A spectator-model way to transverse-momentum-dependent gluon distribution functions

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Abstract

We present exploratory analyses of the 3D gluon content of the proton via a study of unpolarized and polarized gluon TMDs at twist-2, calculated in a spectator model for the parent nucleon. Our approach embodies a flexible parametrization for the spectator-mass function, suited to describe both moderate and small-x effects. All these studies can serve as a useful guidance in the investigation of the gluon dynamics inside nucleons and nuclei, which constitutes one of the major goals of new-generation colliding machines, as the EIC, the HL-LHC, NICA, and the FPF.

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1 Introduction

The study of the proton content via transverse-momentum-dependent (TMD) parton distribution functions represents a challenging line of research plans at current and new-generation colliding machines. While in the last years the investigation of the quark-TMD field has reached important milestones, from the deep knowledge of formal properties to the more and more accurate extraction of quark densities from global fits, the gluon-TMD sector still represents a largely unexplored territory. A first classification of unpolarized and polarized gluon TMD distributions was first made in Ref. [1] and subsequently extended in Refs. [2–4]. Recent phenomenological analyses on gluon TMDs can be found in Refs. [5–9]. A major difficulty that emerges in formal studies of gluon TMDs is their process dependence. Different kinds of reactions are sensitive to distinct *gauge-link* structures, and this leads to a more intricate *modified universality* with respect to what we observe for quark TMDs. Two main gauge links can be identified. They have been classified in the context of small-x analyses as Weiszäcker–Williams and dipole TMDs [10]. They are strictly related to gluon correlators where for T-odd TMDs the f_{abc} and d_{abc} QCD color structures respectively emerge. Therefore, they are also known among the TMD community as f-type and d-type gluon TMDs. At low-x values and large transverse momenta, the gluon content of the proton is described by the so-called *unintegrated gluon distribution* (UGD), whose evolution is governed by the Balitsky–Fadin–Kuraev–Lipatov (BFKL) equation [11, 12] (for recent applications see Refs. [13–23]). Its relation to the low-x limit of gluon TMDs and, more in general, to the Collins–Soper–Sterman (CSS) evolution [24, 25] has been investigated in Refs. [10] and [26, 27], respectively. In this work we present a study on leading-twist T-even gluon TMDs calculated in a *spectator model* for the parent proton. Our framework is suited to analyses both in moderate and small-x ranges.

2 TMD gluon distribution functions

According to the spectator-model approximation, the proton can emit a gluon with longitudinal-momentum fraction x and transverse momentum $\boldsymbol{p}_T$, and the remainders are treated as an effective colored particle with mass M_X and possessing the quantum numbers of a fermion, that we call spectator. The nucleon-gluon-spectator coupling is encoded in a effective vertex that contains two form factors, chosen as dipolar functions of $\boldsymbol{p}_T^2$. The main advantage of using dipolar form factors consists in the possibility of cancelling gluon-propagator singularities, quenching the effects of large transverse momenta where a pure TMD description is not anymore adequate, and removing logarithmic divergences emerging in $\boldsymbol{p}_T$-integrated densities.

In Ref. [28] a pioneering study on quark TMDs was proposed, by considering different di-quark spectator polarization states and nucleon-parton-spectator form factors. In Ref. [29] the weight of azimuthal asymmetries was assessed.

In the present study we present our calculation in the spectator model of T-even gluon TMDs at twist-2. We improved the genuine spectator-model approach by allowing the spectator mass, M_X, to be in a range of values weighed by the following 7-parameter spectral function

$$\rho_{[\text{spect.}]}(M_X) = \mu^{2a}\left(\frac{A}{B+\mu^{2b}} + \frac{C}{\pi\sigma}e^{-\frac{(M_X-D)^2}{\sigma^2}}\right). \tag{1}$$

The expression for a given TMD reads

$$\mathcal{F}^g(x,\boldsymbol{p}_T^2) = \int_M^\infty dM_X\, \rho_{[\text{spect.}]}(M_X)\, \hat{\mathcal{F}}^g(x,\boldsymbol{p}_T^2;M_X)\,, \tag{2}$$

with $\hat{\mathcal{F}}^g$ the corresponding TMD obtained in a pure spectator-model calculation. Model parameters were fitted to simultaneously reproduce the gluon unpolarized ($f_1^g(x)$) and helicity ($g_1^g(x)$) collinear parton distribution functions (PDFs), obtained in global fits at the initial scale $Q_0 = 1.64$ GeV (see Fig. 1). We performed our fit by making use of the so-called bootstrap method. We created N *replicas* of the central value of the NNPDF parametrization by randomly varying it with a Gaussian noise that keeps the same variance of the original parametrization uncertainty. We fitted each replica separately and we obtained N-dimensional vector for each parameter of the model. A complete description of our model together all technical details of our fit procedure can be found in Ref. [30] (see also Refs. [31–36]). We show in Fig. 2 the

p_T^2-dependence of two T-even gluon TMDs calculated at $x = 0.001$ and at the same initial scale, $Q_0 = 1.64$ GeV. Each one of our TMDs exhibit a distinct shape. The unpolarized gluon density $xf_1^g(x, \boldsymbol{p}_T^2)$ (left panel) shows a non-Gaussian pattern in $\boldsymbol{p}_T^2$, a large flattening tail in the $\boldsymbol{p}_T^2 \to 1$ GeV limit, and it goes to a quite small value when $\boldsymbol{p}_T^2 \to 0$. Conversely, the Boer–Mulders gluon distribution $xh_1^{\perp g}(x, \boldsymbol{p}_T^2)$ (right panel), that is connected to the density of transversely polarized gluons inside an unpolarized proton, starts from a finite value at $\boldsymbol{p}_T^2 = 0$ and decreases very fast when $\boldsymbol{p}_T^2$ grows.

