PROCEEDINGS OF SCIENCE

The Sivers asymmetry of vector meson production in semi-inclusive deep inelastic scattering

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The transverse single spin asymmetries of ρ^0 production in semi-inclusive deep inelastic scattering (SIDIS) are recently measured by COMPASS. Among them, the Sivers asymmetry can be described by the convolution of the Sivers function and the unpolarized fragmentation function within the transverse momentum dependent factorization. We perform a phenomenological study and find that the COMPASS data can be well described by the nucleon Sivers functions extracted from previous SIDIS data with pion and kaon productions. Therefore, it provides a universality test of the nucleon Sivers functions within the current experimental precision. Based on the result, we further predict the Sivers asymmetry of ρ^0 production in SIDIS at future experimental facilities, such as the electron-ion colliders. The production of other vector mesons, like K^*, is also discussed.

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1. Introduction

Understanding the internal structure of nucleons at the quark and gluon level is crucial in modern physics. Due to color confinement, quarks and gluons cannot be directly observed. The semi-inclusive deep inelastic scattering (SIDIS) process is key to probing nucleon structure. In the transverse momentum dependent (TMD) factorization framework, the SIDIS cross section is a convolution of TMD parton distribution functions (TMD PDFs), the hard part, and TMD fragmentation functions (TMD FFs).

Spin and momentum correlations in TMD PDFs and TMD FFs cause azimuthal angular asymmetries in final-state hadron distributions. Among these azimuthal asymmetries, the Sivers asymmetry is extensively studied. It is described as a convolution of the Sivers function and the unpolarized fragmentation function. Recently, the COMPASS Collaboration measured the Sivers asymmetry of ρ^0 [1], which is the first measurement of the Sivers asymmetry in vector meson production.

This work calculates the Sivers asymmetry of ρ^0 production at COMPASS kinematical region based on current knowledge of the Sivers function from pion and kaon data. The result provides a test of the universality of the Sivers function. We also present the anticipated Sivers asymmetry of ρ^0 and K^* at EIC and EicC kinematical regions.

2. Theoretical formalism

For the SIDIS process where an unpolarized lepton beam scatters off a transversely polarized nucleon target, within the TMD factorization and evolution framework, the Sivers asymmetry $A_{UT}^{\sin(\phi_h-\phi_S)}$ can be expressed as

$$A_{UT}^{\sin(\phi_h-\phi_S)}\left(x_B, z_h, P_{h\perp}, Q^2\right) = \frac{\mathcal{B}_1\left[\widetilde{f}_{1T}^{\perp}\,\widetilde{D}_1\right]}{\mathcal{B}_0\left[\widetilde{f}_1\,\widetilde{D}_1\right]}, \tag{1}$$

where $P_{h\perp}$ is the final-state hadron transverse momentum, ϕ_h and ϕ_S are the azimuthal angles of the final-state hadron and of the polarization of the target in the virtual photon-nucleon center-of-mass frame, respectively. The shorthand notation $\mathcal{B}_n\left[fD\right]$ is

$$\mathcal{B}_n\left[fD\right] = \sum_q e_q^2 \int_0^\infty \frac{\mathrm{d}b}{2\pi} b^{n+1} J_n\left(\frac{bP_{h\perp}}{z_h}\right)\left(\frac{Q^2}{\zeta_Q(b)}\right)^{-2\mathcal{D}(b,Q)} f_{q/p}\left(x_B, b\right) D_{h/q}\left(z_h, b\right). \tag{2}$$

