Transverse-momentum distributions of hadrons produced in DIS at COMPASS

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CHARLES UNIVERSITY
Faculty of mathematics
and physics

COMPASS

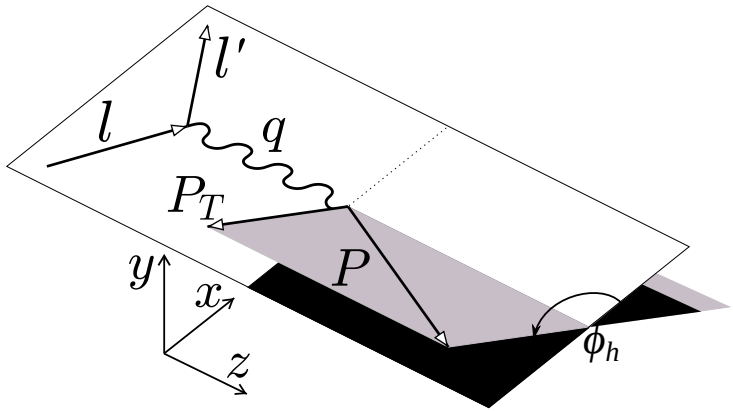
Introduction: Hadron production in unpolarised DIS

The cross section for producing a hadron h in DIS on unpolarised target $\ell \mathrm{N} \to \ell' \mathrm{h X}$:
[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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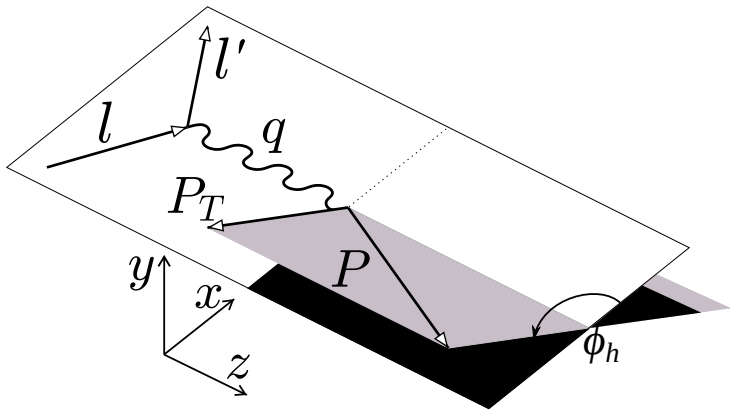

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Introduction: Hadron production in unpolarised DIS

The unpolarised structure function in terms of TMD PDFs and TMD FFs:

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

Gaussian ansatz:

$$f_1^q(x, k_{\mathrm{T}}^2) = f_1^q(x)\, \frac{1}{\pi \langle k_{\mathrm{T}q}^2 \rangle}\, e^{-\frac{k_{\mathrm{T}}^2}{\langle k_{\mathrm{T}q}^2 \rangle}}$$

$$D_1^{h/q}(z, p_\perp^2) = D_1^{h/q}(z)\, \frac{1}{\pi \langle p_{\perp h/q}^2 \rangle}\, e^{-\frac{p_\perp^2}{\langle p_{\perp h/q}^2 \rangle}}$$

Assuming flavour independence of $\langle k_{\mathrm{T}}^2 \rangle$ and $\langle p_\perp^2 \rangle$:

$$F_{\mathrm{UU,T}} = x \sum_q e_q^2 f_1^q(x) D_1^{h/q}(z)\, \frac{1}{\pi \langle P_{\mathrm{T}}^2 \rangle}\, e^{-\frac{P_{\mathrm{T}}^2}{\langle P_{\mathrm{T}}^2 \rangle}}$$

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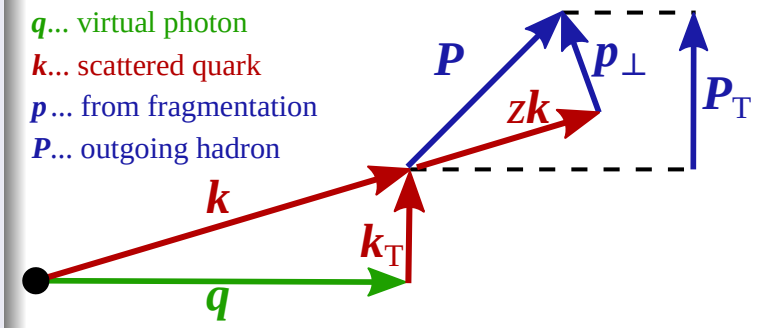

Momentum vectors
$\boldsymbol{P_{\mathrm{T}}} = z\boldsymbol{k_{\mathrm{T}}} + \boldsymbol{p}_\perp$

- $f_1(x, k_{\mathrm{T}}^2, Q^2)$ unpolarised TMD PDF,
- $D_1(z, p_\perp^2, Q^2)$ unpolarised TMD FF,
- $\mathcal{C}$ = sum over flavours and convolution over $\boldsymbol{p}_\perp, \boldsymbol{k_{\mathrm{T}}}$,

