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Longitudinal spin transfer of semi-inclusive Λ production in deep inelastic scattering

Xiaoyan Zhao,[a,*] Tianbo Liu[a,b] and Ya-jin Zhou[a]

[a] *Key Laboratory of Particle Physics and Particle Irradiation (MOE), Institute of Frontier and Interdisciplinary Science, Shandong University*
Qingdao, Shandong 266237, China

[b] *Southern Center for Nuclear-Science Theory (SCNT), Institute of Modern Physics, Chinese Academy of Sciences*
Huizhou, Guangzhou 516000, China

E-mail: zhao_xiaoyan@mail.sdu.edu.cn

Λ particle is an excellent tool for probing spin effects due to its self-analyzing weak decay. We study the longitudinally polarized Λ production in semi-inclusive deep inelastic scattering. In particular, we propose a method based on the spectator diquark model to directly calculate the contributions from the target fragmentation region. The results indicate that these contributions significantly suppress the longitudinal spin transfer to Λ from the current fragmentation region, thereby describing the experimental data from COMPASS, HERMES and CLAS12 quite well.

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*Speaker

1. Introduction

Λ polarization measurements can be used to investigate the spin structure of the target nucleons in semi-inclusive deep inelastic scattering (SIDIS) process [1]. The challenge is that, in existing fixed-target experiments, such as COMPASS, HERMES, and CLAS12, the boundary distinguishing the current fragmentation region (CFR) and target fragmentation region (TFR) for the hadron production is blurred. In addition to the traditional research on the CFR, we consider the contribution of the TFR to the spin transfer to Λ. We perform an estimation based on the spectator diquark model to quantitatively demonstrate the TFR contribution and compare it with experimental data from COMPASS [2], HERMES [3, 4], and CLAS12 [5]. This study diversifies SIDIS processes that can probe the fracture functions, providing a complementary perspective in this field.

2. Longitudinal spin transfer in current and target fragmentation regions

We consider the SIDIS process of producing a longitudinally polarized Λ or $\bar{\Lambda}$ hyperon from a longitudinally polarized lepton and an unpolarized target, denoted as $l(\ell, \lambda_e) + p(P) \to l(\ell') + \Lambda/\bar{\Lambda}(P_h, \lambda_h) + X$. The differential cross section can be expressed as

$$\frac{d\sigma(\lambda_e, \lambda_h)}{dxdydzd^2\boldsymbol{P}_{h\perp}} = \frac{4\pi\alpha_{em}^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\left\{F_{UU} + \lambda_e\lambda_h\sqrt{1-\epsilon^2}F_{UL} + \cdots\right\}, \tag{1}$$

where F is the structure function with the subscripts specifying the polarizations of the target and final-state hadron. Here we choose $\gamma^* N$ collinear frame, and $\perp$ and L denote the transverse and longitudinal components of a vector, respectively.

In principle, final-state hadrons can be generated in two kinematic regions: from the scattered quark fragmentation in the CFR, and from the nucleon target remnants fragmentation in the TFR. In other words, the cross section can be divided into two parts, $\sigma = \sigma^{CFR} + \sigma^{TFR}$. At very high center-of-mass energy, the hadrons produced by the quark that struck by the virtual photon and those produced by the remnants of the nucleon should move in opposite directions, as shown in the simple schematic diagram in Fig. 1. However, when photon has a relatively small transverse momentum $q_\perp$, the hadron may not continue to move along the direction of the virtual photon, making the boundaries between CFR and TFR become blurred. We need to consider both of these two fragmentation regions.

