Recent Progress
in Transverse Spin Physics

(A. Metz, Temple University, Philadelphia)

- Introduction (PDFs, TMDs)

- Color gauge invariance of parton distributions

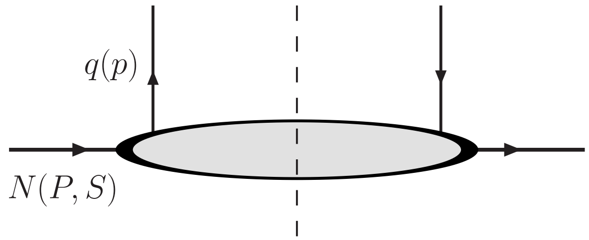
- Transversity distribution and Collins function

- Sivers function

- RHIC specific observables
  1. $p\,p^{\uparrow} \longrightarrow H\ X$
  2. $p\,p^{\uparrow} \longrightarrow \mathrm{jet}\ X$
  3. $p\,p^{\uparrow} \longrightarrow \mathrm{jet}\ H\ X$
  4. $p\,p \longrightarrow \mathrm{jet}\,\mathrm{jet}\ X\ , \ldots$
  5. $p\,p \longrightarrow l^{+}\,l^{-}\ X$

- Summary

Forward Parton Distribution Functions (PDFs)



- Unpolarized PDF: unpolarized quarks in unpolarized nucleon

$$f_1^q(x) = \frac{1}{2}\int \frac{d\xi^-}{2\pi}\, e^{ip\cdot\xi}\,\langle P;S|\,\bar{\psi}(0)\,\gamma^+\,\mathcal{W}_{PDF}\,\psi(\xi)\,|P;S\rangle\Big|_{\xi^+=\xi_T=0}$$

$$\xi^- = \frac{1}{\sqrt{2}}(\xi^0 - \xi^3)$$

- Helicity PDF: long. polarized quarks in long. polarized nucleon

$$g_1^q(x) \sim \langle\ |\,\bar{\psi}\,\gamma^+\gamma_5\,\psi\,|\ \rangle$$

- Transversity PDF: transv. polarized quarks in transv. polarized nucleon

$$h_1^q(x) \sim \langle\ |\,\bar{\psi}\,i\sigma^{j+}\gamma_5\,\psi\,|\ \rangle \qquad \sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$$

Transverse Momentum Dependent Parton Distributions (TMDs)

- Appear in hard semi-inclusive reactions: $l\,N \longrightarrow l'\,H\,X\,, \quad H_1\,H_2 \longrightarrow l^+\,l^-\,X\ \ldots$
- TMD-correlator

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

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

$\longrightarrow$ Sivers function $f_{1T}^{\perp}$ describes strength of spin-orbit correlation

$\longrightarrow$ Partonic nucleon structure beyond collinear approximation

- Leading twist for

$$\bar{\psi}\,\gamma^+\,\psi \qquad \bar{\psi}\,\gamma^+\gamma_5\,\psi \qquad \bar{\psi}\,i\sigma^{j+}\gamma_5\,\psi$$

$\longrightarrow$ 8 TMDs

$\longrightarrow$ Spin-orbit correlations also appear for hydrogen atom in infinite momentum frame (Artru, Benhizia, 2007)

Parton distributions of the nucleon

	Quarks				Gluons			
Forward	$f_1^q\ (q)$	$g_1^q\ (\Delta q)$	$h_1^q\ (\Delta_T q)$		g	Δg		
p_T-dependent	f_1^q	$f_{1T}^{\perp q}$	g_{1L}^q	g_{1T}^q	f_1^g	$f_{1T}^{\perp g}$	g_{1L}^g	g_{1T}^g
	h_{1T}^q	$h_{1L}^{\perp q}$	$h_{1T}^{\perp q}$	$h_1^{\perp q}$	h_{1T}^g	$h_{1L}^{\perp g}$	$h_{1T}^{\perp g}$	$h_1^{\perp g}$
Generalized	H^q	E^q	$\tilde{H}^q$	$\tilde{E}^q$	H^g	E^g	$\tilde{H}^g$	$\tilde{E}^g$
	H_T^q	E_T^q	$\tilde{H}_T^q$	$\tilde{E}_T^q$	H_T^g	E_T^g	$\tilde{H}_T^g$	$\tilde{E}_T^g$

- Except of f_1^q, f_1^g, H^q, H^g all the parton distributions are related to polarization
- Signs and order of magnitude for all valence TMDs of nucleon already known
- Nontrivial relations between GPDs and TMDs:
  $\longrightarrow$ hold in models (Burkardt, 2002,... / Meißner, Metz, Goeke, 2007)
  $\longrightarrow$ cannot have model-independent status (Meißner, Metz, Schlegel, Goeke, 2008)

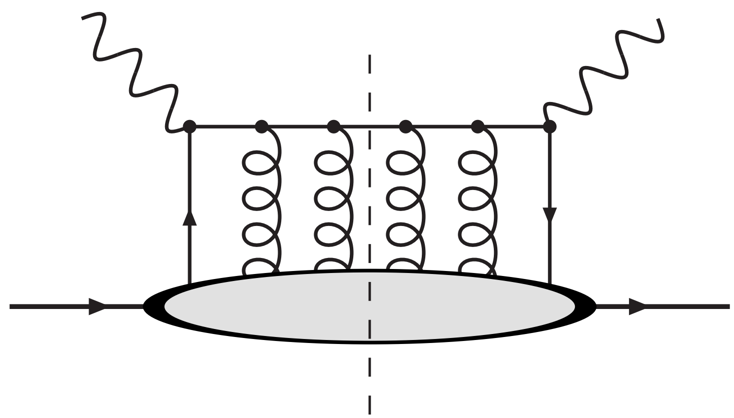
Color gauge invariance

1. Forward parton distributions

$$\int d\xi^- \, e^{ip^+\xi^-} \, \langle \, | \, \bar{\psi}(0) \, \Gamma \, \mathcal{W}_{PDF}(0;\xi^-) \, \psi(\xi^-) \, | \, \rangle$$

