The transverse single-spin asymmetry “spin crisis” in proton-proton collisions

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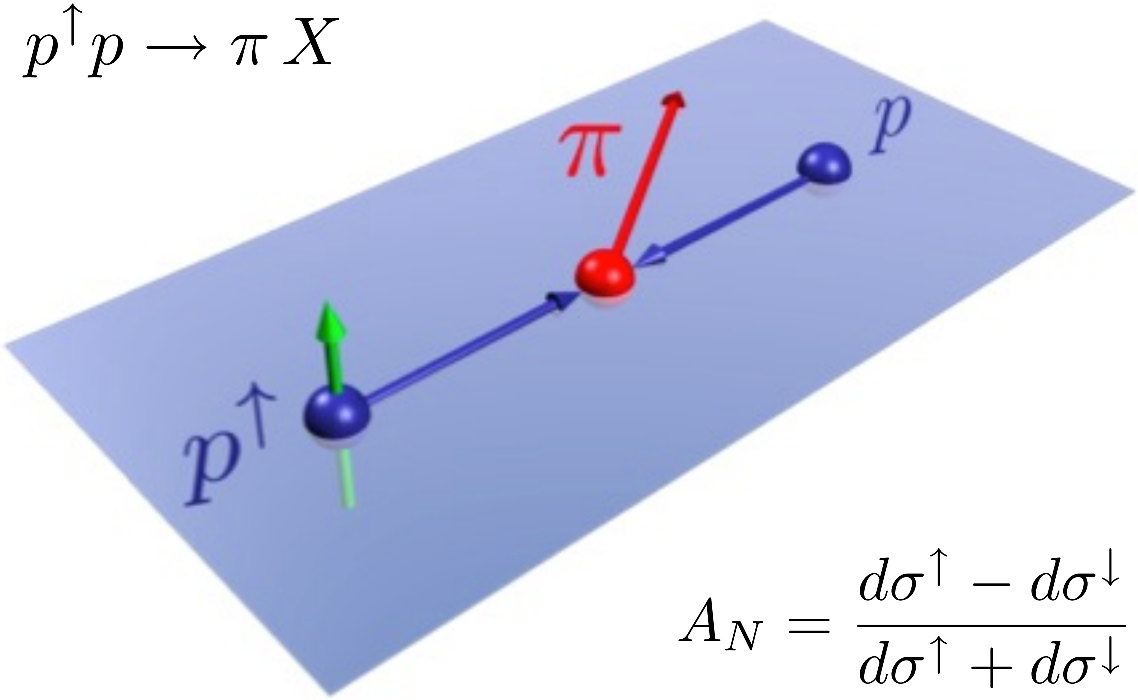
Outline

- Motivation
  - What are transverse single-spin asymmetries (TSSAs)?
  - Experimental data for *pp* collisions: RHIC (also FNAL)
  - Theoretical description: collinear twist-3 formalism
- The crisis
  - “Sign mismatch” between the Qiu-Sterman function and the Sivers function
  - Insight from TSSAs in inclusive DIS
  - Can twist-3 fragmentation resolve the issue?
- Summary and outlook

Motivation

- TSSAs in proton-proton collisions

$$p^{\uparrow}p \to \pi\, X$$



$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}$$

(Figure thanks to K. Kanazawa)

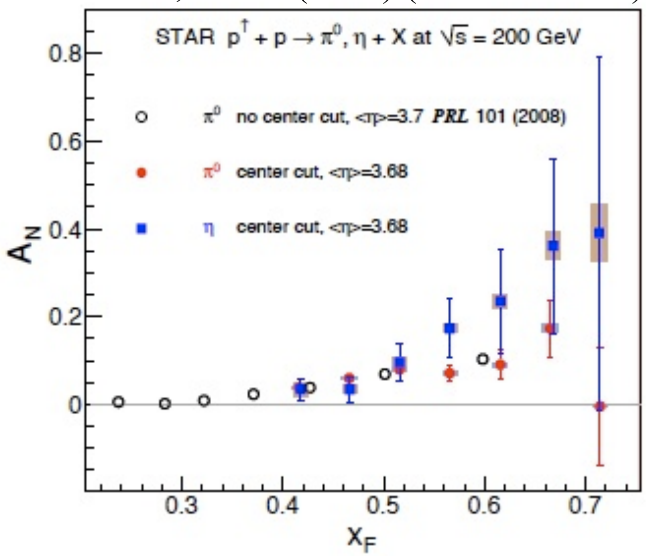
- Large TSSAs observed in the mid-1970s in the detection of hyperons from proton-beryllium collisions (Bunce, et al. (1976))
- Initially thought to contradict pQCD (Kane, Pumplin, Repko (1978)) – within the naïve collinear parton model:

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

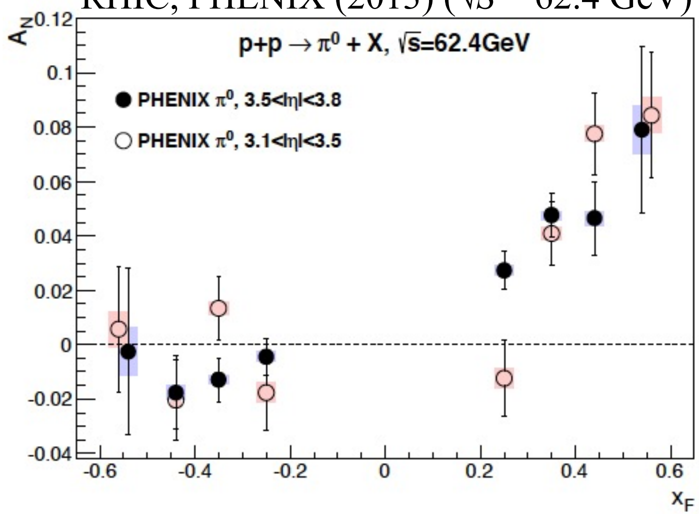
- Higher-twist approach to calculating TSSAs in *pp* collisions introduced in the 1980s (Efremov and Teryaev (1982, 1985))
- Benchmark calculations performed starting in the early 1990s (Qiu and Sterman (1992, 1999); Kouvaris, et al. (2006); Koike and Tomita (2009), etc.)
- RHIC (BRAHMS, STAR, PHENIX) has provided the most recent experimental data on proton-proton TSSAs (also FNAL (E704) in the 1990s)

➢ Experimental data

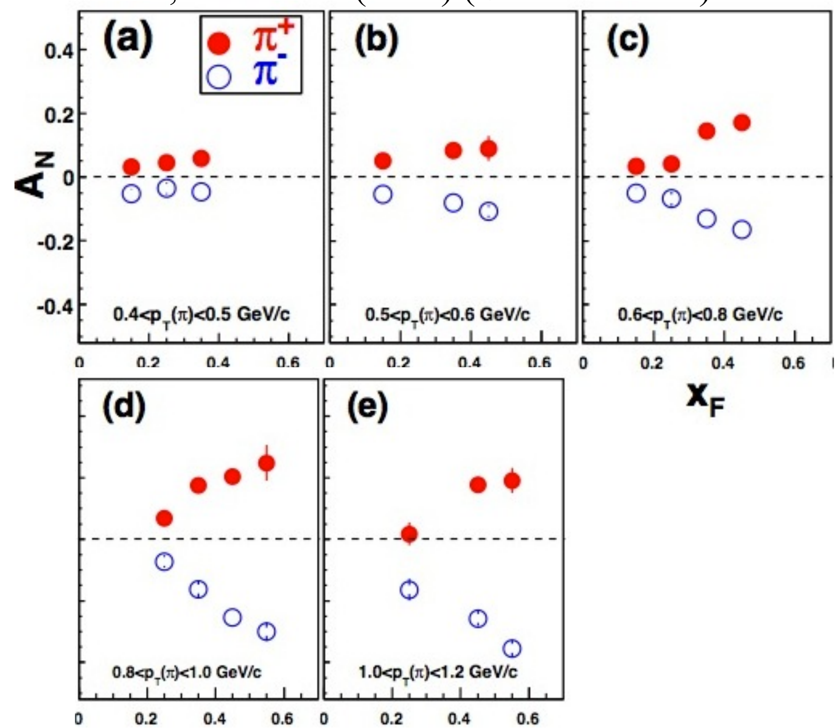
RHIC, STAR (2012) ($\sqrt{S} = 200$ GeV)



RHIC, PHENIX (2013) ($\sqrt{S} = 62.4$ GeV)



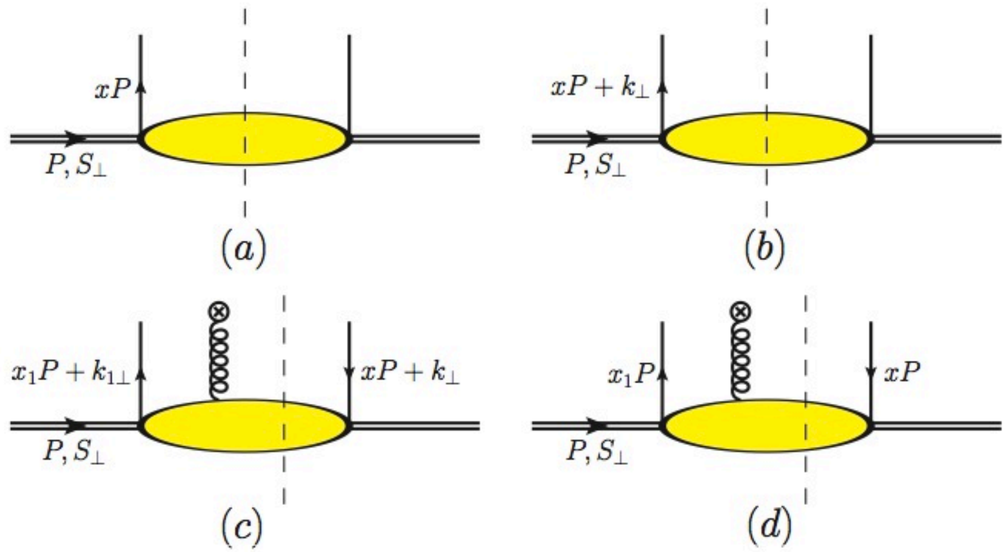
RHIC, BRAHMS (2008) ($\sqrt{S} = 62.4$ GeV)



Also preliminary data from BRAHMS at $\sqrt{S} = 200$ GeV

➢ Theoretical description: collinear twist-3 formalism

Lightcone gauge



(a) ➡ $\Phi^q_{ij}(x; P, S_\perp) = \int \frac{d\xi^-}{2\pi} e^{ixP^+\xi^-} \langle P,\, S_\perp | \bar{\psi}^q_j(0)\psi^q_i(\xi^-)|P,\, S_\perp\rangle \xrightarrow{\gamma^i\gamma_5} g^q_T(x)$

(b) ➡ $\Phi^{q,\mu}_{\partial_\perp,ij}(x; P, S_\perp) = \int \frac{d\xi^-}{2\pi} e^{ixP^+\xi^-} \langle P, S_\perp | \bar{\psi}^q_j(0)\partial^\mu_\perp\psi^q_i(\xi^-)|P, S_\perp\rangle \xrightarrow{\gamma^+\gamma_5} \tilde{g}^q(x)\left(= g^{q(1)}_{1T}(x)\right)$

(d) ➡ $\Phi^{q,\mu}_{A,ij}(x, x_1; P, S_\perp) = \int \frac{d\xi^-}{2\pi} \int \frac{d\zeta^-}{2\pi} e^{ix_1P^+\xi^-} e^{i(x-x_1)P^+\zeta^-}$
$\times \langle P, S_\perp | \bar{\psi}^q_j(0) A^\mu_\perp(\zeta^-)\psi^q_i(\xi^-)|P, S_\perp\rangle \xrightarrow{\gamma^+/\gamma^+\gamma_5} \begin{cases} F^q_{FT}(x, x_1) \\ G^q_{FT}(x, x_1) \\ F^q_{DT}(x, x_1) \\ G^q_{DT}(x, x_1) \end{cases}$

