

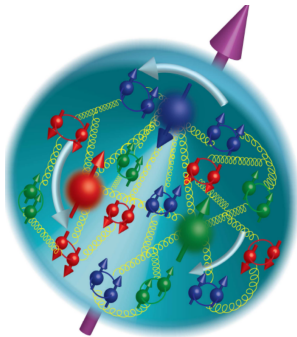
# Gluon TMDs and $J/\psi$ polarization in $ep$ collisions

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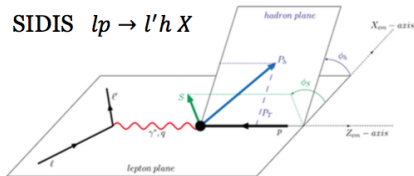


In collaboration with: U. D'Alesio, L. Maxia, F. Murgia, S. Rajesh

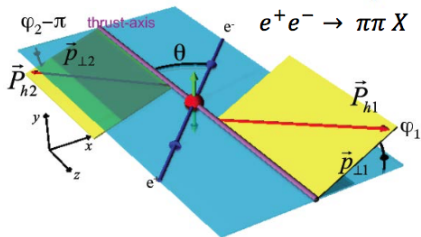
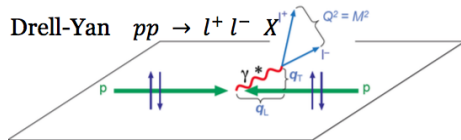
# Gluon TMDs and factorization

Two scale processes  $Q^2 \gg q_T^2$

SIDIS  $lp \rightarrow l'h X$



Drell-Yan  $pp \rightarrow l^+ l^- X$



Factorization proven

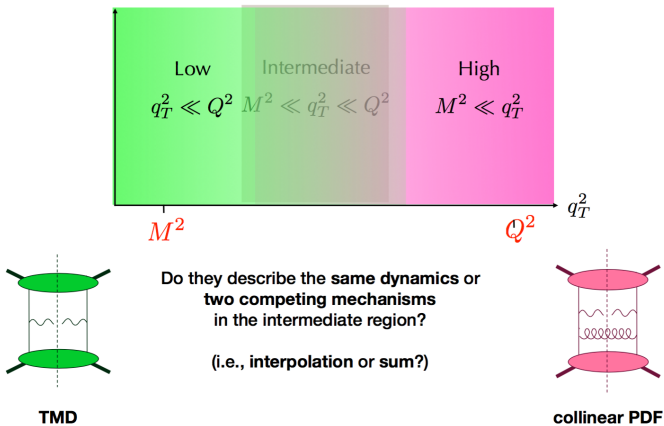
All orders in  $\alpha_s$

Leading order in powers of  $1/Q$  (twist)

Collins, Cambridge University Press (2011)

## 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, Tael, JHEP 09 (2020)



Useful to test assumptions on TMD factorization

| GLUONS | <i>unpolarized</i> | <i>circular</i> | <i>linear</i>                |
|--------|--------------------|-----------------|------------------------------|
| 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)

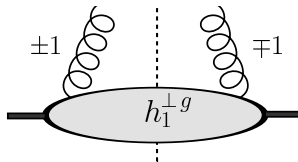
Meissner, Metz, Goeke, PRD 76 (2007)

- ▶  $f_1^g$  : 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  $\pm 1$  gluon helicity states

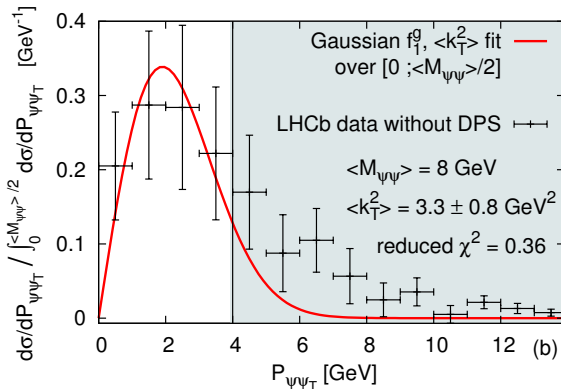
Like the unpolarized gluon TMD, it is  $T$ -even and exists in different versions:

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

Gluons probed in heavy quark production in both  $ep$  and  $pp$  scattering

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

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



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

# C = +1 quarkonium production

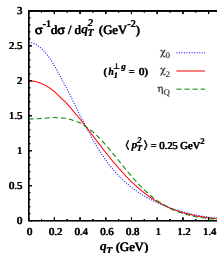
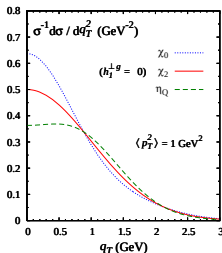
$q_T$ -distribution of  $\eta_Q$  and  $\chi_{QJ}$  ( $Q = c, b$ ) in the kinematic region  $q_T \ll 2M_Q$

$$\frac{1}{\sigma(\eta_Q)} \frac{d\sigma(\eta_Q)}{dq_T^2} \propto f_1^g \otimes f_1^g [1 - R(q_T^2)] \quad [\text{pseudoscalar}]$$

$$\frac{1}{\sigma(\chi_{Q0})} \frac{d\sigma(\chi_{Q0})}{dq_T^2} \propto f_1^g \otimes f_1^g [1 + R(q_T^2)] \quad [\text{scalar}]$$

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

Boer, CP, PRD 86 (2012)



Proof of factorization at NLO for  $pp \rightarrow \eta_Q X$  in the Color Singlet Model (CSM)

Ma, Wang, Zhao, PRD 88 (2013); PLB 737 (2014)

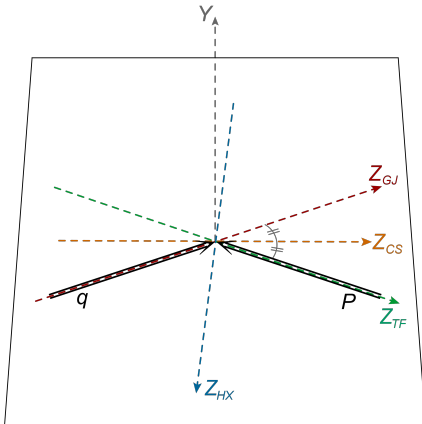
Echevarria, JHEP 1910 (2019)

Future fixed target experiments at LHC and NICA



# Quarkonium polarization

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

$$\mathcal{W}_T^{\mathcal{P}} \equiv \mathcal{W}_{11}^{\mathcal{P}} = \mathcal{W}_{-1-1}^{\mathcal{P}}$$

$$\mathcal{W}_L^{\mathcal{P}} \equiv \mathcal{W}_{00}^{\mathcal{P}}$$

$$\mathcal{W}_{\Delta}^{\mathcal{P}} \equiv \sqrt{2} \operatorname{Re} \mathcal{W}_{10}^{\mathcal{P}}$$

$$\mathcal{W}_{\Delta\Delta}^{\mathcal{P}} \equiv \mathcal{W}_{1-1}^{\mathcal{P}} = \mathcal{W}_{-11}^{\mathcal{P}}$$

- ▶  $\mathcal{P} = L, T$ :  $\gamma^*$  polarization
- ▶  $\Lambda = T, L, \Delta, \Delta\Delta$ :  $J/\psi$  helicity

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

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

Usual SIDIS variables:

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

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

$$d\sigma \equiv \frac{d\sigma}{dx_B dy d^4P_\psi d\Omega}$$

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

Alternatively, in terms of the polarization parameters  $\lambda, \mu, \nu$  :

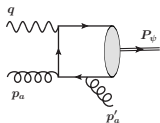
$$d\sigma \propto \frac{\alpha^2}{yQ^2} (\mathcal{W}_T + \mathcal{W}_L) \left[ 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \varphi + \frac{1}{2} \nu \sin^2 \theta \cos 2\varphi \right]$$