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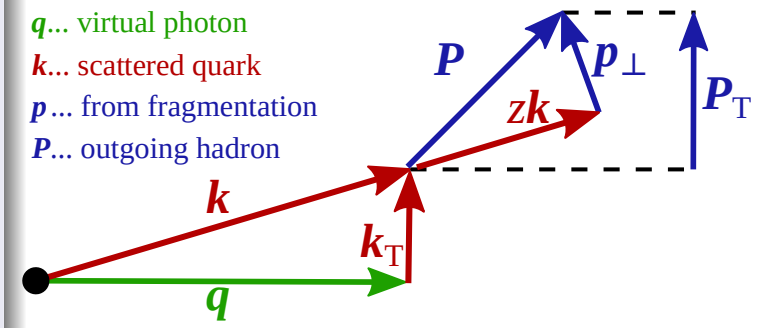

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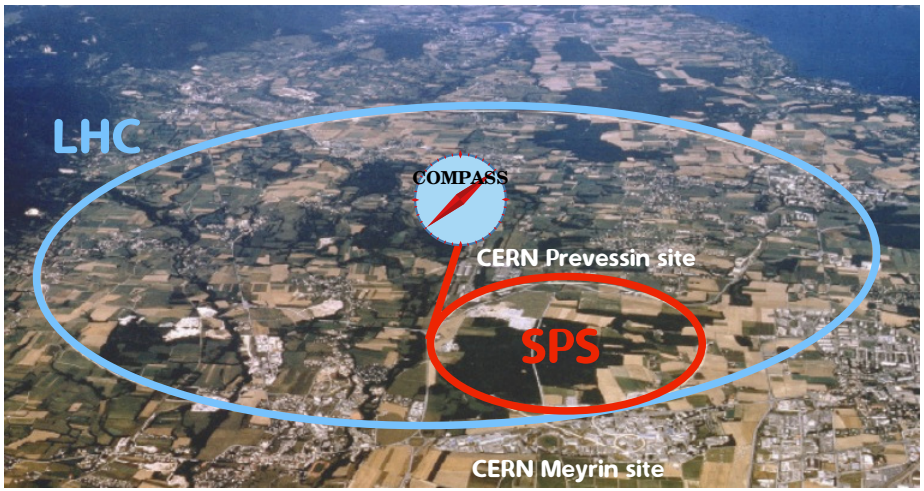
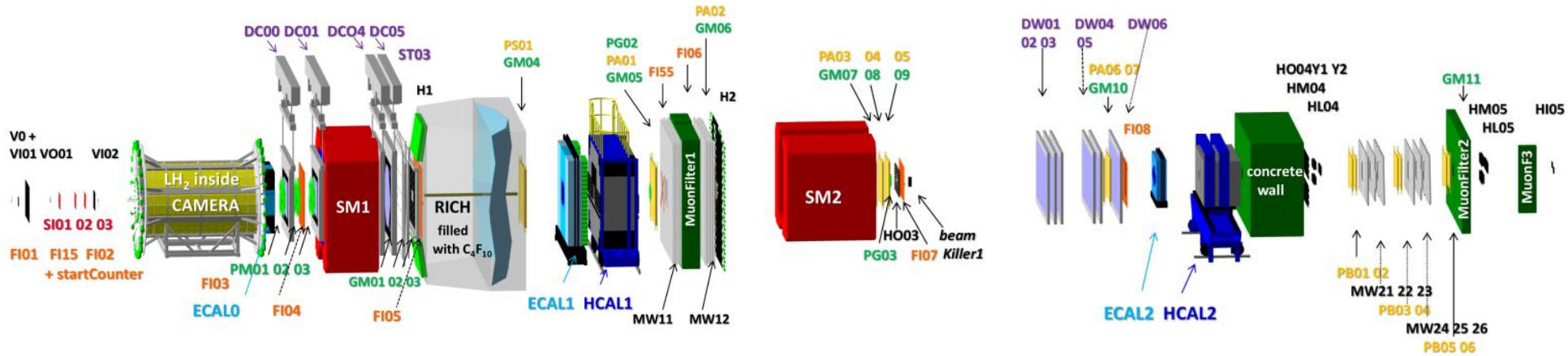
Introduction: COMPASS



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 (^{6}LiD) target (beam 160 GeV/c, 200 GeV/c in 2011) Summary by F. Bradamante on Monday.
  - Hadron spectroscopy: hadron beams and nuclear targets.
  - Drell–Yan: 190 GeV/c π^- beam and $p^\uparrow$, Al and W targets – R. Longo, Friday.
  - Hard exclusive processes and SIDIS: 160 GeV/c $\mu^\pm$ beam and liquid H_2 target. DVCS & HEMP – N. d'Hose, Wednesday.



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: exclusive measurements, 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.
- P_{T}^2-distributions – this talk.
- Azimuthal asymmetries – A. Moretti (next talk).

