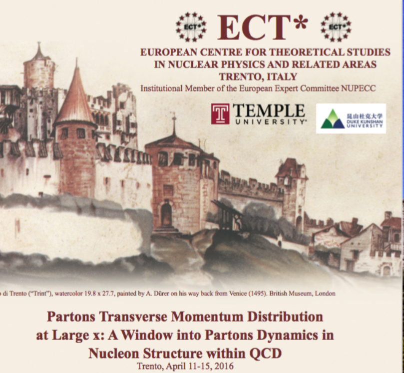
Phenomenology of Gluon TMDs

Cristian Pisano



INFN Istituto Nazionale di Fisica Nucleare

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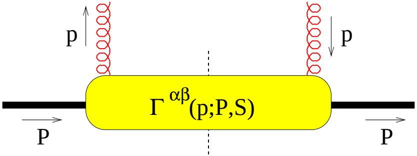
3DSPIN MAPPING THE PROTON IN 3D

UNIVERSITÀ DI PAVIA

- Definition of the gluon TMDs of the proton
  - Unpolarized TMD distribution f_1^g
  - linear polarization of gluons inside an unpolarized proton $h_1^{\perp\, g}$
  - Gluon Sivers function $f_{1T}^{\perp\, g}$
- Discussion of their experimental determination
  - *ep* collisions (EIC)
  - *pp* collisions (RHIC, LHC)

The gluon correlator describes the hadron → gluon transition



Gluon momentum $p^\alpha = x\,P^\alpha + p_T^\alpha + p^-\,n^\alpha$, with $n^2{=}0$ and $n{\cdot}P{=}1$

Definition of $\Gamma^{\alpha\beta}$ for a spin-1/2 hadron

$$\Gamma^{\alpha\beta} = \frac{n_\rho\,n_\sigma}{(p{\cdot}n)^2}\int\frac{\mathrm{d}(\xi{\cdot}P)\,\mathrm{d}^2\xi_T}{(2\pi)^3}\;e^{ip\cdot\xi}\,\langle P,S|\,\mathrm{Tr}\big[\,F^{\alpha\rho}(0)\,U_{[0,\xi]}\,F^{\beta\sigma}(\xi)\,U'_{[\xi,0]}\,\big]\,|P,S\rangle\,\big]_{\xi\cdot n=0}$$

Mulders, Rodrigues, PRD 63 (2001) 094021

U, U': process dependent gauge links

transverse projectors: $g_T^{\alpha\beta} \equiv g^{\alpha\beta} - P^\alpha n^\beta - n^\alpha P^\beta$, $\epsilon_T^{\alpha\beta} \equiv \epsilon^{\alpha\beta\gamma\delta}P_\gamma n_\delta$

Spin vector: $S^\alpha = S_L\left(P^\alpha - M_h^2\,n^\alpha\right) + S_T$, with $S_L^2 + \boldsymbol{S}_T^2 = 1$

Parametrization of $\Gamma^{\alpha\beta}$ (at "Leading Twist" and omitting gauge links)

$$\Gamma_U^{\alpha\beta}(x,\boldsymbol{p}_T) = \frac{1}{2x}\left\{-g_T^{\alpha\beta} f_1^g(x,\boldsymbol{p}_T^2) + \left(\frac{p_T^\alpha p_T^\beta}{M_h^2} + g_T^{\alpha\beta}\frac{\boldsymbol{p}_T^2}{2M_h^2}\right) h_1^{\perp\, g}(x,\boldsymbol{p}_T^2)\right\} \text{ [unp. hadron]}$$

$$\Gamma_L^{\alpha\beta}(x,\boldsymbol{p}_T) = \frac{1}{2x} S_L\left\{i\epsilon_T^{\alpha\beta}\, g_{1L}^g(x,\boldsymbol{p}_T^2) + \frac{p_{T\rho}\,\epsilon_T^{\rho\{\alpha}p_T^{\beta\}}}{M_h^2}\, h_{1L}^{\perp\, g}(x,\boldsymbol{p}_T^2)\right\} \text{ [long. pol. hadron]}$$

$$\Gamma_T^{\alpha\beta}(x,\boldsymbol{p}_T) = \frac{1}{2x}\left\{g_T^{\alpha\beta}\frac{\epsilon_T^{\rho\sigma}p_{T\rho}S_{T\sigma}}{M_h} f_{1T}^{\perp\, g}(x,\boldsymbol{p}_T^2) + i\epsilon_T^{\alpha\beta}\frac{p_T\cdot S_T}{M_h} g_{1T}^{\perp\, g}(x,\boldsymbol{p}_T^2) - \frac{p_{T\rho}\epsilon_T^{\rho\{\alpha}S_T^{\beta\}} + S_{T\rho}\epsilon_T^{\rho\{\alpha}p_T^{\beta\}}}{4M_h} h_{1T}^g(x,\boldsymbol{p}_T^2) + \frac{p_{T\rho}\,\epsilon_T^{\rho\{\alpha}p_T^{\beta\}}}{2M_h^2}\frac{p_T\cdot S_T}{M_h} h_{1T}^{\perp\, g}(x,\boldsymbol{p}_T^2)\right\}$$

