Towards leading-twist $T$-odd TMD gluon distributions

Alessandro Bacchetta$^{1,2}$, Francesco Giovanni Celiberto$^{3,4,5}$, and Marco Radici$^2$

$^1$Dipartimento di Fisica, Università di Pavia, via Bassi 6, I-27100 Pavia, Italy
$^2$INFN Sezione di Pavia, via Bassi 6, I-27100 Pavia, Italy
$^3$European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT*), I-38123 Villazzano, Trento, Italy
$^4$Fondazione Bruno Kessler (FBK), I-38123 Povo, Trento, Italy
$^5$INFN-TIFPA Trento Institute of Fundamental Physics and Applications, I-38123 Povo, Trento, Italy

E-mail: f.celiberto@ectstar.eu

(Received January 25, 2021)

We present exploratory studies of the 3D proton tomography through polarized $T$-odd gluon TMDs at leading twist, obtained in a spectator-model framework. We embody in our approach a flexible parameterization for the spectator-mass spectral function, suited to catch both small- and moderate-$x$ effects. All these studies are relevant to unveil the gluon dynamics inside hadrons, which represents a core research line of studies at new-generation colliders, such as the Electron-Ion Collider, NICA-SPD, the High-Luminosity LHC, and the Forward Physics Facility.

KEYWORDS: gluon TMDs, 3D proton tomography, Hadron Structure, factorization, QCD

1. Introduction

One of the ultimate goals of frontier researches in particle physics is unraveling the inner structure of nucleons in terms of the distribution of their constituents. The collinear factorization is a well-established formalism that has collected many successes since the advent of the parton model. A key role in the description of high-energy hadronic and lepto-hadronic collisions is played by the one-dimensional parton distribution functions (PDFs). However, there are fundamental questions about the deep nature of strong interactions that are still open and whose answers go beyond the reach of a pure collinear description. As an example, unveiling the origin of proton mass and spin requires a viewpoint stretched to a three-dimensional, tomographic description, which is naturally provided by the so-called transverse-momentum-dependent (TMD) factorization.

While quite solid results have been obtained both on the formal and the phenomenological side for quark TMD densities, the gluon-TMD field is still an almost uncharted territory. In Ref. [1] a first classification of unpolarized and polarized gluon TMD distributions was afforded. It was then extended in Refs. [2–4], whereas first phenomenological predictions were subsequently provided [5–12].

A striking difference between TMD and collinear densities is represented by the gauge-link sensitivity. In particular, the fact that TMDs are sensitive to the transverse components of the gauge link makes them process dependent (see Refs. [13–15]). Quark TMDs depend on processes through the $[+]$ and $[-]$ staple links, which determine the direction of future- and past-pointing Wilson lines, respectively. The gluon TMDs have a more complicated gauge-link dependence, since they are sensitive on combinations of staple links. This fact leads to a more diversified kind of modified universality. Two major gluon gauge links emerge: the $f$-type and the $d$-type ones. They are also known in the context of small-$x$ studies as Weiszäcker–Williams and dipole structures, respectively. The antisymmetric $f_{abc}$ QCD color structure is part of the $f$-type $T$-odd gluon-TMD correlator, whereas the symmetric $d_{abc}$ structure appears in the $d$-type $T$-odd one. This brings to a dependence of $f$-type
2. \( T \)-odd gluon TMDs in a spectator model

The spectator-model framework is based on a simple and intuitive assumption, namely that the incoming proton with mass \( M \) and four-momentum \( P \) emits a gluon having longitudinal fraction \( x \), four-momentum \( p \), and transverse momentum \( p_T \), and the remainders are effectively treated as an on-shell spectator particle with mass \( M_\chi \) and spin-1/2. The nucleon-gluon-spectator vertex is modeled as follows

\[
\mathcal{G}^\mu = \left( \tau_1(p^2) \gamma^\mu + \tau_2(p^2) \frac{i}{2M} \sigma^{\mu\nu} p_\nu \right), \tag{1}
\]

