# Collinear Twist-3 Factorization in Proton-Proton Collisions

(A. Metz, Temple University)

- Transverse single-spin asymmetries (SSAs) in proton-proton collisions and in semi-inclusive DIS

- Transverse momentum dependent parton correlators (TMDs)
  - Sivers function and Collins function, and their properties
  - Generalized Parton Model and transverse SSA $A_N$ in $p^\uparrow p \to h\,X$

    $\to$ see also talks by Prokudin, Pisano, ...

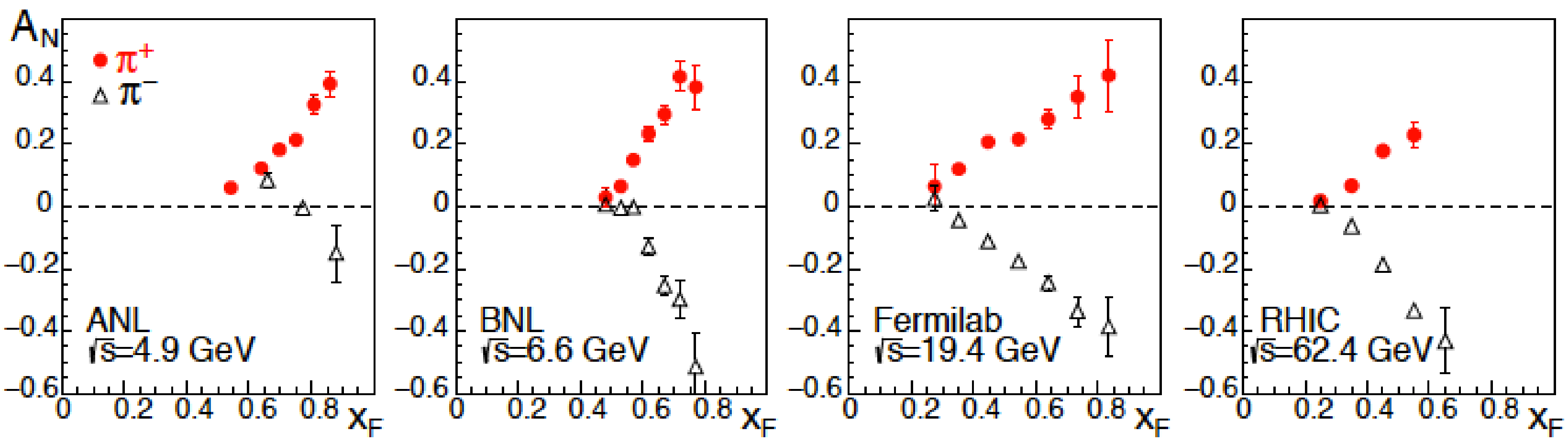
- Transverse single-spin asymmetries in collinear twist-3 approach
  - $A_N$ in $p^\uparrow p \to h\,X$
  - $A_N$ in $\ell\,N^\uparrow \to \ell\,X$
  - $A_N$ in $p^\uparrow p \to \gamma\,X$

- Summary

## Transverse SSA in $p^{\uparrow}p \to \pi X$: Data

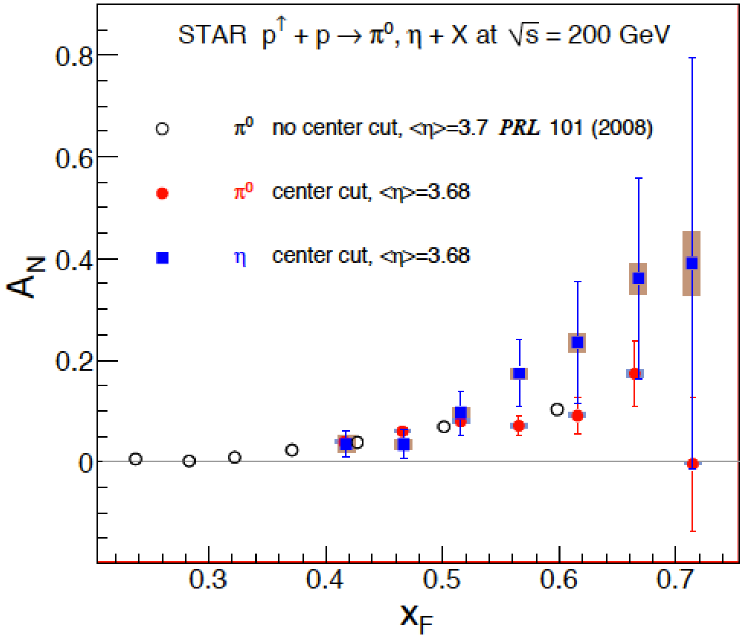
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \sim \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}$$

- Charged pions: sample data

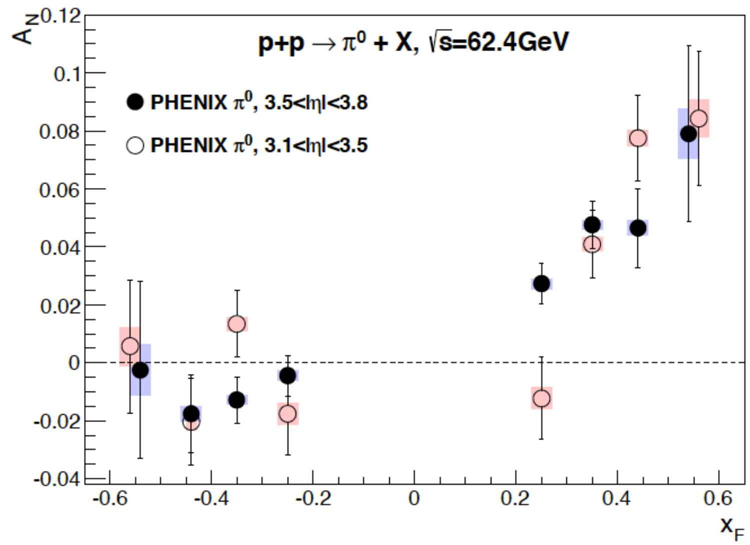



(from Aidala, Bass, Hasch, Mallot, 2012)

- Neutral pions: sample data




STAR, 2012 $\sqrt{s} = 200\,\mathrm{GeV}$



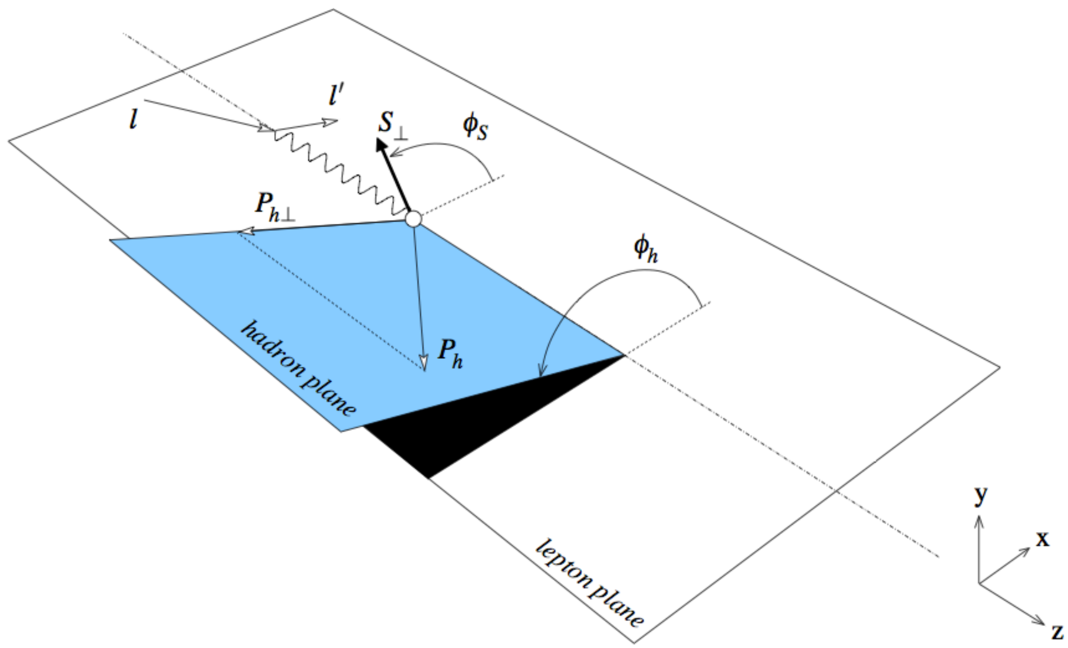

PHENIX, 2013 $\sqrt{s} = 62.4\,\mathrm{GeV}$

- General features
  - very striking effects at large $x_F$
  - $A_N$ survives at large $\sqrt{s}$
  - $A_N^{\pi^+}$ and $A_N^{\pi^-}$ have roughly same magnitude but opposite sign
  - $A_N^{\pi^0}$ systematically smaller than $A_N^{\pi^\pm}$
  - $A_N$ is twist-3 observable and cannot be explained in collinear parton model
  - data on transverse SSAs represent 40-year old puzzle