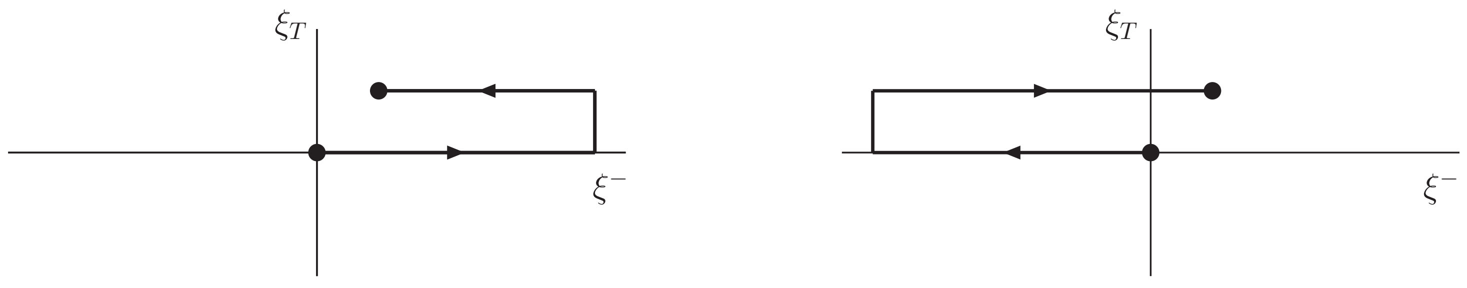
$$\mathcal{W}_{PDF}(0;\xi^-) = \mathcal{P} \exp\Big(- ig \int_0^{\xi^-} d\eta^- \, A^+(0,\eta^-,\vec{0}_T) \Big)$$

Gauge-link generated by rescattering



2. TMDs

$$\int d\xi^- d^2\vec{\xi}_T\, e^{i(p^+\xi^- - \vec{p}_T\cdot\vec{\xi}_T)}\, \langle\,|\,\bar{\psi}(0)\,\Gamma\,\mathcal{W}_{TMD}(0,\vec{0}_T;\xi^-,\vec{\xi}_T)\,\psi(\xi^-,\vec{\xi}_T)\,|\,\rangle$$



- $\mathcal{W}_{TMD}(0,\vec{0}_T;\xi^-,\vec{\xi}_T) = [0,\vec{0}_T;\infty,\vec{0}_T] \times [\infty,\vec{0}_T;\infty,\vec{\xi}_T] \times [\infty,\vec{\xi}_T;\xi^-,\vec{\xi}_T]$
(Belitsky, Ji, Yuan, 2002)

- Different links for semi-inclusive DIS and Drell-Yan $\longrightarrow$ Universality?
Time-reversal: $f_{1T}^{\perp}\big|_{DY} = -f_{1T}^{\perp}\big|_{DIS}$ $\qquad$ $h_1^{\perp}\big|_{DY} = -h_1^{\perp}\big|_{DIS}$
(Collins, 2002)

- Gauge links more complicated for $p\,p \longrightarrow \text{jet jet } X$, . . .
$\longrightarrow$ Even depend on partonic subprocess
(Bomhof, Mulders, Pijlman, 2004)

Transversity distribution and Collins function

- Transversity in Drell-Yan (Ralston, Soper, 1979)

$$A_{TT} \sim \frac{h_1^{q/H_1}(x_1)\, h_1^{\bar{q}/H_2}(x_2) + (x_1 \leftrightarrow x_2)}{f_1^{q/H_1}(x_1)\, f_1^{\bar{q}/H_2}(x_2) + (x_1 \leftrightarrow x_2)}$$

$\longrightarrow$ Promising observable (collinear factorization, stable under QCD corrections, ...)
$\longrightarrow$ No data at present

- Exploiting the Collins effect in SIDIS (Collins, 1992)

$$\sigma_{UT} \sim h_1^q(x, \vec{p}_T^{\,2})\, H_1^{\perp\, q/H}(z, \vec{k}_T^{\,2}) + \ldots$$

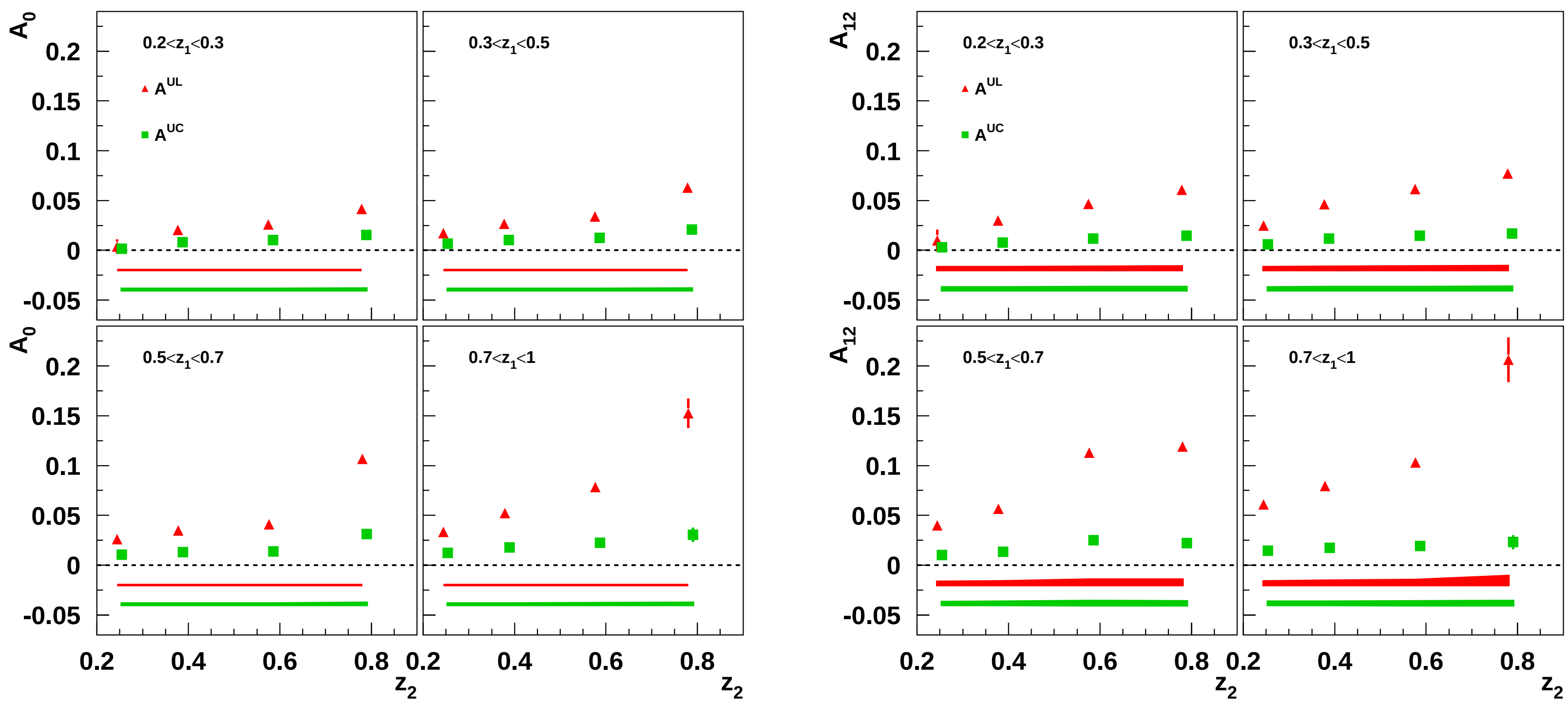
$\longrightarrow$ $H_1^{\perp\, q/H}$: fragmentation of transversely polarized quark into unpolarized hadron
$\longrightarrow$ Data from COMPASS and HERMES

