TMDs from dijet production in SIDIS

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Work done in collaboration with Miguel G. Echevarría and Ignazio Scimemi

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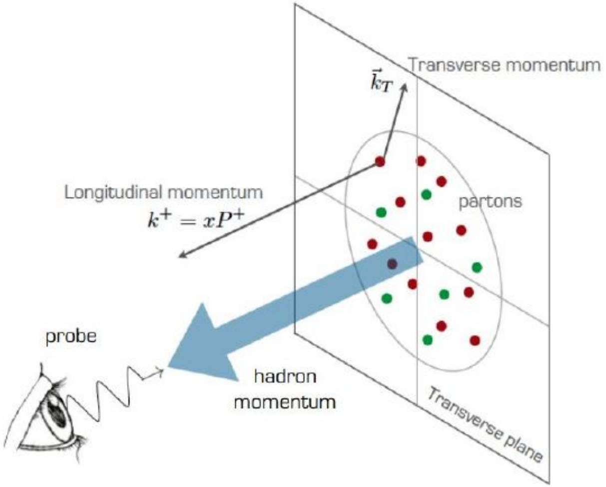
Outline

- TMDs and the Sivers function
- SIDIS with dijets at the EIC
- Factorization theorem
- Sivers model
- Results
- Conclusion

Transverse momentum-dependent parton distributions (TMDs)

“Maps” of hadron structure in momentum space

- 3D structure in momentum space: TMD($x,k^2_\perp$)
- Information on spin and OAM of the partons inside the hadron
- Information on transverse parton dynamics: SIDIS and Drell-Yan



Credit picture: A. Bacchetta

TMDs: the Sivers function

Definition:
$f_{1T}^{\perp}$ describes **transverse momentum distribution** of unpolarized quarks and gluons inside a **transversely polarized proton**

Physical picture:
Correlates parton transverse momentum $\mathbf{k_T}$ with proton's transverse spin $\mathbf{S_T}$

Motivation:
Quark-hadron spin-momentum structure

Dijet production in SIDIS most promising channel for probing gluon Sivers effect

quark pol.

nucleon pol.	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	$h_{1T},\ h_{1T}^{\perp}$

(a) Twist-2 TMD PDFs

Table: Quark TMD distribution functions (spin ½)
Andrea Signori: Introduction to transverse momentum imaging

Take-home: The Sivers function reveals hidden spin-momentum correlations in the proton

What we look at: SIDIS with dijets at the EIC

The process:

Semi-Inclusive Deep Inelastic Scattering (SIDIS) with two jets in the final state

$$\ell + h(P) \to \ell' + J_1(p_1) + J_2(p_2) + X.$$

Breit Frame

Virtual photon and target-hadron directions are back-to-back

Key variables

- Jet imbalance:

$$\boldsymbol{r}_\perp = \boldsymbol{p}_{1\perp} + \boldsymbol{p}_{2\perp}\,, \quad r_T = |\boldsymbol{r}_\perp|$$

- Hard transverse momenta:

$$\boldsymbol{p}_\perp = \frac{\boldsymbol{p}_{1\perp} - \boldsymbol{p}_{2\perp}}{2}, \quad p_T = |\boldsymbol{p}_\perp|$$

Factorization condition

$$r_T \ll p_T$$

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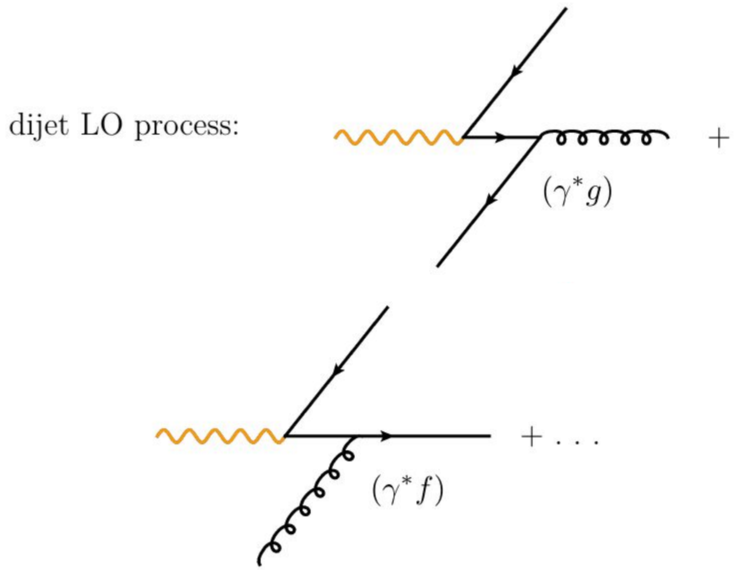

