



Transverse single-spin asymmetries in pion and photon production from proton-proton collisions

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Outline

➤ Motivation

- What are transverse single-spin asymmetries (TSSAs)?
- Collinear twist-3 vs. Generalized Parton Model (GPM) formalisms

➤ TSSAs in single-inclusive processes

$$\underline{p^\dagger p \rightarrow \pi X}$$

- The “sign mismatch” issue between the Qiu-Sterman (QS) and Sivers functions
- Towards an explanation using collinear twist-3 fragmentation
- Further tests using $e N^\dagger \rightarrow \pi X$ measurements

$$\underline{p^\dagger p \rightarrow \gamma X}$$

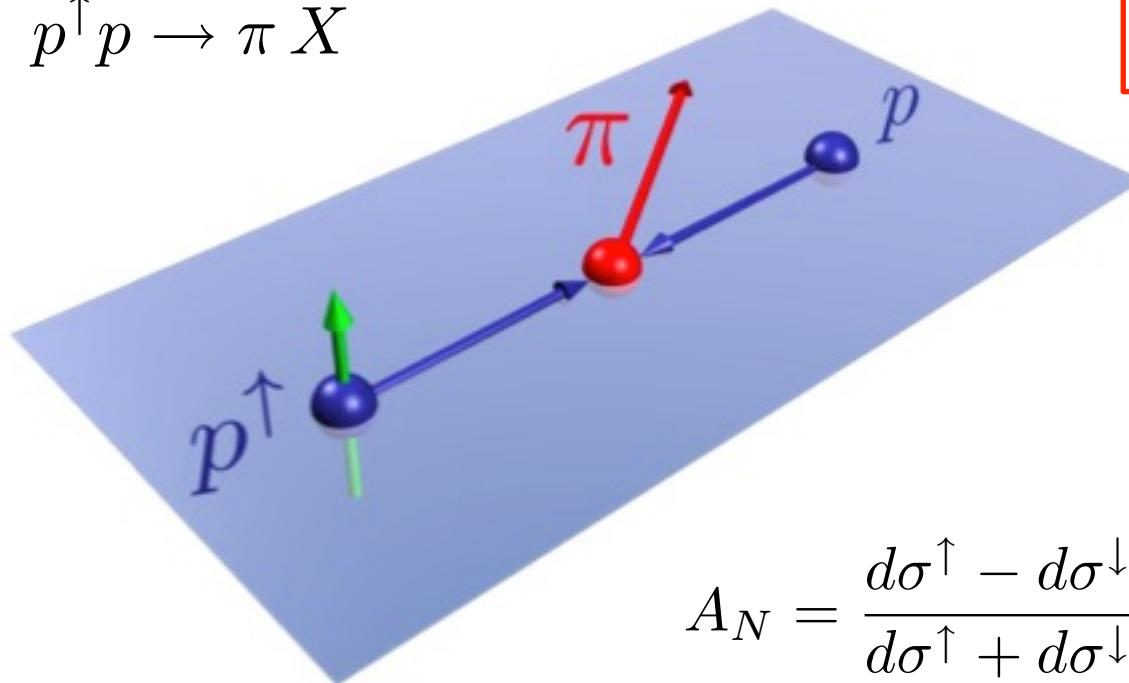
- “Clean” access to the QS function
- Could test the process dependence of the Sivers function (on same footing as A_N in DY)
- Could distinguish between collinear twist-3 and GPM frameworks

➤ Summary and outlook

Motivation

- What are TSSAs?

$$p^\uparrow p \rightarrow \pi X$$



- Naïve T-odd effect
- $P_{h\perp}$ is the only scale

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

Data available from RHIC (BRAHMS, PHENIX, STAR),
FNAL (E704, E581), AGS, and ANL

(Figure thanks to K. Kanazawa)



➤ Collinear twist-3 vs. Generalized Parton Model (GPM)

Collinear twist-3

Uses collinear functions ($P_{h\perp} \gg \Lambda_{QCD}$)

$$\begin{aligned} d\sigma = & H \otimes f_{a/A^\uparrow(3)} \otimes f_{b/B(2)} \otimes D_{c/C(2)} \\ & + H' \otimes f_{a/A^\uparrow(2)} \otimes f_{b/B(3)} \otimes D_{c/C(2)} \\ & + H'' \otimes f_{a/A^\uparrow(2)} \otimes f_{b/B(2)} \otimes D_{c/C(3)} \end{aligned}$$



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QS function \nearrow

$$\begin{array}{ll} F_{FT}(x, x) & F_{FT}(0, x), G_{FT}(0, x) \\ H_{FU}(x, x) & H_{FU}(0, x) \\ \hat{H}(z), H(z), \hat{H}_{FU}(z, z_1) & \end{array}$$



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GPM

Uses TMD functions ($P_{h\perp} \gg ?? \sim \Lambda_{QCD}$)

$$\begin{aligned} d\sigma = & H \otimes f_{1T}^\perp \otimes f_1 \otimes D_1 \\ & + H' \otimes h_1 \otimes h_1^\perp \otimes D_1 \\ & + H'' \otimes h_1 \otimes f_1 \otimes H_1^\perp \end{aligned}$$



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GPM

Uses TMD functions ($P_{h\perp} \gg ?? \sim \Lambda_{QCD}$)

$$\begin{aligned} d\sigma = & H \otimes f_{1T}^\perp \otimes f_1 \otimes D_1 & \text{Sivers} \\ & + H' \otimes h_1 \otimes h_1^\perp \otimes D_1 & \text{Boer-Mulders} \\ & + H'' \otimes h_1 \otimes f_1 \otimes H_1^\perp & \text{Collins} \end{aligned} \quad \left. \right\} \begin{array}{l} \text{Enter in azimuthal} \\ \text{asymmetries in SIDIS} \\ (Q \gg P_{h\perp} \sim \Lambda_{QCD}) \end{array}$$

➤ Collinear twist-3 vs. Generalized Parton Model (GPM)

Collinear twist-3

Uses collinear functions ($P_{h\perp} \gg \Lambda_{QCD}$)

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 \end{aligned}$$

There is no soft scale



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$$\begin{array}{ll} F_{FT}(x, x) & F_{FT}(0, x), G_{FT}(0, x) \\ H_{FU}(x, x) & H_{FU}(0, x) \\ \hat{H}(z), H(z), \hat{H}_{FU}(z, z_1) & \end{array}$$

GPM

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$$\begin{aligned} d\sigma = & H \otimes f_{1T}^\perp \otimes j_1 \otimes D_1 & \text{Sivers} \\ & + H' \otimes h_1 \otimes h_1^\perp \otimes D_1 & \text{Boer-Mulders} \\ & + H'' \otimes h_1 \otimes f_1 \otimes H_1^\perp & \text{Collins} \end{aligned}$$

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

$$\pi H_{FU}(x, x) = h_1^{\perp(1)}(x) \Big|_{SIDIS}$$

$$\hat{H}(z) = H_1^{\perp(1)}(z)$$

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NO (twist-2) TMD analogues

$F_{FT}(x, x)$

$H_{FU}(x, x)$

$\hat{H}(z)$

$F_{FT}(0, x), G_{FT}(0, x)$

$H_{FU}(0, x)$

$\hat{H}(z), \hat{H}_{FU}(z, z_1)$

GPM

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TSSAs in Single-Inclusive Processes

Collinear twist-3

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→ For many years the SGP term involving the QS/Sivers-type function F_{FT} was thought to be the dominant contribution to TSSAs in $p^\uparrow p \rightarrow \pi X$

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

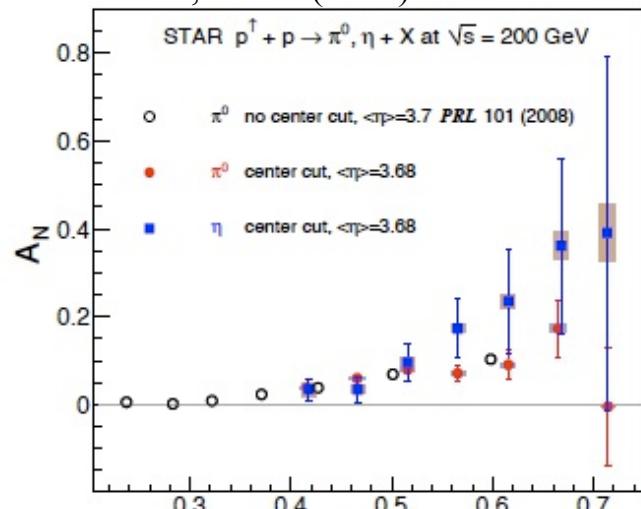
$$F_{FT} \sim T_F$$

(Qiu and Sterman (1999), Kouvaris, et al. (2006))

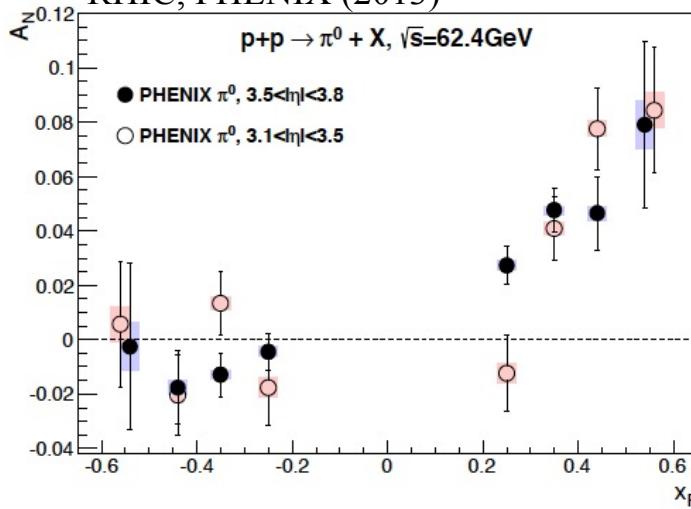
➤ The “sign mismatch” issue

$$p^\uparrow p \rightarrow h X$$

RHIC, STAR (2012)

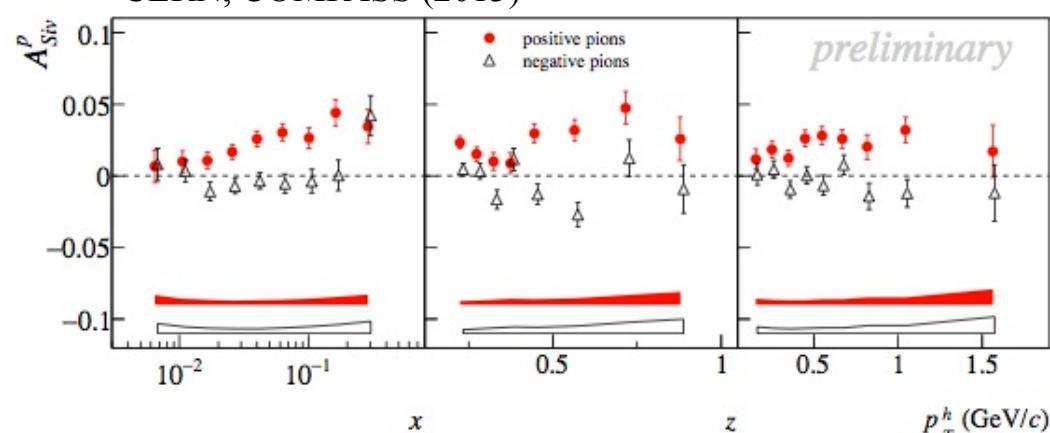


RHIC, PHENIX (2013)



$$\ell N^\uparrow \rightarrow \ell' h X$$

CERN, COMPASS (2013)

