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Gauge invariance, causality and gluonic poles

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ABSTRACT

We explore the electromagnetic gauge invariance of the hadron tensor of the Drell–Yan process with one transversely polarized hadron. The special role is played by the contour gauge for gluon fields. The prescription for the gluonic pole in the twist 3 correlator is related to causality property and compared with the prescriptions for exclusive hard processes. As a result we get the extra contributions, which naively do not have an imaginary phase. The single spin asymmetry for the Drell–Yan process is accordingly enhanced by the factor of two.

1. Introduction

The problem of the electromagnetic gauge invariance in the deeply virtual Compton scattering (DVCS) and similar exclusive processes has intensively been discussed during last few years, see for example [1–5]. This development explored the similarity with the earlier studied inclusive spin-dependent processes [6], and the transverse component of momentum transfer in DVCS corresponds to the transverse spin in DIS.

The gauge invariance of relevant amplitudes is ensured by means of twist three contributions and the use of the equations of motion providing a possibility to exclude the three-particle (quark–gluon) correlators from the amplitude. After combining with the two-particle correlator contributions, one gets the gauge invariant expression for the physical amplitude or, in the case of lepton–hadron processes, for the corresponding hadron tensor [6].

This method was originally developed in the case of the particular inclusive processes with transverse polarized hadrons, like structure function g_2 in DIS [6] and Single Spin Asymmetry (SSA) [7] due to soft quark (fermionic poles [8]). At the same time, the colour gauge invariance of the so-called gluonic poles contributions [9] was previously explored [10] by other methods relying on the Wilson exponentials [11–14].

Here we combine the approaches described above and apply them in the relevant case of the Drell–Yan (DY) process where one of hadrons is the transversally polarized nucleon.

The SSA in the DY process was first considered in QCD in the case [15,16] of the longitudinally polarized hadron. This observable is especially interesting if the second hadron is a pion, because of the sensitivity [17,18] to the shape of pion distribution amplitude, being currently the object of major interest [19,20] (see also [21] and references therein).

The imaginary phases in the SSA with longitudinally polarized nucleon are due to the hard perturbative gluon loops [15,16] or twist 4 contribution of the pion distribution amplitude [17,18,22]. At the same time, the source of the imaginary part, when one calculates the single spin asymmetry associated with $P + P^{\uparrow\downarrow} \to \ell\bar{\ell} + X$ process, is the quark propagator in the diagrams with quark–gluon (twist three) correlators. This leads [23] to the gluonic pole contribution to SSA. It has been reproduced (up to the derivative term, corresponding to the case of single inclusive Drell–Yan process, when only one of the leptons is observed) in the case of the non-zero boundary condition imposed on gluon fields, and the asymmetric boundary conditions have been considered as a privileged ones [24]. The reason is that these boundary conditions provide the purely real quark–gluon function $B^V(x_1, x_2)$ which parameterizes $\langle \bar{\psi}\gamma^+ A^T_\alpha \psi\rangle$ matrix element. By this fact the diagrams with two-particle correlators do not contribute to the imaginary part of the hadron tensor related to the SSA. This property seems quite natural, as the corresponding diagram does not have a cut capable of producing the imaginary phase [25].

In our Letter, we perform a thorough analysis of the transverse polarized DY hadron tensor in the light of the QED gauge invariance, the causality and gluonic pole contributions.

We show that to restore the electromagnetic gauge invariance of the transverse polarized DY hadron tensor, it is mandatory to add the extra diagram contribution (cf. [26] where the similar

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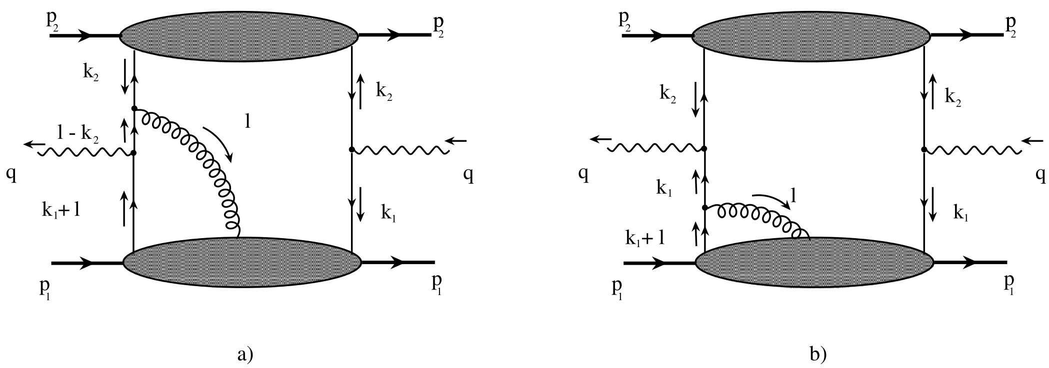

Fig. 1. The Feynman diagrams which contribute to the polarized Drell–Yan hadron tensor.

contribution was associated with the so-called special propagator), also at the twist three level. In contrast to the naive assumption, we demonstrate that this new additional contribution is directly related to the certain complex prescription in the gluonic pole $1/(x_1 - x_2)$ of the quark–gluon function $B^V(x_1, x_2)$. It is essential that this prescription is process-dependent, supporting the idea of effective process-dependent Sivers function (see, e.g., [27] and references therein) related to this correlator.

