郑州大学

The Collins asymmetry in electroproduction of Kaon at the EICs within TMD factorization

薛世晨

第五届“强子谱和强子结构研讨会”2021.01.23-25

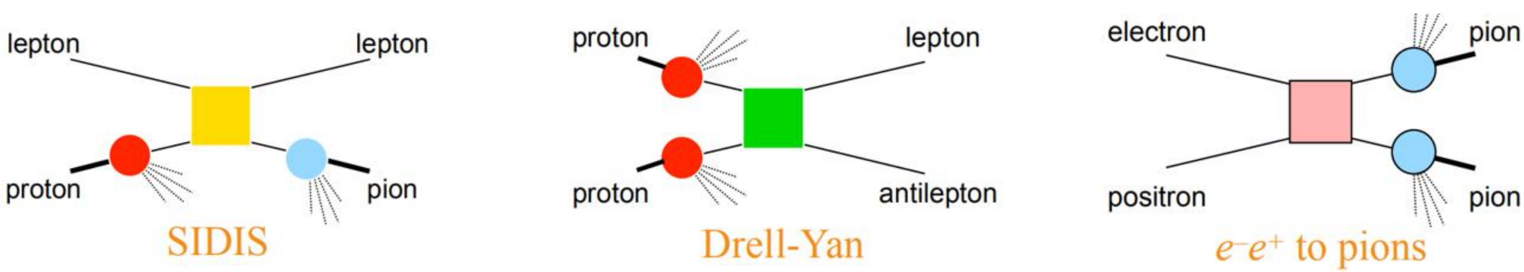
Collaborated with Xiaoyu Wang, De-Min Li(Zhengzhou U.) and Zhun Lu(Southeast U., China)
Based on S. C. Xue, X. Wang, D. M. Li and Z. Lu, arXiv: 2003.05679, accepted by EPJC

OUTLINE

- Introduction
- Framework
- Numerical Estimate
- Conclusion

Introduction

- Understanding the structure of the nucleon is one of the main tasks in hadronic physics.
- Based on QCD, the internal structure of a polarized nucleon explored in high energy process is described by TMD PDFs.
- These TMD PDFs can be extracted from the asymmetries arising in high energy scattering processes.



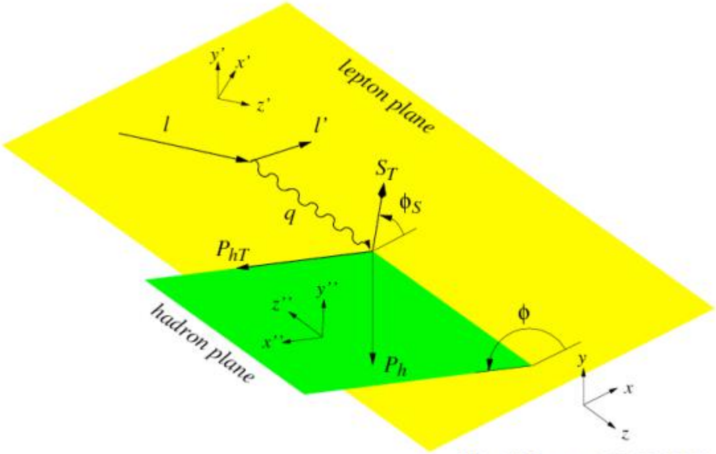
Introduction

Structure Functions

SIDIS differential cross section

18 structure functions $F(x, z, Q^2, P_T)$,
model independent. (one photon exchange approximation)

Bacchetta et al., JHEP0702, 093 (2007)



[Diehl&Sapeta EPJC2005]

$$\frac{d\sigma}{dx\,dy\,dz\,dP_T^2\,d\phi_h\,d\psi} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\times\Big\{F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h + \lambda_e\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi_h}\sin\phi_h$$

$$+ S_L\Big[\sqrt{2\epsilon(1+\epsilon)}F_{UL}^{\sin\phi_h}\sin\phi_h + \epsilon F_{UL}^{\sin 2\phi_h}\sin 2\phi_h\Big] + \lambda_e S_L\Big[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}F_{LL}^{\cos\phi_h}\cos\phi_h\Big]$$

$$+ S_T\Big[\big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\big)\sin(\phi_h-\phi_S) + \epsilon F_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) + \epsilon F_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)$$

