Spin asymmetries for C-even quarkonium production as a probe of gluon TMDs

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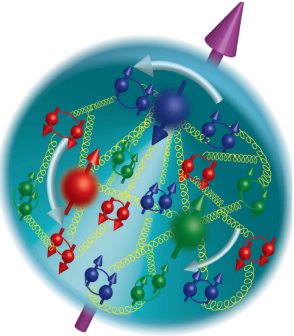
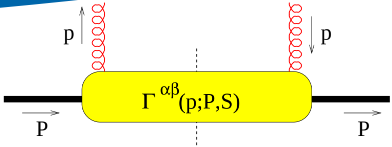


University of Pavia (Italy)
May 27 2024

Gluon TMDs

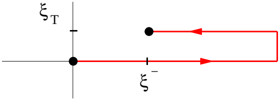


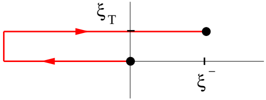
Gauge invariant definition of $\Gamma^{\mu\nu}$

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

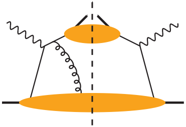
Mulders, Rodrigues, PRD 63 (2001)
Buffing, Mukherjee, Mulders, PRD 88 (2013)
Boer, Cotogno, Van Daal, Mulders, Signori, Zhou, JHEP 1610 (2016)

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

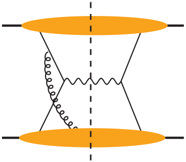




$\mathcal{U}^{[-]}_{[0,\xi]}$



FSI in SIDIS



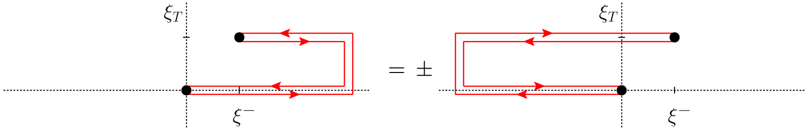
ISI in DY

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

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

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

$[++]$ and $[--]$ gluon TMDs are related by time reversal



Boer, Mulders, CP, Zhou (2016)

Motivation to study gluon TMDs in both *pp* and *ep* collisions

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

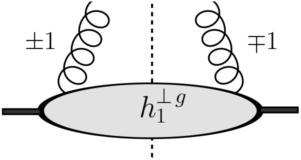
In contrast to quark TMDs, gluon TMDs are almost unknown, however models exist:

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

Linear polarization of gluons

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)

J/ψ-pair production at the LHC

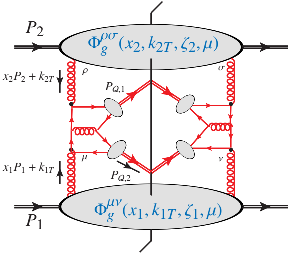
J/ψ-pair production at the LHC

J/ψ's are relatively easy to detect. Accessible at the LHC: already studied by LHCb, CMS & ATLAS

LHCb PLB 707 (2012)
CMS JHEP 1409 (2014)
ATLAS EPJC 77 (2017)

gg fusion dominant, negligible $q\bar{q}$ contributions even at fixed target energies

Lansberg, Shao, NPB 900 (2015)

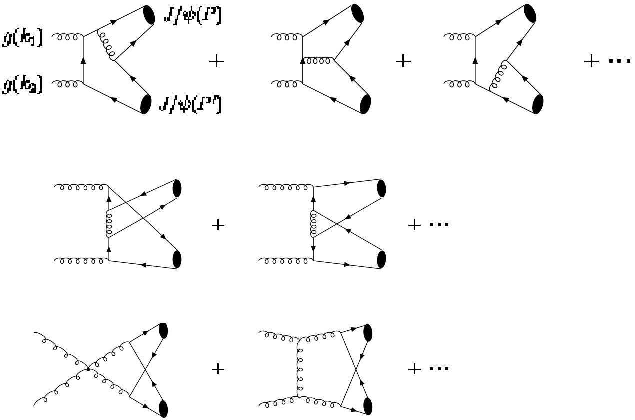


No final state gluon needed for the Born contribution in the Color Singlet Model. Pure colorless final state, hence simple color structure because one has only ISI

Lansberg, Shao, PRL 111 (2013)

