Single-spin asymmetry $A_{UUT}^{\sin\phi_{S_h}}$ of proton and Λ production in SIDIS at subleading twist

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OUTLINE

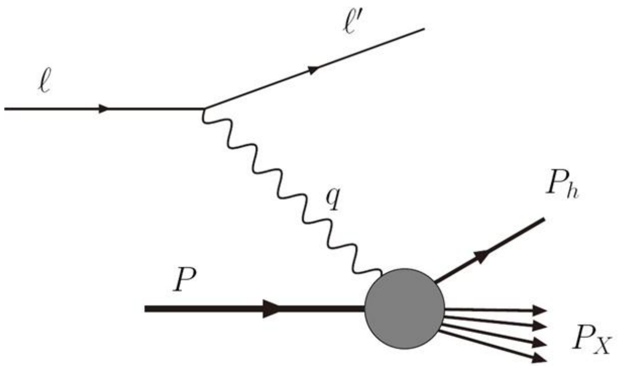
1. Formalism
2. Calculation on the structure functions
3. Numerical Estimate at JLab12 and COMPASS
4. Summary

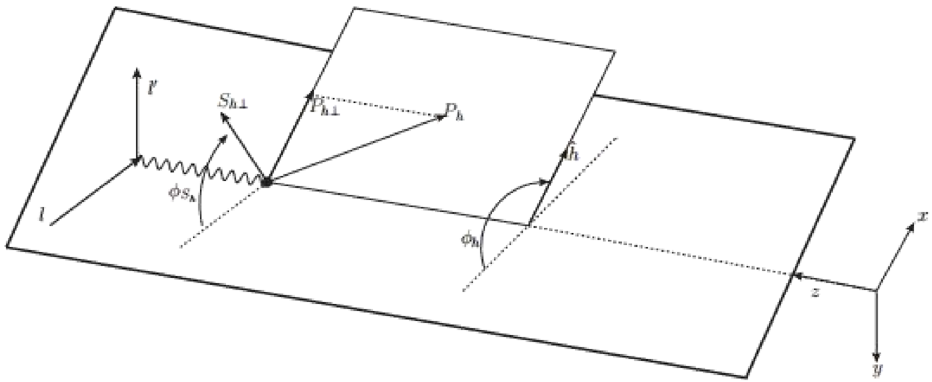
Based on arXiv:1808:10565(2018)

Formalism

- Transversely polarized hadron production in semi-inclusive DIS by scattering off the unpolarized target

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





- The invariants defined as

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

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

Formalism

- The general form for the differential cross section with an unpolarized nucleon target in SIDIS (D.Boer and P.J. Mulders, Phys. Rev. D57,5780(1998))

$$\frac{d\sigma}{dxdydzd\phi d\psi dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}(1+\frac{\gamma^2}{2x})\Big\{F_{UUU} + |S_{hT}|\sin\phi_{S_h}\sqrt{2\varepsilon(1+\varepsilon)}F_{UUT}^{\sin\phi_{S_h}} + \cdots\Big\}$$

$$A_{UUT}^{\sin\phi_{S_h}} \equiv \frac{F_{UUT}^{\sin\phi_{S_h}}}{F_{UUU}}$$

the differential cross section

the single spin asymmetry

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

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

Formalism

- The $P_{h\perp}$ dependent SSA $A_{UUT}^{\sin\phi_{S_h}}$ has the form

$$A_{UUT}^{\sin\phi_{S_h}}(P_{h\perp}) = \frac{\int dx \int dy \int dz\, \mathcal{C}_{\mathrm{UT}}\, F_{UUT}^{\sin\phi_{S_h}}}{\int dx \int dy \int dz\, \mathcal{C}_{\mathrm{UU}}\, F_{\mathrm{UUU}}},$$

- The kinematical factors C_{UU} and C_{UT} are defined as

$$\mathcal{C}_{\mathrm{UU}} = \frac{1}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right),$$

$$\mathcal{C}_{\mathrm{UT}} = \frac{1}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\sqrt{2\varepsilon(1+\varepsilon)},$$

- 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))

Formalism

- Introduce the convolution integral

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

- The spin-averaged structure function F_{UUU} can in the be given as

$$F_{UUU} = \mathcal{I}[f_1 D_1] ,$$

- The structure function in the numerator F_{UUT} are given as

$$F_{UUT}^{\sin\phi_{S_h}} = \frac{2M}{Q}\mathcal{I}\left\{\left(\frac{M_h}{M} f_1 \frac{\tilde{D}_T}{z} - xh\, H_1\right) + \frac{\boldsymbol{k}_T \cdot \boldsymbol{p}_T}{2M M_h}\left[\left(\frac{M_h}{M} h_1^\perp \tilde{H}_T^\perp - x f_1\, D_{1T}^\perp\right) - \left(\frac{M_h}{M} h_1^\perp \frac{\tilde{H}_T}{z} + x g^\perp G_{1T}\right)\right]\right\}$$

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

$$F_{UUT}^{\sin\phi_{S_h}} \approx \frac{2M}{Q}\mathcal{I}\left[-xhH_1 + \frac{\boldsymbol{k}_T \cdot \boldsymbol{p}_T}{2M M_h}\left(-x f^\perp D_{1T}^\perp - x g^\perp G_{1T}\right)\right].$$

Need further studies!

