



universe



Communication

A Journey into the Proton Structure: Progresses and Challenges

Francesco Giovanni Celiberto

Special Issue

Advance in Quark-Gluon-Plasma (QGP) Physics

Edited by
Prof. Dr. Maria Vasileiou



<https://doi.org/10.3390/universe8120661>

A Journey into the Proton Structure: Progresses and Challenges

Francesco Giovanni Celiberto ^{1,2,3} 

¹ European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT*), I-38123 Trento, Italy; fceliberto@ectstar.eu

² Fondazione Bruno Kessler (FBK), I-38123 Trento, Italy

³ INFN-TIFPA Trento Institute of Fundamental Physics and Applications, I-38123 Trento, Italy

Abstract: Unraveling the inner dynamics of gluons and quarks inside nucleons is a primary target of studies at new-generation colliding machines. Finding an answer to fundamental problems of Quantum ChromoDynamics, such as the origin of nucleon mass and spin, strongly depends on our ability of reconstructing the 3D motion of partons inside the parent hadrons. We present progresses and challenges in the extraction of TMD parton densities, with particular attention to the ones describing polarization states of gluons, which still represent a largely unexplored field. Then, we highlight connections with corresponding parton densities in the high-energy limit, the so-called unintegrated gluon distributions or UGDs and, more in general, to recent developments in high-energy physics.

Keywords: proton structure; spin physics; TMD factorization



Citation: Celiberto, F.G. A Journey into the Proton Structure: Progresses and Challenges. *Universe* **2022**, *8*, 661. <https://doi.org/10.3390/universe8120661>

Academic Editor: Maria Vasileiou

Received: 18 November 2022

Accepted: 12 December 2022

Published: 15 December 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Unveiling the Multidimensional Structure of the Proton

The advent of new-generation particle accelerators [1–20], such as the High-Luminosity Large Hadron Collider (HL-LHC) [21] and the Electron-Ion Collider (EIC) [22–24], will start a new era in the search for long-awaited signals of New Physics beyond the Standard Model (SM) of particle physics. At the same time, it has opened up a great window of opportunities for precision studies of the dynamics of strong interactions, responsible for the strong nuclear force, that “bind us all”. Among these analyses, deepening our knowledge of the proton content represents a primary target of efforts made by a very active scientific community, whose richness and spread grow over time. The most powerful tool to gather information about the inner structure of the proton is the so-called language of parton correlators, that allows us to address the distribution of proton elementary constituents (quark and gluons, generally called partons) in space, momentum and energy. Of special interest are the transverse-momentum-dependent (TMD) parton distribution functions (PDFs), which permit us to unravel the proton content in a three-dimensional representation, namely via a faithful 3D tomographic imaging. A TMD-like description is needed to find an answer to more fundamental questions, such as understanding the origin of the proton spin [25].

From a physical viewpoint, TMD PDFs (or simply TMDs) come out as 3D generalizations of 1D collinear PDFs, since they account for struck-parton transverse-momentum effects. A TMD description is required in order to correctly depict observables sensitive to the intrinsic transverse motion of colliding partons. The latter, quantified by TMDs, leaves its imprint on transverse momenta of particles tagged in the final state. It can be accessed through experimental measurements of semi-inclusive final states featuring observed transverse momenta or transverse imbalances much smaller than the reference hard scale(s). To achieve a complete tomographic reconstruction of the proton, the information encoded in TMDs needs to be complemented by the one carried by another family of 3D maps: the generalized parton distributions (GPDs). While TMDs give us access to the proton 3D content in momentum space, GPDs permit us to unveil the 3D dynamics of partons in the

position space. More in particular, information on the transverse position of a parton in the parent hadron is gathered from exclusive reactions with the proton being deflected at small angles. GPDs quantify the parton transverse-spatial distribution via a Fourier transform of the transverse momentum transferred to the proton.

Formally, both TMDs and GPDs are projections of more general distributions, defined in terms of the fully unintegrated and off-diagonal correlator. These quantities are known as generalized TMDs (GTMDs) and they are often referred as “mother” distributions of TMDs and GPDs [26–36]. However, beyond this purely formal link, no general relations between TMDs and GPDs are known. Some nontrivial connections have been found only via models [37–39]. Striking examples are the so-called chromodynamic lensing relations [37,40–42] connecting time-reversal effects in single-spin asymmetries and spatial distortions of the GPDs in the impact-parameter space (see also Ref. [43]). These functional relations do not hold anymore when higher Fock states and/or higher-order diagrams are considered in models [39,44–46].

2. TMD Gluon Distribution Functions

Unpolarized and polarized gluon TMDs at twist-2 (leading twist) for a spin-1/2 target were identified for the first time in Refs. [47] (see also Refs. [33,39]). TMD distributions are sensitive to the resummation of logarithmically enhanced terms proportional to the observed transverse momentum. While our knowledge of this perturbative contribution is well known [48–50], the genuine nonperturbative TMD content is a largely uncharted territory. The distribution of linearly polarized gluons in an unpolarized nucleon, $h_1^{\perp g}$, is a key ingredient to explain spin effects observed in unpolarized-hadron collisions [51–56], whose size is expected to grow in the low- x domain [57,58]. The Sivers function, $f_{1T}^{\perp g}$, tells us about the distribution of unpolarized gluons in a transversely polarized nucleon. It plays a core role to explain transverse-spin asymmetries rising in collisions of polarized hadrons. Remarkably, the Sivers function can be accessed via unpolarized electron-nucleon scatterings thanks to its connection with the Odderon in the forward-QCD limit [59].

TMDs turn out to be process-dependent due to the presence of transverse *gauge links* (Wilson lines) [60–62]. Whereas quark TMDs depend on $[\pm]$ staple links that determine the direction of future- or past-pointing Wilson lines, gluon TMDs exhibit a more involved gauge-link dependence, since they are sensitive to combinations of two or more staple links. As a consequence, they feature a more complicated level of modified universality.

There exist two principal gluon gauge links, known as f -type and the d -type structures. In the context of low- x investigations they are often called Weizsäcker–Williams and dipole links, respectively. The antisymmetric f_{abc} QCD color structure is typical of the f -type time-reversal odd (T-odd) gluon-TMD correlator, while the symmetric d_{abc} structure determines the d -type T-odd one. This makes f -type (d -type) gluon TMDs dependent on $[\pm, \pm]$ ($[\pm, \mp]$) gauge-link combinations. Much more intricate, box-loop structures rise along with reactions in which multiple color exchanges connect both the initial and final state [63]. This fact, however, brings to violations of the TMD factorization [64,65].

More in general, a rigorous proof of the validity of TMD factorization relies on establishing proper factorization theorems affording us a precise definition of initial-scale and evolved densities, and thus defining their universality properties and evolution equations. These theorems need to be proven process by process. Up to now, TMD theorems have been obtained for a few reactions sensitive to quark TMDs: Drell–Yan and semi-inclusive deep inelastic scattering at low observed transverse momenta [66,67], as well as lepton annihilations into two almost back-to-back hadrons [66–68]. The factorization for the inclusive production of single hadrons has been discussed only recently [69–71].

Conversely, proper factorization theorems for gluon-TMD sensitive processes are almost completely lacking, so that factorization is usually assumed in phenomenological studies. TMD factorization is expected to hold for gluon-induced color-singlet final states, such as Higgs-boson hadroproduction [53,72,73]. Quite recently, a factorization formula was derived for the inclusive hadroproduction of pseudoscalar quarkonium states [74]

in the color-singlet channel [75–78]. This led to an enhancement of the description of the quarkonium production mechanism that now includes TMD-like inputs, known as shape functions [74,79,80]. However, the bound-state nature of a quarkonium particle, instead of a point-like object, makes it difficult to extend that result to gluon-TMD studies through other quarkonia, such as vectors [79,81–84].

From a phenomenological perspective, the gluon-TMD field is an almost uncharted territory. First studies of the unpolarized and the Sivers TMDs were performed Refs. [73,82,83] and [85–88], respectively. Thus, exploratory analyses of gluon TMDs by means of flexible for the nonperturbative content of these densities are required. Progresses along this direction were proposed in the spectator-model approach [47,89,90], which was formerly adopted to model quark TMDs [39,91–95]. In the gluon-TMD case, it assumes that the struck nucleon with mass m_H and momentum κ_H emits a gluon with momentum κ , transverse momentum κ_T and longitudinal fraction x . The remainders are effectively modeled by and effective on-shell particle with mass m_χ and spin 1/2. Within this framework, taken and at the diagrammatic tree level, all the initial energy-scale twist-2 TMDs can be calculated. Spectator-model gluon T-even functions were recently resented in Refs. [57,96,97].

