Unpolarised Semi-Inclusive DIS at COMPASS

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on behalf of the COMPASS collaboration

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CHARLES UNIVERSITY
Faculty of mathematics
and physics

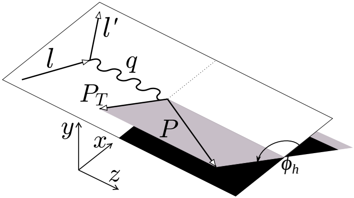
COMPASS

Introduction: Hadron production in unpolarised DIS

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),
- 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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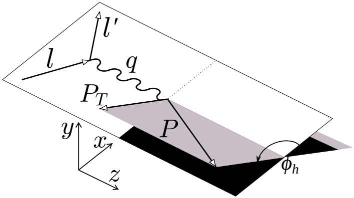

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Introduction: Hadron production in unpolarised DIS

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

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

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

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

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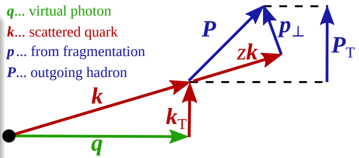

Momentum vectors
$\boldsymbol{P}_\mathbf{T} = z\boldsymbol{k}_\mathbf{T} + \boldsymbol{p}_\perp$

- $f_1(x, k_T^2, Q^2)$ 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.
- $\hat{\boldsymbol{h}} = \boldsymbol{P}_\mathbf{T}/P_T$,
- $\mathcal{C}$ = sum over flavours and convolution over $\boldsymbol{p}_\perp, \boldsymbol{k}_\mathbf{T}$,
- … = 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,
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- P_T-dependent distributions $\propto F_{UU,T} = \mathcal{C}[f_1 D_1]$.

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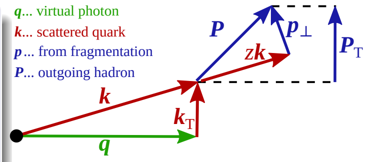

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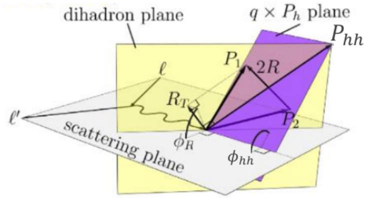
  - Boer–Mulders function.
- P_T-dependent distributions $\propto F_{UU,T} = \mathcal{C}[f_1 D_1]$.

Introduction: Hadron pair production in unpolarised DIS

- Leading twist: [A. Bianconi *et al.*, Phys.Rev.D 62 (2000)]
- Sub-leading twist:
  [A. Bacchetta & M. Radici, Phys.Rev.D 69 (2004)]
- Hadrons 1, 2 with masses M_1, M_2 and $z_1 > z_2$.
- $\boldsymbol{P_{\mathrm{hh}}} = \boldsymbol{P_1} + \boldsymbol{P_2}$,
- $\boldsymbol{R} = \frac{z_2 \boldsymbol{P_1} - z_1 \boldsymbol{P_2}}{z_1 + z_2}$ (other definitions exist as well),
- M_{hh} is the invariant mass of the pair.
- Accessing the same PDFs as in the 1h case.
- Fragmentation functions: 2h-unpolarised FF D_1
  2h-Collins FF $H_1^{\perp}$, interference FF $H_1^{\sphericalangle}$.



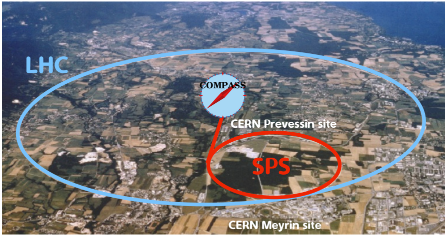
In particular, possibilities to access Boer–Mulders TMD PDF $h_1^{\perp}$:

$$\cos 2\phi_{\mathrm{hh}} \text{ amplitude: } \varepsilon_2 A_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{hh}}} = \varepsilon_2 \frac{\mathcal{C}\left[\frac{w_1(p_\perp, k_\mathrm{T})}{M(M_1+M_2)} h_1^{\perp} H_1^{\perp}\right]}{\mathcal{C}[f_1 D_1]}$$

$$\cos(\phi_{\mathrm{hh}} + \phi_{\mathrm{R}}) \text{ amplitude: } \varepsilon_2 |\boldsymbol{R_T}| A_{\mathrm{UU}}^{\cos(\phi_{\mathrm{hh}}+\phi_{\mathrm{R}})} = \varepsilon_2 |\boldsymbol{R_T}| \frac{\mathcal{C}\left[\frac{w_2(p_\perp, k_\mathrm{T})}{M(M_1+M_2)} h_1^{\perp} H_1^{\sphericalangle}\right]}{\mathcal{C}[f_1 D_1]}$$