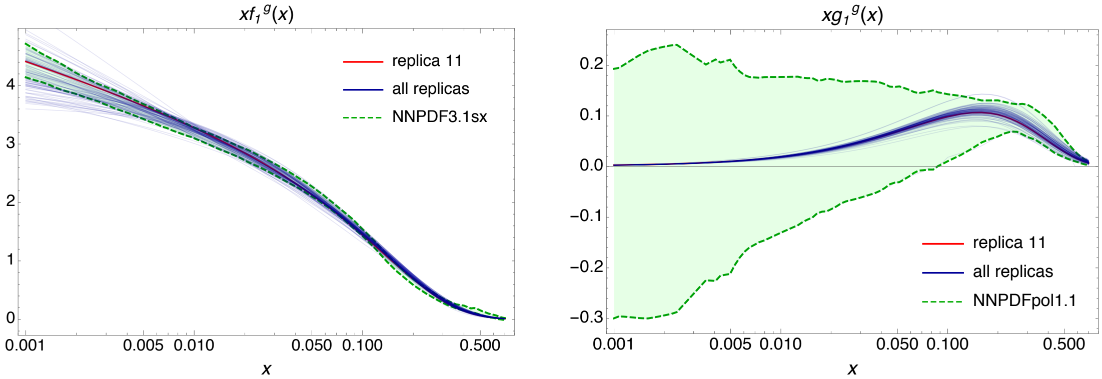

Figure 1: x-dependence of the unpolarized (left) and helicity (right) gluon PDFs densities calculated in the spectator model at the initial scale $Q_0 = 1.64$ GeV. Green bands with dashed borders stand for the `NNPDF3.1x` [37] and the `NNPDFpol1.1` [38] parametrizations. Blue curves depict the 100 replicas for our integrated TMDs. Red curve for the most representative replica #11.

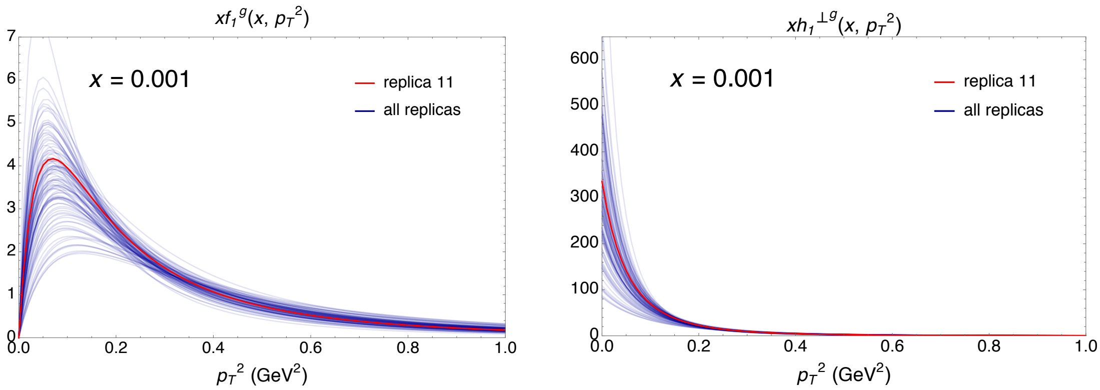

Figure 2: Transverse-momentum dependence of the unpolarized (left) and Boer–Mulders (right) gluon TMD densities calculated in the spectator model, for $x = 10^{-3}$ and at the initial scale $Q_0 = 1.64$ GeV. Red curve for the most representative replica #11.

3 Conclusion

We presented a model dependent calculation of all twist-2 T-even gluon TMDs based on the assumption that what remains of the proton after gluon emission can be described as an effective spin-1/2 spectator particle. We improved the genuine spectator-model description by weighing its mass via a versatile spectral function. We fitted model parameters to reproduce the x-shape of collinear unpolarized and helicity gluon PDFs that were extracted from global fits. At the current level, our model does not incorporate any gauge-link dependence, and the extension to twist-2 T-odd gluon TMD distributions is underway. Another intriguing perspective is represented by encoding in the description of the unpolarized gluon TMD genuine small-x effect from the BFKL resummation [11, 12]. Exploratory studies on gluon-TMD phenomenology via our model can represent a useful guidance in accessing the proton content at new-generation colliding machines, as the *Electron-Ion Collider* (EIC) [39], the *High-Luminosity Large Hadron Collider* (HL-LHC) [40], NICA [41], and the *Forward Physics Facility* [42, 43].

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