Azimuthal asymmetries and transverse-momentum-dependent distributions of charged hadrons at COMPASS

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on behalf of the COMPASS Collaboration

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Content of this talk

• Brief introduction on nucleon structure
• The COMPASS experiment
• Unpolarized SIDIS cross section and TMD observables
• Contribution from exclusive hadrons
• New preliminary results from COMPASS
• Conclusions
Parton Model and collinear QCD successful in explaining large amounts of data at high energies. Such good description is based on three Parton Distribution Functions (PDFs):

- **Unpolarized PDF** $f_1^q(x, Q^2)$
  - Very well known

- **Helicity** $g_1^q(x, Q^2)$
  - Well known

- **Transversity** $h_1^q(x, Q^2)$
  - First measurements in 2005 (HERMES, COMPASS)

**Deep Inelastic Scattering (DIS)**

Difference of parallel and anti-parallel quark polarizations, when the nucleon has a fixed **longitudinal** polarization.

Difference of parallel and anti-parallel quark polarizations, when the nucleon has a fixed **transverse** polarization.

**Semi – Inclusive Deep Inelastic Scattering (SIDIS)**
However, collinear QCD not adequate to explain all measured phenomena (spin crisis, hyperon polarization, $pp \rightarrow \pi$ inclusive asymmetry ...)

Transverse degrees of freedom:
- parton transverse spin $s_T$,
- its transverse momentum $k_T$,
- their correlations,
- the correlation of each of them with the nucleon transverse spin $S_T$.

From three collinear PDFs to 8 transverse-momentum-dependent (TMD) PDFs.

<table>
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<tr>
<th>Quark</th>
<th>U unpolarized</th>
<th>L longitudinally polarized</th>
<th>T transversely polarized</th>
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<td>Nucleon</td>
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<td>U unpolarized</td>
<td>$f_1^q(x, k_T^2)$ number density</td>
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<td>$h_1^q(x, k_T^2)$ Boer-Mulders</td>
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<td>L longitudinally polarized</td>
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Boer-Mulders function $h_1^q(x, k_T^2)$ one of the missing pieces can be accessed in unpolarized SIDIS.
The COMPASS experiment

COMPASS contribution to the understanding of the nucleon structure
• via spin asymmetries (TSA, LSA with polarized target)
  important results on the extraction of transversity and Sivers functions
• via SIDIS with unpolarized target

COMPASS (COmmon Muon Proton Apparatus for Structure and Spectroscopy):
• 24 institutions from 13 countries (about 220 physicists)
• a fixed target experiment
• located in the CERN North Area, along the SPS M2 beamline

Broad research program:
• SIDIS with $\mu$ beam, with (un)polarized deuteron or proton target.
• Hadron spectroscopy with hadron beams and nuclear targets
• Drell-Yan measurement with $\pi^-$ beam with polarized target
• Deeply Virtual Compton Scattering (DVCS)
• ... 

A multipurpose apparatus:
• Two-stage spectrometer, about 330 detector planes
• $\mu$ identification, RICH, calorimetry
INTRODUCTION

Cross section for unpolarized SIDIS

SIDIS cross section for the leptoproduction of a hadron \( h \) on an unpolarized nucleon target:

\[
\frac{d\sigma}{dx \, dy \, dz \, d\varphi_h \, dP_T^2} = \frac{2\pi\alpha^2}{x y Q^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{y^2}{2x}\right) \cdot \left(F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} F_{UU}^{\cos\varphi_h} \cos\varphi_h + \varepsilon F_{UU}^{2\varphi_h} \cos2\varphi_h + \lambda_l \sqrt{2\varepsilon(1-\varepsilon)} F_{LU}^{\sin\varphi_h} \sin\varphi_h \right)
\]

- \( x \) is the Bjorken variable
- \( Q^2 \) the photon virtuality
- \( y = 1 - \frac{E_{\ell'}}{E_{\ell}} \) the inelasticity with \( E_{\ell'} \) the energy of the incoming (scattered) lepton
- \( \gamma = 2Mx/Q \) with \( M \) the target mass
- \( \varepsilon(y) \) is a kinematic factor
- \( \lambda_l \) is the beam polarization.
- \( z \) is the fraction of photon energy carried by the hadron
- \( \varphi_h \) its azimuthal angle in the Gamma Nucleon System
- \( P_T \) its transverse momentum w.r.t. the photon

