Transverse momentum dependent gluon distributions at a future EIC

Cristian Pisano

Trieste (Italy), 18 - 22 July 2017

INFN Istituto Nazionale di Fisica Nucleare

erc

3DSPIN MAPPING THE PROTON IN 3D

UNIVERSITÀ DI PAVIA

Quark TMDs

QUARKS	*unpolarized*	*chiral*	*transverse*
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_{1T}, $h_{1T}^\perp$

Angeles-Martinez *et al.*, Acta Phys, Pol. B46 (2015)

- $h_1^{\perp\, q}$: T-odd distribution of transversely polarized quarks inside an unp. hadron
- h_{1T}^q, $h_{1T}^{\perp\, q}$: helicity flip distributions: T-even and chiral odd
- Transversity $h_1^q \equiv h_{1T}^q + \frac{\boldsymbol{p}_T^2}{2M_p^2}\, h_{1T}^{\perp\, q}$ survives under p_T integration

They are known and can all be accessed in semi-inclusive DIS (SIDIS)

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

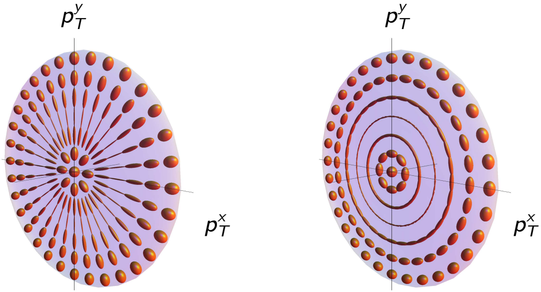
Angeles-Martinez *et al.*, Acta Phys, Pol. B46 (2015)
Mulders, Rodrigues, PRD 63 (2001)
Meissner, Metz, Goeke, PRD 76 (2007)

- $h_1^{\perp\, g}$: T-even distribution of linearly polarized gluons inside an unp. 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

The distribution of linearly polarized gluons inside an unpolarized proton: $h_1^{\perp\, g}$

Visualization of the gluon polarization in the transverse momentum plane
$h_1^{\perp g}$ is taken to be a Gaussian



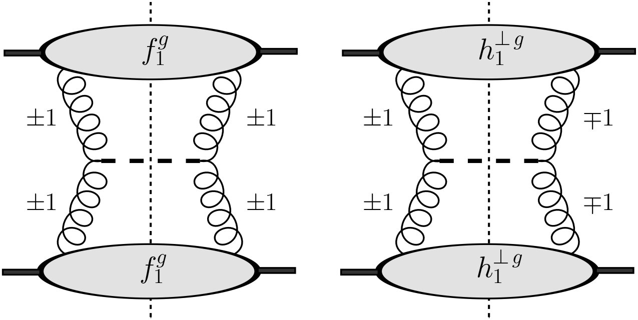
$h_1^{\perp g} > 0$ $\qquad$ $h_1^{\perp g} < 0$

The ellipsoid axis lengths are proportional to the probability of finding a gluon with a linear polarization in that direction

Higgs boson production happens mainly via $gg \to H$

Pol. gluons affect the Higgs transverse spectrum at NNLO pQCD

Catani, Grazzini, NPB 845 (2011)



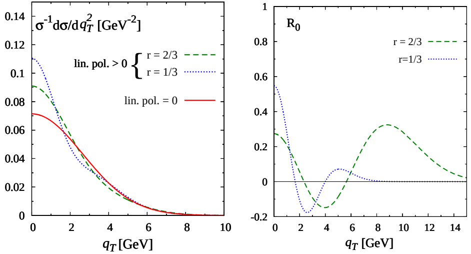
The nonperturbative distribution can be present at tree level and would contribute to Higgs production at low q_T

Boer, den Dunnen, CP, Schlegel, Vogelsang, PRL 108 (2012)

