. [5], transversity distribution of the nucleon was extracted using the experimental data from COMPASS [6], HERMES [7] and Belle [8] Collaborations. Afterwards, in Ref. [9] the tensor charge of the nucleon extracted in the framework of covariant quark-diquark model. Moreover, tensor form factors of the nucleon have been investigated by the help of QCD sum rule [10, 11], axial vector meson dominance model [12], quark model [13, 14], chiral quark soliton model [15, 16], light-cone QCD sum rule [17, 18], di-hadron production [19], lattice QCD [20–22], relativistic confined quark model [23] and skyrmion model [24]. Besides, the tensor form factors of the octet hyperons are investigated in the framework of chiral quark soliton model [16] and light-cone QCD sum rule [25].

In the present work, we will investigate the isovector and isoscalar tensor form factors $N(1535) \to N$ transition up to a momentum transfer of $Q^2 \leq 10$ GeV$^2$ with the help of light-cone QCD sum rule. To our knowledge, this is the first study in the literature committed to the examination of the $N(1535) \to N$ transition tensor form factors. In the light-cone QCD sum rule method, the hadronic observables are described in connection with the properties of the vacuum and distribution amplitudes (DAs) of the hadrons under the investigation [26–28]. Since the hadronic observables are described in connection with the features of the QCD vacuum and the DAs, any ambiguity in these variables reflects to the ambiguity of the predictions of the hadronic observables. Note that the electromagnetic [29], axial [30] and gravitational [31] form factors for $N(1535) \to N$ transition have been evaluated with the help of light-cone QCD sum rule.

This article is organized in the following manner: In Section II we present the details of our light-cone QCD sum rule calculations. In Section III we analyze the obtained results, and give our conclusions.
II. ISOVECTOR AND ISOSCALAR TENSOR FORM FACTORS OF \( N(1535) \rightarrow N \) TRANSITION

The matrix element of the isovector and isoscalar tensor current between nucleon and \( N(1535) \) baryons is defined by three dimensionless invariant form factors as presented \([32, 33]\).

\[
\langle N(p')|T_{\mu\nu}|N(1535)(p)\rangle = \bar{u}(p') \left[ i\sigma_{\mu\nu}H^{I=0;1}(q^2) + \frac{\gamma^\mu q^\nu - \gamma^\nu q^\mu}{2m} E^{I=0;1}(q^2) + \frac{\tilde{P}_\mu q^\nu - \tilde{P}_\nu q^\mu}{2m^2} \tilde{H}_{T}^{I=0;1}(q^2) \right] \gamma_5 u(p),
\]

where \( m = (m_N + m_{N(1535)})/2 \), \( \sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu, \gamma_\nu] \), \( q = p - p' \), \( \tilde{P} = p' + p \) and; \( E^{I=0} = E^u - F^d \) and \( E^{I=0} = E^u + F^d \) for any of the form factors, \( F = E_T, H_T \) or \( \tilde{H}_T \).

To derive the light-cone QCD sum rules for isovector and isoscalar tensor form factors of \( N(1535) \rightarrow N \) transition, we consider subsequent correlator for our analysis

\[
\Pi_{\mu\nu}(p, q) = i \int d^4x e^{ipx} \langle 0| T[J_N(0)T_{\mu\nu}(x)]|N(1535)(p)\rangle, \tag{2}
\]

where \( T_{\mu\nu}(x) \) is the tensor current and \( J_N(0) \) are interpolating currents for nucleon states. The explicit forms of the \( J_N(0) \) and \( T_{\mu\nu}(x) \) are given as

\[
J_N(0) = 2e^{abc} \sum_{\ell=1}^2 (u^{aT}(x)CJ_\ell^I u^b(x)), \quad T_{\mu\nu}(x) = \bar{u}(x) \sigma_{\mu\nu} u(x) \pm \bar{u}(x) \sigma_{\mu\nu} d(x), \tag{3}
\]

where \( J_1^I = I, J_2^I = J_N^I = \gamma_5, J_3^I = t \), which is an arbitrary parameter that fixes the mixing of two local operators and \( C \) denotes charge conjugation.