Future:

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

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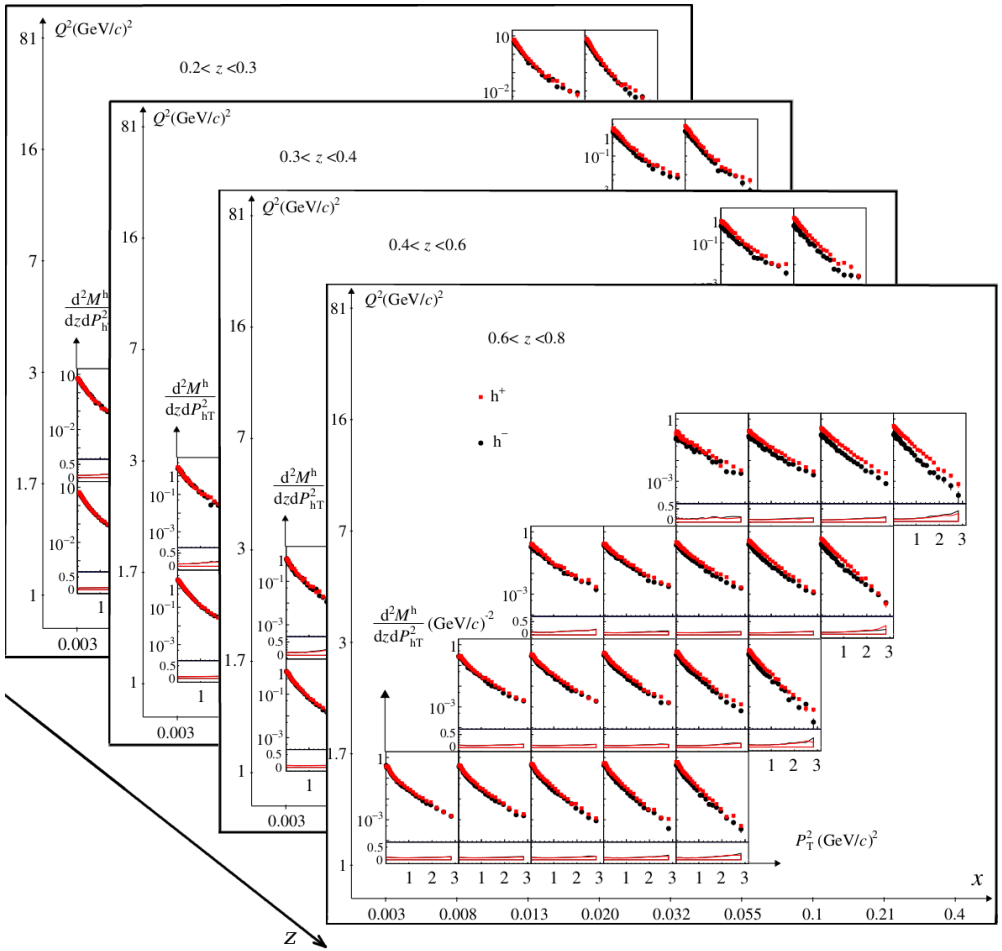
Measurement on ^{6}LiD:

- [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.



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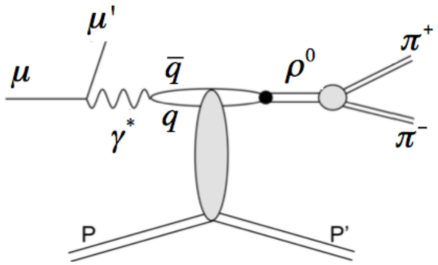
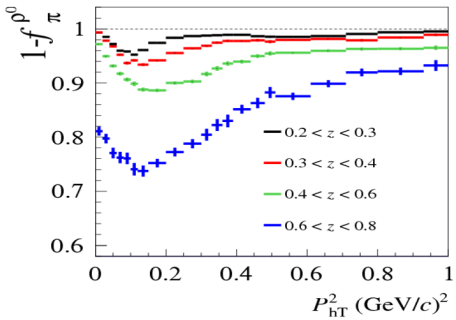
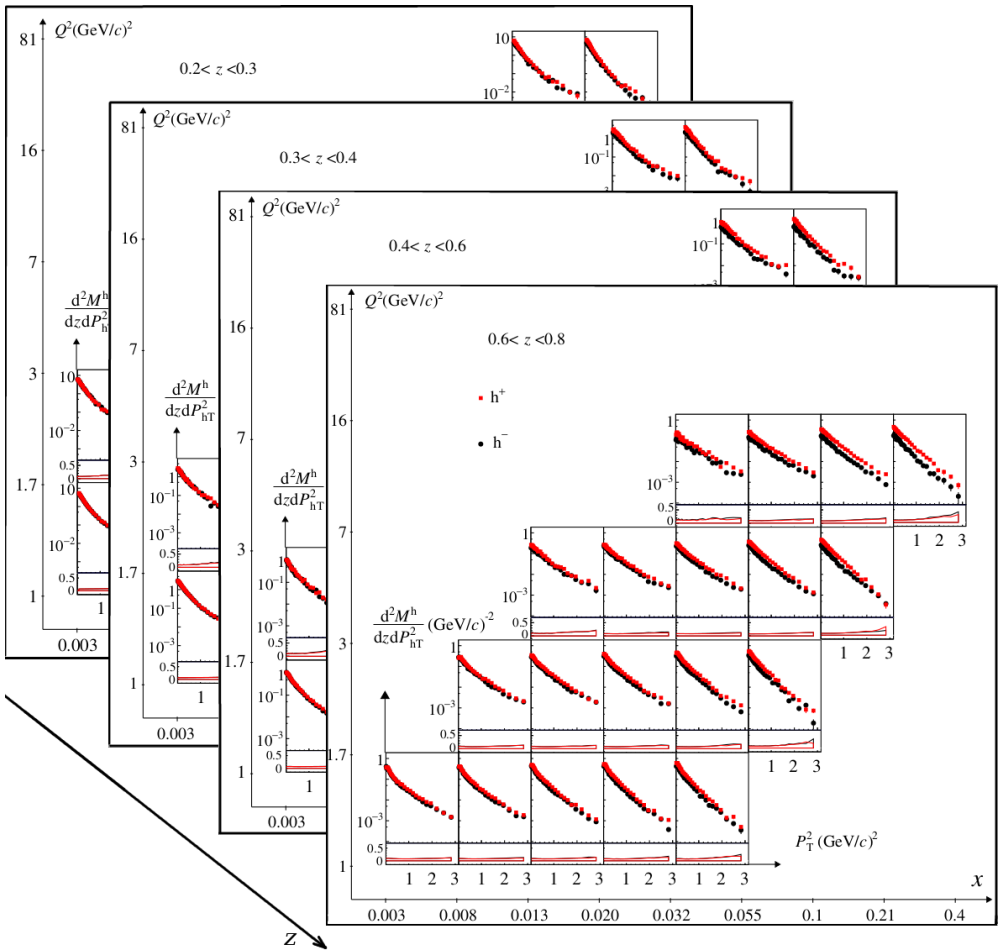


