Unpolarised SIDIS studies at COMPASS

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on behalf of the COMPASS collaboration

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International Workshop on Hadron Structure and Spectroscopy
1. Introduction

2. Published measurements on $^6$LiD

3. New measurements on LH$_2$

4. Conclusion
Outline

1 Introduction

2 Published measurements on $^6$LiD

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4 Conclusion
Introduction: COMPASS

Collaboration: 24 institutes, 13 countries.
Fixed target, multi-purpose.
Broad research programme:

- **SIDIS**: $\mu^+$ beam and L/T-polarised proton (NH$_3$) or deuteron ($^6$LiD) target (beam 160 GeV/c, 200 GeV/c in 2011)
- **Hadron spectroscopy**: hadron beams and nuclear targets.
- **Drell–Yan**: 190 GeV/c $\pi^-$ beam and $p^+$, Al and W targets.
- **DVCS and SIDIS**: 160 GeV/c $\mu^\pm$ beam and liquid H$_2$ target.

It is located at M2 beamline of CERN’s SPS.

2016–2017 setup with CAMERA recoil proton detector and ECAL0 calorimeter for DVCS studies.
The cross section for producing a hadron $h$ in DIS on unpolarised target $\ell N \rightarrow \ell' hX$:

\[
\frac{d\sigma}{dxdydzd\phi_h dP^2_T} = \frac{2\pi\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{2xM^2}{Q^2} \right) \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \\
+ \sqrt{2\varepsilon(1+\varepsilon)} F^\cos\phi_h \cos\phi_h + \varepsilon F^\cos 2\phi_h \cos 2\phi_h + \lambda \sqrt{2\varepsilon(1-\varepsilon)} F^\sin\phi_h \sin\phi_h \\
= \sigma_0 \left( 1 + \varepsilon_1 A^\cos\phi_h \cos\phi_h + \varepsilon_2 A^\cos 2\phi_h \cos 2\phi_h + \lambda \varepsilon_3 A^\sin\phi_h \sin\phi_h \right)
\]

- $x$, $y$, $Q^2$ are usual DIS variables,
- $\lambda$ is the beam polarisation ($\approx 0.8$ at COMPASS),
- $\varepsilon \approx \frac{1-y}{1-y+\frac{1}{2}y^2}$, $M$ nucleon mass,
- $z$ is the fraction of $\gamma^*$ energy carried by $h$.
- $P_T$ is the transverse momentum of $h$ in the $\gamma N$ frame, $\phi_h$ is its azimuthal angle.
- $F_{f(\phi_h)}^{XU}(x,z,P^2_T,Q^2)$ are structure functions.
- $A_{f(\phi_h)}^{XU}(x,z,P^2_T,Q^2)$ are commonly called azimuthal asymmetries.

SIDIS in the $\gamma$–nucleon frame.
Introduction: Unpolarised SIDIS cross section

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

\[ = \sigma_0 \left( 1 + \varepsilon_1 A_{UU}^{\cos \phi_h} \cos \phi_h + \varepsilon_2 A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + \lambda \varepsilon_3 A_{LU}^{\sin \phi_h} \sin \phi_h \right) \]

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- $F_{f}^{(\phi_h)}(x,z,P_T^2,Q^2)$ are structure functions.
- $A_{f}^{(\phi_h)}(x,z,P_T^2,Q^2)$ are commonly called azimuthal asymmetries.
The structure functions in terms of TMD PDFs and TMD FFs, up to order $1/Q$:

- $F_{UU,T} = C \left[ f_1 D_1 \right]$, Cahn effect
- $F_{UU,L} = 0$
- $F_{UU}^{\cos \phi_h} = 2M/Q \left[ -\frac{\hat{h} \cdot k_T}{M} f_1 D_1 - \frac{(\hat{h} \cdot p_\perp) k_T^2}{M^2 M_h} h_1^\perp H_1^\perp + \ldots \right]$  
- $F_{UU}^{\cos 2\phi_h} = C \left[ -\frac{2(\hat{h} \cdot k_T)(\hat{h} \cdot p_\perp) - k_T \cdot p_\perp}{M M_h} h_1^\perp H_1^\perp \right]$
- $F_{UU}^{\sin \phi_h} = 2M/Q \left[ \ldots \right]$

