Single- and double-spin asymmetries in hard scattering processes

Daniel A. Pitonyak

Department of Physics
Temple University, Philadelphia, PA

Supported by NSF (PHY-0855501/PHY-1205942)

Thomas Jefferson National Accelerator Facility
Jan. 16, 2013
Biographical Information

- Bachelor of Science, Lebanon Valley College (Annville, PA), May 2008
  Mathematical physics research on quantum information theory
- Doctor of Philosophy, Temple University (Philadelphia, PA), expected May 2013
  Hadronic spin physics research under Andreas Metz
- Attended course on the “3D Partonic Structure of the Nucleon” at the International School of Physics “Enrico Fermi” in Varenna, Italy (July 2011)
- Participant at the Lindau Nobel Laurates Meeting (devoted to physics) in Lindau, Germany (July 2012)
Publications:


Rigorous, field-theoretic proof of the Schaefer-Teryaev sum rule for the Collins function (and the $D_1$ sum rule)

Also calculations of FFs and corresponding sum rules in a quark-pion coupling model
Motivation for studying spin asymmetries

Double-spin asymmetries (DSAs)
  - Collinear twist-3 factorization
  - Previous studies of $A_{LT}$
  - $A_{LT}$ in $p^+ \bar{p} \rightarrow (\gamma, h, jet) X$ : a unique observable

Single-spin asymmetries (SSAs)
  - $A_{UT}$ in lepton-nucleon inclusive DIS
    (and the “sign mismatch” between $p^+ p \rightarrow h X$ and Sivers effect in SIDIS)
  - Possible resolutions to the “sign mismatch” crisis
    (including a new calculation of the fragmentation term in $p^+ p \rightarrow h X$)

Conclusions and outlook
Motivation for studying spin asymmetries

$$A_N = \frac{\sigma(\vec{S}_\perp) - \sigma(-\vec{S}_\perp)}{\sigma(\vec{S}_\perp) + \sigma(-\vec{S}_\perp)}$$

- Extract PDFs and FFs through experiment
- Rich internal (spin) structure of hadrons
  - Study correlations between hadron spin and parton spins and orbital motion
- Explore pQCD (collinear factorization, TMD factorization, resummation, etc.)

What do these observables tell us about perturbative and non-perturbative QCD dynamics?
Double-spin asymmetries

- Collinear twist-3 factorization

  - Large transverse SSAs observed in the mid-1970s in the detection of Lambdas from proton-beryllium collisions (Bunce, et al. (1976))

  - Initially thought to contradict pQCD (Kane, Pumplin, Repko (1978)):
    \[ A_N \sim \alpha_s m_q / P_{h\perp} \]

  - Higher-twist approach to calculating transverse SSAs in \( pp \) collisions introduced in the 1980s (Efremov and Teryaev (1982, 1985))

  - Benchmark calculations performed starting in the early 1990s (Qiu and Sterman (1992, 1999); Kouvaris, et al. (2006); Koike and Tomita (2009), etc.)

  - In general, for \( AB \rightarrow CX \) (\( \Lambda_{QCD} \ll Q \)):
    \[
    d\sigma(S_A, S_B, P_{C\perp}) = H \otimes f_{a/A(3)} \otimes f_{b/B(2)} \otimes D_{c/C(2)} \\
    + H' \otimes f_{a/A(2)} \otimes f_{b/B(3)} \otimes D_{c/C(2)} \\
    + H'' \otimes f_{a/A(2)} \otimes f_{b/B(2)} \otimes D_{c/C(3)}
    \]
• Longitudinal-transverse double-spin asymmetry \((p^\uparrow \vec{p} \rightarrow CX)\)

\[
d\sigma(S_\perp, \Lambda, P_{C\perp}) = H \otimes f_{a/A(3)} \otimes f_{b/B(2)} \otimes D_{c/C(2)} + H' \otimes f_{a/A(2)} \otimes f_{b/B(3)} \otimes D_{c/C(2)} + H'' \otimes f_{a/A(2)} \otimes f_{b/B(2)} \otimes D_{c/C(3)}
\]

