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Constraining gluon poles

I.V. Anikin [a,b,*], O.V. Teryaev [a]

[a] Bogoliubov Laboratory of Theoretical Physics, JINR, 141980 Dubna, Russia
[b] Institut für Theoretische Physik, Universität Regensburg, D-93040 Regensburg, Germany

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ABSTRACT

In this letter, we revise the QED gauge invariance for the hadron tensor of Drell–Yan type processes with the transversely polarized hadron. We perform our analysis within the Feynman gauge for gluons and make a comparison with the results obtained within the light-cone gauge. We demonstrate that QED gauge invariance leads, first, to the need of a non-standard diagram and, second, to the absence of gluon poles in the correlators $\langle \bar\psi \gamma_\perp A^+ \psi\rangle$ related traditionally to $dT(x,x)/dx$. As a result, these terms disappear from the final QED gauge invariant hadron tensor. We also verify the absence of such poles by analyzing the corresponding light-cone Dirac algebra.

1. Introduction

In the recent times, we have observed the renaissance in the nucleon structure studies through the Drell–Yan type processes in the existing (FermiLab, Relativistic Heavy Ion Collider, see [1,2]) and future (J-Parc, NICA) experiments. One of the most interesting subjects of such experimental studies in this direction is the so-called single spin asymmetry (SSA) which is expressed with the help of the hadron tensor, see for instance [3] or [4,5].

Lately, we have reconsidered [6] this process in the contour gauge. We have found that there is a contribution from the *non-standard* diagram which produces the imaginary phase required to have the SSA. This additional contribution leads to an extra factor of 2 for the asymmetry. This conclusion was supported by analysis of the QED gauge invariance of the hadron tensor.

In comparison, the analysis presented in [7] which uses the axial and Feynman gauges does not support the latter conclusion. For this reason, we perform here the detailed analysis of hadron tensor in the Feynman gauge with the particular emphasis on the QED gauge invariance. We find that the QED gauge invariance can be maintained only by taking into account the non-standard diagram. Moreover, the results in the Feynman and contour gauges coincide if the gluon poles in the correlators $\langle \bar\psi \gamma_\perp A^+ \psi\rangle$ are absent. This is in agreement with the relation between gluon poles and the Sivers function which corresponds to the "leading twist" Dirac matrix γ^+. We confirm this important property by comparing the light-cone dynamics for different correlators.

As a result, we derive the QED gauge invariant hadron tensor which completely coincides with the expression obtained within the light-cone contour gauge for gluons, see [6].

2. Kinematics

We study the hadron tensor which contributes to the single spin (left-right) asymmetry measured in the Drell–Yan process with the transversely polarized nucleon (see Fig. 1):

$$N^{(\uparrow\downarrow)}(p_1) + N(p_2) \to \gamma^*(q) + X(P_X) \\ \to \ell(l_1) + \bar\ell(l_2) + X(P_X). \quad (1)$$

Here, the virtual photon producing the lepton pair ($l_1 + l_2 = q$) has a large mass squared ($q^2 = Q^2$) while the transverse momenta are small and integrated out. The left-right asymmetry means that the transverse momenta of the leptons are correlated with the direction $\mathbf{S} \times \mathbf{e}_z$ where S_μ implies the transverse polarization vector of the nucleon while $\mathbf{e}_z$ is a beam direction [8].

Since we perform our calculations within a *collinear* factorization, it is convenient to fix the dominant light-cone directions as

$$p_1 \approx \frac{Q}{x_B\sqrt{2}} n^*, \quad p_2 \approx \frac{Q}{y_B\sqrt{2}} n, \\ n^{*\mu} = (1/\sqrt{2}, \mathbf{0}_T, 1/\sqrt{2}), \quad n^\mu = (1/\sqrt{2}, \mathbf{0}_T, -1/\sqrt{2}). \quad (2)$$

So, the hadron momenta p_1 and p_2 have the plus and minus dominant light-cone components, respectively. Accordingly, the quark

* Corresponding author.
E-mail addresses: anikin@theor.jinr.ru (I.V. Anikin), teryaev@theor.jinr.ru (O.V. Teryaev).

