Review of COMPASS results on transverse spin effects in SIDIS and fragmentation functions

Nour Makke on behalf of the COMPASS collaboration

Trieste University and INFN

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

COMPASS measures all of them
SIDIS cross section: Collins and Sivers SSA

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

8 transverse target spin dependent asymmetries

Correlation between the transverse spin of the nucleon and the transverse momentum of the quark

\[ \Rightarrow \text{access Sivers PDF} \]

Correlation between the transverse spin of the nucleon and the transverse polarisation of the quark

\[ \Rightarrow \text{access transversity PDF (} h_1^q) \]
The COMPASS spectrometer

Fixed target experiment @ CERN
High energy beam: 160 GeV/c
Beam intensity $2.10^8 \mu^+/spill$ (4.8s)

Two stages spectrometer (with SM1/2 magnets), 180 mrad angular acceptance

Muon identification
Variety of tracking detectors
Hadron identification for SIDIS measurements

Nucleon spin structure Study with longitudinally and transversely polarized targets:
- Gluon polarisation
- Helicity PDFs
- Transversity PDFs

3 target cells: 30-60-30 cm
Oppositely polarised

- $d(\text{LiD})$
- $p(N\text{H}_3)$

$p_T$:
- 50% 90%

$F$:
- 40% 16%

Hadron identification by RICH

$\pi^\pm$, $K^\pm$

Thresholds:
- $\pi$: 3 GeV/c
- $K$: 9 GeV/c
- $P$: 18 GeV/c
Results

Collins & Sivers asymmetry

proton \((\text{NH}_3)\) target, 160 GeV muon-beam
2007, 2010 runs

deuteron \((^6\text{LiD})\) target, 160 GeV muon-beam
Collins asymmetries on proton

Combined 2007 & 2010 results: Very good agreement between the 2 independent data sets

- Precise measurement
- Asymmetries compatible with zero at small $x$
- Significant signal in the valence region
- Opposite signs for $h^+$ & $h^-$, for $\pi^+$ & $\pi^-$

K$^+$ negative trend in the valence region (as for $\pi^+$)
K$^-$ positive in average

2010 PLB 717 (2012) 376
Collins asymmetries on deuterium

Charged hadrons
2002-04 data

Charged $\pi$, $K$ and $K^0$
2003-04 data

Asymmetries compatible with zero
$\rightarrow$ Cancellation between
$\Delta_T u(x)$ and $\Delta_T d(x)$

$\sigma_{\text{sys}} < 0.3 \sigma_{\text{stat}}$
Sivers asymmetries on proton

Combined 2007 & 2010 results: Very good agreement between the 2 independent data sets

- vs x: Large signal for positive hadrons over all the measured range
- vs z: Increasing signal
- Linear $p_T^h$ dependence at small $p_T^h$, constant for large $p_T^h$

$K^+$ positive in average

Signal larger than $\pi^+$

Important role of sea quark?

$K^-$ compatible with zero

$\sigma_{sys} \sim 0.6\sigma_{stat}$
Sivers asymmetries on deuterium

Charged hadrons
2002-04 data

Charged $\pi$, $K$ and $K^0$
2003-04 data

All asymmetries on deuterium target compatible with zero

$\rightarrow$ Cancellation between $\Delta_T u(x)$ and $\Delta_T d(x)$
Results

hadron pair asymmetry
an alternative way to access poorly known transversity

deuteron ($^6$LiD) target, 160 GeV muon-beam

proton ($\text{NH}_3$) target, 160 GeV muon-beam
2007, 2010 runs
Hadron pair asymmetries on proton – $h^+h^-$

2007

COMPASS PLB 713 (2012) 10,

2010

$\rightarrow$ Large $x$-dependent asymmetry, up to 10%

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Hadron pair asymmetries on proton

Recent results from all data on proton target (2007 & 2010) for all pairs

$\pi^+\pi^-$ pairs: trend very similar to the Collins asymmetries
- compatible with zero asymmetries at small $x$,
- large signal in the valence region
- clear dip around $\rho^0$ mass

