On transverse single-spin asymmetries in D-meson production at the SPD NICA experiment

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Outline

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   - Numerical results. Predictions for NICA
3. Summary

Generalized Parton Model (GPM) and it's application to calculation of SSA

Factorization schemes in different p_T-regions

The traditional Collinear Parton Model (CPM) is applicable in a region of high-p_T production

$$\mu \sim p_T \gg \Lambda_{QCD},$$

so we can neglect influence of small intrinsic $\mathbf{q_T}$ of initial partons $(\langle q_T^2 \rangle \simeq 1 \text{ GeV}^2)$.

But if we're interested in particle production in a region of $p_T \simeq \sqrt{\langle q_T^2 \rangle} \ll \mu$, we should take into account intrinsic q_T. It can be done within TMD approach, factorization for which has been proven in the limit $q_T \ll \mu$ [J. Collins, Camb. Monogr., Part. Phys. Nucl. Phys. Cosmol. 32, 1-624 (2011)]. In our case, the hard scale μ is given by $m_{cT} = \sqrt{m_c^2 + p_T^2}$ with c-quark mass $m_c = 1.2$ GeV. We use a phenomenological TMD-ansatz, a so called Generalized Parton Model (GPM), initial partons in which are on-shell:

$$q_\mu = xP_\mu^+ + yP_\mu^- + q_{T\mu}, (q_\mu)^2 = 0, \tag{1}$$

and a factorized prescription for TMD parton distribution functions (PDFs) is used:

$$F_a(x, q_T, \mu_F) = f_a(x, \mu_F) G_a(q_T), \tag{2}$$

where $f_a(x, \mu_F)$ – corresponding CPM PDF, $G_a(q_T)$ – Gaussian distribution $G_a(q_T) = \exp(-q_T^2 / \langle q_T^2 \rangle_a) / (\pi \langle q_T^2 \rangle_a)$.

Factorization formula for the GPM

Within the GPM we can write the following expression for the differential cross-section of $2 \to 2$ subprocess $a(q_1) + b(q_2) \to c(k) + \bar{c}(q_3)$:

$$d\hat{\sigma}(ab \to c\bar{c}) = (2\pi)^4 \delta^{(4)}(q_1+q_2-k-q_3) \frac{\overline{|M(ab \to c\bar{c})|^2}}{2x_1 x_2 s} \frac{d^3k}{(2\pi)^3 2k_0} \frac{d^4 q_3}{(2\pi)^3} \delta_+(q_3^2), \quad (3)$$

where we consider gg and $q\bar{q}$ as initial partons ab, respectively.
Four-momenta of initial partons are on mass-shell ($q_1^2 = q_2^2 = 0$) and have longitudinal (along the Z-axis) and transverse parts:

$$q_1^\mu = \left(x_1 \frac{\sqrt{s}}{2} + \frac{\mathbf{q}_{1T}^2}{2\sqrt{s}x_1}, \mathbf{q}_{1T}, x_1 \frac{\sqrt{s}}{2} - \frac{\mathbf{q}_{1T}^2}{2\sqrt{s}x_1} \right)^\mu, \quad (4)$$

$$q_2^\mu = \left(x_2 \frac{\sqrt{s}}{2} + \frac{\mathbf{q}_{2T}^2}{2\sqrt{s}x_2}, \mathbf{q}_{2T}, -x_2 \frac{\sqrt{s}}{2} + \frac{\mathbf{q}_{2T}^2}{2\sqrt{s}x_2} \right)^\mu. \quad (5)$$

Single Spin Asymmetry

$$F_g^{\uparrow}(x, q_T, \mu_F) = F_g(x, q_T, \mu_F) + \frac{1}{2}\Delta^N F_g^{\uparrow}(x, q_T, \mu_F)\mathbf{S}\cdot(\hat{\mathbf{P}}\times\hat{\mathbf{q}}_T). \quad (6)$$

In inclusive process $p^{\uparrow}p \to DX$ SSA is defined as:

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{d\Delta\sigma}{2d\sigma}. \quad (7)$$

