Recent transverse spin results from COMPASS

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On behalf of the COMPASS Collaboration
longitudinally polarised muon beam
beam intensity: $2 \cdot 10^8 \, \mu^+$/spill (4.8s/16.2s)
beam momentum: 160 GeV/c

longitudinally or transversely polarised target
luminosity: $\sim 5 \cdot 10^{32} \, \text{cm}^{-2} \, \text{s}^{-1}$
The COMPASS spectrometer

TWO STAGE SPECTROMETER

- calorimetry
- particle identification

160 GeV

Target

160 GeV

SciFi

Silicon

Drift chambers

Micromegas

Gems

MWPC

Straws

ECal & HCal

RICH

SM1

SM2

μ Filter

Trigger-hodoscopes

50 m

PID

LAT

50 m
Polarized Target in 2007

New COMPASS target magnet:

- 180 mrad geometrical acceptance

Target material: NH$_3$

- high polarisation: $\sim$90%
- dilution factor f$\sim$0.15
- very long relaxation time ($\sim$ 4000 h)
- Target Polarization reversed every week
2002-4: $^6\text{LiD}$ target, 20% time dedicated to transverse data taking. Many results: Collins, Sivers, other 6 SSA, 2h, $\Lambda$, unpolarized SSA.

2007: $\text{NH}_3$ target, 50% time dedicated to transverse data taking; preliminary results on Collins, Sivers, 2h, $\Lambda$. 
SIDIS cross section:
18 structure functions,
8 transverse target
dependent spin asymmetries
with different azimuthal dependences

From A. Bacchetta et al.,
Azimuthal modulations: Sivers SSA

\[ \phi_s \text{ azimuthal angle of spin vector of initial quark} \]

\[ \phi_h \text{ azimuthal angle of hadron momentum} \]

\[ \Phi_s = \phi_h - \phi_s \] Sivers angle

\[ A_{Siv} = \frac{A_s^h}{f \cdot P_T} = \frac{\sum q e_q^2 \cdot (\Delta_0^T q \cdot D_q^h)}{\sum q e_q^2 \cdot q \cdot D_q^h} \] Sivers PDF \( \otimes \) FF
Azimuthal modulations: Collins SSA

\[ \phi_S, \text{ azimuthal angle of spin vector of fragmenting quark (} \phi_S' = \pi - \phi_S) \]

\[ \phi_h, \text{ azimuthal angle of hadron momentum} \]

\[ \Phi_C = \phi_h - \phi_s' = \phi_h + \phi_s - \pi \quad \text{Collins angle} \]

\[ A_{Coll} = \frac{A_C^h}{f \cdot P_T \cdot D_{nn}} = \frac{\sum q e_q^2 \cdot \Delta T q \cdot \Delta^0 T D_q^h}{\sum q e_q^2 \cdot q \cdot D_q^h} \]

“transversity” PDF \( \otimes \) Collins FF
Data Selection

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

Hadron selection
- $p_T > 0.1 \text{ GeV/c}$
- $z > 0.2$
Results:
Sivers asymmetries on deuteron

Values corrected for the purity; systematic error below 30% of the statistical one
Results:
Collins asymmetries on deuteron

Values corrected for the purity; systematic error below 30% of the statistical one.
Results: Sivers asymmetries on proton

Results on the second half of the collected data (Transversity 2008).

Systematic errors \( \sim 0.5 \sigma_{\text{stat}} \)

The measured asymmetries are small, compatible with zero.
Sivers asymmetry: comparison with predictions

COMPASS 2007 transverse proton data (part)

\[ A_{pSiv} \]

-0.1
-0.05
0
0.05
0.1

\[ h^+ \]

\[ h^- \]

Anselmino et al
arXiv:0805.2677
COMPASS preliminary

\[ 10^{-3} \quad 10^{-2} \quad 10^{-1} \]
\[ 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \]
\[ 0.5 \quad 1 \quad 1.5 \]

\[ x \quad z \quad p_T \text{ (GeV/c)} \]
comparison with predictions from
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
Results:

Collins asymmetry on proton

1 year spent to further analyse the data collected in the first part of 2007 data taking; results in an increase of usable statistics for the Collins asymmetries by ~ a factor 3, while previous results for Sivers have been confirmed.

