Left-right asymmetry for meson production in SIDIS process*

SUN Bo(孙博) SHE Jun(佘俊) ZHANG Bing(张冰) MAO Ya-Jun(冒亚军)[1)] MA Bo-Qiang(马伯强)[2)]

(School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China)

Abstract We analyze the left-right asymmetry in the semi-inclusive deep inelastic scattering (SIDIS) process using a method where no weighting function are used. Considering all flavor of quarks, we reanalyze the $\pi^{\pm}$ production and extend our calculation on the $K^{\pm}$ production. The predictions on HERMES, COMPASS and JLab kinematics with transversely polarized nucleon target are shown in this paper.

Key words semi-inclusive deep inelastic scattering, transversity, left-right asymmetry

PACS 13.60.Le, 13.85.Ni, 13.87.Fh

1 Introduction

In 1991, the left-right asymmetry was reported by E704 collaboration for the first time[1], where large asymmetry was found in $p^{\uparrow}p \rightarrow \pi X$ process with 200 GeV transversely polarized beam. Their results suggest that the transverse spin effect is also significant even in the high energy region. However, the theory based on the naive parton model predicted a vanishing asymmetry. In order to explain these phenomena, two mechanisms were proposed. In 1991, Sivers provided a possible mechanism[2] that the asymmetry is originated from the quark intrinsic transverse momentum. This mechanism is now described by a parton distribution function, the Sivers function; In 1993, Collins provided another mechanism[3, 4] that the asymmetry is generated in the hadronization processes with a spin dependent fragmentation function, the Collins function. Although these two mechanisms are completely different, both of them contribute to the asymmetry.

Contrast to the complexity of the hadron-hadron collision process, we turn our attention to a much cleaner and simpler process, the semi-inclusive deep inelastic scattering (SIDIS) process. Since the contribution of the Sivers and Collins effects are combined during the interaction of high energy particles, various weighting functions are used in most analysis. After multiplying the weighting function, we can extract each effect separately. This is the conventional way to deal with the SIDIS data. However, in Ref.[5], it was pointed out that the selection of the weighting functions is based on a certain theory, the "weighting function" method may change if the theory changes. The authors suggested to analyze the SIDIS data using the method at the E704 experiment where no weighting functions were multiplied.

As we know, there are other theory which try to explain the left-right asymmetry, e.g. the valence quark orbital angular moment effect[6], but apparently the weighting functions do not work in these theories. Thus we think it is reasonable to adopt the no-weighting function method.

In Ref. [5], only u and d quarks were considered in the calculation, however, besides u and d quarks, $\bar{u}$ and $\bar{d}$ quarks are also favored in the fragmentation process to the $\pi^{\pm}$ production, so the sea quarks contribution especially for $\bar{u}$ and $\bar{d}$ should not be ignored. Considering all flavors of quarks, we reanalyze the $\pi^{\pm}$ production and then extend our calculation on the $K^{\pm}$ production.

2 Theoretical description

On the theoretical side, we adopt the factorization

Received 7 August 2009

* Supported by National Natural Science Foundation of China (10721063, 10575003, 10528510) and Key Grant Project of Chinese Ministry of Education (305001)

1) E-mail: maoyj@pku.edu.cn

2) E-mail: mabq@phy.pku.edu.cn

theorem to describe the cross section. By introducing various distribution or fragmentation functions, we can express the cross section for an SIDIS process explicitly under the $\gamma^* p$ frame[7, 8], in which the z axis is defined as the direction parallel to the exchanged virtual photon. However, most of the experiment analysis were under the ℓp frame, i.e. the laboratory frame, where z axis is defined as the direction parallel to the beam direction. In order to compare with experiment, we need to transform the cross section from $\gamma^* p$ frame to ℓp frame by a rotation of angle θ, θ is the angle between the beam and the virtual photon. Thus the cross section is written as[9]:

$$\begin{aligned}
&\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}y\mathrm{d}\phi_s^\ell\mathrm{d}z\mathrm{d}\phi_h^\ell\mathrm{d}P_{h\perp}^2}= \\
&\frac{\alpha^2}{2sx(1-\epsilon)}\frac{\cos\theta}{1-\sin^2\theta\sin^2\phi_s^\ell}\times\Bigg\{\mathcal{F}[f_1D_1]- \\
&\frac{S_T\cos\theta}{\sqrt{1-\sin^2\theta\sin^2\phi_s^\ell}}\sin(\phi_h^\ell-\phi_s^\ell)\mathcal{F}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_\perp}{M_p}f_{1T}^\perp D_1\right]- \\
&\frac{S_T\cos\theta}{\sqrt{1-\sin^2\theta\sin^2\phi_s^\ell}}\sin(\phi_h^\ell+\phi_s^\ell)\mathcal{F}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_\perp}{M_h}h_1H_1^\perp\right]+ \\
&+\text{other terms}\Bigg\}\equiv\mathrm{d}\sigma_{\mathrm{UU}}+\mathrm{d}\sigma_{\mathrm{Siv}}+\mathrm{d}\sigma_{\mathrm{Col}}+\dots, \qquad (1)
\end{aligned}$$