[transv. pol. hadron]

- f_1^g : unpolarized TMD gluon distribution
- $h_1^{\perp\, g}$: distribution of linearly polarized gluons inside an unpol. hadron

Mulders, Rodrigues, PRD 63 (2001) 094021

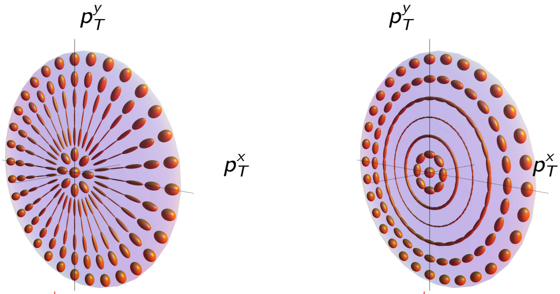
- $f_{1T}^{\perp\, g}$: T-odd distribution of unp. gluons inside a transversely pol. hadron

Sivers, PRD 41 (1990) 83

$h_1^{\perp\, g}$ is a T-even, helicity-flip distribution, and a rank-2 tensor in p_T

$h_1^{\perp g}(x, \boldsymbol{p}_T^2) \neq 0$ in the absence of ISI or FSI, but, as any TMD, it will receive contributions from ISI/FSI $\longrightarrow$ it can be nonuniversal

In the transverse momentum plane ($h_1^{\perp\, g}$ taken to be a Gaussian):



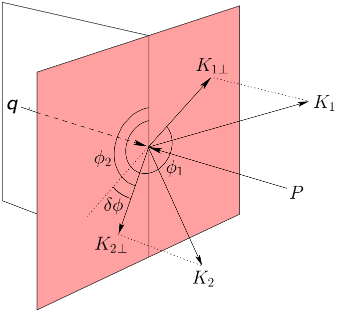
$h_1^{\perp\, g} > 0$ $\qquad$ $h_1^{\perp\, g} < 0$

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

Ideal process: $e(\ell) + p(P) \to e(\ell') + Q(K_1) + \bar{Q}(K_2) + X$

- the $Q\bar{Q}$ 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^*

$\phi_\ell = \phi_{\ell'} = 0$



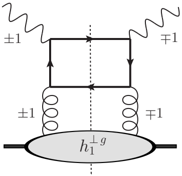
$$\boldsymbol{q}_T \equiv \boldsymbol{K}_{1\perp} + \boldsymbol{K}_{2\perp}$$

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

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

Heavy quark pair production in DIS
Angular structure of the cross section

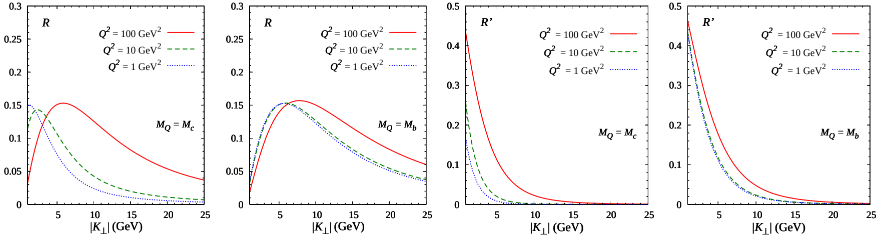
y_1 (y_2) rapidities of Q $(\bar{Q})$ in the $\gamma^* p$ cms; x_B, y: DIS variables



$$\boldsymbol{q}_T \equiv \boldsymbol{K}_{1\perp} + \boldsymbol{K}_{2\perp} = |\boldsymbol{q}_T|(\cos\phi_T, \sin\phi_T)$$
$$\boldsymbol{K}_\perp \equiv (\boldsymbol{K}_{1\perp} - \boldsymbol{K}_{2\perp})/2 = |\boldsymbol{K}_\perp|(\cos\phi_\perp, \sin\phi_\perp)$$

$$\frac{d\sigma}{dy_1\, dy_2\, dy\, dx_B\, d^2\boldsymbol{q}_T\, d^2\boldsymbol{K}_\perp} \propto \left\{ A_0 + A_1 \cos\phi_\perp + A_2 \cos 2\phi_\perp \right\} f_1^g \qquad |\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$$
$$+ \frac{\boldsymbol{q}_T^2}{M_p^2}\, h_1^{\perp g} \left\{ B_0 \cos 2(\phi_\perp - \phi_T) + B_1 \cos(\phi_\perp - 2\phi_T) + B_1' \cos(3\phi_\perp - 2\phi_T) + B_2 \cos 2\phi_T + B_2' \cos 2(2\phi_\perp - \phi_T) \right\}$$

Upper bounds on the asymmetries $R \equiv |\langle \cos 2(\phi_\perp - \phi_T)\rangle|$ and $R' \equiv |\langle \cos 2\phi_T \rangle|$

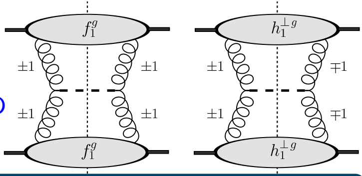


CP, Boer, Brodsky, Buffing, Mulders, JHEP 1310 (2013) 024
Boer, Brodsky, Mulders, CP, PRL 106 (2011) 132001

