Studies of TMDs at COMPASS

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on behalf of COMPASS

Outline:

- Transversity: single hadrons, hadron pairs, $\Lambda$ baryons
- TMDs: measured with transversely, longitudinally and unpolarized nucleons
COMPASS Detector (muon setup)

- high energy muon beam (160 GeV)
- high intensity \((2 \cdot 10^8 \mu^+ / \text{spill})\)
- naturally polarized (\(\sim 80\%\))
- two stages spectrometer:
  - large angular acceptance \((0 \leq \theta_{lab} \leq 180 \text{ mrad})\)
  - broad kinematical range in \(x\) and \(Q^2\)
COMPASS Polarized Target

$^6$LiD or NH$_3$
50/90 % polarization
40/16 % dilution factor

Polarized Target ($\geq$ 2006)

COMPASS 2007 TRANSVERSE PROTON DATA

$Z_{vtx}$ [cm]
COMPASS 2007 proton data

Hadron identification

- Upgraded in 2005
- Likelihood-based algorithm
- $p_{\pi}^{\text{thr}} \sim 3 \text{ GeV/c}$
- $p_{K}^{\text{thr}} \sim 9 \text{ GeV/c}$
- $p_{p}^{\text{thr}} \sim 17 \text{ GeV/c}$
- $p_{2007}^{\text{max}} = 50 \text{ GeV/c}$
- Purity of the $\pi$ sample $> 99\%$

Purity of the sample

- $x$ vs. $p_T^h$ (GeV/c)

$K^+, K^-$

COMPASS 2007 proton data

purity of $\pi^\pm$ sample $> 99\%$
In leading order three parton distributions are needed to describe the structure of the nucleon:

- **Quark distribution** in unpolarized DIS: $\ell N \rightarrow \ell' X$

- **Helicity distribution** in polarized DIS: $\ell' \vec{N} \rightarrow \ell' X$

- **Transversity distribution** in polarized SIDIS:
  1. $\ell N^\uparrow \rightarrow \ell' hX$  Collins FF
  2. $\ell N^\uparrow \rightarrow \ell' hhX$  Interference FF
  3. $\ell N^\uparrow \rightarrow \ell' \Lambda^\uparrow X$  FF of $q^\uparrow \rightarrow \Lambda^\uparrow$

\[ \Delta q(x) = q^{\uparrow \uparrow}(x) - q^{\uparrow \downarrow}(x) \]

\[ \Delta_T q(x) = q^{\uparrow \uparrow}(x) - q^{\uparrow \downarrow}(x) \]
1. Collins Asymmetry: $\ell \, N^\uparrow \rightarrow \ell' \, hX$

Measuring transversity with Collins-FF $\Delta^0_T D^h_q$:

fragmentation of a transversely polarized quark into an unpolarized hadron

$\sim$ azimuthal asymmetry:

$N_h \propto 1 \pm A \cdot \sin \phi_{Coll}$

$\phi_{Coll} = \phi_h + \phi_S - \pi$

$\phi_h$: azimuthal angle of hadron
$\phi_S$: azimuthal angle of spin of initial quark
1. Collins Asymmetry: $\ell N^\uparrow \rightarrow \ell' hX$

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$A_{\text{Coll}} = \frac{A}{f P_T D_{nn}} \propto \sum q e_q^2 \cdot \Delta_T q \otimes \Delta_T^0 D_q^h$

$f = \text{target dilution}$

$P_T = \text{target polarization}$

$D_{nn} = \frac{1-y}{1-y+y^2} = \text{transverse spin transfer}$
Heiner Wollny (CEA-Saclay Irfu/SPhN)  
GPD 2010, Trento, 10-15 Oct

Collins Asymmetries: $^6$LiD (2003-2004)

![Figure 6: Collins asymmetry against $x$, $z$ and $p_T$ for the “all” charged pions and kaons samples from the 2003–2004 data, and the “all” $K^0_S$’s sample from the 2002–2004 data.](image)

**6 Results and conclusion**

The final results for the Collins and Sivers asymmetries $A_{Coll}$ and $A_{Siv}$ for charged pions and charged and neutral kaons on the deuteron target vs. the three kinematic variables $x$, $z$ and $p_T$ are given in Figs. 6–9.

