Transverse target spin asymmetries on a proton target at COMPASS

Andreas Richter
Physikalisches Institut IV
Universität Erlangen-Nürnberg
on behalf of the COMPASS collaboration

HEP 09, 09/07/18, Krakow, Poland
Transverse Spin Physics

Three distribution functions are necessary to describe the spin structure of the nucleon in LO:

\[ q(x) = q_+(x) + q_-(x) \]

momentum distribution

\[ \Delta q(x) = q_+(x) - q_-(x) \]

helicity distribution

\[ \Delta_T q(x) = q_{\uparrow}(x) - q_{\downarrow}(x) \]

transversity distribution

well known

known

little known
Transverse Spin Physics in SIDIS

For measuring Transversity:
quark spin must flip
\[ \Delta_T q(x) \] decouples from inclusive DIS

product of \[ \Delta_T q(x) \] and another chiral-odd function needed
\[ \Delta_T q(x) \] can be extracted via SIDIS on a transversely polarized target.

Channels measured by COMPASS:
\[ l N \rightarrow l' h X \] Collins asymmetry
\[ l N \rightarrow l' h h X \] hadron pair asymmetry
\[ l N \rightarrow l' \Lambda X \] \( \Lambda \) polarisation
Two steps:
• Scattering of the lepton on the quark (**distribution function**)
• Production of hadrons from the struck quark (**fragmentation function**)

Kinematic variables:
• $Q^2 = -q^2 \approx 4 \frac{E E'}{\sin \theta} \sin \theta/2$ negative four-momentum transfer squared
• $\nu = E - E'$ photon energy
• $x_{bj} = \frac{Q^2}{2M \nu}$ Momentum fraction of struck quark
• $y = \frac{\nu}{E}$ inelasticity
• $z = \frac{E_h}{\nu}$ exclusivity
COMPASS Spectrometer at CERN
(2007 run, proton target)

- high energy beam
- large angular acceptance
- broad kinematical range

Two stage spectrometer:
- large angle spectrometer (SM1)
- small angle spectrometer (SM2)

tracking, calorimetry, PID

beam: 160 GeV/c
intensity: $2 \cdot 10^8 \, \mu^+/\text{spill}$
(4.8 s / 16.8 s)
luminosity: $5 \cdot 10^{32} \, \text{cm}^{-2} \, \text{s}^{-1}$
Polarized Proton Target (NH$_3$)

Polarization: $P_T \approx 90\%$

Dilution factor $f \approx 0.15$

3 target cells with opposite polarization

Transverse target polarization: dipole field changed by microwave reversal: once a week
Two important possible azimuthal asymmetries in the distribution of single hadrons in SIDIS on a transversely polarized target are shown:

a) **Collins effect:**
Fragmentation of a transversely polarized quark with finite transverse momentum into a Spin 0 hadron.

\[
A_{\text{Coll}} = \frac{A_C^h}{f \cdot P_T \cdot D_{nn}} = \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_0^T D_q h}{\sum_q e_q^2 \cdot q \cdot D_q h}
\]

- **possibility to measure transversity!**

b) **Sivers effect:**
Fragmentation of an "unpolarized" (unknown spin state) quark inside a transversely polarized nucleon.

- **Gives a measure of the correlation between transverse momentum and transverse spin.**

A non-zero Sivers function needs orbital angular momentum of the quarks.

\[
A_{\text{Siv}} = \frac{A_S^h}{f \cdot P_T} = \frac{\sum_q e_q^2 \cdot \Delta_0^T q \cdot D_q h}{\sum_q e_q^2 \cdot q \cdot D_q h}
\]
The Coordinate System

Collins and Sivers terms depend on different combination of angles:

Collins:
\[ A_{\text{Coll}} \sim \sin \Phi_C \]
\[ \Phi_C = \phi_h - \phi_{S'} = \phi_h + \phi_S - \pi \]

Sivers:
\[ A_{\text{Siv}} \sim \sin \Phi_S \]
\[ \Phi_S = \phi_h - \phi_S \]

