Gluon TMD distributions: an overview

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Introduction - why gluon TMDs?

- Collinear pQCD: hadron structure described through PDFs, $f(x) \Rightarrow$ 1D picture
- TMDs, $f(x, \boldsymbol{k}_T)$:
  - describe the 3D nucleon structure in momentum space
  - give access to spin-$\boldsymbol{k}_T$ correlations
- TMD factorization proven for two scale processes: SIDIS, Drell-Yan, $e^+e^- \to h_1 h_2 X \Rightarrow$ access to quark TMDs

[Signori & Cerutti talks on Monday]

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[Signori & Cerutti talks on Monday]

Why gluon TMDs?

- Gluons dominate the nucleon at high energy, yet gluon TMDs far less constrained than quark TMDs
- Distinct, richer colour/gauge-link structures than quarks $\Rightarrow$ further tests of QCD

Introduction - the gluon correlator

Gluon TMDs correlator

$$\Gamma_g^{\mu\nu}(x, \boldsymbol{k}_T) \sim \langle P, S | \, F^{+\mu}(0) \, \mathcal{U}_{[0,\xi]} \, F^{+\nu}(\xi) \, \mathcal{U}'_{[\xi,0]} \, | P, S \rangle$$

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For unpolarised nucleons:

$$\Gamma_U^{\mu\nu}(x, \boldsymbol{k}_T) = \frac{x}{2} \left\{ -g_T^{\mu\nu} f_1^g(x, \boldsymbol{k}_T^2) + \left(\frac{\boldsymbol{k}_T^\mu \boldsymbol{k}_T^\nu}{M_N^2} + g_T^{\mu\nu} \frac{\boldsymbol{k}_T^2}{2M_N^2} \right) h_1^{\perp g}(x, \boldsymbol{k}_T^2) \right\}$$

$\Rightarrow$ gluons inside *unpolarised* nucleons can be polarised!

$h_1^{\perp g}(x, \boldsymbol{k}_T^2)$ linearly polarised gluon TMD **[Mulders & Rodrigues, PRD 63 (2001) 094021]**

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For transversely polarised nucleons:

$$\Gamma_T^{\mu\nu} = \frac{x}{2} \left\{ g_T^{\mu\nu} \frac{\epsilon_T^{\rho\sigma} k_{T\rho} k_{T\sigma}}{M_N} f_{1T}^{\perp g}(x, \boldsymbol{k}_T^2) + \cdots \right\}$$

$\Rightarrow$ gluon Sivers TMD

Introduction - gluon TMDs

N \ g	U	Circular	Linear
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	$g_{1T}^{\perp g}$	h_1^g, $h_{1T}^{\perp g}$

Time-reversal even Time-reversal odd
Non-zero in the collinear limit

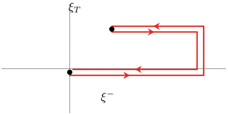
- some of them are related to each other by positivity bounds

[Mulders & Rodrigues, PRD 63 (2001) 094021]

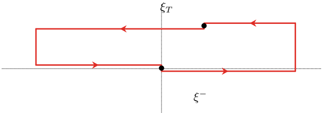
- Initial- (ISI) and Final-State Interactions (FSI) can make TMDs process dependent

Gauge-link structure

$\Gamma_g^{\mu\nu}$ proportional to two Wilson lines, that can be future- $(+)$ or past-pointing $(-)$:



$[+,+]$ (WW)



$[+,-]$ (dipole)

Link structure	Example of process
$[+,+]$ / $[-,-]$	$\gamma^* g \to q\bar{q}$ (DIS dijet, $Q\bar{Q}$)
$[+,-]$ / $[-,+]$	dijet/γ+jet in pp / pA collisions

The same nucleon yields different gluon TMDs in different reactions
$\Rightarrow$ modified universality

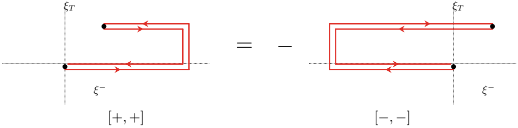
[Bomhof, Mulders, Pijlman, EPJC 47 (2006) 147; Dominguez, Marquet, Xiao, Yuan, PRD 83 (2011) 105005]

Process dependence

- an example of generalised universality: $f_{1T}^{\perp g}$
- related processes:
  - $ep^{\uparrow} \to e'Q\bar{Q}X$, $ep^{\uparrow} \to e'$ jet jet $X \;\Rightarrow\; [+,+]$
  - $p^{\uparrow}p \to \gamma\gamma X$ (and/or any other CS final state) $\Rightarrow\; [-,-]$