- Collins function from $e^+ e^- \longrightarrow H_1\, H_2\, X$

$$\sigma_{e^+e^-} \sim H_1^{\perp\, q/H_1}(z_1, \vec{k}_{1T}^{\,2})\, H_1^{\perp\, \bar{q}/H_2}(z_2, \vec{k}_{2T}^{\,2}) + \ldots$$

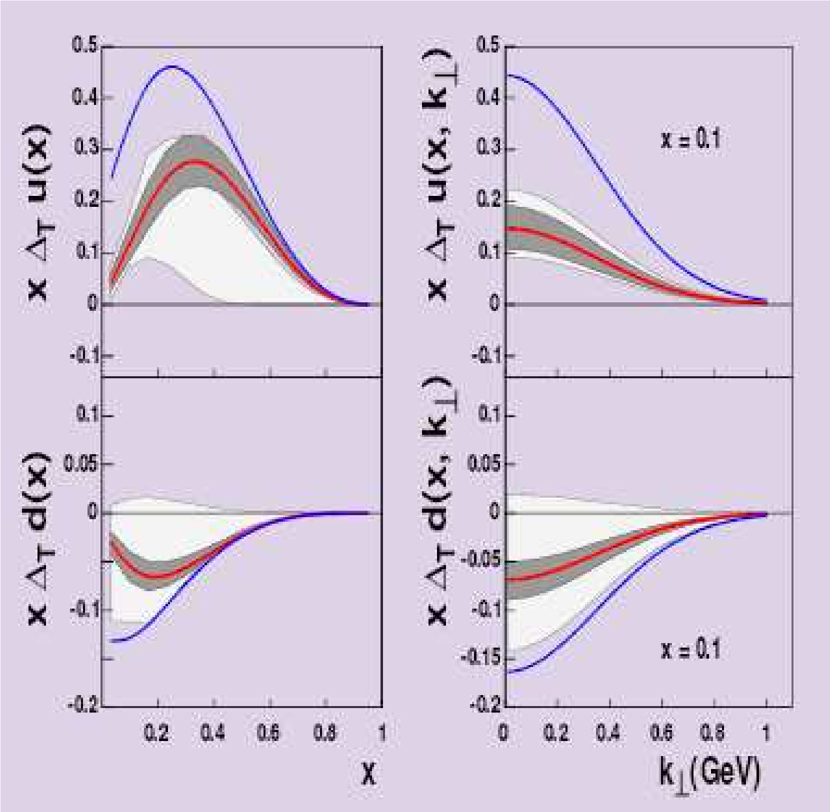
$\longrightarrow$ Data from Belle
$\longrightarrow$ Method relies on universality of Collins function
(Metz, 2002 / Collins, Metz, 2004)

- Belle data (Belle Collaboration, 2008)



$\longrightarrow$ Impressive precision

- Extraction of transversity (Prokudin, DIS 2008)



→ $h_1^u(x) > 0$ $h_1^d(x) < 0$ (in agreement with most models)

→ Soffer bound not saturated

→ Significant improvement compared to previous fit (from same group)

→ Statistical errors already rather small, systematic errors hard to quantify at present

→ Information on antiquarks would be valuable (stronger disagreement between models, future insights from RHIC possible)

Sivers function

- Sivers function in SIDIS

$$\sigma_{UT} \sim f_{1T}^{\perp q}(x, \vec{p}_T^{\,2})\, D_1^{q/H}(z, \vec{k}_T^{\,2}) + \ldots$$

$\longrightarrow$ Data from COMPASS deuteron target: $\pi^\pm\,,\ K^\pm\,,\ K^0$
$\longrightarrow$ Data from HERMES on hydrogen target: $\pi^\pm\,,\ \pi^0\,,\ K^\pm$