1) In the figures, the data points for negative hadrons, which are calculated in the same $x$, $z$- and $p_T$-bin as for the positive hadrons, have been slightly shifted for graphical reasons.

Extensive studies to evaluate the size of the systematic error have been performed. For some of these studies the $z$ cut has been opened and the data sample has been enlarged by a factor of three. The measured Collins and Sivers asymmetries were checked against stability among the five different periods of data taking, against the use of different estimators to extract the asymmetries, against the reduction of the fiducial volume of our spectrometer and against the influence of the trigger system of the experiment. In these studies no deviations from the real asymmetries beyond the expected statistical fluctuations was observed. Furthermore experimental false asymmetries have been studied by combining the data set in such a way that the extracted asymmetries are expected to be zero. During all these tests no asymmetries deviating from zero with statistical significance were observed.

1) All the numerical values, including the purities, are available on HEPDATA.

**all asymmetries are small, compatible with zero**

![systematical error: $\sigma_{sys} \leq 0.3 \sigma_{stat}$](image)
Collins Asymmetries: $\text{NH}_3$ (2007)

- Large asymmetries for proton $\sim 10\%$
Collins Asymmetries: \( \text{NH}_3 \) (2007)

- Large asymmetries for proton \( \sim 10\% \)
- Small asymmetries for deuteron
  \( \sim \) cancellation of \( \Delta_T u \) and \( \Delta_T d \)

COMPASS

- COMPASS 2007 proton data

DIS 2010

- positive hadrons
- negative hadrons

PLB 692 (2010), 240

\( \vec{A}^P_{\text{Coll}} \)
Collins Asymmetries for $\pi^\pm$ and $K^\pm$: NH$_3$ (2007)

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COMPASS 2007 proton data

$A^p_{Coll}$

$A^p_{Coll}$
Collins Asymmetries for $\pi^\pm$: NH$_3$ (2007)

Good agreement in overlap region (HERMES results are not $D_{nn}$ corrected)
Collins Asymmetries for $\pi^\pm$: NH$_3$ (2007)

Predictions from fit to COMPASS deuteron, HERMES proton and Belle $e^+e^-$ data

COMPASS 2007 proton data

COMPASS proton data ready to be included in global analysis
Collins Asymmetries for $\pi^{\pm}$: NH\textsubscript{3} (2007)

COMPASS Predictions from fit to COMPASS deuteron, HERMES proton and Belle $e^+e^-$ data

PRELIMINARY

COMPASS proton data ready to be included in global analysis
2. Dihadron Interference: $\ell N^\uparrow \rightarrow \ell' hhX$

Measuring transversity with polarized Dihadron-Interference-FF $H_1^\perp$:

fragmentation of transversely polarized quark into two unpolarized hadrons and rest $X$

$\sim$ azimuthal asymmetry:

$$N_{h^+h^-} \propto 1 \pm A \cdot \sin \phi_{RS} \cdot \sin \theta$$

$$\phi_{RS} = \phi_R + \phi_S - \pi$$
Measuring transversity with polarized Dihadron-Interference-FF $H_1^{<}$:

fragmentation of transversely polarized quark into two unpolarized hadrons and rest $X$

$N_{h^+ h^-} \propto 1 \pm A \cdot \sin \phi_{RS} \cdot \sin \theta$

$\phi_{RS} = \phi_R + \phi_S - \pi$

$\langle \sin \theta \rangle = 0.94$

For this analysis: $\sin \theta$ can be neglected

$h^+ h^-$ cm. frame
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$\left< \sin \theta \right> = 0.94$
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$$\phi_{RS} = \phi_R + \phi_S - \pi$$

$$A_{RS} = \frac{A}{f \, P_T D_{nn}} \propto \sum_q e_q^2 \cdot \Delta_T q \cdot H_1^{\perp}$$