Polarized gluons and Higgs boson production
$p\,p \to H\,X$

At LHC the dominant channel is $gg \to H$

$h_1^{\perp\,g}$ contributes to the Higgs q_T-spectrum at LO

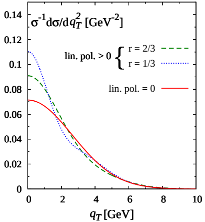


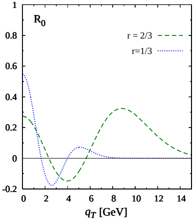
q_T-distribution of the Higgs boson

$$\frac{1}{\sigma}\,\frac{d\sigma}{d\boldsymbol{q}_T^2} \propto 1 + R_0(\boldsymbol{q}_T^2) \qquad R_0 = \frac{h_1^{\perp\,g} \otimes h_1^{\perp\,g}}{f_1^g \otimes f_1^g} \qquad |h_1^{\perp\,g}(x, \boldsymbol{p}_T^2)| \leq \frac{2M_p^2}{\boldsymbol{p}_T^2}\, f_1^g(x, \boldsymbol{p}_T^2)$$

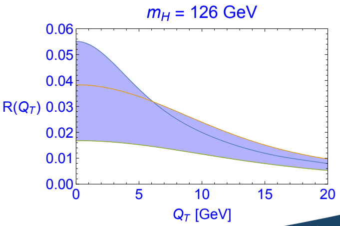
Boer, den Dunnen, CP, Schlegel, Vogelsang, PRL 108 (2012) 032002
Boer, den Dunnen, CP, Schlegel, PRL 111 (2013) 032002
Echevarria, Kasemets, Mulders, CP, JHEP 1507 (2015) 158

Gaussian Model





With TMD evolution



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

$C = +1$ quarkonia

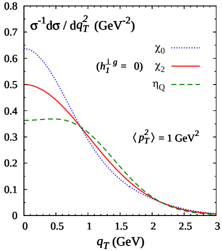
q_T-distribution of η_Q and χ_{QJ} $(Q = c, b)$ at $q_T \ll 2M_Q$

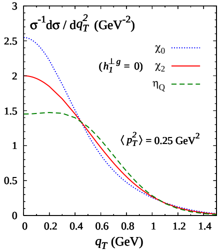
$$\frac{1}{\sigma(\eta_Q)} \frac{d\sigma(\eta_Q)}{d\boldsymbol{q}_T^2} \propto f_1^g \otimes f_1^g \left[1 - R_0(\boldsymbol{q}_T^2)\right] \qquad \text{[pseudoscalar]}$$

$$\frac{1}{\sigma(\chi_{Q0})} \frac{d\sigma(\chi_{Q0})}{d\boldsymbol{q}_T^2} \propto f_1^g \otimes f_1^g \left[1 + R_0(\boldsymbol{q}_T^2)\right] \qquad \text{[scalar]}$$

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

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

Study of $p\,p \to \eta_c\, X$ at NLO with TMD evolution (LHCb data)

Echevarria, Kasemets, Lansberg, CP, Signori, in preparation

Advantage: study of the TMD evolution by tuning the hard scale

Boer, CP, PRD 91 (2015) 074024

TMD Master Formula

$$d\sigma = \frac{1}{2s}\,\frac{\mathrm{d}^3 \boldsymbol{K}_H}{(2\pi)^3\, 2K_H^0}\,\frac{\mathrm{d}^3 \boldsymbol{K}_\mathrm{j}}{(2\pi)^3\, 2K_\mathrm{j}^0}\sum_{a,b,c}\int \mathrm{d}x_a\,\mathrm{d}x_b\,\mathrm{d}^2\boldsymbol{p}_{aT}\,\mathrm{d}^2\boldsymbol{p}_{bT}\,(2\pi)^4$$
$$\times\,\delta^4(p_a+p_b-q)\,\mathrm{Tr}\left\{\Phi_g(x_a,\boldsymbol{p}_{aT})\Phi_g(x_b,\boldsymbol{p}_{bT})\left|\mathcal{M}^{ab\to Hc}\right|^2\right\}$$

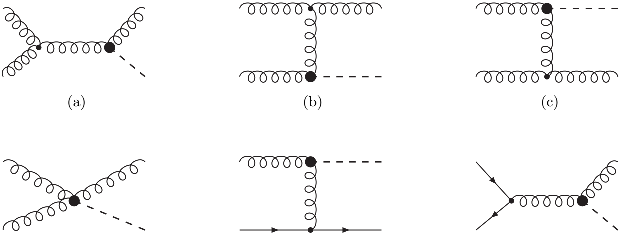
Higgs and jet almost back to back in the $\perp$ plane: $|\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$

$$\boldsymbol{q}_T = \boldsymbol{K}_{HT} + \boldsymbol{K}_{\mathrm{j}T}, \qquad \boldsymbol{K}_\perp = (\boldsymbol{K}_{HT} - \boldsymbol{K}_{\mathrm{j}T})/2$$