Formalism

- Nonzero contributions with the collinear twist-3 factorization (Z.-B. Kang, F. Yuan and J. Zhou, Phys. Lett. B 691, 243(2010); A. Metz and D. Pitonyak, Phys. Lett. B 723, 365 (2013); K. Kanazawa, Y. Koike, A. Metz, and D. Pitonyak, PRD 89, 111501(R) (2014)).

- The contribution from the quark-gluon-quark correlators may still be important, the twist-3 FFs might not be necessarily negligible (R. Kundu and A. Metz, Phys. Rev. D 65 014009(2002). A. Accardi, A. Bacchetta, W. Melnitchouk and M. Schlegel, JHEP 0911, 093(2009). B. Pasquini and S. Rodini, arXiv:1806.10932 [hep-ph].)

- Focus on the contribution from the twist-3 TMD distribution functions and twist-2 fragmentation functions

$$F_{UUT}^{\sin\phi_{S_h}} \approx \frac{2M}{Q}\mathcal{I}\Big[-xhH_1 + \frac{k_T\cdot p_T}{2MM_h}(-xf^\perp D_{1T}^\perp - xg^\perp G_{1T})\Big].$$

The TMD twist-3 distribution functions

- The quark-quark corrector

$$\Phi(x, \boldsymbol{p}_T; S) = \int \frac{d\xi^- d^2\xi_T}{(2\pi)^3} e^{ip\cdot\xi} \langle P, S|\bar{\psi}(0)\mathcal{L}[0,\xi]\psi(\xi)|P, S\rangle\Big|_{\xi^+=0},$$

$$\frac{1}{4}\mathrm{Tr}[(\Phi(x, \boldsymbol{p}_T; S) + \Phi(x, \boldsymbol{p}_T; -S))\, i\sigma^{\alpha\beta}\gamma_5] = -\frac{M}{P^+}\epsilon_T^{\alpha\beta} h,$$

$$\frac{1}{4}\mathrm{Tr}[(\Phi(x, \boldsymbol{p}_T; S) + \Phi(x, \boldsymbol{p}_T; -S))\, \gamma^{\alpha}] = \frac{p_T^\alpha}{P^+} f^\perp,$$

$$\frac{1}{4}\mathrm{Tr}[(\Phi(x, \boldsymbol{p}_T; S) + \Phi(x, \boldsymbol{p}_T; -S))\, \gamma^{\alpha}\gamma_5] = -\frac{\epsilon_T^{\alpha\rho} p_{T\rho}}{P^+} g^\perp .$$

T−odd: h and $g^\perp$

T−even: $f^\perp$

- Using the similar spectator model calculation in the work (Bacchetta, Conti, Radici, PRD78, 074010(2008)) and considering the following sum for axial-vector diquark propagator (Brodsky et al., NPB593, 311(2011))

$$d_{\mu\nu}(P-k) = -g_{\mu\nu} + \frac{(P-k)_\mu n_{-\nu} + (P-k)_\nu n_{-\mu}}{(P-k)\cdot n_-} - \frac{M_v^2}{[(P-k)\cdot n_-]^2} n_{-\mu} n_{-\nu}$$

The TMD twist-3 distribution functions

- The distributions contributed by the scalar diquark

$$h(x,\boldsymbol{p}_T^2)_s = -\frac{N_s^2(1-x)^3}{16\pi^3 M}\frac{e_s e_q}{4\pi}\frac{(m+xM)(L_s^2-\boldsymbol{p}_T^2)}{L_s^2(\boldsymbol{p}_T^2+L_s^2)^3},$$

$$f^{\perp}(x,\boldsymbol{p}_T^2)_s = -\frac{N_s^2(1-x)^2}{16\pi^3}\frac{(\boldsymbol{p}_T^2-2mM(1-x)-(1-x^2)M^2+m_s^2)}{(\boldsymbol{p}_T^2+L_s^2)^4}.$$

- The distributions contributed by the axial-vector diquark

$$h(x,\boldsymbol{p}_T^2)_a = 0,$$

$$f^{\perp}(x,\boldsymbol{p}_T^2)_a = \frac{N_a^2(1-x)}{16\pi^3}\frac{(x\boldsymbol{p}_T^2+2mM(1-x)^2+(x-1)m^2+(x^3-2x^2+1)M^2-m_a^2)}{L_a^2(\boldsymbol{p}_T^2+L_a^2)^3}.$$

- Model results for the twist-3 T-odd distribution function $g^{\perp}$ have been given in Wenjuan Mao and Zhun Lu, Phys. Rev. D87.014012.