In particular, the nucleon-gluon-spectator vertex was modeled as

$$Y_{ab}^\mu = \delta_{ab} \left[\eta_1(p^2) \gamma^\mu + \eta_2(p^2) \frac{i}{2m_H} \sigma^{\mu\nu} \kappa_\nu \right], \quad (1)$$

where the $\eta_{1,2}$ form factors are two dipolar functions of κ_T^2 . In our model the spectator mass is not a fixed parameter, but it ranges from m_H to $+\infty$ and it is weighted through a spectral function $\Xi_\chi^{[s.m.]}(m_H)$, which reproduce both the small- and the moderate- x behavior of gluon collinear PDFs. The analytic expression of the spectral function contains seven parameters and reads

$$\Xi_\chi^{[s.m.]}(m_H) = \mu^{2a} \left(\frac{\mathcal{A}}{\mathcal{B} + \mu^{2b}} + \frac{\mathcal{C}}{\pi\sigma} e^{-\frac{(m_H - m_D)^2}{\sigma^2}} \right). \quad (2)$$

In Ref. [96] model parameters were fixed by making a simultaneous fit of unpolarized and helicity TMDs, f_1^g and g_1^g , to their collinear counterparts from NNPDF [98,99] at the initial scale of $\mu_0 = 1.64$ GeV. We made use of the replica method [100,101] to determine the statistical uncertainty of our fit. Further details on the fitting procedure and quality can be found in Ref. [96]. Since our tree-level approximation does not depend on the gauge link, our model T-even TMDs are process-universal. A preliminary application of our T-even gluon TMDs to the hadroproduction of pseudoscalar quarkonium states were presented in Ref. [96], while the extension of our framework to the T-odd case was discussed in Refs. [102–106].

With the aim of unveiling the 3D dynamics of gluons inside the proton, we investigate the following distributions which describe the 2D κ_T -density of gluons for distinct combinations of their polarization and the nucleon spin. For an unpolarized proton, we identify the unpolarized distribution

$$x\mathcal{F}_u^g(x, \kappa_x, \kappa_y) = x f_1^g(x, \kappa_T^2) \quad (3)$$

as the distribution of an unpolarized gluon with x and κ_T , whereas the Boer–Mulder distribution

$$x\mathcal{F}_{\vec{\kappa}_T}^g(x, \kappa_x, \kappa_y) = \frac{x}{2} \left[f_1^g(x, \kappa_T^2) - \frac{\kappa_y^2 - \kappa_x^2}{2m_H^2} h_1^{\perp g}(x, \kappa_T^2) \right] \quad (4)$$

stands for the density of a linearly-polarized gluon in the transverse plane with x and κ_T .

Contour plots in Figure 1 exhibit κ_T -patterns of $x\mathcal{F}$ densities in Equations (3) and (4) at $\mu_0 = 1.64$ GeV and $x = 10^{-3}$ for an unpolarized proton moving towards the reader. For the sake of simplicity, results are shown for the most representative replica, namely the number

11. The color code quantifies the weight of the oscillation of each density along the $\kappa_{x,y}$ directions. The unpolarized distribution in Equation (3) possesses a cylindrical symmetry, while the Boer–Mulders density in Equation (4) has a dipolar behavior. The departure from the cylindrical symmetry is larger at low- x , namely in a regime where the Boer–Mulders function is expected to give a relevant contribution [57,58]. To better visualize these oscillations, we present in Figure 2 ancillary, slice panels portraying the corresponding distributions at $\kappa_y = 0$ and for x ranging from 10^{-1} down to 10^{-3} . We clearly observe that both our functions increase as x lowers. This is in line with the well-known pattern in x of collinear PDFs, from which we have extracted the small- x behavior via our fit procedure.

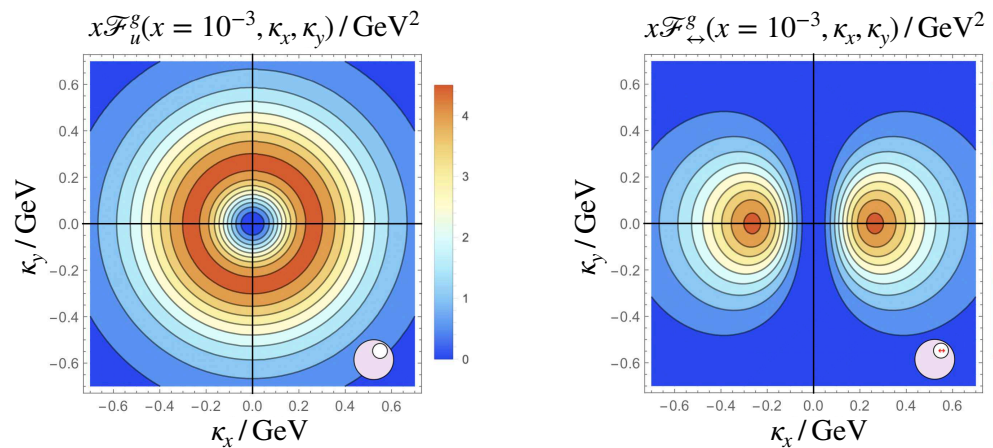


Figure 1. 3D tomographic reconstruction of the unpolarized (**left**) and Boer–Mulders (**right**) gluon TMD distributions in the proton, as functions of the gluon transverse momentum, at the initial energy scale, $\mu_0 = 1.64$ GeV, and for $x = 10^{-3}$. Plots refer to replica 11.

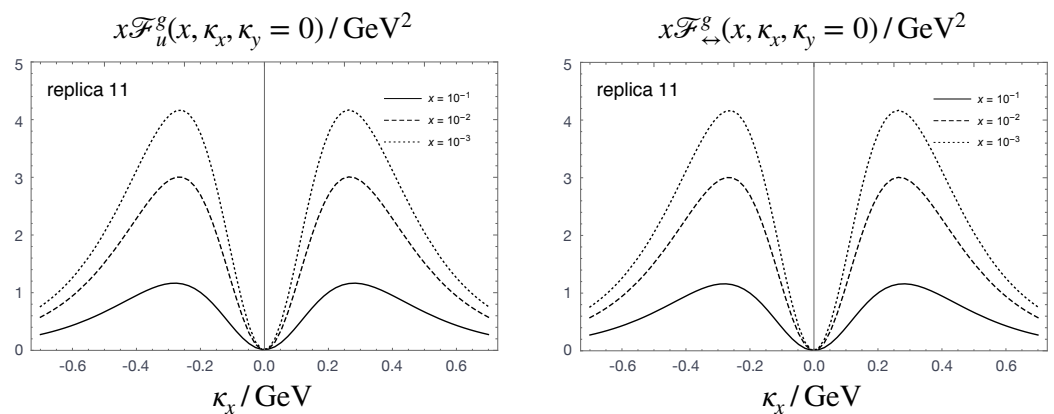


Figure 2. Ancillary, slice plots for the unpolarized (**left**) and Boer–Mulders (**right**) gluon TMD distributions in the proton, as functions of κ_x , while $\kappa_y = 0$, at the initial energy scale, $\mu_0 = 1.64$ GeV, and for x ranging from 10^{-1} down to 10^{-3} .

From an analytic perspective, in our model the $f_1^g/h_1^{\perp g}$ ratio is asymptotically constant in the $x \rightarrow 0^+$ limit. This consistently matches the prediction genuinely, coming from the linear Balitsky–Fadin–Kuraev–Lipatov (BFKL) evolution [107–110], that at small- x the “number” of unpolarized gluons equals the linearly-polarized one, up to higher-twist effects [111–116]. In this way, a first intersection point between our model gluon TMDs and the high-energy dynamics has been revealed.

3. Prospects

We reported progresses on accessing the core of the proton via TMD gluon distributions. The presented results are relevant to explore the multidimensional structure of the

proton, where the intrinsic motion of partons plays a key role to describe observables sensitive to different combinations of parton and hadron spins. In the low- x domain, a key role is played by the connections between TMD and BFKL effects. The high-energy resummation allows us to shed light on the proton structure at small- x via single-forward emissions. In particular, it gives us direct access to the unintegrated gluon distribution (UGD) in the proton, whose evolution is regulated by the BFKL Green's function. Pioneering analyses of the UGD were performed through the study of: deep-inelastic-scattering structure functions [117,118], light vector-meson helicity amplitudes and cross sections [58,119–132], forward Drell–Yan [133–136] and single-forward quarkonium [137–145] final states. Starting from the information on the gluon motion carried by the UGD, determinations of small- x improved collinear PDFs were obtained [98,146,147]. The connection between the unpolarized and linearly polarized gluon TMDs, f_1^g and $h_1^{\perp g}$, and the UGD was investigated in Refs. [57,148–150]. Future studies of the proton structure at new-generation colliding machines will benefit from the recently discovered property of natural stability of the high-energy resummation [151] (see also Refs. [152–212]). Finally, to get a complete 3D picture of the proton, the information about small- x gluon dynamics needs to be complemented by the valence-quark one at moderate- and large- x . A key role along this direction will be played by new data collected via future fixed-target programs, such as the JLab CLAS12 [213–220] and the LHC one [221–225] with possible polarized targets [226–228].

Funding: This research received no external funding.

Data Availability Statement: Data produced in this work are summarized in figures. They can be made available upon request.

