Spin asymmetries in lepton-hadron and hadron-hadron collisions

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EXPERIMENTS

- Lepton-Hadron: CERN, DESY, JLab
- Hadron-Hadron: RHIC, FermiLab

Outline

- Introduction
- Transversity parton distribution in the Drell-Yan process
- Single spin asymmetries and p_T-dependent correlators
- T-odd parton densities and color gauge invariance
- Experimental evidence for single spin asymmetries
- Factorization and universality of p_T-dependent correlators
- Phenomenology of the Sivers effect
- Single spin asymmetries in inclusive DIS
- Summary

General strategy

1. Factorization

$$\sigma \propto (\text{pert. part}) \otimes (\text{non-pert. part}) + \mathcal{O}\left(\frac{1}{Q}\right)$$

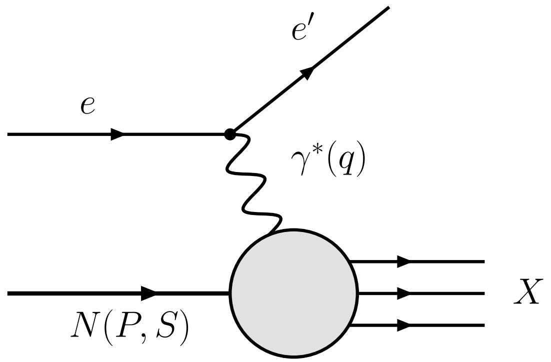
- required for interpretation
- does not hold for each hard process
- required scale: $Q > 1\,\mathrm{GeV}$

2. Universality

- allows one to make predictions
- can be non-trivial

Inclusive deep-inelastic scattering

- Process



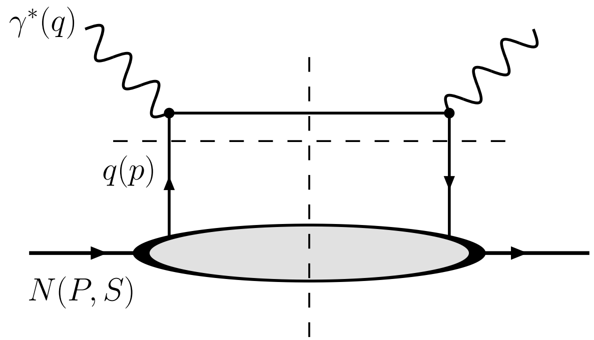
Variables

$$Q^2 = -q^2 > 0 \qquad x = \frac{Q^2}{2P\cdot q} \qquad \Phi_l^S$$

- Optical theorem

$$\sigma_{\gamma^* N\to X} \propto \mathrm{Im}\, A(\gamma^* N \to \gamma^* N, \vartheta = 0)$$

- Parton model



$\longrightarrow$ factorization

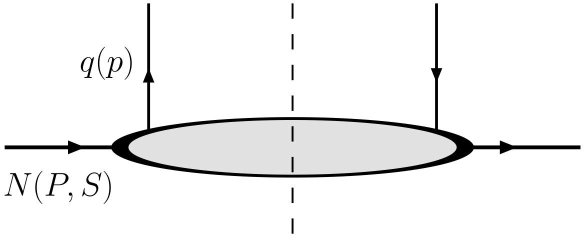
$q(x, Q^2) \quad (f_1^q) \qquad \Delta q(x, Q^2) \quad (g_1^q)$

$(g, \ \Delta g)$

$$p^+ = \tfrac{1}{\sqrt{2}}(p^0 + p^3) = xP^+$$

Partonic functions

1. Forward parton densities



- Unpolarized pdf

$$f_1(x) = \int \frac{d\xi^-}{4\pi} \, e^{ixP^+\xi^-} \, \langle P,S| \, \bar{\psi}(0) \, \gamma^+ \, \psi(\xi^-) \, |P,S\rangle$$

$$\xi^- = \frac{1}{\sqrt{2}}(t-z) \qquad\qquad \xi^+ = \xi_T = 0$$

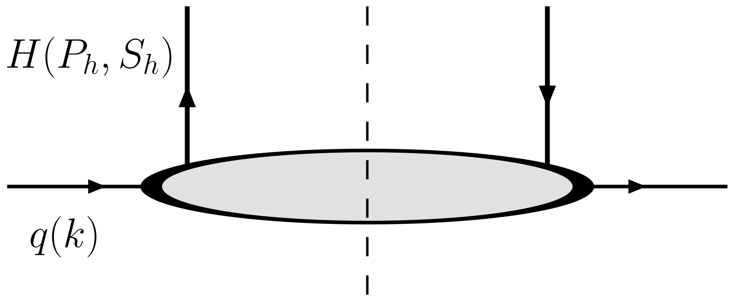
- Helicity pdf

$$g_1(x) \propto \langle \; | \, \bar{\psi}(0) \, \gamma^+ \gamma_5 \, \psi(\xi^-) \, | \; \rangle$$

- Transversity pdf

$$h_1(x) \propto \langle \; | \, \bar{\psi}(0) \, i\sigma^{i+} \gamma_5 \, \psi(\xi^-) \, | \; \rangle \qquad \sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$$

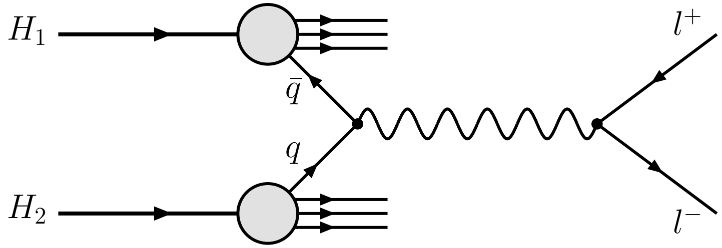
2. Forward fragmentation functions



$$\sum\!\!\!\!\!\!\!\int_X \langle 0|\, \psi\, |H; X\rangle\, \Gamma\, \langle H; X|\, \bar{\psi}\, |0\rangle$$

Depending on $z = \frac{P_h^-}{k^-}$

Transversity in Drell-Yan



$$A_{TT}^{H_1 H_2} = a_{TT} \frac{\sum_q e_q^2 \, h_1^{q/H_1}(x_1, Q^2) h_1^{\bar{q}/H_2}(x_2, Q^2) + (x_1 \leftrightarrow x_2)}{\sum_q e_q^2 \, f_1^{q/H_1}(x_1, Q^2) f_1^{\bar{q}/H_2}(x_2, Q^2) + (x_1 \leftrightarrow x_2)}$$

