Latest results from COMPASS TMD physics

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on behalf of the COMPASS Collaboration
OUTLINE

• the COMPASS experiment

• COMPASS results on TMDs from SIDIS off
  • transversely polarised d and p targets
  • Collins and Sivers asymmetries
  • longitudinally polarised d target
  • unpolarised d target

• future TMD measurements
Weihai, August 9, 2011 Anna Martin

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

fix target experiment at the CERN SPS
proposed 1996, approved 1998, data taking since 2002

goals

- meson and baryon spectroscopy
- \(\pi\) polarizability

- nucleon spin structure with a high energy muon beam and longitudinally polarised targets
  - gluon polarisation
  - helicity PDFs

and transversely polarised targets
  - transversity PDFs
COMPASS spectrometer

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

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

| SciFi | Straws |
| Silicon | DC |
| Micromega (P)GEM | MWPC |
| LDC |

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

~ 50 m

MuonWall

calorimetry, PID
RICH detector
COMPASS spectrometer

μ beam

Polarised Target

~ 50 m

MuonWall

E/HCAL

calorimetry, PID

RICH detector

SM1

SM2

RICH

SciFi Silicon Micromega(P)GEM Straws DC MWPCLDC

variety of tracking detectors to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad
longitudinally polarised muon beam
\( p_\mu = 160 \text{ GeV/c} \)

DIS cuts:  
\( Q^2 > 1 (\text{GeV/c})^2 \)

\( 0.1 < y < 0.9 \)

\( W > 5 \text{ GeV/c}^2 \)
the polarized target system (>2005)

$^3$He – $^4$He dilution refrigerator (T~50mK)

- solenoid 2.5T
- dipole magnet 0.6T

μ $^6$LiD p (NH$_3$)

- polarization 50% 90%
- dilution factor 40% 16%

acceptance ± 180 mrad

3 target cells
- 30, 60, and 30 cm long
- opposite polarisation

Weihai, August 9, 2011
COMPASS data taking

2002
2003
2004

polarised deuteron target — L & T (25% of the time)

2005
CERN shutdown

2006
polarised deuteron target — L only

2007
polarised proton target — L & T (50% of the time)

2008 / 2009 spectroscopy

2010
polarised proton target — T only

2011
polarised proton target — L only

ΔG
results

data analysis ongoing
first results soon
some results on TMDs from 2002-2007 data

Collins asymmetry and the transversity PDF

Sivers asymmetry

other azimuthal asymmetries and TMD PDFs from SIDIS off transversely polarised longitudinally polarised unpolarised targets
The Structure of the Nucleon

Three distribution functions are necessary to describe the quark structure of the nucleon at LO in the collinear case. 

\[ \Delta_T q \quad \text{or} \quad h_1 : \text{correlation between the transverse spin of the nucleon and the transverse spin of the quark} \]

\[ f_1, \quad \text{number density} \]

\[ g_1, \quad \text{helicity} \Delta q \]

\[ h_1, \quad \text{transversity} \]

\[ \int \text{d}x \left[ \Delta_T q(x) - \Delta_T \bar{q}(x) \right] \]

Collins effect: LR asymmetry in the hadronisation of transversely polarised quarks

Can be measured in SIDIS off transversely polarised nucleons

\[ Jaffe and Ji, '91 \]
Collins asymmetry

in SIDIS off transversity polarised nucleons

amplitude of the $\sin \Phi_C$ modulation in the azimuthal distribution of the final state hadrons

$$N_h^\pm(\Phi_C) = N_h^0 \left[ 1 \pm P_T \cdot D_{NN} \cdot A_{Coll} \cdot \sin \Phi_C \right]$$

$\Phi_C = \phi_h + \phi_S - \pi$

- $\phi_h$ azimuthal angle of the hadron,
- $\phi_S$ azimuthal angle of the nucleon spin

transversity

"Collins FF"

$$A_{Coll} \approx \sum_q e_q^2 \Delta_T q \otimes \Delta_T^0 D_q^h \over \sum_q e_q^2 q \otimes D_q^h$$

today the most promising way to access transversity
Collins asymmetry
in SIDIS off transversity polarised nucleons