where we use a compact notation:

$$\mathcal{F}[\omega fD]=\sum_a e_a^2\int\mathrm{d}^2\boldsymbol{p}_\perp\mathrm{d}^2\boldsymbol{k}_\perp\delta^2(\boldsymbol{p}_\perp-\boldsymbol{k}_\perp-\boldsymbol{P}_{h\perp}/z)\,\omega(\boldsymbol{p}_\perp,\boldsymbol{k}_\perp)f^a(x,p_\perp^2)D^a(z,z^2k_\perp^2), \qquad (2)$$

and

$$\epsilon=\frac{1-y-\frac{1}{4}y^2\gamma^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}y^2\gamma^2}, \qquad \hat{\boldsymbol{h}}\equiv\boldsymbol{P}_{h\perp}/|\boldsymbol{P}_{h\perp}|. \qquad (3)$$

The angles ϕ_h^ℓ and ϕ_s^ℓ are defined as: $\phi_h^\ell=\phi_h-\phi^\ell$, $\phi_s^\ell=\phi_s-\phi^\ell$, where ϕ^ℓ denotes the orientation angle of the lepton plane.

The left-right asymmetry in this paper is defined as:

$$A=-\frac{1}{S_T}\frac{N(\psi_s)-N(\psi_s+\pi)}{N(\psi_s)+N(\psi_s+\pi)}=-\frac{1}{S_T}\frac{\mathrm{d}\sigma^\uparrow-\mathrm{d}\sigma^\downarrow}{\mathrm{d}\sigma^\uparrow+\mathrm{d}\sigma^\downarrow}, \qquad (4)$$

where S_T is the transverse polarization of the target, ψ_s is the azimuthal angle of the spin vector. Since no weighting functions are applied here, we cannot integrate the produced hadron over the whole space, or it must lead to a vanishing result. Similar to the E704 experiment, we limit the detected region in a certain range, e.g. $-\pi/4$ to $\pi/4$. As the target spin changes from up to down, a left-right asymmetry is obtained. After integral over ϕ^ℓ, we find that Sivers effect is $O(1)$, but other terms such as the Collins effect are $O(\sin^2\theta)$. θ can be calculated by[9]:

$$\sin\theta=\gamma\sqrt{\frac{1-y-\frac{1}{4}y^2\gamma^2}{1+\gamma^2}}, \qquad \gamma=2xM_p/Q. \qquad (5)$$

For most instance, θ is very small, and the direction of the virtual photon is very close to the direction of the incident beam. That is: the Sivers effect is dominant and other effects are suppressed in our analysis. And for convenience, the Collins effect which is not known so clearly yet is not considered in our analysis. The asymmetry can be written as:

$$A_{\mathrm{UT}}(x,y,z,P_{h\perp})\approx-\frac{1}{S_T}\frac{\int\mathrm{d}\phi_s^\ell\mathrm{d}\phi_h^\ell\;(\mathrm{d}\sigma_{\mathrm{Siv}}+\mathrm{d}\sigma_{\mathrm{Col}}+\cdots)}{\int\mathrm{d}\phi_s^\ell\mathrm{d}\phi_h^\ell\;\mathrm{d}\sigma_{\mathrm{UU}}}. \qquad (6)$$

3 Numerical calculations

Before the numerical calculations, we need an input for the distribution and fragmentation functions. The Sivers function has already been studied by HERMES and COMPASS Collaborations[10, 11], but at that time, only the information of u and d quarks could be extracted. Recently, besides the charged pion production, neutral pion and charged kaon azimuthal asymmetries were also analyzed by HERMES and COMPASS Collaboration[12, 13]. Thanks to these experiment, the parameters of the Sivers function were improved, and besides the u and d quarks the Sivers function for the sea, quarks were extracted for the first time[14]. For the fragmentation functions, all recent analysis were based exclusively on the single-inclusive e^+e^- annihilation (SIA) data. In these experiments, it is impossible to distinguish "valence" from "sea" without assumptions. Fortunately, the measurements coming from both proton-proton collisions and deep-inelastic lepton-nucleon scattering have matured enough to yield complementary information on the fragmentation process in the last few years. Using these data, individual fragmentation functions for all flavors quarks as well as gluons were extracted in a global analysis[15].