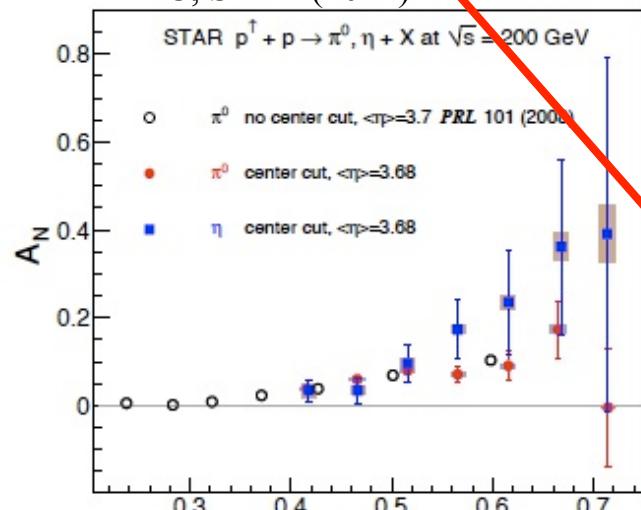


$$\pi F_{FT}(x, x) = f_{1T}^{\perp(1)}(x)$$

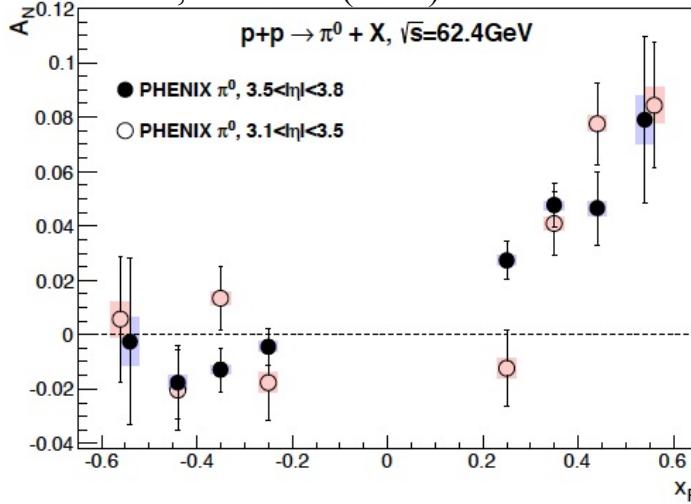
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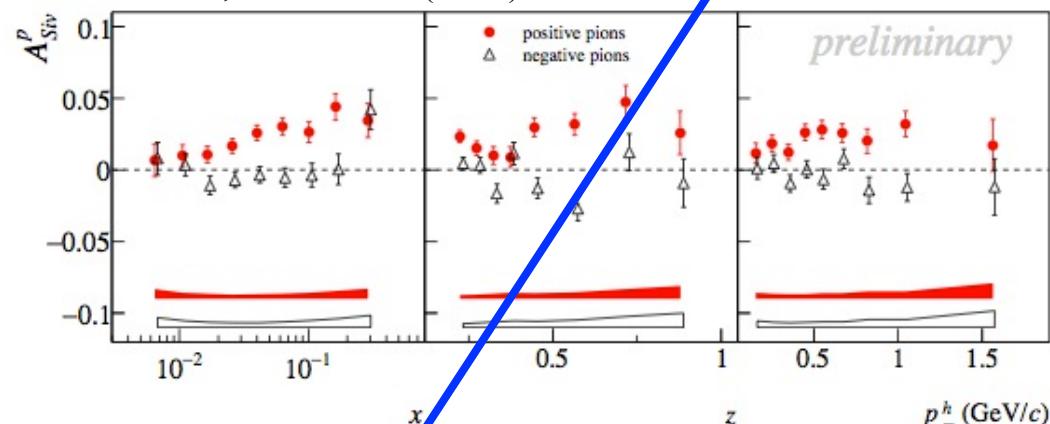


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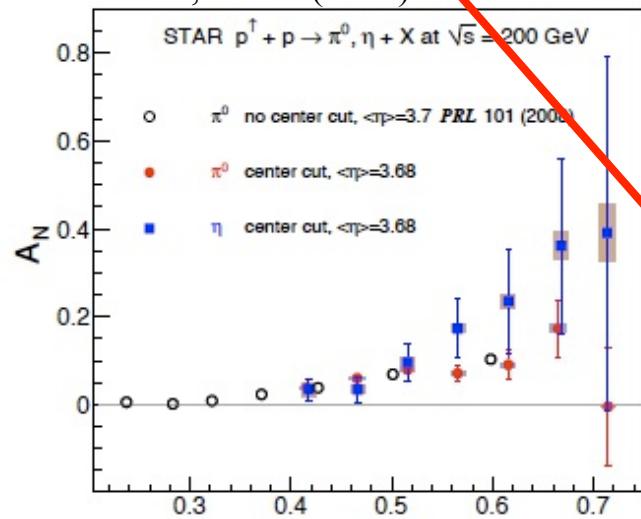


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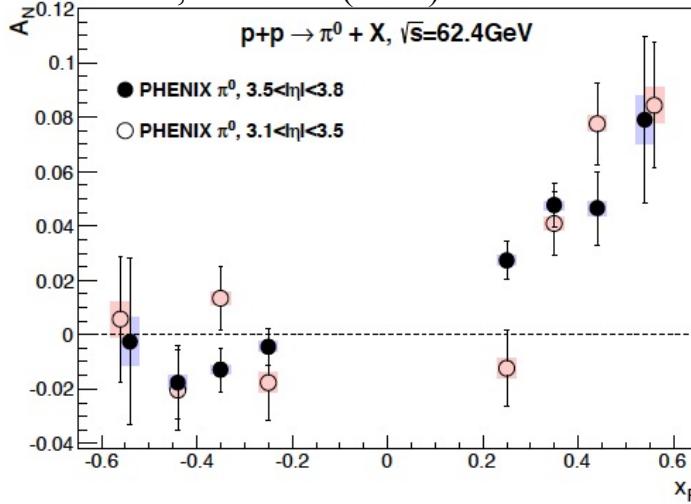
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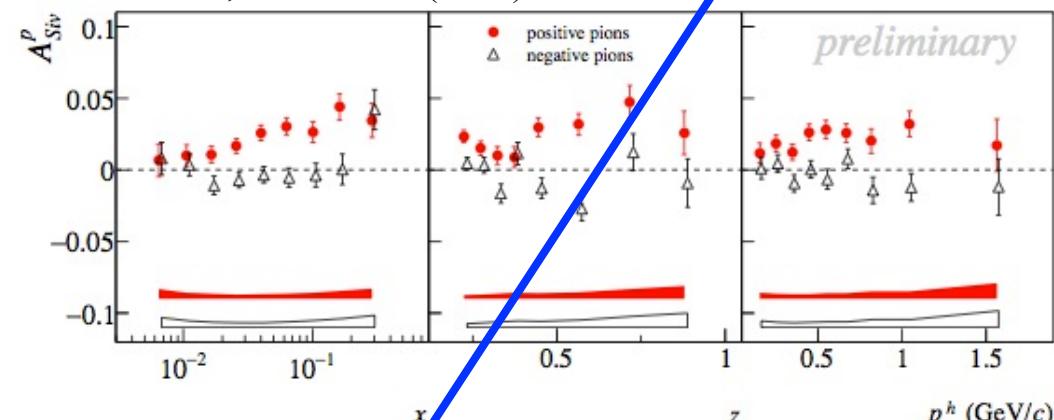


RHIC, PHENIX (2013)



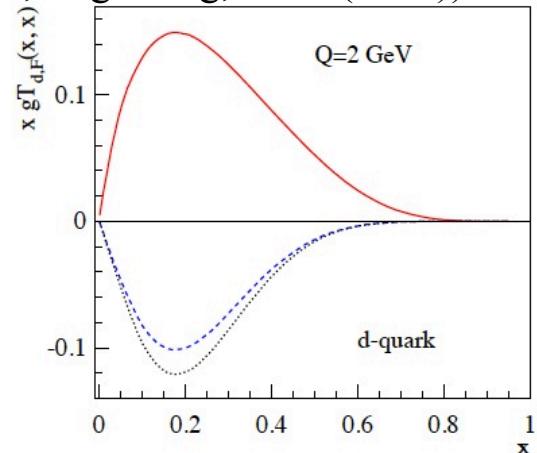
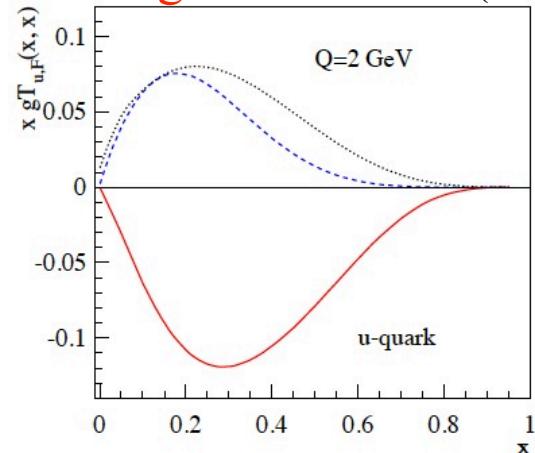
$$\ell N^\uparrow \rightarrow \ell' h X$$

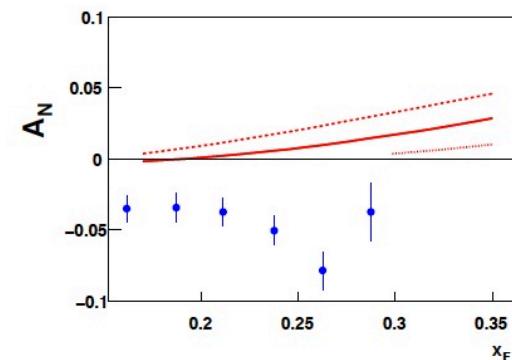
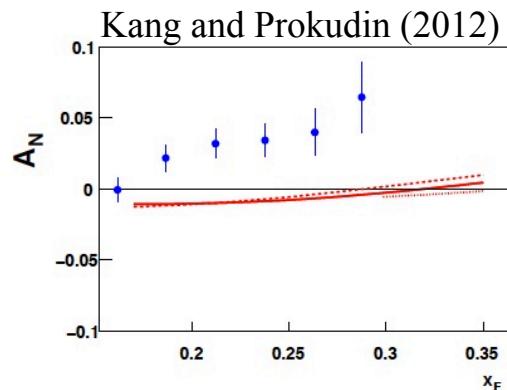
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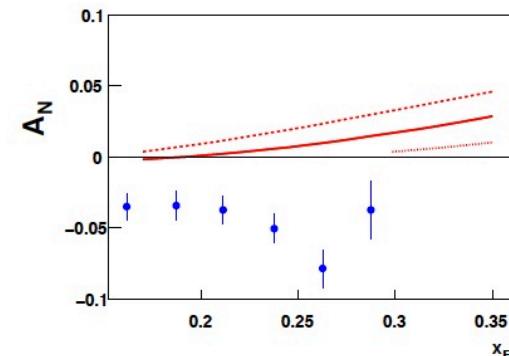
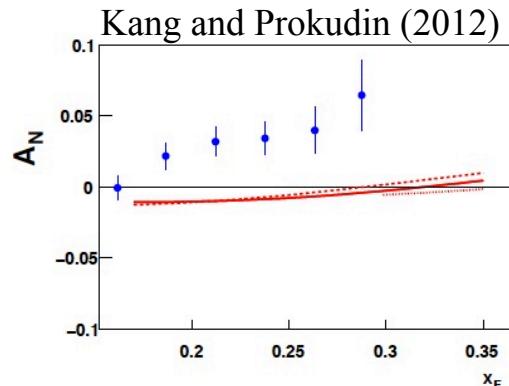
“sign mismatch” (Kang, Qiu, Vogelsang, Yuan (2011))



