Azimuthal asymmetries in SIDIS

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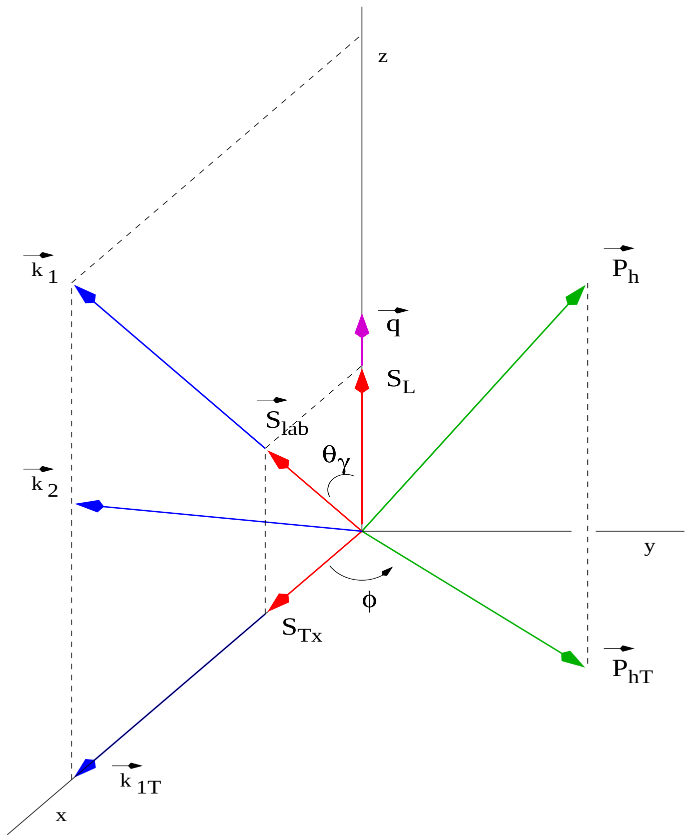
- SIDIS Cross Section
- Single–spin azimuthal asymmetry (SSAA)
- Spin-independent azimuthal asymmetry (SIAA)
  – Different mechanisms
  – Experimental results
- Double–spin azimuthal asymmetry (DSAA)
  – "Kinematic" twist-3 effects
  – $A_{LL}^{\cos\phi}$ for π^+ at HERMES energies
  – Acceptance-independent asymmetry
- Conclusions

SIDIS kinematics



$$Q^2 = -q^2 = (k - k')^2$$
$$\nu = E - E'$$
$$W^2 = 2M\nu + M^2 - Q^2$$
$$x = Q^2/2P \cdot q \quad \overset{\text{Lab}}{=} \quad x = Q^2/2M\nu$$
$$y = P \cdot q/P \cdot k \quad \overset{\text{Lab}}{=} \quad y = \nu/E$$
$$z = P \cdot P_h/P \cdot q \quad \overset{\text{Lab}}{=} \quad z = E_\pi/\nu$$

$P_\perp \equiv P_{hT}$-hadron transverse momentum

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

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

SIDIS Cross Section

Mulders,Tangerman, NPB 461 (1996) 197

Up to order $1/Q$

$$
\begin{aligned}
d\sigma^{eN\to ehX} \propto & \\
+ & \quad d\sigma^{(0)}_{UU} + \frac{1}{Q}\cos\phi\, d\sigma^{(1)}_{UU} \\
+ & \quad \frac{1}{Q}\sin\phi\,\lambda\, d\sigma^{(2)}_{LU} \\
+ & \quad \frac{1}{Q}\sin\phi\, S_L\, d\sigma^{(3)}_{UL} + \sin 2\phi\, S_L\, d\sigma^{(4)}_{UL} \\
+ & \quad \sin(\phi+\phi_S)\, S_T\, d\sigma^{(5)}_{UT} \\
+ & \quad \frac{1}{Q}\sin(2\phi-\phi_S)\, S_T\, d\sigma^{(6)}_{UT} \\
+ & \quad \sin(3\phi-\phi_S)\, S_T\, d\sigma^{(7)}_{UT} \\
+ & \quad \lambda S_L\, d\sigma^{(8)}_{LL} \\
+ & \quad \frac{1}{Q}\lambda S_L\cos\phi\, d\sigma^{(9)}_{LL} \\
+ & \quad \lambda S_T\cos(\phi-\phi_S)\, d\sigma^{(10)}_{LT} \\
+ & \quad \frac{1}{Q}\lambda S_T\cos(2\phi-\phi_S)\, d\sigma^{(11)}_{LT} \\
+ & \quad \ldots
\end{aligned}
$$

Single-spin asymmetry

Longitudinally polarized beam/target

HERMES Collaboration, PRL 84 (2000) 4047; PRD 64 (2001) 097101.