- Parameters are taken from Bacchetta, Conti, Radici, PRD78, 074010(2008)

$$f^u = {c_s}^2 f^s + {c_a}^2 f^a, \qquad f^d = {c_{a'}}^2 f^{a'}$$

The TMD twist-3 distribution functions

- Model results for the distribution functions $f^{\perp}$

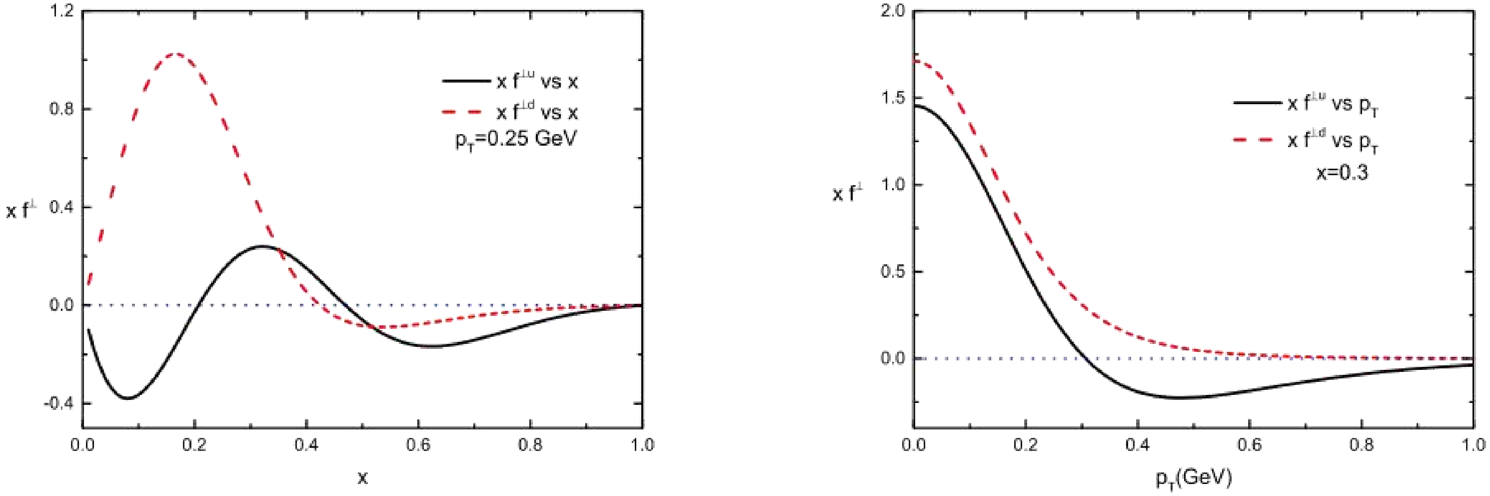


FIG. 1: Left panel: model results for $xf^{\perp u}(x,\boldsymbol{p}_T^2)$ (solid line) and $xf^{\perp d}(x,\boldsymbol{p}_T^2)$ (dashed line) as functions of x at $p_T = 0.3\,\mathrm{GeV}$. Right panel: model results for $xf^{\perp u}$ (solid line) and $xf^{\perp d}$ (dashed line) as functions of p_T at $x = 0.3$.

The TMD twist-3 distribution functions

- Model results for the distribution function h

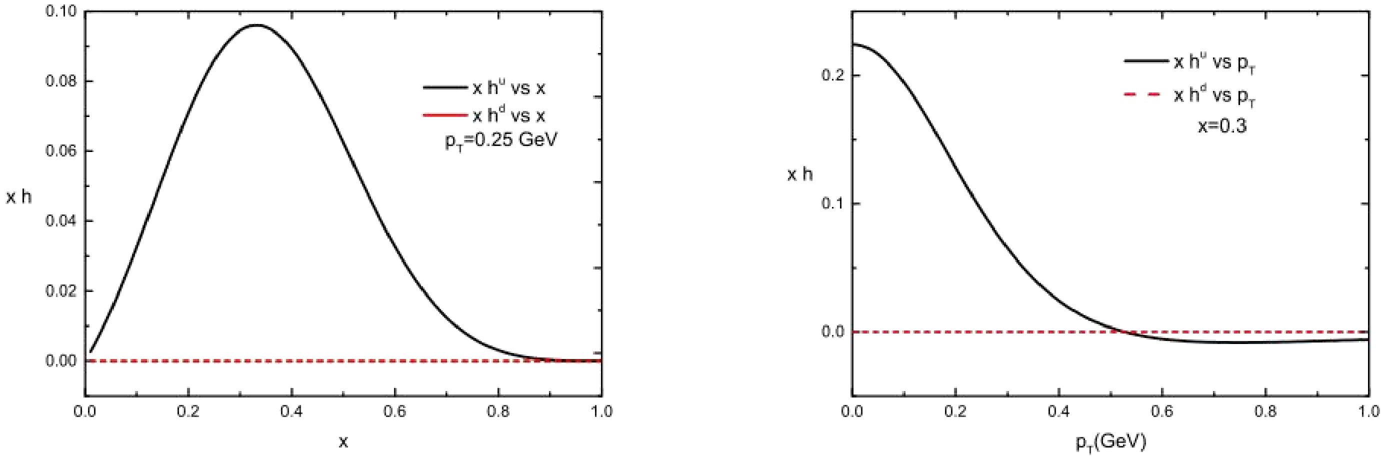


FIG. 2: Similar to Fig. 1, but for the model results of $xh^u(x, \boldsymbol{p}_T^2)$ (solid line) and $xh^d(x, \boldsymbol{p}_T^2)$ (dashed line).

