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Single- and double-spin asymmetries in hard scattering processes

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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:

- A. Metz and D. Pitonyak, "Fragmentation contribution to the transverse single-spin asymmetry in proton-proton collisions," arXiv:1212.5037 [hep-ph].
- A. Metz, D. Pitonyak, A. Schaefer and J. Zhou, "Analysis of the double-spin asymmetry A_{LT} in inelastic nucleon-nucleon collisions," Phys. Rev. D **86**, 114020 (2012).
- A. Metz, D. Pitonyak, A. Schaefer, M. Schlegel, W. Vogelsang and J. Zhou, "Single-spin asymmetries in inclusive deep inelastic scattering and multiparton correlations in the nucleon," Phys. Rev. D **86**, 094039 (2012).
- Z.-T. Liang, A. Metz, D. Pitonyak, A. Schaefer, Y.-K. Song and J. Zhou, "Double spin asymmetry A_{LT} in direct photon production," Phys. Lett. B **712**, 235 (2012).
- S. Meissner, A. Metz and D. Pitonyak, "Momentum sum rules for fragmentation functions," Phys. Lett. B **690**, 296 (2010).

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

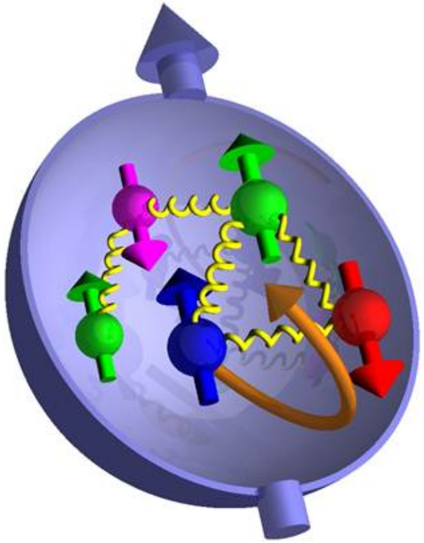
➡ Also calculations of FFs and corresponding sum rules in a quark-pion coupling model

Outline

- Motivation for studying spin asymmetries
- Double-spin asymmetries (DSAs)
  - Collinear twist-3 factorization
  - Previous studies of A_{LT}
  - A_{LT} in $p^\uparrow \vec{p} \to (\gamma, h, jet)\, X$: a unique observable
- Single-spin asymmetries (SSAs)
  - A_{UT} in lepton-nucleon inclusive DIS
    (and the "sign mismatch" between $p^\uparrow p \to h\, X$ and Sivers effect in SIDIS)
  - Possible resolutions to the "sign mismatch" crisis
    (including a new calculation of the fragmentation term in $p^\uparrow p \to h\, X$)
- 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?

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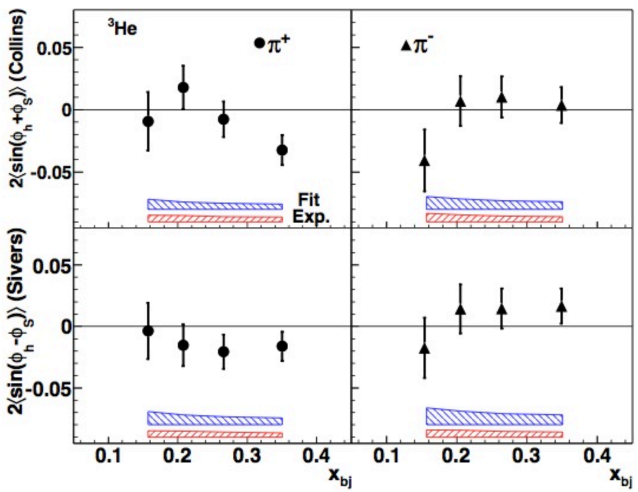
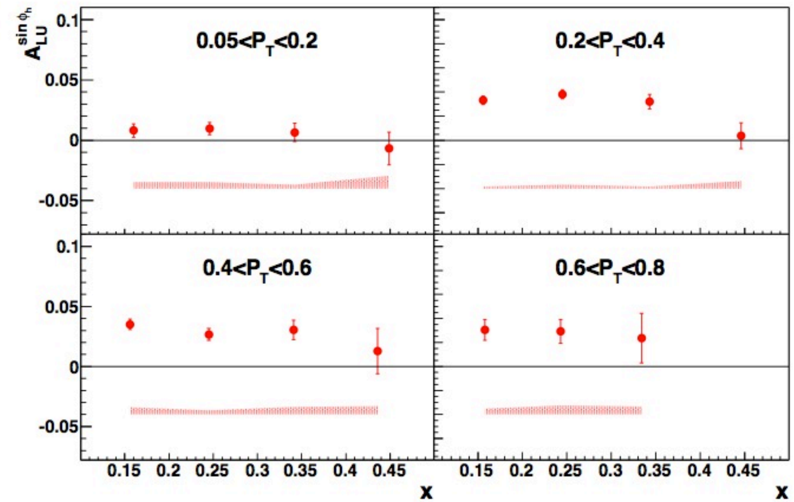
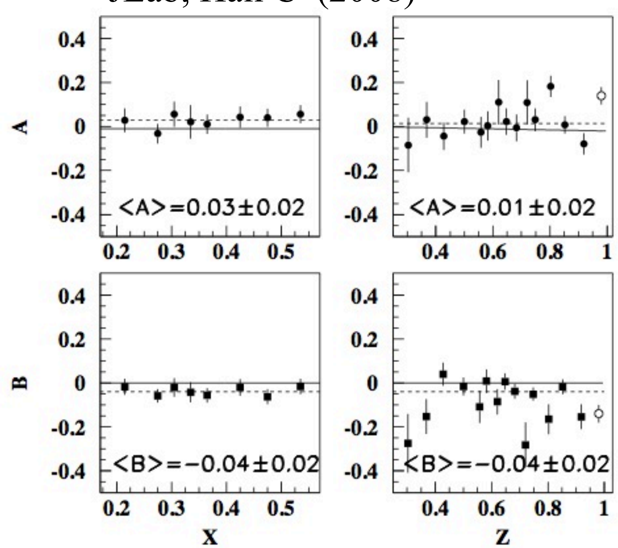


JLab, Hall B (CLAS) (2011)



JLab, Hall C (2008)



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)):