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

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

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

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

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

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

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

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

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

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

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

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

Non-zero SSAA in SIDIS have initiated a number of phenomenological approaches to evaluate these asymmetries using different input distribution and fragmentation functions.

K.O.,Bianchi,De Sanctis,Nowak, NPA 689 (2001) 784.
Bo-Qiang Ma, Ivan Schmidt, Jian-Jun Yang, hep-ph/0110324

The "kinematic" contribution to $A_{UL}^{\sin\phi}$, coming from the transverse component of the target polarization ($\sim \sin\theta_\gamma$) in all approaches is NOT more then 50%.

However, these are model dependent predictions !

$A_{UL}^{\sin\phi}$
$\Rightarrow$ Longitudinal effect OR Transversal "kinematic" effect ???
$\Rightarrow$ Longitudinal AND Transversal "kinematic" effect ???

Spin-independent $cos\phi$ asymmetry

UNpolarized beam and target

$$< \cos\phi >_{UU} = \frac{\int d\sigma \cos\phi d\phi}{\int d\sigma d\phi}$$

$P_{hT} = 0$ in the zeroth order in $\alpha_S \Rightarrow < \cos\phi >_{UU} = 0$
However

1. Perturbative QCD effects

   Georgi, Politzer, PRL, 40 (1978) 3

   $\gamma^* + q \longrightarrow q + g$
   $\gamma^* + g \longrightarrow q + q$
   In first order in α_S negative $< \cos\phi >$

2. Non-zero intrinsic transverse momentum effects

   Cahn, PLB 78 (1978) 269; PR D40 (1989) 3107

   Due to non-zero transverse momenta of partons as a consequence of being confined inside hadrons of finite size, non-perturbative p_T/Q effects generate negative $< \cos\phi >$ asymmetry as well.

3. Higher-twist effects

   Berger, PLB 89 (1980) 241

   Hadronization effects – pion bound-state effects generate positive $< \cos\phi >$ asymmetry at semi-exclusive limit $(z \longrightarrow 1)$

Else

4. pQCD effects + p_T/Q effects

   Chay, Ellis, Stirling, PRD 45 (1992) 46
   K.O., H.Avakian, N.Bianchi, P.Di Nezza, EPJC 5 (1998) 681

   The study of the $< \cos\phi >$ dependence on cutoff P_{hC} may identify the transition region between non-perturbative and perturbative physics.

5. p_T/Q effects + Higher-twist effects

   Brandenburg, Khose, Muller, PLB 347 (1995) 413

   Higher twist effects may be isolated in semi-exclusive pion production at moderate values of Q.

pQCD + p_T/Q + Higher-twist effects ???

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. E
PL B130 (1983) 118; ZP C34 (1987) 277

