Transverse spin physics at COMPASS

Federica Sozzi
Trieste University and INFN Trieste
on behalf of the COMPASS collaboration

Outline
• Transversity measurements at COMPASS
  • Collins effect
  • hadron pair asymmetry
• Sivers effect
• Prospects at COMPASS
Transversity

At leading order, the inner structure of the nucleon can be described with three Parton Distribution Function (PDF):

- \( q(x) \) momentum distribution: describes the probability of finding a quark with a fraction \( x \) of the nucleon momentum;

- \( \Delta q(x) \) helicity distribution: describes the probability, in a longitudinal polarized nucleon (w.r.t. the direction of motion), of finding a quark with spin parallel to the nucleon spin;

- \( \Delta_T q(x) \) transversity distribution: describes the probability, in a transversely polarized nucleon (w.r.t. the direction of motion), of finding a quark with spin parallel to the nucleon spin;
Transversity in SIDIS

the Transversity DF is chiral-odd:

observable effects are given only by the product of $\Delta_T q(x)$ and an other chiral-odd function

can be measured in SIDIS on a transversely polarized target via “quark polarimetry”
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can be measured in SIDIS on a transversely polarized target
via “quark polarimetry”

$I N^\uparrow \rightarrow I' h X$  “Collins” asymmetry
  “Collins” Fragmentation Function
$I N^\uparrow \rightarrow I' h h X$  hadron-pair asymmetry
  “Interference” Fragmentation Function
$I N^\uparrow \rightarrow I' \Lambda X$  $\Lambda$ polarisation
  Fragmentation Function of $q^\uparrow \rightarrow \Lambda$

....

All these channels measured at COMPASS
COMPASS spectrometer 2002-2004

- Longitudinally polarised muon beam
- Longitudinally or transversely polarised deuteron ($^6$LiD) target
- Momentum and calorimetry measurement
- Particle identification

- Luminosity: $5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- Beam intensity: $2 \cdot 10^8 \mu^+/$spill (4.8s/16.8s)
- Beam momentum: 160 GeV/c
The COMPASS polarized target

solid state target operated in frozen spin mode

2002-2004 data taking:
- target material: $^6\text{LiD}$
  - polarization ~ 50%
  - dilution factor ~ 0.38

2007: Data taking with a transversely polarised proton target ($\text{NH}_3$)

$^3\text{He} - ^4\text{He}$ Dilution refrigerator (T~50mK)

superconductive Solenoid (2.5 T) Dipole (0.5 T)

two 60 cm long cells with opposite polarization (to reduce systematics)
The COMPASS polarized target

solid state target operated in frozen spin mode

2002-2004 data taking:
- target material: $^6\text{LiD}$
  - polarization $\sim 50\%$
  - dilution factor $\sim 0.38$

- $^3\text{He} - ^4\text{He}$ Dilution refrigerator (T~50mK)
- superconductive Solenoid (2.5 T)
- Dipole (0.5 T)

2 configurations:
- reversed once a week (relaxation time $> 2000$h)
Data selection

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

hadron selection:
• $z > 0.2$
  
  (z>0.25 for leading hadron selection)
• $p_t > 0.1 \text{GeV/c}$

Statistics 2002 - 2004:
8.5 M positive hadrons
7.0 M negative hadrons
Collins asymmetries 2002-2004 data

$\Phi_C = \phi_h - \phi_s'$ is the “Collins angle”

$$A_{Coll} = \frac{A_C^h}{f \cdot P_T \cdot D_{nn}} = \frac{\sum q e_q^2 \Delta_T \cdot q \cdot \Delta^0 D^h_q}{\sum q e_q^2 \cdot q \cdot D^h_q}$$

Information on Collins FF from Belle


**Collins asymmetries 2002-2004 data**

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\[ A_{Coll} = \frac{A^h_C}{f \cdot P_T \cdot D_{nn}} = \frac{\sum e_q^2 \cdot \Delta_T \cdot \Delta^{0}_T \cdot D_{q}^h}{\sum e_q^2 \cdot q \cdot D_{q}^h} \]

[Graph showing Collins asymmetry vs. various variables like $x_{Bj}$, $z$, and $p_t$]

- only statistical errors shown (systematic errors considerably smaller)
- small asymmetries