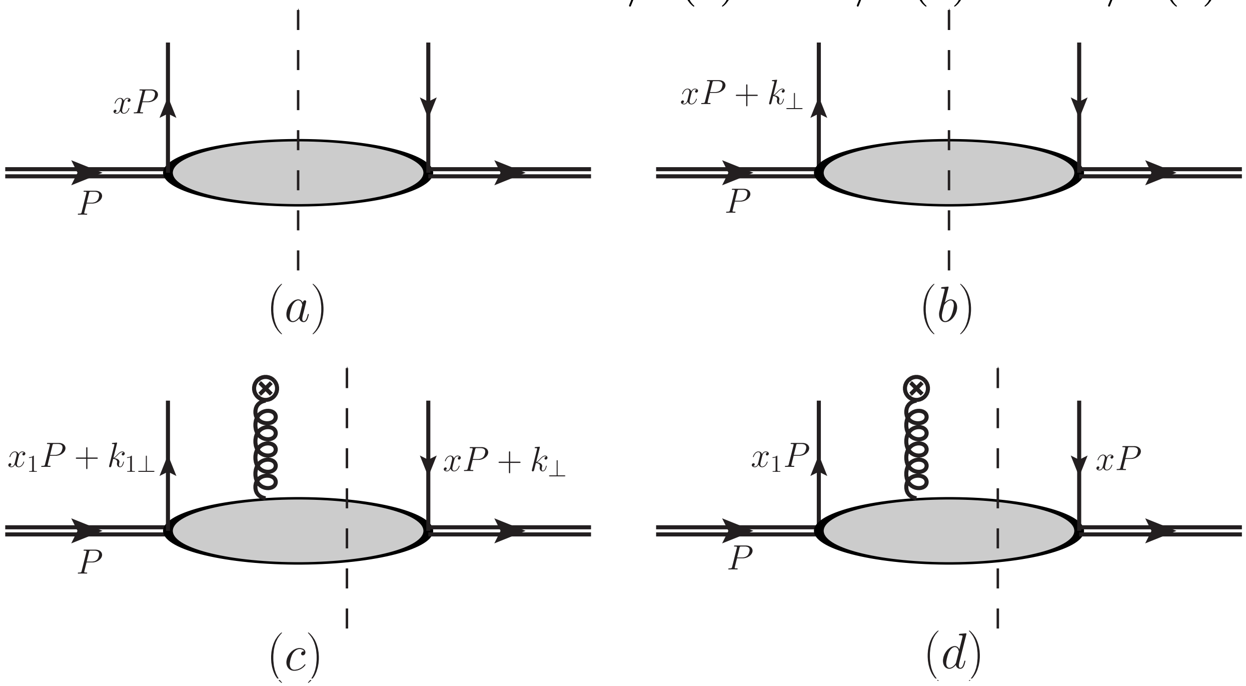
$$A_N \sim \alpha_s m_q / P_{h\perp}$$

- 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 $AB \to C\,X \;\; (\Lambda_{QCD} \ll Q)$:

$$\begin{aligned} d\sigma(S_A, S_B, P_{C\perp}) = \; & H \otimes f_{a/A(3)} \otimes f_{b/B(2)} \otimes D_{c/C(2)} \\ & + H' \otimes f_{a/A(2)} \otimes f_{b/B(3)} \otimes D_{c/C(2)} \\ & + H'' \otimes f_{a/A(2)} \otimes f_{b/B(2)} \otimes D_{c/C(3)} \end{aligned}$$

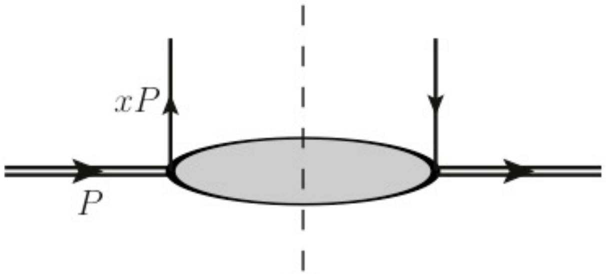
- Longitudinal-transverse double-spin asymmetry ($p^{\uparrow}\,\vec{p} \to C\; X$)

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



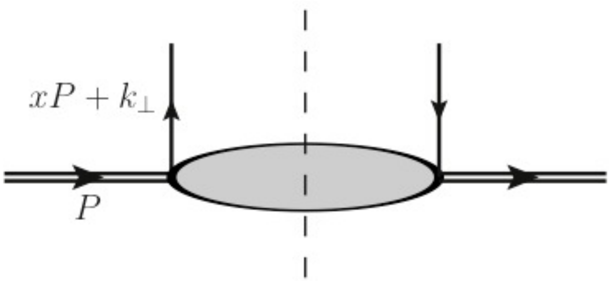
(see, e.g., Zhou, et al. (2010))

Lightcone gauge



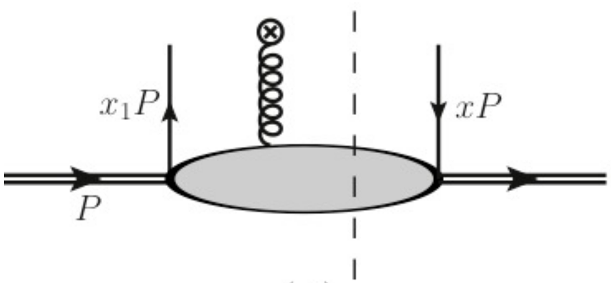
(a)

$$\Longrightarrow \langle \bar{\psi}\psi \rangle \Longrightarrow g_T(x)$$



(b)

$$\Longrightarrow \langle \bar{\psi}\partial_\perp \psi \rangle \Longrightarrow \tilde{g}(x) \left(= g_{1T}^{(1)}(x)\right)$$



(d)

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

Graph (c) gives a twist-4 contribution

$$\boxed{\begin{array}{c} T_F \sim G_F \sim F_{FT} \\ \tilde{T}_F \sim \tilde{G}_F \sim G_{FT} \end{array}}$$

- 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

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

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

$$\begin{aligned} l^0 \frac{d^3\sigma}{d^3 l} = \frac{\alpha_{em}^2}{12\, s \sin^4\vartheta_w} \sum_{a,b} |V_{ab}|^2 \int_{x_b^{min}}^1 \frac{dx_b}{x_a x_b} \frac{1}{x_b s + t} \Big\{ \ldots + \\ &- 2\pi M\, \lambda_b\, \varepsilon_T^{ij} l_T^i S_{aT}^j\, \tilde{H}^{ab} \left[\left(T_F^a(x_a,x_a) - x_a \frac{d}{dx_a} T_F^a(x_a,x_a) \right) + K(\hat{s})\, T_F^a(x_a,x_a) \right] g_1^b(x_b) \\ &- 2M\, \lambda_b\, \vec{l}_T \cdot \vec{S}_{aT}\, \tilde{H}^{ab} \left[\left(\tilde{g}^a(x_a) - x_a \frac{d}{dx_a} \tilde{g}^a(x_a) \right) + K(\hat{s})\, \tilde{g}^a(x_a) + 2x_a\, g_T^a(x_a) \right] g_1^b(x_b) \\ &+ \ldots \Big\}, \end{aligned}$$

$$\text{with} \quad K(\hat{s}) = \frac{2M_W^2(\hat{s} - M_W^2 - \Gamma_W^2)}{(\hat{s} - M_W^2)^2 + M_W^2 \Gamma_W^2}.$$

- A_{LT} in $\vec{l}\, p^{\uparrow} \to jet\, X$ (Kang, et al. (2011))

