Beam spin asymmetry of neutral pion in semi-inclusive electroproduction

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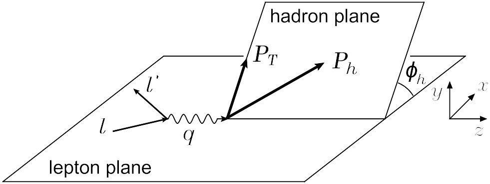
Outline

1. Status of beam single spin asymmetry measurement in SIDIS
2. Interpretation of beam SSA — twist-tree TMD PDFs and FFs
3. Contribution of $g^{\perp}(x, \boldsymbol{k}_T^2)$ to the beam SSA of π^0 production
4. Conclusion

What is Beam single spin asymmetry?

- Semi-inclusive DIS by longitudinally polarized lepton beam off the unpolarized nucleon target:

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

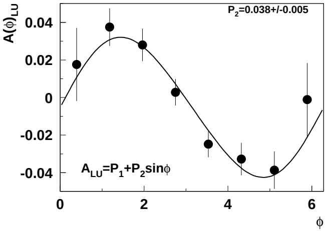


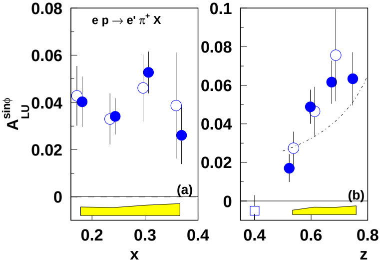
- Beam single spin asymmetry (SSA) of pion in semi-inclusive DIS:

$$A(\phi)_{LU} = \frac{1}{P}\frac{N^+ - N^-}{N^+ + N^-}, \qquad A_{LU}^{\sin\phi} = \frac{2}{PN^{\pm}}\sum_{i=1}^{N^{\pm}} \sin\phi_i$$

Experimental measurements of Beam SSA

- Beam SSA of π^+ by CLAS, PRD69,114002(2004):

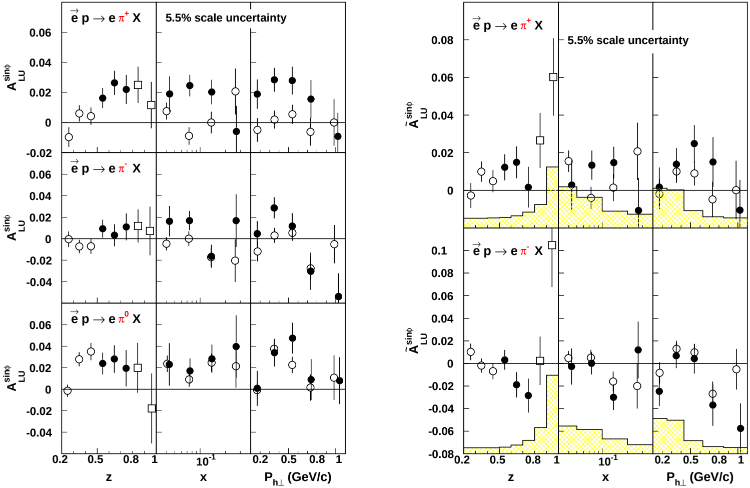




- $E_{beam} = 4.3$ GeV

Experimental measurements of Beam SSA

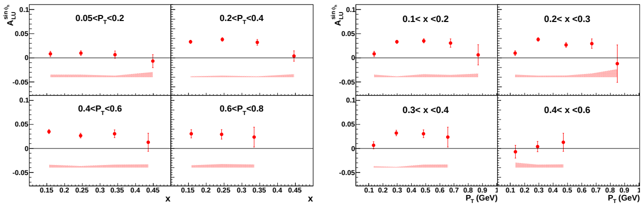
- Beam SSAs of $\pi^{\pm}$, π^0 measured by HERMES, PLB648,164(2007). $A_{LU}^{\sin\phi}$ & $\tilde{A}_{LU}^{\sin\phi}$: VM contribution included &subtracted:



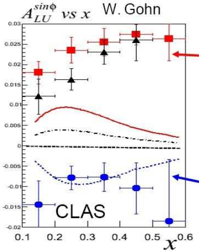
- $E_{beam} = 27.6$ GeV

Experimental measurements of beam SSA

- Precision measurement on beam SSA of π^0 ($E_{beam} = 5.776$ GeV) by CLAS, PLB704,397(2011):



