ISSN 1547-4771, Physics of Particles and Nuclei Letters, 2023, Vol. 20, No. 3, pp. 400–403. © Pleiades Publishing, Ltd., 2023.
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PHYSICS OF ELEMENTARY PARTICLES AND ATOMIC NUCLEI. THEORY

Double Longitudinal-Spin Asymmetries in Direct Photon Production at NICA

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Received October 27, 2022; revised November 25, 2022; accepted December 5, 2022

Abstract—In this paper we calculate double longitudinal-spin asymmetries in the direct photon production at the NICA collider in the leading order of the collinear parton model. Predictions for potential measurements of asymmetries are presented at different energies of the NICA collider.

DOI: 10.1134/S1547477123030597

INTRODUCTION

The study of double longitudinal spin asymmetries (DLSAs) in the production of direct photons, jets, and charged pions is required to study the contribution of quark and gluon polarization to the total proton spin:

$$\frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g = \frac{1}{2}, \quad (1)$$

$$\Delta\Sigma = \sum_{q=u,d,s}\int_0^1 \Delta q(x)dx, \quad \Delta G = \int_0^1 \Delta g(x)dx, \quad (2)$$

where $L_q(L_g)$ are the orbital moments of quarks (gluons) and $\Delta\Sigma(\Delta G)$ is spin. Extracting the gluon helical distribution function $\Delta g(x)$ is one of the tasks of the physics program of the NICA collider [1], where it is planned to study collisions of beams of longitudinally polarized protons $p^{\rightarrow}p^{\rightarrow(\leftarrow)}$. DLSAs have previously been experimentally studied in the production of neutral pions [2], charged pions [3], jets [4], dijets [5, 6], heavy mesons [7], and J/ψ mesons [8]. Despite the high statistical characteristics of these processes, their description requires a simulation of hadronization effects. From this point of view, the more preferable channel is the production of direct photons, in which DLSAs were measured by the PHENIX collaboration at energies of 200 [9] and 510 GeV [10]. In the NICA experiment, it is planned to carry out measurements in $p^{\rightarrow}p^{\rightarrow(\leftarrow)}$ collisions at energies of 20 and 27 GeV.

BASIC FORMALISM

The DLSA in collisions of longitudinally polarized protons is determined by the formula

$$A_{LL} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} = \frac{d\Delta\sigma}{d\sigma}, \quad (3)$$

where σ^{++} (σ^{+-}) are the cross sections of proton collision processes with the same helicity and different helicity; $\Delta\sigma$ and σ are the production cross sections for polarized and unpolarized protons.

The introduction of the distribution functions of polarized partons makes it possible to represent the polarized cross sections in the form

$$d\Delta\sigma^{\gamma} = \sum_{a,b=q\bar{q},g}\int dx_a dx_b \Delta f_a(x_a,\mu^2)\Delta f_b(x_b,\mu^2)d\Delta\sigma_{ab}^{\gamma}, \quad (4)$$

where $\Delta\sigma_{ab}^{\gamma}$ are the polarized photon production cross sections at the parton level, $\Delta f_{a(b)}(x_{1,2},\mu^2)$ are parton distribution functions $a(b)$ in polarized protons, and x_a and x_b are the momentum fractions of protons colliding at an energy in the COM frame of $\sqrt{S} \simeq \sqrt{2(P_1P_2)}$ with impulses $P_1^{\mu} = \frac{\sqrt{S}}{2}(1,0,0,1)$ and $P_2^{\mu} = \frac{\sqrt{S}}{2}(1,0,0,-1)$.

In the leading order (LO) approximation of the collinear parton model (CPM) containing the terms $\mathcal{O}(\alpha_s\alpha_{em})$, direct photons are produced in the strongly dominant subprocess of Compton scattering $q + g \rightarrow q + \gamma$ and quark-antiquark annihilation with the production of a photon and a gluon $q + \bar{q} \rightarrow g + \gamma$, where for $p_T \simeq 2$–6 GeV $q = u,d,s$.