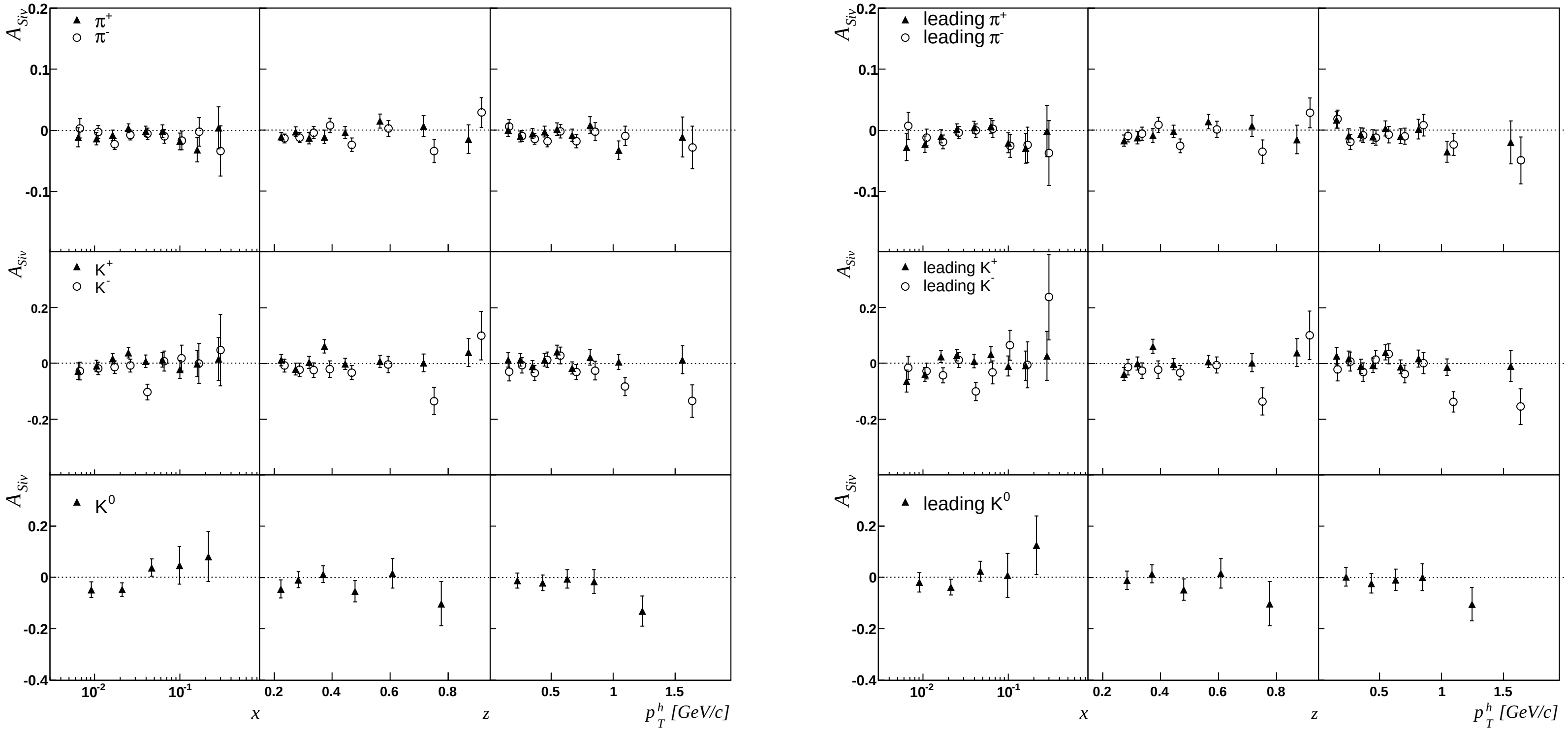
- Exact result in large N_c limit (Pobylitsa, 2003)

$$f_{1T}^{\perp u}(x, \vec{p}_T^{\,2}) = -f_{1T}^{\perp d}(x, \vec{p}_T^{\,2})$$

$\longrightarrow$ Sivers asymmetry should be small for deuteron target
(confirmed by COMPASS data)

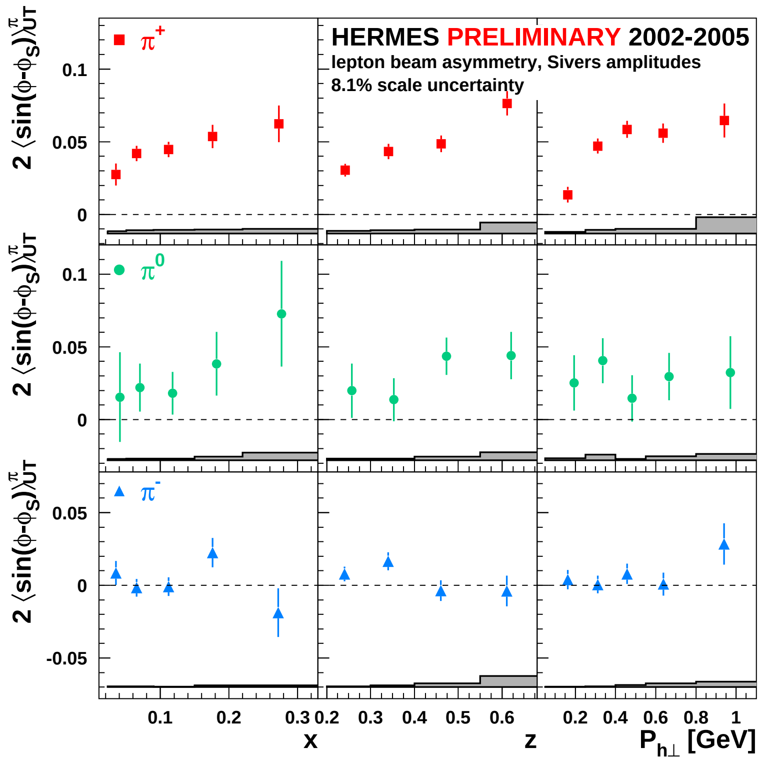
- Extractions of the Sivers function
Efremov et al., 2004 / Collins et al., 2005
Anselmino et al., 2005
Vogelsang, Yuan, 2005
Arnold et al., 2008
Anselmino et al., 2008

