TMD experiments from COMPASS SIDIS

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on behalf of COMPASS Collaboration

Hadron China 2017, 24-28, 2017, Nanjing
OUTLINE

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  - Nucleon PDFs
- Collins asymmetry
  - Collins Asymmetry for single-hadron production
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- Sivers asymmetry
  - Sivers Asymmetry for single-hadron production
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- Gluon Sivers asymmetry
- Conclusion
COMPASS at CERN

Polarised Target
(NH$_3$ for p, $^6$LiD for d)

Pol. $\mu$ beam from SPS
160-200 GeV, pol. = 80%

two stage spectrometer
tracking, calorimetry, PID

DIS & SI-DIS setup
with muon & PT

SciFi Silicon Micromegas GEMs

MuonWall

Straws SDC MWPC W45

E/HCAL

MuonWall

E/HCAL

RICH

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The Polarized Target System

DNP technique with a dilution refrigerator ($T_{\text{min}}=30\text{mK}$), a 2.5T superconducting magnet and microwave (70GHz) system

- 2/3 target sections (60+60 cm/30+60+30 cm)
- longitudinal & transverse pol. modes

$\rightarrow$ Polarization of proton($\text{NH}_3$) $\sim 90\%$

$\rightarrow$ Polarization of deuteron($^6\text{LiD}$) $\sim 50\%$

$^6\text{Li}$ ($\sim \alpha+d$) also polarized
$\rightarrow$ dilution factor $f=50\%$

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At LO, taking account of transverse momentum ($k_T$) of the quarks.
Sivers & BM-functions

- **Nucleon**
  - Unpol.
  - Long. pol.
  - Trans. pol.

**Sivers- and BM-functions are related to quark OAM and expected to be process dependent**


\[ f_{1T}^{\perp}(x, k_{\perp}^2)_{SIDIS} = -f_{1T}^{\perp}(x, k_{\perp}^2)_{DY} \]

\[ h_{1}^{\perp}(x, k_{\perp}^2)_{SIDIS} = -h_{1}^{\perp}(x, k_{\perp}^2)_{DY} \]

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SIDIS $x$-section for single hadron production

\[
\frac{d\sigma}{dx dy dz dP_T^2 d\phi_h d\psi} = \left[ \frac{\alpha}{xyQ^2(2-\varepsilon)} \right] \times \left( F_{UU,I} + \varepsilon F_{UU,L} \right) \times \\
\left[ 1 + \cos \phi_h \times \sqrt{2\varepsilon(1+\varepsilon)} - A_{UU}^{\cos \phi_h} + \cos(2\phi_h) \times \varepsilon A_{UU}^{\cos (2\phi_h)} \right] \times \\
\lambda \sin \phi_h \times \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin \phi_h} + \\
S_L \left[ \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_h A_{LU}^{\sin \phi_h} + \varepsilon \sin(2\phi_h) A_{LU}^{\sin (2\phi_h)} \right] + \\
S_T \lambda \left[ \sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_h A_{LL}^{\cos \phi_h} \right] + \\
\left[ \sin \phi_s \times \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin \phi_s} \right] + \\
\sin(\phi_h - \phi_s) \times \left( A_{UT}^{\sin (\phi_s - \phi_s)} \right) + \\
\sin(\phi_h + \phi_s) \times \left( \varepsilon A_{UT}^{\sin (\phi_s + \phi_s)} \right) + \\
\sin(2\phi_h - \phi_s) \times \left( \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin (2\phi_s - \phi_s)} \right) + \\
\sin(3\phi_h - \phi_s) \times \left( \varepsilon A_{UT}^{\sin (3\phi_s - \phi_s)} \right) + \\
\cos \phi_s \times \left( \sqrt{2\varepsilon(1+\varepsilon)} A_{LT}^{\cos \phi_s} \right) + \\
\cos(\phi_h - \phi_s) \times \left( \sqrt{1-\varepsilon^2} A_{LT}^{\cos (\phi_s - \phi_s)} \right) + \\
\cos(2\phi_h - \phi_s) \times \left( \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos (2\phi_s - \phi_s)} \right)
\]

\[ A_{UU}(\phi_h, \phi_s) = \frac{F_{UU}(\phi_h, \phi_s)}{D_{UU,I} + \varepsilon D_{UU,L}} \]

S: nucleon covariant spin vector
\lambda: lepton helicity

\[ \sin \phi_s A_{UT}^{\sin \phi_s} \]
\[ \phi_s = \phi_h - \phi_s \]