The numerator and denominator of A_N have the form:

$$d\Delta\sigma \propto \int dx_1 \int d^2q_{1T} \int dx_2 \int d^2q_{2T} \int dz \left[\hat{F}_g^{\uparrow}(x_1, \mathbf{q}_{1T}, \mu_F) - \hat{F}_a^{\downarrow}(x_1, \mathbf{q}_{1T}, \mu_F)\right]\times$$
$$\times F_b(x_2, q_{2T}, \mu_F) d\hat{\sigma}(ab \to c\bar{c}X) D_{D/c}(z, \mu_F), \quad (8)$$
$$d\sigma \propto \int dx_1 \int d^2q_{1T} \int dx_2 \int d^2q_{2T} \int dz F_a(x_1, q_{1T}, \mu_F) F_b(x_2, q_{2T}, \mu_F)\times$$
$$\times d\hat{\sigma}(ab \to c\bar{c}X) D_{D/c}(z, \mu_F), \quad (9)$$

where $\hat{F}_a^{\uparrow,\downarrow}(x, q_T, \mu_F)$ is the distribution of unpolarized parton a in polarized proton and $D_{D/c}(z, \mu_F)$ is D-meson fragmentation function (FF) with light-cone momentum fraction $z = p_D^+/k_c^+$.
Following the Trento conventions [A. Bacchetta, U. DAlesio, M. Diehl and C. A. Miller, Phys. Rev. D **70**, 117504 (2004)], the Sivers function can be introduced as

$$\Delta\hat{F}_a^{\uparrow}(x_1, \mathbf{q}_{1T}, \mu_F) \equiv \hat{F}_a^{(\uparrow)}(x_1, \mathbf{q}_{1T}, \mu_F) - \hat{F}_a^{(\downarrow)}(x_1, \mathbf{q}_{1T}, \mu_F) =$$
$$= \Delta^N F_a^{\uparrow}(x_1, \mathbf{q}_{1T}^2, \mu_F)\cos(\phi_1) \equiv \left(-2\frac{q_{1T}}{M_p}\right) F_{1T}^{\perp a}(x_1, \mathbf{q}_{1T}^2, \mu_F)\cos(\phi_1). \quad (10)$$

Fragmentation approach

In the fragmentation approach [D'Alesio *et.al.*, Phys. Rev. D **70**, 074009 (2004)], the cross-section of the inclusive production of D-meson is related with the partonic cross-section as follows:

$$E_D \frac{d\sigma}{d^3 p_D} \left(a + b \to D_{D/c}(p) + X\right) = \int\limits_0^1 dz J(z) D_{D/c}(z, \mu^2) E_c \frac{d\hat{\sigma}}{d^3 k_c} \left(a + b \to c(k_c) + X\right), \quad (11)$$

where $D_{D/c}(z, \mu^2)$ – FF of c-quark to D meson, light-cone momentum fraction of D meson is defined as $z = p_D^+/k_c^+$ and $J(z)$ – Jacobian, which connects phase-spaces of c-quark and D-meson and is defined through $\frac{d^3 k_c}{E_c} = J(z) \frac{d^3 p_D}{E_D}$ (then for massless particles it is just $\frac{1}{z^2}$).

In collinear case (where $\frac{\vec{k}_c}{k_c} = \frac{\vec{p}_D}{p_D}$) $J(z) = \frac{k_c}{p_D} \frac{dE_c}{dE_D}$. Then for $E_c = \frac{E_D + p_D}{2z} \left[1 + \frac{m_c^2 z^2}{(E_D + p_D)^2}\right]$ and $k_{Tc} = p_{TD} \frac{|\vec{k}_c|}{|\vec{p}_D|} = p_{TD} \frac{\sqrt{E_c^2 - m_c^2}}{\sqrt{E_D^2 - m_D^2}}$ Jacobian is:

$$J(z) = \frac{(E_D + p_D)^2}{4 p_D^2 z^2} \left[1 - \frac{m_c^2 z^2}{(E_D + p_D)^2}\right]^2. \quad (12)$$

Fragmentation function

In our analysis we use the phenomenological FF of Peterson in the following form [C. Peterson *et.al.*, Phys. Rev. D **27**, 105 (1983)]:

$$D_{D/c}(z) = \frac{N}{[1 - 1/z - \epsilon/(1-z)]^2}, \tag{13}$$

which satisfies normalization condition:

$$\int dz D_{D/c}(z) = 1. \tag{14}$$

For the Peterson parametrization we take $\epsilon = 0.06$.