- Kinematics

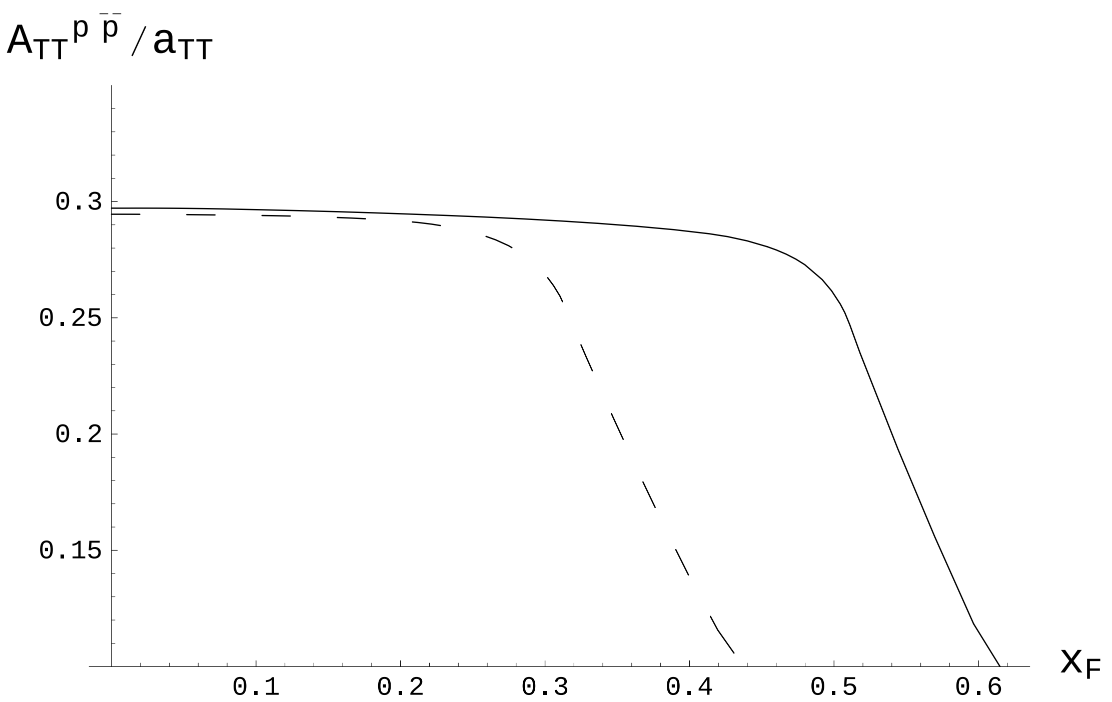
$$Q^2 \approx (x_1 P_1 + x_2 P_2)^2 \approx x_1 x_2 (P_1 + P_2)^2 = x_1 x_2 s$$

$$y = \frac{1}{2} \ln \frac{x_1}{x_2} \qquad x_1 = \sqrt{\frac{Q^2}{s}} \, e^{y} \qquad x_2 = \sqrt{\frac{Q^2}{s}} \, e^{-y} \qquad x_F = x_1 - x_2$$

- Results
  A_{TT}^{pp} small at RHIC ($\sqrt{s} = 200\,\mathrm{GeV}$) (Martin, Schäfer, Stratmann, Vogelsang, 1997)
  A_{TT}^{pp} moderate at JPARC ($\sqrt{s} = 10\,\mathrm{GeV}$)
  $A_{TT}^{p\bar{p}}$ large at GSI ($6\,\mathrm{GeV} < \sqrt{s} < 15\,\mathrm{GeV}$)

(Anselmino, Barone, Drago, Nikolaev, 2004)

$$\begin{aligned} s &= 30\,\mathrm{GeV}^2 \qquad 45\,\mathrm{GeV}^2 \\ Q^2 &= 16\,\mathrm{GeV}^2 \\ h_1^q(x, Q_0^2) &= g_1^q(x, Q_0^2) \text{ at low scale } Q_0^2 \end{aligned}$$

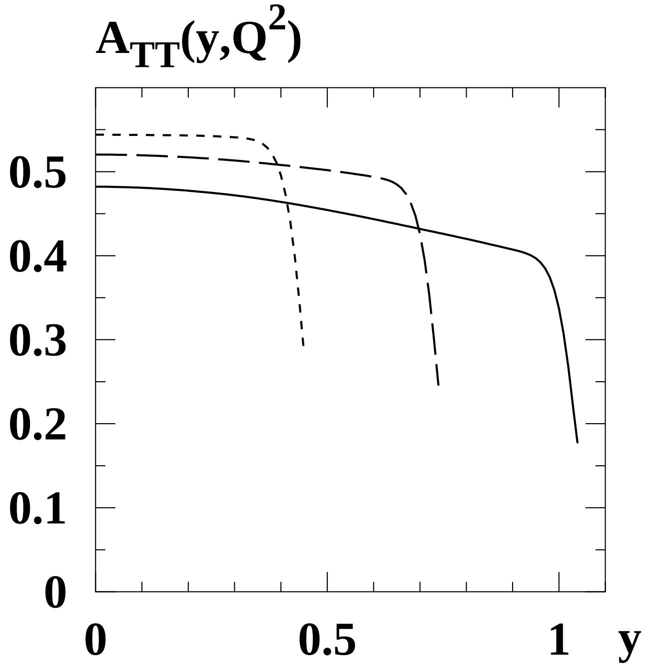


(Efremov, Goeke, Schweitzer, 2004)

$$s = 45\,\mathrm{GeV}^2$$

$$Q^2 = 5\,\mathrm{GeV}^2 \qquad 9\,\mathrm{GeV}^2 \qquad 16\,\mathrm{GeV}^2$$

$h_1^q(x, Q_0^2)$ from chiral quark soliton model



Classification of single spin asymmetries

1. Typ A

$$\sigma \propto A + \vec{S} \cdot \vec{P}\, B$$

- odd under parity
- even under (naïve) time-reversal
- Examples: $p\,\vec{p} \longrightarrow e^-\,\bar{\nu}_e\,X$ $(\bar{u}\,\vec{d} \longrightarrow W^- \longrightarrow e^-\,\bar{\nu}_e$ on parton level$)$
  $\vec{e}\,p \longrightarrow e\,p$ via exchange of Z

2. Typ B

$$\sigma \propto A + \vec{S} \cdot (\vec{P}_1 \times \vec{P}_2)\, B$$

- even under parity
- odd under naïve time-reversal
- requires two non-collinear momenta
- requires non-trivial phase on amplitude level

p_T-dependent parton densities

$$\int \frac{d\xi^- d^2\vec{\xi}_T}{2(2\pi)^3}\, e^{i(xP^+\xi^- - \vec{p}_T\cdot\vec{\xi}_T)}\, \langle P,S|\, \bar{\psi}(0)\,\gamma^+\,\psi(\xi^-,\vec{\xi}_T)\,|P,S\rangle$$

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

Parameterization of

$$\Phi^{[\Gamma]}(x,\vec{p}_T,S) = \int \frac{d\xi^- d^2\vec{\xi}_T}{2(2\pi)^3}\, e^{i(xP^+\xi^- - \vec{p}_T\cdot\vec{\xi}_T)}\, \langle P,S\,|\,\bar{\psi}(0)\,\Gamma\,\psi(\xi^-,\vec{\xi}_T)\,|\,P,S\rangle$$

Leading order (8 functions, 2 T-odd)

$$\Phi^{[\gamma^+]} \quad = \quad f_1 - \frac{\varepsilon_T^{ij} p_{Ti} S_{Tj}}{M}\, f_{1T}^{\perp}$$

$$\Phi^{[\gamma^+\gamma_5]} \quad = \quad \lambda\, g_{1L} + \frac{\vec{p}_T\cdot\vec{S}_T}{M}\, g_{1T}$$