The Gamma Nucleon System (GNS)
Cross section for unpolarized SIDIS

\[
\frac{d\sigma}{dx \ dy \ dz \ d\varphi_h dP_T^2} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1 + \frac{y^2}{2x}\right) \\
\cdot \left( F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} F_{UU}^{\cos\varphi_h} \cos\varphi_h + \varepsilon F_{UU}^{\cos2\varphi_h} \cos2\varphi_h + \lambda_l\sqrt{2\varepsilon(1-\varepsilon)} F_{LU}^{\sin\varphi_h} \sin\varphi_h \right)
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The structure functions \(F_{XY[Z]}^{f(\varphi_h)}\) can be written in terms of TMD PDFs and TMD FFs. Up to order \(1/Q\):

\[
F_{UU,T} = C[f_1D_1]
\]
\[
F_{UU}^{\cos\varphi_h} = \frac{2M}{Q} C \left[ -\frac{(\hat{h}\cdot\vec{k}_T)}{M} f_1D_1 - \frac{(\hat{h}\cdot\vec{p}_\perp)k_T^2}{M^2M_h} h_1^+ H_1^+ + \ldots \right]
\]
\[
F_{UU}^{\cos2\varphi_h} = C \left[ -\frac{2(\hat{h}\cdot\vec{k}_T)(\hat{h}\cdot\vec{p}_\perp)}{M M_h} \vec{k}_T \cdot \vec{p}_\perp h_1^+ H_1^+ \right]
\]

Two main observables:

- \(\rightarrow\) azimuthal asymmetries
- \(\rightarrow\) transverse-momentum-dependent distributions

The Gamma Nucleon System (GNS)
Hadrons from the decay of exclusive diffractive vector mesons (exclusive hadrons)

- The two most important channels: \( \rho^0 \rightarrow \pi^+\pi^- \) and \( \phi \rightarrow K^+K^- \)
- observed in the data looking at their total energy fraction
- Their amount depends on kinematics
- Show a modulation in the azimuthal angle

The \( z_h^+ + z_h^- = z_t \) distribution (two hadrons with opposite charge)

Fraction of pions from SIDIS, as a function of \( P_{T}^2 \) per \( z \) bin

\( |\phi_h| - z \) correlation for “exclusive” hadrons
Contribution from exclusive hadrons

Impact on the azimuthal asymmetries calculated for the deuteron data
[COMPASS, NPB 886 (2014) 1046]
[COMPASS, NPB 956 (2020) 115039]

Example: $\cos \varphi_h$ asymmetry
$0.1 < P_T/(\text{GeV}/c) < 0.3$

- Comparison of not-subtracted (open points) and corrected (close points) asymmetries for positive hadrons.
- Correction applied at the asymmetry level

**Fraction $r$ of exclusive hadrons**
as a function of $x$, in bins of $z$ and $P_T$.
The 2016 COMPASS run

In 2016 (and 2017) the data-taking was dedicated to the measurement of Deeply Virtual Compton Scattering (DVCS).

In parallel, new SIDIS data have been collected in COMPASS, with:

- 160 GeV/c $\mu$ beam ($\mu^+$ and $\mu^-$ with balanced statistics)
- Unpolarized, 2.5 m long liquid hydrogen target

Part of the data (~11% of the available statistics) have been analyzed to get preliminary results on SIDIS unpolarized observables.