To acquire the sum rules for isovector and isoscalar tensor form factors of \( N(1535) \rightarrow N \) transition the correlator in Eq. (2) is obtained from the subsequent three steps:

- the correlator is saturated by complete set of hadronic states, which are the same quantum numbers as interpolating currents (hadronic representation);
- the correlator is obtained in connection with quark and gluon degrees of freedom interacting with non-perturbative QCD vacuum (QCD representation);
- then matching these two independent representations of the correlator to one another employing the quark-hadron duality ansatz. To keep under control undesirable contributions coming from the higher and excited states we perform Borel transformation, in addition to continuum subtraction to both representations of the obtained corresponding sum rules.

As we mentioned above in order to evaluate the correlator in connection with hadron features, a complete hadronic set with the same quantum numbers as the interpolation currents is inserted. After that, the correlation function is becoming

\[
\Pi_{\mu\nu}^{had}(p, q) = \frac{\lambda_N}{m_N^2 - p'^2} \langle 0| J_N(0)|N(p', s')\rangle \langle N(p', s')|T_{\mu\nu}(x)|N(1535)(p, s)\rangle + ..., \tag{4}
\]

where

\[
\langle 0| J_N(0)|N(p', s')\rangle = \lambda_N u_N(p', s'), \tag{5}
\]

with \( \lambda_N \) and \( u_N(p', s') \) being the residue and Dirac spinor of nucleon, respectively. Summation over the spins of the nucleon is performed as

\[
\sum_{s'} u_N(p', s')\bar{u}_N(p', s') = p' + m_N. \tag{6}
\]

Substituting Eq. (1), Eq. (5) and Eq. (6) into Eq. (4), we acquire the correlator in the way of the hadronic features as

\[
\Pi_{\mu\nu}^{had}(p, q) = \frac{\lambda_N}{m_N^2 - p'^2} (p' + m_N) \left[ i\sigma_{\mu\nu}H^{I=0;1}(q^2) + \frac{\gamma^\mu q^\nu - \gamma^\nu q^\mu}{2M} E^{I=0;1}(q^2) + \frac{\tilde{P}_\mu q^\nu - \tilde{P}_\nu q^\mu}{2M^2} \tilde{H}_{T}^{I=0;1}(q^2) \right] \gamma_5 u(p), \tag{7}
\]

The next step is to evaluate the correlator in Eq. (2) with respect to quarks and gluon properties in deep Eu-
clidean region. Employing the expression for $J_\nu(0)$ and $T_{\mu\nu}(x)$ and Wicks theorem, the QCD representation of the correlator is obtained as,

$$\Pi_{\mu\nu}^{QCD}(p, q) = -\int d^4xe^{ix} \left\{ (\gamma_5)_{\gamma\delta} C_{\alpha\beta} (i\sigma_{\mu\nu})_{\omega\rho} + t (I)_{\gamma\delta} (C\gamma_5)_{\alpha\beta} (i\sigma_{\mu\nu})_{\omega\rho} \right\} \times \left\{ \langle 0|\epsilon^{abc} u^a_\rho (0) u^b_\sigma (x) \sigma^c_\delta (0) |N(1535) (p) \rangle (\delta^\delta_\sigma \delta^\beta_\delta S_u (-x)_{\delta\omega} + \delta^\delta_\sigma \delta^\beta_\delta S_d (-x)_{\delta\omega} ) \pm \langle 0|\epsilon^{abc} u^a_\rho (0) u^b_\sigma (0) \sigma^c_\delta (x) |N(1535) (p) \rangle \delta^\delta_\sigma \delta^\beta_\delta S_d (-x)_{\beta\omega} \right\},$$

(8)

where $S_q(x)$ is the light-quark propagator and it is given as ($m_q = 0$)

$$S_q(x) = i \frac{\not{q} - \not{p}_q}{2\pi^2 x^4} - \frac{\langle \bar{q}q \rangle}{192} \frac{\langle \bar{q}Gq \rangle}{x^2}$$

$$- \frac{i\not{g}_s}{32\pi^2 x^2} G^{\mu\nu} (x) \left[ \gamma_\mu \sigma_{\mu\nu} + \sigma_{\mu\nu} J \right].$$