Single Spin Asymmetry in the CGI-GPM framework

In GPM we can write the numerator of the asymmetry as follows:

$$d\Delta\sigma \propto \left(-2\frac{q_{1T}}{M_p}\right) F_{1T}^{\perp a}(x_1, \mathbf{q}_{1T}^2, \mu_F)\cos(\phi_1) \otimes F_b(x_2, q_{2T}, \mu_F)\otimes$$
$$\otimes H^U_{ab\to c\bar{c}} \otimes D_{D/c}(z, \mu_F), \quad (15)$$

where $H^U_{ab\to c\bar{c}} = \overline{|M(ab \to c\bar{c})|^2}$ and pair of initial partons ab can be gg or $q\bar{q}$.

Figure 1 : Example diagrams for contributions to the numerator of TSSA in CGI-GPM for $gg \to c\bar{c}$-process. Left panel: ISI, right panel: FSI

Formally, the numerator of the asymmetry in the CGI-GPM approach ([L. Gamberg and Z.-B. Kang, Phys. Lett. B **696**, 109 (2011); D'Alesio *et.al.*, Phys. Rev. D **96**, 036011 (2017)]) can be obtained from eq. (15) with the substitution:

$$F_{1T}^{\perp a} H^U_{ab\to c\bar{c}} \to$$
$$\to \frac{C_I^{(f)} + C_{F_c}^{(f)} + C_{F_{\bar{c}}}^{(f)}}{C_U} F_{1T}^{\perp a(f)} H^U_{ab\to c\bar{c}} + \frac{C_I^{(d)} + C_{F_c}^{(d)} + C_{F_{\bar{c}}}^{(d)}}{C_U} F_{1T}^{\perp a(d)} H^U_{ab\to c\bar{c}} \equiv$$
$$\equiv F_{1T}^{\perp a(f)} H^{Inc(f)}_{ab\to c\bar{c}} + F_{1T}^{\perp a(d)} H^{Inc(d)}_{ab\to c\bar{c}}. \quad (16)$$

Color factors and Feynman rules in the CGI-GPM framework

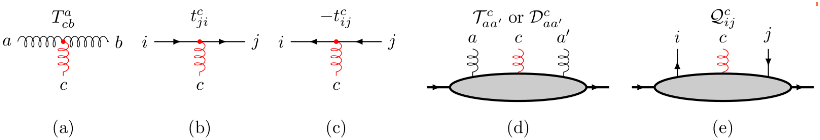

Figure 2 : CGI-GPM color rules for the eikonal three-gluon (a), quark-gluon (b) and antiquark-gluon (c) vertices. The color projectors for the gluon (d) and the quark Sivers functions (e) are shown as well. The eikonal gluon has color index c. Figure is from [D'Alesio *et.al.*, Phys. Rev. D **96**, 036011 (2017)].

The color factors are:

$$\mathcal{T}^c_{aa'} = \mathcal{N}_\mathcal{T} T^c_{aa'}, \mathcal{D}^c_{aa'} = \mathcal{N}_\mathcal{D} D^c_{aa'}, \mathcal{Q}^c_{ij} = \mathcal{N}_\mathcal{Q} t^c_{ij}, \qquad (17)$$

where $T^a_{cb} \equiv -if_{acb}$, $D^a_{bc} \equiv d_{abc}$, $\mathcal{N}_\mathcal{T} = \frac{1}{Tr[T^c T^c]} = 1/(N_c(N_c^2-1))$, $\mathcal{N}_\mathcal{D} = \frac{1}{Tr[D^c D^c]} = 1/((N_c^2-4)(N_c^2-1))$, $\mathcal{N}_\mathcal{Q} = \frac{1}{Tr[t^c t^c]} = 2/(N_c^2-1)$.

