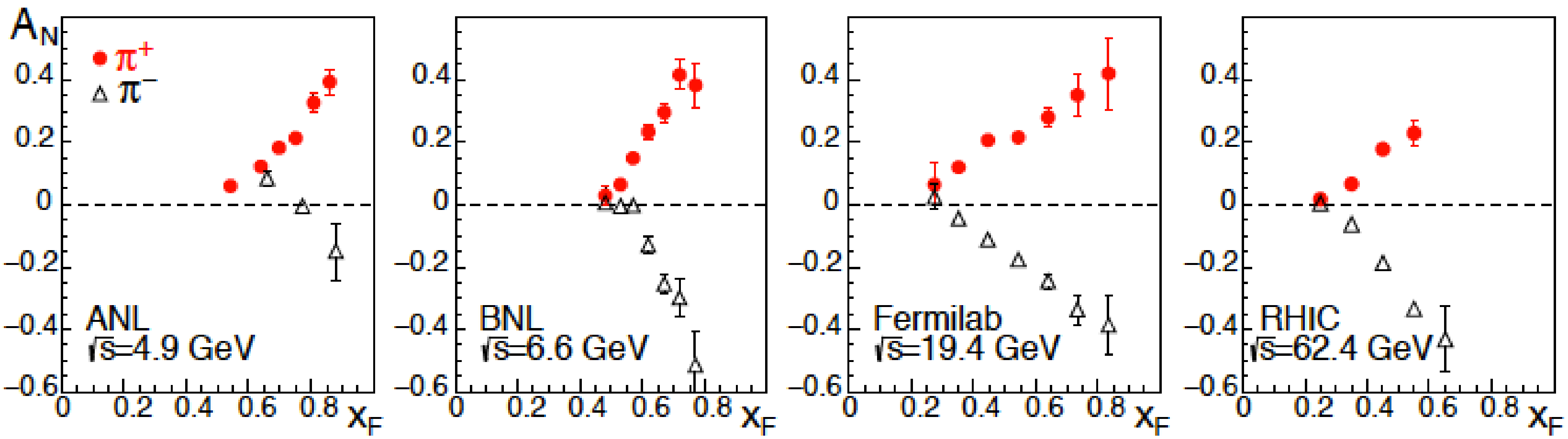
Transverse Single-Spin Asymmetries: Are They Understood?

- Motivation/Introduction
- Transverse momentum dependent parton distributions (TMDs) (definition, overview, processes)
- TMD factorization and its breakdown
- Universality properties of TMDs
- Phenomenology of single-spin asymmetries (SSAs) and what did we learn
  1. Sivers asymmetry in semi-inclusive DIS $(\ell\, N^{\uparrow} \rightarrow \ell\, H\; X)$
  2. Transverse SSA in proton-proton collisions $(p^{\uparrow} p \rightarrow H\; X)$
  3. Transverse SSA in inclusive DIS $(\ell\, N^{\uparrow} \rightarrow \ell\, X)$
- Summary

Example: Transverse SSA in $p^\uparrow p \to \pi\, X$

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

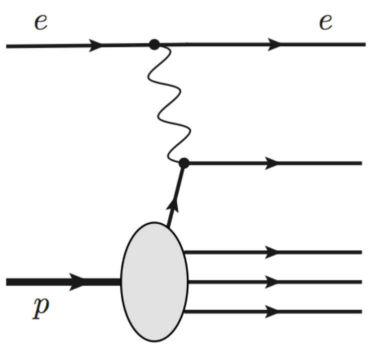


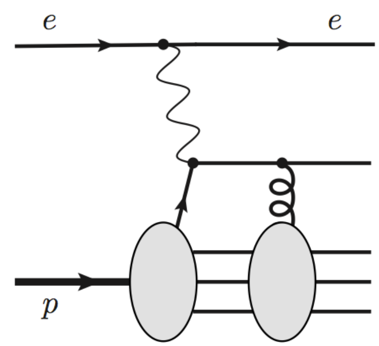
(Aidala, Bass, Hasch, Mallot, 2012)

- Very striking effects
- Many more data available by now (BRAHMS, PHENIX, STAR, ...)
- Twist-2 collinear parton approximation does not work (Kane, Pumplin, Repko, 1978)
- How can the large SSAs be understood in QCD ?
- What lessons can we learn from SSAs ?

  $\rightarrow$ we can explore new areas in studies of (1) nucleon structure, (2) QCD factorization,...

Deep-Inelastic Scattering ($e\,p \to e\,X$), Parton Model and Beyond



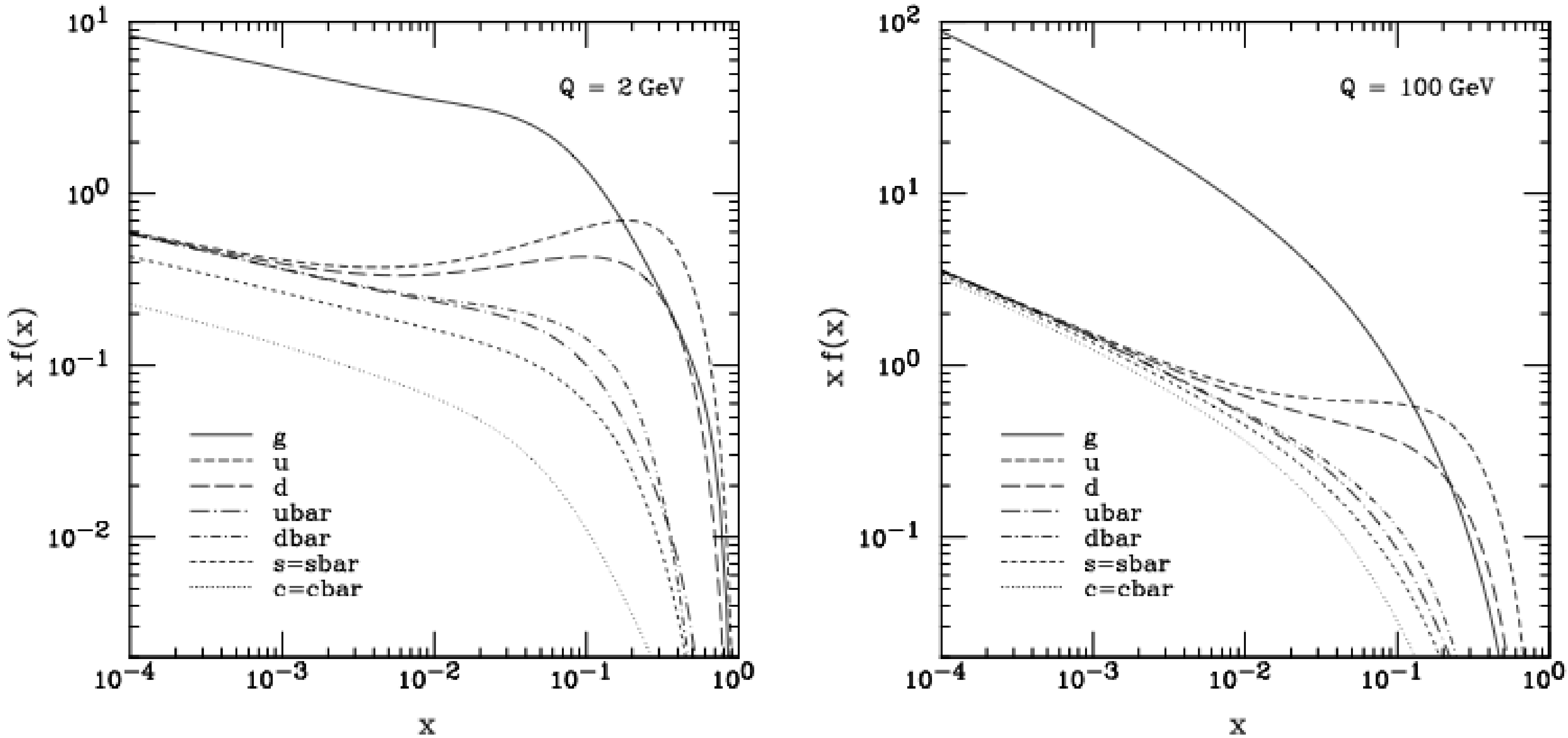


- Fast moving nucleon consists of quasi-free partons
- Partons' longitudinal momentum is fraction x of the nucleon momentum $(0 \le x \le 1)$
- Prescription for calculation of cross section

$$\sigma_{ep\to eX} = \sum_a \int_0^1 dx\, f_1^a(x)\, \hat{\sigma}_{ea}(x_{Bj}/x) + \mathcal{O}\left(\frac{1}{Q}\right) \qquad x_{Bj} = \frac{Q^2}{2P\cdot q}$$