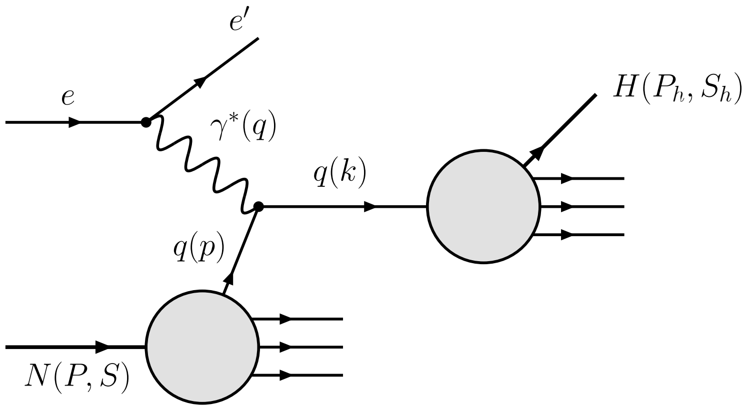
$$\Phi^{[i\sigma^{i+}\gamma_5]} \quad = \quad S_T^i\, h_{1T} + \frac{p_T^i}{M}\left(\lambda\, h_{1L}^{\perp} + \frac{\vec{p}_T\cdot\vec{S}_T}{M}\, h_{1T}^{\perp}\right) - \frac{\varepsilon_T^{ij} p_{Tj}}{M}\, h_1^{\perp}$$

Parton densities of the nucleon

	Quarks				Gluons			
Forward	f_1	g_1	h_1		g	Δg		
p_T-dependent	f_1	$f_{1T}^{\perp}$	g_{1L}	g_{1T}	g	Δg_L	g_T	Δg_T
	h_{1T}	$h_{1L}^{\perp}$	$h_{1T}^{\perp}$	$h_1^{\perp}$	$h^{\perp}$	Δh_T	$\Delta h_L^{\perp}$	$\Delta h_T^{\perp}$
Generalized	H	E	$\tilde{H}$	$\tilde{E}$	H^g	E^g	$\tilde{H}^g$	$\tilde{E}^g$
	H_T	E_T	$\tilde{H}_T$	$\tilde{E}_T$	H_T^g	E_T^g	$\tilde{H}_T^g$	$\tilde{E}_T^g$

p_T-dependent processes

1. $e\,N \to e'\,H\,X$



2. $H_1\,H_2 \to l^+\,l^-\,X$

3. $e^+\,e^- \to H_1\,H_2\,X$

4. $H_1\,H_2 \to jet_1\,jet_2\,X \qquad H_1\,H_2 \to jet\,H\,X \qquad H_1\,H_2 \to jet\,\gamma\,X$

T-odd parton densities

- (Sivers, 1990)

$$\int \frac{d\xi^- d^2\vec{\xi}_T}{2(2\pi)^3} e^{i(xP^+\xi^- - \vec{p}_T\cdot\vec{\xi}_T)} \langle P,\uparrow | \bar{\psi}(0)\, \gamma^+ \, \psi(\xi^-, \vec{\xi}_T) \, |P,\uparrow\rangle$$

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

$\longrightarrow$ single-spin/azimuthal asymmetry

- (Boer, Mulders, 1998)

$$h_1^{\perp}(x, \vec{p}_T^{\,2}) \propto \langle P, \mathrm{unp} \,|\, \bar{\psi}(0)\, i\sigma^{i+}\gamma_5 \, \psi(\xi^-, \vec{\xi}_T) \,|\, P, \mathrm{unp}\rangle$$

Time-reversal:

$f_{1T}^{\perp} = -f_{1T}^{\perp} = 0 \qquad\qquad h_1^{\perp} = 0$

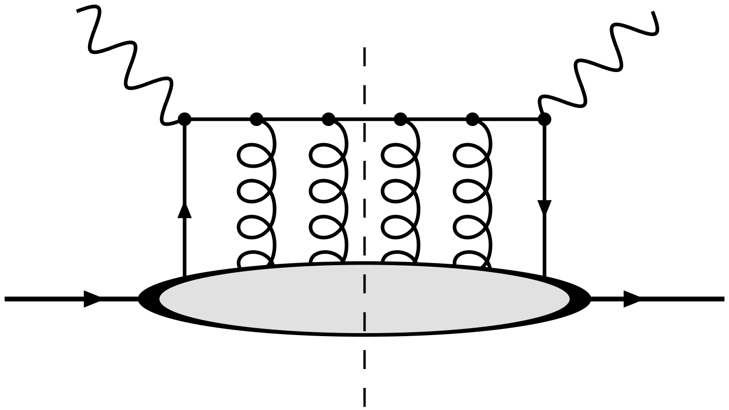
Color gauge invariance

1. Forward partonic functions

$$\int d\xi^- \, e^{ixP^+\xi^-} \, \langle \, | \, \bar{\psi}(0) \, \Gamma \, \mathcal{L}(0;\xi^-) \, \psi(\xi^-) \, | \, \rangle$$

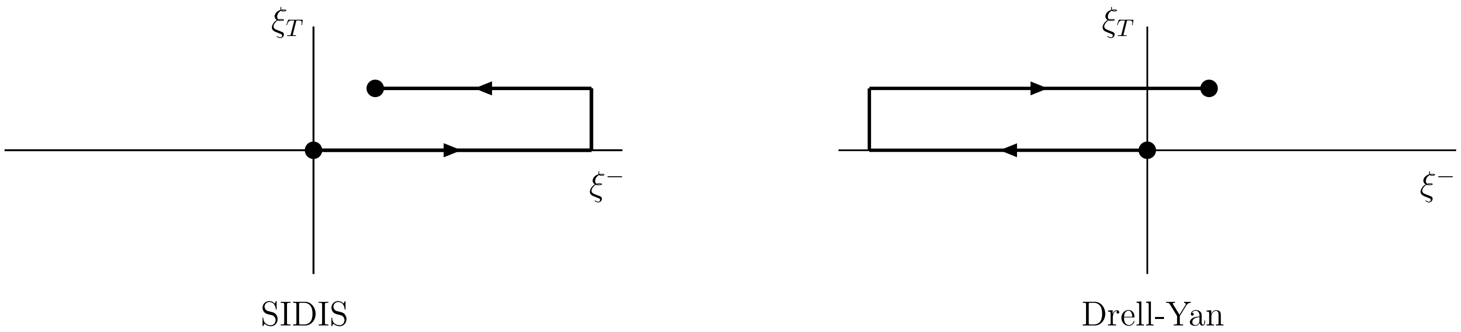
$$\mathcal{L}(0;\xi^-) = \mathcal{P}\exp\left(-ig \int_0^{\xi^-} d\eta^- \, A^+(0,\eta^-,\vec{0}_T) \right)$$

