Gluon TMDs and J/ψ polarization in SIDIS*

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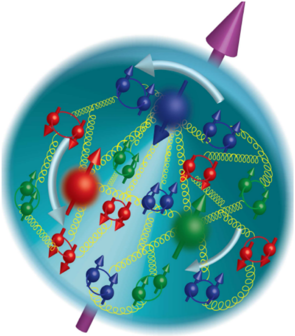

*ArXiv:2110.07529 (with U. D'Alesio, L. Maxia, F. Murgia, S. Rajesh)

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Gluon TMDs

Gluon TMDs

GLUONS	*unpolarized*	*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}^g	h_{1T}^g, $h_{1T}^{\perp g}$

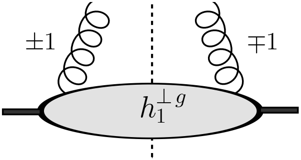
Angeles-Martinez *et al.*, Acta Phys, Pol. B46 (2015)
Mulders, Rodrigues, PRD 63 (2001)
Meissner, Metz, Goeke, PRD 76 (2007)

- f_1^g : unpolarized TMD gluon distribution
- $h_1^{\perp g}$: distribution of linearly polarized gluons inside an unp. hadron

In contrast to quark TMDs, gluon TMDs are almost unknown

Gluons inside an unpolarized hadron can be linearly polarized

It requires nonzero transverse momentum



Interference between ± 1 gluon helicity states

Like the unpolarized gluon TMD, it is T-even and exists in different versions:

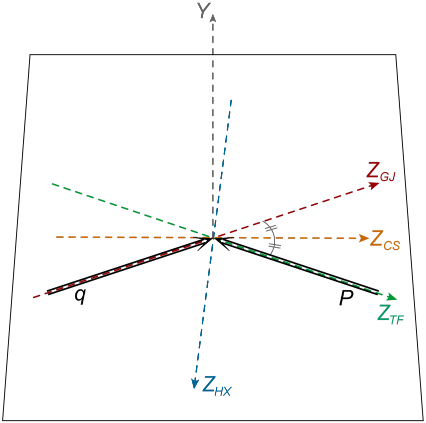
- $[++] = [--]$ (WW)   (SIDIS and DY-like process)

Gluons can be probed in heavy quark production in both *ep* and *pp* scattering

Lansberg, CP, Scarpa, Schlegel, PLB 784 (2018)
Boer, CP, PRD 86 (2012)

Quarkonium polarization in SIDIS

We study $\gamma^*(q) + p(P) \to J/\psi(P_\psi) + X$ in the J/ψ rest frame



HX: Helicity
TF: Target
CS: Collins-Soper
GJ: Gottfried-Jackson

The frames are related to each other by a rotation around the Y axis

Model-independent arguments (hermiticity, parity conservation) lead to eight independent helicity structure functions:

Lam, Tung, PRD 18 (1978)
Boer, Vogelsang, PRD 74 (2006)

$$\mathcal{W}_T^{\mathcal{P}} \equiv \mathcal{W}_{11}^{\mathcal{P}} = \mathcal{W}_{-1-1}^{\mathcal{P}}$$
$$\mathcal{W}_L^{\mathcal{P}} \equiv \mathcal{W}_{00}^{\mathcal{P}}$$
$$\mathcal{W}_\Delta^{\mathcal{P}} \equiv \sqrt{2}\,\mathrm{Re}\,\mathcal{W}_{10}^{\mathcal{P}}$$
$$\mathcal{W}_{\Delta\Delta}^{\mathcal{P}} \equiv \mathcal{W}_{1-1}^{\mathcal{P}} = \mathcal{W}_{-11}^{\mathcal{P}}$$

- $\mathcal{P} = \perp, \parallel$: γ^* polarization (w.r.t. P, q)
- $\Lambda = T, L, \Delta, \Delta\Delta$: J/ψ helicity

However, by looking at the angular dependence of the decaying leptons only four linear combinations can be disentangled

$$\mathcal{W}_\Lambda \equiv \left[1 + (1-y)^2\right] \mathcal{W}_\Lambda^{\perp} + (1-y)\mathcal{W}_\Lambda^{\parallel} \qquad \text{with} \qquad \Lambda = T, L, \Delta, \Delta\Delta$$

Usual SIDIS variables:

$$Q^2 = -q^2 \,, \qquad x_B = \frac{Q^2}{2P\cdot q} \,, \qquad y = \frac{P\cdot q}{P\cdot \ell} \,, \qquad z = \frac{P\cdot P_\psi}{P\cdot q}$$

Cross section differential in $\Omega = (\theta, \varphi)$, solid angle of the decaying lepton ℓ^+

$$\mathrm{d}\sigma \equiv \frac{\mathrm{d}\sigma}{\mathrm{d}x_B\,\mathrm{d}y\,\mathrm{d}^4 P_\psi\,\mathrm{d}\Omega}$$

$$\mathrm{d}\sigma \propto \frac{\alpha^2}{yQ^2}\left[\mathcal{W}_T(1+\cos^2\theta) \;+\; \mathcal{W}_L(1-\cos^2\theta) \;+\; \mathcal{W}_\Delta \sin 2\theta \cos\varphi \;+\; \mathcal{W}_{\Delta\Delta}\sin^2\theta\cos 2\varphi\right]$$

