Transverse Spin and Momentum effects in the COMPASS Experiment

Giulio Sbrizzai
Trieste University and INFN
on behalf of the COMPASS Collaboration

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OUTLINE

- The COMPASS experiment
- SIDIS
  - Hadron azimuthal asymmetries
    - unpolarized target
    - transversely polarized target
  - Two hadrons azimuthal asymmetries
- Conclusions and outlook
Fixed target experiment at CERN SPS approved in 1997 with a broad physics programme

- **muon beam:**
  - nucleon spin structure
  - $\Delta G/G$
  - helicity distributions
  - transverse spin effects
  - $\Lambda$ physics
  - $\rho^0$ production
  - ...

- **hadron beam:**
  - hadron spectroscopy
  - search for exotics
  - central production
  - diffractive production
  - pion/kaon polarizabilities
  - ...

**Common Muon and Proton Apparatus for Structure and Spectroscopy**
Data taking since 2002

<table>
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<tr>
<th>muon beam</th>
<th>deuteron ($^6$LiD)</th>
<th>2002</th>
<th>L/T target polarization</th>
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<td>polarized target</td>
<td>2003</td>
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<td>proton</td>
<td>(NH$_3$)</td>
<td>2007</td>
<td>L/T target polarization</td>
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<td></td>
<td>polarized target</td>
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hadron beam | LH target          | 2008 |
            |                    | 2009 |

**longitudinally polarised muon beam**

- beam intensity: $2 \times 10^8 \mu^+$/spill (4.8s/16.2s)
- beam momentum: **160 GeV/c**
- luminosity: $\sim 5 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
The COMPASS Spectrometer – muon beam

built to cover a large kinematical range

two stage spectrometer:
• Large Angle Spectrometer (SM1)
• Small Angle Spectrometer (SM2)

several tracking detectors of different type
• to cope with high particle rates
• to cover a large angular acceptance $\sim 0$-180 mrad

particle ID:
• calorimeters
• muon walls
• RICH
The polarized target

**Solid state** target operating in **frozen spin mode 120 cm long**

Composed by 2 or 3 cells with **opposite polarization** reversed every week during transverse data taking

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2002-4 $^6$LiD
- dilution factor: 0.38
- polarization: 50%

2007 NH$_3$
- dilution factor: 0.14
- polarization: 90%

**Common Muon and Proton Apparatus for Structure and Spectroscopy**
The COMPASS experiment

SIDIS

Hadron azimuthal asymmetries
- unpolarized target
- transversely polarized target

Two hadrons azimuthal asymmetries

Conclusions and outlook
SIDIS: a key process to investigate the spin structure of the nucleon

lepton interacts with a single parton of the nucleon (via photon exchange)

- virtual photon four-momentum

- lepton and hadron momenta:
  \[ Q^2 = -q^2 > 0 \quad \nu = E - E' \]

- variables:
  \[ x = Q^2 / 2M\nu \quad y = \nu/E \]

- target fragmentation

- current fragmentation

- at least one hadron is detected in the final state

- detection variable:
  \[ z = E_h / \nu \]
Data selection and kinematics

DIS event selection:

$Q^2 > 1 \text{ (GeV/c)}^2$

$0.1 < y < 0.9$

$W > 5 \text{ GeV/c}^2$
Data selection and kinematics

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

Hadron selection
\( p_T > 0.1 \text{ GeV/c} \)
\( z > 0.2 \)
SIDIS cross section

\[
\frac{d\sigma}{dx \, dy \, d\psi \, dz \, d\phi_h \, dP^2_{h\perp}} =
\begin{align*}
\frac{\alpha^2}{xyQ^2} & \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h \, F_{UU}^{\cos \phi_h} \\
&+ \varepsilon \cos(2\phi_h) \, F_{UU}^{2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_h \, F_{LU}^{\sin \phi_h} \\
&+ S_{||} \left[ \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_h \, F_{UL}^{\sin \phi_h} + \varepsilon \sin(2\phi_h) \, F_{UL}^{2\phi_h} \right] \\
&+ S_{||} \lambda_e \left[ \sqrt{1-\varepsilon^2} \, F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_h \, F_{LL}^{\cos \phi_h} \right] \\
&+ |S_{\perp}| \sin(\phi_h - \phi_S) \left[ F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)} \right] \\
&\quad + \varepsilon \sin(\phi_h + \phi_S) \, F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) \, F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\quad + \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_S \, F_{UT}^{\sin \phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) \, F_{UT}^{\sin(2\phi_h-\phi_S)} \\
&+ |S_{\perp}| \lambda_e \left[ \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) \, F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_S \, F_{LT}^{\cos \phi_S} \\
&\quad + \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) \, F_{LT}^{\cos(2\phi_h-\phi_S)} \right] \right\},
\end{align*}
\]