- $f_1(x, k_T^2, Q^2)$ unpolarised TMD PDF,
- $h_1^\perp(x, k_T^2, Q^2)$ Boer–Mulders function,
- $D_1(z, p_\perp^2, Q^2)$ unpolarised TMD FF,
- $H_1^\perp(z, p_\perp^2, Q^2)$ Collins function.
- $\hat{h} = P_T / P_T$,
- $C = \text{sum over flavours and convolution over } p_\perp, k_T$,
- $\ldots = \text{twist-three terms.}$

**Observables sensitive to $k_T$ and $p_\perp$:**
- azimuthal asymmetries $A_{UU}^{\cos \phi_h}, A_{UU}^{\cos 2\phi_h}, A_{UU}^{\sin \phi_h}$,
  - $k_T$ via Cahn effect,
  - Boer–Mulders function.
- $P_T$-dependent distributions
  - $\propto F_{UU,T} = C[f_1 D_1]$. 
The structure functions in terms of TMD PDFs and TMD FFs, up to order \(1/Q\):

\[
\begin{align*}
F_{UU,T} &= \mathcal{C} \left[ f_1 D_1 \right], \\
F_{UU,L} &= 0, \quad \text{Cahn effect} \\
F_{UU}^{\cos \phi_h} &= \frac{2M}{Q} \mathcal{C} \left[ -\frac{\hat{h} \cdot k_T}{M} f_1 D_1 - \frac{(\hat{h} \cdot p_\perp) k_T^2}{M^2 M_h} h_1^\perp H_1^\perp + \ldots \right] \\
F_{UU}^{\cos 2\phi_h} &= \mathcal{C} \left[ -\frac{2(\hat{h} \cdot k_T)(\hat{h} \cdot p_\perp) - k_T \cdot p_\perp}{M M_h} h_1^\perp H_1^\perp \right] \\
F_{UU}^{\sin \phi_h} &= \frac{2M}{Q} \mathcal{C} \left[ \ldots \right]
\end{align*}
\]

- \(f_1(x, k_T^2, Q^2)\) unpolarised TMD PDF,
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- \(\ldots = \text{twist-three terms}\).

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- azimuthal asymmetries
  \(A_{UU}^{\cos \phi_h}, A_{UU}^{\cos 2\phi_h}, A_{UU}^{\sin \phi_h}\),
  \(k_T\) via Cahn effect,
  Boer–Mulders function.
- \(P_T\)-dependent distributions
  \(\propto F_{UU,T} = \mathcal{C}[f_1 D_1]\).
Published unpolarised SIDIS results:

- $P_T$-dependent multiplicities on $^6$LiD target [COMPASS, Phys.Rev.D97 (2018)].
- Background to the asymmetries from decays of exclusive vector mesons [COMPASS, Nucl.Phys.B 956 (2020)].

Ongoing analysis presented in this talk:

- 2016–2017 data taken with 2.5 m long LH$_2$ target.
- Primary goal: DVCS measurement, but useful for SIDIS as well.
- Advantages:
  - pure proton target,
  - alternating $\mu^\pm$ beam with balanced statistics (stability tests for systematics),
  - MC development in synergy with DVCS analysis.
- Part of the data (about 11%) used for preliminary results, released in August 2020.

Future:

- 2021 run with $^6$LiD target (transversely polarised).
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Published measurements on $^6$LiD: Azimuthal asymmetries

- [COMPASS, Nucl.Phys.B 886 (2014)]
- Isoscalar target, effectively deuteron.
- Unidentified charged hadrons studied.
- **1D analysis**
  (bins in $x$, $z$ and $P_T$ separately).
- **3D analysis** (3D grid of bins).
- Strong kinematic dependence of the $\cos\phi_h$ and $\cos 2\phi_h$ asymmetries.
- At the time, some features were not understood (e.g. positive $A_{UU}^{\cos \phi_h}$)
- Exclusive vector meson contribution has been proved important later.
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Published measurements on $^6$LiD: $P_T$-dependent multiplicities

- [COMPASS, Phys.Rev.D97 (2018)]
- 4D analysis (bins in $x$, $Q^2$, $z$ and $P^2_T$)
- Unidentified charged hadrons studied.
- QED radiative effects taken into account.
- Contribution of the decay of exclusive vector mesons
  - Subtracted in each bin.
  - $\rho^0$: small $P_T$, large $z$, small $Q^2$.
  - $\phi$: tiny $P_T$, medium $z$, small $Q^2$. 