- Most recent measurement for $\pi^{\pm}$ and π^0 at $E_{beam} = 5.5$ GeV :



1. Status of beam single spin asymmetry measurement in SIDIS
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Interpretation of beam SSA

- General form for the cross-section with longitudinally polarized beams (Bacchetta et.al, JHEP0702, 093)

$$\frac{d\sigma}{dx dy\, dz dP_T^2 d\phi_h} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\ F_{LU}^{\sin\phi_h}\Big\},$$

$$A_{LU}^{\sin\phi}(P_T) = \frac{\int dx \int dy \int dz\ \frac{1}{xyQ^2}\frac{y^2}{2(1-\varepsilon)} \times \left(1+\frac{\gamma^2}{2x}\right)\sqrt{2\varepsilon(1-\varepsilon)}\ F_{LU}^{\sin\phi}}{\int dx \int dy \int dz\ \frac{1}{xyQ^2}\frac{y^2}{2(1-\varepsilon)} \times \left(1+\frac{\gamma^2}{2x}\right) F_{UU}}$$

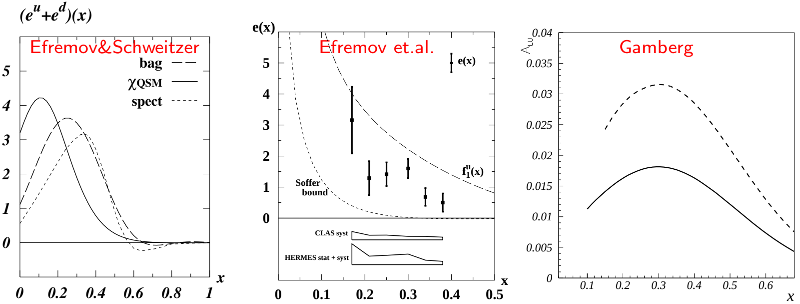
- Cannot be explained by pQCD (Ahmed & Gehrmann, PLB465, 297)
- In the (assumed) TMD factorization (Bacchetta, Mulders, Pijlman PLB595,309; Bacchetta et.al, JHEP0702, 093)

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left[\frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}}\cdot\boldsymbol{k}_{\boldsymbol{T}}}{M}\left(\frac{M_h}{M}h_1^\perp\frac{\tilde{E}}{z} + x\, g^\perp D_1\right) - \frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}}\cdot\boldsymbol{p}_{\boldsymbol{T}}}{M_h}\left(\frac{M_h}{M}f_1\frac{\tilde{G}^\perp}{z} + x\, e H_1^\perp\right)\right],$$

- TMD correlator for unpolarized nucleon at twist three

$$\Phi_U^{\text{twist-3}}(x,k_T) = \frac{M}{2P^+}\left\{ e + f^\perp \frac{\not{k}_T}{M} - g^\perp \gamma_5 \frac{\epsilon_T^{\rho\sigma}\gamma_\rho k_{T\sigma}}{M} + i\,h \frac{[\not{n}_+,\,\not{n}_-]}{2} \right\}$$

- Chiral-odd twist-3 TMD e (Jaffe & Ji, NPB375,527) studied by
  - bag model: Jaffe&Ji,92; Avakian et.al, PRD81,074035
  - spectator model: Jakob & Mulders & Rodriges,NPA626,937; Gamberg & Hwang & Oganessyan PLB584,276.
  - chiral quark soliton model: Efremov & Schweitzer, JHEP0308, 093



twist-3 TMD PDFs in beam SSA—$g^\perp$

$$\Phi_U^{\text{twist-3}}(x,k_T) = \frac{M}{2P^+}\left\{ e + f^\perp \frac{\not{k}_T}{M} - g^\perp \gamma_5 \frac{\epsilon_T^{\rho\sigma}\gamma_\rho k_{T\sigma}}{M} + i\,h \frac{[\not{n}_+,\ \not{n}_-]}{2} \right\}$$

