Spin effects and partonic intrinsic $k_\perp$

- Parton intrinsic motion ($k_\perp$) in unpolarized inclusive processes
- $k_\perp$ and SSA in SIDIS
- $k_\perp$ and SSA in pp interactions
- Spin-$k_\perp$ correlations in distribution ($f_{q/p}$) and fragmentation ($D_{h/q}$) functions
- Factorization, QCD evolution, universality with spin-$k_\perp$ dependent $f_{q/p}$ and $D_{h/q}$

Based on works in collaboration with M. Boglione, U. D’Alesio, A. Kotzinian, E. Leader, S. Melis, F. Murgia and A. Prokudin


Mauro Anselmino, BNL, 21/02/2006
Partonic intrinsic motion

Plenty of theoretical and experimental evidence for transverse motion of partons within nucleons and of hadrons within fragmentation jets

uncertainty principle \[ \Delta x \approx 1 \text{ fm} \Rightarrow \Delta p \approx 0.2 \text{ GeV/c} \]

gluon radiation

\( q_T \) distribution of lepton pairs in D-Y processes
$p_T$ distribution of hadrons in SIDIS

$\gamma^* p \rightarrow hX$

Hadron distribution in jets in $e^+e^-$ processes

Large $p_T$ particle production in $pN \rightarrow hX$

Transverse motion is usually integrated, but there might be important spin-$k_{\perp}$ correlations
Unpolarized SIDIS (LO)

\[ d\sigma^{lp\rightarrow lhX} = \sum_q f_q(x, Q^2) \otimes d\sigma^{lq\rightarrow lq} \otimes D_q(z, Q^2) \]

In collinear parton model

\[ x = \frac{Q^2}{2p \cdot q} \quad Q^2 = -q^2 \quad y = \frac{p \cdot q}{l \cdot p} \]

\[ \sigma^{lq\rightarrow lq} \propto \hat{s}^2 + \hat{u}^2 \propto 1 + (1 - y)^2 \]

thus no dependence on azimuthal angle \( \phi_h \) at first order of PT.

The experimental data reveal that

\[ d\sigma^{lp\rightarrow lh^\pm X} / d\phi_h \propto A + B \cdot \cos(\phi_h) + D \cdot \cos(2\phi_h) \]

Cahn: the observed azimuthal dependence is related to the intrinsic $k_\perp$ of quarks (at least for small $P_T$ values)

$$k_\perp = (0, k_\perp \cos(\varphi), k_\perp \sin(\varphi), 0)$$

These modulations of the cross section with azimuthal angle are denoted as “Cahn effect”.

assuming collinear fragmentation, $\varphi = \Phi_h$

$$\hat{s} = sx \left[ 1 - \frac{2k_\perp}{Q} \sqrt{1 - y} \cdot \cos(\varphi) \right] + O\left(\frac{k_\perp^2}{Q}\right)$$

$$\hat{u} = sx (1 - y) \left[ 1 - \frac{2k_\perp}{Q \sqrt{1 - y}} \cdot \cos(\varphi) \right] + O\left(\frac{k_\perp^2}{Q}\right)$$

$$\frac{d\sigma_{ep \to ehX}}{d\phi_h} \propto \hat{s}^2 + \hat{u}^2 \propto A + B \cdot \cos(\phi_h) + D \cdot \cos(2\phi_h)$$

These modulations of the cross section with azimuthal angle are denoted as “Cahn effect”.
SIDIS with intrinsic $k_\perp$

Factorization holds at large $Q^2$, and $P_T \approx k_\perp \approx \Lambda_{QCD}$

$$d\sigma^{lp\rightarrow lhX} = \sum_q f_q(x, k_\perp; Q^2) \otimes d\hat{\sigma}^{lq\rightarrow lq}(y, \vec{k}_\perp; Q^2) \otimes D_q^h(z, p_\perp; Q^2)$$
The situation is more complicated as the produced hadron has also intrinsic transverse momentum with respect to the fragmenting parton.