  - $f_1^a(x)$ is parton distribution (probability density, non-perturbative, universal)
  - $\hat{\sigma}_{ea}$ is partonic cross section (perturbative, process-dependent)
  - momentum fraction x can be measured ($x = x_{Bj}$ in parton model)
  - prototype of factorization formula in perturbative QCD
  - in full QCD: $f_1^a = f_1^a(x, \mu^2)$; higher order corrections to $\hat{\sigma}_{ea}$; power corrections
  - final state interaction of active parton can be incorporated into definition of f_1^a

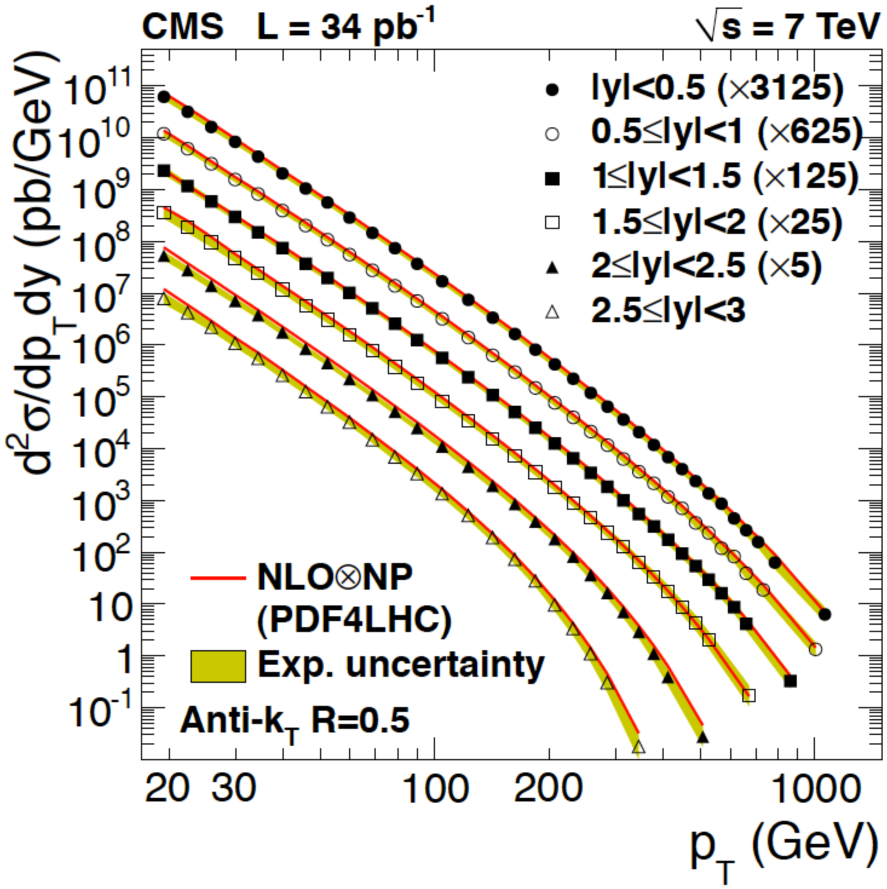
- Unpolarized parton distributions from fits to data using full QCD



(CTEQ6 parameterization)

  - unpolarized PDFs are rather well known
  - at small momentum fractions x the gluon PDF dominates

- Perturbative QCD machinery is remarkably successful (Example: $p\,p \to \mathrm{jet}\,X$)

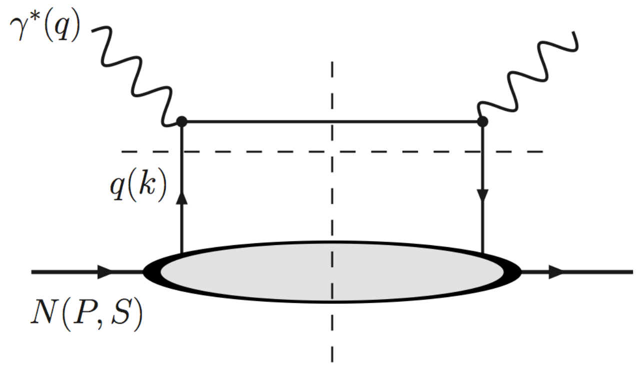


- Yet many open questions remain
  - what about partons' transverse motion ? → 3-D structure
  - under which circumstances do we have QCD factorization ?
  - etc.

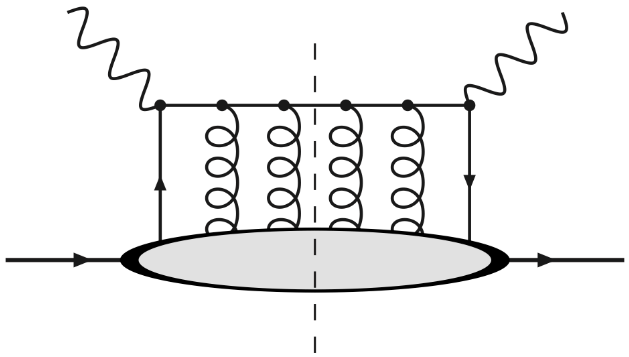
  → SSAs can give new insights into those questions

Definition of Forward Parton Distributions (PDFs)

handbag diagram for $\ell\, N \to \ell\, X$



adding quark re-scattering



- Factorization into perturbative and non-perturbative part
- Field-theoretic definition of unpolarized PDF $(P^+ \sim (P^0 + P^z) \quad P^- \sim (P^0 - P^z))$

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

- Three leading twist quark PDFs: $f_1^q \quad g_1^q \quad h_1^q$
- Wilson line (gauge link) $\mathcal{W}_{PDF}$ ensures color gauge invariance
- $\mathcal{W}_{PDF}$ generated by quark re-scattering (FSI of active quark)
- Forward PDFs are universal

TMDs: Definition and Overview

- Definition for unpolarized quarks (notation: Mulders, Tangerman, 1995)

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

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

  - partonic nucleon structure beyond collinear approximation
    $\rightarrow$ 3-D structure in $(x,\vec{k}_T)$-space
  - Sivers function $f_{1T}^{\perp}$ describes strength of spin-orbit correlation (Sivers, 1989)
  - Sivers function can give rise to SSAs in scattering processes
  - $\mathcal{W}_{TMD}$ ensures color gauge invariance
  - $f_{1T}^{\perp q}$ would vanish without $\mathcal{W}_{TMD}$ (Collins, 1992)
    $\rightarrow$ experimental evidence for significance of quark re-scattering ?