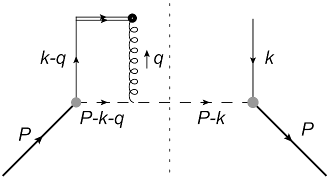
- New source to the beam SSA at twist-3 (Metz & Schlegel, EPJA22, 489; Afanasev & Carlson 03)
- Quark helicity non-flipped (chiral-even effect)
- Including the dependence on the light-cone vector n_- gives rise to $g^\perp$(Bacchetta & Mulders & Pijlman, PLB595,309)

$$\Phi^{[+]}(P,k,n_-) = \cdots + \frac{1}{P\cdot n_-}\gamma_5 \epsilon^{\mu\nu\rho\sigma}\gamma_\mu P_\nu n_{-\rho} k_\sigma B_4$$
$$\sim \frac{M}{2P^+}\, g^\perp \gamma_5 \frac{\epsilon_T^{\rho\sigma}\gamma_\rho k_{T\sigma}}{M}$$

- $g^\perp$: T-odd TMD, require initial/final-state interaction to be nonzero, analog of Sivers function
- $g^\perp$ provides the opportunity to study spin-orbital correlation at twist-3 level

Calculation of $g^{\perp}(x, \boldsymbol{k}_T^2)$

$$-\frac{\epsilon_T^{ij} k_{Tj}}{P^+}\, g^{\perp}(x, \boldsymbol{k}_T^2) = \frac{1}{2}\mathrm{Tr}[\Phi^{[+]}\gamma^i\gamma_5]$$



- Light-cone divergence appears with point-like coupling λ, (Gamberg et.al, PLB639,508):

$$\varepsilon_T^{ij} k_{Tj}\, g^{\perp}(x, \vec{k}_T^{\,2}) = -\frac{e_q e_s \lambda^2}{2(2\pi)^3}\frac{q}{(\vec{k}_T^{\,2}+\tilde{m}^2)}\sum_{\pm}\int\frac{d^4q}{(2\pi)^4}$$

$$\times\ \frac{v\cdot(2P-2k+q)\left[\varepsilon_T^{ij}k_{Tj}(P^+q^- - P^-q^+) + \varepsilon_T^{ij}q_{Tj}(P^-k^+ - P^+k^-)\right]}{[(q\cdot v)\pm i\varepsilon][q^2\mp i\varepsilon][(p-q)^2 - m_q^2 \mp i\varepsilon][(P-k+q)^2 - m_s^2 \mp i\varepsilon]}$$

- Divergence also exist in the quark-target model. Challenge to the TMD factorization at twist-3 level.

Calculation of $g^{\perp}(x, \boldsymbol{k}_T^2)$

- Phenomenological approach to avoid the light-cone divergence — using form factor to replace the point-like coupling(Gamberg et.al, PLB639,508; Kang, Qiu, Zhang, PRD81,114030; ZL, Schmidt PLB712, 451):

$$\lambda \to \lambda(p^2) = \frac{N_X(p^2 - m^2)}{(p^2 - \Lambda^2)^2}$$

- Use a spectator model with axial-diquark, distinguish the axial-diquark by its isospin (Bacchetta, Conti, Radici, PRD78, 074010), $a(ud)$: isoscalar, $a'(uu)$: isovector

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

- Sum for axial-diquark polarizations (Brodsky et.al,NPB593,311):

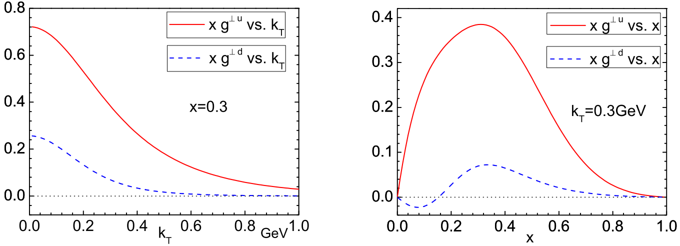
$$d_{\mu\nu}(P-k) = -\, g_{\mu\nu} \, + \, \frac{(P-k)_\mu n_{-\nu} \, + \, (P-k)_\nu n_{-\mu}}{(P-k)\cdot n_-}$$
$$- \, \frac{M_v^2}{\left[(P-k)\cdot n_-\right]^2} \, n_{-\mu} n_{-\nu}.$$

