Newest COMPASS results on longitudinal and transverse nucleon spin structure

Stefano Levorato INFN Trieste
on behalf of the COMPASS collaboration
OUTLOOK

• The COMPASS experiment at CERN

• Longitudinal asymmetries in DIS

• Hadron multiplicities in SIDIS

• The Structure of the Nucleon (SIDIS): Transversity and TMD

• Unpolarized SIDIS

A selection of the many available results!
Common Muon Proton Apparatus for Structure and Spectroscopy

main task: study of hadron structure and spectroscopy

data taking since 2002

participants: ~240 scientists
28 institutions from 12 countries
Rich and diversified physics programme:
- Nucleon structure with 160 GeV \( \mu \)
- Hadron Spectroscopy with 190 GeV \( \pi \)

On transversely, longitudinally polarized target, \( \text{LH}_2 \) or nuclei targets:
Measurement of elicity, transversity, \( \Lambda \), GPD, meson spectroscopy \( \pi, K \) polarizabilities ....
Not all covered in this talk !!!
<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
<th>Energy</th>
<th>Polarisation</th>
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<td>2002</td>
<td>nucleon structure with 160 GeV $\mu$</td>
<td>L&amp;T polarised deuteron target</td>
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<td>2005</td>
<td>CERN accelerators shut down</td>
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<td>2008</td>
<td>hadron spectroscopy</td>
<td>190 GeV $\pi$</td>
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<td>2012</td>
<td>Primakoff &amp; DVCS / SIDIS test</td>
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<td>CERN accelerators shut down</td>
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<td>Test beam Drell-Yan process with $\pi$ beam and T polarised proton target</td>
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The COMPASS spectrometer, an overview

- Two/three target cells, oppositely polarized
- 180 mrad geometrical acceptance
- 2.5T solenoid field
- Low temperature 50mK
- Regular polarization reversals by field rotation
- \(^6\)LiD (Longitudinal deuteron polarization: 50%)
- NH\(_3\) (Longitudinal proton polarization: 90%)
• The COMPASS experiment at CERN

• Longitudinal asymmetries in DIS

• Pion and Kaon multiplicities

• The Structure of the Nucleon : Transversity and TMD

• Unpolarized SIDIS

A selection of the many available results!
The nucleon spin structure DIS-SIDIS processes

**DIS:**
\[ \Delta q + \Delta \bar{q} \]
\[ \Delta g \text{ (From } Q^2 \text{ evolution of } g_1) \]

**SIDIS:**
\[ \Delta q, \Delta \bar{q} \]
\[ \Delta g \]

**DIS variables**
- Photon virtuality: \( Q^2 = -q^2 \)
- Bjorken scaling variable: \( x = \frac{Q^2}{2P \cdot q} \)
- Relative photon energy: \( y = \frac{E-E'}{E} \)

**SIDIS variables**
\[ z = \frac{P \cdot P_h}{P \cdot q} = \frac{E_h}{E - E'} \]

**Hadron transverse momentum** \( p_T^h \)
The goal is the determination of $\Delta q(x, Q^2), \Delta G$
Deep inelastic scattering processes: longitudinal polarization $A_1$ asymmetry

- **Inclusive cross section**

\[
\frac{d^2\sigma}{d\Omega dE'} \sim c_1 F_1(x, Q^2) + c_2 F_2(x, Q^2) + c_3 g_1(x, Q^2) + c_4 g_2(x, Q^2) \\
\text{spin independent} \quad \quad \text{spin dep. structure functions}
\]

\[
g_1(x, Q^2) = \frac{1}{2} \sum_q e_q^2 \Delta q(x) \approx A_1(x, Q^2) \cdot F_1(x, Q^2)
\]

Absorption of polarised photons

\[
\sigma_{1/2} \sim q^+ \quad \sigma_{3/2} \sim q^-
\]

\[
q(x) = q^+(x) + q^-(x) \\
\Delta q(x) = q^+(x) - q^-(x)
\]

