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### THE SIVERS ASYMMETRY IN DEEP INELASTIC CHARGED LEPTON SCATTERING ON A TRANSVERSE POLARIZED PROTON TARGET

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**Abstract.** In the paper, it has been proposed a calculation algorithm that allows obtaining the value of the Sivers asymmetry in semi-inclusive deep inelastic scattering of charged leptons on a transversely polarized proton using the event generator PYTHIA8 and the StringSpinner plug-in. The calculation was performed in the kinematics of the COMPASS experiment: a muon with an energy of 160 GeV scatters on a stationary proton target. The proposed algorithm was shown to make it possible to estimate high accurately the Sivers asymmetry of the final hadron.

**Keywords:** semi-inclusive deep inelastic scattering, polarization, Sivers asymmetry, event generator

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### АСИММЕТРИЯ СИВЕРСА В ГЛУБОКОНЕУПРУГОМ РАССЕЯНИИ ЗАРЯЖЕННЫХ ЛЕПТОНОВ НА ПОПЕРЕЧНО-ПОЛЯРИЗОВАННЫХ ПРОТОНАХ

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**Аннотация.** В статье предложен алгоритм расчета, позволяющий получать значение асимметрии Сиверса в полуинклюзивном глубоконеупругом рассеянии заряженных лептонов на поперечно-поляризованном протоне с помощью генератора событий PYTHIA8 и плагина StringSpinner. Расчет был проведен в кинематике эксперимента COMPASS: мюон с энергией 160 ГэВ рассеивается на покоящейся протонной мишени. Показано, что с помощью предложенного алгоритма можно с высокой точностью определять асимметрию Сиверса конечного адрона.

**Ключевые слова:** полуинклюзивное глубоконеупругое рассеяние, поляризация, асимметрия, генератор событий



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## Introduction

Information about the internal structure of nucleons is vitally important for understanding the nature of the interactions responsible for the production of atomic nuclei. Therefore, the study of this structure is one of the central problems of modern elementary particle physics [1]. A particularly intriguing question is how the characteristics of the quarks and gluons making up the nucleon affect its spin [2]. Measurements of deep inelastic scattering (DIS) have been discussed as an approach for gaining insights into the spin structure of nucleons [3]. Deep inelastic scattering is generally understood as the scattering of an ultrarelativistic lepton (electron or muon) by a hadron (for example, a proton) or by a hadron system (for example, a deuteron). The lepton in this type of scattering is detected in the final state, with noticeably lower energy than the initial lepton. In other words, the incident particle loses a sufficiently large amount of energy in such scattering, which weakly changes the direction of motion relative to the direction of the incident lepton [3].

The DIS process can be represented by the Feynman diagram in the single-photon exchange (SPE) approximation, when a lepton interacts with a target by exchanging a virtual photon (Fig. 1).

Multiple  $X$ -hadrons are produced in DIS during collisions of charged leptons (electrons or muons) at high energy with hadrons. In this process, the lepton interacts with the particles comprising the nucleon, i.e., partons. According to the parton model proposed by Feynman, a parton is a point-like particle (quark  $q$  or gluon  $g$ ) that carries a fraction of the momentum of a hadron  $h$  (in particular, a proton) [4].

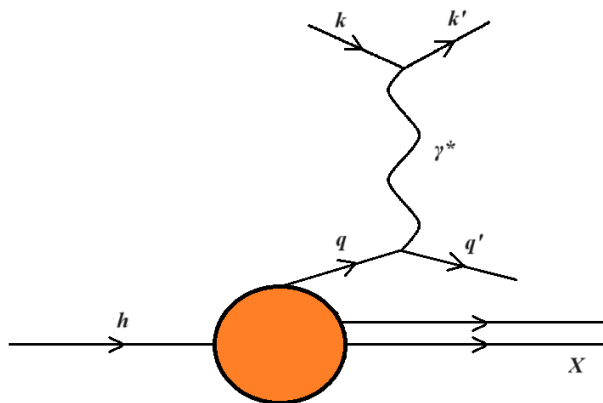


Fig. 1. Feynman diagram for deep inelastic scattering (single-photon  $\gamma^*$ -exchange) of lepton by hadron quark producing a large number of particles  $X$ :

$\gamma^*$  is the virtual photon;  $k, k'$  are the incident and scattered lepton, respectively;  $q, q'$  are the quark before and after interaction, respectively;  $h$  is the hadron

The phenomenon of multiple hadron production in DIS is called hadronization, referring to production of hadrons from colored quarks and gluons. The physical cause of hadronization is that quarks and gluons cannot exist in a free state, combining into colorless particles, that is, hadrons, as a result of chromodynamic interaction.