Diffractively produced $\rho^0\to\pi^+\pi^-$, creating a background to SIDIS.

$1-\rho^0$ contamination fraction.
Published measurements on $^6$LiD: $P_T$-dependent multiplicities

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- 4D analysis (bins in $x$, $Q^2$, $z$ and $P_T^2$)
- Unidentified charged hadrons studied.
- QED radiative effects taken into account.
- Contribution of the decay of exclusive vector mesons
  - Contamination estimated from HEPGEN MC generator
    - Subtracted in each bin.
    - $\rho^0$: small $P_T$, large $z$, small $Q^2$.
    - $\phi$: tiny $P_T$, medium $z$, small $Q^2$.

Diffractively produced $\rho^0 \rightarrow \pi^+ \pi^-$, creating a background to SIDIS.

$1 - \rho^0$ contamination fraction.
Published measurements on $^6{\text{Li}}D$: Asymmetries and the EVMs

- The exclusive VMs inherit $\gamma^*$ polarisation.
- The decay hadrons obtain large azimuthal modulations. Especially in $\cos \phi_h$.
- They were measured in the data selecting
  - only $\mu'h^+h^-$,
  - $z_1 + z_2 > 0.95$.
- The contamination fraction from HEPGEN.
- Subtraction at the asymmetry level.

Diffractive $\rho^0$ production.

Total $z$ for $h^+h^-$. 

$\phi_h-z$ correlation.
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The contamination fraction: $3D(P_T, z, x)$ representation.

Before (empty) and after (full) subtraction.

$0.1 < P_T/(GeV/c) < 0.3$. 
Published measurements on $^6\text{LiD}$: Asymmetries and the EVMs

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New measurements on LH$_2$: Event selection and binning

The $x$ and $Q^2$ range covered.

**DIS event selection**
- $Q^2 > 1$ (GeV/c)$^2$,
- $W > 5$ GeV/c$^2$,
- $0.003 < x < 0.13$,
- $0.2 < y < 0.9$,
- $\theta_\gamma < 60$ mrad,
- Exclusive VM decay cut: if only $\mu' h^+ h^-$ outgoing, $z_1 + z_2 = z_t < 0.95$.

**Hadron selection**
- $0.1 < z < 0.85$,
- $0.1 < P_T/(\text{GeV}/c) < 1.73$. 

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Jan Matoušek (Charles University)  Unpolarised SIDIS studies at COMPASS  18. 11. 2020, IWHSS  14 / 24
New measurements on LH$_2$: Event selection and binning

**experimental data**

- event selection
  - HEPGEN MC
- invisible exclusive VM decay subtraction
  - Monte Carlo (LEPTO or DJANGOH)
- acceptance correction
  - DJANGOH MC
- radiative correction
- azimuthal asymmetries
- PT-dependent distributions

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**Selected range with moderate acceptance corrections.**

**Hadron selection**
- $0.1 < z < 0.85$,
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[COMPASS, Nucl.Phys.B 956 (2020)]
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New measurements on LH$_2$: Event selection and binning

**Binning**

- Based on the published results.
- Asymmetries:
  - 1D in $x$, $z$ and $P_T$.
  - 3D in $x$, $z$ and $P_T$
- $P_T$-dependent distributions
  - 4D in $x$, $Q^2$, $z$ and $P_T^2$.
  - Larger bins w.r.t the publication (2 bins in every variable merged).
New measurements on LH$_2$: Exclusive VM decay subtraction

- Different approach w.r.t published $d$ asymmetries.
- ‘Visible’ exclusive $h^+h^-$ removed in event selection.
  - About 80% of the decays are ‘visible’.
- ‘Invisible’ decays (only one $h$ observed)
  - HEPGEN MC generator with azimuthal modulations.
  - Normalised to the data using $E_{\text{miss}}$ distribution of the ‘visible’ decays.
  - Subtracted in every bin (including $\phi_h$ bins).

The number of signal events in the peak after SIDIS (from LEPTO) background subtraction is used to normalise HEPGEN.

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Jan Matoušek (Charles University)  Unpolarised SIDIS studies at COMPASS  18.11.2020, IWHSS 16/24
New measurements on LH$_2$: Exclusive VM decay subtraction

The VM-contamination fraction.

