New measurements of transverse spin asymmetries at COMPASS

Anna Martin

on behalf of the COMPASS Collaboration
fixed target experiment on the M2 beam line at CERN SPS
a facility, built by the COMPASS Collaboration, in the years 1997-2001
with a wide physics program

initially approved for 5 years of data taking,
the experiment took data from 2002 to 2022

and the spectrometer
is still there,
being used by the
AMBER Collaboration
the COMPASS spectrometer

designed to
• use high energy muon and hadron beams, and different targets
• have large angular acceptance, as flat as possible
• cover a broad kinematical range

two stages spectrometer
Large Angle Spectrometer (SM1), Small Angle Spectrometer (SM2)
  equipped with
  Very Small, Small, Large Area trackers
  RICH, muon detectors, calorimeters,
  trigger hodoscopes
the COMPASS spectrometer

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Very Small, Small, Large Area trackers
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2005 upgrade:
• large acceptance PT magnet, RICH ...
several upgrades in the years
to fulfill the requirements of
the different measurements
## 15 years of data taking

**dedicated to nucleon structure and spectroscopy**

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
<th>Physics Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002-04</td>
<td>160 GeV/c $\mu^+$ beam L and T polarized $d$ ($^6$LiD) target</td>
<td>$\Delta$G, SIDIS</td>
</tr>
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<tr>
<td>2008-09</td>
<td>hadron beams LH and nuclear targets</td>
<td>Hadron Spectroscopy</td>
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<td></td>
<td></td>
<td>Primakoff</td>
</tr>
<tr>
<td>2010</td>
<td>160 GeV/c $\mu^+$ beam T polarized $p$ ($NH_3$) target</td>
<td>SIDIS</td>
</tr>
<tr>
<td>2011</td>
<td>190 GeV/c $\mu^+$ beam L polarized $p$ ($NH_3$) target</td>
<td>SIDIS</td>
</tr>
<tr>
<td>2012</td>
<td>$\pi^-$ ($\mu$) beam Ni (LH) target</td>
<td>Primakoff</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(DVCS)</td>
</tr>
<tr>
<td>2015</td>
<td>190 GeV/c $\pi^-$ beam T polarized $p$ ($NH_3$) target</td>
<td>Drell-Yan</td>
</tr>
<tr>
<td>2016, 17</td>
<td>160 GeV/c $\mu^+$ and $\mu^-$ beam LH target</td>
<td>DVCS / SIDIS</td>
</tr>
<tr>
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### Addendum to the COMPASS Proposal

- G. Reicherz
- Polarised targets

### COMPASS II Proposal

- J. Matoušek
- GPDs/TMDs

### Addendum to the COMPASS II Proposal

- V. Andrieux
- TMDs
- A. Vijayakumar, poster

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15 years of data taking
dedicated to nucleon structure and spectroscopy

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<tr>
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Addendum to the COMPASS Proposal

COMPASS II Proposal

Collins and Sivers asymmetries

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

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

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

\[
+ S_{\parallel} \left[ \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_h F_{UL}^{\sin \phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin 2\phi_h} \right]
\]

\[
+ S_{\parallel} \lambda_e \left[ \sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_h F_{LL}^{\cos \phi_h} \right]
\]

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

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

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

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

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

in the parton model

**Sivers asymmetry**

\[
A_{Siv} = \frac{F_{UT}^{\sin(\phi_h - \phi_S)}}{F_{UU}} \approx \frac{\sum_q e_q^2 f_{1T}^q \otimes D_{1q}}{\sum_q e_q^2 f_{1}^q \otimes D_{1q}}
\]

**Collins asymmetry**

\[
A_{Coll} = \frac{F_{UT}^{\sin(\phi_h + \phi_S)}}{F_{UU}} \approx \frac{\sum_q e_q^2 h_{1}^q \otimes H_{1q}^1}{\sum_q e_q^2 f_{1}^q \otimes D_{1q}}
\]
SIDIS cross-section

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

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\]

flavour separation: proton and neutron (or deuteron) data are both essential
transverse spin asymmetries from 2002-2004 data

deuteron target
first results published in 2005

PRL 94, 202002 (2005)

compatible with zero
within the large statistical errors
transverse spin asymmetries from 2002-2004 data

deuteron target
first results published in 2005

PRL 94, 202002 (2005)

NPB765 (2007) 31

compatible with zero within the large statistical errors
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deuteron target
first results published in 2005

HERMES, proton target

PRL 94, 202002 (2005)

compatible with zero
within the large statistical errors

PRL 94, 012002 (2005)
clear signal

similar situation for the Sivers asymmetry
transverse spin asymmetries from 2002-2004 data

deuteron target
first results published in 2005

HERMES, proton target

compatible with zero within the large statistical errors

similar situation for the Sivers asymmetry

the COMPASS results were interpreted as cancellation between u- and d-quark contributions

the different beam energy (160 vs 27.5 GeV/c) could also have a role
transverse spin asymmetries from 2007 and 2010 data

proton target
first results published in 2010 and 2012

Collins

very clear signal in the valence region
opposite sign for $h^+$ and $h^-$, mirror symmetry vs $x$

in very good agreement with the HERMES results
transverse spin asymmetries from 2007 and 2010 data

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proton target
first results published in 2010 and 2012