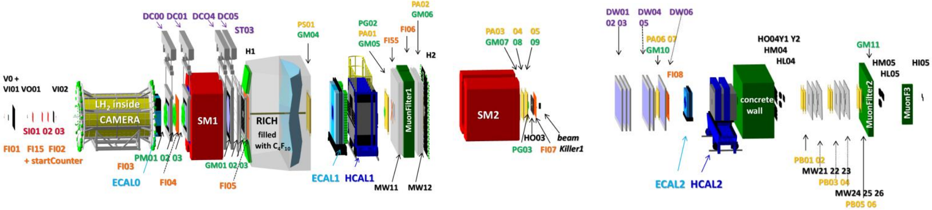
$$\cos \phi_{\mathrm{R}} \text{ amplitude: } \varepsilon_1 \frac{|\boldsymbol{R_T}|}{Q} A_{\mathrm{UU}}^{\cos \phi_{\mathrm{R}}} = \varepsilon_1 \frac{|\boldsymbol{R_T}|}{Q} \frac{\mathcal{C}\left[\frac{1}{z} f_1 \tilde{D}^{\sphericalangle} + \frac{xM}{M_{\mathrm{hh}}} \tilde{h} H_1^{\sphericalangle} + \frac{k_\mathrm{T}^2}{M M_{\mathrm{hh}}} h_1^{\perp} H_1^{\sphericalangle}\right]}{\mathcal{C}[f_1 D_1]}$$

Cahn effect is also expected in $\cos \phi_{\mathrm{hh}}$ modulation: $\varepsilon_1 A_{\mathrm{UU}}^{\cos \phi_{\mathrm{hh}}}$



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 (^{6}LiD) 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: 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 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 these preliminary results.

Future:

- 2022 run with ^{6}LiD target (transversely polarised).

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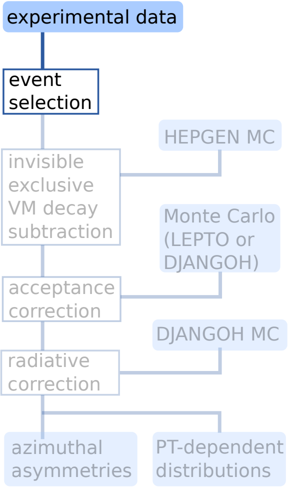
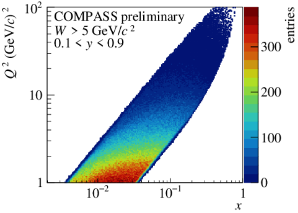
Measurements on LH_2: Event selection and binning





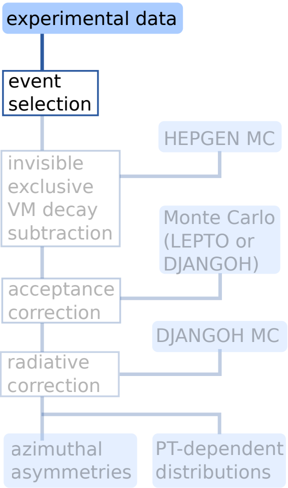
The x and Q^2 range covered.

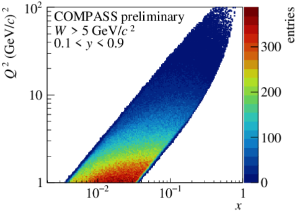
DIS event selection

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

Hadron selection

- $0.1 < z < 0.85$,
- $0.1 < P_T/(\mathrm{GeV}/c) < 1.73$.





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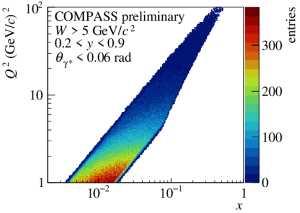

Selected range with moderate acceptance corrections.