- Overview of leading twist quark TMDs

$$\langle\,|\,\bar\psi^q\,\gamma^+\,\psi^q\,|\,\rangle \quad\sim\quad f_1^q - \frac{\varepsilon_T^{ij}\,k_T^i\,S_T^j}{M}\,f_{1T}^{\perp q}$$

$$\lambda\,\langle\,|\,\bar\psi^q\,\gamma^+\gamma_5\,\psi^q\,|\,\rangle \quad\sim\quad \lambda\,\Lambda\,g_1^q + \frac{\lambda\,\vec k_T\cdot\vec S_T}{M}\,g_{1T}^q$$

$$s_T^i\,\langle\,|\,\bar\psi^q\,i\sigma^{i+}\gamma_5\,\psi^q\,|\,\rangle \quad\sim\quad \vec s_T\cdot\vec S_T\,h_1^q + \frac{\Lambda\,\vec k_T\cdot\vec s_T}{M}\,h_{1L}^{\perp q} - \frac{\varepsilon_T^{ij}\,k_T^i\,s_T^j}{M}\,h_1^{\perp q}$$
$$+\frac{1}{2M^2}\Big(2\,\vec k_T\cdot\vec s_T\,\vec k_T\cdot\vec S_T - \vec k_T^{\,2}\,\vec s_T\cdot\vec S_T\Big)\,h_{1T}^{\perp q}$$

quark polarization

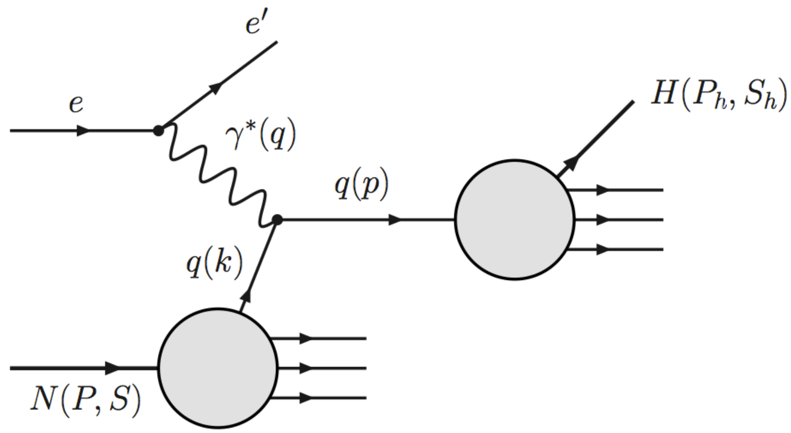
	U	L	T
U	f_1^q		$h_1^{\perp q}$
L		g_1^q	$h_{1L}^{\perp q}$
T	$f_{1T}^{\perp q}$	g_{1T}^q	h_1^q $h_{1T}^{\perp q}$

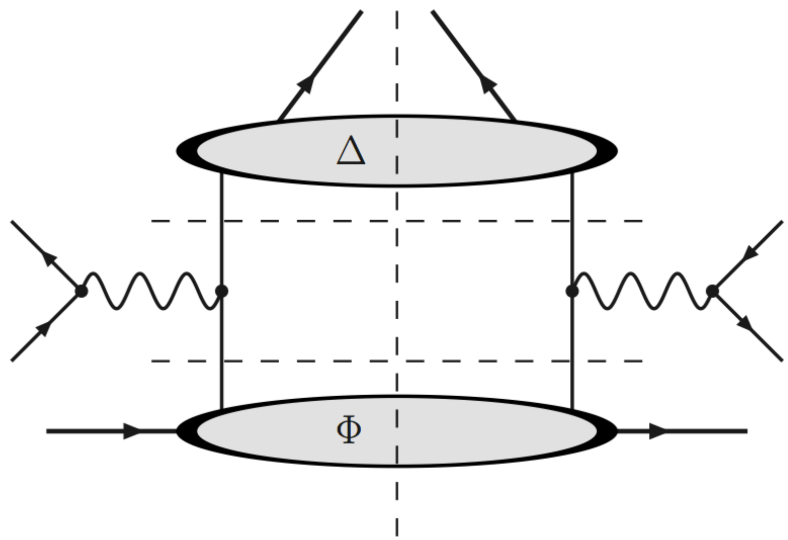
- 2 (naive) T-odd TMDs: $f_{1T}^{\perp q}$ $h_1^{\perp q}$
- dipole and quadrupole pattern
- physics of each TMD is unique

- also: 8 leading twist TMD quark fragmentation functions (FFs)
  particularly important: $H_1^\perp$ (Collins function) describing $q^\uparrow \to H\,X$

Processes Directly Sensitive to TMDs

1. Semi-inclusive deep-inelastic scattering: $\ell\, N \to \ell\, H\, X$



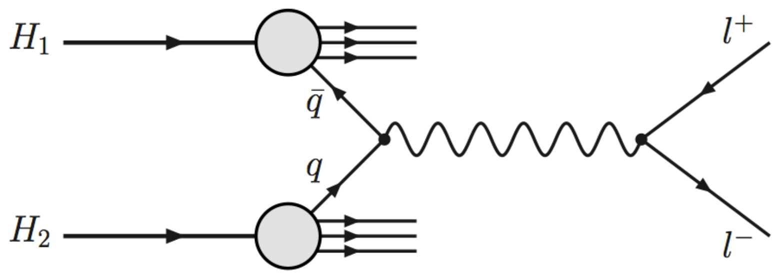


$$\sigma \sim \hat{\sigma}_{pert} \otimes \Phi \otimes \Delta$$

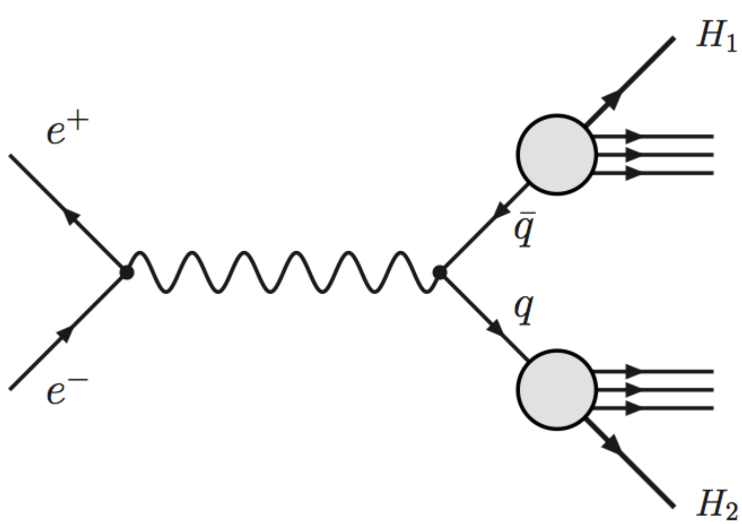
Factorization formula depends on kinematical situation:

- Cross section integrated upon $P_{h\perp}$
- Cross section differential in $P_{h\perp}$, and $P_{h\perp} \sim Q$
- Cross section differential in $P_{h\perp}$, and $P_{h\perp} \ll Q \to$ realm of TMDs

2. Drell-Yan process: $H_1\, H_2 \to \ell^+\, \ell^-\, X$



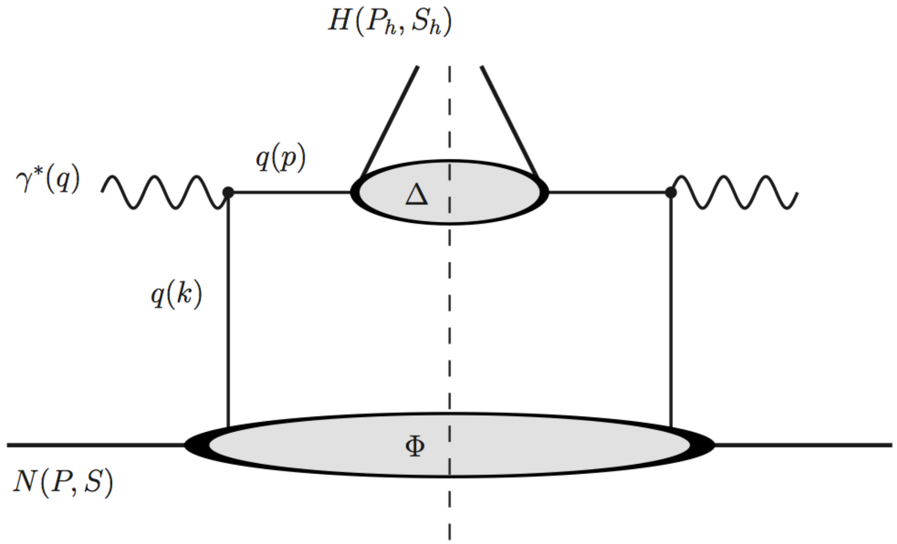
3. Electron-positron annihilation: $e^+\, e^- \to H_1\, H_2\, X$