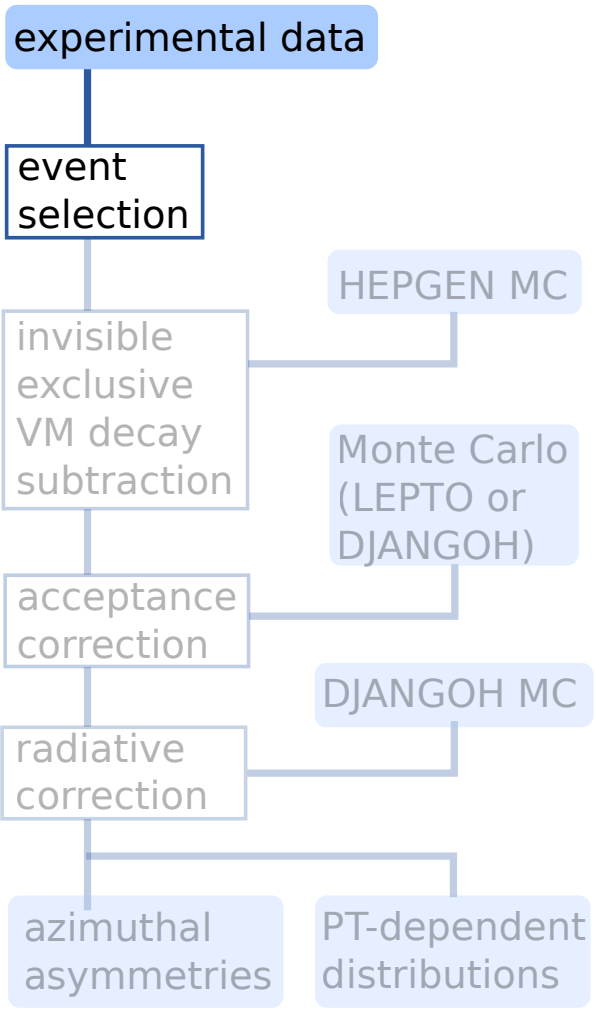
Diffractively produced $\rho^0 \to \pi^+\pi^-$, creating a background to SIDIS.

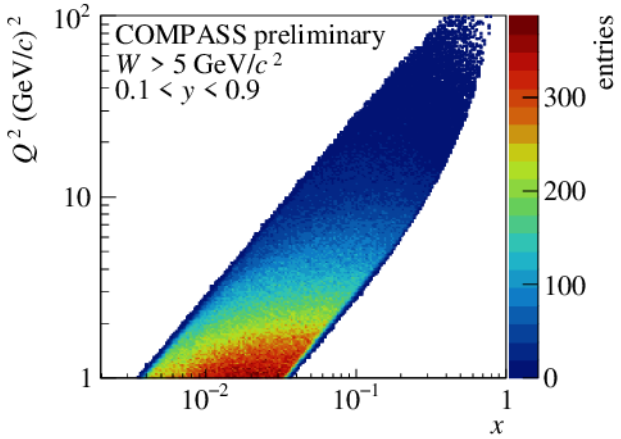


$1 - \rho^0$ contamination fraction.