Acknowledgments: This work was supported by the INFN/NINPHA project. The author thanks Alessandro Bacchetta, Marco Radici and Pieter Taelis for collaboration, and the Università degli Studi di Pavia for the warm hospitality.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Begel, M.; Hoeche, S.; Schmitt, M.; Lin, H.W.; Nadolsky, P.M.; Royon, C.; Lee, Y.J.; Mukherjee, S.; Baldenegro, C.; Campbell, J.; et al. Precision QCD, Hadronic Structure & Forward QCD, Heavy Ions: Report of Energy Frontier Topical Groups 5, 6, 7 submitted to Snowmass 2021. *arXiv* **2022**, arXiv:2209.14872.
2. Dawson, S.; Meade, P.; Ojalvo, I.; Vernieri, C.; Adhikari, S.; Abu-Ajamieh, F.; Alberta, A.; Bahl, H.; Barman, R.; Basso, M.; et al. Report of the Topical Group on Higgs Physics for Snowmass 2021: The Case for Precision Higgs Physics. In Proceedings of the 2022 Snowmass Summer Study, Seattle, WA, USA, 17–26 July 2022.
3. Bose, T.; Boveia, A.; Doglioni, C.; Griso, S.P.; Hirschauser, J.; Lipeles, E.; Liu, Z.; Shah, N.R.; Wang, L.T.; Agashe, K.; et al. Report of the Topical Group on Physics Beyond the Standard Model at Energy Frontier for Snowmass 2021. In Proceedings of the 2022 Snowmass Summer Study, Seattle, WA, USA, 17–26 July 2022.
4. Anchordoqui, L.A.; Ariga, A.; Ariga, T.; Bai, W.D.; Balazs, K.; Batell, B.; Boyd, J.; Bramante, J.; Campanelli, M.; Carmona, A.; et al. The Forward Physics Facility: Sites, experiments, and physics potential. *Phys. Rep.* **2022**, *968*, 1–50.
5. Feng, J.L.; Kling, F.; Reno, M.H.; Rojo, J.; Soldin, D.; Anchordoqui, L.A.; Boyd, J.; Ismail, A.; Harland-Lang, L.; Kelly, K.J.; et al. The Forward Physics Facility at the High-Luminosity LHC. *arXiv* **2022**, arXiv:2203.05090.
6. Hentschinski, M.; Royon, C.; Peredo, M.A.; Baldenegro, C.; Bellora, A.; Boussarie, R.; Celiberto, F.G.; Cerci, S.; Chachamis, G.; Contreras, J.G.; et al. White Paper on Forward Physics, BFKL, Saturation Physics and Diffraction. In Proceedings of the 2022 Snowmass Summer Study, Seattle, WA, USA, 17–26 July 2022.
7. Acosta, D.; Barberis, E.; Hurley, N.; Li, W.; Colin, O.M.; Wood, D.; Zuo, X. The Potential of a TeV-Scale Muon-Ion Collider. In Proceedings of the 2022 Snowmass Summer Study, Seattle, WA, USA, 17–26 July 2022.
8. Ayshev, A. et al. [the ILC International Development Team and the ILC community] The International Linear Collider: Report to Snowmass 2021. *arXiv* **2022**, arXiv:2203.07622.
9. Brunner, O.; Burrows, P.N.; Calatroni, S.; Lasheras, N.C.; Corsini, R.; D'Auria, G.; Doebert, S.; Faus-Golfe, A.; Grudiev, A.; Latina, A.; et al. The CLIC project. *arXiv* **2022**, arXiv:2203.09186.
10. Arbuzov, A.; Bacchetta, A.; Butenschoen, M.; Celiberto, F.G.; D'Alesio, U.; Deka, M.; Denisenko, I.; Echevarria, M.G.; Efremov, A.; Ivanov, N.Y.; et al. On the physics potential to study the gluon content of proton and deuteron at NICA SPD. *Prog. Part. Nucl. Phys.* **2021**, *119*, 103858.
11. Abazov, V.M. et al. [The SPD collaboration] Conceptual design of the Spin Physics Detector. *arXiv* **2021**, arXiv:2102.00442.

12. Bernardi, G.; Brost, E.; Denisov, D.; Landsberg, G.; Aleksa, M.; d'Enterria, D.; Janot, P.; Mangano, M.L.; Selvaggi, M.; Zimmermann, F.; et al. The Future Circular Collider: A Summary for the US 2021 Snowmass Process. *arXiv* **2022**, arXiv:2203.06520.
13. Amoroso, S.; Apyan, A.; Armesto, N.; Ball, R.D.; Bertone, V.; Bissolotti, C.; Bluemlein, J.; Boughezal, R.; Bozzi, G.; Britzger, D.; et al. Snowmass 2021 whitepaper: Proton structure at the precision frontier. In Proceedings of the 2022 Snowmass Summer Study, Seattle, WA, USA, 17–26 July 2022.
14. Celiberto, F.G.; Fucilla, M.; Ivanov, D.Y.; Mohammed, M.M.A.; Papa, A. High-energy QCD at colliders: Semi-hard reactions and unintegrated gluon densities: Letter of Interest for SnowMass 2021. In Proceedings of the 2021 Snowmass Summer Study, Seattle, WA, USA, 11–20 July 2021.
15. Klein, S.; Takaki, D.T.; Adam, J.; Aidala, C.; Angerami, A.; Audurier, B.; Bertulani, C.; Bierlich, C.; Blok, B.; Brandenburg, J.D.; et al. New opportunities at the photon energy frontier. In Proceedings of the 2021 Snowmass Summer Study, Seattle, WA, USA, 11–20 July 2021.
16. Canepa, A.; D'Onofrio, M. Future Accelerator Projects: New Physics at the Energy Frontier (FERMILAB-PUB-22-248-PPD). 2022. Available online: <https://lss.fnal.gov/archive/2022/pub/fermilab-pub-22-248-ppd.pdf> (accessed on 4 November 2022).
17. Black, K.M.; Jindariani, S.; Li, D.; Maltoni, F.; Meade, P.; Stratakis, D.; Acosta, D.; Agarwal, R.; Agashe, K.; Aimè, C.; et al. Muon Collider Forum Report. *arXiv* **2022**, arXiv:2209.01318.
18. de Blas, J.; Buttazzo, D.; Capdevilla, R.M.; Curtin, D.; Franceschini, R.; Maltoni, F.; Meade, P.R.; Meloni, F.; Su, S.F.; Vryonidou, E.; et al. The physics case of a 3 TeV muon collider stage. *arXiv* **2022**, arXiv:2203.07261.
19. Aimè, C.; Apyan, A.; Mahmoud, M.A.; Bartosik, N.; Batsch, F.; Bertolin, A.; Bonesini, M.; Bottaro, S.; Buttazzo, D.; Capdevilla, R.M.; et al. Muon Collider Physics Summary. *arXiv* **2022**, arXiv:2203.07256.
20. Bartosik, N.; Krizka, K.; Griso, S.P.; Aimè, C.; Apyan, A.; Agashe, K.; Allanach, B.C.; Andreetto, P.; Asadi, P.; Mahmoud, M.A.; et al. Simulated Detector Performance at the Muon Collider. In Proceedings of the 2022 Snowmass Summer Study, Seattle, WA, USA, 17–26 July 2022.
21. Chapon, E.; d'Enterria, D.; Ducloue, B.; Echevarria, M.G.; Gossiaux, P.B.; Kartvelishvili, V.; Kasemets, T.; Lansberg, J.P.; McNulty, R.; Price, D.D.; et al. Prospects for quarkonium studies at the high-luminosity LHC. *Prog. Part. Nucl. Phys.* **2022**, *122*, 103906.
22. Accardi, A.; Albacete, J.L.; Anselmino, M.; Armesto, N.; Aschenauer, E.C.; Bacchetta, A.; Boer, D.; Brooks, W.K.; Burton, T.; Chang, N.B.; et al. Electron Ion Collider: The Next QCD Frontier: Understanding the glue that binds us all. *Eur. Phys. J. A* **2016**, *52*, 268.
23. Khalek, R.A.; Accardi, A.; Adam, J.; Adamiak, D.; Akers, W.; Albaladejo, M.; Al-bataineh, A.; Alexeev, M.G.; Ameli, F.; Antonioli, P.; et al. Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report. *Nucl. Phys. A* **2022**, *1026*, 122447.
24. Khalek, R.A.; D'Alesio, U.; Arratia, M.; Bacchetta, A.; Battaglieri, M.; Begel, M.; Boglione, M.; Boughezal, R.; Boussarie, R.; Bozzi, G.; et al. Snowmass 2021 White Paper: Electron Ion Collider for High Energy Physics. In Proceedings of the 2022 Snowmass Summer Study, Seattle, WA, USA, 17–26 July 2022.
25. Ashman, J. et al. [European Muon Collaboration] A Measurement of the Spin Asymmetry and Determination of the Structure Function $g(1)$ in Deep Inelastic Muon-Proton Scattering. *Phys. Lett. B* **1988**, *206*, 364–370. [[CrossRef](#)]
26. Ji, X. Viewing the proton through “color” filters. *Phys. Rev. Lett.* **2003**, *91*, 062001. [[CrossRef](#)]
27. Belitsky, A.V.; Ji, X.d.; Yuan, F. Quark imaging in the proton via quantum phase space distributions. *Phys. Rev. D* **2004**, *69*, 074014.
28. Meissner, S.; Metz, A.; Schlegel, M.; Goeke, K. Generalized parton correlation functions for a spin-0 hadron. *J. High Energy Phys.* **2008**, *8*, 38.
29. Meissner, S.; Metz, A.; Schlegel, M. Generalized parton correlation functions for a spin-1/2 hadron. *J. High Energy Phys.* **2009**, *8*, 56.
30. Lorce, C.; Pasquini, B.; Vanderhaeghen, M. Unified framework for generalized and transverse-momentum dependent parton distributions within a 3Q light-cone picture of the nucleon. *J. High Energy Phys.* **2011**, *5*, 41.
31. Lorce, C.; Pasquini, B. Quark Wigner Distributions and Orbital Angular Momentum. *Phys. Rev. D* **2011**, *84*, 014015.
32. Lorce, C.; Pasquini, B.; Xiong, X.; Yuan, F. The quark orbital angular momentum from Wigner distributions and light-cone wave functions. *Phys. Rev. D* **2012**, *85*, 114006.
33. Lorce, C.; Pasquini, B. Structure analysis of the generalized correlator of quark and gluon for a spin-1/2 target. *J. High Energy Phys.* **2013**, *9*, 138.
34. Burkardt, M.; Pasquini, B. Modelling the nucleon structure. *Eur. Phys. J. A* **2016**, *52*, 161.
35. Bertone, V. Matching generalised transverse-momentum-dependent distributions onto generalised parton distributions at one loop. *Eur. Phys. J. C* **2022**, *82*, 941.
36. Echevarria, M.G.; Gutierrez Garcia, P.A.; Scimemi, I. GTMDs and the factorization of exclusive double Drell-Yan. *arXiv* **2022**, arXiv:2209.07510.
37. Burkardt, M. Impact parameter dependent parton distributions and transverse single spin asymmetries. *Phys. Rev. D* **2002**, *66*, 114005.
38. Burkardt, M. Chromodynamic lensing and transverse single spin asymmetries. *Nucl. Phys. A* **2004**, *735*, 185–199.
39. Meissner, S.; Metz, A.; Goeke, K. Relations between generalized and transverse momentum dependent parton distributions. *Phys. Rev. D* **2007**, *76*, 034002.
40. Burkardt, M.; Hwang, D.S. Sivers asymmetry and generalized parton distributions in impact parameter space. *Phys. Rev. D* **2004**, *69*, 074032.

