Single Spin Asymmetry in $e + p^{\uparrow} \to e + J/\psi + X$

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We report on a recent investigation of the single spin asymmetry (SSA) in low virtuality electroproduction of J/ψ in color evaporation model. We show that this can be used as a probe for the still unknown gluon Sivers function.

1 Introduction

Large single spin asymmetries (SSA) observed when an unpolarized beam of electrons or protons is scattered off a transversely polarized target can be explained with the inclusion of $\boldsymbol{k}_{\perp}$ dependence in parton distribution functions (pdf's) and fragmentation functions(ff's) [1]. One is led to a generalized factorization formula called TMD factorization [2, 3], which in some processes has been proved at leading twist and leading order [4] and has been argued to hold at all orders. The inclusion of the effect of transverse momentum of partons in parton distribution (pdf) and fragmentation functions leads to a new class of parton distributions that include the effects of spin and transverse momentum of the partons. One of these functions is the Sivers function which describes the probability of finding an unpolarized parton inside a transversely polarized hadron. In this work, we propose charmonium production as a probe to investigate the Sivers function and as a first step, estimate SSA in photoproduction (low virtuality electroproduction) of charmonium in scattering of electrons off transversely polarized protons. At leading order (LO), this receives contribution only from a single partonic subprocess $\gamma g \to c\bar{c}$. Hence, SSA in $e + p^{\uparrow} \to e + J/\psi + X$, if observed, can be used as a clean probe of gluon Sivers function. In addition, charmonium production mechanism can also have implications for this SSA and therefore, its study can help probe the production mechanism for charmonium.

2 Estimate of the Sivers Asymmetry

There are several models for charmonium production. We use the color evaporation model (CEM) as its simplicity makes it suitable for an initial study of SSA in the charmonium production. This model was first proposed by Halzen and Matsuda [5] and Fritsch [6]. In this model, a statistical treatment of color is made and the probability of finding a specific quarkonium state is assumed to be independent of the color of heavy quark pair. In later versions of this model it has been found that the data are better fitted if a phenomenological factor is included in the differential cross section formula, which depends on a Gaussian distribution of the transverse momentum of the charmonium [7]. We have used Weizsacker-Williams equivalent photon approximation for the photon distribution of the electron [8, 9], to calculate the cross section for the process $e + p^\uparrow \to e + J/\psi + X$ at low virtuality of the photon. The underlying partonic process at LO is $\gamma g \to c\bar{c}$ and therefore, the only $k_\perp$ dependent pdf appearing is the gluon Sivers function. For a complete calculation of photoproduction of J/ψ one has to consider higher order contributions and also the resolved photon contributions [7]. Also the gauge links or Wilson lines present in the TMD distributions are important at higher order [10].

According to CEM, the cross section for charmonium production is proportional to the rate of production of $c\bar{c}$ pair integrated over the mass range $2m_c$ to $2m_D$

$$\sigma = \frac{1}{9}\int_{2m_c}^{2m_D} dM \frac{d\sigma_{c\bar{c}}}{dM} \tag{1}$$

where m_c is the charm quark mass and $2m_D$ is the $D\bar{D}$ threshold, M^2 is the squared invariant mass of the $c\bar{c}$ pair.

To calculate SSA in scattering of electrons off a polarized proton target, we assume a generalization of CEM expression by taking into account the transverse momentum dependence of the Weizsacker-Williams (WW) function and gluon distribution function. The numerator of the SSA can be written as

$$\begin{aligned}\frac{d^4\sigma^\uparrow}{dydM^2d^2\boldsymbol{q}_T} - \frac{d^4\sigma^\downarrow}{dydM^2d^2\boldsymbol{q}_T} = \frac{1}{s}\int [d^2\boldsymbol{k}_{\perp\gamma} d^2\boldsymbol{k}_{\perp g}] \Delta^N f_{g/p^\uparrow}(x_g, \boldsymbol{k}_{\perp g}) f_{\gamma/e}(x_\gamma, \boldsymbol{k}_{\perp\gamma}) \\ \times\, \delta^2(\boldsymbol{k}_{\perp\gamma} + \boldsymbol{k}_{\perp g} - \boldsymbol{q}_T)\hat{\sigma}_0^{\gamma g \to c\bar{c}}(M^2)\end{aligned} \tag{2}$$