# Transverse SSAs in $\ell N^{\uparrow} \to \ell h X$

- Kinematical variables and structure of cross section

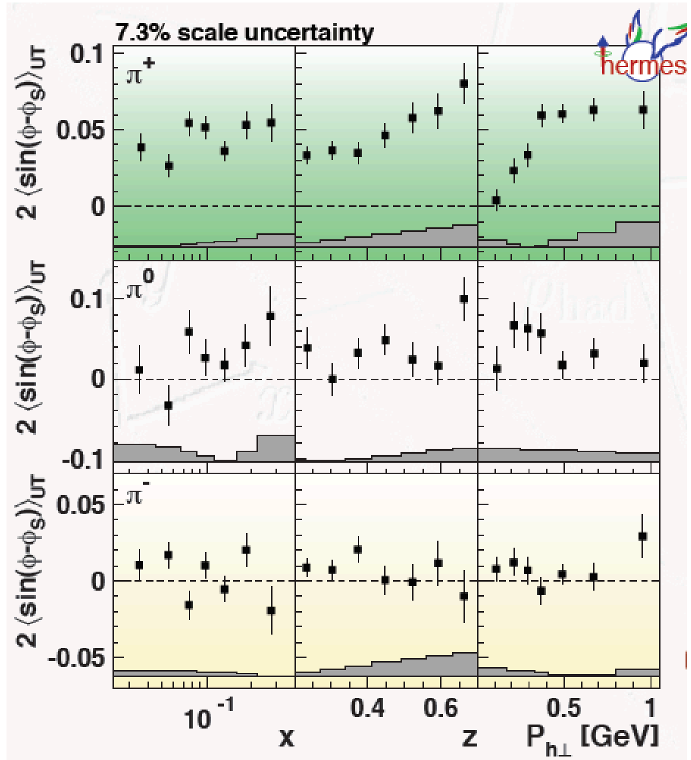
$$x \quad Q^2 \quad \phi_S \quad z \quad P_{h\perp} \quad \phi_h$$



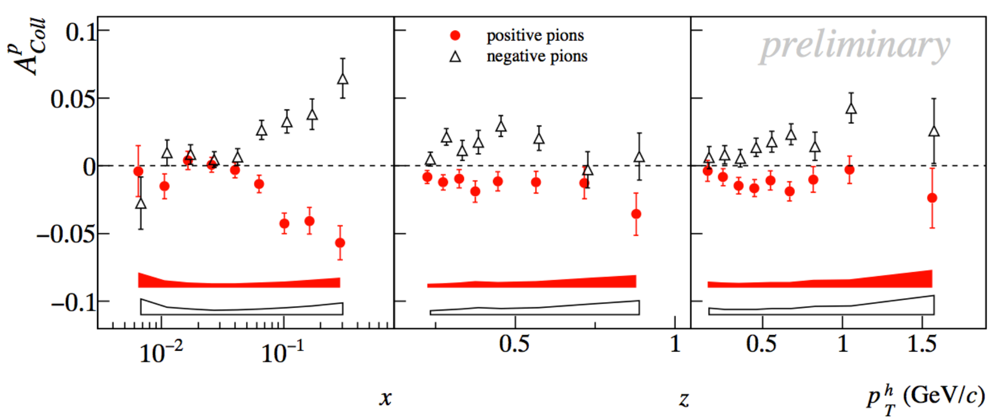

  - 18 structure functions (model-independent)
  - At low $P_{h\perp}$, 8 structure functions are related to 8 leading twist TMDs
  - Transverse target polarization: Sivers component and Collins component

$$d\sigma^{\uparrow} \sim \sin(\phi_h - \phi_S)\, f_{1T}^{\perp} \otimes D_1 + \sin(\phi_h + \phi_S)\, h_1 \otimes H_1^{\perp} + \ldots$$

- Sivers asymmetry: sample data (HERMES)




- Collins asymmetry: sample data (COMPASS)



# TMDs: Definition

- Definition: unpolarized quarks in transversely polarized nucleon

$$\Phi^{[\gamma^+]q}(x, \vec{k}_T) = \frac{1}{2} \int \frac{d\xi^-}{2\pi} \frac{d^2\vec{\xi}_T}{(2\pi)^2} e^{ik\cdot\xi} \langle P, S | \bar{\psi}^q(0) \gamma^+ \mathcal{W}_{TMD} \psi^q(\xi^-, \vec{\xi}_T) | P, S \rangle$$

$$= f_1^q(x, \vec{k}_T^2) - \frac{\vec{S}_T \cdot (\hat{P} \times \vec{k}_T)}{M} f_{1T}^{\perp q}(x, \vec{k}_T^2)$$

- 3-D structure in $(x, \vec{k}_T)$-space

- Sivers function $f_{1T}^{\perp}$ describes strength of correlation $\vec{S}_T \cdot (\hat{P} \times \vec{k}_T)$ (Sivers, 1989)

- Also: TMD quark fragmentation functions (FFs) for $q(s_q, k) \to h(P_h) + X$
  Collins function $H_1^{\perp}$ describes strength of correlation $\vec{s}_{qT} \cdot (\hat{k} \times \vec{P}_{hT})$ (Collins, 1992)

- Sivers function and Collins function can give rise to SSAs in scattering processes

# Flavor Structure of Sivers Function

- Large-$N_c$ result (Pobylitsa, 2003)

$$f_{1T}^{\perp u} = -f_{1T}^{\perp d}$$

- Relation to GPD $E$ and anomalous magnetic moment (Burkardt, 2002)

$$f_{1T}^{\perp a} \sim \kappa^a$$

  - relation is model-dependent (Meissner, A.M., Goeke, 2007)
  - predicted correct sign of Sivers asymmetry in SIDIS

- Burkardt sum rule: conservation of transverse momentum (Burkardt, 2004)
  - average transverse momentum of quark in transversely polarized nucleon

