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Model prediction for the transverse single target-spin asymmetry in inclusive DIS

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Summary. — The single-spin asymmetry of unpolarized leptons scattering deep-inelastically off transversely polarized nucleons is discussed. This observable is generated by a two-photon exchange between lepton and nucleon. In a partonic description of the asymmetry the non-perturbative part is given in terms of multiparton correlations: quark-gluon correlation functions and quark-photon correlation functions. Recently, a model for quark-gluon correlation functions was presented where these objects were expressed through non-valence light cone wave functions. Using this model, estimates for the single-spin asymmetries for a proton and a neutron are presented.

PACS 13.60.Hb – Total and inclusive cross sections (including deep-inelastic processes).
PACS 13.88.+e – Polarization in interactions and scattering.

1. – Introduction

One of the most fundamental and basic processes in hadronic physics is the deep-inelastic scattering (DIS) of leptons off nucleons, $\mathrm{l}(l) + \mathrm{N}(P) \to \mathrm{l}(l') + \mathrm{X}$. Single-spin observables in inclusive DIS with either the lepton or nucleon being transversely polarized strictly vanish due to time-reversal invariance for a single-photon exchange [1]. This argument fails if two (or more) photons are exchanged between lepton and nucleon.

Experimentally, a recent measurement of the single-spin asymmetry (SSA) for a transversely polarized nucleon, denoted by A_{UT}, was performed by the HERMES Collaboration [2], and again a result consistent with zero was found within an error of about 10^{-3}. Interestingly, preliminary data taken from (ongoing) precision measurements of A_{UT} at Jefferson Lab seem to indicate a non-zero effect [3].

A theoretical description of the SSA A_{UT} in a partonic picture needs to deal with two distinctive and complementary physical situations: The exchange of two photons between the lepton and either i) one *single* quark or ii) two *different* quarks. The asymmetry has been studied in refs. [4-7] for massless quarks. It was found that this observable generically behaves like M/Q where M denotes the nucleon mass, $Q^2 = -q^2$, and $q = l - l'$ the 4-momentum transfer to the nucleon. Thus the asymmetry is a power suppressed ("twist-3") observable, and can be expressed in terms of multipartonic non-perturbative quark-gluon (scenario i)) and quark-photon (scenario ii) correlation functions. Effects of a finite quark mass proportional to the transversity distribution $h_1^q(x)$ are also relevant for scenario i) and have been studied in ref. [8].

2. – A_{UT} in a partonic picture

The DIS differential cross section can be analyzed in terms of the commonly used DIS variables that are defined as $x_B = Q^2/(2P \cdot q)$ and $y = P \cdot q / P \cdot l$. For the description of A_{UT} a transverse (to the lepton plane) spin vector S_T of a polarized nucleon is needed. An azimuthal angle ϕ_s between S_T and the lepton plane determines the spatial orientation of S_T.

An analysis of the SSA A_{UT} in inclusive DIS in a partonic picture has to be performed at subleading twist accuracy [4, 6, 7]. This requires the introduction of typical hadronic matrix elements of certain partonic operators that encode non-trivial correlations of the transverse nucleon spin and the transverse partonic motion [9], as well as multipartonic correlations [10, 7]. However, the effects of transverse partonic motion and multipartonic correlations are not independent. In fact, they can related to each other by means of the QCD-equation of motion (EOM) [9]. An additional dependence originates from the relation between the Sivers function and the so-called Qiu-Sterman matrix element [11]. If one applies the twist-3 factorization formalism of ref. [12] to the SSA A_{UT} all of these hadronic matrix elements are to be convoluted with corresponding partonic hard cross sections, and eventually summed up (cf. [6]).