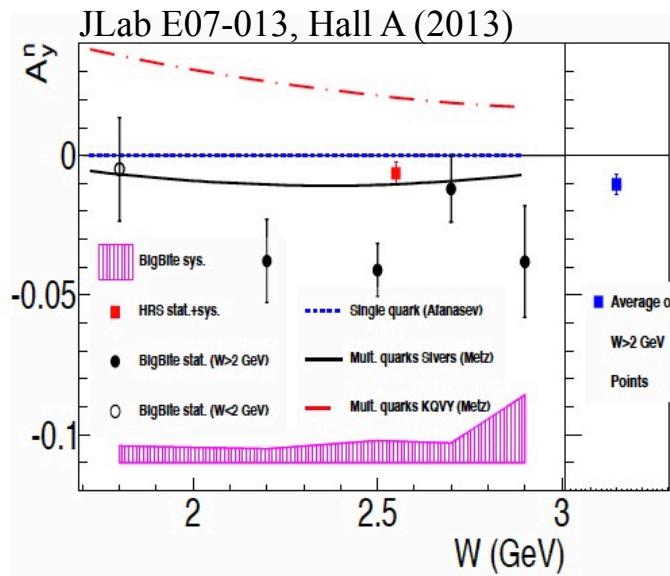


Proton-proton data from BRAHMS for π^+ (left) and π^- (right)

Nodes in Sivers cannot resolve issue



Nodes in Sivers cannot resolve issue



Neutron TSSA in inclusive DIS

Metz, DP, Schäfer, Schlegel, Vogelsang, Zhou - PRD 86 (2012)

Sivers input agrees reasonably well with the JLab data → FIRST INDICATION on the PROCESS DEPENDENCE of the Sivers function (see also Gamberg, Kang, Prokudin (2013))

KQVY input gives the wrong sign → QS function cannot be the main cause of the large TSSAs seen in pion production



$$\begin{aligned} d\sigma = & \ H \otimes f_{a/A^\uparrow(3)} \otimes f_{b/B(2)} \otimes D_{c/C(2)} \\ & + \ H' \otimes f_{a/A^\uparrow(2)} \otimes f_{b/B(3)} \otimes D_{c/C(2)} \\ & + \ H'' \otimes f_{a/A^\uparrow(2)} \otimes f_{b/B(2)} \otimes D_{c/C(3)} \end{aligned}$$

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Negligible
(Kanazawa and
Koike (2000))



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

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Negligible
(Kanazawa and
Koike (2000))



- Collinear twist-3 fragmentation term: $H'' \otimes h_1 \otimes f_1 \otimes (\hat{H}, H, \hat{H}_{FU}^{\Im})$

$$\hat{H}(z) = H_1^{\perp(1)}(z)$$

Collins-type function

$$2z^3 \int_z^\infty \frac{dz_1}{z_1^2} \frac{1}{\frac{1}{z} - \frac{1}{z_1}} \hat{H}_{FU}^{\Im}(z, z_1) = H(z) + 2z\hat{H}(z)$$

3-parton correlator

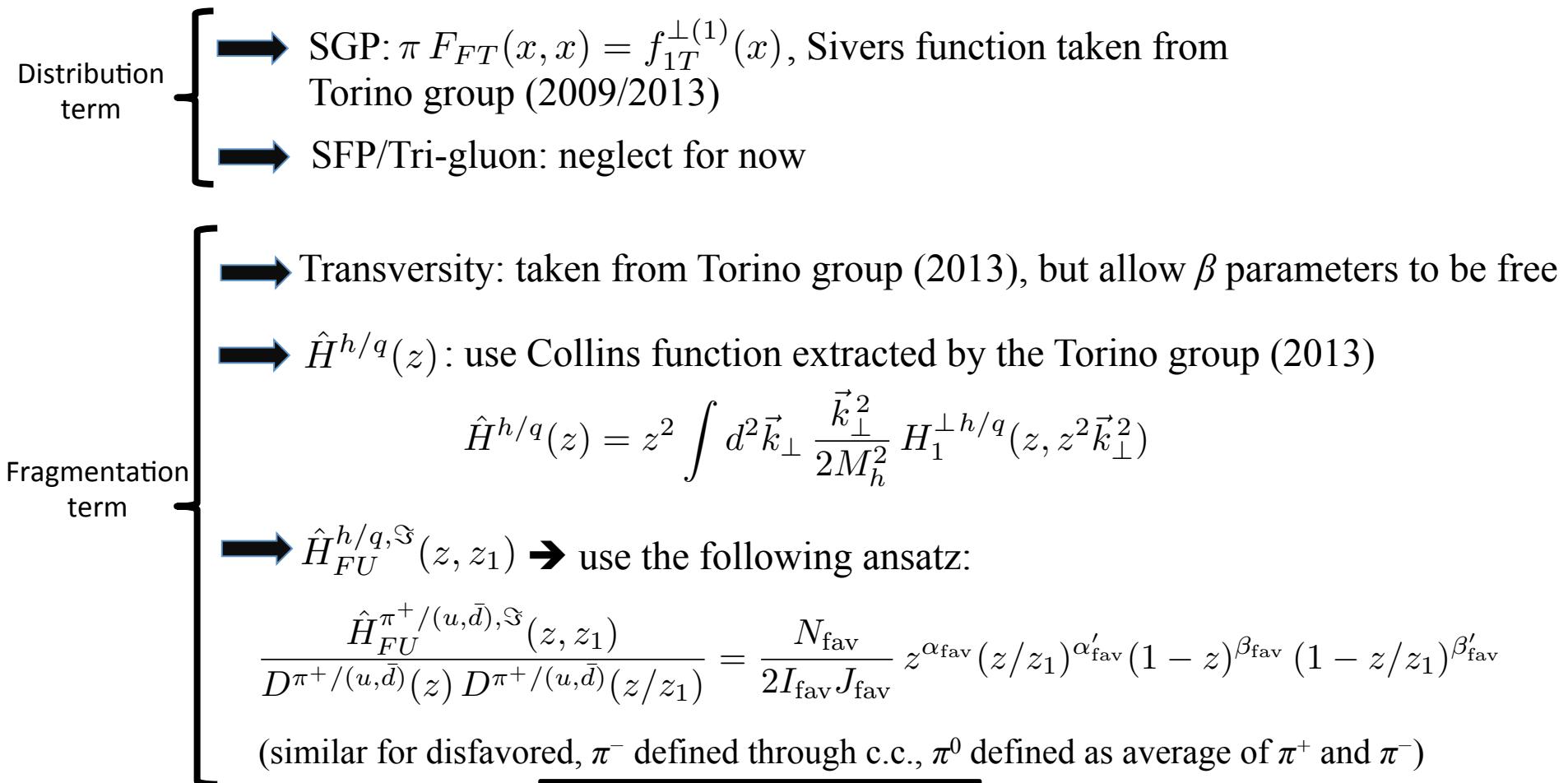
$$\begin{aligned} \frac{P_h^0 d\sigma_{pol}}{d^3 \vec{P}_h} &= -\frac{2\alpha_s^2 M_h}{S} \epsilon_{\perp\mu\nu} S_\perp^\mu P_{h\perp}^\nu \sum_i \sum_{a,b,c} \int_{z_{min}}^1 \frac{dz}{z^3} \int_{x'_{min}}^1 \frac{dx'}{x'} \frac{1}{x'S + T/z} \frac{1}{-x\hat{u} - x'\hat{t}} \\ &\times \frac{1}{x} h_1^a(x)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

(Metz and DP - PLB 723 (2013))

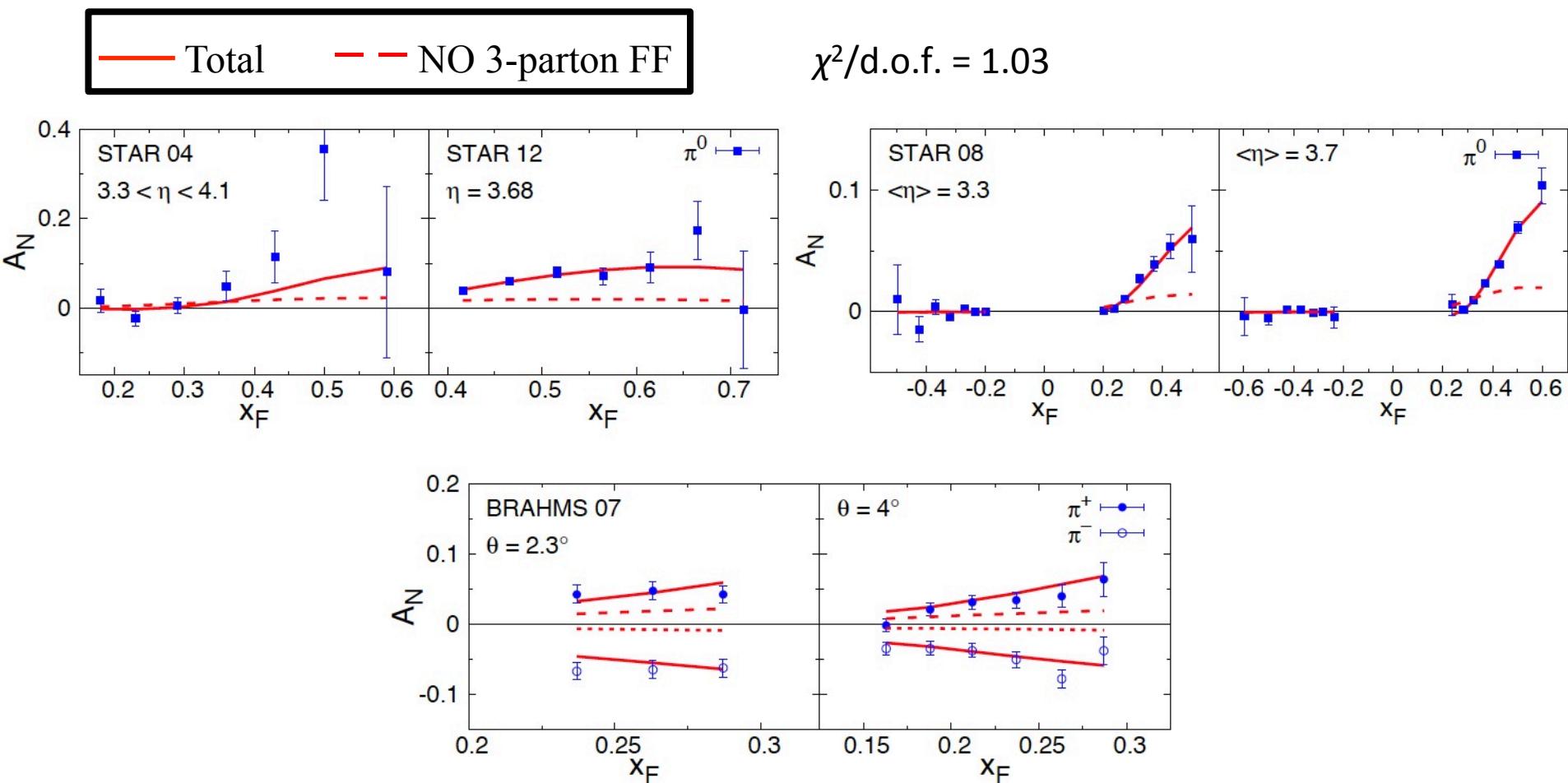


➤ Towards an explanation using twist-3 fragmentation
(Kanazawa, Koike, Metz, DP - PRD 89(RC) (2014))

