New COMPASS Results on Transverse Spin Physics

Franco Bradamante
Trieste University & INFN

On behalf of the COMPASS Collaboration

INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS
37th Course
Probing Hadron Structure with Lepton and Hadron Beams
Erice-Sicily: September 16-24, 2015
Transverse Spin and Momentum Structure of the Nucleon

A large international theoretical and experimental effort

**Hard polarised pp scattering**
RHIC / BNL

**SIDIS off transversely polarised targets**
DESY (HERMES)
CERN (COMPASS)
JLab
and EIC

**(polarised) Drell-Yan**
CERN (COMPASS) TAKING DATA
FUTURE: FNAL, JParc, RHIC, JINR, IHEP, GSI

Erice, September 17, 2015

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CERN (COMPASS) TAKING DATA

*Future*: FNAL, JParc, RHIC, JINR, IHEP, GSI
The TMD PDFs can be measured in SIDIS

a simple process, a special tool

\[ d\sigma^{\ell p \rightarrow \ell h X} \sim \sum_q e_q^2 f_q(x, k_{\perp}) \cdot d\sigma^{\ell q \rightarrow \ell q} \cdot D_q^h(z, p_T) \]

p, n, d targets, final state particle identification \( \rightarrow \) flavor separation

all the TMD PDFs appear in the cross-section and the different effects can be disentangled
Complementarity of the SIDIS experiments

huge activity on TMD $Q^2$ evolution

EIC

COMPASS

hermes

Jefferson Lab

$Q^2$ (GeV$^2$)

$x$

10^{-3} 10^{-2} 10^{-1} 1$
Transverse Spin and Momentum Structure of the Nucleon

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three distribution functions are necessary to describe the quark structure of the nucleon at LO in the **collinear case**  ALL OF EQUAL IMPORTANCE !

**transversity PDF** $\Delta_T \mathbf{q}$ or $h_I$: correlation between the transverse spin of the nucleon and the transverse spin of the quark

<table>
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<td>T</td>
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<td>transversity $\Delta_T \mathbf{q}$</td>
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Transversity PDF

- correlation between the transverse spin of the nucleon and the transverse spin of quarks

- **proposed in ’77** (Ralston & Soper)

- **different properties than helicity**
  - chiral-odd, cannot be measured in inclusive DIS
  - no contribution from the gluons
  - first moment: tensor charge  *(being computed on the lattice)*

- **first ideas on possible measurements in the 90s**  *(Collins, …)*

- **first measurements in 2005**
Transverse Spin and Momentum Structure of the Nucleon

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Three distribution functions are necessary to describe the quark structure of the nucleon at LO in the **collinear case** ALL OF EQUAL IMPORTANCE!

**transversity PDF** $\Delta_T q$ or $h_1$: correlation between the transverse spin of the nucleon and the transverse spin of the quark

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**nucleon polarisation**

**quark polarisation**

$\Delta q$: helicity

$\Delta_T q$: transversity

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Transverse Spin and Momentum Structure of the Nucleon

A large international theoretical and experimental effort

Three distribution functions are necessary to describe the quark structure of the nucleon at LO in the \textit{collinear case} \textbf{ALL OF EQUAL IMPORTANCE}!

\textbf{transversity PDF} $\Delta_T q$ or $h_I$: correlation between the transverse spin of the nucleon and the transverse spin of the quark

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.

\begin{tabular}{|c|c|c|c|}
\hline
 & U & L & T \\
\hline
U & $f_I$ & number density & $f_{IT}$ \hspace{1cm} \textit{U} \\
\hline
L & & & $g_{IT}$ \hspace{1cm} \textit{L} \\
\hline
T & $h_{IT}$ & & $h_I$ \hspace{1cm} \textit{T} \\
\hline
\end{tabular}

\begin{align*}
\Delta^T_0 q & \hspace{1cm} \textit{U} \\
\Delta^T q & \hspace{1cm} \textit{T}
\end{align*}