Negligible Color Octet contributions, in particular at low $P_T^{\Psi\Psi}$

At LO pQCD in the Color Singlet Model, one needs to consider 36 diagrams



Qiao, Sun, Sun, JPG 37 (2010)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q\mathrm{d}Y\mathrm{d}^2 q_T \mathrm{d}\Omega} \approx A\, f_1^g \otimes f_1^g + B\, f_1^g \otimes h_1^{\perp g} \cos(2\phi_{CS}) + C\, h_1^{\perp g} \otimes h_1^{\perp g} \cos(4\phi_{CS})$$

Lansberg, CP, Scarpa, Schlegel, PLB 784 (2018)

- valid up to corrections $\mathcal{O}(q_T/Q)$
- Y: rapidity of the J/ψ-pair, along the beam in the hadronic c.m. frame
- $\mathrm{d}\Omega = \mathrm{d}\cos\theta_{CS}\, \mathrm{d}\phi_{CS}$: solid angle for J/ψ-pair in the Collins-Soper frame

Analysis similar to the one for $pp \to \gamma\gamma X$, $pp \to J\psi\, \gamma^{(*)} X$, $pp \to H\,\mathrm{jet}\, X$

Qiu, Schlegel, Vogelsang, PRL 107 (2011)
den Dunnen, Lansberg, CP, Schlegel, PRL 112 (2014)
Lansberg, CP, Schlegel, NPB 920 (2017)
Boer, CP, PRD 91 (2015)

The three contributions can be disentangled by defining the transverse moments

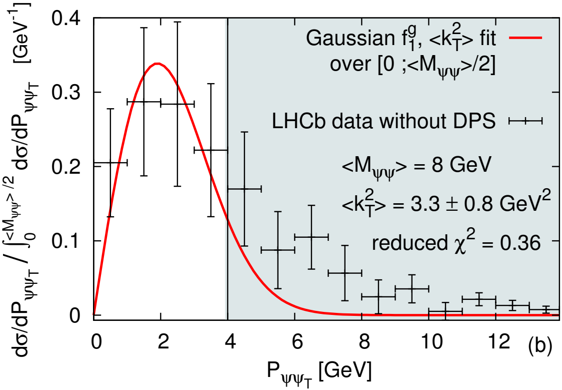
$$\langle \cos n\phi_{CS} \rangle \equiv \frac{\int_0^{2\pi} \mathrm{d}\phi_{CS}\, \cos(n\,\phi_{CS})\, \frac{\mathrm{d}\sigma}{\mathrm{d}Q\mathrm{d}Y\mathrm{d}^2 q_T \mathrm{d}\Omega}}{\int_0^{2\pi} \mathrm{d}\phi_{CS}\, \frac{\mathrm{d}\sigma}{\mathrm{d}Q\mathrm{d}Y\mathrm{d}^2 q_T \mathrm{d}\Omega}} \qquad (n = 2, 4)$$

$$\int \mathrm{d}\phi_{CS}\, \mathrm{d}\sigma \implies f_1^g \otimes f_1^g$$

$$\langle \cos 2\phi_{CS} \rangle \implies f_1^g \otimes h_1^{\perp g}$$

$$\langle \cos 4\phi_{CS} \rangle \implies h_1^{\perp g} \otimes h_1^{\perp g}$$

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



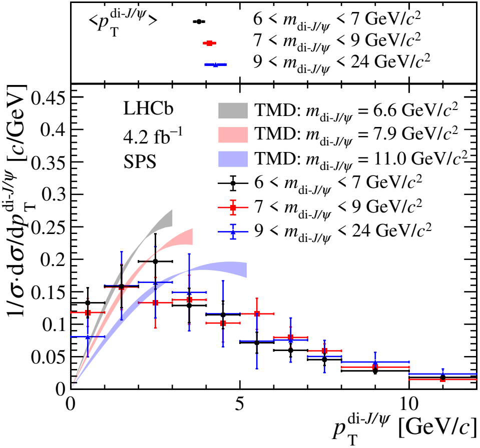
Lansberg, CP, Scarpa, Schlegel, PLB 784 (2018)
LHCb Coll., JHEP 06 (2017)

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

Extraction of f_1^g at $\sqrt{s} = 13$ TeV

p_T-distribution at $\sqrt{s} = 13$ TeV

No obvious broadening can be seen due to the large uncertainties



Lansberg, CP, Scarpa, Schlegel, PLB 784 (2018)
LHCb Coll., JHEP 088 (2024)