Results of $g^{\perp}(x, \boldsymbol{k}_T^2)$ for valence quarks(Mao, ZL, PRD87,014012)

$$g^{\perp s}(x, \boldsymbol{k}_T^2) = -\frac{N_s^2(1-x)^2}{(32\pi^3)}\frac{e_s e_q}{4\pi}\left[\frac{(1-x)\Lambda_s^2 + (1+x)M_s^2 - (1-x)M^2}{L_s^2(L_s^2+\boldsymbol{k}_T^2)^3}\right],$$

$$g^{\perp v}(x, \boldsymbol{k}_T^2) = \frac{N_v^2(1-x)^2}{(32\pi^3)}\frac{e_v e_q}{4\pi}\left[\frac{(1-x)(xM+m)^2 + (1-x)^2M^2 - M_v^2 + xL_v^2}{(1-x)L_v^2(L_v^2+\boldsymbol{k}_T^2)^3}\right.$$
$$\left. - \frac{x}{(1-x)\boldsymbol{k}_T^2(L_v^2+\boldsymbol{k}_T^2)^2}\ln\left(\frac{L_v^2+\boldsymbol{k}_T^2}{L_v^2}\right)\right].$$

$$g^{\perp u} = c_s^2\, g^{\perp s} + c_a^2\, g^{\perp a}, \qquad g^{\perp d} = c_a^{\prime 2}\, g^{\perp a'},$$



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

Twist-3 TMD fragmentation functions

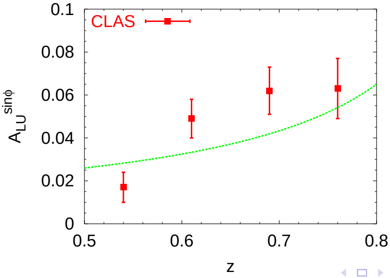
- Quark-gluon-quark fragmentation correlator

$$\tilde{\Delta}_A^{\alpha}(z,k_T) = \frac{M_h}{2z}\left\{\left(\tilde{D}^{\perp} - i\,\tilde{G}^{\perp}\right)\frac{k_{T\rho}}{M_h}\left(g_T^{\alpha\rho} + i\epsilon_T^{\alpha\rho}\gamma_5\right) + \left(\tilde{H} + i\,\tilde{E}\right) i\gamma_T^{\alpha}\right\}$$

- $\tilde{G}^{\perp}$ (T-odd) and $\tilde{E}$ (chiral-odd) still unknown.

$$\frac{\tilde{G}^{\perp}}{z} = \frac{G^{\perp}}{z} - \frac{m}{M_h}H_1^{\perp}, \qquad \frac{\tilde{E}}{z} = \frac{E}{z} - \frac{m}{M_h}D_1$$

- $h_1^{\perp} \bigotimes E$ term (instead of $h_1^{\perp} \bigotimes \tilde{E}$ term) to beam SSA (Yuan PLB589,28):



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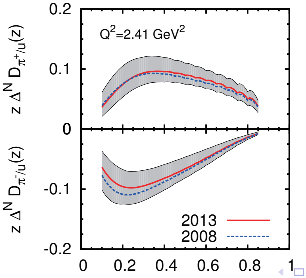
Beam SSA of π^0

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left[\frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}}\cdot\boldsymbol{k}_{\boldsymbol{T}}}{M}\left(\frac{M_h}{M}h_1^{\perp}\frac{\tilde{E}}{z} + x\,g^{\perp}D_1\right)\right.$$
$$\left.-\frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}}\cdot\boldsymbol{p}_{\boldsymbol{T}}}{M_h}\left(\frac{M_h}{M}f_1\frac{\tilde{G^{\perp}}}{z} + x\,eH_1^{\perp}\right)\right],$$

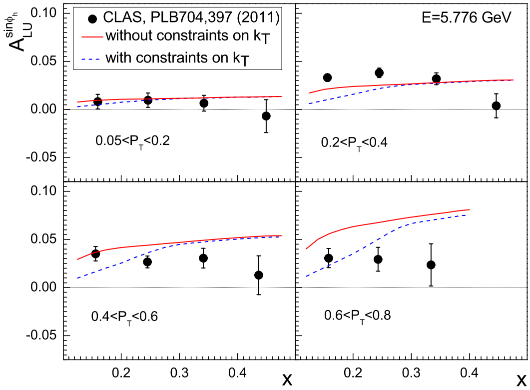
- Using the WW approximation to ignore $f_1\,\frac{\tilde{G^{\perp}}}{z}$ and $h_1^{\perp}\,\frac{\tilde{E}}{z}$ terms
- Isospin symmetry $\Rightarrow$ in π^0 production, $eH_1^{\perp}$ term is negligible:

$$H_1^{\perp\pi^0/q} = (H_1^{\perp fav} + H_1^{\perp unf})/2 \approx 0$$

- Recent extraction of Collins function (Anselmino et.al, arXiv:1303.3822)