It should be pointed out that, although an universal transverse momentum dependent distributions for different processes do not exist[16], we choose the Sivers function also from SIDIS process.

Using the parametrization mentioned above, we present our prediction on HERMES experiment for a proton target, on Compass experiment for proton, neutron and deuteron targets, on JLab experiment for proton and neutron targets.

Firstly, we reanalyze the results on $\pi^{\pm}$ production for different experiments, these results are shown in Fig. 1 — Fig. 4. In Fig. 1, we make a comparison with the results obtained in Ref. [5], It can be found that the sea quarks have an observable contribution to the asymmetry, especially suppress the asymmetry at large x and z region. Then we extend our calculation to the $K^{\pm}$ production, the results are shown in Fig. 5 — Fig. 8. Notice that the Sivers distributions of the ū and s quarks given in Ref. [14] are extremely small but with a large uncertainty where even their sign are not determined within the error, so it must lead a large uncertainty to our prediction on K^- production.

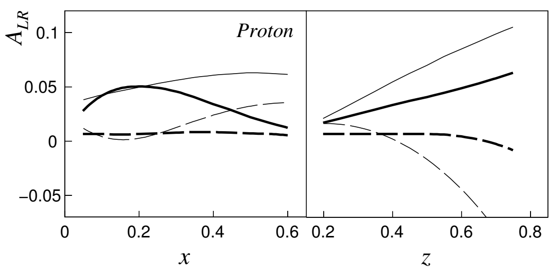

Fig. 1. The x and z-dependence of the left-right asymmetry for $\pi^{\pm}$ production on HERMES kinematics. Solid lines for π^+ and dashed lines for π^-. Thick curves are our results and thin curves are results from Ref. [5].

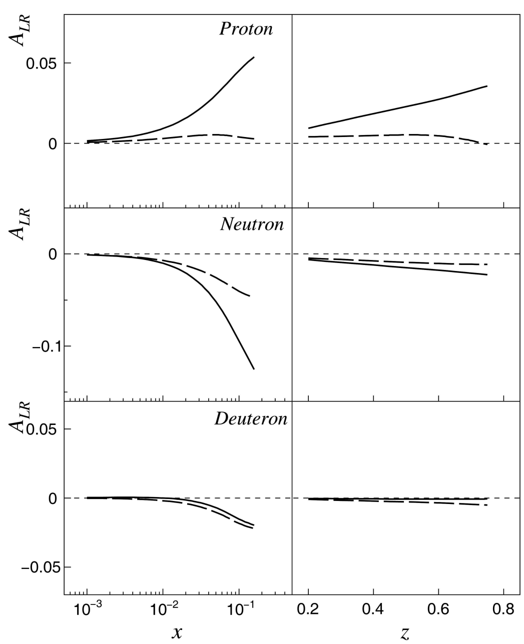

Fig. 2. Similar as Fig. 1, but at COMPASS kinematics.

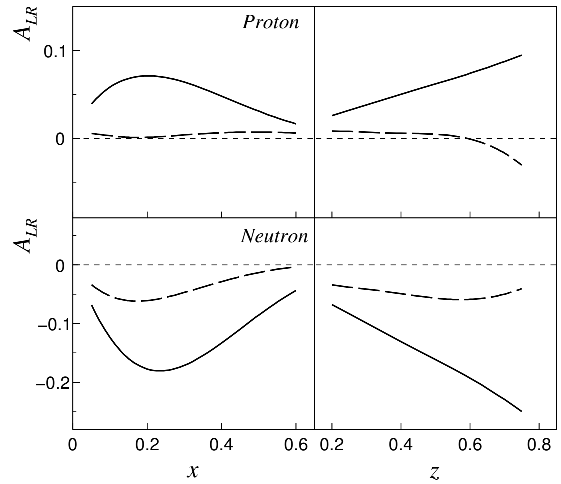

Fig. 3. Similar as Fig. 1, but at JLab kinematics with a beam energy of 6 GeV.

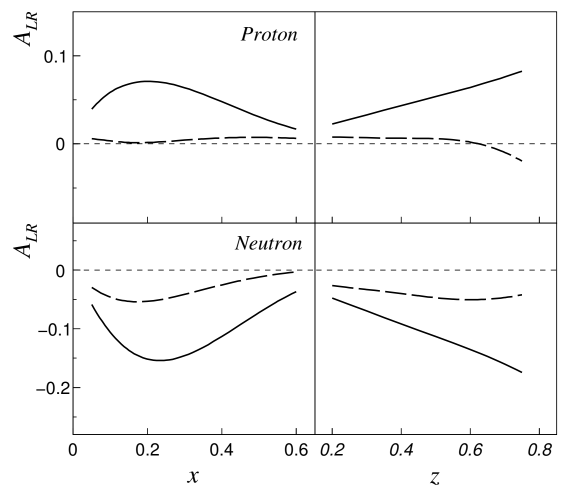

Fig. 4. Similar as Fig. 1, but at JLab kinematics with a beam energy of 12 GeV.