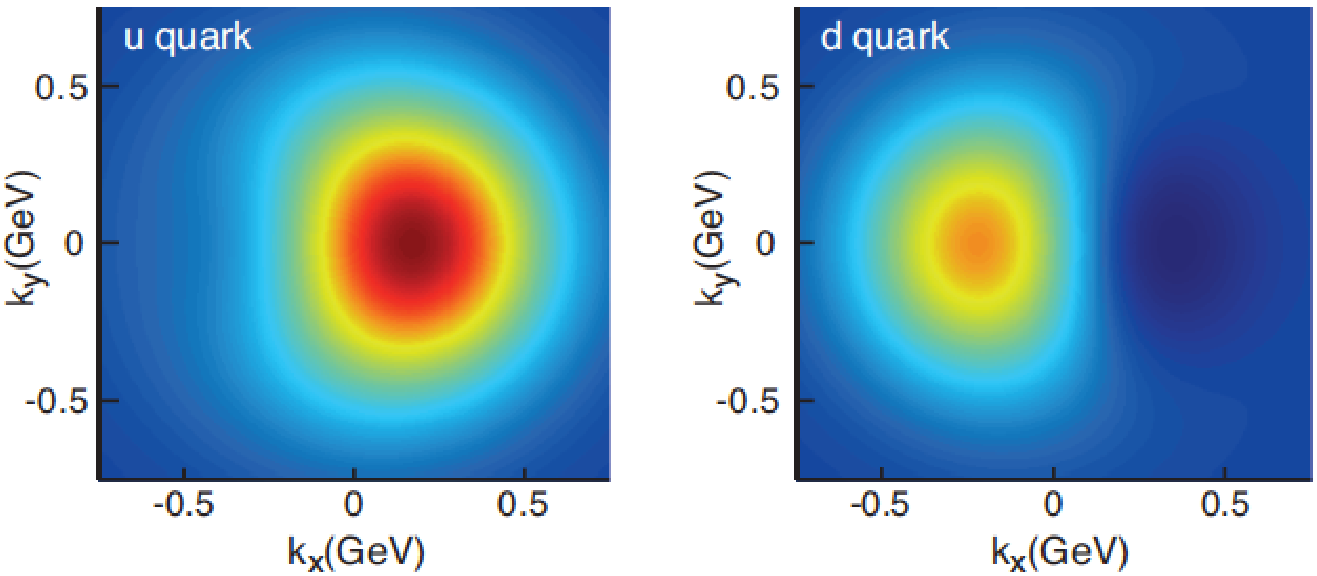
$$\begin{aligned}\langle k_T^i(x)\rangle &= \int d^2k_T\, k_T^i\, \Phi^{[\gamma^+]}(x,\vec{k}_T) \\ &= \varepsilon_T^{ij} S_T^j\, f_{1T}^{\perp(1)}(x) \quad \text{with} \;\; f_{1T}^{\perp(1)}(x) = \int d^2\vec{k}_T\, \frac{\vec{k}_T^{\,2}}{2M^2}\, f_{1T}^{\perp}(x,\vec{k}_T^{\,2})\end{aligned}$$

  - sum rule

$$\sum_a \int_0^1 dx\, \langle k_T^{i,a}(x)\rangle = 0 \quad \rightarrow \quad \sum_a \int_0^1 dx\, f_{1T}^{\perp(1)\,a} = 0$$

- Comparison with extractions from data
  - first extraction of $f_{1T}^{\perp}$: Efremov et al, 2005
  - various (improved) extractions available by now

$$\Phi^{[\gamma^+]}(x,\vec{k}_T) = f_1^q(x,\vec{k}_T^{\,2}) - \frac{\vec{S}_T\cdot(\hat{P}\times\vec{k}_T)}{M}\, f_{1T}^{\perp q}(x,\vec{k}_T^{\,2}) \qquad (x=0.1)$$




(from arXiv:1212.1701, based on Anselmino et al, 2011)

  - Sivers effect generates distorted distribution of unpolarized quarks
  - agreement with large-$N_c$ prediction $f_{1T}^{\perp u} = -f_{1T}^{\perp d}$

# Flavor Structure of Collins Function

- Schäfer-Teryaev sum rule: conservation of transverse momentum
  (Schäfer, Teryaev, 1999 / Meissner, A.M., Pitonyak, 2010)
  - average transverse momentum of hadron in transversely polarized quark

$$\langle P_T^i(z)\rangle \sim H_1^{\perp(1)}(z) \quad \text{with} \quad H_1^{\perp(1)}(z) = z^2 \int d^2\vec{k}_T \, \frac{\vec{k}_T^{\,2}}{2M_h^2} \, H_1^{\perp}(z, z^2\vec{k}_T^{\,2})$$

  - sum rule

$$\sum_h \int_0^1 dz \, \langle P_T^{i,h}(z)\rangle = 0 \quad \to \quad \sum_h \int_0^1 dz \, z M_h \, H_1^{\perp(1)\,h} = 0$$

  - implication: consider fragmentation into (charged) pions only

$$H_1^{\perp,\text{fav}} = H_1^{\perp,\pi^+/u} = H_1^{\perp,\pi^-/d} \qquad\qquad H_1^{\perp,\text{dis}} = H_1^{\perp,\pi^-/u} = H_1^{\perp,\pi^+/d}$$

$$\to \quad H_1^{\perp,\text{fav}} \sim -H_1^{\perp,\text{dis}}$$

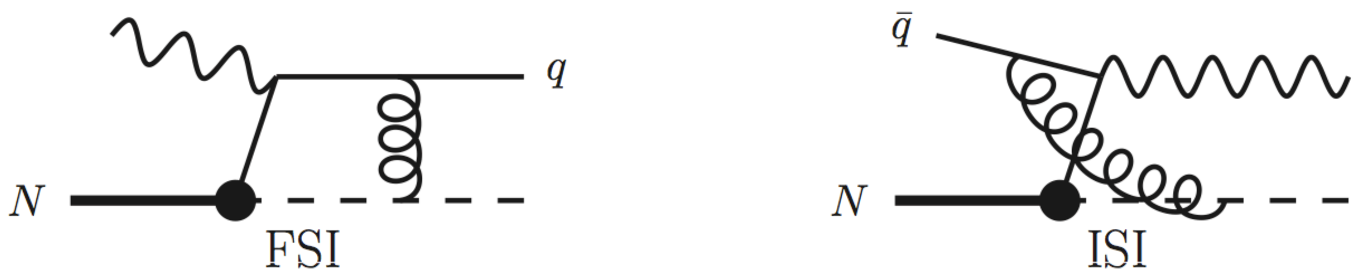
in agreement with information on $A_{\text{SIDIS}}^{\text{Col}}$ from experiment (HERMES, 2004)

# Universality Properties of TMDs

- Prediction based on operator definition in quantum field theory (Collins, 2002)

$$f_{1T}^{\perp}\big|_{DY} = -\, f_{1T}^{\perp}\big|_{SIDIS}$$

- Underlying physics: re-scattering of active partons with hadron remnants:
  Final state interaction in semi-inclusive DIS vs Initial state interaction in Drell-Yan
  (Brodsky, Hwang, Schmidt, 2002)
  $\rightarrow$ change in the direction of $\mathcal{W}_{TMD}$

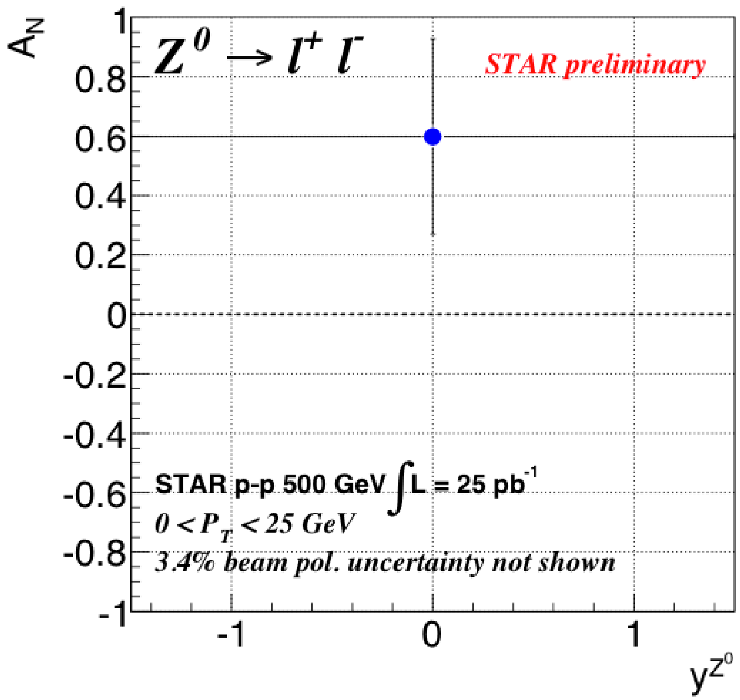



  - FSI and ISI provide imaginary part, but lead to opposite sign
  - check is crucial test of TMD factorization and collinear twist-3 factorization; mind matching of two approaches (Ji, Qiu, Vogelsang, Yuan, 2006)

- Several labs worldwide aim at measurement of Sivers effect in Drell-Yan:
  BNL, CERN, FermiLab, GSI, IHEP, JINR, J-PARC

- Experimental verification of sign reversal is pending (DOE milestone HP13!)