COMPASS 2007 proton data

preliminary
Results:
Collins asymmetry on proton

COMPASS 2007 proton data $x > 0.05$
preliminary
Collins asymmetry: comparison with predictions

COMPASS 2007 proton data

\[ A_{Coll}^p \]

- Anselmino et al
- Talk by A. Prokudin at DIS08
- COMPASS preliminary

h^+

\[ A_{Coll}^p \]

h^-

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

From A. Bacchetta et al., JHEP 0702:093,2007. e-Print: hep-ph/0611265
Other single spin asymmetries, deuteron target

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

"pretzelosity" \( \otimes \) Collins FF

Asymmetries found compatible with zero on deuteron: again cancellation between proton and neutron?
Two Hadron Asymmetries

Another channel that can be used to access transversity is the inclusive production of hadron pairs.

The measurement is based on an azimuthal asymmetry in the angle $\phi_{RS} = \phi_{R\perp} - \phi_s$, in which $\phi_{R\perp}$ is the angle of the plane containing the two hadrons

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

$$A_{RS} = \frac{1}{f \cdot P_T \cdot D} \cdot A = \frac{\sum q e^2_q \cdot \Delta_T q(x) \cdot H_q^<(z, M_H^2)}{\sum q e^2_q \cdot q(x) \cdot D_q^h(z, M_h^2)}$$

A. Bacchetta, M. Radici, hep-ph/0407345
X. Artru, hep-ph/0207309
Two Hadron Asymmetries: results on proton

$x_F > 0.1$
$z > 0.1$
$Z_{sum} = z_1 + z_2 < 0.9$
$R_T > 0.07 \text{GeV/c}$

In the valence region the asymmetries are different from zero, signal larger than measured by HERMES.
Two Hadron Asymmetries:

results on proton

in the valence region the asymmetries are different from zero, signal larger than measured by HERMES

COMPASS 2007 transverse proton data
Two Hadron Asymmetries: comparison with predictions

COMPASS 2007 transverse proton data

Courtesy of A.Bacchetta
SIDIS cross section: unpolarized part

\[ \frac{d\sigma}{dx \, dy \, d\psi \, dz \, d\phi_h \, dP^2_{h \perp}} = \]

\[ \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ \right. \\
\left. F_{UU, T} + \varepsilon F_{UU, L} + \sqrt{2 \varepsilon (1+\varepsilon)} \cos \phi_h \, F_{UU}^{\cos \phi_h} \right. \\
+ \varepsilon \cos(2\phi_h) \, F_{UU}^{\cos 2\phi_h} + \lambda_\varepsilon \sqrt{2 \varepsilon (1-\varepsilon)} \sin \phi_h \, F_{LU}^{\sin \phi_h} \\
+ S_{\parallel} \left[ \sqrt{2 \varepsilon (1+\varepsilon)} \sin \phi_h \, F_{UL}^{\sin \phi_h} + \varepsilon \sin(2\phi_h) \, F_{UL}^{\sin 2\phi_h} \right] \\
+ S_{\parallel} \lambda_\varepsilon \left[ F_{LL}^{\cos \phi_h} \right. \\
+ \sin(\phi_h - \phi_S) \left( F_{UT, T}^{\sin(\phi_h - \phi_S)} + \varepsilon \, F_{UT, L}^{\sin(\phi_h - \phi_S)} \right) \\
+ \varepsilon \sin(\phi_h + \phi_S) \, F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) \, F_{UT}^{\sin(3\phi_h - \phi_S)} \\
+ \sqrt{2 \varepsilon (1+\varepsilon)} \sin \phi_S \, F_{UT}^{\sin \phi_S} + \sqrt{2 \varepsilon (1+\varepsilon)} \sin(2\phi_h - \phi_S) \, F_{UT}^{\sin(2\phi_h - \phi_S)} \\
+ \lambda_\varepsilon \left[ \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) \, F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2 \varepsilon (1-\varepsilon)} \cos \phi_S \, F_{LT}^{\cos \phi_S} \\
+ \sqrt{2 \varepsilon (1-\varepsilon)} \cos(2\phi_h - \phi_S) \, F_{LT}^{\cos(2\phi_h - \phi_S)} \right] \left. \right\} . \]

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SIDIS cross section: unpolarized part

Also the azimuthal asymmetries in the unpolarized cross section give information on TMD effects...

