Transverse single-spin asymmetry in $p^{\uparrow}l \rightarrow D + X$ as a probe of the gluon Sivers function

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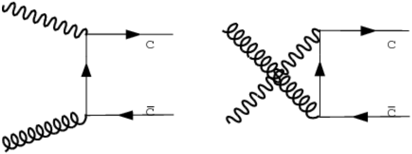
Introduction

This talk is about the low-virtualitiy leptoproduction of open-charm as a probe of the gluon Sivers function (GSF), in a generalised parton model framework.



Transverse Single Spin Asymmetry in $ep^{\uparrow} \to D + X$, R. M. Godbole, A. Misra and A.K (2017) [1709.03074]

$Q^2 \approx 0$, scattered lepton undetected.

The Sivers function

Sivers function: Proposed by Dennis Sivers to explain transverse single-spin asymmetries (SSA) observed in the hadroproduction of pions. Encodes the correlation between the azimuthal distribution (in k_T-space) of an unpolarised parton in a transversely polarised hadron.

D. W. Sivers, Phys. Rev. D 41 (1990) 83, Phys. Rev. D 43 (1991) 261

Use of such TMDs in polarised hard, single-scale processes such as $lp^{\uparrow} \to \pi, D + X$ and $p^{\uparrow}p \to \pi, D + X$ done under the assumption of TMD factorisation — nowadays referred to as the generalised parton model (GPM) framework.

$$\frac{E_C\, d\sigma^{AB\to C\,X}}{d^3\boldsymbol{p}_C} = \sum_{a,b,c,d} \int dx_{a,b} d^2\boldsymbol{k}_{\perp a,b}\, dz d^3\boldsymbol{k}_C\, \delta(\boldsymbol{k}_C \cdot \hat{\boldsymbol{p}}_c)\, \hat{f}_{a/A}(x_a, \boldsymbol{k}_{\perp a})\, \hat{f}_{b/B}(x_b, \boldsymbol{k}_{\perp b})$$

$$\times\, \frac{\hat{s}}{x_a x_b s} \frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}}(x_a, x_b, \hat{s}, \hat{t}, \hat{u})\, \frac{\hat{s}}{\pi}\, \delta(\hat{s}+\hat{t}+\hat{u})\, \frac{1}{z^2}\, J(z, |\boldsymbol{k}_C|)\, \hat{D}_{C/c}(z, \boldsymbol{k}_C)$$

Generalised Parton Model

Despite the absence of a formal proof of factorisation a lot of work has been done in the GPM framework.

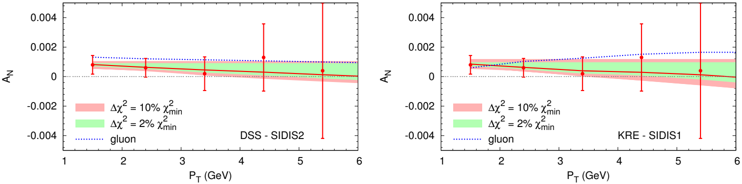
- describes experimental data on unpolarised cross-sections for $pp \to \gamma, \pi + X$ (upto a K-factor) better than collinear LO or NLO calculations.
  U. D'Alesio and F. Murgia, Phys. Rev. D70 074009 (2004) [hep-ph/0408092] and references 2-4 therein
  J. Huston *et al.*, Phys. Rev. D51 6139
  J.F. Owens, Rev. Mod. Phys. 59, 465 (1987)
- provides a good description on SSA in $p^{\uparrow}p \to \pi + X$ (in the forward region) over a wide range of c.m energies. M. Boglione, U. D'Alesio and F. Murgia, Phys. Rev. D77 051502 [0712.4240]
  U. D'Alesio and F. Murgia, Phys. Rev. D70 074009 (2004) [hep-ph/0408092]
  U. D'Alesio and F. Murgia, Prog.Part.Nucl.Phys. 61 394-454 (2008) [0712.4328]

What is known about the GSF?