$f = \text{target dilution}$

$P_T = \text{target polarization}$

$D_{nn} = \frac{1-y}{1-y+\frac{y^2}{2}} = \text{transverse spin transfer}$
Dihadron Asymmetries: $^6$LiD (2003-2004)

all asymmetries are small, compatible with zero
Dihadron Asymmetries: \textbf{NH}_3 (2007)

\begin{itemize}
  \item Large asymmetries for proton $\sim 10 \%$
\end{itemize}
Dihadron Asymmetries: NH$_3$ (2007)

COMPASS 2007 transverse proton data

- Large asymmetries for proton $\sim 10\%$

$A_{RS}^{p}$

$\pm h^{-}$ pairs

$x, z, M_{inv}$

COMPASS 2007 transverse proton data

-2 1 10 0.2 0.4 0.6 0.8 0.5 1 1.5 2

-0.1 0 0.1 0.2 0.4 0.6 0.8

20000 30000 40000

COMPASS 2007 preliminary data

$\pm h^{-}$ pairs, $x > 0.032$

$\pm h^{-}$ pairs, $x \leq 0.032$

DIS 2009
Large asymmetries for proton $\sim 10\%$

COMPASS measurement covers much larger range in $x$
Dihadron Asymmetries: \textbf{NH}_3 (2007)

- Large asymmetries for proton $\sim 10\%$

COMPASS 2007 transverse proton data

- COMPASS measurement covers much larger range in $x$

HERMES values scaled with $1/D_{nn}$

COMPASS 2007 transverse proton data - $h^+h^-$ pairs

COMPASS 2007 transverse proton data - $h^+h^-$ pairs, $x > 0.032$

COMPASS 2007 transverse proton data - $h^+h^-$ pairs, $x \leq 0.032$

COMPASS 2007 transverse proton data - $\pi^+\pi^-$ pairs, HERMES, (scaled with $1/D_{nn}$)

COMPASS 2007 transverse proton data - $h^+h^-$ pairs, $x > 0.032$

COMPASS 2007 transverse proton data - $h^+h^-$ pairs, $x \leq 0.032$

COMPASS 2007 transverse proton data - $\pi^+\pi^-$ pairs, HERMES, (scaled with $1/D_{nn}$)
Dihadron Asymmetry: NH$_3$ (2007)

COMPASS 2007 transverse proton data

- $h^+h^-$ pairs
- Bacchetta et al.

COMPASS 2007 transverse proton data

- $h^+h^-$ pairs
- Ma et al.: SU6
- Ma et al.: pQCD, arXiv:0711.0817
Measuring transversity with polarized $\Lambda$-FF $\Delta_T D^\Lambda_q$:

transversely polarized quark transfers its spin to $\Lambda$-Baryon

$\Lambda$-Polarization: $P_\Lambda \propto f P_T D_{nn} \sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T D^\Lambda_q$

measured via parity violating decay
3. Transverse $\Lambda$-Polarization: $\ell \ N^\uparrow \rightarrow \ell' \ \Lambda^\uparrow \ X$

Measuring transversity with polarized $\Lambda$-FF $\Delta_T D^\Lambda_q$:

transversely polarized quark transfers its spin to $\Lambda$-Baryon

$\Lambda$-Polarization: $P_\Lambda \propto f\ P_T D_{nn} \ \sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T D^\Lambda_q$

measured via parity violating decay

![Graphs showing transverse proton data](image_url)
Transverse $\Lambda$-Polarization: $\text{NH}_3$ (2007)

Systematic errors have been estimated to be smaller than statistical errors: $\sigma_{\text{sys}} \leq 0.74 \sigma_{\text{stat}}$

$P_T^\Lambda$, $P_T^{\Lambda}$ small, compatible with zero $\rightarrow$ small analyzing power of $\Delta_T D_q^\Lambda$

$P_T^\Lambda$, $P_T^{\Lambda}$ for deuteron also compatible with zero
Eight parton distribution functions when taking into account $k_{\perp}$
Three parton distribution functions when integrating over $k_{\perp}$
Three parton distribution functions when integrating over $k_{\perp}$

| Nucleon | U | L | T |
|---------|---|---|---|
| U       |   |   |   |
| L       |   |   |   |
| T       |   |   |   |