41. Gamberg, L.; Schlegel, M. Final state interactions and the transverse structure of the pion using non-perturbative eikonal methods. *Phys. Lett. B* **2010**, *685*, 95–103.
42. Pasquini, B.; Rodini, S.; Bacchetta, A. Revisiting model relations between T-odd transverse-momentum dependent parton distributions and generalized parton distributions. *Phys. Rev. D* **2019**, *100*, 054039.
43. Diehl, M. Introduction to GPDs and TMDs. *Eur. Phys. J. A* **2016**, *52*, 149.
44. Burkardt, M.; Hannafious, B. Are all Boer-Mulders functions alike? *Phys. Lett. B* **2008**, *658*, 130–137. [[CrossRef](#)]
45. Bacchetta, A.; Radici, M. Constraining quark angular momentum through semi-inclusive measurements. *Phys. Rev. Lett.* **2011**, *107*, 212001.
46. Pasquini, B.; Boffi, S. Nucleon spin densities in a light-front constituent quark model. *Phys. Lett. B* **2007**, *653*, 23–28.
47. Mulders, P.J.; Rodrigues, J. Transverse momentum dependence in gluon distribution and fragmentation functions. *Phys. Rev. D* **2001**, *63*, 094021.
48. Bozzi, G.; Catani, S.; de Florian, D.; Grazzini, M. The $q(T)$ spectrum of the Higgs boson at the LHC in QCD perturbation theory. *Phys. Lett. B* **2003**, *564*, 65–72.
49. Catani, S.; Grazzini, M. QCD transverse-momentum resummation in gluon fusion processes. *Nucl. Phys. B* **2011**, *845*, 297–323.
50. Echevarria, M.G.; Kasemets, T.; Mulders, P.J.; Pisano, C. QCD evolution of (un)polarized gluon TMDPDFs and the Higgs q_T -distribution. *J. High Energy Phys.* **2015**, *2015*, 158. [[CrossRef](#)]
51. Boer, D.; Brodsky, S.J.; Mulders, P.J.; Pisano, C. Direct Probes of Linearly Polarized Gluons inside Unpolarized Hadrons. *Phys. Rev. Lett.* **2011**, *106*, 132001.
52. Sun, P.; Xiao, B.W.; Yuan, F. Gluon Distribution Functions and Higgs Boson Production at Moderate Transverse Momentum. *Phys. Rev. D* **2011**, *84*, 094005.
53. Boer, D.; den Dunnen, W.J.; Pisano, C.; Schlegel, M.; Vogelsang, W. Linearly Polarized Gluons and the Higgs Transverse Momentum Distribution. *Phys. Rev. Lett.* **2012**, *108*, 032002.
54. Pisano, C.; Boer, D.; Brodsky, S.J.; Buffing, M.G.; Mulders, P.J. Linear polarization of gluons and photons in unpolarized collider experiments. *J. High Energy Phys.* **2013**, *10*, 24.
55. den Dunnen, W.J.; Lansberg, J.P.; Pisano, C.; Schlegel, M. Accessing the Transverse Dynamics and Polarization of Gluons inside the Proton at the LHC. *Phys. Rev. Lett.* **2014**, *112*, 212001.
56. Lansberg, J.P.; Pisano, C.; Schlegel, M. Associated production of a dilepton and a $Y(J/\psi)$ at the LHC as a probe of gluon transverse momentum dependent distributions. *Nucl. Phys. B* **2017**, *920*, 192–210.
57. Celiberto, F.G. 3D tomography of the nucleon: Transverse-momentum-dependent gluon distributions. *Nuovo Cim. C* **2021**, *44*, 36.
58. Bolognino, A.D.; Celiberto, F.G.; Ivanov, D.Y.; Papa, A.; Schäfer, W.; Szczurek, A. Exclusive production of ρ -mesons in high-energy factorization at HERA and EIC. *Eur. Phys. J. C* **2021**, *81*, 846.
59. Boussarie, R.; Hatta, Y.; Szymanowski, L.; Wallon, S. Probing the Gluon Sivers Function with an Unpolarized Target: GTMD Distributions and the Odderons. *Phys. Rev. Lett.* **2020**, *124*, 172501.
60. Brodsky, S.J.; Hwang, D.S.; Schmidt, I. Final state interactions and single spin asymmetries in semiinclusive deep inelastic scattering. *Phys. Lett. B* **2002**, *530*, 99–107.
61. Collins, J.C. Leading twist single transverse-spin asymmetries: Drell-Yan and deep inelastic scattering. *Phys. Lett. B* **2002**, *536*, 43–48.
62. Ji, X.d.; Yuan, F. Parton distributions in light cone gauge: Where are the final state interactions? *Phys. Lett. B* **2002**, *543*, 66–72.
63. Bomhof, C.; Mulders, P.; Pijlman, F. The Construction of gauge-links in arbitrary hard processes. *Eur. Phys. J. C* **2006**, *47*, 147–162.
64. Rogers, T.C.; Mulders, P.J. No Generalized TMD-Factorization in Hadro-Production of High Transverse Momentum Hadrons. *Phys. Rev. D* **2010**, *81*, 094006.
65. Rogers, T.C. Extra spin asymmetries from the breakdown of transverse-momentum-dependent factorization in hadron-hadron collisions. *Phys. Rev. D* **2013**, *88*, 014002.
66. Collins, J.C.; Soper, D.E. Back-To-Back Jets in QCD. *Nucl. Phys. B* **1981**, *193*, 381–443. [[CrossRef](#)]
67. Collins, J. Foundations of perturbative QCD. *Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol.* **2011**, *32*, 1–624.
68. Bacchetta, A.; Echevarria, M.G.; Mulders, P.J.G.; Radici, M.; Signori, A. Effects of TMD evolution and partonic flavor on e^+e^- annihilation into hadrons. *J. High Energy Phys.* **2015**, *11*, 76.
69. Kang, Z.B.; Shao, D.Y.; Zhao, F. QCD resummation on single hadron transverse momentum distribution with the thrust axis. *J. High Energy Phys.* **2020**, *12*, 127.
70. Makris, Y.; Ringer, F.; Waalewijn, W.J. Joint thrust and TMD resummation in electron-positron and electron-proton collisions. *J. High Energy Phys.* **2021**, *02*, 70.
71. Boglione, M.; Simonelli, A. Kinematic regions in the $e^+e^- \rightarrow hX$ factorized cross section in a 2-jet topology with thrust. *J. High Energy Phys.* **2022**, *2*, 13.
72. Boer, D.; den Dunnen, W.J.; Pisano, C.; Schlegel, M. Determining the Higgs spin and parity in the diphoton decay channel. *Phys. Rev. Lett.* **2013**, *111*, 032002.
73. Gutierrez-Reyes, D.; Leal-Gomez, S.; Scimemi, I.; Vladimirov, A. Linearly polarized gluons at next-to-next-to leading order and the Higgs transverse momentum distribution. *J. High Energy Phys.* **2019**, *11*, 121.
74. Echevarria, M.G. Proper TMD factorization for quarkonia production: $pp \rightarrow \eta_{c,b}$ as a study case. *J. High Energy Phys.* **2019**, *10*, 144.