- For the twist-2 distribution function f_1, we adopt the model results in Bacchetta, Conti, Radici, Phys. Rev. D78, 074010(2008).

The TMD twist-2 fragmentation functions

- To estimate the asymmetry, we also need to know the twist-2 fragmentation functions $\mathrm{H}_1, G_{1T}, D_{1T}^{\perp}$

$$\frac{\epsilon_T^{\alpha\beta} k_{T\alpha} S_{hT\beta}}{M} D_{1T}^{\perp}(z, \boldsymbol{k}_T^2) = \frac{1}{2} \mathrm{Tr}[(\Delta(z, \boldsymbol{k}_T; \boldsymbol{S}_{hT}) - \Delta(z, \boldsymbol{k}_T; -\boldsymbol{S}_{hT}))\gamma^-],$$

$$S_{hL} G_{1L}(z, \boldsymbol{k}_T^2) + \frac{\boldsymbol{k}_T \cdot \boldsymbol{S}_{hT}}{M_h} G_{1T}(z, \boldsymbol{k}_T^2) = \frac{1}{4} \mathrm{Tr}[(\Delta(z, \boldsymbol{k}_T; \boldsymbol{S}_{hT}) - \Delta(z, \boldsymbol{k}_T; -\boldsymbol{S}_{hT}))\gamma^- \gamma_5],$$

$$S_T^{\alpha} H_1(z, \boldsymbol{k}_T^2) = \frac{1}{4} \mathrm{Tr}[(\Delta(z, \boldsymbol{k}_T; \boldsymbol{S}_{hT}) - \Delta(z, \boldsymbol{k}_T; -\boldsymbol{S}_{hT})) i\sigma^{\alpha -}\gamma_5],$$

with the fragmentation correlation function

$$\Delta(z, \boldsymbol{k}_T; \boldsymbol{S}_{hT}) = \frac{1}{2z} \sum_X \int \frac{d\xi^+ d^2\boldsymbol{\xi}_T}{(2\pi)^3} e^{ik\cdot\xi} \langle 0| \mathcal{U}_{(+\infty,\xi)}^{n^+} \psi(\xi) |P_h, S_h; X\rangle \langle P_h, S_h; X| \bar{\psi}(0) \mathcal{U}_{(0,+\infty)}^{n^+} |0\rangle \Big|_{\xi^-=0},$$

and the spin vector of the outgoing hadron

$$S_h^{\mu} = S_{hL} \frac{(P_h \cdot n_+) n_-^{\mu} - (P_h \cdot n_-) n_+^{\mu}}{M_h} + S_{hT}^{\mu}.$$

The TMD twist-2 fragmentation functions

- For the fragmentation function $D_1^{(s)}(z, k_T^2)$, we can obtain its expression as

$$D_1^{(s)}(z,\boldsymbol{k}_T^2) = D_1^v(z,\boldsymbol{k}_T^2) = \frac{g_D^2}{2(2\pi)^3}\frac{1}{z^2}e^{\frac{-2k^2}{\Lambda^2}}\frac{(1-z)[z^2k_T^2+(M+zm)^2]}{z^4(k_T^2+L^2)^2},$$

- Assuming the SU(6) spin-flavor symmetry for the final state hadron, the relation between quark flavors and diquark types for proton and Λ we can write as

$$D^{\mathrm{u}\to p} = \frac{3}{2}D^{(s)} + \frac{1}{2}D^{(v)}, \quad D^{\mathrm{d}\to p} = D^{(v)}, D^{\mathrm{s}\to p} = 0$$

$$D^{\mathrm{u}\to\Lambda} = D^{\mathrm{d}\to\Lambda} = \frac{1}{4}D^{(s)} + \frac{3}{4}D^{(v)}, \quad D^{\mathrm{s}\to\Lambda} = D^{(s)},$$

- For $D_1^p(z)$, we fit it to the HKNS LO parametrization at the initial scale $\mu_{LO}^2 = 1\mathrm{GeV}^2$

$$g_D = 1.588^{+0.1}_{-0.096}, \quad m_D = 0.849^{+0.04}_{-0.0376}\mathrm{GeV},$$

$$\lambda = 10.192^{+1.34}_{-1.11}\mathrm{GeV}, \quad \alpha = 0.5(\mathrm{fixed}), \quad \beta = 0(\mathrm{fixed}).$$