There are two recent parametrizations of the optimal Sivers function $\widetilde{f}_{1T,q/p}^{\perp}(x,b)$, the BPV20 parametrization [2] and the ZLSZ parametrization [3]. For the optimal unpolarized TMD PDF $\widetilde{f}_{1,q/p}(x,b)$, we adopt the parametrization in Ref. [4]. We obtain the optimal unpolarized TMD FF $\widetilde{D}_{1,h/q}(z,b)$ by following the approach in Ref. [4]. The optimal unpolarized TMD FF $\widetilde{D}_{1,h/q}(z,b)$ can be expressed as

$$\widetilde{D}_{1,h/f}(z,b) = \frac{1}{z^2}\sum_{f'}\int_z^1 \frac{\mathrm{d}y}{y} y^2 \mathbb{C}_{f\to f'}\left(y, b, \mu_{\mathrm{OPE}}^{\mathrm{FF}}\right) D_{1,h/f'}\left(\frac{z}{y}, \mu_{\mathrm{OPE}}^{\mathrm{FF}}\right) D_{\mathrm{NP}}(z,b), \tag{3}$$

where the coefficient functions $\mathbb{C}_{f\to f'}$ are the Wilson coefficients. The scale $\mu_{\rm OPE}^{\rm FF}$ is chosen as $\mu_{\rm OPE}^{\rm FF} = 2e^{-\gamma_E} z_h/b + 2\,\text{GeV}$. $D_{1,h/f'}(z,\mu)$ represents the collinear FF and is obtained by fitting the Pythia data using the following parametrization form,

$$D_{h/i}\left(z, Q_0^2\right) = N_i^h z^{\alpha_i^h} (1-z)^{\beta_i^h}, \quad \left(i = u, d, s, g, \bar{u}, \bar{d}, \bar{s}\right). \tag{4}$$

The parameters in this form are listed in Table 1.

function	N	α	β
$D_{\rho^0/u} = D_{\rho^0/\bar{u}} = D_{\rho^0/d} = D_{\rho^0/\bar{d}}$	0.4224 ± 0.0013	-0.6119 ± 0.0035	1.2448 ± 0.0037
$D_{\rho^0/s} = D_{\rho^0/\bar{s}}$	0.3346 ± 0.0044	-0.7777 ± 0.0127	2.0681 ± 0.0229
$D_{\rho^0/g}$	129.04 ± 21.159	3.2234 ± 1.6011	9.9508 ± 8.5609

Table 1: Parameters determined for ρ^0

For the $D_{\rm NP}(z,b)$, which characterize the nonperturbative TMD effect, we assume the function form for the ρ^0 meson as those parametrized for pion and kaon [4],

$$D_{\rm NP}(z,b) = \exp\left[-\frac{\eta_1 z + \eta_2(1-z)}{\sqrt{1+\eta_3(b/z)^2}}\frac{b^2}{z^2}\right]\left(1+\eta_4\frac{b^2}{z^2}\right), \tag{5}$$

and adopt three sets of η values in the numerical calculation, where the first set, labeled by 'scenario 1', is the same with pion and kaon ($\eta_1 = 0.260$, $\eta_2 = 0.476$, $\eta_3 = 0.478$, and $\eta_4 = 0.483$), and in 'scenario 2' ('scenario 3') all the η values are multiplied by a factor 0.3 (3). The TMD FF with these three scenarios of $D_{\rm NP}$ exhibit different transverse momentum distributions, with scenario 2 the TMD FF has the most concentrated transverse momentum distribution, followed by scenario 1, and scenario 3 displays the most diffuse transverse momentum distribution.

3. Results

The numerical results for the Sivers asymmetry of ρ^0 at the kinematic region of COMPASS are shown in Fig 1. One can see that the results obtained with both parametrizations are above zero and align well with the data of COMPASS. The Sivers functions in both of these parametrizations are extracted from the data of pions and kaons. Our results show that the numerical calculations using these two parametrizations are both in agreement with the data of ρ^0 meson. This serves as a test for the universality of the Sivers function within the current experimental precision.

The expectations for the Sivers asymmetry of the ρ^0 and K^{*-} mesons at the kinematic regions of EIC and EicC are depicted in Fig. 2 and Fig. 3, respectively. The K^* mesons are the vector mesons whose main decay channel is K meson and π meson. To evaluate the Sivers effect of the K^* mesons at the kinematic regions of EIC and EicC, we follow the collinear FFs of K^* mesons in Ref. [5]. As illustrated in Figs. 2 and 3, it is evident that the scenario 2 corresponds to the most significant Sivers asymmetry. This tells us that the more concentrated the transverse momentum distribution of the fragmentation function, the more significant the Sivers asymmetry for ρ^0 and K^* mesons. According to Figs. 2 and 3, it is found that there is a more significant Sivers effect at the kinematic region of EicC than at the kinematic region of EIC.