\[ \frac{d\sigma_{ep \rightarrow ehX}}{d\phi_h} \propto \int d^2k_\perp \left\{ [1 + (1 - y)^2] f_q(x, k_\perp^2) D_h^q(z, (\vec{P}_T - z\vec{k}_\perp)^2) - 4\sqrt{1 - y(2 - y)} \frac{k_\perp \cos(\varphi)}{Q} f_q(x, k_\perp^2) D_h^q(z, (\vec{P}_T - z\vec{k}_\perp)^2) \right\} + \mathcal{O}\left(\frac{k_\perp^2}{Q^2}\right) \]
assuming:

\[
\begin{align*}
 f_q(x, k_{\perp}^2) &= f_q(x) \frac{1}{\pi \langle k_{\perp}^2 \rangle} e^{-\frac{k_{\perp}^2}{\langle k_{\perp}^2 \rangle}} \\
 D_h^q(z, p_{\perp}^2) &= D_h^q(z) \frac{1}{\pi \langle p_{\perp}^2 \rangle} e^{-\frac{p_{\perp}^2}{\langle p_{\perp}^2 \rangle}}
\end{align*}
\]

one finds

\[
\frac{d^5 \sigma^{ep \rightarrow ehX}}{dx dy dz P_T dP_T d\phi_h} \propto \left\{ [1 + (1 - y)^2] - 4 \frac{\sqrt{1 - y(2 - y) \langle k_{\perp}^2 \rangle z P_T}}{(\langle p_{\perp}^2 \rangle + z^2 \langle k_{\perp}^2 \rangle)Q} \cos(\phi_h) \right\} \\
\quad \cdot f_q(x) D_h^q(z) \frac{1}{\pi \langle P_T^2 \rangle} e^{-\frac{P_T^2}{\langle P_T^2 \rangle}}
\]

with

\[
\langle P_T^2 \rangle = \langle p_{\perp}^2 \rangle + z^2 \langle k_{\perp}^2 \rangle
\]

clear dependence on \( \langle p_{\perp}^2 \rangle \) & \( \langle k_{\perp}^2 \rangle \) (assumed to be constant)

Find best values by fitting data on \( \Phi_h \) and \( P_T \) dependences
EMC data, $\mu p$ and $\mu d$, $E$ between 100 and 280 GeV. Dashed line = exact kinematics, red solid line = only terms up to $O(k_\perp/Q)$. 

For $x_F > 0.1$ and $x_F > 0.2$.
The closed area shows effects of varying by 20%

\[ \langle \cos(\phi_h) \rangle = \frac{\int \sigma \cos(\phi_h) d\phi_h}{\int \sigma d\phi_h} \]

Data from E665, \( E_{\text{Lab}} = 490 \) GeV. \( \sigma \) is integrated from \( P_T^{\text{cut}} \) to \( P_T^{\text{max}} \). At low \( P_T^{\text{cut}} \) the non perturbative \( k_\perp \) contributions dominate. At large \( P_T^{\text{cut}} \) NLO pQCD contributions take over \((\gamma^* g \rightarrow q \bar{q}, \gamma^* q \rightarrow q g)\)
EMC data

\[ \langle \cos(\phi_h) \rangle = \frac{\int \sigma \cos(\phi_h) \, d\phi_h}{\int \sigma \, d\phi_h} \]

\[ w_1(y) = \frac{(2-y)\sqrt{1-y}}{1+(1-y)^2} \]
Fitting the unpolarized data leads to the best values

\[
\langle k^2 \rangle = 0.25 \text{ GeV}^2 \\
\langle p^2 \rangle = 0.2 \text{ GeV}^2
\]
Large $P_T$ data explained by NLO QCD corrections
\[ pp \rightarrow \pi^0 X \] (collinear configurations)

factorization theorem

\[
d\sigma = \sum_{a,b,c,d=q,\bar{q},g} f_{a/p} \otimes f_{b/p} \otimes d\hat{\sigma}^{ab\rightarrow cd} \otimes D_{\pi/c}
\]

PDF

pQCD elementary interactions

FF
The cross section

\[
\frac{E_C \, d\sigma^{AB \to CX}}{d^3 p_C} = \sum_{a,b,c,d} \int d^4p_a \, d^4p_b \, dz \, f_{a/A} (x_a, Q^2) \, f_{b/B} (x_b, Q^2)
\]

\[
\times \frac{\hat{s}}{\pi z^2} \frac{d\hat{\sigma}^{ab \to cd}}{dt} (\hat{s}, \hat{t}, \hat{u}, x_a, x_b) \, \delta(\hat{s} + \hat{t} + \hat{u}) \, D_{C/c}(z, Q^2)
\]