Collins

2010 data PLB 717 (2012) 376

very clear signal in the valence region

the HERMES p and the COMPASS p and d data were immediately used to extract the Sivers function and transversity (with Belle results)
accessing transversity

- u-quark transversity is different from zero
- indication that u- and d-quark transversity PDFs have opposite sign

SIDIS and $e^+e^-$ data only
accessing transversity

- u-quark transversity is different from zero
- indication that u- and d-quark transversity PDFs have opposite sign
- d-quark transversity much worse determined than u-quark transversity because of the scarcity of deuteron (neutron) data: all the HERMES data and most of the COMPASS data were collected with p target

→ 2022 COMPASS run
the 2022 run

request to CERN (2017):

one year of data taking dedicated to SIDIS off transversely polarized deuteron (\(^6\)LiD) in the same conditions of the 2010 proton run

aim:

balance the proton and deuteron statistics to improve, in particular, the knowledge of the d-quark transversity and of the tensor charge, in a unique \(x - Q^2\) range, complementary to that of the future JLab experiments
the 2022 run

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expected statistical uncertainties $\sigma_{2022}^d \approx 0.6 \cdot \sigma_{2010}^p$ for all the TSAs

impact on the Collins asymmetry
the 2022 run

expected impact on transversity
quantified using the point-by-point extraction from SIDIS and $e^+e^-$ data and replicas

present: all p and d data
the 2022 run

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**present:** all p and d data

**projected:** all p and 2022 d data
the 2022 run

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**present:** all p and d data

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and on the tensor charge

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<thead>
<tr>
<th></th>
<th>$\delta_u = \int \Omega_x dx h_1^{u\nu}(x)$</th>
<th>$\delta_d = \int \Omega_x dx h_1^{d\nu}(x)$</th>
<th>$g_T = \delta_u - \delta_d$</th>
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<tbody>
<tr>
<td>present</td>
<td>0.201 ± 0.032</td>
<td>$-0.189 ± 0.108$</td>
<td>0.390 ± 0.087</td>
</tr>
<tr>
<td>projected</td>
<td>0.201 ± 0.019</td>
<td>$-0.189 ± 0.040$</td>
<td>0.390 ± 0.044</td>
</tr>
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</table>
we took data from June 8 to November 9, 2022, with some short break

in total 10 data taking periods,
each divided in 2 sub periods
with opposite polarization in the target cells
to minimize possible systematic effects

data analysis started during data taking, and is going on as expected
the 2022 run

some distribution
the 2022 run

the processing of all the collected data has been completed
the data quality tests have been performed

in June 2023 (IWHSS2023) we could give
solid estimate of the final statistical uncertainties
which are in agreement with the expectations of the proposal

a very successful run,
these data will allow us to performed
on d target all the measurements done
on p target, and more
... in the future

---

d & p  Collins and Sivers asymmetries (1D)  several papers
p  d & p  di-hadron asymmetries (1D)  several papers
p  d & p  other TSAs (1D)  conf
p  multiD measurements of TSAs \((x, Q^2, z, P_T) bins\)  conf
p  interplay 1h -2h asymmetries  PLB 753 (2016) 406
p  Sivers (et al) asymmetry in Q^2 bins  PLB 770 (2017) 138
p  \(P_T\) - weighted Sivers asymmetries  NPB 940 (2019) 34
p  transversity induced \(\Lambda/\bar{\Lambda}\) polarization  PLB 824 (2022) 136834
p  d & p  TSAs for high \(P_T\) pairs from PGF events  PLB 772 (2017) 85
p  \(J/\Psi\) Sivers asymmetry  conf
p  inclusive \(p^0\) TSAs  PLB 845 (2023) 138155
the 2022 run

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d & p Collins and Sivers asymmetries (1D)  
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**today, the very new results for the**
**Collins and Sivers asymmetries**
**for charged hadrons from \(\sim 50\%\) of the data collected in 2022**
results - Sivers asymmetry

~50% of the data collected in 2022
SIDIS of 160 GeV $\mu^+$ off deuteron

$Q^2 > 1 \text{ (GeV/c)}^2$
$W^2 > 25 \text{ (GeV/c}^2)^2$
$0.1 < y < 0.9$
$z > 0.2$
$p_T > 0.1 \text{ GeV/c}$
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results - Sivers asymmetry

~50% of the data collected in 2022
SIDIS of 160 GeV $\mu^+$ off deuteron

$Q^2 > 1 \text{ (GeV/c)}^2$
$W^2 > 10 \text{ (GeV/c}^2)^2$
$0.1 < y < 0.9$
$z > 0.1$
$p_T > 0.1 \text{ GeV/c}$
results - Collins asymmetry

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- $p_T > 0.1$ GeV/c

NEW

- $W^2 > 10$ (GeV/c)$^2$
- $z > 0.1$

SPIN2023, Durham, September 27, 2023
Summary

In the last 20 years, COMPASS has performed many relevant SIDIS measurements with transversely polarized targets.

The 2022 run with the transversely polarized deuteron target has been successful, and a lot of new results will come. They will stay unique for several years.

First results shown here for the first time:

Collins and Sivers asymmetries for charged hadrons

- much higher precision than the previous COMPASS data
- an important step forward to constrain the extraction of the transversity function, the tensor charge, and of the Sivers function
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thank you!