The TMD twist-2 fragmentation functions

- Model result of the unpolarized fragmentation function $D_1(z)$

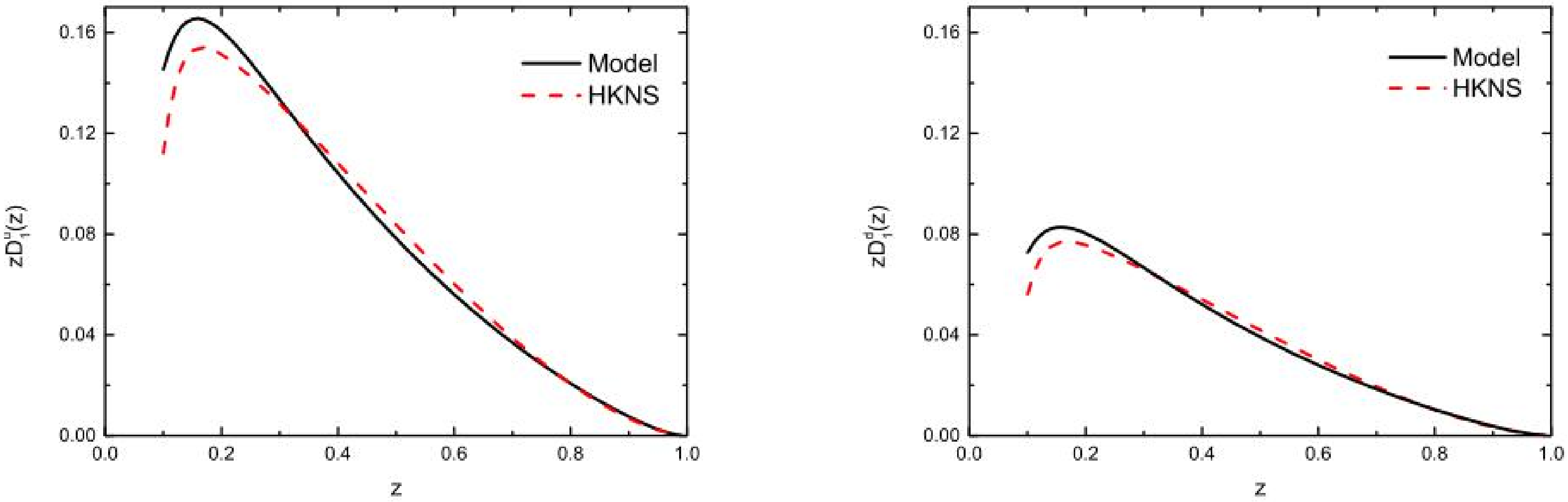


FIG. 3: Unpolarized fragmentation functions $zD_1^u(z)$ (left panel) and $zD_1^d(z)$ (right panel) of the proton (solid lines) compared with the HKNS parametrization (dashed lines), respectively.

The TMD twist-2 fragmentation functions

- For the fragmentation function $D_{1T}^{\perp}(z, k_T^2)$, we adopt the form in Y. Yang, Z. LU and I. Schmidt PRD96, 034010(2017)

- For the fragmentation function $H_1(z, k_T^2)$ and $G_{1T}(z, k_T^2)$, we obtain the results

$$G_{1T}^{R}(z,\boldsymbol{k}_T^2)=a_R\frac{g_D^2}{(2\pi)^3}\frac{1}{z^2}e^{\frac{-2k^2}{\Lambda^2}}\frac{M_h(zm+M_h)(1-z)}{z^3(\boldsymbol{k}_T^2+L_f^2)^2},$$

$$H_1^{R}(z,\boldsymbol{k}_T^2)=a_R\frac{g_D^2}{2(2\pi)^3}\frac{1}{z^2}e^{\frac{-2k^2}{\Lambda^2}}\frac{(1-z)[(zm+M_h)^2]}{z^4(\boldsymbol{k}_T^2+L_f^2)^2},$$

with $$L_f^2=\frac{1-z}{z^2}M_h^2+m^2+\frac{m_D^2-m^2}{z}.$$

The TMD twist-2 fragmentation functions

- Model result of the fragmentation functions $zD^{\perp u}_{1T}$, $zH^{u}_{1}(z)$ and $zG^{u}_{1T}(z)$