\[
= \sum_{a,b,c,d} \int d^4p_a \, d^4p_b \, f_{a/A} (x_a, Q^2) \, f_{b/B} (x_b, Q^2)
\]

\[
\times \frac{1}{\pi z} \frac{d\hat{\sigma}^{ab \to cd}}{dt} (\hat{s}, \hat{t}, \hat{u}, x_a, x_b) \, D_{C/c}(z, Q^2)
\]

\[x_a x_b zs = -x_a t - x_b u\]

\[\hat{s}, \hat{t}, \hat{u}\] elementary Mandelstam variables

\[s, t, u\] hadronic Mandelstam variables
RHIC data $\sqrt{s} = 200$ GeV

$p p \rightarrow \pi^0 \ X$

$p p \rightarrow \gamma \ X$
\( \langle k_\perp \rangle = 0.8 \text{ GeV} \quad \text{no} \langle k_\perp \rangle \)

F. Murgia, U. D’Alesio

FNAL data, PLB 73 (1978)

\[ p \ p \rightarrow \pi^0 \ X \quad \sqrt{s} \approx 20 \ \text{GeV} \]

original idea by Feynman-Field

non collinear configurations
Transverse single spin asymmetries: elastic scattering

\[ A_N \equiv \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \propto \hat{S} \cdot (\vec{p} \times \vec{P_T}) \propto \sin \theta \]

Example: \( pp \rightarrow pp \)

5 independent helicity amplitudes

\[ A_N \propto \text{Im}\left[\Phi_5 (\Phi_1 + \Phi_2 + \Phi_3 - \Phi_4)^*\right] \]

\[ M_{++;++} \equiv \Phi_1 \]
\[ M_{--;;++} \equiv \Phi_2 \]
\[ M_{+-;--} \equiv \Phi_3 \]
\[ M_{--;+-} \equiv \Phi_4 \]
\[ M_{--;++} \equiv \Phi_5 \]
for a generic configuration:

\[ A_N = \frac{\sigma\uparrow - \sigma\downarrow}{\sigma\uparrow + \sigma\downarrow} \propto \tilde{S} \cdot (\vec{p} \times \vec{P}_T) \propto P_T \sin(\Phi_S - \Phi) \]
Single spin asymmetries at partonic level. Example: $qq' \rightarrow qq'$

$A_N \neq 0$ needs helicity flip + relative phase

QED and QCD interactions conserve helicity, up to corrections $O(m_q / E)$

$A_N \propto \frac{m_q}{E} \alpha_s$ at quark level

but large SSA observed at hadron level!
BNL-AGS $\sqrt{s} = 6.6$ GeV
$0.6 < p_T < 1.2$

$pp \rightarrow \pi X$

E704 $\sqrt{s} = 20$ GeV
$0.7 < p_T < 2.0$

observed transverse Single Spin Asymmetries

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

experimental data on SSA
STAR-RHIC $\sqrt{s} = 200$ GeV
$1.1 < p_T < 2.5$

$A_N$ stays at high energies ...
$l N^\uparrow \rightarrow l \pi X$

"Sivers moment"

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

$$2\langle \sin(\Phi - \Phi_S) \rangle = A_{UT}^{\sin(\Phi - \Phi_S)}$$

$$\equiv 2 \int d\Phi d\Phi_S (d\sigma^\uparrow - d\sigma^\downarrow) \sin(\Phi - \Phi_S)$$

$$\int d\Phi d\Phi_S (d\sigma^\uparrow + d\sigma^\downarrow)$$
\[ l N^\uparrow \rightarrow l \pi X \]

“Collins moment”

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

\[ 2\langle \sin(\Phi + \Phi_S) \rangle = A_{UT}^{\sin(\Phi + \Phi_S)} \]

\[ \equiv 2 \int d\Phi d\Phi_S (d\sigma^\uparrow - d\sigma^\downarrow) \sin(\Phi + \Phi_S) \]

\[ \int d\Phi d\Phi_S (d\sigma^\uparrow + d\sigma^\downarrow) \]
Transverse $\Lambda$ polarization in unpolarized $p$-Be scattering at Fermilab

\[ p \ N \to \Lambda^{\uparrow} \ X \]

\[ P_\Lambda = \frac{d\sigma^{\Lambda^{\uparrow}} - d\sigma^{\Lambda^{\downarrow}}}{d\sigma^{\Lambda^{\uparrow}} + d\sigma^{\Lambda^{\downarrow}}} \]
$p^+ p \rightarrow p p$

