TMD measurements at COMPASS

4th Workshop on the QCD Structure of the Nucleon (QCD-N'16)

Giulio Sbrizzai – Trieste INFN
on behalf of the COMPASS Collaboration
Common Muon and Proton Apparatus for Structure and Spectroscopy

wide physics program carried on using both muon and hadron beam

luminosity: $\sim 5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
beam intensity: $2 \cdot 10^8 \mu^+$/spill (4.8s/16.2s)
beam momentum: 160 GeV/c

deuteron ($^6\text{LiD}$)
proton ($\text{NH}_3$)

H$_2$ target

longitudinally polarized muon beam

Transversely (T) or Longitudinally (L) polarised Target

2002 L/T
2003 L/T
2004 L/T
2006 L
2007 L/T
2010 T
2011 L
2012 L

nuclear targets
2004
2008
LH target
2009
2012
T polarised DY
2014
2015

12/07/2016 Giulio Sbrizzai QCD-N'16
Accessing Spin and TMD PDFs and FFs

- **SIDIS off polarized p, d, n targets**
  \[ \sigma_{\ell p \to \ell' h X} \sim q(x) \otimes \hat{\sigma}^{lq \rightarrow lq} \otimes D_q^h(z) \]

- **Hard polarised pp scattering**

- **Polarised Drell-Yan**
  \[ \sigma^{hp \rightarrow \mu\mu} \sim \bar{q}_h(x_1) \otimes q_p(x_2) \otimes \hat{\sigma}^{\bar{q}q \rightarrow \mu\mu}(\hat{s}) \]

- **$e^+ e^- \rightarrow h_1 h_2$**
  \[ \sigma^{e^+ e^- \rightarrow h_1 h_2} \sim \hat{\sigma}^{\ell\ell \rightarrow \bar{q} q}(\hat{s}) \otimes D_q^{h_1}(z_1) \otimes D_{\bar{q}}^{h_2}(z_2) \]
SIDIS event selection

$Q^2 > 1 \text{ (GeV/c)}^2$

$0.1 < y < 0.9$

$W > 5 \text{ GeV/c}^2$

complementary to HERMES and Jlab 6/12
charged hadron selection
\[ z > 0.2 \]
\[ p_t^h > 0.1 \text{ GeV/c} \]

definition of the produced hadron and target polarisation azimuthal angles \( \phi_h \) and \( \phi_S \)
polarised SIDIS azimuthal cross section

Bacchetta et al. JHEP 0702:093, 2007

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

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

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

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

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

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

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

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

14 independent modulations in $\varphi_h$ and $\varphi_S$
polarised SIDIS azimuthal cross section

Bacchetta et al. JHEP 0702:093,2007

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

unpolarised part

transverse spin dependent part

target polarisation

beam polarisation

\[ F = \sum_q PDF_q(x) \otimes FF^h_q(z) \]
OUTLINE

→ Hadron Transverse Momentum ($P_T^h$) dependent Multiplicities

→ Unpolarised Azimuthal Asymmetries (Boer-Mulders, Cahn effect)

→ Transverse Spin dependent Asymmetries
  → Collins, Sivers
  → $P_T^h$ weighted Sivers asymmetries

NEW
Unpolarised SIDIS
Relevance of unpolarised SIDIS for the TMDs

- The cross-section dependence from $P_{hT}$ results from:
  - intrinsic $k_\perp$ of the quarks
  - $p_\perp$ generated in the quark fragmentation
  - A Gaussian ansatz for $k_\perp$ and $p_\perp$ leads to
    - $\left\langle P_{hT}^2 \right\rangle = z^2 \left\langle k_\perp^2 \right\rangle + \left\langle p_\perp^2 \right\rangle$

Results have been produced from 2004/2006 deuteron data

*multi dimensional analysis performed*
h+ / h- difference more pronounced at large x and large z

0.4 < z < 0.6

paper in a few months
Unpolarised Azimuthal Asymmetries measured from 2004 deuteron data

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

convoluted with the Collins FF

multiD performed both on \( \cos \phi \) and \( \cos 2\phi \)
Unpolarised Azimuthal Asymmetries measured from 2004 deuteron data

\[ A_{UU}^{\cos 2\phi} \approx \frac{1}{Q^2} Cahn + BM \]

convoluted with the Collins FF

multiD performed both on \( \cos \phi \) and \( \cos 2\phi \)
Polarised SIDIS
The Collins asymmetry