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

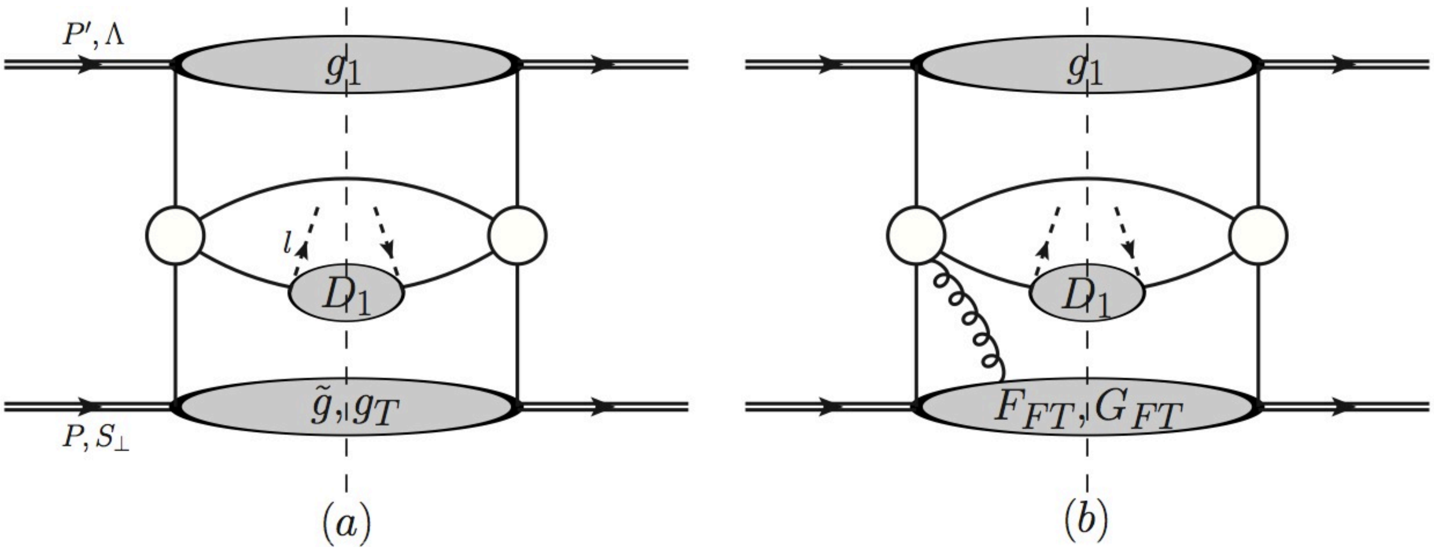
- A_{LT} in Drell-Yan (Jaffe and Ji (1991, 1992); Tangerman and Mulders (1994))

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

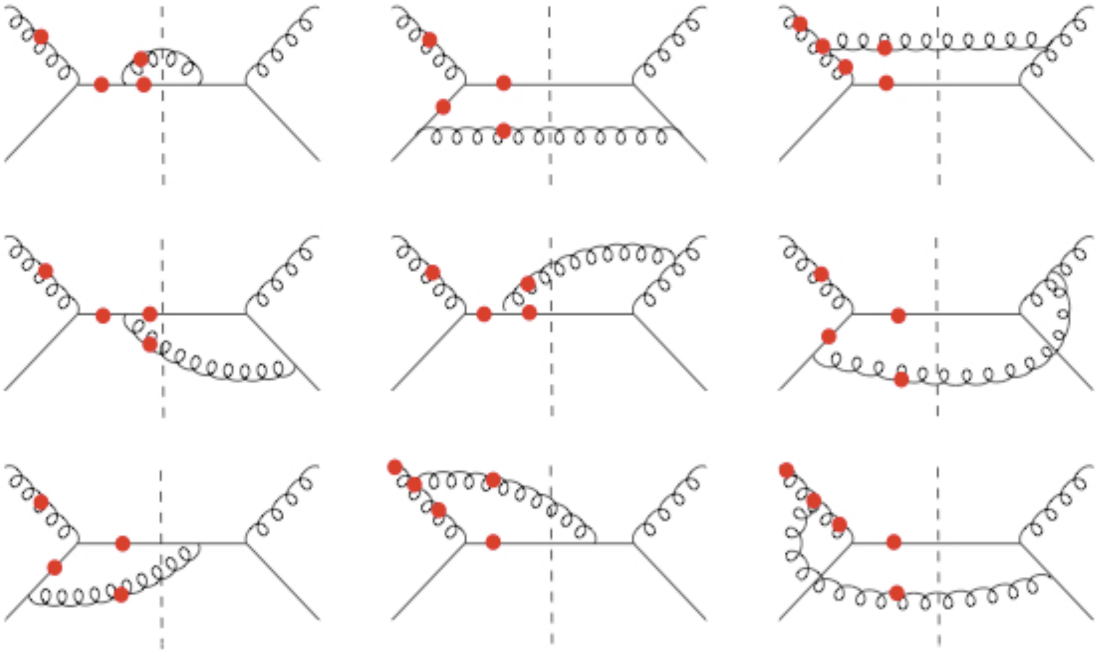
None of these processes requires a complete set of collinear twist-3 functions (for a transversely polarized nucleon) for their description

➢ A_{LT} in $p^{\uparrow}\,\vec{p} \to (\gamma, h, jet)\,X$: 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

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

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

- Example: *qg* → *qg* hard scattering coefficients

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

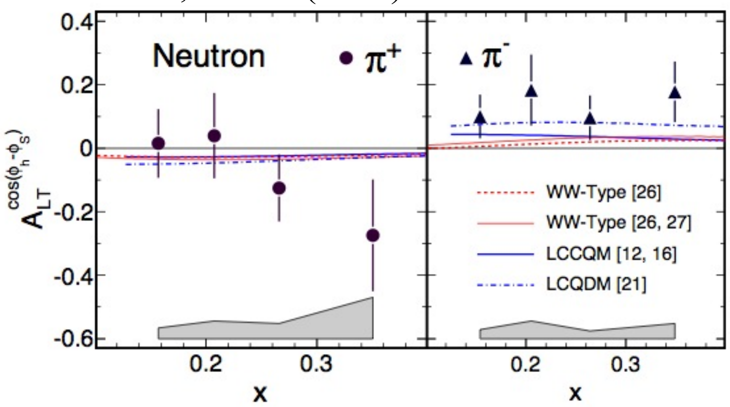
$$H_{G_{DT}} = \frac{1}{2}\left[\frac{\hat{s}(\hat{s}^2-\hat{t}\hat{u})}{\hat{t}^2\hat{u}} - \frac{\hat{u}^2(\hat{t}-\hat{u})}{\hat{s}\hat{t}^2} - \frac{(\hat{s}^2+\hat{u}^2)(\hat{t}^2-3\hat{s}\hat{u})}{(1-\xi)\hat{s}\hat{t}^2\hat{u}} + \frac{2\hat{s}(\hat{s}-\hat{u})}{\xi\hat{t}\hat{u}}\right]$$
$$+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

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

- 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 $\Longrightarrow$ <u>cannot</u> 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

JLab, Hall A (2012)



$\tilde{g}(x)$ → Obtain through its relation to $g_{1T}(x, \vec{k}_\perp^2)$

$g_T(x)$ → Use info from A_{LT} in inclusive DIS and/or Wandzura-Wilczek approximation

$F_{FT}(x, x_1)$
$G_{FT}(x, x_1)$ → Limited information

<u>Braun, et al. (2011)</u>
- Use *qqqg* Fock states
- F-type functions greatest when $x \neq x_1$

<u>Kang and Qiu (2009)</u>
- 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 Δg 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))

