Azimuthal asymmetries in unpolarised semi-inclusive DIS at COMPASS

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on behalf of the COMPASS collaboration

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SPIN2021
Matsue, Japan

CHARLES UNIVERSITY
Faculty of mathematics
and physics

COMPASS

Outline

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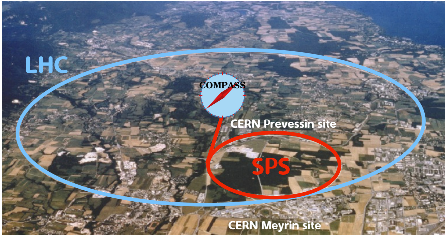
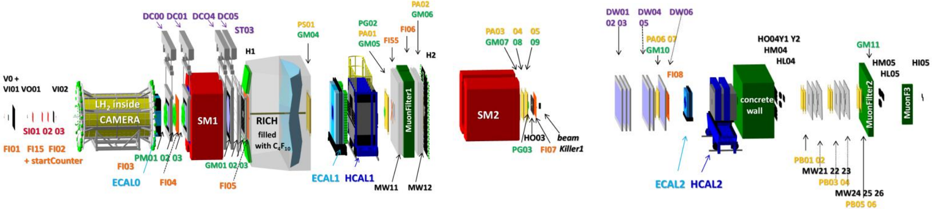
Introduction: COMPASS



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

- Collaboration: 24 institutes, 13 countries.
- Fixed target, multi-purpose.
- Broad research programme:
  - SIDIS: μ^+ beam and L/T-polarised proton (NH_3) or deuteron (^6LiD) target (beam 160 GeV/c, 200 GeV/c in 2011)
  - Hadron spectroscopy: hadron beams and nuclear targets.
  - Drell–Yan: 190 GeV/c π^- beam and $p^\uparrow$, Al and W targets.
  - DVCS and SIDIS: 160 GeV/c $\mu^\pm$ beam and liquid H_2 target.



2016–2017 setup with CAMERA recoil proton detector and ECAL0 calorimeter for DVCS studies.

Introduction: Unpolarised SIDIS cross section

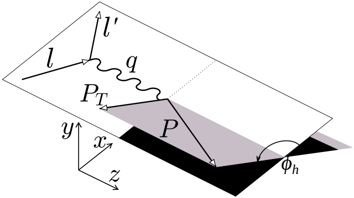
The cross section for producing a hadron h in DIS on unpolarised target $\ell \mathrm{N} \to \ell' \mathrm{hX}$:
[A. Bacchetta *et al.*, JHEP 0702 (2007)]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}y\mathrm{d}z\mathrm{d}\phi_{\mathrm{h}}\mathrm{d}P_{\mathrm{T}}^2} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{2xM^2}{Q^2}\right)\Big(F_{\mathrm{UU,T}} + \varepsilon F_{\mathrm{UU,L}}$$

$$+ \sqrt{2\varepsilon(1+\varepsilon)}F_{\mathrm{UU}}^{\cos\phi_{\mathrm{h}}}\cos\phi_{\mathrm{h}} + \varepsilon F_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{h}}}\cos 2\phi_{\mathrm{h}} + \lambda\sqrt{2\varepsilon(1-\varepsilon)}F_{\mathrm{LU}}^{\sin\phi_{\mathrm{h}}}\sin\phi_{\mathrm{h}}\Big)$$

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

- where x, y, Q^2 are usual DIS variables,
- λ is the beam polarisation (≈ 0.8 at COMPASS),
- $\varepsilon \approx \frac{1-y}{1-y+\frac{1}{2}y^2}$, M nucleon mass,
- z is the fraction of γ^* energy carried by h.
- P_{T} is the transverse momentum of h in the γN frame, ϕ_{h} is its azimuthal angle.
- $F_{\mathrm{XU}}^{f(\phi_{\mathrm{h}})}(x, z, P_{\mathrm{T}}^2, Q^2)$ are structure functions.
- $A_{\mathrm{XU}}^{f(\phi_{\mathrm{h}})}(x, z, P_{\mathrm{T}}^2, Q^2)$ are commonly called azimuthal asymmetries.



SIDIS in the γ–nucleon frame.