Collins FF: gives a LR asymmetry in the hadronisation of transversely polarised quarks

Products of Collins FFs can be measured in
\[ e^+ e^- \rightarrow \pi^+ \pi^- X \]
first low statistics results from LEP data

2005 first data from BELLE

today the most promising way to access transversity
Collins asymmetry

\[ A_{\text{Coll}} \approx \frac{\sum e_q^2 \Delta_T q \otimes \Delta^0_T D_q^h}{\sum e_q^2 q \otimes D_q^h} \]

first results in 2005 measured by HERMES (proton target) and COMPASS (deuteron target) different from zero compatible with zero

final COMPASS results on deuteron

2002-2004 data  

charged pion and kaon asymmetries also compatible with zero understood as u – d cancellation
Collins asymmetry

the COMPASS $d$, HERMES $p$, and BELLE data are well described in global fits → first extractions of the Collins FFs and the transversity PDFs, and tensor charge


$Q^2$ dependence?

→ COMPASS $p$ data
Collins asymmetry – proton

final COMPASS results from 2007 data

- at small $x$, the asymmetries are **compatible with zero**
- large signal in the valence region of opposite sign for positive and negative hadrons
Collins asymmetry – proton  2007 data

\[ A^p_{\text{Coll}} \]

- For \( h^- \) and \( h^+ \) particles,
- For \( \pi^- \) and \( \pi^+ \) particles,
- For \( K^- \) and \( K^+ \) particles,

The data shows the Collins asymmetry for different hadrons, with preliminary and final results indicated. The plots display the asymmetry as a function of various variables such as transverse momentum and other kinematic quantities.
Collins asymmetry – proton

same sign and strength:
a very important, not obvious result!

\[ \pi^- - \pi^+ + h^- - h^+ \]

COMPASS sign convention

indication for not a higher twist effect,
no strong \( Q^2 \) dependence of the Collins FF
Two Hadron Asymmetry


\[ A_{RS} = \frac{\sum_q e_q^2 \cdot \Delta T \cdot q(x) \cdot H^2_{q/z}(M_{h^2}, z)}{\sum_q e_q^2 \cdot q(x) \cdot D^2_{q/z}(M_{h^2}, z)} \]

h+h- pairs

deytron 2003-4

proton 2007

Preliminary
Collins asymmetry

summary:

• large transverse spin effects observed in SIDIS off p by the COMPASS and HERMES experiments in the valence region

• there is a left-right asymmetry in the hadronisation of transversely polarised quarks

• the transversity distribution is different from zero

• the transversity distribution can be measured in SIDIS off transversely polarised nucleons

more precise SIDIS data are needed, over all the x range, at different $Q^2$ to study its properties

COMPASS contribution in the near future:

results from the 2010 proton data

factor ~ 4 in statistics with respect to the 2007 results
results on TMDs
from 2002-2007 data

Collins asymmetry and the transversity PDF
Sivers asymmetry

other azimuthal asymmetries and TMD PDFs
from SIDIS off transversely polarised longitudinally polarised unpolarised targets
The Structure of the Nucleon

three distribution functions are necessary to describe the quark structure of the nucleon at LO in the collinear case
taking into account the quark intrinsic transverse momentum $k_T$,
at leading order 8 PDFs are needed for a full description of the nucleon structure

“TMDs”

Sivers function
correlation between the transverse spin of the nucleon and the transverse momentum of the quark
sensitive to orbital angular momentum

Boer-Mulders function
correlation between the transverse spin and the transverse momentum of the quark in unpol nucleons

