Azimuthal asymmetries in unpolarised semi-inclusive DIS at COMPASS

Jan Matoušek
Charles University, Prague, Czechia
on behalf of the COMPASS collaboration

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Outline

1. Introduction
2. Published measurements on $^6$LiD
3. New measurements on LH$_2$
4. Conclusion
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1. Introduction

2. Published measurements on $^6\text{LiD}$

3. New measurements on LH$_2$

4. Conclusion
Introduction: COMPASS

Collaboration: 24 institutes, 13 countries.
Fixed target, multi-purpose.
Broad research programme:
- **SIDIS**: $\mu^+$ beam and L/T-polarised proton ($\text{NH}_3$) or deuteron ($^6\text{LiD}$) 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 $\text{H}_2$ 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.
Introduction: Unpolarised SIDIS cross section

The cross section for producing a hadron h in DIS on unpolarised target $\ell N \rightarrow \ell' h X$:

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

- where $x$, $y$, $Q^2$ 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.
- $F_{XU}^{f(\phi_h)}(x, z, P_T^2, Q^2)$ are structure functions.
- $A_{XU}^{f(\phi_h)}(x, z, P_T^2, Q^2)$ are commonly called azimuthal asymmetries.

SIDIS in the $\gamma$–nucleon frame.
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$$

$$+ \sqrt{2\varepsilon(1+\varepsilon)} F_{UU}^{\cos \phi_h} \cos \phi_h + \varepsilon F_{UU}^{\cos 2\phi_h} \cos 2\phi_h + \lambda \sqrt{2\varepsilon(1-\varepsilon)} F_{LU}^{\sin \phi_h} \sin \phi_h \right)
$$

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

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The structure functions in terms of TMD PDFs and TMD FFs, up to order $1/Q$

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

- $f_1(x, k_T^2, Q^2)$ 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.
- $\hat{h} = P_T / P_T$,
- ... = other twist-three contributions.
- $C =$ sum over flavours and convolution over $p_\perp, k_T$,

$$
C[w f g] = x \sum q e_q^2 \int d^2 p_\perp d^2 k_T \delta(P_T - p_\perp - z k_T) f_q^q(x, k_T^2) g_q^q(z, p_\perp^2)
$$

Observables sensitive to $k_T, p_\perp$:
- azimuthal asymmetries $A_{UU}^{\cos \phi_h}, A_{UU}^{\cos 2\phi_h}, A_{LU}^{\sin \phi_h}$,
- $k_T$ via Cahn effect,
- Boer–Mulders function.
- $P_T$-dependent distributions

$\propto F_{UU,T} = C[f_1 D_1]$. 
→ talk of Anna Martin.
The structure functions in terms of TMD PDFs and TMD FFs, up to order $1/Q$:

$$F_{UU,T} = C \left[ f_1 D_1 \right],$$

$$F_{UU,L} = 0,$$

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

$$F_{UU}^{\cos 2\phi_h} = C \left[ -\frac{2(\hat{h} \cdot k_T)(\hat{h} \cdot p_{\perp}) - k_T \cdot p_{\perp} h_1^\perp H_1^\perp}{MM_h} \right]$$

$$F_{LU}^{\sin \phi_h} = \frac{2M}{Q} C \left[ \ldots \right]$$

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- $C = \text{sum over flavours and convolution over } p_{\perp}, k_T$,

$$C[wfg] = x \sum e_q^2 \int d^2 p_{\perp} d^2 k_T \delta(P_T - p_{\perp} - z k_T) f^q(x, k_T^2) g^q(z, p_{\perp}^2)$$

- Azimuthal asymmetries $A_{UU}^{\cos \phi_h}, A_{UU}^{\cos 2\phi_h}, A_{LU}^{\sin \phi_h}$,
- $k_T$ via Cahn effect,
- Boer–Mulders function.

- $P_T$-dependent distributions $\propto F_{UU,T} = C[f_1 D_1]$.
- Talk of Anna Martin.
Published unpolarised SIDIS results:

- Azimuthal asymmetries on $^6\text{LiD}$ target [COMPASS, Nucl.Phys.B 886 (2014)].
- $P_T$-dependent multiplicities on $^6\text{LiD}$ target [COMPASS, Phys.Rev.D 97 (2018)].
- Background to the asymmetries from decays of exclusive diffractive 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 2020 and 2021.

Future:

- 2021–2022 runs with $^6\text{LiD}$ target (transversely polarised).
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Ongoing analysis presented in this talk:

- 2016–2017 data taken with 2.5 m long LH₂ target.
- Primary goal: DVCS measurement, but useful for SIDIS as well.
- Advantages:
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Future:

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2 Published measurements on $^6$LiD

3 New measurements on LH$_2$

4 Conclusion
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 diffractive vector meson contribution has been proved important later.
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Published measurements on $^6$LiD: Asymmetries and the EVMs

- The exclusive diffractive 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.

\[
\begin{align*}
\text{Diffractive } \rho^0 \text{ production.}
\end{align*}
\]

\[
\begin{align*}
\text{Total } z \text{ for } h^+ h^-.
\end{align*}
\]

\[
\begin{align*}
\phi_h - z \text{ correlation.}
\end{align*}
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The contamination fraction: $3D(P_T, z, x)$ representation.

