Longitudinal-transverse double-spin asymmetry with a cos ϕ_s modulation in SIDIS

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OUTLINE

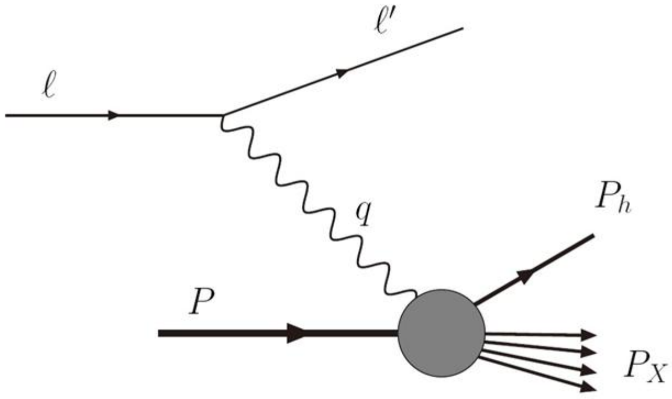
1. Formalism
2. Calculation on the structure functions
3. Numerical Estimate at CLAS12 and EIC
4. Summary

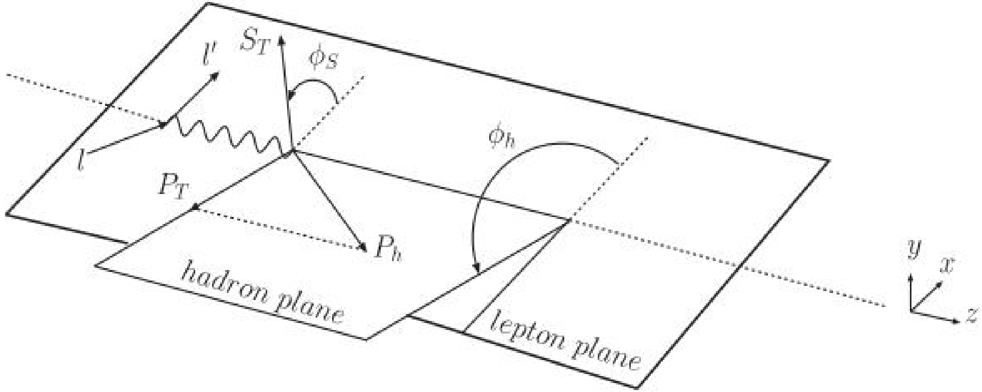
Based on Phys. Rev. D 94,074014 (2016)

FORMALISM

- Semi-inclusive DIS by longitudinal polarized lepton beam off a transversely polarized nucleon target

$$e^{\rightarrow}(l) + p^{\uparrow}(P) \rightarrow e(l') + h(P_h) + X$$





FORMALISM

- The invariants defined as

$$x = \frac{Q^2}{2\,P\cdot q}, \quad y = \frac{P\cdot q}{P\cdot l}, \quad z = \frac{P\cdot P_h}{P\cdot q}, \quad \gamma = \frac{2Mx}{Q}$$

$$Q^2 = -q^2, \quad s = (P+\ell)^2, \quad W^2 = (P+q)^2,$$

- The ratio of the longitudinal and transverse photon flux (Bacchetta et al., JHEP0702, 093 (2007))

$$\varepsilon = \frac{1 - y - \frac{1}{4}\gamma^2 y^2}{1 - y + \frac{1}{2}y^2 + \frac{1}{4}\gamma^2 y^2}.$$

FORMALISM

◆ The general form for the differential cross section with a transversely polarized nucleon target (Bacchetta et al., JHEP0702, 093 (2007))

$$\frac{d^6\sigma}{dxdydzd\phi_h d\phi_S dP_{hT}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right) \times |S_T|\lambda_e\{\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}(x,z,P_{hT}) + \sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}(x,z,P_{hT}) + \text{leading twist terms}\}, \quad (3)$$

$$A_{LT}^{\cos\phi_S} \equiv \frac{F_{LT}^{\cos\phi_S}}{F_{UU}}$$

$$A_{LT}^{\cos(2\phi_h-\phi_S)} \equiv \frac{F_{LT}^{\cos(2\phi_h-\phi_S)}}{F_{UU}}$$

At twist-3 level

Two double spin asymmetries

FORMALISM

- Sizable SSAs or DSAs cannot be explained by pQCD (Ahmed & Gehrmann, PLB465, 297 (1999)).
- In the (assumed) TMD factorization (Bacchetta, Mulders, Pijlman PLB595, 309 (2004); Bacchetta et al., JHEP0702, 093 (2007))
- With the notation (Bacchetta et al., JHEP0702, 093 (2007))

$$\mathcal{C}[\omega f D] = x \sum_q e_q^2 \int d^2\boldsymbol{p}_T d^2\boldsymbol{k}_T \delta^{(2)}(\boldsymbol{k}_T - \boldsymbol{p}_T - \boldsymbol{P}_{hT}/z)$$

$$\times \omega(\boldsymbol{p}_T, \boldsymbol{k}_T) f^q(x, \boldsymbol{k}_T^2) D^q(z, \boldsymbol{p}_T^2),$$