$q(x)$=Quark momentum DF
\[\Delta q(x)\]=Difference in DF of quarks with spin parallel or antiparallel to the nucleon’s spin in a longitudinally polarized nucleon;

\[
A_1(x, Q^2) = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \quad \text{LO} \quad \sum_q e_q^2 \Delta q(x, Q^2) = \frac{\sum_q e_q^2 q(x, Q^2)}{N_u + N_d}
\]

\[
A_{exp} = \frac{N_u - N_d}{N_u + N_d}
\]

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Deep inelastic scattering processes: $A_1^d(x)$, $g_1^d(x)$ results from Deuteron Data

**Final sample:** 135 million events


Data at $E = 160$ GeV (from 2006)

- Good agreement with world data
- Small statistical uncertainty at low $x$
- Compatible with zero at low $x$
- $g_1^d(x, Q^2) = \frac{F_2^d(x, Q^2)}{2x(1 + R(x, Q^2))} A_1^d(x, Q^2)$
- $F_2$ from SMC PRD 58 (1998) 11201
- R1998 PLB 452 (1999) 194

Used with improvements

Good agreement $A_1^d(x)$ and of $g_1^d(x)$ with world data $g_1^d(x)$ compatible with zero at lowest measured values of $x$, contrary to hints from SMC
Deep inelastic scattering processes: $A_1^p(x)$, $g_1^p(x)$ results from Proton Data

**Final sample:** 85 million events @ 160 GeV + 77 million events @ 200 GeV

- 2007 results already published
  PLB 690 (2010) 466
- Increased beam energy in 2011
  160 GeV $\rightarrow$ 200 GeV
- Higher $Q^2$ and lower $x$ reached
- $^{14}$N correction applied
- Good agreement

$$g_1^p(x, Q^2) = \frac{F_2^p(x, Q^2)}{2x(1 + R(x, Q^2))} A_1^p(x, Q^2)$$

$g_1^p(x)$ clearly positive at lowest measured values of $x$
Deep inelastic scattering processes

Final sample: 85 million events + 77 million events @ 200 GeV

- 2007 results already published
  PLB 690 (2010) 466
- Increased beam energy
  160 GeV → 200 GeV
- Higher \( Q^2 \) and lower \( x \)
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- Good agreement

\[ g_1^p(x, Q^2) = \frac{F_2^p}{2x(1-x)} \]

From COMPASS data alone (and \( a_8 \) from PRD 82 (2010) 114018):
\[
a_8(Q^2 = 3 \ (\text{GeV/c})^2) = 0.320 \pm 0.02_{\text{stat}} \pm 0.04_{\text{syst}} \pm 0.05_{\text{evol}}
\]
(consistent with value from the COMPASS NLO QCD fit of world data).
In MS identified with total contribution of quark helicities to the nucleon spin
To perform flavor separation SIDIS is needed.

To perform flavor separation SIDIS is needed.

\[ A_1^h = \frac{\sum q e_q^2 \Delta q(x) \int D_q^h(z)dz}{\sum q e_q^2 q(x) \int D_q^h(z)dz} \]

Basic concept:

- measured:
  \[ A_1^d, A_1^{K^\pm}, A_{1d}^{\pi^\pm}, A_1^p, A_{1p}^{K^\pm}, A_{1p}^{\pi^\pm} \]
- determined:
  \[ \Delta u, \Delta\bar{u}, \Delta d, \Delta\bar{d}, \Delta s = \Delta\bar{s} \]
- inputs:
  unpol. LO PDFs (MRST04)
  LO FFs (DSS)
- curves:
  DSSV param.
- results: \[ \Delta s \geq 0 ?? \]

Results for \( \Delta s \) depend very much on the strange quark FFs used.
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   A selection of the many available results!
Fragmentation functions (FF, $D^h_q$) describe parton fragmentation into hadrons → needed in analyses which deal with a hadron(s) in the final state.

In Leading Order QCD $D^h_q$ describes probability density for a quark of flavour $q$ to fragment into hadron of type $h$.

SIDIS data are crucial to understand quark fragmentation process.