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

unpolarized

these modulations will be addressed in this talk

transverse polarization
SIDIS cross section

\[ \sigma_{l' h X} \propto \sum q(x) \otimes \sigma_{l' q' X} \otimes D(z) \]

the complete **SIDIS cross section**, including the quarks transverse momentum, has **18 structure functions** \((PDF \otimes FF)\), 8 leading order

most of them can be accessed by measuring the corresponding azimuthal modulation (independent azimuthal modulations in \(\phi_s, \phi_h\))

**φ** \(s\) is the azimuthal angle of the **nucleon spin**

w.r.t. the scattering plane

**φ** \(h\) is the azimuthal angle of the **hadron momentum**

w.r.t. the scattering plane

the relevant azimuthal angles \(\phi_s, \phi_h\)

are evaluated in the **Gamma Nucleon System**
The COMPASS experiment

SIDIS

Hadron azimuthal asymmetries

- unpolarized target
- transversely polarized target

Two hadrons azimuthal asymmetries

Conclusions and outlook
three azimuthal modulations in the unpolarized cross section:

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

\[ F_{UU}^{\cos \phi} \]
mainly Cahn effect
kinematical effect due to the quark transverse momentum

\[ F_{UU}^{\cos 2\phi} \]
given by Boer-Mulders function, one of the most famous TMD PDF, convoluted with the Collins FF

\[ F_{UU}^{\sin \phi} \]
kinematical effect proportional to the beam polarization
(no clear interpretation in term of PM)

recently increasing interest!

the Boer-Mulders function correlates the quark transverse momentum and the quark spin in an unpolarized nucleon
measurement done on deuteron target
data combined to cancel possible polarization dependent terms

To extract the asymmetries:
the azimuthal distributions have to be corrected by the apparatus acceptance ➔ dedicated MC simulations for L and T target polarization data

\[ N_{corr}(\phi) = N_0 \cdot \left[ 1 + A_{\cos \phi} \cdot \cos(\phi) + A_{\cos 2\phi} \cdot \cos(2\phi) + A_{\sin \phi} \cdot \sin(\phi) \right] \]

fit function

these asymmetries have been measured for the first time separately for positive and negative hadrons
Results

\[ A_{\sin \phi} \] / \( \xi \)

\[ \xi = \frac{2y\sqrt{1-y}}{1 + (1-y)^2} \]

\( \sin \phi \): small amplitudes, compatible with zero

\[ h^+ \]

COMPASS 2004 data (\(^6\)LiD)

preliminary

\[ h^- \]

COMPASS 2004 data (\(^6\)LiD)

red bands are systematic errors
Results

$\cos \phi$: strong signal both for positive and negative hadrons

$A_{\cos \phi} / \varepsilon_c$

$\varepsilon_c = \frac{2(2 - y)\sqrt{1 - y}}{1 + (1 - y)^2}$

Red bands are systematic errors
Results

$\cos 2\phi$: different from zero and different for positive and negative hadrons

$$A_{\cos 2\phi}/\varepsilon_2$$

$$\varepsilon_2 = \frac{2(2 - y)}{1 + (1 - y)^2}$$

red bands are systematic errors
Comparison with predictions

\[ \cos \phi \]

\[ A_{D, \cos \phi}^h \]

\[ h^+ \]

\[ \text{COMPASS 2004 } ^6\text{LiD (part)} \]

\[ \text{preliminary} \]

M. Anselmino, M. Boglione, A. Prokudin, C. Türk

does not include Boer – Mulders contribution
Comparison with predictions

$$\cos 2\phi$$

V. Barone, A. Prokudin, B.Q. Ma

COMPASS 2004$^6$LiD (part)

V. Barone, A. Prokudin, B.Q. Ma

sum of all contributions
Cahn effect
Boer-Mulders
QCD (first order)
8 azimuthal modulations can be measured in SIDIS on transversely polarized target

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

The most known are:

**Sivers asymmetry**

**Collins asymmetry**
Collins asymmetry is a very important measurement; it gives access to the:

**Transversity PDF**

which is one of the three PDF needed to describe the spin structure of the nucleon at leading order (with helicity PDF and unpolarized PDF)

- it gives the probability to find a quark with spin parallel or anti-parallel to the nucleon's spin in a transversely polarized nucleon

- it is chiral odd → can be measured only in SIDIS on transversely polarized target (convoluted with another chiral odd function)

**Transversity \( \otimes \) Collins FF**

left right asymmetry in the fragmentation of the transversely polarized quark in an unpol. hadron
Collins asymmetry appears as a modulation in $\Phi_c$

$\Phi_c = \phi_h - \phi_{S'} = \phi_h + \phi_S - \pi$

$\phi_{S'}$, azimuthal angle of the spin vector of the fragmenting quark

$\phi_h$, azimuthal angle of the hadron momentum

Collins angle

Collins asymmetry appears as a modulation in $\Phi_c$
COMPASS measurement on transversely polarized deuteron (2002-2004 data)

Values corrected for the purity; systematic error below 30% of the statistical one
Collins asymmetries on deuteron are compatible with zero at variance with HERMES which measured a signal for both positive and negative hadrons on transversely polarized proton.

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

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

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

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

measurements on deuteron (isoscalar target) important to access \( \Delta_T d \)

- data taken with deuteron (COMPASS), proton (HERMES) and \( e^+ e^- \rightarrow \) hadrons (BELLE) global fit \( \rightarrow \) consistent description
first extraction of the: transversity PDF and the Collins FF for u and d quarks
The effect is still there at higher $Q^2$ (w.r.t. HERMES)

at small $x$, the asymmetries are compatible with zero
in the valence region the asymmetries are different from zero,
of opposite sign for positive and negative hadrons,
and have the same strength and sign as HERMES
COMPASS measurements on proton confirm present picture and are consistent with prediction (from global fit)

last prediction from Anselmino group
\[
\frac{d \sigma}{dx \, dy \, d\psi \, dz \, d\phi_h \, dP_{h\perp}^2} = \frac{\alpha^2 \, y^2}{x \, y \, Q^2 \, 2 \, (1 - \varepsilon)} \left( 1 + \frac{\gamma^2}{2 \, x} \right) \left\{ F_{UU, T} + \varepsilon \, F_{UU, L} + \sqrt{2 \, \varepsilon \, (1 + \varepsilon)} \, \cos \, \phi_h \, F_{UU}^{\cos \, \phi_h} \\
+ \varepsilon \, \cos(2 \, \phi_h) \, F_{UU}^{\cos \, 2 \, \phi_h} + \lambda_e \, \sqrt{2 \, \varepsilon \, (1 - \varepsilon)} \, \sin \, \phi_h \, F_{LU}^{\sin \, \phi_h} \\
+ S_{\parallel} \left[ \sqrt{2 \, \varepsilon \, (1 + \varepsilon)} \, \sin \, \phi_h \, F_{UL}^{\sin \, \phi_h} + \varepsilon \, \sin(2 \, \phi_h) \, F_{UL}^{\sin \, 2 \, \phi_h} \right] \\
+ S_{\parallel} \lambda_e \left[ \sqrt{1 - \varepsilon^2} \, F_{LL} + \sqrt{2 \, \varepsilon \, (1 - \varepsilon)} \, \cos \, \phi_h \, F_{LL}^{\cos \, \phi_h} \right] \\
+ |S_{\perp}| \sin(\phi_h - \phi_S) \left( F_{UT, T}^{\sin(\phi_h - \phi_S)} + \varepsilon \, F_{UT, L}^{\sin(\phi_h - \phi_S)} \right) \\
+ \varepsilon \, \sin(\phi_h + \phi_S) \, F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \, \sin(3 \, \phi_h - \phi_S) \, F_{UT}^{\sin(3 \, \phi_h - \phi_S)} \\
+ \sqrt{2 \, \varepsilon \, (1 + \varepsilon)} \, \sin \, \phi_S \, F_{UT}^{\sin \, \phi_S} + \sqrt{2 \, \varepsilon \, (1 + \varepsilon)} \, \sin(2 \, \phi_h - \phi_S) \, F_{UT}^{\sin(2 \, \phi_h - \phi_S)} \right\} \\
+ |S_{\perp}| \lambda_e \left[ \sqrt{1 - \varepsilon^2} \, \cos(\phi_h - \phi_S) \, F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2 \, \varepsilon \, (1 - \varepsilon)} \, \cos \, \phi_S \, F_{LT}^{\cos \, \phi_S} \\
+ \sqrt{2 \, \varepsilon \, (1 - \varepsilon)} \, \cos(2 \, \phi_h - \phi_S) \, F_{LT}^{\cos(2 \, \phi_h - \phi_S)} \right\},
\]
The **Sivers** function is one of the most studied **TMD** parton distribution functions