- Momentum
- Helicity
- Transversity

Quark
Eight parton distribution functions when taking into account $k_\perp$

| Nuclide | U | L | T |
|---------|---|---|---|
| U       |   |   |   |
| L       |   |   |   |
| T       |   |   |   |

- momentum
- helicity
- quark
- Boer-Mulders
- worm-gear LT
- transversity
- pretzelosity
- Sivers
- worm-gear TL
General Expression of polarized SIDIS Cross-Section

\[ \frac{d\sigma}{dx dy d\psi dz dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} \right. \\
+ \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin\phi_h F_{LU}^{\sin\phi_h} \\
+ S_\parallel \left[ \sqrt{2\varepsilon(1+\varepsilon)} \sin\phi_h F_{UL}^{\sin\phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin 2\phi_h} \right] \\
+ S_\perp \lambda_e \left[ \sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_h F_{LL}^{\cos\phi_h} \right] \left\} \right. \\
+ |S_\perp| \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)} \right) \\
+ \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)} \\
+ \sqrt{2\varepsilon(1+\varepsilon)} \sin\phi_S F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h-\phi_S)} \\
+ |S_\perp| \lambda_e \left[ \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_S F_{LT}^{\cos\phi_S} \right] \\
\left. + \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h-\phi_S)} \right\}, \]
SIDIS Cross-Section: Transversely Polarized Target

\[
\frac{d\sigma}{dx \, dy \, d\psi \, dz \, d\phi_h \, dP_{h\perp}^2} = \alpha^2 \frac{y^2}{xyQ^2} \frac{1}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ \ldots \right\}
\]

\[
+ |S_\perp| \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right)
\]

\[
+ \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)}
\]

\[
+ \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_S F_{UT}^{\sin \phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)}
\]

\[
+ |S_\perp| \lambda_e \left[ \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_S F_{LT}^{\cos \phi_S} \right]
\]

\[
+ \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right\}
\]

A. Bacchetta et al
JHEP 0702:093, 2007
E-print number: hep-ph/0611265
SIDIS Cross-Section: Transversely Polarized Target

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

Collins \(\checkmark\)

Figure 1: Definition of azimuthal angles and their respective notation in the text.

A. Bacchetta et al, JHEP 0702:093, 2007

E-print number: hep-ph/0611265
\[
\frac{d\sigma}{dx \; dy \; d\psi \; dz \; d\phi_h \; dP^2_{h\perp}} = \frac{\alpha^2}{x y Q^2} \frac{y^2}{2 (1 - \varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ \ldots \right. \\
+ |S_\perp| \left[ \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \\
+ \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \\
+ \sqrt{2\varepsilon(1 + \varepsilon)} \sin \phi_S F_{UT}^{\sin(\phi_S)} + \sqrt{2\varepsilon(1 + \varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \\
+ |S_\perp| \lambda_e \left[ \sqrt{1 - \varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\varepsilon(1 - \varepsilon)} \cos \phi_S F_{LT}^{\cos \phi_S} \\
+ \sqrt{2\varepsilon(1 - \varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right] \right\} 
\]
Sivers Asymmetry

\[ F_{UT,T}^{\sin(\phi_h-\phi_S)} \propto \Delta_0^T q \otimes D_q^h \]

Sivers PDF \( \Delta_0^T q \): correlation between intrinsic transverse momentum of the quarks and the transverse polarization of the nucleon
Sivers Asymmetry

\[ F_{UT,T}^{\sin(\phi_h-\phi_S)} \propto \Delta_0^T q \otimes D_q^h \]

Sivers PDF \( \Delta_0^T q \): correlation between intrinsic transverse momentum of the quarks and the transverse polarization of the nucleon

\[ \sim \text{azimuthal asymmetry:} \]

\[ N_h \propto 1 \pm A \cdot \sin(\phi_h - \phi_S) \]

\( \phi_h \): azimuthal angle of hadron

\( \phi_S \): azimuthal angle of spin of initial quark
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\[ N_h \propto 1 \pm A \cdot \sin(\phi_h - \phi_S) \]

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\( \phi_S \): azimuthal angle of spin of initial quark

\[ A_{Siv} = \frac{A}{f P_T} \propto \sum_q e_q^2 \cdot \Delta_0^T q \otimes D_q^h \]
Sivers Asymmetries: $^6$LiD (2003-2004)

Heiner Wollny (CEA-Saclay Irfu/SPhN)

Figure 7: Sivers asymmetry against $x$, $z$ and $p_T$ for the "all" charged pions and kaons samples from the 2003–2004 data, and "all" $K^0_S$'s sample from the 2002–2004 data.