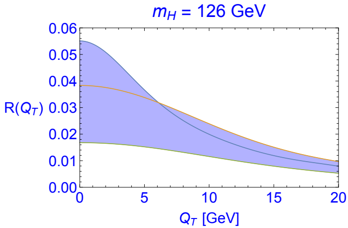
q_T-distribution of the Higgs boson

$$\frac{1}{\sigma}\frac{d\sigma}{d\boldsymbol{q}_T^2} \propto 1 + R(\boldsymbol{q}_T^2) \qquad R = \frac{h_1^{\perp\,g} \otimes h_1^{\perp\,g}}{f_1^g \otimes f_1^g} \qquad |h_1^{\perp\,g}(x,\boldsymbol{p}_T^2)| \leq \frac{2M_p^2}{\boldsymbol{p}_T^2} f_1^g(x,\boldsymbol{p}_T^2)$$

Gaussian Model



TMD evolution



Echevarria, Kasemets, Mulders, CP, JHEP 1507 (2015) 158

Study of $H \to \gamma\gamma$ and interference with $gg \to \gamma\gamma$

Boer, den Dunnen, CP, Schlegel, PRL 111 (2013)

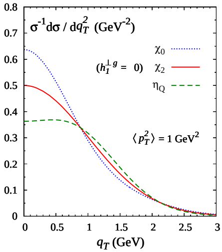
q_T-distribution of η_Q and χ_{QJ} $(Q = c, b)$ in the kinematic region $q_T \ll 2M_Q$

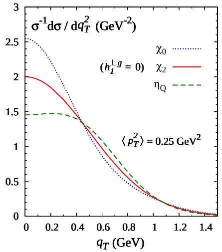
$$\frac{1}{\sigma(\eta_Q)}\frac{d\sigma(\eta_Q)}{d\boldsymbol{q}_T^2} \propto f_1^g \otimes f_1^g\,[1 - R(\boldsymbol{q}_T^2)] \qquad \text{[pseudoscalar]}$$

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

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

Boer, CP, PRD 86 (2012) 094007





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

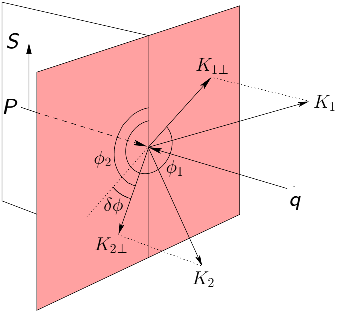
Ma, Wang, Zhao, PRD 88 (2013), 014027; PLB 737 (2014) 103

Heavy quark pair production at an EIC

Gluon TMDs probed directly in $e(\ell) + p(P, S) \rightarrow e(\ell') + Q(K_1) + \overline{Q}(K_2) + X$

Boer, Mulders, CP, Zhou, JHEP 1608 (2016)

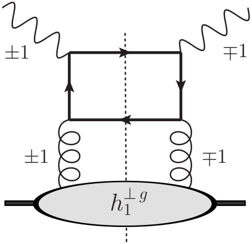
- the $Q\overline{Q}$ pair is almost back to back in the plane $\perp$ to q and P
- $q \equiv \ell - \ell'$: four-momentum of the exchanged virtual photon γ^*



$$\boldsymbol{q}_T \equiv \boldsymbol{K}_{1\perp} + \boldsymbol{K}_{2\perp}$$

$$\boldsymbol{K}_\perp \equiv (\boldsymbol{K}_{1\perp} - \boldsymbol{K}_{2\perp})/2$$

$\Longrightarrow$ Correlation limit: $|\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$, $\quad |\boldsymbol{K}_\perp| \approx |\boldsymbol{K}_{1\perp}| \approx |\boldsymbol{K}_{2\perp}|$



$\phi_T, \phi_\perp, \phi_S$ azimuthal angles of $q_T, K_\perp, S_T$

At LO in pQCD: only $\gamma^* g \to Q\overline{Q}$ contributes

$$\mathrm{d}\sigma(\phi_S, \phi_T, \phi_\perp) = \mathrm{d}\sigma^U(\phi_T, \phi_\perp) + \mathrm{d}\sigma^T(\phi_S, \phi_T, \phi_\perp)$$