Final Results
all deuteron data

*NP B765 (2007) 31-70*
• na"ive interpretation of the results (parton model, valence region)

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

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

Small asymmetries $\Rightarrow \Delta_T u(x) + \Delta_T d(x) \sim 0$
Interpretation

- naïve interpretation of the results (parton model, valence region)

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Small asymmetries \(\Rightarrow \Delta_T^u (x) + \Delta_T^d (x) \sim 0\)
expected even if \(\Delta_T^0 D_2 \approx -\Delta_T^0 D_1\)
suggested by data on proton target – HERMES experiment

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

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

Small asymmetries \(\Delta_T u (x) + \Delta_T d (x) \approx 0\)

expected even if \(\Delta_T^0 D_2 \approx -\Delta_T^0 D_1\)

suggested by data on proton target – HERMES experiment

SIDIS measurements allow flavor separation analysis

\(\rightarrow\) Hadron identification is important
Charged hadrons:

\[ \pi^\pm, K^\pm \]

based on RICH response (likelihood algorithm)

Cherenkov thresholds

\[
\begin{align*}
\pi &\sim 3 \text{ GeV/c} \\
K &\sim 9 \text{ GeV/c} \\
p &\sim 17 \text{ GeV/c}
\end{align*}
\]
Hadron identification

Charged hadrons: $\pi^\pm K^\pm$

based on RICH response (likelihood algorithm)

Neutral kaons $K^0$

- Secondary vertex with 2 outgoing tracks with opposite charge
- Target pointing ($\theta < 10\text{mrad}$)
- Cut on Armenteros plot ($p_T^h > 25\text{ MeV/c}$)
**Hadron identification**

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- \( |M_{\text{inv}} - M_{K^0}| < 20 \text{ MeV/c}^2 \)

\[ S/B \sim 15 \]
Hadron identification

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<table>
<thead>
<tr>
<th>Statistics 2003-2004:</th>
<th>positive</th>
<th>negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi )</td>
<td>5.2M</td>
<td>4.5M</td>
</tr>
<tr>
<td>( K )</td>
<td>0.9M</td>
<td>0.6M</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Statistics 2002-2004:</th>
<th>( K^0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.26M</td>
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</tbody>
</table>
Collins asymmetries $\pi^\pm K^\pm$

- only statistical errors shown (systematic errors considerably smaller)
- small asymmetries

Final Results
all deuteron data
Collins asymmetries $K^0$

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- small asymmetries

Final Results
all deuteron data
hep-ex/0802.2160
(subm. PLB)
Two Hadrons Asymmetries

in inclusive production of hadron pairs, one can define the angle $\phi_{R\perp}$ and measure an azimuthal asymmetry from the modulation of the number of events in $\phi_{RS} = \phi_{R\perp} - \phi_s$.

$$N^{\pm}(\Phi_{RS}) = N^0 \cdot \left\{ 1 \pm A \cdot \sin \Phi_{RS} \right\}$$

$$A_{RS} = \frac{1}{f \cdot P_T \cdot D} \cdot A = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot H_q^\perp(z, M_n^2)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z, M_n^2)}$$

A. Bacchetta, M. Radici, hep-ph/0407345
X. Artru, hep-ph/0207309

Interference fragmentation function presently unknown, being measured at BELLE
Two Hadrons Asymmetries

2 different analysis:
1) **hadron pairs ordered with charge**:

<table>
<thead>
<tr>
<th></th>
<th>without PID</th>
<th>( \pi^+ \pi^- )</th>
<th>( \pi^+ K^- )</th>
<th>( K^+ \pi^- )</th>
<th>( K^+ K^- )</th>
</tr>
</thead>
<tbody>
<tr>
<td>total</td>
<td>5.3*10^6</td>
<td>3.7*10^6</td>
<td>2.4*10^5</td>
<td>3.0*10^5</td>
<td>8.7*10^4</td>
</tr>
</tbody>
</table>

Different hadron combination \( \rightarrow \) different invariant mass spectra
Two Hadrons Asymmetries

2) **z-ordered pairs**: select in the event the two hadrons with the highest relative energy $z$:

   
   for leading hadron pairs the signal enhancement is predicted, hadrons with higher energy carry more information about the fragmenting quark polarization