There are several models of hadronization in nuclear and elementary particle physics [5]: string fragmentation, independent fragmentation and cluster hadronization.

String fragmentation is one of the best-developed models of hadronization in high-energy particle physics. This is a process of multiple breaking of a gluon string between colored quarks, producing colorless hadrons at the break points [6]. In this case, the produced particles whose rapidities are close to the rapidity of the projectile or target are called fragments of the projectile or target, respectively.

The probability of production of a colorless hadron from a fragmenting colored string is described by the fragmentation function (FF).

The quark and antiquark forming the string must have sufficient energy for fragmenting. The probability of detecting a parton (quark) in a nucleon with a fraction of the nucleon momentum at the squared four-momentum  $Q^2$  transferred by a virtual photon is called the parton distribution function (PDF) [7].

It was established in the experiment of the European Muon Collaboration (EMC) that the nucleon spin is not equal to the total spin of valence quarks. This problem is known as the spin crisis [8]. The HERMES [9] and COMPASS [10] experiments were conducted to study this problem, considering the phenomena of semi-inclusive (with production and detection of a hadron) deep inelastic scattering (SIDIS) of leptons by a transversely polarized proton. Azimuthal asymmetry was observed for mesons produced by scattering [11]. The occurrence of azimuthal asymmetries is associated with polarization effects.

Simulation of the processes in the PYTHIA8 Monte Carlo event generator [12] is one of the approaches to testing theoretical models. PYTHIA8 does not take into account the polarization effects, therefore, third-party plugins are required to generate events with polarized particles. One of these plugins is StringSpinner [13], introducing polarization effects based on the  $^3P_0$  model [14] into the fragmentation model. This plugin was created to calculate the Collins asymmetry, and the simulation results are in good agreement with the experiment [15].

The goal of this study was to develop an algorithm and a program for calculating Siverts asymmetry in semi-inclusive deep inelastic scattering (SIDIS) of leptons using the PYTHIA8 Monte Carlo event generator and the StringSpinner plugin.

### Experimental procedure

Consider semi-inclusive deep inelastic scattering by a transversely polarized proton target in the single-photon exchange approximation:

$$l + p^\uparrow \rightarrow l' + h + X,$$

where  $l, l'$  are the incident and scattered lepton, respectively;  $p^\uparrow$  is the transversely polarized proton;  $h$  is the detected hadron, and  $X$  are the remaining particles.

A schematic 3D diagram of the process is shown in Fig. 2.

The  $x_r, y_r$  and  $z_r$  axes in Fig. 2 denote the target's rest system: the  $z_r$  axis is aligned with the momentum of the scattered quark; the  $x_r$  axis lies in the plane where scattering occurs; the  $y_r$  axis is perpendicular to the scattering plane.

It is convenient to describe the SIDIS kinematics using the Bjorken variable characterizing the fraction of the parton momentum relative to the nucleon momentum [3]:

$$x_{\text{Bj}} = \frac{Q^2}{2Pq}, \quad (1)$$

where  $Q^2 = -q^2$  is the squared four-momentum transfer of the virtual photon  $\gamma^*$ ;  $P$  is the four-momentum transfer of the target proton.

In addition, we introduce a variable  $y$ , which is a fraction of the energy of the incident lepton transferred to the virtual photon [3]:

$$y = \frac{P \cdot q}{P \cdot k'}. \quad (2)$$

We also introduce a variable  $z$ , which is the fraction of the momentum of the virtual photon transferred to the ejected hadron  $h$ :

$$z = \frac{P \cdot P_h}{P \cdot k'}, \quad (3)$$

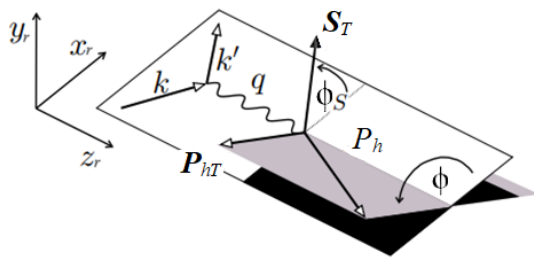


Fig. 2. Diagram of semi-inclusive deep inelastic scattering in single-photon exchange approximation [9]:

$k, k'$  are the four-momenta of the incident and scattered lepton;  $S_T$  is the nucleon polarization vector  $P_h, P_{hT}$  are the four-momentum of the hadron and its transverse momentum;  $\phi$  is the angle between the scattering plane and the direction of the hadron momentum;  $\phi_S$  is the angle between the polarization vector and the scattering plane;  $q = k - k'$  is the four-momentum of the virtual photon



The structure of particles and their properties were determined by a method based on finding the scattering cross section. Let us consider the differential cross section of hadron production in SIDIS at leading twist (first-order expansion in powers of  $1/Q^2$  [16]). It was proved in [17] that the scattering cross section can be expanded into a sum of fragmentation functions.

