Azimuthal asymmetries in semi-inclusive DIS: are they interrelated?

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- SIDIS Cross Section $\Leftrightarrow$ factorization

  $\Rightarrow$ Current and Target fragmentation

- Azimuthal asymmetries in SIDIS

  $\Rightarrow$ Single–spin

  $\Rightarrow$ UNpolarized and Double–polarized

  - ⋆ "Kinematic" twist-3 effects
  - ⋆ Measuring $\cos\phi$ asymmetries simultaneously

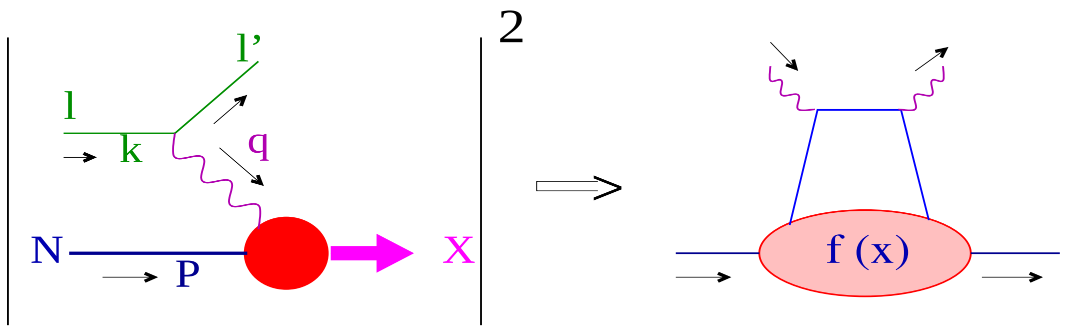
- Summary

SIDIS Cross Section

The hard scale Q allows factorization of the cross section

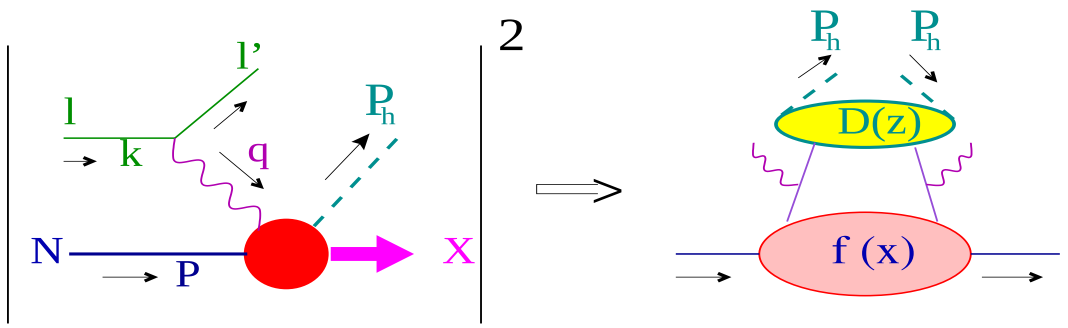
DIS:

$$d\sigma^{lN\to l'X} = \sum_q f^{H\to q}(x) \otimes d\sigma^{eq\to eq}$$



SIDIS:

$$d\sigma^{lN\to l'hX} = \sum_q f^{H\to q}(x, p_T^2) \otimes d\sigma^{eq\to eq} \otimes D^{q\to h}(z, k_T^2)$$



Current fragmentation

For current fragmentation

$$d\sigma = \sum_q f^{N\to q} \otimes d\hat{\sigma} \otimes D^{q\to h}$$

Target fragmentation involves complex soft part: fracture functions.

A check on the precision of current fragmentation $\Delta\eta \approx 2$ (so-called Berger's criterium.)

The definition of rapidity

$$\eta = \frac{1}{2}\ln\frac{E_h + P_z}{E_h - P_z} = \ln\frac{E_h + P_z}{M_{h\perp}}, \quad M_{h\perp}^2 = m_h^2 + P_{h\perp}^2.$$