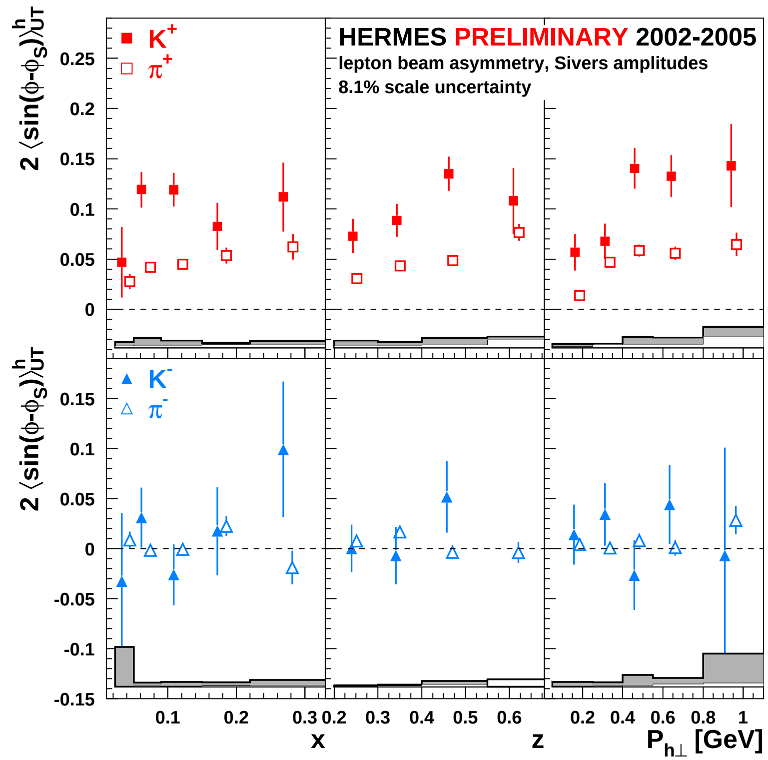
- COMPASS data (COMPASS Collaboration, 2008)



⟶ All asymmetries basically consistent with zero

- HERMES data (HERMES Collaboration, 2007)

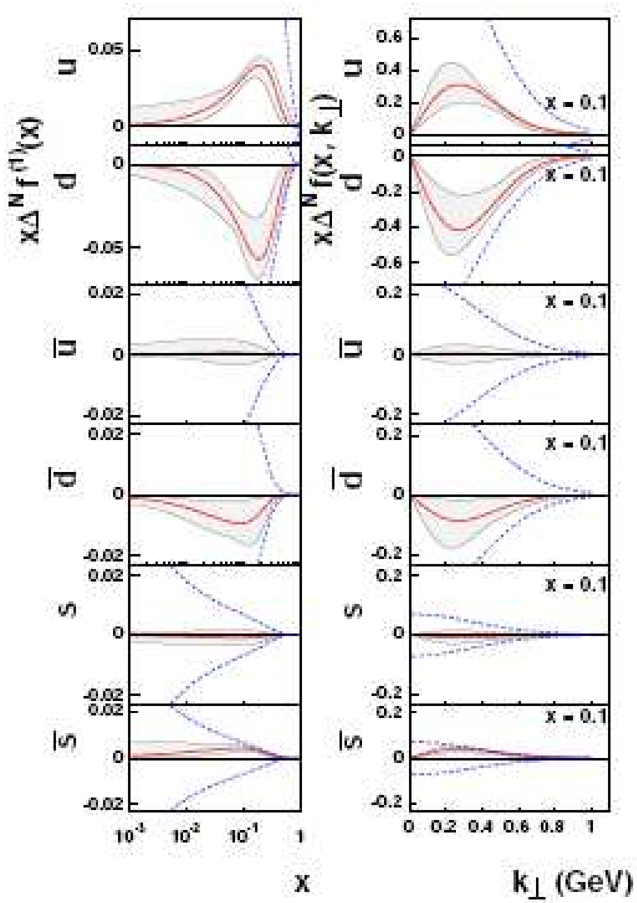




$\longrightarrow$ Nonzero effects for π^+ , π^0 , K^+

$\longrightarrow$ Effect for K^+ larger than for π^+

- Results for Sivers functions (Anselmino et al., 2008)



→ Effects for u and d quark roughly equal in magnitude but opposite in sign (in agreement with large N_c-prediction)

→ Recall also $\kappa^u \approx -\kappa^d$ and $L^u \approx -L^d$

→ Antiquark Sivers functions small, but effect for $\bar{s}$ nonzero

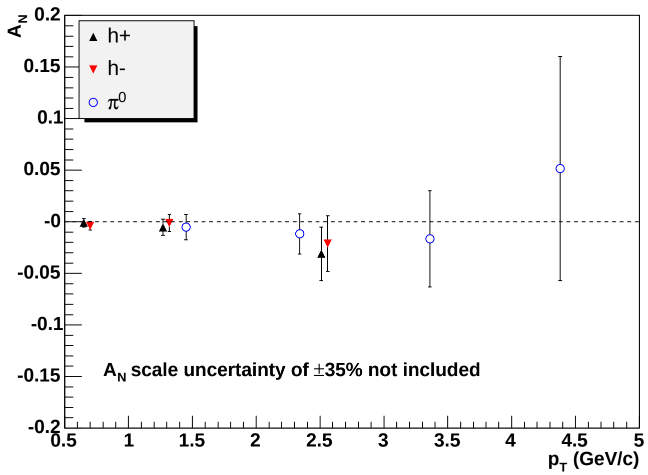
- Gluon Sivers effect
  $\longrightarrow$ Strong indication from different sources that

Gluon Sivers function is small

1. Using Burkardt sum rule (Burkardt, 2004) and large N_c
   (Efremov, Goeke, Menzel, Metz, Schweitzer, 2004)

$$\langle \vec{p}_T \rangle \equiv \sum_{a=q,\bar{q},g} \int_0^1 dx \int d^2\vec{p}_T \, \frac{\vec{p}_T^{\,2}}{2M^2} \, f_{1T}^{\perp a}(x, \vec{p}_T^{\,2}) = \sum_{a=q,\bar{q},g} \int_0^1 dx \, f_{1T}^{\perp(1)a}(x)$$