the \( \tau_1 \) and \( \tau_2 \) functions being dipolar form factors in \( p_T^2 \). A dipolar choice for the couplings is useful to remove gluon-propagator divergences, suppress large-\( p_T \) effects which are beyond the reach of a pure TMD description, and dampen logarithmic singularities coming from \( p_T \)-integrated distributions. All the unpolarized and polarized spectator-model \( T \)-even gluon TMDs at twist-2 in the proton were obtained in [45]. In that work the naive spectator-model approach was improved by allowing the spectator mass \( M_\chi \) to spread over a continuous range of values via a flexible spectral function suited to capture both small- and moderate-\( x \) effects (see Eqs. (16) and (17) of Ref. [45]). The model parameters encoded in the definition of the spectral function and in the spectator-model correlator were determined through a simultaneous fit of the unpolarized and helicity gluon TMD densities, \( f_1^g \) and \( g_1^g \), to the corresponding collinear PDF distributions obtained from NNPDF [50, 51] at the initial scale \( Q_0 = 1.64 \) GeV. The size of the statistical uncertainty was assessed by means of the bootstrap method.

Since the tree-level approximation for the gluon correlator does not account for the gauge link, our \( T \)-even TMD distributions turn out to be process-independent. In order to generate \( T \)-odd structures in the gluon correlator, we need to go beyond the tree level and include its interference with a distinct channel. Similarly to the quark TMD case, we have considered the one-gluon exchange in eikonal approximation. This diagram corresponds to the truncation at first order of the whole gauge-link operator. The main effect of this procedure is that the obtained \( T \)-odd functions become sensitive to gauge links, and thus process dependent. For the given \( f \)-type gauge link, two Sivers TMDs \( (f_{1T}^g)^{[+,-]} \) and two linearity TMDs \( (h_1)^{[+,-]} \) are obtained by suitably projecting the transverse part of the corresponding gluon correlator. For each pair, the two partners are connected by the following modified-universality relation

\[
\begin{align*}
(f_{1T}^g)^{[+,-]}(x, p_T^2) & \equiv - (f_{1T}^g)^{[-,+]}(x, p_T^2); \\
(h_1)^{[+,-]}(x, p_T^2) & \equiv - (h_1)^{[-,+]}(x, p_T^2). \tag{2}
\end{align*}
\]
In our preliminary analysis we have employed a simplified expression for the nucleon-gluon-spectator vertex, with the $\tau_2$ form factor in Eq. (1) set to zero. For the sake of consistency, we have fitted the model parameters to NNPDF parametrizations by using the simplified expression for the vertex.

In upper panels of Fig. 1 we present the transverse-momentum dependence of the $p_T$-weighted $[+,+]$ Sivers function for two representative values of the longitudinal fraction, $x = 10^{-3}$ and $x = 10^{-1}$, and at the initial scale $Q_0 = 1.64$ GeV. Corresponding results for the $[+,+]$ linearity function are given in lower panels. By inspecting our plots, it emerges that both the distributions have a non-Gaussian pattern in $p_T^2$, with a large flattening tail at large $p_T^2$-values and a small but nonzero value when $p_T^2 \to 0$, which suggests that in this limit both TMDs diverge at most as $1/|p_T|$. At variance with the $T$-even unpolarized and the Boer–Mulders gluon functions (see Fig. (4) of Ref. [45]), the bulk of our $f$-type $T$-odd functions increases when $x$ grows. This suggests that transverse single-spin asymmetries could be less manifest in the low-$x$ regime. We remark, however, that our results could change even radically when the full-vertex calculation will become available.

3. Conclusions and prospects

We have enhanced our spectator-model framework by performing preliminary calculation of two $f$-type $T$-odd gluon TMDs: the Sivers and the linearity functions. The full calculation of all the $T$-odd gluon TMDs, including the $d$-type ones is underway. They can serve as a useful guidance to

![Graphs showing transverse-momentum dependence of the $[+,+]$ Sivers (upper) and linearity (lower) densities for $x = 10^{-3}$ (left) and $x = 10^{-1}$ (right), and at the initial scale $Q_0 = 1.64$ GeV. Black curves refer to the most representative replica #11.](image)
shed light on gluon-TMD dynamics at new-generation particle colliders and experiments, such as the Electron-Ion Collider (EIC) [52], NICA-SPD [53], the High-Luminosity Large Hadron Collider (HL-LHC) [54], and the Forward Physics Facility (FPF) [55].