Gauge-link generated by rescattering



2. p_T-dependent partonic functions

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



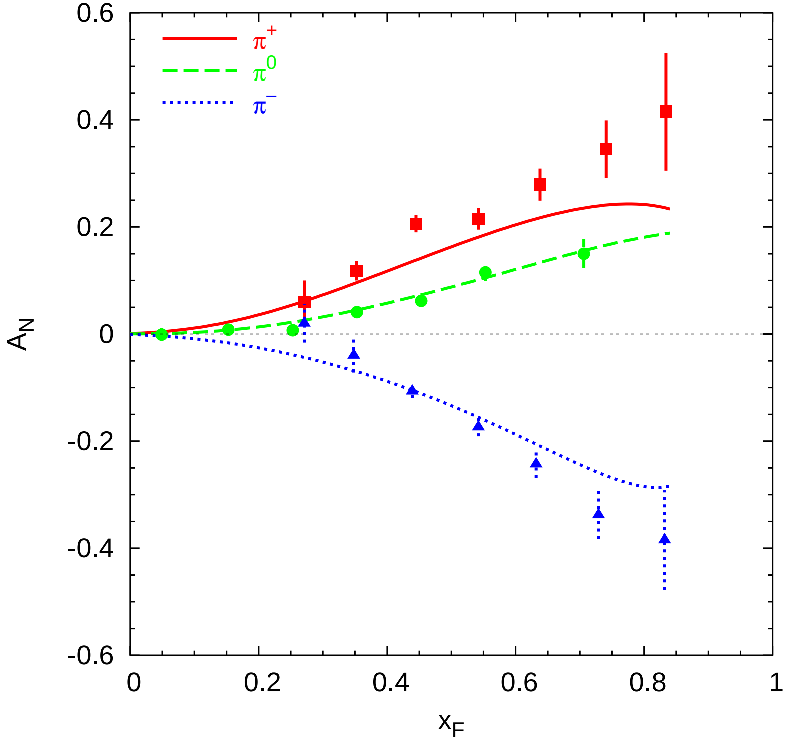
- $\mathcal{L}(0,\vec{0}_T;\xi^-,\vec{\xi}_T) = \mathcal{L}(0,\vec{0}_T;\infty,\vec{0}_T) \times \mathcal{L}(\infty,\vec{0}_T;\infty,\vec{\xi}_T) \times \mathcal{L}(\infty,\vec{\xi}_T;\xi^-,\vec{\xi}_T)$
  (Belitsky, Ji, Yuan, 2002)

- Gauge-link $\longrightarrow$ T-odd pdfs can be non-zero
  (Brodsky, Hwang, Schmidt, 2002; Collins, 2002)

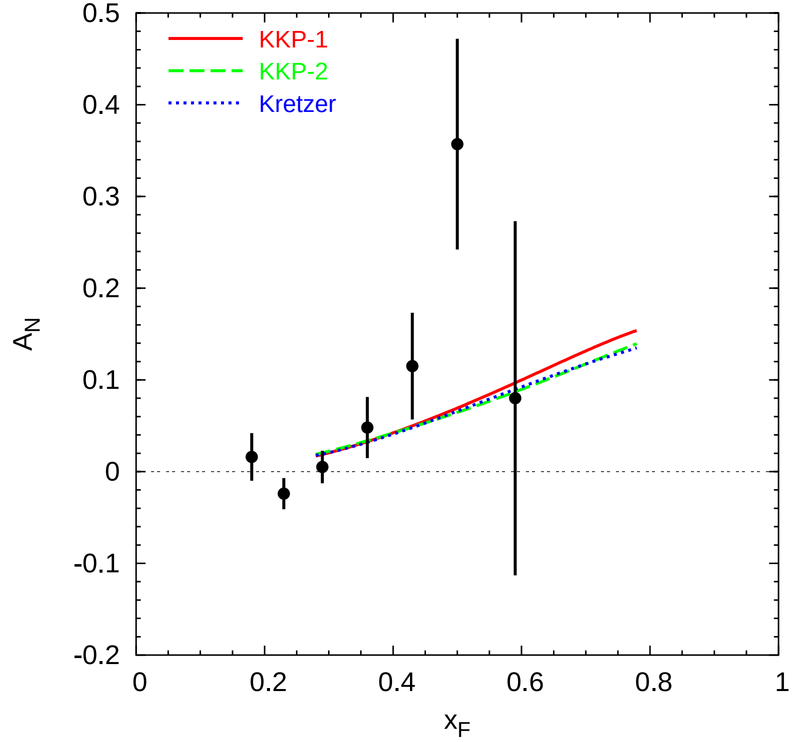
- Different links for semi-inclusive DIS and Drell-Yan $\longrightarrow$ Universality?
  Time-reversal: $f_{1T}^{\perp}\big|_{DY} = -f_{1T}^{\perp}\big|_{DIS}$ $\qquad$ $h_1^{\perp}\big|_{DY} = -h_1^{\perp}\big|_{DIS}$
  (Collins, 2002)