Other $\pi, K$ pair combinations
$K^+K^-, \pi^+K^-, K^+\pi^-$
No significant signal/clear trend observed
Hadron pair asymmetries on deuteron

Asymmetries compatible with zero
→ cancellation of the u and d quark transversity

For identified pairs $\pi^+\pi^-, K^+K^-, \pi^+K^-, K^+\pi^-$
all measured asymmetries compatible with zero
Results on unpolarised data

**deuteron** ($^6\text{LiD}$) target, 160 GeV muon-beam


hadron-pair multiplicities (2004)

and unpolarized azimuthal asymmetries (from 2004 (will not be shown here))
motivation:

**transversity** $h_1^q$ from hadron pair transverse spin asymmetry

\[
A_{UT}^{\sin(\Phi_R + \Phi_S) \sin \theta}(x, z, M_h; Q^2) = -C_y \frac{|R|}{M_h} \sum_q e_q^2 h_1^q(x; Q^2) H_{1,sp}^q(z, M_h; Q^2) \frac{1}{\sum_q e_q f_1^q(x; Q^2) D_1^q(z, M_h; Q^2)}
\]

But **di-hadron fragmentation functions** unknown

⇒ Extract them via hadron pair multiplicities
motivation:
transversity from hadron pair transverse spin asymmetry

\[ A_{UT}^{\sin(\Phi_R+\Phi_S)\sin \theta}(x, z, M_h; Q^2) = -C_y \frac{|R|}{M_h} \frac{\sum_q e_q^2 h_1^q(x; Q^2) H_{1,sp}^q(z; M_h; Q^2)}{\sum_q e_q^2 f_1^q(x; Q^2) D_1^q(z; M_h; Q^2)} \]

Hadron pair multiplicities to extract di-hadron fragmentation functions
First measurement in \( M_{\text{inv}}, z=z_1+z_2 \), \( Q^2 \) bins

Significant \( z, M_{\text{inv}} \) dependence
in agreement with Lepto

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Charged pion multiplicities vs $(x,y,z)$

Main motivation:

**Fragmentation functions** via single hadron multiplicities (at LO)

\[
M^h = \frac{\sum_q e_q^2 (p(x, Q^2)D_q^h(z) + \bar{q}(x, Q^2)D_{\bar{q}}^h(z))}{\sum_q e_q^2 (p(x, Q^2) + \bar{q}(x, Q^2))}
\]

Kinematic domain:
- $Q^2 > 1 \text{ (GeV/c)}^2$
- $0.1 < y < 0.7$
- $W > 5 \text{ GeV/c}$
- $0.004 < x_B < 0.7$
- $0.2 < z_h < 0.85$

*2006 data on deuterium ($^6\text{LiD}$) target*

- Precise measurement
- Wide kinematic coverage
- Input for global QCD fit

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Charged kaon multiplicities vs (x,y,z)

Play a key role in the strange quark polarization puzzle

COMPASS Preliminary
- K^+
- K^-

Systematic uncertainty fully correlated at low y, low z

Reduced systematic errors
SIDIS cross section: azimuthal asymmetries

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

\[
A_{\cos \phi_h}^{UU} = \frac{1}{Q} \text{Cahn} + \frac{1}{Q} \text{BM}
\]

\[
A_{\cos 2\phi_h}^{UU} = \text{BM} + \frac{1}{Q^2} \text{Cahn}
\]

**Cahn effect + Boer-Mulders DF**

**Boer-Mulders x Collins FF + Cahn effect**

**Cahn effect**
kinematical effect due to quark transverse momentum

\[
\frac{d\sigma}{d\phi_h} = 1 - 4 \frac{(k_T^2)}{Q(P_t^2)} P_{\cos \phi_h} \cos \phi_h + ...
\]