TMD Factorization for p_T-Dependent Processes

Sample process: $\ell\, N \to \ell\, H\, X$

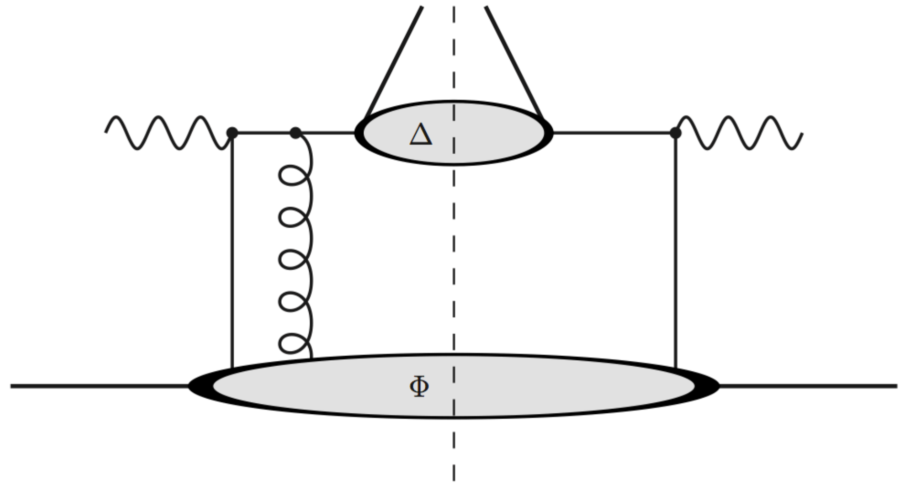
1. Tree level
   (Ralston, Soper, 1979)



$$\frac{d\sigma_{unp}}{d^3\vec{l}'\, d^3\vec{P}_h} \;\propto\; \int d^2\vec{k}_T\, d^2\vec{p}_T\, f_1(x, \vec{k}_T^{\,2})\, D_1(z, \vec{p}_T^{\,2})\, \delta^{(2)}(\vec{k}_T + \vec{q}_T - \vec{p}_T) + \ldots$$

$$f_1^q(x, \vec{k}_T^{\,2}) \;=\; \frac{1}{2}\int \frac{d\xi^-}{2\pi}\, \frac{d^2\vec{\xi}_T}{(2\pi)^2}\, e^{ik\cdot\xi}\, \langle P, S|\, \bar{\psi}^q(0)\, \gamma^+\, \psi^q(\xi^-)\, |P, S\rangle$$

2. Tree level (gauge invariant)
(... / Belitsky, Ji, Yuan, 2002 / Boer, Mulders, Pijlman, 2003 / ...)

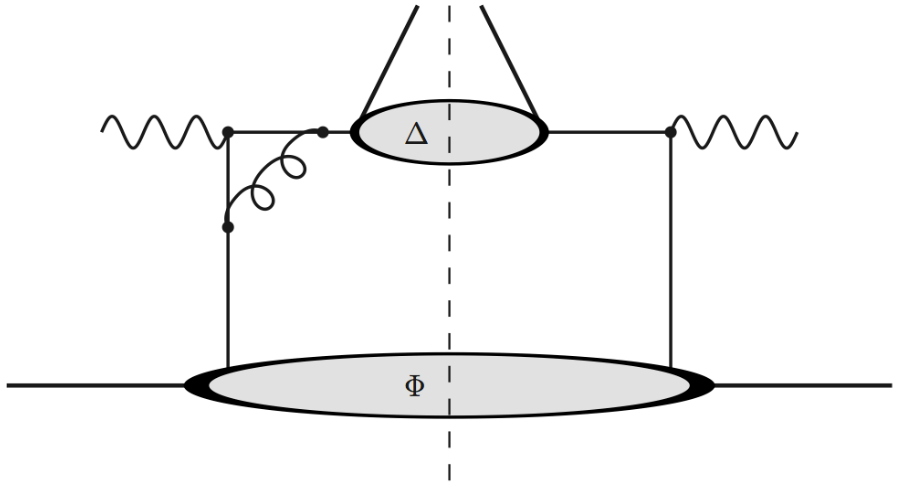


$$\frac{d\sigma_{unp}}{d^3\vec{l}'\, d^3\vec{P}_h} \propto \int d^2\vec{k}_T\, d^2\vec{p}_T\, f_1(x, \vec{k}_T^{\,2})\, D_1(z, \vec{p}_T^{\,2})\, \delta^{(2)}(\vec{k}_T + \vec{q}_T - \vec{p}_T) + \ldots$$

$$f_1^q(x, \vec{k}_T^{\,2}) = \frac{1}{2} \int \frac{d\xi^-}{2\pi} \frac{d^2\vec{\xi}_T}{(2\pi)^2}\, e^{ik\cdot\xi} \langle P, S|\, \bar{\psi}^q(0)\, \gamma^+\, \mathcal{W}_{TMD}\, \psi^q(\xi^-)\, |P, S\rangle$$

- Complications: Rapidity divergences, Wilson line self energies $\longrightarrow$ under control
(Collins, Soper, 1981 / Collins, Hautmann, 2000 / Cherednikov, Stefanis, 2007 / Collins 2011 / Echevarria, Idilbi, Schimemi, 2011 / ...)

3. Beyond tree level
(Collins, Soper, 1981 / Collins, Soper, Sterman, 1985 /
Ji, Ma, Yuan, 2004 / Collins, Metz, 2004 / ...)



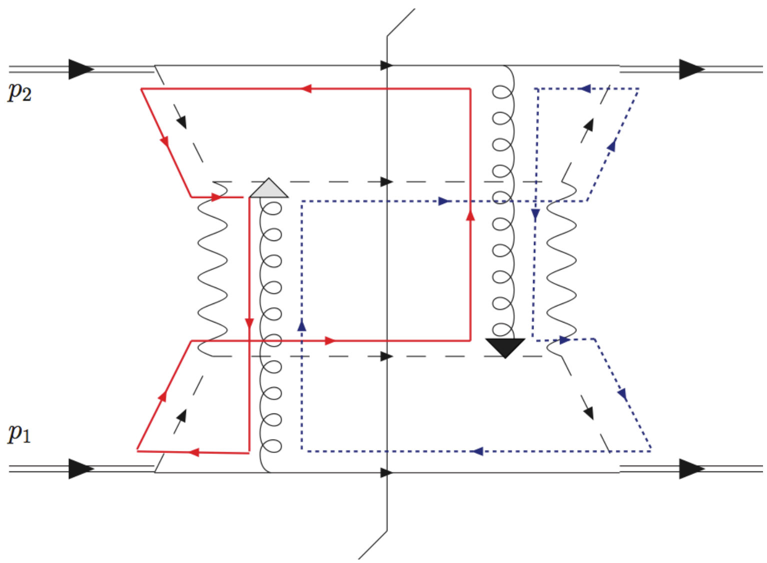
$$\frac{d\sigma_{unp}}{d^3\vec{l}'\, d^3\vec{P}_h} \propto \int d^2\vec{k}_T\, d^2\vec{p}_T\, d^2\vec{l}_T\, f_{1\,\mathrm{sub}}(x, \vec{k}_T^2)\, D_{1\,\mathrm{sub}}(z, \vec{p}_T^2)$$

$$\times\, S(\vec{l}_T)\, H\, \delta^{(2)}(\vec{k}_T + \vec{q}_T + \vec{l}_T - \vec{p}_T) + \ldots$$