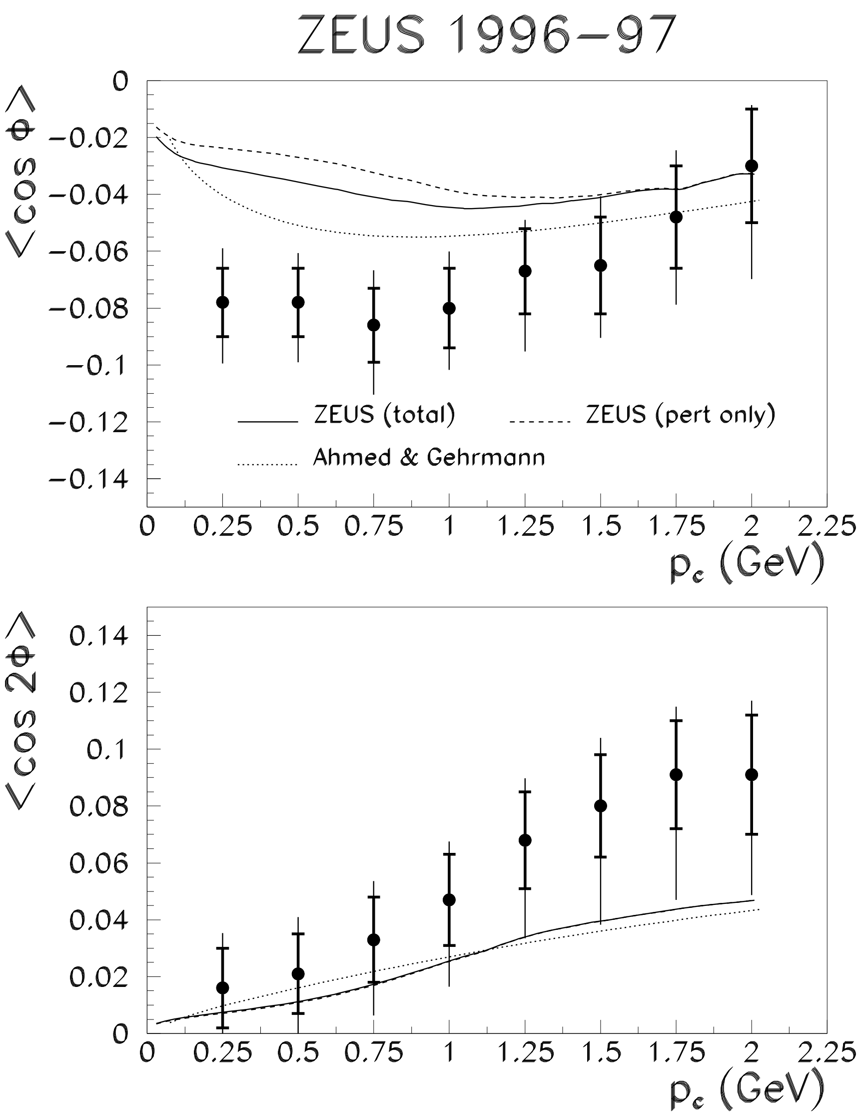
E665, PR D48 (1993) 5057;

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.

Experimental results

Resent results from ZEUS Collaboration:

ZEUS, PL B481 (2000) 199



Double-Spin $cos\phi$ asymmetry

K.O., P. J. Mulders, E. De Sanctis, in preparation

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

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

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

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

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

DSAA

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

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 $g_1(z, p_T^2)$:

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

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

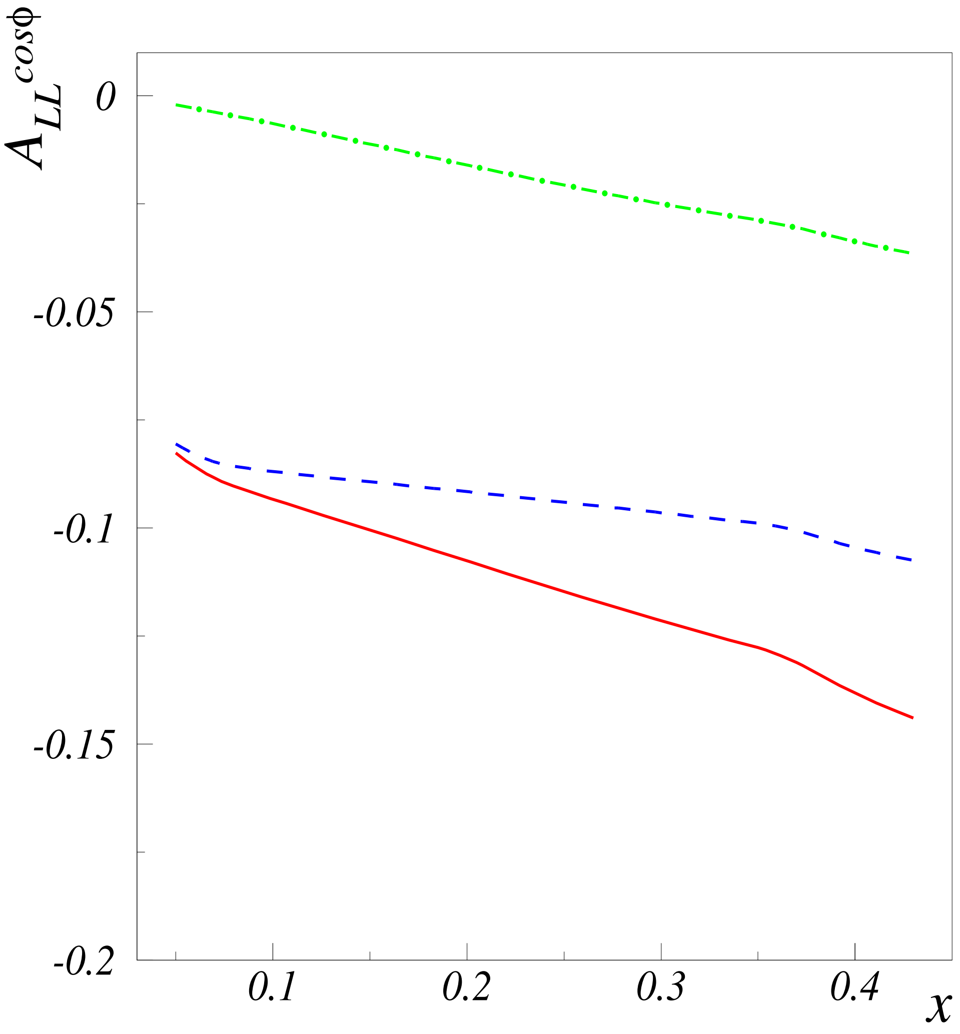
$D_1^{\pi^+}(z)$ from

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 SUM

Acceptance effects

$$
\begin{aligned}
d\sigma_{LL} &\equiv d\sigma^{++} + d\sigma^{--} - d\sigma^{+-} - d\sigma^{-+} \\
&= d\sigma_{LL}^{(8)} + \cos\phi\, d\sigma_{LL}^{(9)} + \cos 2\phi\, d\sigma_{LL}^{(12)} + \cdots
\end{aligned}
$$

$$
\begin{aligned}
d\sigma_{UU} &\equiv d\sigma^{++} + d\sigma^{--} + d\sigma^{+-} + d\sigma^{-+} \\
&= d\sigma_{UU}^{(0)} + \cos\phi\, d\sigma_{UU}^{(1)} + \cos 2\phi\, d\sigma_{UU}^{(13)} + \cdots
\end{aligned}
$$

Acceptance can be expanded in Fourier series:

$$
\epsilon(\phi) = 1 + \sum_m \left(A_m \cos(m\phi) + B_m \sin(m\phi)\right)
$$

Then the $A_{LL}^{\cos\phi}$ asymmetry will looks like

$$
A_{LL}^{\cos\phi} = \frac{d\sigma_{LL}^{(9)} + A_1 \cdot d\sigma_{LL}^{(8)} + \frac{1}{2}[A_1 \cdot d\sigma_{LL}^{(12)} + A_2 \cdot d\sigma_{LL}^{(9)}]}{d\sigma_{UU}^{(0)} + \frac{1}{2}[A_1 \cdot d\sigma_{UU}^{(1)} + A_2 \cdot d\sigma_{UU}^{(13)}]}
$$

It is quite complicated-:)

Study of $A_{UL}^{\cos m\phi}$, $A_{LU}^{\cos m\phi}$ $(m = 1, 2)$ may give a way to study the acceptance weights !?

Is it possible to get rid of acceptance effects ???

Acceptance independent asymmetry

This work is in progress

Instead of

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

lets consider the asymmetry defined in the following way

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

Note: *the acceptance effects are canceled* !

