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PHYSICS OF ELEMENTARY PARTICLES AND ATOMIC NUCLEI. THEORY

On Transverse Single-Spin Asymmetries in *D*-Meson Production at the SPD NICA Experiment

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Abstract—In the present study we are interested in the Sivers effect in process $p^{\uparrow}p \to DX$. We calculate the transverse single-spin asymmetry (TSSA) of D-meson production within two phenomenological models, namely the Generalized Parton Model (GPM) and it's Colour Gauge-Invariant formulation (CGI-GPM), which takes into account the transverse momenta of initial partons. The last one allows us to study process-independent Sivers functions. To predict production cross-section of D-mesons we use a fragmentation approach with scale-independent Peterson fragmentation function, taking in mind nonzero masses of c-quark and D-mesons. Estimates for the TSSAs, as a function of transverse momentum and Feynman variable $x_{\rm F}$ of D-meson, within the conditions of the planned SPD NICA experiment are presented for the first time.

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INTRODUCTION

To the present time a problem of description of a proton three-dimensional structure and its spin properties remain unsolved. The Transverse Momentum Dependent (TMD) Parton Distribution Functions (PDFs) can allow us access to that information [1, 2]. One of the widely used instruments for investigation of proton spin structure in collisions $p^{\uparrow}p \to hX$ of polarized protons with the unpolarized ones is a Sivers effect [3, 4].

A Sivers function provides access to the density of unpolarized gluons g (or quarks q) with intrinsic transverse-momentum $\mathbf{q}_{\rm T}$ inside a transversely polarized proton $p^{\uparrow}$, with three-momentum $\mathbf{P}$ and spin polarization vector $\mathbf{S}$,

$$F_g^{\uparrow}(x,\mathbf{q}_{\rm T}) = F_{\rm g}(x,q_{\rm T}) + \frac{1}{2}\Delta^N F_{\rm g}^{\uparrow}(x,q_{\rm T})\mathbf{S}\cdot(\hat{\mathbf{P}}\times\hat{\mathbf{q}}_{\rm T}), \quad (1)$$

where x is the proton light-cone momentum fraction carried by the gluon, $F_{\rm g}(x,q_{\rm T})$ is the unpolarised TMD parton density, $\Delta^N F_{\rm g}^{\uparrow}(x,q_{\rm T})$ is the Sivers function, $q_{\rm T} = |\mathbf{q}_{\rm T}|$ and symbol (^) denotes a unit vector, $\hat{\mathbf{a}} = \mathbf{a}/|\mathbf{a}|$.

In the present work we study the Sivers effect in the production of D-mesons at the NICA collider, which in perspective can allow us to refine parameters of a gluon Sivers function (GSF) through measurements of the TSSA.

THEORETICAL MODELS

When we are interested in the production of final-state particles with transverse momenta much smaller than the hard scale of the reaction $\mathbf{k}_{\rm T} \ll \mu$ (which is set by a heavy final state), we already can't neglect small momenta of initial-state particles $\sqrt{\langle \mathbf{q}_{\rm T}^2\rangle} \simeq |\mathbf{k}_{\rm T}|$. So the collinear parton model (CPM) is no longer applicable in that region. The TMD-factorization is proven in the limit of small transverse momenta of final-state particles, so it is more relevant in the region $\mathbf{k}_{\rm T} \ll \mu$ [5]. For the phenomenological purposes a Generalized Parton Model (GPM) can be applied as a simplified version of TMD-factorization even in processes for which TMD factorization has not been rigorously proven yet.

The main idea of the GPM is that the TMD PDFs can be parametrized by a simple factorized ansatz:

$$F_a(x,q_{\rm T},\mu_{\rm F}) = f_a(x,\mu_{\rm F})G_a(q_{\rm T}), \quad (2)$$

where $f_a(x,\mu_{\rm F})$ is corresponding collinear PDF for parton "a", and the dependence on transverse parton momentum is described by a Gaussian distribution $G_a(q_{\rm T}) = \exp[-q_{\rm T}^2/\langle q_{\rm T}^2\rangle_a]/(\pi\langle q_{\rm T}^2\rangle_a)$ with normalization condition $\int d^2q_{\rm T}G_a(q_{\rm T}) = 1$.

Such a way, a master-formula for the differential cross section of production of heavy final state $\mathcal{C}$ in collision of two protons can be written as:

$$d\sigma(pp \to \mathcal{C}X) = \int dx_1 \int d^2\mathbf{q}_{1T} \int dx_2 \int d^2\mathbf{q}_{2T} \times F_a(x_1, \mathbf{q}_{1T}, \mu_F) F_b(x_2, \mathbf{q}_{2T}, \mu_F) d\hat{\sigma}, \quad (3)$$

where $d\hat{\sigma}$ is the partonic cross section for $ab \to \mathcal{C}X$ partonic subprocess.