- Leading twist contribution for collinear, soft, and hard gluon radiation
- Avoid double counting by subtraction formalism $\longrightarrow$ modified definitions of TMDs
- Further development: absorb all soft gluon effects in TMDs after Fourier transform to b_T-space (Collins, 2011)
- SSAs can provide strong tests of TMD factorization

Breakdown of TMD Factorization

- Sample process: $p\, p \to \text{jet jet } X$
- Originally thought to show Generalized TMD Factorization
  $\to$ definition of TMDs depends on partonic subprocess
  (Bomhof, Mulders, Pijlman, 2004 / ... / Collins, Qiu, 2007 / Collins, 2007)
- However, even Generalized TMD Factorization breaks down (Rogers, Mulders, 2010)



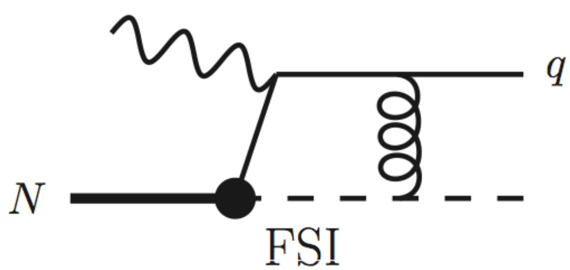
  - complicated color flow does not allow one to define two individual TMDs (color-entanglement)
  - specific to non-Abelian gauge theory

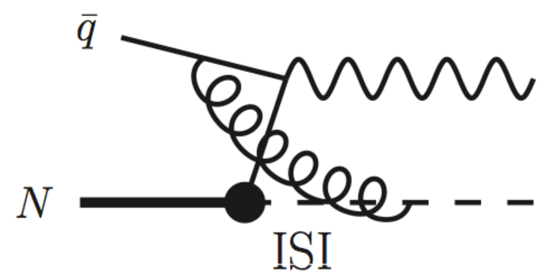
Breakdown of Universality: TMDs in SIDIS vs DY

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

$$f_{1T}^{\perp}\big|_{DY} = -\, f_{1T}^{\perp}\big|_{SIDIS} \qquad\qquad h_1^{\perp}\big|_{DY} = -\, h_1^{\perp}\big|_{SIDIS}$$

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





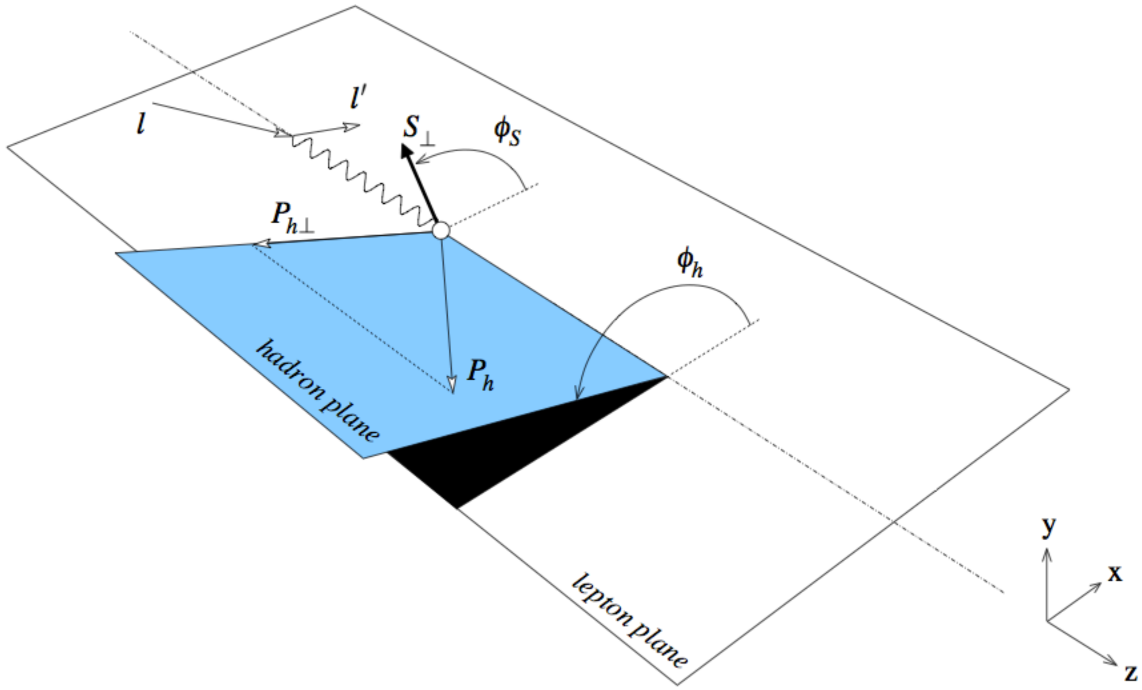
- Several labs worldwide aim at measurement of Sivers effect in Drell-Yan:
BNL, CERN, FermiLab, GSI, IHEP, JINR, J-PARC

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

- TMD FFs expected to be universal (Metz, 2002 / Collins, Metz, 2004 / ...)
$\rightarrow$ supported by existing phenomenology

Kinematics and SSAs for Semi-Inclusive DIS: $\ell N^{\uparrow} \to \ell H X$

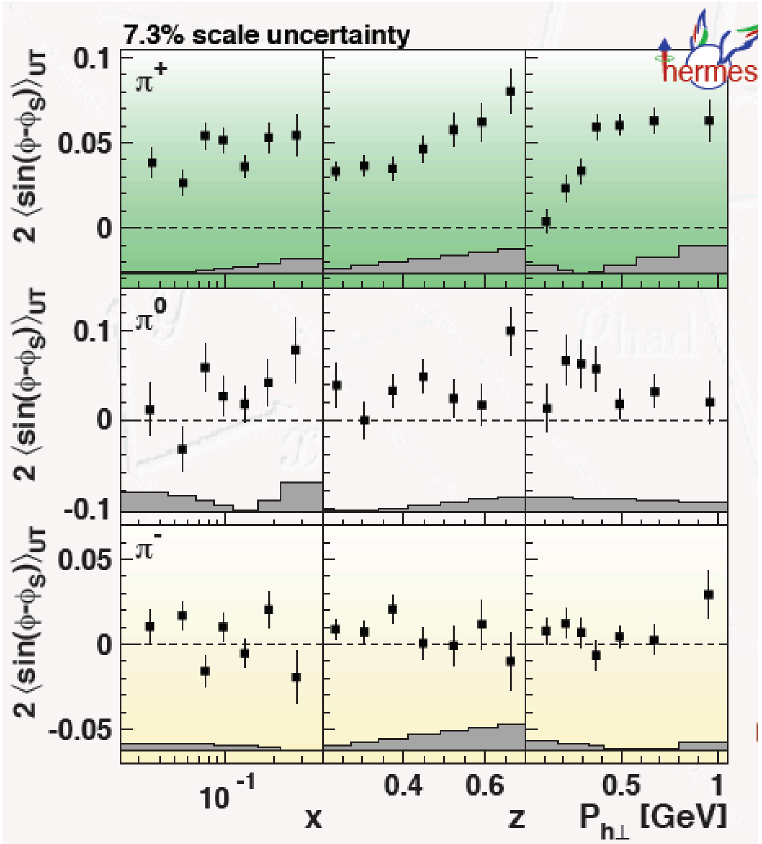
- 6 independent kinematical variables: $x \quad Q^2 \quad \phi_S \quad z \quad P_{h\perp} \quad \phi_h$