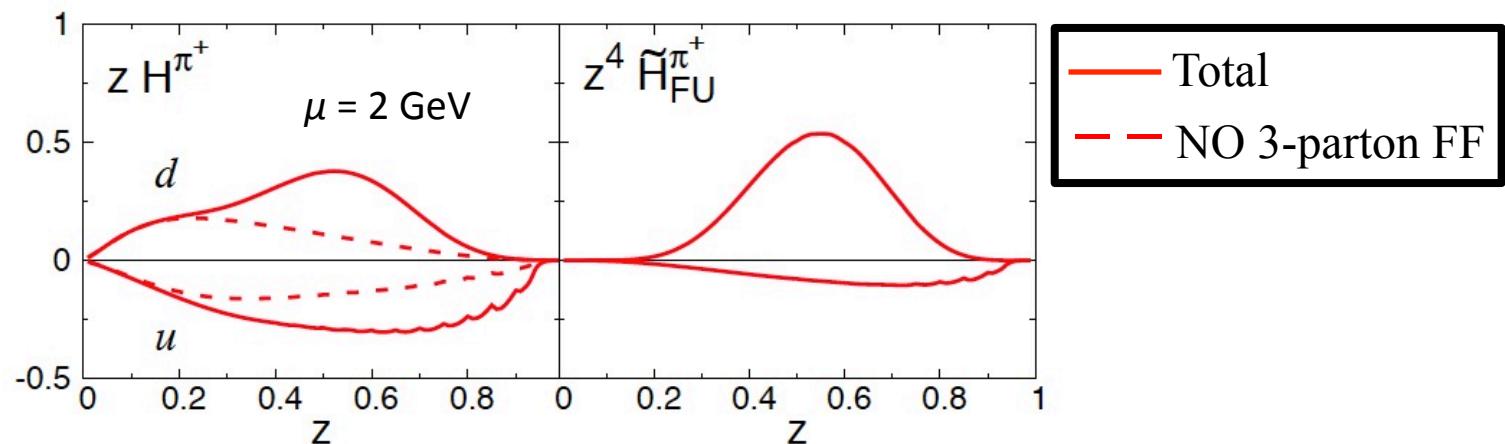
- Numerical study (Note: we only use $\sqrt{S} = 200$ GeV data → higher $P_{h\perp}$ values)



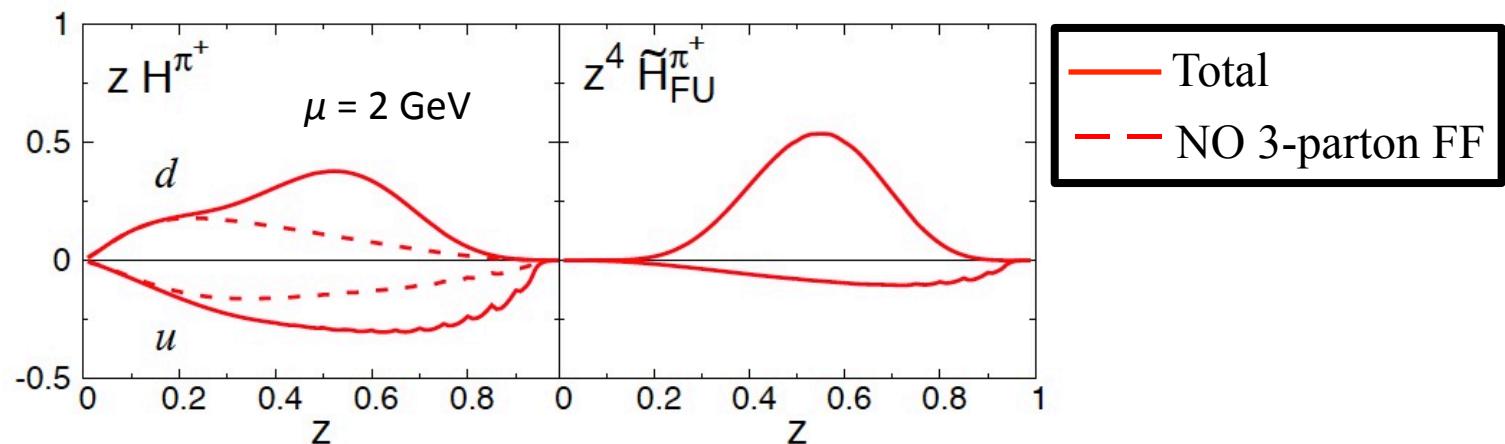
8 free parameters



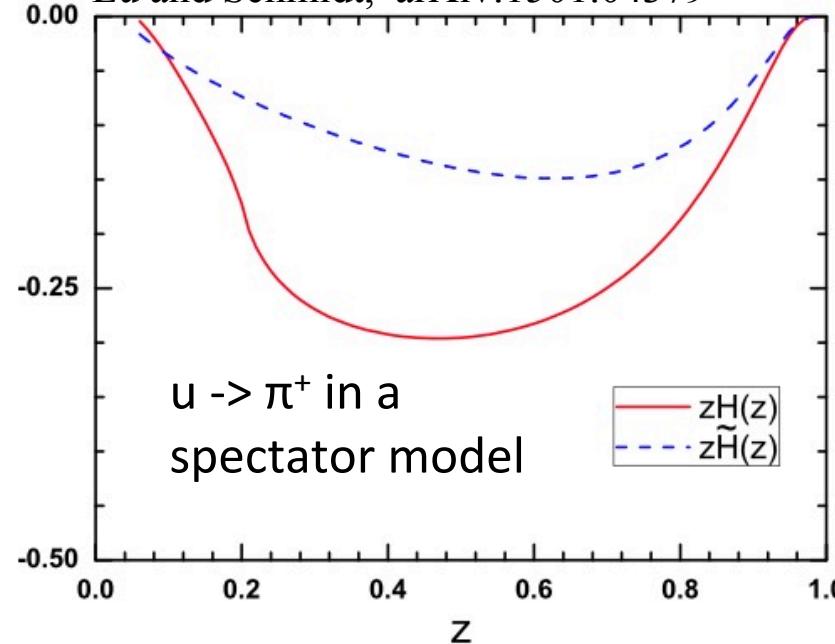
- Including the (total) fragmentation term leads to very good agreement with the RHIC data, especially with its characteristic rise towards large x_F
- Without the 3-parton FF, one has difficulty describing the RHIC data
- H term dominates the asymmetry



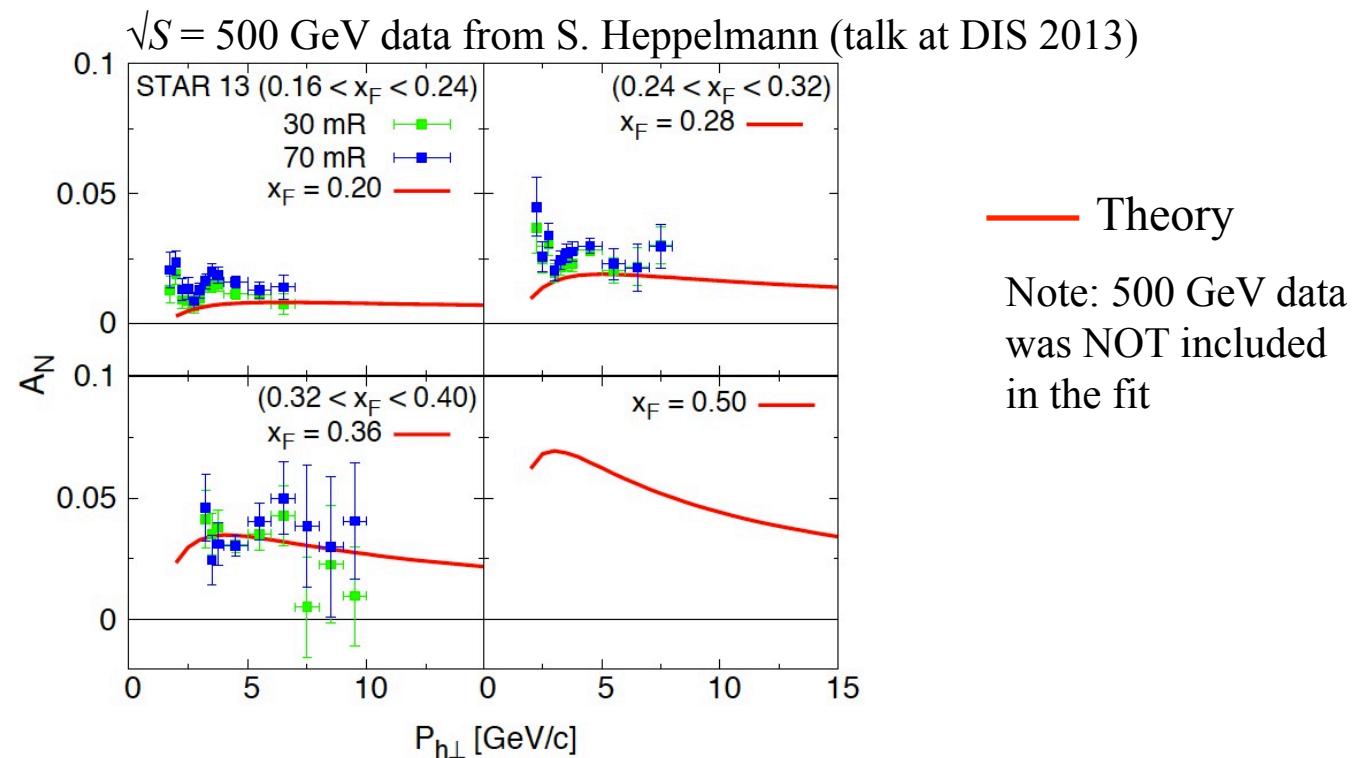
- Favored and disfavored collinear twist-3 FFs are roughly equal in magnitude but opposite in sign