2. Using COMPASS and PHENIX data
   (Brodsky, Gardner, 2005 / Anselmino, D' Alesio, Melis, Murgia, 2005)



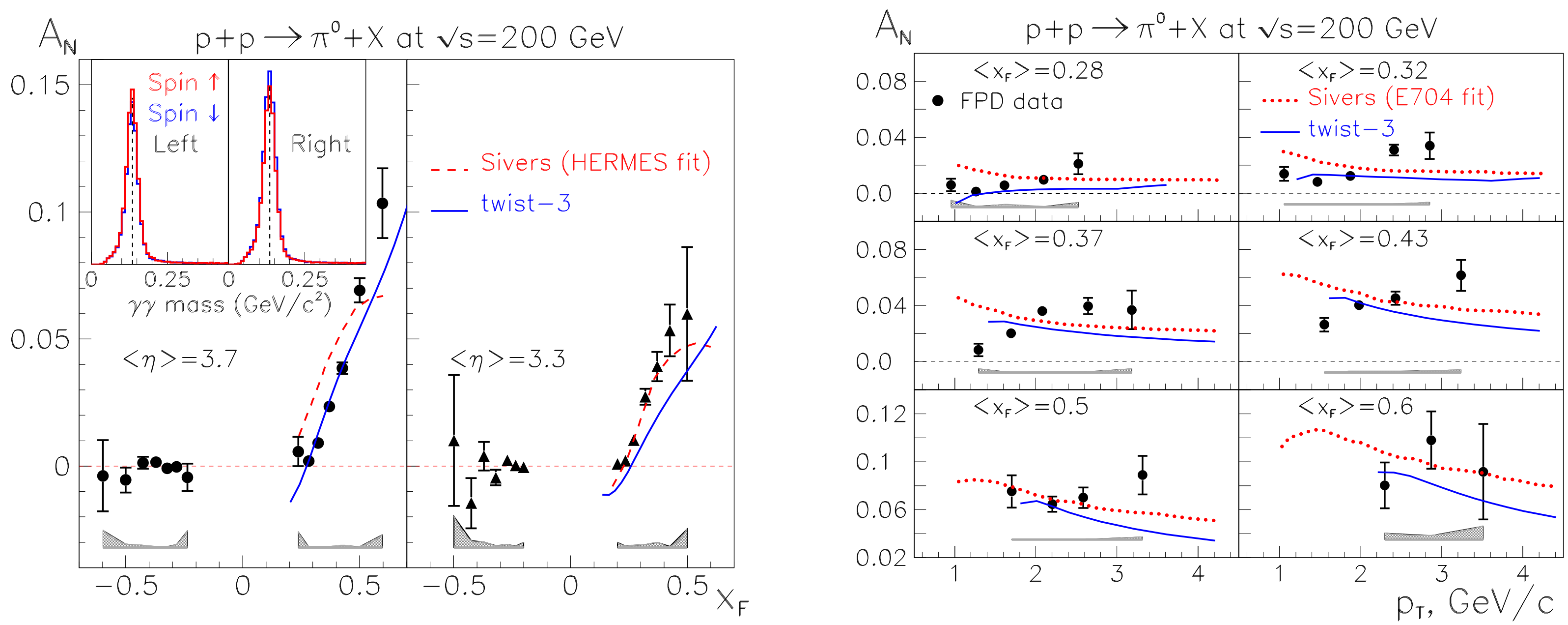
(PHENIX Collaboration, 2005)

Transverse SSA in $p\,p^{\uparrow} \;\to H\;X$

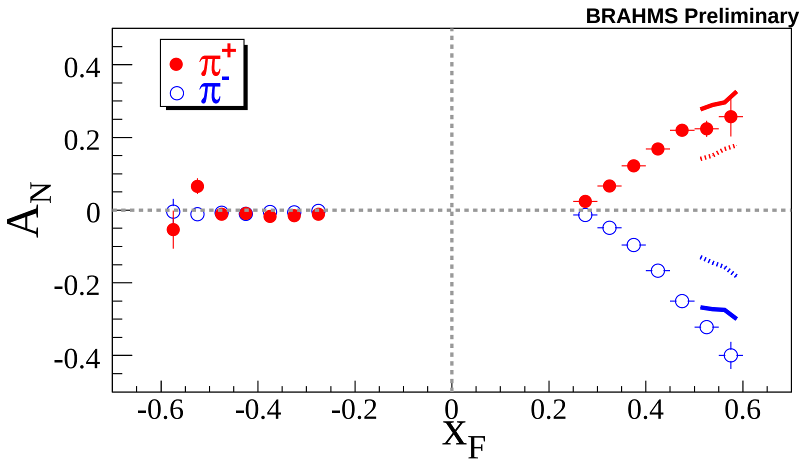
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \qquad\qquad x_F = \frac{2P_{hL}}{\sqrt{s}}$$

$\longrightarrow$ Nonzero SSAs for positive x_F (BRAHMS, STAR)

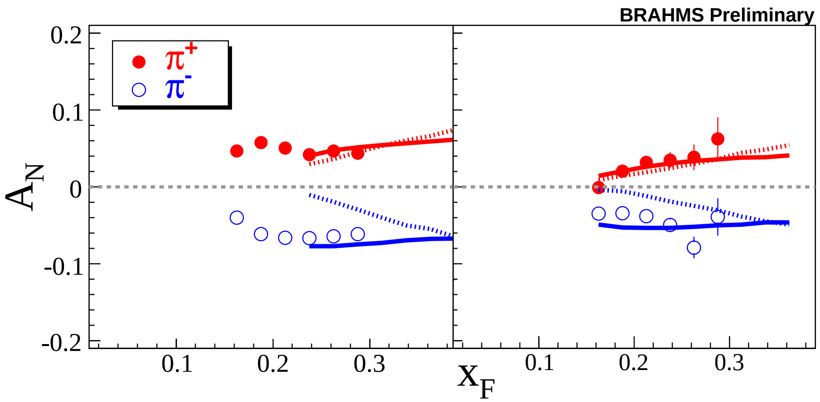
- STAR data (STAR Collaboration, 2008)
  π^0 production at $\sqrt{s} = 200\,\mathrm{GeV}$



- BRAHMS data (BRAHMS Collaboration, 2008)
  $\pi^{\pm}\,,\ K^{\pm}\,,\ p$ production at $\sqrt{s} = 62.4\,\mathrm{GeV}$
  $\pi^{\pm}\,,\ K^{\pm}$ production at $\sqrt{s} = 200\,\mathrm{GeV}$



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



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

$\longrightarrow$ Asymmetry decreases with increasing $\sqrt{s}$ (p_T)

- Theory for $p\, p^{\uparrow} \;\; \longrightarrow H\; X$

1. A_N vanishes in leading twist collinear pQCD-description

2. Approach using (twist-2) TMDs (Anselmino et al., 1995, ...)
   $\longrightarrow$ Sivers effect
   $\longrightarrow$ Collins effect

3. Approach using collinear twist-3 quark-gluon-quark correlators
   (Efremov, Teryaev, 1985 / Qiu, Sterman, 1991)
   $\longrightarrow$ Twist-3 initial state (Kouvaris, Qiu, Vogelsang, Yuan, 2006; etc.)