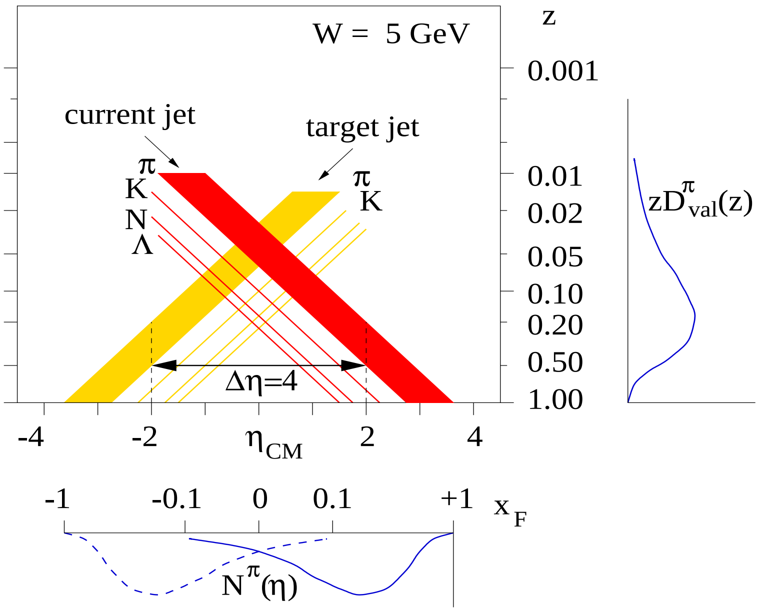
For the center of mass rapidity one has

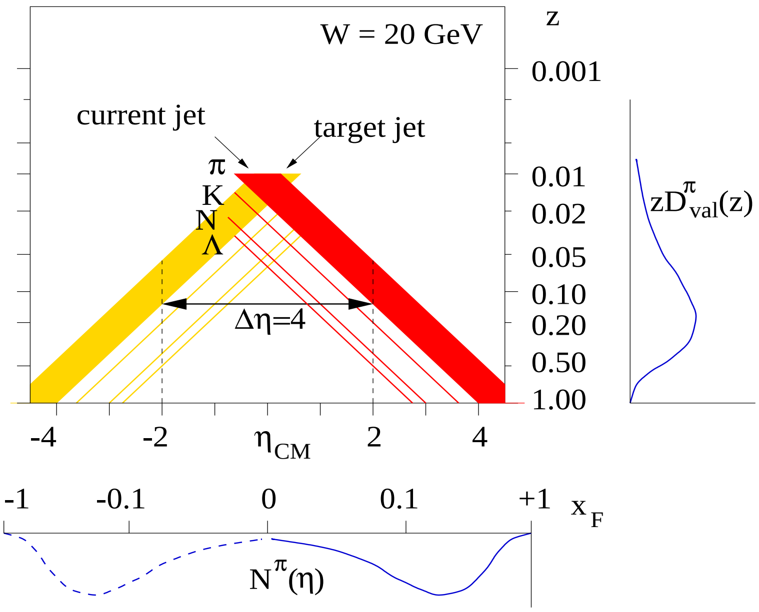
Mulders, hep-ph/0010199

$$\eta_{cm} = \ln z + \ln\frac{W}{M_{h\perp}}, \quad W^2 = \frac{(1-x)Q^2}{x}.$$

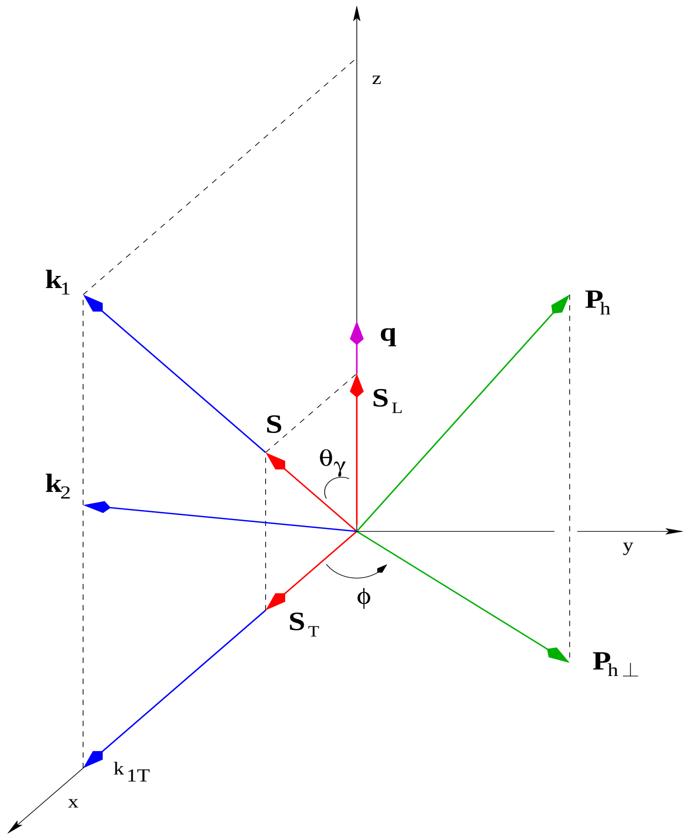
Berger's Criterium

Mulders, hep-ph/0010199





$l\vec{p} \to l'hX$ kinematics



$Q^2 = -q^2 = (k - k^{'})$ $\qquad$ $S_T = S \sin\theta_\gamma$

$\nu = E - E^{'}$

$W^2 = 2M\nu + M^2 - Q^2$

$x = Q^2/2P \cdot q \quad \overset{\text{Lab}}{=} \quad x = Q^2/2M\nu$

$y = P \cdot q/P \cdot k \quad \overset{\text{Lab}}{=} \quad y = \nu/E$

$z = P \cdot P_h/P \cdot q \quad \overset{\text{Lab}}{=} \quad z = E_\pi/\nu$

$P_{h\perp}$ - hadron transverse momentum

ϕ is the azimuthal angle between (kq) and $(P_h q)$ planes

$\sin\theta_\gamma = \sqrt{\frac{4M^2x^2}{Q^2+4M^2x^2}(1 - y - \frac{M^2x^2y^2}{Q^2})}$

Azimuthal asymmetries in Hard Scattering Processes

From Parity Conservation

Single-spin azimuthal asymmetries

$$A_S(\phi) = N^+(\phi) - N^-(\phi) \quad \Rightarrow \quad ODD \equiv \sum_{m=1} \delta N^{(m)} \sin m\phi$$