Matrix elements within the CGI-GPM

Using the Feynman rules of the CGI-GPM, following matrix elements can be obtained (see, e.g., [D'Alesio *et.al.*, Phys. Rev. D **96**, 036011 (2017)]):

$$H^{Inc}_{q\bar{q}\to c\bar{c}} = -H^{Inc}_{\bar{q}q\to\bar{c}c} = \frac{N_c^2-1}{2N_c^2}\left(\frac{\tilde{t}^2+\tilde{u}^2+2m_c^2\tilde{s}}{\tilde{s}^2}\right), \quad (18)$$

$$H^{Inc}_{q\bar{q}\to\bar{c}c} = -H^{Inc}_{\bar{q}q\to c\bar{c}} = \frac{3}{2}\frac{1}{N_c^2}\left(\frac{\tilde{t}^2+\tilde{u}^2+2m_c^2\tilde{s}}{\tilde{s}^2}\right), \quad (19)$$

$$H^{Inc(f)}_{gg\to c\bar{c}} = -H^{Inc(f)}_{gg\to\bar{c}c} = -\frac{N_c}{4(N_c^2-1)}\frac{1}{\tilde{t}\tilde{u}}\left(\frac{\tilde{t}^2}{\tilde{s}^2}+\frac{1}{N_c^2}\right)\left(\tilde{t}^2+\tilde{u}^2+4m_c^2\tilde{s}-\frac{4m_c^4\tilde{s}^2}{\tilde{t}\tilde{u}}\right), \quad (20)$$

$$H^{Inc(d)}_{gg\to c\bar{c}} = -H^{Inc(d)}_{gg\to\bar{c}c} = -\frac{N_c}{4(N_c^2-1)}\frac{1}{\tilde{t}\tilde{u}}\left(\frac{\tilde{t}^2-2\tilde{u}^2}{\tilde{s}^2}+\frac{1}{N_c^2}\right)\left(\tilde{t}^2+\tilde{u}^2+4m_c^2\tilde{s}-\frac{4m_c^4\tilde{s}^2}{\tilde{t}\tilde{u}}\right), \quad (21)$$

where $\tilde{s}=(q_1+q_2)^2$, $\tilde{t}=(q_1-k)^2-m_c^2$, $\tilde{u}=(q_1-q_3)^2-m_c^2$.

SSA in D-meson production at SPS and NICA

LEBC-EHS data, $0 \leq y \leq 4$, $\sqrt{S} = 27.4$ GeV.

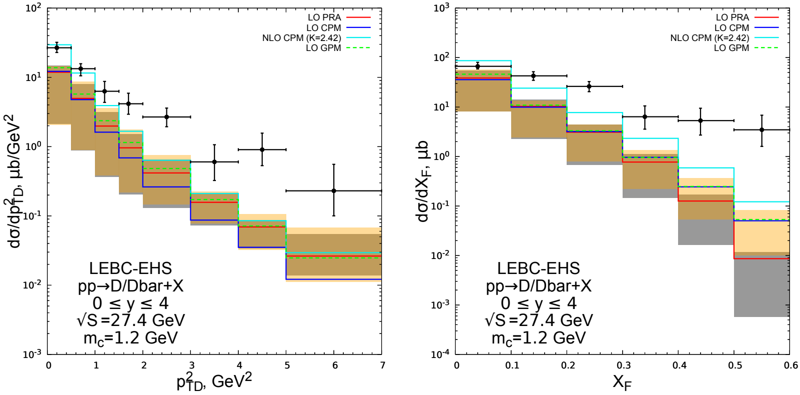

Figure 3 : Differential cross sections $d\sigma/dp_T^2$ and $d\sigma/dx_F$ at $\sqrt{s} = 27.4$ GeV of $D^0/\bar{D}^0 + D^+/D^-$ mesons. Phenomenological fragmentation function of Peterson with $\epsilon = 0.06$ and $N = f(c \to D^0) + f(c \to D^+) = 0.767$ is used [Gladilin L., Eur. Phys. J. C **75** (2015) 19]. Here NLO CPM means LO CPM with K-factor 2.42 [Int. J. Mod. Phys. E **12**, 211-269 (2003)]. Experimental data are from Ref. [M. Aguilar-Benitez *et al.* [LEBC-EHS Collaboration], Phys. Lett. B **189**, no. 4, 476 (1987)].

LEBC-EHS data, $0 \leq y \leq 4$, $\sqrt{S} = 27.4$ GeV.