Significance was observed. Also, the correlation between the measured Collins and Sivers asymmetries which originates from the non-uniform $\phi_h/\phi_S$ acceptance of the spectrometer has been studied and the corresponding systematic error has been evaluated to be negligible as compared with the statistical error. The smallness of the asymmetries makes the systematic error due to the uncertainties on $P_T$ and $f_{tot}$ totally negligible. These studies altogether lead to the final conclusion that the systematic errors are considerably smaller (well below 30%) than the statistical errors.

All the measured asymmetries are small, a trend which was already observed in the published data of the non-identified hadrons. Small asymmetries are not a surprise, it was expected that transverse spin effects be small in the deuteron due to the opposite sign which was predicted for the u- and d-quark distributions, very much like in the helicity case.

The interpretation of the results on the deuteron can be done only in conjunction with corresponding proton data, measured by the HERMES Collaboration albeit at lower energy. Proton target data have been collected by COMPASS in 2007, but the results are not final at the time of writing. As shown in Refs. [8,11] a simple analysis of the HERMES charged pion data and of the non-identified charged hadron data in COMPASS, assuming that all the hadrons are pions, led to the following conclusions:

1. The favoured and unfavoured Collins functions have about the same size and the COMPASS deuteron data are needed for the extraction of the d-quark transversity;
2. The null result for the Sivers asymmetry for the COMPASS data is a clear indication of the d-quark transversity;

Systematical error: $\sigma_{sys} \leq 0.3 \sigma_{stat}$

All asymmetries are small, compatible with zero.
positive asymmetry for $h^+$

asymmetry for $h^-$ small, compatible with zero

for $h^+$ additional absolute systematical uncertainty of $\pm 0.01$
Sivers Asymmetries: $\text{NH}_3$ (2007)

For $h^+$ additional absolute systematical uncertainty of $\pm 0.01$

- Positive asymmetry for $h^+$
- Asymmetry for $h^-$ small, compatible with zero
- Small asymmetries for deuteron
  $\sim$ opposite sign of $\Delta_0^T u$ and $\Delta_0^T d$
Sivers Asymmetries for $\pi^\pm$ and $K^\pm$: $\text{NH}_3$ (2007)

**COMPASS 2007 proton data**

**preliminary**

**new**

**new**
Sivers Asymmetries: $\text{NH}_3$ (2007)

**COMPASS 2007 proton data**

- Preliminary results from COMPASS and HERMES (PRL 103 (2009))
- Possible $W$ dependence

**COMPASS 2007 transverse proton data**

- Charged hadrons
- Charged $\pi$
- Charged $K$

Heiner Wollny (CEA-Saclay Irfu/SPhN)
SIDIS Cross-Section: transversely polarized target

\[
\frac{d\sigma}{dx
dy
d\psi
dz
d\phi_h
dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ \ldots \right\}
\]

\[ + |S_\perp| \left[ \sin (\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)} \right) \right. \]
\[ + \varepsilon \sin (\phi_h + \phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon \sin (3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)} \]
\[ + \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_S F_{UT}^{\sin \phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin (2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h-\phi_S)} \]
\[ + |S_\perp| \lambda_e \left[ \sqrt{1-\varepsilon^2} \cos (\phi_h - \phi_S) F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_S F_{LT}^{\cos \phi_S} \right. \]
\[ + \sqrt{2\varepsilon(1-\varepsilon)} \cos (2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h-\phi_S)} \right\},
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+ |S_\perp| \left[ \sin(\phi_h - \phi_S) \left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)} \right) \right. \\
+ \epsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \epsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)} \\
+ \sqrt{2\epsilon(1+\epsilon)} \sin\phi_S F_{UT}^{\sin\phi_S} + \sqrt{2\epsilon(1+\epsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h-\phi_S)} \\
+ |S_\perp|\lambda_e \left[ \sqrt{1-\epsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)} \cos\phi_S F_{LT}^{\cos\phi_S} \\
+ \sqrt{2\epsilon(1-\epsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h-\phi_S)} \right] \right\},
\]