Double-spin azimuthal asymmetries

$$A_{\lambda S}(\phi) = N^{++}(\phi) + N^{--}(\phi) - N^{+-}(\phi) - N^{-+}(\phi)$$

$$\Downarrow$$

$$EVEN \equiv \sum_{m=0} \Delta N^{(m)} \cos m\phi$$

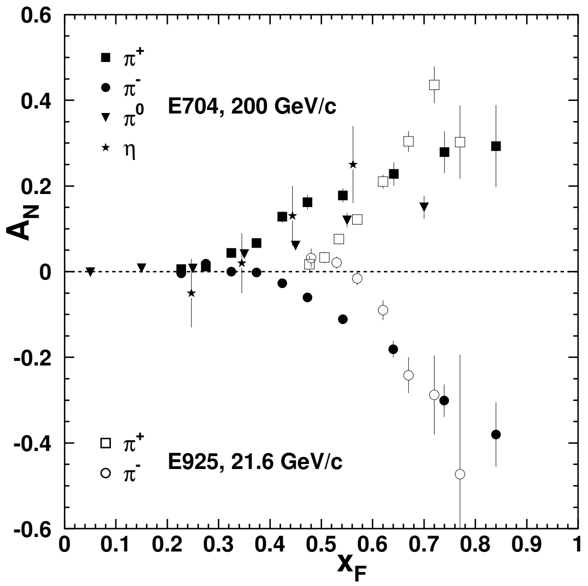
Spin-independent azimuthal asymmetries

$$A(\phi) = EVEN \equiv \sum_{m=0} N^{(m)} \cos m\phi$$

Single-spin azimuthal asymmetries

In naive parton model due to non-interacting collinear partons; parity, helicity conservation expected SSA $= 0$

However SSA are NON-zero – originate from multi-parton correlations in initial/final states and non-zero intrinsic parton transverse momentum.



$$A_N = \frac{N^+ - N^-}{N^+ + N^-}$$

In pQCD

$$A_N \sim \alpha_S \frac{m}{\sqrt{S}}$$

SSA are NON-zero in semi-inclusive DIS as well

Recent results from HERMES (*longitudinal*) and SMC (*transversal*) on single target-spin azimuthal asymmetries

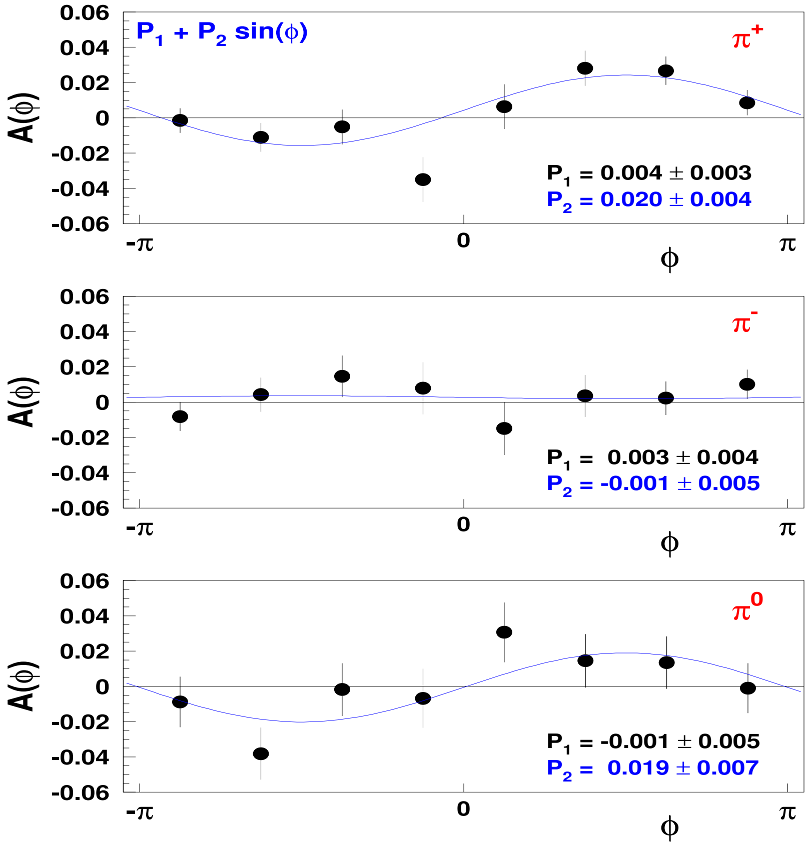
HERMES results

[PRL 84, 2000]; [PRD 64, 2001]

Unpolarized beam and longitudinally polarized target

$$A(\phi) = \frac{1}{\langle P \rangle} \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$

$\langle P \rangle$ – average target polarization
$\pm$ positive/negative target helicity



For π^+:
$A_{UL}^{\sin\phi} = 0.022 \pm 0.005 \pm 0.003$
$A_{UL}^{\sin 2\phi} = -0.002 \pm 0.005 \pm 0.010$
$A_{LU}^{\sin\phi} = -0.005 \pm 0.008 \pm 0.004$