Focusing on the longitudinal spin transfer D_{LL}^h from the lepton to the $\Lambda/\bar{\Lambda}$ hyperon, we can express it as the ratio of the structure functions. This can be further expanded into the transverse momentum dependent (TMD) parton distribution function (PDF) f_{1q}, unpolarized and longitudinally polarized TMD fragmentation function (FF) D_{1q}^h and G_{1Lq}^h in the CFR [6], and $\boldsymbol{P}_{h\perp}$-dependent fracture functions M_q^h and ΔM_{Lq}^h in the TFR [7], respectively,

$$D_{LL}^h(x, z, \boldsymbol{P}_{h\perp}, Q^2) = \frac{F_{UL}(x, z, \boldsymbol{P}_{h\perp}, Q^2)}{F_{UU}(x, z, \boldsymbol{P}_{h\perp}, Q^2)} = \frac{\mathcal{I}\left[f_{1q}G_{1Lq}^h\right] + x\left|\frac{\partial\zeta}{\partial z}\right|\sum_q e_q^2 \Delta M_{Lq}^h}{\mathcal{I}\left[f_{1q}D_{1q}^h\right] + x\left|\frac{\partial\zeta}{\partial z}\right|\sum_q e_q^2 M_q^h}. \tag{2}$$

Here $\mathcal{I}\left[f_q D_q^h\right] \equiv \sum_q e_q^2 \int d^2\boldsymbol{p}_\perp d^2\boldsymbol{k}_\perp \delta^2(z\boldsymbol{p}_\perp + \boldsymbol{k}_\perp - \boldsymbol{P}_{h\perp}) x f_q(x, p_\perp^2; Q) D_q^h(z, k_\perp^2; Q)$, with $\boldsymbol{p}_\perp$ and $\boldsymbol{k}_\perp$ being the transverse momenta of the quark. ζ is the longitudinal momentum fraction carried by the produced hadron in TFR.

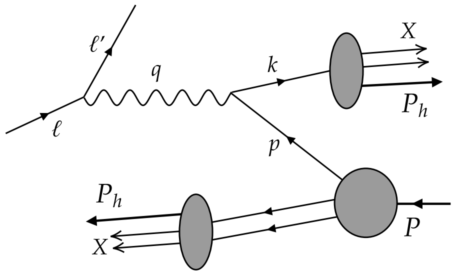


Figure 1: Semi-inclusive production of the hadron h in current and target fragmentation regions.

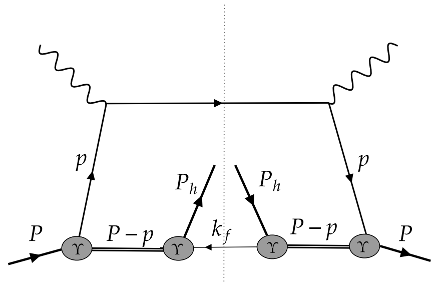


Figure 2: The lowest-order diagram of the target fragmentation process in the diquark model.

3. Numerical result and discussion

The spin transfer is a direct experimental observable in COMPASS [2], HERMES [3, 4], and CLAS12 [5], and we can examine D^h_{LL} on the x, and Feynman variable x_F dependencies. For the TMD PDF and FFs, some parametrization schemes on market can be used. However, the fracture functions are in general less studied due to the scarcity of experimental data. We calculate it in the spectator diquark model, which includes both the spin-0 (scalar) or spin-1 (axial-vector) spectator systems [8]. The fragmentation process is modeled as $p(uud) \to u + R(ud)$ and $R(ud) \to \Lambda(uds) + \bar{s}$, as shown in Fig. 2, where only a scalar diquark $R(ud)$ survives according to the SU(6) wave function of Λ hyperon. This implies that the polarized fracture functions including ΔM^h_{Lq} in Eq. (2) are zero.

In the spectator diquark model, the matrix element can be written in this form,

$$\left\langle P_h, S_h; k_f|\psi(0)|P,S\right\rangle = \bar{U}(P_h,S_h)\Upsilon_2 v(k_f)\frac{i}{(P-p)^2-M_s^2}\frac{i}{\not{p}-m}\Upsilon_1 U(P,S), \tag{3}$$

where $U(P,S)$, $U(P_h,S_h)$ and $v(k_f)$ are the Dirac spinors of the corresponding particles. The symbols m and M_s are the masses of the quark and the diquark, respectively. $\Upsilon_i = g_i\mathbf{1}$ is the hadron-quark-diquark vertex with g_i being a Gaussian form factor [9]. By inserting Eq. (3) into the fracture correlator which is given in Ref. [7], we can obtain the unpolarized fracture function M^h_u,