$|\boldsymbol{K}_\perp|$: evolution scale, only $|\boldsymbol{q}_T|$ of the pair needs to be small

At LO in pQCD the partonic subprocesses that contribute are

$$g\,g \to H\,g \qquad g\,q \to H\,q \qquad q\,\bar{q} \to H\,g$$



(a) (b) (c) (d) (e) (f)

Quark masses taken to be zero, except for $M_t \to \infty$

Kauffman, Desai, Risal, PRD 55 (1997) 4005

No indications that TMD factorization can be broken due to color entanglement

Rogers, Mulders, PRD 81 (2010) 094006

Focus on $gg \to Hg$ (dominant at the LHC). In the hadronic c.m.s.:

$$\boldsymbol{q}_T = |\boldsymbol{q}_T|(\cos\phi_T, \sin\phi_T) \quad \boldsymbol{K}_\perp = |\boldsymbol{K}_\perp|(\cos\phi_\perp, \sin\phi_\perp) \quad \phi \equiv \phi_T - \phi_\perp$$

$$\mathrm{d}\sigma \equiv \frac{\mathrm{d}\sigma}{\mathrm{d}y_H\,\mathrm{d}y_\mathrm{j}\,\mathrm{d}^2\boldsymbol{K}_\perp\,\mathrm{d}^2\boldsymbol{q}_T} \qquad \frac{\mathrm{d}\sigma}{\sigma} \equiv \frac{\mathrm{d}\sigma}{\int_0^{q_{T\mathrm{max}}^2}\mathrm{d}\boldsymbol{q}_T^2 \int_0^{2\pi}\mathrm{d}\phi\,\mathrm{d}\sigma}$$

Normalized cross section for $p\,p \to H\,\mathrm{jet}\,X$

$$\frac{\mathrm{d}\sigma}{\sigma} = \frac{1}{2\pi}\,\sigma_0(\boldsymbol{q}_T^2)\left[1 + R_0(\boldsymbol{q}_T^2) + R_2(\boldsymbol{q}_T^2)\cos 2\phi + R_4(\boldsymbol{q}_T^2)\cos 4\phi\right]$$

$$\sigma_0(\boldsymbol{q}_T^2) \equiv \frac{f_1^g \otimes f_1^g}{\int_0^{q_{T\mathrm{max}}^2}\mathrm{d}\boldsymbol{q}_T^2\, f_1^g \otimes f_1^g}$$

The three contributions can be isolated by defining the observables

$$\langle \cos n\phi \rangle_{q_T} \equiv \frac{\int_0^{2\pi} \mathrm{d}\phi \, \cos n\,\phi \, \mathrm{d}\sigma}{\mathrm{d}\sigma} \qquad (n = 0, 2, 4)$$

such that

$$\langle \cos n\phi \rangle = \int_0^{q^2_{T\mathrm{max}}} \mathrm{d}\boldsymbol{q}_T^2 \, \langle \cos n\phi \rangle_{q_T}$$

$$\frac{1}{\sigma} \frac{\mathrm{d}\sigma}{\mathrm{d}^2 \boldsymbol{q}_T} \equiv \langle 1 \rangle_{q_T} \quad \Longrightarrow \quad 1 + R_0 \propto f_1^g \otimes f_1^g + h_1^{\perp g} \otimes h_1^{\perp g}$$

$$\langle \cos 2\phi \rangle_{q_T} \quad \Longrightarrow \quad R_2 \propto f_1^g \otimes h_1^{\perp g}$$

$$\langle \cos 4\phi \rangle_{q_T} \quad \Longrightarrow \quad R_4 \propto h_1^{\perp g} \otimes h_1^{\perp g}$$

f_1^g: Gaussian + tail

$$f_1^g(x, \boldsymbol{p}_T^2) = f_1^g(x)\,\frac{R^2}{2\,\pi}\,\frac{1}{1+\boldsymbol{p}_T^2\,R^2} \qquad R = 2\ \mathrm{GeV}^{-1}$$

$h_1^{\perp\,g}$: Maximal polarization and Gaussian + tail

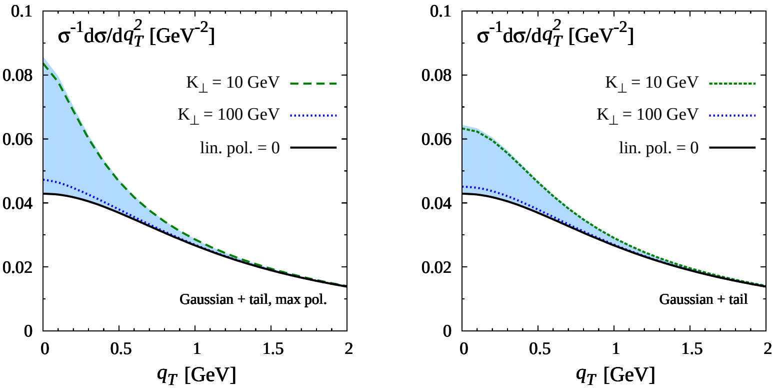
$$h_1^{\perp\,g}(x, \boldsymbol{p}_T^2) = \frac{2M_p^2}{\boldsymbol{p}_T^2}\, f_1^g(x, \boldsymbol{p}_T^2) \qquad [max\ pol.]$$

$$h_1^{\perp\,g}(x, \boldsymbol{p}_T^2) = 2\, f_1^g(x)\,\frac{M_p^2 R_h^4}{2\,\pi}\,\frac{1}{(1+\boldsymbol{p}_T^2 R_h^2)^2} \qquad R_h = \frac{3}{2}\,R$$