In more detail, we show that the causal pole prescription in the quark propagator, involved in the hard part of the standard diagram, supports the choice of a contour gauge and, in turn, the representation of the quark–gluon function $B^V(x_1, x_2)$ in the form of the gluonic pole with the mentioned complex prescription. This representation must be extended on the diagram, which naively does not contribute to the imaginary part. They ensure an extra contribution to the imaginary part which is necessary to maintain the electromagnetic gauge invariance. Finally, the account for this extra contributions corrects the SSA formula for the transverse polarized Drell–Yan process by the factor of 2.

Our analysis is also important in view of the recent investigation of DY process within both the collinear and the transverse momentum factorization schemes with hadrons replaced by on-shell parton states [28]. They examined these two factorization approaches and claimed the substantial differences between them in the calculations of the angular asymmetries. This may be compared with the calculations of the angular distribution of the DY lepton pair production in the framework of the transverse momentum-dependent factorization approach [29]. It was found that in the intermediate transverse momentum region the collinear factorization and the transverse momentum-dependent factorization are consistent in the description of the lepton pair angular distributions. This corrected the earlier claims of [30], questioning (like [28]) the unique predictions for the SSAs within collinear and transverse momentum-dependent factorization approaches. Because of these controversies, the properties of transverse momentum integrated SSAs which we are elaborating here are of additional importance.

2. Causality and contour gauge for the gluonic pole

We study the contribution to the hadron tensor which is related to the single spin (left–right) asymmetry measured in the Drell–Yan process with the transversely polarized nucleon: $N^{(\uparrow\downarrow)}(p_1) + N(p_2) \to \gamma^*(q) + X(P_X) \to \ell(l_1) + \bar{\ell}(l_2) + X(P_X)$, where 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 [31].

The DY process with the transversely polarized target manifests [23] the gluonic pole contributions. Since we perform our calculations within a *collinear* factorization, it is convenient (see, e.g., [32]) to fix the dominant light-cone directions for the DY process shown in Fig. 1

$$p_1 \approx \frac{Q}{x_B\sqrt{2}} n^*, \qquad p_2 \approx \frac{Q}{y_B\sqrt{2}} n \quad \text{with}$$
$$n^*_\mu = \left(1/\sqrt{2}, \mathbf{0}_T, 1/\sqrt{2}\right), \qquad n_\mu = \left(1/\sqrt{2}, \mathbf{0}_T, -1/\sqrt{2}\right), \tag{1}$$

so that the hadron momenta p_1 and p_2 have the plus and minus dominant light-cone components, respectively. Accordingly, the quark and gluon momenta k_1 and ℓ lie along the plus direction while the antiquark momentum k_2 – along the minus direction.

Focusing on the Dirac vector projection, containing the gluonic pole, let us start with the standard hadron tensor generated by the diagram depicted in Fig. 1(a):

$$\mathcal{W}^{(1)}_{\mu\nu} = \int d^4k_1\, d^4k_2\, \delta^{(4)}(k_1 + k_2 - q) \int d^4\ell\, \Phi^{(A)[\gamma^+]}_\alpha(k_1, \ell)\bar{\Phi}^{[\gamma^-]}(k_2) \times \mathrm{tr}\left[\gamma_\mu\gamma^-\gamma_\nu\gamma^+\gamma_\alpha \frac{\ell^+\gamma^- - k_2^-\gamma^+}{-2\ell^+k_2^- + i\epsilon}\right], \tag{2}$$

where

$$\Phi^{(A)[\gamma^+]}_\alpha(k_1, \ell) \stackrel{\mathcal{F}_2}{=} \left\langle p_1, S^T \middle| \bar{\psi}(\eta_1)\gamma^+ g A_\alpha(z)\psi(0) \middle| S^T, p_1 \right\rangle,$$
$$\bar{\Phi}^{[\gamma^-]}(k_2) \stackrel{\mathcal{F}_1}{=} \langle p_2|\bar{\psi}(\eta_2)\gamma^-\psi(0)|p_2\rangle. \tag{3}$$

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

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

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

$$dy e^{iy\lambda} \quad \text{and} \quad dx_1\, dx_2 e^{ix_1\lambda_1 + i(x_2 - x_1)\lambda_2}. \tag{5}$$

Analyzing the γ-structure of (2), we may conclude that the first term in the quark propagator singles out the combination: $\gamma^+\gamma_\alpha\gamma^-$ with $\alpha = T$ which will lead to the matrix element of the twist three operator, $\langle\bar{\psi}\gamma^+A^T_\alpha\psi\rangle$ with the transverse gluon field. After factorization, this matrix element will be parametrized via the function $B^V(x_1, x_2)$. The second term in the numerator of the quark propagator separates out the combination $\gamma^+\gamma_\alpha\gamma^+$ with $\alpha = -$. Therefore, this term will give $\langle\bar{\psi}\gamma^+A^+\psi\rangle$ which, as we