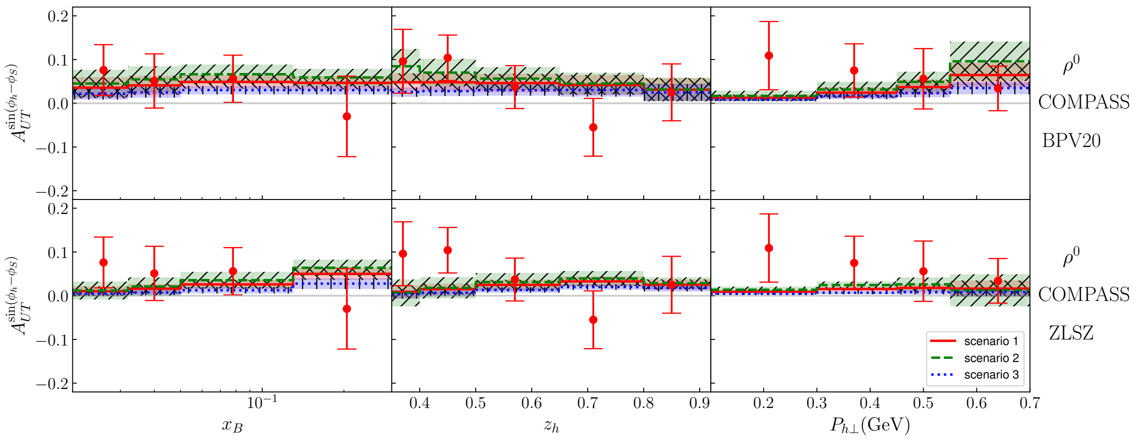

Figure 1: The numerical results of Sivers asymmetry are compared with the COMPASS measurement [1] for ρ^0 production. The red squares with error bars represent data points from COMPASS. The bands with hatches represent the corresponding 1-σ confidence intervals.