The hard cross sections relevant for scenario i) are calculated in perturbation theory to $\mathcal{O}(\alpha^3)$ to obtain a non-zero result. This includes interferences of real lepton-quark(& gluon) scattering amplitudes describing the radiation of a photon emitted by either the lepton or the quark. Such real contributions typically contain phase space integrations. Interferences from virtual two-photon-exchange one-loop diagrams and single photon exchange diagrams may also contribute. The various hard cross sections can be combined by application of QCD-EOM inspired relations between effects of transverse partonic motion and multipartonic correlations, and eventually the soft divergences indicated by poles in $1/\varepsilon$ cancel [6].

The hard cross sections can be computed along the same lines for scenario (2). To leading order only tree-level diagrams interfere without phase space integrations [7]. Hence, no soft divergences appear in intermediate steps of the calculation.

Adding the results of refs. [6, 8, 7] leads to the following parton picture formula for the single transverse spin dependent DIS cross section at $\mathcal{O}(\alpha_{\rm em}^3)$,

$$
(1)\quad E' \frac{\mathrm{d}\sigma_{UT}}{\mathrm{d}^3 l'} = -|S_T| \sin\phi_s \frac{4\alpha_{\rm em}^3}{yQ^4} \frac{M}{Q} \frac{x_B y}{\sqrt{1-y}} \times \sum_q \Bigg[e_q^3 \int_0^1 \mathrm{d}x \Big(\hat{C}_+(x, x_B, y)\, G_F^q(x_B, x) + \hat{C}_-(x, x_B, y)\, \tilde{G}_F^q(x_B, x) \Big) + e_q^3 (1-y) \frac{m_q}{M} h_1^q(x_B) + \frac{2-y}{2y} f(y) e_q^2 \left(1 - x_B \frac{\mathrm{d}}{\mathrm{d}x_B}\right) G_F^{\gamma, q}(x_B, x_B) \Bigg].
$$

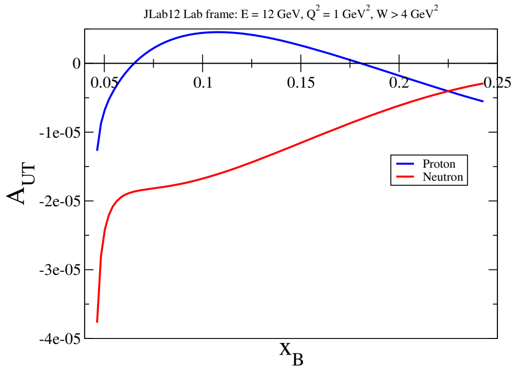

Fig. 1. – Prediction for the asymmetry A_{UT} at JLab12 obtained from a model [13].

The perturbative coefficient functions $\hat{C}_{\pm}$ in eq. (1) are integrable distributions and their functional form is given in ref. [6]. Assuming that the non-perturbative quark-gluon correlation functions $G_F^q(x,x')$ and $\tilde{G}_F^q(x,x')$(1) are analytic the x-integral in (1) is well-defined. In addition the finite quark mass term of ref. [8, 7] has been added to eq. (1) as well as the contribution of ref. [7] describing scenario ii) where the two photons couple to different quarks. The latter term involves a quark-photon correlation function G_F^{γ}(2).

The SSA A_{UT} can be computed from (1) in the following way ($\mathrm{d}\sigma = E'\mathrm{d}\sigma/\mathrm{d}^3k'$):

$$A_{UT} = \frac{\mathrm{d}\sigma_{UT}(\phi_s) - \mathrm{d}\sigma_{UT}(\phi_s - \pi)}{2\mathrm{d}\sigma_{UU}}\,, \tag{2}$$

with the well-known parton model result for the unpolarized cross section [9],

$$\mathrm{d}\sigma_{UU} = \frac{4\alpha_{\mathrm{em}}^2}{Q^4 y} f(y) \sum_q e_q^2 x_B f_1^q(x_B)\,, \tag{3}$$

with f_1 the unpolarized collinear parton distribution, and $f(y) = -y + y^2/2$.