The TSSA under study in the present paper for the process $p^{\uparrow}p \to DX$ has the following standard definition:

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{d\Delta\sigma}{2d\sigma}. \quad (4)$$

The numerator and denominator of A_N have the form:

$$d\Delta\sigma \propto \int dx_1 \int d^2q_{1\mathrm{T}} \int dx_2 \int d^2q_{2\mathrm{T}} \int dz \times [\hat{F}_{\mathrm{g}}^{\uparrow}(x_1, q_{1\mathrm{T}}, \mu_{\mathrm{F}}) - \hat{F}_a^{\downarrow}(x_1, q_{1\mathrm{T}}, \mu_{\mathrm{F}})] \times F_{\mathrm{b}}(x_2, q_{2\mathrm{T}}, \mu_{\mathrm{F}}) d\hat{\sigma}(ab \to c\bar{c}X) D_{D/c}(z, \mu_{\mathrm{F}}), \quad (5)$$

$$d\sigma \propto \int dx_1 \int d^2q_{1\mathrm{T}} \int dx_2 \int d^2q_{2\mathrm{T}} \int dz F_a \times (x_1, q_{1\mathrm{T}}, \mu_{\mathrm{F}}) F_{\mathrm{b}}(x_2, q_{2\mathrm{T}}, \mu_{\mathrm{F}}) \times d\hat{\sigma}(ab \to c\bar{c}X) D_{D/c}(z, \mu_{\mathrm{F}}), \quad (6)$$

where $\hat{F}_a^{\uparrow,\downarrow}(x, q_{\mathrm{T}}, \mu_{\mathrm{F}})$ is the distribution of unpolarized parton a in polarized proton and $D_{D/c}(z, \mu_{\mathrm{F}})$ is D-meson fragmentation function (FF) with light-cone momentum fraction is defined as $z = p_D^+ / k_c^+$ [6]. Here as a hadronization model we use a fragmentation approach, which involves a mass of a charm quark [6]. To describe a fragmentation of the charm quark we use a phenomenological Peterson's FF [7] with parameter $\epsilon_c = 0.06$.

Within the standard GPM though the GSF is assumed to be a process dependent. The problem is solved by involving the effects of initial-state interaction (ISI) and final-state interaction (FSI) through an additional gluon exchange [8, 9]. In the case of gluon Sivers effect, the process-dependent GSF can be presented as a linear combination of two independent and universal GSFs of f-type ($F_{1\mathrm{T}}^{g(f)}$) and d-type ($F_{1\mathrm{T}}^{g(d)}$) corresponding to two independent ways of combining three gluons into a color singlet. The coupling of additional "eikonal" gluon from the GSF to the hard process leads only to modification of the color structure of the latter one.

A similar study we have already performed for a production of another heavy final state—J/ψ mesons [10]. But charmonia production is not the only channel for the GSF measurements at the NICA collider, and in the following section we provide a predictions of the A_N for the D-meson production as another probe of the GSF.

NUMERICAL PREDICTIONS FOR THE NICA FACILITY

Here we present our theoretical results for the TSSA A_N^D of the D-meson production within the kinematics of the SPD NICA experiment. These kinematic conditions define the total collision energy as $\sqrt{s} = 27$ GeV, the rapidity of produced D-mesons must be in the interval $|y_D| < 3$ and the transverse momentum of D-meson $0 < p_{\mathrm{T}} < 3$ GeV. We calculate the TSSA as a function of the transverse momentum p_T and the Feynman variable x_{F} of the produced D-meson. In all our calculations we take into account a charm quark mass equal to $m_{\mathrm{c}} = 1.2$ GeV.

The renormalization and factorization scales we define to be equal to $\mu_{\mathrm{F}} = \mu_{\mathrm{R}} = \xi\sqrt{k_{\mathrm{T}}^2 + m_{\mathrm{c}}^2}$, where k_{T} is the transverse momentum of a charm quark. To estimate theoretical uncertainties, which come from the arbitrariness in a choice of the hard scale, we vary the parameter ξ in a closed interval $1/2 \leq \xi \leq 2$. The uncertainties are shown on our plots as shaded bands.

In Fig. 1 we compare the predictions of TSSA within the GPM in two different parametrizations of the GSF, namely a parametrization of D'Alesio with co- uthors [11] (red solid line) and the SIDIS1 parametrization [12] (blue dashed line). We note that TSSA in SIDIS1 parametrization is significantly larger than one in D'Alesio parametrization.