(see, e.g., Zhou, et al. (2010))
Graph (c) gives a twist-4 contribution

\[ \langle \bar{\psi} \partial_{\perp} \psi \rangle \rightarrow \tilde{g}(x) \left( = g^{(1)}_{1T}(x) \right) \]

\[ \langle \bar{\psi} A_{\perp} \psi \rangle \rightarrow \begin{cases} F_{FT}(x, x_1) \\ G_{FT}(x, x_1) \\ F_{DT}(x, x_1) \\ G_{DT}(x, x_1) \end{cases} \]

Lightcone gauge

\[ T_F \sim G_F \sim F_{FT} \]

\[ \tilde{T}_F \sim \tilde{G}_F \sim G_{FT} \]
• Relations between F-type and D-type functions (see, e.g., Eguchi, et al. (2006))

\[ F_{DT}(x, x_1) = PV \frac{1}{x-x_1} F_{FT}(x, x_1) \]

\[ G_{DT}(x, x_1) = PV \frac{1}{x-x_1} G_{FT}(x, x_1) + \delta(x - x_1) \tilde{g}(x) \]

• \( g_T \) can be related to D-type functions through the EOM (see, e.g., Efremov and Teryaev (1985); Jaffe and Ji (1992)):

\[ x g_T(x) = \int dx_1 [G_{DT}(x, x_1) - F_{DT}(x, x_1)] \]

There are 3 independent collinear twist-3 functions relevant for a transversely polarized nucleon:

\( \tilde{g}, F_{FT}, G_{FT} \) or \( \tilde{g}, F_{DT}, G_{DT} \)
Previous studies of $A_{LT}$

- The analysis of $A_{LT}$ in processes with one large scale could give insight into both the $A_{LL}$ and $A_{UT}$ domains

- $A_{LT}$ in inclusive DIS

$$\frac{l^0 d\sigma}{d^3 l} = -\frac{8\alpha_e^2 x^2 y M}{Q^6} \sum_a e_a^2 \lambda l_T \cdot \vec{S}_T g_T^a(x)$$

- $A_{LT}$ in $W$ boson decay from $pp$ collisions (Metz and Zhou (2011))

$$\frac{l^0 d^3 \sigma}{d^3 l} = \frac{\alpha_e^2}{12 s \sin^4 \vartheta_w} \sum_{a,b} |V_{ab}|^2 \int_{x_b^{\text{min}}}^{1} \frac{dx_b}{x_a x_b} \frac{1}{x_b s + t} \left\{ \ldots + ight.$$  

$$\left. - 2\pi M \lambda_b \epsilon^{ij}_T l_T^n S_{aT}^{ij} \tilde{H}^{ab} \left[ T_F^a(x_a, x_a) - x_a \frac{d}{dx_a} T_F^a(x_a, x_a) \right] + K(\hat{s}) T_F^a(x_a, x_a) \right] g_1^b(x_b)$$  

$$- 2M \lambda_b \tilde{l}_T \cdot \vec{S}_{aT} \tilde{H}^{ab} \left[ \tilde{g}^a(x_a) - x_a \frac{d}{dx_a} \tilde{g}^a(x_a) \right] + K(\hat{s}) \tilde{g}^a(x_a) + 2x_a g_T^a(x_a) \right] g_1^b(x_b)$$  

$$+ \ldots \right\},$$

with  

$$K(\hat{s}) = \frac{2M_W^2(\hat{s} - M_W^2 - \Gamma_W^2)}{(\hat{s} - M_W^2)^2 + M_W^2 \Gamma_W^2}.$$
• $A_{LT}$ in $\vec{l} p^+ \rightarrow jet X$ (Kang, et al. (2011))

$$P_J^0 \frac{d^3 \sigma}{d^3 P_J} = \frac{\alpha_{em}^2}{s} \sum_a \frac{e_a^2}{(s+t)x} \left\{ \ldots + \lambda_1 2M \vec{S}_T \cdot \vec{P}_{JT} \left[ \left( \bar{g}^a(x) - x \frac{d}{dx} \bar{g}^a(x) \right) \frac{\hat{s}}{t\hat{u}} H_{LL} + x g_T^a(x) \frac{2}{\hat{t}} \right] \right\}$$