Both measurements of azimuthal asymmetries and $P_T^2$ distributions require Monte Carlo simulations for

- the acceptance correction (LEPTO generator) $\rightarrow$ standard
- the subtraction of exclusive hadrons (HEPGEN generator) $\rightarrow$ NEW

to normalize the HEPGEN Monte Carlo to the data, the missing energy $E_{miss}$ distribution is used.
The 2016 COMPASS run

**DIS events selected with standard cuts:**

\[ Q^2 > 1 \text{ (GeV/c)}^2 \]
\[ W > 5 \text{ GeV/c}^2 \]
\[ 0.003 < x < 0.130, \]
\[ 0.2 < y < 0.9 \]
\[ \theta_\gamma < 60 \text{ mrad} \]

\[ x - Q^2 \text{ correlation in the data (left) and for the exclusive } \rho \text{ events (right)} \]

**Selection of hadrons:**

\[ z > 0.1 \]
\[ P_T > 0.1 \text{ GeV/c} \]

Distributions of \( z \) and \( P_T \)

normalized to their integral,

for the data, LEPTO,

HEPGEN \( \rho \) and HEPGEN \( \phi \).
Azimuthal asymmetries: the ratio of the azimuthal-angle-dependent structure functions over the unpolarized

\[
A^\cos \phi_h^{UU} = \frac{F^\cos \phi_h^{UU}}{F_{UU,T} + \varepsilon F_{UU,L}} \quad A^\cos 2\phi_h^{UU} = \frac{F^\cos 2\phi_h^{UU}}{F_{UU,T} + \varepsilon F_{UU,L}} \quad A^\sin \phi_h^{LU} = \frac{F^\sin \phi_h^{LU}}{F_{UU,T} + \varepsilon F_{UU,L}}
\]

- Measured as the **amplitude of the modulation in the azimuthal angle** of the hadrons (fit)
  - either as a function of \( x, z \) or \( P_T \) (1-dimensional analysis), or with a simultaneous binning (3D)
- After correcting for the contribution of the exclusive hadrons
- And for acceptance

Estimated exclusive hadrons contaminations

Raw asymmetries for the exclusive hadrons
Azimuthal asymmetries – 1D

**1D results:** asymmetries shown as a function of $x$ or $z$ or $P_T$ (integrating over the other two variables).

As observed with the previous measurements by COMPASS on deuteron and by HERMES:

- Strong kinematic dependences
- Interesting differences between positive and negative hadrons.

Results in qualitative agreement with the COMPASS measurement on deuteron

[COMPASS, NPB 886 (2014) 1046]
Azimuthal asymmetries – 3D

Total contamination of exclusive hadrons: increases with $z$ and decreases along $x$ and $P_T$. 80% reduction after discarding exclusive events in the data

Raw asymmetry in $\cos \phi_h$ for exclusive hadrons: almost no dependence on $x$, mild on $P_T$, strong on $z$
Azimuthal asymmetries – 3D

3D azimuthal asymmetries for positive and negative hadrons

\[ A_{UU}^{\cos \phi_h} \] as a function of \( x \),
in bins of \( z \) (rows) and \( P_T \) (columns).

Clear signal, strong dependence on \( P_T \);
compatible with zero at high \( z \).
In agreement with COMPASS deuteron results.

Expectation from Cahn effect:
\[ A_{UU}^{\cos \phi_h} \propto -zP_T \]

Comparison with the 1D case:
lowest \( z \) and highest \( P_T \) bin not included in the average
Azimuthal asymmetries – 3D

3D azimuthal asymmetries for positive and negative hadrons

\[ A_{UU}^{\cos 2 \phi_h} \] as a function of \( x \), in bins of \( z \) (rows) and \( P_T \) (columns).

Clear signal, strong dependence on \( x \) and \( P_T \); interesting change of sign along \( z \) at high \( P_T \).

The larger contribution from the \( h_1^+ H_1^- \) convolution → direct information on \( h_1^+ \) may be extracted

Comparison with the 1D case: lowest \( z \) and highest \( P_T \) bin not included in the average
Azimuthal asymmetries – 3D

3D azimuthal asymmetries for positive and negative hadrons

\( A_{LU}^{\sin \phi_h} \) as a function of \( x \),
in bins of \( z \) (rows) and \( P_T \) (columns).