Lu and Schmidt, arXiv:1501.04379



Note: $\tilde{H}(z)$ is not defined with $1/(1-z/z_1)$ factor in the integral



→ Our analysis shows a flat $P_{h\perp}$ dependence for A_N seen so far at RHIC → remains flat even to larger $P_{h\perp}$ values



➤ TSSA in $e N^\dagger \rightarrow \pi X$

(Gamberg, Kang, Metz, DP, Prokudin - PRD **90** (2014))

(see talk by
A. Metz -> DP)

$$\begin{aligned} P_h^0 \frac{d\sigma_{UT}}{d^3 \vec{P}_h} = & -\frac{8\alpha_{\text{em}}^2}{S} \varepsilon_{\perp\mu\nu} S_{P\perp}^\mu P_{h\perp}^\nu \sum_q e_q^2 \int_{z_{\min}}^1 \frac{dz}{z^3} \frac{1}{S+T/z} \frac{1}{x} \\ & \times \left\{ -\frac{\pi M}{\hat{u}} D_1^{h/q}(z) \left(F_{FT}^q(x, x) - x \frac{dF_{FT}^q(x, x)}{dx} \right) \left[\frac{\hat{s}(\hat{s}^2 + \hat{u}^2)}{2\hat{t}^3} \right] \right. \\ & + \frac{M_h}{-x\hat{u} - \hat{t}} h_1^q(x) \left\{ \left(\hat{H}^{h/q}(z) - z \frac{d\hat{H}^{h/q}(z)}{dz} \right) \left[\frac{(1-x)\hat{s}\hat{u}}{\hat{t}^2} \right] \right. \\ & \left. \left. + \frac{1}{z} H^{h/q}(z) \left[\frac{\hat{s}(\hat{s}^2 + (x-1)\hat{u}^2)}{\hat{t}^3} \right] + 2z^2 \int_z^\infty \frac{dz_1}{z_1^2} \frac{1}{\frac{1}{z} - \frac{1}{z_1}} \hat{H}_{FU}^{h/q, \Im}(z, z_1) \left[\frac{x\hat{s}^2\hat{u}}{\xi_z \hat{t}^3} \right] \right\} \right\} \end{aligned}$$

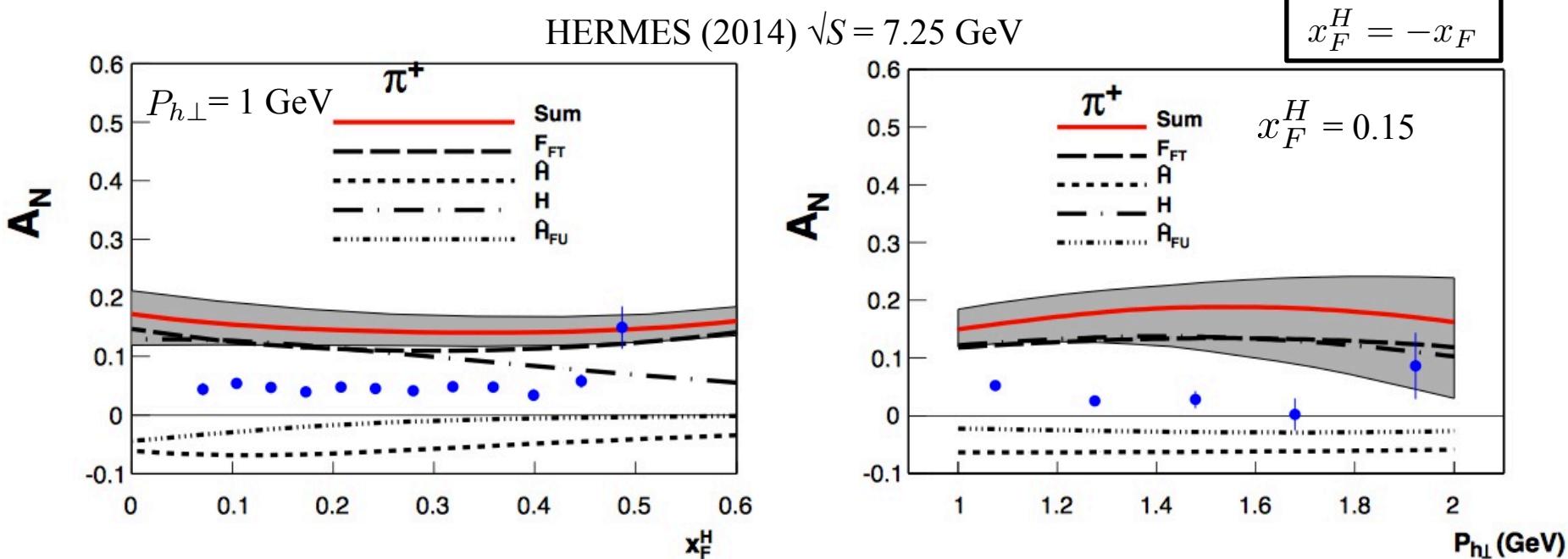
- TSSA in $e N^\uparrow \rightarrow \pi X$
 (Gamberg, Kang, Metz, DP, Prokudin - PRD **90** (2014))

$$\begin{aligned}
 P_h^0 \frac{d\sigma_{UT}}{d^3 \vec{P}_h} = & -\frac{8\alpha_{\text{em}}^2}{S} \varepsilon_{\perp\mu\nu} S_{P\perp}^\mu P_{h\perp}^\nu \sum_q e_q^2 \int_{z_{\min}}^1 \frac{dz}{z^3} \frac{1}{S + T/z} \frac{1}{x} \\
 & \times \left\{ -\frac{\pi M}{\hat{u}} D_1^{h/q}(z) \left(F_{FT}^q(x, x) - x \frac{dF_{FT}^q(x, x)}{dx} \right) \left[\frac{\hat{s}(\hat{s}^2 + \hat{u}^2)}{2\hat{t}^3} \right] \right. \\
 & + \frac{M_h}{-x\hat{u} - \hat{t}} h_1^q(x) \left\{ \hat{H}^{h/q}(z) \left[z \frac{d\hat{H}^{h/q}(z)}{dz} \right] \left[\frac{(1-x)\hat{s}\hat{u}}{\hat{t}^2} \right] \right. \\
 & \left. \left. + \frac{1}{z} H^{h/q}(z) \left[\frac{\hat{s}(\hat{s}^2 + (x-1)\hat{u}^2)}{\hat{t}^3} \right] + 2z^2 \int_z^\infty \frac{dz_1}{z_1^2} \frac{1}{\frac{1}{z} - \frac{1}{z_1}} \hat{H}_{FU}^{h/q, \Im}(z, z_1) \left[\frac{x\hat{s}^2\hat{u}}{\xi_z \hat{t}^3} \right] \right\} \right\}
 \end{aligned}$$

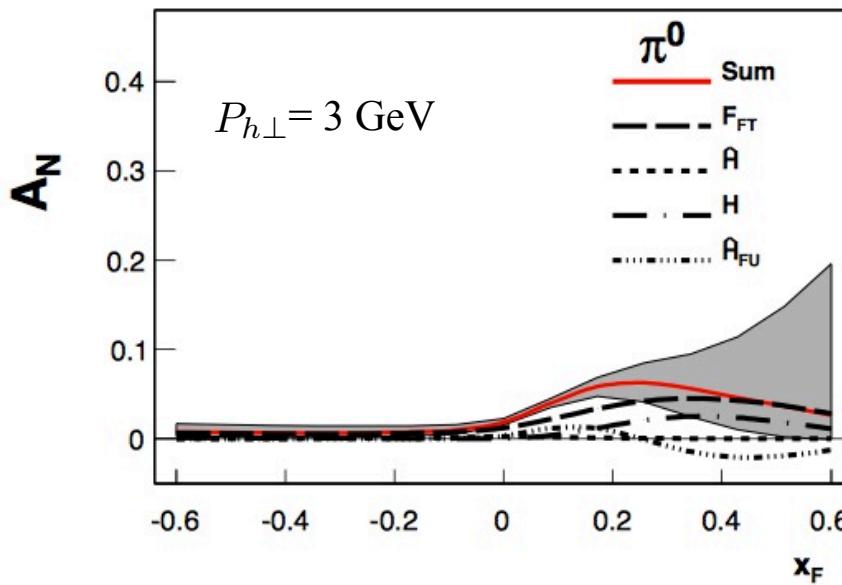
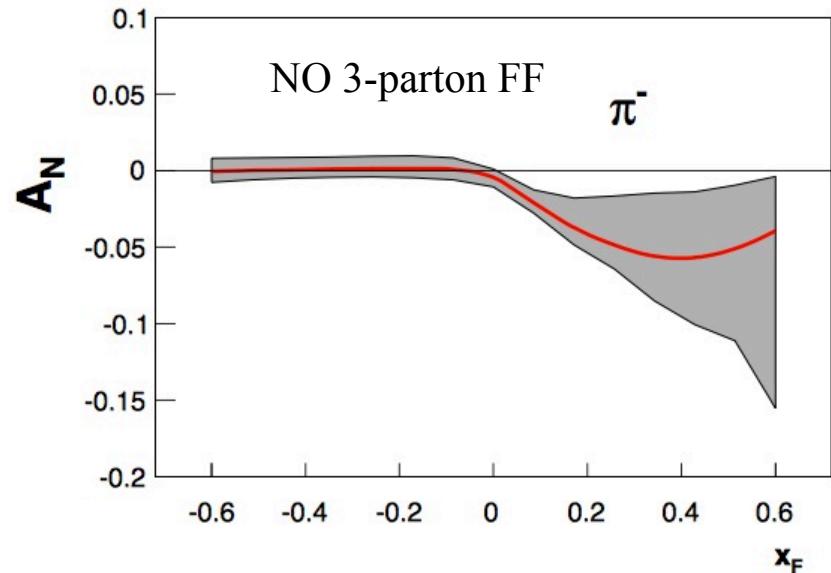
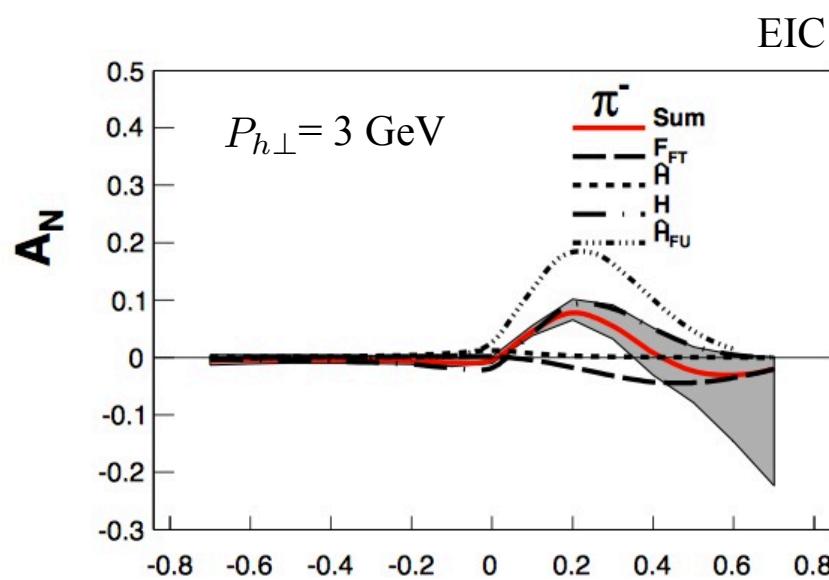
Use Sivers function from SIDIS (Anselmino, et al. (2009))