- STAR measurement of $A_N$ for $p^\uparrow p \to W^\pm X$ and $p^\uparrow p \to Z^0 X$




  - very interesting measurement
  - agrees with expected sign
  - however, theoretical prediction has large uncertainties ($f_{1T}^{\perp \bar{q}}$, evolution, ...)

- Universality of TMD fragmentation functions (A.M., 2002 / Collins, A.M., 2004 / ... )

$$H_1^\perp|_{SIDIS} = H_1^\perp|_{e^+e^-}$$

  - nontrivial result
  - agrees with existing phenomenology

## Generalized Parton Model and Flavor Structure of $A_N$

(Anselmino, Boglione, Murgia, 1994 / ...)

- Assumes TMD factorization for unpolarized and polarized cross section in $pp \to hX$

$$d\sigma = H \otimes \Phi(x_a, \vec{k}_{Ta}) \otimes \Phi(x_b, \vec{k}_{Tb}) \otimes \Delta(z, \vec{k}_{Tc})$$

- Main advantages
  - decent description of twist-2 unpolarized cross section at LO
  - can mimic effects of higher order corrections of collinear treatment
  - contains certain kinematical higher twist effects that may be important
  - provides simple intuitive picture of $A_N$ (through Sivers and Collins mechanisms)

- Main drawbacks
  - no derivation of TMD factorization
  - (arbitrary) infrared cutoff for $k_T$ integrations needed
  - physics of ISI/FSI for Sivers effect not taken into account ($\to$ different source?)
  - especially twist-3 observables in GPM and collinear twist-3 approach differ

Example: $A^{DIS}_{LT,tw-3} \sim g_T \qquad A^{DIS}_{LT,GPM} \sim g_{1T}$

- Flavor structure of $A_N$ (use: no antiquarks, dominance of $qg \to qg$ channel)
  - Sivers contribution

$$d\sigma^{\uparrow}_{\rm Siv}(\pi^+) \;\sim\; f_{1T}^{\perp u} \otimes f_1^g \otimes D_1^{\rm fav} + f_{1T}^{\perp d} \otimes f_1^g \otimes D_1^{\rm dis}$$

$$d\sigma^{\uparrow}_{\rm Siv}(\pi^-) \;\sim\; f_{1T}^{\perp d} \otimes f_1^g \otimes D_1^{\rm fav} + f_{1T}^{\perp u} \otimes f_1^g \otimes D_1^{\rm dis}$$

    * can explain reversed sign for $A_N^{\pi^+}$ and $A_N^{\pi^-}$
    * partial cancellation between favored and disfavored fragmentation

  - Collins contribution

$$d\sigma^{\uparrow}_{\rm Col}(\pi^+) \;\sim\; h_1^u \otimes f_1^g \otimes H_1^{\perp,\rm fav} + h_1^d \otimes f_1^g \otimes H_1^{\perp,\rm dis}$$

$$d\sigma^{\uparrow}_{\rm Col}(\pi^-) \;\sim\; h_1^d \otimes f_1^g \otimes H_1^{\perp,\rm fav} + h_1^u \otimes f_1^g \otimes H_1^{\perp,\rm dis}$$

    * $h_1^u$ and $h_1^d$ have opposite signs
    * can explain reversed sign for $A_N^{\pi^+}$ and $A_N^{\pi^-}$, and nonzero $A_N^{\pi^0}$ as $|h_1^u| > |h_1^d|$
    * favored and disfavored fragmentation have the same sign
    * can be larger than Sivers contribution

# Transverse SSA in $p^{\uparrow}p \to h\,X$ in Twist-3 Factorization

- Estimate in naïve (twist-2) parton model (Kane, Pumplin, Repko, 1978)

$$A_N \sim \alpha_s \frac{m_q}{P_{h\perp}} \qquad \text{Note: } A_N \not\sim \alpha_s \frac{m_q}{\sqrt{s}}$$

  - $\alpha_s$ due to NLO graphs needed for imaginary part
  - transverse spin effects proportional to mass of polarized particle
  - calculation clearly reveals twist-3 nature of $A_N$

- Collinear twist-3 factorization in full glory ($P_{h\perp}$ is the only scale)
(Ellis, Furmanski, Petronzio, 1983 / Efremov, Teryaev, 1983, 1984 /
Qiu, Sterman, 1991, 1998 / Koike et al, 2000, ... / etc.)

  - General structure of cross section

$$\begin{aligned}
d\sigma^{\uparrow} &= H \otimes f_{a/A(3)} \otimes f_{b/B(2)} \otimes D_{C/c(2)} && \rightarrow \quad \text{Sivers-type} \\
&+ H' \otimes f_{a/A(2)} \otimes f_{b/B(3)} \otimes D_{C/c(2)} && \rightarrow \quad \text{Boer-Mulders-type} \\
&+ H'' \otimes f_{a/A(2)} \otimes f_{b/B(2)} \otimes D_{C/c(3)} && \rightarrow \quad \text{"Collins-type"}
\end{aligned}$$

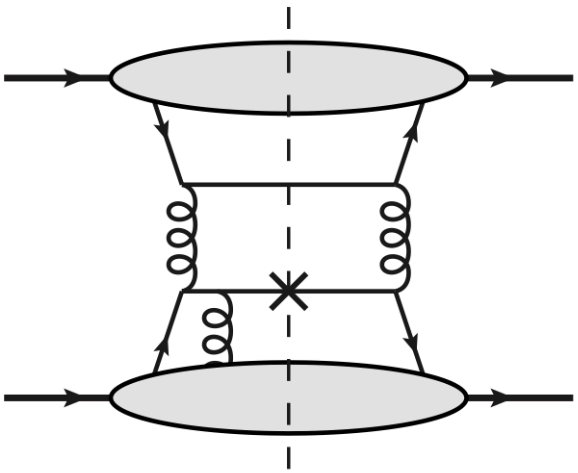
– Sivers-type contribution

∗ contribution from QS function $T_F$ (Qiu, Sterman,1991)

$$\int \frac{d\xi^- d\zeta^-}{4\pi} e^{ixP^+\xi^-} \langle P, S|\bar{\psi}^q(0)\,\gamma^+\,F_{QCD}^{+i}(\zeta^-)\,\psi^q(\xi^-)|P, S\rangle = -\varepsilon_T^{ij} S_T^j\, T_F^q(x,x)$$

vanishing gluon momentum $\rightarrow$ soft gluon pole matrix element

∗ sample diagram for $qq \rightarrow qq$ channel



$\rightarrow$ quark propagator goes on-shell for vanishing gluon momentum

$\rightarrow$ provides required imaginary part

$\rightarrow$ attach extra gluon in all possible ways and consider all graphs and channels

$\rightarrow$ contributions from both ISI and FSI

* generic structure of $d\sigma^{\uparrow}_{\rm Siv}$

$$d\sigma^{\uparrow}_{\rm Siv} \sim \sum_i \sum_{a,b,c} H^i \otimes T^a_F(x_a, x_a) \otimes f^b_1 \otimes D^c_1 \qquad \rightarrow \quad \text{SGPs}$$

$$+ \sum_i \sum_{a,b,c} \tilde{H}^i \otimes \big(T^a_F(0, x_a) + \tilde{T}^a_F(0, x_a)\big) \otimes f^b_1 \otimes D^c_1 \quad \rightarrow \quad \text{SFPs}$$

→ soft gluon pole (SGP) contribution has relation to TMD approach

→ soft fermion pole (SFP) contribution has no relation to TMD approach

→ SFP matrix elements may be small (Kang et al, 2010 / Braun et al, 2011)

→ $H^i$ and $\tilde{H}^i$ contain also physics of ISI/FSI (in contrast to GPM)

* relation between QS function and Sivers function (Boer, Mulders, Pijlman, 2003)

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

→ provides very intuitive interpretation of $T_F$

→ relation between $A^{\rm Siv}_{\rm SIDIS}$ in SIDIS and $A_N$ in $p^{\uparrow}p \rightarrow h\, X$ possible