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

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

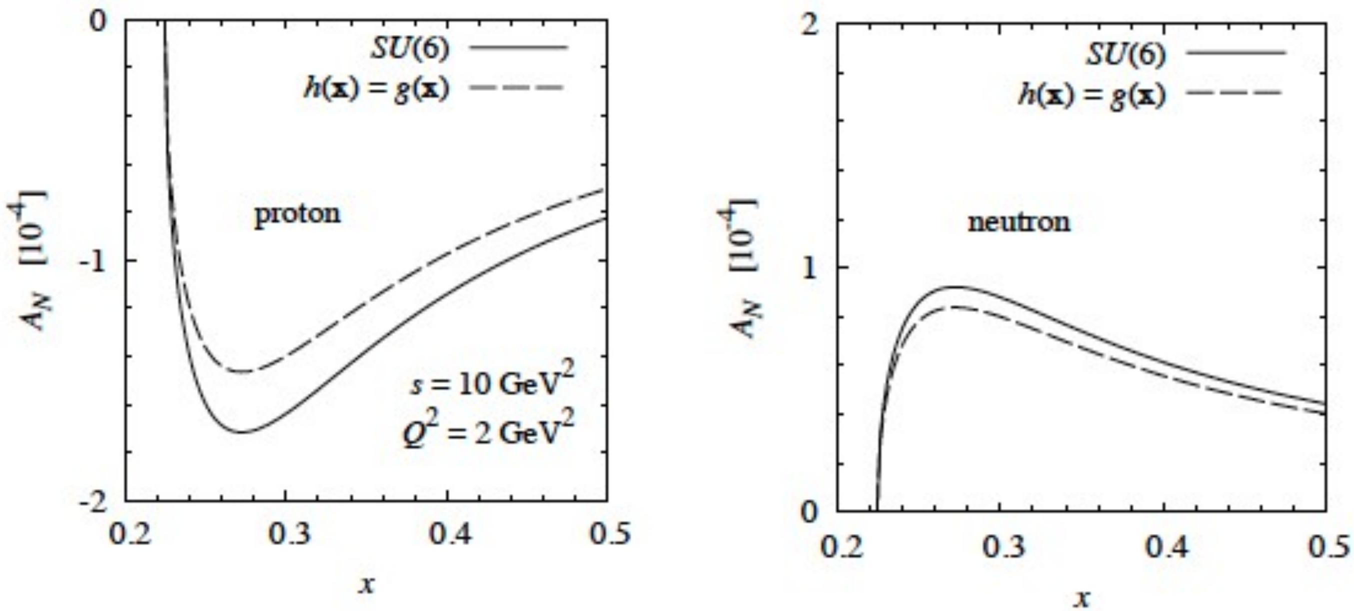
    ➡ Large discrepancy between numerical estimate and measurement would raise questions about the formalism

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

Single-spin asymmetries

- SSA in inclusive DIS (Metz, DP, Schaefer, Schlegel, Vogelsang, Zhou, PRD **86** (2012))
  - Work has been done on both photons coupling to the same quark: Metz, Schlegel, Goeke (2006); Afanasev, Strikman, Weiss (2007); Schlegel (2012)

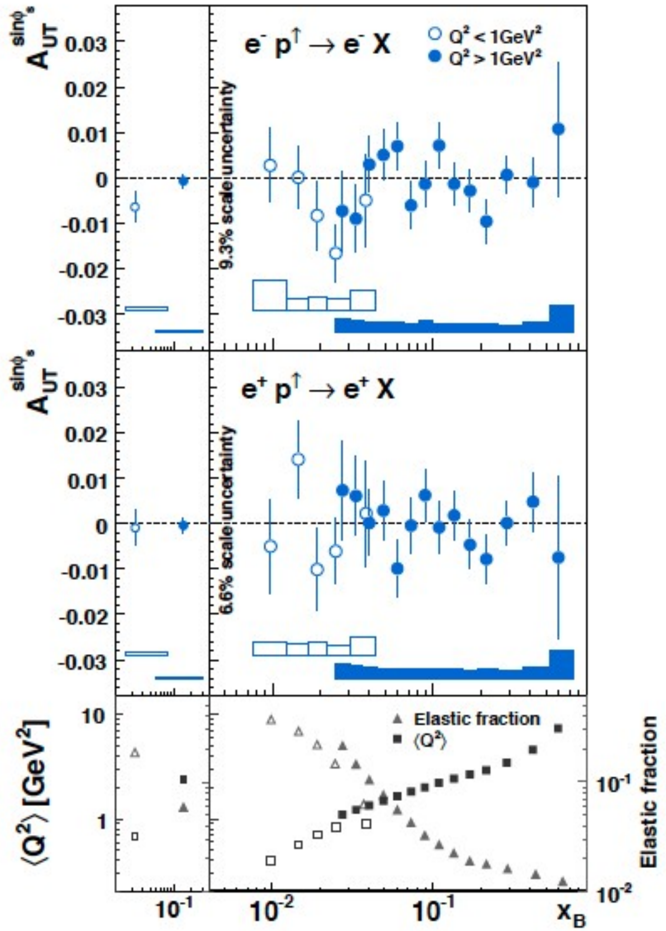
Afanasev, Strikman, Weiss (2007)



- HERMES Collaboration (2009)
  - Measured SSA for a transversely polarized proton
  - Found proton SSA to be zero within 10^{-3}

$$\boxed{|\text{Proton SSA}| < 10^{-3}}$$

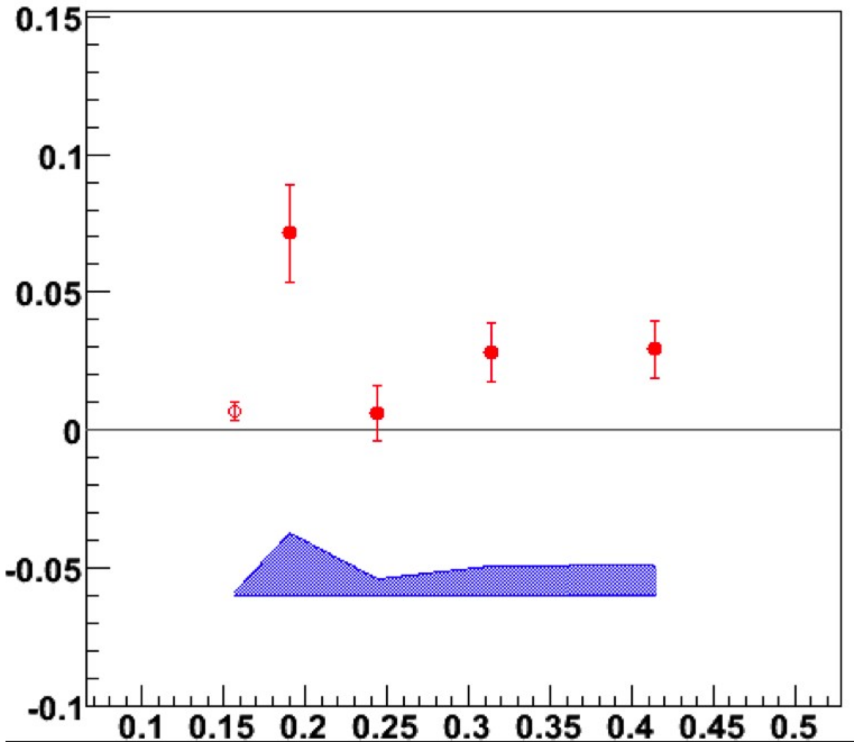
Airapetian, et al. (2009)