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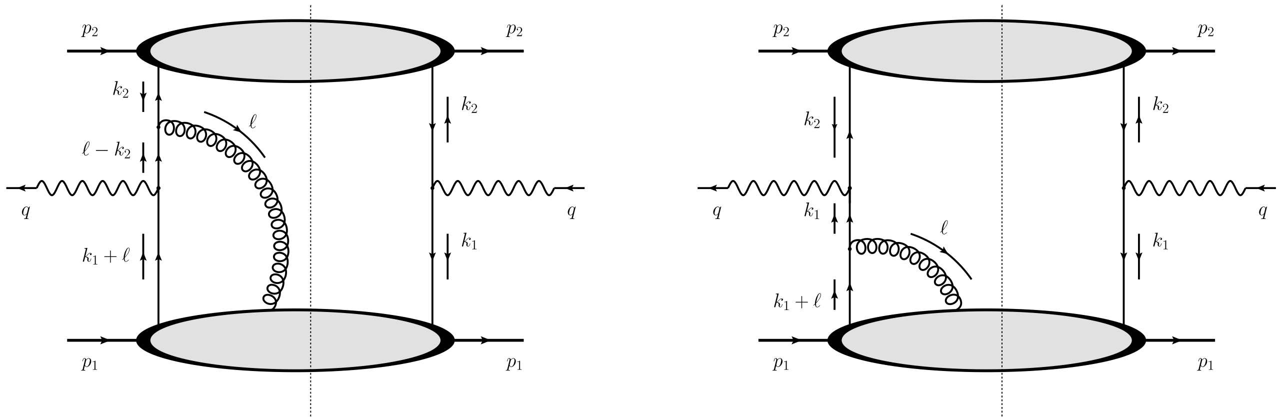

Fig. 1. The Feynman diagrams which contribute to the polarized Drell–Yan hadron tensor.

and gluon momenta k_1 and ℓ lie along the plus direction while the antiquark momentum k_2 – along the minus direction. The photon momentum reads (see Fig. 1)

$$q = l_1 + l_2 = k_1 + k_2 \tag{3}$$

which, after factorization, will take the form:

$$q = x_1 p_1 + y p_2 + q_T. \tag{4}$$

3. The DY hadron tensor

We work within the Feynman gauge for gluons. The standard hadron tensor generated by the diagram depicted in Fig. 1 (the left panel) reads

$$d\mathcal{W}^{\mu\nu}_{\text{(Stand.)}} = \int d^4k_1\, d^4k_2\, \delta^{(4)}(k_1+k_2-q) \times \int d^4\ell\, \Phi^{(A)\,[\gamma_\beta]}_{\alpha}(k_1,\ell)\, \bar{\Phi}^{[\gamma^-]}(k_2) \times \text{tr}\big[\gamma^\mu \gamma^\beta \gamma^\nu \gamma^+ \gamma^\alpha S(\ell - k_2)\big], \tag{5}$$

where

$$\Phi^{(A)\,[\gamma_\beta]}_{\alpha}(k_1,\ell) = \mathcal{F}_2\Big[\langle p_1, S^T|\bar{\psi}(\eta_1)\gamma_\beta g A_\alpha(z)\psi(0)|S^T, p_1\rangle\Big], \tag{6}$$

$$\bar{\Phi}^{[\gamma^-]}(k_2) = \mathcal{F}_1\Big[\langle p_2|\bar{\psi}(\eta_2)\gamma^-\psi(0)|p_2\rangle\Big]. \tag{7}$$

Throughout this paper, $\mathcal{F}_1$ and $\mathcal{F}_2$ denote the Fourier transformation with the measures

$$d^4\eta_2\, e^{ik_2\cdot\eta_2} \quad\text{and}\quad d^4\eta_1\, d^4z\, e^{-ik_1\cdot\eta_1 - i\ell\cdot z}, \tag{8}$$

respectively, while $\mathcal{F}_1^{-1}$ and $\mathcal{F}_2^{-1}$ mark the inverse Fourier transformation with the measures

$$dy\, e^{iy\lambda} \quad\text{and}\quad dx_1 dx_2\, e^{ix_1\lambda_1 + i(x_2-x_1)\lambda_2}. \tag{9}$$