→ flavor structure of $A_N$ like in TMD approach

→ because of ISI/FSI magnitude and sign of $A_N$ may differ from TMD approach

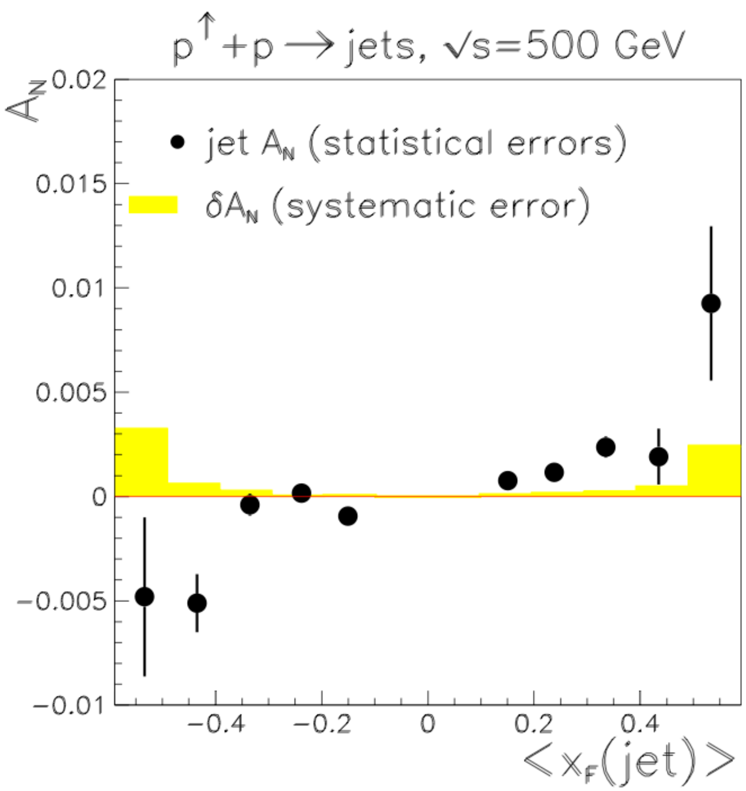
∗ phenomenology

→ early successful fits

(i) without SFPs (Kouvaris, Qiu, Vogelsang, Yuan, 2006)

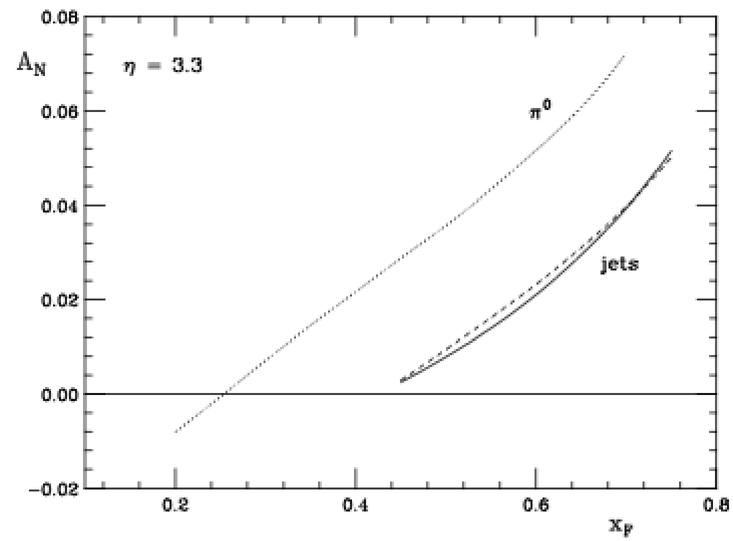
(ii) with SFPs (Kanazawa, Koike, 2010, 2011)

→ but small $A_N^{jet}$, relative to observed $A_N^{\pi^0}$, may pose challenge




AnDY-Collaboration, 2013

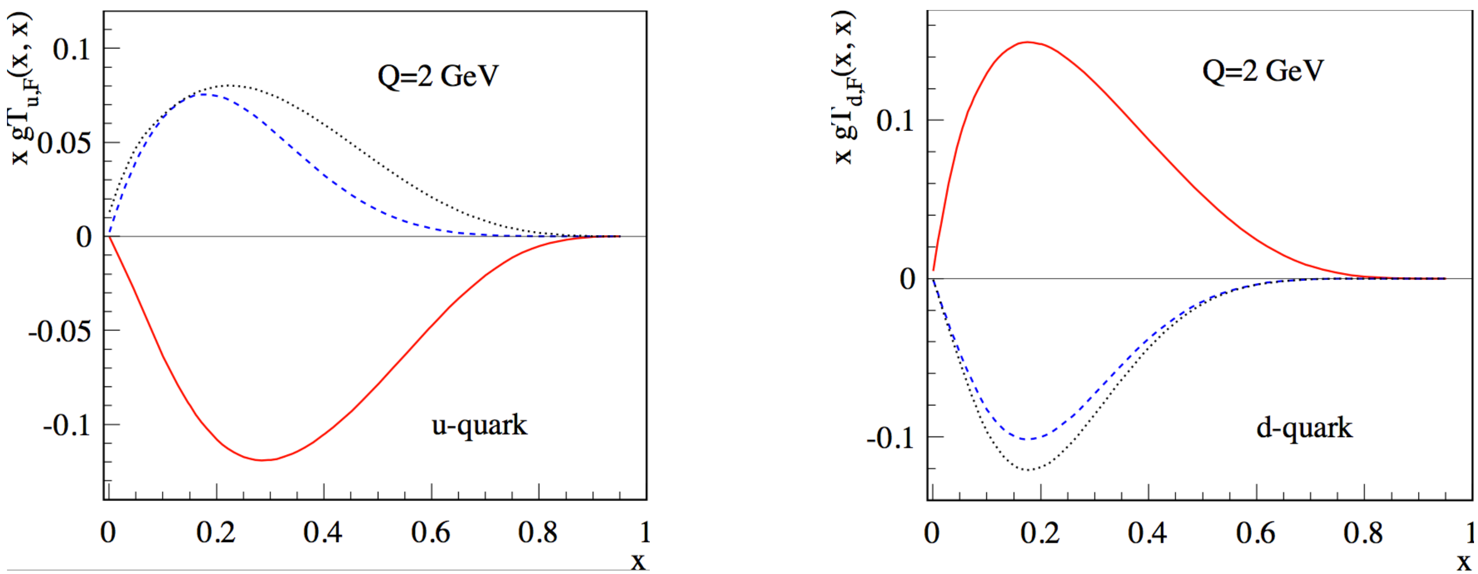
$\sqrt{s} = 200\,\mathrm{GeV}$




Kouvaris, Qiu, Vogelsang, Yuan, 2006

– Sivers-type contribution and sign-mismatch problem (Kang, Qiu, Vogelsang, Yuan, 2011)

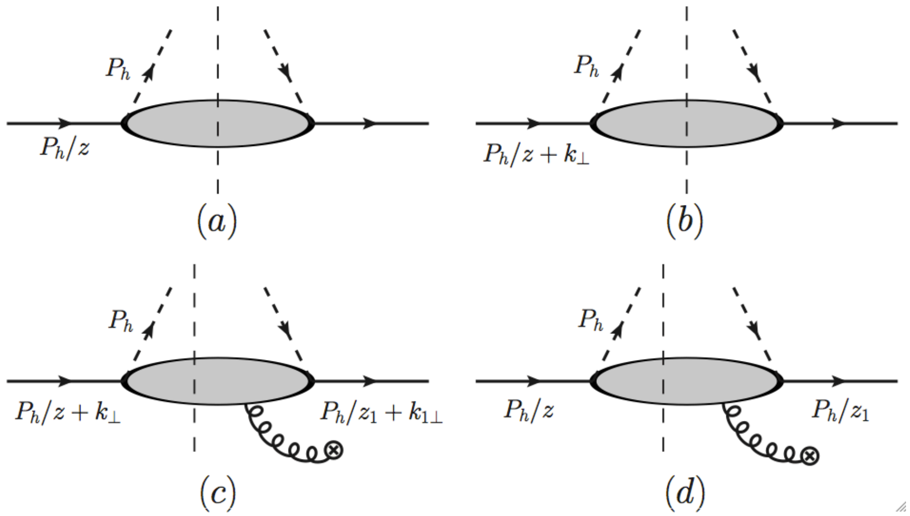
* Assume SSA in $p^{\uparrow}p \to h\,X$ is dominated by Sivers-type contribution
* $T_F$ can be extracted from different sources (direct extraction vs Sivers input)




* Striking sign mismatch !
* Which of the signs for $T_F$ is correct ?
* Model calculation suggests sign coming from Sivers input (Braun et al, 2011)
* One may doubt the dominance of the Sivers-type contribution in $A_N$
* Boer-Mulders type contribution small (Koike, Kanazawa, 2000)
* Can the large $A_N$ in $p^{\uparrow}p \to H\,X$ be caused by the "Collins-type" contribution ?