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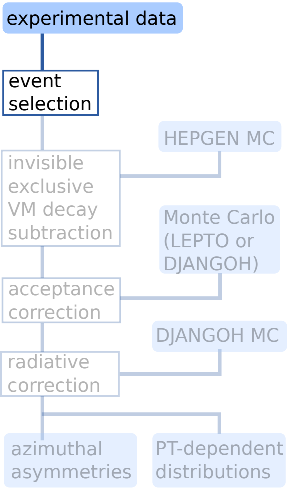

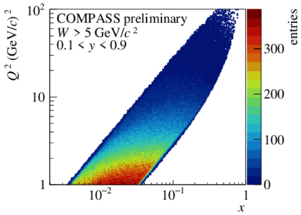

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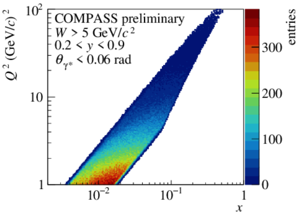

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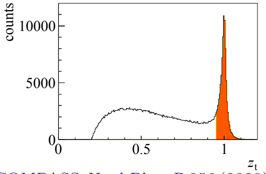
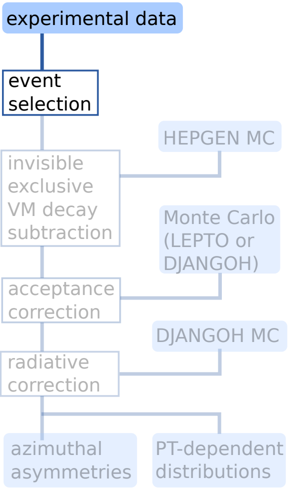
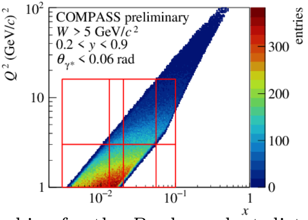


[COMPASS, Nucl.Phys.B 956 (2020)]

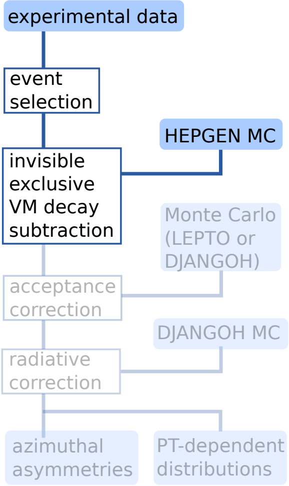




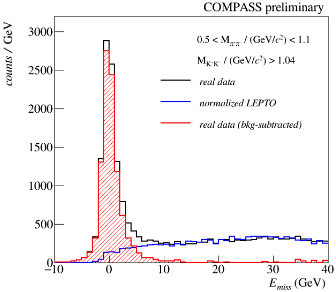
Q^2 and x bins for the P_T-dependent distributions.

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).

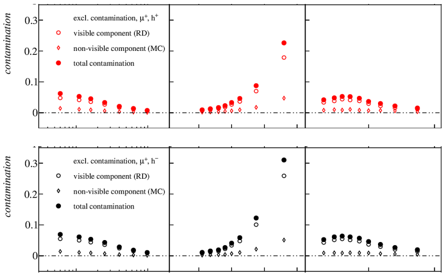


- Different approach w.r.t published d asymmetries.
- 'Visible' exclusive h^+h^- removed in event selection.
  - About 80 % of the decays are 'visible'.
- 'Invisible' decays (only one h observed)
  - HEPGEN MC generator with azimuthal modulations.
  - Normalised to the data using E_{miss} distribution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

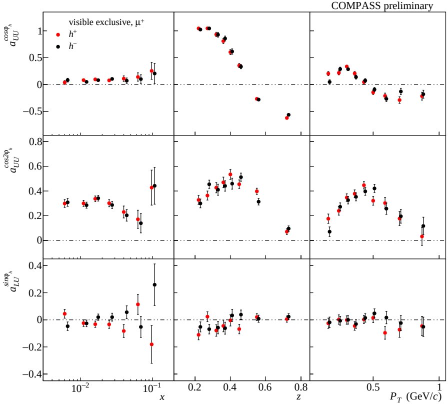


The number of signal events in the peak after SIDIS (from LEPTO) background subtraction is used to normalise HEPGEN.

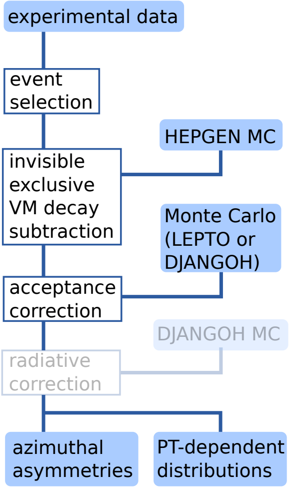
Measurements on LH_2: Exclusive VM decay subtraction



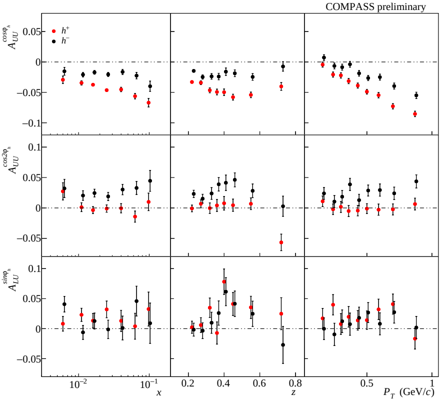
The VM-contamination fraction.