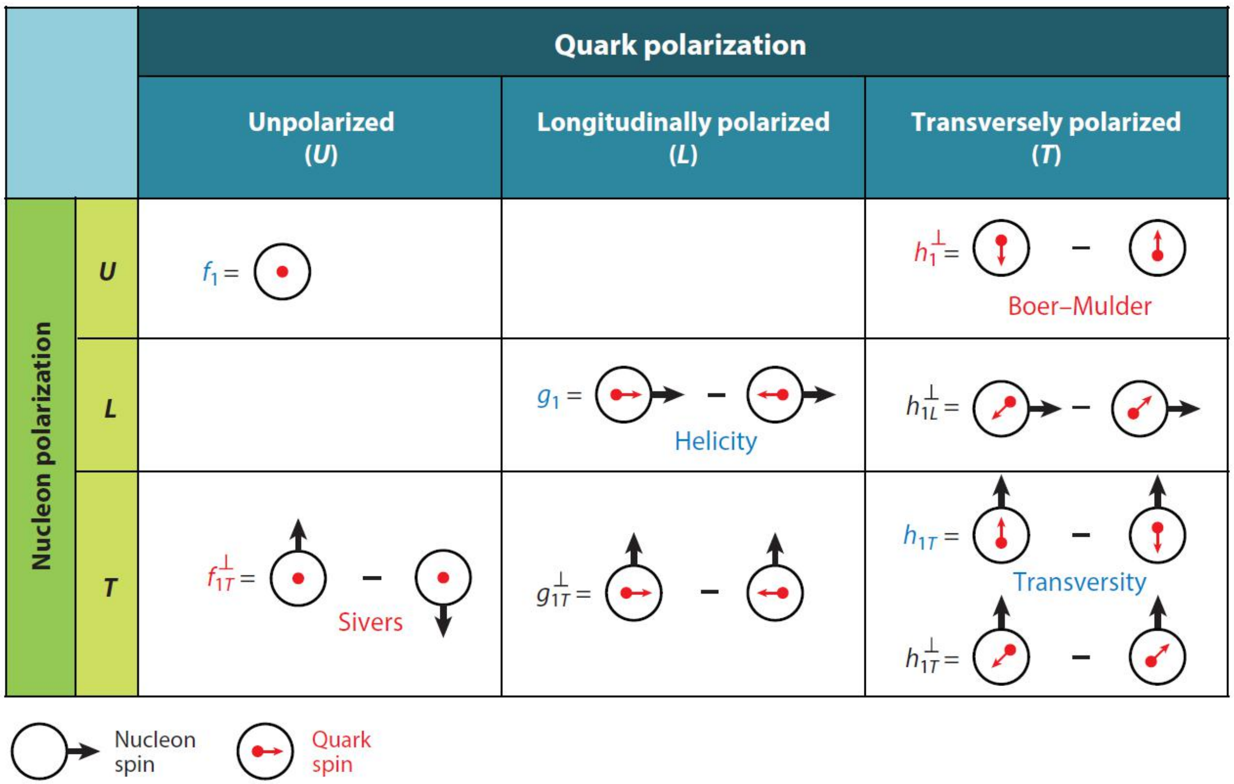
$$+ \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S + \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\Big]$$

$$+ \lambda_e S_T\Big[\sqrt{1-\epsilon^2}F_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)$$

$$+ \sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos\phi_S}\cos\phi_S + \sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\Big]\Big\}$$

Introduction

TMD PDFs at leading-twist



Unpolarized distribution function, helicity, transversity: Survive at collinear limit