Rewrite in terms of *F* or *D*

Twist-3 collinear PDFs for a transversely polarized *p*

(c) gives a twist-4 contribution

(see, e.g., Zhou, Yuan, Liang (2010))

- Symmetry properties

$$F^q_{FT}(x,\,x_1) = F^q_{FT}(x_1,\,x) \;\text{ and }\; G^q_{FT}(x,\,x_1) = -G^q_{FT}(x_1,\,x)$$
$$F^q_{DT}(x,\,x_1) = -F^q_{DT}(x_1,\,x) \;\text{ and }\; G^q_{DT}(x,\,x_1) = G^q_{DT}(x_1,\,x)$$

- Relations between F-type and D-type functions (see, e.g., Eguchi, et al. (2006))

$$F^q_{DT}(x,x_1) = PV\frac{1}{x-x_1}\,F^q_{FT}(x,x_1)$$

$$G^q_{DT}(x,x_1) = PV\frac{1}{x-x_1}\,G^q_{FT}(x,x_1) + \delta(x-x_1)\,\tilde{g}^q(x)$$

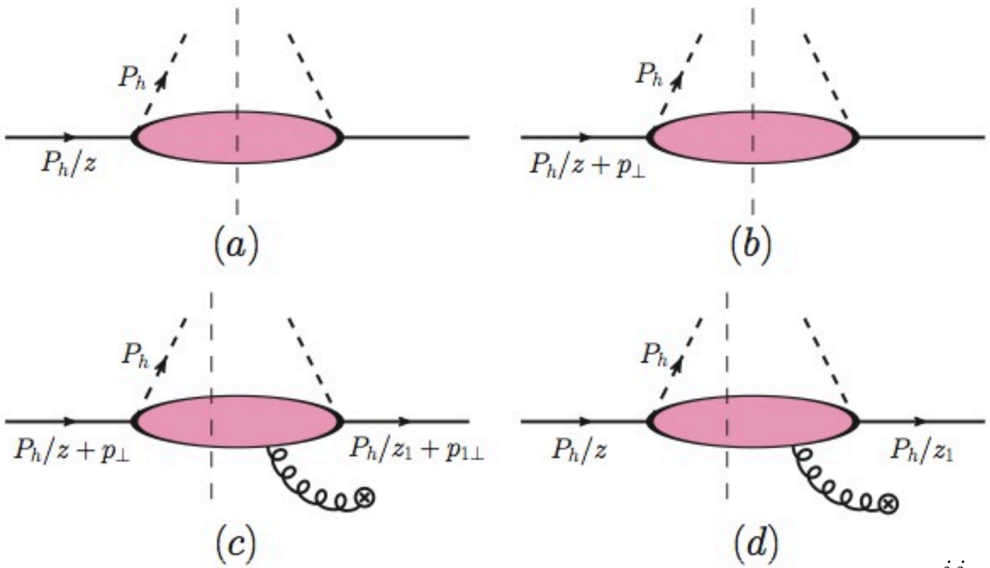
- g_T can be related to D-type functions through the EOM (see, e.g., Efremov and Teryaev (1985); Jaffe and Ji (1992); Boer, Mulders, Teryaev (1998)):

$$x\,g^q_T(x) = \int dx_1\,[G^q_{DT}(x,\,x_1) - F^q_{DT}(x,\,x_1)]$$

There are 3 independent collinear twist-3 functions relevant for a transversely polarized *p*

$$\tilde{g},\ F_{FT},\ G_{FT}$$
$$or$$
$$\tilde{g},\ F_{DT},\ G_{DT}$$

Lightcone gauge



(a) $\longrightarrow$ $\Delta_{ij}^{h/q}(z;P_h) = \sum_X z\int \frac{d\xi^+}{2\pi} e^{i\frac{P_h^-}{z}\xi^+}\langle 0|\psi_i^q(\xi^+)|P_h;X\rangle\langle P_h;X|\bar\psi_j^q(0)|0\rangle \xrightarrow{i\sigma^{ij}\gamma_5/\mathbb{1}} \begin{cases} H^{h/q}(z)\\ E^{h/q}(z)\end{cases}$

(b) $\longrightarrow$ $\Delta_{\partial_\perp,ij}^{h/q,\mu}(z;P_h) = \sum_X z\int \frac{d\xi^+}{2\pi} e^{i\frac{P_h^-}{z}\xi^+}\langle 0|\partial_\perp^\mu\psi_i^q(\xi^+)|P_h;X\rangle\langle P_h;X|\bar\psi_j^q(0)|0\rangle \xrightarrow{i\sigma^{i-}\gamma_5} \hat H^{h/q}(z) = \left(H_1^{\perp\, h/q(1)}(z)\right)$

(d) $\longrightarrow$ $\Delta_{A,ij}^{h/q,\mu}(z,z_1;P_h) = \sum_X \frac{1}{z}\int\frac{d\xi^+}{2\pi}\int\frac{d\zeta^+}{2\pi} e^{i\frac{P_h^-}{z_1}\xi^+} e^{i\left(\frac{1}{z}-\frac{1}{z_1}\right)P_h^-\zeta^+}$
$\times\langle 0|A_\perp^\mu(\zeta^+)\psi_i^q(\xi^+)|P_h;X\rangle\langle P_h;X|\bar\psi_j^q(0)|0\rangle \xrightarrow{i\sigma^{i-}\gamma_5} \begin{cases}\hat H_{FU}^{h/q}(z,z_1)\\ \hat H_{DU}^{h/q}(z,z_1)\end{cases}$

Twist-3 collinear FFs for an unpolarized *h*

Rewrite in terms of *F* or *D*

Note: $\hat H_{FU}$ and $\hat H_{DU}$ have real and imaginary parts.

(c) gives a twist-4 contribution

- Relations between F-type and D-type function

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

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

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

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

$$E^{h/q}(z) = -2z^3\int\frac{dz_1}{z_1^2}\hat{H}_{DU}^{h/q,\Re}(z,z_1)$$

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

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

or

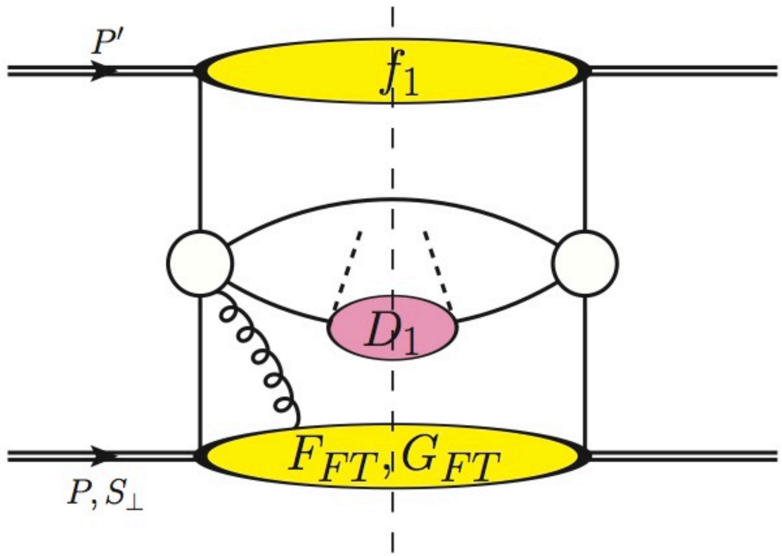
$\hat{H},\ \hat{H}_{DU}$

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

Collinear twist-3 approach

(Efremov and Teryaev (1982, 1985); Qiu and Sterman (1992, 1999))

$P_{hT} >> \Lambda_{QCD}$



- T-odd effect ➡ need to generate an imaginary part ➡ soft-gluon pole (SGP) or soft-fermion pole (SFP) ➡ internal particle goes on-shell
- One can also have SGPs with tri-gluon correlations

- SGP term (Qiu and Sterman (1999), Kouvaris, et al. (2006)):

$$E_\ell \frac{d^3\Delta\sigma(\vec{s}_T)}{d^3\ell} = \frac{\alpha_s^2}{S}\sum_{a,b,c}\int_{z_{\min}}^1 \frac{dz}{z^2} D_{c\to h}(z)\int_{x'_{\min}}^1 \frac{dx'}{x'}\frac{1}{x'S+T/z}\phi_{b/B}(x')$$
$$\times\ \sqrt{4\pi\alpha_s}\left(\frac{\epsilon^{\ell s_T n\bar{n}}}{z\hat{u}}\right)\frac{1}{x}\left[T_{a,F}(x,x) - x\left(\frac{d}{dx}T_{a,F}(x,x)\right)\right]H_{ab\to c}(\hat{s},\hat{t},\hat{u})$$

Qiu-Sterman function

- SFP term (Koike and Tomita (2009)):

$$E_h\frac{d^3\Delta\sigma^{\rm SFP}}{dP_h^3} = \frac{\alpha_s^2}{S}\frac{M_N\pi}{2}\epsilon^{pnP_hS_\perp}\int_{z_{min}}^1\frac{dz}{z^3}\int_{x'_{min}}^1\frac{dx'}{x'}\int\frac{dx}{x}\frac{1}{x'S+T/z}\delta\left(x - \frac{-x'U/z}{x'S+T/z}\right)$$
$$\times\Bigg[\sum_{a,b,c}\left(G_F^a(0,x)+\tilde{G}_F^a(0,x)\right)\Big\{q^b(x')\left(D^c(z)\hat{\sigma}_{ab\to c}+D^{\bar{c}}(z)\hat{\sigma}_{ab\to\bar{c}}\right)$$
$$+q^{\bar{b}}(x')\left(D^c(z)\hat{\sigma}_{a\bar{b}\to c}+D^{\bar{c}}(z)\hat{\sigma}_{a\bar{b}\to\bar{c}}\right)\Big\}$$
$$+\sum_{a,b}\left(G_F^a(0,x)+\tilde{G}_F^a(0,x)\right)\left(q^b(x')D^g(z)\hat{\sigma}_{ab\to g}+q^{\bar{b}}(x')D^g(z)\hat{\sigma}_{a\bar{b}\to g}\right)$$
$$+\sum_{a,c}\left(G_F^a(0,x)+\tilde{G}_F^a(0,x)\right)G(x')\left(D^c(z)\hat{\sigma}_{ag\to c}+D^{\bar{c}}(z)\hat{\sigma}_{ag\to\bar{c}}\right)$$
$$+\sum_{a}\left(G_F^a(0,x)+\tilde{G}_F^a(0,x)\right)G(x')D^g(z)\hat{\sigma}_{ag\to g}\Bigg]$$

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

- Tri-gluon correlators (Beppu, Kanazawa, Koike, Yoshida (2013)):