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Heiner Wollny (CEA-Saclay Irfu/SPhN)
Pretzelosity

\[ F_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T}^{\perp,q} \otimes \Delta_T^0 D_q^h, \]

Pretzelosity PDF \( h_{1T}^{\perp,q} \): correlation of parton transverse momentum and transverse polarization in a transversely polarized nucleon.
Pretzelosity: NH$_3$ (2007)

$$F_{UT}^{3\phi_h-\phi_S} \propto h_{1T}^\perp \Delta_T^0 D_q^h,$$

Pretzelosity PDF $h_{1T}^\perp$:

correlation of parton transv. momentum and transv. polarization in a transversely polarized nucleon

$A_{UT}^{\sin(3\phi_h-\phi_S)}$

- positive
- negative

$all \ hadrons$

COMPASS 2007 proton data

new

COMPASS

Proton
Pretzelosity: \( \text{NH}_3 \text{ (2007)} \) & \( ^6\text{LiD (2002-2004)} \)

\[
F_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T}^{\perp,q} \otimes \Delta_T^0 D_q^h,
\]

Pretzelosity PDF \( h_{1T}^{\perp,q} \):

correlation of parton transv. momentum and transv. polarization in a transversely polarized nucleon

\[
\begin{align*}
\sin(3\phi_h-\phi_S) & \quad h_{1T}^{\perp,q} \otimes \Delta_T^0 D_q^h,
\end{align*}
\]
Worm-gear (TL)

\[ F_{LT}^{\cos(\phi_h - \phi_S)} \propto g_{1T}^q \otimes D_h^q, \]

worm-gear PDF \( g_{1T}^q \):

correlation of parton transverse momentum and longitudinal polarization in a transversely polarized nucleon
Worm-gear (TL): \( NH_3 (2007) \)

\[
F_{LT}^{\cos (\phi_h - \phi_s)} \propto g_1^q \otimes D_h^q,
\]

worm-gear PDF \( g_1^q \):

correlation of parton transv. momentum and long. polarization in a transversely polarized nucleon
Worm-gear (TL): $\text{NH}_3$ (2007) & $^6\text{LiD}$ (2002-2004)

$F_{LT}^{\cos(\phi_h-\phi_S)} \propto g_{1T}^q \otimes D_h^q,$

worm-gear PDF $g_{1T}^q$:
correlation of parton transv. momentum and long. polarization in a transversely polarized nucleon

$F_{LT}^{\cos(\phi_h-\phi_S)} \propto g_{1T}^q \otimes D_h^q,$

worm-gear PDF $g_{1T}^q$:
correlation of parton transv. momentum and long. polarization in a transversely polarized nucleon
Twist-3 Structure Functions: $NH_3$ (2007)

COMPASS 2007 proton data
COMPASS all hadrons

$A_{LT}^\sin\phi_S$

$A_{LT}^\cos\phi_S$

$A_{UT}^\sin(2\phi_h - \phi_S)$

$A_{UT}^\cos(2\phi_h - \phi_S)$
\[
\frac{d\sigma}{dx \, dy \, d\psi \, dz \, d\phi_h \, dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} \\
+ \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} \right\}
\]

- \( F_{UU}^{\cos \phi} \) and \( F_{UU}^{\cos 2\phi} \): Cahn Effect + Boer-Mulders (+ pQCD)
- \( F_{LU}^{\sin \phi_h} \): beam asymmetry (beam polarization: \( P_{\mu^+} \approx -80\% \))
SIDIS Cross-Section: unpolarized target