**Boer-Mulders PDF**
Correlation between the quark transverse momentum and the quark spin in an unpolarized nucleon quark
SIDIS cross section: azimuthal asymmetries

\[ \cos \Phi \]
- Large signal in the whole x range
- Strong z dependence

\[ \cos 2\Phi \]
- Different for \( h^+ \) & \( h^- \)
- Significant signal at small x
- Strong dependence upon x,z, \( p_T \)

Investigate unexpected kinematic dependences observed via a multi-dimensional analysis

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SIDIS cross section: azimuthal asymmetries

Difficult to reproduce by models
Conclusions

COMPASS has investigated transverse spin effect via SIDIS off deuterium and proton targets

Results on Collins and Sivers asymmetries for charged and identified hadrons
Clear signals on p to be deeply investigated via multidimensional analysis \((x, Q^2, z, p_T)\) of the p data

Possible measurements on p and d with different beam energies on a longer time scale

Results on hadron pair transverse spin asymmetries off p and d very similar trend for \(\pi^+\pi^-\) than for the Collins asymmetries

COMPASS has produced interesting results on SIDIS off unpolarised deuterium
  - Single hadron multiplicities vs \((x,y,z)\) and \(p_T^2\)
  - Hadron pair multiplicities for the first time in \((z,Q^2,M_{inv})\)

Unpolarized azimuthal asymmetries & multiplicities on p from the SIDIS data which will be collected in parallel with DVCS after 2015
backup
Collins asymmetries on protons: COMPASS vs HERMES

COMPASS x range limited to x>0.032 region (overlap with HERMES)

Good agreement:
Non trivial result, COMPASS Q² larger by a factor 2-3 than HERMES’s Q² in the last 3 x bins  → Weak Q² dependence of the Collins effect
Sivers asymmetries on protons: COMPASS vs HERMES

COMPASS x range limited to x>0.032 region (overlap with HERMES)

HERMES $\pi^+$ and $K^+$ asymmetries larger than COMPASS

COMPASS $Q^2$ larger by a factor 2-3 than HERMES’s $Q^2$ in the last 3 x bins

→ Important role of the $Q^2$ dependence in Sivers case
Collins asymmetries vs model predictions

Comparison with fit to HERMES p, COMPASS p & d, BELLE e+e- data by M. Anselmino et al., arXiv:1303.3822

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\( \rightarrow \) Good agreement for \( x, z, p_T^h \) within the uncertainties
Collins asymmetries vs model predictions

Comparison with fit to HERMES p, COMPASS p & d, BELLE e+e- data by
M. Anselmino et al., arXiv:1303.3822
Sivers asymmetries on proton – $Q^2$ evolution

Charged hadrons, 2010 data compared with model calculation by S.M. Aybat, A. Prokudin and T. C. Rogers, PRL 108 (2012) 242003

$x > 0.032$

$<Q^2> = 8.7 \text{(GeV/c)}^2$

Full $x$ range

$<Q^2> = 3.8 \text{(GeV/c)}^2$

Good agreement between data and model calculations
Dihadron asymmetry on deuteron – $\pi^+\pi^-$ and $K^+K^-$

$\pi^+\pi^-$: Compatible with zero asymmetries
$K^+K^-$: Low statistics
Dihadron asymmetry on deuteron – $\pi^+K^-$ & $K^+\pi^-$

2002-04

No clear signal
Unidentified hadron multiplicities vs (x,y,z)

COMPASS Preliminary

- $h^+$
- $h^-$

- 3-dimensional High precision measurement
- Wide kinematic domain
Dihadron asymmetry on proton: $\pi^+\pi^-$ vs model

Combined 2007 & 2010 data


$\langle A_{UTP} \sin \theta \rangle$ vs $x$ and $z$ with $M_{\text{inv}}^{\pi^+\pi^-} < 1.5$ (GeV/c$^2$)

Bachetta, Radici
Ma et al.: SU6
Ma et al.: pQCD

good agreement with Bachetta’s calculation
Sivers asymmetry on proton – $Q^2$ evolution

Charged hadrons, 2010 data compared with model calculation by M. Anselmino, M. Boglione, S. Melis  
arXiv:1204.1239

Good agreement between data and model calculations.