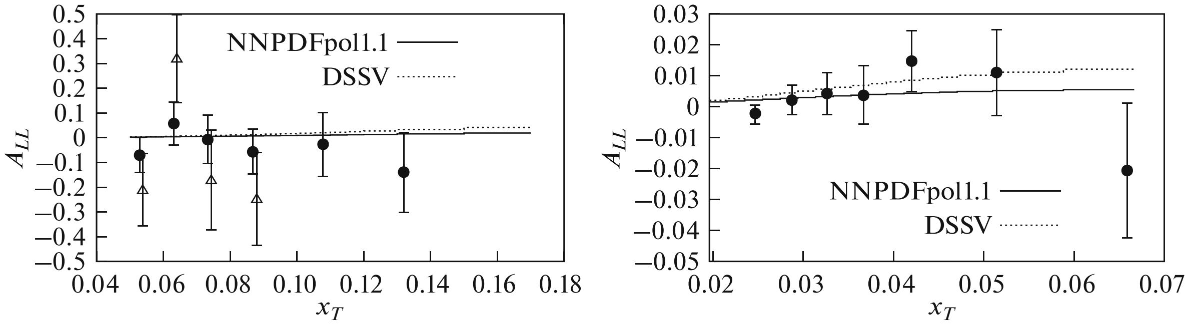

Fig. 1. Double longitudinal spin asymmetries in the direct production of photons at $\sqrt{S}$ = 200 GeV (left) and $\sqrt{S}$ = 510 GeV (right). The solid line is the polarized distribution functions of NNPDFpol1.1, the dotted line is the DSSV distribution function, and the dots on the left (right) are the experimental data of the PHENIX collaboration [9, 10].

Squared amplitude of amplitude moduli of polarized and unpolarized hard parton scattering processes $a + b \to \gamma + c$ look like this [11]:

$$\left|\overline{M_{qg\to\gamma q}}\right|^2 = -\frac{16}{3}\pi^2\alpha_{em}\alpha_s e_q^2 \frac{\hat{s}^2 + \hat{t}^2}{\hat{s}\hat{t}}, \quad (5)$$

$$\Delta\left|\overline{M_{qg\to\gamma q}}\right|^2 = -\frac{16}{3}\pi^2\alpha_{em}\alpha_s e_q^2 \frac{\hat{s}^2 - \hat{t}^2}{\hat{s}\hat{t}}, \quad (6)$$

$$\left|\overline{M_{q\bar{q}\to\gamma g}}\right|^2 = \frac{128}{9}\pi^2\alpha_{em}\alpha_s e_q^2 \frac{\hat{u}^2 + \hat{t}^2}{\hat{u}\hat{t}}, \quad (7)$$

$$\Delta\left|\overline{M_{q\bar{q}\to\gamma g}}\right|^2 = -\frac{128}{9}\pi^2\alpha_{em}\alpha_s e_q^2 \frac{\hat{u}^2 + \hat{t}^2}{\hat{u}\hat{t}}, \quad (8)$$

where $\hat{s} = (q_1 + q_2)^2$, $\hat{t} = (q_1 - p_\gamma)^2$, and $\hat{u} = (q_2 - p_\gamma)^2$ are the Mandelstam variables; e_q is the charge of the quark.

By algebraic transformations, the formula (4) can be reduced to a form convenient for calculations:

$$d\Delta\sigma^\gamma = \sum_{a,b=q\bar{q},g}\int dx_a dx_b \Delta f_a(x_a,\mu^2)\Delta f_b(x_b,\mu^2) \times \frac{\Delta\left|\overline{M_{ab\to\gamma X}}\right|^2}{8\pi}\frac{p_{\gamma T}}{x_a x_b s^2} dp_{\gamma T} dy_\gamma. \quad (9)$$

In our work, we take the renormalization scale equal to the factorization scale $\mu = \mu_R = \mu_F$.

The most up-to-date sets of polarized distribution functions are presented in the works [12–15]; their comparison and discussion of uncertainties are given in the paper [16].

RESULTS

In Fig. 1 we present the results of our DLSA calculations in the production of direct photons within the LO CPM in comparison with the experimental data of the PHENIX collaboration [9, 10] at collision energies of longitudinally polarized protons $\sqrt{S}$ = 200 GeV and $\sqrt{S}$ = 510 GeV, photon rapidities $|y_\gamma| < 0.35$ and $|y_\gamma| < 0.25$, on the left and right panels, respectively. Theoretical calculations performed using polarized distribution functions DSSV [13] and NNPDFpol1.1 [14], with the central choice of a hard scale $\mu = p_T$, are indicated by solid and dashed lines, respectively. Both results lie within the limits of the experimental errors, except for one point in the region of large transverse momenta.

Dependence predictions A_{LL}^γ from $x_T = 2p_T/\sqrt{S}$ at the energy of the NICA collider of $\sqrt{S}$ = 20 and $\sqrt{S}$ = 27 GeV and rapidities $|y_\gamma| < 3$ are shown in Fig. 2. The shaded area illustrates the corridor of uncertainty, which is associated with the choice of a hard scale $p_T/2 < \mu < 2p_T$. The presented dependences show that DLSAs are positive and increase monotonically with increasing p_T and a decrease in collision energy. However, the study of the area of relatively high p_T is limited to the experimentally accessible area associated with small statistics.

