Spin asymmetries for quarkonium production as a probe of gluon TMDs

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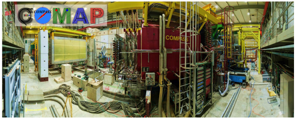

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COMPASS - LHCspin - AMBER
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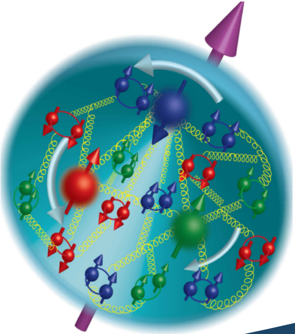
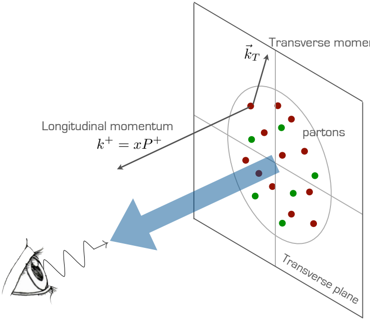


Gluon TMDs

Three-dimensional distributions: provide information on the partonic longitudinal momentum and the two-dimensional transverse momentum

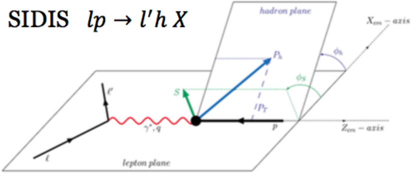


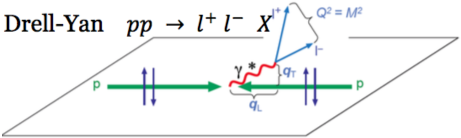
Renormalization scale μ and the Collins-Soper scale ζ not shown explicitly

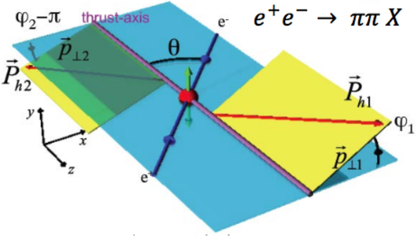
More detailed information on the proton's structure as compared to PDFs: 1D description is not always satisfactory, see i.e. spin effects

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

SIDIS $lp \to l'h\,X$







Factorization proven

All orders in α_s

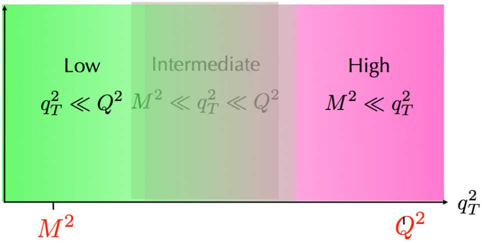
Leading order in powers of $1/Q$ (twist)

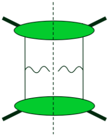
Collins, Cambridge University Press (2011)

Boussarie et al, TMD handbook 2304.03302

Three physical scales, two theoretical tools

Bacchetta, Boer, Diehl, Mulders, JHEP 08 (2008)
Bacchetta, Bozzi, Echevarria, CP, Prokudin, Radici, PLB 797 (2019)
Boer, Bor, Maxia, CP, Yuan, JHEP 08 (2023)

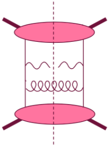




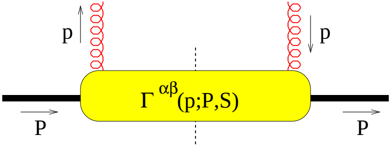
TMD

Do they describe the **same dynamics** or **two competing mechanisms** in the intermediate region?