\( \phi_h \): azimuthal angle of the hadron
\( \phi_S \): azimuthal angle of the spin of the initial quark
\( \phi_{S'} \): azimuthal angle of the spin of the fragmenting quark

with \( \phi_{S'} = \pi - \phi_S \) (spin flip)
Data Taking

Statistics after all cuts:

<table>
<thead>
<tr>
<th>2002-04 (deuteron target)</th>
<th>hadrons for Collins</th>
<th>hadrons for Sivers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total statistics</td>
<td>$15.5 \cdot 10^6$</td>
<td>$15.5 \cdot 10^6$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2007 (proton target)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>statistics of first results</td>
<td>$11 \cdot 10^6$</td>
<td>$11 \cdot 10^6$</td>
</tr>
<tr>
<td>(Transversity 08)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>reproduction of data with</td>
<td>$29 \cdot 10^6$</td>
<td>$11 \cdot 10^6$</td>
</tr>
<tr>
<td>improved quality (used for</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collins)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

for Collins: usable statistics improved by a factor of 3
Data Quality and Systematic Checks

Tests on data for constant detector performance:

1. A dedicated set of quality checks has been developed and applied to satisfy this condition
   - Detector and trigger performances
   - Event reconstruction
   - K⁰ reconstruction
   - Stability of many kinematical variables:
     \[(Z_{\text{vtx}}, E_\mu, \phi_\mu, x_{\text{Bj}} Q^2, y, W, E_{\text{had}}, \phi_{\text{hadLab}}, \theta_{\text{hadLab}}, \phi_{\text{hadGNS}}, \theta_{\text{hadGNS}}, p_T)\]

2. Several systematics tests have been performed:
   - Splitting of the target into sectors
   - False asymmetries tests
   - Different methods for asymmetry extraction
Event Selection

**DIS cuts:**
- \( Q^2 > 1 \text{ (GeV/c)}^2 \)
- \( 0.1 < y < 0.9 \)
- \( W > 5 \text{ GeV/c}^2 \)

**Hadron cuts:**
- \( z > 0.2 \)
- \( p_T > 0.1 \text{ GeV/c} \)

after cuts: distribution of \( x_{bj} \)
Asymmetry Extraction

Splitting middle cell into two parts
• two pairs of cells with opposite polarization
• two independent values for the asymmetries per period

Extraction: 2D Binned Maximum Log-Likelihood Fit:
8 X 8 grid in $\phi_h$ and $\phi_s$

In each bin $j = \{1, 2, \ldots, 64\}$ one expects $N_j$ counts:

$$N_j^{\uparrow \downarrow} = a_j g_j^{\uparrow \downarrow} (A)$$

with:

- $\uparrow \downarrow$ sign of the target polarization
- $a_j$ acceptance in bin $j$
- $g_j^{\uparrow \downarrow} (A)$ all 8 spin dependent modulations of the cross section in bin $j$
Asymmetries compatible with 0 within present statistical errors

Only statistical errors shown, systematic errors: 0.5 $\sigma_{\text{stat}}$
Sivers Asymmetries Proton Data

Comparison with predictions of Anselmino et al.:
Sivers Asymmetries – Comparison with HERMES

COMPASS 2007 proton data (part.)

preliminary

2 \langle \sin(\phi - \phi_S) \rangle_{UT} \quad \pi^+

2 \langle \sin(\phi - \phi_S) \rangle_{UT} \quad \pi^-

HERMES: arxiv:0906.3918
Sivers Asymmetries Deuteron Data

- small asymmetries, compatible with 0
- only statistical errors shown, systematic errors considerably smaller

Final results, all deuteron data: NP B765 (2007) 31-70

the result was interpreted as a strong indication for cancellation of u and d quark Sivers function
Reproduced Data

- Reproduction with improved quality
- Improved quality checks
- Increased systematic checks

Instabilities of the spectrometer in the first part of the run

→ for Sivers: extraction for full 2007 data difficult

Asymmetry extraction:
Extended Unbinned Maximum Likelihood Fit:

\[ L = e^{-N_e} \prod_{i=1}^{N} p(\phi_S^i, \phi_h^i; a_1 \cdots a_m) \]

with

- \(N\): number of hadrons
- \(N_e\): expected number of hadrons
- \((a_1 \cdots a_m)\): the unknown parameters
- \(p\): probability density of the sampling variables \(\Phi_S\) and \(\Phi_h\)

\[ \int \int p(\phi_S, \phi_h; a_1 \cdots a_m) d\phi_S d\phi_h = N_e(a_1 \cdots a_m) \]