75. Einhorn, M.B.; Ellis, S.D. Hadronic Production of the New Resonances: Probing Gluon Distributions. *Phys. Rev. D* **1975**, *12*, 2007. [\[CrossRef\]](#)
76. Chang, C.H. Hadronic Production of J/ψ Associated With a Gluon. *Nucl. Phys. B* **1980**, *172*, 425–434. [\[CrossRef\]](#)
77. Berger, E.L.; Jones, D.L. Inelastic Photoproduction of J/ψ and Upsilon by Gluons. *Phys. Rev. D* **1981**, *23*, 1521–1530. [\[CrossRef\]](#)
78. Baier, R.; Ruckl, R. Hadronic Production of J/ψ and Upsilon: Transverse Momentum Distributions. *Phys. Lett. B* **1981**, *102*, 364–370. [\[CrossRef\]](#)
79. Fleming, S.; Makris, Y.; Mehen, T. An effective field theory approach to quarkonium at small transverse momentum. *J. High Energy Phys.* **2020**, *4*, 122.
80. D’Alesio, U.; Maxia, L.; Murgia, F.; Pisano, C.; Rajesh, S. J/ψ polarization in semi-inclusive DIS at low and high transverse momentum. *J. High Energy Phys.* **2022**, *3*, 37.
81. Boer, D.; D’Alesio, U.; Murgia, F.; Pisano, C.; Tael, P. J/ψ meson production in SIDIS: Matching high and low transverse momentum. *J. High Energy Phys.* **2020**, *9*, 40.
82. Lansberg, J.P.; Pisano, C.; Scarpa, F.; Schlegel, M. Pinning down the linearly-polarised gluons inside unpolarised protons using quarkonium-pair production at the LHC. *Phys. Lett. B* **2018**, *784*, 217–222. [\[CrossRef\]](#)
83. Scarpa, F.; Boer, D.; Echevarria, M.G.; Lansberg, J.P.; Pisano, C.; Schlegel, M. Studies of gluon TMDs and their evolution using quarkonium-pair production at the LHC. *Eur. Phys. J. C* **2020**, *80*, 87.
84. Echevarria, M.G.; Makris, Y.; Scimemi, I. Quarkonium TMD fragmentation functions in NRQCD. *J. High Energy Phys.* **2020**, *10*, 164.
85. Adolph, C. et al. [The COMPASS Collaboration] First measurement of the Sivers asymmetry for gluons using SIDIS data. *Phys. Lett. B* **2017**, *772*, 854–864.
86. D’Alesio, U.; Murgia, F.; Pisano, C.; Tael, P. Probing the gluon Sivers function in $p^\uparrow p \rightarrow J/\psi X$ and $p^\uparrow p \rightarrow D X$. *Phys. Rev. D* **2017**, *96*, 036011.
87. D’Alesio, U.; Flore, C.; Murgia, F.; Pisano, C.; Tael, P. Unraveling the Gluon Sivers Function in Hadronic Collisions at RHIC. *Phys. Rev. D* **2019**, *99*, 036013.
88. D’Alesio, U.; Murgia, F.; Pisano, C.; Tael, P. Azimuthal asymmetries in semi-inclusive J/ψ + jet production at an EIC. *Phys. Rev. D* **2019**, *100*, 094016.
89. Lu, Z.; Ma, B.Q. Gluon Sivers function in a light-cone spectator model. *Phys. Rev. D* **2016**, *94*, 094022. [\[CrossRef\]](#)
90. Pereira-Resina-Rodrigues, J.M. Modelling Quark and Gluon Correlation Functions. Ph.D. Thesis, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands, 2001.
91. Bacchetta, A.; Conti, F.; Radici, M. Transverse-momentum distributions in a diquark spectator model. *Phys. Rev. D* **2008**, *78*, 074010.
92. Bacchetta, A.; Radici, M.; Conti, F.; Guagnelli, M. Weighted azimuthal asymmetries in a diquark spectator model. *Eur. Phys. J. A* **2010**, *45*, 373–388.
93. Gamberg, L.P.; Goldstein, G.R. T-odd effects in unpolarized Drell-Yan scattering. *Phys. Lett. B* **2007**, *650*, 362–368.
94. Gamberg, L.P.; Goldstein, G.R.; Schlegel, M. Transverse Quark Spin Effects and the Flavor Dependence of the Boer-Mulders Function. *Phys. Rev. D* **2008**, *77*, 094016.
95. Jakob, R.; Mulders, P.J.; Rodrigues, J. Modeling quark distribution and fragmentation functions. *Nucl. Phys. A* **1997**, *626*, 937–965.
96. Bacchetta, A.; Celiberto, F.G.; Radici, M.; Tael, P. Transverse-momentum-dependent gluon distribution functions in a spectator model. *Eur. Phys. J. C* **2020**, *80*, 733.
97. Bacchetta, A.; Celiberto, F.G.; Radici, M.; Tael, P. A spectator-model way to transverse-momentum-dependent gluon distribution functions. *SciPost Phys. Proc.* **2022**, *8*, 40.
98. Ball, R.D.; Bertone, V.; Bonvini, M.; Marzani, S.; Rojo, J.; Rottoli, L. Parton distributions with small- x resummation: Evidence for BFKL dynamics in HERA data. *Eur. Phys. J. C* **2018**, *78*, 321.
99. Nocera, E.R.; Ball, R.D.; Forte, S.; Ridolfi, G.; Rojo, J. A first unbiased global determination of polarized PDFs and their uncertainties. *Nucl. Phys. B* **2014**, *887*, 276–308.
100. Forte, S.; Garrido, L.; Latorre, J.I.; Piccione, A. Neural network parametrization of deep inelastic structure functions. *J. High Energy Phys.* **2002**, *5*, 62.
101. Ball, R.D.; Forte, S.; Stegeman, R. Correlation and combination of sets of parton distributions. *Eur. Phys. J. C* **2021**, *81*, 1046.
102. Bacchetta, A.; Celiberto, F.G.; Radici, M. Toward twist-2 T -odd transverse-momentum-dependent gluon distributions: The f -type Sivers function. *Proc. Sci.* **2022**, *EPS-HEP2021*, 376.
103. Bacchetta, A.; Celiberto, F.G.; Radici, M. Toward twist-2 T -odd transverse-momentum-dependent gluon distributions: The f -type linearity function. *Proc. Sci.* **2022**, *PANIC2021*, 378.
104. Bacchetta, A.; Celiberto, F.G.; Radici, M. Towards leading-twist T -odd TMD gluon distributions. *arXiv* **2022**, arXiv:2201.10508.
105. Bacchetta, A.; Celiberto, F.G.; Radici, M. Unveiling the proton structure via transverse-momentum-dependent gluon distributions. *arXiv* **2022**, arXiv:2206.07815.
106. Bacchetta, A.; Celiberto, F.G.; Radici, M.; Signori, A. Phenomenology of gluon TMDs from $\eta_{b,c}$ production. *Zenodo* **2022**, *in press*. [\[CrossRef\]](#)
107. Fadin, V.S.; Kuraev, E.; Lipatov, L. On the Pomeron singularity in Asymptotically Free Theories. *Phys. Lett. B* **1975**, *60*, 50–52. [\[CrossRef\]](#)