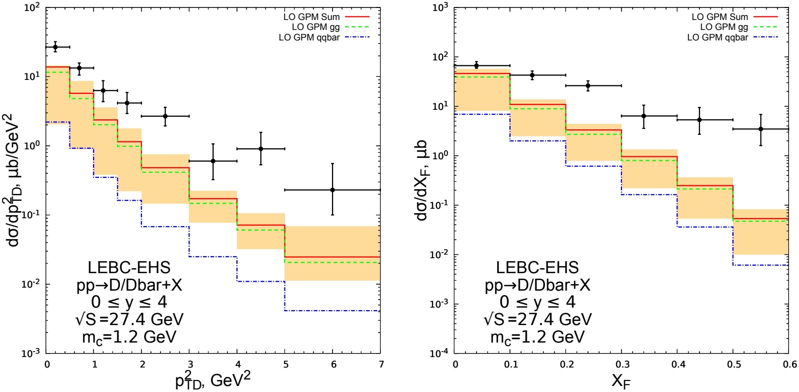

Figure 4 : Contributions of subprocesses $gg \to c[\to D]\bar{c}$ and $q\bar{q} \to c[\to D]\bar{c}$ within the GPM. Experimental data are from Ref. [M. Aguilar-Benitez *et al.* [LEBC-EHS Collaboration], Phys. Lett. B **189**, no. 4, 476 (1987).

Predictions for D-meson cross sections at NICA, $|y| \leq 3$, $\sqrt{S} = 27$ GeV.

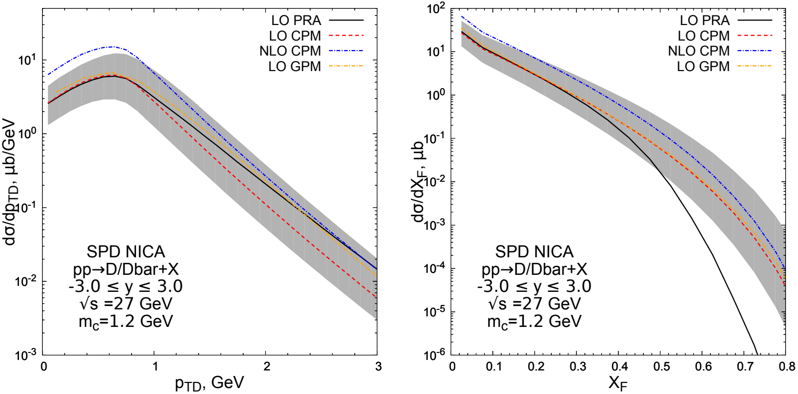

Figure 5 : Predictions for differential cross sections $d\sigma/dp_T$ and $d\sigma/dx_F$ on SPD NICA. Phenomenological fragmentation function of Peterson with $\epsilon = 0.06$ and $N = f(c \to D^0) + f(c \to D^+) + f(c \to D_s^+) = 0.859$ is used [Gladilin L., Eur. Phys. J. C **75** (2015) 19]. Here NLO CPM means LO CPM with K-factor 2.42 [R. Vogt, Int. J. Mod. Phys. E **12**, 211-269 (2003)].

Predictions for SSA of D-meson production at SPD NICA, $|y| \leq 3$, $\sqrt{S} = 27$ GeV.

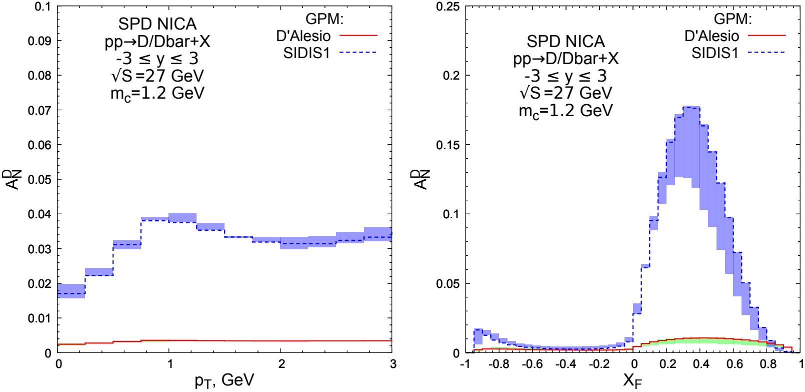

Figure 6 : Predictions for SSA on SPD NICA within the GPM. Phenomenological fragmentation function of Peterson with $\epsilon = 0.06$ and $N = f(c \to D^0) + f(c \to D^+) + f(c \to D_s^+) = 0.859$ is used [Gladilin L., Eur. Phys. J. C **75** (2015) 19].