While quark Sivers functions have been studied extensively (mainly in SIDIS), a lot less is known about the gluon Sivers function (GSF). Very few clear, direct measurements have been performed. A first indirect estimate of the GSF, in a GPM framework was performed by D'Alesio, Murgia and Pisano:

U. D'Alesio, F. Murgia, and C. Pisano, JHEP 09, 119 (2015) [1506.03078]

- They fit the GSF to midrapidity data on pion production, $p^\uparrow p \to \pi^0 + X$ at RHIC.
- The QSFs used in the extraction were fit to earlier SIDIS data.



Both fits describe PHENIX pion production data very well!

Heavy probes so far

- Hadroproduction of open-charm $p^{\uparrow}p \to D^0 + X$ at RHIC

  M. Anselmino, M. Boglione, U. D'Alesio, E. Leader, and F. Murgia, Phys. Rev. D70, 074025 (2004) [hep-ph/0407100]

  R. M. Godbole, AK, A. Misra, and V. S. Rawoot, Phys. Rev. D91, 014005 (2015) [1405.3560]

  U. D'Alesio, F. Murgia, C. Pisano, P. Taels, Phys. Rev. D96 036011 (2017) [1705.04169]

- Low-virtuality leptoproduction of closed-charm $ep^{\uparrow} \to J/\psi + X$

  R. M. Godbole, A. Misra, A. Mukherjee, and V. S. Rawoot, Phys. Rev. D85, 094013 (2012) [1201.1066], Phys. Rev. D88, 014029 (2013) [1304.2584]

  R. M. Godbole, AK, A. Misra, and V. S. Rawoot, Phys. Rev. D91, 014005 (2015) [1405.3560]

Open-charm leptoproduction

Here, we consider the low-virtuality leptoproduction of open-charm $p^{\uparrow}l \to D + X$.

This may have some advantages:

- At LO, sensitive only to the gluon content of the proton.
- SSAs in this process can only arise from a non-zero GSF (no Collins effect).
- Has the same initial/final state interactions as SIDIS, for which TMD factorisation has been established.
- Might therefore complement studies of SSA in SIDIS & $lp^{\uparrow} \to h + X$ by providing an additional handle on the GSF.
- Unlike closed-charm, open-charm production is not affected by issues of production model dependence.

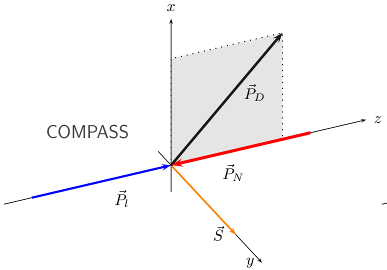
  F. Yuan, Phys. Rev. D78, 014024 (2008) [0801.4357]

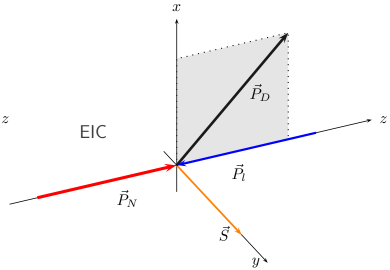
Formalism

SSA for $p^{\uparrow} l \to D + X$ given by:

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

where $d\sigma^{\uparrow}$ ($d\sigma^{\downarrow}$) is the invariant cross-section for scattering of a transversely polarised proton off an unpolarised lepton, with the polarisation of A being upwards (downwards) w.r.t plane of production of C.





Formalism

Numerator:

$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \quad = \quad \frac{E_D\, d\sigma^{p^{\uparrow} l \to DX}}{d^3\boldsymbol{p}_D} - \frac{E_D\, d\sigma^{p^{\downarrow} l \to DX}}{d^3\boldsymbol{p}_D}$$

$$= \int dx_g\, dx_\gamma\, dz\, d^2\boldsymbol{k}_{\perp g}\, d^2\boldsymbol{k}_{\perp \gamma}\, d^3\boldsymbol{k}_D\, \delta(\boldsymbol{k}_D \cdot \hat{\boldsymbol{p}}_c)\, \delta(\hat{s} + \hat{t} + \hat{u} - 2m_c^2)\, \mathcal{C}(x_g, x_\gamma, z, \boldsymbol{k}_D)$$

$$\times\ \Delta^N f_{g/p^{\uparrow}}(x_g, \boldsymbol{k}_{\perp g})\ f_{\gamma/l}(x_\gamma, \boldsymbol{k}_{\perp \gamma})\ \frac{d\hat{\sigma}^{g\gamma \to c\bar{c}}}{d\hat{t}}(x_g, x_\gamma, \boldsymbol{k}_{\perp g}, \boldsymbol{k}_{\perp \gamma}, \boldsymbol{k}_D)\ D_{D/c}(z, \boldsymbol{k}_D)$$