- 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

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

Observation of Nonzero Sivers Asymmetry in SIDIS

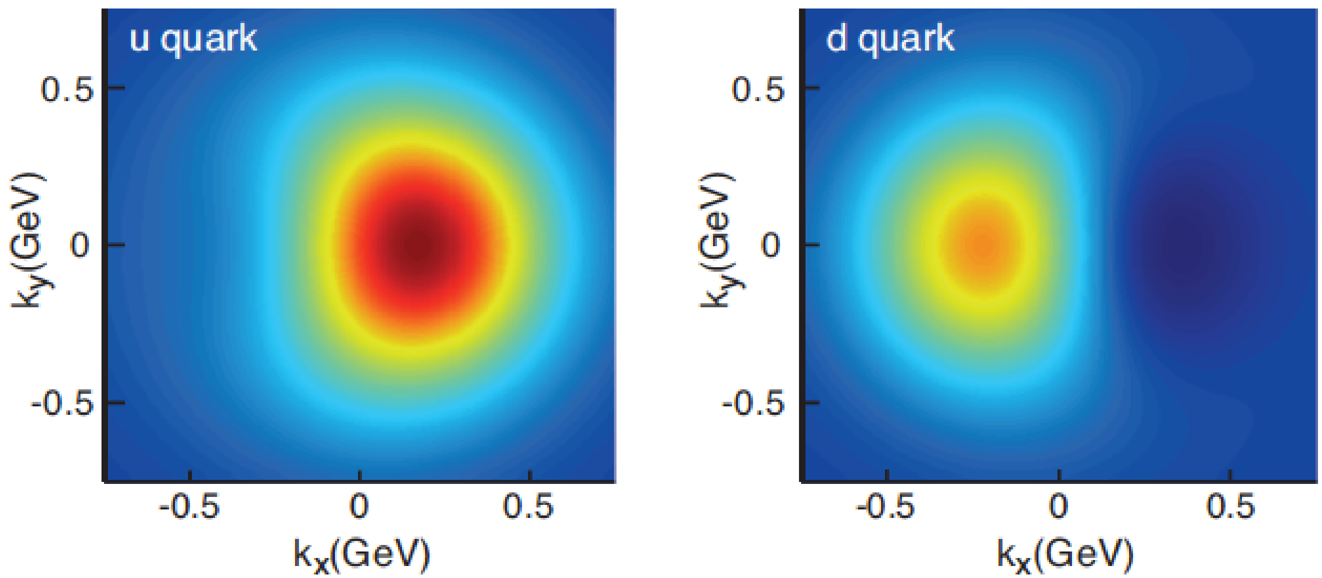


- In the meantime, many (consistent) data from HERMES, COMPASS, JLab
- Evidence for quark re-scattering $\longrightarrow$ process dependence of $f_{1T}^{\perp}$ can be expected
- Have we fully understood the Sivers asymmetry in semi-inclusive DIS ?
- In any case, verification of process dependence of $f_{1T}^{\perp}$ would provide further evidence for underlying re-scattering picture

3-D structure of the Nucleon: Distortion due to Sivers Effect

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

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



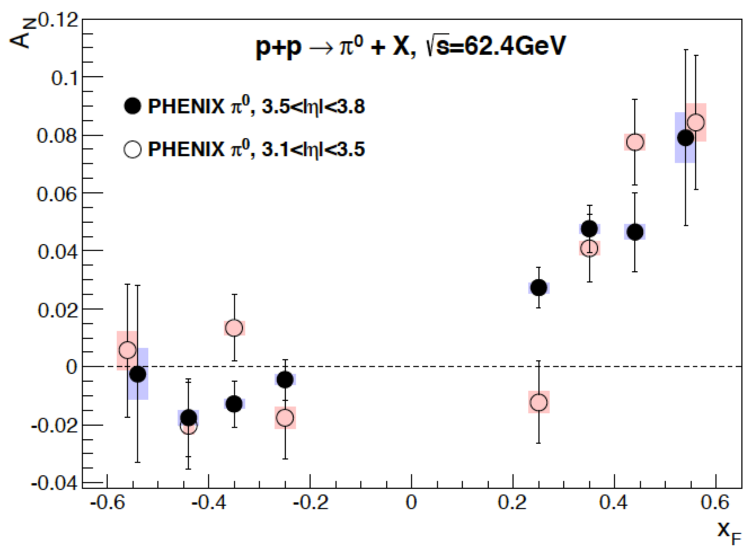
(from arXiv:1212.1701, based on Anselmino et al, 2011)

- Sivers effect generates distorted distribution of unpolarized quarks
- 3-D imaging of the nucleon now possible (plots based on data!)

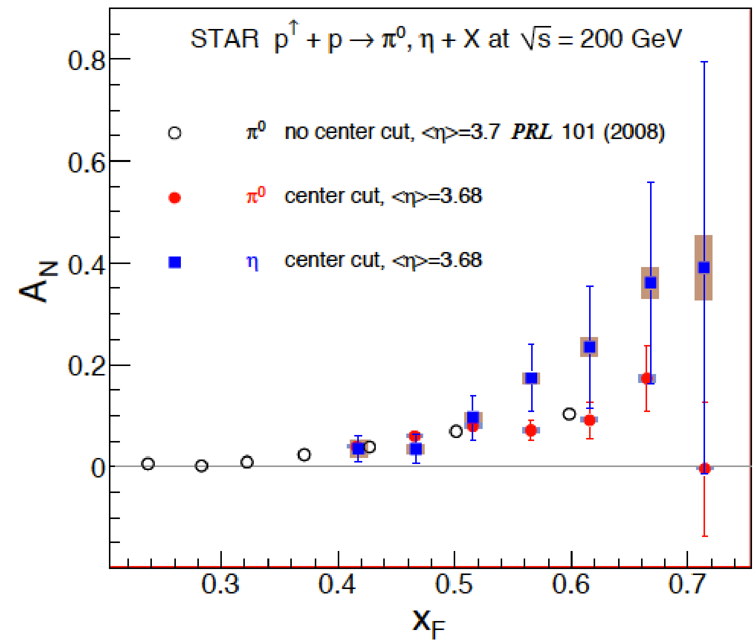
Transverse SSA in $p^{\uparrow}p \to H\ X$

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

1. Recent sample data from RHIC



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

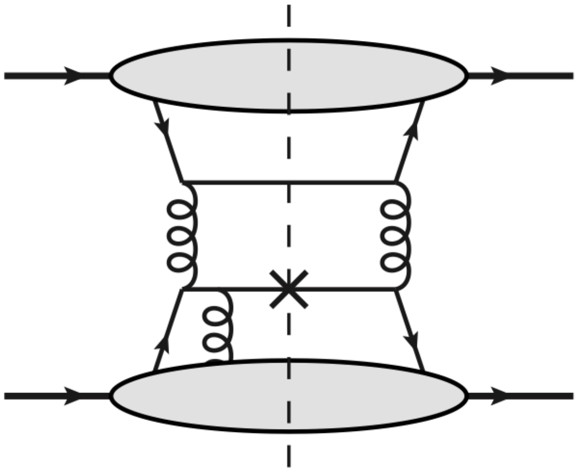


STAR, 2012 $\sqrt{s} = 200\,\mathrm{GeV}$

- Significant nonzero effects at positive x_F
- $A_N^{\pi^0}$ systematically smaller than magnitude of $A_N^{\pi^{\pm}}$

2. Collinear twist-3 factorization
(Ellis, Furmanski, Petronzio, 1983 / Efremov, Teryaev, 1983, 1984 / Qiu, Sterman, 1991, 1998 / etc.)