The azimuthal modulations of hadrons from the ‘visible’ VM decays. The ‘invisible’ ones have very similar modulations.
The impact of the VM-subtraction (‘visible’ and ‘invisible’) on the $P_T$-dependent distributions.
New measurements on LH$_2$: Results for the asymmetries

- **Acceptance correction**
  - LEPTO generator, full Geant simulation of COMPASS.
  - QED radiative effects – not yet taken into account
    - Plan to use DJANGOH generator \([\text{DJANGO6}]\)
      (→ evaluate impact on hadronic variables as well)

- **1D results**
  - Strong kinematic dependences, differences between $h^\pm$,
    qualitative agreement with published deuteron results
    \([\text{COMPASS, Nucl.Phys.B 886 (2014)}]\).

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![Graph showing azimuthal asymmetries](image-url)
New measurements on LH$_2$: Results for the asymmetries

Qualitative agreement with published deuteron results [COMPASS, Nucl.Phys.B 956 (2020)].
New measurements on LH2: Results for the $P_T$-distributions

- The distributions are normalised to the first bin.
- Gaussian model for $f_1$ and $D_1$:
  \[
  \frac{d^2N}{dz dP_T} \propto \exp \left( - \frac{P_T^2}{\langle P_T^2 \rangle} \right)
  \]
  \[
  \langle P_T^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_{\perp}^2 \rangle.
  \]
- Deviation from the simple exponential visible at $P_T > 1 \text{ (GeV/c)}^2$. 
New measurements on LH₂: Results for the $P_T$-distributions

COMPASS preliminary

0.20 < z < 0.30

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

COMPASS preliminary

0.30 < z < 0.40

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

COMPASS preliminary

0.40 < z < 0.60

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

COMPASS preliminary

0.60 < z < 0.80

$Q^2 (\text{GeV}/c)^2$
New measurements on LH₂: Results for the $P_T$-distributions

\[ \frac{d^2N}{dzdp_T} \propto \exp \left( - \frac{P_T^2}{\langle P_T^2 \rangle} \right) \]

- Deviations from the linear trend expected from the simple Gaussian model
  \[ \langle P_T^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_{\perp}^2 \rangle. \]
- Possible dependence of $\langle p_{\perp}^2 \rangle$ on $z$ or of $\langle k_T^2 \rangle$ on $x$. 

Exponential fit in $P_T < 1 \ (GeV/c)^2$ range.
New measurements on LH$_2$: Results for the $P_T$-distributions

\[
\frac{d^2 N}{dz dP_T} \propto \exp \left( - \frac{P_T^2}{\langle P_T^2 \rangle} \right)
\]

The fitted $\langle P_T^2 \rangle$ versus $z^2$ in the $x$ and $Q^2$ bins.

- Deviations from the linear trend expected from the simple Gaussian model
  \[
  \langle P_T^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_\perp^2 \rangle.
  \]
- Possible dependence of $\langle p_\perp^2 \rangle$ on $z$ or of $\langle k_T^2 \rangle$ on $x$.

Exponential fit in $P_T < 1$ (GeV/c)$^2$ range.
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Conclusion

Interesting observables in unpolarised SIDIS

- **Azimuthal asymmetries**: sensitive to $k_T$ (via Cahn effect) and to Boer–Mulders function.
- **$P_T$-dependent distributions**: sensitive to $k_T$ and $p_\perp$ dependence of $f_1$ and $D_1$.
- Contamination from decays of exclusive VMs plays an important role in both measurements.

**COMPASS measurements**

- Published results on $^6$LiD target: [COMPASS, Nucl.Phys.B 886 (2014)],
- **New preliminary results** (August 2020) on liquid H$_2$ target.
  - 11% of the statistics,
  - More robust method for exclusive VM subtraction.
  - Alternating $\mu^\pm$ beam – systematic check.
  - Qualitative agreement with deuteron, rich kinematic dependences.
  - More results will come.

- **Scheduled 2021 measurement** with (transversely polarised) $^6$LiD target.

These measurements provide important input to general understanding of the transverse-momentum-dependent structure of the nucleon and of the fragmentation process.
Conclusion

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Thank you for your attention!
Normalised kinematic distributions: real data, LEPTO, HEPGEN $\rho^0$ and HEPGEN $\phi$. 
 COMPASS preliminary

$A_{UU} \text{ vs. } P_T \text{ (GeV/c)}$
Backup: Comparison with the asymmetry measured on deuteron
Backup: Comparison of the $P_T$-distributions with deuteron