Gluon Sivers function

Denominator:

$$d\sigma^{\uparrow} + d\sigma^{\downarrow} \quad = \quad \frac{E_D\, d\sigma^{p^{\uparrow} l \to DX}}{d^3\boldsymbol{p}_D} + \frac{E_D\, d\sigma^{p^{\downarrow} l \to DX}}{d^3\boldsymbol{p}_D}$$

$$= 2 \int dx_g\, dx_\gamma\, dz\, d^2\boldsymbol{k}_{\perp g}\, d^2\boldsymbol{k}_{\perp \gamma}\, d^3\boldsymbol{k}_D\, \delta(\boldsymbol{k}_D \cdot \hat{\boldsymbol{p}}_c)\, \delta(\hat{s} + \hat{t} + \hat{u} - 2m_c^2)\, \mathcal{C}(x_g, x_\gamma, z, \boldsymbol{k}_D)$$

$$\times\ f_{g/p}(x_g, \boldsymbol{k}_{\perp g})\ f_{\gamma/l}(x_\gamma, \boldsymbol{k}_{\perp \gamma})\ \frac{d\hat{\sigma}^{g\gamma \to c\bar{c}}}{d\hat{t}}(x_g, x_\gamma, \boldsymbol{k}_{\perp g}, \boldsymbol{k}_{\perp \gamma}, \boldsymbol{k}_D)\ D_{D/c}(z, \boldsymbol{k}_D)$$

$$\Delta^N f_{g/p^{\uparrow}}(x_g, \boldsymbol{k}_{\perp g}) = \Delta^N f_{g/p^{\uparrow}}(x_g, k_{\perp g})\ \hat{S}(\mathbf{k}_{\perp g} \times \mathbf{P})$$

Parametrisation of unpolarised densities

- Unpolarised TMD:

$$f_{g/p}(x, \mathbf{k}_\perp; Q) = f_{g/p}(x, Q) \frac{1}{\pi \langle k_\perp^2 \rangle} e^{-k_\perp^2/\langle k_\perp^2 \rangle}$$

with $\langle k_\perp^2 \rangle = 0.25$ GeV^2 to be consistent with the use of DMP fits.

- TMD FF:

$$D_{D/c}(z, \mathbf{k}_D) = D_{D/c}(z) \frac{1}{\pi \langle k_{\perp D}^2 \rangle} e^{-k_D^2/\langle k_{\perp D}^2 \rangle}$$

with $\langle k_{\perp D}^2 \rangle = 0.25$ GeV^2

- Weizsacker-Williams distribution with Gaussian transverse-momentum spread:

$$f_{\gamma/l}(x, \mathbf{k}_\perp; s) = f_{\gamma/l}(x, s) \frac{1}{\pi \langle k_{\perp\gamma}^2 \rangle} e^{-k_{\perp g}^2/\langle k_{\perp\gamma}^2 \rangle}$$

with $\langle k_{\perp\gamma}^2 \rangle = 0.1$ GeV^2

Parametrisation of GSF

Gluon Sivers function:

$$\Delta^N f_{g/p^\uparrow}(x, k_\perp; Q) = 2\mathcal{N}_g(x) f_{g/p}(x, Q) \frac{\sqrt{2e}}{\pi} \sqrt{\frac{1-\rho}{\rho}} k_\perp \frac{e^{-k_\perp^2/\rho\langle k_\perp^2\rangle}}{\langle k_\perp^2\rangle^{3/2}}$$

(parametrisation used by D'Alesio, Murgia and Pisano in JHEP 09 (2015) 119)