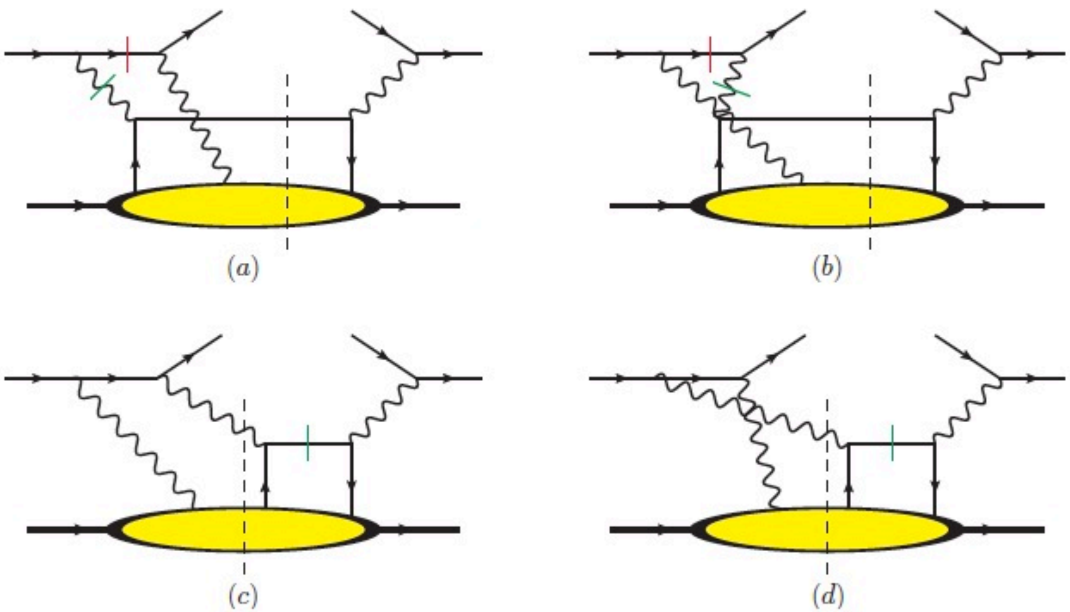
- JLab Hall A, VERY PRELIM. (2011)
  - Measured SSA for a transversely polarized neutron
  - Found neutron SSA to be between 0.006 and 0.07
  - First nonzero measurement of a SSA in inclusive DIS

Neutron SSA ~ $+10^{-2}$

Joseph Katich (2011) (PhD thesis)



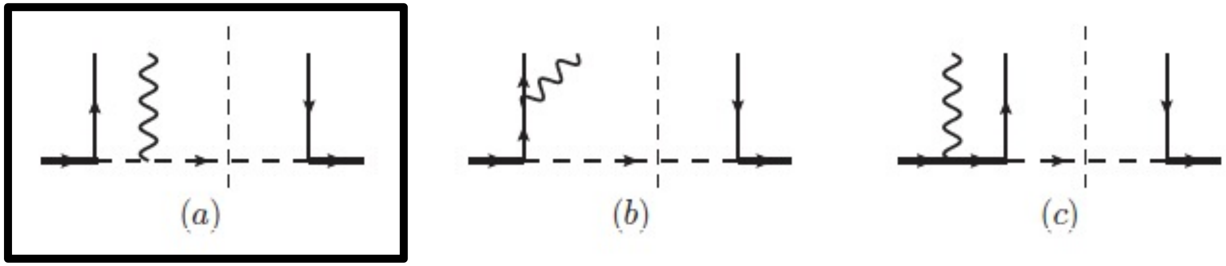
- We focus on the contribution from the two photons coupling to different quarks



$$k'^0 \frac{d\sigma^N_{pol}}{d^3\vec{k}'} = \frac{8\pi\alpha^2_{em}\, xy^2\, M}{Q^8} \frac{\hat{s}^2 + \hat{t}^2}{\hat{u}^2} \left(2 + \frac{\hat{u}}{\hat{t}}\right) \varepsilon^{S_N P k k'} \sum_q e_q^2\, x \tilde{F}_{FT}^{q/N}(x,x)$$

with $\tilde{F}_{FT}(x,x) = F_{FT}(x,x) - x\dfrac{d}{dx}F_{FT}(x,x)$

- 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



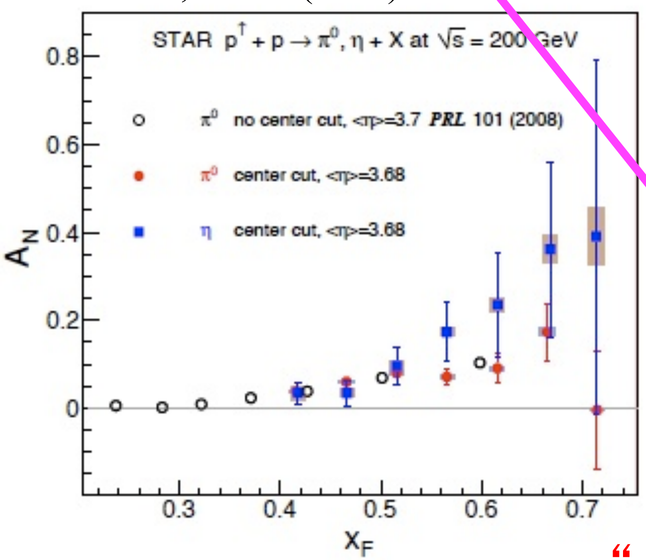
$$F_{FT}^{u/p} = -\frac{\alpha_{em}}{6\pi C_F \alpha_s M}(g\,T_F^{u/p}) \qquad F_{FT}^{d/p} = -\frac{2\alpha_{em}}{3\pi C_F \alpha_s M}(g\,T_F^{d/p})$$

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

➢ "Sign mismatch" crisis and possible resolutions

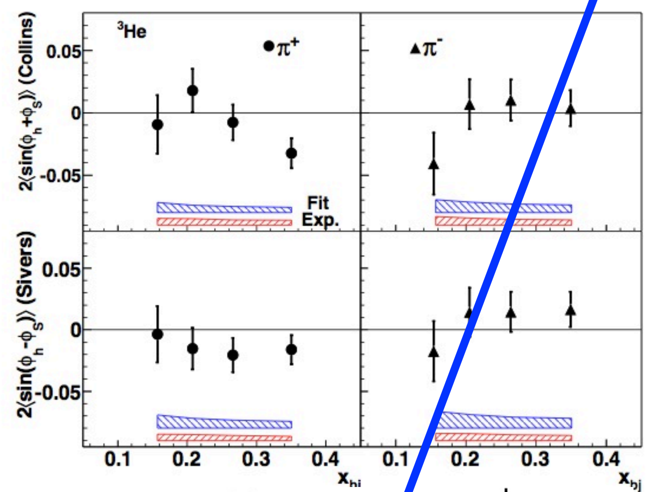
$\boxed{p^{\uparrow} p \to h\, X}$

RHIC, STAR (2012)



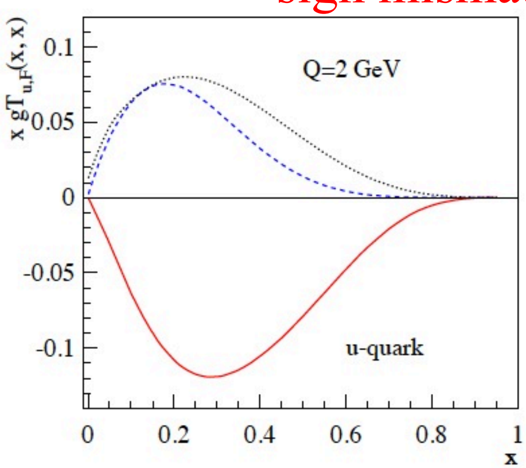
SIDIS

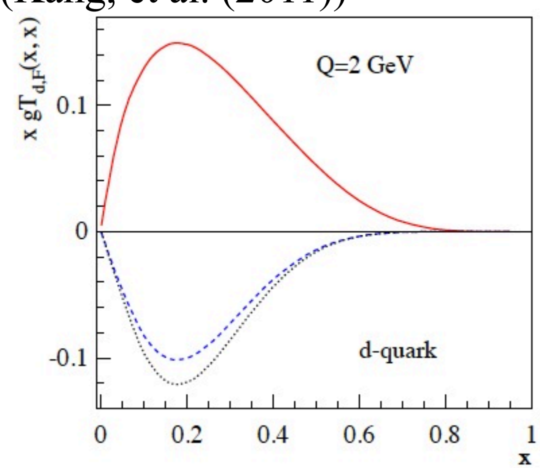
JLab, Hall A (2011)