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



- 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)].



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

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

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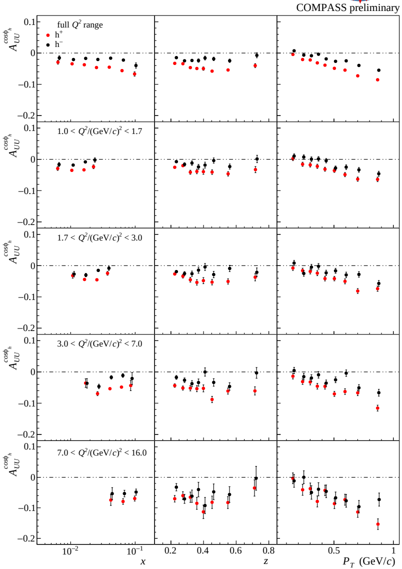
- Assuming no flavour dependence,

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

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



Rows are bins in Q^2.

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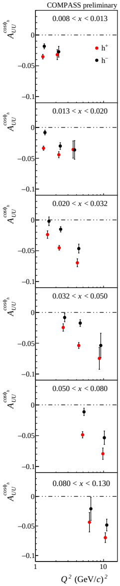
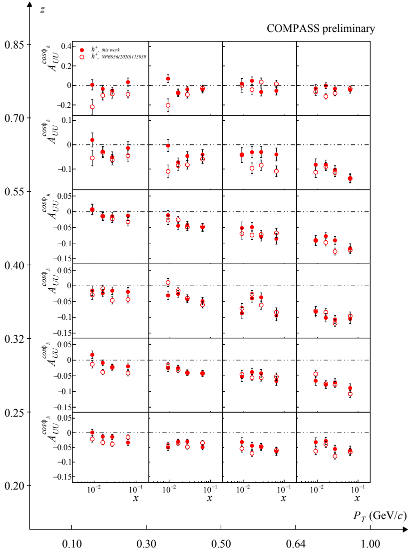
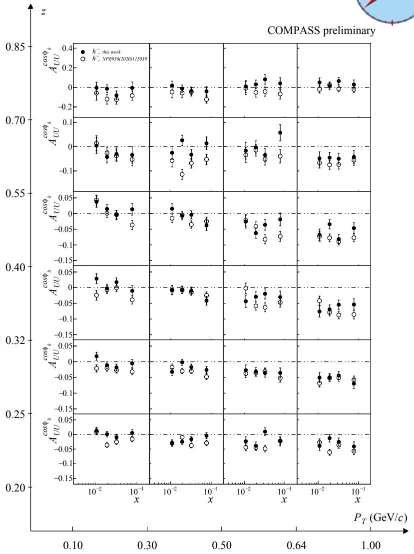
- Despite that, the asymmetry grows with Q^2.
- The difference between h^+ and h^- decreases with Q^2.



Rows are bins in x.

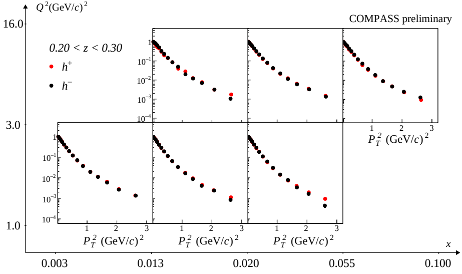
Measurements on LH_2: Results for the 1h-asymmetries

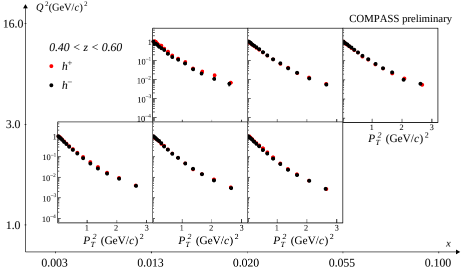




Qualitative agreement with published deuteron results also for $\cos 2\phi_{\mathrm{h}}$.