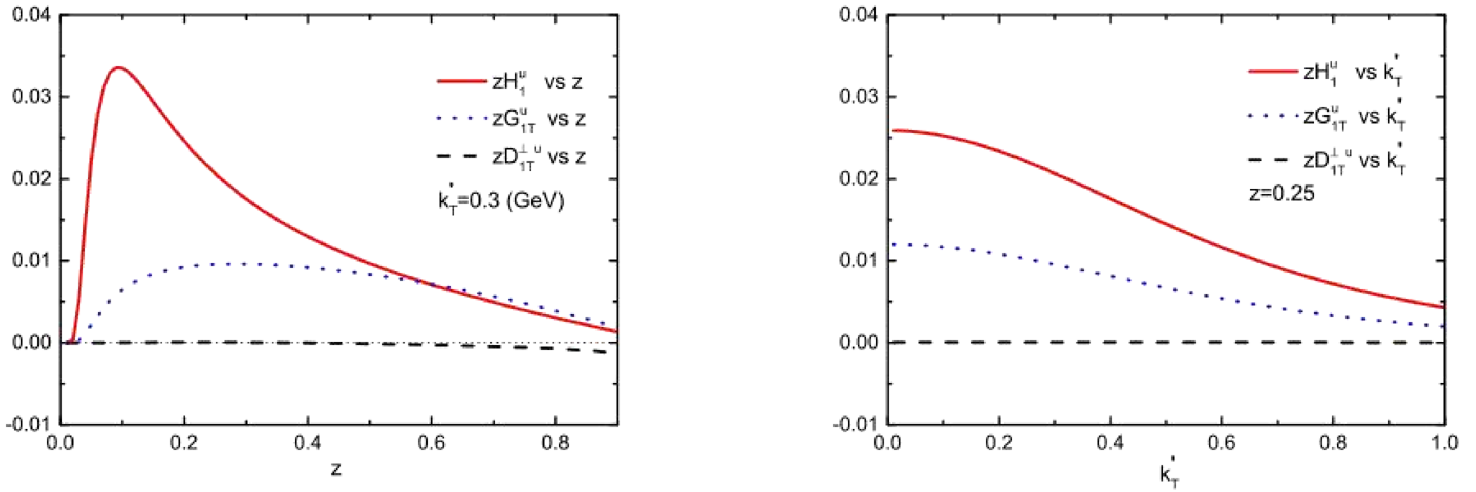


FIG. 4: Left panel: the model results of zH_1^u (solid line), zG_{1T}^u (dotted line) and $zD_{1T}^{\perp u}$ (dashed line) for the proton as functions of z at $k_T' = 0.3\,\mathrm{GeV}$; Right panel: the model results of zH_1^u (solid line), zG_{1T}^u (dotted line) and $zD_{1T}^{\perp u}$ (dashed line) for the proton as functions of k_T' at $z = 0.25$.

The TMD twist-2 fragmentation functions

- Model result of the fragmentation functions $zD_{1T}^{\perp d}$, $zH_1^d(z)$ and $zG_{1T}^d(z)$

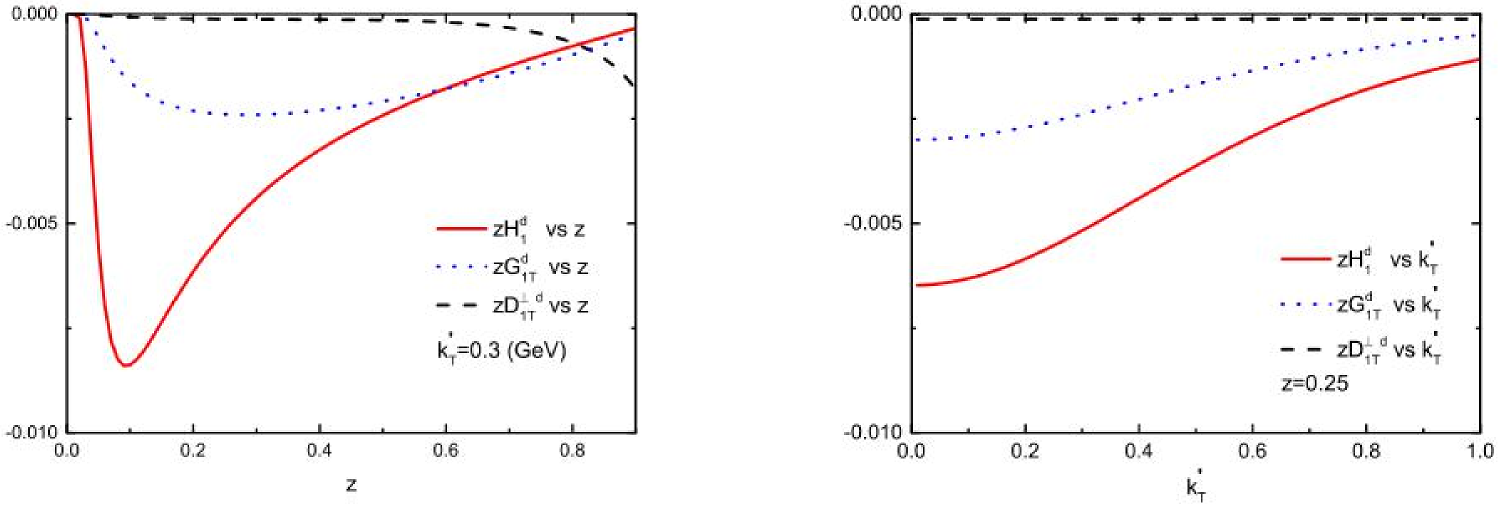


FIG. 5: Similar to Fig. 4, but for the model results of zH_1^d (solid line), zG_{1T}^d (dotted line) and $zD_{1T}^{\perp d}$ (dotted line).

Numerical estimate at JLab 12GeV

- Constraints for quark transverse momentum p_T^2 (Boglione, Melis, Prokudin, Phy. Rev. D84, 034033(2011)) :

$$\begin{cases} p_T^2 \leq (2-x)(1-x)Q^2, & \text{for} \quad 0 < x < 1; \\ p_T^2 \leq \frac{x(1-x)}{(1-2x)^2} Q^2, & \text{for} \quad x < 0.5. \end{cases}$$

- At JLab 12GeV, the kinematics are as follows

$$0.1 < x < 0.6, \quad 0.3 < z < 0.7, \quad Q^2 > 1\mathrm{GeV}^2,$$
$$W^2 > 4\,\mathrm{GeV}^2, P_{h\perp} > 0.05\,\mathrm{GeV}.$$

- The invariant mass of the hadron final state

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

Numerical estimate at JLab 12GeV

- The single-spin asymmetry of proton production in SIDIS at JLab 12GeV.