Angular structure of the unpolarized cross section for $ep \to e' Q\overline{Q}X$, $\quad |\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$

$$\frac{\mathrm{d}\sigma^U}{\mathrm{d}^2\boldsymbol{q}_T\,\mathrm{d}^2\boldsymbol{K}_\perp} \propto \left\{ A_0^U + A_1^U \cos\phi_\perp + A_2^U \cos 2\phi_\perp \right\} f_1^g(x, \boldsymbol{q}_T^2) + \frac{\boldsymbol{q}_T^2}{M_p^2}\, h_1^{\perp\, g}(x, \boldsymbol{q}_T^2)$$
$$\times \left\{ B_0^U \cos 2\phi_T + B_1^U \cos(2\phi_T - \phi_\perp) + B_2^U \cos 2(\phi_T - \phi_\perp) + B_3^U \cos(2\phi_T - 3\phi_\perp) + B_4^U \cos 2(\phi_T - 2\phi_\perp) \right\}$$

The different contributions can be isolated by defining

$$\langle W(\phi_\perp, \phi_T)\rangle = \frac{\int \mathrm{d}\phi_\perp \mathrm{d}\phi_T\, W(\phi_\perp, \phi_T)\, \mathrm{d}\sigma}{\int \mathrm{d}\phi_\perp \mathrm{d}\phi_T\, \mathrm{d}\sigma}, \quad W = \cos 2\phi_T,\ \cos 2(\phi_\perp - \phi_T), \ldots$$

$h_1^{\perp\, g}$ in $ep \to e' Q\overline{Q} X$

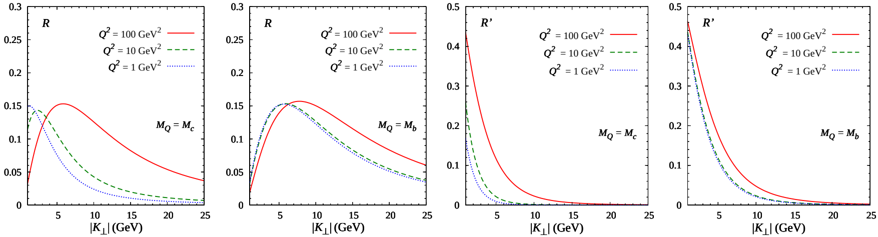
Maximal asymmetries

Positivity bound for $h_1^{\perp\, g}$: $\quad |h_1^{\perp\, g}(x, \boldsymbol{p}_T^2)| \leq \dfrac{2M_p^2}{\boldsymbol{p}_T^2}\; f_1^g(x, \boldsymbol{p}_T^2)$

It can be used to estimate maximal values of the asymmetries

Asymmetries usually larger when Q and $\overline{Q}$ have same rapidities

Upper bounds on $\quad R \equiv |\langle \cos 2(\phi_T - \phi_\perp)\rangle|$ and $R' \equiv |\langle \cos 2\phi_T \rangle|$ at $y = 0.01$



CP, Boer, Brodsky, Buffing, Mulders, JHEP 1310 (2013)
Boer, Brodsky, Mulders, CP, PRL 106 (2011)

Spin asymmetries in $ep^\uparrow \to e' Q\overline{Q} X$

Angular structure of the single polarized cross section for $ep^\uparrow \to e' Q\overline{Q} X$, $\quad |\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$

$$\mathrm{d}\sigma^T \propto \sin(\phi_S - \phi_T)\Big[A_0^T + A_1^T \cos\phi_\perp + A_2^T \cos 2\phi_\perp\Big] f_{1T}^{\perp\,g} + \cos(\phi_S - \phi_T)\Big[B_0^T \sin 2\phi_T$$
$$+ B_1^T \sin(2\phi_T - \phi_\perp) + B_2^T \sin 2(\phi_T - \phi_\perp) + B_3^T \sin(2\phi_T - 3\phi_\perp) + B_4^T \sin(2\phi_T - 4\phi_\perp)\Big] h_{1T}^{\perp\,g}$$
$$+ \Big[B_0'^{\,T} \sin(\phi_S + \phi_T) + B_1'^{\,T} \sin(\phi_S + \phi_T - \phi_\perp) + B_2'^{\,T} \sin(\phi_S + \phi_T - 2\phi_\perp)$$
$$+ B_3'^{\,T} \sin(\phi_S + \phi_T - 3\phi_\perp) + B_4'^{\,T} \sin(\phi_S + \phi_T - 4\phi_\perp)\Big] h_{1T}^{g}$$