(i.e., **interpolation** or **sum**?)



collinear PDF



Gauge invariant definition of $\Gamma^{\mu\nu}$

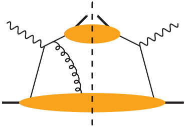
$$\Gamma^{[\mathcal{U},\mathcal{U}']\mu\nu} \propto \langle P,S|\,\mathrm{Tr_c}\left[\,F^{+\nu}(0)\,\mathcal{U}^{\mathcal{C}}_{[0,\xi]}\,F^{+\mu}(\xi)\,\mathcal{U}^{\mathcal{C}'}_{[\xi,0]}\,\right]|P,S\rangle$$

Mulders, Rodrigues, PRD 63 (2001)
Buffing, Mukherjee, Mulders, PRD 88 (2013)
Boer, Cotogno, Van Daal, Mulders, Signori, Zhou, JHEP 1610 (2016)

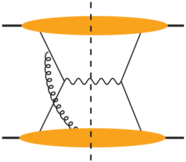
The gluon correlator depends on two path-dependent gauge links

$$\mathcal{U}^{\mathcal{C}}_{[0,\xi]} = \mathcal{P}\mathrm{exp}\left(-ig\int_{\mathcal{C}[0,\xi]} \mathrm{d}s_\mu\, A^\mu(s)\right)$$

The path $\mathcal{C}$ depends on the color interactions, *i.e.* on the specific process

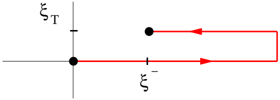


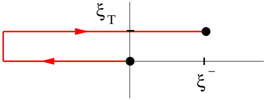
FSI in SIDIS



ISI in DY

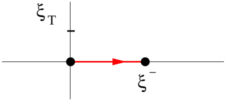
$\mathcal{U}^{[+]}_{[0,\xi]}$





$\mathcal{U}^{[-]}_{[0,\xi]}$

$\int \mathrm{d}k_T \longrightarrow \xi_T = 0 \longrightarrow$



the same in both cases

$ep \to e' Q\overline{Q}X$, $ep \to e'$ jet jet X probe gluon TMDs with $[++]$ gauge links

$pp \to \gamma\gamma X$ (and/or other CS final state) probes gluon TMDs with $[--]$ links

$pp \to \gamma$ jet X probes an entirely independent gluon TMD: $[+-]$ links

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

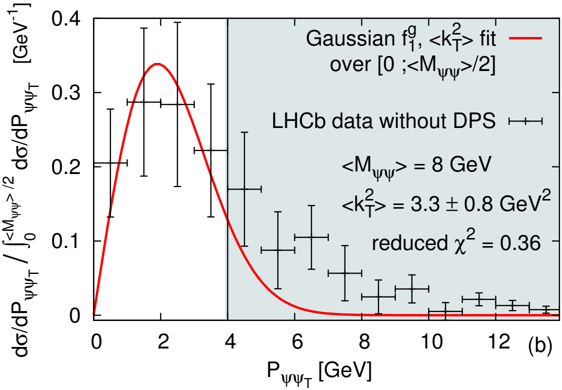
Angeles-Martinez *et al.*, Acta Phys, Pol. B46 (2015)
Mulders, Rodrigues, PRD 63 (2001)
Meissner, Metz, Goeke, PRD 76 (2007)

- $h_1^{\perp g}$: T-even distribution of linearly polarized gluons inside an unp. hadron
- $f_{1T}^{\perp g}$: T-odd distributions of unp. gluons inside a transversely pol. hadron
- h_{1T}^g, $h_{1T}^{\perp g}$: helicity flip distributions like h_{1T}^q, $h_{1T}^{\perp q}$, but T-odd, chiral even!
- $h_1^g \equiv h_{1T}^g + \frac{\boldsymbol{p}_T^2}{2M_p^2} h_{1T}^{\perp g}$ does not survive under p_T integration, unlike transversity

In contrast to quark TMDs, gluon TMDs are almost unknown, however models exist:

Bacchetta, Celiberto, Radici, Taels, EPJC 80 (2020)
Chakrabarti, Choudhary, Gurjar, Kishore, Maji, Mondal, Mukherjee, PRD 108 (2023)
Bacchetta, Celiberto, Radici, 2402.17556

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

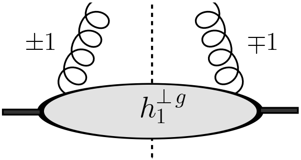


Lansberg, CP, Scarpa, Schlegel, PLB 784 (2018)
LHCb Coll., JHEP 06 (2017)