- The unpolarized structure function F_{UU} can in the be given as

$$F_{UU} = \mathcal{C}[f_1 D_1],$$

FORMALISM

- Focus on the $\cos\phi_S$ azimuthal asymmetry, the structure function can be given as

$$F_{LT}^{\cos\phi_S}(x,z,P_{hT}) = \frac{2M}{Q}\mathcal{C}\bigg\{-\bigg(xg_T D_1 + \frac{M_h}{M}h_1\frac{\tilde{E}}{z}\bigg) + \frac{\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2MM_h}\bigg[\bigg(xe_T H_1^\perp - \frac{M_h}{M}g_{1T}\frac{\tilde{D}^\perp}{z}\bigg) + \bigg(xe_T^\perp H_1^\perp + \frac{M_h}{M}f_{1T}^\perp\frac{\tilde{G}^\perp}{z}\bigg)\bigg]\bigg\},$$

- Considering the transverse momentum of the outgoing pion is integrated to ignore the contributions from the Collins function and the twist-3 TMD fragmentation functions $\tilde{D}^\perp$, $\tilde{G}^\perp$

FORMALISM

- After the integral $\int \mathbf{d}^2\mathbf{P}_{\mathbf{hT}}$ is performed, the fourfold differential cross section has the form

$$\frac{d^4\sigma}{dx\,dy\,dz\,d\phi_S} = \frac{2\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right) \times \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}(x,z).$$

- The collinear counter part of the structure function can be written as

$$F_{LT}^{\cos\phi_S}(x,z) = \int d^2\boldsymbol{P}_{hT} F_{LT}^{\cos\phi_S}(x,z,P_{hT}) = -x\sum_q e_q^2 \frac{2M}{Q}\left(x g_T^q(x) D_1^q(z) + \frac{M_h}{M} h_1^q(x)\frac{\tilde{E}^q(z)}{z}\right).$$

FORMALISM

- The longitudinal-transver spin asymmetry may be defined as

$$A_{LT} \sim \frac{\sigma(+\lambda_e, S_T) - \sigma(-\lambda_e, S_T)}{\sigma(+\lambda_e, S_T) + \sigma(-\lambda_e, S_T)},$$

- Thus, the x-dependent or z-dependent $\cos\phi_S$ asymmetry can be written as

$$A_{LT}^{\cos\phi_S}(x) = \frac{\int dy \int dz \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\sqrt{2\varepsilon(1-\varepsilon)}F_{LT}^{\cos\phi_s}(x,z)}{\int dy \int dz \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)F_{UU}(x,z)},$$

$$A_{LT}^{\cos\phi_s}(z) = \frac{\int dx \int dy \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\sqrt{2\varepsilon(1-\varepsilon)}F_{LT}^{\cos\phi_s}(x,z)}{\int dx \int dy \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)F_{UU}(x,z)}.$$

STRUCTURE FUNCTION

- From the collinear counter part of the structure function

$$F_{LT}^{\cos\phi_S}(x,z) = \int d^2 \boldsymbol{P}_{hT} F_{LT}^{\cos\phi_S}(x,z,P_{hT})$$
$$= -x\sum_q e_q^2 \frac{2M}{Q}\left(x g_T^q(x) D_1^q(z)\right.$$
$$\left. + \frac{M_h}{M} h_1^q(x) \frac{\tilde{E}^q(z)}{z}\right).$$

$$\frac{1}{2}\sum_q e_q^2 g_T^q(x) = g_1(x) + g_2(x),$$
$$g_1(x) = \frac{1}{2}\sum_q e_q^2 g_1^q(x),$$
$$g_2(x) = g_2^{\mathrm{WW}}(x) + g_2^{\mathrm{tw-3}}(x).$$

- Here we use the WW (Wandzura-Wilczek) approximation

$$g_2 \overset{\mathrm{WW}}{\approx} g_2^{\mathrm{WW}}(x) = -g_1(x) + \int_x^1 dy \frac{g_1(y)}{y},$$

STRUCTURE FUNCTION

- For the genuine twist-3 contribution $g_2^{\text{twist-3}}$, we use the result from V.M. Braun, T. Lautenschlager, A.N. Manashov and B. Pirnay, Phys. Rev. D 83, 094023(2011)

at the reference scale $Q^2 = 1GeV^2$ for proton and neutron targets

$$g_{2,p}^{\text{tw}-3}(x) = 0.0436772\left(\ln x + \bar{x} + \frac{1}{2}\bar{x}^2\right) + \bar{x}^3(1.57357 - 5.94918\bar{x} + 6.74412\bar{x}^2 - 2.19114\bar{x}^3), \quad (17)$$

$$g_{2,n}^{\text{tw}-3}(x) = 0.0655158\left(\ln x + \bar{x} + \frac{1}{2}\bar{x}^2\right) + \bar{x}^3(0.130996 - 1.12101\bar{x} + 2.31342\bar{x}^2 - 1.20598\bar{x}^3), \quad (18)$$

STRUCTURE FUNCTION

- In the valence region, applying the isospin symmetry

$$g_{2,p}^{\text{tw}-3}(x) = \frac{4}{9} g_2^{\text{tw}-3,u}(x) + \frac{1}{9} g_2^{\text{tw}-3,d}(x),$$

$$g_{2,n}^{\text{tw}-3}(x) = \frac{1}{9} g_2^{\text{tw}-3,u}(x) + \frac{4}{9} g_2^{\text{tw}-3,d}(x),$$

we obtain the expression for g_T^q

$$g_T^u(x) = \int_x^1 dy \frac{g_1^u(y)}{y} + \frac{6}{5}\left(4 g_{2,p}^{\text{tw}-3}(x) - g_{2,n}^{\text{tw}-3}(x)\right),$$

$$g_T^d(x) = \int_x^1 dy \frac{g_1^d(y)}{y} + \frac{6}{5}\left(4 g_{2,n}^{\text{tw}-3}(x) - g_{2,p}^{\text{tw}-3}(x)\right).$$