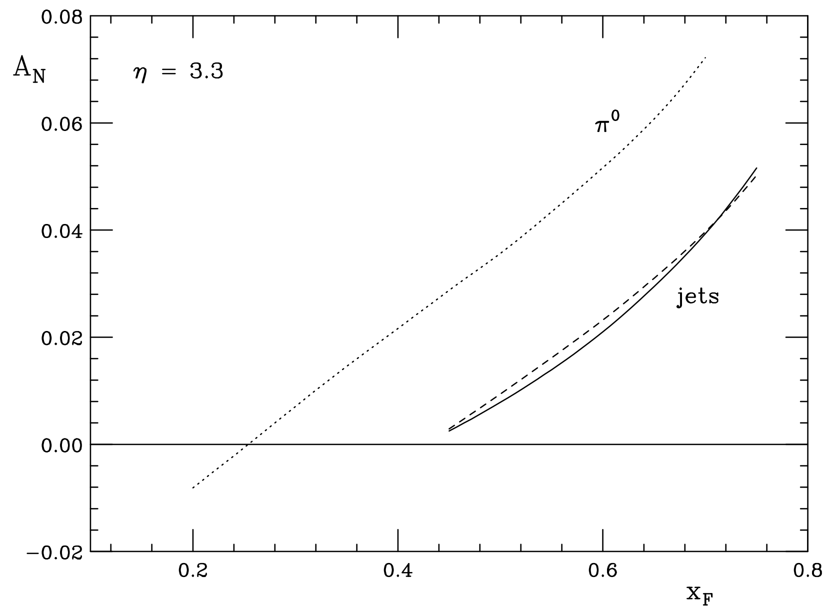
$$\langle\, |\bar{\psi}\, A_T\, \psi|\, \rangle(x) \sim f_{1T}^{\perp(1)}(x)$$

   $\longrightarrow$ Twist-3 final state (Koike et al., 2002, ...)

4. Discussion
   $\longrightarrow$ Intrinsic transverse momenta are not directly related to p_T of hadron
   $\longrightarrow$ TMD approach so far does not contain gauge link complications
   $\longrightarrow$ Collins effect contribution calculated to be small (Anselmino et al., 2004), but statement probably has to be revised (Yuan, 2008)
   $\longrightarrow$ Twist-3 final state approach probably has to be revised
   $\longrightarrow$ New data challenge theory

Transverse SSA in $p\, p^{\uparrow} \; \longrightarrow$ jet X

- No data yet
- No contribution from Collins effect (twist-3 final state)
- Direct information on Sivers effect (twist-3 initial state)
- May also help to discriminate between TMD and collinear approach



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

Calculation by Kouvaris, Qiu, Vogelsang, Yuan (2006) in twist-3 approach

$\longrightarrow$ Important information in order to understand SSAs in hadron-hadron collisions

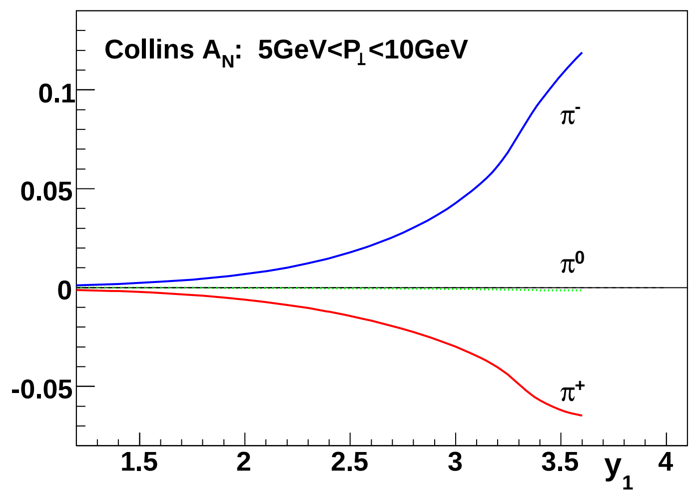
Transverse SSA in $p\,p^{\uparrow} \to \mathrm{jet}\, H\, X$

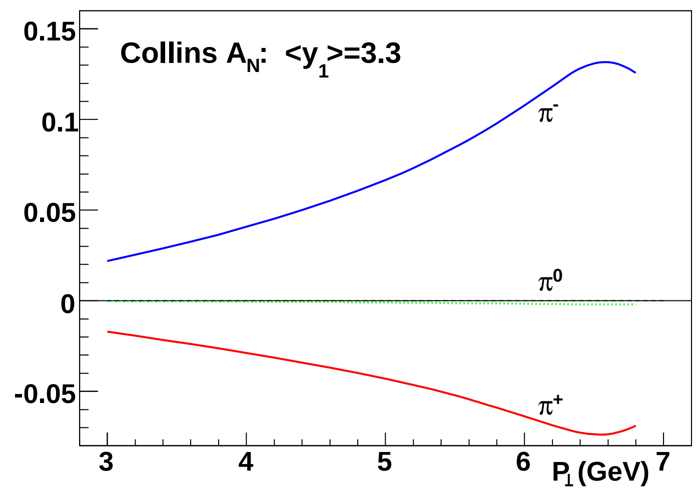
(Yuan, 2007, 2008)

- Identified hadron inside jet
- Jet at large transverse momentum, hadron (relative) at low transverse momentum k_T

$$\mathrm{SSA} \sim h_1^q(x)\, H_1^{\perp\, q/H}(z, \vec{k}_T^{\,2})$$

- Collins function universal





- Collins effect can give sizeable contribution to A_N in $\boldsymbol{p\,p^{\uparrow} \to \pi\, X}$
  (Yuan, 2008)

Di-jet production and related processes

- Detection of two almost back-to-back jets ($\longrightarrow$ realm of TMDs)

- STAR data (STAR Collaboration, 2007)

- Also enormous recent activity on theory side
  Bacchetta, Bomhof, Mulders, Pijlman, 2004, 2005, 2006, 2007
  Qiu, Vogelsang, Yuan, 2007
  Collins, Qiu, 2007

- At best non-standard factorization (TMDs depend on partonic subprocess)