Measurements on LH_2: Results for the P_T-distributions



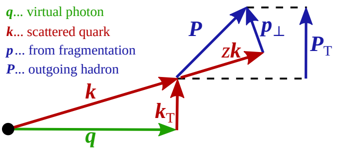


- The distributions are normalised to the first bin.
- Gaussian model for f_1 and D_1:

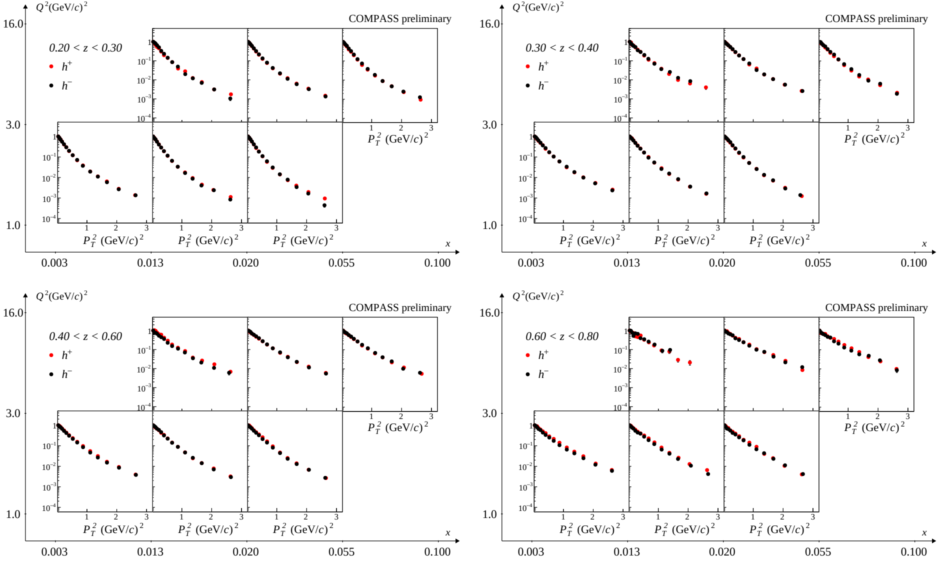
$$\frac{\mathrm{d}^2 N}{\mathrm{d}z\mathrm{d}P_\mathrm{T}} \propto \exp\left(-\frac{P_\mathrm{T}^2}{\langle P_\mathrm{T}^2\rangle}\right)$$

$$\langle P_\mathrm{T}^2\rangle = z^2\langle k_\mathrm{T}^2\rangle + \langle p_\perp^2\rangle.$$

- Deviation from the simple exponential visible at $P_\mathrm{T} > 1\ (\mathrm{GeV}/c)^2$.

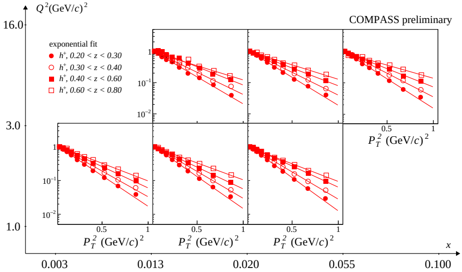


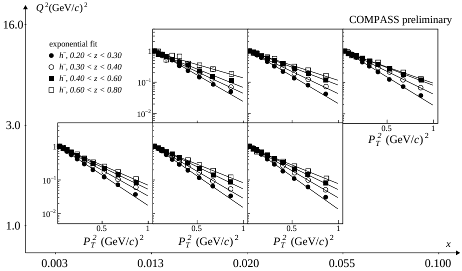
Measurements on LH_2: Results for the P_T-distributions



Measurements on LH_2: Results for the P_T-distributions

$$\frac{\mathrm{d}^2 N}{\mathrm{d}z\mathrm{d}P_\mathrm{T}} \propto \exp\left(-\frac{P_\mathrm{T}^2}{\langle P_\mathrm{T}^2 \rangle}\right)$$





Exponential fit in $P_\mathrm{T} < 1$ (GeV/c)^2 range.

