Gluon TMDs and J/ψ polarization in SIDIS

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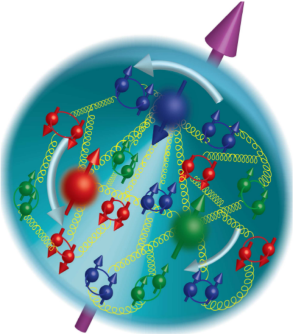


In collaboration with: U. D'Alesio, L. Maxia, F. Murgia, S. Rajesh

Fondazione di Sardegna

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, $h_{1T}^{\perp g}$

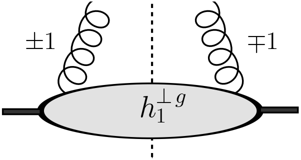
Angeles-Martinez *et al.*, Acta Phys, Pol. B46 (2015)
Mulders, Rodrigues, PRD 63 (2001)
Meissner, Metz, Goeke, PRD 76 (2007)

- 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:

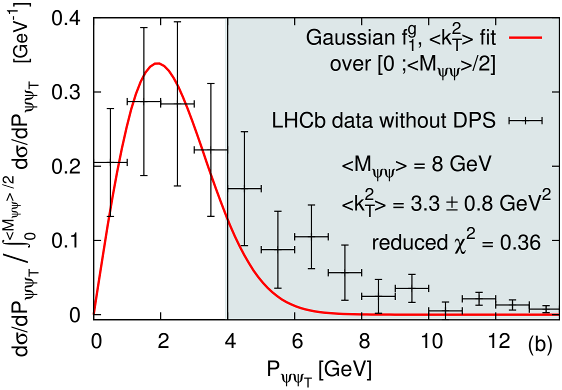
- $[++] = [--]$ (WW) (SIDIS and DY-like process)

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)

$q_T = P_T^{\Psi\Psi} \leq M_{\Psi\Psi}/2$ in order to have two different scales

Color Singlet production mechanism $\Longrightarrow$: $[-,-]$ gauge link structure (like DY)



Lansberg, CP, Scarpa, Schlegel, PLB 784 (2018)
LHCb Coll., JHEP 06 (2017)

$C = +1$ quarkonium production

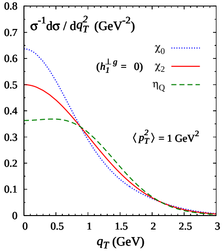
q_T-distribution of η_Q and χ_{QJ} $(Q = c, b)$ in the kinematic region $q_T \ll 2M_Q$

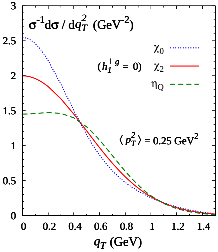
$$\frac{1}{\sigma(\eta_Q)}\frac{d\sigma(\eta_Q)}{d\boldsymbol{q}_T^2} \propto f_1^g \otimes f_1^g\,[1 - R(\boldsymbol{q}_T^2)] \qquad \text{[pseudoscalar]} \qquad R(\boldsymbol{q}_T^2) = \frac{h_1^{\perp\,g} \otimes h_1^{\perp\,g}}{f_1^g \otimes f_1^g}$$

$$\frac{1}{\sigma(\chi_{Q0})}\frac{d\sigma(\chi_{Q0})}{d\boldsymbol{q}_T^2} \propto f_1^g \otimes f_1^g\,[1 + R(\boldsymbol{q}_T^2)] \qquad \text{[scalar]}$$

$$\frac{1}{\sigma(\chi_{Q2})}\frac{d\sigma(\chi_{Q2})}{d\boldsymbol{q}_T^2} \propto f_1^g \otimes f_1^g$$

Boer, CP, PRD 86 (2012)





Proof of factorization at NLO for $p\,p \to \eta_Q\,X$ in the Color Singlet Model (CSM)

Ma, Wang, Zhao, PRD 88 (2013); PLB 737 (2014)
Echevarria, JHEP 1910 (2019)

Future fixed target experiments at LHC and NICA

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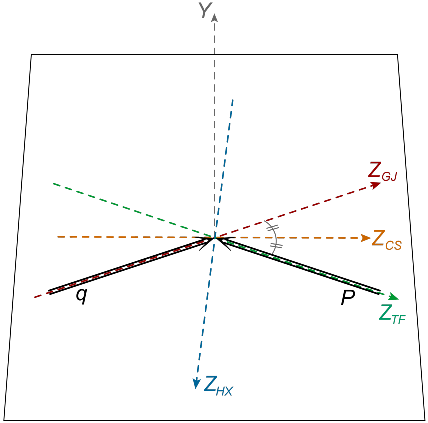
Quarkonium polarization in SIDIS

