doi:

AIERKE RYMBEKOVA
Joint Institute for Nuclear Research
(6 Joliot-Curie St, Dubna, Moscow Region, Russia; e-mail: aierke@jinr.ru)

PACS

Study of polarised gluon structure of proton via prompt-photon production in the SPD experiment at the NICA collider

Photons produced in the hard scattering of partons, named prompt photons, provide information about the internal structure of hadrons. The NICA collider has the possibility to provide new data to study the production of prompt photons in non-polarised and polarised proton-proton collisions which gives an access to spin-dependent parton distribution functions for gluons. Unpolarised and polarised physics with prompt photons and capabilities of the SPD detector in such measurements will be discussed in this article.
K e y w o r d s: polarised structure of nucleon, prompt photons, gluons, SPD.

1. Prompt photons

Prompt photons are photons produced in the hard scattering of partons. According to the factorization theorem, the inclusive cross section for the production of a prompt photon in a collision of h_A and h_B hadrons can be written as follows:

$$d\sigma_{AB} = \sum_{a,b=q,\bar{q},g} \int dx_a dx_b f_a^A(x_a, Q^2) f_b^B(x_b, Q^2) \times \times d\sigma_{ab\to\gamma X}(x_a, x_b, Q^2). \quad (1)$$

The function f_a^A (f_b^B) is the parton density for h_A (h_B) hadron, x_a (x_b) is the fraction of the momentum of h_A (h_B) hadron carried by parton a (b) and Q^2 is the square of the 4-momentum transferred in the hard scattering process, and $\sigma_{ab\to\gamma X}(x_a, x_b, Q^2)$ represents the cross section for the hard scattering of partons a and b [1].

The prompt-photon production in hadron collisions is the most direct way to access the gluon structure of hadrons. There are two main hard processes for the production of prompt photons: 1) gluon Compton scattering, $gq(\bar{q}) \to \gamma q(\bar{q})$, which prevails, and 2) quark-antiquark annihilation, $q\bar{q} \to \gamma g$.

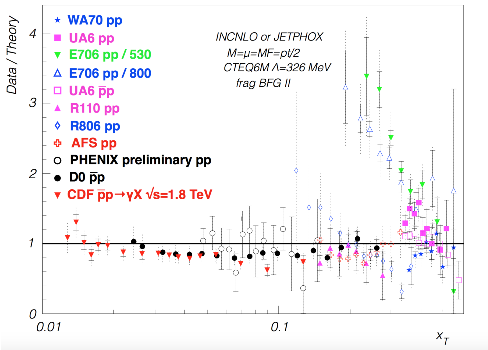

Fig. 1. Measured cross sections of prompt-photon production divided to the predicted those by theory as function of x_T [2].

Unpolarised measurements of the differential cross section of the prompt-photon production in proton-proton(antiproton) collisions have already been performed by the fixed-target and collider experiments. Fig. 1 shows the ratio of the measured cross sections to one predicted by theory as function of $x_T = 2p_T/\sqrt{s}$ [2]. One can see that for the fixed-target results corresponding $\sqrt{s} \sim 20$ GeV there is a signifi-

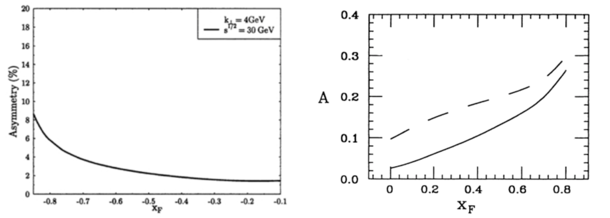

Fig. 2. Theoretical predictions for A_γ^N at $\sqrt{s} = 30$ GeV and $p_T = 4$ GeV/c for (left) positive [4] and (right) negative [5] values of x_F.

cant disagreement with theoretical expectations that is absent for the high-energy collider results. A new precise measurement could clarify the problem.

2. Spin asymmetries

A measurement of the single transverse spin asymmetry $A_\gamma^N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$ in the prompt-photon production at high p_T in polarised p-p and d-d collisions could provide information about the gluon Sivers function which is mostly unknown at the moment. The numerator of A_γ^N can be expressed as [3]:

$$\begin{aligned} &\sigma^\uparrow - \sigma^\downarrow = \\ &\sum_i \int_{x_{min}}^1 dx_a \int d^2\mathbf{k}_{Ta} d^2\mathbf{k}_{Tb} \frac{x_a x_b}{x_a - (p_T/\sqrt{s})e^y} \\ &[q_i(x_a \mathbf{k}_{Ta}) \Delta_N G(x_b, \mathbf{k}_{Tb}) \times \frac{d\widehat{\sigma}}{d\widehat{t}}(q_i G \to q_i \gamma) + \\ &+ G(x_a, \mathbf{k}_{Ta}) \Delta_N q_i(x_b, \mathbf{k}_{Tb}) \frac{d\widehat{\sigma}}{d\widehat{t}}(G q_i \to q_i \gamma)] \end{aligned} \qquad (2)$$