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$$\left. + \sqrt{2\varepsilon(1+\varepsilon)}F_{\mathrm{UU}}^{\cos\phi_\mathrm{h}}\cos\phi_\mathrm{h} + \varepsilon F_{\mathrm{UU}}^{\cos 2\phi_\mathrm{h}}\cos 2\phi_\mathrm{h} + \lambda\sqrt{2\varepsilon(1-\varepsilon)}F_{\mathrm{LU}}^{\sin\phi_\mathrm{h}}\sin\phi_\mathrm{h}\right)$$
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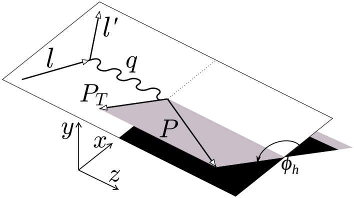

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The structure functions in terms of TMD PDFs and TMD FFs, up to order $1/Q$:

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

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

$$F_{\mathrm{UU}}^{\cos\phi_{\mathrm{h}}} = \frac{2M}{Q}\mathcal{C}\left[-\overbrace{\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\mathbf{T}}}{M} f_1 D_1}^{\text{Cahn effect}} - \frac{(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_{\perp})k_{\mathrm{T}}^2}{M^2 M_{\mathrm{h}}} h_1^{\perp} H_1^{\perp} + \ldots\right]$$

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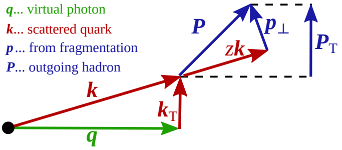

Momentum vectors

$$\boldsymbol{P}_{\mathbf{T}} = z\boldsymbol{k}_{\mathbf{T}} + \boldsymbol{p}_{\perp}$$

- $f_1(x, k_{\mathrm{T}}^2, Q^2)$ unpolarised TMD PDF,
- $h_1^{\perp}(x, k_{\mathrm{T}}^2, Q^2)$ 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.
- $\hat{\boldsymbol{h}} = \boldsymbol{P}_{\mathbf{T}}/P_{\mathrm{T}}$,
- $\ldots$ = other twist-three contributions.
- $\mathcal{C}$ = sum over flavours and convolution over $\boldsymbol{p}_{\perp}, \boldsymbol{k}_{\mathbf{T}}$,

$$\mathcal{C}\left[w\, f\, g\right] = x\sum e_q^2 \int \mathrm{d}^2 p_{\perp}\mathrm{d}^2 k_{\mathrm{T}}\,\delta(P_{\mathrm{T}} - p_{\perp} - z k_{\mathrm{T}}) f^q(x, k_{\mathrm{T}}^2) g^q(z, p_{\perp}^2)$$

Observables sensitive to k_{T}, $p_{\perp}$:

- azimuthal asymmetries $A_{\mathrm{UU}}^{\cos\phi_{\mathrm{h}}}$, $A_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{h}}}$, $A_{\mathrm{LU}}^{\sin\phi_{\mathrm{h}}}$,
  - k_{T} via Cahn effect,
  - Boer–Mulders function.
- P_{T}-dependent distributions $\propto F_{\mathrm{UU,T}} = \mathcal{C}[f_1 D_1]$. $\rightarrow$ talk of Anna Martin.

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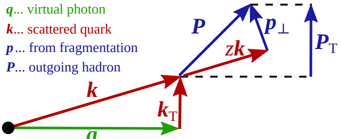

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Introduction: COMPASS measurements of unpolarised SIDIS

Published unpolarised SIDIS results:

- Azimuthal asymmetries on ^{6}LiD target [COMPASS, Nucl.Phys.B 886 (2014)].
- P_{T}-dependent multiplicities on ^{6}LiD target [COMPASS, Phys.Rev.D97 (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}LiD target (transversely polarised).

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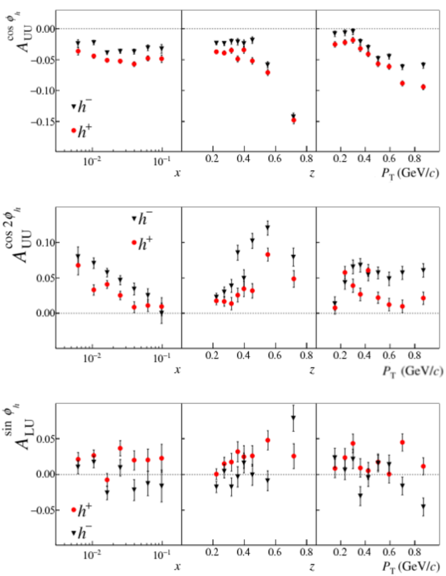
1. Introduction
2. Published measurements on ^{6}LiD
3. New measurements on LH_2
4. Conclusion

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 $A_\mathrm{UU}^{\cos\phi_\mathrm{h}}$)
- Exclusive diffractive vector meson contribution has been proved important later.