The predictions of the TSSA within the CGI-GPM are presented on Figs. 2 and 3. On the first one, the TSSA is shown as a function of the transverse momentum of D-meson, while on the second one the TSSA is a function of x_{F}. On the left panels of corresponding figures, we put the TSSA in D'Alesio parametrization of the GSF, and plots on the right panels correspond to the TSSA in the SIDIS1 parametrization. By orange dashed lines we depicted a contribution of a quark Sivers function to the TSSA. Blue dash-dotted lines correspond to the *f*-type of the GSF, while red double-dot-dashed lines correspond to the *d*-type of the GSF. Black solid lines are the sum of all the contributions, and shaded bands show summary uncertainties.

The predictions of the CGI-GPM allow negative values for the TSSA, while the GPM predicts strictly positive ones. Moreover, we should note that the *d*-type GSF within the CGI-GPM is the dominant one, and the other two contributions almost cancel each other. We see also that as the GPM, as the CGI-GPM show that the TSSA in D'Alesio parametrization of the GSF is much smaller than the one in SIDIS1. Precise experimental measurements can in principle allow us to choose a more relevant parame-

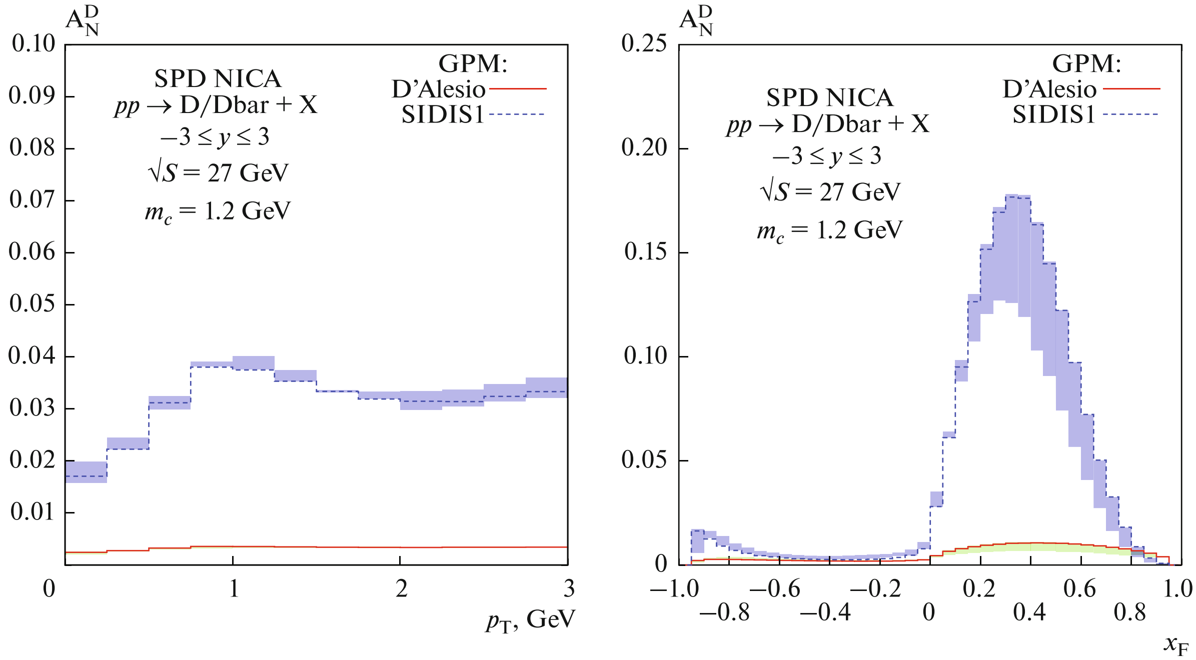

Fig. 1. Predictions for TSSA on SPD NICA within the GPM as a function of transverse momentum (left panel) and x_F (right panel) of D-meson. The TSSA in D'Alesio parametrization is shown by a red solid line, SIDIS1—by a blue dashed line.