Boer-Mulders,Sivers: Time reversal odd

Introduction

Transversity distribution function

- **Fundamental distribution to encode the nucleon structure**
- **Chiral-odd**
- **Hard to access compared to helicity and unpolarized distribution function**

Introduction

How to access transversity

- **(TMD) factorization frame in SIDIS ——Collins function**
  J. C. Collins, NPB 396, 161 (1993)
- **Collinear factorization in SIDIS——twist-3 fragmentation function**
  X.Wang, Z. Lu PRD 93, 074009 (2016)
- **Collinear factorization in SIDIS——dihadron fragmentation function**
  A. Bacchetta et al., PRL107, 012001(2011)
- **Drell-Yan process——the antiquark transversity**
  V. Barone et al., Phys.Rept. 359 (2002) 1-168

Although progress has been made, sea quark transversity is almost unknown.

Introduction

郑州大学

Collins function

- **Correlation between fragmenting quark transverse spin and unpolarized hadron transverse momentum**
- **Analyzer of quark spin in nucleon**
- **Kaon Collins function has been extracted from the e^+e^- annihilation data from BaBar** M. Anselmino et al., PRD 93, 034025 (2016)

The Collins asymmetry in Kaon production SIDIS process makes an ideal tool to access sea quark transversity due to its strange constituent.

Introduction

What have we done?

We predict the Collins asymmetry for charged Kaon production at EICs.

- **apply the TMD factorization formalism**
- **Approach-TMD evolution formalism**
- **adopt the parametrization of the non-perturbative Sudakov form factor**
- **NLL accuracy**

OUTLINE

郑州大学

- Introduction
- **Framework**
- Numerical Estimate
- Conclusion

Framework

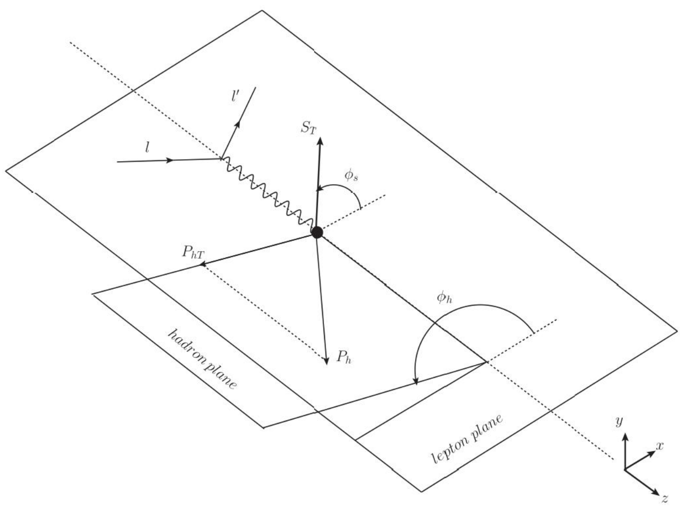
- **We consider the SIDIS process**

$$e(\ell) + p^{\uparrow}(P) \longrightarrow e(\ell') + K(P_h) + X(P_X)$$

- **The invariants defined as**

$$x_B = \frac{Q^2}{2P \cdot q}, \quad y = \frac{P \cdot q}{P \cdot \ell} = \frac{Q^2}{x_B s}, \quad z_h = \frac{P \cdot P_h}{P \cdot q},$$
$$Q^2 = -q^2, \quad s = (P + \ell)^2,$$

- **The definition of azimuthal angles in SIDIS**



Framework

- The 5-fold differential cross section with a transversely polarized target has the following general form

$$\frac{d^5\sigma(S_T)}{dx_B dy dz_h d^2\boldsymbol{P}_{hT}} = \sigma_0(x_B, y, Q^2)\left[F_{UU} + \sin(\phi_h+\phi_s)\frac{2(1-y)}{1+(1-y)^2}F_{UT}^{\sin(\phi_h+\phi_s)} + \ldots\right],$$

