TMD measurements at COMPASS

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1  Motivation
2  COMPASS experiment
3  Collins-Sivers
4  Other TMD’s
Nucleon structure

Three twist-2 quark DF’s in collinear approximation ($\int dk_\perp$)

$$\Phi_{Coll}^{Tw^{-2}}(x) = \frac{1}{2} \left\{ q(x) + S_L \gamma_5 \Delta q(x) + S_T \gamma_5 \gamma^1 \Delta_T q(x) \right\} n^+$$

$$\frac{S_z^N}{\hbar} = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L^q_z + L^g_z$$

NR limit [boost, rotat.]=0

$$\Rightarrow \Delta_T q(x, Q^2) = \Delta q(x, Q2)$$

$$\Rightarrow$$ Expect non small $\Delta_T q$

≈30% : Spin puzzle
Transverse Momentum Distributions

Twist-2 DF

- $f_I$: Number Density
- $g_I$: Helicity
- $h_{1L}$: Worm-gear
- $f_{1T}$: Sivers
- $g_{1T}$: Transversity

Survive $k_T$ integration

Twist-3 DF

- $f_{1L}$: Boer-Mulders
- $h_{1L}$: relativistic effects and no mix with gluons in spin $\frac{1}{2}$ nucleon

Sivers & BM: Naive T-odd elements:
- contain information about OAM
- sign change between SIDIS and DY

Fragmentation Functions (FF)

- Chiral-Odd TMD ($\gamma_5 \gamma^1$)
TMD formalism in SIDIS

\[
\frac{d\sigma}{dx dy d\phi_s dz d\phi_h dP^2_{h\perp}} = \frac{\alpha^2 y^2}{x y Q^2 2(1 - \varepsilon)}.
\]

\[
\left\{ F_{UU,T} + \ldots \right. \\
+ \varepsilon \cos(2\phi_h) \cdot F_{UU}^{\cos(2\phi_h)} + \ldots \\
+ S_L [\varepsilon \sin(2\phi_h) \cdot F_{UL}^{\sin(2\phi_h)} + \ldots] \\
+ S_T [\varepsilon \sin(\phi_h + \phi_S) \cdot F_{UT}^{\sin(\phi_h + \phi_S)} + \ldots] \\
+ \sin(\phi_h - \phi_S) \cdot (F_{UL}^{\sin(\phi_h - \phi_S)} + \ldots) \\
+ \varepsilon \sin(3\phi_h - \phi_S) \cdot F_{UT}^{\sin(3\phi_h - \phi_S)} + \ldots] \\
+ S_L \lambda_e [\sqrt{1 - \varepsilon^2} \cdot F_{LL} + \ldots] \\
+ S_T \lambda_e [\sqrt{1 - \varepsilon^2} \cos(\phi_h - \phi_S) \cdot F_{LT}^{\cos(\phi_h - \phi_S)} + \ldots] \right. 
\]

Unpolarized

Polarized Target

Polarized Beam and Target

\( S_L, S_T \): Target Polarization; \( \lambda_e \): Beam Polarization

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Claude Marchand - IIFF 2013
COMpass at CERN

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

Fixed target experiment at CERN SPS
Data taking since 2002

2002-2007, 2010-2011: Nucleon spin structure with muon beam on polarized targets (L,T)
2008-2009: Meson and baryon spectroscopy with pion beam

2014-2015: Polarized Drell-Yan with pion beam
2016-2017: Deep Virtual Compton Scattering (GPD)
Compass setup 2002-2011

- High acceptance

160 GeV/c long. polarized muon beam (~80% pol., 10⁷ μ/s)

1.2 m long transversely polarized targets:
- 2002-2004: $^6$LiD, 50% pol., 40% dilution factor
- 2007, 2011: NH₃, 90% pol., 15% dilution factor
SIDIS event selection