Boer, den Dunnen, NPB 886 (2014) 421

q_T-distribution

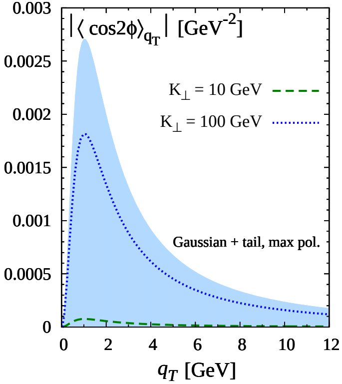
Configuration in which the Higgs and the jet have same rapidities

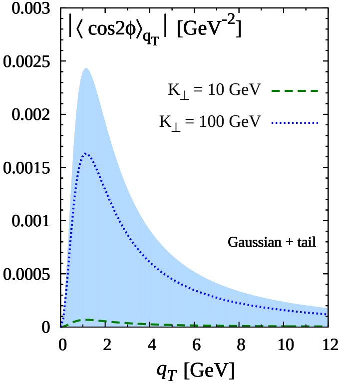


Effects largest at small q_T (hard to measure), but model dependent!

Azimuthal $\cos 2\phi$ asymmetries

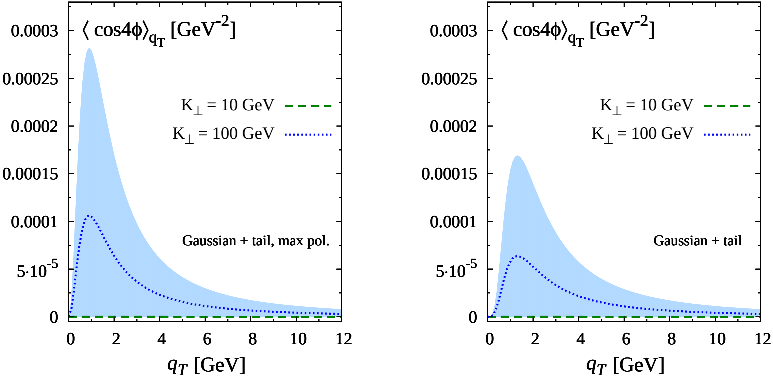
Sensitive to the sign of $h_1^{\perp\, g}$: $\langle \cos 2\phi \rangle_{q_T} < 0 \implies h_1^{\perp\, g} > 0$





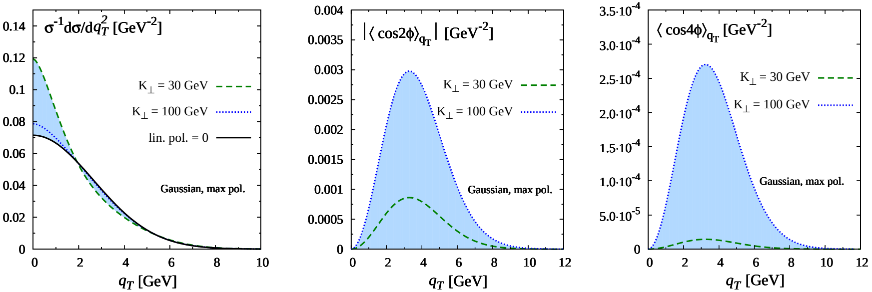
$q_{T\max} = M_H/2$ $\quad\quad$ $\langle \cos 2\phi \rangle \approx 12\%$ at $K_\perp = 100$ GeV

Azimuthal $\cos 4\phi$ asymmetries



$q_{T\max} = M_H/2$ $\langle \cos 4\phi \rangle \approx 0.1 - 0.2\%$ at $K_\perp = 100$ GeV

Gaussian model for the unpolarized TMDs



$q_{T\max} = K_\perp/2$,
$\langle \cos 2\phi \rangle \approx 9\%$, $\langle \cos 4\phi \rangle \approx 0.4\%$ at $K_\perp = 100$ GeV

Quarkonium $\mathcal{Q} \equiv Q\bar{Q}[^3S_1]$ and isolated γ produced almost back-to-back

den Dunnen,blue Lansberg, CP, Schlegel, PRL 112 (2014) 212001

- Accessible at the LHC : only the transverse momentum of the $\mathcal{Q} + \gamma$ pair needs to be small, not the individual ones
- Study of TMD evolution by tuning the invariant mass of $\mathcal{Q} + \gamma$ (evolution scale)
- Color octet (CO) contributions to $\mathcal{Q} + \gamma$ likely smaller than for inclusive $\mathcal{Q}$

  Kim, Lee, Song, PRD 55 (1997) 5429
  Li, Wang, PLB 672 (2009) 51
  Lansberg, PLB 679 (2009) 340