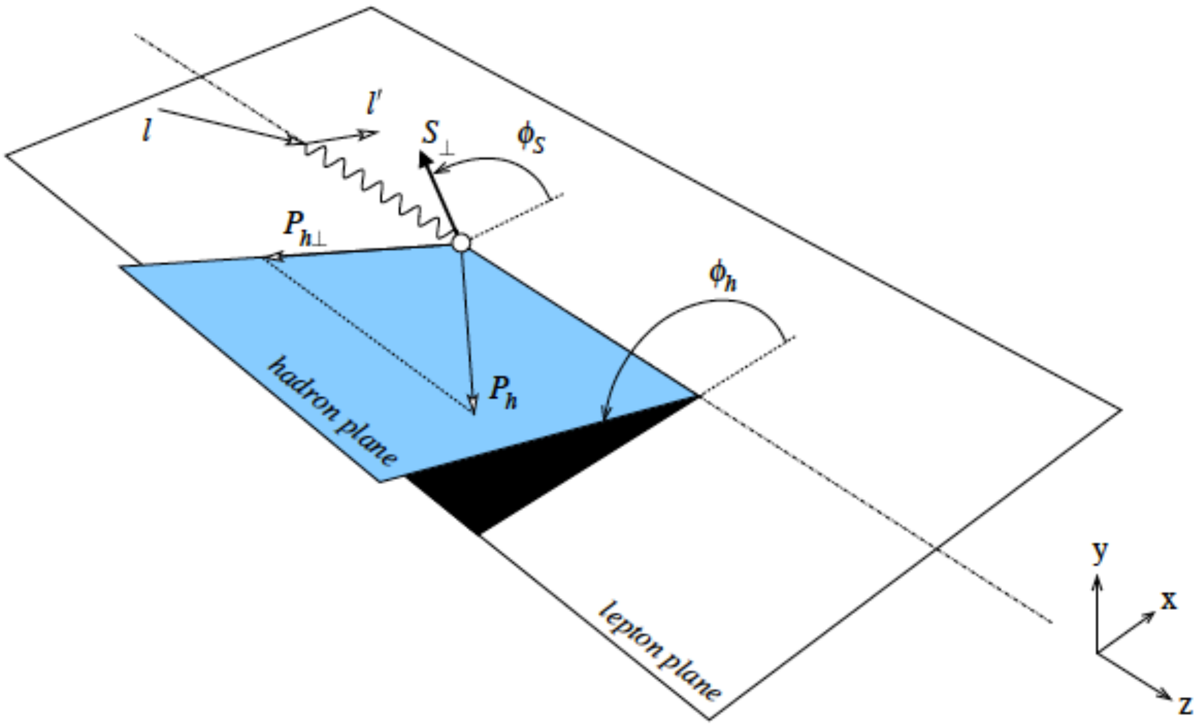
$$E_{P_h}\frac{d^3\Delta\sigma}{d^3P_h} = \frac{2\pi M_N \alpha_s^2}{S}\epsilon^{P_h p n S_\perp}\sum_{i,j}\int\frac{dx}{x}\int\frac{dx'}{x'}f_i(x')\int\frac{dz}{z^2}D_j(z)\delta(\hat{s}+\hat{t}+\hat{u})\frac{1}{z\hat{u}}$$

$$\times\Big[\zeta_{ij}\Big(\frac{d}{dx}O(x)-\frac{2O(x)}{x}\Big)\hat{\sigma}^{(O)}_{gi\to j}+\Big(\frac{d}{dx}N(x)-\frac{2N(x)}{x}\Big)\hat{\sigma}^{(N)}_{gi\to j}\Big]$$

➡ For many years the SGP term involving the Qiu-Sterman function was thought to be the dominant contribution to TSSAs in $p^\uparrow p \to hX$

➢ An aside: TSSAs in SIDIS and the TMD formalism

$$A_{UT}^{\sin(\phi_h - \phi_s)} = \frac{\int d\phi_h d\phi_S \, \sin(\phi_h - \phi_S)\, d\sigma}{\int d\phi_h d\phi_S \, d\sigma}$$



(Figure from Bacchetta, et al. (2007))

Sivers function

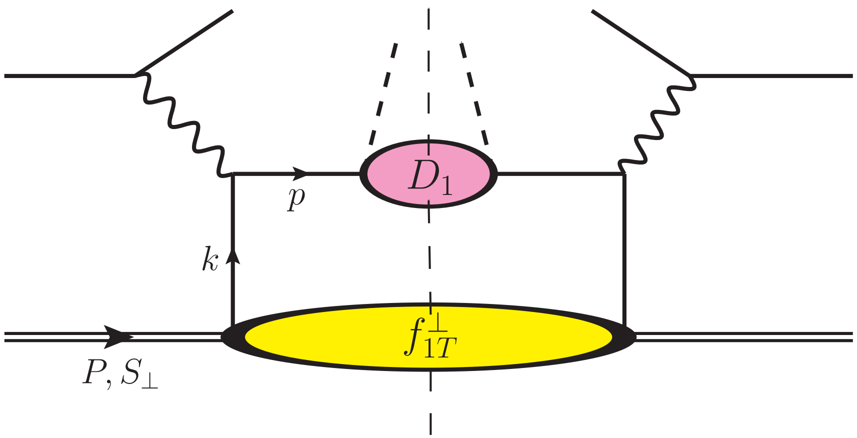
$$A_{UT}^{\sin(\phi_h-\phi_s)} = \frac{w(k_\perp)\, f_{1T}^{\perp,q}(x,\vec{k}_\perp) \otimes D_1^{h/q}(z,\vec{p}_\perp)}{f_1^q(x,\vec{k}_\perp) \otimes D_1^{h/q}(z,\vec{p}_\perp)}$$

Sivers asymmetry

TMD approach

(Sivers (1990, 1991); Collins (1993))

$Q >> P_{hT} \geq \Lambda_{QCD}$

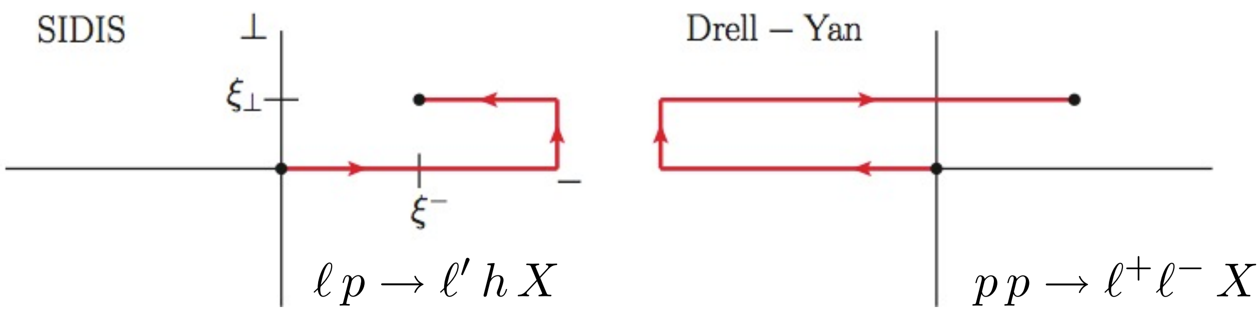


– T-odd effect ➡ imaginary phase is generated by “Wilson line”

➡ multiple re-interactions of the quark with the target remnants

$$\int \frac{d\xi^- d^2\vec{\xi}_\perp}{(2\pi)^3} e^{ik\cdot\xi} \langle P, S_\perp | \bar{\psi}^q(0)\gamma^+ \mathcal{W}_{SIDIS}(0,\xi|n)\psi^q(\xi)|P,S_\perp\rangle\Big|_{\xi^+=0} = -\frac{\epsilon_\perp^{ij} k_\perp^i S_\perp^j}{M} f_{1T}^{\perp q}(x,\vec{k}_\perp^2)$$

W is a product of gauge links $[a\,;b]$: $[a^+, a^-, \vec{a}_\perp; b^+, b^-, \vec{b}_\perp] = \mathcal{P}\exp\left[-ig\int_a^b d\eta\cdot A(\eta)\right]$



$$f_{1T}^\perp(x,\vec{k}_\perp^2)\big|_{SIDIS} = -f_{1T}^\perp(x,\vec{k}_\perp^2)\big|_{DY} \qquad \text{(Collins (2002))}$$

Recall the definition of $F_{FT}(x,x)$:

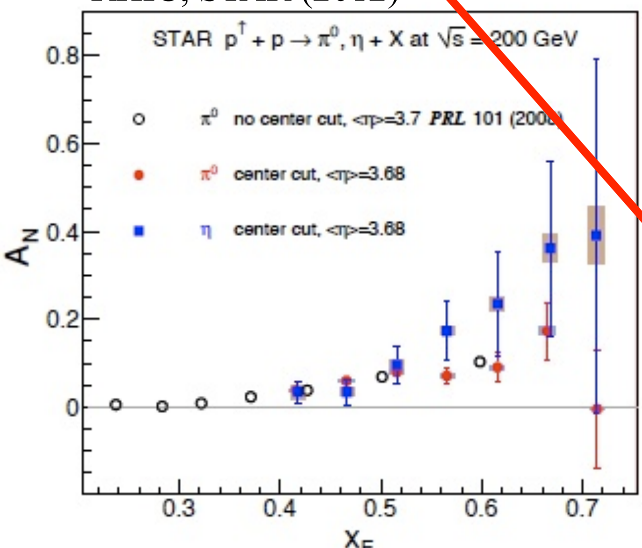
$$\int \frac{d\xi^- d\zeta^-}{2(2\pi)^2} e^{ixP^+\xi^-} \langle P, S_\perp | \bar{\psi}^q(0)\gamma^+ gF^{+i}(\zeta^-)\psi^q(\xi^-)|P,S_\perp\rangle = -M\epsilon_\perp^{ij} S_\perp^j\, F_{FT}^q(x,x)$$

- The TSSA "spin crisis" (aka the "sign mismatch" crisis)

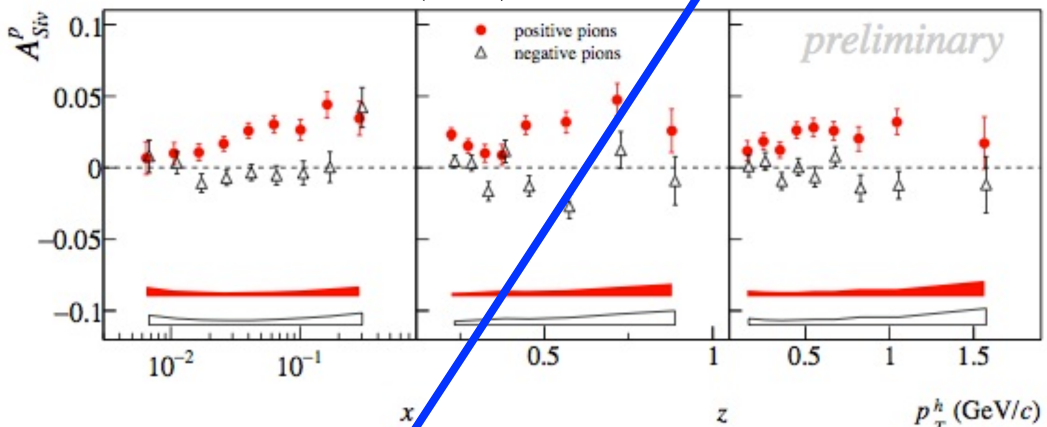
$p^{\uparrow}p \rightarrow h\,X$

$\ell N^{\uparrow} \rightarrow \ell'\,h\,X$

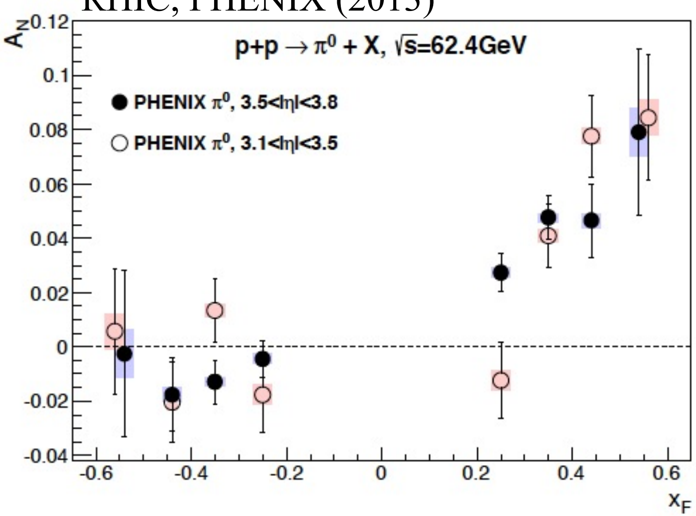
RHIC, STAR (2012)