\textit{the new 5 TMD PDFs" vanish when integrating over the transverse momentum}
Transverse Spin and Momentum Structure of the Nucleon

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three distribution functions are necessary to describe the quark structure of the nucleon at LO in the **collinear case** ALL OF EQUAL IMPORTANCE !

transversity PDF \( \Delta_T q \) or \( h_1 \): correlation between the transverse spin of the nucleon and the transverse spin of the quark

Boer-Mulders function \( h_1 \)

correlation between the transverse spin and the transverse momentum of the quark in unpol nucleons

\( T \)-odd TMDs

Sivers function \( f_{IT} \)

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

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Sivers PDF $f_{1T}^{\perp}$

- correlation between the transverse spin of the nucleon and the transverse momentum of the parton

- introduced in 1992, demonstrated it can be different from zero in 2002

- requires final/initial state interactions

- being T-odd, time-reversal invariance implies:

  $$f_{1T}^{\perp}|_{\text{SIDIS}} = -f_{1T}^{\perp}|_{\text{DY}}$$

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

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

18 structure functions $F_{XY}^Z$

14 different azimuthal modulations

all measured
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\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_1 \otimes D_1 \right. \\
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\left. + \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. \\
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\left. + g_{LT} \otimes D_1 \right. \\
\left. + |S_\perp| \lambda_e \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\},
\]

18 structure functions \( F_{XY}^Z \)
14 different azimuthal modulations
all measured

LO: the structure functions are convolutions of TMD PDFs and FFs

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SIDIS

MAJOR RESULT: in the past 10 years 2 of these new PDF’s have been measured and shown to be different from zero by COMPASS and HERMES

the transversity PDF

the Sivers PDF

A STEP TOWARDS THE 3-D STRUCTURE OF THE NUCLEON
MAJOR RESULT: in the past 10 years 2 of these new PDF’s have been measured and shown to be different from zero by COMPASS and HERMES

the transversity PDF amplitude of the sine modulation in $\phi_h + \phi_s - \pi$

Collins asymmetry $\sim h_1 \otimes H_1^\perp$

the Sivers PDF amplitude of the sine modulation in $\phi_h - \phi_s$

Sivers asymmetry $\sim f_{1T}^\perp \otimes D_1$

A STEP TOWARDS THE 3-D STRUCTURE OF THE NUCLEON
Sivers asymmetry $\sim f_{IT}^{\perp} \otimes D_1$

2004: first evidence for non-zero values on proton compatible with zero on deuteron data well described by theory

2005: first extractions of the Sivers function

Anselmino et al, proceedings of Transversity2005  hep-ph/0511017

~ opposite u- and d-quark contributions

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Sivers asymmetry

2004: first evidence for non-zero values on proton compatible with zero on deuteron

final results on proton $z > 0.2$
Sivers asymmetry

$\sim f_{IT}^{\perp} \otimes D_1$

2004: first evidence for non-zero values on proton compatible with zero on deuteron

final results on proton $z > 0.2$

smaller values at COMPASS (higher $Q^2$)
a lot of work ongoing to describe $Q^2$ evolution of TMDs
Sivers function

from COMPASS and HERMES SIDIS data
it is clearly different from zero – *in spite it is* $T$-odd

final state interactions, gauge link

\[
[f_{1T}^{q\perp}]_{\text{SIDIS}} = -[f_{1T}^{q\perp}]_{\text{DY}}
\]
Sivers function
from COMPASS and HERMES SIDIS data
it is clearly different from zero -- in spite it is T-odd

final state interactions, gauge link

change of sign when measured in the Drell-Yan process

COMPASS - data taking ongoing!
RHIC
FNAL
future: FAIR, JPark, NICA
Drell-Yan at COMPASS

190 GeV $\pi^-$ beam
transversely polarised proton (NH3) target
thick hadron absorber

several azimuthal asymmetries
in particular the amplitude of the
$\sin \phi_{CS}$ modulation is

\[ \sim f_{1/\pi} \otimes f_{1T/p} \]