(9)

The $\langle 0|\epsilon^{abc} u^a_\rho (x_1) u^b_\rho (x_2) \sigma^c_\delta (x_3) |N(1535) (p) \rangle$ matrix element in Eq. (8) is can be written in terms of the DAs of $N(1535)$ state and it is necessary for further computations. The comprehensive expression of this matrix elements are presented in the Ref. [34]. After employing the explicit forms of the above matrix elements and the light-quark propagator, we acquire an expressions in x-space. Then we apply fourier transforms to transfer these expressions into the momentum space.

The desired light-cone sum rules are obtained by matching both representations of the correlation function. In order to do this, we have to choose different and independent Lorentz structures. For this purpose, we choose $p_\mu q_\nu \gamma_5$, $p_\mu \gamma_\nu \gamma_5$ and $p_\mu q_\nu \gamma_5$ structures for $E_T^{I=0,1}(Q^2)$, $H_T^{I=0,1}(Q^2)$ and $\tilde{H}_T^{I=0,1}(Q^2)$ form factors, respectively. As a result, we get the light-cone sum rules,

$$E_T^{I=0}(Q^2) = \frac{\lambda_N}{m_N - p^2} \equiv \bar{m}_1 \Pi_1^{QCD},$$

$$H_T^{I=0}(Q^2) = \frac{\lambda_N}{m_N - p^2} \equiv -\bar{m}_2 \Pi_2^{QCD},$$

$$\tilde{H}_T^{I=0}(Q^2) = \frac{\lambda_N}{m_N - p^2} \equiv -\bar{m}_3 \Pi_3^{QCD},$$

(10)

$$E_T^{I=1}(Q^2) = \frac{\lambda_N}{m_N - p^2} \equiv \bar{m}_4 \Pi_4^{QCD},$$

$$H_T^{I=0}(Q^2) = \frac{\lambda_N}{m_N - p^2} \equiv -\bar{m}_5 \Pi_5^{QCD},$$

$$\tilde{H}_T^{I=0}(Q^2) = \frac{\lambda_N}{m_N - p^2} \equiv -\bar{m}_6 \Pi_6^{QCD},$$

(11)

The $\Pi_i^{QCD}$ functions appearing in Eqs. (10) to (12) are quite long and not illuminating. However, as an example, we give the result of the $\Pi_1^{QCD}$. The remaining five of these functions have more or less similar forms.
where, $A_i$, $P_i$, $V_i$, $S_i$ and $T_i$ are distributions amplitudes of different twists. They have been expressed with respect to $N(1535)$ state wavefunctions. The explicit forms of these wavefunctions are presented in Ref. [34]. To eliminate contributions coming from the excited and continuum states the Borel transformation and continuum subtraction are performed. The suppression of the excited and continuum states can be accomplished by means of the subsequent subtraction rules [35]:

\[
\Pi_1^{QCD} = 2 m_N^2 \left\{ \int_0^1 da \frac{\alpha}{(q - pa)^4} \int_0^1 dx_2 \left[ (1 - t)[2A_1 - 2A_2 - A_3 + 3A_4 + 2V_1 + 2V_2 - 4V_3 + 2V_4 - 4V_5] + (1 + t)[2P_1 - 2P_2 + 2S_1 - 2S_2 + 2T_2 + 4T_3 - 6T_5 - 4T_7] \right] \right\} \]

where

\[
\begin{align*}
\int dz \frac{d}{(q - z)p^2} &\to \int_0^1 \frac{dz}{z} \rho(z)e^{-s(z)/M^2}, \\
\int dz \frac{d}{(q - z)p^2} &\to \frac{1}{M^2} \int_0^1 \frac{dx}{x^2} \rho(z)e^{-s(z)/M^2} + \frac{\rho(x_0)}{Q^2 + x_0^2 m_N^2} e^{-s_0/M^2}, \\
\int dz \frac{d}{(q - z)p^6} &\to \frac{1}{2M^4} \int_0^1 \frac{dz}{z^3} \rho(z)e^{-s(z)/M^2} - \frac{1}{2M^4} \frac{x_0}{x_0(Q^2 + x_0^2 m_N^2)} e^{-s_0/M^2} \\
&\quad + \frac{x_0^2 e^{-s_0/M^2}}{2Q^2 + x_0^2 m_N^2} \left[ \frac{d}{dx_0} \frac{\rho(x_0)}{x_0(Q^2 + x_0^2 m_N^2)} \right].
\end{align*}
\]