Single-spin asymmetry

Longitudinally polarized beam or target

$$
\begin{aligned}
d\sigma \propto & \\
& + \quad \frac{1}{Q}\sin\phi\lambda d\sigma_{LU}^{(2)} \\
& + \quad \frac{1}{Q}\sin\phi S_L d\sigma_{UL}^{(3)} + \sin 2\phi S_L d\sigma_{UL}^{(4)} \\
& + \quad \sin\phi \sin\theta_\gamma S_{lab} d\sigma_{UT}^{(5)} \\
& + \quad \frac{1}{Q}\sin 2\phi \sin\theta_\gamma S_{lab} d\sigma_{UT}^{(6)} \\
& + \quad \sin 3\phi \sin\theta_\gamma S_{lab} d\sigma_{UT}^{(7)}
\end{aligned}
$$

HERMES Collaboration, PRL 84 (2000) 4047

$$d\sigma_{LU}^{(2)} \propto \sum_a e_a^2 \tilde{e}^a(x) H_1^{\perp(1)a}(z)$$

$$d\sigma_{UL}^{(4)} \propto \sum_a e_a^2 h_{1L}^{\perp(1)a}(x) H_1^{\perp(1)a}$$

$$d\sigma_{UL}^{(3)} \propto \sum_a e_a^2 \left(h_L^a(x) H_1^{\perp(1)a}(z) - h_{1L}^{\perp(1)a}(x) \frac{\tilde{H}^a(z)}{z} \right)$$

$$d\sigma_{UT}^{(5)} \propto \sum_a e_a^2 h_1^a(x) H_1^{\perp(1)a}(z)$$

$\tilde{e}(x) = e(x) - \frac{m}{M}\frac{f_1(x)}{x}$

$h_L(x) = h_1(x) - \frac{d}{dx} h_{1L}^{(1)}(x)$

$\tilde{H}(z) = H(z) - 2zH_1^{\perp(1)}(z)$

Single-spin $\sin\phi$ asymmetry

$$A_{UL}^{\sin\phi} = \frac{\int d\phi \sin\phi [d\sigma^+ - d\sigma^-]}{\frac{1}{2}\int d\phi [d\sigma^+ + d\sigma^-]},$$

$$A_{UL}^{\sin\phi} = 2\frac{d\sigma_{UL}^{(3)} + \sin\theta_\gamma d_{UT}^{(5)}}{d\sigma_{UU}^{(0)}},$$

where

$$d\sigma_{UL}^{(3)} \propto \sum_a e_a^2 \left(h_L^a(x) H_1^{\perp(1)a}(z) - h_{1L}^{\perp(1)a}(x) \frac{\tilde{H}^a(z)}{z} \right)$$

$$d\sigma_{UT}^{(5)} \propto \sum_a e_a^2 h_1^a(x) H_1^{\perp(1)a}(z)$$

$$d\sigma_{UU}^{(0)} \propto \sum_a e_a^2 f_1^a(x) D_1^{\perp(1)a}(z)$$

The asymmetry could result from **twist-3** chiral-odd effects ($\sim h_L$). It could also be a reflection of the **Collins effect** because of the target spin, while parallel to the beam, has a transverse component ($\mathcal{O}(1/Q)$) in the virtual photon frame ($\sim h_1$).

Which one of them is relevant and responsible for such asymmetry?

This is a still an open issue.

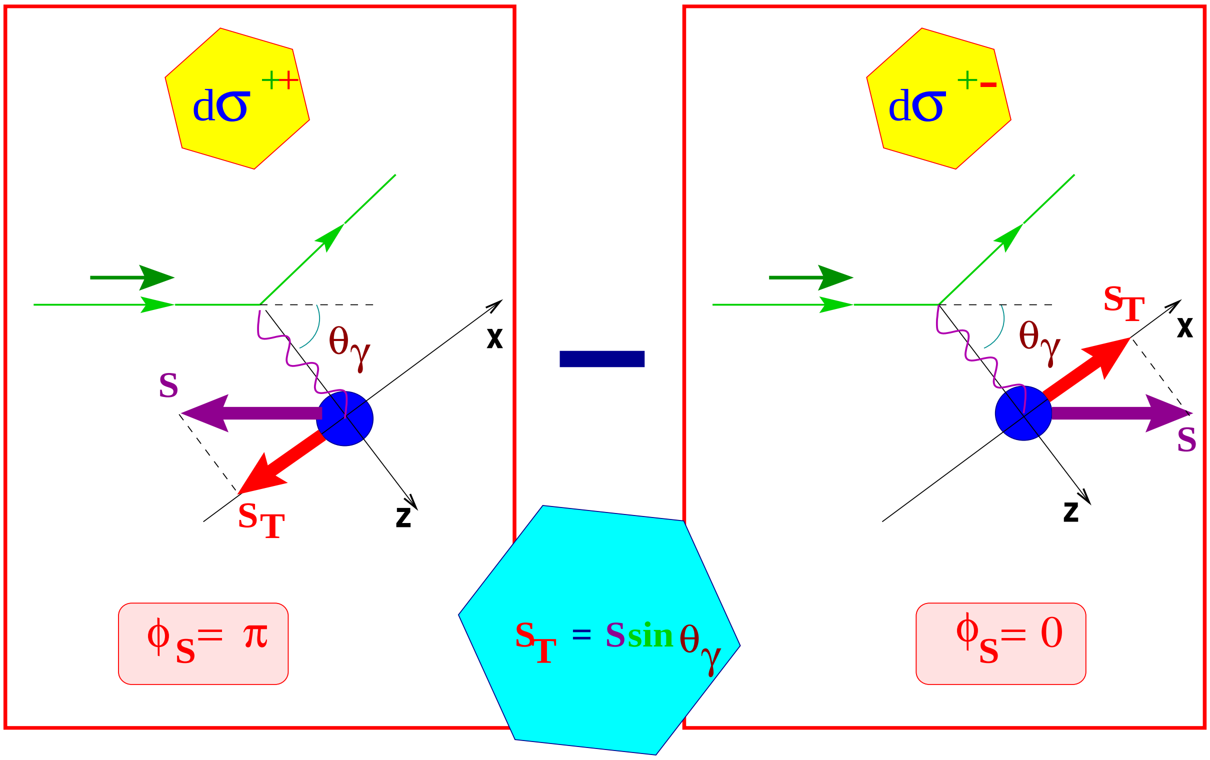
$\Rightarrow$ HERMES Run with *transverse* target $2002++$