Alternatively, in terms of the polarization parameters λ, μ, ν :

$$\mathrm{d}\sigma \propto \frac{\alpha^2}{yQ^2}\left(\mathcal{W}_T + \mathcal{W}_L\right)\left[1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\varphi + \frac{1}{2}\,\nu\,\sin^2\theta\cos 2\varphi\right]$$

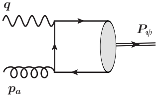
$$\lambda = \frac{\mathcal{W}_T - \mathcal{W}_L}{\mathcal{W}_T + \mathcal{W}_L} \,, \qquad \mu = \frac{\mathcal{W}_\Delta}{\mathcal{W}_T + \mathcal{W}_L} \,, \qquad \nu = \frac{2\mathcal{W}_{\Delta\Delta}}{\mathcal{W}_T + \mathcal{W}_L}$$

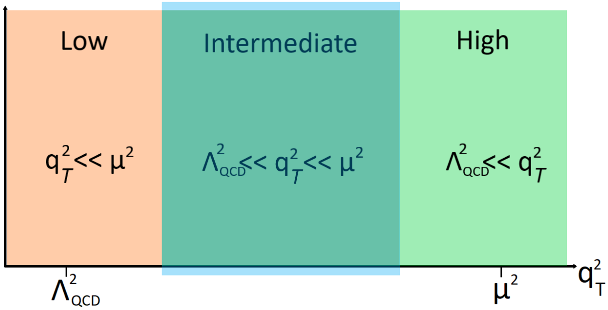
TMD vs collinear factorization

Three physical scales, two theoretical tools

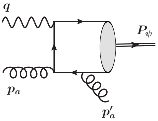
Bacchetta, Boer, Diehl, Mulders, JHEP 08 (2008)
Bacchetta, Bozzi, Echevarria, CP, Prokudin, Radici, PLB 797 (2019)
Boer, D'Alesio, Murgia, CP, Taels, JHEP 09 (2020)

TMD





Collinear



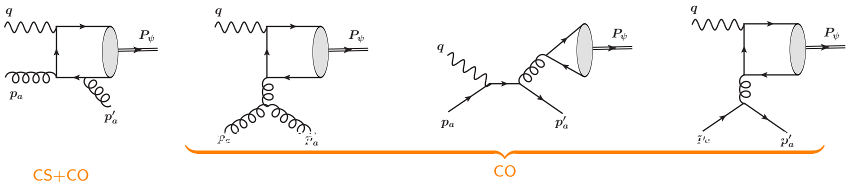
TMD factorization proven only for light hadron production in SIDIS

Matching in the intermediate region: a test of TMD factorization

The helicity structure functions can be calculated within the NRQCD framework: double expansion in α_s and v

Contributing partonic subprocesses at the orders α_s^2 and v^4

$$\gamma^*(q) + a(p_a) \to J/\psi(P_\psi) + a(p'_a) \qquad a = g, q, \bar{q}$$



Fock states included in the calculation: ${}^3S_1^{[1]}$, ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, ${}^3P_0^{[8]}$

($Q^2 = 0$) Beneke, Kramer, Vanttinen, PRD 57 (1998)
(W_T, W_L) Yuan, Chao, PRD 63 (2001)
(unpolarized) Kniehl, Zwirner, NPB 621 (2002)

q_T: transverse momentum of the photon w.r.t. P_ψ, P

Frame-independent leading power behavior of the structure functions up to corrections of $\mathcal{O}(\Lambda_{\rm QCD}/|\boldsymbol{q}_T|)$, $\mathcal{O}(|\boldsymbol{q}_T|/Q)$ in the region $\Lambda_{\rm QCD}^2 \ll \boldsymbol{q}_T^2 \ll Q^2$

$$\mathcal{W}_{L,T}^{\perp} = \widehat{w}_{L,T}^{\perp} \, \frac{\alpha_s}{2\pi^2 \boldsymbol{q}_T^2} \left[L\left(\frac{Q^2 + M_\psi^2}{\boldsymbol{q}_T^2} \right) f_1^g(x,\mu^2) + \left(P_{gg} \otimes f_1^g + P_{gi} \otimes f_1^i \right)(x,\mu^2) \right]$$

$$\mathcal{W}_{L}^{\parallel} = \widehat{w}_{L}^{\parallel} \, \frac{1}{\boldsymbol{q}_T^2} \left[L\left(\frac{Q^2 + M_\psi^2}{\boldsymbol{q}_T^2} \right) f_1^g(x,\mu^2) + \left(P_{gg} \otimes f_1^g + P_{gi} \otimes f_1^i \right)(x,\mu^2) \right]$$