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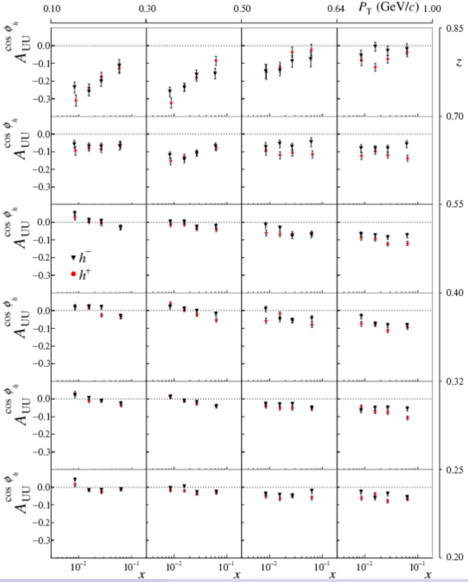
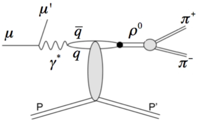
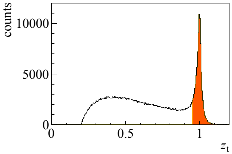


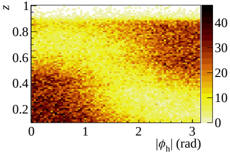
- [COMPASS, Nucl.Phys.B 956 (2020)].
- The exclusive diffractive VMs inherit γ^* polarisation.
- The decay hadrons obtain large azimuthal modulations. Especially in $\cos\phi_h$.
- They were measured in the data selecting
  - only $\mu' h^+ h^-$,
  - $z_1 + z_2 > 0.95$.
- The contamination fraction from HEPGEN.
- Subtraction at the asymmetry level.



Diffractive ρ^0 production.



Total z for h^+h^-.



ϕ_h–z correlation.

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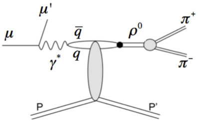

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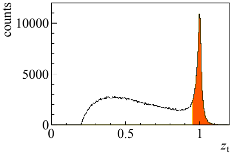

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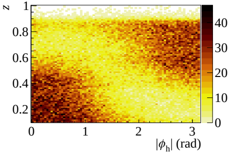

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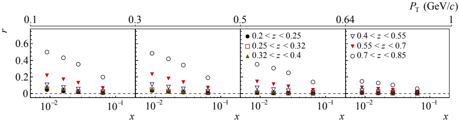
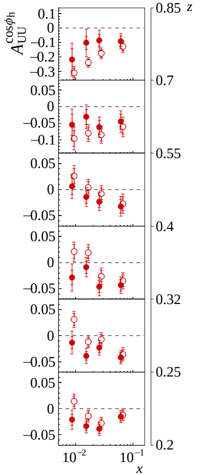


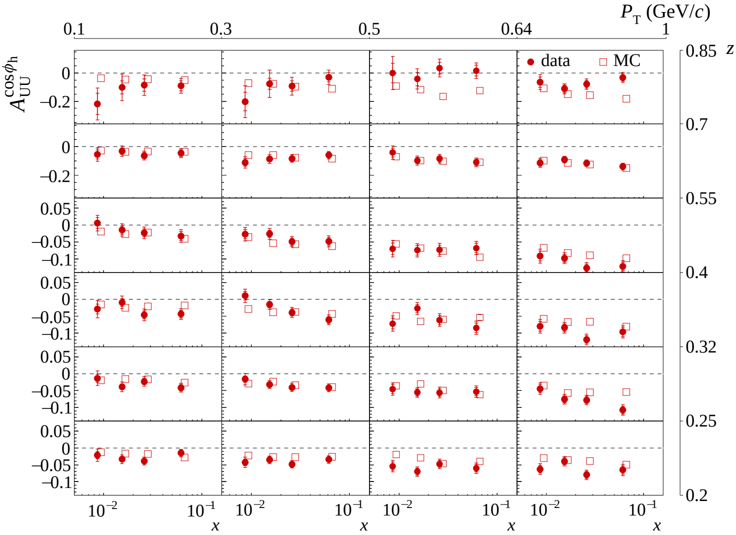
The contamination fraction: 3D(P_{T}, z, x) representation.