- Weighting cross section according to

$$\sigma_W \sim \int dp_T \, w(p_T) \, \sigma(p_T)$$

  may lead to drastic simplifications (Bomhof, Mulders, 2007)
  (non-universality condenses in calculable factors)

TMDs in semi-inclusive DIS

σ_{UU} : $f_1(x)\, D_1(z)$ $\cos(2\Phi_h)\, h_1^\perp(x)\, H_1^\perp(z)$

σ_{LL} : $g_{1L}(x)\, D_1(z)$

σ_{LT} : $\cos(\Phi_h - \Phi_S)\, g_{1T}(x)\, D_1(z)$

σ_{UL} : $\sin(2\Phi_h)\, h_{1L}^\perp(x)\, H_1^\perp(z)$

σ_{UT} : $\sin(\Phi_h - \Phi_S)\, f_{1T}^\perp(x)\, D_1(z)$ $\sin(\Phi_h + \Phi_S)\, h_1(x)\, H_1^\perp(z)$

$\sin(3\Phi_h - \Phi_S)\, h_{1T}^\perp(x)\, H_1^\perp(z)$

$\longrightarrow$ Complete experiment for TMDs possible

$\longrightarrow$ Program for COMPASS, HERMES, JLab, EIC

TMDs in Drell-Yan

σ_{UU} :	$f_1(x_1)\, f_1(x_2)$	$h_1^{\perp}(x_1)\, h_1^{\perp}(x_2)$	
σ_{LL} :	$g_{1L}(x_1)\, g_{1L}(x_2)$		
σ_{TT} :	$h_1(x_1)\, h_1(x_2)$		
σ_{LT} :	$g_{1L}(x_1)\, g_{1T}(x_2)$		
σ_{UL} :	$h_1^{\perp}(x_1)\, h_{1L}^{\perp}(x_2)$		
σ_{UT} :	$f_1(x_1)\, f_{1T}^{\perp}(x_2)$	$h_1^{\perp}(x_1)\, h_1(x_2)$	$h_1^{\perp}(x_1)\, h_{1T}^{\perp}(x_2)$

$\longrightarrow$ Complete experiment for TMDs possible

$\longrightarrow$ Advantage: more structure functions than independent TMDs

$\longrightarrow$ Program for COMPASS, FAIR, J-PARC, RHIC

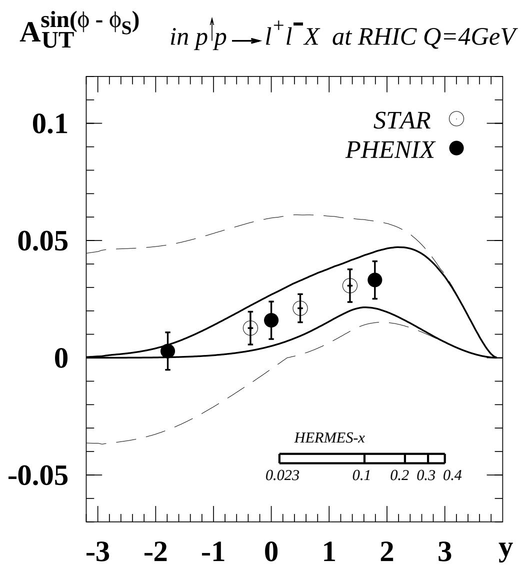
Sivers effect at RHIC

(Collins et al., 2005)

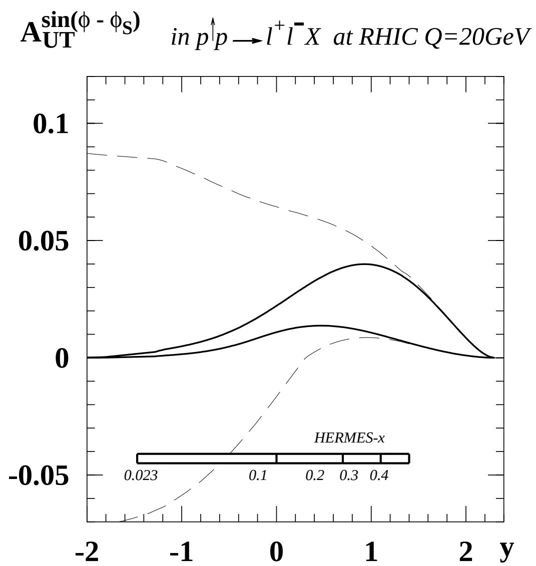
⟶ Sivers function from SIDIS data

⟶ Simple model for antiquark Sivers function

$$f_{1T}^{\perp(1)\bar{q}}(x) = \pm \frac{f_1^{\bar{u}}(x) + f_1^{\bar{d}}(x)}{f_1^u(x) + f_1^d(x)} \, f_{1T}^{\perp(1)q}(x)$$



$Q^2 = 16\,\mathrm{GeV}^2$



$Q^2 = 400\,\mathrm{GeV}^2$

⟶ Prediction $f_{1T}^{\perp}\big|_{DY} = -f_{1T}^{\perp}\big|_{DIS}$ may be checked

⟶ In pp-collisions strong sensitivity to $f_{1T}^{\perp\bar{q}}$

Summary

1. Transverse spin physics got enormous boost during recent years

2. Large variety of observables ($e^+ e^-$, $l\, H$, $H\, H$) and correlation functions

3. Interesting, non-trivial QCD issues (universality, factorization)

4. Information on h_1 , $H_1^\perp$, $f_{1T}^\perp$ from SIDIS and e^+e^- annihilation

5. First information on BM-function $h_1^\perp$ from Drell-Yan and SIDIS

6. Important constraints from RHIC A_N measurements in $p\, p^\uparrow \longrightarrow H\, X$ and $p\, p^\uparrow \longrightarrow \mathrm{jet\, jet}\, X$

7. Possible future measurements at RHIC
   - $p\, p^\uparrow \longrightarrow \mathrm{jet}\, X$ $\longrightarrow$ more direct handle on Sivers effect
   - $p\, p^\uparrow \longrightarrow \mathrm{jet}\, H\, X$ $\longrightarrow$ new, complementary information on h_1 and $H_1^\perp$, etc.
   - $p\, p \longrightarrow l^+\, l^-\, X$ $\longrightarrow$ clean and comprehensive TMD study, etc.
   - etc.