The average values of the p_T distributions slightly increase with mass

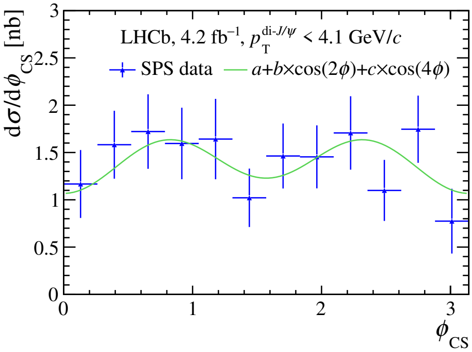
Extraction of f_1^g at $\sqrt{s} = 13$ TeV

Azimuthal asymmetries

$$\langle \cos 2\phi \rangle = -0.029 \pm 0.050\,(\text{stat}) \pm 0.009\,(\text{syst})$$
$$\langle \cos 4\phi \rangle = -0.087 \pm 0.052\,(\text{stat}) \pm 0.013\,(\text{syst})$$

Theoretical predictions consistent with measureaments

Scarpa, Boer, Echevarria, Lansberg, CP, Schlegel EPJC 80 (2020)



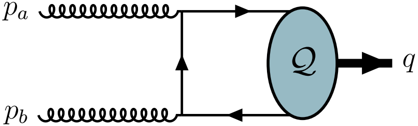
LHCb Coll., JHEP 088 (2024)

The results are consistent with zero, but the presence of an azimuthal asymmetry at a few percent level is allowed

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

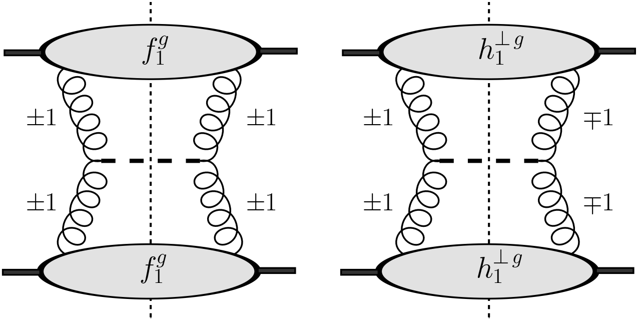


$$p\,p \to [Q\overline{Q}]\,X \qquad \left(gg \to [Q\overline{Q}]\right)$$

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

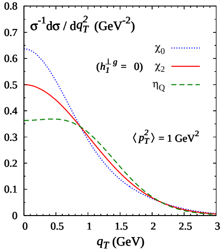
q_T-distribution of η_Q and χ_{QJ} $(Q = c, b)$ in the kinematic region $q_T \ll 2M_Q$

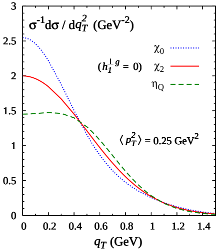
$$\frac{1}{\sigma(\eta_Q)} \frac{d\sigma(\eta_Q)}{d\boldsymbol{q}_T^2} \propto f_1^g \otimes f_1^g \left[1 - R_{UU}(\boldsymbol{q}_T^2)\right] \quad \text{[pseudoscalar]} \qquad R_{UU}(\boldsymbol{q}_T^2) = \frac{h_1^{\perp g} \otimes h_1^{\perp g}}{f_1^g \otimes f_1^g}$$

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

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

Boer, CP, PRD 86 (2012)





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

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 $p(S_A) + p(S_B) \to \mathcal{Q}\, X$

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

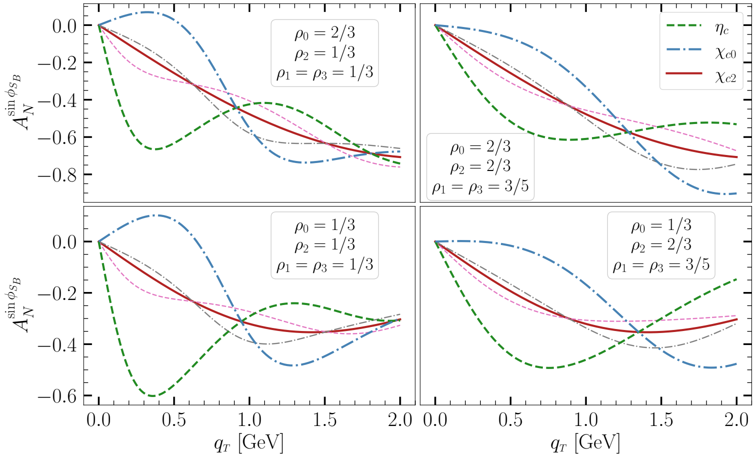
Kato, Maxia, CP, 2403.20017 (submitted to PRD)

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