Here $\sigma^\uparrow$ and $\sigma^\downarrow$ are the cross sections of the prompt-photon production for the opposite transverse polarisations of one of the colliding protons, $q_i(x_a, \mathbf{k}_{Ta})[G(x_a, \mathbf{k}_{Ta})]$ is the quark [gluon] distribution function with specified $\mathbf{k}_T$ and $\Delta_N G(x_b, \mathbf{k}_{Tb})[\Delta_N q_i(x_b, \mathbf{k}_{Tb})]$ is the gluon [quark] Sivers function. $\frac{d\widehat{\sigma}}{d\widehat{t}}$ represents corresponding gluon Compton scattering cross section. Fig. 2 shows theoretical predictions for A_γ^N at $\sqrt{s} = 30$ GeV and $p_T = 4$ GeV/c for positive [4] (left) and negative [5] (right) values of x_F. The study of the prompt-photon production at the large transverse momentum with longitudinally polarised proton beams could provide the access to gluon polarisation Δg via the measurement of the longitudinal double spin asymmetry A_{LL}^γ [6]. Assuming the dominance of the gluon Compton scattering process, the asymmetry A_{LL}^γ can be presented as [7]

$$\begin{aligned} A_{LL} \approx &\frac{\Delta g(x_a)}{g(x_a)} \cdot \left[\frac{\sum_q e_q^2 [\Delta q(x_b) + \Delta \bar{q}(x_b)]}{\sum_q e_q^2 [q(x_b) + \bar{q}(x_b)]} \right] \cdot \\ &\cdot \widehat{a}_{LL}(gq \to \gamma q) + (a \leftrightarrow b) \end{aligned} \qquad (3)$$

The second factor in the equation coincides, to lowest order with the spin asymmetry A_1^p well-known from polarised DIS, the partonic asymmetry $\widehat{a}_{LL}$ is calculable in perturbative QCD. Previous results for gluon polarisation show that gluon polarisation is consistent with zero: $|\Delta g/g| < \pm 0.2$ [8] while the A_1^p asymmetry is about 0.2 for $x \simeq 0.1$ [9].

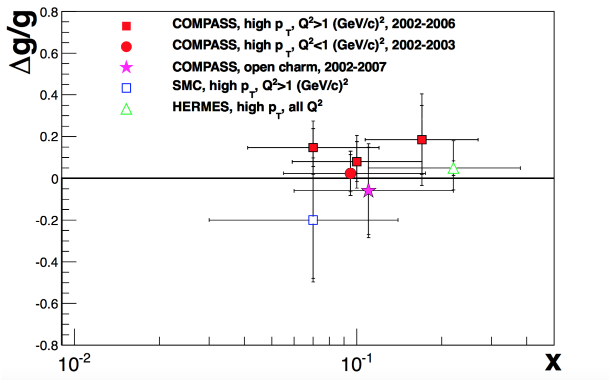

Fig. 3. A compilation of gluon polarisation measurements from open charm and high-p_T hadron production [8].

Thus, under the given experimental conditions, it is possible to gain access to the gluon Sivers function, as well as to the gluon polarisation (helicity).

3. The SPD detector at NICA

Study of gluon structure through prompt-photon production is planned at the SPD experiment at the new accelerator complex NICA (Nuclotron-based Ion Collider fAsility) which is currently under construction at the Joint Institute for Nuclear Research (Dubna, Russia).

The possibility to have high luminosity collisions (up to $10^{32} cm^{-2} s^{-1}$ at $\sqrt{s_{pp}} = 27$ GeV) of polarised protons and deuterons at the NICA collider allows studying spin- and polarisation-dependent effects in hadron collisions.

The current design of the SPD setup foresees three modules: two end-caps and a barrel section. Each part has an individual magnetic system: solenoidal for the end-caps and toroidal for the barrel part of the setup. Main detector systems are the follows: Range System (RS) (for muon identification), Electromagnetic calorimeter (ECal), PID/Time-of-Flight system, Main Tracker (TR) and Vertex Detector (VD).

Photons should be detected by the lead-scintillator electromagnetic calorimeter ("shashlyk" type), which is placed inside the Range System and consists of three parts: the barrel one and two end-caps. Each part has a depth of about 12.5 X_0, which is sufficient to fully contain the highly energetic electromagnetic showers considered in this analysis. Energy resolution is planned to be about $5\%/\sqrt{E[GeV]}$. The acceptance of the calorimeter in polar angle is between 2° and 178° .