\(p\) parametrization contains the single hadron cross-section
Collins Asymmetries - Proton Data

Asymmetries different from 0 for valence region

- asymmetries of opposite sign for positive and negative hadrons
- systematic errors: $0.5 \, \sigma_{\text{stat}}$
- small asymmetries, compatible with 0 at small $x_{bj}$
Collins Asymmetries - Proton Data

Comparison with predictions of Anselmino et al.:
Collins Asymmetries – Comparison with HERMES

COMPASS 2007 transverse proton data

- $h^+ \text{ COMPASS, } x > 0.05$
- $h^+ \text{ COMPASS, } x \leq 0.05$
- $\pi^+ \text{ HERMES (Dnn corr.)}$

Dnn not approved by HERMES; approximated with $\langle y \rangle$

HERMES: arxiv:0706.2242

→ same strength and sign as HERMES
Collins Asymmetries - Deuteron Data

- small asymmetries, compatible with 0
- only statistical errors shown, systematic errors considerably smaller

Final results, all deuteron data: NP B765 (2007) 31-70
Interpretation Collins Deuteron

Small asymmetries $\rightarrow$ cancellation between $\Delta_T u(x)$ and $\Delta_T d(x)$

Deuteron data $\rightarrow$ access to $\Delta_T d(x)$

Phenomenological models can describe data from COMPASS on deuteron, HERMES on proton and BELLE at the same time:
- Vogelsang, Yuan: hep-ph/0507266
- Efremov, Goeke, Schweitzer: hep-ph/0603054
- Anselmino, Prokudin at SPIN 2008

Now also possible with COMPASS (d), COMPASS (p) and BELLE.

HERMES (p), COMPASS (d), BELLE

**global fit**

Soffer bound
Two Hadron Asymmetries

In the production of hadron pairs one can define the angle $\phi_R$ and measure an azimuthal asymmetry from the modulation of the numbers of events in $\Phi_{RS} = \phi_R - \phi_{S'}$.

\[ \Phi_{RS} = 1 \pm A \cdot \sin \Phi_{RS} \]

\[ A_{RS} = \frac{1}{f \cdot P_T \cdot D} \cdot A = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot H^2_{q}(z, M_h^2)}{\sum_q e_q^2 \cdot q(x) \cdot D^h_{q}(z, M_h^2)} \]

$\Phi_{RS}$: azimuthal angle of $R_T$

$\phi_{S'} = \pi - \phi_{s'}$: azimuthal angle of the spin of the fragmenting quark

$\vec{p}_h = \vec{p}_1 + \vec{p}_2$

$\vec{R}_T = \frac{z_2 \vec{p}_{1T} - z_1 \vec{p}_{2T}}{z_1 + z_2}$

Transversity distribution function, being measured at BELLE

Interference fragmentation function

A. Bacchetta, M. Radici, hep-ph/0407345
X. Artru, hep-ph/0207309
Two Hadron Asymmetries – Proton Data

Hadron cuts:
- \( z_{1,2} > 0.1 \)
- \( x_{F1,2} > 0.1 \)
- \( z_1 + z_2 < 0.9 \) (exclusive \( \rho \))
- \( R_T > 0.07 \text{ GeV/c} \)

Statistics after all cuts:

Proton target

\( h^+ h^- \) pairs

\( 11.28 \cdot 10^6 \)
Two Hadron Asymmetries – Proton Data

Comparison with predictions of Bacchetta (Courtesy of A. Bacchetta):

COMPASS 2007 transverse proton data

Comparison with HERMES:

HERMES: JHEP 0806:017, 2008
\[ \Lambda \text{ Polarimetry} \]

Information on \( \Delta_T q(x) \) can be accessed in the process:

\[
\mu \ N^\uparrow \rightarrow \mu' \Lambda^\uparrow X
\]