$T$-odd

SIDIS give access to all of them
SIDIS cross-section

\[
\frac{d\sigma}{dx
dy
d\phi_h
dP_{h\perp}^2} = \frac{\alpha^2}{x y Q^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos\phi_h F^{\cos\phi_h}_{UU} \\
+ \varepsilon \cos(2\phi_h) F^{\cos 2\phi_h}_{UU} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin\phi_h F^{\sin\phi_h}_{UU} \\
+ S_{||} \sqrt{2\varepsilon(1+\varepsilon)} \sin\phi_h F^{\sin\phi_h}_{UL} + \varepsilon \sin(2\phi_h) F^{\sin 2\phi_h}_{UL} \right\} + S_{||} \lambda_e \left[ \sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_h F^{\cos\phi_h}_{LL} \right]
\]

**Sivers**

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

**Collins**

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

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

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

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

18 structure functions
14 azimuthal modulations
the Sivers function

a long debate

1992 introduced by D. Sivers
1993 J. Collins demonstrate that it must vanish
2002 S. Brodsky et al.: it can be $\neq 0$ because of FSI
2002 J. Collins: process dependent, change of sign SIDIS $\leftrightarrow$ DY

....

2005 first measurements of the Sivers asymmetry in SIDIS

$$A_{Siv} = \sum_q e_q^2 \tilde{f}_{IT}^q \otimes D_l^q$$

$$\frac{F_{UR}^{sin(\phi_h - \phi_S)}}{F_{UU}}$$

strong signal seen by HERMES for $\pi^+$ on protons
no signal seen by COMPASS for $h^+$ and $h^-$ on deuterons
Sivers asymmetry

2005 first measurements of the Sivers asymmetry in SIDIS
strong signal seen by HERMES for $\pi^+$ on protons
no signal seen by COMPASS for $h^+$ and $h^-$ on deuterons

final COMPASS results on deuteron
2002-2004 data

similar results for identified hadrons
$u$ and $d$ quark contributions cancel in the deuteron
Sivers asymmetry

2005 first measurements of the Sivers asymmetry in SIDIS
strong signal seen by HERMES for $\pi^+$ on protons
no signal seen by COMPASS for $h^+$ and $h^-$ on deuterons

→ first extractions of the Sivers function from HERMES $p$ (and COMPASS $d$) data

M. Anselmino et al., Transversity2005

good description of the experimental results

still, waiting for higher energy proton data
Sivers asymmetry

2010: final COMPASS results from 2007 proton data

PLB 692 (2010) 240

evidence for a positive signal for $h^+$, which extends to small $x$, in the region not measured before

systematic errors

$h^- \sim 0.5 \sigma_{\text{stat}}$
$h^+ \sim 0.8 \sigma_{\text{stat}}$ plus a scale (abs) uncertainty of $\pm 0.01$

preliminary results for charged $\pi e K$: SPIN2010
Sivers asymmetry

- good agreements
- same sign
- COMPASS results in the overlap region smaller by a factor \( \sim 2 \)

higher precision measurements needed soon
\( \Rightarrow 2010 \) run
also to investigate W dependence
the Sivers function

a long debate

1992 introduced by D. Sivers
1993 J. Collins demonstrate that it must vanish
2002 S. Brodsky et al.: it can be $\neq 0$ because of FSI
2002 J. Collins: process dependent, change of sign $\text{SIDIS} \leftrightarrow \text{DY}$
...
2005 first measurements of the Sivers asymmetry in SIDIS
strong signal seen by HERMES for $\pi^+$ on protons
no signal seen by COMPASS for $h^+$ and $h^-$ on deuterons
2010 final results for the Sivers asymmetry from COMPASS 2007 proton data
different from zero for $h^+$
results from 2010 proton data coming soon
(factor $\sim$8 in statistics, much smaller systematic uncertainty)

conclusion: the Sivers function is different from zero and can be measured in SIDIS
and one can try to test the change of sign $\text{SIDIS} \leftrightarrow \text{DY}$
COMPASS II proposal – Drell Yan