Gluon Sivers sign change

$$f_{1T}^{\perp g\,[ep^{\uparrow}\to e'Q\bar{Q}X]} = -f_{1T}^{\perp g\,[p^{\uparrow}p\to\gamma\gamma X]}$$



[Boer, Mulders, Pisano, Zhou, JHEP 08 (2016) 001]

A word on evolution and matching

- evolution of TMDs requrires knowledge of:
  - Collins-Soper kernel (CSK) $K(b,\mu)$
  - anomalous dimension & matching coefficients
- gluon CSK far less constrained w.r.t. the quark one
- matching coefficients for gluon distributions far less known
- recent progress for matching coefficients

[Alvaro, Kato, Pasquini, Pisano, Rodini, PRD 114 054001 (2026)]

Distribution	Twist of leading matching	Tw2	Tw3	Accuracy	Ref.
f_1^g	Tw2	f_g, f_1	$\cdots$	N^{3}LO	[24,25]
$h_1^{\perp g}$	Tw2	f_g, f_1	$\cdots$	N^{3}LO	[28]
g_{1L}^g	Tw2	$\Delta f_g, g_1$	$\cdots$	N^{3}LO	[26]
g_{1T}^g	Tw2-3	$\Delta f_g, g_1$	$\mathcal{F}, \mathcal{T}$	NLO/LO	This work
$f_{1T}^{\perp g}$	Tw3	$\cdots$	$2F_2^+ + F_4^+$	LO	This work
h_{1T}^g	Tw3	$\cdots$	$2F_2^+ - 2F_4^+$	LO	This work
$h_{1L}^{\perp g}$	Tw3-4	$\cdots$	$2F_2^+ - 2F_4^+$	LO	This work
$h_{1T}^{\perp g}$	Tw4-5	$\cdots$	$\cdots$	LO	This work

- recent studies involving gluon CSK

[Anedda, Bertone, Bozzi, Cerutti, EPJC 86 (2026) 8, 1024; Boer et al., arXiv:2609.01000 [hep-ph]]

ep collisions

- Heavy-quark pairs $ep \to e' Q\bar{Q} X$ and dijets

[Boer, Brodsky, Mulders, Pisano, PRL 106 (2011) 132001] [Echevarria, Gutierrez Garcia, Scimemi arXiv:2603.00375 [hep-ph]]

$$d\sigma \sim \sigma_0 \left(A + \frac{q_T^2}{M^2} B \cos 2(\phi_T - \phi_\perp) \right)$$

with $B \propto h_1^{\perp g}$

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- many opportunities with quarkonia at the EIC

  [Boer, Flett, Flore, Kikoła, Lansberg, Nefedov, Van Hulse, PPNP 142 (2025) 104162]

  - unpolarised SIDIS with J/ψ at low P_T: access to $h_1^{\perp g}$
  - J/ψ photoproduction at low P_T [Rajesh, Kishore, Mukherjee, PRD 98 (2018) 014007]
  - associated onium production: J/ψ (+ jet, + γ) leptoproduction at low P_T

    [Jana, Mukherjee, Rajesh. arXiv:2606.31124 [hep-ph]]

pp collisions

Opportunities with quarkonia:

- $C = +1$ quarkonia:
  - η_Q [Ma, Wang, Zhao, PRD 88 (2013) 1, 014027 & Echevarria, JHEP 10 (2019) 144]
  - χ_Q [Boer, Pisano, PRD 86 (2012); Ma, Wang, Zhao, PLB 737 (2014) 103-108; Kato, Maxia, Pisano, PRD 110 (2024) 3, 034038]
- di-J/ψ at high-energy: gg-dominated, sensitive to f_1^g and $h_1^{\perp g}$

  [Lansberg, Pisano, Scarpa, Schlegel, PLB 784 (2018) 217-222; Scarpa et al., EPJC 80 (2020) 2, 87]

  $\Rightarrow$ LHCb data available [LHCb Collaboration, JHEP 03 (2024) 088]
- associated J/ψ production:
  - $J/\psi + \gamma$ [den Dunnen, Lansberg, Pisano, Schlegel, PRL 112 (2014) 212001]
  - $J/\psi + Z$ [Lansberg, Pisano, Schlegel, NPB 920 (2017) 192-210]
- more discussions for the HL-LHC in [Chapon et al., PPNP 122 (2022) 103906]

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Other opportunities:

- Higgs / diphoton q_T spectra: access to linearly polarised gluons

  [Higgs: Boer et al., PRL 108 (2012) 032002 & PRL 111 (2013) 3, 032002; Echevarria et al., PRD 90 (2014) 014003; Gutierrez-Reyes et al., JHEP 11 (2019) 121]

  [di-γ: Qiu, Schlegel, Vogelsang, PRL 107 (2011) 062001]

Status of phenomenology

A non-exhaustive list:

- Models for (un)polarised gluon TMDs:
  - spectator models [Bacchetta, Celiberto, Radici, Taels EPJC 80 (2020) 8, 733]
  - light-front wave functions, MV/CGC at small x

    [see e.g.: Marquet, Roiesnel, Taels, PRD 97 014004 (2018); Lyubovitskij & Schmidt, PRD 104, 014001 (2021); Chakrabarti et al., PRD 108 (2023) 014009, Yu et al., PLB 855 (2024) 138831]
  - Gluon Sivers: still only models/bounds, (CGI-)GPM from RHIC data

    [D'Alesio et al., PRD 96 (2017) 036011 & PRD 99 (2019) 3, 036013]
  - Lattice first steps toward $h_1^{\perp g}$ via LaMET

    [S. Zhao, PRD 109 (2024) 014002]

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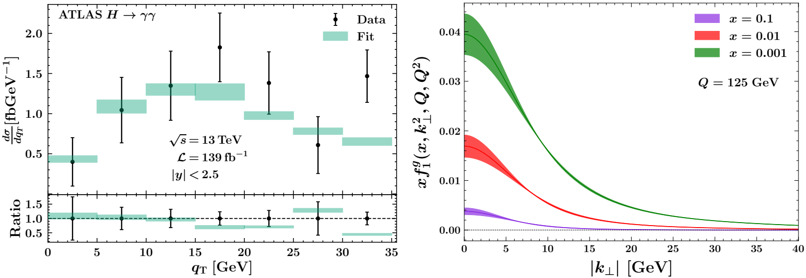
- Two independent extractions of f_1^g now exist:
  - from LHC Higgs q_T-distribution, MAP, up to N^{3}LL

    [Anedda, Bertone, Bozzi, Cerutti, EPJC 86 (2026) 8, 1024]
  - from LHCb di-J/ψ data at NNLL

    [Boer et al., arXiv:2609.01000 [hep-ph]]

$gg \to H$

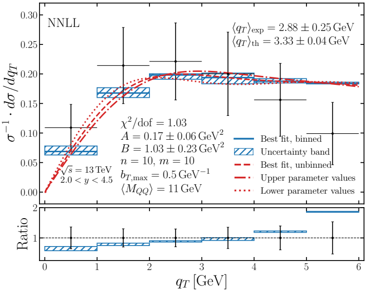
[Anedda, Bertone, Bozzi, Cerutti, EPJC 86 (2026) 8, 1024]

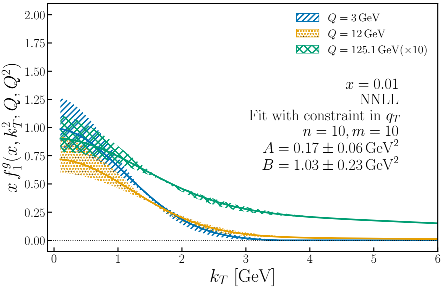


- Extraction up to N^{3}LL from ATLAS and CMS data for Higgs q_T-spectra
- simple Gaussian parameterisation with 1 parameter, fixed scale $\mu = M_H$
- 30 data points, $\chi^2/N_{dat} = 1.49$
- g_2 parameter entering the CSK fixed from quarks
- linearly polarised gluons contribution estimated to be $\mathcal{O}(2-3\%)$

di-J/ψ at LHCb

[Boer et al., arXiv:2609.01000 [hep-ph]]

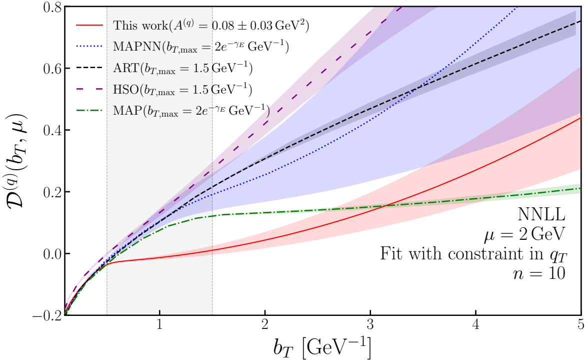




- Extraction at N^{2}LL from LHCb data for di-J/ψ prodcution spectra
- several tests of gluon TMD evolution
- contribution of linearly polarised gluons about 0.5% of the total cross section

di-J/ψ at LHCb

[Boer et al., arXiv:2609.01000 [hep-ph]]