References

[1] P. J. Mulders, J. Rodrigues, Phys. Rev. D 63 (2001), 094021 doi:10.1103/PhysRevD.63.094021 [arXiv:hep-ph/0009343 [hep-ph]].
[2] S. Meissner, A. Metz, K. Goeke, Phys. Rev. D 76 (2007), 034002 doi:10.1103/PhysRevD.76.034002 [arXiv:hep-ph/0703176 [hep-ph]].
[3] C. Lorcé, B. Pasquini, JHEP 09 (2013), 138 doi:10.1007/JHEP09(2013)138 [arXiv:1307.4497 [hep-ph]].
[4] D. Boer, S. Cotogno, T. van Daal, P. J. Mulders, A. Signori, Y. J. Zhou, JHEP 10 (2016), 013 doi:10.1007/JHEP10(2016)013 [arXiv:1607.01654 [hep-ph]].
[5] Z. Lu, B. Q. Ma, Phys. Rev. D 94 (2016) no.9, 094022 doi:10.1103/PhysRevD.94.094022 [arXiv:1611.00125 [hep-ph]].
[6] J. P. Lansberg, C. Pisano, JHEP 09 (2013), 138 doi:10.1007/JHEP09(2013)138 [arXiv:1307.4497 [hep-ph]].
[26] A. D. Bolognino, F. G. Celiberto, D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, Eur. Phys. J. C 78 (2018) no.9, 772 doi:10.1140/epjc/s10052-018-6253-7 [arXiv:1808.05483 [hep-ph]].
[27] A. D. Bolognino, F. G. Celiberto, D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, Acta Phys. Polon. Supp. 12 (2019) no.4, 773 doi:10.5506/APhysPolBSupp.12.773 [arXiv:1902.04511 [hep-ph]].
[28] A. D. Bolognino, F. G. Celiberto, M. Fucilla, D. Yu. Ivanov, A. Papa, Eur. Phys. J. C 79 (2019) no.11, 939 doi:10.1140/epjc/s10052-019-7392-1 [arXiv:1909.03068 [hep-ph]].
[29] A. D. Bolognino, F. G. Celiberto, D. Yu. Ivanov, A. Papa, W. Schäfer, A. Szczurek, Eur. Phys. J. C 81 (2021), 9 doi:10.1140/epjc/s10052-021-09593-9 [arXiv:2107.13415 [hep-ph]].
[30] F. G. Celiberto, D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, Eur. Phys. J. C 81 (2021) no.4, 293 doi:10.1140/epjc/s10052-021-09063-2 [arXiv:2008.00501 [hep-ph]].
[31] F. G. Celiberto, D. Yu. Ivanov, A. Papa, Phys. Rev. D 102 (2020) no.9, 094019 doi:10.1103/PhysRevD.102.094019 [arXiv:2008.10513 [hep-ph]].
[32] A. D. Bolognino, F. G. Celiberto, M. Fucilla, D. Yu. Ivanov, A. Papa, Phys. Rev. D 103 (2021) no.9, 094004 doi:10.1103/PhysRevD.103.094004 [arXiv:2103.07396 [hep-ph]].
[33] F. G. Celiberto, M. Fucilla, D. Yu. Ivanov, A. Papa, Eur. Phys. J. C 81 (2021) no.8, 780 doi:10.1140/epjc/s10052-021-09448-3 [arXiv:2105.06432 [hep-ph]].
[34] F. G. Celiberto, M. Fucilla, D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, Phys. Rev. D 104 (2021) no.11, 114007 doi:10.1103/PhysRevD.104.114007 [arXiv:2109.11875 [hep-ph]].
[35] F. G. Celiberto, M. Fucilla, D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, [arXiv:2111.13090 [hep-ph]].
[36] F. G. Celiberto, M. Fucilla, D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, [arXiv:2110.12649 [hep-ph]].