  CO further suppressed w.r.t. CS contributions when $\mathcal{Q} - \gamma$ back-to-back

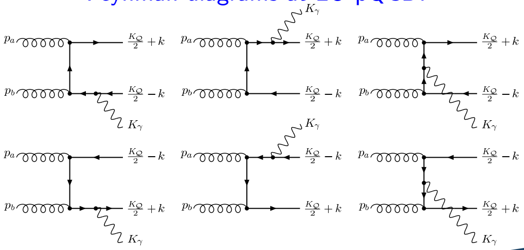
  Mathews, Sridhar, Basu, PRD 60 (1999) 014009

TMD factorization approach, in combination with the color-singlet model, for $q_T^2 \ll Q^2$, with $q_T = K_{\mathcal{Q}\perp} + K_{\gamma\perp}$, $Q^2 \equiv q^2 = (K_{\mathcal{Q}} + K_\gamma)^2$

TMD Master Formula

$$\mathrm{d}\sigma = \frac{1}{2s} \frac{d^3 \boldsymbol{K}_{\mathcal{Q}}}{(2\pi)^3\, 2K^0_{\mathcal{Q}}} \frac{d^3 \boldsymbol{K}_\gamma}{(2\pi)^3\, 2K^0_\gamma} \int dx_a\, dx_b\, d^2\boldsymbol{p}_{aT}\, d^2\boldsymbol{p}_{bT}\, (2\pi)^4 \delta^4(p_a+p_b-q) \times \mathrm{Tr}\left\{ \Gamma_g(x_a,\boldsymbol{p}_{aT}) \Gamma_g(x_b,\boldsymbol{p}_{bT}) \overline{\sum_{\text{colors}}} \left| \mathcal{A}\left(g\, g \to Q\bar{Q}[^3S_1] \right) \right|^2 \right\}$$

Feynman diagrams at LO pQCD:



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

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

Analysis similar to the one for $pp \to \gamma\gamma X$

Qiu, Schlegel, Vogelsang, PRL 107 (2011) 062001

The three contributions can be disentangled by defining the transverse moments

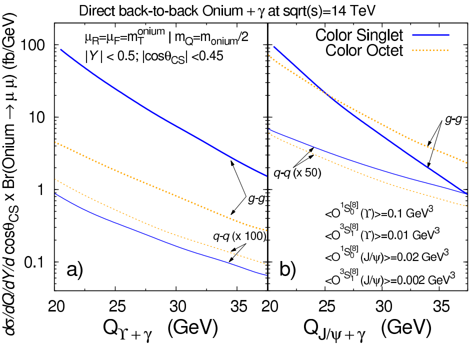
$$\mathcal{S}_{q_T}^{(n)} \equiv \frac{\int_0^{2\pi} \mathrm{d}\phi_{CS}\, \cos(n\,\phi_{CS})\, \frac{\mathrm{d}\sigma}{\mathrm{d}Q\mathrm{d}Y\mathrm{d}^2q_T\mathrm{d}\Omega}}{\int_0^{q_T^{2\,\max}} dq_T^2 \int_0^{2\pi} \mathrm{d}\phi_{CS}\, \frac{\mathrm{d}\sigma}{\mathrm{d}Q\mathrm{d}Y\mathrm{d}^2q_T\mathrm{d}\Omega}} \qquad (n = 0, 2, 4) \quad q_T^{2\,\max} = \frac{Q^2}{4}$$

$$\mathcal{S}_{q_T}^{(0)} \Longrightarrow f_1^g \otimes f_1^g$$

$$\mathcal{S}_{q_T}^{(2)} \Longrightarrow f_1^g \otimes h_1^{\perp g}$$

$$\mathcal{S}_{q_T}^{(4)} \Longrightarrow h_1^{\perp g} \otimes h_1^{\perp g}$$

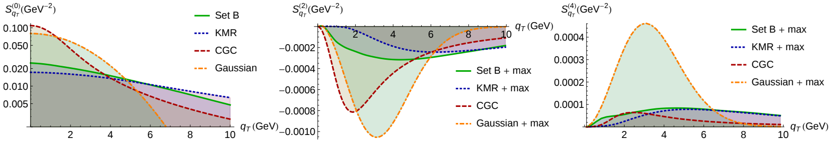
Process dominated by gg fusion



CS yield is clearly dominant for the Υ, above the CO one for J/ψ at low Q
Further suppression of CO contributions by isolating $\mathcal{Q}$ (not needed for Υ)

Kraan, AIP Conf. Proc. 1038 (2008) 45
Kikola, NP Proc. Suppl. 214 (2011) 177

$$Q = 20 \text{ GeV}, \qquad Y = 0, \qquad \theta_{CS} = \pi/2$$



den Dunnen, Lansberg, CP, Schlegel, PRL 112 (2014) 212001

f_1^g: Models for Unintegrated Gluon Distributions
$h_1^{\perp g}$: predictions only in the CGC: otherwise saturated to its upper bound