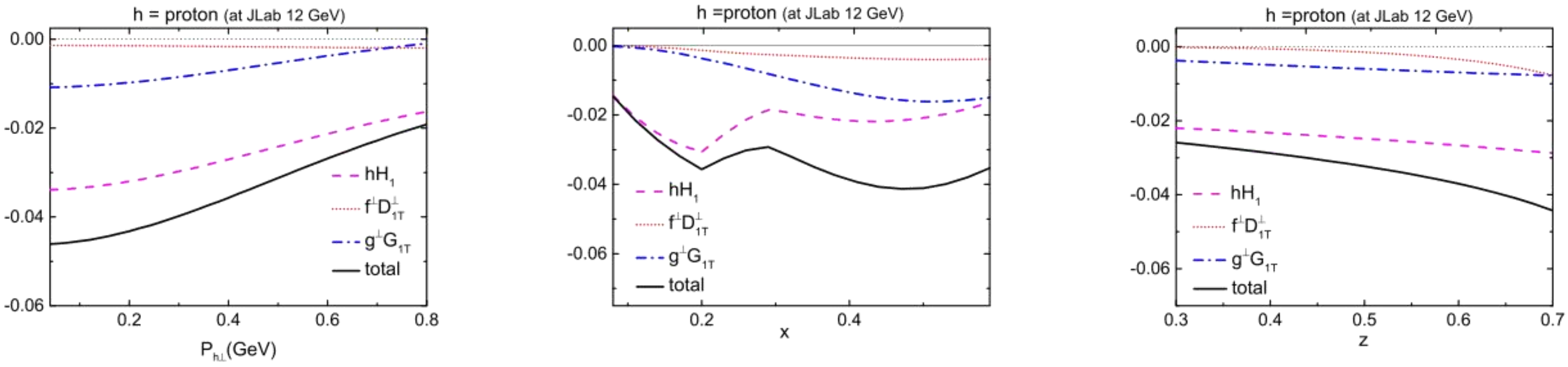


FIG. 7: Predictions on the transverse SSA $A_{UUT}^{\sin\phi_{S_h}}$ for proton production in SIDIS at JLab 12 GeV. The dashed, dotted and dash-dotted curves represent the asymmetries from the hH_1, $f^{\perp}D_{1T}^{\perp}$ and $g^{\perp}G_{1T}$ terms, respectively. The solid curves correspond to the total contribution.

Numerical estimate at JLab 12GeV

- The single-spin asymmetry of Λ production in SIDIS at JLab 12GeV.

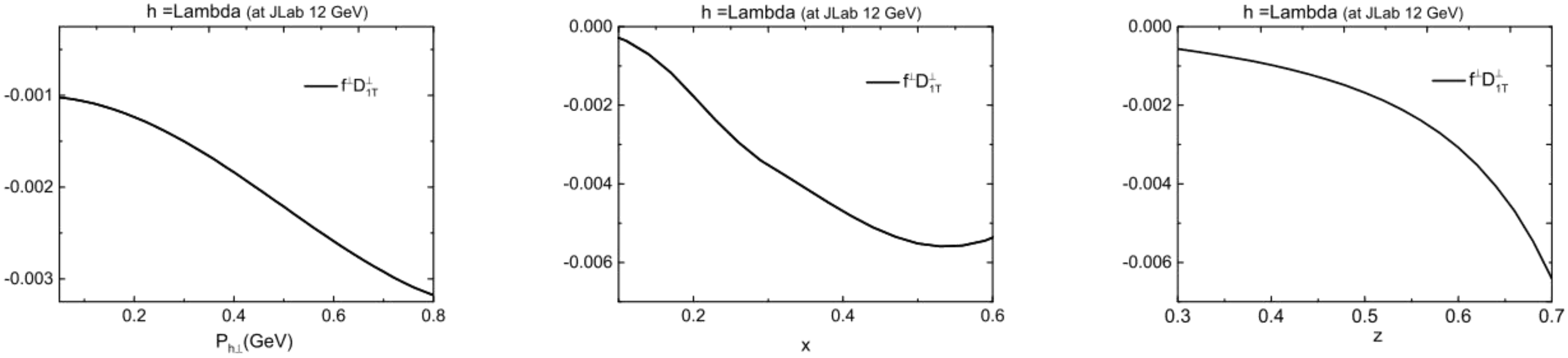


FIG. 8: Predictions on the transverse SSA $A_{UUT}^{\sin\phi_{S_h}}$ for Λ production in SIDIS at JLab. The solid curves correspond to the total asymmetry (it only receives contribution from the $f^\perp D_{1T}^\perp$ term).

Numerical estimate at COMPASS

- At COMPASS, the kinematical cuts are as follows (M. G. Alekseev et al. [COMPASS Collaboration], Phys. Lett. B 692, 240 (2010) [arXiv:1005.5609 [hep-ex]])

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

- At the twist-3 level, the effect will be suppressed by 1/Q, since the averaged Q value at COMPASS is much higher than that at JLab 12GeV

$$E_{beam} = 160\mathrm{GeV}$$

Suppressed by 1/Q ！

Numerical estimate at COMPASS

- The single-spin asymmetry of proton production in SIDIS at COMPASS.