   
   16 combinations, 4 particle combinations times 4 charge combinations
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for leading hadron pairs the signal enhancement is predicted, hadrons with higher energy carry more information about the fragmenting quark polarization

16 combinations, 4 particle combinations times 4 charge combinations
Two Hadrons Asymmetries

K/π and π/K with opposite charge

K/π and π/K with same charge

COMPASS 2003-2004

Preliminary

Leading K/π+ pairs
Leading π/K+ pairs

Leading K/π− pairs
Leading π/K− pairs

D1009
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The Sivers DF $\Delta_0^T q$ is probably the most famous between TMDs… gives a measure of the correlation between the intrinsic transverse momentum of unpolarized quarks in a transversely polarized nucleon.

In SIDIS the number of produced hadrons depend on the “Sivers angle”:

$$N_h^\pm(\Phi_s) = N_h^0 \cdot \left\{ 1 \pm A_S^h \cdot \sin \Phi_s \right\}$$

$$\Phi_s = \phi_h - \phi_s$$

$$A_{Siv} = \frac{A_S^h}{f \cdot P_T} = \frac{\sum q e_q^2 \Delta_0^T q \cdot D_q^h}{\sum q e_q^2 \cdot q \cdot D_q^h}$$
Sivers asymmetries $\pi^\pm \ K^\pm$

COMPASS: 2003-2004

Final Results
all deuteron data
hep-ex/0802.2160
(subm. PLB)

- only statistical errors shown (systematic errors considerably smaller)
- Small asymmetries
Sivers asymmetries $K^0$

- only statistical errors shown (systematic errors considerably smaller)
- Small asymmetries
Interpretation

- naïve interpretation of COMPASS data (parton model, valence region)

\[
A^{d, \pi^+}_{SiV} \simeq A^{d, \pi^-}_{SiV} \simeq \frac{\Delta^T_0 u_v + \Delta^T_0 d_v}{u_v + d_v}
\]

Small asymmetries suggest
\[
\Delta^T_0 d_v \simeq -\Delta^T_0 u_v
\]

- the measured asymmetry on deuteron compatible with zero has been interpreted as

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

S.J. Brodsky and 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.
Other single spin asymmetries

In the complete SIDIS cross section more terms are present:
18 structure functions, 8 transverse target dependent spin asymmetries with different azimuthal dependences

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

\[ f^{q\perp}_{1T} \otimes D^{h}_{1q} \]

\[ h^{q}_{1} \otimes (H^{h}_{1q}) \]

All 8 asymmetries measured at COMPASS

From A. Bacchetta et al.,
Other single spin asymmetries

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

\[
+ |S_\perp| \left[ \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) + \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \right]
\]

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

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

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

\[
f_{1T}^{q} \otimes D_{1q}^h
\]

\[
h_{1}^{q} \otimes H_{1q}^{h}
\]

Sivers function

Collins function

All 8 asymmetries measured at COMPASS

moreover results on Cahn asymmetries coming soon

From A. Bacchetta et al.,
Conclusions

Full set of measurements on the data collected on a deuterium target in 2002-2004, analysis finalized
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Full set of measurements on the data collected on a deuterium target in 2002-2004, analysis finalized

In 2007 COMPASS data taking with a NH$_3$ target, 50% of the time dedicated to transverse measurements. Major spectrometer improvement:
• larger acceptance (from 70 to 180 mrad),
• upgraded RICH (higher efficiency, better response)

First results coming soon ...
Conclusions

Full set of measurements on the data collected on a deuterium target in 2002-2004, analysis finalized

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First results coming soon ...

Longer terms project (after 2010)
 Plans for
• Precision SIDIS measurements for flavor separation
• Drell-Yan measurements (first test done during 2007 data taking)
backup
Other single spin asymmetries

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

Remaining four can be interpreted as twist-3 contributions

All asymmetries measured for the first time, found compatible with zero: again cancellation between proton and neutron?
Lambda asymmetries