- $\mathcal{N}_g(x)$ parametrises the x-dependence of the GSF:

$$\mathcal{N}_g(x) = N_g x^{\alpha_g} (1-x)^{\beta_g} \frac{(\alpha_g + \beta_g)^{\alpha_g + \beta_g}}{\alpha_g^{\alpha_g} \beta_g^{\beta_g}}$$

- Must obey $|\mathcal{N}_g(x)| < 1$ in order for the Sivers function to satisfy the positivity bound: $\Delta^N f_{g/p^\uparrow}(x, \mathbf{k}_\perp)/2 f_{g/p}(x, \mathbf{k}_\perp) \leq 1$
- $\rho \in (0,1)$ characterizes the $k_\perp$ dependence.

Parametrisation of GSF

We will look at the asymmetries from:

1. GSF with the positivity bound saturated, i.e., $\mathcal{N}_g(x) = 1$ and $\rho = 2/3$ — Upper bound on asymmetry for fixed width $\langle k_\perp^2 \rangle$.
2. SIDIS1 and SIDIS2 extractions of the Sivers function by DMP (JHEP 09, 119 (2015)).

SIDIS1	$N_g = 0.65$	$\alpha_g = 2.8$	$\beta_g = 2.8$	$\rho = 0.687$	$\langle k_\perp^2 \rangle = 0.25$ GeV^2
SIDIS2	$N_g = 0.05$	$\alpha_g = 0.8$	$\beta_g = 1.4$	$\rho = 0.576$	

Table: Parameters of the GSF fits by DMP.

SIDIS1 is larger in the moderate-x ($x > 0.08$) region, SIDIS2 is larger in the small-x ($x < 0.08$) region.

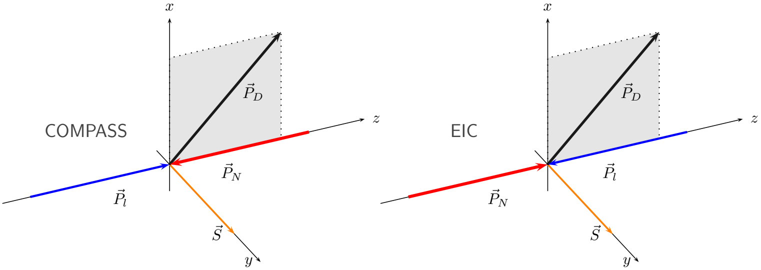
Results

We study the SSA for two experimental scenarios:

1. COMPASS: $\mu p^{\uparrow} \to D^0 + X$ at $\sqrt{s} = 17.4$ GeV.
2. The proposed Electron-Ion Collider (EIC): $p^{\uparrow} e \to D^0 + X$ at $\sqrt{s} = 140$ GeV.

Collinear gluon PDF: GRV98-LO, Charm FF: Kniehl and Kramer

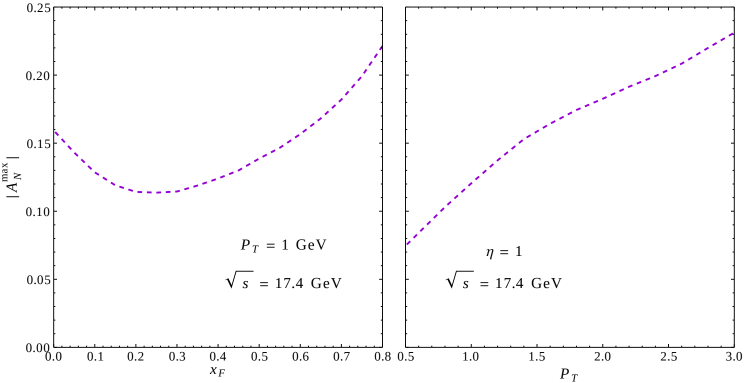
B.A. Kniehl and G. Kramer, Phys. Rev. D74, 037502 (2006), hep-ph/0607306



Conventions for $x_F, y > 0$ differ for the two experiments.