STRUCTURE FUNCTION

- To estimate the asymmetry, we also need to know the chiral-odd fragmentation function $\tilde{E}^q(z)$ (there is still no theoretical or experimental information on it.)

$$F_{LT}^{\cos\phi_S}(x,z) = \int d^2 \boldsymbol{P}_{hT} F_{LT}^{\cos\phi_S}(x,z,P_{hT})$$

$$= -x\sum_q e_q^2 \frac{2M}{Q}\left(x g_T^q(x) D_1^q(z) + \frac{M_h}{M} h_1^q(x) \frac{\tilde{E}^q(z)}{z}\right).$$

the motion relation

$$\frac{E^q(z)}{z} = \frac{\tilde{E}^q(z)}{z} + \frac{m_q}{M_h} D_1^q(z),$$

chiral quark model result

$$E^q(z) = \frac{m_q'}{M_h}\frac{z}{1-z} D_1^q(z),$$

- For a rough estimate, we assume

$$\tilde{E}^q(z) = \frac{m_q'}{M_h}\frac{z^2}{1-z} D_1^q(z).$$

STRUCTURE FUNCTION

- For the transversity $h_1^q(x)$, we adopt the standard parametrization
  M. Anselmino, M. Boglione *et al.* Phys. Rev. D 87 094019(2013)

$$F_{LT}^{\cos\phi_S}(x,z) = \int d^2 \boldsymbol{P}_{hT} F_{LT}^{\cos\phi_S}(x,z,P_{hT})$$
$$= -x\sum_q e_q^2 \frac{2M}{Q}\left(x g_T^q(x) D_1^q(z) + \frac{M_h}{M} h_1^q(x)\frac{\tilde{E}^q(z)}{z}\right).$$

$$h_1^q(x) = \frac{1}{2}\mathcal{N}_q^T(x)[f_1^q(x) + g_1^q(x)],$$

with

$$\mathcal{N}_q^T(x) = N_q^T x^\alpha (1-x)^\beta \frac{(\alpha+\beta)^{\alpha+\beta}}{\alpha^\alpha \beta^\beta}.$$

- For the distribution $f_1^q(x)$, we adopt GRV98 LO parametrization
- For the distribution $g_1^q(x)$, we adopt GRV2000 LO parametrization
- For the fragmentation function $D_1^q(z)$, we adopt LO set of the DSS parametrization

NUMERICAL ESTIMATE

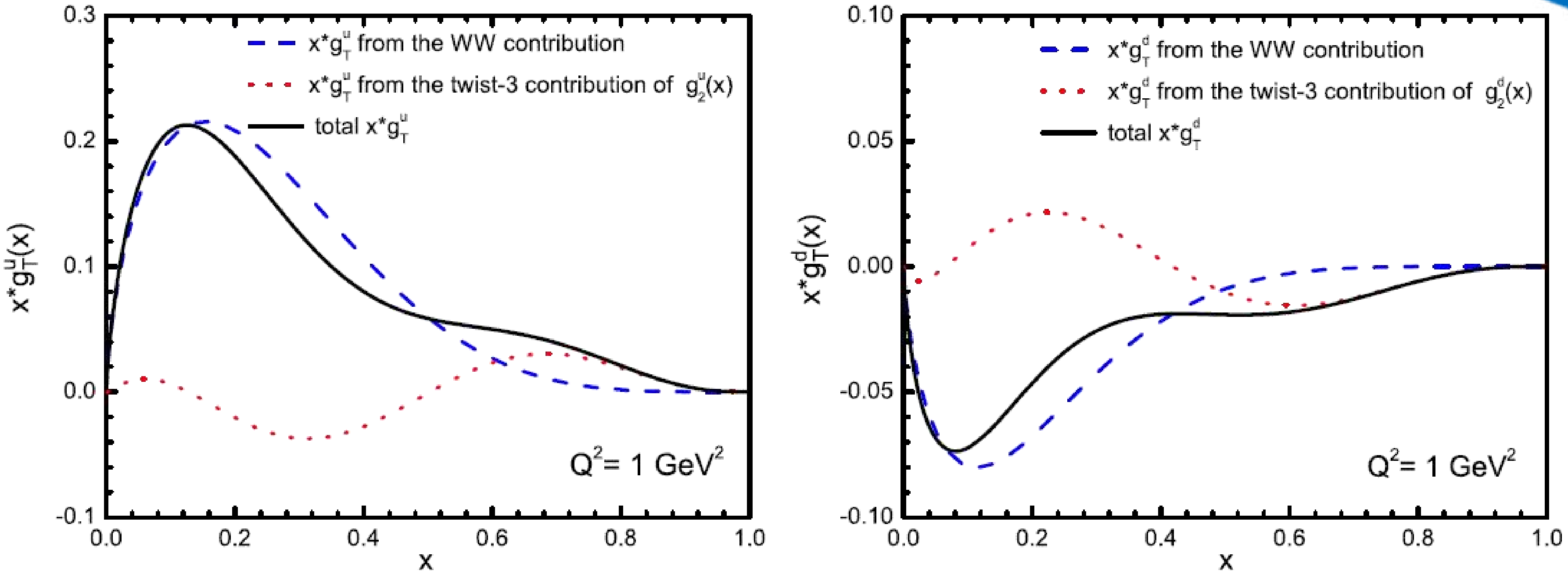


FIG. 2. The twist-3 distribution function $xg_T^q(x)$ for up and down quarks vs x at $Q^2 = 1\times$ GeV^2.