$\mathcal{S}^{(2,4)}_{q_T}$ smaller than $\mathcal{S}^{(0)}_{q_T}$: can be integrated up to $q_T = 10$ GeV

$$2.0\% \,(\text{KMR}) < \quad |\int \mathrm{d}q_T^2 \mathcal{S}^{(2)}_{q_T}| \quad < 2.9\% \,(\text{Gauss})$$

$$0.3\% \,(\text{CGC}) < \quad \int \mathrm{d}q_T^2 \, \mathcal{S}^{(4)}_{q_T} \quad < 1.2\% \,(\text{Gauss})$$

Possible determination of the shape of f_1^g and verification of a non-zero $h_1^{\perp g}$

- $h_1^{\perp g}$ receives contributions from ISI/FSI (gauge links) which make it process dependent and can even break factorization

- It is possibile to define five independent $h_1^{\perp g}$ functions with specific color structures. Depending on the process, one extracts different combinations

  Buffing, Mukherjee, Mulders, PRD 88 (2013) 054027

- In $ep \to e' Q\bar{Q}X$ and in all the processes with a colorless final state, $pp \to \gamma\gamma X$, $pp \to H/\eta_c/\chi_{c0}/...X$, only two $h_1^{\perp g}$ functions appear (in the same combination)

- In $pp \to Q\bar{Q}X$ and $pp \to \mathrm{jet\,jet}\,X$ problems due to factorization breaking. Same holds for quarkonium production in pp in the CO and CEM models

  CP, Boer, Brodsky, Buffing, Mulders, JHEP 1310 (2013) 024
  Mukherjee, Rajesh, arXiv:1511.04319

3DSPIN MAPPING THE PROTON IN 3D

UNIVERSITÀ DI PAVIA

- Direct extraction from A_N in $e\,p^\uparrow \to e'\,Q\,\bar{Q}\,X$ and in $e\,p^\uparrow \to e'\,\text{jet}\,\text{jet}\,X$ (EIC)

  D. Boer, P. Mulders, CP, J. Zhou, in preparation

- Single spin asymmetries for $p^\uparrow p \to \gamma\gamma X$ (RHIC)

  Qiu, Schlegel, Vogelsang, PRL 107 (2011) 062001

- Other observables can probe GSF in future experiments (AFTER@LHC, RHIC):

$A_{UT}^{\sin\phi_S}$ in $p\,p^\uparrow \to \eta_Q\,X$ e in $p\,p^\uparrow \to \chi_{QJ}\,X$ per $q_T \ll 2M_Q$ al LO (CSM)

$$A_{UT}^{\sin\phi_S}(\eta_Q) = \frac{|\boldsymbol{S}_T|}{2(1-R_0)\,f_1^g \otimes f_1^g}\left\{f_1^g \otimes f_{1T}^{\perp\,g} - h_1^{\perp\,g} \otimes h_{1T}^g - h_1^{\perp\,g} \otimes h_{1T}^{\perp\,g}\right\}$$

$$A_{UT}^{\sin\phi_S}(\chi_{Q0}) = \frac{|\boldsymbol{S}_T|}{2(1+R_0)\,f_1^g \otimes f_1^g}\left\{f_1^g \otimes f_{1T}^{\perp\,g} + h_1^{\perp\,g} \otimes h_{1T}^g + h_1^{\perp\,g} \otimes h_{1T}^{\perp\,g}\right\}$$

$$A_{UT}^{\sin\phi_S}(\chi_{Q2}) = \frac{|\boldsymbol{S}_T|}{2\,f_1^g \otimes f_1^g}\,f_1^g \otimes f_{1T}^{\perp\,g}$$

Sezione d'urto polarizzata per $p\,p^\uparrow \to J/\psi + \gamma\,X$ al LO (CSM) $\quad [\phi \equiv \phi_T - \phi_\perp]$

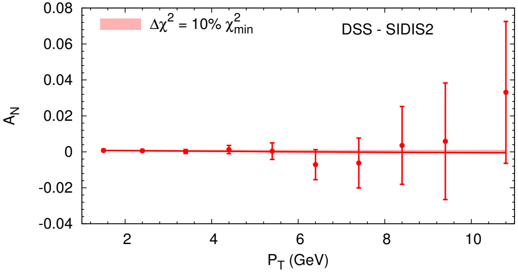
$$\frac{\mathrm{d}\sigma_{UT}}{\mathrm{d}y_\psi\,\mathrm{d}y_\gamma\,\mathrm{d}^2\boldsymbol{K}_\perp\,\mathrm{d}^2\boldsymbol{q}_T} \propto \sin\phi_S\,f_1^g \otimes f_{1T}^{\perp\,g} + B\Big\{\sin(\phi_S - 2\phi)\,f_1^g \otimes h_{1T}^g + \sin\phi_S\cos 2\phi\,[f_1^g \otimes h_{1T}^{\perp\,g} + h_1^{\perp\,g} \otimes f_{1T}^{\perp\,g}] + \sin\phi_S\cos 4\phi\,[h_1^{\perp\,g} \otimes h_{1T}^g + h_1^{\perp\,g} \otimes h_{1T}^{\perp\,g}] + \cos\phi_S\sin 2\phi\,[f_1^g \,\overline{\otimes}\, h_{1T}^{\perp\,g} + h_1^{\perp\,g} \,\overline{\otimes}\, f_{1T}^{\perp\,g}] + \cos\phi_S\sin 4\phi\,[h_1^{\perp\,g} \,\overline{\otimes}\, h_{1T}^g + h_1^{\perp\,g} \,\overline{\otimes}\, h_{1T}^{\perp\,g}]\Big\}$$