3. – Model for the quark-gluon correlations from light cone wave functions

In order to utilize eq. (1) to estimate the sign and size of the transverse target spin asymmetry A_{UT} on a proton and neutron one needs information on the full support of the non-perturbative quark-gluon correlation functions $G_F^q(x,x')$, $\tilde{G}_F^q(x,x')$(3), as well as the quark-photon correlation function $G_F^{\gamma;q}(x,x)$ in the soft photon limit $x' = x$ and the transversity distribution $h_1^q(x)$. Currently, only extractions from data exist for the so-called "Soft Gluon Pole matrix element" $G_F^q(x,x)$ [14] and the transversity distribution. However, a recent model calculation gives predictions for G_F^q and $\tilde{G}_F^q$ on the full support $x \neq x'$ [13]. In this work the twist-3 quark-gluon correlation functions are expressed in terms on non-valence-like light cone wave functions, and analytical results at a scale

(1) Definitions in terms of hadronic matrix elements for both functions can be found in ref. [10].
(2) Notice a slight redefinition $G_F^{\gamma}(x,x) \equiv \frac{1}{2e^2} F_{FT}(x,x)$ of the object F_{FT} introduced in [7].
(3) Note that $G_F^q(x,x') = G_F^q(x',x)$ and $\tilde{G}_F^q(x,x') = -\tilde{G}_F^q(x',x)$. Hence, $\tilde{G}_F^q(x,x) = 0$.

$\mu_0 = 1\,\text{GeV}$ were obtained. One specific feature of this model is that $G^q_{F,\text{Model}}(x, x, \mu_0) = 0$ due to the absence of final state interactions. This is in obvious contradiction to parametrizations from data for $G^q_F(x, x)$ [14], and the model does not properly describe the physics of $G^q_F(x, x')$ in a small interval around $x' \sim x$. Nevertheless it may realistically probe the physics outside of this interval, *i.e.*, where x' is further away from x. Under the approximation that the quark-photon matrix element $G^{\gamma,q}_F$ is proportional to the quark-gluon matrix element G^q_F [7] one also has $G^{\gamma,q}_{F,\text{Model}}(x, x, \mu_0) = 0$. Hence, for massless quarks the asymmetry A_{UT} in (2) is completely determined by $G^{u,d}_{F,\text{Model}}(x, x', \mu_0)$ and $\tilde{G}^{u,d}_{F,\text{Model}}(x, x', \mu_0)$ at a fixed scale $Q = 1\,\text{GeV}$. The model prediction for A_{UT} is shown in fig. 1. In this plot fixed target kinematics have been used for an electron beam energy $E = 12\,\text{GeV}$ (JLab12 kinematics). A missing mass $W = (P + q)^2 > 4\,\text{GeV}^2 = W_{\min}$ was assumed to ensure that the asymmetry is probed in the DIS region. This defines a maximal Bjorken-x $x_{B,\max} = Q^2/(Q^2 + W_{\min} - M^2) \sim 0.25$ for $Q = 1\,\text{GeV}$. For a fixed scale the energy transfer from the electron to the nucleon y varies with x_B, that is, $y = Q^2/(2MEx_B)$. Typical experimental values $y \sim 0.4$–0.6 are probed at $x_B \sim 0.1$ at $Q = 1\,\text{GeV}$.

4. – Conclusions

The plot in fig. 1 shows that one can expect rather small asymmetries of about 10^{-5} from the model of ref. [13]. Although the JLab data [3] for the SSA A_{UT} on a neutron is still preliminary it gives hints that the asymmetry is much larger in reality for a neutron. This discrepancy may point to missing physics in the integration region $x \sim x'$ in eq. (1) which is left out in the model of ref. [13]. One may consider larger values of $Q > 1\,\text{GeV}$. At larger scales a non-zero "Soft Gluon Pole" $G^q_F(x, x, \mu > 1\,\text{GeV}) \neq 0$ can be obtained from evolution of the model results of ref. [13]. However, one would not expect the asymmetry to be dramatically larger at higher scales due to the factor M/Q in eq. (1).

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