• $A_{LT}$ in Drell-Yan (Jaffe and Ji (1991, 1992); Tangerman and Mulders (1994))

$$A_{LT} = \frac{\sin 2\theta \cos \phi}{1 + \cos^2 \theta} \frac{1}{Q} \sum_a e_a^2 \left\{ M_B g_1^a(x_A)x_B \left[ g_1^a(x_B) + \bar{g}_1^a(x_B) \right] + M_A x_A \left[ h_L^a(x_A) + \bar{h}_L^a(x_A) \right] h_1^a(x_B) \right\} \sum_a e_a^2 f_1^a(x_A)f_1^a(x_B)$$

None of these processes requires a complete set of collinear twist-3 functions (for a transversely polarized nucleon) for their description.
\( A_{LT} \) in \( p^\uparrow \bar{p} \rightarrow (\gamma, h, jet) X \): a unique observable

- Focus on hadron (and jet) production (Metz, DP, Schaefer, Zhou, PRD 86 (2012))
- Photon production studied previously (Liang, Metz, DP, Schaefer, Song, Zhou, PLB 712 (2012))
• Example: $qg \rightarrow qg$ channel

(Note that h.c. diagrams have not been shown)

- The $PV$ piece survives instead of the pole part
• 12 channels, over 200 diagrams

\[
\frac{l^0 d\sigma(\vec{S}_\perp, \Lambda)}{d^3 l'} = -\frac{2\alpha_s^2 M}{S} \vec{l} \cdot \vec{S}_\perp \Lambda \sum_i \sum_{a,b,c} \int_{z_{\text{min}}}^{1} \frac{dz}{z^2} D_1^{C/c}(z) \int_{x'_{\text{min}}}^{1} \frac{dx'}{x'} \frac{1}{x'S + T/z} \frac{1}{z \hat{m}_i} g_1^b(x') \frac{1}{x} \\
\times \left\{ \left[ \tilde{g}^a(x) - x \frac{d \tilde{g}^a(x)}{dx} \right] H^i_\perp \right. + \left. \int dx_1 \left[ G^a_{DT}(x, x_1) H^i_{G_{DT}} - F^a_{DT}(x, x_1) H^i_{F_{DT}} \right] \right\}
\]

Involves a complete set of collinear twist-3 functions for a transversely polarized nucleon.
Example: $qg \rightarrow qg$ hard scattering coefficients

$$H_g = \frac{1}{2} \left[ \frac{(s - \hat{u})\hat{u}}{\hat{s}\hat{t}} \right] + \frac{1}{2N_c^2} \left[ \frac{\hat{s} - \hat{u}}{\hat{u}} \right] + \frac{1}{2(N_c^2 - 1)} \left[ \frac{(s - \hat{u})^2}{\hat{t}^2} \right]$$

$$H_{G_{DT}} = \frac{1}{2} \left[ \frac{s(s^2 - \hat{t}\hat{u}) - \hat{u}^2(\hat{t} - \hat{u})}{\hat{t}^2\hat{u}} - \frac{(s^2 + \hat{u}^2)(\hat{t}^2 - 3\hat{s}\hat{u})}{(1 - \xi)\hat{s}\hat{t}^2\hat{u}} + \frac{2\hat{s}(s - \hat{u})}{\xi\hat{t}\hat{u}} \right]$$

$$+ \frac{1}{2N_c^2} \left[ \frac{1}{1 - \xi} - \frac{s^2 + 2\hat{u}^2}{\hat{s}\hat{u}} + \frac{2(s - \hat{u})}{\xi\hat{s}} \right] - \frac{1}{2(N_c^2 - 1)} \left[ \frac{(s - \hat{u})^2}{\hat{t}^2} \left( -\frac{1}{1 - \xi} - \frac{2}{\xi} \right) \right]$$