“golden region” $M_{inv} > 4$ GeV

Drell-Yan run 2015 ongoing

Sivers function still different from zero? … $Q^2$ evolution…

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COMPASS has measured the TSA in the 4 $Q^2$ ranges of the “future” Drell-Yan experiment

“golden” region: $Q^2 > 16$ GeV$^2$

Graph showing the COMPASS preliminary data with different ranges of $Q^2/(GeV/c)^2$.
Sivers asymmetry – Drell-Yan range

COMPASS has measured the TSA in the 4 $Q^2$ ranges of the “future” Drell-Yan experiment

“golden” region: $Q^2 > 16$ GeV$^2$

clearly positive
test of change of sign feasible

Transversity 2014
MAJOR RESULT: in the past 10 years 2 of these new PDF’s have been measured and shown to be different from zero by COMPASS and HERMES

the transversity PDF amplitude of the sine modulation in $\phi_h + \phi_s - \pi$
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A STEP TOWARDS THE 3-D STRUCTURE OF THE NUCLEON

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how has TRANSVERSITY been measured

the observable in SIDIS is the “Collins asymmetry”

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

\[
A_{Coll} \approx \frac{\sum_q e_q^2 h^q_i \otimes H^\perp_{1q}}{\sum_q e_q^2 f^q_j \otimes D_q}
\]

the best way to access transversity
how has TRANSVERSITY been measured

the observable in SIDIS is the “Collins asymmetry”

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

$A_{Coll} \approx \frac{\sum_q e_q^2 h_I^q \otimes H_{1q}^+}{\sum_q e_q^2 f_1^q \otimes D_q}$

Collins FF, chiral odd
left-right asymmetry
of the hadrons in the hadronization process
of a transversely polarized quark
$\Rightarrow$ QUARK POLARIMETRY
assessed in $e^+e^-$ annihilation into hadrons

the best way to access transversity
Collins FF \[ e^+ e^- \] annihilation into hadrons

\[ \approx H_1^\perp \otimes H_1^\perp \]

\[ \sqrt{s} = 10.58 \text{ GeV} \]

\[ \sqrt{s} < 3.6 \text{ GeV} \]

PRD90 2014

PRD78, 2008 PRD86, 2012

Unlike-sign couples / Like-sign couples

Unlike-sign couples / All charges

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Collins asymmetry

$\sim h_i \otimes H_i^\perp$

2004: first evidence for non-zero Collins asymmetry on $p$ from HERMES

final COMPASS results

2002-2004 data
NPB765 2007, PLB673 2009

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Transversity from SIDIS Collins asymmetry

simultaneous fit of HERMES p, COMPASS p & d, and Belle data
parametrisations of Transversity and Collins functions

very good $\chi^2$

Anselmino et al., PRD87 2013

$\delta u = 0.39^{+0.18}_{-0.12}$
$\delta d = -0.25^{+0.30}_{-0.10}$

$\delta u = 0.31^{+0.16}_{-0.12}$
$\delta d = -0.27^{+0.10}_{-0.10}$

Kang et al, PRD91 2015

$\delta u^{[0.0065,0.35]} = +0.30^{+0.12}_{-0.08}$
$\delta d^{[0.0065,0.35]} = -0.20^{+0.28}_{-0.11}$

higher order corrections, $x z$

$x h_1(x,Q^2)$

$-z H^{-}(z,Q^2)$

fav

unfav
dihadron asymmetry

alternative way to access transversity in SIDIS off transversely polarised nucleons
dihadron asymmetry

alternative way to access transversity in SIDIS off transversely polarised nucleons

azimuthal asymmetry in $\Phi_{RS} = \phi_R + \phi_S - \pi$

$$ N^\pm(\Phi_{RS}) = N^0 \cdot \left\{ 1 \pm P_T D \cdot A_{RS} \cdot \sin \Phi_{RS} \right\} $$