Gaussian model: $$f_1^g(x, \boldsymbol{k}_T^2) = \frac{f_1^g(x)}{\pi \langle k_T^2 \rangle} \exp\left(-\frac{\boldsymbol{k}_T^2}{\langle k_T^2 \rangle} \right)$$

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)

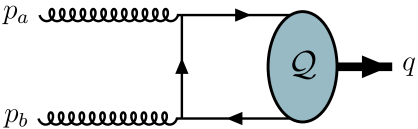
Gluons can be probed in heavy quark production in both *ep* and *pp* scattering

Mukherjee, Rajesh, EPJC 77 (2017)
Lansberg, CP, Scarpa, Schlegel, PLB 784 (2018)
Rajesh, Kishore, Mukherjee, PRD 98 (2018)
Bacchetta, Boer, CP, Taels, EPJC 80 (2020)

C–even quarkonium production

Color Singlet (CS) production of C-even quarkonia from two gluons is possible

This is not allowed for J/ψ or Υ because of the Landau-Yang theorem

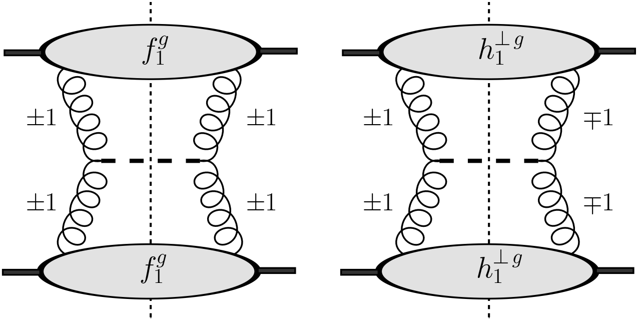


$$p\,p \to [Q\overline{Q}]\,X \qquad (gg \to [Q\overline{Q}])$$

Hard scale can only be the particle mass: $Q = M$ (charm, bottom)

TMD Factorization requires the resulting particle $\mathcal{Q}$ to have small q_T ($q_T \ll M$)

Pol. gluons affect the transverse spectrum of scalar quarkonia at NNLO pQCD



The nonperturbative distribution can be present at tree level and would contribute to (pseudo)scalar quarkonium production at low q_T

$C = +1$ quarkonium production

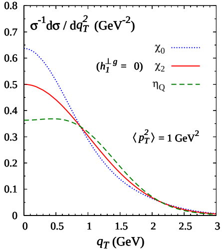
q_T-distribution of η_Q and χ_{QJ} $(Q = c, b)$ in the kinematic region $q_T \ll 2M_Q$

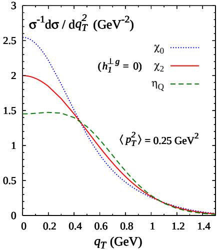
$$\frac{1}{\sigma(\eta_Q)} \frac{d\sigma(\eta_Q)}{d\boldsymbol{q}_T^2} \propto f_1^g \otimes f_1^g \, [1 - R_{UU}(\boldsymbol{q}_T^2)] \quad \text{[pseudoscalar]} \qquad R_{UU}(\boldsymbol{q}_T^2) = \frac{h_1^{\perp\, g} \otimes h_1^{\perp\, g}}{f_1^g \otimes f_1^g}$$

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

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

Boer, CP, PRD 86 (2012)





Proof of factorization at NLO for $p\, p \to \eta_Q/\chi_{Q0,2}\, X$ 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

Structure of the cross section for the doubly polarized process $p(S_A) + p(S_B) \to \mathcal{Q}\,X$