NUMERICAL ESTIMATE at CLAS12

- At CLAS12, the kinematics are as follows

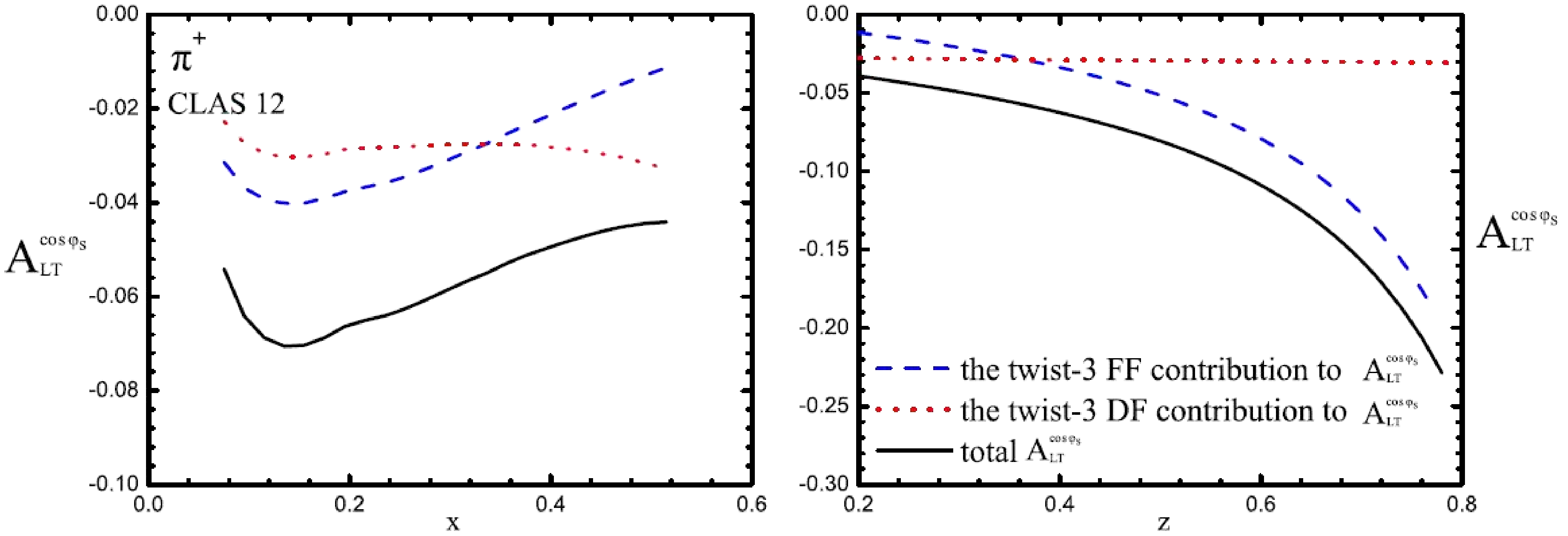
$$0.072 < x < 0.532, \quad 0.2 < z < 0.8, \quad E_e = 11\,\mathrm{GeV},$$
$$W^2 > 4\,\mathrm{GeV}^2, \quad 1 < Q^2 < 6.3\,\mathrm{GeV}^2,$$