$$M^h_u = \frac{g^2_{1s}g^2_{2s}x\left[(m+xM)^2+\boldsymbol{p}^2_\perp\right]}{2(2\pi)^6\zeta^2(1-\zeta-x)^2(p^2-m^2)^2}\frac{\left[(1-x-\zeta)M_h-\zeta m_f\right]^2+\left[(1-x)\boldsymbol{P}_{h\perp}+\zeta\boldsymbol{p}_\perp\right]^2}{x(1-x)M^2-xM_s^2-(1-x)p^2-\boldsymbol{p}^2_\perp}. \tag{4}$$

We fit the model calculation of f_{1q} with the JR14 parametrization [10] to determine the diquark model parameters, which result in,

$$m_{u/d} = 0.3\,\text{GeV},\ m_s = 0.5\,\text{GeV},\ M_s = 1.2\,\text{GeV},\ \Lambda_s = 2.3\,\text{GeV},\ g_s = 14.98. \tag{5}$$

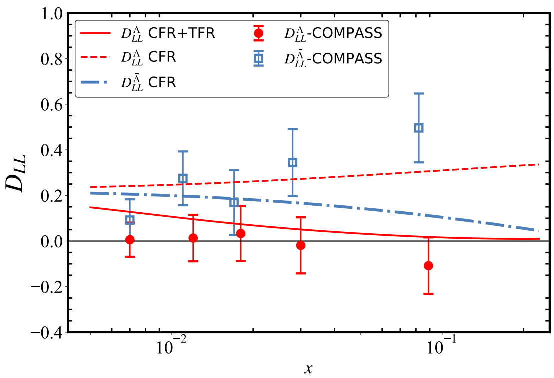
By integrating Eq. (2) over $\boldsymbol{P}_{h\perp}$, the D^h_{LL} considering both the CFR and the TFR can be written as

$$D^h_{LL} = \frac{\sum_q e_q^2\int d^2\boldsymbol{P}_{h\perp}\mathcal{I}\left[f_{1q}(x,p^2_\perp)G^h_{1Lq}(z,k^2_\perp)\right]}{\sum_q e_q^2\int d^2\boldsymbol{P}_{h\perp}\left[\mathcal{I}\left[f_{1q}(x,p^2_\perp)D^h_{1q}(z,k^2_\perp)\right]+x\left|\frac{\partial\zeta}{\partial z}\right|M^h_q(x,z,\boldsymbol{P}_{h\perp})\right]}. \tag{6}$$

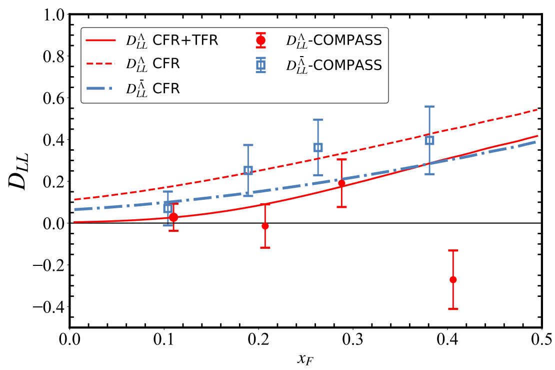
For the TMDs in the CFR, we take the Gaussian ansatz which was widely used,

$$f_{1q}(x, p_\perp^2) = f_{1q}(x)\frac{e^{-\frac{\boldsymbol{p}_\perp^2}{\Delta_p^2}}}{\pi\Delta_p^2}, \quad D_{1q}^h(z, k_\perp^2) = D_{1q}^h(z)\frac{e^{-\frac{\boldsymbol{k}_\perp^2}{\Delta_h^2}}}{\pi\Delta_h^2}, \quad G_{1Lq}^h(z, k_\perp^2) = G_{1Lq}^h(z)\frac{e^{-\frac{\boldsymbol{k}_\perp^2}{\Delta_h^2}}}{\pi\Delta_h^2}, \tag{7}$$

