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Nuclear Physics B (Proc. Suppl.) 251–252 (2014) 56–61

NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS

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Transverse Single Spin Asymmetries and Charmonium Production

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Abstract

We estimate transverse spin single spin asymmetry(TSSA) in the process $e + p^{\uparrow} \to J/\psi + X$ using color evaporation model of charmonium production. We take into account transverse momentum dependent(TMD) evolution of Sivers function and parton distribution function and show that the there is a reduction in the asymmetry as compared to our earlier estimates wherein the Q^2 - evolution was implemented only through DGLAP evolution of unpolarized gluon densities.

Keywords: Single Spin Asymmetry, Charmonium

1. Introduction

Single spin asymmetries(SSA's) arise in the scattering of transversely polarized nucleons off an unpolarized nucleon (or virtual photon) target, when the final state hadrons have asymmetric distribution in the transverse plane perpendicular to the beam direction. SSA for inclusive process $A^{\uparrow} + B \to C + X$ depends on the polarization vector of the scattering hadron A and is defined by

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \tag{1}$$

Non - zero SSAs have been observed over the years-in pion production at Fermilab[1] and at RHIC[2] in $pp^{\uparrow}$ collisions as well as in Semi-inclusive deep inelastic scattering (SIDIS) experiments at HERMES[3] and COMPASS[4]. These results have generated a lot of interest amongst theoreticians to investigate the mechanism involved and to understand the underlying physics.

The initial attempts to provide theoretical predictions of asymmetry, based on collinear factorization of pQCD, led to estimates which were too small as compared to the experimental results[5]. In collinear factorization formalism, the parton distribution functions (PDF's) and fragmentation functions (FF's) are integrated over intrinsic transverse momentum of the partons and hence depend only on longitudinal momentum fraction x. The observation that SSAs calculated within collinear formalism were almost vanishing suggested that these asymmetries may be due to parton's transverse motion and spin orbit correlation. A generalization of factorization theorem, in the form of transverse momentum dependent (TMD) factorization which includes the transverse momentum dependence of PDF's and FF's, was proposed as a possible approach to account for the asymmetries[6].

One of the TMD PDF's of interest is Sivers function, which gives the probability of finding an unpolarized quark inside a transversely polarized proton. The Sivers function, $\Delta^N f_{a/p^{\uparrow}}(x, \mathbf{k}_{\perp\mathbf{a}})$, defined by

$$\begin{aligned}\Delta^N f_{a/p^{\uparrow}}(x, \mathbf{k}_{\perp\mathbf{a}}) &\equiv \hat{f}_{a/p^{\uparrow}}(x, \mathbf{k}_{\perp a}) - \hat{f}_{a/\downarrow}(x, \mathbf{k}_{\perp a}) \\ &= \hat{f}_{a/\uparrow}(x, \mathbf{k}_{\perp a}) - \hat{f}_{a/\uparrow}(x, -\mathbf{k}_{\perp a})\end{aligned} \tag{2}$$

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http://dx.doi.org/10.1016/j.nuclphysbps.2014.04.010
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is related to the number density of partons inside a proton with transverse polarization S, three momentum $\mathbf{p}$ and intrinsic transverse momentum $\mathbf{k}_\perp$ of partons, and its spin dependence is given by

$$\Delta^N f_{a/p^\uparrow}(x, \mathbf{k}_{\perp \mathbf{a}}) = \Delta^N f_{a/p^\uparrow}(x, k_\perp)\, \mathbf{S} \cdot (\hat{\mathbf{p}} \times \hat{\mathbf{k}}_\perp) \quad (3)$$

Parametrizations of quark Sivers distributions have been obtained from fits of SSA in SIDIS experiments[7]. However, not much information is available on gluon Sivers function. Processes that have been studied with the aim of getting information about this TMD are back to back correlations in azimuthal angles of of jet produced in $pp^\uparrow$ scattering[8] and D meson production in $pp^\uparrow$ scattering[9]. Heavy quark and quarkonium systems have also been proposed as natural probes to study gluon Sivers function due to the fact that the production is sensitive to intrinsic transverse momentum especially at low momentum[10]. It has been suggested, in the context of deep inelastic scattering[11] that the initial and final state interactions may lead to non-vanishing SSAs. Single transverse spin asymmetry in heavy quarkonium production in lepton-nucleon and nucleon-nucleon collisions has been investigated by Yuan *etal* taking into account the initial and final state interactions [10] and it has been shown that the asymmetry is very sensitive to the production mechanism. The three main models of heavy quarkonium production, which have been proposed and tested in unpolarized scattering, are Color Singlet Model[12], Color Evaporation Model (CEM)[13, 14] and the NRQCD factorization approach[15]. It was argued in Ref.[10] that the asymmetry should be non-zero in ep collisions only in color-octet model and in pp collisions only in color-singlet model. Thus, SSA in charmonium production can be used to throw some light on the issue of production mechanism. In this work, we present estimates of SSA in the process $e + p^\uparrow \to J/\psi + X$ and compare the results obtained using TMD evolution of PDF's with our earlier results which were obtained using DGLAP evolution only.