The ϕ_S dependent terms can be singled out by means of azimuthal moments A_N^W

$$A_N^{W(\phi_S,\phi_T)} \equiv 2\,\frac{\int \mathrm{d}\phi_T\,\mathrm{d}\phi_\perp\, W(\phi_S,\phi_T)\,\mathrm{d}\sigma_T(\phi_S,\,\phi_T,\,\phi_\perp)}{\int \mathrm{d}\phi_T\,\mathrm{d}\phi_\perp\,\mathrm{d}\sigma_U(\phi_T,\phi_\perp)}$$

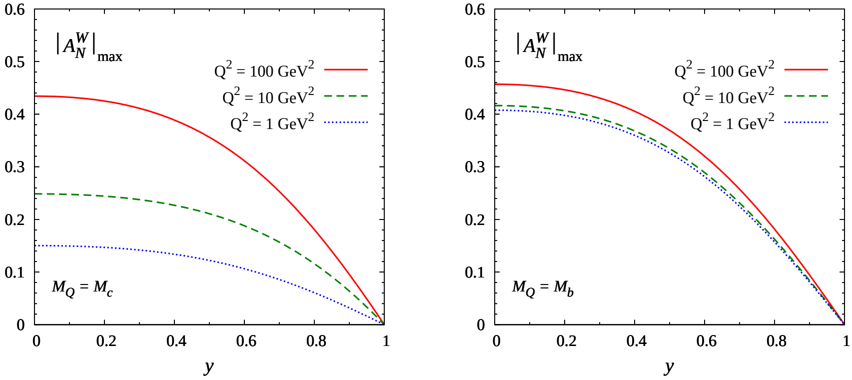
$$A_N^{\sin(\phi_S-\phi_T)} \propto \frac{f_{1T}^{\perp\,g}}{f_1^g} \qquad A_N^{\sin(\phi_S+\phi_T)} \propto \frac{h_1^g}{f_1^g} \qquad A_N^{\sin(\phi_S-3\phi_T)} \propto \frac{h_{1T}^{\perp\,g}}{f_1^g}$$

Same modulations as in SIDIS for quark TMDs ($\phi_T \to \phi_h$)

3DSPIN MAPPING THE PROTON IN 3D

UNIVERSITÀ DI PAVIA

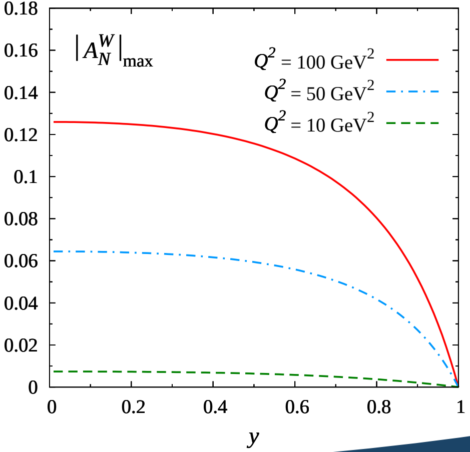
Maximal values for $|A_N^W|$, $W = \sin(\phi_S + \phi_T)$, $\sin(\phi_S - 3\phi_T)$ $(|\boldsymbol{K}_\perp| = 1$ GeV$)$



Contribution to the denominator also from $\gamma^* q \to gq$, negligible at small-x

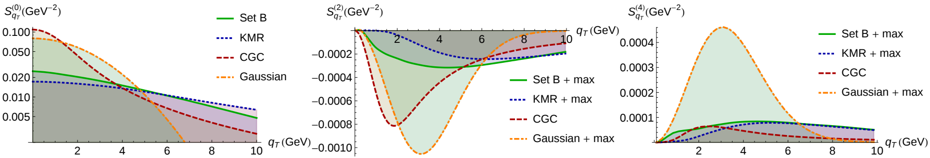
Asymmetries much smaller than in $c\bar{c}$ case for $Q^2 \leq 10$ GeV^2