4. Prompt photons at SPD

The object-oriented C++ toolkit SPDroot based on the FairRoot framework [10] was used for the Monte Carlo simulation of the detector response. The SPD setup description is based on the ROOT geometry while transportation of secondary particles through material of the setup and simulation of the detector response is provided by the GEANT4 code. The standard multipurpose generators like PYTHIA6, PYTHIA8, FRITIOF could be used for simulation of primary interactions.

Energy deposition in a connected area in the ECal is called a cluster. If in the course of extrapolation, the track does not rest against a cluster, such a cluster is considered as neutral, and vice versa. The main issue of the future analysis will be the correct identification of prompt-photon clusters.

The study of background contributions and possibilities of their suppression is almost the main task. On the experience of previous experiments the main background components are:

- decay photons. Most of them (almost 96 %) are coming from the π^0 and η mesons decays;
- fragmentation photons produced in the process of fragmentation of color partons with large transverse momenta;
- photons produced in the other parts of the facility due to the interaction of particles with material of the setup;
- neutral hadrons like n, K^0 etc. and their antiparticles that are identified in the calorimeter as neutral clusters;
- "charged" clusters in the ECal misidentified as "neutral" ones due to inefficiency of the track finding and reconstruction algorithms;
- the so-called "double" clusters which are the result of overlapping of showers produced by different particles in ECal. The special case is the clusters produced by energetic π^0 decays into two photons flying at a very small angle relative to each other.

The expected contributions of each background component mentioned above as a function of transverse momentum p_T calculated using cluster energy and position are shown in Fig. 4 for *p*-*p* collisions at $\sqrt{s} = 26$ GeV.

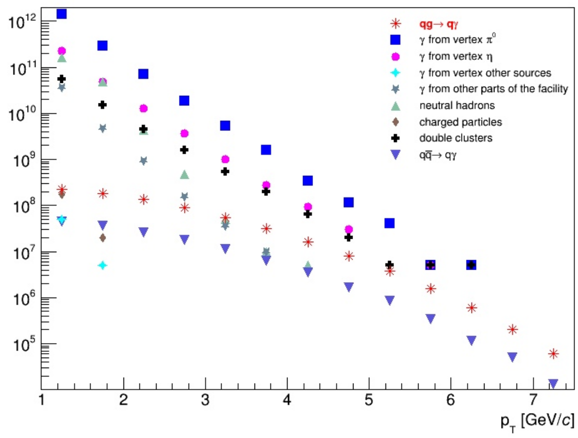

Fig. 4. Contributions of each background component for *p*-*p* collisions at $\sqrt{s} = 26$ GeV shown together with the prompt-photon production.

As it could be concluded from Fig. 4, the low p_T region is useless for any studies of prompt photons due to a huge background. The ratio of the signal to the background at p_T= 1 GeV/c is about 10^{-4}. Only at high values of the transverse momentum it is possible to separate statistically signal and background. A reasonable cut on transverse momentum of photon has to be applied in order to maximize the accuracy of the planned measurements.

The background suppression process could be divided into two stages. At first, all photons from reconstructed 2γ decays of π^0 and η mesons are rejected. After such rejection the sample still contains an admixture of photons from 2γ decays. This residual admixture could be statistically subtracted basing on the Monte Carlo information about properties of the SPD setup. The subtraction procedure can be illustrated by the following equation

$$\sigma \sim N_{prompt} = N_{single\,\gamma} - N_{\pi^0,\eta} \times k \; , \qquad (4)$$

where $N_{single\,\gamma}$ is a number of candidates to be prompt photons, N_{π^0} is a number of reconstructed 2γ decays of π^0 and η and k is a factor to be determined from the Monte Carlo procedure. The typical value of the k factor is 0.76.

To estimate the accuracy of asymmetries measurement, the signal and background Monte Carlo samples were produced. For simulation of primary p-p collisions with $\sqrt{s} = 26$ GeV the PYTHIA6 [11] generator with the standard settings was used. Estimation was performed for 10^7 s (one year) of data taking with an average luminosity $10^{32} s^{-1} cm^{-2}$. 100% polarisation of proton beams was supposed.

Using the Eq. (4) and the cut $p_T > 6$ GeV/c which removed most of the background and assuming that the relative accuracy $dk/k = 0.02$ could be achieved, the preliminary results on the expected accuracy of the A_N and A_{LL} asymmetries measurement in the SPD experiment were obtained. The results for four subranges of x_F-variable are shown in comparison with the E704 measurements [12] and theoretical predictions [4, 5] in Fig. 5. Expected A_N and A_{LL} accuracies are multiplied by the factor of 5 and shown by the error bars in respect to zero values of asymmetries. The uncertainties related to polarisation and luminosity measurements are not taken into account.