Measurement 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

- $0.1 < z < 0.85$,
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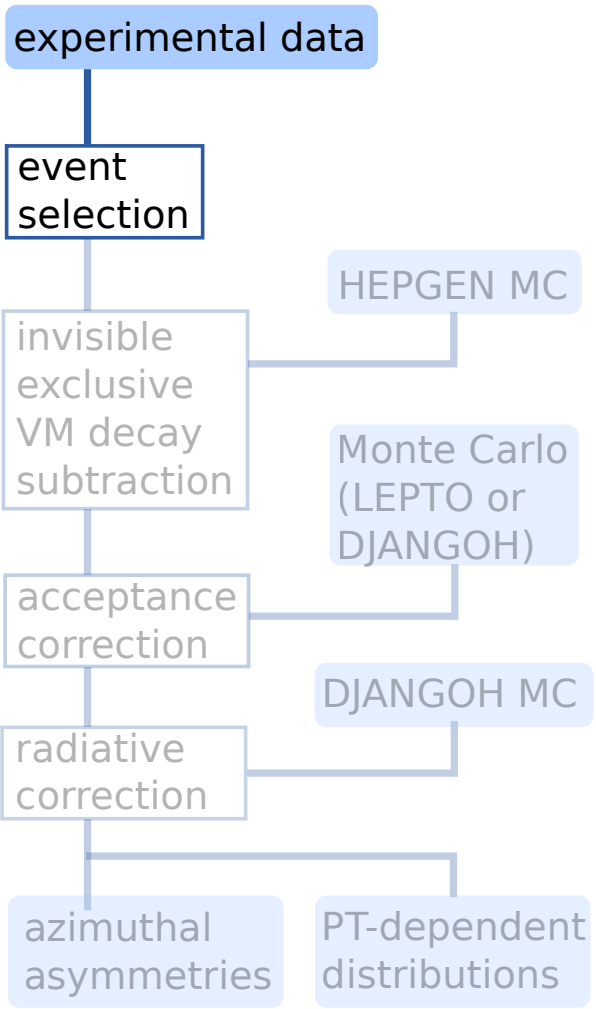

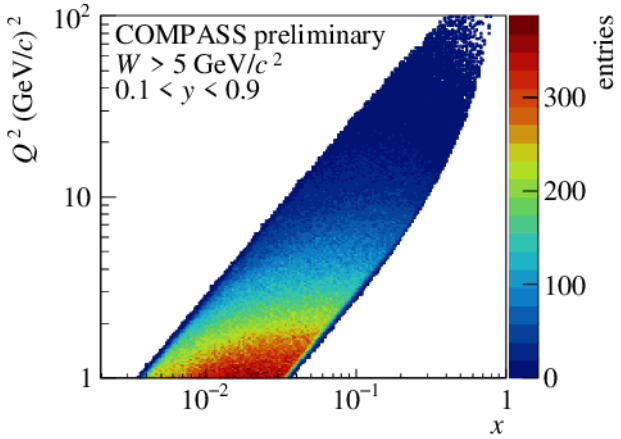

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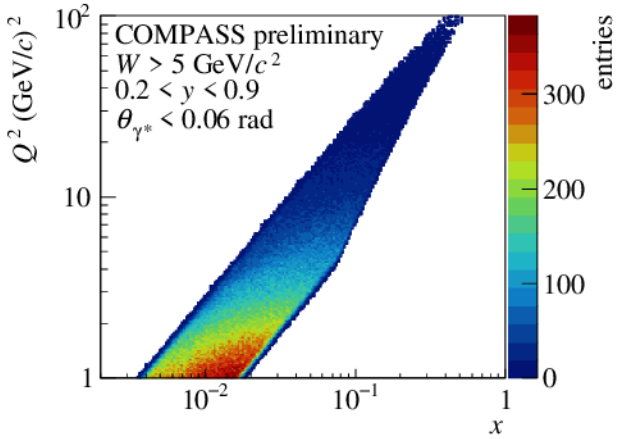

Selected range with moderate acceptance corrections.