Comparison with the 1D case:
lowest \( z \) and highest \( P_T \) bin not included in the average
Transverse-momentum-dependent distributions

- give complementary information on $k_T$ and $p_\perp$ w.r.t. azimuthal asymmetries
- are interesting for the TMD evolution studies: a lot of theoretical work to reproduce the experimental distributions over large energy range

In gaussian approximation, at small values of $P_T$, the number of hadrons is expected to follow:

$$
\frac{d^2 N^h(x, Q^2; z, P_T^2)}{dz \ dP_T^2} \propto \exp \left( - \frac{P_T^2}{\langle P_T^2 \rangle} \right)
$$

$$
\langle P_T^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_\perp^2 \rangle
$$

**Graphical Representation**

- Three panels showing $Q^2$ versus $P_T^2$ for different values of $z$.
- Data points for $h^+$ and $h^-$ are highlighted.
- Normalization: first $P_T^2$ bin.
$P_T^2$ - dependent distributions

In good agreement with previous deuteron results [COMPASS, PRD97 (2018) 032006]
$P_T^2$ - dependent distributions

Distributions fitted with an exponential function up to $P_T = 1$ (GeV/c)$^2$

Evolution of the slope with $z$
$P_T^2$ - dependent distributions

Distributions fitted with an exponential function up to $P_T = 1 \ (GeV/c)^2$

Evolution of the slope with $z$

Deviations from the linear trend $\langle P_T^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_{\perp}^2 \rangle$ possible dependences of $\langle p_{\perp}^2 \rangle$ on $z$ and of $\langle k_T^2 \rangle$ on $x$. 

$h^+$ $h^-$

$\langle P_T^2 \rangle$ versus $z^2$ in the $x$ and $Q^2$ bins
Conclusions

• Two observables in unpolarized SIDIS are particularly interesting for the TMD physics: transverse momentum dependent distributions and azimuthal asymmetries.

• After the first measurements on a deuteron target, COMPASS has produced new preliminary results for both of them, using a proton target.

• Both the $P_T^2$ distributions and the azimuthal asymmetries look interesting with rich kinematic dependences.

• A new step forward in our understanding of the nucleon structure.
backup
AZIMUTHAL ASYMMETRIES 3D
Comparison with deuteron results

Current results (full points) compared to published results on deuteron [COMPASS, NPB 956 (2020) 115039].

Proton and deuteron results are in good agreement, as observed in other experiments (HERMES).
AZIMUTHAL ASYMMETRIES 3D
Comparison with deuteron results

Current results (full points) compared to published results on deuteron [COMPASS, NPB 956 (2020) 115039].

Proton and deuteron results are in good agreement, as observed in other experiments (HERMES).
Comparison with deuteron results

The new preliminary results are compared to published results on a deuteron target [COMPASS, PRD97(2018) 032006].

The old results (an example in the right plot) have been renormalized over the first point and averaged over $x$ and $Q^2$ in order to match the current binning, while the $z$ and $P_T^2$ binning has not been modified.

The agreement between new proton results and old deuteron ones is good.

New preliminary results (closed markers) compared to renormalized published results on deuteron (empty markers).

The binning for the current analysis has been chosen to be easily compared to the published one (an example on the right).
Correction for acceptance applied to each $\phi$ bin, taken as the ratio of reconstructed and generated hadrons:

$$c_{acc}(\phi) = \frac{N_{h}^{rec}(\phi)}{N_{h}^{gen}(\phi)}$$

Azimuthal modulations of the acceptance in 1D binning, for $\mu^+$ beam and positive (red) and negative hadrons (black).
AZIMUTHAL ASYMMETRIES 3D
Acceptance modulations

\[ \text{ACC } \alpha_{uU}^{\cos \phi_h} \]

COMPASS preliminary

\[ \text{ACC } \alpha_{uU}^{\cos \phi_h} \]

\[ P_T \text{ (GeV/c)} \]

\[ 0.10 \quad 0.30 \quad 0.50 \quad 0.64 \quad 1.00 \quad 1.73 \]
The acceptance is shown here in the first z bin, for positive and negative hadrons. A flat plateau at values larger than 50% and, in some bins, a decrease at large $P_T^2$. 

$$c_{acc}(P_T^2) = \frac{N^\text{rec}_h(P_T^2)}{N^\text{gen}_h(P_T^2)}$$