5. Conclusions

The study of the polarised and non-polarised gluon content of the nucleon is one of the main physics tasks of the planned SPD experiment at the NICA collider. The prompt-photon production via the gluon Compton scattering is the most promising process for that. The precision measurement of the A_N and A_{LL} spin asymmetries with transversely and longitudinally polarised proton and deuteron beams provides access to the gluon Sivers and helicity functions, respectively. Preliminary studies of the background conditions shows that the accuracy for the asymmetries of about 2% could be achieved in the wide range of x_F.

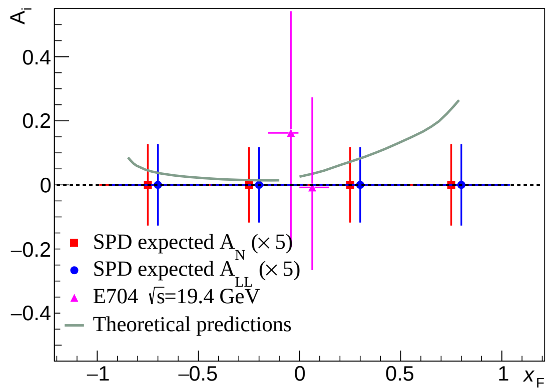

Fig. 5. Expected accuracy of A_N and A_{LL} asymmetries with $p_T > 6$ GeV/c as a function of x_F-variable.

1. Conceptual and technical design of the Spin Physics Detector (SPD) at the NICA collider https://indico.jinr.ru/getFile.py/access?resId=11&materialId=3&confId=718 (2018).
2. P. Aurenche, M. Fontannaz, J.-P. Guillet, E. Pilon, M. Werlen. A New critical study of photon production in hadronic collisions, *Phys. Rev. D* **73**, 094007 (2006) [DOI: https://doi.org/10.1103/PhysRevD.73.094007].
3. I. Schmidt, J. Soffer, J.-J. Yang. Transverse single spin asymmetries in photon production, *Phys. Lett. B* **612** 258B–262 (2005) [DOI: https://doi.org/10.1016/j.physletb.2005.03.008].
4. N. Hammon, B. Ehrnsperger, A. Schaefer. Single-transverse spin asymmetry in prompt photon production, *J. Phys. G* **24** 991 (1998) [DOI: https://doi.org/10.1088/0954-3899/24/5/007]
5. J.-W. Qiu, G. F. Sterman. Single transverse spin asymmetries in direct photon production, *Nucl. Phys. B* **378** 52 (1992) [DOI: https://doi.org/10.1016/0550-3213(92)90003-T]
6. H.-Y. Cheng, S.-N. Lai. Spin Asymmetry in Proton Proton Collisions as a Probe of Sea and Gluon Polarization in a Proton, *Phys. Rev. D* **41** 91 (1990) [DOI: https://doi.org/10.1103/PhysRevD.41.91].
7. G. Bunce, N. Saito, J. Soffer, W. Vogelsang. Prospects for spin physics at RHIC, *Ann. Rev. Nucl. Part. Sci.* **50** 525B–575 (2000) [DOI: https://doi.org/10.1146/annurev.nucl.50.1.525].
8. C. Adolph, et. al. Leading and next-to-leading order gluon polarization in the nucleon and longitudinal double spin asymmetries from open charm muoproduction, *Phys. Rev. D* **87** 052018 (2013) [DOI:

https://doi.org/10.1103/PhysRevD.87.052018]

9. C. Adolph, et. al. The Spin Structure Function g_1^{p} of the Proton and a Test of the Bjorken Sum Rule, *Phys. Rev. B* **753** (2015) [DOI: https://doi.org/10.1016/j.physletb.2015.11.064]
10. M. Al-Turany, D. Bertini, R. Bertini, et al. The FairRoot framework, *IOP Publishing* **396** 022001 (2012) [DOI:https://doi.org/10.1088/1742-6596/396/2/022001]
11. T. Sjostrand, S. Mrenna, P. Z. Skands. PYTHIA 6.4 Physics and Manual, *JHEP* **0605** 026 (2006) [DOI:https://doi.org/10.1088/1126-6708/2006/05/026]
12. D. L. Adams, et al. Measurement of single spin asymmetry for direct photon production in pp collisions at 200-GeV/c, *Phys. Lett. B* **345** 569-575 (1995) [DOI: https://doi.org/10.1016/0370-2693(94)01695-9].

Received 26.07.19