“Ancient Interference / Di-hadron FF”

$A_{RS} \approx \frac{\sum q e_q^2 \frac{h^q_i}{H_q}}{\sum q e_q^2 f_1^q \cdot D^{2h}_q}$

“spin independent di-hadron FF”

being measured at Belle Babar COMPASS

A. Bacchetta, M. Radici, hep-ph/0407345
X. Artru, hep-ph/0207309
dihadron asymmetry

again essential information is coming from the B-factories
dihadron asymmetry

2008: first evidence for non-zero di-h FF on p from HERMES, low statistics

final COMPASS results

deuteron:
compatible with zero

proton:
same sign and shape
slightly higher
than Collins asymmetry for \( h^+ \)

PLB 713 2012, PLB736 2014

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Transversity from di-hadron asymmetry
Transversity from di-hadron asymmetry

fit of linear combinations from HERMES p, COMPASS p & d, and Belle data

Radici, Courtoy, Bacchetta, Guagnellia, JHEP 1505 2015

Soffer bound

flexible scenario, $Q^2=2.4$ GeV$^2$

low statistics d data

Anselmino et al., PRD87 2013

Kang et al, PRD91 2015
Transversity from Collins and di-hadron asymmetries
point by point extraction
Transversity from Collins and di-hadron asymmetries

point by point extraction

one can use directly the COMPASS p and d asymmetries, and the Belle data to evaluate the analysing power (with some “reasonable” assumptions)

advantage: no MC nor parametrisation is needed

open points: dihadron
closed points: Collins

Martin Bradamante Barone
PRD91 2015
Transversity from Collins and di-hadron asymmetries

New speculations: are the Collins and the di-hadron asymmetries independent?

COMPASS Collaboration
Como 2013, DSpin2013, PLB 736 2014, SPIN 2014,

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interplay between Collins and di-hadron asymmetries

known intriguing results

• Collins asymmetry for $h^+$ and for $h^-$
  “mirror symmetry”

• di-hadron asymmetry
  only somewhat larger than $h^+$ Collins asymmetry

→ similar analysing powers

hints for a common origin of the Collins FF and Di-hFF
interplay between Collins and di-hadron asymmetries

four steps:

1. Study the dependence of the Collins asymmetry on the detection of other hadrons in the jet

\[ \mu p \rightarrow \mu' h^+ X \rightarrow h^+ \text{ Collins asymmetry} \]
\[ \mu p \rightarrow \mu' h^+ h^- X \rightarrow h^+ \text{ Collins-Like asymmetry} \]
\[ \rightarrow \text{ use of the 2h sample} \]

2. Study the correlation between hadron-pair azimuthal angles and between the corresponding asymmetries

3. Investigate the correlations between the \( h^+ \) and \( h^- \) asymmetries as a function of \( \Delta \phi = \phi_{h^+} - \phi_{h^-} \)

4. Investigate the correlation between the CL asymmetries and the di-hadron asymmetry
interplay between Collins and di-hadron asymmetries

1. Comparison of Collins and CL asymmetries

very close results: the “2h” sample can be used to investigate the correlations between Collins and di-hadron asymmetries

\[ A_{\sin \Phi_c} \]

\[ h^+ \text{Collins-Like} \]
\[ \mu p \rightarrow \mu' h^+ h^- X \]

\[ h^+ \text{Collins} \]
\[ \mu p \rightarrow \mu' h^X \]
2. Correlation between di-hadron azimuthal angles

\[ \Phi_R \quad \text{azimuthal angle of } \vec{R}_T \]

\[ \Phi_{2h} = \frac{1}{2} [\phi_1 + \phi_2 + \text{sign}(\Delta \phi) \cdot \pi] \]

\[ \Delta \phi = \phi_1 - \phi_2 \]

1 = \( h^+ \)

2 = \( h^- \)

\[ \xi_i = \frac{z_i}{z_2 p_1 + z_1 p_2} \]
2. Correlation between di-hadron azimuthal angles