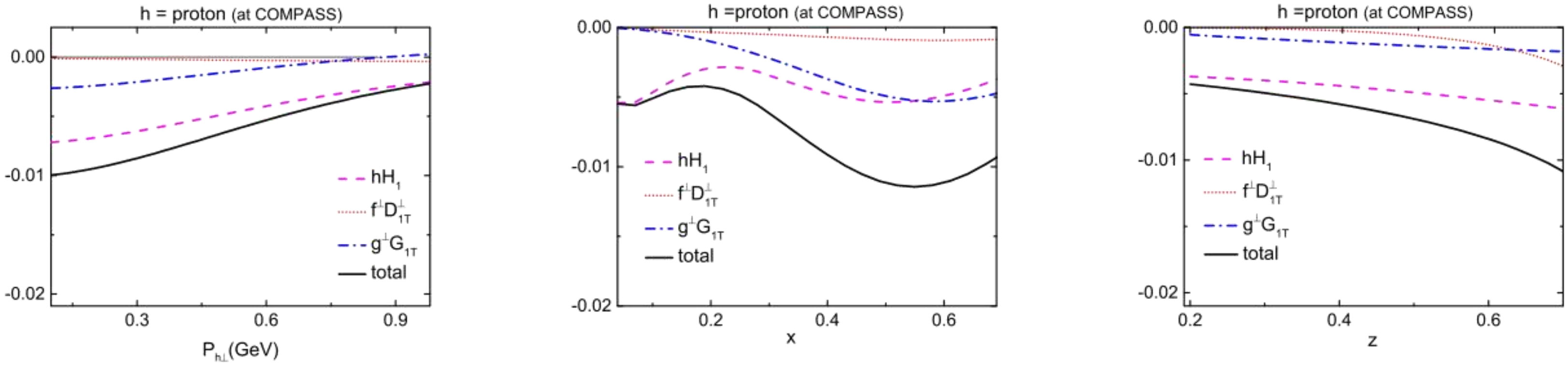


FIG. 9: Predictions on the transverse SSA $A_{UUT}^{\sin\phi_{S_h}}$ for the proton production in SIDIS at COMPASS, contributed by the hH_1 (dashed lines), $f^\perp D_{1T}^\perp$ (dotted lines) and $g^\perp G_{1T}$ (dashed-dotted) terms, respectively. The solid curves correspond to the total contribution.

Numerical estimate at COMPASS

- The single-spin asymmetry of Λ production in SIDIS at COMPASS.

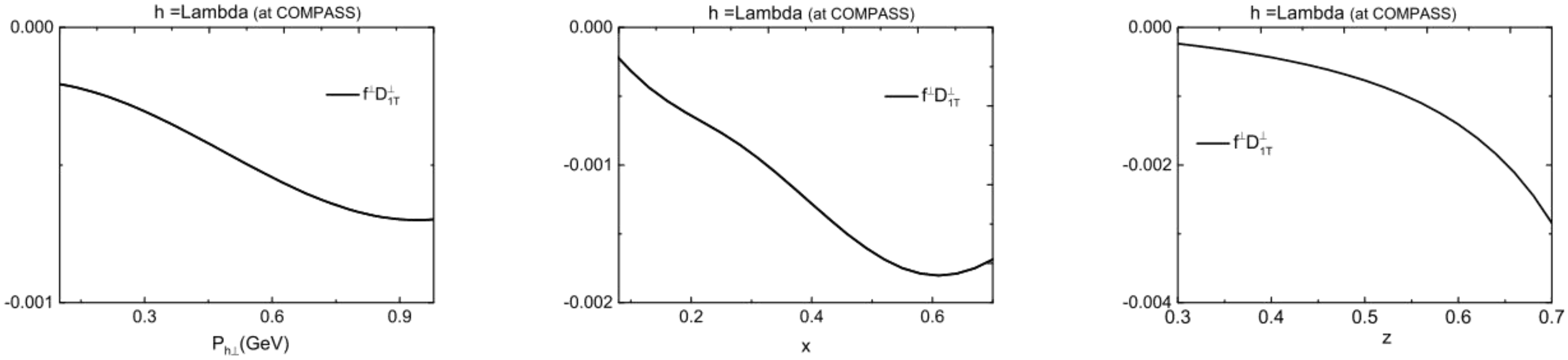


FIG. 10: Predictions on the transverse SSA $A_{UUT}^{\sin\phi_{S_h}}$ for the Λ production in SIDIS at COMPASS, contributed by the $f^{\perp}D_{1T}^{\perp}$ term (The asymmetry only receives contribution from $f^{\perp}D_{1T}^{\perp}$ term in our model).

SUMMARY

- We predict the single-spin asymmetry $A_{UUT}^{\sin\phi_{S_h}}$ of proton and Λ production in SIDIS at JLab 12GeV and COMPASS with a muon beam of 160GeV.
- We consider the contributions from both the twist-3 TMD distribution functions $h, f^{\perp}$ and $g^{\perp}$ and the twist-2 fragmentation functions $H_1, D_{1T}^{\perp}$ and G_{1T}.
- The asymmetry of proton at JLab 12GeV is sizable, around 4 percent, while at COMPASS it is about 1 percent.
- The asymmetry of Λ is much smaller, since only the $f^{\perp}D_{1T}^{\perp}$ can survive in our model calculation.

THANK YOU!