Figure: LO diagrams for dijet production in SIDIS in an ep collider
Rafael F. del Castillo, Miguel G. Echevarria, Yiannis Makris, Ignazio Scimemi:
TMD factorization for dijet and heavy-meson pair in DIS

Factorized cross-section

Unpolarized cross-section

Rafael F. del Castillo, Miguel G. Echevarria, Yiannis Makris, Ignazio Scimemi
TMD factorization for dijet and heavy-meson pair in DIS

$$\frac{d\sigma^U(\gamma^* g)}{d\Pi d\boldsymbol{r}_\perp} = \sum_q \sigma_0^{gU} H_{\gamma^* g\to q\bar{q}}(\mu) \int \frac{d^2\boldsymbol{b}_\perp}{(2\pi)^2} \exp(i\boldsymbol{b}_\perp \cdot \boldsymbol{r}_\perp)\, f_1^g(\xi, b_T; \mu, \zeta_1)$$
$$\times\, S_{\gamma g}(\boldsymbol{b}_\perp, \eta_1, \eta_2; \mu, \zeta_2)\, \mathcal{C}_q(\boldsymbol{b}_\perp, R; \mu) J_q(p_T, R, \mu) \mathcal{C}_{\bar{q}}(\boldsymbol{b}_\perp, R; \mu) J_{\bar{q}}(p_T, R; \mu)$$

T-polarized cross-section

$$\frac{d\sigma^T(\gamma^* g)}{d\Pi d\boldsymbol{r}_\perp} = \sum_q i\sigma_0^{gU} H_{\gamma^* g\to q\bar{q}}(\mu) \int \frac{d^2\boldsymbol{b}_\perp}{(2\pi)^2} \exp(i\boldsymbol{b}_\perp \cdot \boldsymbol{r}_\perp)\, S_T \sin(\phi_S - \phi_b)(b_T M)\, f_{1T}^{\perp g}(\xi, b_T; \mu, \zeta_1)$$
$$\times\, S_{\gamma g}(\boldsymbol{b}_\perp, \eta_1, \eta_2; \mu, \zeta_2)\, \mathcal{C}_f(\boldsymbol{b}_\perp, R; \mu) J_f(p_T, R; \mu) \mathcal{C}_{\bar{f}}(\boldsymbol{b}_\perp, R; \mu) J_{\bar{f}}(p_T, R; \mu)$$