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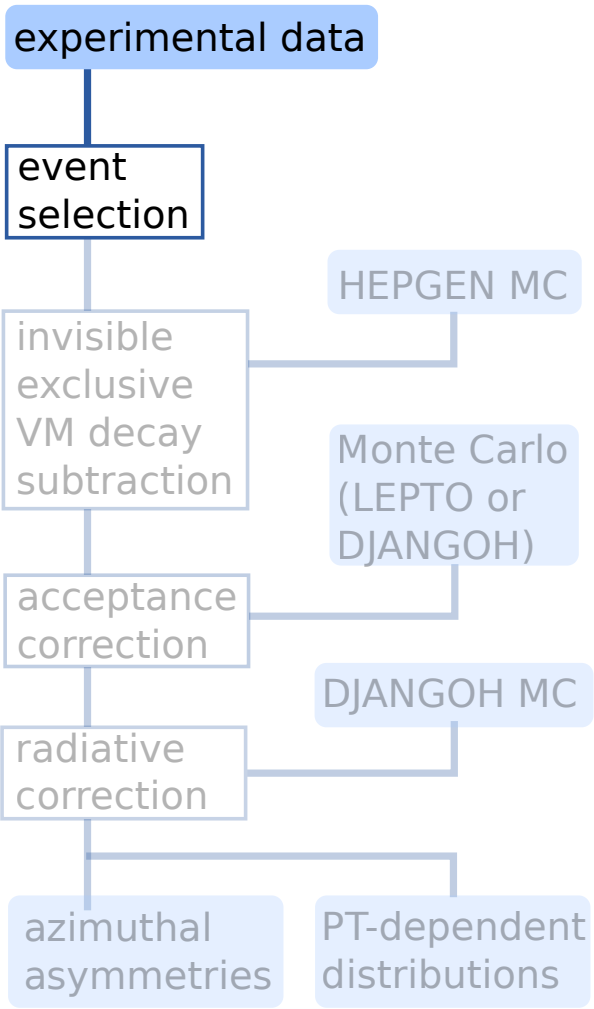

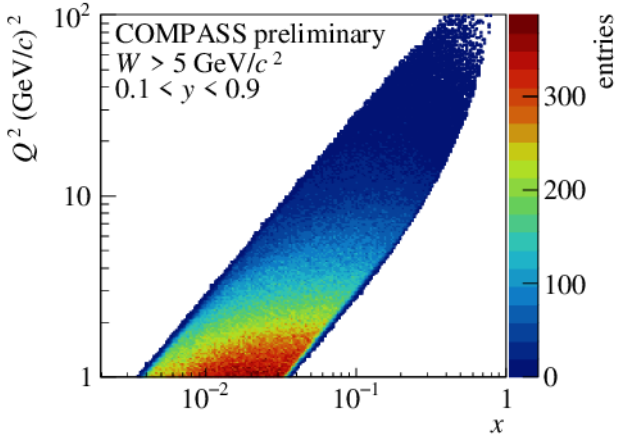

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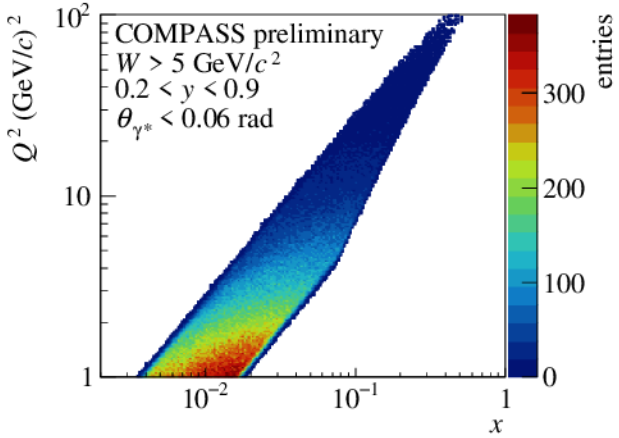

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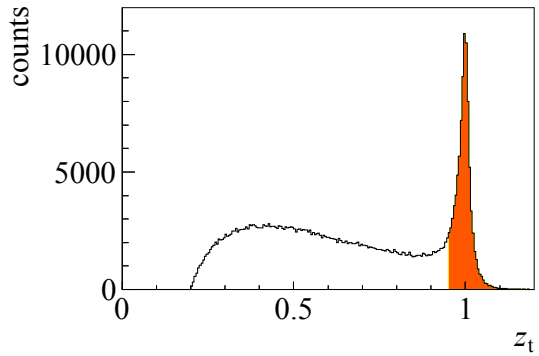

[COMPASS, Nucl.Phys.B 956 (2020)]