- The Collins asymmetry can be written in terms of the structure functions

$$A_{UT}^{\sin(\phi_h+\phi_s)} = \frac{\sigma_0(x_B, y, Q^2)}{\sigma_0(x_B, y, Q^2)}\frac{2(1-y)}{1+(1-y)^2}\frac{F_{UT}^{\sin(\phi_h+\phi_s)}}{F_{UU}},$$

$$F_{UU}(Q; P_{hT}) = \mathcal{C}[f_1 D_1],$$

$$F_{UT}^{\sin(\phi_h+\phi_s)}(Q; P_{hT}) = \mathcal{C}\left[\frac{-\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}h_1 H_1^{\perp}\right].$$

$$\mathcal{C}[\omega f D] = x\sum_q e_q^2\int d^2\boldsymbol{p}_T d^2\boldsymbol{k}_T \delta^{(2)}(\boldsymbol{p}_T - \boldsymbol{k}_T - \boldsymbol{P}_{h\perp}/z)\omega(\boldsymbol{p}_T, \boldsymbol{k}_T) f^q(x, p_T^2)\, D^q(z, k_T^2).$$

Framework

郑州大学

Performing the Fourier Transformation

$$
\begin{aligned}
F_{UU}(Q;P_{hT}) &= \mathcal{C}[f_1 D_1] \\
&= \sum_q e_q^2 \int d^2\boldsymbol{p}_T d^2\boldsymbol{k}_T \delta^{(2)}\left(\boldsymbol{p}_T - \boldsymbol{k}_T - \boldsymbol{P}_{hT}/z_h\right) f_1^q(x_B, p_T^2)\, D_1^q(z_h, k_T^2) \\
&= \frac{1}{z_h^2}\sum_q e_q^2 \int d^2\boldsymbol{p}_T d^2\boldsymbol{K}_T \delta^{(2)}\left(\boldsymbol{p}_T + \boldsymbol{K}_T/z_h - \boldsymbol{P}_{hT}/z_h\right) f_1^q(x_B, p_T^2)\, D_1^q(z_h, K_T^2) \\
&= \frac{1}{z_h^2}\sum_q e_q^2 \int d^2\boldsymbol{p}_T d^2\boldsymbol{K}_T \int \frac{d^2b}{(2\pi)^2} e^{-i\left(\boldsymbol{p}_T + \boldsymbol{K}_T/z_h - \boldsymbol{P}_{hT}/z_h\right)\cdot \boldsymbol{b}} f_1^q(x_B, p_T^2)\, D_1^q(z_h, K_T^2) \\
&= \frac{1}{z_h^2}\sum_q e_q^2 \int \frac{d^2b}{(2\pi)^2} e^{i\boldsymbol{P}_{hT}/z_h\cdot \boldsymbol{b}} \tilde{f}_1^q(x_B, b)\, \tilde{D}_1^q(z_h, b).
\end{aligned}
$$

introducing the TMDs definition

$$
\int d^2\boldsymbol{p}_T e^{-i\boldsymbol{p}_T\cdot\boldsymbol{b}} f_1^q(x_B, p_T^2) = \tilde{f}_1^q(x_B, b)
$$

$$
\int d^2\boldsymbol{K}_T e^{-i\boldsymbol{K}_T/z_h\cdot\boldsymbol{b}} D_1^q(z_h, K_T^2) = \tilde{D}_1^q(z_h, b)
$$