J. Lansberg, CP, M. Schlegel, in preparation

Assumption: Factorization and universality of TMDs (Test of the GPM)

Motivation: New highly precise mid-rapidity RHIC data for A_N in $p^\uparrow p \to \pi^0 X$

$\sqrt{s} = 200$ GeV $\qquad |\eta_\pi| \leq 0.35$



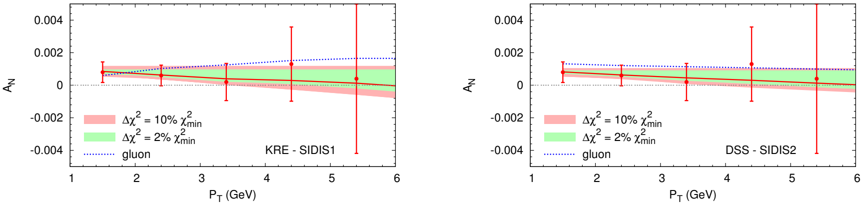
[PHENIX Coll.] PRD 90 (2014) 012006

Data for $A_N(p^\uparrow p \to \text{jet}\, X)$ not included in the fit, but consistent with new bound

[STAR Coll.] PRD 86 (2012) 032006

$$A_N = A_N^{\rm quark} + A_N^{\rm gluon} \qquad \chi^2 = \sum \frac{\left(A_N^{\rm gluon} + A_N^{\rm quark} - A_N^{\rm exp}\right)^2}{\sigma^2_{\rm exp} + \sigma^2_{\rm quark}} \qquad (4 \; \textit{parameters})$$

$\sigma_{\rm quark}$: Estimated theoretical uncertainty on the quark contribution



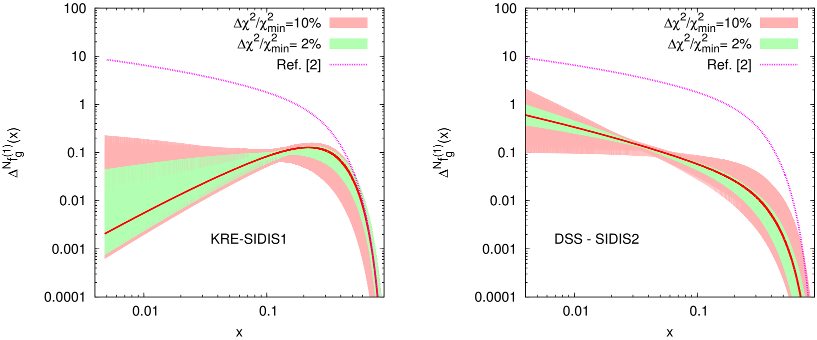
Uncertainty bands: envelope of A_N curves generated by all parameter sets in the explored phase space giving $\chi^2 \leq \chi^2_{\rm min} + \Delta\chi^2$, $\Delta\chi^2 = (2\%, 10\%)\, \chi^2_{\rm min}$

Open issues: factorization, process dependence, relation to twist-three approach

Boer, Lorcé, CP, Zhou, AdHEP (2015)

Small, positive GSF, mainly constrained in the range $0.05 < x < 0.3$ (SIDIS)

$$\Delta^N f^{(1)}_{g/p^\uparrow}(x) \equiv \int d^2\boldsymbol{k}_\perp \frac{k_\perp}{4M_p} \Delta^N f_{g/p^\uparrow}(x, k_\perp) = -f_{1T}^{\perp(1)g}(x)$$



D'Alesio, Murgia, CP, JHEP 1509 (2015) 119

Ref. [2]: Old bound on the gluon Sivers function

Anselmino, D'Alesio, Melis, Murgia, PRD74 (2006) 094011

Gluon TMDs could be directly probed by looking at p_T distributions and azimuthal asymmetries in $e\,p^\uparrow \to e'\,Q\,\bar{Q}\,X$ and $e\,p^\uparrow \to e'\,\mathrm{jet}\,\mathrm{jet}\,X$ at a future EIC

In pp collisions, $h_1^{\perp\,g}$ leads to a modulation of the angular independent transverse momentum distribution of scalar (H, χ_{c0}, χ_{b0}) and pseudoscalar (η_c, η_b) particles

First determination of $h_1^{\perp g}$ and f_1^g could come from $J/\psi(\Upsilon) + \gamma$ production at the LHC. Other opportunity offered by $J/\psi + J/\psi$ production at the LHC

J. Lansberg, CP, F. Scarpa, in preparation

Together with a similar study in the Higgs sector, quarkonium production can be used to extract gluon TMDs and to study their process and scale dependences

First extraction of the GSF $f_{1T}^\perp$ from A_N data on $pp \to \pi^0\,X$ (RHIC)