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

**h± selection:** \( p_t^h > 0.1 \text{ GeV/c} \)
\[z > 0.2 \quad + \text{low } y \text{ low } z\]

**Graph:**
- \(<Q^2>(\text{GeV/c}^2)\)
- \(Q^2 (\text{GeV/c}^2)^2\)
- \(p_l = 160 \text{ GeV/c}\)
- \(27.5 \text{ GeV/c}\)
- \(6 \text{ GeV/c}\)
- Complementary to HERMES, Jlab, JLab12

**Graph Caption:**
- Pions
- COMPASS 2010 PROTON DATA
- Preliminary
Azimuthal modulations: Collins SSA

$\phi_s$, azimuthal angle of spin vector of fragmenting quark ($\phi_{s'} = \pi - \phi_s$)

$\phi_h$, azimuthal angle of hadron momentum

$\Phi_C = \phi_h - \phi_{s'} = \phi_h + \phi_s - \pi$  Collins angle

\[
A_{\text{Coll}} = \frac{A_C^h}{f \cdot P_T \cdot D_{nn}} = \frac{\sum_q e_q^2 \cdot h_1^q \otimes H_{1q}^h}{\sum_q e_q^2 \cdot f_1^q \cdot D_{1q}^h}
\]

“transversity” PDF $\otimes$ Collins FF

Transversity coupled to another chiral-odd function: Collins fragmentation function
describing the correlation between the fragmenting quark spin and the hadron momentum
Collins asymmetries, results on proton

Results from 2007 and 2010 data taking

- at small $x$ asymmetries compatible with zero
- Strong signal in the valence region of opposite sign for $\pi^+$ and $\pi^-$
- opposite sign
  - $D_{\pi^-}$-Dfav

$K^+$ negative trend in the valence region
$K^-$ positive in average

$syst error \sim 0.6$ stat error

INPC2013
Collins asymmetries, results on proton

Results from 2007 and 2010 data taking

- at small $x$ asymmetries compatible with zero
- Strong signal in the valence region of opposite sign for $\pi^+$ and $\pi^-$
- opposite sign
  - $D_{uf} \sim D_{fav}$

$K^\circ$ compatible with zero

syst error $\sim 0.6$ stat error
Collins asymmetries, results on proton

Comparison between HERMES and COMPASS, limiting COMPASS range to the x>0.032 region, overlap with HERMES

Good agreement:
- Non trivial result:
- $Q^2$ COMPASS larger of HERMES’s of a factor 2-3 in the last x bins
- weak $Q^2$ dependence of the Collins effect
Collins asymmetries, results on deuterium

Asymmetries on deuteron target compatible with zero

Some small effects expected even if $H_{1 \text{ unf}} \sim -H_{1 \text{ fav}}$

→ cancellation between $\Delta_T u(x)$ and $\Delta_T d(x)$

handle on $\Delta_T d(x)$

systematic error below 30% of the statistical one

fit by Torino group (arxiv 1303.3822)
dihadron asymmetry

independent channel to access transversity

\[
\phi_C = \phi_h - \phi_{S'} = \phi_h + \phi_S - \pi
\]

\[
\phi_h = \frac{(\vec{q} \times \vec{l}) \cdot \vec{p}_T^h}{|\vec{q} \times \vec{l}| \cdot |\vec{p}_T^h|} \arccos \left( \frac{(\vec{q} \times \vec{l}) \cdot (\vec{q} \times \vec{p}_T^h)}{|\vec{q} \times \vec{l}| \cdot |\vec{q} \times \vec{p}_T^h|} \right)
\]

\[
N(\phi_C) = N^0 \cdot \left\{ 1 + f P_T D \cdot A_{Coll} \cdot \sin \phi_C \right\}
\]