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

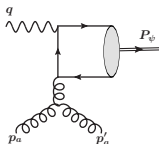
The helicity structure functions can be calculated within the NRQCD framework:  
double expansion in  $\alpha_s$  and  $v$

Contributing partonic subprocesses at the orders  $\alpha_s^2$  and  $v^4$

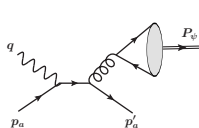
$$\gamma^*(q) + a(p_a) \rightarrow J/\psi(P_\psi) + a(p'_a) \quad a = g, q, \bar{q}$$



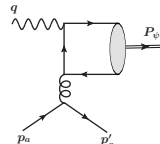
(a)



(b)



(c)



(d)

The six diagrams of type (a) are the only ones corresponding to the Color-Singlet production mechanism

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

Beneke, Kramer, Vanttinen, PRD 57 (1998)

$q_T$ : transverse momentum of the photon w.r.t.  $P_\psi, P$

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

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

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

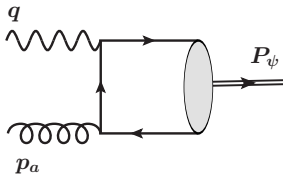
$$\mathcal{W}_L^L = \hat{w}_L^L \frac{1}{\mathbf{q}_T^2} \left[ L \left( \frac{Q^2 + M_\psi^2}{\mathbf{q}_T^2} \right) f_1^g(x, \mu^2) + (P_{gg} \otimes f_1^g + P_{gi} \otimes f_1^i)(x, \mu^2) \right]$$

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

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

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

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:

$$\mathcal{W}_T^T = \hat{w}_T^T f_1^g(x, q_T^2) \quad \mathcal{W}_T^L = \hat{w}_T^L f_1^g(x, q_T^2) \quad \mathcal{W}_L^L = \hat{w}_L^L f_1^g(x, q_T^2)$$

$$\mathcal{W}_{\Delta\Delta}^T = \hat{w}_{\Delta\Delta}^T h_1^{\perp g}(x, q_T^2)$$

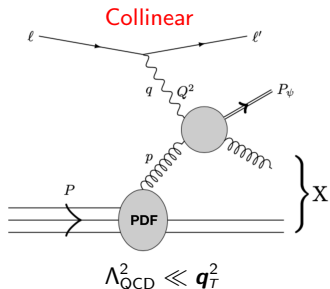
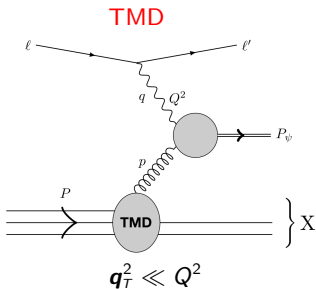
$\mathcal{W}_{\Delta\Delta}^T$  gives access to  $h_1^{\perp g}$  and to the poorly known  $^3P_0$  LDME

Smearing effects need to be included to match the result in the intermediate overlapping region  $\Lambda_{\text{QCD}}^2 \ll q_T^2 \ll Q^2$

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)



Imposing the matching of the TMD and collinear results in the overlapping region  $\Lambda_{\text{QCD}}^2 \ll q_T^2 \ll Q^2$ :  $f_1^g \longrightarrow \mathcal{C}[f_1^g \Delta^{[n]}]$

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

Boer, D'Alesio, Murgia, CP, Taels, JHEP 09 (2020)

D'Alesio, Maxia, Murgia, CP, Rajesh, in preparation



- ▶ Polarization states of  $J/\psi$  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  $\nu$  polarization parameter
- ▶ Our TMD formulae, at the order  $\alpha_s$  correctly match with the collinear factorization results at high transverse momentum at the order  $\alpha_s^2$
- ▶ 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  $J/\psi$  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, Tael, EPJC 80 (2020)

Boer, CP, Tael, PRD 103 (2021)