where

\[
s(z) = (1 - z)m_N^2 + \frac{1 - z}{z} Q^2,
\]

\[
x_0 = \frac{\sqrt{(Q^2 + s_0 - m_N^2)^2 + 4m_N^2 Q^2} - (Q^2 + s_0 - m_N^2)}{2m_N^2}.
\]
\[ \lambda_N = \left[ \frac{m_0^2}{2} \left\{ \frac{M^6}{256\pi^4} (5 + 2t + t^2) E_2(y) \right\} + \frac{\langle \bar{q}q \rangle^2}{6} \left( 6(1 - t^2) - (1 - t)^2 \right) - \frac{m_0^2}{4M^2} \left[ 12(1 - t^2) - (1 - t)^2 \right] \right\}^{1/2}, \tag{16} \]

where

\[ y = s_0/M^2, \]

and

\[ E_n(y) = 1 - e^{-y} \sum_{i=0}^{n} \frac{y^i}{i!}. \]

### III. NUMERICAL ANALYSIS AND CONCLUSION

In this section, we have obtained numerical analysis of \( N(1535) \to N \) transition tensor form factors. The DAs of \( N(1535) \) state have been evaluated by means of the light-cone QCD sum rule in Ref. [34]. The numerical values of the input parameters inside the DAs of \( N(1535) \) state are given in Table I, which are obtained at renormalization scale \( \mu^2 = 2.0 \text{ GeV}^2 \). Furthermore, we use \( \lambda_N^N m_N = -3.88(2)(19) \times 10^{-2} \text{ GeV}^3 \) and \( \lambda_N^{(1535)} m_{N(1535)} = 8.97(45) \times 10^{-2} \text{ GeV}^3 \), given in Ref. [36] at renormalization \( \mu^2 = 4.0 \text{ GeV}^2 \), by rescaling to \( \mu^2 = 2.0 \text{ GeV}^2 \). Beside these values, we use: \( m_{N(1535)} = 1.51 \pm 0.01 \text{ GeV}, \ m_N = 0.94 \text{ GeV} \) [37], \( m_0^2 = 0.8 \pm 0.1 \text{ GeV}^2 \) and \( \langle \bar{q}q \rangle = (-0.24 \pm 0.01)^3 \text{ GeV}^3 \) [38].

The predictions for the isovector and isoscalar tensor form factors depend on three auxiliary parameters; the Borel mass parameter \( M^2 \), arbitrary mixing parameter \( t \) and continuum threshold \( s_0 \). For the quality of the numerical values of the physical observables, we should minimize the dependence of the results on these parameters. The \( M^2 \) can change in the interval that the results relatively weakly depend on it with respect to the standard definition. The upper limit of it is acquired demanding the maximum pole contributions and its lower limit is acquired the convergence of the operator product expansion and exceeding of the perturbative part over nonperturbative contributions. The \( t \) is chosen such that, the estimations of the isovector and isoscalar tensor form factors are reasonably insensitive of the values of \( t \). The working region for the \( s_0 \) is chosen such that the maximum pole contribution is obtained and the results relatively weakly depend on its choices. These constraints lead to the working intervals for auxiliary parameters as

\[ 2.50 \text{ GeV}^2 \leq M^2 \leq 3.50 \text{ GeV}^2, \]
\[ 2.50 \text{ GeV}^2 \leq s_0 \leq 3.00 \text{ GeV}^2, \]
\[ -3.00 \leq t \leq -5.00. \]