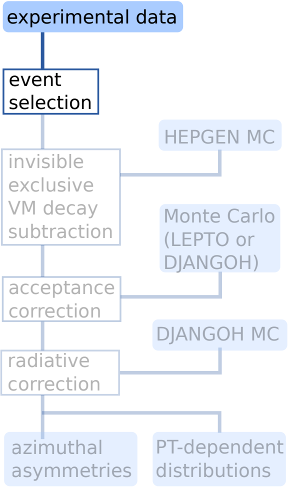
Before (empty) and after (full) subtraction.

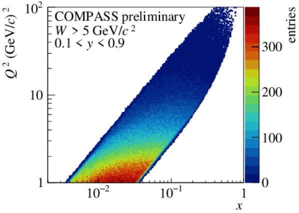
$0.1 < P_{\mathrm{T}}/(\mathrm{GeV}/c) < 0.3$.

Published measurements on ^{6}LiD: Asymmetries and the EVMs



After exclusive diffractive VM decay contribution is subtracted, rather good agreement with an MC model based on Cahn effect and string fragmentation [A. Kerbizi *et al.*, Phys.Rev.D 97 (2018)] can be reached [COMPASS, Nucl.Phys.B 956 (2020)].





The x and Q^2 range covered.

DIS event selection

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

Hadron selection

- $0.1 < z < 0.85$,
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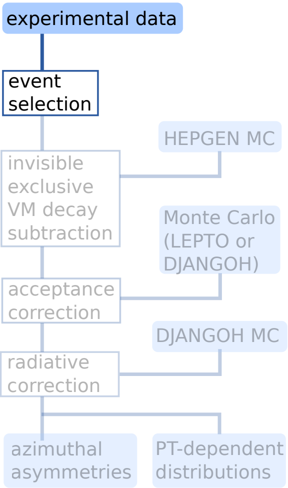
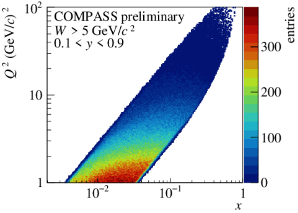
New measurements on LH_2: Event selection and binning





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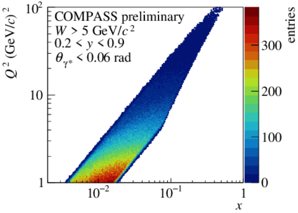

Selected range with moderate acceptance corrections.

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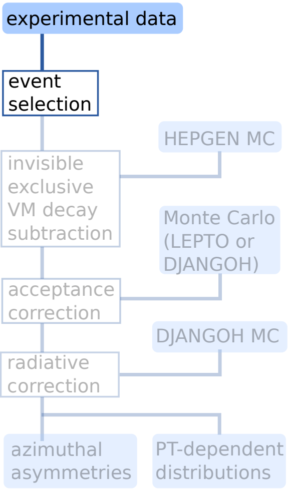

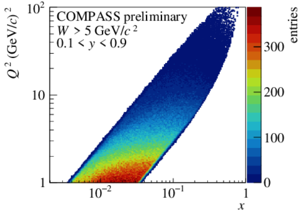

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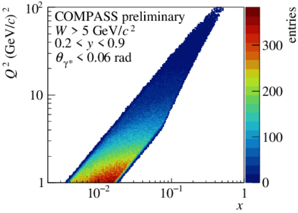

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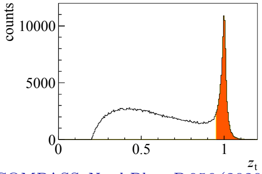
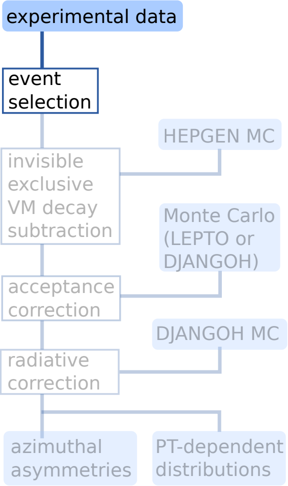
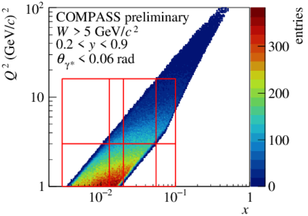