- The invariant mass of the photon-nucleon system is

$$W^2 = (P+q)^2 \approx \frac{1-x}{x} Q^2.$$

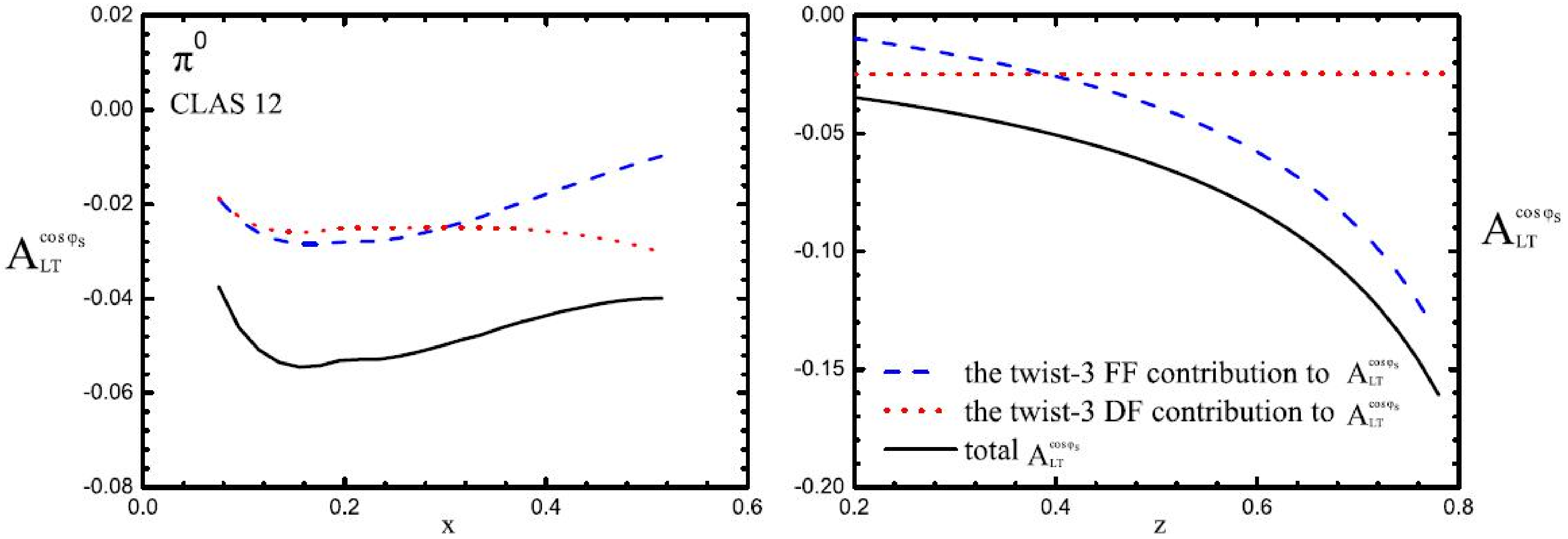
NUMERICAL ESTIMATE at CLAS12

- The x- and z- dependent double-spin asymmetry $A_{LT}^{\cos\phi_S}$ of π^+ production in SIDIS at CLAS12.



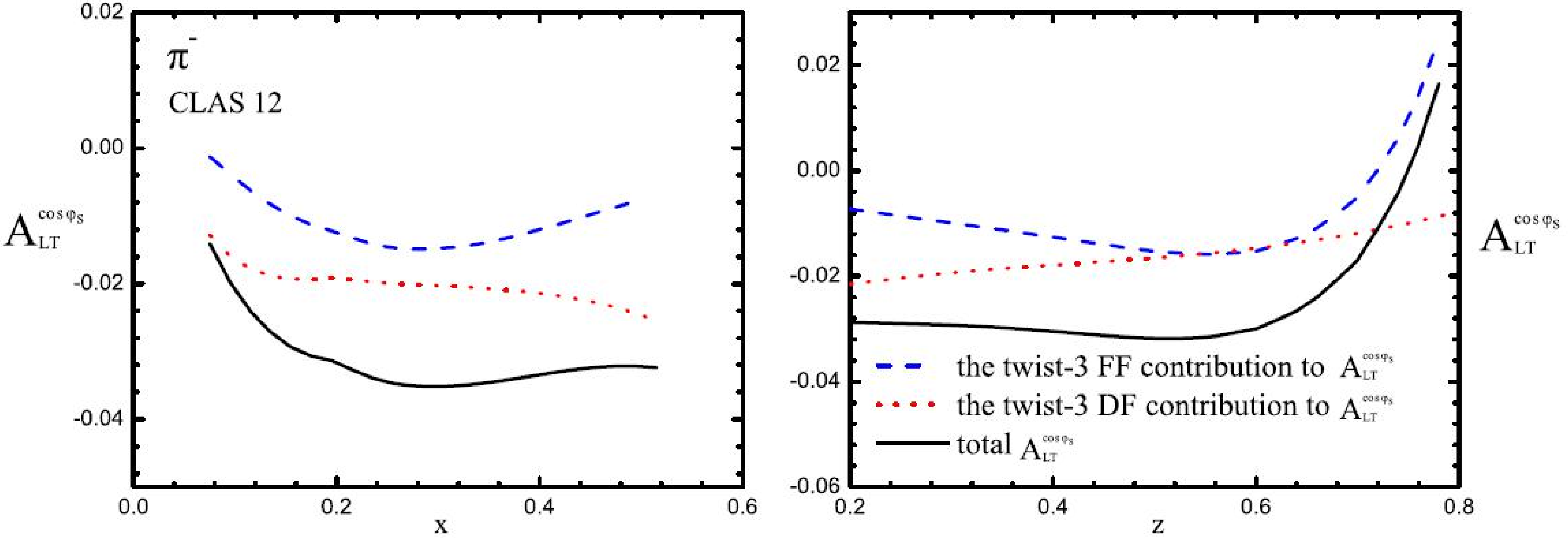
NUMERICAL ESTIMATE at CLAS12

- The x- and z- dependent double-spin asymmetry $A_{LT}^{\cos\phi_S}$ of π^0 production in SIDIS at CLAS12.



NUMERICAL ESTIMATE at CLAS12

- The x- and z- dependent double-spin asymmetry $A_{LT}^{\cos\phi_S}$ of π^- production in SIDIS at CLAS12.



NUMERICAL ESTIMATE at EIC

- At EIC, the kinematical cuts are as follows

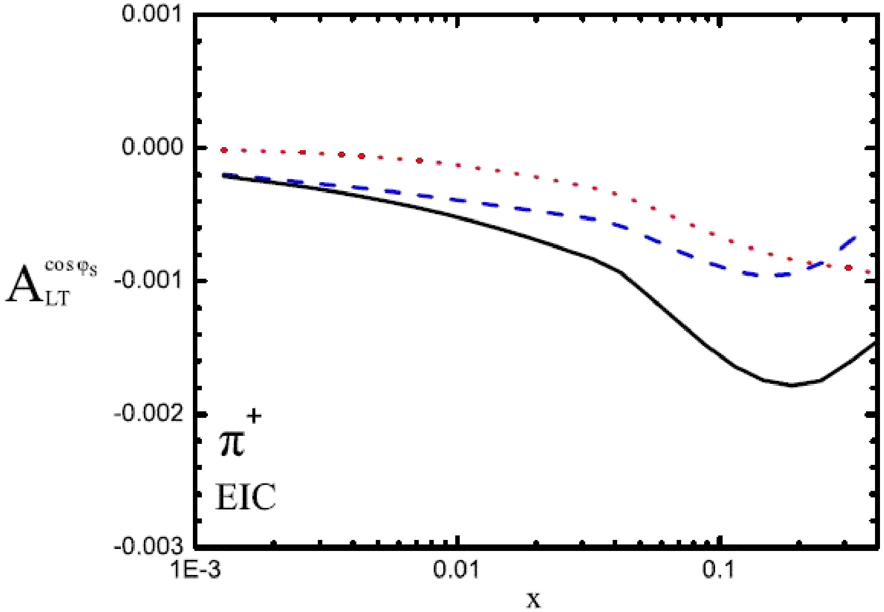
$$Q^2 > 1\ \mathrm{GeV}^2, \quad 0.001 < x < 0.4, \quad 0.01 < y < 0.95,$$