Correlation between the corresponding di-hadron asymmetries evaluated using $\phi_R$ or $\phi_{2h}$
2. Correlation between di-hadron azimuthal angles

Correlation between the corresponding di-hadron asymmetries evaluated using $\phi_R$ or $\phi_{2h}$

very much the same:

$\phi_{2h}$ can be used to measure the di-hadron asymmetries

$\phi_{2h} + \phi_S - \pi$ is a sort of mean of the Collins angles of $h^+$ and $h^-$
interplay between Collins and di-hadron asymmetries

3. Correlations between the $h^+$ and $h^-$ CL asymmetries

as function of $x$ they are mirror symmetric

as function of $\Delta \phi = \phi_1 - \phi_2$ they are
- mirror symmetric
- maximum at $\Delta \phi = \pi$
- $\sim$ zero at $\Delta \phi = 0$

$h^+$ and $h^-$ CL asymmetries

hep-ex/1507.07593

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interplay between Collins and di-hadron asymmetries

3. Correlations between the $h^+$ and $h^-$ CL asymmetries

**analytical calculations** (A. Kotzianian, PRD91 2015)

\[
\frac{d\sigma^{h_1h_2}}{d\phi_1 d\phi_2 d\phi_S} = \sigma_U + S_T[\sigma_{C1} \sin(\phi_1 + \phi_S - \pi) + \sigma_{C2} \sin(\phi_2 + \phi_S - \pi)]
\]

\[\downarrow\text{change of variables} \quad (\phi_1, \phi_2) \rightarrow (\phi_1, \Delta\phi)\]

\[
A_{CL1} = \frac{1}{D_{NN}} \frac{\sigma_{C1} + \sigma_{C2} \cos\Delta\phi}{\sigma_U}
\]

\[
A_{CL2} = \frac{1}{D_{NN}} \frac{\sigma_{C2} + \sigma_{C1} \cos\Delta\phi}{\sigma_U}
\]

![Graph showing the correlation between $A_{CL}$ and $\Delta\phi$](hep-ex/1507.07593)
interplay between Collins and di-hadron asymmetries

3. Correlations between the $h^+$ and $h^-$ CL asymmetries

analytical calculations (A. Kotzionian, PRD91 2015)

$$
\frac{d\sigma_{h_1h_2}}{d\phi_1d\phi_2d\phi_s} = \sigma_U + S_T[\sigma_{c1} \sin(\phi_1 + \phi_s - \pi) + \sigma_{c2} \sin(\phi_2 + \phi_s - \pi)]
$$

↓ change of variables $(\phi_1, \phi_2) \rightarrow (\phi_{1,2}, \Delta\phi)$

$$
\begin{align*}
A_{CL1} &= \frac{1}{D_{NN}} \frac{\sigma_{c1} + \sigma_{c2} \cos\Delta\phi}{\sigma_U} \\
A_{CL2} &= \frac{1}{D_{NN}} \frac{\sigma_{c2} + \sigma_{c1} \cos\Delta\phi}{\sigma_U}
\end{align*}
$$

↓ agreement with the data if

$$
\sigma_{c2} = -\sigma_{c1} \quad \text{i.e.}
$$

$$
\begin{align*}
A_{CL1} &= \frac{1}{D_{NN}} \frac{\sigma_{c1}}{\sigma_U} (1 - \cos\Delta\phi) \\
A_{CL2} &= -\frac{1}{D_{NN}} \frac{\sigma_{c1}}{\sigma_U} (1 - \cos\Delta\phi) = -A_{CL1}
\end{align*}
$$

h1

a $(1 - \cos\Delta\phi)$

h2

$-a (1 - \cos\Delta\phi)$

h1

a $(1 - \cos\Delta\phi)$

h2

$-a (1 - \cos\Delta\phi)$

Δϕ(rad)
4. Correlation between the CL and di-h asymmetries

\[
\frac{d\sigma^{h_1 h_2}}{d\phi_1 d\phi_2 d\phi_S} = \sigma_U + S_T [\sigma_{C1} \sin(\phi_1 + \phi_S - \pi) + \sigma_{C2} \sin(\phi_2 + \phi_S - \pi)]
\]