\[
F^{\sin \phi_h}_{LU} = \frac{2M}{Q} C \left[ -\hat{h} \cdot k_T \left( x e H_1^+ + \frac{M_h}{M} f_1 \frac{\tilde{G}^+}{z} \right) + \frac{\hat{h} \cdot p_T}{M} \left( x g^+ D_1 + \frac{M_h}{M} h_1^+ \frac{\tilde{E}}{z} \right) \right] + \text{Cahn effect} + \text{Boer-Mulders DF}
\]

\[
F^{\cos \phi_h}_{UU} = \frac{2M}{Q} C \left[ -\hat{h} \cdot k_T \left( x h_1^+ + \frac{M_h}{M} f_1 \frac{\tilde{D}^+}{z} \right) - \frac{\hat{h} \cdot p_T}{M} \left( x f^+ D_1 + \frac{M_h}{M} h_1^+ \frac{\tilde{H}}{z} \right) \right] + \text{Boer-Mulders x Collins FF} + \text{Cahn effect}
\]

**Cahn effect**

kinematical effect due to quark intrinsic momentum

\[
\frac{d\sigma}{d\phi_h} \propto 1 - 4 \frac{\langle k_t^2 \rangle}{Q \langle P_t^2 \rangle} D_{\cos \phi_h} (y) \cos \phi + \ldots
\]

**Boer-Mulders PDF**

quark with spin parallel to the nucleon spin in an unpolarised nucleon

pQCD contributions expected to be important for $pT>1\text{GeV}/c$
Results:

\[ A_{\sin \phi} / \varepsilon_s \]

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

$\cos \phi$ asymmetries on deuteron

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

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

cos2\(\phi\) asymmetries on deuteron

\[ A_{\cos 2\phi} / \varepsilon_2 \]

\[ \varepsilon_2 = \frac{2(2-y)}{1 + (1-y)^2} \]
$\cos \phi$ and $\cos 2\phi$

comparison with predictions

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M. Anselmino, M. Boglione, A. Prokudin, C. Türk
does not include Boer – Mulders contribution

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

COMPASS investigated transverse spin and TMD effects using a deuterium target in 2002-2004:

- Collins and Sivers compatible with zero
- $\cos \phi$ strong effect, $\cos 2\phi$ up to 10%

From the analysis of 2007 data, with a NH$_3$ target:

- Collins asymmetries are different from zero also in COMPASS kinematic domain
- no evidence of Sivers signal within the statistical errors
- 2h asymmetries are different from zero, signal stronger than Hermes

...more work ongoing to produce results on the other 6 SSA and on identified hadrons.
Conclusions

COMPASS investigated transverse spin and TMD effects using a deuterium target in 2002-2004:
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Future:
• Request to take data a full year with a proton target to
  • improve statistics for Collins to investigate evolution and better measure both valence and low x region (COMPASS unique!)
  • clarify the situation with Sivers, statistical errors expected to be similar to those of Hermes.
• Drell-Yan measurements (longer term project)
Lambda asymmetries

Information on $\Delta Tq$ can be accessed in the processes:

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

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

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

$\sum q e_q^2 \Delta Tq(x) \Delta T D_{\Lambda/q}(z) = f P ND(y) \frac{\sum q e_q^2 q(x) D_{\Lambda/q}(z)}{\sum q e_q^2 q(x) D_{\Lambda/q}(z)}$

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

$\Lambda$ polarization axis
Data Selection

Preliminary COMPASS 2007 transverse proton data (part)

$\bar{\Lambda}$

$N_{\bar{\Lambda}} \sim 13,600$

$\Lambda$

$N_{\Lambda} \sim 27,900$

$m(p_{\pi^+}) - m(PDG)$ [GeV/c$^2$]

$\alpha = \frac{p_{T_1} - p_L}{p_{T_1} + p_L}$
Lambda asymmetries

~60% higher statistics with respect deuteron data (after)
Systematic errors have been estimated to be smaller than statistical errors from false polarization.
No dependence on x.
$\langle \sin \theta \rangle = 0.94$
Mean of kinematical quantities

COMPASS 2007 PROTON DATA
positive hadrons

\( \langle y \rangle \) vs. \( x \)

\( \langle Q^2 \rangle \) [GeV/(c^2)] vs. \( x \)

COMPASS 2007 PROTON DATA
\( n, \) COMPASS


\( \langle z \rangle \) vs. \( x \)

\( \langle p_T \rangle \) [GeV/c] vs. \( x \)
COMPASS 2007 proton data

preliminary
Collins asymmetry: comparison with Hermes

Hermes: lepton-beam asymmetries