Hadron multiplicities can be expressed in terms of parton distribution functions (pdfs) and fragmentation functions (FFs), in LO pQCD this reads:

$$\frac{dM^h(x,z,Q^2)}{dz} = \sum_q e_q^2 q(x,Q^2) D^h_q(z,Q^2) / \sum_q e_q^2 q(x,Q^2)$$
COMPASS extracted $\pi^\pm$ multiplicities

Results published in PLB 764 (2017) 001

COMPASS performed LO fit, using HKNS FF programme

Results agrees with world FFs. As expected $D_{\text{fav}} > D_{\text{unf}}$
SIDIS: Multiplicities of $\pi$ on Iso-Scalar Target and $\pi^+/\pi^-$ multiplicity ratio

COMPASS extracted $\pi^\pm$

The ratio of $\pi^+/\pi^-$ is interesting to study due to significant cancellation of experimental systematic errors.

Here, a good agreement between HERMES and COMPASS.

Difference between HERMES and JLab likely explained by different $W$.

Good agreement between COMPASS and EMC data for unidentified hadrons.
SIDIS: Multiplicities of K on Iso-Scalar Target and multiplicity ratio

- COMPASS extracted Kaon multiplicities
- More than 620 data points
- Recently published in PLB 767 (2017) 133
SIDIS: Multiplicities of $K$ on Iso-Scalar Target and multiplicity ratio

- COMPASS extracted Kaon multiplicities
- More than 620 data
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There are large differences observed between COMPASS and HERMES for the multiplicity ratio (which agrees for $\pi$ case)
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  A selection of the many available results!
Taking into account the quark intrinsic transverse momentum $k_T$, at leading order other 6 TMD PDFs are needed for a full description of the nucleon structure.

**The structure of the nucleon**

SIDIS gives access to all of them.
hard interaction of a lepton with a nucleon via virtual photon exchange

\[ \sigma^{lN \rightarrow lhX} \propto \sum_q f(x) \otimes \sigma^{lq \rightarrow lq} \otimes D_q^h(z) \]

\[
x = \frac{Q^2}{2P \cdot q} \\
y = \frac{P \cdot q}{P \cdot \ell} = \frac{E - E'}{E} \\
Q^2 = -q^2 \\
W^2 = (P + q)^2 \\
z = \frac{P \cdot P_h}{P \cdot q} = \frac{E_h}{E - E'}
\]
Semi Inclusive Deep Inelastic Scattering (SIDIS)

\[ \frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \]
\[ \frac{\alpha^2}{x\,y\,Q^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} \right\} \]
\[ + \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} \]
\[ + S_{||} \left[ \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_h F_{UL}^{\sin \phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin 2\phi_h} \right] + S_{||} \lambda_e \left[ \sqrt{1-\varepsilon^2} \right] \]
\[ + f_{1T}^\perp D_1 \frac{\sin(\phi_h - \phi_S)}{\sin(\phi_h + \phi_S)} \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \]
\[ + \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \]
\[ + \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_S F_{UT}^{\sin \phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \]
\[ + g_{1T}^\perp D_1 \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_S F_{LT}^{\cos \phi_S} \]
\[ + \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right\}, \]

14 independent azimuthal modulations
amplitudes of the modulations \( \rightarrow \) TMD PDFs

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Semi Inclusive Deep Inelastic Scattering (SIDIS)

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

14 independent azimuthal modulations

amplitudes of the modulations \( \Rightarrow \) TMD PDFs

SIDIS

- allows to disentangle the effects related to the different TMD PDFs and to access all of them
- by identifying the final state hadrons and using different targets allows for flavour separation \( \Rightarrow \) very powerful tool

all the amplitudes (AA) have been measured in COMPASS
some SIDIS results on

TRANSVERSITY and TMD PDFs
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 \( \sim h_1 \otimes H_1 \)

the Sivers PDF amplitude of the sine modulation in \( \phi_h - \phi_s \)
Sivers asymmetry \( \sim f_{1T} \otimes D_1 \)

A STEP TOWARDS THE 3-D STRUCTURE OF THE NUCLEON
2004: first evidence for non-zero Collins asymmetry on $p$ from HERMES

