

Toward twist-2 T -odd transverse-momentum-dependent gluon distributions: the f -type linearity function

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We present preliminary results on the leading-twist transverse-momentum-dependent (TMD) gluon linearity function, which is directly connected to nucleon transverse-spin asymmetries originating from the density of linearly-polarized gluons. The function is calculated in a spectator-model framework for the parent proton and for the f -type gauge-link structure. Our work represents a further step toward the definition of a complete set of gluon TMD distributions at twist-2 that can be used to access the gluon dynamics inside nucleons and nuclei at new-generation colliders.

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1. Introductory remarks

The study of the inner structure of nucleons in terms of the distribution of their constituents has always represented a frontier research field in particle physics. The well-established *collinear* factorization has played an important role in the description of high-energy hadronic and lepto-hadronic collisions in terms of *one-dimensional* parton distribution functions (PDFs). There are fundamental questions, however, that are still open and whose answers cannot be made from a purely collinear perspective. To shed light on the origin of proton spin and mass as well as on azimuthal asymmetries determined by the interplay between nucleon and parton polarizations, a *three-dimensional* vision is required. The *transverse-momentum-dependent* (TMD) factorization represents the most powerful tool to afford such a *tomographic* description. At variance with the quark-TMD sector, where significant results have been collected both on the formal and phenomenological sides, gluon TMDs are still a largely unexplored territory. The first classification of (un)polarized TMD gluon densities was done in [1] and then extended in [2–4]. First phenomenological studies were conducted in [5–12]. A remarkable feature that distinguishes TMD densities from their collinear counterparts is the sensitivity to the gauge link, which leads to the well-known TMD process dependence [13–15]. While quark TMDs depend on processes via the $+$ and $-$ staple links respectively depicting the direction of future- and past-pointing Wilson lines, gluon TMDs depend on combinations of those gauge links, thus bringing to a more diversified *modified universality*. Two major gluon gauge links appear: the f -type (or Weiszäcker–Williams) and the d -type (or dipole) ones. The f -type T -odd gluon-TMD correlator is characterized by the f_{abc} QCD color structure, whereas the symmetric d_{abc} structure emerges in the d -type T -odd one. It turns out that f -type TMDs depend on $[\pm, \pm]$ gauge links, while d -type TMDs depend on $[\pm, \mp]$ ones. Box-loop gauge links are probed via reactions where multiple color exchanges connect both initial and final states [16], thus generating factorization-breaking effects [17]. The connection between TMD and *high-energy* factorization was investigated in recent studies on the BFKL unintegrated gluon density [18–34]. Detailed studies on spectator-model quark TMDs in the proton were done in [35, 36]. A common framework was recently built [37] (see also [38, 39]) for all the T -even gluon TMDs at twist-2. These functions were calculated in an enhanced spectator model for the parent proton and they encode effective high-energy resummation effects. In [40] we presented a first extension of our framework to T -odd gluon TMDs by means of the f -type Sivvers function, which carries information on the distribution of unpolarized gluons inside transversely polarized protons. In this work we present a preliminary analysis of another T -odd gluon TMD, the f -type linearity function, which can explain observed single-spin asymmetries originating from the density of linearly-polarized gluons inside transversely polarized protons.

2. The f -type linearity function in a spectator model

The spectator-model framework relies on the assumption that an incoming nucleon, having mass M and four-momentum P , emits a parton with four-momentum p , transverse momentum \mathbf{p}_T and longitudinal fraction x , and what remains is considered as an effective on-shell spectator particle having mass M_X and spin-1/2. We model the nucleon-gluon-spectator vertex in the following way

$$Y^\mu = \left(g_1(p^2)\gamma^\mu + g_2(p^2)\frac{i}{2M}\sigma^{\mu\nu}p_\nu \right). \quad (1)$$