$$\frac{\mathrm{d}\sigma[\mathcal{Q}]}{\mathrm{d}y\,\mathrm{d}^2\boldsymbol{q}_T} = F_{UU}^{\mathcal{Q}} + F_{UL}^{\mathcal{Q}}\,S_{BL} + F_{LU}^{\mathcal{Q}}\,S_{AL} + F_{UT}^{\mathcal{Q},\sin\phi_{S_B}}\,|\boldsymbol{S}_{BT}|\sin\phi_{S_B} + F_{TU}^{\mathcal{Q},\sin\phi_{S_A}}\,|\boldsymbol{S}_{AT}|\sin\phi_{S_A}$$
$$+F_{LL}^{\mathcal{Q}}\,S_{AL}\,S_{BL} + F_{LT}^{\mathcal{Q},\cos\phi_{S_B}}\,S_{AL}\,|\boldsymbol{S}_{BT}|\cos\phi_{S_B} + F_{TL}^{\mathcal{Q},\cos\phi_{S_A}}\,|\boldsymbol{S}_{AT}|\,S_{BL}\cos\phi_{S_A}$$
$$+|\boldsymbol{S}_{AT}||\boldsymbol{S}_{BT}|\left[F_{TT}^{\mathcal{Q},\cos(\phi_{S_A}-\phi_{S_B})}\cos(\phi_{S_A}-\phi_{S_B}) + F_{TT}^{\mathcal{Q},\cos(\phi_{S_A}+\phi_{S_B})}\cos(\phi_{S_A}+\phi_{S_B})\right]$$

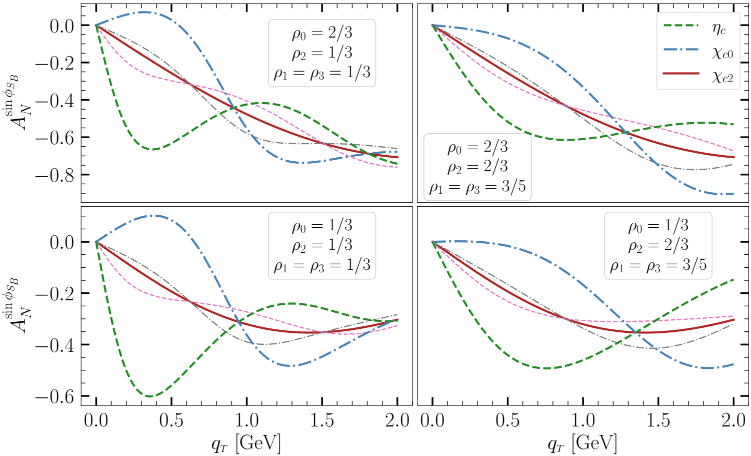
Kato, Maxia, CP, 2403.20017

Single spin asymmetries for different quarkonia are sensitive to different TMDs

$$F_{UT}^{\eta_Q,\sin\phi_{S_B}} \propto -f_1^g \otimes f_{1T}^{\perp g} + h_1^{\perp g} \otimes h_1^g - h_1^{\perp g} \otimes h_{1T}^{\perp g}$$
$$F_{UT}^{\chi_{Q0},\sin\phi_{S_B}} \propto -f_1^g \otimes f_{1T}^{\perp g} - h_1^{\perp g} \otimes h_1^g + h_1^{\perp g} \otimes h_{1T}^{\perp g}$$
$$F_{UT}^{\chi_{Q2},\sin\phi_{S_B}} \propto -f_1^g \otimes f_{1T}^{\perp g}$$

Such observables are in principle measurable at the planned LHCspin experiment

Asymmetries maximally allowed by positivity bounds on gluon TMDs can be sizeable



Gaussian parameterizations for the gluon TMDs for several values of variables ρ_i

Conclusions

- Quarkonia are good probes for gluon TMDs: first extraction of unpolarized gluon TMD from LHC data on double-J/ψ production
- Model-independent feature: $h_1^{\perp\,g}$, $h_{1L}^{\perp\,g}$, h_1^g, $h_{1T}^{\perp\,g}$, enter the production of P-odd η_Q states with opposite signs w.r.t. the P-even χ_{Q0} states
- On the other hand, the effects of linearly polarized gluons on higher angular momentum quarkonia like χ_{Q2} are strongly suppressed
- The gluon Sivers function $f_{1T}^{\perp\,g}$ can be accessed by looking at χ_{Q2}; then SSAs for η_Q and χ_{Q0} can be used to determine h_1^g and $h_{1T}^{\perp\,g}$
- Transverse SSAs could be measured in principle at LHCSpin (AMBER?)