STUDY OF PARTON SPIN-DEPENDENT DISTRIBUTIONS IN HARD PROTON-PROTON COLLISION THROUGH MEASUREMENT OF HANDEDNESS

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Abstract

Polarization of partons emitted in hard scattering of an unpolarized proton beam from a polarized hydrogen target can be found through a measurement of a jet handedness. Two definitions of handedness are suggested with zero and essentially nonzero contributions of gluon jets. A sensitivity of the handedness to the valence, sea quark and gluon polarized distributions are considered. Handedness properties under the charge conjugation and flavor $SU(2)$ transformations are investigated. An option to study the spin-dependent parton distributions in hard scattering of the unpolarized HERA proton beam from the polarized internal hydrogen target is discussed.

1 INTRODUCTION

As it follows from the lepton proton deep inelastic scattering experiments [1, 2] the valence quark contribution to the proton spin is abnormally small which could be explained by a substantial sea quark polarization/ or gluon polarization/ or orbital angular momentum contribution [3]. Since there is no first order Born contribution of the gluon polarized density $\Delta G(x)$ to cross sections of deep inelastic lepton proton scattering its value is known worse than quark spin-dependent distributions. Even the sign of its first momentum ΔG can not be fixed [4] from the EMC data.

A possibility to investigate the polarized gluon distribution $\Delta G(x)$ in hard $\vec{p}\vec{p}$ collisions is discussed in the RHIC Spin Collaboration program [5]. Reactions $\vec{p}\vec{p} \to \gamma X$ and $\vec{p}\vec{p} \to 2$ jets are probably the most promising processes for studying $\Delta G(x)$ [6]. In order to make these experiments feasible polarized colliding proton beams of high energies ($\sqrt{S}$ = 50 -500 GeV) are proposed to be used in the future. Another way to study the polarized gluon distribution has been recently proposed in ref. [7] where scattering of an unpolarized proton beam from a polarized hydrogen target has been considered. In the latter case polarizations of quarks and gluons emitted in hard $p\vec{p}$ collisions can in principle be experimentally determined through jet handedness measurements [8, 9, 10]. The jet handedness H^f is proportional to the parent parton polarization ξ_f ($f = u, \bar{u}, d, \bar{d}, g$ *etc.*)

$$H^f = \alpha_f \xi_f. \tag{1}$$

Here and below we shall consider a longitudinal polarization only. An analyzing power α_f can be found in a process where the polarization ξ_f is known. Then measuring the handedness of a jet and making use of relation (1) one determines a parton polarization in another reaction, invariant kinematical variables of the jet for both processes being identical.

How to define a jet handedness? The simplest way is to choose three particles with the largest momenta in a jet since their momenta are presumably most informative for studying a polarization of a parent quark. We shall consider the case when three leading particles are charged pions. It is possible in this case to define a handedness in two different ways (see (10) and (11)). The former definition of H_1 gives nonzero value for the handedness in the reaction

$$e^+e^- \Longrightarrow Z^0 \Longrightarrow q\bar{q} \Longrightarrow 2\ jets. \tag{2}$$

For the latter one the jet handedness H_2 is equal to zero if one considers a sum of equal numbers of quark and antiquark jet events, the invariant kinematical variables for quark and antiquark jets being equal. For the former definition of handedness it is equal to zero for gluon jets. After calibrating the analyzing power in reaction (2) one measures the jet handedness in the process

$$p\vec{p} \Longrightarrow jet + X \tag{3}$$

and determines the double helicity asymmetry C_{ll} . The value of C_{ll} has been shown to be sensitive to $\Delta G(x)$ and the spin-dependent distribution of valence u-quarks $\Delta u_v(x)$. Its dependence on the polarized distribution of valence d-quarks $\Delta d_v(x)$ and especially of spin-dependent sea quark distribution can be neglected. Since the ratio of contributions of $\Delta G(x)$ and $\Delta u_v(x)$ to C_{ll} is different for different kinematical conditions the gluon and valence u-quark spin-dependent distributions can be found separately. The distributions $\Delta u_v(x)$ and $\Delta d_v(x)$ can be found in semi-inclusive polarized deep-inelastic lepton-proton (deuteron) scattering $\vec{l} + \vec{p}(\vec{D}) \to l' + \pi^{\pm} + X$ [11]. If $\Delta u_v(x)$ and $\Delta d_v(x)$ are reliably fixed then $\Delta G(x)$ can be extracted from process (3) with a higher precision.