Transverse asymmetry kinematical contribution

$$A = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}}$$

K.O.,et.al., [hep-ph/9808368]

Leads to positive g_1.



ϕ_S is the azimuthal angle of the target spin vector

Spin-independent $cos\phi$ asymmetry

$$\langle \cos\phi \rangle_{UU} \equiv \frac{\int d\sigma \cos\phi d\phi}{\int d\sigma d\phi} = \frac{1}{2}\frac{d\sigma_{UU}^{(1)}}{d\sigma_{UU}^{(0)}},$$

where

$$d\sigma_{UU}^{(0)} \propto \sum_a e_a^2 f_1^a(x) D_1^a(z)$$

$$d\sigma_{UU}^{(1)} \propto -\sum_a e_a^2 \left(f^{\perp(1)a}(x) D_1^a(z) - f_1^a(x) \tilde{D}^{\perp(1)a} \right)$$

$$f^{\perp(1)}(x) = f_1^{(1)}(x)/x + \tilde{f}^{\perp(1)}$$
$$\tilde{D}^{\perp(1)}(z) = D^{\perp(1)}(z) - zD_1^{(1)}(z)$$

When the interaction dependent (tilde) functions are set to zero (the Wandzura-Wilczek approximation), the asymmetry reduces to a kinematical effect conditioned by intrinsic transverse momentum of partons in the nucleon.

Cahn,PLB 78 (1978) 269; PRD 40 (1989) 3107

Experimental results

Measurements indicates the large negative $\langle \cos\phi \rangle$ moment.

EMC, PLB 130 (1983) 118; ZP C34 (1987) 277
E665, PR D48 (1993) 5057;

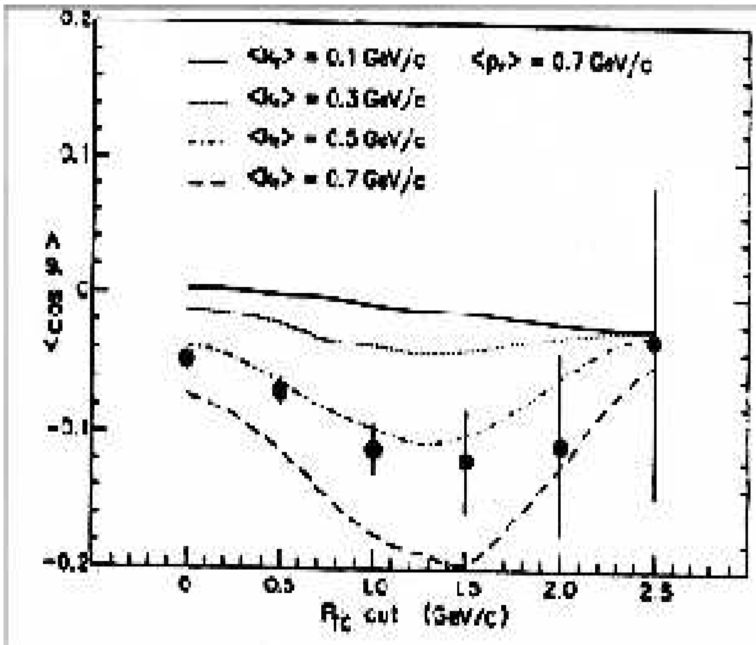


FIG. 13. The dependence of $\langle \cos\phi \rangle$ on transverse momentum cutoff. The curves are the predictions of Chay, Ellis, and Stirling [5] for $\langle p_T \rangle$=0.7 GeV/c and several values of average intrinsic transverse momentum. The data have been corrected for acceptance.

The simple QCD-improved parton model rather well describes the data, and the most important contribution to azimuthal dependence of UNpolarized SIDIS comes from kinematical effect of the intrinsic transverse momentum as calculated by Cahn.