Framework

郑州大学

- **The Collins structure function**

$$
\begin{aligned}
F_{UT}^{\sin(\phi_h+\phi_s)}(Q;P_{hT}) &= \mathcal{C}[\frac{-\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}h_1H_1^{\perp}] \\
&= \sum_q e_q^2\int d^2\boldsymbol{p}_T d^2\boldsymbol{k}_T\delta^{(2)}(\boldsymbol{p}_T-\boldsymbol{k}_T-\boldsymbol{P}_{hT}/z_h)\frac{-\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}h_1^q(x_B,p_T^2)H_1^{\perp,q}(z_h,k_T^2) \\
&= \sum_q e_q^2\frac{1}{z_h^2}\int d^2\boldsymbol{p}_T d^2\boldsymbol{K}_T\delta^{(2)}(\boldsymbol{p}_T+\boldsymbol{K}_T/z_h-\boldsymbol{P}_{hT}/z_h)\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{K}_T}{z_hM_h}h_1^q(x_B,p_T^2)H_1^{\perp,q}(z_h,K_T^2) \\
&= \sum_q e_q^2\frac{1}{z_h^2}\int d^2\boldsymbol{p}_T d^2\boldsymbol{K}_T\int\frac{d^2b}{(2\pi)^2}e^{-i(\boldsymbol{p}_T+\boldsymbol{K}_T/z_h-\boldsymbol{P}_{hT}/z_h)\cdot\boldsymbol{b}}\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{K}_T}{z_hM_h}h_1^q(x_B,p_T^2)H_1^{\perp,q}(z_h,K_T^2) \\
&= \sum_q e_q^2\frac{1}{z_h^2}\frac{1}{z_h}\int\frac{d^2b}{(2\pi)^2}e^{i\boldsymbol{P}_{hT}/z_h\cdot\boldsymbol{b}}\hat{h}_\alpha\tilde{h}_1^q(x_B,b)\tilde{H}_1^{\perp\alpha,q}(z_h,b). \qquad (10)
\end{aligned}
$$

- **The transversity distribution function and Collins function in b space are defined as**

$$
\int d^2\boldsymbol{p}_T e^{-i\boldsymbol{p}_T\cdot\boldsymbol{b}}h_1^q(x_B,p_T^2)=\tilde{h}_1^q(x_B,b);
$$

$$
\int d^2\boldsymbol{K}_T e^{-i\boldsymbol{K}_T/z_h\cdot\boldsymbol{b}}\frac{K_T^\alpha}{M_h}H_1^{\perp,q}(z_h,K_T^2)=\tilde{H}_1^{\perp\alpha,q}(z_h,b).
$$

Framework

郑州大学

- The evolution of the TMDs is usually performed in b space.
- The solution of the energy dependence for TMDs has the general form as

$$\tilde{F}(x_B, b; Q) = \mathcal{F} \times e^{-S} \times \tilde{F}(x_B, b; \mu)$$

$$\tilde{D}(z_h, b; Q) = \mathcal{D} \times e^{-S} \times \tilde{D}(z_h, b; \mu)$$

- The Sudakov-like form factor can be separated into a perturbatively calculable part and a nonperturbative part

$$S(Q; b) = S_{\text{pert}}(Q; b_*) + S_{\text{NP}}(Q; b)$$

$$S_{\text{pert}}(Q; b_*) = \int_{\mu_b^2}^{Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2} \left[A(\alpha_s(\bar{\mu})) \ln(\frac{Q^2}{\bar{\mu}^2}) + B(\alpha_s(\bar{\mu})) \right]$$

$$S_{\text{NP}}^{\text{pdf}}(Q; b) = \frac{g_2}{2} \ln(\frac{Q}{Q_0}) b^2 + g_1^{\text{pdf}} b^2,$$

$$S_{\text{NP}}^{\text{ff}}(Q; b) = \frac{g_2}{2} \ln(\frac{Q}{Q_0}) b^2 + g_1^{\text{ff}} b^2.$$

Framework

郑州大学

- **Unpolarized structure function**

$$F_{UU}(Q;P_{hT}) = \frac{1}{z_h^2}\int_0^\infty \frac{db\, b}{(2\pi)} J_0(P_{hT}/z_h\, b)\widetilde{F}_{UU}(Q;b)$$

$$= \frac{1}{z_h^2}\sum_q e_q^2 \int_0^\infty \frac{db\, b}{(2\pi)} J_0(P_{hT}/z_h\, b) e^{-S_{\rm pert}(Q;b_*)-S_{\rm NP}^{\rm SIDIS}(Q;b)}$$

$$\left(\sum_i C_{q\leftarrow i}^{(\rm SIDIS)} \otimes f_1^{i/p}(x_B,\mu_b)\right) \times \left(\sum_j \hat{C}_{j\leftarrow q}^{(\rm SIDIS)} \otimes D_1^{K/j}(z_h,\mu_b)\right) .$$