The double helicity asymmetry C_{ll} does not contain a contribution of gluon jets. It is the main advantage of C_{ll} compared to the double spin asymmetry A_{ll} considered in ref. [7]. To determine A_{ll} measuring the jet handedness in process (3) one is to use the latter definition of a handedness (H_2). For this case one has to separate contributions of quark jets from jets of antiquarks with the same flavor in process (2). It is probably better to calibrate the quark analyzing powers in lepton nucleon deep inelastic scattering where a number of quark jets is much larger than that of antiquarks. For a measurement of A_{ll} one needs to know a value of a gluon analyzing power α_g. It can in principle be obtained from the decay of Υ which goes through a three gluon intermediate state. But it is probably difficult to get a number of decay events under consideration enough to have a reasonable statistical accuracy of the analyzing power α_g.

In Section 2 we give two definitions of handedness H_1 and H_2 and discuss properties of quark and gluon analyzing powers which follow from the charge conjugation and $SU_f(2)$ invariance of strong interaction. In Section 3 we discuss the results of calculations of double helicity asymmetries for reaction (3) and their sensitivity to contributions of valence, sea quark and gluon spin-dependent distributions. We consider here a possibility to measure C_{ll} in hard fixed-target $p\vec{p}$ scattering at HERA. We summarize our results in Section 4.

2 HANDEDNESS

A concept of handedness was proposed many years ago by O.Nachtmann [8] and A.Efremov [9] and has been recently used in refs. [7,10,12,13,14]. Let us consider a parton fragmentation into spinless particles (or the case when one averages over spins of final hadrons). Due to a parity conservation in strong interactions a correlation in the decay distribution with the polarization pseudovector of a parent quark or gluon S^μ depends on the scalar $S^\mu n_\mu$. A pseudovector $n^\mu = (n_0, \vec{n})$, $n_\mu n^\mu = -1$ is defined by the following relations

$$V_\mu = \varepsilon_{\mu\nu\lambda\theta} k_1^\nu k_2^\lambda k_3^\theta, \tag{4}$$

$$n^\mu = V^\mu / \sqrt{-V_\nu V^\nu} \tag{5}$$

where k_1, k_2, k_3 are momenta of three particles in a jet and $\varepsilon_{\mu\nu\lambda\theta}$ denotes a totally antisymmetrical tensor. Relations (4), (5) show that a minimal number of outgoing particles giving an information about polarization of a parent parton is equal to three. The main experimental problem is to choose such particles in a jet and a subspace in a phase space of a process under consideration to get an analyzing power α_f as large as possible. We have chosen three particles with the largest momenta because they are probably the most informative relatively to the value of S_μ. We use a definition of handedness which is applicable to a case when three leading particles are charged pions. Let the particle with the largest momentum be named the first one. We shall consider only such events when the two rest particles have positive and negative electrical charges. They will be called the second and third particles respectively. A jet is called right-handed or left-handed if

$n_l < 0$ or $n_l > 0$ respectively where

$$n_l = (\vec{n}\vec{k})/|\vec{k}|. \tag{6}$$

The vector $\vec{n}$ has been defined by (4), (5) and

$$k = k_1 + k_2 + k_3 = (\varepsilon, \vec{k}). \tag{7}$$

If the electrical charge of the first particle is positive the jet will be called the positive one, otherwise it will be named the negative jet. The numbers of right-handed and left-handed events for positive jet produced by a parton f ($f = u, \bar{u}, d, \bar{d}, g$ etc.) will be denoted as R^f_+ and L^f_+ respectively. R^f_- and L^f_- have the same meaning for negative jets. A handedness for these two cases is defined as

$$H^f_\pm = (L^f_\pm - R^f_\pm)/N^f_\pm \tag{8}$$

where $N^f_\pm = L^f_\pm + R^f_\pm$. A value of a jet handedness is proportional to a polarization ξ_f of the parton f

$$H^f_\pm = \alpha^f_\pm \xi_f. \tag{9}$$

Considering a sum (a difference) of $L^f_+ - R^f_+$ and $L^f_- - R^f_-$ we have from (8), (9)

$$H^f_1 = [(L^f_+ - R^f_+) + (L^f_- - R^f_-)]/N^f = \alpha^f_1 \xi_f \tag{10}$$

$$H^f_2 = [(L^f_+ - R^f_+) - (L^f_- - R^f_-)]/N^f = \alpha^f_2 \xi_f \tag{11}$$

where

$$\alpha^f_1 = \alpha^f_+ W^f_+ + \alpha^f_- W^f_-,\ \alpha^f_2 = \alpha^f_+ W^f_+ - \alpha^f_- W^f_-, \tag{12}$$

$$W^f_\pm = N^f_\pm / N^f,\ N^f = N^f_+ + N^f_-. \tag{13}$$

The values of handedness H_1 and H_2 correspond to the former and latter definitions of handedness mentioned in the Introduction.