Double-Spin $cos\phi$ asymmetry

Longitudinally polarized beam and target

$$
\begin{aligned}
d\sigma \propto & \\
+ \quad & \lambda S_L d\sigma_{LL}^{(8)} \\
+ \quad & \frac{1}{Q}\lambda S_L \cos\phi d\sigma_{LL}^{(9)} \\
+ \quad & \lambda S_{lab} \cos\phi \sin\theta_\gamma d\sigma_{LT}^{(10)} \\
+ \quad & \frac{1}{Q}\lambda S_{lab} \cos 2\phi \sin\theta_\gamma d\sigma_{LT}^{(11)}
\end{aligned}
$$

$$d\sigma_{LL}^{(8)} \propto \sum_a e_a^2\, g_1^a(x)\, D_1^a(z)$$

$$d\sigma_{LL}^{(9)} \propto \sum_a e_a^2 \left(g_1^a(x)\, \tilde{D}^{\perp a(1)}(z) - g_L^{\perp a(1)}(x) D_1^a(z) - h_{1L}^{\perp(1)a}(x) \tilde{E}^a(z) \right)$$

$$d\sigma_{LT}^{(10)} \propto \sum_a e_a^2 g_{1T}^{a(1)}(x)\, D_1^a(z)$$

Mulders, Tangerman, NPB 461 (1996) 197

$$g_L^{\perp(1)}(x) = \frac{g_1^{(1)}(x)}{x} + \frac{m}{Mx} h_{1L}^{\perp(1)}(x) + g_L^{\perp(\tilde{1})}(x)$$

$$\tilde{D}^{\perp(1)}(z) = D^{\perp(1)}(z) - z D_1^{(1)}(z)$$

$$\tilde{E}(z) = E(z) - \frac{m}{M_h} z D_1(z)$$

$$g_{1T}^{(1)} = x g_T(x) - \frac{m}{M} h_1(x) - x\tilde{g}_T(x)$$

Double-Spin Azimuthal asymmetry

K.O., P.J.Mulders, E.De Sanctis, [hep-ph/0201061]; PLB

$$A_{LL}^{\cos\phi} = \frac{\int d^2 P_{hT} |P_{hT}| \cos\phi \left(d\sigma^{++} + d\sigma^{--} - d\sigma^{+-} - d\sigma^{-+} \right)}{\frac{1}{4} \int d^2 P_{hT} \left(d\sigma^{++} + d\sigma^{--} + d\sigma^{+-} + d\sigma^{-+} \right)}$$

Here $++, --$ $(+-, -+)$ denote the antiparallel (parallel) polarization of the beam and target: leads to positive $g_1(x)$.

$$A_{LL}^{\cos\phi} = 4 \frac{d\sigma_{LL}^{(9)} + \sin\theta_\gamma d\sigma_{LT}^{(10)}}{d\sigma_{UU}^{(0)}}$$

$$d\sigma_{LL}^{(9)} \propto \sum_a e_a^2 \left(g_1^a(x)\, \tilde{D}^{\perp a(1)}(z) - g_L^{\perp a(1)}(x) D_1^a(z) - h_{1L}^{\perp(1)a}(x) \tilde{E}^a(z) \right)$$

$$d\sigma_{LT}^{(10)} \propto \sum_a e_a^2 g_{1T}^{a(1)}(x)\, D_1^a(z)$$

$$d\sigma_{UU}^{(0)} \propto \sum_a e_a^2 f_1^a(x) D_1^a(z)$$

Approximation

All twist-3 interaction-dependent functions (tilde) are set to zero: the approach is similar to description of unpolarized $\cos\phi$ asymmetry arises from intrinsic p_T effect.

Cahn,PLB 78 (1978) 269; PRD 40 (1989) 3107

$$A_{LL}^{\cos\phi} \propto \frac{g_1^{(1)}(x) D_1(z) + g_{1T}^{(1)}(x)\, D_1(z)}{f_1(x)\, D_1(z)},$$

where we have used

$$g_L^{\perp(1)}(x) \approx \frac{g_1^{(1)}(x)}{x}.$$

Assuming a Gaussian parameterization for the distribution of the initial parton's intrinsic transverse momentum, p_T, in the helicity distribution function $g_1(z, p_T^2)$:

$$g_1^{(1)}(x) = \frac{< p_T^2 >}{2M^2} g_1(x),$$

leads to to similar results obtained in the simple quark-gluon model with non-zero intrinsic transverse momentum in POLARIZED SIDIS.

Kotzinian, NPB, 441 (1995) 234

For $g_{1T}^{(1)}(x)$ was used:

Kotzinian,Mulders, PRD 54 (1996) 1229

$$g_{1T}^{(1)WW}(x) = x g_T^{WW}(x) = x \int_x^1 dy \frac{g_1(y)}{y}.$$

For numerical calculations we use

$f_1(x), g_1(x)$ from

Brodsky,Burkardt,Schmidt, NPB 441(1995) 197

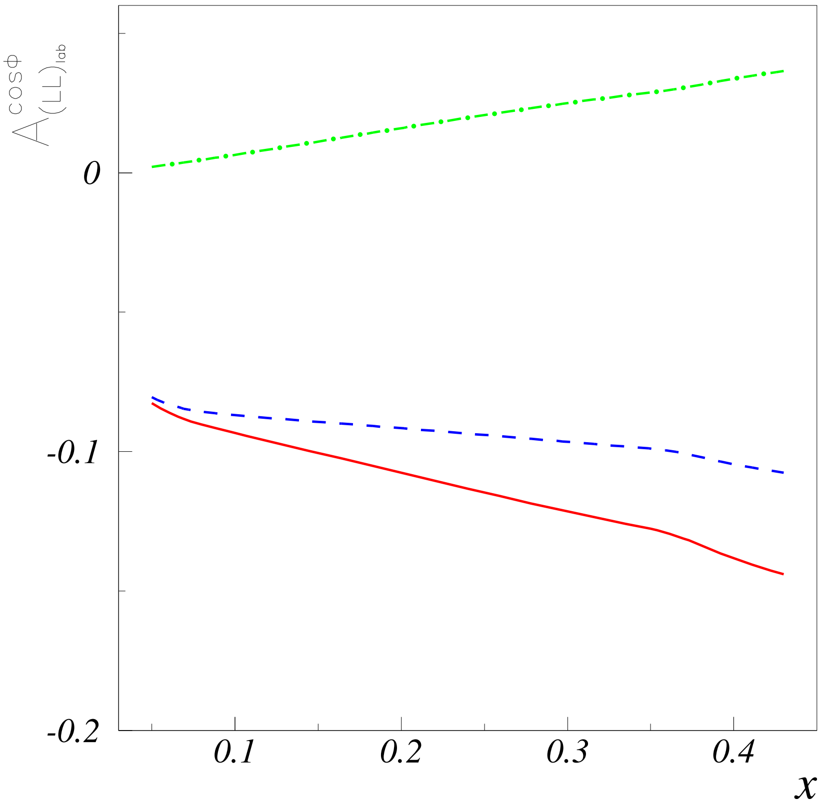
$D_1^{\pi^+}(z)$ from

Reya, PR 69 (1981) 195

$< p_T^2 >= (0.44)^2$ GeV ^{2}

Sjostrand, PYTHIA, CPC 82 (1994) 74

$A_{LL}^{\cos\phi}$ for π^+ at HERMES energies



– "kinematical" $\sin\theta_\gamma$
– p_T/Q kinematical twist-3
– The Difference

Unpolarized and polarized $\cos\phi$ asymmetries

This work is in progress

lets consider the asymmetry defined in the following way

$$A_{LL}(\phi) = \frac{d\sigma^{++} + d\sigma^{--} - d\sigma^{+-} - d\sigma^{-+}}{d\sigma^{++} + d\sigma^{--} + d\sigma^{+-} + d\sigma^{-+}}$$

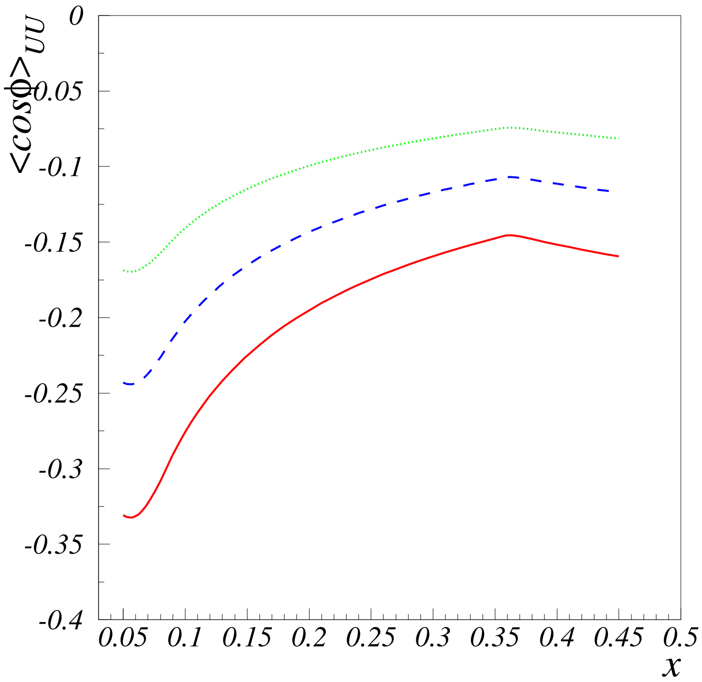
At leading $1/Q$ order

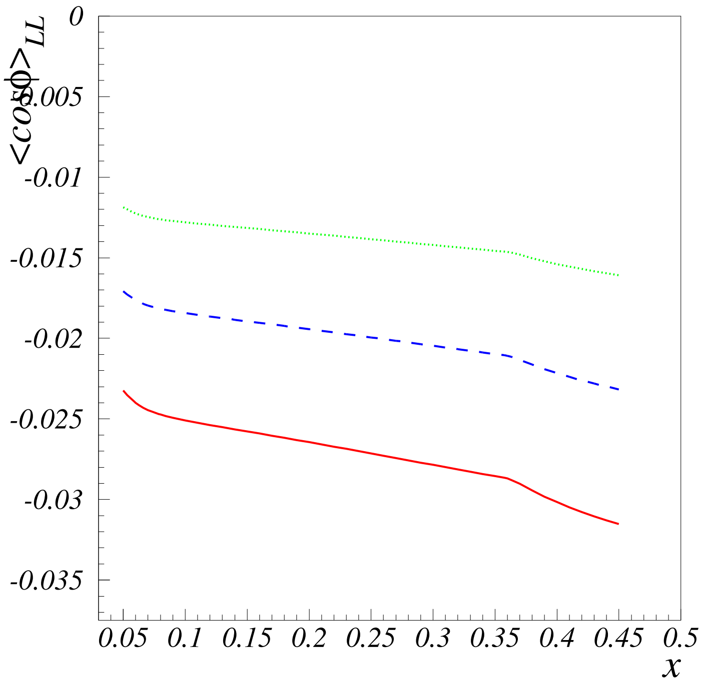
$$A_{LL}(\phi) = \frac{d\sigma_{LL}^{(8)} + d\sigma_{LL}^{(9)} \cos\phi}{d\sigma_{UU}^{(0)} + d\sigma_{UU}^{(1)} \cos\phi}.$$