In Figs. (1) and (2), we show dependency of isovector and isoscalar tensor form factors with respect to Borel mass parameter at three fixed values of continuum threshold and two fixed values of arbitrary mixing parameter in their working interval. The results show good stability against the variations of the Borel mass parameters, as desired. In Figs. (3) and (4), we plot the dependence of the isovector and isoscalar tensor form factors on \( Q^2 \) for various values of \( s_0 \) and \( t \) in their working regions and at the fixed values of \( M^2 = 3.00 \text{ GeV}^2 \) for LCSR-I and LCSR-II values of input parameters entering the DAs. All the form factors taken into account show a similar dependence on \( Q^2 \) for LCSR-I and LCSR-II except the form factor \( H_{10}^{(\bar{Q}^2)} \). This form factor changes its sign in the region under consideration, so its results are not given in the text. We should noted here that the light-cone QCD sum rule approach is trustworthy only \( Q^2 > 1.0 \text{ GeV}^2 \). On the other hand, the baryon mass corrections of the DAs \( m_0^2/Q^2 \) become very large for \( Q^2 < 2.0 \text{ GeV}^2 \), in other words the light-cone QCD sum rules turn out to be untrustworthy. Thus, we expect the light-cone QCD sum rule to be more reliable and effective in the region of \( 2.0 \text{ GeV}^2 \leq Q^2 \leq 10.0 \text{ GeV}^2 \).

As we mentioned above our sum rules work only \( Q^2 \geq 2.0 \text{ GeV}^2 \). However, we want to extend our analysis to the region \( 0 \leq Q^2 < 2 \). To do this, some fit parameters need to be used. Our numerical investigations indicate that the isovector and isoscalar tensor form factors of

| Model       | \( \lambda_N^{(1535)}/\lambda_N^{N} \) | \( f_N(1535)/\lambda_N^{1535} \) | \( \varphi_{10} \) | \( \varphi_{11} \) | \( \varphi_{20} \) | \( \varphi_{21} \) | \( \varphi_{22} \) | \( \eta_{10} \) | \( \eta_{11} \) |
|-------------|----------------------------------------|---------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| LCSR-I      | 0.633                                  | 0.027                           | 0.36           | -0.95         | 0              | 0              | 0              | 0              | 0.94           |
| LCSR-II     | 0.633                                  | 0.027                           | 0.37           | -0.96         | 0              | 0              | 0              | -0.29          | 0.23           |

TABLE I: Input parameters of the \( N(1535) \) state DAs for the two different sets.
The $N(1535) \rightarrow N$ transition is nicely defined employing the p-pole fit function,

$$\mathcal{F}(Q^2) = \frac{\mathcal{F}(0)}{(1 + Q^2/(p m_p^2))^{p}}. \tag{17}$$

The numerical results obtained for $N(1535) \rightarrow N$ transition isovector and isoscalar tensor form factors are given in Table II. The results obtained by employing LCSR-I and LCSR-II parameters were found quite different from each other. The numerical values of the form factors $E_T^{(1)}(Q^2) = 0$, $H_T^{(1)}(Q^2) = 0$ and $\tilde{H}_T^{(1)}(Q^2) = 0$ for the LCSR-II numerical values are smaller than those for the LCSR-I parameters. As one can see from the Table I, the essential difference between input parameters of the DAs is the numerical values for the $\eta_{10}$ and $\eta_{11}$, which are related to the p-wave three-quark wave functions of $N(1535)$ state, and therefore to the distribution of orbital angular momentum. This means these form factors are very sensitive to the shape parameters of the DAs of the $N(1535)$ state that parametrize relative orbital angular momentum of the quarks.