Transverse SSA in $p\,p^{\uparrow} \;\rightarrow \pi\,X$

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

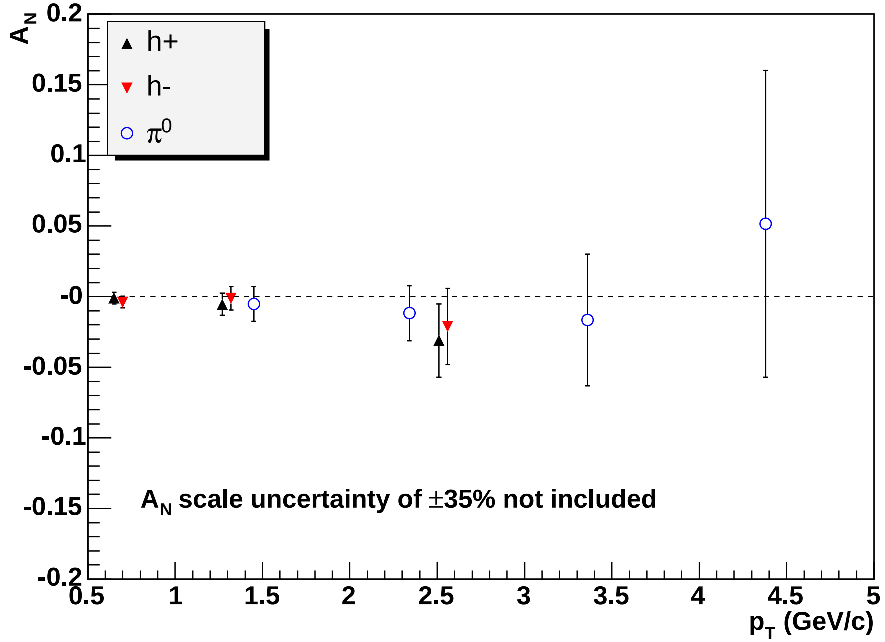


FermiLab, E704, 1990 $\quad \sqrt{s} = 20\,\mathrm{GeV}$



RHIC, STAR, 2004 $\quad \sqrt{s} = 200\,\mathrm{GeV}$

Also data from PHENIX and BRAHMS



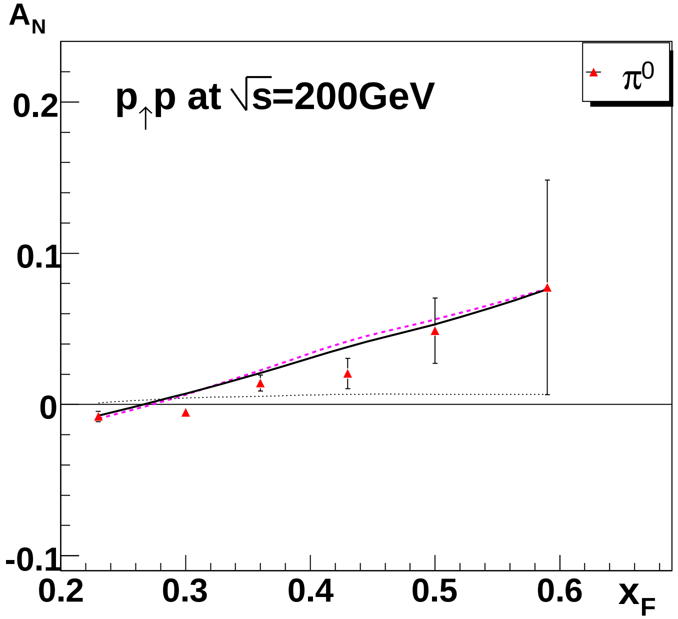
RHIC, PHENIX, 2005

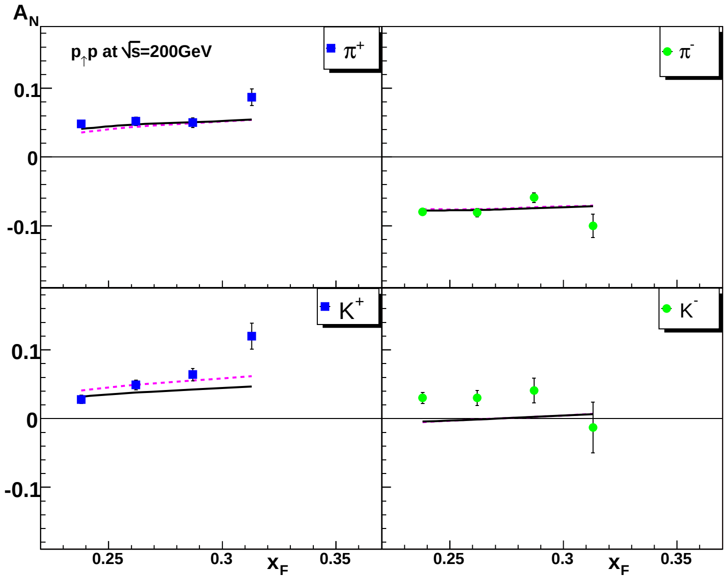
Theory for $p\,p^{\uparrow} \;\rightarrow H\,X$

A_N vanishes in leading twist collinear pQCD-description

1. (Effective) p_T-dependent formalism
   $\longrightarrow$ works well phenomenologically, but theory not really settled

2. Collinear twist-3 formalism
   (Efremov, Teryaev, 1985; Qiu, Sterman, 1991;
   Kouvaris, Qiu, Vogelsang, Yuan, 2006; etc.)
   $\longrightarrow$ description in terms of matrix elements $\langle P, S|\bar{\psi} A_T \psi|P, S\rangle$ on the light-cone





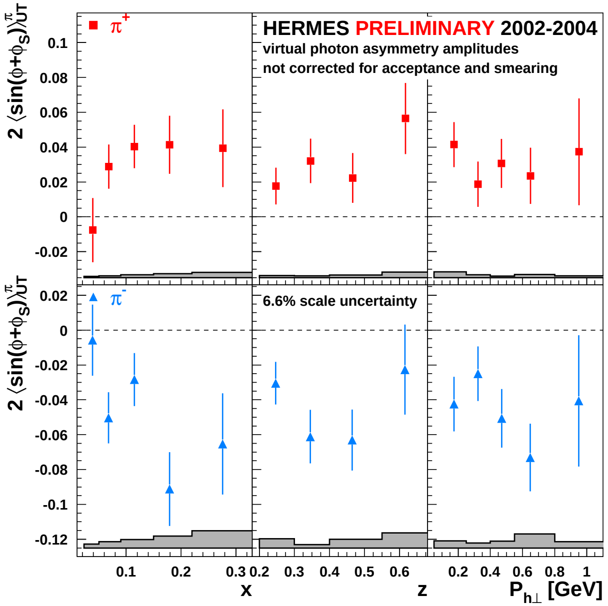
Plots from Kouvaris et al., 2006

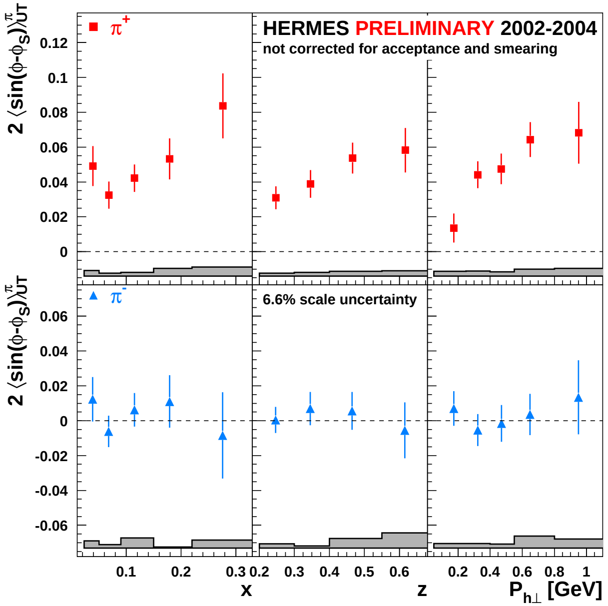
SSAs in semi-inclusive DIS, $l\,p \to l\,H\,X$

1. Longitudinal SSAs (twist-3, $\propto 1/Q$)
   - Target spin asymmetry A_{UL}: data from HERMES
   - Beam spin asymmetry A_{LU}: data from CLAS

2. Transverse SSA (leading twist)

$$
\begin{aligned}
A_{UT} \quad &\propto \quad \sin(\Phi_h + \Phi_S)\, h_1(x)\, H_1^{\perp}(z) + \sin(\Phi_h - \Phi_S)\, f_{1T}^{\perp}(x)\, D_1(z) \\
&+ \quad \sin(3\Phi_h - \Phi_S) \ldots + \mathcal{O}(1/Q)
\end{aligned}
$$





Also COMPASS data on $l\,D^{\uparrow} \to l'\,H\,X$

Semi-inclusive deep-inelastic scattering

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 p_T-dependent parton densities

Drell-Yan process

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} : $g_{1L}(x_1)\, g_{1T}(x_2)$

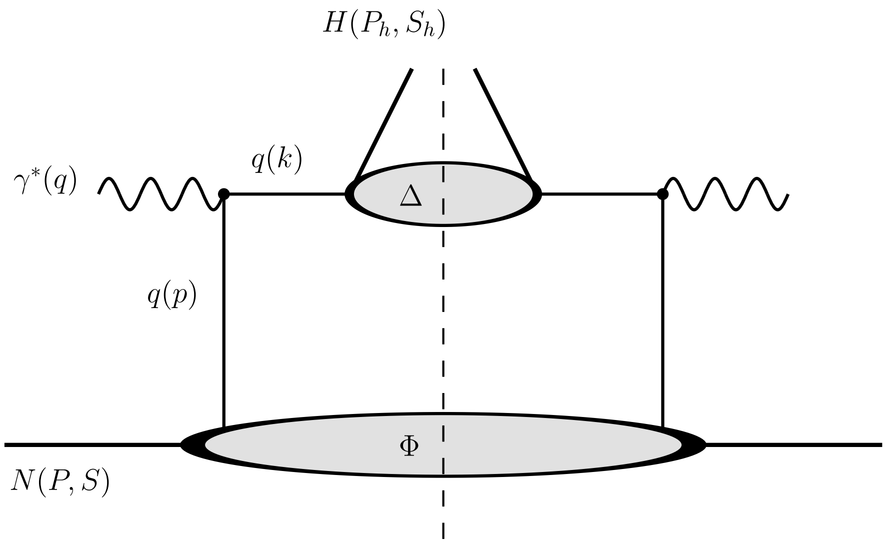
σ_{UL} : $h_1^\perp(x_1)\, h_{1L}^\perp(x_2)$