COMPASS-II proposal:
190 GeV/c $\pi^-$ beam on
transversely polarised proton target

in valence region (u-quark dominance)

\[ \sigma^{DY} \propto f_{u|\pi^-} \otimes f_{u|p} \]

→ extraction of the u-quark Sivers (and Boer-Mulders) function
Weihai, August 9, 2011

Anna Martin

COMPASS II proposal – Drell Yan

projections with
2 years of data
6 · 10^8 π spill (9.6 s)
1.1 m pol. NH₃

one year of data taking
approved
(December 2010)

with the present
CERN schedule
(shut down in 2013)
the data taking
will be in 2014


Sivers_p

BM_π pretzelosity_p

BM_π transversity_p

X_F = X_π - X_p↑

X_F = X_π - X_p↑
results on TMDs
from 2002-2007 data

Collins asymmetry and the transversity PDF
Sivers asymmetry

other azimuthal asymmetries and TMD PDFs
from SIDIS off transversely polarised
longitudinally polarised
unpolarised targets
SIDIS cross-section

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

all the other 6 transverse spin azimuthal asymmetries have been measured on d (2002-2004) and p (2007):
all compatible with zero!
transversely polarised target

\[ F_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{IT}^\perp \otimes H_1^\perp \]

“pretzelosity” PDF
\[ \otimes \text{Collins FF} \]

Weihai, August 9, 2011

Anna Martin
SIDIS cross-section

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

all the other 6 transverse spin azimuthal asymmetries have been measured on d (2002-2004) and p (2007): all compatible with zero!

next: results from 2010 p data
SIDIS cross-section

\[ \frac{d\sigma}{dx dy d\psi dz d\phi_h dP_{h\perp}^2} = \]

\[ \frac{\alpha^2}{x y Q^2} \frac{y^2}{2(1 - \varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2 \varepsilon(1 + \varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} \right\} \]

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

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

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

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

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

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

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

all the longitudinal spin azimuthal asymmetries have been measured on d (2004):
all compatible with zero!
longitudinally polarised target

$F^{\sin 2\phi_h}_{UL} \propto h^\perp_{1L} \otimes H^\perp_1$

“worm gear” PDF
⊗ Collins FF

COMPASS sign convention

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

small, compatible with zero
within the statistical errors
SIDIS cross-section

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

all the longitudinal spin azimuthal asymmetries have been measured on d (2004):
all compatible with zero!

next: results from
2006 d data
2007, 2010 p data
results on TMDs
from 2002-2007 data

Collins asymmetry and the transversity PDF
Sivers asymmetry

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from SIDIS off transversely polarised longitudinally polarised unpolarised targets
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\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_h^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 \right\} F_{UU}^{\cos\phi_h} \\
+ \varepsilon \cos(2\phi_h) F_{UU}^{\cos2\phi_h} + \lambda_c \sqrt{2\varepsilon(1-\varepsilon)} \sin\phi_h F_{LU}^{\sin\phi_h}
\]

\[
F_{UU}^{\cos2\phi_h} = \mathcal{C} \left[ -\frac{2 \left( \hat{h} \cdot \vec{k}_T \right) \left( \hat{h} \cdot \vec{p}_T \right) - \vec{k}_T \cdot \vec{p}_T}{MM_h} \right] \]

Boer-Mulders DF x Collins FF + Cahn effect (twist 4, 1/Q^2)

\[
F_{UU}^{\cos\phi_h} = \frac{2M}{Q} \mathcal{C} \left[ -\frac{\hat{h} \cdot \vec{k}_T}{M_h} \left( xhH_1^\perp + \frac{M_h}{M} f_1 \tilde{D}_1^\perp \right) - \frac{\hat{h} \cdot \vec{p}_T}{M} \left( xf_1^\perp D_1 + \frac{M_h}{M} h_1^\perp \tilde{H} \right) \right]
\]

\[
xh = x\tilde{h} + \frac{p_T^2}{M^2} h_1^\perp \\
xf_1^\perp = xf_1^\perp + f_1 F_{UU}^{\cos\phi_h} \approx \frac{2M}{Q} \mathcal{C} \left[ -\frac{\hat{h} \cdot \vec{p}_T}{M} f_1 D_1 \right]
\]

\[\Rightarrow <k_T^2>\]
**cosφ and cos2φ modulations**

First results for h+ and h- separately from COMPASS in 2008

**cos φ**
- Large signals over all the x range
- Strong dependence on x, z, $P_T^h$
- Different for h+ and h-
- Boer-Mulders contribution?