- comparison with other analyses using Casimir scaling (C_F/C_A)

Conclusions and outlook

- gluon TMDs: access to 3D nucleon structure and further test of QCD effects
- formalism well established, yet less known than quark TMDs
- recent progesses: unpolarised f_1^g extractions from Higgs and di-J/ψ
- room to improve:
  - gluon Sivers
  - tests of TMD factorisation for quarkonium production,
  - gluon evolution and universality tests
- not discussed: TMD shape functions for quarkonia (work in progress)
- eagerly waiting many useful measurements at the HL-LHC and at the future EIC

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Thank you

Backup

$h_1^{\perp g}$ in observables

(a) Scalar / pseudoscalar system (H, η_Q) $h_1^{\perp g}$ induced an angular dependence of the q_T spectrum:

$$\frac{d\sigma}{d^2\boldsymbol{q}_T} \propto \mathcal{C}\left[f_1^g f_1^g\right] \pm \mathcal{C}\left[w_2\, h_1^{\perp g} h_1^{\perp g}\right]$$

(b) Back-to-back pair (dijet, $Q\bar{Q}$, $J/\psi + \gamma$)

$$d\sigma \propto A(q_T) + B(q_T)\cos 2\phi + C(q_T)\cos 4\phi$$

with $\cos 2\phi$, $\cos 4\phi$ coefficients $\propto h_1^{\perp g}$

Convolution: $\mathcal{C}[w\, f\, g] = \int d^2\boldsymbol{p}_T\, d^2\boldsymbol{k}_T\, \delta^2(\boldsymbol{p}_T + \boldsymbol{k}_T - \boldsymbol{q}_T)\, w(\boldsymbol{p}_T, \boldsymbol{k}_T)\, f(x_1, \boldsymbol{p}_T^2)\, g(x_2, \boldsymbol{k}_T^2)$.

[Boer et al., PRL 108, 032002 (2012); Pisano, Boer, Brodsky, Buffing, Mulders, JHEP 10 (2013) 024]

Positivity bounds

model-independent relations

$$\frac{\boldsymbol{k}_T^2}{2M_p^2}\left|h_1^{\perp g}(x,\boldsymbol{k}_T^2)\right| \;\leq\; f_1^g(x,\boldsymbol{k}_T^2), \qquad \left|g_1^g(x,\boldsymbol{k}_T^2)\right| \;\leq\; f_1^g(x,\boldsymbol{k}_T^2),$$

analogous inequalities for the T-odd functions ($f_{1T}^{\perp g}$, h_1^g).

- Saturated by linearly polarised gluons in the small-x/saturation regime for $k_T \gtrsim Q_s$.
- Practical use: sanity checks on models and computation of saturated asymmetries for feasibility studies.

[Mulders & Rodrigues PRD 63 (2001) 094021; saturation: Metz & Zhou, PRD 84 (2011) 051503; Dumitru et al., PRL 115 (2015) 252301]

A sample process – di-J/ψ in pp

$p\,p \to J/\psi\, J/\psi\, X$ via gg fusion (at high-energy), colour-singlet dominated

- Two scales: $M_{\psi\psi}$ (hard) and $\boldsymbol{q}_T = \boldsymbol{P}_{\psi_1 T} + \boldsymbol{P}_{\psi_2 T}$
- TMD regime $|\boldsymbol{q}_T| \ll M_{\psi\psi}$; ϕ azimuthal angle of $\boldsymbol{q}_T$ (Collins-Soper frame)

cross section:

$$\frac{d\sigma}{dq_T^2\, d\phi} \sim \underbrace{\mathcal{C}\left[f_1^g f_1^g\right]}_{q_T \text{ spectrum}} + \cos 2\phi\, \mathcal{C}\left[f_1^g h_1^{\perp g}\right] + \cos 4\phi\, \mathcal{C}\left[h_1^{\perp g} h_1^{\perp g}\right]$$

- $\langle \cos 2\phi \rangle$ (linear) & $\langle \cos 4\phi \rangle$ (quadratic in $h_1^{\perp g}$) $\Rightarrow h_1^{\perp g}$
- Colour-singlet $\Rightarrow$ TMD factorisation expected to hold
- important to control/subtract double-parton scattering

[Lansberg, Pisano, Scarpa, Schlegel, PLB 784 (2018) 217; Scarpa, Boer, Echevarria, Lansberg, Pisano, Schlegel, EPJC 80 (2020) 87]