(analog for \( \overline{\Lambda} \))

**N**: component of target spin perpendicular to \( p_{\gamma^*} \)

**T**: symmetric of N wrt. the normal to the scattering plane

\[
P_{T, \text{exp}}^{\Lambda} = \frac{d\sigma^{\mu N^\uparrow \rightarrow \mu' \Lambda^\uparrow X} - d\sigma^{\mu N^\downarrow \rightarrow \mu' \Lambda^\uparrow X}}{d\sigma^{\mu N^\uparrow \rightarrow \mu' \Lambda^\uparrow X} + d\sigma^{\mu N^\downarrow \rightarrow \mu' \Lambda^\uparrow X}} = \int P_N D(y) \sum_q e_q^2 \Delta_T q(x) \Delta_T D_{\Lambda / q}(z)
\]

\( f = \text{target dilution factor}, \ P_N = \text{target polarization}, \ D(y) = \text{virtual photon depolarization factor} \)

\[
\Delta_T D_{\Lambda / q}(z) = D_{\Lambda^\uparrow / q^\uparrow}(z) - D_{\Lambda^\downarrow / q^\downarrow}(z)
\]
**Λ Polarimetry – Proton Data**

**Preliminary COMPASS 2007**
transverse proton data (part)

\[ \overline{\Lambda} \]

\[ N_{\Lambda} \sim 13,600 \]

\[ \Lambda \]

\[ N_{\Lambda} \sim 27,900 \]
• no dependence on $x_{bj}$
• fragmentation function as function of $z$ seems quite small
Summary and Outlook

Results of the COMPASS 2007 proton transverse run:

- **Collins asymmetry:**
  - different from 0, compatible with HERMES
  - agreement with predictions of Anselmino et al.
  - access to transversity!

- **Sivers asymmetry:**
  - compatible with 0 within present statistical errors in difference to Hermes for $h^+$
  - to be understood

- **Two Hadron Asymmetries**
  - different from 0, signal stronger than HERMES

- **Λ Polarization**
  - fragmentation function as function of $z$ seems quite small

- **Near future:**
  - identified hadrons
  - further transverse data taking (2010)
Just in case...
Systematic Studies

Several systematics tests have been performed:

Splitting of the target into sectors:
1. Left right
2. Up down

False asymmetries test:
1. Combining cells with the same polarization

Target split: different target sectors
1. Combining half upstream target cells (conf 0)
2. Combining half downstream target cells (conf 1)

Different methods for asymmetry extraction
1. 5 different methods
Asymmetry Extraction

Separation of acceptance and spin dependent modulations:

Coupling of two cells \((u, d)\) with opposite polarization \((↑↓)\) and two periods \((p1, p2)\) with opposite target polarization

Reasonable assumption:

\[
\frac{a_{ju}^{↑}}{a_{ju}^{↓}} = C \frac{a_{jd}^{↓}}{a_{jd}^{↑}}
\]

\(4 \cdot 64 = 256\) nonlinear equations \(\left(\tilde{f} | \tilde{a}\right)\)

\(1 + 8 + 3 \cdot 64 = 201\) fit parameters \(\tilde{a}\)

Poisson distribution to account for low statistics:

\[
P_j(\tilde{a}) = \frac{f_j(\tilde{a})^N_j e^{-f_j(\tilde{a})}}{N_j !}
\]

Solution:

\[
\max \prod_{j=1}^{256} P_j(\tilde{a})
\]
Interpretation Sivers Deuteron

Naïve interpretation of the data (parton model, valence region):

\[ A_{Siv}^{d,\pi^+} \simeq A_{Siv}^{d,\pi^-} \simeq \frac{\Delta_0^T u_v + \Delta_0^T d_v}{u_v + d_v} \]

Small asymmetries \( \rightarrow \)

\[ \Delta_0^T d_v \simeq -\Delta_0^T u_v \]

Data on proton target (HERMES) are different from 0.