[COMPASS, Nucl.Phys.B 956 (2020)]

New measurements on LH_2: Event selection and binning

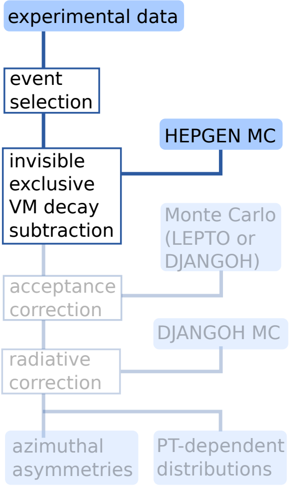




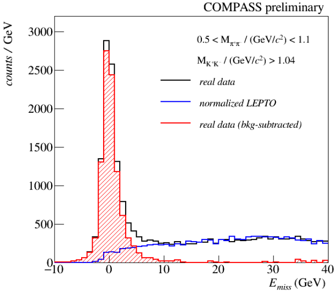
Q^2 and x bins for the P_{T}-dependent distributions.

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).

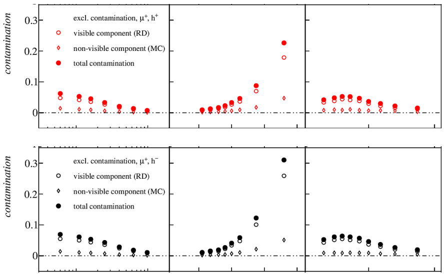


- Different approach w.r.t published d asymmetries.
- ‘Visible’ exclusive h^+h^- removed in event selection.
  - About 80 % of the decays are ‘visible’.
- ‘Invisible’ decays (only one h observed)
  - HEPGEN MC generator with azimuthal modulations.
  - Normalised to the data using E_{miss} distribution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

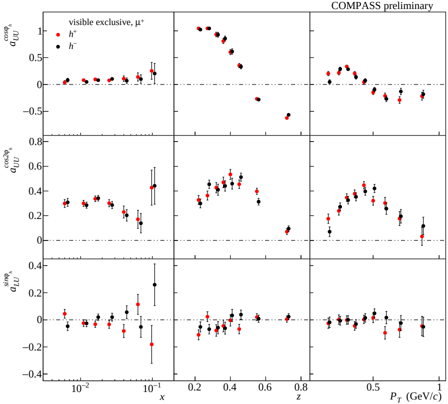


The number of signal events in the peak after SIDIS (from LEPTO) background subtraction is used to normalise HEPGEN.

New measurements on LH_2: Exclusive VM decay subtraction

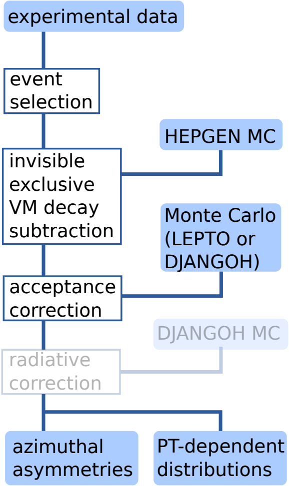


The VM-contamination fraction.

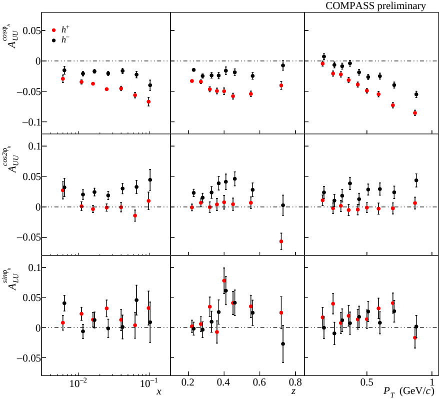


The azimuthal modulations of hadrons from the ‘visible’ VM decays. The ‘invisible‘ ones have very similar modulations.

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)].