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 p_T-dependent parton densities

Factorization of p_T-dependent correlators

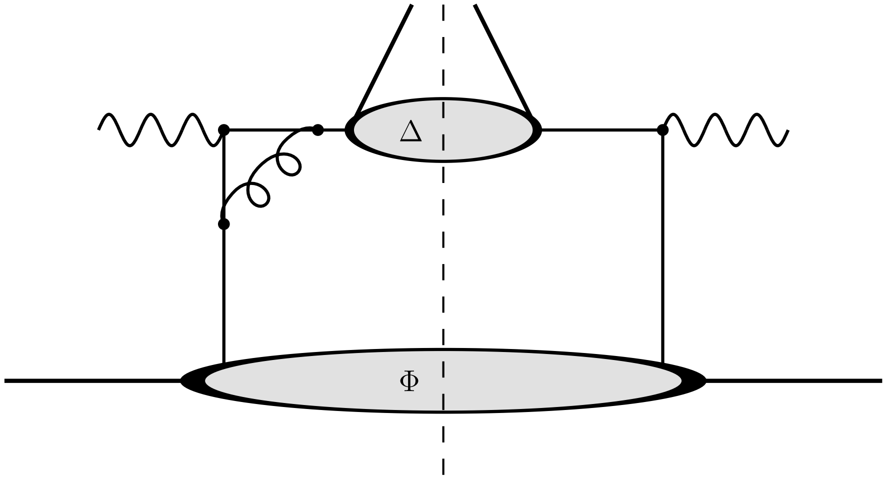
1. Tree level
   (Ralston, Soper, 1979)



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

$$f_1(x, \vec{p}_T^{\,2}) = \int \frac{d\xi^- d^2\vec{\xi}_T}{2(2\pi)^3}\, e^{i(xP^+\xi^- - \vec{p}_T\cdot\vec{\xi}_T)}\, \langle P, S|\, \bar{\psi}(0)\, \gamma^+\, \psi(\xi^-, \vec{\xi}_T)\, |P, S\rangle$$

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



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

- compatible with tree level result
- checked explicitly to $\mathcal{O}(\alpha_s)$ (Ji, Ma, Yuan, 2004)
- independent check through matching with collinear factorization at high P_{hT} (Ji, Qiu, Vogelsang, Yuan, 2006)
- arguments for consistency to all orders

3. Beyond leading twist

Relevant, e.g., for

Target spin asymmetry A_{UL}: data from HERMES
Beam spin asymmetry A_{LU}: data from CLAS

- Classification
  (Mulders, Tangerman, 1995; Afanasev, Carlson, 2003;
  Bacchetta, Mulders, Pijlman, 2004; Goeke, Metz, Schlegel, 2005; etc.)

  Parameterization of

$$\Phi^{[\Gamma]}(x, \vec{p}_T, S) = \int \frac{d\xi^- d^2\vec{\xi}_T}{2(2\pi)^3}\, e^{i(xP^+\xi^- - \vec{p}_T\cdot\vec{\xi}_T)}\, \langle P, S\,|\,\bar{\psi}(0)\,\Gamma\,\mathcal{L}\,\psi(\xi^-, \vec{\xi}_T)\,|\,P, S\rangle$$

- Factorization
  $\longrightarrow$ no established factorization formalism for twist-3 p_T-dependent observables
  like A_{UL}, A_{LU}, etc.
  (Gamberg, Hwang, Metz, Schlegel, 2006)

Universality of p_T-dependent correlators

1. Problem

- Semi-inclusive DIS

$$\sigma\Big|_{DIS} \propto \hat{\sigma}_{pert} \otimes \mathrm{pdf} \otimes \mathrm{ff} \otimes \mathrm{soft}$$

- Drell-Yan

$$\sigma\Big|_{DY} \propto \hat{\sigma}_{pert} \otimes \mathrm{pdf} \otimes \mathrm{pdf} \otimes \mathrm{soft}$$

- $e^+ \, e^- \longrightarrow H_1 \, H_2 \, X$

$$\sigma\Big|_{e^+e^-} \propto \hat{\sigma}_{pert} \otimes \mathrm{ff} \otimes \mathrm{ff} \otimes \mathrm{soft}$$

$$\mathrm{pdf}\Big|_{DIS} \stackrel{?}{=} \mathrm{pdf}\Big|_{DY}$$

$$\mathrm{ff}\Big|_{DIS} \stackrel{?}{=} \mathrm{ff}\Big|_{e^+e^-}$$

$$\mathrm{soft}\Big|_{DIS} \stackrel{?}{=} \mathrm{soft}\Big|_{DY} \stackrel{?}{=} \mathrm{soft}\Big|_{e^+e^-}$$

2. Results
(Collins 2002; Metz 2002; Collins, Metz, 2004)

- Parton densities:

  Time-reversal: $f_{1T}^{\perp}\big|_{DY} = -f_{1T}^{\perp}\big|_{DIS}$ $h_1^{\perp}\big|_{DY} = -h_1^{\perp}\big|_{DIS}$

  6 T-even pdfs are universal

- Fragmentation functions:

  Fragmentation functions in DIS and e^+e^- *a priori* have different links, time-reversal cannot be applied

  Analytical structure: $\mathrm{ff}\big|_{DIS} = \mathrm{ff}\big|_{e^+e^-}$ (for all 8 fragmentation functions)

- Soft factor:

  Time-reversal and analytical structure: $\mathrm{soft}\big|_{DIS} = \mathrm{soft}\big|_{DY} = \mathrm{soft}\big|_{e^+e^-}$

Phenomenology of the Sivers effect

(Collins, Efremov, Goeke, Grosse-Perdekamp, Menzel, Meredith, Metz, Schweitzer, 2004, 2005)

Focus on Sivers effect in semi-inclusive DIS and Drell-Yan

1. Extraction of Sivers function $f_{1T}^{\perp}$ from data on A_{UT} $(e\, p^{\uparrow} \rightarrow e\, \pi\, X)$

   Input/approximations:

   - HERMES data

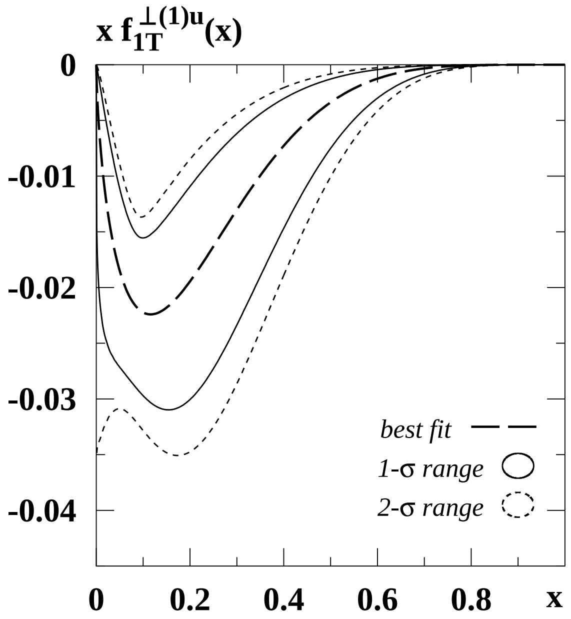
   - Neglect of soft gluon emission

   - Gaussian p_T-behaviour, e.g.,

   $$f_1(x, \vec{p}_T^{\,2}) = \frac{1}{\pi \langle p_T^2 \rangle} f_1(x)\, e^{-\vec{p}_T^{\,2}/\langle p_T^2 \rangle}$$

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

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



$$f_{1T}^{\perp(1)}(x) \equiv \int d^2\vec{p}_T \, \frac{\vec{p}_T^{\,2}}{2M^2} \, f_{1T}^{\perp}(x, \vec{p}_T^{\,2})$$

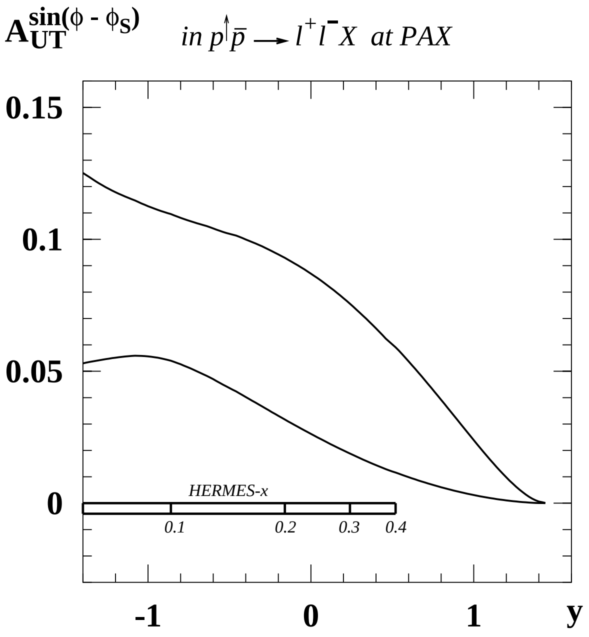
Extractions also by

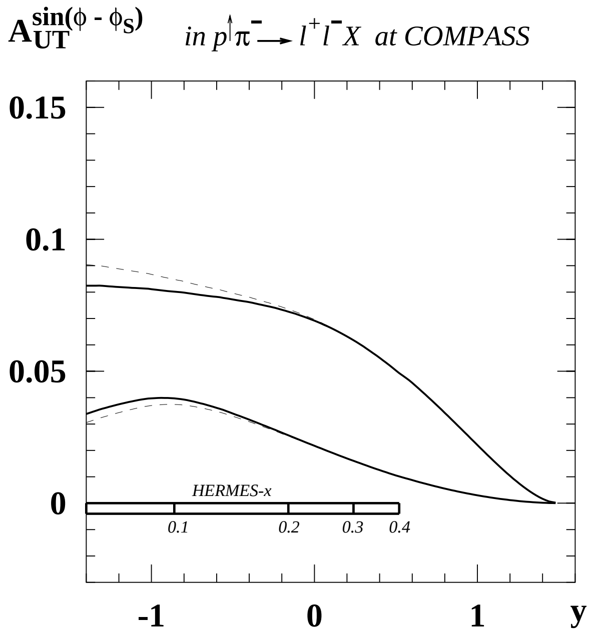
- Anselmino, Boglione, D' Alesio, Kotzinian, Murgia, Prokudin, 2005
- Vogelsang, Yuan, 2005

Comparison in: Anselmino et al., hep-ph/0511017

2. Calculation of the Sivers asymmetry for Drell-Yan

$$y = \frac{1}{2}\ln\frac{x_1}{x_2} \qquad\qquad f_{1T}^{\perp(1)\bar{q}}(x) = \pm\,\frac{f_1^{\bar{u}}(x) + f_1^{\bar{d}}(x)}{f_1^{u}(x) + f_1^{d}(x)}\, f_{1T}^{\perp(1)q}(x)$$





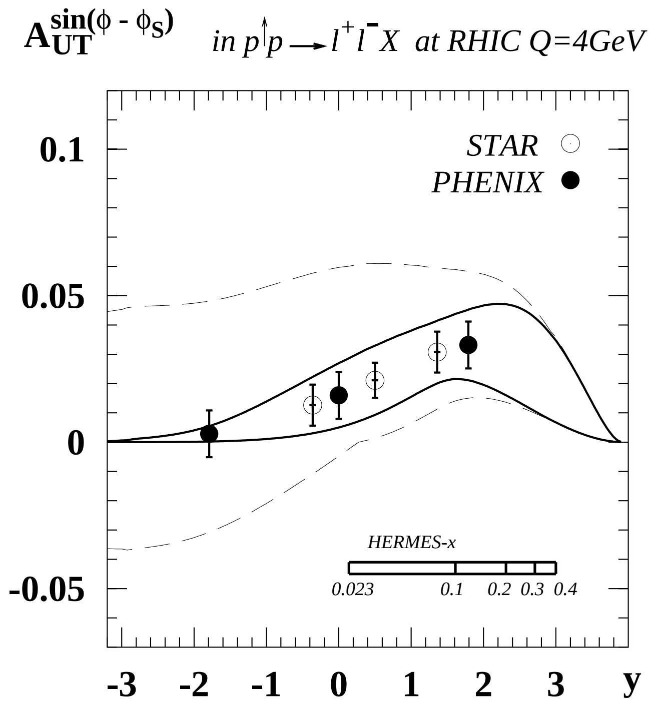
GSI $\quad p^{\uparrow}\,\bar{p} \longrightarrow l^{+}\,l^{-}\,X$

$s = 45\,\mathrm{GeV}^2 \quad Q^2 = 6.25\,\mathrm{GeV}^2$

COMPASS $\quad p^{\uparrow}\,\pi^{-} \longrightarrow l^{+}\,l^{-}\,X$

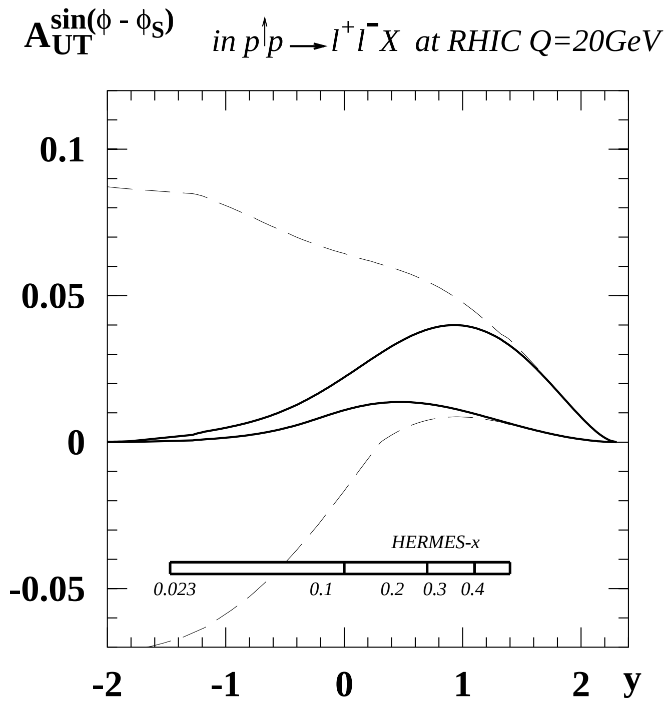
$s = 400\,\mathrm{GeV}^2 \quad Q^2 = 20\,\mathrm{GeV}^2$