**final COMPASS results**

- **deuteron**
  - $A^d_{Coll}$
  - $K^+$, $K^-$

- **proton**
  - $A^p_{Coll}$
  - $\pi^+$, $\pi^-$

*NPB765 2007 PLB673 2009 NPB693 2010 PLB744 2015*

*correlation between transverse spin of the fragmenting quark and transverse momentum of hadrons*
Transversity from SIDIS: Global Fit analysis


fit to HERMES p, COMPASS d, Belle e+e- data

But it is not the only way
Directly use of the COMPASS p and d asymmetries, and the Belle data to evaluate the analyzing power (with some “reasonable” assumptions)

advantage: no Monte Carlo nor parametrization is needed

open points: di hadron
closed points: Collins

A. Martin F. B. V. Barone
PRD91 2015
Sivers asymmetry

correlation between the nucleon transverse polarization and the quark transverse momentum $k_{\perp}$.
clear evidence for a positive signal for $h^+$, which extends to small $x$
COMPASS has measured the TSA in the 4 $Q^2$ ranges of the Drell-Yan experiment.

Drell-Yan
190 GeV pion beam

SIDIS
160 muon beam

fundamental prediction pQCD
sign change between Sivers TMD measured in SIDIS and in Drell-Yan

Next Talk by Robert Heitz
multiD \((x, Q^2; z, P_T)\)

analysis

an example:

Sivers

asymmetry

\(P_T > 0.1 \text{ GeV/c}\)
Compute the Sivers Asymmetry by weighting the spin dependent part by

\[ w = \frac{P_T}{zM} \]

Direct access to the first moment of the Sivers asymmetry!

\[
A_{Siv}^w(x) = \frac{\sigma_{Siv}^w}{\sigma_U} = 2 \frac{\sum_q e_q^2 x f_{1T}^{(1)q}(x) \int D_{1q}(z) \, dz}{\sum_q e_q^2 x f_q^q(x) \int D_{1q}(z) \, dz}
\]
The weighted Sivers asymmetry

\[ w = P_T / zM \quad A_{Siv}^w(x) = \frac{\sigma_{Siv}^w}{\sigma_U} = 2 \frac{\sum_q e_q^2 x f_{1T}^{1q}(x) \int D_{1q}(z) dz}{\sum_q e_q^2 x f_1^q(x) \int D_{1q}(z) dz} \]

\[ A_{Siv}^w(x) \simeq 2 \frac{x f_{1T}^{1u}(x) u(x)}{x f_u^u(x)} \]

assuming u dominance and for π+

\[ A_{Siv}^w(x) \quad \text{SPIN2016, arXiv:1702.00621} \]
\[ A_{Siv}^w(x) \quad \text{PLB717 (2012) 383} \]
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A selection of the many available results!
Relevance for TMDs:

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

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

COMPASS has produced results on $^6\text{LiD}$ ($\sim d$) from 2004/6 data.
Unpolarised SIDIS: multiplicities – $p_{Th}$ distributions on deuteron

Hadron Multiplicities from Unpolarized SIDIS
Relevance for TMDs:

- The cross-section dependence on $p_{Th}$ comes from:
  - Intrinsic $k_T$ of the quarks
  - $p_{\perp}$ generated in the quark fragmentation
    \[ \langle p_{Th}^2 \rangle = \langle p_{\perp}^2 \rangle + z^2 \langle k_T^2 \rangle \]

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

Combined analysis should allow to disentangle the different effects

COMPASS
- Is measuring these observables in SIDIS on LH$_2$ in parallel with DVCS
SIDIS gave and is giving fundamental contributions to the study of the nucleon structure.
The COMPASS contribution is remarkable:
• Longitudinal spin structure → structure function, helicity PDFs
• Transverse spin and momentum structure
  Sivers, transversity, Collins functions different from zero
to progress further
• comparison with different processes, from Drell-Yan to pp hard scattering
• more from SIDIS
  • new precise measurements at new facilities with different energies
    JLab12, EIC
  • COMPASS can still do a lot in the “consolidation” phase
    from existing data,
    with the LH2 data and hopefully in the future d↑

still a long way, a lot to be learned, and a lot of fun!