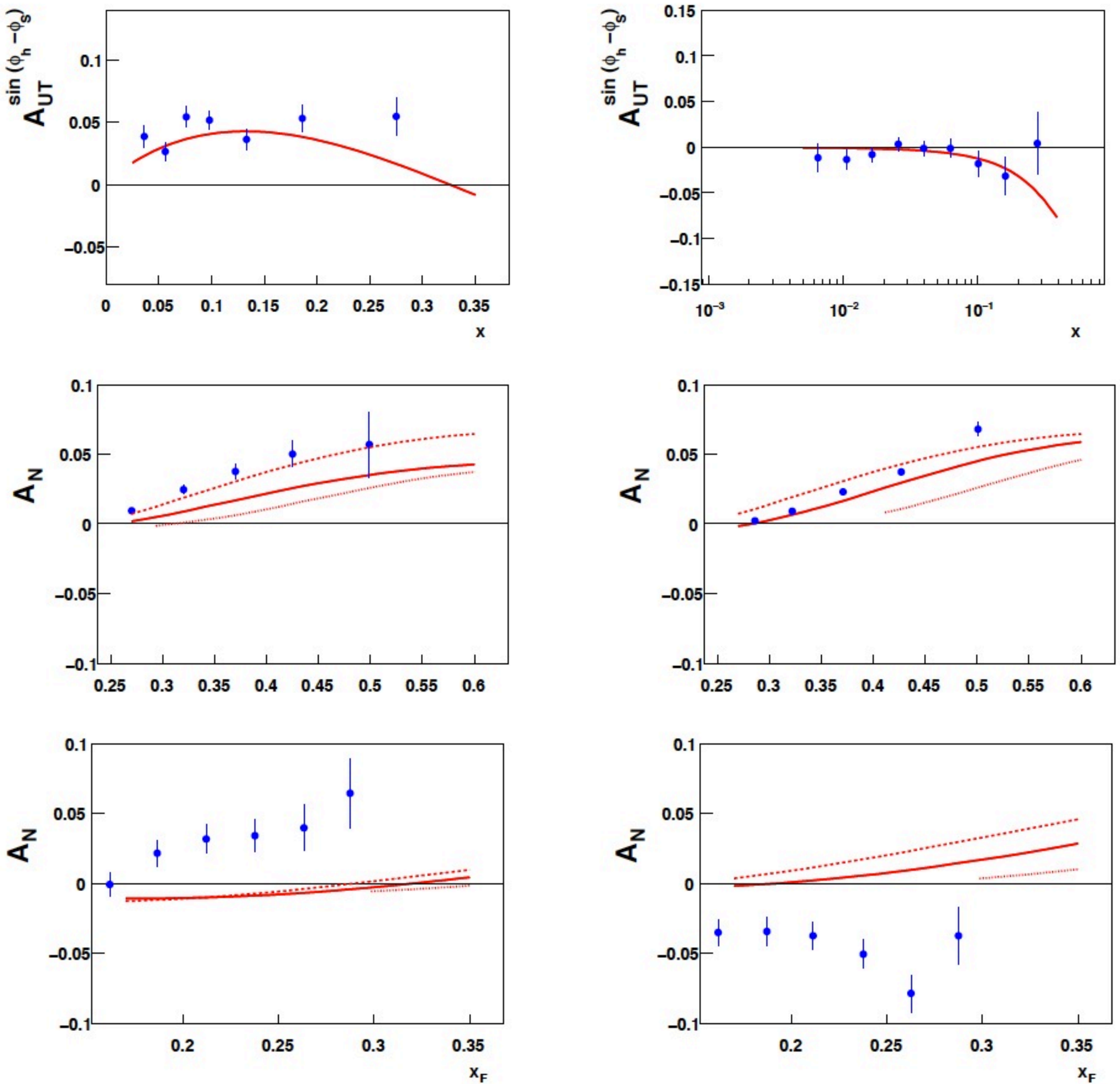
$$g\, T_F(x,x) = -\int d^2\vec{k}_T\, \frac{\vec{k}_T^2}{M}\, f_{1T}^{\perp}(x,\vec{k}_T^2)\Big|_{SIDIS}$$

"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))

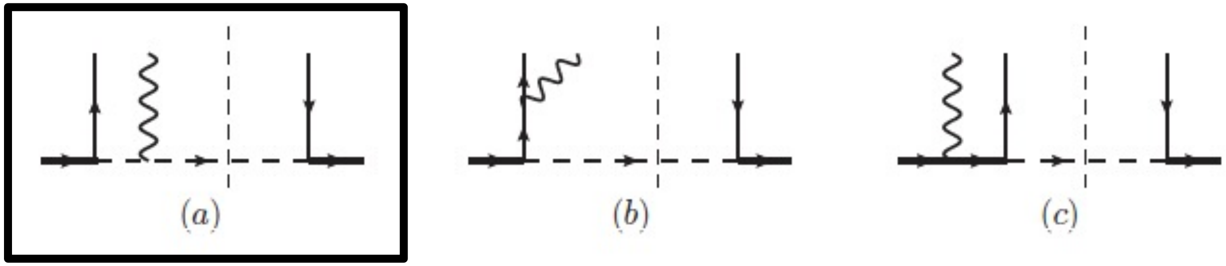


SIDIS data from HERMES (left) and COMPASS (right)

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

Proton-proton data from BRAHMS for π^+ (left) and π^- (right)

- Involves F_{FT} in a QED process ($q\gamma q$ correlator) $\Longrightarrow$ relate to F_{FT} in a QCD process (qgq correlator) through a diquark model