| TABLE II: The obtained numerical values for the parameters of the isovector and isoscalar tensor form factors by employing the p-pole fit functions. |
|-----------------|----------------|---|----------------|----------------|
| Form Factors    | LCSR-I          |   | LCSR-II         |               |
| $E_T^{(1)}(Q^2)$| $m_p$(GeV)  | $p$ | $m_p$(GeV)  | $p$ |
| $7.54 \pm 1.26$ | $1.10 \pm 0.05$ | $3.6 - 4.0$ | $3.48 \pm 0.84$ | $1.07 \pm 0.07$ | $3.8 - 4.2$ |
| $5.05 \pm 1.01$ | $1.13 \pm 0.08$ | $3.6 - 4.0$ | $3.00 \pm 0.66$ | $1.14 \pm 0.10$ | $3.6 - 4.0$ |
| $5.22 \pm 0.27$ | $1.30 \pm 0.10$ | $3.0 - 3.4$ | $1.51 \pm 0.20$ | $1.28 \pm 0.10$ | $3.0 - 3.4$ |
| $3.37 \pm 0.47$ | $1.28 \pm 0.11$ | $3.0 - 3.4$ | $1.10 \pm 0.20$ | $1.32 \pm 0.10$ | $3.0 - 3.4$ |
| $14.51 \pm 4.43$ | $1.02 \pm 0.10$ | $3.6 - 4.0$ | $1.30 \pm 0.39$ | $1.18 \pm 0.14$ | $3.6 - 4.0$ |

To summarize, we have applied isovector and isoscalar tensor current to evaluate the tensor form factors of the $N(1535) \rightarrow N$ transition with the help of light-cone QCD sum rule method. In numerical computations, have used the most general forms of the interpolating current for the nucleon and the tensor current together with two different sets of the input parameters in the DAs of the $N(1535)$ state. We have obtained that the values of $N(1535) \rightarrow N$ transition tensor form factors very sensitive to the input parameters of the DAs of the $N(1535)$ state. We have acquired that the $Q^2$ dependence of $N(1535) \rightarrow$ transition tensor form factors are well defined by a p-pole fit function. To our knowledge, this is the first study in the literature committed to the examination of the $N(1535) \rightarrow N$ transition tensor form factors. Thus, experimental data or theoretical predictions are not yet available to compare our numerical results with them.

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[1] X.-D. Ji, Gauge-Invariant Decomposition of Nucleon Spin, Phys. Rev. Lett. 78 (1997) 610–613, arXiv:hep-ph/9603249, doi:10.1103/PhysRevLett.78.610.
[2] A. V. Radyushkin, Nonforward parton distributions, Phys. Rev. D56 (1997) 5524–5557, arXiv:hep-ph/9704207, doi:10.1103/PhysRevD.56.5524.
[3] P. Hoodbhoy, X.-D. Ji, Helicity flip off forward parton distributions of the nucleon, Phys. Rev. D58 (1998) 054006, arXiv:hep-ph/9801369, doi:10.1103/PhysRevD.58.054006.
[4] M. Diehl, Generalized parton distributions with helicity flip, Eur. Phys. J. C19 (2001) 485–492, arXiv:hep-ph/0101335, doi:10.1007/s100520100635.
[5] M. Anselmino, M. Boglione, U. D’Alesio, A. Kotzinian, F. Murgia, A. Prokudin, C. Turk, Transversity and Collins functions from SIDIS and e+ e- data, Phys. Rev. D75 (2007) 054032, arXiv:hep-ph/0701006, doi:10.1103/PhysRevD.75.054032.
[6] E. S. Ageev, et al., A new measurement of the Collins and Sivers asymmetries on a transversely polarised deuteron target, Nucl. Phys. B765 (2007) 31–70, arXiv:hep-ex/0610068.
A. Airapetian, et al., Single-spin asymmetries in semi-inclusive deep-inelastic scattering on a transversely polarized hydrogen target, Phys. Rev. Lett. 94 (2005) 012002. arXiv:hep-ex/0408013, doi:10.1103/PhysRevLett.94.012002.

K. Abe, et al., Measurement of azimuthal asymmetries in inclusive production of hadron pairs in e+ e− annihilation at Belle, Phys. Rev. Lett. 96 (2006) 232002. arXiv:hep-ex/0507063, doi:10.1103/PhysRevLett.96.232002.

I. C. Cloet, W. Bentz, A. W. Thomas, Transversity quark distributions in a covariant quark-diquark model, Phys. Lett. B659 (2008) 214–220. arXiv:0708.3246, doi:10.1016/j.physletb.2008.09.071.