108. Kuraev, E.A.; Lipatov, L.N.; Fadin, V.S. Multi - Reggeon Processes in the Yang-Mills Theory. *Sov. Phys. JETP* **1976**, *44*, 443–450.
109. Kuraev, E.; Lipatov, L.; Fadin, V.S. The Pomeron Singularity in Nonabelian Gauge Theories. *Sov. Phys. JETP* **1977**, *45*, 199–204.
110. Balitsky, I.; Lipatov, L. The Pomeron Singularity in Quantum Chromodynamics. *Sov. J. Nucl. Phys.* **1978**, *28*, 822–829.
111. Metz, A.; Zhou, J. Distribution of linearly polarized gluons inside a large nucleus. *Phys. Rev. D* **2011**, *84*, 051503.
112. Dominguez, F.; Qiu, J.W.; Xiao, B.W.; Yuan, F. On the linearly polarized gluon distributions in the color dipole model. *Phys. Rev. D* **2012**, *85*, 045003.
113. Marquet, C.; Petreska, E.; Roiesnel, C. Transverse-momentum-dependent gluon distributions from JIMWLK evolution. *J. High Energy Phys.* **2016**, *10*, 65.
114. Tael, P. Quantum Chromodynamics at Small Bjorken- x . Ph.D. Thesis, University of Antwerp, Antwerpen, Belgium, 2017.
115. Marquet, C.; Roiesnel, C.; Tael, P. Linearly polarized small- x gluons in forward heavy-quark pair production. *Phys. Rev. D* **2018**, *97*, 014004.
116. Petreska, E. TMD gluon distributions at small x in the CGC theory. *Int. J. Mod. Phys. E* **2018**, *27*, 1830003. [[CrossRef](#)]
117. Hentschinski, M.; Sabio Vera, A.; Salas, C. Hard to Soft Pomeron Transition in Small- x Deep Inelastic Scattering Data Using Optimal Renormalization. *Phys. Rev. Lett.* **2013**, *110*, 041601.
118. Hentschinski, M.; Sabio Vera, A.; Salas, C. F_2 and F_L at small x using a collinearly improved BFKL resummation. *Phys. Rev. D* **2013**, *87*, 076005.
119. Anikin, I.; Ivanov, D.Y.; Pire, B.; Szymanowski, L.; Wallon, S. QCD factorization of exclusive processes beyond leading twist: $\gamma_T^* \rightarrow \rho_T$ impact factor with twist three accuracy. *Nucl. Phys. B* **2010**, *828*, 1–68.
120. Anikin, I.; Besse, A.; Ivanov, D.Y.; Pire, B.; Szymanowski, L.; Wallon, S. A phenomenological study of helicity amplitudes of high energy exclusive lepton production of the rho meson. *Phys. Rev. D* **2011**, *84*, 054004.
121. Besse, A.; Szymanowski, L.; Wallon, S. Saturation effects in exclusive rhoT, rhoL meson electroproduction. *J. High Energy Phys.* **2013**, *11*, 62.
122. Bolognino, A.D.; Celiberto, F.G.; Ivanov, D.Y.; Papa, A. Unintegrated gluon distribution from forward polarized ρ -electroproduction. *Eur. Phys. J. C* **2018**, *78*, 1023.
123. Bolognino, A.D.; Celiberto, F.G.; Ivanov, D.Y.; Papa, A. ρ -meson lepton production as testfield for the unintegrated gluon distribution in the proton. *Frascati Phys. Ser.* **2018**, *67*, 76–82.
124. Bolognino, A.D.; Celiberto, F.G.; Ivanov, D.Y.; Papa, A. Lepton production of ρ -mesons as discriminator for the unintegrated gluon distribution in the proton. *Acta Phys. Pol. B Proc. Suppl.* **2019**, *12*, 891.
125. Bolognino, A.D.; Szczurek, A.; Schaefer, W. Exclusive production of ϕ meson in the $\gamma^* p \rightarrow \phi p$ reaction at large photon virtualities within k_T -factorization approach. *Phys. Rev. D* **2020**, *101*, 054041.
126. Celiberto, F.G. Unraveling the Unintegrated Gluon Distribution in the Proton via ρ -Meson Lepton Production. *Nuovo Cim. C* **2019**, *42*, 220.
127. Bolognino, A.D.; Celiberto, F.G.; Ivanov, D.Y.; Papa, A. Exclusive emissions of rho-mesons and the unintegrated gluon distribution. *SciPost Phys. Proc.* **2022**, *8*, 89.
128. Bolognino, A.D.; Celiberto, F.G.; Fucilla, M.; Ivanov, D.Y.; Papa, A.; Schäfer, W.; Szczurek, A. Hadron Structure at Small- x via Unintegrated Gluon Densities. *arXiv* **2022**, arXiv:2202.02513.
129. Celiberto, F.G. Phenomenology of the hadronic structure at small- x . *arXiv* **2022**, arXiv:2202.04207.
130. Bolognino, A.D.; Celiberto, F.G.; Ivanov, D.Y.; Papa, A.; Schäfer, W.; Szczurek, A. Exclusive emissions of polarized ρ mesons at the EIC and the proton content at low x . *Zenodo* **2022**, in press. [[CrossRef](#)]
131. Cisek, A.; Schäfer, W.; Szczurek, A. Exclusive production of ρ meson in gamma-proton collisions: $d\sigma/dt$ and the role of helicity flip processes. *arXiv* **2022**, arXiv:2209.06578.
132. Łuszczak, A.; Łuszczak, M.; Schäfer, W. Unintegrated gluon distributions from the color dipole cross section in the BGK saturation model. *Phys. Lett. B* **2022**, *835*, 137582.
133. Motyka, L.; Sadzikowski, M.; Stebel, T. Twist expansion of Drell-Yan structure functions in color dipole approach. *J. High Energy Phys.* **2015**, *5*, 87.
134. Brzeminski, D.; Motyka, L.; Sadzikowski, M.; Stebel, T. Twist decomposition of Drell-Yan structure functions: Phenomenological implications. *J. High Energy Phys.* **2017**, *1*, 5.
135. Motyka, L.; Sadzikowski, M.; Stebel, T. Lam-Tung relation breaking in Z^0 hadroproduction as a probe of parton transverse momentum. *Phys. Rev. D* **2017**, *95*, 114025.
136. Celiberto, F.G.; Gordo Gómez, D.; Sabio Vera, A. Forward Drell-Yan production at the LHC in the BFKL formalism with collinear corrections. *Phys. Lett. B* **2018**, *786*, 201–206.
137. Bautista, I.; Fernandez Tellez, A.; Hentschinski, M. BFKL evolution and the growth with energy of exclusive J/ψ and Υ photoproduction cross sections. *Phys. Rev. D* **2016**, *94*, 054002.
138. Arroyo Garcia, A.; Hentschinski, M.; Kutak, K. QCD evolution based evidence for the onset of gluon saturation in exclusive photo-production of vector mesons. *Phys. Lett. B* **2019**, *795*, 569–575.
139. Hentschinski, M.; Padrón Molina, E. Exclusive J/Ψ and $\Psi(2s)$ photo-production as a probe of QCD low x evolution equations. *Phys. Rev. D* **2021**, *103*, 074008.
140. Gonçalves, V.P.; Navarra, F.S.; Spiering, D. Exclusive ρ and J/Ψ photoproduction in ultraperipheral pA collisions: Predictions of the gluon saturation models for the momentum transfer distributions. *Phys. Lett. B* **2019**, *791*, 299–304.

141. Cepila, J.; Contreras, J.G.; Krelina, M. Coherent and incoherent J/ψ photonuclear production in an energy-dependent hot-spot model. *Phys. Rev. C* **2018**, *97*, 024901.
142. Guzey, V.; Kryshen, E.; Strikman, M.; Zhalov, M. Nuclear suppression from coherent J/ψ photoproduction at the Large Hadron Collider. *Phys. Lett. B* **2021**, *816*, 136202.
143. Jenkovszky, L.; Libov, V.; Machado, M.V.T. The reggeometric pomeron and exclusive production of $J/\psi(2S)$ in ultraperipheral collisions at the LHC. *Phys. Lett. B* **2022**, *824*, 136836.
144. Flore, C.; Lansberg, J.P.; Shao, H.S.; Yedelkina, Y. Large- P_T inclusive photoproduction of J/ψ in electron-proton collisions at HERA and the EIC. *Phys. Lett. B* **2020**, *811*, 135926.
145. Colpani Serri, A.; Feng, Y.; Flore, C.; Lansberg, J.P.; Ozcelik, M.A.; Shao, H.S.; Yedelkina, Y. Revisiting NLO QCD corrections to total inclusive J/ψ and Υ photoproduction cross sections in lepton-proton collisions. *Phys. Lett. B* **2022**, *835*, 137556.
146. Bonvini, M.; Giuli, F. A new simple PDF parametrization: Improved description of the HERA data. *Eur. Phys. J. Plus* **2019**, *134*, 531.
147. Abdolmaleki, H.; Bertone, V.; Britzger, D.; Camarda, S.; Cooper-Sarkar, A.; Giuli, F.; Glazov, A.; Kusina, A.; Luszczak, A.; Olness, F.; et al. Impact of low- x resummation on QCD analysis of HERA data. *Eur. Phys. J. C* **2018**, *78*, 621.
148. Dominguez, F.; Marquet, C.; Xiao, B.W.; Yuan, F. Universality of Unintegrated Gluon Distributions at small x . *Phys. Rev. D* **2011**, *83*, 105005.
149. Hentschinski, M. Transverse momentum dependent gluon distribution within high energy factorization at next-to-leading order. *Phys. Rev. D* **2021**, *104*, 054014.
150. Nefedov, M. Sudakov resummation from the BFKL evolution. *Phys. Rev. D* **2021**, *104*, 054039. [[CrossRef](#)]
151. Celiberto, F.G. Stabilizing BFKL via heavy-flavor and NRQCD fragmentation. *arXiv* **2022**, arXiv:2211.11780.
152. Caporale, F.; Ivanov, D.; Murdaca, B.; Papa, A. Mueller-Navelet small-cone jets at LHC in next-to-leading BFKL. *Nucl. Phys. B* **2013**, *877*, 73–94.
153. Ducloué, B.; Szymanowski, L.; Wallon, S. Confronting Mueller-Navelet jets in NLL BFKL with LHC experiments at 7 TeV. *J. High Energy Phys.* **2013**, *5*, 96.
154. Ducloué, B.; Szymanowski, L.; Wallon, S. Evidence for high-energy resummation effects in Mueller-Navelet jets at the LHC. *Phys. Rev. Lett.* **2014**, *112*, 082003.
155. Caporale, F.; Murdaca, B.; Sabio Vera, A.; Salas, C. Scale choice and collinear contributions to Mueller-Navelet jets at LHC energies. *Nucl. Phys. B* **2013**, *875*, 134–151.
156. Caporale, F.; Ivanov, D.Y.; Murdaca, B.; Papa, A. Mueller–Navelet jets in next-to-leading order BFKL: Theory versus experiment. *Eur. Phys. J. C* **2014**, *74*, 3084; Erratum in *Eur. Phys. J. C* **2015**, *75*, 535. [[CrossRef](#)]
157. Ducloué, B.; Szymanowski, L.; Wallon, S. Evaluating the double parton scattering contribution to Mueller-Navelet jets production at the LHC. *Phys. Rev. D* **2015**, *92*, 076002.
158. Celiberto, F.G.; Ivanov, D.Y.; Murdaca, B.; Papa, A. Mueller–Navelet Jets at LHC: BFKL Versus High-Energy DGLAP. *Eur. Phys. J. C* **2015**, *75*, 292.
159. Celiberto, F.G.; Ivanov, D.Y.; Murdaca, B.; Papa, A. Mueller–Navelet Jets at the LHC: Discriminating BFKL from DGLAP by Asymmetric Cuts. *Acta Phys. Pol. B Proc. Suppl.* **2015**, *8*, 935.
160. Caporale, F.; Ivanov, D.Y.; Murdaca, B.; Papa, A. Brodsky-Lepage-Mackenzie optimal renormalization scale setting for semihard processes. *Phys. Rev. D* **2015**, *91*, 114009.
161. Mueller, A.; Szymanowski, L.; Wallon, S.; Xiao, B.W.; Yuan, F. Sudakov Resummations in Mueller-Navelet Dijet Production. *J. High Energy Phys.* **2016**, *3*, 96.
162. Celiberto, F.G.; Ivanov, D.Y.; Murdaca, B.; Papa, A. Mueller–Navelet jets at 13 TeV LHC: Dependence on dynamic constraints in the central rapidity region. *Eur. Phys. J. C* **2016**, *76*, 224.
163. Celiberto, F.G.; Ivanov, D.Y.; Murdaca, B.; Papa, A. BFKL effects and central rapidity dependence in Mueller-Navelet jet production at 13 TeV LHC. *Proc. Sci.* **2016**, DIS2016, 176.
164. Caporale, F.; Celiberto, F.G.; Chachamis, G.; Gordo Gómez, D.; Sabio Vera, A. Inclusive dijet hadroproduction with a rapidity veto constraint. *Nucl. Phys. B* **2018**, *935*, 412–434.
165. Celiberto, F.G.; Papa, A. Mueller-Navelet jets at the LHC: Hunting data with azimuthal distributions. *Phys. Rev. D* **2022**, *106*, 114004.
166. Celiberto, F.G.; Ivanov, D.Y.; Murdaca, B.; Papa, A. High energy resummation in dihadron production at the LHC. *Phys. Rev. D* **2016**, *94*, 034013.
167. Celiberto, F.G.; Ivanov, D.Y.; Murdaca, B.; Papa, A. Dihadron Production at LHC: BFKL Predictions for Cross Sections and Azimuthal Correlations. *AIP Conf. Proc.* **2017**, *1819*, 060005.
168. Celiberto, F.G.; Ivanov, D.Y.; Murdaca, B.; Papa, A. Dihadron production at the LHC: Full next-to-leading BFKL calculation. *Eur. Phys. J. C* **2017**, *77*, 382.
169. Celiberto, F.G.; Ivanov, D.Y.; Murdaca, B.; Papa, A. Inclusive charged light di-hadron production at 7 and 13 TeV LHC in the full NLA BFKL approach. In Proceedings of the 25th Low- x Meeting, Bisceglie, Italy, 12–18 June 2017.
170. Celiberto, F.G.; Ivanov, D.Y.; Murdaca, B.; Papa, A. Inclusive dihadron production at the LHC in NLA BFKL. In Proceedings of the 17th conference on Elastic and Diffractive Scattering, Prague, Czech Republic, 26–30 June 2017.