Predictions for SSA of D-meson production at SPD NICA, $|y| \leq 3$, $\sqrt{S} = 27$ GeV.

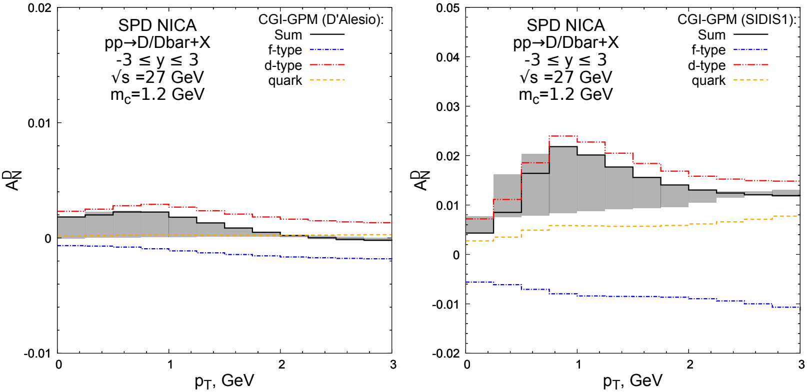

Figure 7 : Predictions for SSA on SPD NICA as function of p_T within the CGI-GPM and parametrizations of D'Alesio (*et. al.*) (left) and SIDIS1 (right). Phenomenological fragmentation function of Peterson with $\epsilon = 0.06$ and $N = f(c \to D^0) + f(c \to D^+) + $ $+ f(c \to D_s^+) = 0.859$ is used [Gladilin L., Eur. Phys. J. C **75** (2015) 19].

Predictions for SSA of D-meson production at SPD NICA, $|y| \leq 3$, $\sqrt{S} = 27$ GeV.

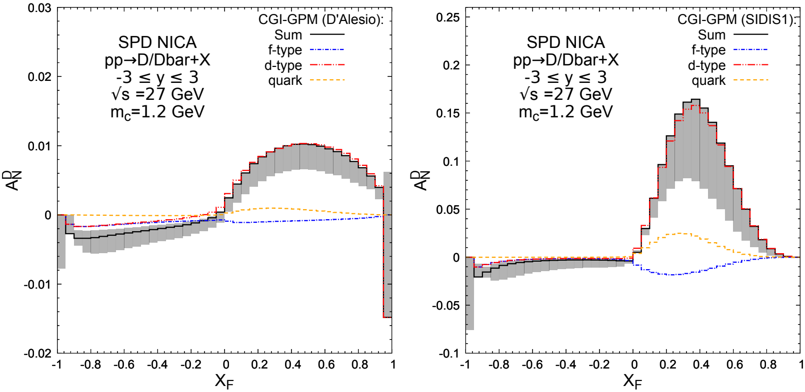

Figure 8 : Predictions for SSA on SPD NICA as function of x_F within the CGI-GPM and parametrizations of D'Alesio (*et. al.*) (left) and SIDIS1 (right). Phenomenological fragmentation function of Peterson with $\epsilon = 0.06$ and $N = f(c \to D^0) + f(c \to D^+) + $ $+ f(c \to D_s^+) = 0.859$ is used [Gladilin L., Eur. Phys. J. C **75** (2015) 19].

Summary

- For LEBC-EHS data we observe a significant underestimation within CPM, GPM and PRA. This underestimation is about factor 2.4 and can be potentially connected to the necessity of taking into account the NLO corrections.
- We found that within both the GPM and the CGI-GPM SIDIS1-parametrization predicts much bigger asymmetry than the D'Alesio parametrization. The CGI-GPM predicts less asymmetry, than the GPM.
- Within the CGI-GPM a contribution of the quark Sivers function (positive) to the D-meson SSA as well as contribution of the gluon Sivers function of f-type (negative) is almost negligible (on an absolute value). Moreover, for the total SSA these two contributions almost cancel each other. In the same time contribution of the gluon Sivers function of d-type is the dominant one.

Thank you for your attention!