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

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

\[
\vec{R} = \frac{z_2 \vec{p}_1 - z_1 \vec{p}_2}{z_1 + z_2} = \xi_2 \vec{p}_1 - \xi_1 \vec{p}_2
\]

\[
N(\phi_{RS}) = N^0 \cdot \left\{ 1 + f P_T D \cdot A_{RS} \cdot \sin \phi_{RS} \right\}
\]

\[\vec{q} \times \vec{R} = \vec{q} \times \vec{R}_T\]
dihadron asymmetry

independent channel to access transversity

Collins

\[ A_{Coll} \approx \frac{\sum q e_q^2 h^q \otimes H^q_\perp}{\sum q e_q^2 f^q_1 \otimes D_q} \]

“Collins FF”

Belle Babar

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dihadron

\[ A_{RS} \approx \frac{\sum q e_q^2 h^q \cdot H^\perp_q}{\sum q e_q^2 f^q_1 \cdot D^{2h}_q} \]

“Interference / Di-hadron FF”

Belle Babar

“spin independent di-hadron FF”

being measured at COMPASS
dihadron asymmetry and Collins asymmetries

remarkable similarity between

- Collins asymmetry for h+ and Collins asymmetry for h-  
  “mirror symmetry”: similar absolute values, opposite sign

- dihadron asymmetry and Collins asymmetries  
  same sign as Collins h+, only somewhat larger than the mean of Collins h+ and  
  – Collins h- (as expected)

first investigation:

correlations between the relevant azimuthal angles and the corresponding asymmetries  
→ information on the nature of the fragmentation

Collins vs 2h interference mechanisms
Azimuthal modulations: Sivers SSA

\( \phi_s \) azimuthal angle of spin vector of initial quark

\( \phi_h \) azimuthal angle of hadron momentum

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

\[
A_{Siv} = \frac{A^h_S}{f \cdot P_T} = \frac{\sum_q e^2_q f^q_{1T} \otimes D^h_{1q}}{\sum_q e^2_q f^q_1 \cdot D^h_{1q}}
\] Sivers PDF \( \otimes \) FF

Sivers PDF: correlation between the intrinsic transverse momentum of unpolarized quarks in a transversely polarized nucleon

Sensitive to orbital angular momentum
Sivers asymmetries, results on proton

- large signal for $\pi^+$ and $K^+$ over all the measured $x$ range
- increasing with $z$
- linear behavior at small $p_T$, saturation for $P_T > 0.4$ GeV/c

$K^+$ positive in average
$K^-$ compatible with 0

- difference between $K^+$ and $\pi^+$: important role of sea quarks?

Results from 2007 and 2010 data taking

syst error $\sim 0.6$ stat error
Sivers asymmetries, results on proton

Comparison between HERMES and COMPASS, limiting COMPASS range to the x>0.032 region, overlap with HERMES

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

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

$\rightarrow Q^2$ dependence of the Sivers effect plays a role

TMD $Q^2$ evolution has been worked out and added in global fits very recently

S. M. Aybat, A. Prokudin, T. C. Rogers
PRL 108 (2012) 242003
M. Anselmino, M. Boglione, S. Melis
PRD 86 (2012) 014028
TMD evolution of Sivers


SIDIS cross section: other transverse spin asymmetries

\[
\frac{d\sigma}{dx \, dy \, d\psi \, dz \, d\phi_H \, dP_T^2} = \frac{\alpha^2}{x y Q^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_H \: F_{UU}^{\cos \phi_H} \right. \\
+ \varepsilon \cos(2\phi_H) \: F_{UU}^{\cos 2\phi_H} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_H \: F_{LU}^{\sin \phi_H} \right. \\
+ \left. S_{\parallel} \left[ \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_H \: F_{UL}^{\sin \phi_H} + \varepsilon \sin(2\phi_H) \: F_{UL}^{\sin 2\phi_H} \right] \right\}
\]

\[
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) \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)} \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. \\
+ \left. 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. \left( \lambda_e \left[ \sqrt{1-\varepsilon^2} \cos(2\phi_H - \phi_S) \: F_{LT}^{\cos(2\phi_H - \phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_H - \phi_S) \: F_{LT}^{\cos(2\phi_H - \phi_S)} \right. \right. \right]\right. \\
+ \left. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \r