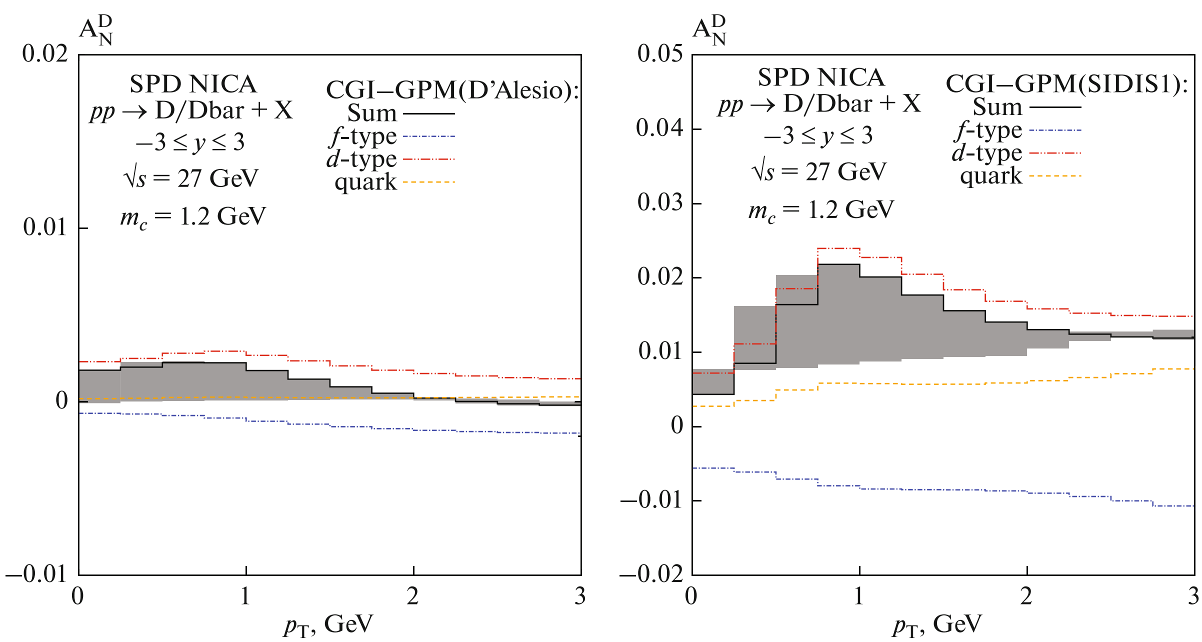

Fig. 2. Predictions for TSSA on SPD NICA within the CGI-GPM as a function of p_T of D-meson with the D'Alesio parametrization (left panel) and SIDIS1 parametrization (right panel) of the GSF. Orange dashed lines stands for contribution of the quark Sivers function, blue dash-dotted lines—for contribution of the f-type GSF, and red double-dot-dashed lines—for the d-type GSF.

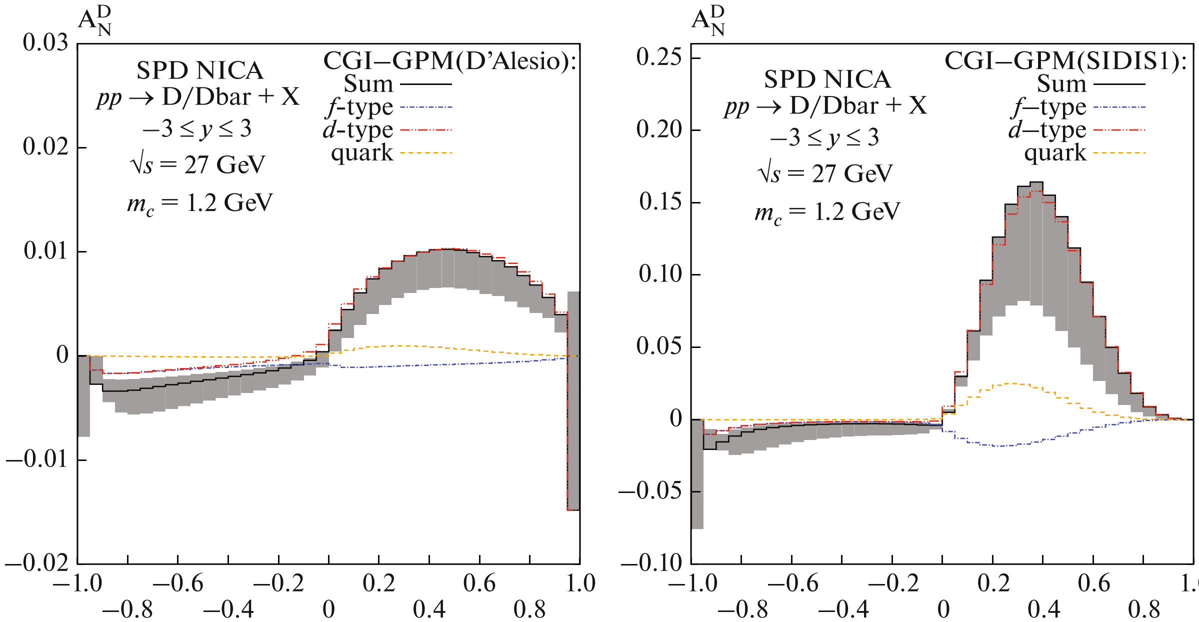

Fig. 3. Predictions for TSSA on SPD NICA within the CGI-GPM as a function of x_F of D-meson with the D'Alesio parametrization (left panel) and SIDIS1 parametrization (right panel) of the GSF. The notations are the same as in Fig. 2.

trization of the GSF within both the GPM and the CGI-GPM.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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