- Sample diagram for $q\,q \to q\,q$ channel



  - attach extra gluon in all possible ways and consider all channels

- General structure of cross section

$$
\begin{aligned}
d\sigma(\vec{S}_T) &= H \otimes f_{a/A(3)} \otimes f_{b/B(2)} \otimes D_{C/c(2)} &&\to \text{Sivers-type} \\
&+ H' \otimes f_{a/A(2)} \otimes f_{b/B(3)} \otimes D_{C/c(2)} &&\to \text{Boer-Mulders-type} \\
&+ H'' \otimes f_{a/A(2)} \otimes f_{b/B(2)} \otimes D_{C/c(3)} &&\to \text{“Collins-type”}
\end{aligned}
$$

- Sivers-type contribution
  - Focus on contribution from QS function T_F (Qiu, Sterman)

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

  - vanishing gluon momentum $\rightarrow$ soft gluon pole matrix element
  - relation to Sivers function (Boer, Mulders, Pijlman, 2003)

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

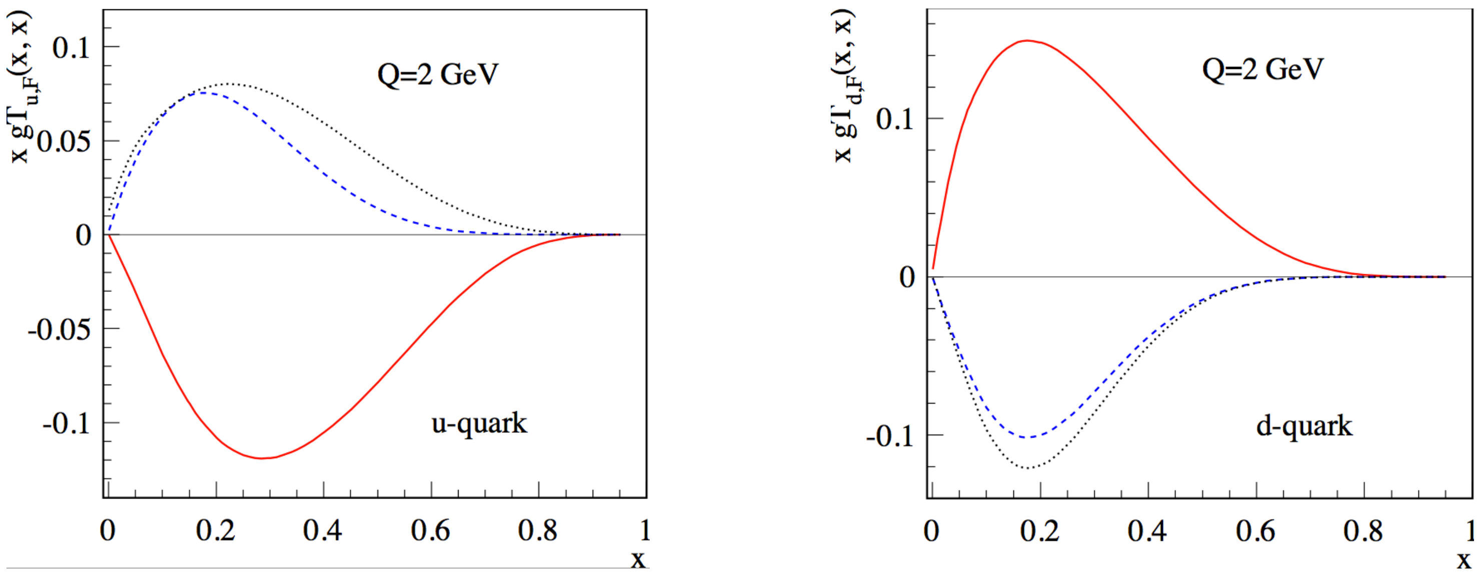
  - relation between Sivers asymmetry in SIDIS and the SSA in $p^{\uparrow}p \rightarrow h \, X$ possible

- Boer-Mulders-type contribution
  - expected to be very small (Koike, Kanazawa, 2000)

- "Collins-type" contribution
  - first study focused on so-called derivative term (Kang, Yuan, Zhou, 2010)
  - full result obtained recently (Metz, Pitonyak, 2012)

3. Sign mismatch for Sivers effect (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)

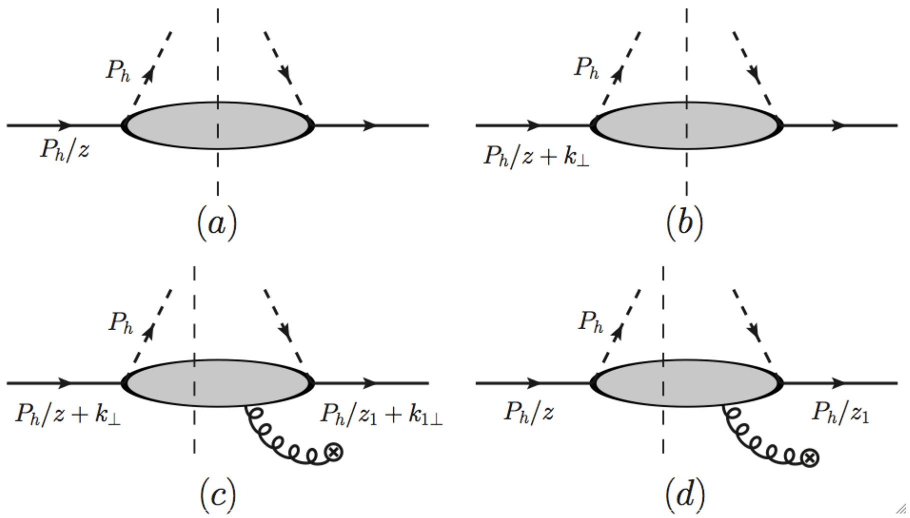


- Striking sign mismatch !
- Which of the signs for T_F is correct ?
- Is the assumption of a dominating Sivers-type contribution unjustified ?
- Analysis of SSA in inclusive DIS $(\ell\, N^{\uparrow} \to \ell\, X)$ actually suggests this
- Can the large SSAs in $p^{\uparrow}p \to H\, X$ be caused by the "Collins-type" contribution ?

Fragmentation Contribution to Transverse SSA in $p^{\uparrow}p \to H\ X$

(Metz, Pitonyak, 2012)

1. Contributing effects



- 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

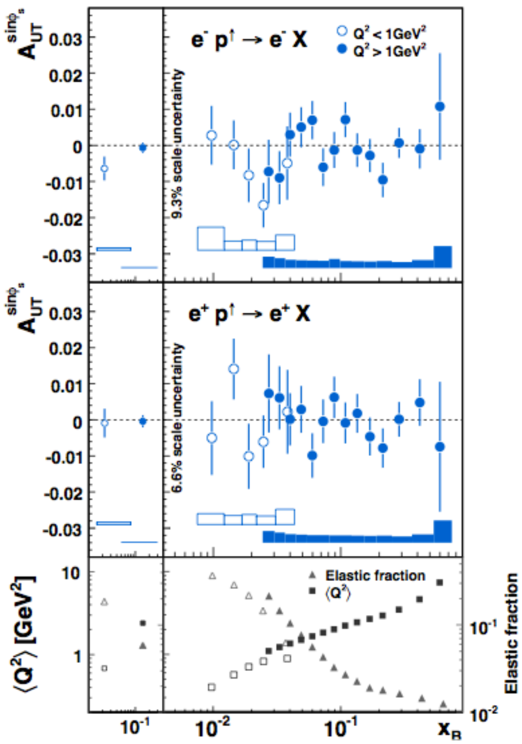
$$\frac{P_h^0 d\sigma(\vec{S}_\perp)}{d^3\vec{P}_h} = -\frac{2\alpha_s^2 M_h}{S}\epsilon_{\perp,\alpha\beta}\, S_\perp^\alpha P_{h\perp}^\beta$$
$$\times \sum_i \sum_{a,b,c} \int_{z_{min}}^1 \frac{dz}{z^3} \int_{x'_{min}}^1 \frac{dx'}{x'}\,\frac{1}{x}\,\frac{1}{x'S+T/z}\,\frac{1}{-x'\hat{t}-x\hat{u}}\,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