# Fragmentation Contribution to Transverse SSA in $p^\uparrow p \to h\,X$

1. Contributing effects (compare for instance $A_{LT}$ in inclusive DIS)




- Collinear twist-3 quark-quark correlator: $H(z)$
- Transverse momentum effect from quark-quark correlator: $\hat{H}(z)$

$\to$ has relation with Collins function: $\hat{H}(z) = z^2 \int d^2\vec{k}_\perp \, \frac{\vec{k}_\perp^{\,2}}{2M_h^2} \, H_1^\perp(z, z^2\vec{k}_\perp^{\,2})$

- Collinear twist-3 quark-gluon-quark correlator: $\hat{H}_{FU}^{\Im}(z, z_1)$

2. Analytical results (Metz, Pitonyak, 2012)

$$\frac{P_h^0 d\sigma(\vec{S}_\perp)}{d^3\vec{P}_h} = -\frac{2\alpha_s^2 M_h}{S}\epsilon_{\perp,\alpha\beta}\, S_\perp^\alpha P_{h\perp}^\beta$$

$$\times \sum_i \sum_{a,b,c} \int_{z_{min}}^1 \frac{dz}{z^3} \int_{x'_{min}}^1 \frac{dx'}{x'}\, \frac{1}{x}\, \frac{1}{x'S + T/z}\, \frac{1}{-x'\hat{t} - x\hat{u}}\, h_1^a(x)\, f_1^b(x')$$

$$\times \left\{ \left[ \hat{H}^c(z) - z\frac{d\hat{H}^c(z)}{dz} \right] S_{\hat{H}}^i + \frac{1}{z} H^c(z)\, S_H^i \right.$$

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

- $\hat{H}, \; H, \; \hat{H}_{FU}^{\Im}$ related

- Derivative term for $\hat{H}$ computed previously (Kang, Yuan, Zhou, 2010)
  $\rightarrow$ does not necessarily dominate

- $S_H^i \sim 1/\hat{t}^3$ and $S_{\hat{H}_{FU}}^i \sim 1/\hat{t}^3$ suggest that contributions from $H$ and $\hat{H}_{FU}^{\Im}$ might dominate in the forward region (large positive $x_F$); color suppression for $S_{\hat{H}_{FU}}^i$

- Imaginary part provided by (non-perturbative) fragmentation

3. Numerical results (Kanazawa, Koike, Metz, Pitonyak, 2014)

- Relation between fragmentation functions due to QCD equation of motion

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

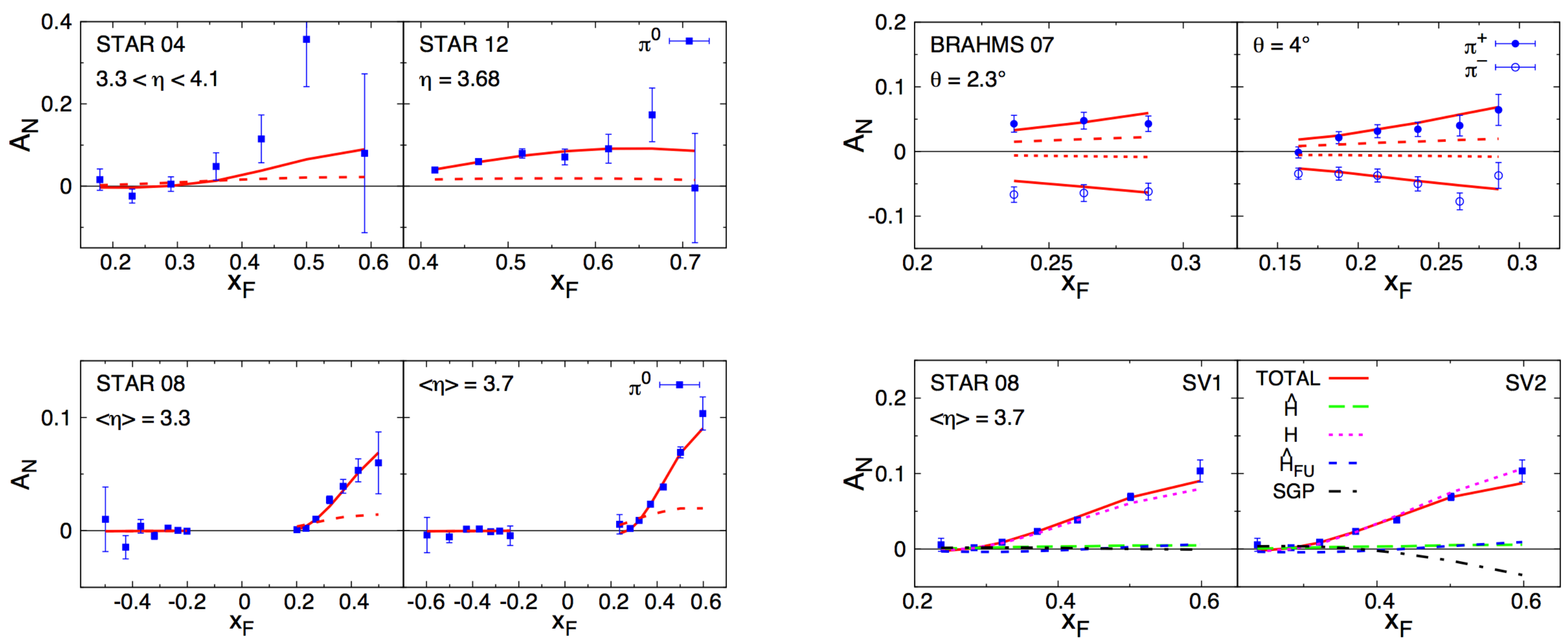
- Ansatz for 3-parton fragmentation function

$$\frac{\hat{H}_{FU}^{\pi^+/(u,\bar{d}),\Im}(z, z_1)}{D_1^{\pi^+/(u,\bar{d})}(z)\, D_1^{\pi^+/(u,\bar{d})}(z/z_1)} \sim N_{\text{fav}}\, z^{\alpha_{\text{fav}}} (z/z_1)^{\alpha'_{\text{fav}}} (1-z)^{\beta_{\text{fav}}}\, (1 - z/z_1)^{\beta'_{\text{fav}}}$$

  - likewise for disfavored fragmentation
  - 8-parameter fit to data for $A_N$ from RHIC