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

$A_{NN} = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}}$
Transverse single spin asymmetries in SIDIS

\[ A_N \propto \vec{S} \cdot (\vec{p} \times \vec{P}_T) \propto P_T \sin(\Phi_\pi - \Phi_S) \]

\( \gamma^* - p \) c.m. frame

in collinear configurations there cannot be (at LO) any \( P_T \)

needs \( k_\perp \) dependent quark distribution in \( p^\uparrow \) (Sivers mechanism) or \( p_\perp \) dependent fragmentation of polarized quark (Collins mechanism)
Brodsky, Hwang, Schmidt model for Sivers function

\[ \gamma^* \rightarrow \pi \rightarrow q \rightarrow \text{diquark} \]

\[ \bar{S} \cdot (\vec{p} \times \vec{P_T}) \propto P_T \sin(\Phi_\pi - \Phi_S) \]

needs \( k_\perp \) dependent quark distribution in \( p^\uparrow \): Sivers function
\[ A^{s\sin(\phi_h - \phi_S)}_{UT} = \]

\[ \sum_{q} d\{\phi_h, \phi_S, k_{\perp}\} \Delta f_{q/p}(x, k_{\perp}) \sin(\varphi - \phi_S) \frac{d\hat{\sigma}_{q^+q^-}}{dQ^2} J \frac{z}{z_h} D^h_q(z, p_{\perp}) \sin(\phi_h - \phi_S) \]

\[ 2\pi \sum_{q} d\phi_h \, d^2 k_{\perp} \, f_q(x, k_{\perp}) \frac{d\hat{\sigma}_{q^+q^-}}{dQ^2} J \frac{z}{z_h} D^h_q(z, p_{\perp}) \]

Sivers mechanism in SIDIS

\[ f_{q/p}(x, k_{\perp}) = f_{q/p}(x, k_{\perp}) + \frac{1}{2} \Delta f_{q/p}(x, k_{\perp}) (\hat{p} \times \hat{k}_{\perp}) \]

\[ p_{\perp} = P_T - z k_{\perp} + O(k_{\perp}^2/Q^2) \]
$A_{UT}^{\sin(\Phi-\Phi_s)}$ from Sivers mechanism

M.A., U.D’Alesio, M.Boglione, A.Kotzinian, A Prokudin
Deuteron target

\[ A_{UT}^{\sin(\Phi_h - \Phi_S)} \propto \left( \Delta^N f_{u/p} + \Delta^N f_{d/p} \right) \left( 4D_u^h + D_d^h \right) \]
First $p_{\perp}$ moments of extracted Sivers functions, compared with models
data from HERMES and COMPASS

\[
\Delta^N f_q^{(1)} = -f_{1T}^{\perp(1)q} = \int d^2k \frac{k_{\perp}}{4m_p} \Delta^N f_{q/p\uparrow}^N(x, k_{\perp})
\]
Predictions for K production at HERMES
Predictions for COMPASS, hydrogen target

- $Q^2 > 1 \text{ (GeV/c)}^2$
- $W^2 > 25 \text{ GeV}^2$
- $P_T > 0.1 \text{ GeV/c}$
- $E_h > 4 \text{ GeV}$
- $0.2 < z_h < 0.9$
- $0.1 < y < 0.9$
predictions for COMPASS, proton target
Collins mechanism for SSA

Asymmetry in the fragmentation of a transversely polarized quark
(Fundamental QCD property? D. Sivers)

Initial q spin is transferred to final q', which fragments

\[ \hat{S}_{q'} \cdot (\hat{p}_{q'} \times \hat{p}_\perp) \propto \sin(\Phi_h + \Phi_S) \]
neglecting intrinsic motion in partonic distributions:

\[
A_N^h = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} = \sum_q \int e_q^2 h_{1q}(x) (1 - y)/(xy^2) \Delta_N D_{h/q}^\uparrow (z, p_\perp) \sin(\Phi_h + \Phi_S)
\]

\[
\sum_q \int e_q^2 f_{q/p}(x) [1 + (1 - y)^2]/(xy^2) D_{q/p} (z, p_\perp)
\]

\[
A_{UT}^{\sin(\Phi_h + \Phi_S)} \equiv 2 \int d\Phi_h d\Phi_S [d\sigma^\uparrow - d\sigma^\downarrow] \sin(\Phi_h + \Phi_S)
\]

\[
\int d\Phi_h d\Phi_S [d\sigma^\uparrow + d\sigma^\downarrow]
\]

some data available from HERMES, first extraction of Collins functions:
W. Vogelsang and F. Yuan (assuming Soffer-saturated \(h_1\))

\[
\left( 2 |h_1| \leq \Delta q + q \right)
\]
fit to HERMES data on $A_{UT} \sin(\Phi_h + \Phi_S)$
spin-\(k_{\perp}\) correlations