**cos 2φ**
- Large signals at small x
- Strong dependence on x, z, $P_T^h$
- Different for h+ and h-
**cos2Φ modulation**

**deuteron data**

Different contributions of the Boer-Mulders term at HERMES and COMPASS?

First fits to extract the B-M function from the cos2Φ asymmetries (Barone et al. 2009)

Cahn contribution not negligible

Work ongoing
and interesting results on hadron distributions in SIDIS off unpolarised deuteron target
hadron multiplicity vs transverse momentum of the final state hadrons

as well as the $\cos \phi_h$ asymmetry, these data can be used to extract the intrinsic transverse momentum
hadron multiplicity vs transverse momentum of the final state hadrons

JF Rajotte, Praha-Spin 2010

COMPASS 2004 LiD (part) Preliminary

\[ \langle p_T^2 \rangle = \langle p_{\perp}^2 \rangle + z^2 \langle k_{\perp}^2 \rangle \]

\[ \langle Q^2 \rangle = 1.92 \]
\[ \langle x_{Bj} \rangle = 0.0148 \]

the expected behaviour

does not reproduce the data as already known

using

\[ \langle p_T^2 \rangle = z^\alpha (1 - z)^\beta \langle p_{\perp}^2 \rangle + z^2 \langle k_{\perp}^2 \rangle \]

the extracted \( \langle k_{\perp}^2 \rangle \) is

- smaller than in previous extractions
- different for h+ and h-
- \( Q^2 \) dependent

interpretation work ongoing: news soon?
hadron multiplicity vs x, z and $Q^2$

Results: 2D ($Q^2, z$) Multiplicities for $\pi^\pm$ & $K^\pm$

- High statistics
- Fine z binning
- Strong $Q^2$ dependence for negative hadrons ($\pi^-$ & $K^-$)

→ FFs (s quark)
future

COMPASS II Proposal

- pion (and kaon) polarizabilities 2012
- Drell-Yan 2014
- Deeply Virtual Compton Scattering with
  - LH target 2015-2016
  - 160 GeV muons test run in 2012
to access GPDs

2 years of data taking approved
by CERN in December 2010

in parallel to DVCS we proposed to measure
SIDIS off unpolarised p target

→ azimuthal asymmetries
→ $P_T^2$ distributions
→ multiplicities and FFs on p
future

COMPASS II Proposal

• pion (and kaon) polarizabilities 2012
• Drell-Yan 2014
• Deeply Virtual Compton Scattering with 2015-2016 test run in 2012
  • LH target
  • 160 GeV muons to access GPDs

statistical errors from one week of data taking with LH target in parallel to DVCS

→ azimuthal asymmetries
→ $P_T^2$ distributions
→ multiplicities
summary

a lot of SIDIS results on TMDs have been produced since 2005
very interesting, with some surprises

• solid evidence for: transversity PDF to be different from zero
  Sivers function to be different from zero
  
  new results will come very soon from COMPASS (2010 data)

• several allowed TMD asymmetries seem to be hardly measurable in SIDIS

• new interesting results from SIDIS off unpolarised nucleons

future:
• COMPASSII will contribute measuring DY and SIDIS
• much more data in different channels (SIDIS, DY, pp) at different energies
  are needed to study these new functions

SIDIS is an excellent tool to study the transverse spin and the transverse
momentum structure of the nucleon

→ JLab 12 GeV
→ ep collider