CERN, COMPASS (2013)

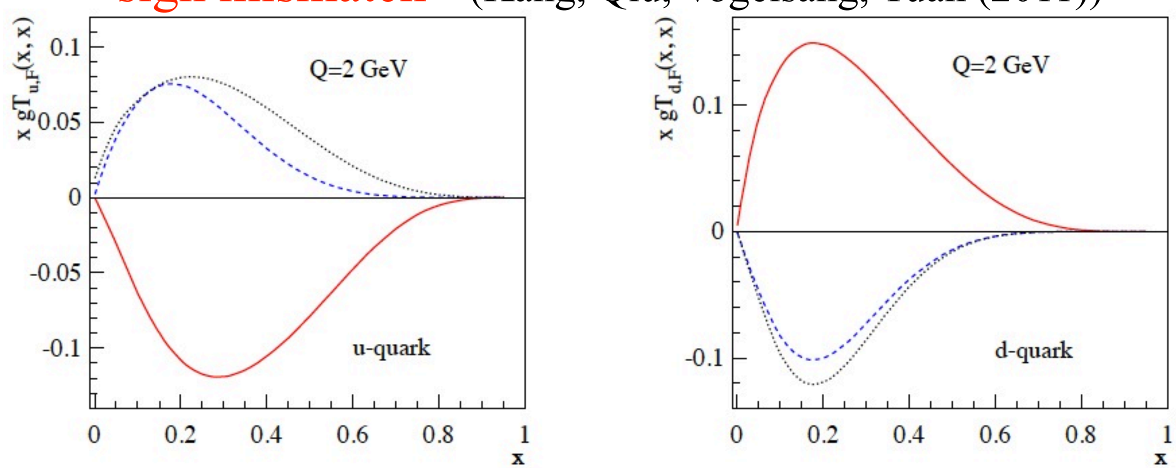


RHIC, PHENIX (2013)

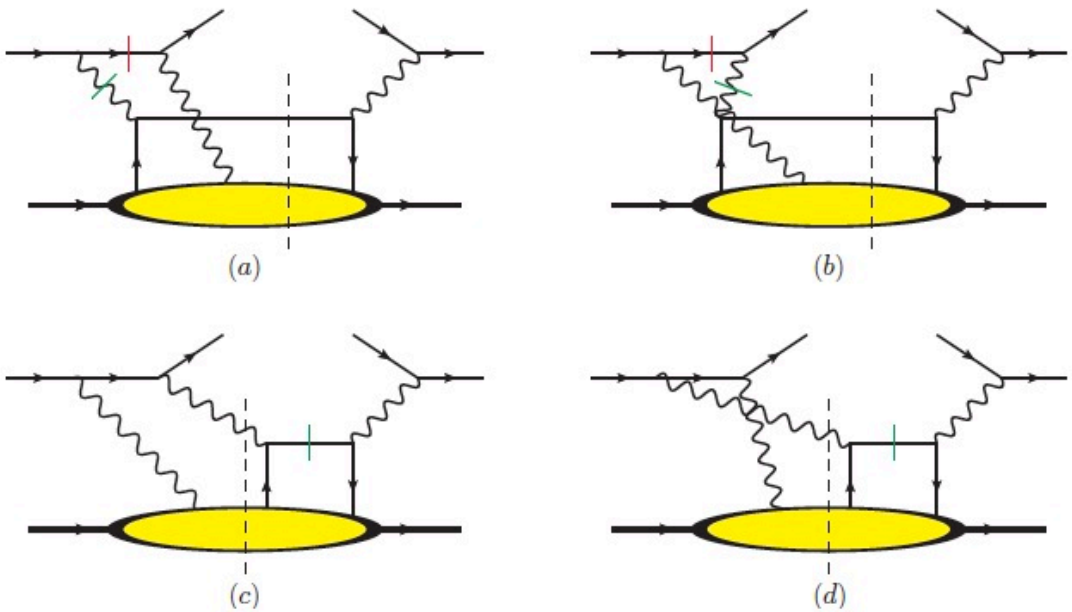


$$\pi\, F_{FT}(x,x) = f_{1T}^{\perp(1)}(x)$$

"sign mismatch" (Kang, Qiu, Vogelsang, Yuan (2011))



- TSSA in inclusive DIS (Metz, DP, Schäfer, Schlegel, Vogelsang, Zhou, PRD **86** (2012))



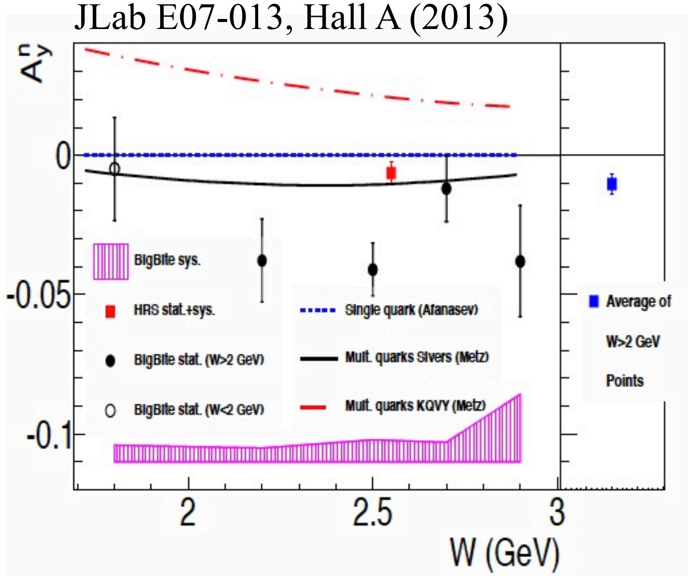
$$k'^0 \frac{d\sigma^N_{pol}}{d^3\vec{k}'} = \frac{8\pi\alpha_{em}^2\, xy^2\, M}{Q^8}\, \frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\left(2+\frac{\hat{u}}{\hat{t}}\right)\varepsilon^{S_N P k k'} \sum_q e_q^2\, x \tilde{F}_{FT}^{q/N}(x,x)$$

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

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

– Neutron TSSA:

JLab E07-013, Hall A (2013)



Sivers input agrees reasonably well with the JLab data

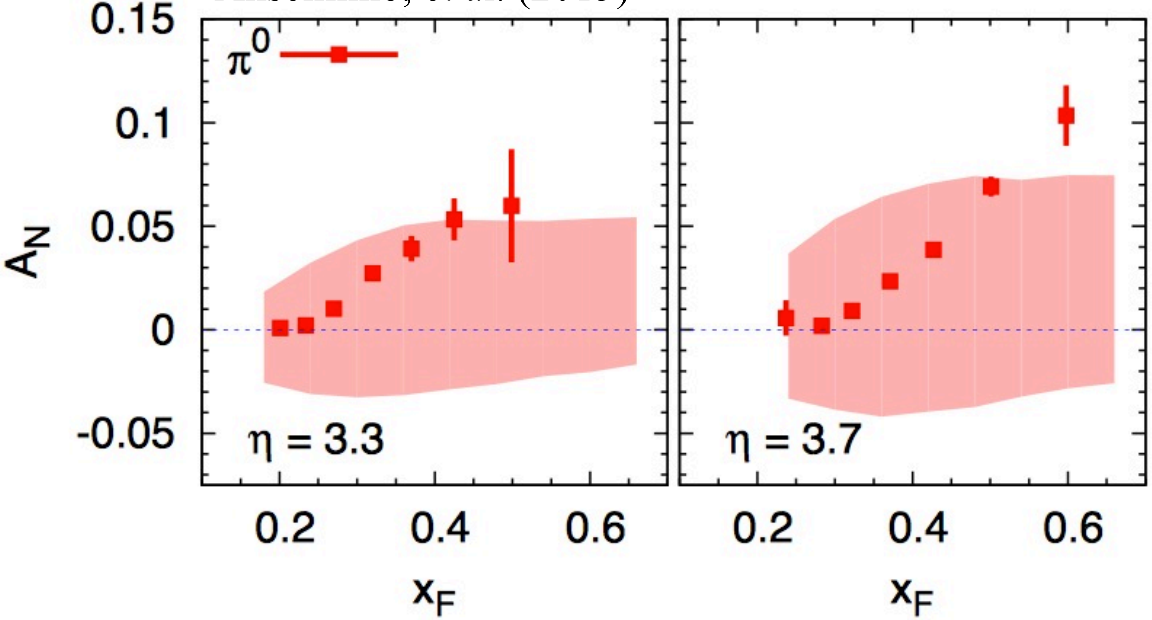
➡ Node in k_T for the Sivers function can be ruled out/Also node in x is disfavored from proton data from HERMES (see also Kang and Prokudin (2012))

➡ FIRST INDICATION that the Sivers effect is intimately connected to the re-scattering of the active parton with the target remnants (PROCESS DEPENDENT)

KQVY input gives the wrong sign ➡ SGP contribution on the side of the transversely polarized incoming proton cannot be the main cause of the large TSSAs seen in pion production (i.e., $T_F(x,x)$ term) (see also recent PHENIX results in Adare, et al. (2013))

- A note on the TMD approach to TSSAs in *pp* collisions
  - ➡ Only a phenomenological model, since there is no proof such a formalism holds in processes with only one (large) scale
  - ➡ Use Sivers function extracted from SIDIS ➔ large uncertainties due to unknown large *x* behavior ➔ cannot draw any definite conclusions

Anselmino, et al. (2013)

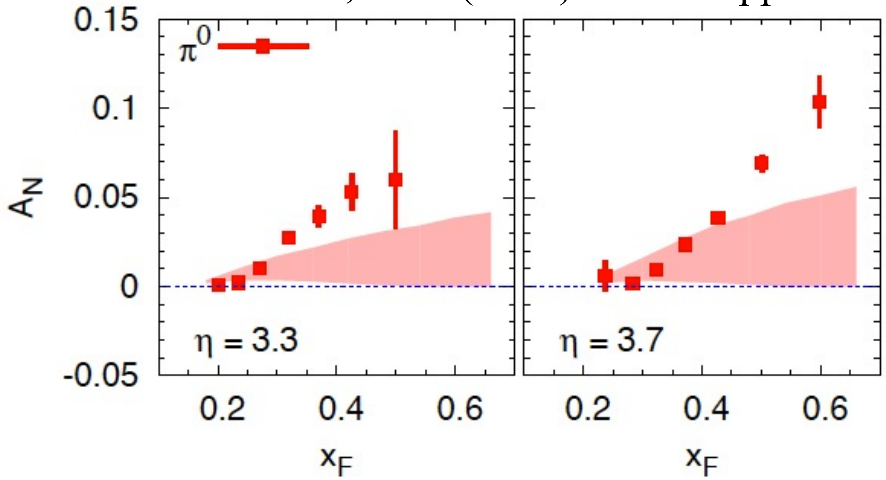


  - ➡ NO sign mismatch problem, but if one takes the re-scattering picture seriously then the issue cannot be avoided

$$
\begin{aligned}
d\sigma = &\ H \otimes f_{a/A(3)} \otimes f_{b/B(2)} \otimes D_{c/C(2)} \\
&\boxed{+\ H' \otimes f_{a/A(2)} \otimes f_{b/B(3)} \otimes D_{c/C(2)}} \rightarrow \text{Negligible (Kanazawa and Koike (2000))} \\
&\boxed{+\ H'' \otimes f_{a/A(2)} \otimes f_{b/B(2)} \otimes D_{C/c(3)}}
\end{aligned}
$$