$$H_{F_{DT}} = \frac{1}{2} \left[ \frac{s(s^2 - \hat{t}\hat{u}) - \hat{u}^2(\hat{t} - \hat{u})}{\hat{t}^2\hat{u}} - \frac{(s^2 + \hat{u}^2)(\hat{t}^2 - 3\hat{s}\hat{u})}{(1 - \xi)\hat{s}\hat{t}^2\hat{u}} \right]$$

$$+ \frac{1}{2N_c^2} \left[ -\frac{1}{1 - \xi} - \frac{s^2 + 2\hat{u}^2}{\hat{s}\hat{u}} \right] - \frac{1}{2(N_c^2 - 1)} \left[ \frac{(s - \hat{u})^2}{(1 - \xi)\hat{t}^2} \right]$$
• Comments on the analytical results
  
  – Analog of the calculation of $A_{UT}$ in the same processes (Qiu and Sterman (1992, 1999); Kouvaris, et al. (2006))

  – Derivative and non-derivative contributions combine in the same compact form found in transverse SSAs in direct photon and inclusive pion production (Qiu and Sterman (1992); Kouvaris, et al. (2006); Koike and Tanaka (2007))

  – Hard parts for $F_{DT}$ and $G_{DT}$ are different ➝ cannot combine into $g_T$ like in, e.g., $A_{LT}$ for inclusive DIS
• Future numerical study
  
  – Must obtain input for the collinear twist-3 functions (relevant for a transversely polarized nucleon) that enter into the result

\[ \tilde{g}(x) \quad \text{Obtain through its relation to } g_{1T}(x, \overline{k^2}) \]

\[ g_T(x) \quad \text{Use info from } A_{LT} \text{ in inclusive DIS and/or Wandzura-Wilczek approximation} \]

\[ F_{FT}(x, x_1) \quad \text{Limited information} \]

\[ G_{FT}(x, x_1) \]

Braun, et al. (2011)

- Use \(qqqg\) Fock states
- F-type functions greatest when \(x \neq x_1\)

Kang and Qiu (2009)

- Use Gaussian form
- F-type functions smallest when \(x \neq x_1\)
• Benefits of a measurement of $A_{LT}$ in pion (photon, jet) production
  
  - Has the ability to probe $\Delta g$ at momentum fractions $x \sim 10^{-3}$ (or even lower)
  
  - First step towards extracting non-diagonal information on 3-parton correlators, i.e., $F_{FT}$ and $G_{FT}$

  Needed to fully determine the evolution of $F_{FT}(x,x) (T_F(x,x))$ that plays a crucial role in transverse SSAs (Kang and Qiu (2009, 2012); Zhou, Yuan, Liang (2009); Schaefer and Zhou (2012); Vogelsang and Yuan (2009); Braun, Manashov, Pirnay (2009); Ma and Wang (2012))

\[
\frac{\partial T_F(x_B, x_B, \mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s}{2\pi} \int_{x_B}^1 \frac{dx}{x} \left[ C_F \left\{ \frac{1 + z^2}{(1 - z)_+} + \frac{3}{2} \delta(1 - z) \right\} T_F(x, x) \\
+ \frac{C_A}{2} \left\{ \frac{1 + z}{1 - z} T_F(xz, x) - \frac{1 + z^2}{1 - z} T_F(x, x) - 2\delta(1 - z)T_F(x, x) + \tilde{T}_F(xz, x) \right\} \right]
\]

- May provide information on whether the collinear twist-3 framework is the appropriate mechanism to describe these (single- and double-spin) asymmetries

  Large discrepancy between numerical estimate and measurement would raise questions about the formalism

• Large $P_{h\perp}$ measurement of $A_{LT}$ in SIDIS should also be possible at JLab12
Single-spin asymmetries