$\longrightarrow$ Prediction $f_{1T}^{\perp}\big|_{DY} = -f_{1T}^{\perp}\big|_{DIS}$ can be checked experimentally



RHIC $\quad p^{\uparrow}\, p \to l^+\, l^-\, X$

$\sqrt{s} = 200\,\mathrm{GeV} \quad Q^2 = 16\,\mathrm{GeV}^2$



RHIC $\quad p^{\uparrow}\, p \to l^+\, l^-\, X$

$\sqrt{s} = 200\,\mathrm{GeV} \quad Q^2 = 400\,\mathrm{GeV}^2$

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

Single spin asymmetries in inclusive DIS

(Metz, Schlegel, Goeke, 2006)

1. One-photon exchange

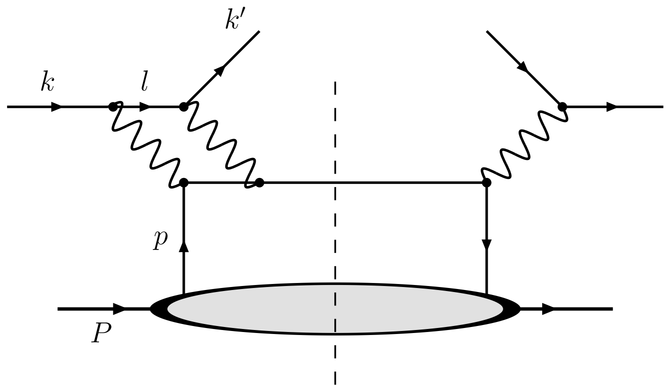
- Unpolarized case
  $\longrightarrow$ 2 structure functions: $F_1 \quad F_2$

$$k'^0 \frac{d\sigma_{unp}}{d^3\vec{k}'} = \frac{4\,\alpha_{em}^2}{Q^4}\left(x\,yF_1(x,Q^2) + \frac{1-y}{y}F_2(x,Q^2)\right)$$

$$y = \frac{P\cdot(k-k')}{P\cdot k} = \frac{\nu_{Lab}}{E_{Lab}}$$

- (Double) polarized case
  $\longrightarrow$ 2 structure functions: $g_1 \quad g_2$

2. Multi-photon exchange



- Lepton single spin asymmetry

$$k'^0 \frac{d\sigma_{L,pol}}{d^3\vec{k}'} = \frac{4\,\alpha_{em}^3}{Q^8}\, m\, x\, y^2\, \varepsilon_{\mu\nu\rho\sigma}\, S^\mu P^\nu k^\rho k'^\sigma \sum_q e_q^3\, x f_1^q(x)$$

- Target single spin asymmetry

$$k'^0 \frac{d\sigma_{N,pol}}{d^3\vec{k}'} = \frac{4\,\alpha_{em}^3}{Q^8} \frac{M\, x^2\, y}{1-y}\, \varepsilon_{\mu\nu\rho\sigma}\, S^\mu P^\nu k^\rho k'^\sigma \sum_q e_q^3\, x g_T^q(x)$$
$$\times \left((1-y)^2 \ln\frac{Q^2}{\lambda^2} + y(2-y)\ln y + y(1-y) \right)$$

$\longrightarrow$ Requires inclusion of p_T-effects and of $\langle P, S|\, \bar{\psi}\, A_T\, \psi\, |P, S\rangle$

Summary

1. Spin asymmetries in lepton-hadron and hadron-hadron collisions is active field
   $\longrightarrow$ information on h_1, unintegrated correlation functions, twist-3 correlators
   $\longrightarrow$ information on application of QCD

2. Leading p_T-dependent parton densities measurable in SIDIS, Drell-Yan, $p\,p \longrightarrow jet_1\,jet_2\,X$ etc.

3. Factorization of p_T-dependent correlators
   - All-order factorization formula exists for
     $l\,N \longrightarrow l\,H\,X \qquad H_1\,H_2 \longrightarrow l^+\,l^-\,X \qquad e^+\,e^- \longrightarrow H_1\,H_2\,X$
   - Survives all available checks
   - Status of factorization beyond leading twist unclear
   - Situation more complicated for $p\,p \longrightarrow H\;X \qquad p\,p \longrightarrow H_1\,H_2\,X$
     (Bacchetta, Bomhof, Mulders, Pijlman, 2004, 2005, 2006; Vogelsang, Yuan,...)

4. Universality of p_T-dependent correlators
   - T-odd parton densities in DIS and Drell-Yan have reversed sign
   - Everything else is universal

5. Single spin asymmetry in inclusive DIS through multi-photon exchange

6. SSAs measured in processes like $p\,p^{\uparrow} \to \pi\,X$ and $p\,p^{\uparrow} \to jet_1\,jet_2\,X$
   $\longrightarrow$ information on twist-3 matrix elements, and on $f_{1T}^{\perp}$ etc.

7. Different SSAs ($A_{UL},\ A_{LU},\ A_{UT}$) observed in $l\,p \to l\,H\,X$ and $l\,D \to l\,H\,X$
   $\longrightarrow$ information on h_1, as well as $f_{1T}^{\perp}$ and $H_1^{\perp}$, etc.

8. Angular distribution in unpolarized Drell-Yan
   $\longrightarrow$ information on $h_1^{\perp}$

9. Azimuthal $\cos 2\phi$-asymmetry in $e^+\,e^- \longrightarrow H_1\,H_2\,X$ (Belle Collaboration)
   $\longrightarrow$ information on $H_1^{\perp}$

10. Future
    - Belle
    - COMPASS, HERMES, JLab ($12\,\mathrm{GeV}$-upgrade)
      ELIC, ERHIC
    - RHIC, RHIC-II (pp)
      JPARC (pp, $\sqrt{s} \simeq 10\,\mathrm{GeV}$), U70 ($pp$, $\sqrt{s} \simeq 12\,\mathrm{GeV}$)
      FAIR@GSI ($\bar{p}p$, $\sqrt{s} \simeq 15\,\mathrm{GeV}$)
      $\longrightarrow$ dedicated Drell-Yan measurement would allow one to check
      $f_{1T}^{\perp}\big|_{DY} = -f_{1T}^{\perp}\big|_{DIS}$ $\qquad$ $h_1^{\perp}\big|_{DY} = -h_1^{\perp}\big|_{DIS}$
    - etc.