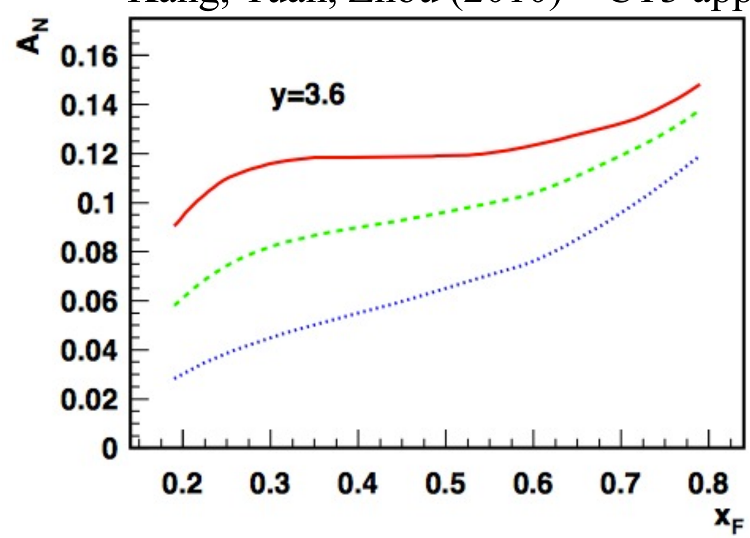
- Collinear twist-3 fragmentation term:

Anselmino, et al. (2012) – TMD approach



- Uses Collins function extracted from e^+e^- and SIDIS

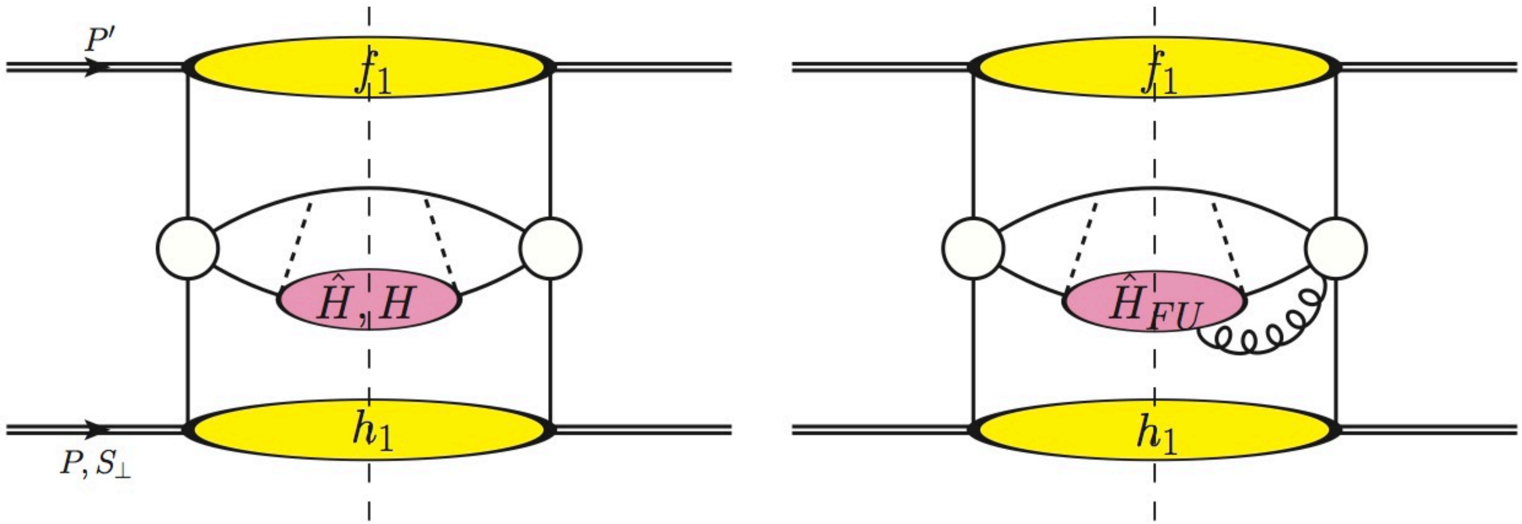
Kang, Yuan, Zhou (2010) – CT3 approach



- Only looks at "derivative term" using simple parameterization

– Could at the very least give a contribution comparable to SGP term

– Calculation of *qq* and *qgq* correlator terms (Metz and DP, PLB **723** (2013))



$$\frac{P_h^0 d\sigma_{pol}}{d^3\vec{P}_h} = -\frac{2\alpha_s^2 M_h}{S}\,\epsilon_{\perp\mu\nu}\,S_\perp^\mu P_{h\perp}^\nu \sum_i \sum_{a,b,c} \int_{z_{min}}^1 \frac{dz}{z^3} \int_{x'_{min}}^1 \frac{dx'}{x'} \frac{1}{x'S + T/z} \frac{1}{-x\hat{u} - x'\hat{t}}$$

$$\times \frac{1}{x}\, h_1^a(x)\, f_1^b(x') \left\{ \left(\hat{H}^{C/c}(z) - z\frac{d\hat{H}^{C/c}(z)}{dz} \right) S_{\hat{H}}^i + \frac{1}{z}\, H^{C/c}(z)\, S_H^i \right.$$

$$\left. + 2z^2 \int \frac{dz_1}{z_1^2}\, PV \frac{1}{\frac{1}{z} - \frac{1}{z_1}}\, \hat{H}_{FU}^{C/c,\Im}(z, z_1)\, \frac{1}{\xi}\, S_{\hat{H}_{FU}}^i \right\}$$

Fragmentation structure is richer than that for the TMD formalism

➡ Also has been studied for TSSA in SIDIS (Kanazawa and Koike (2013))

- First time we have a complete pQCD result for this term within the collinear twist-3 approach
- "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
- Must determine numerical significance of 3-parton fragmentation correlator
- Cannot rule out SFPs (Koike and Tomita (2009); Kanazawa and Koike (2010)) or tri-gluon correlators (Beppu, Kanazawa, Koike, Yoshida (2013)) on the distribution side, but these are unlikely alone to resolve the "sign mismatch" issue

Unpolarized FF

Unpolarized PDF ($f_1(x)$)

Distribution term (SGP)

$$E_\ell \frac{d^3\Delta\sigma(\vec{s}_T)}{d^3\ell} = \frac{\alpha_s^2}{S} \sum_{a,b,c} \int_{z_{\min}}^1 \frac{dz}{z^2} D_{c\to h}(z) \int_{x'_{\min}}^1 \frac{dx'}{x'} \frac{1}{x'S + T/z} \phi_{b/B}(x')$$
$$\times \sqrt{4\pi\alpha_s} \left(\frac{\epsilon^{\ell s_T n \bar{n}}}{z\hat{u}} \right) \frac{1}{x} \left[T_{a,F}(x,x) - x \left(\frac{d}{dx} T_{a,F}(x,x) \right) \right] H_{ab\to c}(\hat{s},\hat{t},\hat{u})$$

Fragmentation term

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

Transversity PDF

➢ Can twist-3 fragmentation resolve the issue?
(Kanazawa, Koike, Metz, DP, in preparation)

- Numerical study (Note: we only use $\sqrt{S} = 200$ GeV data ➔ higher P_T values)

Distribution term (SGP)

➡ Unpolarized PDFs (GRV98 LO) and unpolarized FFs (DSS LO)

➡ SGP: $\pi\, F_{FT}(x,x) = f_{1T}^{\perp(1)}(x)$, Sivers function taken from Torino group (2009/2013)

➡ SFP/Tri-gluon: neglect for now ➔ need more data to constrain

Fragmentation term

➡ Transversity: taken from Torino group (2013), but allow β parameters to be flavor-dependent and free:

$$h_1^q(x) = \frac{1}{2} N_q^T(x)\,[f_1^q(x) + g_1^q(x)] \ \text{ where } N_q^T(x) = N_q^T x^{\alpha^T}(1-x)^{\beta_q^T}\frac{(\alpha^T+\beta_q^T)^{(\alpha^T+\beta_q^T)}}{(\alpha^T)^{\alpha^T}\,(\beta_q^T)^{\beta_q^T}}$$

(Helicity distributions from GRSV2000 LO)

➡ $\hat{H}^{h/q}(z)$: use Collins function extracted by the Torino group (2013)

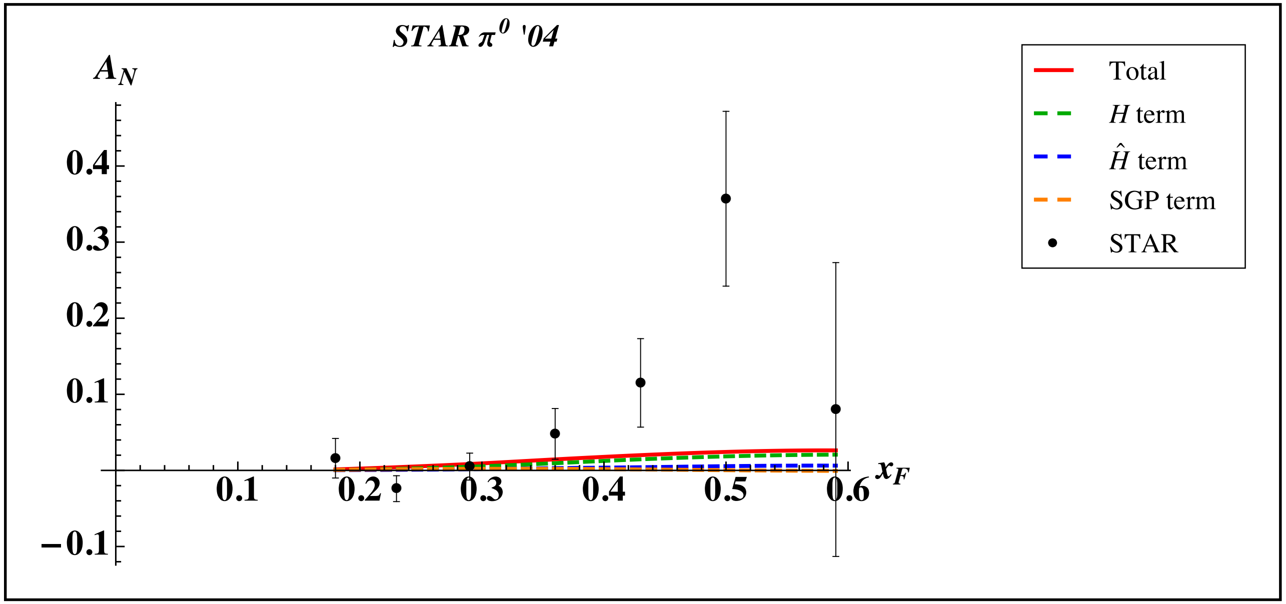
➡ 3-parton fragmentation correlator ➔ use the following ansatz:

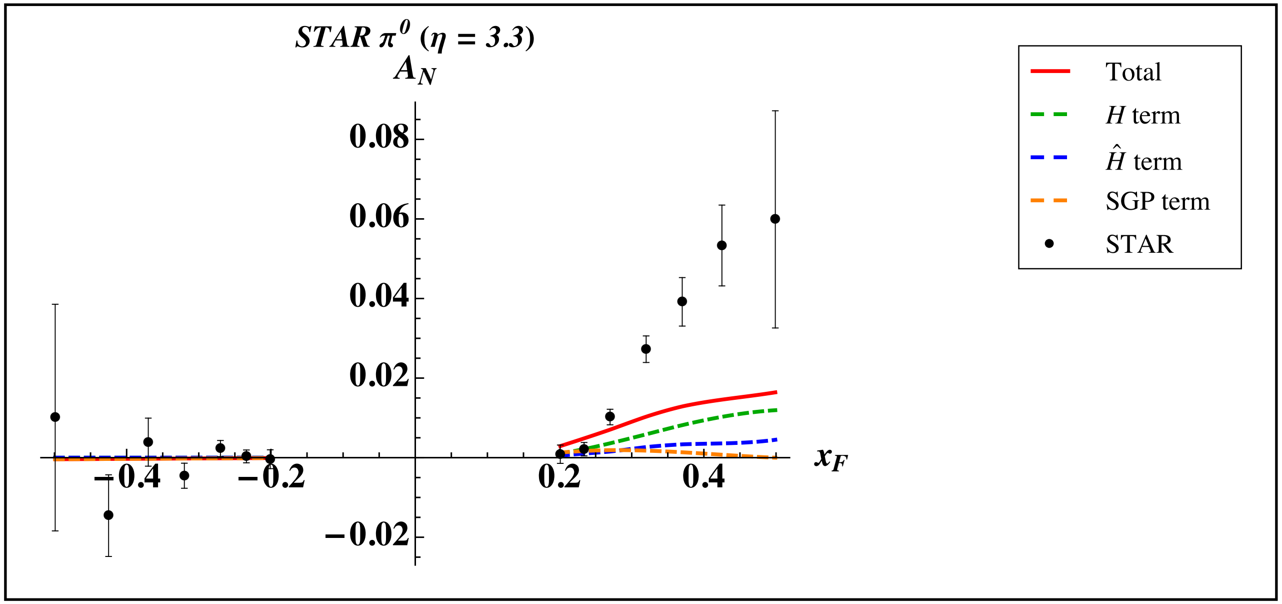
$$\hat{H}_{FU}^{fav,\Im}(z,z_1) = N_{fav}\,(1-z)^{\beta_{fav}}\,(1-z/z_1)^{\beta'_{fav}}\,D_1^{h/q}(z)\,D_1^{h/q}(z/z_1)$$

$$\hat{H}_{FU}^{dis,\Im}(z,z_1) = N_{dis}\,(1-z)^{\beta_{dis}}\,(1-z/z_1)^{\beta'_{dis}}\,D_1^{h/q}(z)\,D_1^{h/q}(z/z_1)$$

A_N vs. x_F

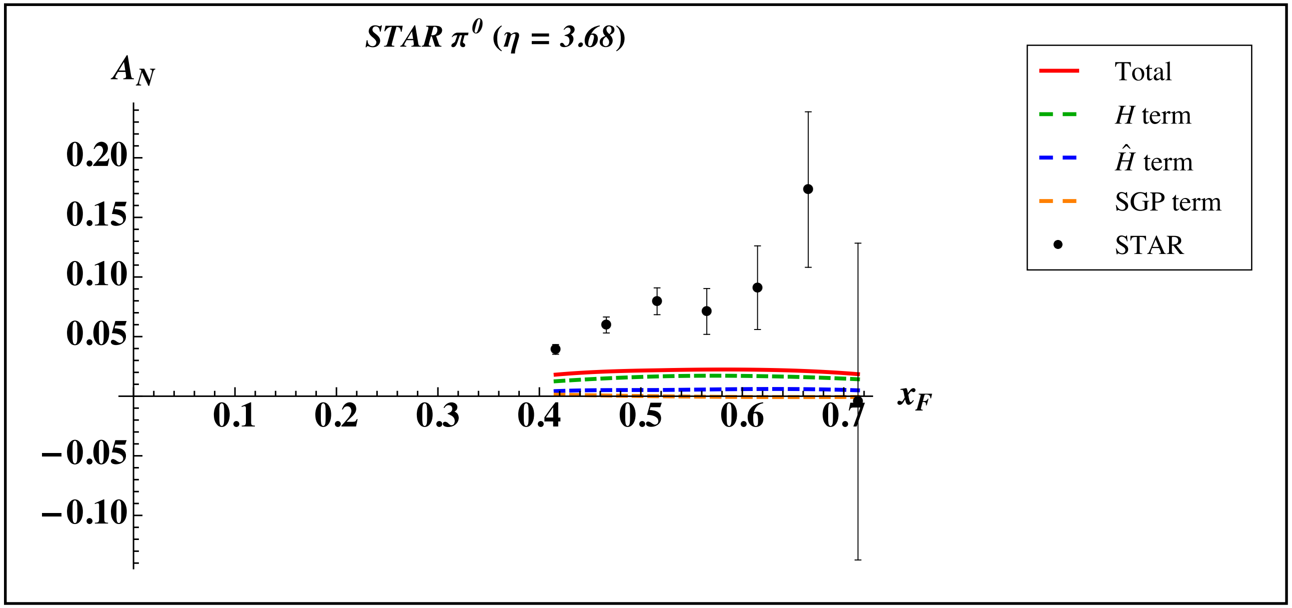
3-parton FF = 0

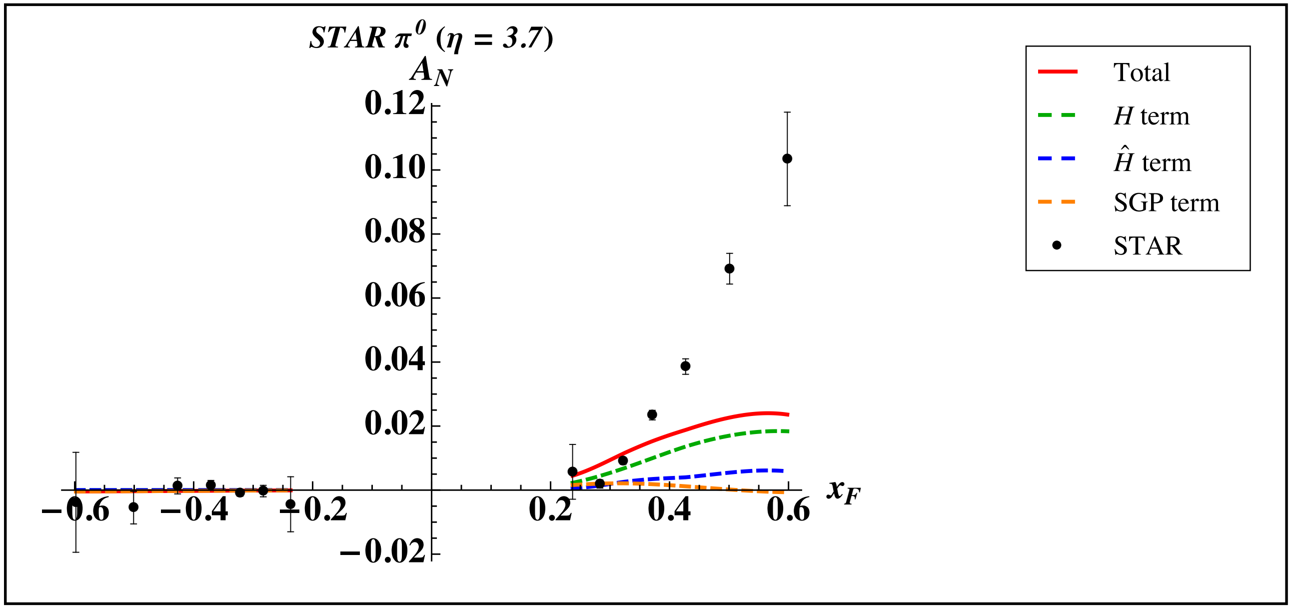




A_N vs. x_F

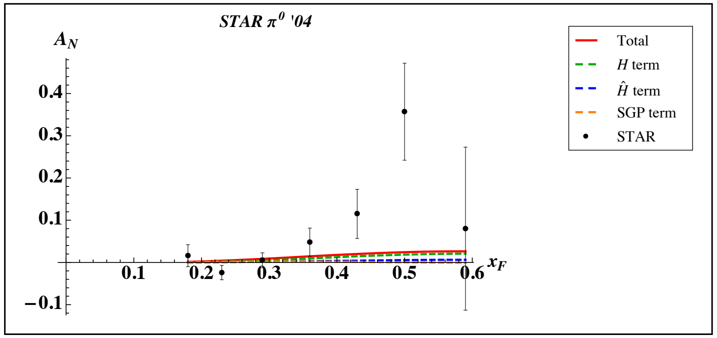
3-parton FF = 0

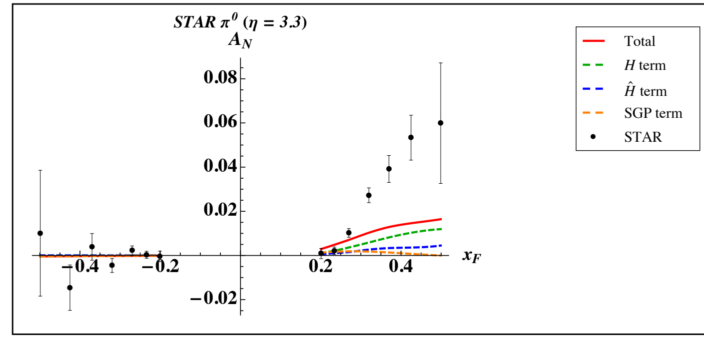


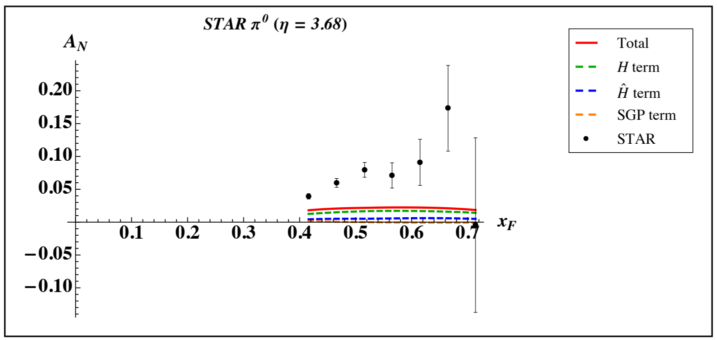


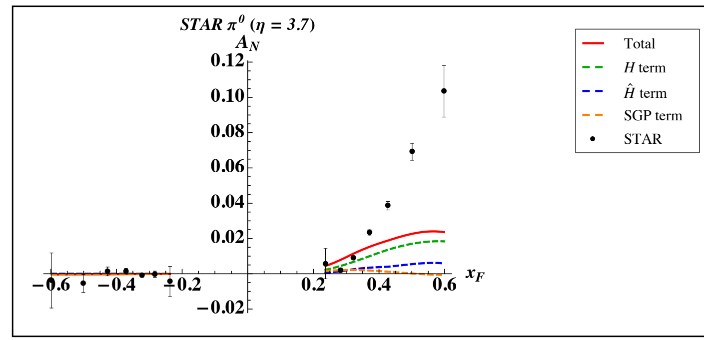
A_N vs. x_F

3-parton FF = 0









➡ Without the 3-parton FF, one has difficulty obtaining a rise in A_N towards large x_F that is characteristic of the RHIC data