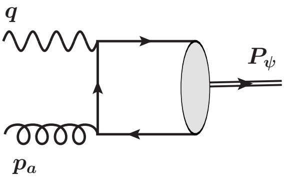
$$\mathcal{W}_{\Delta\Delta}^{\perp} = \widehat{w}_{\Delta\Delta}^{\perp} \, \frac{1}{\boldsymbol{q}_T^2} \left(\delta P_{gg} \otimes f_1^g + \delta P_{gi} \otimes f_1^i \right)(x,\mu^2)$$

$\widehat{w}_{\Lambda}^{\mathcal{P}}$: partonic structure functions for $\gamma^{*\mathcal{P}} g \to J/\psi^{\Lambda}$: depend on NRQCD LDMEs

$$L\left(\frac{Q^2 + M_\psi^2}{\boldsymbol{q}_T^2} \right) \equiv 2C_A \ln\left(\frac{Q^2 + M_\psi^2}{\boldsymbol{q}_T^2} \right) - \frac{11C_A - 4n_f T_R}{6}$$

TMD factorization

When $q_T^2 \ll Q^2$ at $\mathcal{O}(\alpha_s)$ only color-octet (CO) production channels dominate



Neglecting smearing effects in quarkonium formation:

$$\mathcal{W}_T^{\perp} = \widehat{w}_T^{\perp}\, f_1^g(x, \boldsymbol{q}_T^2) \qquad \mathcal{W}_L^{\perp} = \widehat{w}_L^{\perp}\, f_1^g(x, \boldsymbol{q}_T^2) \qquad \mathcal{W}_L^{\parallel} = \widehat{w}_L^{\parallel}\, f_1^g(x, \boldsymbol{q}_T^2)$$

$$\mathcal{W}_{\Delta\Delta}^{\perp} = \widehat{w}_{\Delta\Delta}^{\perp}\, h_1^{\perp\, g}(x, \boldsymbol{q}_T^2)$$

$\mathcal{W}_{\Delta\Delta}^{\perp}$ gives access to $h_1^{\perp\, g}$ and to the poorly known $^3P_0$ LDME

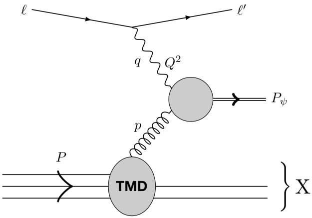
Smearing effects need to be included to match the result in the intermediate overlapping region $\Lambda_{\rm QCD}^2 \ll \boldsymbol{q}_T^2 \ll Q^2$

Shape functions

Smearing effects are encoded in the *shape functions* $\Delta^{[n]}$ (TMD generalizations of NRQCD LDMEs)

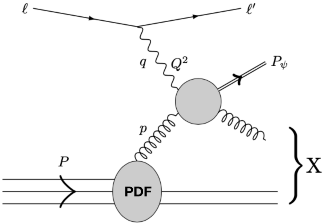
Echevarria, JHEP 10 (2019)
Fleming, Makris, Mehen, JHEP 04 (2020)

TMD



$\boldsymbol{q}_T^2 \ll Q^2$

Collinear



$\Lambda_{\rm QCD}^2 \ll \boldsymbol{q}_T^2$

Imposing the matching of the TMD and collinear results in the overlapping region $\Lambda_{\rm QCD}^2 \ll \boldsymbol{q}_T^2 \ll Q^2$: $\quad f_1^g \longrightarrow \mathcal{C}[f_1^g\, \Delta^{[n]}]$

$$\Delta^{[n]}(\boldsymbol{k}_T^2, \mu^2) = \frac{\alpha_s}{2\pi^2 \boldsymbol{k}_T^2}\, C_A\, \langle 0|\mathcal{O}_8^Q(n)|0\rangle\, \ln\frac{\mu^2}{\boldsymbol{k}_T^2} \qquad k_T^2 \gg M_p^2$$

Boer, D'Alesio, Murgia, CP, Taels, JHEP 09 (2020)
D'Alesio, Maxia, Murgia, CP, Rajesh, ArXiv:2110.07529

Conclusions

- Polarization states of J/ψ mesons produced in semi-inclusive DIS can be studied in different frames at the future EIC
- In the TMD region, we have shown that the distribution of linearly polarized gluons can, if sizable, affect the ν polarization parameter
- Our TMD formulae, at the order α_s correctly match with the collinear factorization results at high transverse momentum at the order α_s^2
- If TMD factorization is applicable to this process, shape functions will have to be included in the expression of the cross section
- EIC data will shed light on gluon TMDs, shape functions and on the mechanisms underlying quarkonium production and polarization
- Other TMD observables/frameworks proposed for J/ψ production at EIC

Godbole, Misra, Mukherjee, Rawoot, PRD 85 (2012)
Godbole, Kaushik, Misra, Rawoot, PRD 91 (2015)
Mukherjee, Rajesh, EPJC 77 (2017)
Rajesh, Kishore, Mukherjee, PRD 98 (2018)
Bacchetta, Boer, CP, Taels, EPJC 80 (2020)
Boer, CP, Taels, PRD 103 (2021)