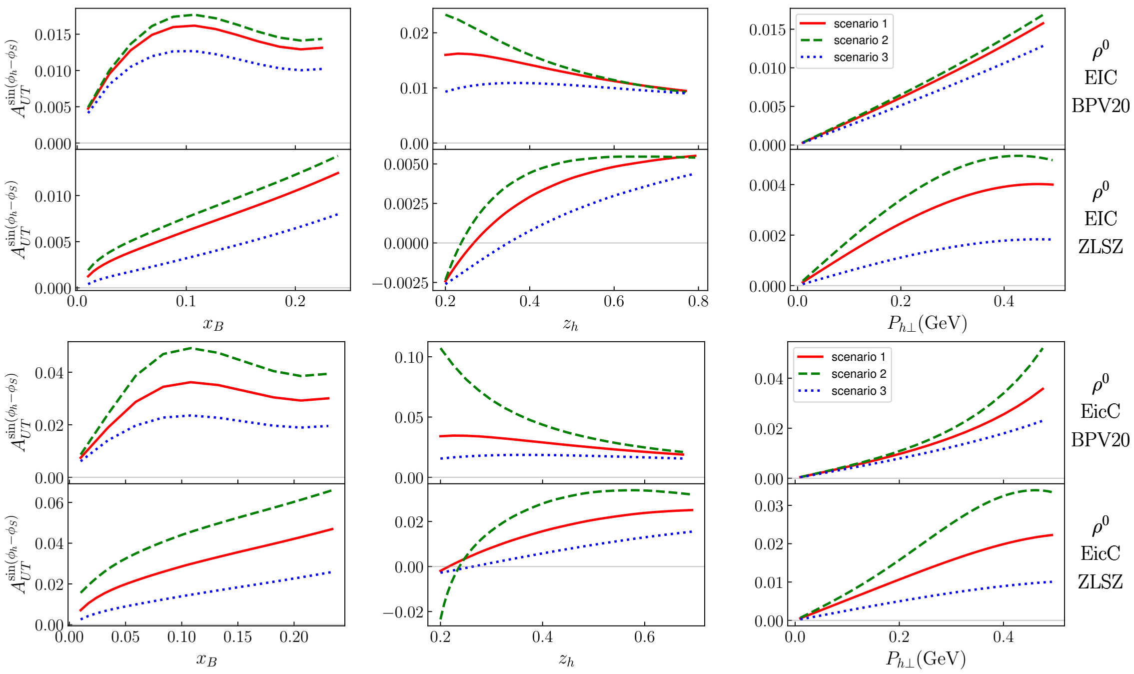

Figure 2: The anticipated Sivers asymmetry of ρ^0 meson at the kinematic regions of EIC and EicC.

4. Summary

We present a study of the Sivers asymmetry of the vector mesons ρ^0 and K^*. The numerical results with BPV20 and ZLSZ parametrizations are consistent with the COMPASS measurement of ρ^0's Sivers asymmetry. This consistency serves as a test of the universality of the Sivers function. The Sivers asymmetry for ρ^0 and K^* at the EIC and EicC kinematic regions shows significant differences between the BPV20 and ZLSZ parametrizations. These differences provide an opportunity to further test the universality of the Sivers function and refine its extraction.

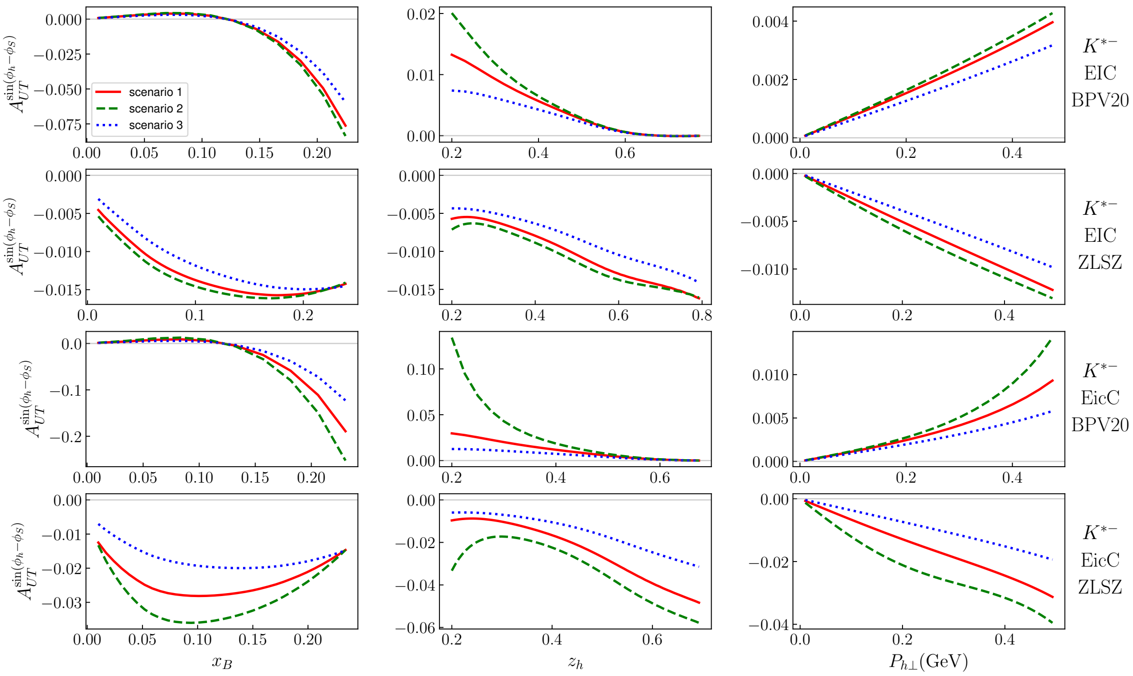

Figure 3: The expectations of K^* meson

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