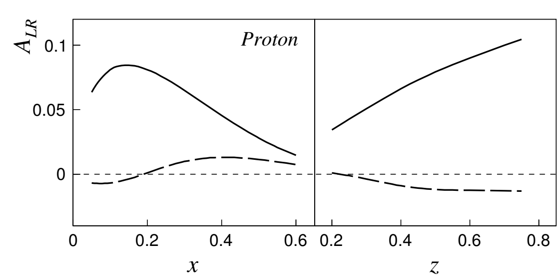

Fig. 5. The x and z-dependence of the left-right asymmetry for $K^{\pm}$ production on HERMES kinematics. Solid lines for K^+ and dashed lines for K^-.

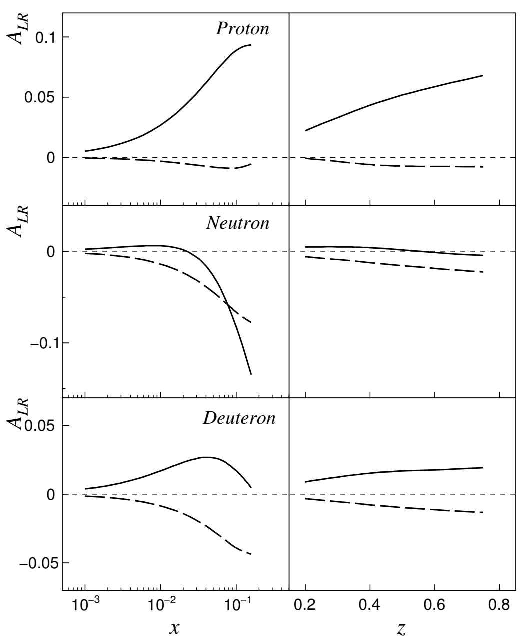

Fig. 6. Similar as Fig. 5, but at COMPASS kinematics.

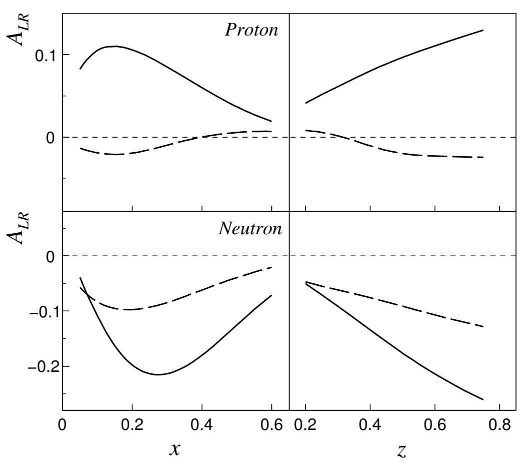

Fig. 7. Similar as Fig. 5, but at JLab kinematics with a beam energy of 6 GeV.

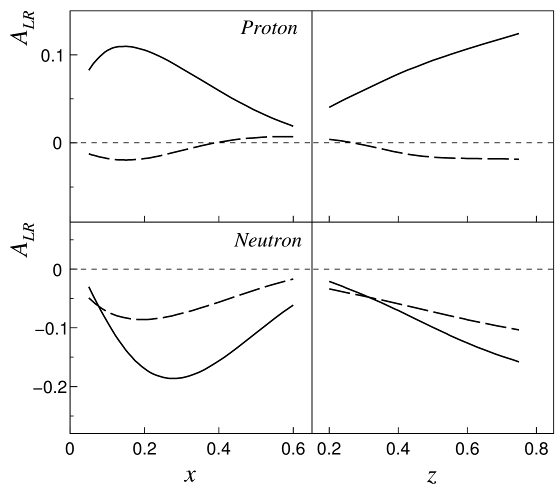

Fig. 8. Similar as Fig. 5, but at JLab kinematics with a beam energy of 12 GeV.

4 Conclusion

Following the method in Ref. [5], we reanalyze the left-right asymmetry in the SIDIS process with the new Sivers and fragmentation functions, all flavors of quarks are considered in our analysis. We found the contribution of sea quarks should not be ignored in $\pi^{\pm}$ production, although their Sivers distributions are small. The asymmetry on $K^{\pm}$ production are also presented in this paper. It should be cautious that the results for K^{-} production might be not accurate enough, and the parametrization of $\bar{u}$ and s quarks need further constrained.

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