$A_{UU}$ vs $\cos \phi_h$ before (empty) and after (full) subtraction. $0.1 < P_T/(\text{GeV}/c) < 0.3$. 

$\phi_h - z$ correlation.

Jan Matoušek (Charles University) Azimuthal asymmetries in unpol. SIDIS 18. 10. 2021, SPIN2021 10/22
Published measurements on $^6$LiD: Asymmetries and the EVMs

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

**experimental data**

- **event selection**
  - HEPGEN MC
  - Monte Carlo (LEPTO or DJANGOH)

- **invisible exclusive VM decay subtraction**
  - DJANGOH MC

- **acceptance correction**
  - HEPGEN MC

- **radiative correction**
  - DJANGOH MC

- **azimuthal asymmetries**
  - PT-dependent distributions

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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**Selected range with moderate acceptance corrections.**

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New measurements on LH₂: Event selection and binning

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- Monte Carlo (LEPTO or DJANGOH)

**invisible exclusive VM decay subtraction**

**acceptance correction**

- HEPGEN MC
- DJANGOH MC

**radiative correction**

**azimuthal asymmetries**

**PT-dependent distributions**

\[ Q^2 \text{ and } x \text{ bins for the } P_T\text{-dependent distributions.} \]

### 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.

![Graph showing event distribution](image)
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.
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 [DJANGO6] (→ evaluate impact on hadronic variables as well)

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

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

Qualitative agreement with published deuteron results [COMPASS, Nucl. Phys. B 956 (2020)].

Jan Matoušek (Charles University)  Azimuthal asymmetries in unpol. SIDIS  18. 10. 2021, SPIN2021
The $Q^2$-dependence of $\cos \phi_h$ modulation

- Cahn effect was expected to be the dominant contribution to $A_{UU}^{\cos \phi_h}$

$$F_{UU}^{\cos \phi_h} = \frac{2M}{Q} C \left[ -\frac{\hat{h} \cdot k_T}{M} f_1 D_1 + \ldots \right]$$

- Assuming no flavour dependence,

$$A_{UU}^{\cos \phi_h} = -\frac{2z P_T \langle k_T^2 \rangle}{Q \langle P_T^2 \rangle}.$$  

- Despite that, the asymmetry grows with $Q^2$.
- The difference between $h^+$ and $h^-$ decreases with $Q^2$.  

Rows are bins in $Q^2$.  

COMPASS preliminary
The $Q^2$-dependence of $\cos \phi_h$ modulation

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COMPASS preliminary
New measurements on \( \text{LH}_2 \): Results for the asymmetries

The \( Q^2 \)-dependence of \( \cos 2\phi_h \) modulation

\[
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}}{MM_h} h_1^\perp H_1^\perp \right]
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- Here we do not see clear trends with \( Q^2 \).

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COMPASS preliminary

\[0.008 < x < 0.013\]

\[0.013 < x < 0.020\]

\[0.020 < x < 0.032\]

\[0.032 < x < 0.050\]

\[0.050 < x < 0.080\]

\[0.080 < x < 0.130\]
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Conclusion

Interesting observables in unpolarised SIDIS

- **Azimuthal asymmetries**: sensitive to $k_T$ (via Cahn effect) and to the convolution of Boer–Mulders and Collins functions.

- **$P_T$-dependent distributions**: sensitive to $k_T$ and $p_\perp$ dependence of $f_1$ and $D_1$.
  → talk of Anna Martin.

- Contamination from decays of exclusive diffractive VMs plays an important role in both measurements.

COMPASS measurements


- **New preliminary results** (August 2020, March 2021) on liquid $\text{H}_2$ target.
  - 11% of the statistics,
  - More robust method for exclusive VM subtraction.
  - Alternating $\mu^\pm$ beam – systematic check.
  - Qualitative agreement with deuteron target data, rich kinematic dependences.
  - More results will come.

- **2021–2022 measurements** with (transversely polarised) $^6\text{LiD}$ target.

These measurements provide important input to general understanding of the transverse-momentum-dependent structure of the nucleon and of the fragmentation process.
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Thank you for your attention!
Backup: Kinematic distributions

Normalised kinematic distributions: real data, LEPTO, HEPGEN $\rho^0$ and HEPGEN $\phi$. 
Back up: Comparison with the asymmetry measured on deuteron
Backup: Comparison with the asymmetry measured on deuteron

COMPASS preliminary