- **Collins structure function**

$$F_{UT}(Q;P_{hT}) = \frac{-1}{2z_h^3}\sum_q e_q^2 \int_0^\infty \frac{db\, b^2}{(2\pi)} J_1(P_{hT}/z_h\, b) e^{-S_{\rm pert}(Q;b_*)-S_{\rm NP\ Collins}^{\rm SIDIS}(Q;b)}$$

$$\left(\sum_i \delta C_{q\leftarrow i}^{(\rm SIDIS)} \otimes h_1^{i/p}(x_B,\mu_b)\right)\left(\sum_j \delta\hat{C}_{j\leftarrow q}^{(\rm SIDIS)} \otimes \hat{H}_{K/j}^{(3)}(z_h,\mu_b)\right) .$$

OUTLINE

郑州大学

- Introduction
- Framework
- **Numerical Estimate**
- Conclusion

Numerical Estimate

郑州大学

- **Parametrization for the collinear transversity distribution function**

Valence quark $$h_1^q(x,Q_0) = N_q^h x^{a_q}(1-x)^{b_q}\frac{(a_q+b_q)^{a_q+b_q}}{a_q^{a_q}b_q^{b_q}}\frac{1}{2}(f_1^q(x,Q_0)+g_1^q(x,Q_0))$$

Z. B. Kang et al., PRD 93, 014009 (2016)

Sea quark $$h_1^q(x,Q_0) = N_s\frac{1}{2}(f_1^q(x,Q_0)+g_1^q(x,Q_0))$$

- **Parametrization for Collins function**

$$\Delta^N D_{h/q^\uparrow}(z_h,p_\perp) = \tilde{\Delta}^N D_{h/q^\uparrow}(z_h)\, h(p_\perp)\, \frac{e^{-p_\perp^2/\langle p_\perp^2\rangle}}{\pi\langle p_\perp^2\rangle}$$

M. Anselmino et al., PRD 93, 034025 (2016)

$$\hat{H}_{h/j}^{(3)}(z_h) = \frac{\sqrt{2e}}{M_C} N_q^C(z_h)\, D_{h/q}(z_h)\left(\frac{M_C^2}{M_C^2+\langle p_\perp^2\rangle}\right)^2\langle p_\perp^2\rangle$$