Sivers

\[ \sin \phi_C A_{UT}^{\sin \phi_C} \]
\[ \phi_C = \phi_h - \phi_s' \]
\[ = \phi_h + \phi_s - \pi \]

Collins

Transverse Target Spin Asymmetries

15 asymmetries:
2-"UU", 1-"LU", 2-"UL", 2-"LL", 5-"UT", 3-"LT"

All measured in COMPASS for p & d

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\[ \varepsilon = \frac{1-y-\frac{1}{4}y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}y^2} \]
\[ = \frac{2M}{Q} \]
Collins & Sivers asymmetries

Collins F.F. (polarized quark fragmentation) can be used for quark polarimeter

Collins mechanism

Sivers effect
Collins Asymmetry on Proton

Collins Asymmetry:

Clearly non-zero in valence region, negative for $\pi^+$, positive for $\pi^-$.

Similar trend for $K$, negative for $K^+$, positive for $K^-$.

Event Selection:

- $Q^2 > 1$ (GeV/c)$^2$
- $W > 5$ GeV/c²
- $0.05 < y < 0.9$
- $z > 0.1$
- $|P^h_T| > 0.07$ GeV/c

Deuteron target asymmetries compatible with zero (COMPASS PLB673 (2009) 127)

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Collins Asymmetry compared with a Fit

The fit reproduces the COMPASS data well

global fit by Anselmino group with HERMES, COMPASS, Belle data [PRD87(2013) 094019]
Di-hadron Asymmetry & Transversity

\[ lN^\uparrow \to l'h^+ h^- X \]

\[ A_{UT}^{\sin \phi_{RS}} \approx \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot H_q}{\sum_q e_q^2 \cdot f_q T q \cdot D_q^{2h}} \]

**Transversity PDF**

"Di-hadron FF"

Modulation according to

\[ \phi_{RS} = \phi_R - \phi_S' = \phi_R + \phi_S - \pi \]

\( \phi_R \): azimuthal angle of \( R \) (Relative hadron momentum vector)

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

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

\[ R = \frac{z_2p_1 - z_1p_2}{z_1 + z_2} = : \xi_2 p_1 - \xi_1 p_2. \]

\[ \phi_R = \frac{(q \times l) \cdot R}{|q \times l| \cdot |q \times R|} \arccos \left( \frac{(q \times l) \cdot (q \times R)}{|q \times l| \cdot |q \times R|} \right) \]

\[ N_{h+h^-}(x, y, z, M_{h+h^-}^2, \cos \theta, \phi_{RS}) \]

\[ \propto \sigma_{UU} \left( 1 + f(x, y) P_T D_{mn}(y) A_{UT}^{\sin \phi_{RS} \sin \theta \sin \phi_{RS}} \right) \]

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Di-hadron Asymmetry on Proton

COMPASS 2007/2010 proton

Clearly negative in the valence region

Event Selection
Q^2 > 1 (GeV/c)^2
W > 5 GeV/c^2
0.1 < y < 0.9
z > 0.1
|R_T| > 0.07 GeV/c

Deuteron data also published
PLB 713 (2012) 10
The asymmetry is compatible with zero!


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Interplay; Di-hadron & Collins Asymmetries

[1] Mirror symmetry between Collins $h^+$ and $h^-$

[2] Di-hadron asymmetry similar to the Collins $h^+$

$\Rightarrow$ Hint of common physical origin between Di-hadron FF and Collins mechanism

Further study on the Collins asymmetries for the di-hadron events gave indication that they are driven by the common origin.
Sivers Asymmetry on Proton

Event Selection
$Q^2 > 1 \text{ (GeV/c)}^2$
$W > 5 \text{ GeV/c}^2$
$0.05 < y < 0.9$
$z > 0.1$
$|p_T^h| > 0.07 \text{ GeV/c}$

Significantly large signal for $\pi^+$ and $K^+$

Compatible with zero for $\pi^-$, $K^-$ and $K^0$

Deuter proton target asymmetries compatible with zero
(COMPASS PLB673 (2009) 127)

PLB 744 (2015) 250

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Sivers Asymmetry on Proton; $\pi^+ \& K^+$

$K^+$ signal is even larger than that of $\pi^+$

➔ possible contribution from sea quarks
The fits reproduce the COMPASS data reasonably well.