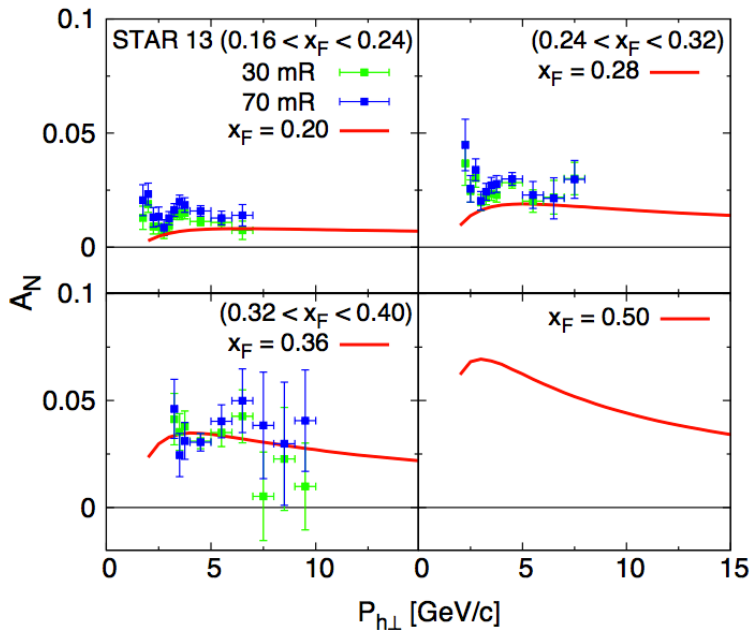
- Input for transversity $h_1$, Collins function $H_1^\perp$ $(\hat{H})$, and Sivers function $f_{1T}^\perp$ from $A_{\text{SIDIS}}^{\text{Siv}}$ , $A_{\text{SIDIS}}^{\text{Col}}$ , $A_{e^+e^-}^{\cos(2\phi)}$ (Anselmino et al, 2008, 2013)

- Comparison with data




  - good fit can be obtained $(\chi^2/\mathrm{d.o.f.} = 1.03)$
  - data cannot be described without 3-parton fragmentation function $\hat{H}^{\Im}_{FU}$
  - numerics dominated by contribution from $H$ (fixed by $\hat{H}$ and $\hat{H}^{\Im}_{FU}$)
  - fit is rather flexible ($\chi^2/\mathrm{d.o.f.} = 1.10$ for SV2 input)

- Transverse momentum dependence of $A_N$




  - preliminary STAR data show rather flat $P_{h\perp}$ dependence of $A_N$
  - collinear twist-3 calculation can describe this trend
  - note: data not included in fit, only statistical errors shown

- Overall outcome
  - simultaneous description of $A_N$, and $A_{\mathrm{SIDIS}}^{\mathrm{Siv}}$ , $A_{\mathrm{SIDIS}}^{\mathrm{Col}}$ , $A_{e^+e^-}^{\cos(2\phi)}$ possible
  - breakthrough in understanding $A_N$ (?)
  - information on $\hat{H}_{FU}^{\Im}$ from other sources required
  - some support from model calculation (Lu, Schmidt, 2015)

4. Lorentz-invariance relations (Kanazawa, Koike, A.M., Pitonyak, Schlegel, 2015)

- Additional constraint, beyond QCD equation of motion

- Both $\hat{H}$ and $H$ can be expressed through $\hat{H}_{FU}^{\Im}$

- Example

$$\hat{H}^{h/q}(z) = -\frac{2}{z}\int_z^1 dz_1 \int_{z_1}^{\infty} \frac{dz_2}{z_2^2} \frac{\frac{2}{z_1} - \frac{1}{z_2}}{\left(\frac{1}{z_1} - \frac{1}{z_2}\right)^2} \hat{H}_{FU}^{h/q,\Im}(z_1, z_2) \sim \langle P_{hT}(z)\rangle$$

  - fragmentation contribution to $A_N$ given by 3-parton correlator $\hat{H}_{FU}^{h/q,\Im}(z_1, z_2)$
  - intuitive interpretation for twist-3 fragmentation contribution
  - Schäfer-Teryaev sum rule suggests flavor structure of $A_N$

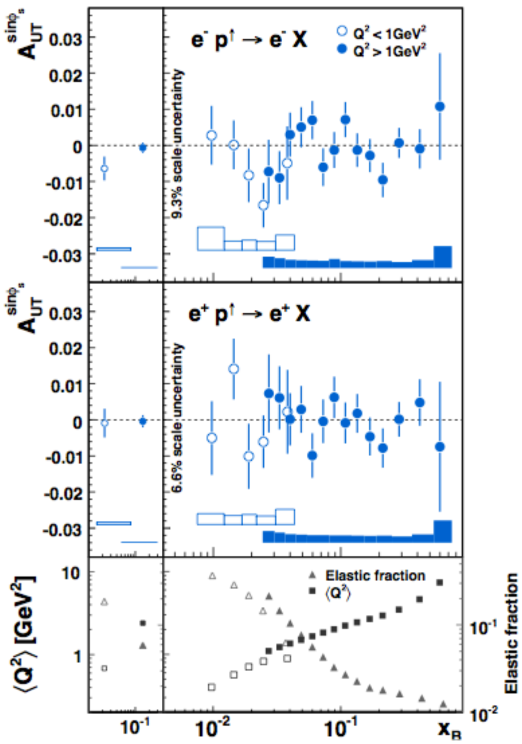
- Updated phenomenology needed for
  - $A_N$ in $p^{\uparrow} p \to h\, X$ (Kanazawa, Koike, A.M., Pitonyak, 2014)
  - $A_N$ in $\ell\, N^{\uparrow} \to h\, X$ (Gamberg, Kang, A.M., Pitonyak, Prokudin, 2014)

# Transverse SSA in Inclusive DIS, $e\, N^{\uparrow} \ \to e\, X$

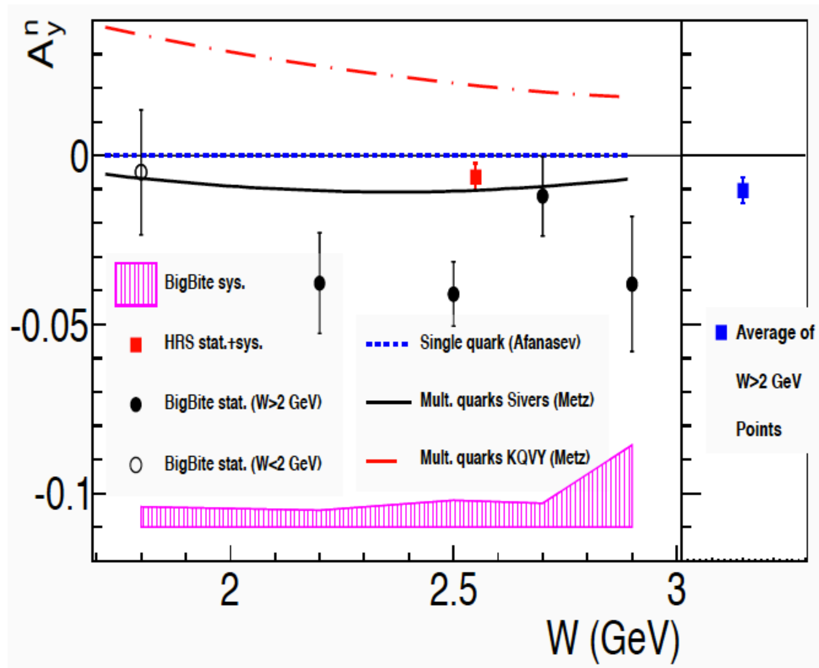
(A.M., Pitonyak, Schäfer, Schlegel, Vogelsang, Zhou, 2012)

1. Recent data

$A_N^p$ (HERMES, 2009)




$A_N^n$ (JLab Hall A, 2013)
(obtained with $^3\mathrm{He}^{\uparrow}$ target)




$A_N^p = 0$ within uncertainties $(10^{-3})$

$A_N^n \neq 0$

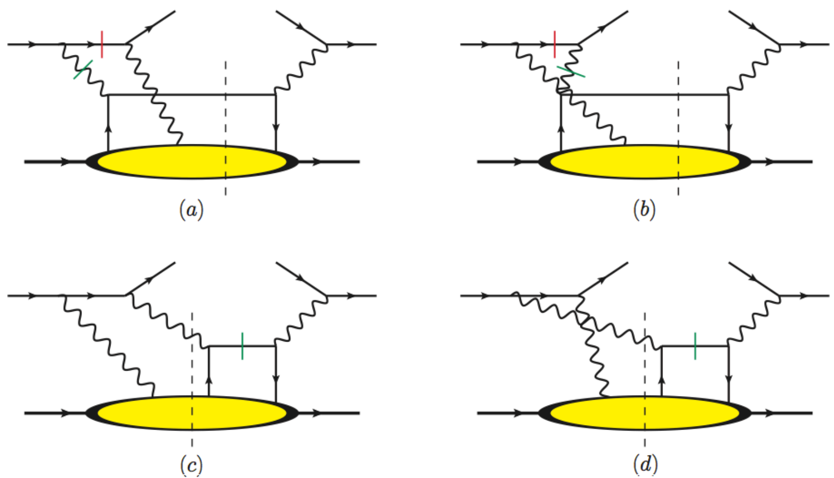
- Can one (qualitatively) understand these data ?
- Can one learn something beyond inclusive DIS ?