  - Work has been done on both photons coupling to the same quark: Metz, Schlegel, Goeke (2006); Afanasev, Strikman, Weiss (2007); Schlegel (2012)

Afanasev, Strikman, Weiss (2007)

![Graphs showing single-spin asymmetries for proton and neutron](image)
• HERMES Collaboration (2009)
  – Measured SSA for a transversely polarized proton
  – Found proton SSA to be zero within $10^{-3}$

$|\text{Proton SSA}| < 10^{-3}$
JLab Hall A, VERY PRELIM. (2011)  

- Measured SSA for a transversely polarized neutron
- Found neutron SSA to be between 0.006 and 0.07
- First nonzero measurement of a SSA in inclusive DIS

**Neutron SSA \( \sim +10^{-2} \)**
We focus on the contribution from the two photons coupling to different quarks.

\[ k^0 \frac{d\sigma_{pol}^N}{d^3 \vec{k}'} = \frac{8\pi\alpha_{em}^2 x y^2 M}{Q^8} \frac{\hat{s}^2 + \hat{t}^2}{\hat{u}^2} \left( 2 + \frac{\hat{u}}{\hat{t}} \right) \varepsilon_{S_{N P k k'}} \sum_q e_q^2 x \tilde{F}_{FT}^{q/N}(x, x) \]

with \( \tilde{F}_{FT}(x, x) = F_{FT}(x, x) - x \frac{d}{dx} F_{FT}(x, x) \)
Involves $F_{FT}$ in a QED process ($q\gamma q$ correlator) relate to $F_{FT}$ in a QCD process ($qgq$ correlator) through a diquark model

\[ F_{FT}^{u/p} = -\frac{\alpha_{em}}{6\pi C_F \alpha_s M} (g T_{F}^{u/p}) \quad F_{FT}^{d/p} = -\frac{2\alpha_{em}}{3\pi C_F \alpha_s M} (g T_{F}^{d/p}) \]

\[ F_{FT}^{u/n} = \frac{\alpha_{em}}{3\pi C_F \alpha_s M} (g T_{F}^{d/p}) \quad F_{FT}^{d/n} = -\frac{\alpha_{em}}{6\pi C_F \alpha_s M} (g T_{F}^{u/p}) \]
“Sign mismatch” crisis and possible resolutions

\[ p^+ p \rightarrow h X \]

RHIC, STAR (2012)

\[ gT_F(x, x) = - \int d^2 \vec{k}_T \frac{\vec{k}_T^2}{M} f_{1T}^+ (x, \vec{k}_T^2) \]

“sign mismatch” (Kang, et al. (2011))
• Attempt to simultaneously fit SIDIS and $pp$ data through a node in $x$ or $k_T$ in the Sivers function (Kang and Prokudin (2012))

SIDIS data from HERMES (left) and COMPASS (right)

Proton-proton data from STAR at $y = 3.3$ (left) and $y = 3.7$ (right)

Proton-proton data from BRAHMS for $\pi^+$ (left) and $\pi^-$ (right)
- Involves $F_{FT}$ in a QED process ($q\gamma q$ correlator) relate to $F_{FT}$ in a QCD process ($qgq$ correlator) through a diquark model

$$F_{FT}^{u/p} = -\frac{\alpha_{em}}{6\pi C_F \alpha_s M} (gT_F^{u/p})$$  $$F_{FT}^{d/p} = -\frac{2\alpha_{em}}{3\pi C_F \alpha_s M} (gT_F^{d/p})$$

$$F_{FT}^{u/n} = \frac{\alpha_{em}}{3\pi C_F \alpha_s M} (gT_F^{d/p})$$  $$F_{FT}^{d/n} = -\frac{\alpha_{em}}{6\pi C_F \alpha_s M} (gT_F^{u/p})$$

- Use 3 different inputs for $F_{FT}$ in a QCD process ($T_F$ in the relations given above):
  1) Sivers: fit from Anselmino, et al. (2008) of Sivers asymmetry from SIDIS data
  2) KQVY: fit from Kouvaris, et al. (2006) for SSAs in $pp$ collisions
  3) KP: simultaneous fit from Kang and Prokudin (2012) of $pp$ and SIDIS data
Proton SSA:

- Sivers input agrees exactly with the HERMES data.