Use Collins function from SIDIS/ e^+e^- (Anselmino, et al. (2013))

Take from pp fit KKMP



- Theoretical results are above the data, but NLO calculation most likely needed given that the data are dominated by quasi-real photoproduction
- Jefferson Lab Hall A also has data for a neutron target, but $P_{h\perp}$ is too low
→ 12 GeV update will give valuable data at higher $P_{h\perp}$
- This process can help better constrain the 3-parton FF that has been fitted in pp
→ crucial to measure at EIC



- EIC is a unique position to measure A_N in the forward region like in pp collisions
- Clearly nonzero signal ($\sim 10\%$) predicted for π^0 for $x_F > 0$, like in pp
- Can provide further constraints/tests of the mechanism used to describe A_N in pp



- TSSA in $p^\uparrow p \rightarrow \gamma X$
(Kanazawa, Koike, Metz, DP – PRD 91 (2015))

$$E_\gamma \frac{d^3 \Delta \sigma^{\chi-o}}{d^3 \vec{q}} = \frac{\alpha_{em} \alpha_s \pi M_N}{S} \epsilon^{pnqS_\perp} \int \frac{dx'}{x'} \int \frac{dx}{x} \delta(\hat{s} + \hat{t} + \hat{u}) \\ \times \sum_a e_a^2 \left[\left(E_F^a(x, x) - x \frac{dE_F^a(x, x)}{dx} \right) h^{\bar{a}}(x') \frac{\hat{\sigma}_1^{\text{SGP}}}{-\hat{t}} + E_F^a(x, x) h^{\bar{a}}(x') \hat{\sigma}_2^{\text{SGP}} \right]$$

$$E_F \sim H_{FU}$$

$$E_\gamma \frac{d^3 \Delta \sigma^{\chi-e,\text{SGP}}}{d^3 \vec{q}} = -\frac{\alpha_{em} \alpha_s \pi M_N}{S} \frac{\pi M_N}{NC_F} \epsilon^{pnqS_\perp} \int \frac{dx'}{x'} \int \frac{dx}{x} \delta(\hat{s} + \hat{t} + \hat{u}) \\ \times \sum_a e_a^2 \frac{1}{-\hat{u}} \left[\frac{1}{2N} f^{\bar{a}}(x) \hat{\sigma}_{\bar{a}a} - \frac{N}{2} f^g(x) \hat{\sigma}_{ga} \right] \left[x' \frac{dG_F^a(x', x')}{dx'} - G_F^a(x', x') \right]$$

$$E_\gamma \frac{d^3 \Delta \sigma^{\chi-e,\text{SFP}}}{d^3 \vec{q}} = -\frac{\alpha_{em} \alpha_s \pi M_N}{S} \frac{\pi M_N}{2N} \epsilon^{pnqS_\perp} \int \frac{dx'}{x'} \int \frac{dx}{x} \delta(\hat{s} + \hat{t} + \hat{u}) \\ \times \sum_a \left[\sum_b e_a e_b \hat{\sigma}_{ab}^{\text{SFP}} \left\{ G_F^a(0, x') + \tilde{G}_F^a(0, x') \right\} f^b(x) \right. \\ + \sum_b e_a e_b \hat{\sigma}_{a\bar{b}}^{\text{SFP}} \left\{ G_F^a(0, x') + \tilde{G}_F^a(0, x') \right\} f^{\bar{b}}(x) \\ \left. + e_a^2 \hat{\sigma}_{ag}^{\text{SFP}} \left\{ G_F^a(0, x') + \tilde{G}_F^a(0, x') \right\} f^g(x) \right]$$

$$T_F \sim G_F \sim F_{FT}$$

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New result from this work

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$$E_\gamma \frac{d^3 \Delta\sigma^{\chi-e, \text{SGP}}}{d^3 \vec{q}} = -\frac{\alpha_{em} \alpha_s \pi M_N}{S} \frac{\pi M_N}{NC_F} \epsilon^{pnq S_\perp} \int \frac{dx'}{x'} \int \frac{dx}{x} \delta(\hat{s} + \hat{t} + \hat{u}) \\ \times \sum_a e_a^2 \frac{1}{-\hat{u}} \left[\frac{1}{2N} f^{\bar{a}}(x) \hat{\sigma}_{\bar{a}a} - \frac{N}{2} f^g(x) \hat{\sigma}_{ga} \right] \left[x' \frac{dG_F^a(x', x')}{dx'} - G_F^a(x', x') \right]$$

Qiu and Sterman (1992);
 Kouvaris, et al. (2006);
 Gamberg and Kang (2012);
 Gamberg, et al. (2013)

Include fragmentation photons

$$E_\gamma \frac{d^3 \Delta\sigma^{\chi-e, \text{SFP}}}{d^3 \vec{q}} = -\frac{\alpha_{em} \alpha_s \pi M_N}{S} \frac{\pi M_N}{2N} \epsilon^{pnq S_\perp} \int \frac{dx'}{x'} \int \frac{dx}{x} \delta(\hat{s} + \hat{t} + \hat{u}) \\ \times \sum_a \left[\sum_b e_a e_b \hat{\sigma}_{ab}^{\text{SFP}} \left\{ G_F^a(0, x') + \tilde{G}_F^a(0, x') \right\} f^b(x) \right. \\ \left. + \sum_b e_a e_b \hat{\sigma}_{a\bar{b}}^{\text{SFP}} \left\{ G_F^a(0, x') + \tilde{G}_F^a(0, x') \right\} f^{\bar{b}}(x) \right. \\ \left. + e_a^2 \hat{\sigma}_{ag}^{\text{SFP}} \left\{ G_F^a(0, x') + \tilde{G}_F^a(0, x') \right\} f^g(x) \right]$$

Ji, et al. (2006);
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New result from this work

$$E_F \sim H_{FU}$$

$$E_\gamma \frac{d^3 \Delta\sigma^{\chi-e, \text{SGP}}}{d^3 \vec{q}} = -\frac{\alpha_{em} \alpha_s \pi M_N}{S} \frac{\pi M_N}{NC_F} \epsilon^{pnq S_\perp} \int \frac{dx'}{x'} \int \frac{dx}{x} \delta(\hat{s} + \hat{t} + \hat{u}) \\ \times \sum_a e_a^2 \frac{1}{-\hat{u}} \left[\frac{1}{2N} f^{\bar{a}}(x) \hat{\sigma}_{\bar{a}a} - \frac{N}{2} f^g(x) \hat{\sigma}_{ga} \right] \left[x' \frac{dG_F^a(x', x')}{dx'} - G_F^a(x', x') \right]$$

Qiu and Sterman (1992);
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Note: Contribution from tri-gluon correlators calculated by Koike and Yoshida (2012)

Ji, et al. (2006);
 Kanazawa and Koike (2011, 2013)

$$T_F \sim G_F \sim F_{FT} \\ \tilde{T}_F \sim \tilde{G}_F \sim G_{FT}$$



➤ TSSA in $p^\uparrow p \rightarrow \gamma X$
 (Kanazawa, Koike, Metz, DP – PRD 91 (2015))

Use Boer-Mulders function
 from DY (Barone, et al. (2010))

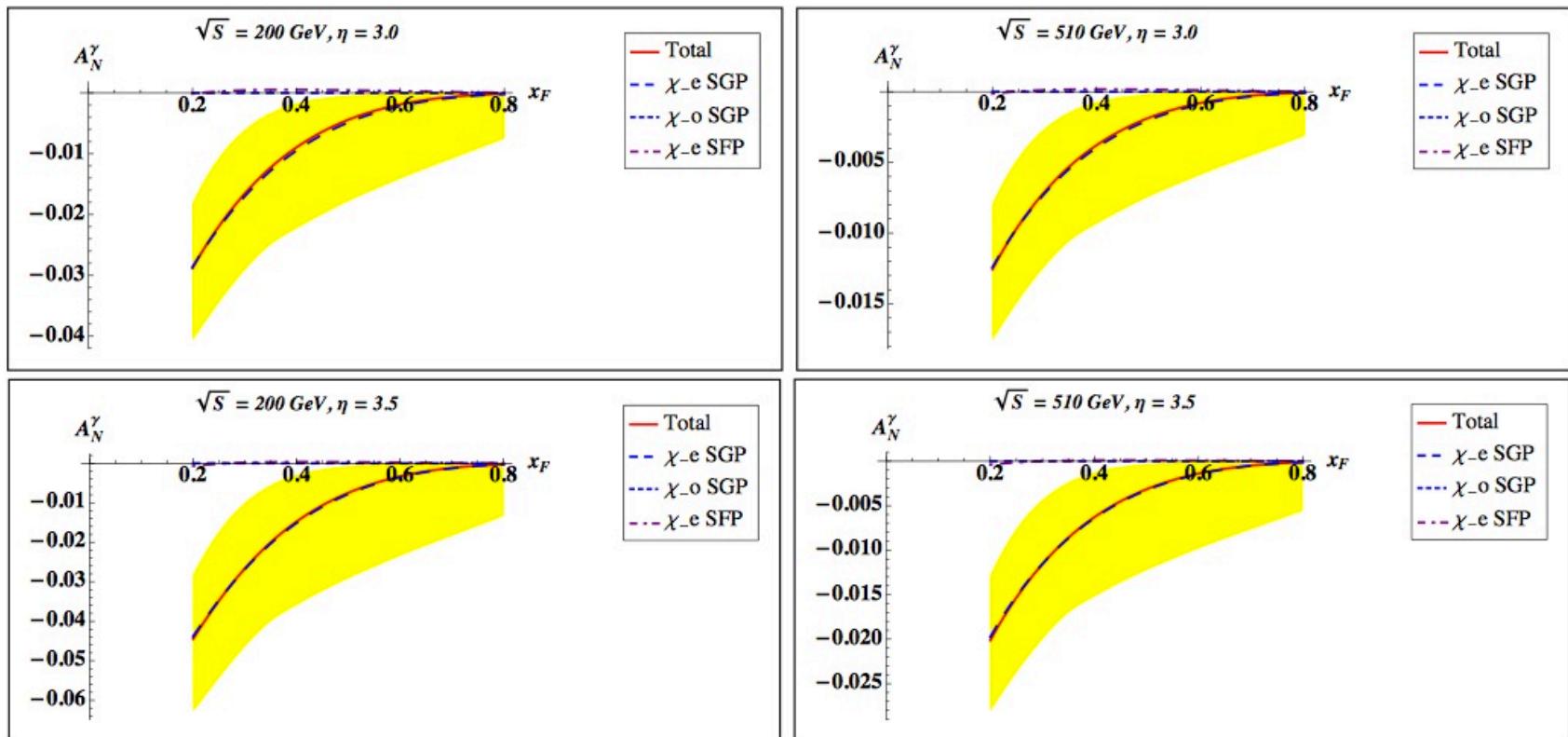
$$E_\gamma \frac{d^3 \Delta\sigma^{\chi-o}}{d^3 \vec{q}} = \frac{\alpha_{em} \alpha_s \pi M_N}{S} \epsilon^{pnqS_\perp} \int \frac{dx'}{x'} \int \frac{dx}{x} \delta(\hat{s} + \hat{t} + \hat{u}) \\ \times \sum_a e_a^2 \left[\left(E_F^a(x, x) - x \frac{dE_F^a(x, x)}{dx} \right) h^{\bar{a}}(x') \frac{\hat{\sigma}_1^{\text{SGP}}}{-\hat{t}} + \boxed{E_F^a(x, x) h^{\bar{a}}(x') \hat{\sigma}_2^{\text{SGP}}} \right]$$