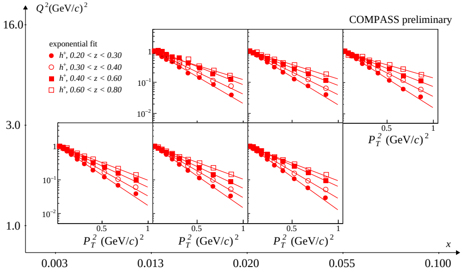
- Deviations from the linear trend expected from the simple Gaussian model

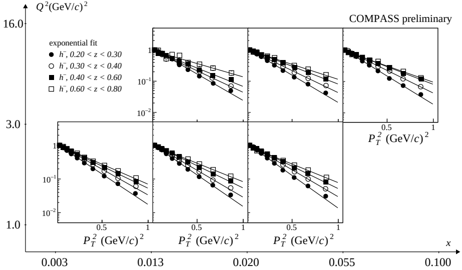
$$\langle P_\mathrm{T}^2 \rangle = z^2 \langle k_\mathrm{T}^2 \rangle + \langle p_\perp^2 \rangle.$$

- Possible dependence of $\langle p_\perp^2 \rangle$ on z or of $\langle k_\mathrm{T}^2 \rangle$ on x.
- Momentum conserv.: $P_\mathrm{T} \to 0$ at $z \to 1$.

Measurements on LH_2: Results for the P_T-distributions

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





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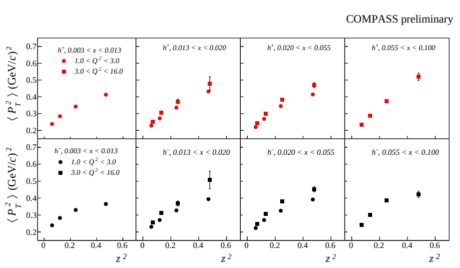

The fitted $\langle P_T^2\rangle$ versus z^2 in the x and Q^2 bins.

- 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.
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Conclusion

Interesting observables in unpolarised SIDIS

- Azimuthal asymmetries: sensitive to k_T (via Cahn effect) and to Boer–Mulders function.
- 2h-asymmetries – additional infomation on Boer–Mulders and Cahn.
- 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)], [COMPASS, Phys.Rev.D97 (2018)], [COMPASS, Nucl.Phys.B 956 (2020)].
- 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.
- 2022 measurement with (transversely polarised) ^{6}LiD target just about to start.

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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Interesting observables in unpolarised SIDIS

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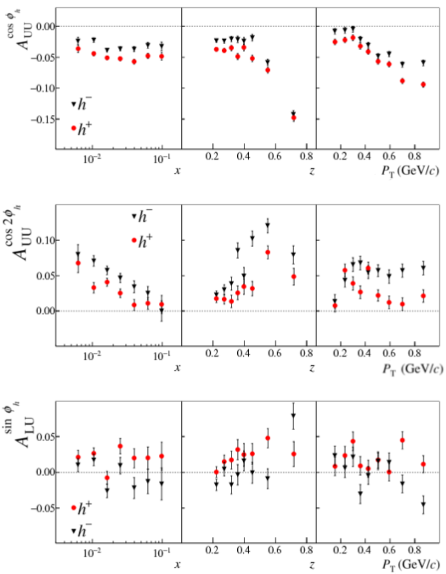
Thank you for your attention!

Backup: Azimuthal asymmetries on ^{6}LiD

- [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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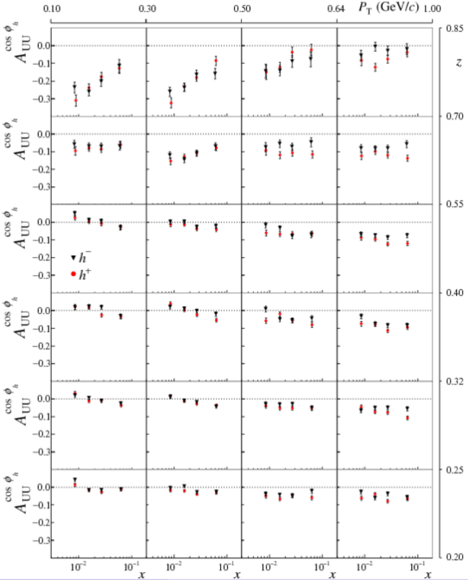
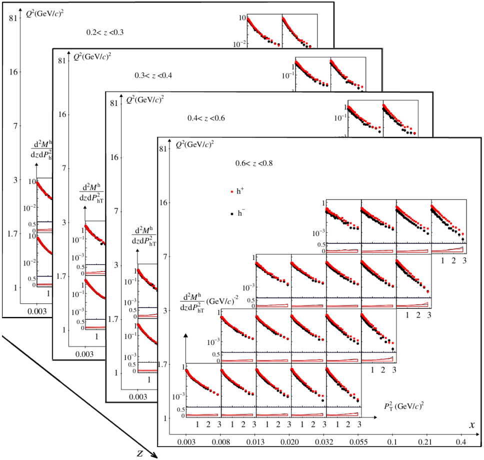


- [COMPASS, Phys.Rev.D97 (2018)]
- 4D analysis
  (bins in x, Q^2, z and P_{T}^2)
- Unidentified charged hadrons studied.
- QED radiative effects taken into account.
- Contribution of the decay of exclusive vector mesons
  - Contamination estimated from HEPGEN MC generator [A. Sandacz & P. Sznajder, arXiv:1207.0333].
  - Subtracted in each bin.
  - ρ^0: small P_{T}, large z, small Q^2.
  - ϕ: tiny P_{T}, medium z, small Q^2.