where y is the rapidity and q_T in the transverse momentum of the charmonium; $\Delta^N f_{g/p^\uparrow}(x_g, \boldsymbol{k}_{\perp g})$ is the gluon Sivers function, $f_{\gamma/e}(x_\gamma, \boldsymbol{k}_{\perp\gamma})$ is the photon distribution of the electron, given in the WW approximation. The denominator would have a similar expression involving the unpolarized gluon distribution of the proton; $f_{g/p}(x_g, \boldsymbol{k}_{\perp g})$, for which we use a gaussian form of $k_\perp$ distribution and a similar gaussian form for the transverse momentum dependence of the WW function. To extract the asymmetry produced by the Sivers function, we calculate the weighted asymmetry [11]

$$A_N^{\sin(\phi_{q_T} - \phi_S)} = \frac{\int d\phi_{q_T}[d\sigma^\uparrow - d\sigma^\downarrow]\sin(\phi_{q_T} - \phi_S)}{\int d\phi_{q_T}[d\sigma^\uparrow + d\sigma^\downarrow]} \tag{3}$$

where ϕ_{q_T} and ϕ_S are the azimuthal angles of the J/ψ and proton spin respectively. For the gluon Sivers function we have used a model in our analysis, which has been used in the literature to calculate SSA in semi-inclusive deep inelastic scattering (SIDIS) [12] and DY process [13] (see [14] for details). The parameters are taken from [15]. Other parameters we use are

$$\langle k_{\perp g}^2 \rangle = \langle k_{\perp\gamma}^2 \rangle = 0.25\, GeV^2.$$

Also it is to be noted that in the model we consider for charmonium production, namely the color evaporation model, the only relevant scale is M^2 which is the invariant mass of the heavy quark pair. This is integrated between a narrow region, from $4m_c^2$ to $4m_D^2$ irrespective of the center-of-mass energy of the experiment. So the scale evolution of the TMDs is not expected to affect the asymmetry too much.

In Fig. 1 we have shown a comparison of the y and q_T dependence of the asymmetry at JLab, HERMES, COMPASS and eRHIC. Model I refers to the parametrization in [13] and (a) refers to the parametrization of the gluon Sivers function in terms of an average of the u and d quark Sivers function [14]. Different experiments cover different kinematical regions, and our

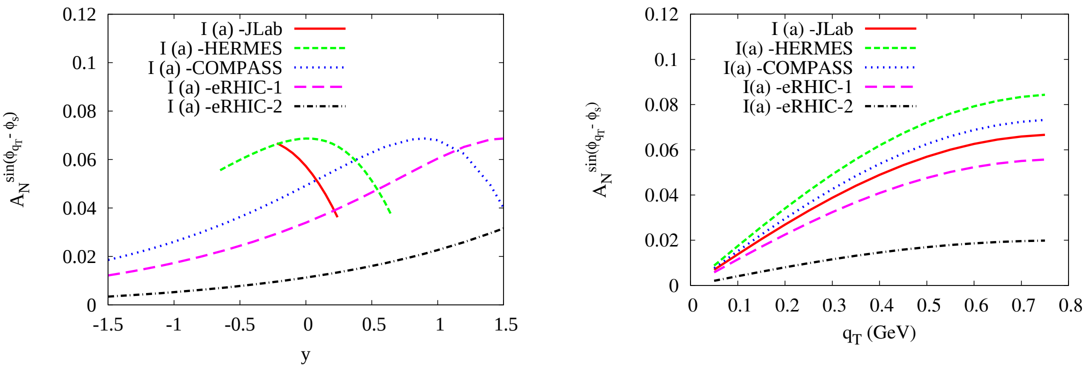

Figure 1: (Color online) The single spin asymmetry $A_N^{\sin(\phi_{q_T} - \phi_S)}$ for the $e + p^\uparrow \to e + J/\psi + X$ as a function of y (left panel) and q_T (right panel). The plots are for model I (a) (see text) compared for JLab ($\sqrt{s} = 4.7$ GeV) (solid red line), HERMES ($\sqrt{s} = 7.2$ GeV) (dashed green line), COMPASS ($\sqrt{s} = 17.33$ GeV) (dotted blue line), eRHIC-1 ($\sqrt{s} = 31.6$ GeV) (long dashed pink line) and eRHIC-2 ($\sqrt{s} = 158.1$ GeV) (dot-dashed black line).

results clearly show that the asymmetry is sizable, and that it is worthwhile to look at SSA's in charmonium production in order to extract information on the gluon Sivers function.

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