\[\sigma_{C2} = -\sigma_{C1}\]

\[
A_{2h} = \frac{1}{D_{NN}} \frac{\sigma_{C1}}{\sigma_U} \sqrt{2(1 - \cos\Delta\phi)}
\]

a very simple relationship between di-hadron and single hadron asymmetries in the 2h sample

in agreement with data

correlation between the CL and di-h asymmetries

ratio of the integrals: \(4/\pi\)

slightly larger than \(h^+\)

“A common origin”
Other important COMPASS results

on Transverse Spin Asymmetries

preliminary results:

• full multidimensional analysis \((x, Q^2, z, p_T)\)
• gluon Sivers PDF from high \(p_T\) pairs
  \(J/\Psi\) production
• ...

and different new analysis ongoing

and on TMD observables in unpolarised SIDIS
Relevance of unpolarised SIDIS for TMDs

The cross-section dependence on $p_{Th}$ comes from:
- intrinsic $k_T$ of the quarks
- $p_\perp$ generated in the quark fragmentation

Gaussian ansatz:

$$\langle p_{Th}^2 \rangle = \langle p_\perp^2 \rangle + z^2 \langle k_T^2 \rangle$$

The azimuthal modulations in the unpolarized cross-sections come from:
- intrinsic $k_T$ of the quarks
- Boer-Mulders PDF

Combined analysis should allow to disentangle the different effects
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COMPASS

- has produced results on $^6LiD (~d)$ from 2004/6 data
- will measure SIDIS on LH$_2$ in parallel with DVCS
unpolarised SIDIS – $p_{Th}$ distributions

Fit distributions with

- 1 exponential for $p_{Th}^2 \in [0.05, 0.68]$
- 2 exponentials for $p_{Th}^2 \in [0.05, 3]$

Need 2 exponentials to describe the $p_{Th}^2$ shape of the COMPASS data
unpolarised SIDIS – $p_{Th}$ distributions

COMPASS Preliminary

$Q^2$ (GeV/c)$^2$

$0.2 < z < 0.3$

$M^{h^+}$

$M^{h^-}$

$p_{Th}^2$

$\sigma^{SV}/M$

$2006$ data

SPIN2014

Franco Bradamante
unpolarised SIDIS  – $p_{Th}$ distributions

$Q^2 \ (GeV/c)^2$

0.3 < z < 0.4

$\sigma^{IIS}/M$

COMPASS Preliminary

2006 data
SPIN2014

Franco Bradamante
unpolarised SIDIS – $\rho_{Th}$ distributions

COMPASS Preliminary

$0.4 < z < 0.6$

$Q^2$ (GeV/c)$^2$

$0.4 < z < 0.6$

total: 4918 data points

2006 data

SPIN2014

Franco Bradamante
unpolarised SIDIS - azimuthal modulations
unpolarised SIDIS - azimuthal modulations

\[ \cos \phi_h \]

\[ \cos 2\phi_h \]
CONCLUSIONS & OUTLOOK

In the GPM new PDF’s have been introduced which allow to understand the many transverse spin phenomena known since decades

COMPASS has given a decisive contribution to establish their properties

The Sivers function is presently being measured by COMPASS in the first Drell-Yan experiment on a polarized proton target

- first test of sign change of a T-odd PDF from SIDIS to Drell-Yan

Many results on unpolarized SIDIS cross-section

\[ k_T \text{ vs } p_\perp \]  
- Boer-Mulders PDF
- future data on LH target

Interplay between Collins and di-hadron FF’s

- same structure functions \( \Rightarrow \) same origin

COMPASS-II \( \Rightarrow \) COMPASS-III ?
Thank you!