correlates the **quark transverse momentum** and the **nucleon spin**
in a transversely polarized nucleon

it is related to **angular orbital momentum** of the quark in a transversely polarized nucleon
Sivers asymmetry appears as a modulation in $\Phi_S$

$\phi_h$ azimuthal angle of the hadron momentum

$\phi_S$ azimuthal angle of the nucleon spin

$\Phi_S = \phi_h - \phi_S$

Sivers angle $\rightarrow$ measured azimuthal modulation

$$A_{Siv} = \frac{A_S^h}{f \cdot P_T} = \frac{\sum_q e_q^2 \cdot \Delta_0^T q \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

Sivers TMD PDF $\otimes$ Unpolarized FF
COMPASS measurement on transversely polarized deuteron (2002-2004 data)

Values corrected for the purity; systematic error below 30% of the statistical one
global fit together with \textit{HERMES data on proton}

extraction of Sivers function

naïve interpretation (parton model, valence region)

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

small asymmetries suggest \[ \Delta_0^T d_v \approx -\Delta_0^T u_v \]
COMPASS Sivers asymmetry: measurement on transversely polarized proton (DIS09)

- The measured asymmetries are small, compatible with zero.
- Systematic errors are ~ 0.5 $\sigma_{\text{stat}}$.
- Intriguing results, not easy to explain in the present theoretical picture.
COMPASS Sivers asymmetries on proton: comparison with prediction from Anselmino et al.

marginal agreement between data and predictions

more precise high energy data urgently needed

based on Quark Soliton Model

marginal agreement between data and predictions
other 6 single spin asymmetries on a transversely polarized target, all measured by COMPASS on deuteron and found to be compatible with zero.
The function $F_{UT} \sin(3\phi_h - \phi_S)$ correlates the quark transverse momentum and the quark spin in a transversely polarized nucleon.

![Graph showing the correlation between $\sin(3\phi_h - \phi_S)$ and $A_{UT}$ for different values of $x$, $z$, and $P_T^h (GeV/c)$.

The graph includes data for positive and negative cases, as well as for all hadrons and specific data from 2002-2004.
OUTLINE

The COMPASS experiment

SIDIS

Hadron azimuthal asymmetries
  - unpolarized target
  - transversely polarized target

Two hadrons azimuthal asymmetries

Conclusions and outlook
Transversity can be also accessed in inclusive production of hadron pairs by measuring an azimuthal asymmetries in the angle: \( \Phi_{RS} = \Phi_{RT} - \Phi_{S'} \)

is the angle of \( R_T \) w.r.t the gamma

\[
R_T = \frac{z_2 P_1 - z_1 P_2}{z_1 + z_2}
\]

COMPASS measured small asymmetries (compatible with zero) on deuteron
2 hadrons COMPASS asymmetry on transversely polarized proton

\[ x_F > 0.1 \]
\[ z_1, z_2 > 0.1 \]
\[ Z = z_1 + z_2 < 0.9 \]
\[ R_T > 0.07 \text{ GeV/c} \]

in the valence region the asymmetries are different from zero and the signal is larger than for the Collins asymmetry.
2 hadrons: comparison with predictions

Ma et al. private communication

Bacchetta et al. private communication
Conclusions and outlook

- many interesting results on transverse momentum and transverse spin from COMPASS data both on deuteron and proton polarized target → flavour separation

- near future

- new results on unpolarized azimuthal asymmetries on deuteron (final results)

- on proton

  - Collins and Sivers asymmetries on identified hadrons
  - 2 hadrons asymmetries on identified hadrons
Conclusions and outlook

Next year

- Data taking with transversely polarized proton foreseen → new precise results
BACKUP
prediction by Anselmino group in Phys. Rev. D


COMPASS 2007 proton data