H.-x. He, X.-D. Ji, The Nucleon’s tensor charge, Phys. Rev. D52 (1995) 2960–2963. arXiv:hep-ph/9412235, doi:10.1103/PhysRevD.52.2960.

H.-x. He, X.-D. Ji, QCD sum rule calculation of the Nucleon’s tensor charge, Phys. Rev. D54 (1996) 6897–6902. arXiv:hep-ph/9607408, doi:10.1103/PhysRevD.54.6897.

L. P. Gamberg, G. R. Goldstein, Flavor spin symmetry estimate of the nucleon tensor charge, Phys. Rev. Lett. 87 (2001) 242001. arXiv:hep-ph/0107176, doi:10.1103/PhysRevLett.87.242001.

T. Ledwig, A. Silva, H.-C. Kim, Tensor charges and form factors induced by isovector and isoscalar currents in QCD, Phys. Lett. B407 (1997) 331–334. arXiv:hep-ph/9703411, doi:10.1016/S0370-2693(97)00737-5.

B. Pasquini, M. Pincetti, S. Boffi, Chiral-odd generalized parton distributions in constituent quark models, Phys. Rev. D72 (2005) 094029. arXiv:hep-ph/0510376, doi:10.1103/PhysRevD.72.094029.

C. Lorce, Tensor charges of light baryons in the Infinite Momentum Frame, Phys. Rev. D79 (2009) 074027. arXiv:0708.4168, doi:10.1103/PhysRevD.79.074027.

T. Ledwig, A. Silva, H.-C. Kim, Tensor charges and form factors of SU(3) baryons in the self-consistent SU(3) chiral quark-soliton model, Phys. Rev. D82 (2010) 034022. arXiv:1004.3612, doi:10.1103/PhysRevD.82.034022.

G. Erkol, A. Ozpineci, Tensor form factors of nucleon in QCD, Phys. Lett. B704 (2011) 551–558. arXiv:1107.4584, doi:10.1016/j.physletb.2011.09.089.

T. M. Aliiev, T. Barakat, K. Simsek, P. Hagler, et al., Nucleon Generalized Parton Distributions from Full Lattice QCD, Phys. Rev. D77 (2008) 094502. arXiv:0705.4295, doi:10.1103/PhysRevD.77.094502.

M. Göckeler, P. Hagler, R. Horsley, D. Pleiter, P. E. L. Rakow, A. Schäfer, G. Schierholz, J. M. Zanotti, Quark helicity flip generalized parton distributions from two-flavor lattice QCD, Phys. Lett. B627 (2005) 113–123. arXiv:hep-lat/0507001, doi:10.1016/j.physletb.2005.09.002.

T. Bhattacharya, V. Cirigliano, S. Cohen, R. Gupta, A. Joseph, H.-W. Lin, B. Yoon, Iso-vector and Iso-scalar Tensor Charges of the Nucleon from Lattice QCD, Phys. Rev. D92 (9) (2015) 094511. arXiv:1506.06411, doi:10.1103/PhysRevD.92.094511.

T. Gutsche, M. A. Ivanov, J. G. Korner, S. Ko- kalenko, V. E. Lyubovitskij, Nucleon tensor form factors in a relativistic confined quark model, Phys. Rev. D 94 (11) (2016) 114030. arXiv:1608.00420, doi:10.1103/PhysRevD.94.114030.

J. M. Ohness, The Nucleon ‘tensor charges’ and the Skyrme model, Phys. Rev. D47 (1993) 2136–2139. arXiv:hep-ph/9207274, doi:10.1103/PhysRevD.47.2136.

A. kucukarslan, U. Özdem, A. Ozpineci, Tensor form factors of the octet hyperons in QCD, Phys. Rev. D94 (9) (2016) 094010. arXiv:1610.08358, doi:10.1103/PhysRevD.94.094010.

V. M. Braun, I. E. Filyanov, QCD Sum Rules in Exclusive Kinematics and Pion Wave Function, Z. Phys. C44 (1989) 157, [Yad. Fiz.50,818(1989)]. doi:10.1007/BF01548594.