pretzelosity $h_{1T} \otimes H_1$

wormgear $g_{1T} \otimes D_1$

Remaining four can be interpreted as twist-3 contributions
other transverse spin asymmetries on p (also results on d)

different factors $D(y)$
$\rightarrow$ different statistical errors

Anna Martin
other transverse spin asymmetries on p

$$A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$

"Worm Gear" PDF

**Worm-gear**

$$\propto g_{1T}^t(x, p_T^2) \otimes D_1(z, k_T^2)$$

- describes the probability to find longitudinally polarized quarks in a transversely polarized nucleon ($\rightarrow "\text{trans-helicity}"")
- accessible in LT DSAs through the leading-twist $\cos(\phi_h - \phi_s)$ Fourier component

same trend
longitudinal spin azimuthal asymmetries

first measurement on d 2004 data: all compatible with zero

\[ F_{UL}^{\sin 2\phi_h} \propto h_{1L}^\perp \otimes H_I^\perp \]

“worm gear” PDF
\otimes Collins FF

Probability to find a transversely polarized quark in a longitudinally polarized nucleon

being measured with better statistics on d and on p

COMPASS 2002-4
HADRON ASYMMETRY
from L-POLARIZED D-TARGET

EPJC 70 (2010) 39
SIDIS cross section: unpolarized part

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

From A. Bacchetta et al., JHEP 0702:093,2007. e-Print: hep-ph/0611265
SIDIS cross section: unpolarized part

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

\[ A_{\sin \phi_h}^{UU} \text{ higher twist effect proportional to beam polarization} \]
\[ A_{\cos \phi_h}^{UU} = \frac{1}{Q} \text{Cahn} + \frac{1}{Q} \text{BM} \quad \text{Cahn effect} + \text{Boer-Mulders DF} \]
\[ A_{\cos 2\phi_h}^{UU} = \text{BM} + \frac{1}{Q^2} \text{Cahn} \quad \text{Boer-Mulders} \times \text{Collins FF} + \text{Cahn effect} \]

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

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

**Boer-Mulders PDF**
Correlation between the quark transverse momentum and the quark spin in an unpolarized nucleon quark

pQCD contributions expected to be important for \( p_T > 1 \text{GeV/c} \)
TMD: Boer-Mulders in SIDIS

A. Airapetian et al, Phys. Rev. D 87 (2013) 012010

transversely polarised quarks with $p_T$ in unpolarised nucleon

$h_1^\perp$ is chiral-odd and naive T-odd (like $f_{1T}^\perp$) requires FSI/ISI

Opposite sign for $\pi^+$ and $\pi^-$, larger magnitude for $\pi^-$

$h_{1,1,u}^\perp$ and $h_{1,1,d}^\perp$ have same sign

Large signal with same sign for $K^\pm$

sea fragmentation important
Compass has investigated so far following transverse spin and TMD on p and d:

- Collins/Sivers for $\pi^+, \pi^-, K^+, K^-, K^0$ on p,d
- Other 6 TMD (2 twist 2, 4 twist3) for h+, h- on p,d (WG, pretzelosity,...)
- 2-hadron asymmetries for $\pi\pi$, $\pi K$ and $KK$ on p, $h+h$- on d
- Longitudinal azimuthal spin asymmetries on d (WG)
- Unpolarized hadron azimuthal distributions on d (BM)

Still a lot to extract from 2002-2010 data:
- Collins/Sivers: multi dimensional analysis
- Further investigations for single and di hadron asymmetries
- Longitudinal azimuthal spin asymmetries on p
- Unpolarized hadron azimuthal distributions on d with PID
- ...............................................................

Future:
- 2014-2015: Sivers, BM in polarized Drell-Yan