It is easy to get the relations

$$\alpha^f_\pm = -\alpha^{\bar f}_\mp, \tag{14}$$

$$W^f_\pm = W^{\bar f}_\mp, \tag{15}$$

$$\alpha^u_\pm = -\alpha^d_\mp, \tag{16}$$

$$W^u_\pm = W^d_\mp \tag{17}$$

considering events shown in Fig. 1. Any charged particle in Fig. 1a corresponds to a particle shown in Fig. 1b with the same momentum but with an opposite sign of the electrical charge. If the jet shown in Fig. 1a is left-handed then the jet shown in Fig. 1b is right-handed and vice versa in accordance with our definition of handedness. A validity of (15) and the relations

$$L^f_+ = R^{\bar f}_-, \; R^f_+ = L^{\bar f}_-, \tag{18}$$

follows from the invariance of QCD to the charge conjugation transformation if $\xi_f = \xi_{\bar f}$ and $N^f = N^{\bar f}$ $(f = u, d, s, \ldots,\; \bar f = \bar u, \bar d, \bar s, \ldots)$. Combining (13), (15), (18) with (8), (9) we get relation (14). Considering the isotope SU(2) group as the group of an approximate symmetry of QCD one can easily prove a validity of relations (16), (17) in analogous way (comparing Figs. 1a and 1c). [1] A charge conjugation invariance of QCD gives for gluons ⇐ *Fig.*

$$\alpha^g_+ = -\alpha^g_-, \tag{19}$$

$$W^g_+ = W^g_- = 1/2. \tag{20}$$

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[1] Here we neglect small contributions of heavy quarks.

Combining (19), (20) with (10), (12) we conclude that

$$\alpha_1^g = 0, \quad H_1^g = 0. \tag{21}$$

Relations (21) show that a gluon jet does not contribute to H_1. It means that one needs not to calibrate gluon jets (which is difficult to do) if the former definition of handedness H_1 is used.

The analyzing power can be experimentally found, for instance, from the investigation of process (2) where the quark polarization and all the cross sections have been predicted in the Weinberg-Salam-Glashow theory [10]. Let θ denote an angle between the outgoing quark or antiquark momentum and the incident electron one. A value of the antiquark polarization is the same as for a quark of the same flavor but has an opposite sign. As a number of jet events for quarks at some value of θ $N^f(\theta)$ $(f = u,\ d,\ s,\ c)$ is not equal to that for antiquarks $N^{\bar{f}}(\theta)$ we can find α_1^f and α_2^f making use of (10), (11). But to increase a statistics we are to integrate over θ. We should take into account that at $\sqrt{S} = m_Z$

$$N^f(\theta) = N^{\bar{f}}(\pi - \theta), \quad \xi_{\bar{f}} = -\xi_f. \tag{22}$$

Using (14), (15) and (22) it is easy to check the validity of the following relations

$$\begin{aligned} L_1^f - R_1^f \equiv (L_+^f - R_+^f + L_+^{\bar{f}} - R_+^{\bar{f}}) + (L_-^f - R_-^f + L_-^{\bar{f}} - R_-^{\bar{f}}) = \\ = \alpha_1^f \xi_f [N^f(\theta) + N^f(\pi - \theta)] \end{aligned} \tag{23}$$

$$\begin{aligned} L_2^f - R_2^f \equiv (L_+^f - R_+^f + L_+^{\bar{f}} - R_+^{\bar{f}}) - (L_-^f - R_-^f + L_-^{\bar{f}} - R_-^{\bar{f}}) = \\ = \alpha_2^f \xi_f [N^f(\theta) - N^f(\pi - \theta)] \end{aligned} \tag{24}$$

An integration of (23) over a region symmetrical about the plane perpendicular to the beam direction gives nonzero result therefore we can find α_1^f using all jet events without distinguishing quark and antiquark contributions. An integral for the right-hand side expression in (24) is equal to zero. To determine a value of α_2^f from the experimental data we are to consider a difference between forward and backward scattering events which does not vanish after the integration over the region discussed above.

Summing over contributions of u and d-quarks and taking into consideration (12), (16) we obtain for H_1 from (23)

$$H_1 = \sum_{f=u,d} (L_1^f - R_1^f) / \sum_{f=u,d} N^f = \alpha_1^u (\xi_u \sigma_u - \xi_d \sigma_d)/(\sigma_u + \sigma_d), \tag{25}$$

where σ_f denotes the cross section of the f-quark production for the kinematical region under discussion. For H_2 we have the relation

$$\begin{aligned} H_2 = \sum_{f=u,d} (L_2^f - R_2^f) / \sum_{f=u,d} (N_{forw}^f - N_{back}^f) = \\ = \alpha_2^u (\xi_u \delta\sigma_u + \xi_d \delta\sigma_d)/(\delta\sigma_u + \delta\sigma_d) \end{aligned} \tag{26}$$

from (24) where $\delta\sigma_f$ denotes a difference of the cross section for a forward and backward quark production. A generalization of relations (25), (26) for a four flavor case is obvious.