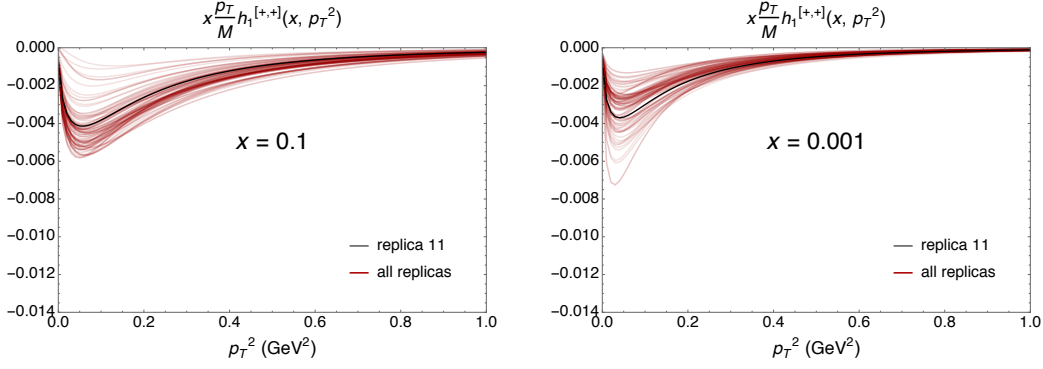


Figure 1: Transverse-momentum dependence of the $[+, +]$ linearity function for $x = 10^{-1}$ (left) and $x = 10^{-3}$ (right), and at the initial scale $Q_0 = 1.64$ GeV. Black curve stands for the most representative replica #11.

In Eq. (1) g_1 and g_2 are dipolar functions of \mathbf{p}_T^2 . Employing dipolar form factors is quite useful, since it permits us to quench gluon-propagator divergences, suppress large- \mathbf{p}_T effects that are beyond the reach of a genuine TMD description, and cancel logarithmic singularities arising from \mathbf{p}_T -integrated densities. All the leading-twist T -even gluon TMDs in the proton were calculated in [37] by defining an enhanced version of the tree-level spectator model. In particular, the M_X mass of the colored spin-1/2 spectator was integrated over a continuous range weighed by a flexible spectral function suited to catch both small- and moderate- x effects (see Eqs. (16) and (17) of [37]). Parameters embodied by the spectral mass and the pure spectator-model correlator were fixed by making a simultaneous fit of our unpolarized and helicity TMD distributions, f_1^g and g_1^g , to the corresponding collinear PDF functions from NNPDF [41, 42] at the initial scale $Q_0 = 1.64$ GeV. Statistical uncertainties are described via the bootstrap method. The spectator-model T -even functions are process-independent, since the tree-level approximation for the gluon correlator does not account for the gauge link. The interference term between two scattering amplitudes with different imaginary parts is needed to generate any T -odd structure. The most straightforward option is to go beyond the tree-level gluon correlator by including the interference with the one-gluon exchange process (in *eikonal* approximation). The latter represents the first-order approximation of the gauge link operator. The main consequence of this strategy is that the calculated T -odd TMDs is gauge-link sensitive, and thus process dependent. The two linearity functions corresponding to the f -type gauge link are obtained by suitably projecting the transverse part of the corresponding gluon correlator, and they are equal up to a minus sign

$$h_1^{g [+,+]}(x, \mathbf{p}_T^2) \equiv -h_1^{g [-,-]}(x, \mathbf{p}_T^2). \quad (2)$$

In our preliminary analysis we use a simplified expression of the nucleon-gluon-spectator vertex, where the g_2 form factor in Eq. (1) is set to zero. For the sake of consistency, we fitted again model parameters to NNPDF results by using the simplified formula for the vertex. Fig. 1 shows the \mathbf{p}_T^2 -shape of the $[+, +]$ linearity function at $x = 10^{-1}$ and at $x = 10^{-3}$, and at the initial scale $Q_0 = 1.64$ GeV. The absolute value of our density is clearly a non-Gaussian function of \mathbf{p}_T^2 , with a large flattening tail at large \mathbf{p}_T^2 -values and a small nonzero value when \mathbf{p}_T^2 goes to zero. We remark that this behavior could radically change when the full-vertex calculation will become available.

3. Closing statements

We have extended our spectator-model framework by including a preliminary version of the f -type gluon linearity TMD function. Once the calculation of all the T -odd gluon TMDs will be completed, we will include standard TMD evolution and perform phenomenological analyses on the relevant spin asymmetries that can be studied at new-generation colliding facilities, as the *Electron-Ion Collider* (EIC) [43], the *High-Luminosity Large Hadron Collider* (HL-LHC) [44], NICA-SPD [45], and the *Forward Physics Facility* (FPF) [46].

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