In Fig. 3, similar predictions are presented depending on the speed of photon y at $\sqrt{S}$ = 20 GeV and $\sqrt{S}$ = 27 GeV, respectively. The largest values of asymmetries are predicted when choosing distribution functions DSSV [13]. Our results are consistent with the results of earlier predictions for close energies $\sqrt{S}$ = 39 GeV in [17].

CONCLUSIONS

In this paper we calculated the double longitudinal asymmetries in the production of direct photons in $\vec{p}\,\vec{p}^{\,(\leftarrow)}$ collisions at the NICA collider at energies of $\sqrt{S}$ = 20 GeV and $\sqrt{S}$ = 27 GeV, in the LA CPM, with polarized distribution functions NNPDFpol1.1 [14]

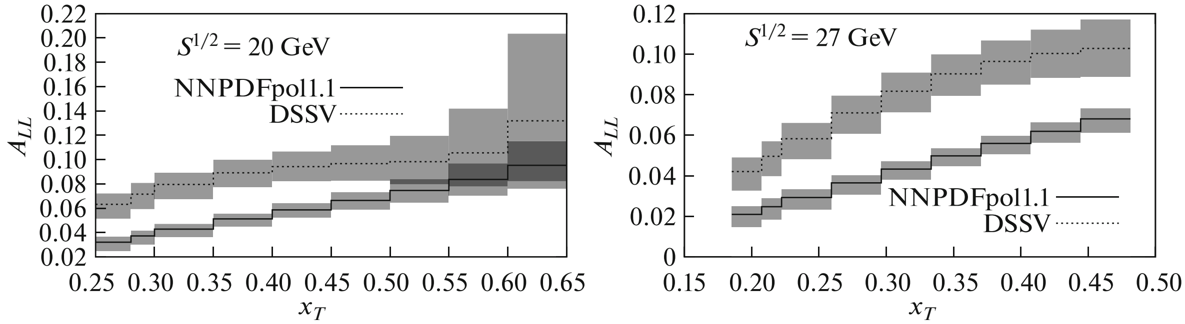

Fig. 2. Same as in Fig. 1 for energies $\sqrt{S} = 20$ GeV (left) and $\sqrt{S} = 27$ GeV (right). The shaded area illustrates the uncertainty $p_T/2 < \mu < 2p_T$.

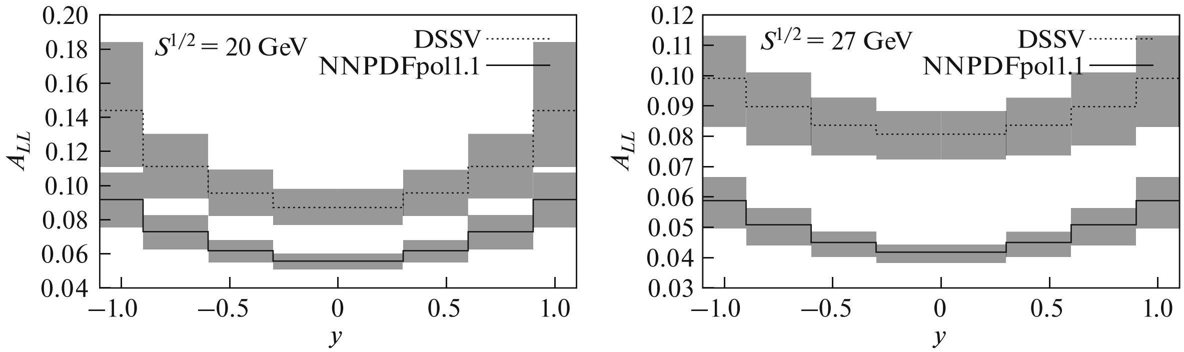

Fig. 3. Same as in Fig. 2, depending on the rapidity of the photon.

and DSSV [13]. The choice of the latter leads to predictions of the largest asymmetries, up to 18%, which makes it possible to observe them experimentally. We confirm the adequacy of the chosen model by a satisfactory description of the existing experimental data of the PHENIX collaboration [9, 10]. More accurate predictions can be obtained by calculations taking into account the contribution of higher corrections using QCD perturbation theory.

ACKNOWLEDGMENTS

We thank A. Guskov, I. Denisenko, O. Teryaev, and other members of the SPD NICA collaboration for their useful comments and fruitful discussions.

FUNDING

The work was partially carried out with support from the State Task of the Ministry of Science and Higher Education of the Russian Federation for educational and research institutions, project FSSS-2020-0014.

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