171. Caporale, F.; Chachamis, G.; Murdaca, B.; Sabio Vera, A. Balitsky-Fadin-Kuraev-Lipatov Predictions for Inclusive Three Jet Production at the LHC. *Phys. Rev. Lett.* **2016**, *116*, 012001.
172. Caporale, F.; Celiberto, F.G.; Chachamis, G.; Sabio Vera, A. Multi-Regge kinematics and azimuthal angle observables for inclusive four-jet production. *Eur. Phys. J. C* **2016**, *76*, 165.
173. Caporale, F.; Celiberto, F.G.; Chachamis, G.; Gordo Gómez, D.; Sabio Vera, A. BFKL azimuthal imprints in inclusive three-jet production at 7 and 13 TeV. *Nucl. Phys. B* **2016**, *910*, 374–386.
174. Caporale, F.; Celiberto, F.G.; Chachamis, G.; Sabio Vera, A. Inclusive four-jet production: A study of Multi-Regge kinematics and BFKL observables. *Proc. Sci.* **2016**, DIS2016, 177.
175. Caporale, F.; Celiberto, F.G.; Chachamis, G.; Gordo Gómez, D.; Sabio Vera, A. Inclusive Four-jet Production at 7 and 13 TeV: Azimuthal Profile in Multi-Regge Kinematics. *Eur. Phys. J. C* **2017**, *77*, 5.
176. Celiberto, F.G. BFKL phenomenology: Resummation of high-energy logs in semi-hard processes at LHC. *Frascati Phys. Ser.* **2016**, *63*, 43–48.
177. Caporale, F.; Celiberto, F.G.; Chachamis, G.; Gordo Gómez, D.; Sabio Vera, A. Inclusive three- and four-jet production in multi-Regge kinematics at the LHC. *AIP Conf. Proc.* **2017**, *1819*, 060009.
178. Caporale, F.; Celiberto, F.G.; Chachamis, G.; Gordo Gomez, D.; Murdaca, B.; Sabio Vera, A. High energy effects in multi-jet production at LHC. In Proceedings of the 25th Low-x Meeting, Bisceglie, Italy, 12–18 June 2017; Volume 5, p. 47.
179. Chachamis, G.; Caporale, F.; Celiberto, F.; Gomez Gordo, D.; Sabio Vera, A. Inclusive three jet production at the LHC for 7 and 13 TeV collision energies. *Proc. Sci.* **2016**, DIS2016, 178. [\[CrossRef\]](#)
180. Caporale, F.; Celiberto, F.G.; Chachamis, G.; Gordo Gómez, D.; Sabio Vera, A. Probing the BFKL dynamics in inclusive three jet production at the LHC. *EPJ Web Conf.* **2017**, *164*, 07027.
181. Caporale, F.; Celiberto, F.G.; Chachamis, G.; Gordo Gómez, D.; Sabio Vera, A. Stability of Azimuthal-angle Observables under Higher Order Corrections in Inclusive Three-jet Production. *Phys. Rev. D* **2017**, *95*, 074007. [\[CrossRef\]](#)
182. Chachamis, G.; Caporale, F.; Celiberto, F.G.; Gordo Gomez, D.; Sabio Vera, A. Azimuthal-angle Observables in Inclusive Three-jet Production. *Proc. Sci.* **2018**, DIS2017, 67.
183. Caporale, F.; Celiberto, F.G.; Gordo Gomez, D.; Sabio Vera, A.; Chachamis, G. Multi-jet production in the high energy limit at LHC. In Proceedings of the 25th Low-x Meeting, Bisceglie, Italy, 12–18 June 2017.
184. Bolognino, A.D.; Celiberto, F.G.; Ivanov, D.Y.; Mohammed, M.M.; Papa, A. Hadron-jet correlations in high-energy hadronic collisions at the LHC. *Eur. Phys. J. C* **2018**, *78*, 772.
185. Bolognino, A.D.; Celiberto, F.G.; Ivanov, D.Y.; Mohammed, M.M.A.; Papa, A. High-energy effects in forward inclusive dijet and hadron-jet production. *Proc. Sci.* **2019**, DIS2019, 49.
186. Bolognino, A.D.; Celiberto, F.G.; Ivanov, D.Y.; Mohammed, M.M.; Papa, A. Inclusive hadron-jet production at the LHC. *Acta Phys. Pol. B Proc. Suppl.* **2019**, *12*, 773.
187. Celiberto, F.G. Hunting BFKL in semi-hard reactions at the LHC. *Eur. Phys. J. C* **2021**, *81*, 691.
188. Celiberto, F.G.; Ivanov, D.Y.; Papa, A. Diffractive production of Λ hyperons in the high-energy limit of strong interactions. *Phys. Rev. D* **2020**, *102*, 094019.
189. Celiberto, F.G. Emergence of high-energy dynamics from cascade-baryon detections at the LHC. *arXiv* **2022**, arXiv:2208.14577.
190. Celiberto, F.G.; Ivanov, D.Y.; Mohammed, M.M.A.; Papa, A. High-energy resummed distributions for the inclusive Higgs-plus-jet production at the LHC. *Eur. Phys. J. C* **2021**, *81*, 293.
191. Hentschinski, M.; Kutak, K.; van Hameren, A. Forward Higgs production within high energy factorization in the heavy quark limit at next-to-leading order accuracy. *Eur. Phys. J. C* **2021**, *81*, 112; Erratum in *Eur. Phys. J. C* **2021**, *81*, 262. [\[CrossRef\]](#)
192. Celiberto, F.G.; Ivanov, D.Y.; Mohammed, M.M.A.; Papa, A. High-energy resummation in inclusive hadroproduction of Higgs plus jet. *SciPost Phys. Proc.* **2022**, *8*, 39.
193. Celiberto, F.G.; Fucilla, M.; Papa, A.; Ivanov, D.Y.; Mohammed, M.M.A. Higgs-plus-jet inclusive production as stabilizer of the high-energy resummation. *Proc. Sci.* **2022**, EPS-HEP2021, 589.
194. Celiberto, F.G.; Fucilla, M.; Ivanov, D.Y.; Mohammed, M.M.A.; Papa, A. Higgs boson production in the high-energy limit of pQCD. *Proc. Sci.* **2022**, PANIC2021, 352.
195. Celiberto, F.G.; Fucilla, M.; Ivanov, D.Y.; Mohammed, M.M.A.; Papa, A. BFKL phenomenology: Resummation of high-energy logs in inclusive processes. *SciPost Phys. Proc.* **2022**, *10*, 2.
196. Celiberto, F.G.; Fucilla, M.; Ivanov, D.Y.; Mohammed, M.M.A.; Papa, A. The next-to-leading order Higgs impact factor in the infinite top-mass limit. *J. High Energy Phys.* **2022**, *8*, 92.
197. Boussarie, R.; Ducloué, B.; Szymanowski, L.; Wallon, S. Forward J/ψ and very backward jet inclusive production at the LHC. *Phys. Rev. D* **2018**, *97*, 014008.
198. Celiberto, F.G.; Ivanov, D.Y.; Murdaca, B.; Papa, A. High-energy resummation in heavy-quark pair photoproduction. *Phys. Lett. B* **2018**, *777*, 141–150.
199. Bolognino, A.D.; Celiberto, F.G.; Fucilla, M.; Ivanov, D.Y.; Murdaca, B.; Papa, A. Inclusive production of two rapidity-separated heavy quarks as a probe of BFKL dynamics. *Proc. Sci.* **2019**, DIS2019, 67.
200. Bolognino, A.D.; Celiberto, F.G.; Fucilla, M.; Ivanov, D.Y.; Papa, A. High-energy resummation in heavy-quark pair hadroproduction. *Eur. Phys. J. C* **2019**, *79*, 939.