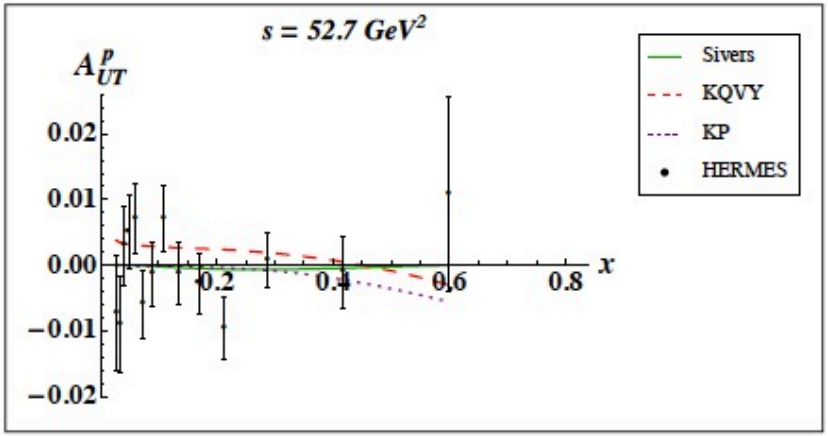


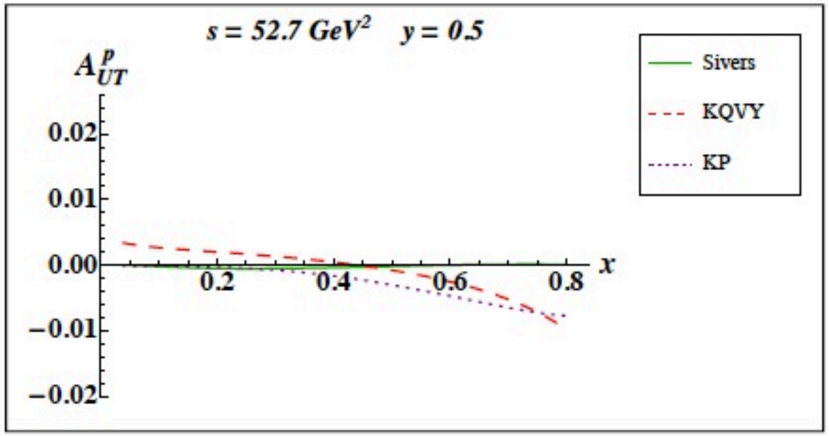
$$F_{FT}^{u/p} = -\frac{\alpha_{em}}{6\pi C_F \alpha_s M}(g\,T_F^{u/p}) \qquad F_{FT}^{d/p} = -\frac{2\alpha_{em}}{3\pi C_F \alpha_s M}(g\,T_F^{d/p})$$

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

- 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:





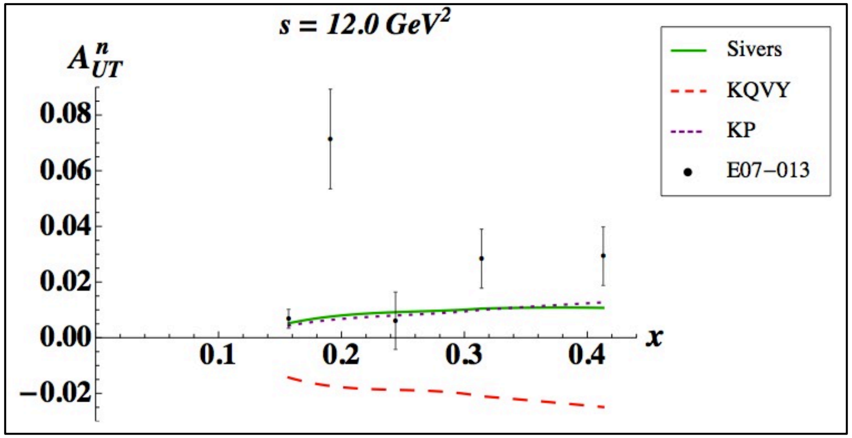
Sivers input agrees exactly with the HERMES data

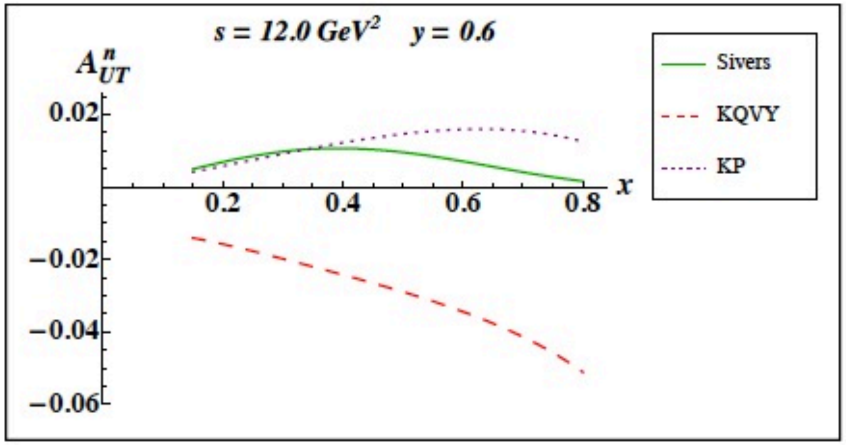
KP input appears to become too large at large x (result of the node in x for the up quark Sivers function)

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

KQVY input also appears to become too large at large x and actually diverges as $x \to 1$

- 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

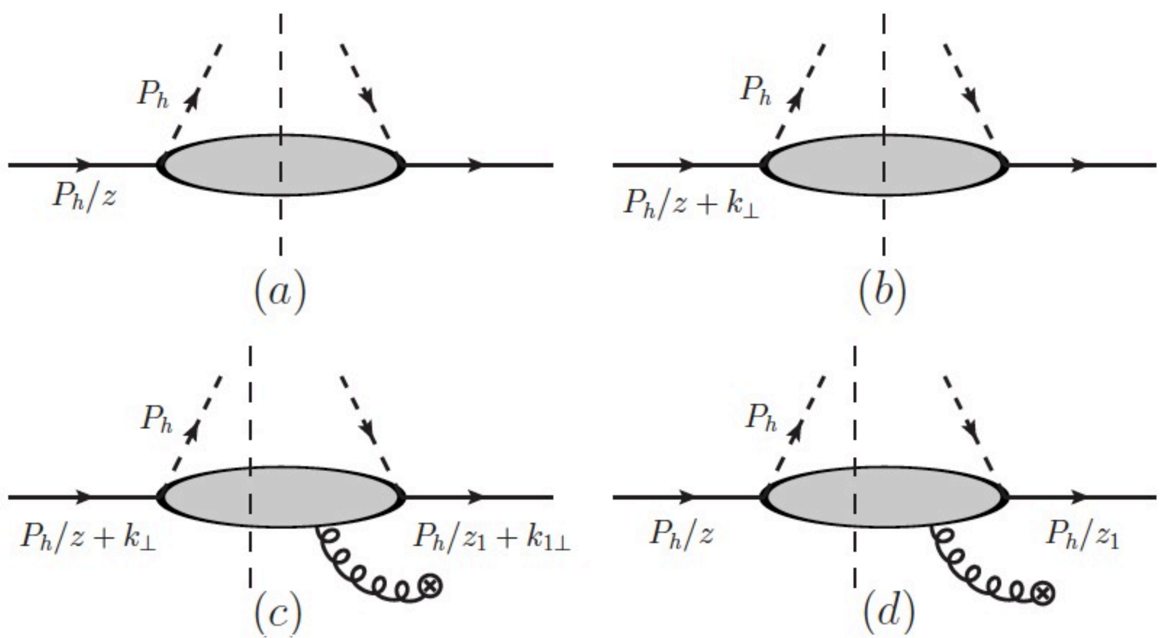
KQVY input gives the <u>wrong sign</u> → SGP contribution on the side of the transversely polarized incoming proton cannot be the main cause of the large SSAs seen in pion production (i.e., $T_F\,(x,x)$ term)

$$d\sigma(S_\perp, P_{h\perp}) = H \otimes f_{a/A(3)} \otimes f_{b/B(2)} \otimes D_{c/C(2)}$$
$$\boxed{+\ H' \otimes f_{a/A(2)} \otimes f_{b/B(3)} \otimes D_{c/C(2)}} \Rightarrow$$