[37] A. D. Bolognino, F. G. Celiberto, M. Fucilla, D. Yu. Ivanov, A. Papa, [arXiv:2110.12772 [hep-ph]].
[38] F. G. Celiberto, M. Fucilla, D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, [arXiv:2110.09358 [hep-ph]].
[39] F. G. Celiberto, D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, [arXiv:2107.13037 [hep-ph]].
[40] A. D. Bolognino, F. G. Celiberto, F. Fucilla, D. Yu. Ivanov, A. Papa, [arXiv:2107.12120 [hep-ph]].
[41] M. Nefedov, Phys. Rev. D 104 (2021) no.5, 054039 doi:10.1103/PhysRevD.104.054039 [arXiv:2105.13915 [hep-ph]].
[42] M. Hentschinski, Phys. Rev. D 104 (2021) no.5, 054014 doi:10.1103/PhysRevD.104.054014 [arXiv:2107.06203 [hep-ph]].
[43] A. Bacchetta, F. Conti, M. Radici, Phys. Rev. D 78 (2008), 074010 doi:10.1103/PhysRevD.78.074010 [arXiv:0807.0323 [hep-ph]].
[44] A. Bacchetta, M. Radici, F. Conti, M. Guagnelli, Eur. Phys. J. A 45 (2010), 373-388 doi:10.1140/epja/i2010-11016-y [arXiv:1003.1328 [hep-ph]].
[45] A. Bacchetta, F. G. Celiberto, M. Radici, P. Taels, Eur. Phys. J. C 80 (2020) no.8, 733 doi:10.1140/epjc/s10052-020-8327-6 [arXiv:2005.02288 [hep-ph]].
[46] A. Bacchetta, F. G. Celiberto, M. Radici, P. Taels, [arXiv:2107.13446 [hep-ph]].
[47] F. G. Celiberto, Nuovo Cim. C 44 (2021) no.2-3-3, 36 doi:10.1393/ncc/i2021-21036-3 [arXiv:2101.04630 [hep-ph]].
[48] A. Bacchetta, F. G. Celiberto, M. Radici, [arXiv:2111.01686 [hep-ph]].
[49] A. Bacchetta, F. G. Celiberto, M. Radici, [arXiv:2111.03567 [hep-ph]].
[50] R. D. Ball, V. Bertone, M. Bonvini, S. Marzani, J. Rojo, L. Rottoli, Eur. Phys. J. C 78 (2018) no.4, 321 doi:10.1140/epjc/s10052-018-5774-4 [arXiv:1710.05935 [hep-ph]].
[51] E. R. Nocera et al. [NNPDF], Nucl. Phys. B 887 (2014), 276-308 doi:10.1016/j.nuclphysb.2014.08.008 [arXiv:1406.5539 [hep-ph]].
[52] R. Abdul Khalek, A. Accardi, J. Adam, D. Adamiak, W. Akers, M. Albaladejo, A. Al-bataineh, M. G. Alexeev, F. Ameli, P. Antonioli, et al. [arXiv:2103.05419 [physics.ins-det]].
[53] A. Arbuzov, A. Bacchetta, M. Butenschoen, F. G. Celiberto, U. D’Alesio, M. Deka, I. Denisenko, M. G. Echevarria, A. Efremov, N. Y. Ivanov, et al. Prog. Part. Nucl. Phys. 119 (2021), 103858 doi:10.1016/j.ppnp.2021.103858 [arXiv:2011.15005 [hep-ex]].
[54] E. Chapon, D. d’Enterria, B. Duloue, M. G. Echevarria, P. B. Gossiaux, V. Kartvelishvili, T. Kasemets, J. P. Lansberg, R. McNulty, D. D. Price, et al. Prog. Part. Nucl. Phys. 122 (2022), 103906 doi:10.1016/j.ppnp.2021.103906 [arXiv:2012.14161 [hep-ph]].
[55] L. A. Anchordoqui, A. Ariga, T. Ariga, W. Bai, K. Balazs, B. Batell, J. Boyd, J. Bramante, M. Campanelli, A. Carmona, et al. [arXiv:2109.10905 [hep-ph]].