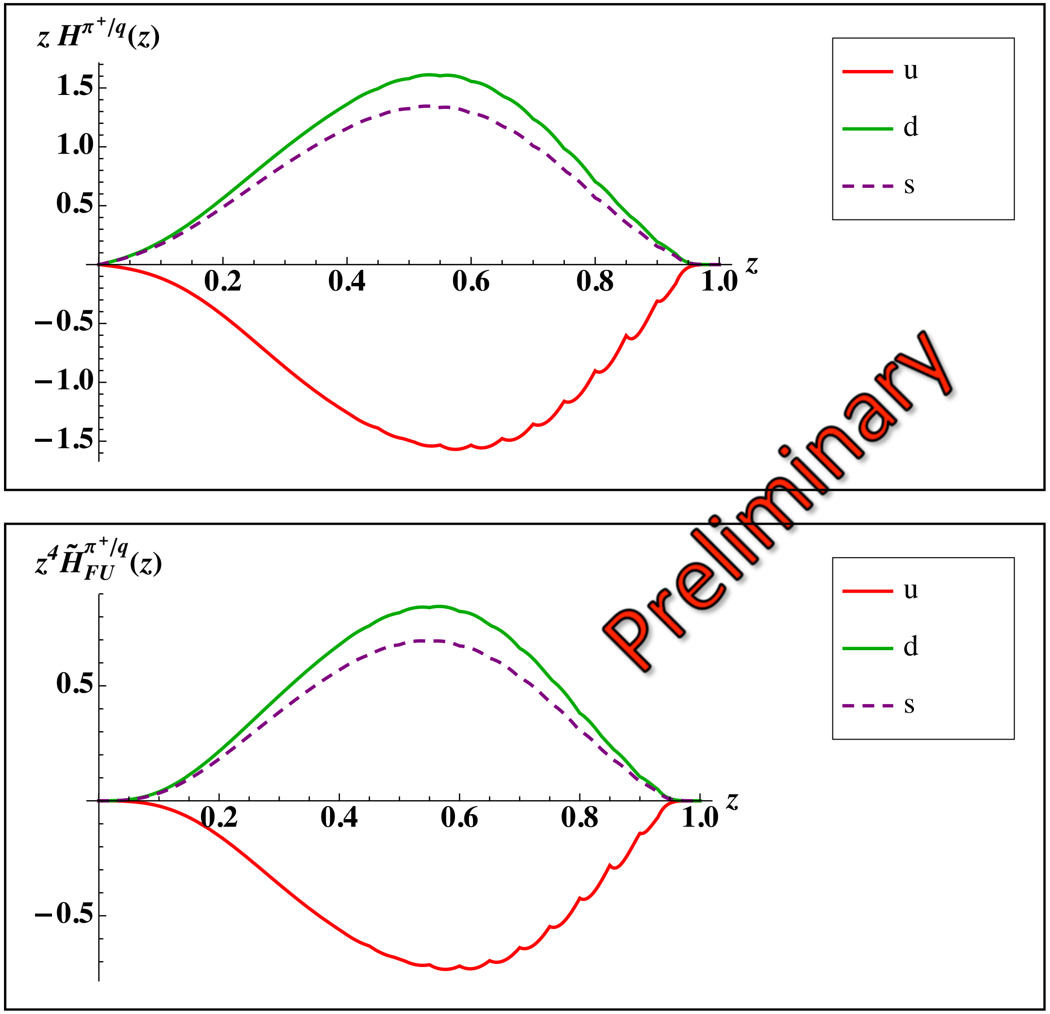
8 free parameters: $N_{fav}, N_{dis}, \beta_{fav}, \beta'_{fav}, \beta_{dis}, \beta'_{dis}, \beta_u^T, \beta_d^T$

Preliminary

$\chi^2/d.o.f. = 1.37$	
$N_{fav} = -15.00$	$N_{dis} = 17.83$
$\beta_{fav} = 0.84$	$\beta_{dis} = 0.00$
$\beta'_{fav} = 10.42$	$\beta'_{dis} = -0.20$
$\beta_u^T = 1.10$	$\beta_d^T = 0.69$

Note: $\chi^2/d.o.f. = 0.96$ when excluding charged pions

➡ Above parameters are from using 2009 Sivers function. Using 2013 Sivers function (at large-x allows for u, d flavor-dependence and leads to a slower decrease than 2009) gives $\chi^2/d.o.f. = 1.56$ ($\chi^2/d.o.f. = 1.12$ excluding charged pions)



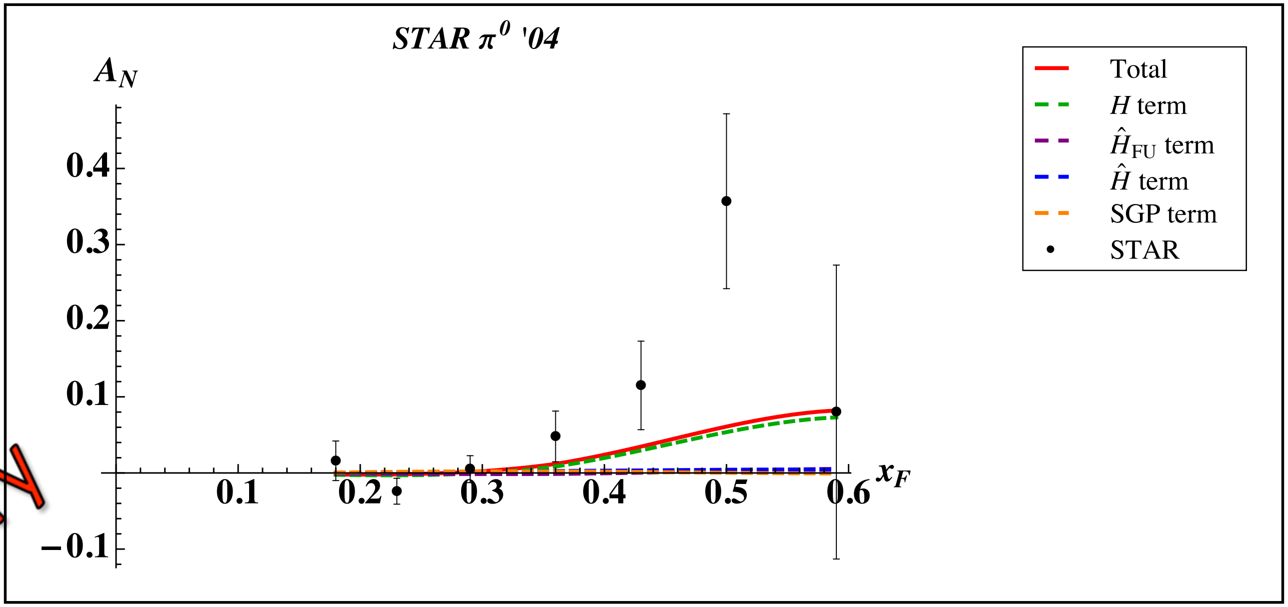
$Q^2 = 4\ \mathrm{GeV}^2$

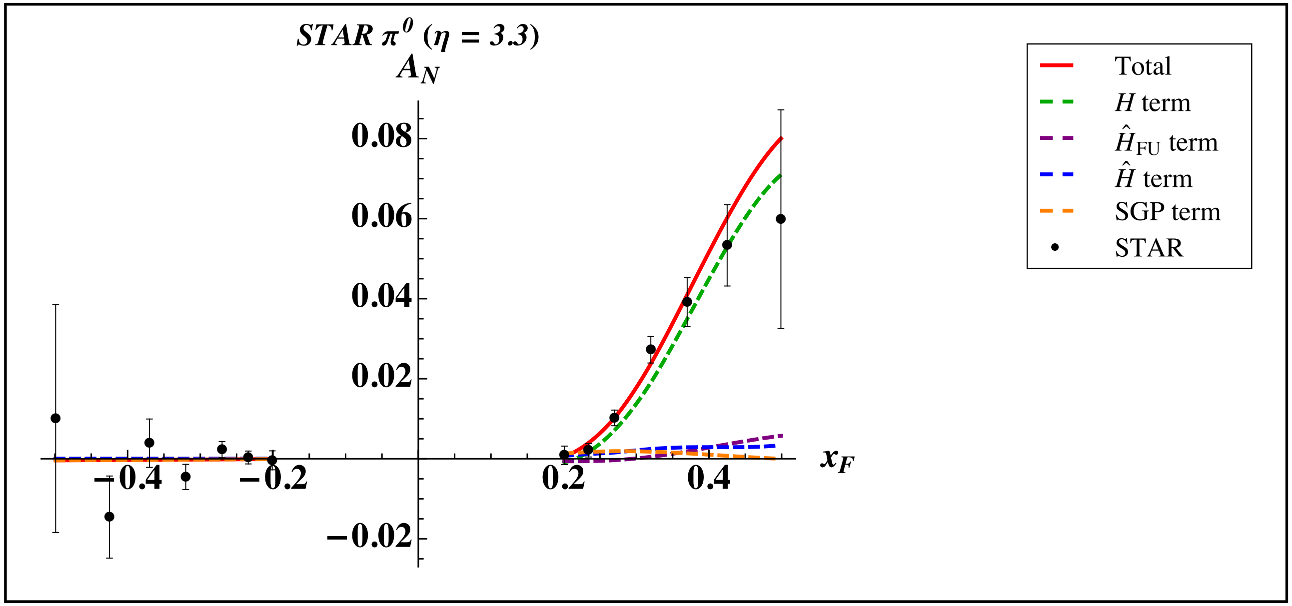
➡ Favored and disfavored (chiral-odd) collinear twist-3 FFs are roughly equal in magnitude but opposite in sign ➔ similar to Collins FF