I. I. Balitsky, V. M. Braun, A. V. Kolesnichenko, Radiative Decay $\sigma \rightarrow \rho \gamma$ in Quantum Chromodynamics, Nucl. Phys. B312 (1989) 509–550. doi:10.1016/0550-3213(89)90570-1.

V. L. Chernyak, I. R. Zhiltzisky, B meson exclusive decays into baryons, Nucl. Phys. B345 (1990) 137–172. doi:10.1016/0550-3213(90)90612-H.

I. V. Anikin, V. M. Braun, N. Offen, Electroproduction of the $N^\ast(1535)$ nuclear resonance in QCD, Phys. Rev. D92 (1) (2015) 014018. arXiv:1505.05759, doi:10.1103/PhysRevD.92.014018.

T. M. Aliiev, T. Barakat, K. Simsek, $N^\ast(1535) \rightarrow N$ transition form-factors due to the axial current, Phys. Rev. D100 (5) (2019) 054030. arXiv:1907.08017, doi:10.1103/PhysRevD.100.054030.

U. Özdem, K. Azizi, Gravitational transition form factors of $N(1535) \rightarrow N$ Phys. Rev. D101 (5) (2020) 054031. arXiv:1912.06375.

P. Hagler, Hadron structure from lattice quantum chromodynamics, Phys. Rept. 490 (2010) 49–175. arXiv:0912.5483, doi:10.1016/j.physrep.2009.12.008.

M. Göckeler, P. Hagler, R. Horsley, Y. Nakamura, D. Pleiter, P. E. L. Rakow, A. Schäfer, G. Schierholz, H. Stüben, J. M. Zanotti, Transverse spin structure of the nucleon from lattice QCD simulations, Phys. Rev. Lett. 98 (2007) 222001. arXiv:hep-lat/0612032, doi:10.1103/PhysRevLett.98.222001.

M. Emmerich, Decay Form factors for $A_{b,c}$ and $B$ with QCD sum rules, PhD thesis, Regensburg University, 2018.

V. M. Braun, A. Lenz, M. Wittmann, Nucleon Form Factors in QCD, Phys. Rev. D73 (2006) 094019. arXiv:hep-ph/0604050, doi:10.1103/PhysRevD.73.094019.

V. M. Braun, S. Collins, B. Gläßle, M. Göckeler, A. Schäfer, R. W. Schiel, W. Söldner, A. Sternbeck, P. Wein, Light-cone Distribution Amplitudes of the Nucleon and Negative Parity Nucleon Resonances from Lattice QCD, Phys. Rev. D89 (2014) 094511. arXiv:1403.4189, doi:10.1103/PhysRevD.89.094511.

M. Tanabashi, et al., Review of Particle Physics, Phys. Rev. D98 (3) (2018) 030001.
FIG. 1: The dependence of the isovector tensor form factors of $N(1535) \rightarrow N$ transition on $M^2$ at $Q^2 = 2.0$ GeV$^2$ and different values of $s_0$ and $t$ at their working windows. (a), (c) and (e) for LCSR-I, and; (b), (d) and (f) for LCSR-II.

[38] B. L. Ioffe, QCD at low energies, Prog. Part. Nucl. Phys. 56 (2006) 232–277. arXiv:hep-ph/0502148.
FIG. 2: The dependence of the isoscalar tensor form factors of $N(1535) \rightarrow N$ transition on $M^2$ at $Q^2 = 2.0$ GeV$^2$ and different values of $s_0$ and $t$ at their working windows. (a) and (c) for LCSR-I, and; (b) and (d) for LCSR-II.
FIG. 3: The dependence of the isovector tensor form factors of $N(1535) \rightarrow N$ transition on $Q^2$ at $M^2 = 3.00$ GeV$^2$ and different values of $s_0$ and $t$ at their working windows. (a) and (c) for LCSR-I, and; (b) and (d) for LCSR-II.
FIG. 4: The dependence of the isoscalar tensor form factors of $N(1535) \to N$ transition on $Q^2$ at $M^2 = 3.00$ GeV$^2$ and different values of $s_0$ and $t$ at their working windows. (a) and (c) for LCSR-I, and; (b) and (d) for LCSR-II.