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

Cahn Effect
kinematical effect due to transv. momentum of partons in the nucleon

- \( F_{UU}^{\cos \phi} \) and \( F_{UU}^{\cos 2\phi} \): Cahn Effect + Boer-Mulders (+ pQCD)
- \( F_{LU}^{\sin \phi} \): beam asymmetry (beam polarization: \( P_{\mu^+} \approx -80\% \))

A. Bacchetta et al
JHEP 0702:093, 2007
E-print number: hep-ph/0611265
\[
\frac{d\sigma}{dx
dy
d\psi
dz
d\phi_h
dP^{2}_{h\perp}} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} \\
+ \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin\phi_h F_{LU}^{\sin\phi_h} \right\}
\]

- **Cahn Effect**: kinematical effect due to transverse momentum of partons in the nucleon

- **Boer-Mulders** \(h^\perp_1\): correlation of parton transverse momentum and transverse polarization in an unpolarized nucleon

- \(F_{UU}^{\cos\phi}\) and \(F_{UU}^{\cos 2\phi}\): Cahn Effect + Boer-Mulders (+ pQCD)

- \(F_{LU}^{\sin\phi_h}\): beam asymmetry (beam polarization: \(P_{\mu^+} \approx -80\%\))
SIDIS Cross-Section: unpolarized target

\[
\frac{d\sigma}{dx dy d\psi dz d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} \right\}
\]

Cahn Effect

kinematical effect due to transv. momentum of partons in the nucleon

\[\sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h}\]

\[\varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h}\]

\[\lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h}\]

Boer-Mulders \(h_\perp^T\):

correlation of parton transv. momentum and transv. polarization in an unpolarized nucleon

\[\pm \text{pQCD}\]

\[F_{UU}^{\cos \phi}\text{ and } F_{UU}^{\cos 2\phi}: \text{Cahn Effect } + \text{ Boer-Mulders}\]

\[F_{LU}^{\sin \phi_h}: \text{beam asymmetry } \text{(beam polarization: } P_{\mu^+} \approx -80\%)\]

Target polarization canceled by event weighting

Detector acceptance corrected by MC simulation
Unpolarized Asymmetries: \(^6\text{LiD (2004 part)}\)

\[ A_{UU}^{\cos \phi} : \text{Mainly Cahn effect} \]

- Large negative asymmetries
- Charge dependent

COMPASS \(^6\text{LiD (25\% of 2004 data)}\)

Heiner Wollny (CEA-Saclay Irfu/SPhN)  GPD 2010, Trento, 10-15 Oct
Unpolarized Asymmetries: $^6\text{LiD (2004 part)}$

$A_{UU}^{\cos 2\phi}$: Boer-Mulders TMD $+\text{Cahn } \propto \left(\frac{k_{\perp}}{Q}\right)^2$

$\nabla$ Large positive asymmetries

$\nabla$ Charge dependent
Unpolarized Asymmetries: $^{6}\text{LiD (2004 part)}$

$A_{\sin \phi}^{LU}$: twist-3 effect due to beam polarization

- $h^+$ positive asymmetry
- $h^-$ small asymmetry, compatible with zero
Many new results from COMPASS:

- **Collins asymmetries** for $\pi^\pm$ and $K^\pm$ for deuteron and proton target
  - New proton results ready to be used in a global analysis

- **Dihadron asymmetries** for deuteron and proton target
  - Ultimate cross-check for Transversity extraction

- **Sivers asymmetries** for $\pi^\pm$ and $K^\pm$ for deuteron and proton target
  - New proton results ready to be used in a global analysis

- **Large azimuthal asymmetries** of charged hadrons produced scattering off unpolarized deuterons
Many new results from COMPASS:

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  - New proton results ready to be used in a global analysis

- **Large azimuthal asymmetries** of charged hadrons produced scattering off unpolarized deuterons

**COMPASS is a major player in nucleon spin physics**
One full year with transverse data taking has nearly finished.
COMPASS-II proposal approved by SPSC

... proposal for two years GPD and two years DY ...

\[ \pi P^\uparrow \rightarrow \mu \bar{\mu} X \]