Results: COMPASS - $|A_N^{\max}|$

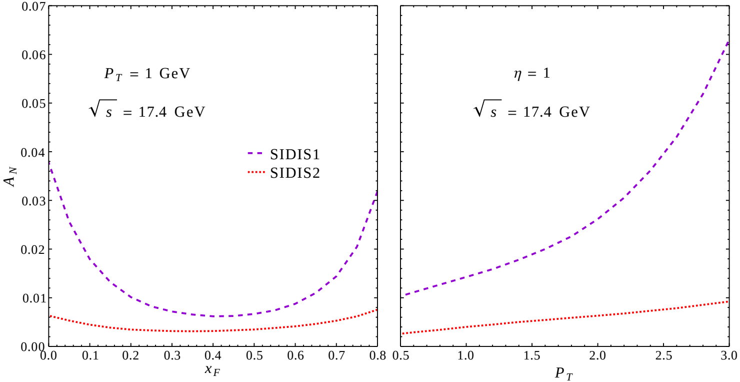
Positivity bound of the GSF saturated: $|A_N^{\max}|$



$|A_N^{\max}|$ at COMPASS as a function of x_F (at fixed $P_T = 1$ GeV, left panel) and P_T (at fixed $\eta = 1$, right panel).

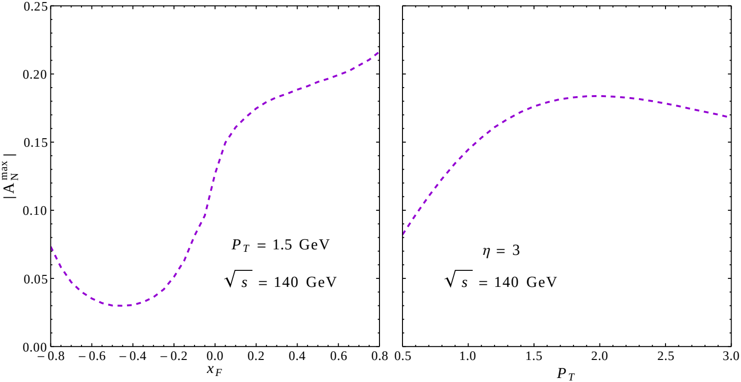
- $|A_N^{\max}|$ depends on $\langle k_\perp^2 \rangle$, not so much on $\langle k_{\perp D}^2 \rangle$.

Results: COMPASS - DMP fits



- Both fits give asymmetries much smaller than allowed by the positivity bound.
- SIDIS1 gives A_N on the level of a few percent.
- SIDIS2 gives A_N of sub-percent level.
- Kinematic regions considered gets contributions from $0.08 < x_g < 0.5$ where SIDIS1 is much larger than SIDIS2.

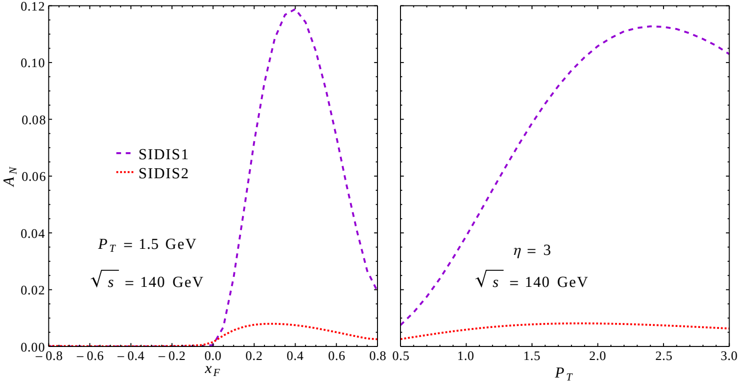
Results: EIC - $|A_N^{\text{max}}|$



$|A_N^{\text{max}}|$ at EIC as a function of x_F (at fixed $P_T = 1.5$ GeV, left panel) and P_T (at fixed $\eta = 3$, right panel).

- c.o.m energy close to that of RHIC — similar results
- A_N suppressed in the backward region

Results: EIC - DMP fits



SSA from DMP fits at EIC as a function of x_F (at fixed P_T, left panel) and P_T (at fixed η, right panel).

- Probe can discriminate between SIDIS1 and SIDSI2.