**Sivers function**

\[
f_{q/p}^{\uparrow}(x, \vec{k}_{\perp}) = f_{q/p}(x, k_{\perp}) + \frac{1}{2} \Delta^{N} f_{q/p}^{\uparrow}(x, k_{\perp}) \vec{S} \cdot (\hat{p} \times \hat{k}_{\perp})
\]

**Collins function**

\[
D_{h/q}^{\uparrow}(z, \vec{p}_{\perp}) = D_{h/q}(z, p_{\perp}) + \frac{1}{2} \Delta^{N} D_{h/q}^{\uparrow}(z, p_{\perp}) \vec{S}_{q} \cdot (\hat{p}_{q} \times \hat{p}_{\perp})
\]

**Amsterdam group notations**

\[
\Delta^{N} f_{q/p}^{\uparrow} = -\frac{2k_{\perp}}{M} f_{1T}^{\perp q}
\]

\[
\Delta^{N} D_{h/q}^{\uparrow} = 2 \frac{p_{\perp}}{z M_{h}} H_{1q}^{\perp q}
\]
spin-$k_{\perp}$ correlations

Boer-Mulders function

$$f_{q^+/p}(x, \vec{k}_{\perp}) = \frac{1}{2} f_{q/p}(x, k_{\perp}) + \frac{1}{2} \Delta^N f_{q^+/p}(x, k_{\perp}) \vec{S}_q \cdot (\hat{p} \times \hat{k}_{\perp})$$

polarizing f.f.

$$D_{\Lambda^+/q}(z, \vec{p}_{\perp}) = \frac{1}{2} D_{h/q}(z, p_{\perp}) + \frac{1}{2} \Delta^N D_{\Lambda^+/q}(z, p_{\perp}) \vec{S}_{\Lambda} \cdot (\hat{p}_q \times \hat{p}_{\perp})$$

Amsterdam group notations

$$\Delta^N f_{q^+/p} = -\frac{k_{\perp}}{M} h_{1q}$$

$$\Delta^N D_{\Lambda^+/q} = 2 \frac{p_{\perp}}{z M_{\Lambda}} D_{1T}^{1q}$$
Hadronic processes: the cross section with intrinsic $k_\perp$

\[
\frac{E_C d\sigma^{AB\rightarrow CX}}{d^3 p_C} = \sum_{a,b,c,d} \int dx_a dx_b dz \frac{d^2 k_\perp_a}{d^2 k_\perp} \frac{d^3 k_\perp_C}{d^3 k_\perp} \delta(k_\perp_C \cdot \hat{p}_C) \hat{f}_{a/A}(x_a, k_\perp_a; Q^2) \hat{f}_{b/B}(x_b, k_\perp_b; Q^2)
\]

\[
\frac{\hat{s}^2}{\pi x_a x_b z^2 s} J(k_\perp_C) \frac{d\hat{\sigma}^{ab\rightarrow cd}}{d\hat{t}}(s, t, \hat{u}, x_a, x_b) \delta(s + t + \hat{u}) \hat{D}_{C/c}(z, k_\perp_C; Q^2)
\]

intrinsic $k_\perp$ in distribution and fragmentation functions and in elementary interactions

factorization is assumed, not proven in general; some progress for Drell-Yan processes, two-jet production, Higgs production via gluon fusion (Ji, Ma, Yuan; Collins, Metz; Bacchetta, Bomhof, Mulders, Pijlman)
The polarized cross section with intrinsic $k_\perp$