COMPASS results for unidentified hadrons on proton is included in the global fits.
Extracted Sivers function by global fits


Q² dependence of Sivers Asymmetries

COMPASS has measured the TSA in different Q² ranges in SIDIS

Drell-Yan

high mass DY

SIDIS

Sivers

h⁺: The data are positive in all the Q²-ranges.

h⁻: The lowest Q² data are compatible with 0 and data become significantly positive in the other ranges.
**Multi Dimensional Sivers Asymmetries**

\[ h^+ : A > 0 \text{ in whole } Q^2, \text{ increasing as } x, z \& Pt. \]

\[ h^- : \text{less and not prominent} \]

\[ PBL 770 (2017)138 \]

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Other TSAs in different $Q^2$ ranges

**transverse target spin Asymmetries**

<table>
<thead>
<tr>
<th>$h^+$</th>
<th>$h^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1&lt;Q^2/(GeV/c)^2&lt;4$</td>
<td>$4&lt;Q^2/(GeV/c)^2&lt;6.25$</td>
</tr>
<tr>
<td>$\langle x \rangle \approx 0.027$</td>
<td>$\langle x \rangle \approx 0.069$</td>
</tr>
</tbody>
</table>

**beam spin & target spin Asymmetries**

PLB 770 (2017) 138

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$P_T^h$ Weighted Sivers Asymmetry

“standard” Sivers Asymmetry:

$$N_h^\pm (\varphi_{Siv.}) = N_h^0 \left[ 1 \pm S_T A_{Siv.} \sin \varphi_{Siv.} \right]$$

$$\varphi_{Siv.} \equiv \varphi_h - \varphi_s$$

LO QCD parton model

$$A_{Siv.} \propto \sum_{\text{quarks}} e_q^2 \cdot f_{1T,q}^\perp \otimes D_{1,q}^h$$

$\otimes$: convolution over transverse momenta

$$f_{1T,q}^\perp \otimes D_{1,q}^h = \int d^2 \vec{P}_T^h \int d^2 \vec{k}_T \int d \vec{p}_\perp \delta^2 (z \vec{k}_T + \vec{p}_\perp - \vec{P}_T^h) \frac{\vec{k}_T \cdot \vec{P}_T^h}{M_{T}^h} f_{1T}^1 D_1$$

$$\vec{P}_T^h \approx \vec{p}_\perp + z \vec{k}_T$$

usually solved using Gaussian model for PDF and FFs

$$f_{1T}^1 (x, k_T^2, Q^2) = f_{1T}^1 (x, Q^2) \frac{1}{\pi \langle k_T^2 \rangle_s} e^{-k_T^2 / \langle k_T^2 \rangle_s}$$

$$D_1 (z, p_\perp^2, Q^2) = D_1 (z, Q^2) \frac{1}{\pi \langle p_\perp^2 \rangle} e^{-p_\perp^2 / \langle p_\perp^2 \rangle}$$

simple product

$$A_{Siv.} = a_G \frac{\sum_{\text{quarks}} e_q^2 \cdot f_{1T,q}^\perp \cdot D_{1,q}^h}{\sum_{\text{quarks}} e_q^2 \cdot f_{1,q} (x) \cdot D_{1,q}^h}$$

$$a_G = \frac{\sqrt{\pi M}}{\sqrt{\langle k_T^2 \rangle_s + \langle p_\perp^2 \rangle / z^2}}$$

Model dependent!
**P_T^h** Weighted Sivers Asymmetry

“**P_T^h** weighted” Sivers Asymmetry: proposed by

J. C. Collins et al. PRD 73 (2006) 014021

If you weight with

\[
N_{h}^{±,W}(\varphi_{Siv.}) = N_{h}^{0,0}W \left[ 1 \pm S_{T}A_{Siv.}^{W} \sin \varphi_{Siv.} \right]
\]

convolution → simple product of Sivers(first moment) and FF

\[
A_{Siv.}^{w} = 2A_{Siv.}^{(1)} = 2 \sum_{\text{quarks}} e_{q}^{2}f_{1T,q}^{\perp (1)}(x) \cdot D_{1,q}^{h}(z)
\]

first moment of Sivers PDF

\[
f_{1T}^{\perp (1)}(x) = \int d^{2}k_{T} \frac{k_{T}^{2}}{2M^{2}} f_{1T}^{\perp}(x, k_{T}^{2})
\]

model independent way (no assumption on the shape of PDFs and FFs)
P_T^h Weighted Sivers Asymmetry

\[ A_{Siv}^w = 2A_{Siv}^{(1)} = 2 \sum_{\text{quarks}} e_q^2 f_{1T,q}^{(1)}(x) \cdot D_{1,q}^h(z) \]

\[ A_{Siv} = a_G \sum_{\text{quarks}} e_q^2 f_{1,q}(x) \cdot D_{1,q}^h(z) \]

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Gluon Sivers Asymmetry

Sivers effect for also gluons? Gluon OAM?