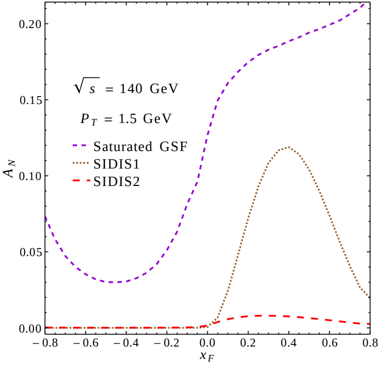
Results: EIC - A_N^μ

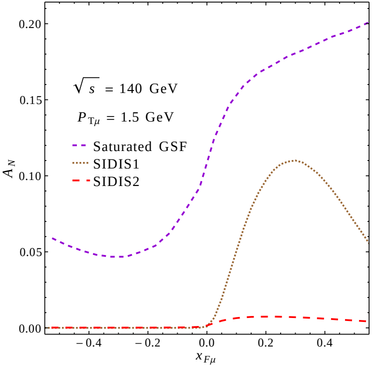
SSA in decay-muons: The proposed ePHENIX detector would be able to study open-charm production through the semileptonic decay channels.

We considered the two possible 3-body decays to muons:

- $D^0 \to K^- \mu^+ \nu_\mu$ with BR $= 3.2\%$
- $D^0 \to K^{*-} \mu^+ \nu_\mu$ with BR $= 1.9\%$

Results: EIC - A_N^{μ}





$(x_{F\,\mu} = 2P_L^{\mu}/\sqrt{s})$

- Asymmetry significantly retained in decay-muons.
- x_F-dependence similar.
- Peak asymmetry values remain almost unchanged.

Conclusions: $p^{\uparrow}l \rightarrow D + X$

The low-virtuality leptoproduction of open-charm can be a clean and direct channel to constrain the GSF.

- The probe should be able to (with enough data) discriminate between the two available fits in literature.
- SSA is significantly retained in the decay-muons.

Thank you!

Additional slides

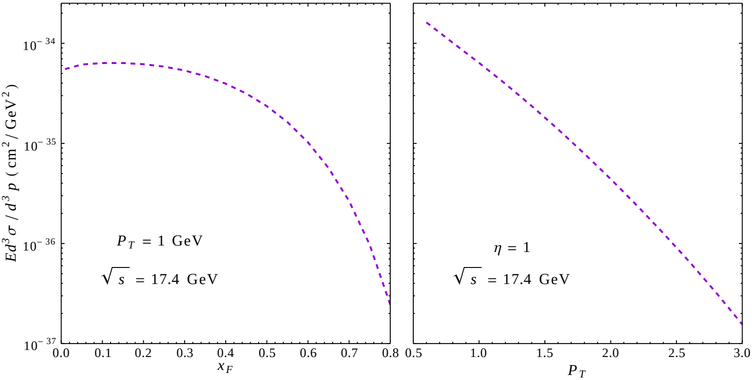


Figure: Unpolarized cross-section at COMPASS as a function of x_F (at fixed P_T, left panel) and P_T (at fixed η, right panel).

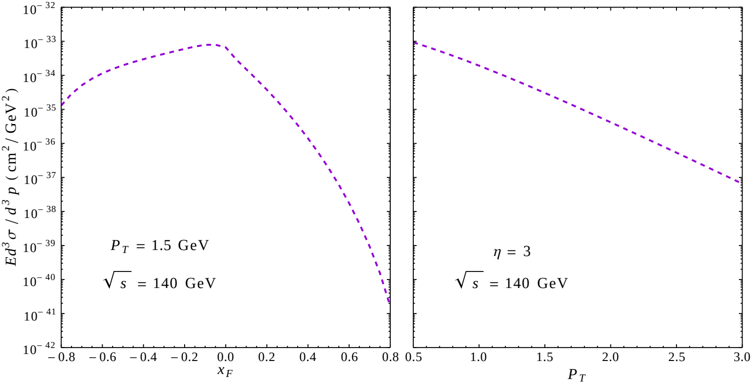


Figure: Unpolarized cross-section at EIC as a function of x_F (at fixed P_T, left panel) and P_T (at fixed η, right panel).