Thus, the differential cross section of hadron production in SIDIS by a transversely polarized proton can be represented as an expansion in powers of the squared four-momentum transfer of the virtual photon  $Q^2$  [18]:

$$\frac{d\sigma}{dx_{Bj} dy dz dP_{hT} d\phi d\phi_S} \propto \left( S_T \left[ \sin(\phi - \phi_S) F_{UT}^{\sin(\phi - \phi_S)} + D_{NN} \sin(\phi + \phi_S) F_{UT}^{\sin(\phi + \phi_S)} \right] + \dots \right), \quad (4)$$

where  $D_{NN}$  is the ratio of the longitudinal to transverse motion of virtual photons,  $D_{NN} = 2(1-y)/[1+(1-y)^2]$ ;  $F_{UT}^{\sin(\phi - \phi_S)}$  is the Siverts structural function proportional to  $\sin(\phi - \phi_S)$ ;  $F_{UT}^{\sin(\phi + \phi_S)}$  is the Collins structural function proportional to  $\sin(\phi + \phi_S)$ .

These structural functions depend on the quantities  $x_{Bj}$ ,  $Q^2$ ,  $z$ ,  $P_{hT}$ . Their subscripts  $U$ ,  $T$  denote polarization:  $U$  corresponds to the unpolarized state,  $T$  to transverse polarization (for example,  $UT$  denotes an unpolarized lepton and a transversely polarized target). Here  $S_T = |\mathbf{S}_T|$  is the magnitude of the transverse polarization vector (see Fig. 2).

Two single-spin azimuthal asymmetries, Siverts and Collins, make the greatest contribution to the hadron production cross section (depending on  $\sin(\phi - \phi_S)$  and  $\sin(\phi + \phi_S)$ , respectively) [19]. The asymmetry of  $\sin(\phi - \phi_S)$  arises due to the Siverts effect: the interaction of a scattered quark in the final state with the remnant of the target nucleon.

The quark distribution function in the transversely polarized proton  $f_{q,p\uparrow}(x_{Bj}, k_T^2)$  can be represented as the difference between the PDF of quarks in the unpolarized proton and the Siverts function [20]:

$$f_{q,p\uparrow}(x_{Bj}, k_T^2) = f_1^q(x_{Bj}, k_T^2) - f_{1T}^{\perp q}(x_{Bj}, k_T^2) (\mathbf{P} \times \mathbf{k}_T) \frac{\mathbf{S}}{M}, \quad (5)$$

where  $M$  is the proton mass ( $M = 938$  MeV);  $\mathbf{k}_T$  is the transverse momentum of the quark;  $\mathbf{P}$  is the momentum of the proton;  $\mathbf{S}$  is the spin vector of the proton;  $f_1^q$  is the quark distribution function in the unpolarized proton;  $f_{1T}^{\perp q}$  is the Siverts function describing the relationship between the transverse momentum of the struck quark and the polarization of the target; the superscript  $\perp q$  indicates that the PDR is integrated with respect to the transverse momentum of the quark, and the subscript 1 indicates the leading twist.

In terms of fragmentation functions, the Siverts asymmetry can be represented as an integral convolution of the Siverts function and the function  $D_1$ , which is the density of the probability that the transverse momentum of the produced hadron belongs to the fragmenting quark  $q$  [21]:

$$A_{Siv} \propto \sin(\phi - \phi_S) \sum_q e_q^2 f_{1T}^{\perp q}(x_{Bj}, k_T^2) * D_1(z, k_T^2), \quad (6)$$

where  $e_q$  is the electric charge of the quark,  $A_{Siv}$  is the Siverts asymmetry. Summation is carried out over quarks  $q$ .

Thus, finding the value of the Siverts asymmetry, we can determine the relationship between the transverse momentum of the struck quark and the polarization of the target for the given parameters of the Bjorken variable and the  $z$  variable. In practice, the Siverts asymmetry can be found if the angular distribution of the multiplicity of produced hadrons in the detector is known.