\[
E_C \frac{d\sigma^{(A,S_A)+(B,S_B)\to C+X}}{d^3p_C} = \sum_{a,b,c,d,\{\lambda\}} \int \frac{dx_a \, dx_b \, dz}{16\pi^2 x_a x_b z^2 s} d^2k_{\perp a} \, d^2k_{\perp b} \, d^3k_{\perp C} \, \delta(k_{\perp C} \cdot \hat{p}_c) \, J(k_{\perp C}) \\
\times \rho_{\lambda_a,\lambda'_a} a/A, S_A \hat{f}_{a/A, S_A} (x_a, k_{\perp a}) \rho_{\lambda_b,\lambda'_b} b/B, S_B \hat{f}_{b/B, S_B} (x_b, k_{\perp b}) \\
\times \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b} \hat{M}^*_\lambda_c,\lambda_d;\lambda'_a,\lambda'_b \delta(\hat{s} + \hat{t} + \hat{u}) \hat{D}_{\lambda_c,\lambda'_c} (z, k_{\perp C})
\]

$\rho_{\lambda_a,\lambda'_a} a/A, S_A$ helicity density matrix of parton $a$ inside polarized hadron $A$

$\hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}$ pQCD helicity amplitudes

$D_{\lambda_c,\lambda'_c} \lambda_c,\lambda'_c$ product of fragmentation amplitudes
Computation of helicity amplitudes

\[ M \propto \bar{u}(p_3, \lambda_3)\gamma^\mu u(p_1, \lambda_1)\bar{u}(p_4, \lambda_4)\gamma_\mu u(p_2, \lambda_2) \]

\[ p_i = (p_i^0, \mathbf{p}_i) \]

**Dirac-Pauli helicity spinors**

\[ u(p_i, \lambda_i) = \sqrt{p_i^0} \left( \begin{array}{c} 1 \\ \lambda_i \end{array} \right) X_{\lambda_i}(\hat{\mathbf{p}}_i) \quad \hat{\mathbf{p}}_i = (\sin \vartheta_i \cos \phi_i, \sin \vartheta_i \sin \phi_i, \cos \vartheta_i) \]

\[ X_+ (\hat{\mathbf{p}}_i) = \left( \begin{array}{c} \cos(\vartheta_i / 2) e^{-i\phi_i / 2} \\ \sin(\vartheta_i / 2) e^{i\phi_i / 2} \end{array} \right) \quad X_- (\hat{\mathbf{p}}_i) = \left( \begin{array}{c} -\sin(\vartheta_i / 2) e^{-i\phi_i / 2} \\ \sin(\vartheta_i / 2) e^{i\phi_i / 2} \end{array} \right) \]

if scattering is not planar all \( \Phi_i \) are different and many phases remain in amplitudes; they strongly suppress the results of integrations over \( k_\perp \).
Maximised (i.e., saturating positivity bounds) contributions to $A_N$

- **quark Sivers contribution**
- **gluon Sivers contribution**
- **Collins contribution**

(E704) $pp \rightarrow \pi^+ X$
- $\sqrt{s} = 19.4$ GeV
- $p_T = 1.5$ GeV/c

(PAX) $p\bar{p} \rightarrow \pi^+ X$
- $\sqrt{s} = 14.14$ GeV
- $p_T = 2$ GeV/c
SSA in $p^+p \rightarrow \pi X$

\[ d\sigma^\uparrow - d\sigma^\downarrow \simeq \Delta^N \frac{f_{a/p^\uparrow}}{f_{b/p}} \otimes \frac{f_{b/p}}{f_{b/p}} \otimes d\hat{\sigma} \otimes D_{\pi/c} \]

+ $h_{1a} \otimes \frac{f_{b/p}}{f_{b/p}} \otimes d\hat{\sigma} \otimes \Delta^N D_{\pi/c}^\uparrow$

“Sivers effect”

“Collins effect”

E704 data, $E = 200 \text{ GeV}$

M.A, M. Boglione, U. D’Alesio, E. Leader, F. Murgia

fit to $A_N$ with Sivers effects alone

maximized value of $A_N$ with Collins effects alone
Conclusions

- Unintegrated (TMD) distribution functions allow a much better description of QCD nucleon structure and hadronic interactions (necessary for correct differential distribution of final state particles, recent paper by Collins, Jung, hep-ph/0508280)

- $k_\perp$ is crucial to understand observed SSA in SIDIS and pp interactions

- Spin-$k_\perp$ dependent distribution and fragmentation functions: towards a complete phenomenology of spin asymmetries

- Open issues: factorization, QCD evolution, universality, higher perturbative orders, …