- results on deuteron (2002-2004 data) compatible with zero
  HERMES p + COMPASS p&d + BELLE $\rightarrow$ extraction of transversity for u and d quarks

  published measurements on transversely polarised proton
  very good agreement between two independent data set

- multi dimensional analysis

- more recent:
  - comparison with di-hadron asymmetries $\rightarrow$ interplay
Collins: Multi-D approach
\(x: Q^2; z: p_T\)

- \(0.1 < z < 0.2\)
- \(0.2 < z < 0.4\)
- \(0.4 < z < 1.0\)

Proton 2010 data
\(0.1 < z < 0.2; p_T > 0.1\) GeV/c
\(0.2 < z < 0.4; p_T > 0.1\) GeV/c
\(0.4 < z < 1.0; p_T > 0.1\) GeV/c

- \(1 < Q^2 < 1.7\)
- \(1.7 < Q^2 < 3\)
- \(3 < Q^2 < 7\)
- \(7 < Q^2 < 16\)
- \(16 < Q^2 < 81\)

\(h^+, h^-\)
Interesting studies comparing with the Di-hadron Transverse Spin Asymmetries

Analysis of the single hadron and dihadron asymmetries performed on a common data sample (2010 transversely polarised proton) standard COMPASS SIDIS sample but with $h^+ h^-$ at least detected (each hadron with $z > 0.1$)

Study of the azimuthal correlations of the two hadrons

$$\Delta \phi = \phi_{h^+} - \phi_{h^-}$$
Interesting studies comparing with the Di-hadron Transverse Spin Asymmetries

\[
\frac{d\sigma_{h^+h^-}}{d\phi_h^+d\phi_h^-d\phi_S} = \sigma_U^{h^+h^-} + S_T \left[ \sigma_{1C}^{h^+h^-} \sin(\phi_h^+ + \phi_S - \pi) + \sigma_{2C}^{h^+h^-} \sin(\phi_h^- + \phi_S - \pi) \right]
\]

"a common origin"
The Sivers asymmetry

- results on deuteron (2002-2004 data) compatible with zero


  very good agreement between two independent data set

- multi dimensional analysis

**Recent Measurements**

- Gluon Sivers
- Sivers from J/ψ
- Weighted Sivers asymmetries  NEW!
Sivers: Multi-D approach
\(x: Q^2; z: p_T\)

Positive signal

\(Q^2 > 16 \Rightarrow \text{DY}\)

TMD \(Q^2\) evolution
Gluon Sivers from high-$P_T^h$ two hadrons pairs

\[ \ell + N \rightarrow \ell' + 2h + X \]

\[ \bar{P}_{2h} = \bar{p}_1 + \bar{p}_2 \]

\[ \phi = \phi_{2h} - \phi_S \]

NN MC to tag the different contributing processes

$\phi_{2h}$ correlated to $\phi_{\text{gluon}}$
Gluon Sivers from $J/\psi$

from 2010 transversely polarised proton data in two $z$ bins $0.30 < z < 0.95$ and $0.95 < z < 1.05$
New measurement: $P_T^h$ weighted Sivers Asymmetry

$$A_{Siv}^w = \frac{1}{M} \frac{\sigma_S^w}{\sigma_U}$$

$$\sigma_S^w = \int \sigma_S(P_T^h) \cdot \frac{P_T^h}{z} dP_T^h$$

$$\sigma(\phi_{Siv}) = \sigma_U + \int \sigma_S(P_T^h) \cdot \frac{P_T^h}{z} dP_T^h \cdot \sin(\phi_{Siv})$$

Standard Sivers Asymmetry:

$$A_{Siv} = \frac{\sigma_S}{\sigma_U}$$

$$\sigma(\phi_{Siv}) = \sigma_U + \sigma_S \sin(\phi_{Siv})$$

Convolution over TM $\rightarrow$ Product of Sivers (first moment) and FF

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

in a model independent way (no assumption on the shape of PDFs and FFs)