Backup: P_T-dependent multiplicities on ^{6}LiD

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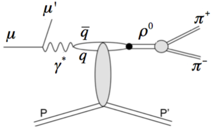
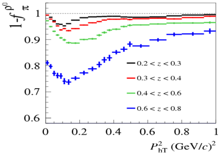
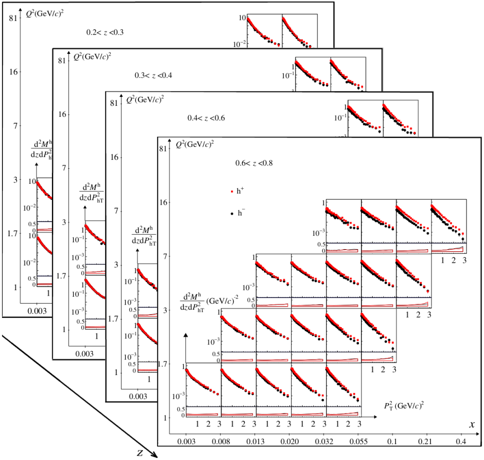


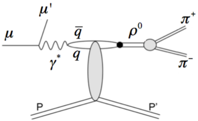
Diffractively produced $\rho^0 \to \pi^+\pi^-$, creating a background to SIDIS.



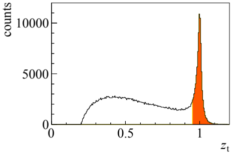
$1-\rho^0$ contamination fraction.



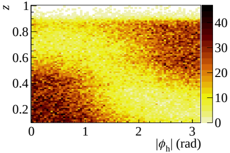
- [COMPASS, Nucl.Phys.B 956 (2020)].
- The exclusive VMs inherit γ^* polarisation.
- The decay hadrons obtain large azimuthal modulations. Especially in $\cos\phi_h$.
- They were measured in the data selecting
  - only $\mu' h^+ h^-$,
  - $z_1 + z_2 > 0.95$.
- The contamination fraction from HEPGEN.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



Diffractive ρ^0 production.



Total z for h^+h^-.



ϕ_h–z correlation.

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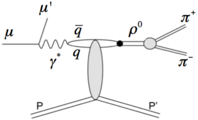

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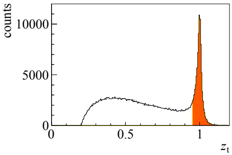

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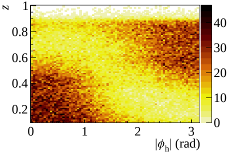

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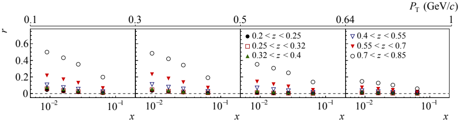
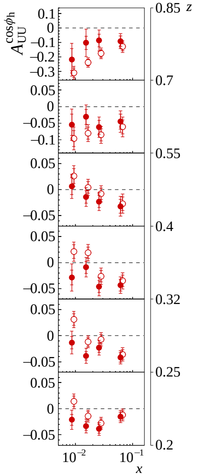
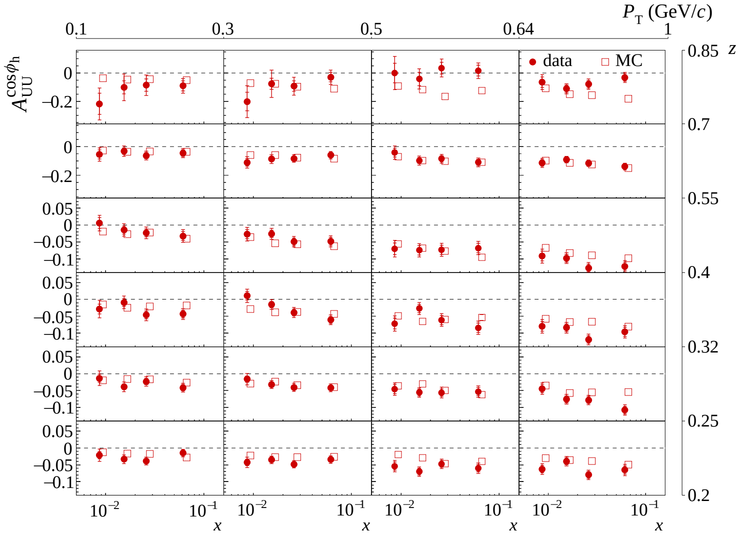


The contamination fraction: 3D(P_T, z, x) representation.