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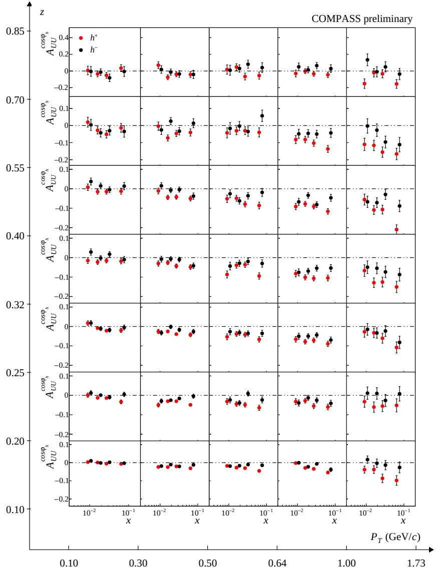

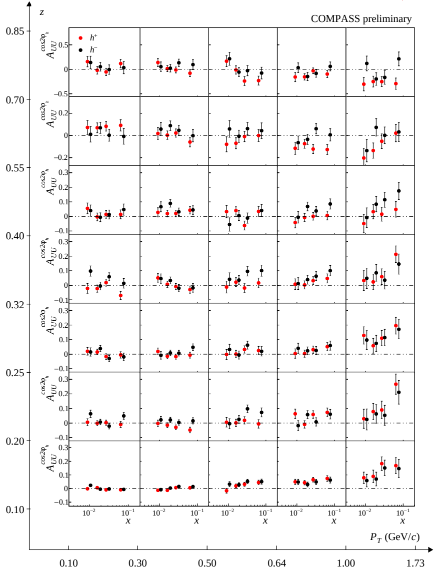

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New measurements on LH_2: Results for the asymmetries

The Q^2-dependence of $\cos\phi_\mathrm{h}$ modulation

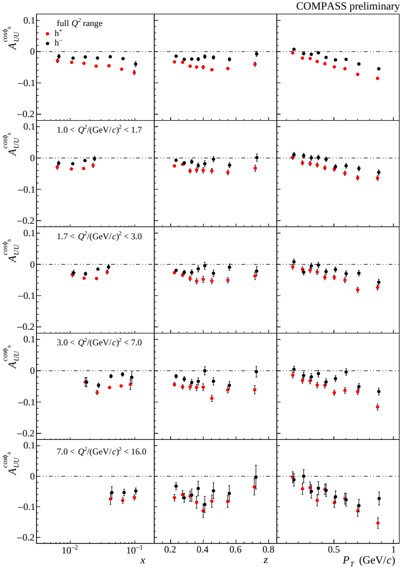
- Cahn effect was expected to be the dominant contribution to $A_{\mathrm{UU}}^{\cos\phi_\mathrm{h}}$

$$F_{\mathrm{UU}}^{\cos\phi_\mathrm{h}} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_\mathrm{T}}{M} f_1 D_1 + \ldots\right]$$

- Assuming no flavour dependence,

$$A_{\mathrm{UU}}^{\cos\phi_\mathrm{h}} = -\frac{2zP_\mathrm{T}\langle k_\mathrm{T}^2\rangle}{Q\langle P_\mathrm{T}^2\rangle}.$$

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



Rows are bins in Q^2.

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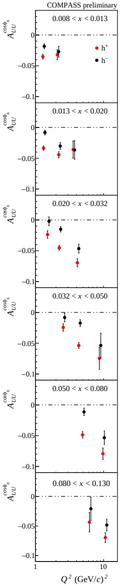
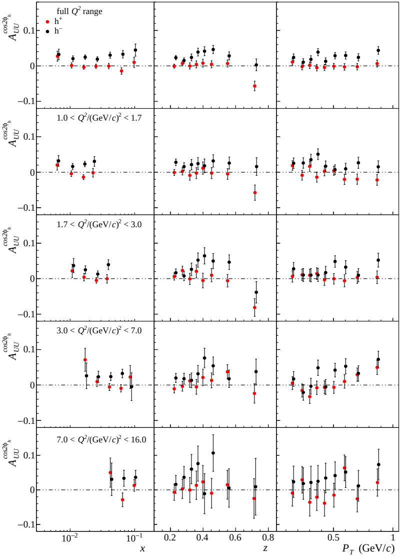


Rows are bins in x.