Predictions and expected statistical errors (2 GeV/c^2 < M_{\mu\mu} < 2.5 GeV/c^2)
Thank You

email: heiner.wollny@cern.ch
Back Up
230 physicists, 10 countries, 25 institutes
Measuring transversity with polarized Dihadron-Interference-FF $H_{1}^{\triangleleft}$:

$N_{h^+h^-} \propto 1 \pm A \cdot \sin \phi_{RS} \cdot \sin \theta$

$\phi_{RS} = \phi_R + \phi_S - \pi$

$A_{RS} = \frac{A}{f} \frac{P_T D_{nn}}{D_{nn}} \propto \sum_q e_q^2 \cdot \Delta_T q \cdot H_{1}^{\triangleleft}$

$H_{1}^{\triangleleft} = H_{1}^{\triangleleft,sp} + \cos \theta H_{1}^{\triangleleft,pp}$

$\langle \cos \theta \rangle = 0.01$
Definition of $R_T$ and $\phi_R$

$$R_T = \frac{z_2 P_{1T} - z_1 P_{2T}}{z_1 + z_2}$$

$$\cos \phi_R = \frac{\vec{q} \times \vec{\ell}}{|\vec{q} \times \vec{\ell}|} \cdot \frac{\vec{q} \times \vec{R}_T}{|\vec{q} \times \vec{R}_T|},$$

$$\sin \phi_R = \frac{(\vec{\ell} \times \vec{R}_T) \cdot \hat{q}}{|\hat{q} \times \vec{\ell}||\hat{q} \times \vec{R}_T|}$$
Transverse $\Lambda$-Polarization: $^6\text{LiD (2002-2004)}$

- Number of $\Lambda$: ~45000
- $Q^2 > 1 \text{ (GeV/c)}^2$
- $0.1 < y < 0.9$

- Number of $\bar{\Lambda}$: ~25000
- $Q^2 > 1 \text{ (GeV/c)}^2$
- $0.1 < y < 0.9$

Systematical errors are smaller than the statistical ones.
The Collins modulation

The Sivers modulation

Charged hadrons

Identified hadrons

Conclusions

Predictions from fit to COMPASS deuteron and HERMES proton SIDIS data:

— Anselmino et al, *Eur. Phys. J. A39* (2009)
Twist-3 Structure Functions: $^6\text{LiD}$ (2002-2004)

COMPASS
Deuteron

$A^\sin \phi_S$ vs. $x$

$A^\cos \phi_S$ vs. $x$

$A^\sin(2\phi_h-\phi_S)$ vs. $x$

$A^\cos(2\phi_h-\phi_S)$ vs. $x$
\[ \frac{d\sigma}{dx\;dy\;d\psi\;dz\;d\phi_h\;dP^2_{h\perp}} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1 - \varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ \ldots \right\} \\
+ S_{||} \left[ \sqrt{2\varepsilon(1 + \varepsilon)} \sin\phi_h F_{UL}^{\sin\phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin 2\phi_h} \right] \\
+ S_{||} \lambda_e \left[ \sqrt{1 - \varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1 - \varepsilon)} \cos\phi_h F_{LL}^{\cos\phi_h} \right] \]
2) The sign of HERMES data was inverted in order to correspond to our definition of spin asymmetry by Eq. (4).

Data with those of the present analysis demonstrates the internal consistency of the results.

Figure 6: The amplitudes of the \( \sin(2\phi) \) and \( \cos(\phi) \), for \( h^\pm \) COMPASS 

Dependence of the asymmetry parameter on the kinematical variables. The dependence of this parameter does not depend on \( z \) that is approximately \( \perp \) to the target plane. 

The amplitudes of the \( \sin(3\phi) \) for \( h^\pm \) COMPASS, \( h^\pm \) HERMES are mostly negative, as for the COMPASS deuteron. The agreement of these data taken in 2002–2004 has been checked by building distributions of "pulls" 

\[ a_{\text{const}} = \frac{D_0}{A_d} \] 

\[ a_{\sin} = \frac{A^h_d}{D_0} \] 

\[ a_{\cos} = \frac{G^h_d}{D_0} \] 

Publication is on the way
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