We study $\gamma^*(q) + p(P) \rightarrow J/\psi(P_\psi) + X$ 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 (gauge invariance, hermiticity, parity conservation) lead to eight independent helicity structure functions:

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

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

- $\mathcal{P} = \perp, \parallel$: 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^+

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

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

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

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

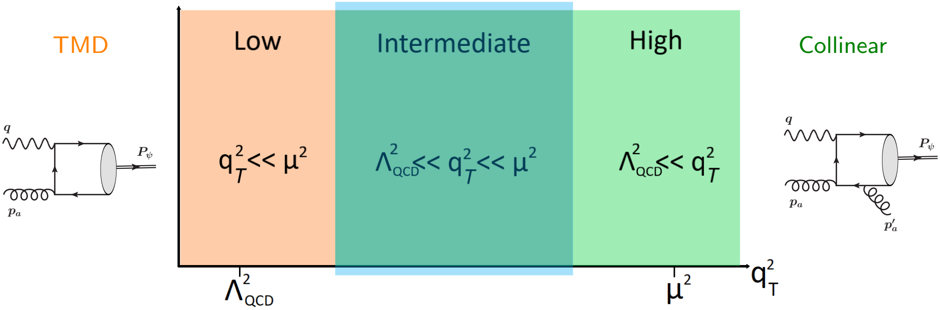
$$\lambda = \frac{\mathcal{W}_T - \mathcal{W}_L}{\mathcal{W}_T + \mathcal{W}_L}\,, \qquad \mu = \frac{\mathcal{W}_\Delta}{\mathcal{W}_T + \mathcal{W}_L}\,, \qquad \nu = \frac{2\mathcal{W}_{\Delta\Delta}}{\mathcal{W}_T + \mathcal{W}_L}$$

TMD vs collinear factorization

Scales and frameworks

Three physical scales, two theoretical tools

Bacchetta, Boer, Diehl, Mulders, JHEP 08 (2008)
Boer, D'Alesio, Murgia, CP, Taels, JHEP 09 (2020)
D'Alesio, Maxia, Murgia, CP, Rajesh, JHEP 037 (2022)



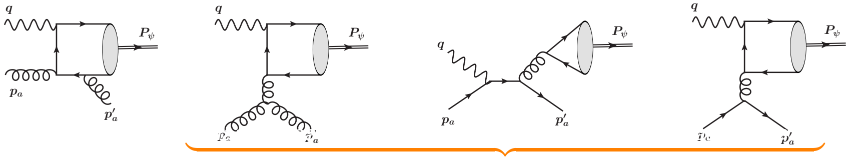
TMD factorization proven only for light hadron production in SIDIS

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

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



CS+CO

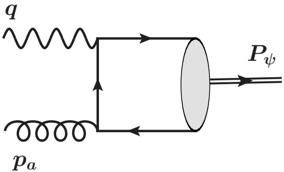
CO

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

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:

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

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

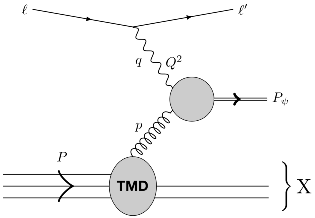
$\mathcal{W}_{\Delta\Delta}^{\perp}$ gives access to $h_1^{\perp\, g}$ and to the poorly known $^3P_0$ LDME

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

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

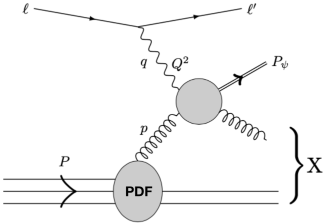
Echevarria, JHEP 10 (2019)
Fleming, Makris, Mehen, JHEP 04 (2020)

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 $\Lambda_{\rm QCD}^2 \ll \boldsymbol{q}_T^2 \ll Q^2$: $\quad f_1^g \longrightarrow \mathcal{C}[f_1^g\, \Delta^{[n]}]$

Boer, D'Alesio, Murgia, CP, Taels, JHEP 09 (2020)
D'Alesio, Maxia, Murgia, CP, Rajesh, JHEP 037 (2022)

Independent of J/ψ polarization and CO quantum numbers

Also process independent?

- 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