Values of α_+^u and α_-^u can be found from deep inelastic scattering of polarized leptons on unpolarized protons or nuclei. For example in deep inelastic νp scattering outgoing u-quarks and d-antiquarks produce jets (we ignore other quark contributions for the sake of simplicity). One can see from relations (14), (15) , (16), (17) and (8), (9) that

$$L_\pm^u - R_\pm^u + L_\pm^{\bar{d}} - R_\pm^{\bar{d}} = \alpha_\pm^u W_\pm^u (N^u \xi_u + N^{\bar{d}} \xi_{\bar{d}}) \tag{27}$$

The formula

$$(L^u_+ - R^u_+ + L^{\bar{d}}_+ - R^{\bar{d}}_+)/(L^u_- - R^u_- + L^{\bar{d}}_- - R^{\bar{d}}_-) = (\alpha^u_+ W^u_+)/(\alpha^u_- W^u_-) \tag{28}$$

is the simplest consequence of (27) which shows that for a determination of the ratio α^u_+/α^u_- we do not need any knowledge about parton distributions in a target, any cross sections etc. Therefore the ratio can be obtained more reliably than each value of α^u_+ and α^u_-. The value of W^u_+/W^u_- in (28) is equal to the ratio of numbers of positive and negative jet events in the u quark fragmentation. It is equal to the ratio of numbers of positive and negative jet events in deep inelastic νp scattering. One can get from (27) that

$$\begin{aligned} H_\pm = (L^u_\pm - R^u_\pm + L^{\bar{d}}_\pm - R^{\bar{d}}_\pm)/(N^u + N^{\bar{d}}) = \\ = \alpha^u_\pm W^u_\pm (\sigma^u \xi_u + \sigma^{\bar{d}} \xi_{\bar{d}})/(\sigma^u + \sigma^{\bar{d}}). \end{aligned} \tag{29}$$

For the calculations of σ^u, $\sigma^{\bar{d}}$, ξ_u, $\xi_{\bar{d}}$ one needs only unpolarized parton distributions which are now well known.

3 HARD $P\vec{P}$ COLLISIONS

Let us denote a number of partons of a flavor f emitted in hard pp collisions with a rapidity η and a transverse momentum P_T as K_f. Let a fraction of jet events with three charged pions having large momenta k_1, k_2, k_3 (needed for a definition of handedness) among all jet events be denoted as β_f. Then we have

$$N^f = \beta_f K^f = l\tau\beta_f \frac{d\sigma^f}{d\eta dP_T}, \tag{30}$$

where l denotes a luminosity and τ is a running time. Formulae for differential cross section $d\sigma_f/d\eta dP_T$ have been taken from ref. [6,7]. Analytical expressions for cross sections of quark-quark, qurk-gluon and gluon-gluon scattering can be found in ref. [6, 7, 15]. The parton polarization in hard scattering of an unpolarized proton beam from a polarized proton target is given by the relation

$$\xi_f = \xi_t \frac{d\Delta\sigma^f}{d\eta dP_T} / \frac{d\sigma^f}{d\eta dP_T}. \tag{31}$$

ξ_t denotes a target polarization and $d\Delta\sigma^f/d\eta dP_T$ is

$$\begin{aligned} \frac{d\Delta\sigma^f}{d\eta dP_T} &= \frac{d\sigma^f}{d\eta dP_T}(P + P_+ \rightarrow f_+ + X) - \frac{d\sigma^f}{d\eta dP_T}(P + P_+ \rightarrow f_- + X) = \\ &= \frac{d\sigma^f}{d\eta dP_T}(P + P_+ \rightarrow f_+ + X) - \frac{d\sigma^f}{d\eta dP_T}(P + P_- \rightarrow f_+ + X) \end{aligned} \tag{32}$$

where P_+ (f_+) and P_- (f_-) denotes a proton (parton) with a positive and negative helicity respectively in the pp center-of-mass system. The equality in relation (32) is valid due to parity conservation in strong interactions. Formulae for $d\Delta\sigma^f/d\eta dP_T$ are given in ref. [7]. For a value of $L^f_\pm - R^f_\pm$ we have the relation

$$L^f_\pm$$