COMPASS preliminary



Rows are bins in Q^2.

The Q^2-dependence of $\cos 2\phi_{\mathrm{h}}$ modulation

- $$F_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{h}}} = \mathcal{C}\left[-\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\mathbf{T}})(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_{\perp}) - \boldsymbol{k}_{\mathbf{T}}\cdot\boldsymbol{p}_{\perp}}{M M_{\mathrm{h}}} h_1^{\perp} H_1^{\perp}\right]$$
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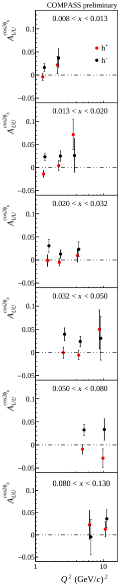

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Outline

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.
  $\rightarrow$ talk of Anna Martin.
- Contamination from decays of exclusive diffractive VMs plays an important role in both measurements.

COMPASS measurements

- Published results on ^{6}LiD target: [COMPASS, Nucl.Phys.B 886 (2014)], [COMPASS, Phys.Rev.D97 (2018)], [COMPASS, Nucl.Phys.B 956 (2020)].
- New preliminary results (August 2020, March 2021) 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 target data, rich kinematic dependences.
  - More results will come.
- 2021–2022 measurements 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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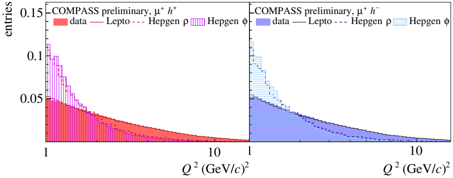
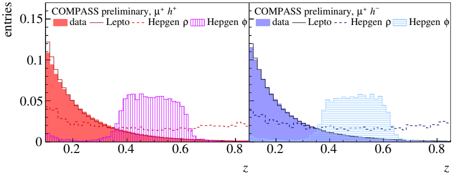
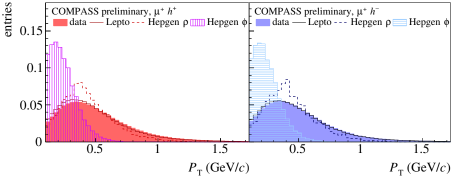
Thank you for your attention!

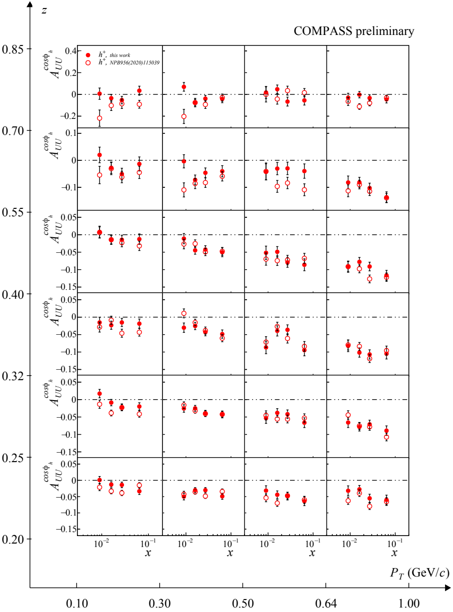


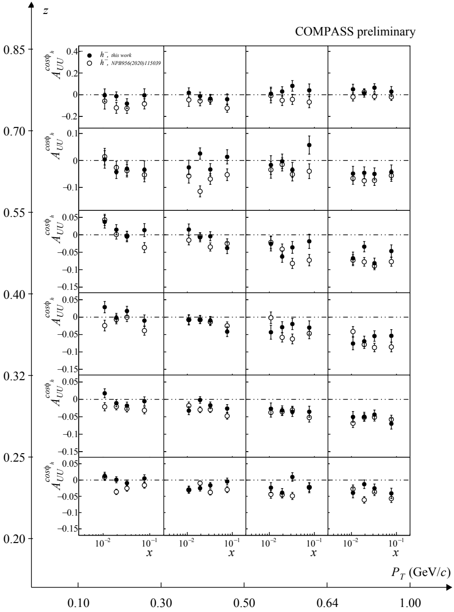




Normalised kinematic distributions: real data, LEPTO, HEPGEN ρ^0 and HEPGEN ϕ.

Backup: Comparison with the asymmetry measured on deuteron





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