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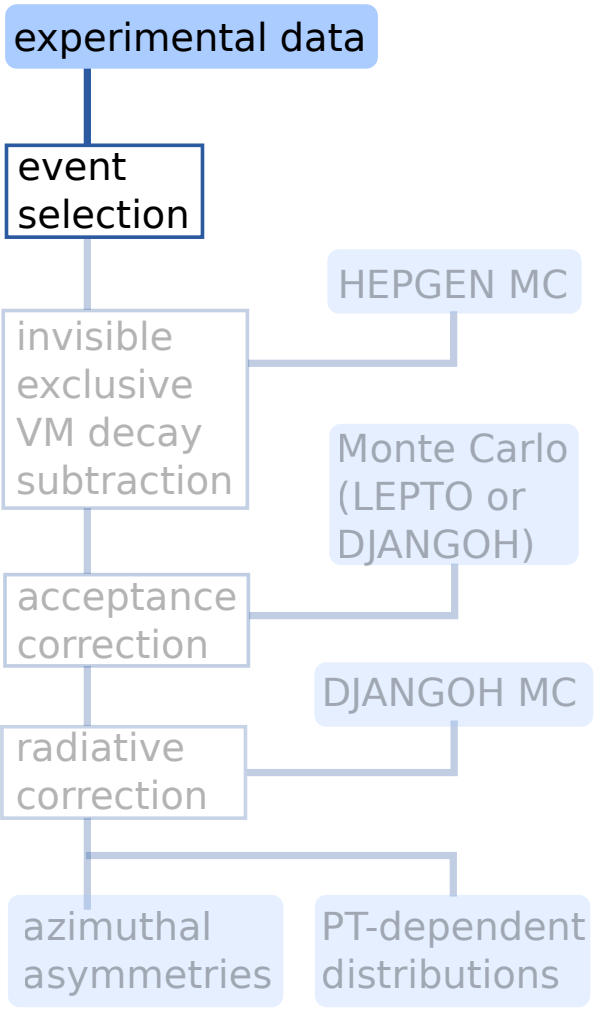
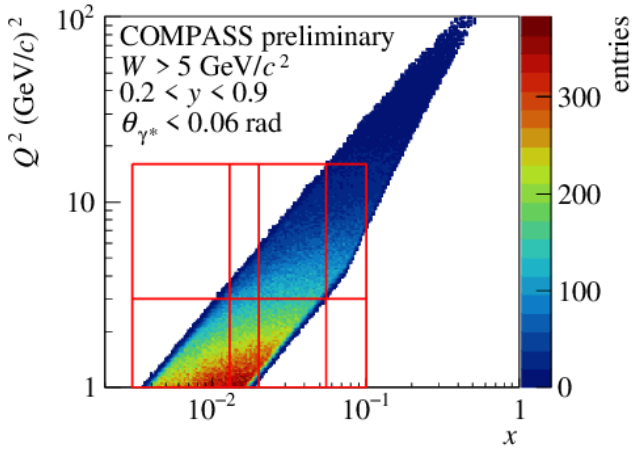


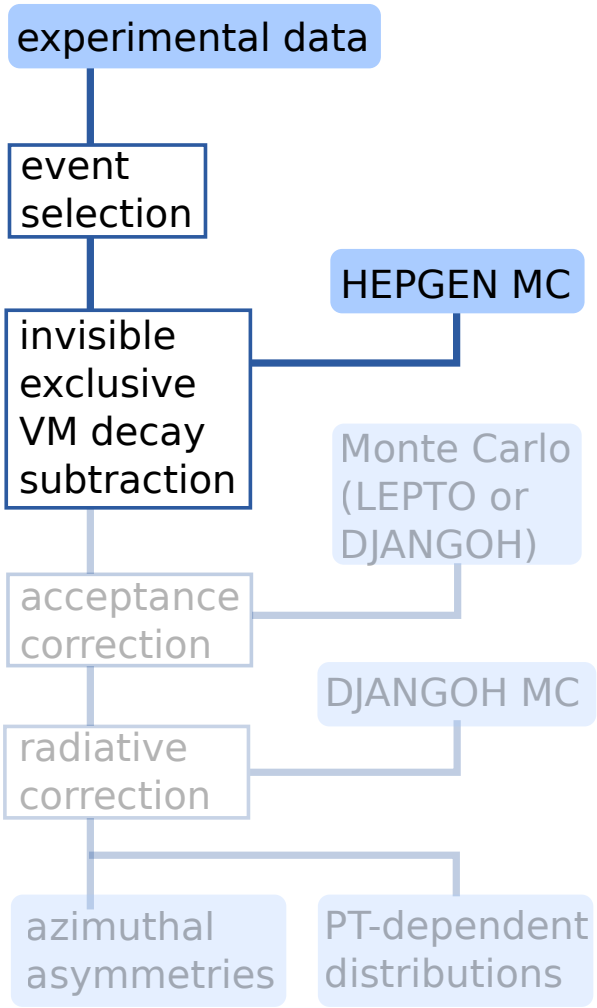


Q^2 and x bins for the P_T-dependent distributions.

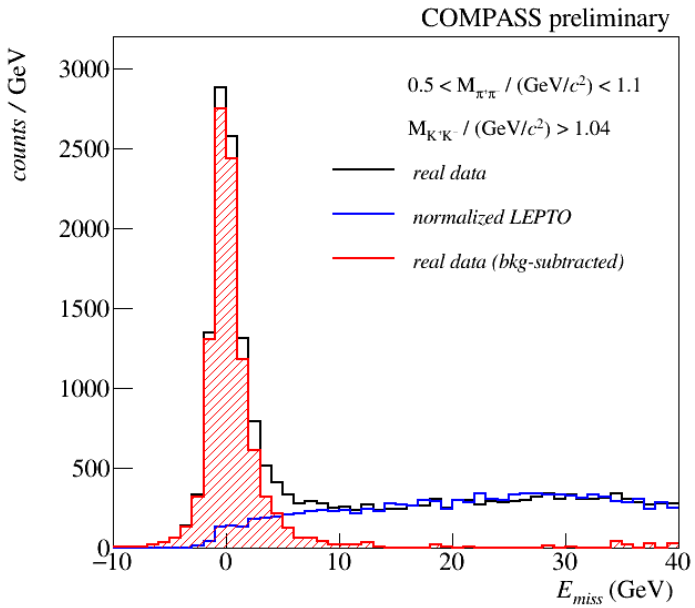
Binning

- Based on the published results on ^{6}LiD.
- 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
    - $4x \times 2Q^2 \times 4z$
    - $4x \times 2Q^2 \times 7z$
  - Additional binning in W
    - $4x \times 3Q^2 \times 4z \times 2W$