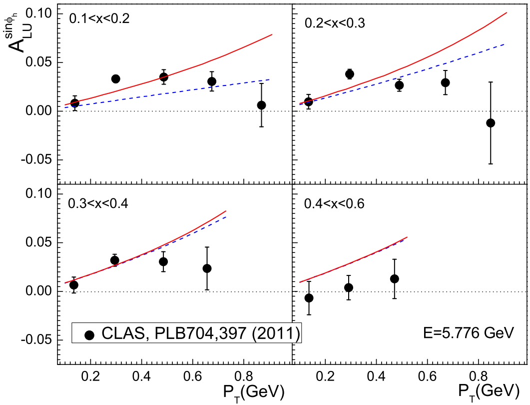
Beam SSA of π^0 vs x at CLAS (5.776GeV)



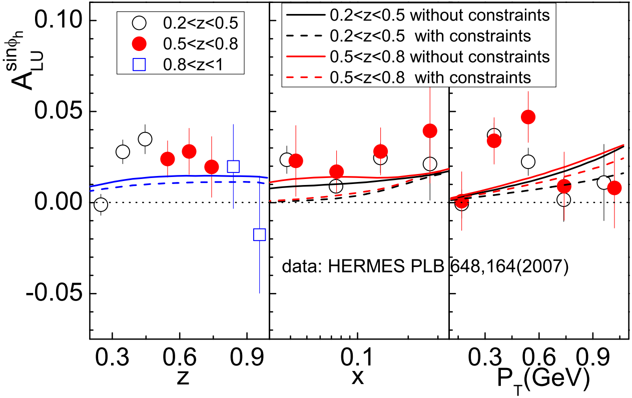
- Constraints for quark transverse momentum k_T (Boglione, Melis, Prokudin, PRD84,034033 (2011)):

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

Beam SSA of π^0 vs P_T at CLAS



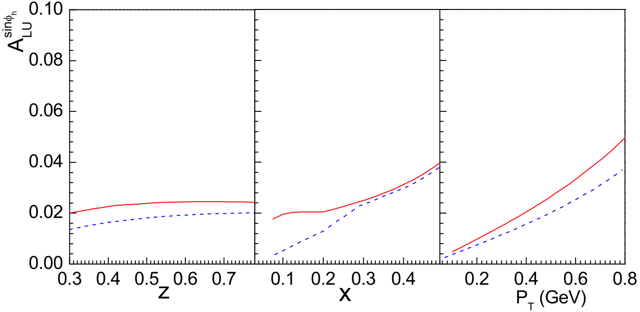
- At small and moderate P_T, $g^{\perp}D_1$ term describes the data
- At larger P_T, there is deviation between calculation and data (contribution of other term? validation of TMD factorization in this region?).



- Kinematics at HERMES:

$$E_{\rm beam} = 27.6\,{\rm GeV},\ \ 0.023 < x < 0.4,$$
$$0 < y < 0.85,\quad 1{\rm GeV}^2 < Q^2 < 15\,{\rm GeV}^2,$$
$$W^2 > 4\,{\rm GeV}^2,\qquad 2\,{\rm GeV} < P_h < 15\,{\rm GeV}.$$

Prediction on beam SSA of π^0 at CLAS 12GeV



- Kinematics at CLAS 12GeV:

$$0.08 < x < 0.6, \quad 0.2 < y < 0.9, \quad 0.3 < z < 0.8,$$
$$Q^2 > 1\,\mathrm{GeV}^2, \quad W^2 > 4\,\mathrm{GeV}^2, \quad 0.05\,\mathrm{GeV} < P_T < 0.8\,\mathrm{GeV}.$$

- dashed curves: with kinematic constraints for k_T
- solid curves: without kinematic constraints for k_T

Conclusion

1. Single spin asymmetries has been proved to be a powerful tool to probe the internal structure of the nucleon
2. Beam spin asymmetries provide the opportunity to access the twist-3 TMD PDFs and FFs
3. As the twist-3 analog of Sivers function, $g^{\perp}(x, \boldsymbol{k}_T^2)$ plays a crucial role for beam SSA of pion production in SIDIS, especially in the case of π^0 production.
4. The measuement of π^0 production could be used to extract $g^{\perp}$, thus could shed light on the spin-orbit correlation at twist-three level