Evolution needed

The CCS-scheme

T-polarized cross-section

Dependence on gluon sivers function

Dependence on ϕ_b : angle between *b* and v_{1T}

CCS

2 Collinear-Soft functions (C)

1 Dijet Soft function (S)

Angular dependencies at one-loop

Different initial scales

Angular dependence in evolution factors Rs

-> Constraint in the angular integration -> some scale choices can not be used

$$
\begin{aligned}
\frac{d\sigma^T(\gamma^* g)}{d\Pi d\boldsymbol{r}_\perp} = \sum_q i\sigma_0^{gU} H_{\gamma^* g\to q\bar{q}}(\mu) \int \frac{b_T db_T d\phi_b}{(2\pi)^2} \exp(i\boldsymbol{b}_\perp \cdot \boldsymbol{r}_\perp) \\
\times S_T b_T M_p \sin(\phi_S - \phi_b) \\
\times \mathcal{R}_F^g\Big((\mu_0, \zeta_{1,0}^g) \to (p_T, p_T^2)\Big) f_{1T}^{\perp g}(\xi, b_T) \\
\times \mathcal{R}_{J_{\bar{q}}}(\mu_J \to p_T)\mathcal{R}_{J_q}(\mu_J \to p_T) J_{\bar{q}}(p_T, R, \mu_J) J_q(p_T, R, \mu_J) \\
\times \mathcal{R}_{\mathcal{C}_{\bar{q}}}(\mu_\mathcal{C} \to p_T)\mathcal{R}_{\mathcal{C}_q}(\mu_\mathcal{C} \to p_T)\mathcal{R}_S^q\Big((\mu_0, \zeta_{2,0}) \to (p_T, 1)\Big) \\
\times \mathcal{C}_{\bar{q}}(b_T, R, \mu_{\mathcal{C}_{\bar{q}}})\mathcal{C}_q(b_T, R, \mu_{\mathcal{C}_q})\mathcal{S}_{\gamma g}(b_T, \zeta_{2,0}, \mu_0)
\end{aligned}
$$

Equation: Factorized cross-section of gluon channel with transversely polarized hadron CCS-scheme

The CCS-scheme

T-polarized cross-section

Dependence on gluon sivers function

Dependence on ϕ_b : angle between *b* and v_{1T}

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\times \mathcal{R}_F^g\Big((\mu_0, \zeta_{1,0}^g) \to (p_T, p_T^2)\Big) f_{1T}^{\perp g}(\xi, b_T) \\
\times \mathcal{R}_{J_{\bar{q}}}(\mu_J \to p_T)\mathcal{R}_{J_q}(\mu_J \to p_T) J_{\bar{q}}(p_T, R, \mu_J) J_q(p_T, R, \mu_J) \\
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\times \mathcal{C}_{\bar{q}}(b_T, R, \mu_{\mathcal{C}_{\bar{q}}})\mathcal{C}_q(b_T, R, \mu_{\mathcal{C}_q})\mathcal{S}_{\gamma g}(b_T, \zeta_{2,0}, \mu_0)
\end{aligned}
$$

Equation: Factorized cross-section of gluon channel with transversely polarized hadron CCS-scheme

The *M*-scheme

T-polarized cross-section

Dependence on gluon sivers function

Dependence on ϕ_b

M

Total function M=CCS-> $M^{[1]} = C^{[1]}+C^{[1]}+S^{[1]}$

Angular dependencies at one-loop

Common initial scales in Cs and S

-> Logs are not entirely resummed

No angular dependence in R

Evolution factor R does NOT have angular dependence

Free choice of initial scale μ

$$\frac{d\sigma^T(\gamma^* g)}{d\Pi d\boldsymbol{r}_\perp} = \sum_q i\sigma_0^{gU} H_{\gamma^* g\to q\bar{q}}(\mu) \int \frac{b_T db_T d\phi_b}{(2\pi)^2} \exp(i\boldsymbol{b}_\perp \cdot \boldsymbol{r}_\perp)$$
$$\times S_T b_T M_p \sin(\phi_S - \phi_b)$$
$$\times \mathcal{R}_F^g\Big((\mu_0, \zeta_{1,0}^g) \to (p_T, p_T^2)\Big) f_{1T}^{\perp g}(\xi, b_T)$$
$$\times \mathcal{R}_{J_{\bar{q}}}(\mu_J \to p_T)\mathcal{R}_{J_q}(\mu_J \to p_T) J_{\bar{q}}(p_T, R, \mu_J) J_q(p_T, R, \mu_J)$$
$$\boxed{\times \mathcal{R}_{\mathcal{M}_g}(\{\mu_0, \zeta_{2,0}\} \to \{p_T, p_T^2\}) \mathcal{M}_g(b_T, R, \zeta_{2,0}, \mu_0)}$$

Equation: Factorized cross-section of gluon channel with transversely polarized hadron M-scheme