It can be studied with the asymmetry for photon-gluon-fusion.

To enhance the PGF, 2-hadrons with high Pt are detected.

The azimuthal angle of the hadron pair, $\phi_{2h}$, is strongly correlated with the gluon azimuthal angle $\phi_g$.

Data sample: 2010 proton target, 2003,4 deuteron target

Event selection:
\[ Q^2 > 1 \text{ (GeV/c)}^2, \ W > 5 \text{GeV/c}^2, \ 0.9 > y > 0.1, \]
\[ P_{T1} > 0.7 \text{GeV/c}, \ P_{T2} > 0.4 \text{GeV/c}, \ z_1, z_2 > 0.1, \ z_1 + z_2 < 0.9 \]

Without charge constraint for the hadron pair.

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Gluon Sivers Asymmetry

However, one has to take account of the background processes;

The asymmetry can be decomposed as:

\[ fP_T A_{2h}^{Siv.} \sin \phi_{Siv.} = fP_T (R_{PGF} A_{PGF}^{Siv.} + R_{QCD} A_{QCD}^{Siv.} + R_{LP} A_{LP}^{Siv.}) \sin \phi_{Siv.} \]

With a help of MC simulation, the process fractions \(R\) are evaluated.

The MC simulation:
- Generator LEPTO + GEANT + Reconstruction program
- PDF: MSTW2008
- Parton shower: on
- FLUKA for secondary interactions
- Special generator tuning for high-Pt events

Fitting the data with Neural Network trained by the MC, each asymmetry is determined.
Gluon Sivers Asymmetry : Results

\[ A_{PGF}^{Siv.p} = -0.26 \pm 0.09\text{(stat.)} \pm 0.06\text{(sys.)} \]
\[ \langle x_g \rangle = 0.15 \]

\[ A_{PGF}^{Siv.d} = -0.14 \pm 0.15\text{(stat.)} \pm 0.10\text{(sys.)} \]
\[ \langle x_g \rangle = 0.15 \]

proton & deuteron combined

\[ A_{PGF}^{Siv.} = -0.23 \pm 0.08\text{(stat.)} \pm 0.05\text{(sys.)} \]

Two standard deviation from zero \(\Rightarrow\) Gluon Sivers effect?
Conclusions

• SIDIS gave and is giving fundamental contribution to the study of the transverse spin structure of the nucleon.

• COMPASS has provided TSA data for proton and deuteron.

• The Collins asymmetries and Sivers Asymmetries were found to be different from zero for proton although they are consistent with zero for deuteron.

• There is an interplay between the single hadron Collins asymmetries and di-hadron asymmetries suggesting common origin in production mechanism.

• The Sivers asymmetries were obtained in different $Q^2$ ranges. One of the ranges corresponds to the di-muon mass range where the Drell-Yan measurement of COMPASS was performed.

• The Sivers asymmetry for PGF was found to be negative with two standard deviation from zero suggesting the possible gluon Sivers effect.
Spares
In good agreement with the calculations in low-z & low Pt ranges.


However, in high-z & high-Pt ranges, clear discrepancies are seen.
Expected property for the Sivers PDF

Sivers function is process dependent.

\[ f_{1T}^{q}(x, k_{\perp}^{2})_{SIDIS} = -f_{1T}^{\bar{q}}(x, k_{\perp}^{2})_{DY} \]

**SIDIS**: with final state interaction (FSI)

**Drell-Yan**: with initial state interaction (ISI)

**Sign change!**

- **SIDIS**: The ejected (red) quark is attracted by the anti-red spectators before annihilating with the red active quark.
- **Drell-Yan**: The approaching anti-quark (anti-red) is repelled by the anti-red spectators.

This is to be checked in the common kinematical region in COMPASS experimentally.

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SIDIS Kinematics

1 : \( p = (E, p) \)

\[ pE = (E \xi, p \xi) \]

\[ Q^2 = - (p - p^2) \]

\[ n = E - E \xi \]

\[ \chi = Q^2 / 2Mn \]

\[ y = n/E \]

\[ z = E_h/n \]

Energy fraction of the hadron

Fragmentation Function

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Gluon Sivers Asymmetry: Results

Asymmetries for PGF

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\[ A_{PGF}^{Siv.d} = -0.14 \pm 0.15 \text{(stast.)} \pm 0.10 \text{(sys.)} \]
\[ \langle x_g \rangle = 0.15 \]

Asymmetries for BG

\[ A_{QCD}^{Siv} = -0.23 \pm 0.08 \text{(stast.)} \pm 0.05 \text{(sys.)} \]

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