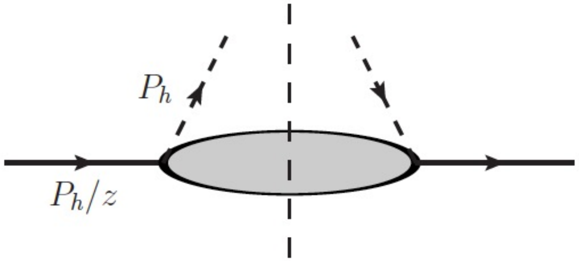
Negligible (Kanazawa and Koike (2000))

$$\boxed{+\ H'' \otimes f_{a/A(2)} \otimes f_{b/B(2)} \otimes D_{c/C(3)}}$$

- 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)



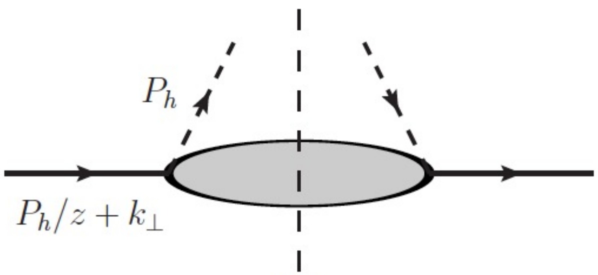
Lightcone gauge



(a)

$$\longrightarrow \langle \psi | \rangle \langle | \bar{\psi} \rangle \longrightarrow H(z)$$

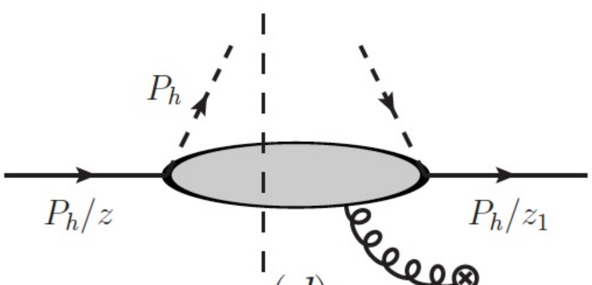
(Note: $|\rangle\langle| = |P_h; X\rangle\langle P_h; X|$)



(b)

$$\longrightarrow \langle \partial_\perp \psi | \rangle \langle | \bar{\psi} \rangle \longrightarrow \hat{H}(z) \left(= H_1^{\perp(1)}(z) \right)$$

Collins function



(d)

$$\longrightarrow \langle A_\perp \psi | \rangle \langle | \bar{\psi} \rangle \longrightarrow \begin{cases} \hat{H}_{FU}(z, z_1) \\ \hat{H}_{DU}(z, z_1) \end{cases}$$

(Note : $\hat{H}_{FU}$ and $\hat{H}_{DU}$ have real and imaginary parts.)

Graph (c) gives a twist-4 contribution

- Relations between F-type and D-type function

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

$$\hat{H}^{q,\Re}_{DU}(z,z_1) = PV\frac{1}{\frac{1}{z}-\frac{1}{z_1}}\hat{H}^{q,\Re}_{FU}(z,z_1)$$

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

$$H^q(z) = 2z^3\int\frac{dz_1}{z_1^2}\hat{H}^{q,\Im}_{DU}(z,z_1)$$

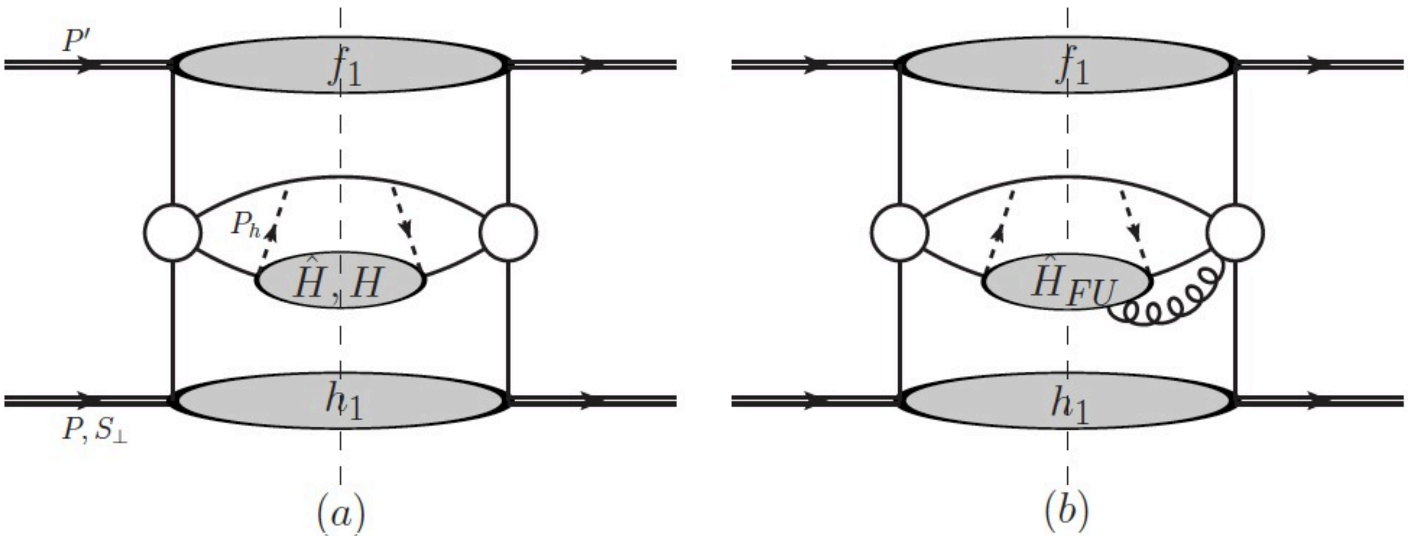
There are 2 independent collinear twist-3 functions relevant for the fragmentation of a quark into an unpolarized hadron

$\hat{H},\ \hat{H}_{FU}$

or

$\hat{H},\ \hat{H}_{DU}$

- For A_{UT} in $p^{\uparrow}p \rightarrow h\,X$ the fragmentation side receives contributions from both *qq* and *qgq* correlators:



  - Only $\hat{H}_{FU}^{\Im}$ 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

$$\frac{P_h^0 d\sigma(\vec{S}_\perp)}{d^3\vec{P}_h} = -\frac{2\alpha_s^2 M_h}{S}\epsilon_{\perp,\alpha\beta}\, S_\perp^\alpha P_{h\perp}^\beta \sum_i \sum_{a,b,c} \int_{z_{min}}^1 \frac{dz}{z^3} \int_{x'_{min}}^1 \frac{dx'}{x'}\, \frac{1}{x}\, \frac{1}{x'S + T/z}\, \frac{1}{-x'\hat{t} - x\hat{u}}\, h_1^a(x)\, f_1^b(x')$$
$$\times \left\{ \left[\hat{H}^c(z) - z\frac{d\hat{H}^c(z)}{dz} \right] S_{\hat{H}}^i + \frac{1}{z} H^c(z)\, S_H^i \; + 2z^2 \int \frac{dz_1}{z_1^2} PV \frac{1}{\frac{1}{z} - \frac{1}{z_1}} \hat{H}_{FU}^{c,\Im}(z, z_1)\, \frac{1}{\xi}\, S_{\hat{H}_{FU}}^i \right\}$$

- "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 Δg 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 → 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 → 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 → $T_F\,(x,x)$ cannot be dominate term in SSA for pion production from *pp* collisions

- "Sign mismatch" between the SSA in $p^{\uparrow}p \to \pi\, X$ 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_{1T} 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)