Evolution of M

$$\mathcal{R}_{\mathcal{M}_{q,g}}(\{\mu_0, \zeta_{2\mu_f}^{\mathcal{M},(\gamma i,\gamma g)}(b)\} \to \{\mu_f, \zeta_f\}) = \left(\frac{\zeta_f}{\zeta_{2,\mu_f}^{\mathcal{M},(\gamma i,\gamma g)}(b)} \right)^{-\mathcal{D}_{q,g}(b,\mu_f)}$$

- ζ: Rapidity scale
- D: Collins-Sopper kernel

No angular dependence in R

Evolution factor R does NOT have angular dependence

Free choice of initial scale μ

The Sivers model

Quark Channel

We take into account u,d,s and sea

Gluon Channel

We use the same parameters as sea quark channel

Ng=Nsea

$$f_{1T}^{\perp}(x,b) = N_q \frac{(1-x)x^{\beta_q}(1+\epsilon_q x)}{n(\beta_q,\epsilon_q)} \exp\left(-\frac{r_0 + x r_1}{\sqrt{1+r_2 x^2 b^2}} b^2\right)$$

$$n(\beta,\epsilon) = (3+\beta+\epsilon+\epsilon\beta)\Gamma(\beta+1)/\Gamma(\beta+4)$$

Equation: Sivers model from Bury, M., Prokudin, A. & Vladimirov, A. Extraction of the Sivers function from SIDIS, Drell-Yan, and $W^{\pm}/Z$ boson production data with TMD evolution.

Observables

U integrated cross-section

$$\frac{d\sigma^{UU}}{dr_T} = r_T \int_{x_{\min}}^{x_{\max}} dx \int_{-\pi}^{\pi} d\phi_r \frac{d\sigma^U}{dx d\eta_1 d\eta_2 dp_T d\boldsymbol{r}_\perp}\Big|_{\eta_1,\,\eta_2,\,p_T}$$

T modulated cross-section

$$\frac{\langle d\sigma^{UT}\rangle}{dr_T} = r_T \int_{x_{\min}}^{x_{\max}} dx \int_{-\pi}^{\pi} d\phi_r \sin(\phi_S - \phi_r) \frac{d\sigma^T}{dx d\eta_1 d\eta_2 dp_T d\boldsymbol{r}_\perp}\Big|_{\eta_1,\,\eta_2,\,p_T}$$

Sivers Asymmetry

$$A^{\text{Sivers}}_{[x_{\min},x_{\max}]} = \frac{\langle d\sigma^{UT}\rangle/dr_T}{d\sigma^{UU}/dr_T}$$