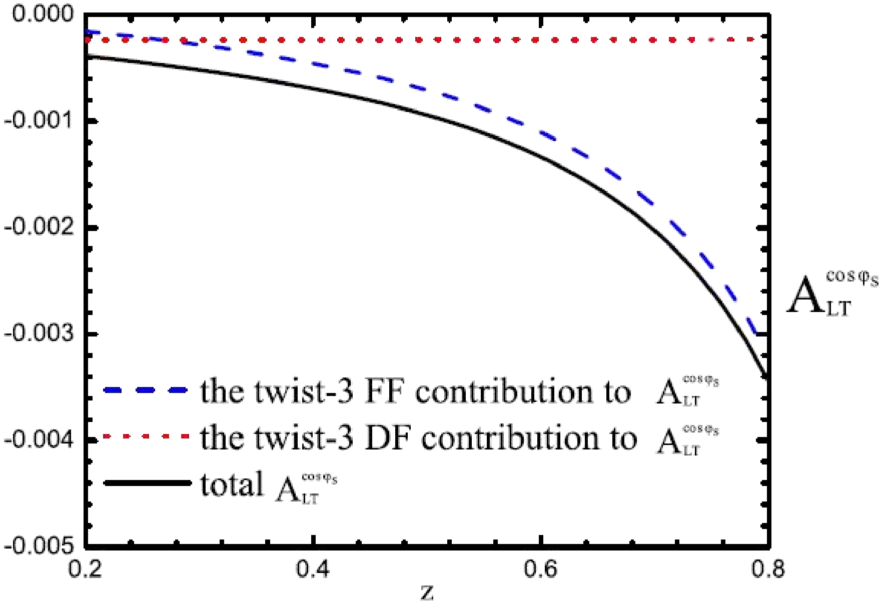
$$0.2 < z < 0.8, \quad \sqrt{s} = 45\ \mathrm{GeV}, \quad W > 5\ \mathrm{GeV}.$$

- At the twist-3 level, the effect will be suppressed by 1/Q, since the averaged Q value at EIC is much higher than that at CLAS12

NUMERICAL ESTIMATE at EIC

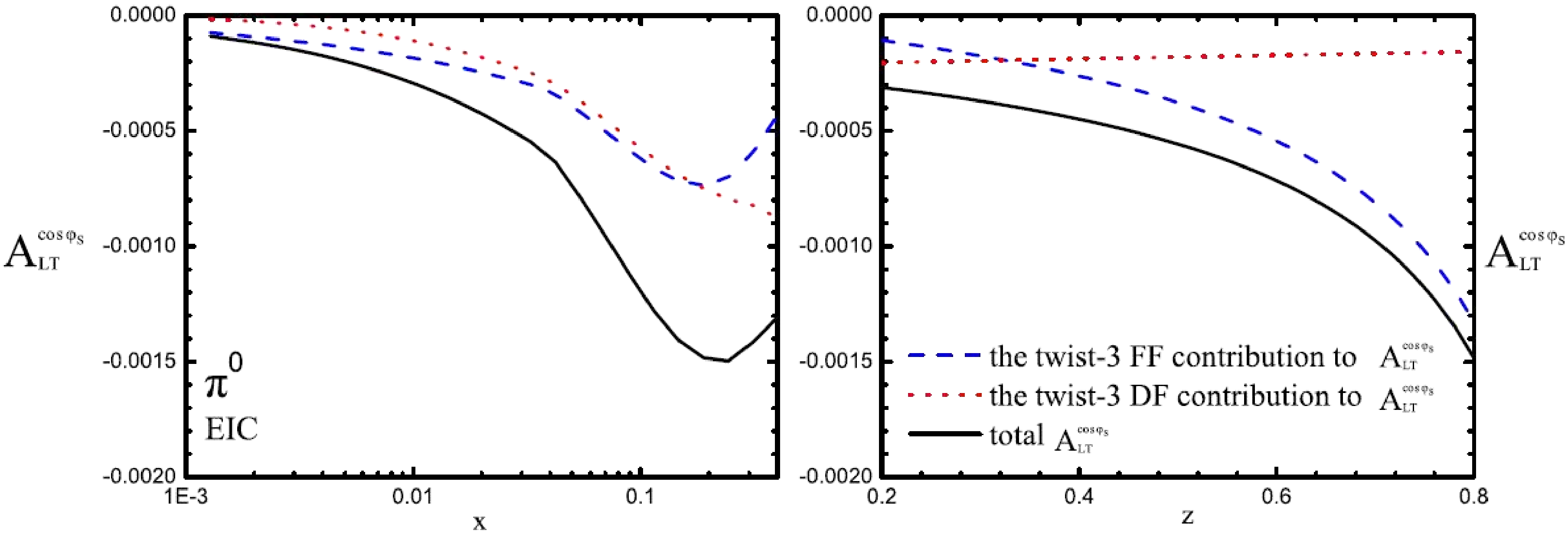
- The x- and z- dependent double-spin asymmetry $A_{LT}^{\cos\phi_S}$ of π^+ production in SIDIS at EIC.