A_N vs. x_F

Including 3-parton FF

Preliminary

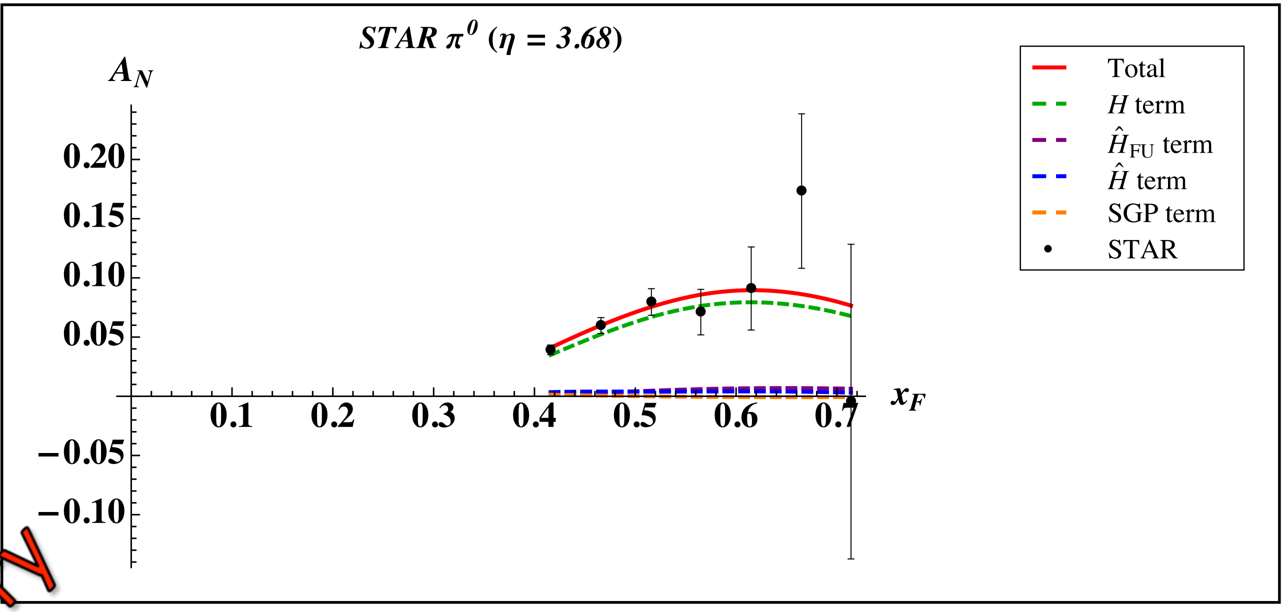


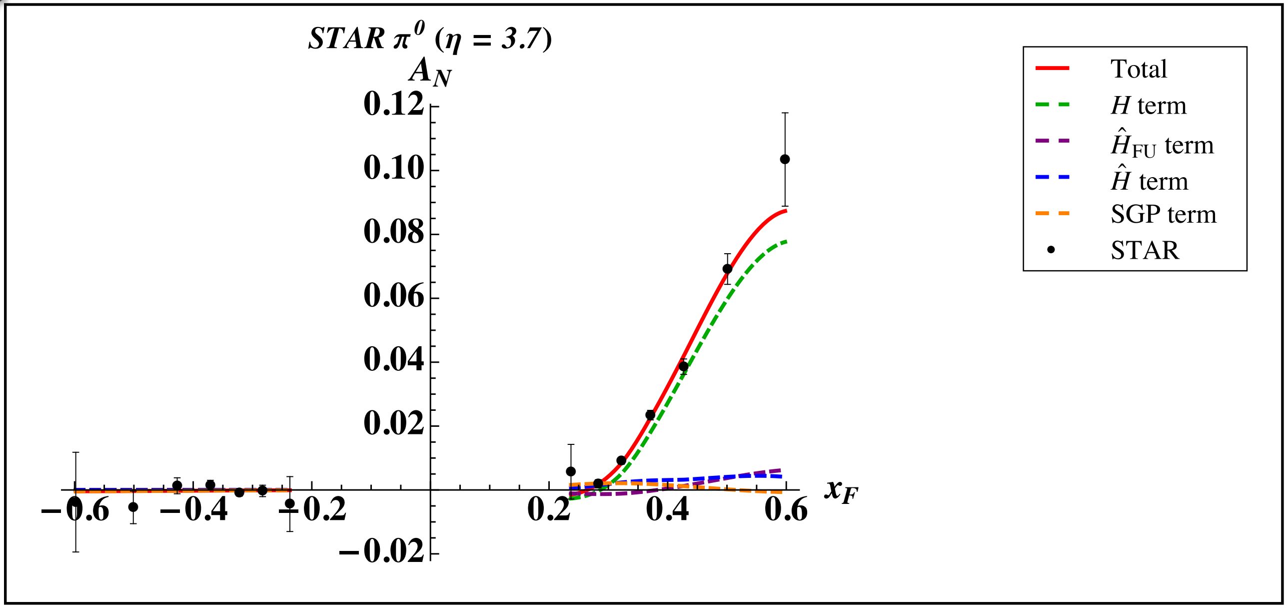


A_N vs. x_F

Including 3-parton FF

Preliminary

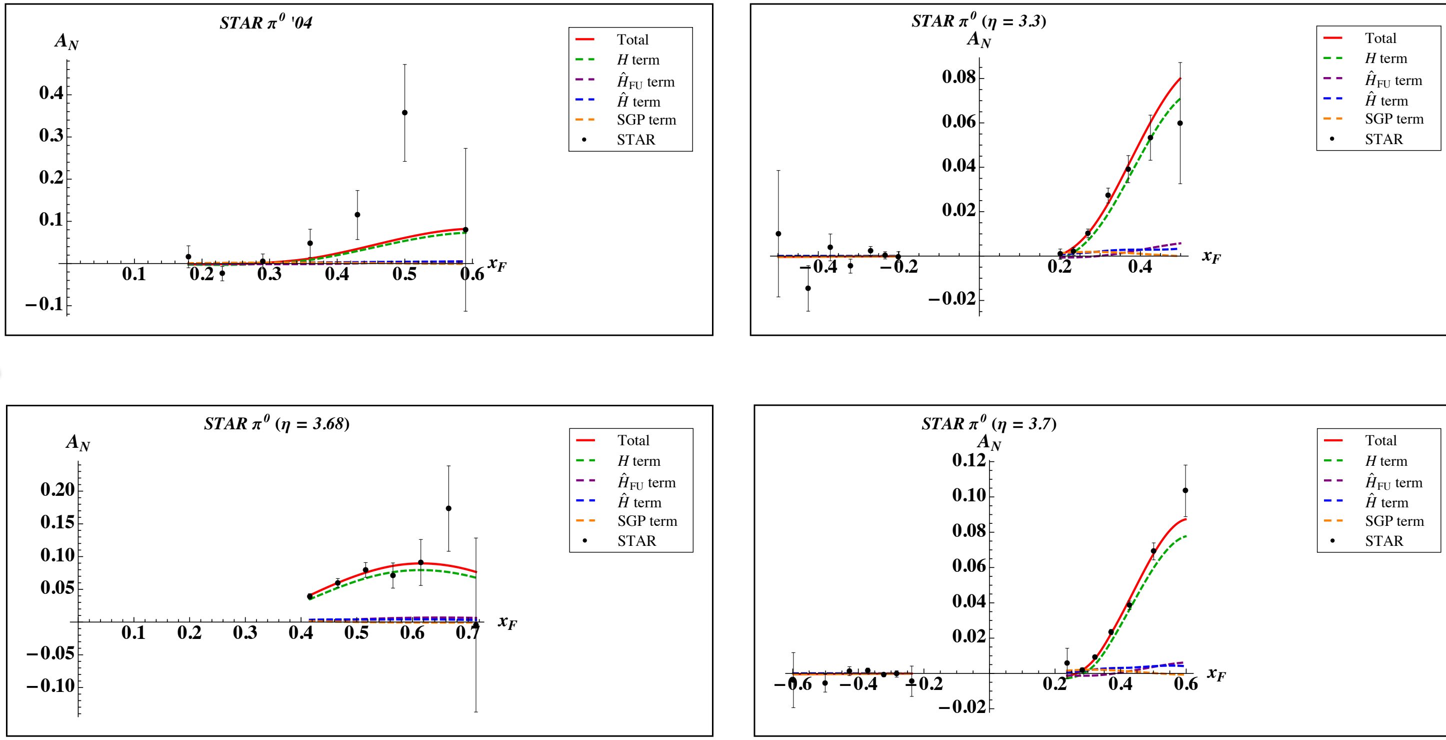




A_N vs. x_F

Including 3-parton FF

Preliminary

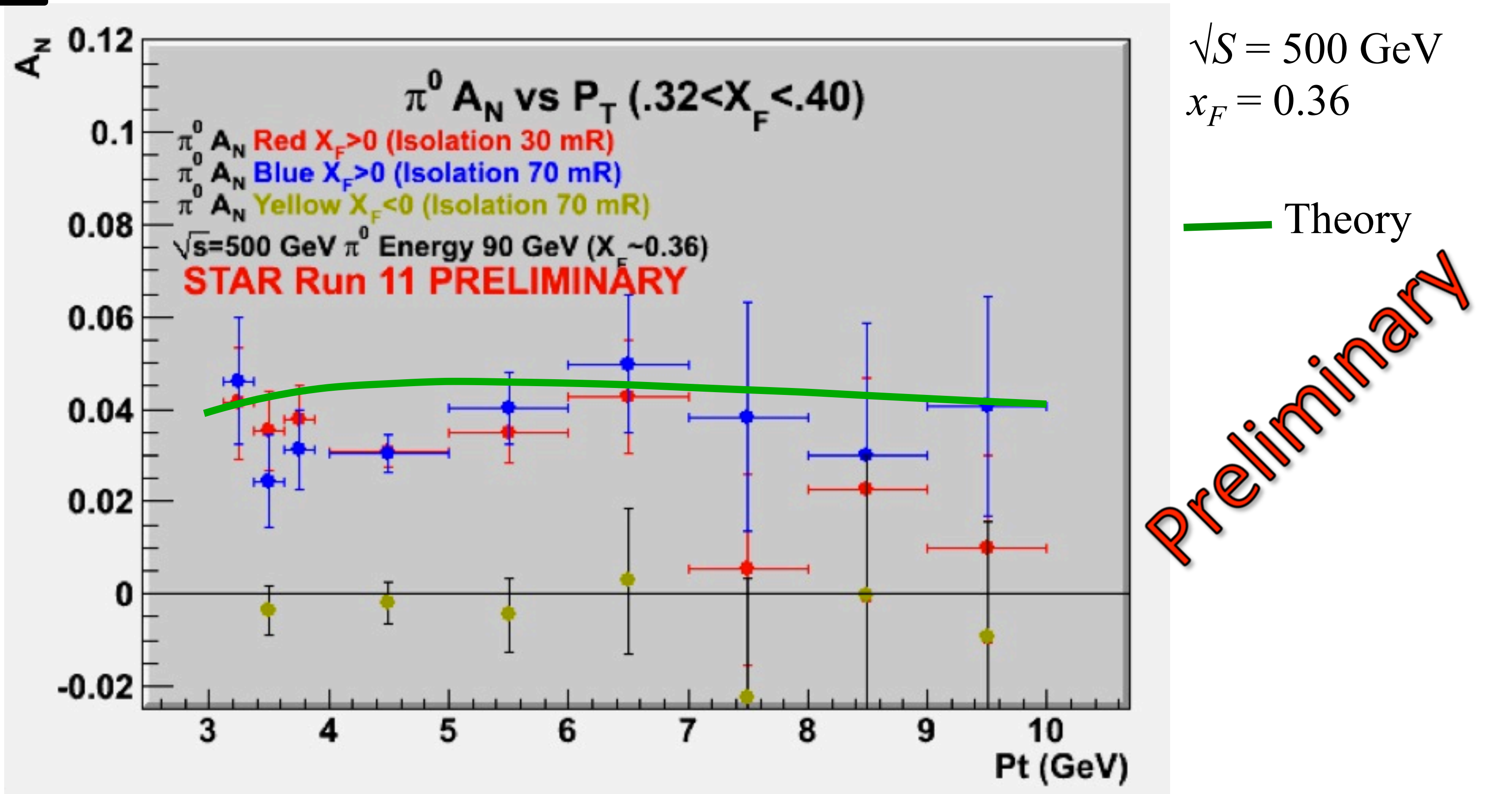


- Fragmentation term has the potential to describe the RHIC data, and in particular can give the characteristic rise towards large x_F
- H term is dominant; Sivers-type, Collins-type, and H_{FU} terms are negligible

- Flat P_T dependence thought to be an issue for collinear twist-3 approach ➔ $A_N \sim 1/P_T$
- First shown by Kanazawa and Koike (2011) that this does not have to be the case

A_N vs. P_T

Talk by S. Heppelmann (CIPANP 2012)



- Our analysis also shows a flat P_T dependence for A_N seen so far at RHIC ➔ remains flat even to larger P_T values

Summary and outlook

- "Sign mismatch" ➡ still do not fully understand the mechanism behind the large TSSAs seen in hadron production from *pp* collisions
- Twist-3 fragmentation has the potential to resolve the issue

➡ Full analytical pQCD result now available

➡ (Prelim) numerical results show this term can describe the RHIC data, in particular the rise in A_N towards large x_F and flat P_T dependence

➡ Our analysis provides a consistency between asymmetries in *pp* (collinear) and SIDIS, e^+e^- (TMD)

➡ Future work: look at kaons and etas, include SFPs (can help with charged hadrons)

- Global analysis involving several reactions will be needed in order to extract all the collinear twist-3 distribution and fragmentation functions in $p^{\uparrow}p \to hX$
  - ➡ Measurement of $p^{\uparrow}p \to jet\ X$ by the AnDY Collaboration (Bland, et al. (2013))
  - ➡ Measurements of Drell-Yan in $p^{\uparrow}p$ and $p^{\uparrow}p \to \gamma\ X$ at RHIC (also DY experiment planned at COMPASS for $\pi p^{\uparrow}$)
  - ➡ Large $P_{h\perp}$ measurement of Sivers and Collins asymmetries in SIDIS should also be possible at JLab12, COMPASS, or a future EIC
  - ➡ HERMES (Airapetian, et al. (2013)) / JLab (Allada, et al. (2013)) have recently published data on $ep^{\uparrow} \to hX$ / $en^{\uparrow} \to hX$
  - ➡ Can one consistently describe all of these reactions?