\( \rightarrow \) Summary of phenomenological works by different groups (describing COMPASS and HERMES data) in Anselmino et al.: hep-ph/0511017

measured asymmetry on deuteron compatible with 0 has been interpreted as

**Evidence for the Absence of Gluon Orbital Angular Momentum in the Nucleon**

S.J. Brodsky, S. Gardner: PLB643 2006 (22)

The approximate cancellation of the SSA measured on a deuterium target suggests that the gluon mechanism, and thus the orbital angular momentums carried by gluons in the nucleon, is small.
Naïve interpretation of the data (parton model, valence region):

\[
A_{Coll}^{d,\pi^+} \approx \frac{\Delta_T u_v + \Delta_T d_v}{u_v + d_v} \frac{4\Delta_T^0 D_1 + \Delta_T^0 D_2}{4D_1 + D_2}
\]

\[
A_{Coll}^{d,\pi^-} \approx \frac{\Delta_T u_v + \Delta_T d_v}{u_v + d_v} \frac{\Delta_T^0 D_1 + 4\Delta_T^0 D_2}{D_1 + 4D_2}
\]

Small asymmetries → **cancellation between** $\Delta_T u(x)$ **and** $\Delta_T d(x)$

**Deuteron data** → **access to** $\Delta_T d(x)$

From proton data of Hermes: $\Delta_T^0 D_2 \approx - \Delta_T^0 D_1$
Other Single Spin Asymmetries

More terms are present in the complete SIDIS cross section: 8 transverse target spin dependent asymmetries with different azimuthal dependencies.

\[
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)^2} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ \right. \\
+ |S_{\perp}| \left[ \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \\
+ \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \\
+ \sqrt{2\varepsilon(1+\varepsilon)} \sin\phi_S F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \\
+ |S_{\perp}|\lambda_c \left[ \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_S F_{LT}^{\cos\phi_S} \\
+ \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right] \right\},
\]

Sivers

Collins

6 further asymmetries
Other Single Spin Asymmetries

Two twist-2 asymmetries can be interpreted in the QCD parton model and will allow to extract unexplored DFs.

The four remaining ones can be interpreted as twist-3 contributions.
Other SSA: Twist-2 - Deuteron

\[ F_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h \]

\[ F_{UT}^{\sin(3\phi_h - \phi_s)} \propto h_{1T}^q \otimes H_{1q}^h \]
Other SSA: Twist-3 - Deuteron

$F_{UT}^{\sin(\phi_s)} \propto \frac{M}{Q} \left( h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h \right)$

$F_{UT}^{\sin(2\phi_h - \phi_s)} \propto \frac{M}{Q} \left( h_1^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h \right)$

→ All those asymmetries are compatible with 0.
Two Hadron Asymmetries
– Proton Data

$\sin \theta$ can be neglected
Two Hadron Asymmetries: Partial Wave Expansion – Proton Data

\[ H^L_h(z, \cos \theta, M_h^2) = H^L_{q,0t}(z, M_h^2) + H^L_{q,lt}(z, M_h^2) \cos \theta \]

A. Bacchetta, hep-ph/0708037

\[ \langle \cos \theta \rangle = 0.01 \]
Small asymmetries are expected:

(Radici/Bacchetta, PRD74(2006)114007)
Λ Polarimetry – Proton Data
Event Selection

- Secondary vertex downstream of primary vertex.
- $P_T > 23$ MeV/c to exclude $e^+e^-$ pairs
- Proton and pion momenta $> 1$ GeV/c
- $Q^2 > 1 \text{ (GeV/c)}^2$
- $0.1 < y < 0.9$
- Use of RICH (2007 data)
- Λ decay distance $D_\Lambda > 7 \sigma_D$
- Collinearity $< 10$ mrad
Λ Polarimetry – Deuteron Data

All 2002–2004 transversity data
$Q^2 > 1 \text{ (GeV/c)}^2$
$0.1 < y < 0.9$

Preliminary

All 2002–2004 transversity data
$Q^2 > 1 \text{ (GeV/c)}^2$
$0.1 < y < 0.9$

Preliminary

All 2002–2004 transversity data

All $Q^2$
$0.1 < y < 0.9$

Preliminary

All 2002–2004 transversity data

All $Q^2$
$0.1 < y < 0.9$

Preliminary