Numerical Estimate

- **Kinematical region for EIC**

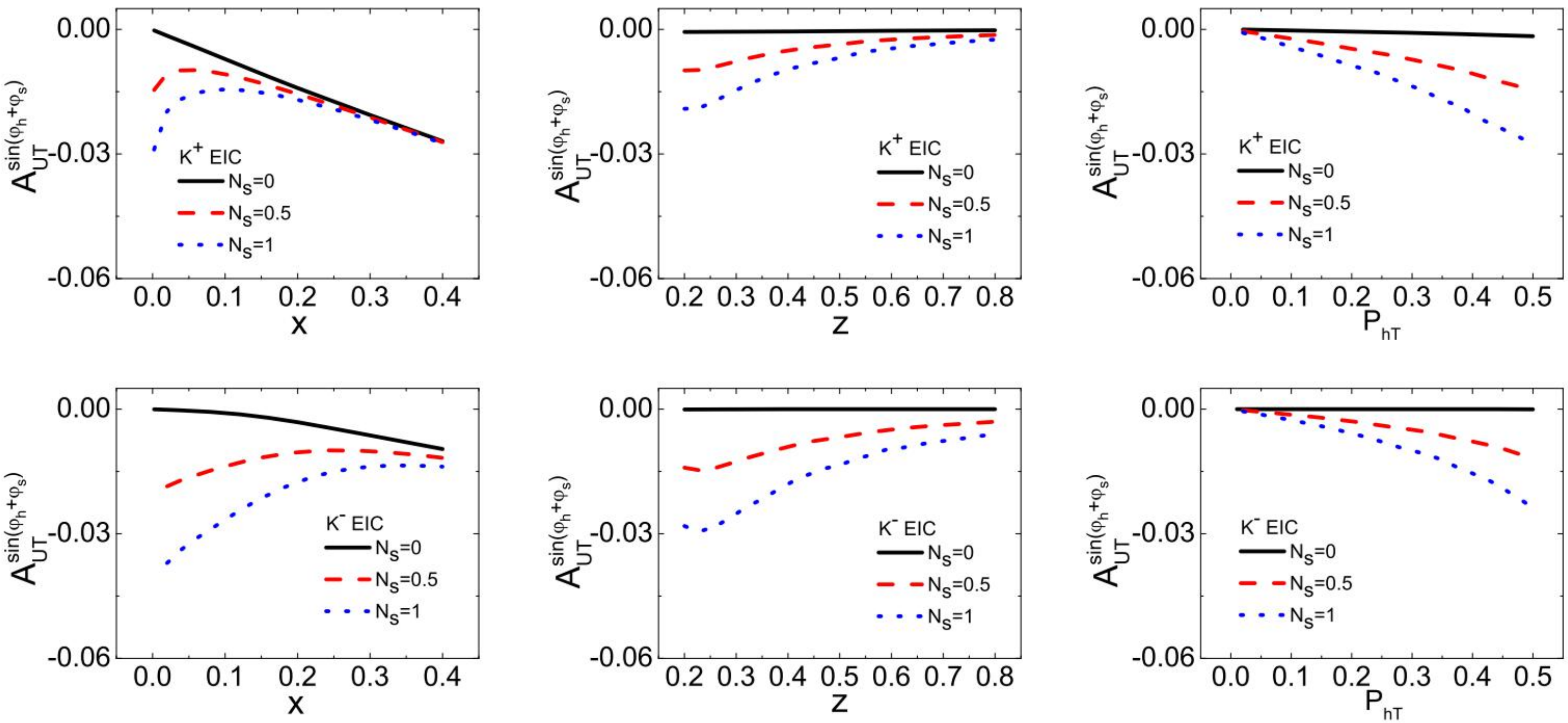
$$0.001 < x < 0.4, \quad 0.07 < y < 0.9, \quad 0.2 < z < 0.8,$$
$$1\ \mathrm{GeV}^2 < Q^2\ , \quad W > 5\ \mathrm{GeV}, \quad \sqrt{s} = 100\ \mathrm{GeV}, \quad P_{hT} < 0.5\ \mathrm{GeV}.$$

- **For EicC**

$$0.005 < x < 0.5, \quad 0.07 < y < 0.9, \quad 0.2 < z < 0.7,$$
$$1\mathrm{GeV}^2 < Q^2 < 200\ \mathrm{GeV}^2\ , \quad W > 2\ \mathrm{GeV}, \quad \sqrt{s} = 16.7\ \mathrm{GeV}, \quad P_{hT} < 0.5\ \mathrm{GeV}$$