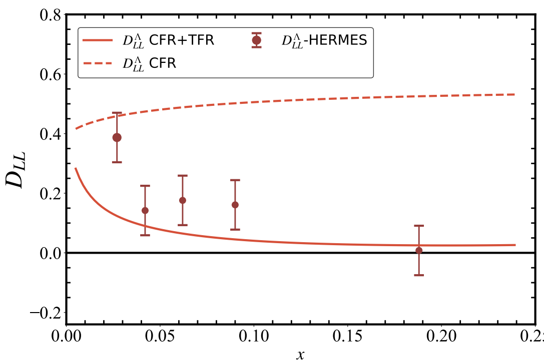
where $\Delta_p^2 = 0.57\,\mathrm{GeV}^2$ and $\Delta_h^2 = 0.118\,\mathrm{GeV}^2$ represent Gaussian widths of a proton and a Λ [12, 13]. For the collinear FFs, $D_{1q}^h(z)$ and $G_{1Lq}^h(z)$, we employ the DSV parametrization [11]. It is fitted to data from e^+e^- annihilation, which should describe the CFR results well. In Fig. 3(a)-3(b) we plot the numerical results for D_{LL}^h comparing with the COMPASS data [2]. Producing the $\bar{\Lambda}$



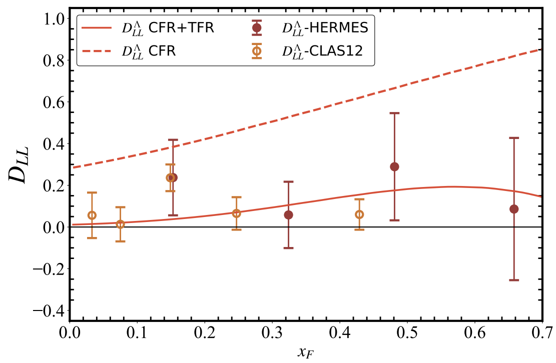
(a) The results of $D_{LL}^{\Lambda/\bar{\Lambda}}(x)$ and COMPASS data.



(b) The results of $D_{LL}^{\Lambda/\bar{\Lambda}}(x_F)$ and COMPASS data.



(c) The results of $D_{LL}^{\Lambda}(x)$ and HERMES data.



(d) The results of $D_{LL}^{\Lambda}(x_F)$ and HERMES and CLAS12 data.

Figure 3: Numerical results for the longitudinal spin transfer comparing with experimental data.

from TFR in the diquark model is challenging due to the difficulty in finding a diquark spectator $R(\bar{u}\bar{d})$ from the sea, so the contribution of the TFR is neglected, i.e., $M_q^{\bar{\Lambda}} = 0$. The dashed-dotted curves represent the $\bar{\Lambda}$ theoretical calculations using the DSV parametrization, and it can describe the experimental data relatively well considering the large uncertainties. However, for Λ, the contribution from only the CFR leads to significant deviations from the experimental data, as shown by the dashed curves. This agrees with our expectations, indicating that the contribution from the TFR cannot be ignored. With the model-calculated values of M_q^{Λ}, the calculation results show good consistence with the measurements. Similar figures for D_{LL}^{Λ} are shown in Fig. 3(c)-3(d) to compare the theoretical estimation with HERMES [4] and CLAS12 [5] measurements. Again there are significant deviations between the CFR contribution and the measurements. The inclusion of the TFR contribution remarkably reduces the predicted value, and the combined contributions from both the CFR and TFR match the data much better than the CFR contribution alone. Based on the discussions and comparisons of these results, it can be reasonably concluded that in current medium- and low-energy experiments, the contribution of target fragmentation for the Λ in the SIDIS process cannot be ignored.

4. Summary and outlook

In this proceeding, we conduct numerical calculations on the two fragmentation mechanisms in SIDIS focusing on the longitudinal spin transfer of Λ and $\bar{\Lambda}$. Incorporating the fracture functions alongside the CFR can describe the experimental data from COMPASS, HERMES, and CLAS12 quite well. We anticipate new and precise experimental measurements at the future EIC of Λ and $\bar{\Lambda}$ production in both the CFR and TFR, to further study and understand the fragmentation mechanism.

Acknowledgments

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