201. Celiberto, F.G.; Fucilla, M.; Ivanov, D.Y.; Papa, A. High-energy resummation in Λ_c baryon production. *Eur. Phys. J. C* **2021**, *81*, 780.
202. Celiberto, F.G.; Fucilla, M.; Ivanov, D.Y.; Mohammed, M.M.A.; Papa, A. Bottom-flavored inclusive emissions in the variable-flavor number scheme: A high-energy analysis. *Phys. Rev. D* **2021**, *104*, 114007.
203. Bolognino, A.D.; Celiberto, F.G.; Fucilla, M.; Ivanov, D.Y.; Papa, A. Heavy flavored emissions in hybrid collinear/high energy factorization. *Proc. Sci.* **2022**, *EPS-HEP2021*, 389.
204. Celiberto, F.G.; Fucilla, M. Diffractive semi-hard production of a J/ψ or a Y from single-parton fragmentation plus a jet in hybrid factorization. *Eur. Phys. J. C* **2022**, *82*, 929.
205. Celiberto, F.G. The high-energy spectrum of QCD from inclusive emissions of charmed B-mesons. *Phys. Lett. B* **2022**, *835*, 137554.
206. Celiberto, F.G.; Fucilla, M.; Mohammed, M.M.A.; Papa, A. Ultraforward production of a charmed hadron plus a Higgs boson in unpolarized proton collisions. *Phys. Rev. D* **2022**, *105*, 114056.
207. Celiberto, F.G.; Fucilla, M. Inclusive J/ψ and Y emissions from single-parton fragmentation in hybrid high-energy and collinear factorization. *Zenodo* 2022, in press. [[CrossRef](#)]
208. Bolognino, A.D.; Celiberto, F.G.; Fucilla, M.; Ivanov, D.Y.; Papa, A. Inclusive production of a heavy-light dijet system in hybrid high-energy and collinear factorization. *Phys. Rev. D* **2021**, *103*, 094004.
209. Bolognino, A.D.; Celiberto, F.G.; Fucilla, M.; Ivanov, D.Y.; Papa, A. Hybrid high-energy/collinear factorization in a heavy-light dijets system reaction. *SciPost Phys. Proc.* **2022**, *8*, 68.
210. Celiberto, F.G.; Fucilla, M.; Papa, A. The high-energy limit of perturbative QCD: Theory and phenomenology. In Proceedings of the 10th International Workshop on QCD—Theory and Experiment, Lecce, Italy, 27–30 June 2022.
211. Bolognino, A.D.; Celiberto, F.G.; Fucilla, M.; Ivanov, D.Y.; Mohammed, M.M.A.; Papa, A. High-energy signals from heavy-flavor physics. *arXiv* **2022**, arXiv:2211.16818.
212. Fucilla, M. The Higgs impact factor at next-to-leading order. *arXiv* **2022**, arXiv:2212.01794.
213. Niccolai, S. The physics program of CLAS12. *Nucl. Phys. B Proc. Suppl.* **2011**, *210–211*, 119–124. [[CrossRef](#)]
214. Avakian, H. Transverse spin physics at CLAS and CLAS12. *AIP Conf. Proc.* **2011**, *1388*, 464–470. [[CrossRef](#)]
215. Burkert, V.D. The JLab 12 GeV upgrade and the initial science program—Selected topics. *Proc. Int. Sch. Phys. Fermi* **2012**, *180*, 303–332.
216. Aghasyan, M.; Avakian, H. Extracting TMDs from CLAS12 data. *Phys. Part. Nucl.* **2014**, *45*, 126–128. [[CrossRef](#)]
217. Matevosyan, H.H.; Kotzinian, A.; Aschenauer, E.C.; Avakian, H.; Thomas, A.W. Predictions for Sivers single spin asymmetries in one- and two-hadron electroproduction at CLAS12 and EIC. *Phys. Rev. D* **2015**, *92*, 054028. [[CrossRef](#)]
218. Avakian, H.; Parsamyan, B.; Prokudin, A. Spin orbit correlations and the structure of the nucleon. *Riv. Nuovo Cim.* **2019**, *42*, 1–48.
219. Brodsky, S.J.; Burkert, V.D.; Carman, D.S.; Chen, J.P.; Cui, Z.F.; Döring, M.; Dosch, H.G.; Draayer, J.; Elouadrhiri, L.; Glazier, D.I.; et al. Strong QCD from Hadron Structure Experiments: Newport News, VA, USA, November 4–8, 2019. *Int. J. Mod. Phys. E* **2020**, *29*, 2030006.
220. Hayward, T.B. et al. [CLAS Collaboration] Observation of Beam Spin Asymmetries in the Process $ep \rightarrow e' \pi^+ \pi^- X$ with CLAS12. *Phys. Rev. Lett.* **2021**, *126*, 152501.
221. Brodsky, S.J.; Fleuret, F.; Hadjidakis, C.; Lansberg, J.P. Physics Opportunities of a Fixed-Target Experiment using the LHC Beams. *Phys. Rep.* **2013**, *522*, 239–255.
222. Lansberg, J.P.; Brodsky, S.J.; Fleuret, F.; Hadjidakis, C. Quarkonium Physics at a Fixed-Target Experiment using the LHC Beams. *Few Body Syst.* **2012**, *53*, 11–25.
223. Lansberg, J.P.; Shao, H.S. Double-quarkonium production at a fixed-target experiment at the LHC (AFTER@LHC). *Nucl. Phys. B* **2015**, *900*, 273–294.
224. Kikoła, D.; Echevarria, M.G.; Hadjidakis, C.; Lansberg, J.P.; Lorcé, C.; Massacrier, L.; Quintans, C.M.; Signori, A.; Trzeciak, B. Feasibility Studies for Single Transverse-Spin Asymmetry Measurements at a Fixed-Target Experiment Using the LHC Proton and Lead Beams (AFTER@LHC). *Few Body Syst.* **2017**, *58*, 139.
225. Hadjidakis, C.; Kikoła, D.; Lansberg, J.P.; Massacrier, L.; Echevarria, M.G.; Kusina, A.; Schienbein, I.; Seixas, J.; Shao, H.S.; Signori, A.; et al. A fixed-target programme at the LHC: Physics case and projected performances for heavy-ion, hadron, spin and astroparticle studies. *Phys. Rep.* **2021**, *911*, 1–83.
226. Pappalardo, L.L.; Carassiti, V.; Di Nezza, P.; Ciullo, G.; Lenisa, P.; Steffens, E.; Vasilyev, A.A. The LHCSpin Project. *Proc. Sci.* **2019**, *DIS2019*, 233.
227. Santimaria, M.; Carassiti, V.; Ciullo, G.; Di Nezza, P.; Lenisa, P.; Mariani, S.; Pappalardo, L.L.; Steffens, E. The LHCspin project. *arXiv* **2021**, arXiv:2111.04515.
228. Passalacqua, B.; Di Nezza, P.; Lenisa, P.; Pappalardo, L.L. The LHCspin project: A polarized fixed target for LHC. *Nuovo Cim. C* **2022**, *45*, 121. [[CrossRef](#)]