Assuming polarization = +1 and dilution factor = 1

$$f_{1T}^{(1)}(x) = \int d^2k_T \frac{k_T^2}{2M^2} f_{1T}(x, k_T^2)$$

J. C. Collins et al. PRD 73 (2006) 014021
The $P_T^h/z$ distributions for each bin of $x$

- $<P_T^h/z> = 1.69$ GeV, $<Q^2> = 1.27$ GeV$^2$ for $0.003 < x < 0.008$
- $<P_T^h/z> = 1.66$ GeV, $<Q^2> = 1.55$ GeV$^2$ for $0.008 < x < 0.013$
- $<P_T^h/z> = 1.61$ GeV, $<Q^2> = 1.83$ GeV$^2$ for $0.013 < x < 0.020$

**COMPASS 2010 proton data**

- $<P_T^h/z> = 1.55$ GeV, $<Q^2> = 2.17$ GeV$^2$ for $0.020 < x < 0.032$
- $<P_T^h/z> = 1.49$ GeV, $<Q^2> = 2.82$ GeV$^2$ for $0.032 < x < 0.050$
- $<P_T^h/z> = 1.49$ GeV, $<Q^2> = 4.34$ GeV$^2$ for $0.050 < x < 0.080$

**preliminary**

- $<P_T^h/z> = 1.49$ GeV, $<Q^2> = 6.76$ GeV$^2$ for $0.080 < x < 0.130$
- $<P_T^h/z> = 1.47$ GeV, $<Q^2> = 10.55$ GeV$^2$ for $0.130 < x < 0.210$
- $<P_T^h/z> = 1.53$ GeV, $<Q^2> = 20.65$ GeV$^2$ for $0.210 < x < 0.700$
Final results compared with the standard Sivers Asymmetries \cite{PLB 717 (2012) 383}

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

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

Gaussian assumption and \( a_{Gauss} \) needed to extract standard Sivers Function

J. C. Collins et al. PRD 73 (2006) 014021
from the ratio \[ \frac{A_{Siv}^w}{A_{Siv}} \]

one can measure

\[ a_{Gauss} \propto \frac{1}{\sqrt{k_{T,Sivers}^2 + p_{\perp}^2 / z^2}} \]

J. C. Collins et al. PRD 73 (2006) 014021
Special: plots from Drell-Yan 2015 polarised proton data

Pion beam on transversely polarized nucleon

COMPASS assets

- SIDIS and DY experiments: large acceptance, same kinematic region
- Unique hadron beam (π, K, p) with valence antiquarks
- Polarized target

2015 data, 644k $J/\psi$
18k HM ($M_{\mu\mu} > 4$ GeV$/c^2$)

Projection 2 years (2015+2018 data)
Conclusions and Outlook

Many important results produced by COMPASS to investigate TMDs in SIDIS higher statistics data on transversely polarised d data still needed

DY data promising, more results soon to come

New data in the near future
  2016-2017 unpolarised SIDIS on p, in parallel with DVCS

COMPASS III ....
backup
the COMPASS spectrometer

- high energy beams
- large angular acceptance
- broad kinematical range

two stages spectrometer
Large Angle Spectrometer (SM1)
Small Angle Spectrometer (SM2)

variety of tracking detectors
to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad with a good azimuthal acceptance

calorimetry, $\mu$ID
RICH

Polarised Target

$\mu$ beam

MuonWall

SM1

SM2

$\sim 50$ m

Hadron identification:
$\pi^\pm K^\pm$
based on RICH-1 response (likelihood algorithm)

Cherenkov thresholds
$\pi \sim 3$ GeV/c
$K \sim 9$ GeV/c
$p \sim 18$ GeV/c
Unpolarised Azimuthal Asymmetries measured from 2004 deuteron data

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

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

multi dimensional analysis performed to further investigate the interesting dependencies found
COMPASS and HERMES results

negligible $Q^2$ evolution? ($Q^2$ factor 2 or 3 larger in COMPASS)
Interesting studies comparing with the Di-hadron Transverse Spin Asymmetries

$$A_{UT}^{\sin \phi_{RS}}$$

$$N_{h^+ h^-}(\phi_{RS}) = N_h^0 \left[ 1 \pm f_T D_{NN} A_{UT}^{\sin \phi_{RS}} \sin(\phi_{RS}) \right]$$

on oppositely charged hadrons pairs

$$lN \rightarrow l' h^+ h^- X$$

$$A_{UT}^{\sin \phi_{RS}} \approx \frac{\sum_q e_q^2 \cdot h_1^q(x) \cdot H_{1q}^Z(z, M_{hh}^2)}{\sum_q e_q^2 \cdot f_1^q(x) \cdot D_{1q}^h(z, M_{hh}^2)}$$

collinear!