2. Transverse Single Spin Asymmetry in $e + p^\uparrow \to J/\psi + X$

The first estimate of SSA in photoproduction (i.e. low virtuality electroproduction) of J/ψ in the scattering of electrons off transversely polarized protons were provided by us in Ref.[16] using Color Evaporation Model. In the process under consideration, at LO, there is contribution only from a single partonic subprocess and therefore, it can be used as a clean probe of gluon Sivers function.

Color Evaporation Model (CEM) was introduced in 1977 by Fritsch and was revived in 1996 by Halzen[13]. This model gives a good description of photoproduction data after inclusion of higher order QCD corrections[17] and also of the hadroproduction CDF data [18] after inclusion of k_T smearing. In CEM, the cross-section for a quarkonium state H is some fraction F_H of the cross-section for producing $Q\bar{Q}$ pair with invariant mass below the $M\bar{M}$ threshold, where M is the lowest mass meson containing the heavy quark Q:

$$\sigma_{CEM}[h_A h_B \to H + X] = F_H \sum_{i,j} \int_{4m^2}^{4m_M^2} d\hat{s}$$
$$\times \int dx_1 dx_2\, f_i(x_1,\mu)\, f_j(x_2,\mu)\, \hat{\sigma}_{ij}(\hat{s})\, \delta(\hat{s} - x_1 x_2 s) \quad (4)$$

We have used a generalization of CEM expression for electroproduction of J/ψ by taking into account the transverse momentum dependence of the gluon distribution function and the William Weizsacker (WW) function which gives the photon distribution of the electron in equivalent photon approximation[19]. The cross section for the process $e + p^\uparrow \to J/\psi + X$ is then given by

$$\sigma^{e+p^\uparrow \to e+J/\psi+X} = \int_{4m_c^2}^{4m_D^2} dM_{c\bar{c}}^2 dx_\gamma dx_g [d^2\mathbf{k}_{\perp\gamma} d^2\mathbf{k}_{\perp g}]$$
$$\times f_{g/p^\uparrow}(x_g, \mathbf{k}_{\perp g}) f_{\gamma/e}(x_\gamma, \mathbf{k}_{\perp\gamma})\, \frac{d\hat{\sigma}^{\gamma g \to c\bar{c}}}{dM_{c\bar{c}}^2} \quad (5)$$

where $f_{\gamma/e}(x_\gamma, \mathbf{k}_{\perp\gamma})$ is the distribution function of the photon in the electron. We assume a gaussian form for the $\mathbf{k}_\perp$ dependence of pdf's [7],

$$f(x, k_\perp) = f(x) \frac{1}{\pi \langle k_\perp^2 \rangle} e^{-k_\perp^2/\langle k_\perp^2 \rangle} \quad (6)$$

where $\langle k_\perp^2 \rangle = 0.25 GeV^2$. $f_{\gamma/e}(x_\gamma, \mathbf{k}_{\perp\gamma})$ is also assumed to have a similar $\mathbf{k}_\perp$ dependence and is given by

$$f_{\gamma/e}(x_\gamma, k_{\perp\gamma}) = f_{\gamma/e}(x_\gamma) \frac{1}{\pi \langle k_{\perp\gamma}^2 \rangle} e^{-k_{\perp\gamma}^2/\langle k_{\perp\gamma}^2 \rangle}. \quad (7)$$

where $f_{\gamma/e}(x_\gamma)$ is the William Weizsacker function given by [20]:

$$f_{\gamma/e}(y, E) = \frac{\alpha}{\pi} \frac{1 + (1-y)^2}{y} \left(ln\frac{E}{m} - \frac{1}{2} \right)$$
$$+ \frac{y}{2}\left[ln\left(\frac{2}{y} - 2 \right) + 1 \right] + \frac{(2-y)^2}{2y} ln\left(\frac{2-2y}{2-y} \right) \quad (8)$$

y being the energy fraction of the electron carried by the photon.

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