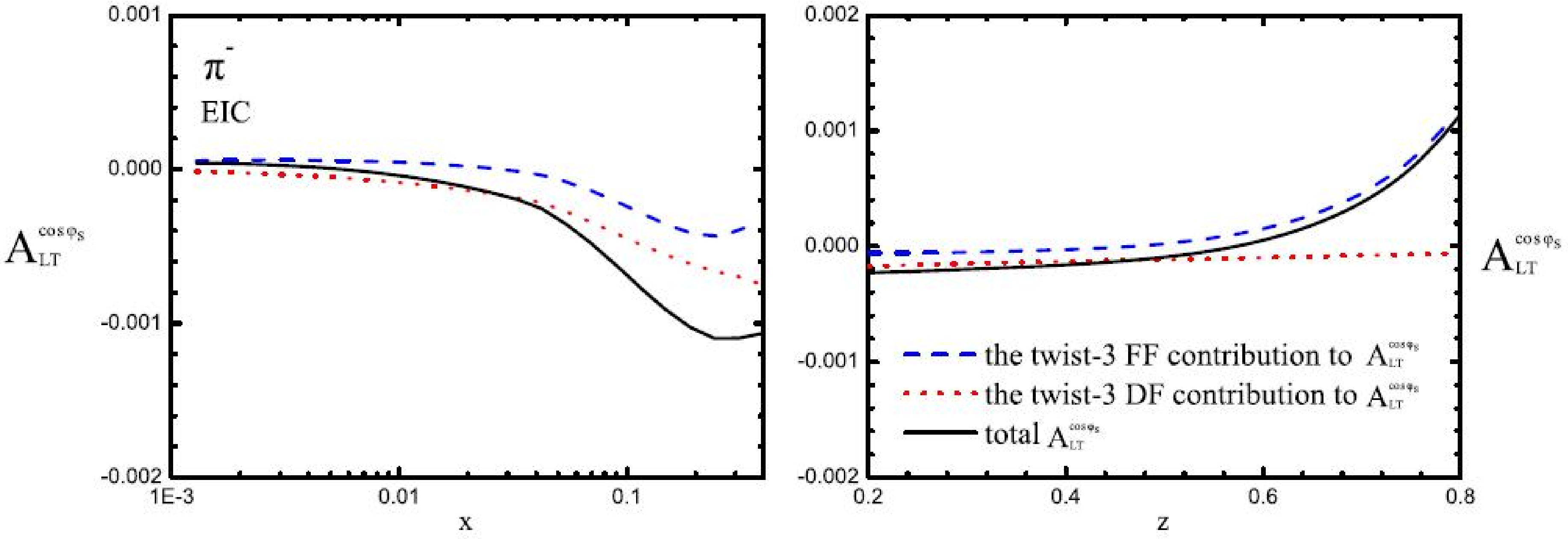
NUMERICAL ESTIMATE at EIC

- The x- and z- dependent double-spin asymmetry $A_{LT}^{\cos\phi_S}$ of π^0 production in SIDIS at EIC.



NUMERICAL ESTIMATE at EIC

- The x- and z- dependent double-spin asymmetry $A_{LT}^{\cos\phi_S}$ of π^- production in SIDIS at EIC.



The transverse double-spin asymmetries in semi-inclusive DIS at subleading with the TMDs

- The structure function at twist-3 level

$$F_{LT}^{\cos\phi_S}(x,z,P_{hT}) = \frac{2M}{Q}\mathcal{C}\Big\{-\Big(xg_T D_1 + \frac{M_h}{M}h_1\frac{\tilde{E}}{z}\Big) + \frac{\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2MM_h}\Big[\Big(xe_T H_1^{\perp} - \frac{M_h}{M}g_{1T}\frac{\tilde{D}^{\perp}}{z}\Big) + \Big(xe_T^{\perp}H_1^{\perp} + \frac{M_h}{M}f_{1T}^{\perp}\frac{\tilde{G}^{\perp}}{z}\Big)\Big]\Big\},$$