$$A_{LL}(\phi) = \frac{\frac{1}{2}\frac{d\sigma_{LL}^{(8)}}{d\sigma_{UU}^{(0)}} + \langle\cos\phi\rangle_{LL} \cos\phi}{1/2 + \langle\cos\phi\rangle_{UU} \cos\phi}.$$

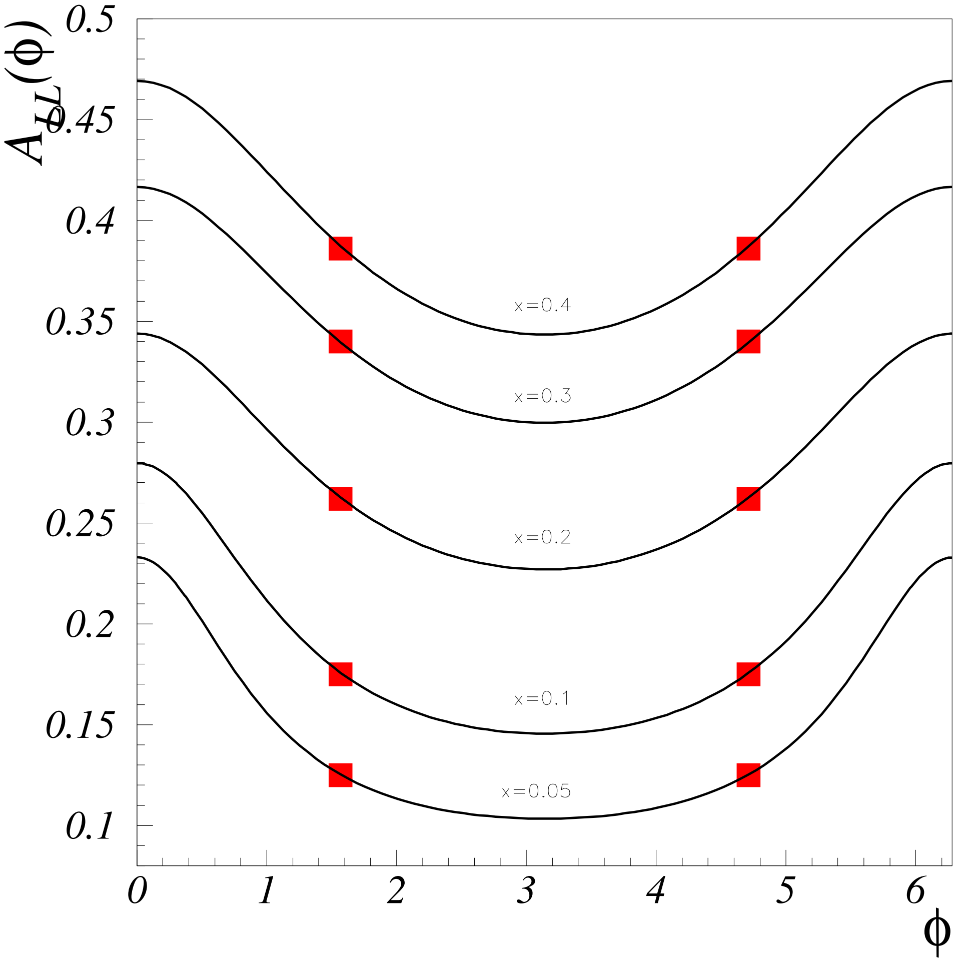
Access to unpolarized and double polarized $\cos\phi$ asymmetries **simultaneously**.

$\langle \cos\phi \rangle_{UU}$ and $\langle \cos\phi \rangle_{LL}$





$A_{LL}(\phi)$



$\square \quad \Rightarrow \quad A_{LL}(x, \phi = \frac{\pi}{2}) = A_{LL}(x, \phi = \frac{3\pi}{2}) = \frac{1}{2} \frac{d\sigma_{LL}^{(8)}(x)}{d\sigma_{UU}^{(0)}(x)}$

Summary

Cross section factorization: Current fragmentation

Azimuthal asymmetries

- **Single-Spin Asymmetries:** Origins, Recent experimental and theoretical results.
- Measuring the transversity $\Leftrightarrow$ Combined results (different experiments; different processes) are needed.

Double-spin asymmetries:

- The "kinematical" contribution from target transverse component is well defined.
- Possibility to investigate the weights of twist-2 and twist-3 contributions at moderate Q^2.
- Possibility to estimate $< p_T^2 >$ in the nucleon.
- **A possibility to measure:** $A_{LL}(\phi)$, leads to measure the unpolarized and double polarized, $\cos\phi$, asymmetries **simultaneously** in many experiments (HERMES, COMPASS, JLAB (upgraded)).