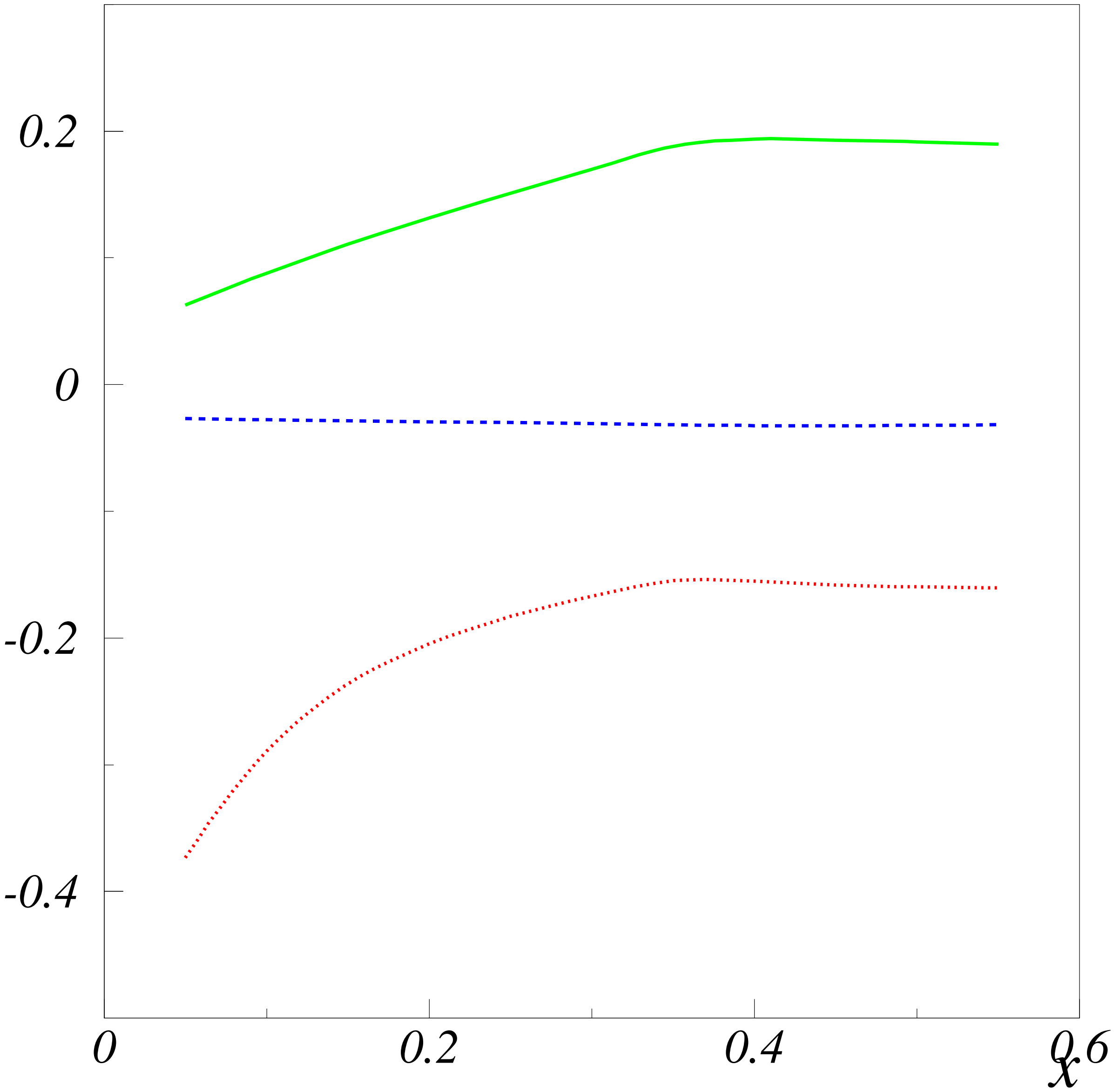
At leading $1/Q$ order

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

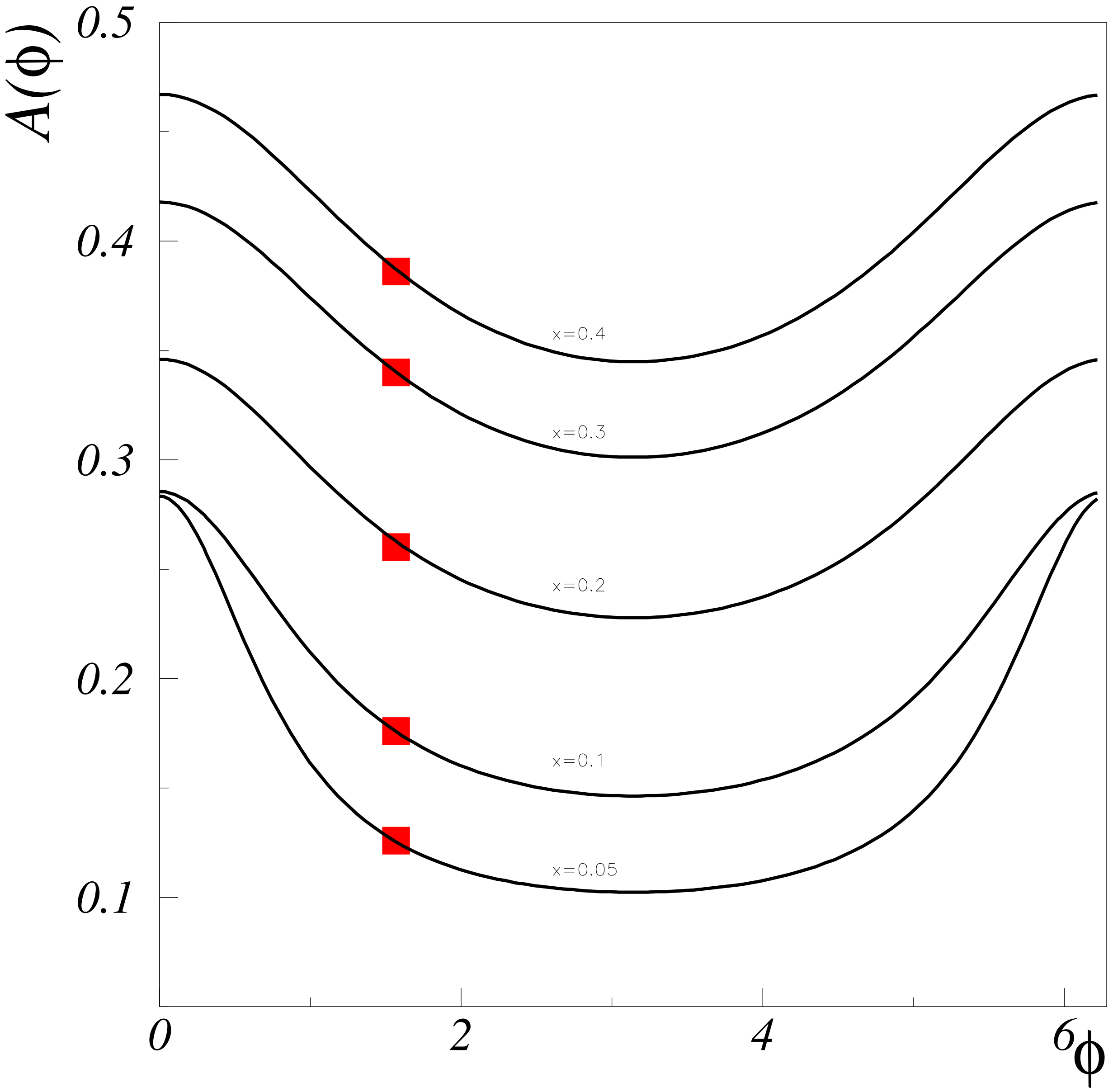
which can be rewritten in the following form

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

Preliminary results: $\langle \cos\phi \rangle_{UU/LL}$



Preliminary results: $A_{LL}(\phi)$



Conclusions

Single target-spin $\sin\phi$ asymmetry was briefly discussed (Alessandro Bacchetta's talk).

The spin-independent and double-spin $\cos\phi$ asymmetries for charged pion electroproduction in semi-inclusive deep inelastic scattering of longitudinally polarized leptons off longitudinally polarized protons focusing on intrinsic transverse momentum effects.

Spin-Independent $\cos\phi$ asymmetry

- we discuss different mechanisms generated $\cos\phi$ asymmetry $\longrightarrow$ some analogy to DSAA
- At moderate Q^2 and small P_{hT} the main contribution to the asymmetry comes from kinematic p_T effects
  EMC, E665 results, HERMES studies
- At high Q^2 – pQCD α_S first order effects
  ZEUS collaboration results

Double-spin $\cos\phi$ asymmetry

- At HERMES kinematics a sizable negative $cos\phi$ double-spin asymmetry for π^+ electroproduction in SIDIS is predicted
  – We take into account only $1/Q$ order contribution to the DSAA arises from intrinsic p_T effects similar to the $\cos\phi$ asymmetry in UNpolarized SIDIS: all functions with tilde are set to zero
  – The "kinematical" contribution from target transverse component $(S_{lab}\sin\theta_\gamma)$ is well defined. It gives very small contribution to $A_{LL}^{\cos\phi}$
  – Double-spin $\cos\phi$ asymmetry is a good observable to investigate the weights of twist-2 and twist-3 contributions at moderate Q^2
  – Gives possibility to estimate $< p_T^2 >$ in the nucleon

- The complete behavior of azimuthal distributions may be predicted only after inclusion of higher-twist and pQCD contributions
  Nevertheless, if one consider the kinematics with $P_{hT} < 1$ GeV and $z < 0.8$, then one can isolate the non-perturbative effects conditioned by

the intrinsic transverse momentum of the partons in the nucleon from pQCD and higher twist effects.

- Acceptance effects were discussed.
  An acceptance-independent asymmetry was considered, which leads to measurements of unpolarized and double polarized $\cos\phi$ asymmetries simultaneously.