Use Sivers function from
 SIDIS (Anselmino, et al. (2009))

$$E_\gamma \frac{d^3 \Delta\sigma^{\chi-e, \text{SGP}}}{d^3 \vec{q}} = -\frac{\alpha_{em} \alpha_s \pi M_N}{S} \frac{\pi M_N}{NC_F} \epsilon^{pnqS_\perp} \int \frac{dx'}{x'} \int \frac{dx}{x} \delta(\hat{s} + \hat{t} + \hat{u}) \\ \times \sum_a e_a^2 \frac{1}{-\hat{u}} \left[\frac{1}{2N} f^{\bar{a}}(x) \hat{\sigma}_{\bar{a}a} - \frac{N}{2} f^g(x) \hat{\sigma}_{ga} \right] \left[x' \frac{dG_F^a(x', x')}{dx'} - \boxed{G_F^a(x', x')} \right]$$

$$E_\gamma \frac{d^3 \Delta\sigma^{\chi-e, \text{SFP}}}{d^3 \vec{q}} = -\frac{\alpha_{em} \alpha_s \pi M_N}{S} \frac{\pi M_N}{2N} \epsilon^{pnqS_\perp} \int \frac{dx'}{x'} \int \frac{dx}{x} \delta(\hat{s} + \hat{t} + \hat{u}) \\ \times \sum_a \left[\sum_b e_a e_b \hat{\sigma}_{ab}^{\text{SFP}} \left\{ G_F^a(0, x') + \tilde{G}_F^a(0, x') \right\} f^b(x) \right. \\ \left. + \sum_b e_a e_b \hat{\sigma}_{a\bar{b}}^{\text{SFP}} \left\{ G_F^a(0, x') + \tilde{G}_F^a(0, x') \right\} f^{\bar{b}}(x) \right. \\ \left. + e_a^2 \hat{\sigma}_{ag}^{\text{SFP}} \left\{ G_F^a(0, x') + \tilde{G}_F^a(0, x') \right\} f^g(x) \right]$$

Assume
 $G_F(0, x') + \tilde{G}_F(0, x') = G_F(x', x')$



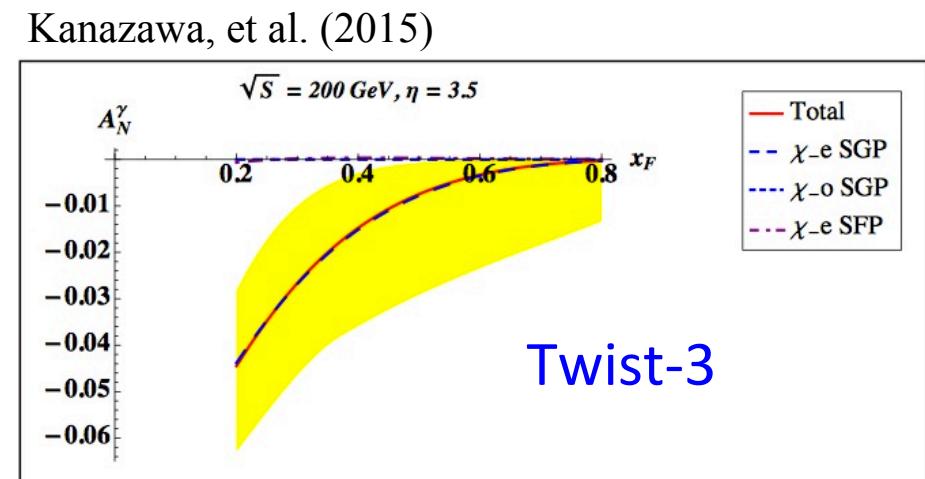
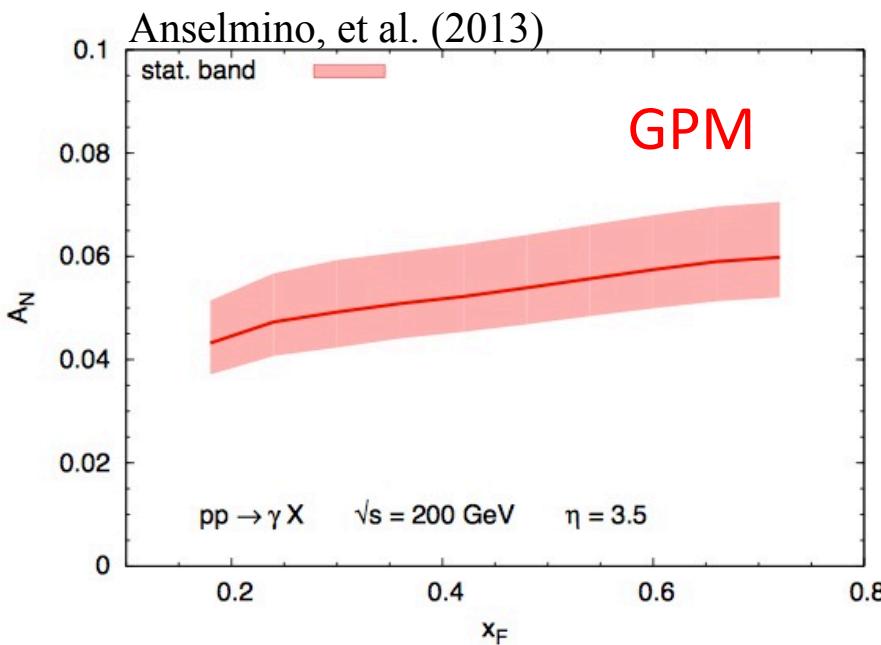
- Measurements planned by PHENIX and STAR at RHIC
- Sivers-type contribution is dominant, others are negligible
 - Can “cleanly” extract QS function to help resolve “sign mismatch” issue
 - Clear measurement of a negative A_N would be a strong indication on the process dependence of the Sivers function (see also TSSA in inclusive DIS – Metz, et al. (2012), and in jet production from A_N DY – Gamberg, Kang, Prokudin (2013))



- GPM has been used to calculate A_N in all of the processes discussed
- How can we distinguish between GPM and twist-3? Which one is “right”?

- GPM has been used to calculate A_N in all of the processes discussed
- How can we distinguish between GPM and twist-3? Which one is “right”?

Answer could be found through A_N in direct photon production



GPM predicts positive asymmetry while twist-3 predicts negative



Summary and outlook

- Collinear twist-3 and GPM both provide frameworks to analyze TSSAs, but the underlying mechanism causing A_N remained unclear for close to 40 years
- Twist-3 fragmentation could finally give us an explanation
 - Describes RHIC pion data very well
 - Our analysis provides a consistency between spin/azimuthal asymmetries in pp (collinear) and SIDIS, e^+e^- (TMD); In particular, the “sign mismatch” is NOT an issue (DO NOT need QS function to be dominant mechanism causing A_N)
 - Future work: include SFPs (can help with charged hadrons), proper evolution of the 3-parton FF; analyze kaons (BRAHMS), etas (PHENIX), and jets (A_N DY, STAR)

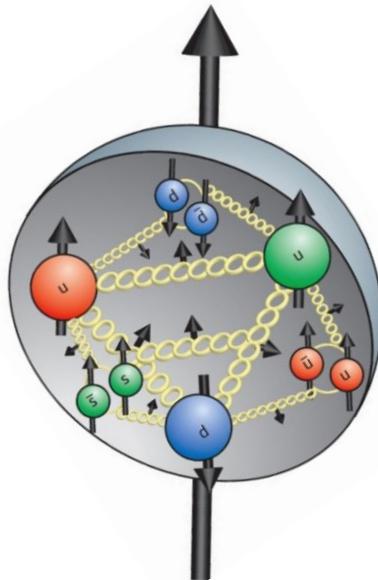


- $e N^\uparrow \rightarrow \pi X$ measurements (both current and future) at HERMES, JLab, COMPASS, and an EIC can provide further tests/constraints
- $p^\uparrow p \rightarrow \gamma X$ (planned to be measured by PHENIX and STAR) can provide a clean extraction of the QS function, test the process dependence of the Sivers function, and distinguish between the twist-3 and GPM formalisms
- Sivers and Collins asymmetries at large $P_{h\perp}$ measured in SIDIS at COMPASS, JLab12, and an EIC also can give valuable information
- Proposed fixed target experiment (AFTER) at the LHC plans to look into TSSAs (see Kanazawa, Koike, Metz, DP, arXiv:1502.04021, to appear in a Special Issue of *Advances in High Energy Physics*)



Further measurements of TSSAs in pp and lN collisions along with continued theoretical work is crucial in order to understand this fundamental hadronic spin physics phenomenon

Backup slides



$$A_N = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + \sigma_R}$$

- Data tells us (if fragmentation mechanism dominates) that the pions care about the transverse spin of the fragmenting quark → fragment in a particular direction (left or right)
- Small and negative x_F → probe sea quarks and gluons in p^\uparrow
 - $gg \rightarrow gg$ channel gives large contribution to unpolarized cross section, but NO gluon “transversity” → no such channel in spin-dependent cross section
 - Little information on sea quark “transversity” → might speculate sea quarks, on average, are less likely to emerge from p^\uparrow with a transverse spin in a certain direction
- Large x_F → probe valence quarks in p^\uparrow
 - From SIDIS we know u quarks (d quarks) are more likely emerge from p^\uparrow with their transverse spin aligned (anti-aligned) with p^\uparrow → pions more likely to fragment in a particular direction (left or right)
 - $gg \rightarrow gg$ channel dies out in this region → unpolarized cross section becomes smaller



Unpolarized FF (DSS)

Unpolarized PDF (GRV98)

Distribution term (SGP)

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

Fragmentation term

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

Transversity PDF (Torino13)