We now implement the *factorization procedure* (see for instance [9,11]) which contains the following steps: (a) the decomposition of loop integration momenta around the corresponding dominant direction: $k_i = x_i p + (k_i\cdot p)n + k_T$ within the certain light cone basis formed by the vectors p and n (in our case, n^* and n); (b) the replacement: $d^4k_i \Longrightarrow d^4k_i\, dx_i \delta(x_i - k_i\cdot n)$ that introduces the fractions with the appropriated spectral properties; (c) the decomposition of the corresponding propagator products around the dominant direction. In Eqn. (5), we have (here, $x_{ij} = x_i - x_j$)

$$S(\ell - k_2) = S(x_{21}p_1 - yp_2) + \frac{\partial S(\ell-k_2)}{\partial \ell_\rho}\Bigg|^{k_2 = yp_2}_{\ell = x_{21}p_1} \ell^T_\rho + \ldots; \tag{10}$$

(d) the use of the collinear Ward identity:

$$\frac{\partial S(k)}{\partial k_\rho} = S(k)\gamma_\rho S(k), \qquad S(k) = \frac{-\not{k}}{k^2 + i\varepsilon};$$

(e) performing of the Fierz decomposition for $\psi_\alpha(z)\,\bar{\psi}_\beta(0)$ in the corresponding space up to the needed projections.

After factorization, the standard tensor, see Eqn. (5), is split into two terms: the first term includes the correlator without the transverse derivative, while the second term contains the correlator with the transverse derivative, see Eqns. (10) and (16)–(18).

The non-standard contribution comes from the diagram depicted in Fig. 1 (the right panel). The corresponding hadron tensor takes the form [6]:

$$d\mathcal{W}^{\mu\nu}_{\text{(Non-stand.)}} = \int d^4k_1\, d^4k_2\, \delta^{(4)}(k_1+k_2-q)\text{tr}\big[\gamma^\mu \mathcal{F}(k_1)\gamma^\nu \bar{\Phi}(k_2)\big], \tag{11}$$

where the function $\mathcal{F}(k_1)$ reads

$$\mathcal{F}(k_1) = S(k_1)\gamma^\alpha \int d^4\eta_1\, e^{-ik_1\cdot\eta_1} \times \langle p_1, S^T|\bar{\psi}(\eta_1)\, gA_\alpha(0)\,\psi(0)|S^T, p_1\rangle. \tag{12}$$

For convenience, we introduce the unintegrated tensor $\overline{\mathcal{W}}_{\mu\nu}$ for the factorized hadron tensor $\mathcal{W}_{\mu\nu}$ of the process. It reads

$$\mathcal{W}^{\mu\nu} = \int d^2\vec{\mathbf{q}}_T d\mathcal{W}^{\mu\nu} = \frac{2}{q^2}\int d^2\vec{\mathbf{q}}_T\, \delta^{(2)}(\vec{\mathbf{q}}_T) \times i\int dx_1\, dy\, \big[\delta(x_1/x_B - 1)\delta(y/y_B - 1)\big]\overline{\mathcal{W}}^{\mu\nu}. \tag{13}$$

After calculation of all relevant traces in the factorized hadron tensor and after some algebra, we arrive at the following contributions for the unintegrated hadron tensor (which involves all relevant contributions except the mirror ones): the standard diagram depicted in Fig. 1, the left panel, gives us

$$\overline{\mathcal{W}}^{\mu\nu}_{\text{(Stand.)}} + \overline{\mathcal{W}}^{\mu\nu}_{\text{(Stand., }\partial_\perp)} = \bar{q}(y)\left\{ -\frac{p_1^\mu}{y}\,\varepsilon^{\nu S^T - p_2}\int dx_2 \frac{x_1 - x_2}{x_1 - x_2 + i\epsilon} B^{(1)}(x_1, x_2)\right.$$