Working conditions

$p_T \sim Q/2 \sim 20$ GeV

$\sqrt{s}=140$ GeV

$\eta_1=\eta_2=0$

Jet radii R=0.7

$\phi_s=0$

$x \in (0.0859, 0.5)$

Results

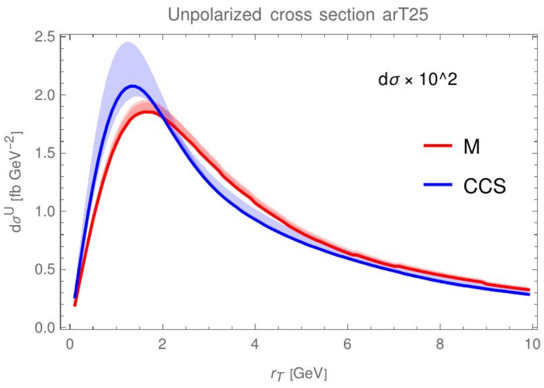


Fig. 1: Unpolarized cross-section

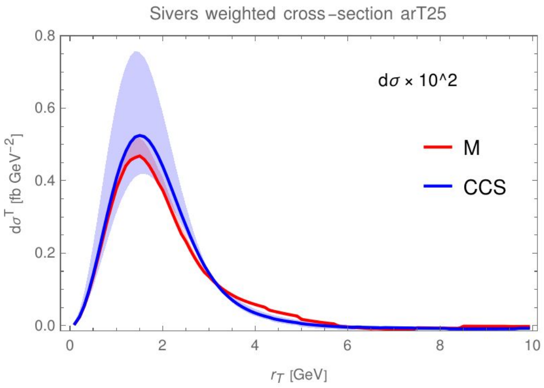


Fig. 2: Sivers dependent modulated cross-section

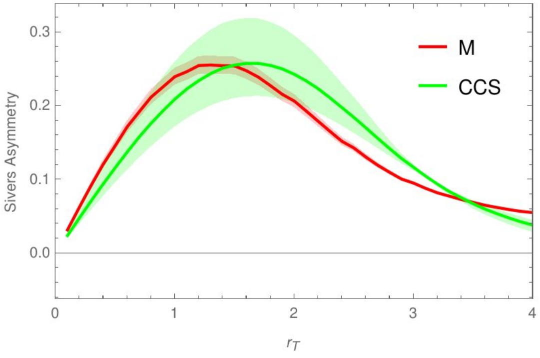


Fig. 3: Sivers asymmetry

Key takeaway: Using only hard scale variation Sivers asymmetry is expected to be large, between 5 to 30%, which is relevant for EIC

Testing the gluon Sivers model

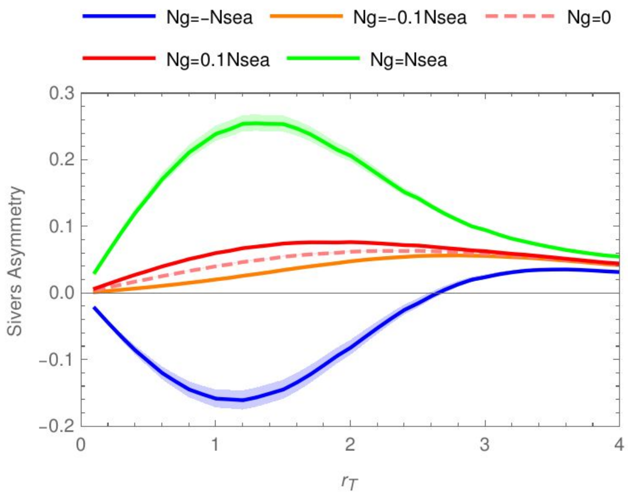


Fig. 4: Sivers asymmetry for different gluon sivers estimations, M-scheme

Key takeaway: The Sivers asymmetry is influenced by the gluon Sivers function; in its absence, the quark channel yields an asymmetry of ~5%.

Summary & Conclusions

1. Dijets at the EIC provide access to the gluon Sivers function

2. Resummation method without angular dependence in R gives more freedom to chosen scales

3. Sivers asymmetry could be up to 5-30%

4. Future work: explore other scales, study different sivers models….

THANK YOU FOR LISTENING!

Backup

Evolution factors

Evolution kernels Jet and Collinear-Soft functions

$$\mathcal{R}_i(\mu_i \to p_T) = e^{K_i(\mu_i \to p_T)} \left(\frac{\mu_i}{m_i}\right)^{\omega_i(\mu_i \to p_T)}, \qquad i = \{\mathcal{C}_q, \mathcal{C}_g, J_q, J_g\}$$

$$\omega_i(\mu_i \to p_T)\Big|_{\mathrm{NLL}} = -\frac{\Gamma_i^0}{\beta_0}\left[\ln r + \left(\frac{\Gamma_1}{\Gamma_0} - \frac{\beta_1}{\beta_0}\right)\frac{\alpha_s(\mu_i)}{4\pi}(r-1)\right],$$

$$K_i(\mu_i \to p_T)\Big|_{\mathrm{NLL}} = -\frac{\gamma_i^0}{2\beta_0}\ln r - \frac{2\pi\Gamma_i^0}{(\beta_0)^2}\left[\frac{r - 1 - r\ln r}{\alpha_s(p_T)} + \left(\frac{\Gamma_1}{\Gamma_0} - \frac{\beta_1}{\beta_0}\right)\frac{1 - r + \ln r}{4\pi} + \frac{\beta_1}{8\pi\beta_0}\ln^2 r\right],$$