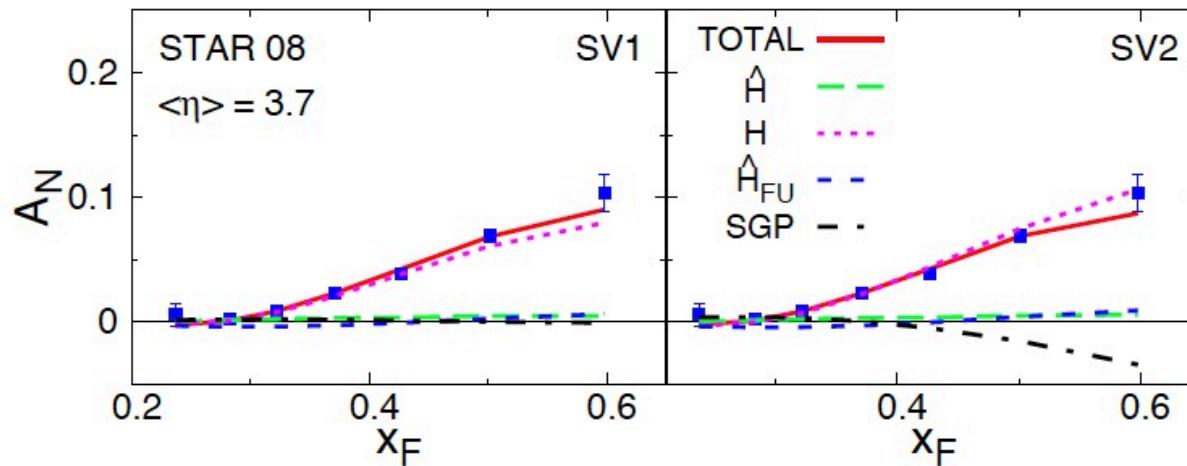
Recall: $H^{h/q}(z) = -2z\hat{H}^{h/q}(z) + 2z^3 \int_z^\infty \frac{dz_1}{z_1^2} \frac{1}{\frac{1}{z} - \frac{1}{z_1}} \hat{H}_{FU}^{h/q, \Im}(z, z_1)$



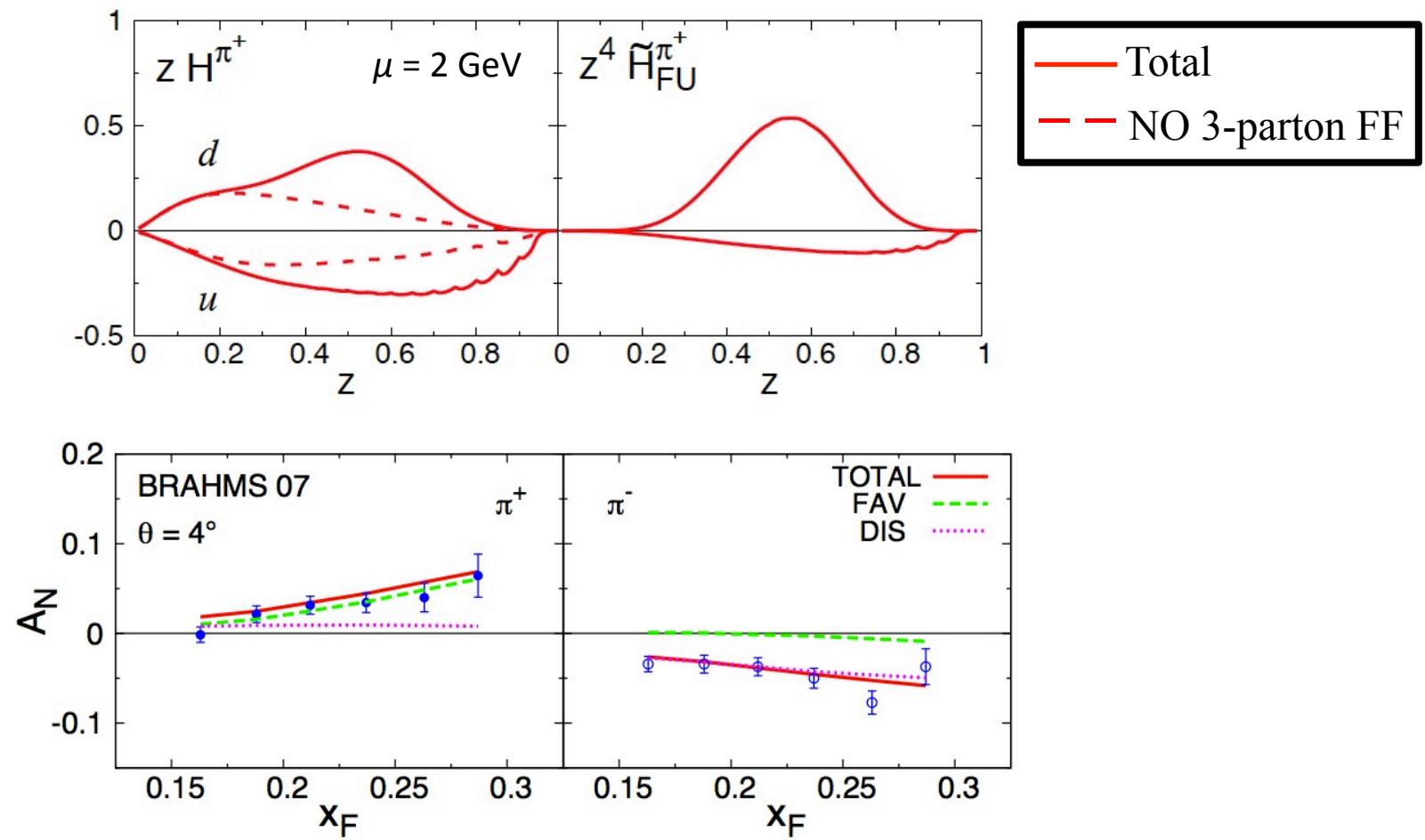
8 free parameters: N_{fav} , $\alpha_{fav} = \alpha'_{fav}$, β_{fav} , $\beta'_{fav} = \beta'_{dis}$
 N_{dis} , $\alpha_{dis} = \alpha'_{dis}$, β_{dis} , $\beta_u^T = \beta_d^T$

$\chi^2/\text{d.o.f.} = 1.03$	
$N_{\text{fav}} = -0.0338$	$N_{\text{dis}} = 0.216$
$\alpha_{\text{fav}} = \alpha'_{\text{fav}} = -0.198$	$\beta_{\text{fav}} = 0.0$
$\beta'_{\text{fav}} = \beta'_{\text{dis}} = -0.180$	$\alpha_{\text{dis}} = \alpha'_{\text{dis}} = 3.99$
$\beta_{\text{dis}} = 3.34$	$\beta_u^T = \beta_d^T = 1.10$

→ Above parameters are from using 2009 Sivers function (SV1). Using 2013 Sivers function (SV2) gives similar values and $\chi^2/\text{d.o.f.} = 1.10$

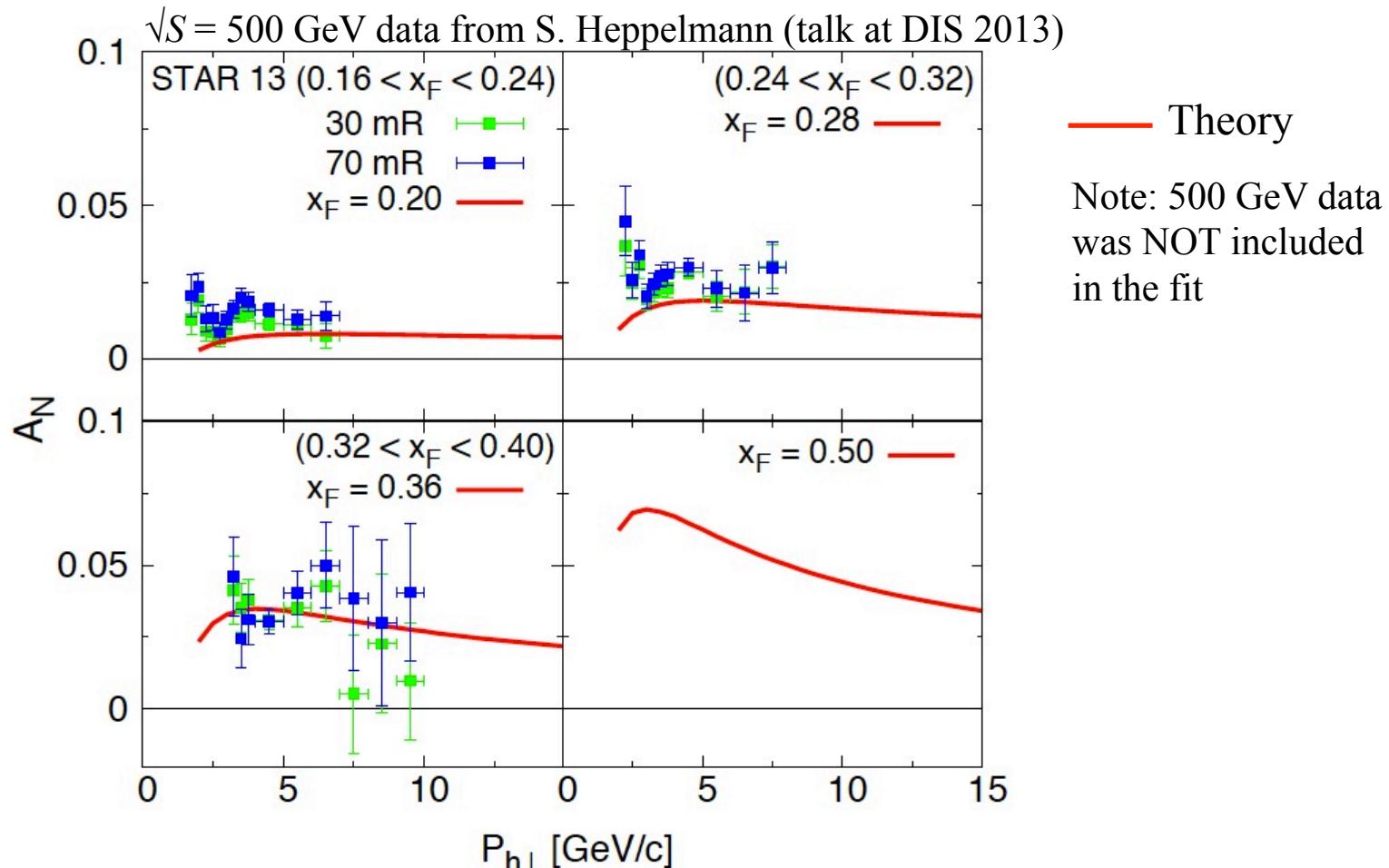


- H term is dominant; Sivers-type, Collins-type, and \hat{H}_{FU} terms are negligible
- SV1 – 2009 Sivers function from Torino group → flavor-*independent* large- x behavior
- SV2 – 2013 Sivers function from Torino group → flavor-*dependent* large- x behavior and slower decrease at large- x than SV1
 - Including 3-parton FF, one can accommodate such a Sivers function through the H term
 - Without the 3-parton FF, one would have serious issues handling such a (negative) SGP contribution to obtain a (large) positive A_N



- Favored and disfavored (chiral-odd) collinear twist-3 FFs are roughly equal in magnitude but opposite in sign → similar to Collins FF
- A_N for π^+ (π^-) dominated by favored (disfavored) fragmentation

- Flat P_T dependence thought to be an issue for collinear twist-3 approach $\rightarrow A_N \sim 1/P_T$
- First argued by Qiu and Sterman (1998) and later shown by Kanazawa and Koike (2011) that this does not have to be the case



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