- KP input appears to become too large at large $x$ (result of the node in $x$ for the up quark Sivers function).

  Node in $x$ in the Sivers function is not preferred, although it cannot be definitively excluded by the current data $\Rightarrow$ need more accurate data at larger $x$.

- KQVY input also appears to become too large at large $x$ and actually diverges as $x \rightarrow 1$. 
○ Neutron SSA:

**Sivers** input agrees reasonably well with the very preliminary JLab data

- Node in $k_T$ for the Sivers function can be ruled out
- Sivers effect intimately connected to the re-scattering of the active parton with the target remnants

**KP** input also agrees reasonable well with the very preliminary data

- Need data at larger $x$ to distinguish between **Sivers** and **KP**

**KQVY** input gives the wrong sign $\rightarrow$ SGP contribution on the side of the transversely polarized incoming proton cannot be the main cause of the large SSAs seen in pion production (i.e., $T_F(x,x)$ term)
$$ \begin{aligned} d\sigma(S_\perp, P_{h\perp}) &= H \otimes f_{a/A}(3) \otimes f_{b/B}(2) \otimes D_{c/C}(2) \\ &+ H' \otimes f_{a/A}(2) \otimes f_{b/B}(3) \otimes D_{c/C}(2) \end{aligned}$$

- Collinear twist-3 fragmentation term:
  - Could at the very least give a contribution comparable to SGP term (Kang, Yuan, Zhou (2010); Kang and Yuan (2011); Anselmino, et al. (2012))
  - Calculation of $qq$ and $qgq$ correlator terms (Metz and DP, arXiv:1212.5037)
Graph (c) gives a twist-4 contribution

\[ \langle \psi \rangle \langle | \bar{\psi} \rangle \rightarrow H(z) \]

(Note: \( |\rangle \langle | = |P_h; X \rangle \langle P_h; X| \))

\[ \langle \partial_\perp \psi \rangle \langle | \bar{\psi} \rangle \rightarrow \hat{H}(z) \]

\[ \left( = H_1^{(1)}(z) \right) \]

Collins function

\[ \langle A_\perp \psi \rangle \langle | \bar{\psi} \rangle \rightarrow \left\{ \begin{array}{l} \hat{H}_{FU}(z, z_1) \\ \hat{H}_{DU}(z, z_1) \end{array} \right\} \]

(Note: \( \hat{H}_{FU} \) and \( \hat{H}_{DU} \) have real and imaginary parts.)
Relations between F-type and D-type function

\[ \hat{H}^{q,\mathcal{S}}_{DU}(z, z_1) = -\frac{1}{z^2} \hat{H}^q(z) \delta \left( \frac{1}{z} - \frac{1}{z_1} \right) + PV \frac{1}{\frac{1}{z} - \frac{1}{z_1}} \hat{H}^{q,\mathcal{S}}_{FU}(z, z_1) \]

\[ \hat{H}^{q,\mathcal{R}}_{DU}(z, z_1) = PV \frac{1}{z - \frac{1}{z_1}} \hat{H}^{q,\mathcal{R}}_{FU}(z, z_1) \]

H can be related to the imaginary part of the D-type function through the EOM:

\[ H^q(z) = 2z^3 \int \frac{dz_1}{z_1^2} \hat{H}^{q,\mathcal{S}}_{DU}(z, z_1) \]

There are 2 independent collinear twist-3 functions relevant for the fragmentation of a quark into an unpolarized hadron.

\[ \hat{H}, \hat{H}_{FU} \]

or

\[ \hat{H}, \hat{H}_{DU} \]
For $A_{UT}$ in $p^\uparrow p \to hX$ the fragmentation side receives contributions from both $qq$ and $qgq$ correlators:

- Only $\hat{H}_q^S$ contributes to the graph on the right
- Number of channels reduces due to vanishing traces
- As in $A_{LT}$ for $pp$ collisions, $PV$ part survives the sum over cuts
"Derivative term" has been calculated previously (Kang, Yuan, Zhou (2010))

Derivative and non-derivative piece combine into a "compact" form as on the distribution side

Important to determine the impact of $qgq$ fragmentation correlator terms

Cannot rule out SFPs (Koike and Tomita (2009); Kanazawa and Koike (2010)) or tri-gluon correlators on the distribution side, but they are unlikely to resolve the "sign mismatch" issue
Global analysis involving several reactions will be needed in order to extract the collinear twist-3 distribution and fragmentation functions in this process.

Large $P_{h\perp}$ measurement of Sivers and Collins asymmetries in SIDIS should also be possible at JLab12.

“Sign mismatch” still do not fully understand the mechanism behind the large transverse SSAs seen in pion production from $pp$ collisions.

Fragmentation term? (SFPs? Tri-gluon correlators?)

Completely different mechanism?
Conclusions and outlook

- Double-spin asymmetries

  - $A_{LT}$ could give insight into both the $A_{LL}$ and $A_{UT}$ domains
    - We have calculated the observable in photon, hadron, and jet production from $pp$ collisions within the collinear twist-3 framework

  - Analog of the calculations of $A_{UT}$ for the same processes

  - Access a complete set of collinear twist-3 functions relevant for a transversely polarized nucleon

  - Future numerical study planned to, in particular, determine impact of 3-parton correlators

  - Measurement can give insight on $\Delta g$ at unexplored $x$, the evolution of $F_{FT}(x,x)$ ($T_{F}(x,x)$), and the general collinear twist-3 mechanism

  - Large $P_{h\perp}$ measurement of $A_{LT}$ in SIDIS should also be possible at JLab12
Single-spin asymmetries

- Studied SSA in inclusive DIS for two photons coupling to different quarks
  - *Sivers* input gives good agreement with HERMES and very preliminary JLab data \(\rightarrow\) can rule out node in \(k_T\) and also gives evidence that Sivers effect is due to quark re-scattering
  - *KP* input for proton data seems too large at large \(x\) due to node in \(x\) in up quark Sivers function, but it describes very preliminary neutron data well \(\rightarrow\) need accurate data at larger \(x\) to distinguish from *Sivers*
  - *KQVY* input for proton also seems too large at large \(x\) and gives the wrong sign for the very preliminary neutron data \(\rightarrow\) \(T_F(x,x)\) cannot be dominate term in SSA for pion production from \(pp\) collisions
• “Sign mismatch” between the SSA in $p^+p \rightarrow \pi X$ and the Sivers effect in SIDIS indicates that we still do not understand the main cause of the SSA in inclusive pion production from $pp$ collisions
  - Unlikely to be resolved through nodes in the Sivers function (e.g., global fitting of $pp$, SIDIS data and SSA in inclusive DIS)
  - We have calculated $qq$ and $qgq$ terms from the fragmentation side
  - SFPs and/or tri-gluon correlators could also be important but are unlikely to resolve the issue
    - Large $P_{h\perp}$ measurement of Sivers and Collins asymmetries in SIDIS should also be possible at JLab12

• Necessary to include all contributions in a global analysis involving several processes that will allow us to determine the relevant functions and their impact on the asymmetry
Examples of future projects

- Numerical study of $A_{LT}$ and the fragmentation term to $A_{UT}$ based on the calculations presented in this talk
- Analytical and numerical calculation of the transverse target SSA in pion production from electron-proton scattering (JLab has recent data, also EIC could measure); also jet production up to NLO
- Investigate gluon TMDs in SIDIS with almost back-to-back jets (EIC will provide insight into gluon TMD sector)
- Study of TMD evolution of $g_{IT}$ and the Collins function (in particular the evolution of the first $k_T$ moment of the Collins function can be obtained through a NLO calculation of the $P_T$ weighted Collins effect in SIDIS)