the azimuthal distribution of the hadrons pairs shows a modulation in the azimuthal angle:

$$\phi_{RS} = \phi_R + \phi_S - \pi$$

COMPASS and HERMES results

**TMD** $Q^2$ evolution? ($Q^2$ factor 2 or 3 larger in COMPASS)
fundamental QCD prediction

\[ f_{1T}^{\perp} (\text{SIDIS}) = -f_{1T}^{\perp} (\text{DY}) \]

COMPASS is taking Drell-Yan data with transversely polarised target (full year dedicated)

superposition DY – SIDIS kinematical region at COMPASS
Sivers in DY range

COMPASS preliminary
Proton 2010 data
data taking period
(target transverse polarisation reversal)

one period (week)

number of hadrons in sub-period 1

\[ N_1 \quad \text{cell a+d first sub-period} \]

number of hadrons in sub-period 2

\[ N_2 \quad \text{cell b+c first sub-period} \]

\[ N_1' \quad \text{cell a+d second sub-period} \]

\[ N_2' \quad \text{cell b+c second sub-period} \]

data taking period

\[ N_1^w = \sum_{k=1}^{N_1} \frac{P_{T,k}^h}{Z_k \cdot M_{Pr}} \]

and the same for \[ N_2^w, N_1'^w, N_2'^w \]

weighted counts are defined as:

\[ N_1^w = \sum_{k=1}^{N_1} \frac{P_{T,k}^h}{Z_k \cdot M_{Pr}} \]

in each \( \varphi_{\text{siv}} \) bin

number of hadrons in sub-period 1

number of hadrons in sub-period 2
Since only the spin dependent part of the cross section is weighted we used different method from the standard ones (DR, UML)

First method implemented:

\[
\Delta^w = N^w_1 - N'^w_1 + N'^w_2 - N^w_2 \\
\Sigma = N_1 + N'_1 + N'_2 + N_2 \\
R'(\Phi_{Siv}) = \frac{\Delta^w}{\Sigma}
\]

\[
R'(\Phi_{Siv}) \simeq \bar{S_T} \cdot \epsilon^w \sin \Phi_{Siv}
\]

assuming azimuthal acceptance to be the same for the two sub-periods

\[
\epsilon^w = \frac{\sigma^w_{0S,I}}{\sigma_{U,I}} = 2A_{S_{iv}}^{(1)}
\]

calculated in 16 bins of $\phi_{Siv}$ and fitted using a $p_0+p_1\sin(\phi_{Siv})$ function
The method chosen to extract the final results is

\[ R(\Phi_{S iv}) = \frac{\Delta w}{\sqrt{\Sigma' w \Sigma}} \]

\( \Delta w = N_1^w N_2'^w - N_1'^w N_2^w \)
\( \Sigma^w = N_1^w N_2'^w + N_1'^w N_2^w \)
\( \Sigma = N_1 N_2' + N_1' N_2 \)

Azimuthal acceptance cancels if the Reasonable Assumption holds

\[ a_1 a_2' = a_1' a_2 \]
Other transverse spin dependent asymmetries

there are also other 6 modulations related to different TMDs they all have been measured at COMPASS

\[
\begin{align*}
&+ |S_\perp| \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \\
&+ \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \\
&+ \sqrt{2\varepsilon(1 + \varepsilon)} \sin \phi_S F_{UT}^{\sin \phi_S} + \sqrt{2\varepsilon(1 + \varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \\
&+ |S_\perp| \lambda_e \left[ \sqrt{1 - \varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\varepsilon(1 - \varepsilon)} \cos \phi_S F_{LT}^{\cos \phi_S} \right] \\
&+ \sqrt{2\varepsilon(1 - \varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right),
\end{align*}
\]

just a reminder

sivers
collins
pretzelosity
worm-gear
higher twist effects

all of them measured and found to be compatible with zero
sensitive to the D-wave component
non spherical shape of the nucleon