Upper bounds for A_N^W for $K_\perp \geq 4$ GeV



Azimuthal asymmetries at the LHC

$$p\,p \to J/\psi(\Upsilon) + \gamma\,X$$



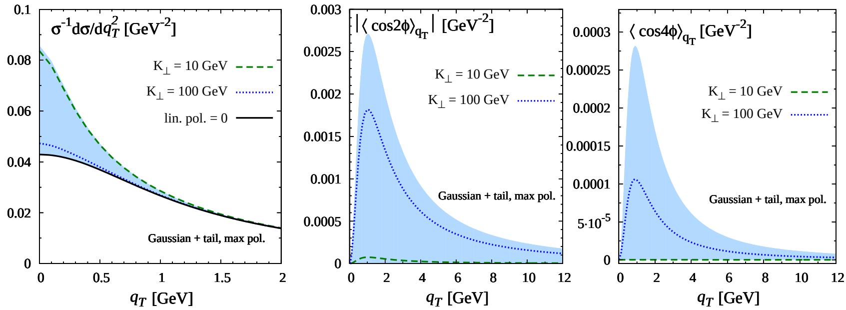
$$\frac{1}{\sigma}\,\frac{\mathrm{d}\sigma}{\mathrm{d}^2 q_T} \equiv \mathcal{S}^{(0)}_{q_T} \equiv \langle 1 \rangle_{q_T} \Longrightarrow f_1^g \otimes f_1^g$$

$$\mathcal{S}^{(2)}_{q_T} \equiv \langle \cos 2\phi \rangle_{q_T} \Longrightarrow f_1^g \otimes h_1^{\perp g}$$

$$\mathcal{S}^{(4)}_{q_T} \equiv \langle \cos 4\phi \rangle_{q_T} \Longrightarrow h_1^{\perp g} \otimes h_1^{\perp g}$$

den Dunnen, Lansberg, CP, Schlegel, PRL 112 (2014)

$p\,p \to H + \mathrm{jet}\,X$



$$\frac{1}{\sigma}\,\frac{d\sigma}{d^2 q_T} \equiv \langle 1 \rangle_{q_T} \Longrightarrow f_1^g \otimes f_1^g + h_1^{\perp g} \otimes h_1^{\perp g}$$

$$\langle \cos 2\phi \rangle_{q_T} \Longrightarrow f_1^g \otimes h_1^{\perp g}$$

$$\langle \cos 4\phi \rangle_{q_T} \Longrightarrow h_1^{\perp g} \otimes h_1^{\perp g}$$

Boer, CP, PRD 91 (2015)

Process dependence of gluon TMDs

Complementary Processes

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

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

Related Processes

In $pp \to \gamma\gamma X$ and/or other CS final state: gluon TMDs have $[--]$ gauge links

Analogue of the sign change of $f_{1T}^{\perp\, q}$ between SIDIS and DY (true also for h_1^g and $h_{1T}^{\perp\, g}$)

$$f_{1T}^{\perp\, g\,[e\,p^\uparrow \to e'\, Q\overline{Q}\, X]} = -f_{1T}^{\perp\, g\,[p^\uparrow\, p \to \gamma\,\gamma\, X]}$$

Motivation to study the gluon Sivers effect at RHIC and AFTER@LHC

Brodsky, Fleuret, Hadjidakis, Lansberg, Phys. Rept. 522 (2013)

T-even gluon TMDs probed in DIS are the same as in $pp \to H/\eta_{c,b}/\ldots X$

$$h_1^{\perp\, g\,[e\,p \to e'\, Q\overline{Q}\, X]} = h_1^{\perp\, g\,[p\,p \to H\, X]}$$

TMD observables at EIC and LHC can be either related or complementary

- Azimuthal asymmetries in heavy quark pair and dijet production in DIS could probe WW-type gluon TMDs (similar to SIDIS for quark TMDs)
- Asymmetries maximally allowed by positivity bounds of gluon TMDs can be sizeable in specific kinematic region
- Study of TMDs in the small-x region: effects of linearly polarized gluons still sizeable, ratio of T-odd TMDs can test our model expectations
- Different behaviour of WW and dipole gluon TMDs accessible at RHIC could be tested experimentally
- Such observables could be part of both the *spin* and the *small-x* program at a future EIC