2. Theory

- $A_N = 0$ for one-photon exchange (Christ, Lee, 1966)

- Two photons coupling to the same quark
  (A.M., Schlegel, Goeke, 2006 / Afanasev, Strikman, Weiss, 2007 / Schlegel 2012)

- Two photons coupling to different quarks
  (A.M., Pitonyak, Schäfer, Schlegel, Vogelsang, Zhou, 2012)

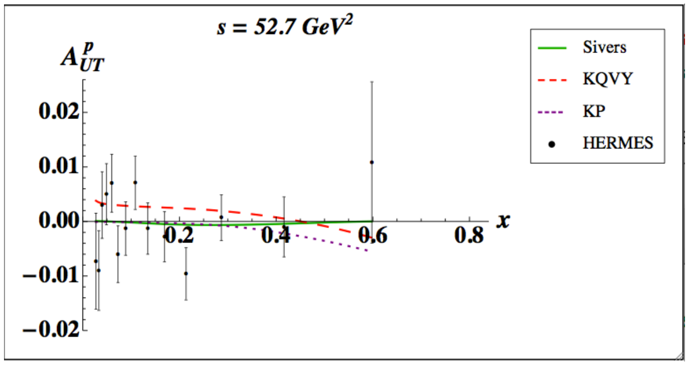


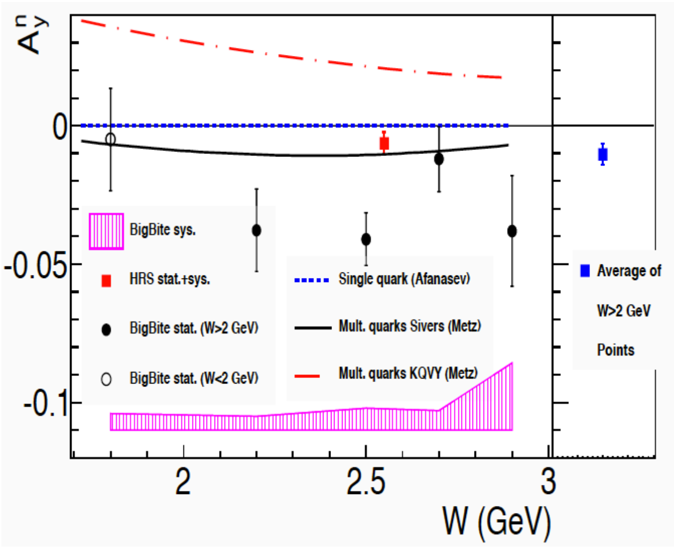

  – express through $q\gamma q$ correlator $F_{FT}$
  – soft photon pole contribution
  – soft fermion pole contribution vanishes
    (see also Koike, Vogelsang, Yuan, 2007)
  – leads to $A_N \sim 1/Q$

- Couplings to different quarks presumably dominate, in particular at larger $x$
  (see also Schlegel, 2013)

- Re-scattering of active parton (lepton) with target remnants (FSI and ISI)
  $\rightarrow$ one can test process-dependence of Sivers effect

- For valence quarks one can find (model-dependent) relation between $F_{FT}$ and $T_F$
- Comparison with data



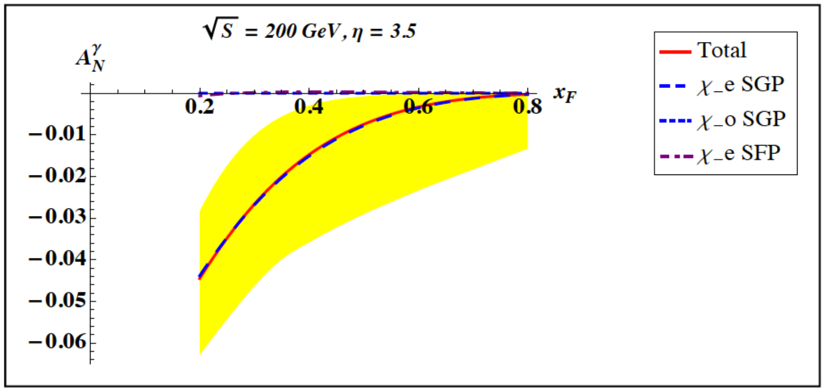

- "KQVY input" for $T_F$ (obtained from $A_N$ in $p^\uparrow p \to h\,X$), in particular, has wrong sign for neutron asymmetry
- indicates that $A_N$ in $p^\uparrow p \to h\,X$ not caused by Sivers-type contribution ($T_F$)
- "Sivers input" for $T_F$ (obtained from $f_{1T}^\perp$) provides description of data
- simultaneous description of $A_{\text{Siv}}$ in SIDIS and $A_N$ in Inclusive DIS
- first indication of process-dependence of Sivers effect (A.M., et al, 2012)
- also: process-dependence compatible with AnDY data on $A_N$ in $p^\uparrow p \to \text{jet}\ X$ (Gamberg, Kang, Prokudin, 2013)

# Transverse SSA in $p^\uparrow p \to \gamma\, X$ in Twist-3 Factorization

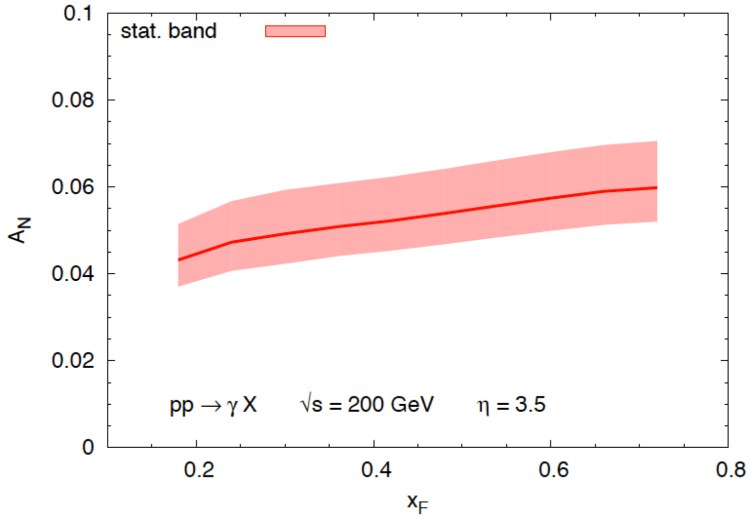
(Kanazawa, Koike, A.M., Pitonyak, 2014)

- Will be measured by PHENIX and STAR
- Numerical results

Collinear twist-3 (Kanazawa et al, 2014)




GPM (Anselmino et al, 2013)




- dominated by SGP contribution related to polarized proton $\longrightarrow$ clean access to $T_F$
- physics of ISI/FSI enters $\longrightarrow$ process-dependence of Sivers function can be checked
- seems ideal for discriminating between collinear twist-3 approach and GPM (different signs)

# Summary

- Observed transverse SSAs in proton-proton collisions are longstanding challenge
- QCD description requires to go beyond twist-2 collinear parton approximation
  $\rightarrow$ exploring new territories in QCD
- TMD factorization using Sivers function and Collins function:
  - is intuitive
  - can be used for processes like SIDIS and Drell-Yan
  - has problems for twist-3 observables like $A_N$ in $p^{\uparrow} p \rightarrow h X$
- Collinear twist-3 factorization:
  - is intuitive, and takes into account physics of ISI/FSI
  - fragmentation contribution may play crucial role
    $\rightarrow$ can also solve sign-mismatch problem
  - simultaneous description of various SSAs possible
  - updated phenomenology for fragmentation contribution needed
  - indications about process-dependence of Sivers function
  - $A_N$ for $p^{\uparrow} p \rightarrow \gamma X$ may provide critical new insights