A. Hornig, Y. Makris and T. Mehen, Jet shapes in dijet events at the lhc in scet

Evolution kernel TMD (similar shape in Dijet-Soft and M-functions)

$$\mathcal{R}_F^{q,g}(\{\mu_0, \zeta_0^{q,g}(b_T)\} \to \{p_T, p_T^2\}) = \left(\frac{p_T^2}{\zeta_{\mu_f}^{q,g}(b_T)}\right)^{-\mathcal{D}_{q,g}(b_T, p_T)}$$

What we look at: SIDIS with Dijets at the EIC

The process:

$$\ell + h(P) \to \ell' + J_1(p_1) + J_2(p_2) + X.$$

Breit Frame

Virtual photon and target-hadron directions are back-to-back

Key variables

- Jet imbalance:

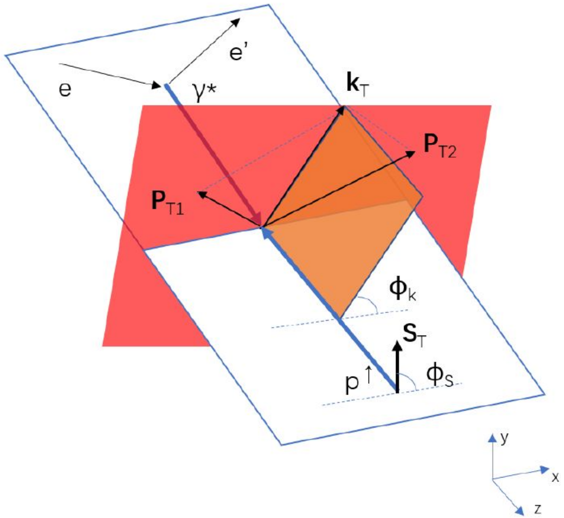
$$\boldsymbol{r}_T = \boldsymbol{p}_{1T} + \boldsymbol{p}_{2T},$$

- Average jet transverse momenta:

$$p_T = \frac{|\boldsymbol{p}_{1T}| + |\boldsymbol{p}_{2T}|}{2}$$

Factorization condition

$$|\boldsymbol{r}_T| \ll p_T$$



L. Zheng, E.C. Aschenauer, J.H. Lee, Bo-Wen Xiao, Zhong-Bao Yin
Accessing the Gluon Sivers Function at a future Electron-Ion Collider

Constraint: $\mathcal{A}$>-1/2

Constraint in the angular integration -> some scale choices can not be used

$$\mathcal{A}(\{\mu_i\}) = \sum_{i\in\{S,\mathcal{C}\}} c_i \int_{\mu_i}^{\mu} \gamma_{\text{cusp}}[\alpha_s] d\ln\mu'$$

$$I_n(\mathcal{A}) \equiv \int_{-\pi}^{+\pi} d\phi_b \, |\cos\phi_b|^{2\mathcal{A}} \, \ln^n|\cos\phi_b|$$

$$I_0(\mathcal{A}) = \frac{2\sqrt{\pi}\,\Gamma(1/2+\mathcal{A})}{\Gamma(1+\mathcal{A})},$$

$$I_1(\mathcal{A}) = \frac{\sqrt{\pi}\,\Gamma(1/2+\mathcal{A})}{\Gamma(1+\mathcal{A})}\left(H_{\mathcal{A}-1/2} - H_{\mathcal{A}}\right)$$

$$I_2(\mathcal{A}) = \frac{\sqrt{\pi}\,\Gamma(1/2+\mathcal{A})}{2\Gamma(1+\mathcal{A})}\left[(H_{\mathcal{A}-1/2} - H_{\mathcal{A}})^2 + \psi^{(1)}\left(\frac{1}{2}+\mathcal{A}\right) - \psi^{(1)}(1+\mathcal{A})\right]$$