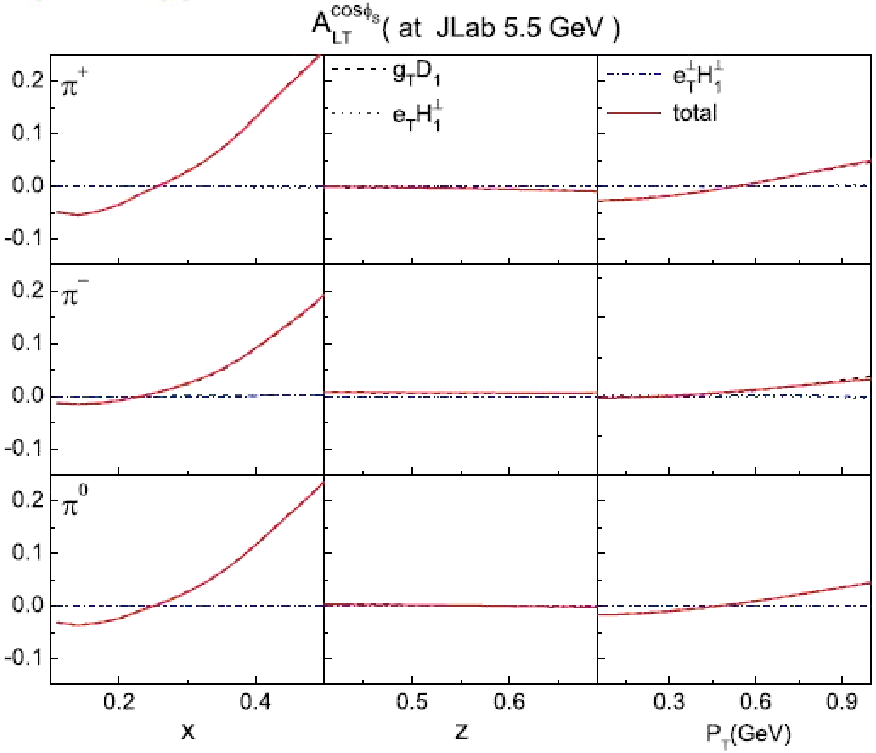
- Use the WW (Wandzura-Wilczek) approximation to ignore the contributions from the twist-3 TMD fragmentation functions

$$F_{\mathrm{LT}}^{\cos\phi_S} \approx \frac{2M}{Q}\mathcal{C}\Big\{-xg_T D_1 - \frac{\boldsymbol{p}_T\cdot\boldsymbol{k}_T}{2zMM_h}(xe_T H_1^{\perp} + xe_T^{\perp}H_1^{\perp})\Big\}$$

Based on Phy. Rev. D 91, 034029 (2015)

Predictions at JLab

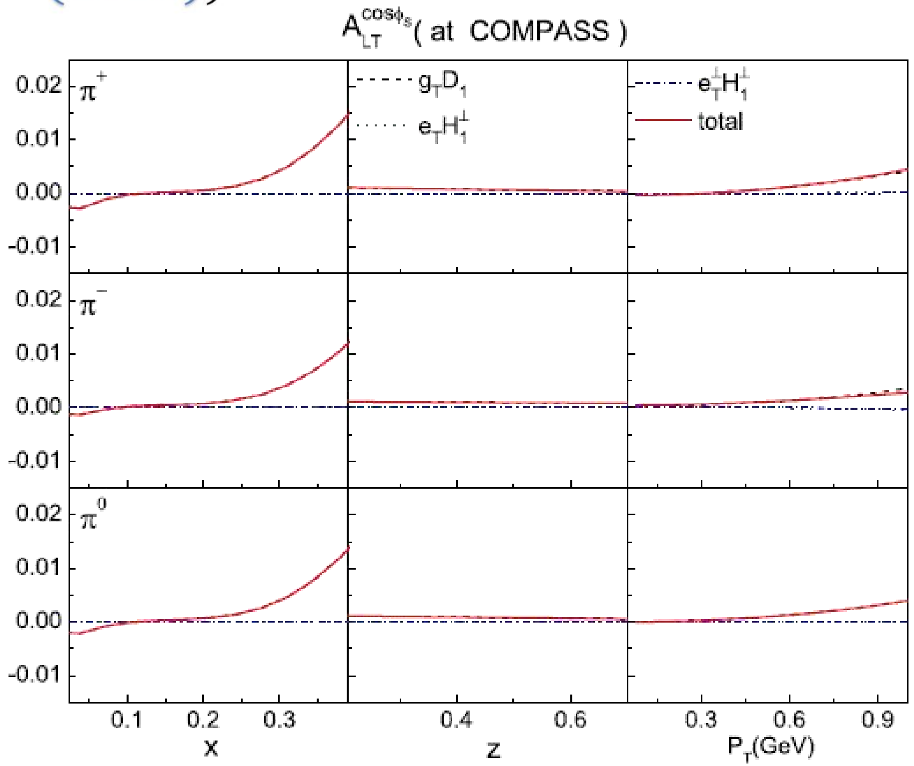
- Kinematics at JLab 5.5GeV (H. Avakian, Nuovo Cimento Soc. Ital. Fis. C 36, 73 (2013)):



$$0.1 < x < 0.6, \quad 0.4 < z < 0.7, \quad Q^2 > 1\ \mathrm{GeV}^2,$$
$$P_T > 0.05\ \mathrm{GeV}, \quad W^2 > 4\ \mathrm{GeV}^2.$$

Predictions at COMPASS

- Kinematics at COMPASS 160GeV(M.G. Alekseev et al., Phys. Lett. B 692, 240 (2010)):



$$0.004 < x < 0.7, \quad 0.1 < y < 0.9, \quad z > 0.2,$$
$$P_T > 0.1\ \text{GeV}, \quad Q^2 > 1\ \text{GeV}^2,$$
$$W > 5\ \text{GeV}, \quad E_h > 1.5\ \text{GeV}.$$

SUMMARY

- We estimate the double-spin asymmetry $A_{LT}^{\cos\phi_S}$ of charged and neutral pion production in SIDIS at CLAS12 and a future EIC.
- We consider the particular case where the transverse momentum of the final-state hadron is integrated out.
- We focus on the constributions from the twist-3 distribution function term $g_T(x)D_1(z)$ and the twist-3 fragmentation function term $h_1(x)\tilde{E}(z)$.
- The asymmetry of pion at CLAS12 is sizable, and $\tilde{E}(z)$ can play an important role in the large-z region.

THANK YOU!