Numerical Estimate

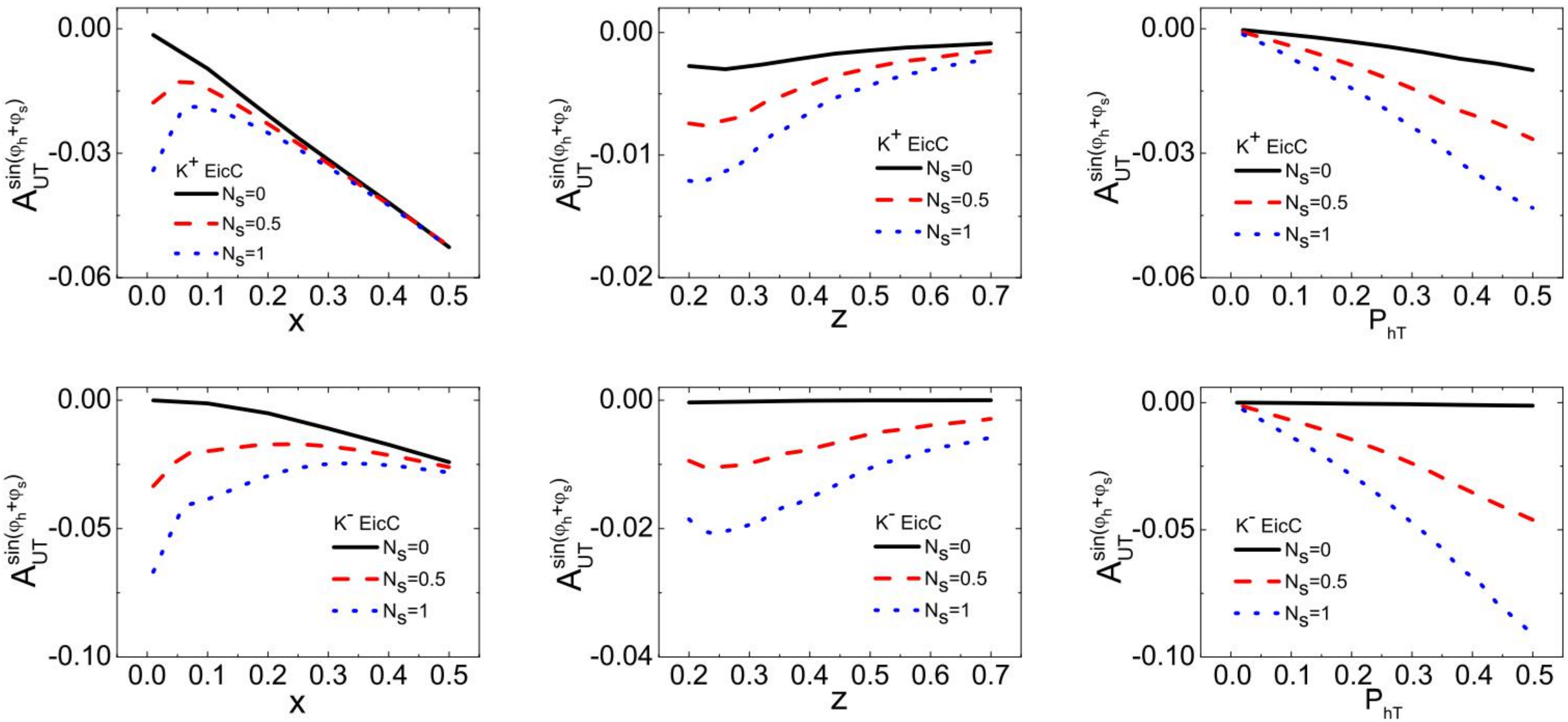
- **For EIC**



Numerical Estimate

郑州大学

- **For EicC**



Numerical Estimate

- **Both sizable at EIC and EicC**
- **The magnitude of the asymmetry increases with increasing Ns of the collinear sea quark transversity function.**
- **The effect of the tranversity of the sea quarks turns out to be smaller in the K^+ production process than that in the K^- process.**
- **For the asymmetry as the function of x, there is a clear peak at $x \approx 0.05$ at EicC when considering the non-zero sea quark transversity, while the peak vanishes with zero sea contribution of transversity. Although the peak turns to be vague at EIC, the tendency still remains.**

OUTLINE

- Introduction
- Framework
- Numerical Estimate
- **Conclusion**

Conclusion

郑州大学

- The measurement on the Collins asymmetry of semi-inclusive Kaon production at future electron ion colliders can provide useful constraints on the sea quark transversity.
- We note that there are large errors in the extraction of the Kaon Collins function, which indicates the importance of more precision e^+e^- data in order to constrain the Kaon Collins function.

郑州大学

Thank you!