The multiplicity distribution of the produced hadron  $h$  depends on the Siverts asymmetry as follows [22]:

$$\frac{dN_h}{dx_{Bj} dz dP_T d\phi_{Siv}} \propto 1 + S_T A_{Siv} \sin(\phi - \phi_S), \quad (7)$$

where  $N_h$  is the number of produced hadrons,  $\phi_{Siv} = \phi - \phi_S$  is the Siverts angle.

The calculation based on the model proposed for the SIDIS process was performed in our modified PYTHIA8 Monte Carlo generator using the StringSpinner plugin. This plugin uses the string+ $^3P_0$  fragmentation model for polarized partons, which is an extension of the classical Lund hadronization model with an added spin degree of freedom [15].

### Results

Let us calculate the Siverts asymmetry by this model. The process is divided into several kinematic regions with respect to the Bjorken variable  $x_{\text{Bj}}$  (the fraction of the transverse four-momentum of parton in the four-momentum of the nucleon), where the azimuthal modulation  $\sin(\phi - \phi_S)$  and the polarization vector  $S_T$  from each event entering the kinematic region are summed separately; then the values obtained are normalized by the number of events. Next, the Siverts asymmetry is calculated by Eq. (4):

$$A_{\text{Siv}} = \frac{\langle \sin(\phi - \phi_S) \rangle}{\langle S_T \rangle}, \quad (8)$$

where the angle brackets denote averaging over the number of selected hadrons.

The kinematics of the COMPASS experiment was used to model the SIDIS processes: an unpolarized muon  $\mu^-$  with an energy of 160 GeV is scattered by a transversely polarized proton target. The events were selected in the kinematic region for the Bjorken variable  $x_{\text{Bj}} \in \{0,003; 0,400\}$ , the variable  $z$  in the range  $0.2 < z < 0.7$ , the variable  $y$  in the range  $0.05 < y < 0.95$ , and the momentum transfer  $Q^2 > 1$  GeV.

Siverts asymmetry of charged pions was calculated as a function of the Bjorken variable  $x_{\text{Bj}}$ . The obtained results were compared with the data from the COMPASS experiment (Fig. 3). The computational data were obtained using PYTHIA8 with modified StringSpinner.

According to the data obtained, the Siverts asymmetry of charged  $\pi$  mesons is nonzero. This confirms the influence of quark polarization on the angular distribution of particles.

The computational results based on the proposed method are in good agreement with experimental data within the uncertainty.

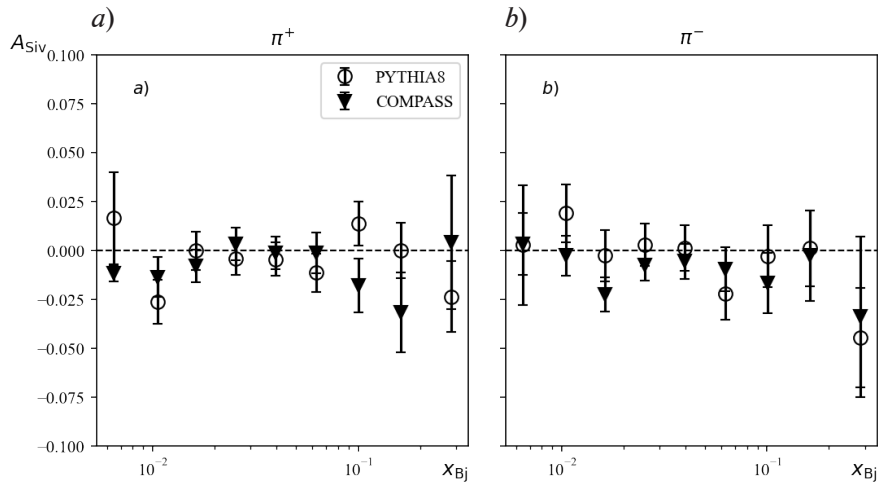


Fig. 3. Experimental (black triangles) and calculated (empty circles) dependences of Siverts asymmetry on Bjorken variable for scattering of 160 GeV muons  $\mu^-$  by transversely polarized protons with production of positive ( $\pi^+$ ) (a) and negative ( $\pi^-$ ) (b) mesons

### Conclusion

In this study, we developed a method for calculating the Siverts asymmetry using the PYTHIA8 software package and the StringSpinner plugin. Since the computational results obtained based on the proposed method are in good agreement with experimental data within the uncertainty, we proved that the model is valid for calculations of Siverts asymmetry of charged pions in semi-inclusive deep inelastic muon scattering by a polarized proton.



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