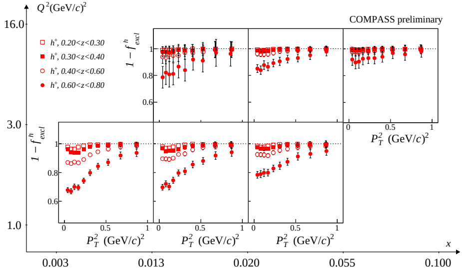
Before (empty) and after (full) subtraction.

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

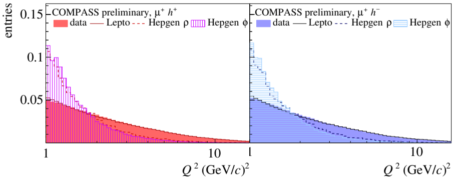


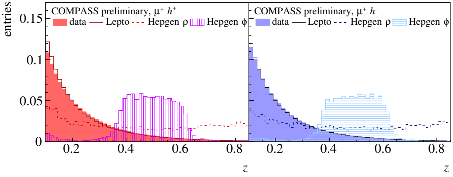
After exclusive VM decay contribution is subtracted, rather good agreement with an MC model based on Cahn effect and string fragmentation [A. Kerbizi *et al.*, Phys.Rev.D 97 (2018)] can be reached [COMPASS, Nucl.Phys.B 956 (2020)].

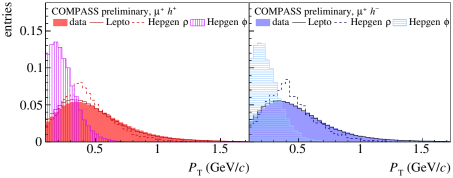
Backup: Asymmetries and the EVMs on ^{6}LiD



The impact of the VM-subtraction (‘visible’ and ‘invisible’) on the P_{T}-dependent distributions.

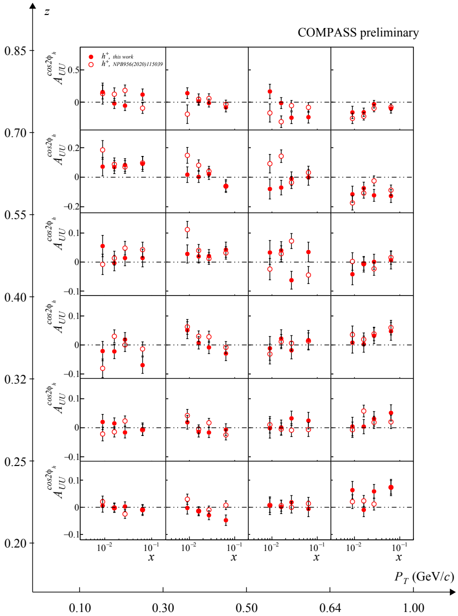


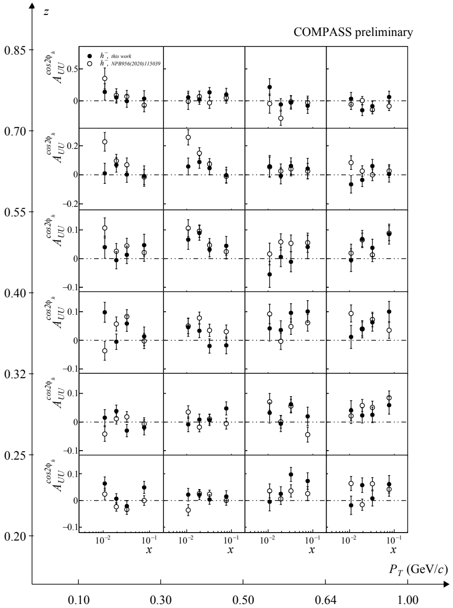




Normalised kinematic distributions: real data, LEPTO, HEPGEN ρ^0 and HEPGEN ϕ.

Backup: $\cos 2\phi_{\mathrm{h}}$ asymmetries





Backup: Comparison of the P_T-distributions with deuteron