- $\hat{H}\,,\ H\,,\ \hat{H}_{FU}^{\Im}$ related, but dynamics in twist-3 approach goes beyond Collins effect
- Derivative term for $\hat{H}$ computed previously (Kang, Yuan, Zhou, 2010)
  $\rightarrow$ does not necessarily dominate
- $\hat{H}$-contribution (Collins effect) has correct sign (Anselmino et al, 2012)
- Phenomenology of all contributions needed

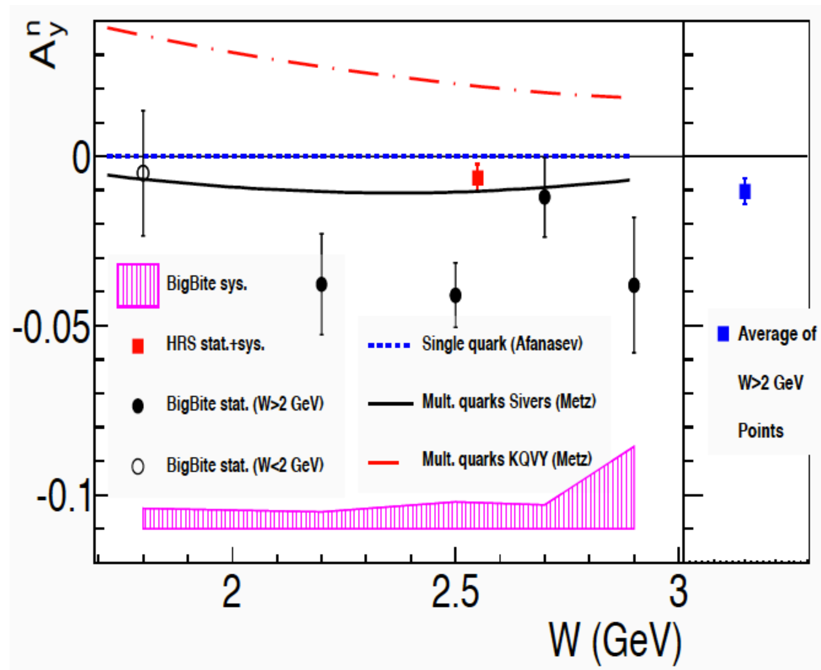
Transverse SSA in Inclusive DIS, $e\,N^{\uparrow} \;\to e\,X$

1. Recent data

A^p_{UT} (HERMES, 2009)



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



$A^p_{UT} = 0$ within uncertainties (10^{-3})

$A^n_{UT} \neq 0$

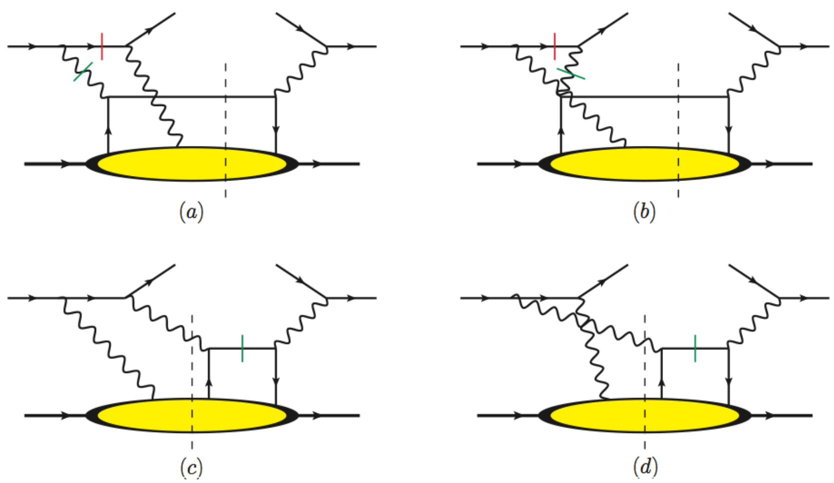
- Can one (qualitatively) understand these data ?
- Can one learn something beyond inclusive DIS ?

2. Theory

- $A_{UT} = 0$ for one-photon exchange (Christ, Lee, 1966)

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

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

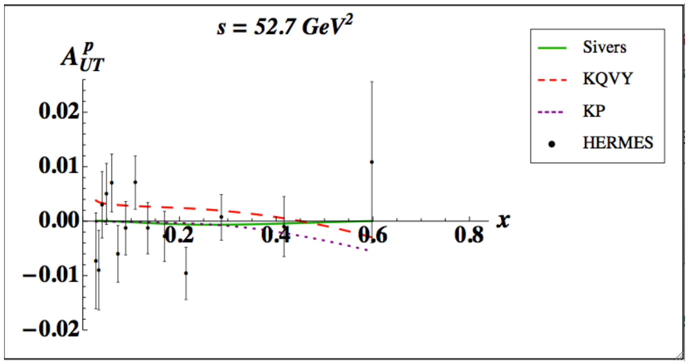


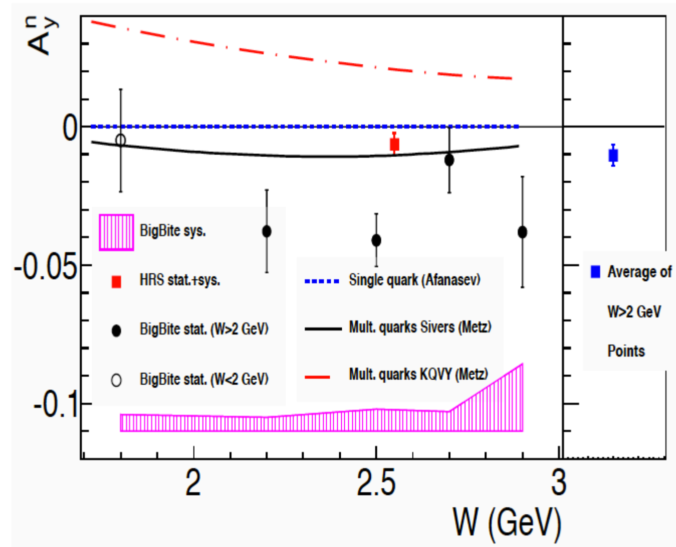
  – express through $q\gamma q$ correlator F_{FT}
  – soft photon pole contribution
  – soft fermion pole contribution vanishes
    (see also Koike, Vogelsang, Yuan, 2007)
  – leads to $A_{UT} \sim 1/Q$

- Couplings to different quarks presumably dominate, in particular at larger x

- 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





  - "Sivers input" for T_F (obtained from $f_{1T}^{\perp}$) provides description of data
  - simultaneous description of transverse SSAs in SIDIS and in Inclusive DIS
  - first indication of process dependence of Sivers effect
  - note: process dependence of Sivers effect also studied recently in $p^{\uparrow}p \to \text{jet}\, X$ (Gamberg, Kang, Prokudin, 2013)
  - "KQVY input" for T_F (obtained from SSA in $p^{\uparrow}p \to H\, X$), in particular, has wrong sign for neutron asymmetry
  - apparently, SSA $p^{\uparrow}p \to H\, X$ indeed not caused by Sivers-type contribution (same conclusion more recently by PHENIX, 2013)

Summary

- Transverse SSAs have been observed in several hard scattering processes

- QCD description requires to go beyond twist-2 collinear parton approximation
  $\rightarrow$ exploring new territories in QCD

- SSAs provide input on
  - TMDs (3-D structure of the nucleon)
  - QCD factorization
  - Universality properties of parton correlation functions

- Simultaneous description of transverse SSAs may be achieved for
  - semi-inclusive DIS (TMD-factorization)
  - processes like $p^{\uparrow}p \rightarrow H\ X$ (collinear twist-3 factorization)
  - inclusive DIS (collinear twist-3 factorization)

- Important indications from phenomenology:
  - Sivers effect is process dependent
  - Large SSAs in $p^{\uparrow}p \rightarrow H\ X$ not caused by the Sivers effect