Information on $\Delta_T q$ can be accessed in the processes:

$$\mu \, N^\uparrow \rightarrow \mu' \, \Lambda \, X$$

$$\mu \, N^\uparrow \rightarrow \mu' \, \bar{\Lambda} \, X$$

$$P_{T, \text{exp}}^\Lambda = \frac{d\sigma_{\mu N^\uparrow \rightarrow \mu' \Lambda^\uparrow X} - d\sigma_{\mu N^\uparrow \rightarrow \mu' \bar{\Lambda}^\uparrow X}}{d\sigma_{\mu N^\uparrow \rightarrow \mu' \Lambda^\uparrow X} + d\sigma_{\mu N^\uparrow \rightarrow \mu' \bar{\Lambda}^\uparrow X}}$$

$$= \sum_q e_q^2 \Delta_T q(x) \Delta_T D_{\Lambda/q}(z)$$

$$= f P_N D(y) \sum_q e_q^2 q(x) D_{\Lambda/q}(z)$$

$\Lambda$ polarization axis

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systematic errors not larger than statistical errors
RICH ID not used yet; some other improvement in selection still foreseen
Selection 2h

\[ \vec{R} = \frac{z_1 \vec{p}_2 - z_2 \vec{p}_1}{z_1 + z_2} \]

DIS cuts:

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

Hadron selection:

- \( z_{1,2} > 0.1 \) (current fragmentation)
- \( x_{F1,2} > 0.1 \)
- \( z_1 + z_2 < 0.9 \) (exclusive rho)
- RICH identification of \( \pi, K \)
sinθ dependance

Cross section $\sigma_{UT}$ for two-π fragmentation depends on $\sin\theta$:
(Interference of s- and p-wave of the 2π-state)

$$\sigma_{UT} \propto \sum_q e_q^2 |S_T| \sin\theta \sin\phi_{RS} \Delta_T q(x) H_q^\perp (z, M_h^2)$$

(A. Bacchetta and M. Radici, hep-ph/0212300)

$\theta$ : Angle of $h_1$ in the two-hadron CMS to the direction of $P_h = P_{h1} + P_{h2}$

$<\sin\theta> = 0.95$

$<\sin\theta> = 0.90$

⇒ small contribution in the kinematic region of COMPASS
Two hadron asymm.s

Expected Small

\( A_{RS} \)

\( M_{inv} [GeV/c^2] \)

\( A_{RS} \)

\( z \)

\( M_R (GeV) \)

\( A_{UT}^{\sin(\phi_R + \phi_S)} \)

Radici/Bacchetta, PRD74(2006)114007

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DIS08
Motivations:

- Hard exclusive meson production (HEMP) is a way, complementary to DVCS, to access GPDs
- Vector mesons Transverse Target Single Spin Asymmetry $A_{UT}(\phi_h, \phi_S)$ connected to GPD $E$

\[ \frac{1}{2} \sum_q \int_{-1}^{+1} dx x (H^q(x, \xi, t = 0) + E^q(x, \xi, t = 0)) = J^{\text{quark}} \]

- $E$ allows flip of proton helicity, while quark helicity is not flipped $\rightarrow$ overall helicity is not conserved
- angular momentum conservation implies transfer of orbital angular momentum
Selection

Besides standard DIS cuts:

• $Q^2 > 1 \text{ GeV}^2/c^2$
• $0.1 < y < 0.9$
• $W > 5 \text{ GeV/c}^2$

Exclusive $\rho$ selection:

• only 3 outgoing particles $\mu$, $\pi^+$, $\pi^-$
• $0.01 < p_T^2 < 0.5 \left[(\text{GeV/c})^2\right]$ 
• missing energy $-2.5 \text{ GeV} < E_{\text{miss}} < 2.5 \text{ GeV}$
• Inv. Mass $-0.3 \text{ MeV/c}^2 < M_{\pi\pi} - M_\rho < 0.3 \text{ MeV/c}^2$

DIS08
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Results

COMPASS transverse $\rho^0$ analysis on 2002-2004 $^3$LiD data

- $A_{UT}$ vs $p_\perp$ [GeV/c]
- $A_{UT}$ vs $-t'$ [(GeV/c)$^2$]
- $A_{UT}$ vs $Q^2$ [(GeV/c)$^2$]

preliminary
Data taking and stability of the data

Look for very small effects
→ data stability is a crucial issue

Many tests done to check the data stability:
• monitor the stability in time of reconstructed $K^0$ mass and RMS, $K^0$ multiplicity
• spectrometer time stability
• stability of kinematical variables

Other specific tests for RICH detector