Measurement on LH_2: Exclusive VM decay subtraction

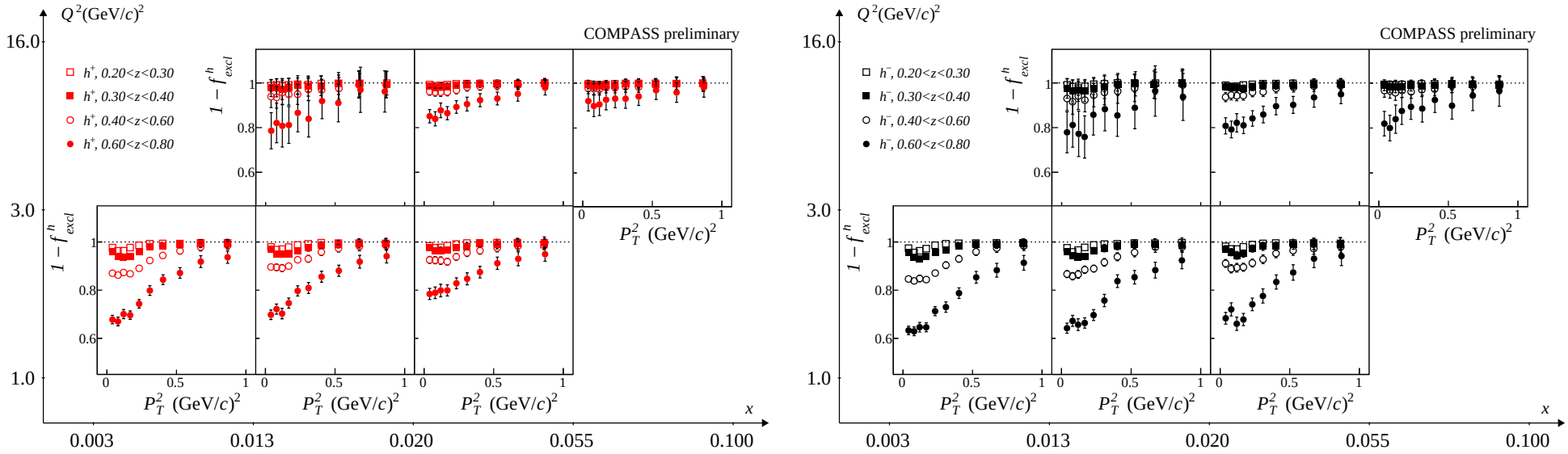


- Different approach w.r.t published d asymmetries.
- 'Visible' exclusive h^+h^- removed in event selection.
  - About 80 % of the decays are 'visible'.
- 'Invisible' decays (only one h observed)
  - HEPGEN MC generator with azimuthal modulations.
  - Normalised to the data using E_{miss} distribution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



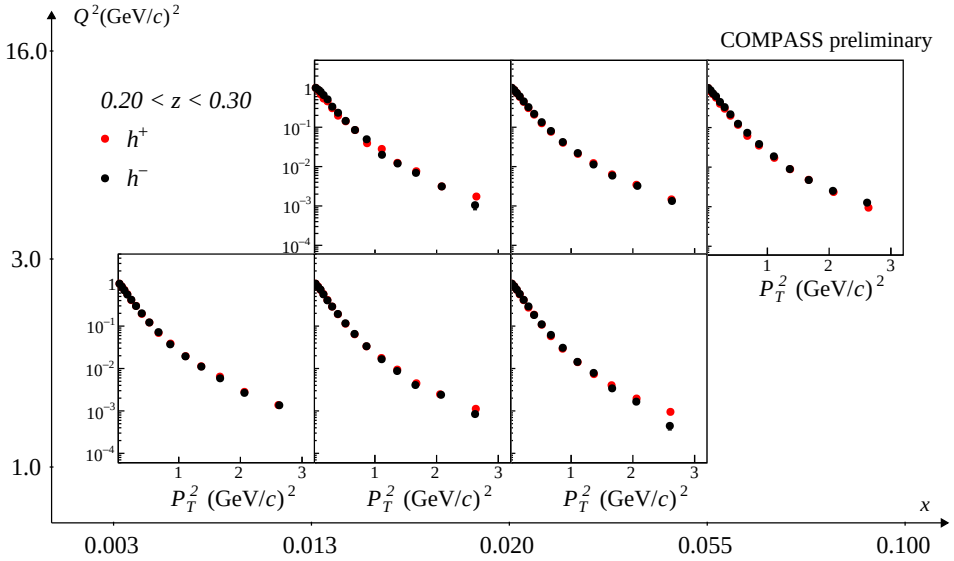
The number of signal events in the peak after SIDIS (from LEPTO) background subtraction is used to normalise HEPGEN.

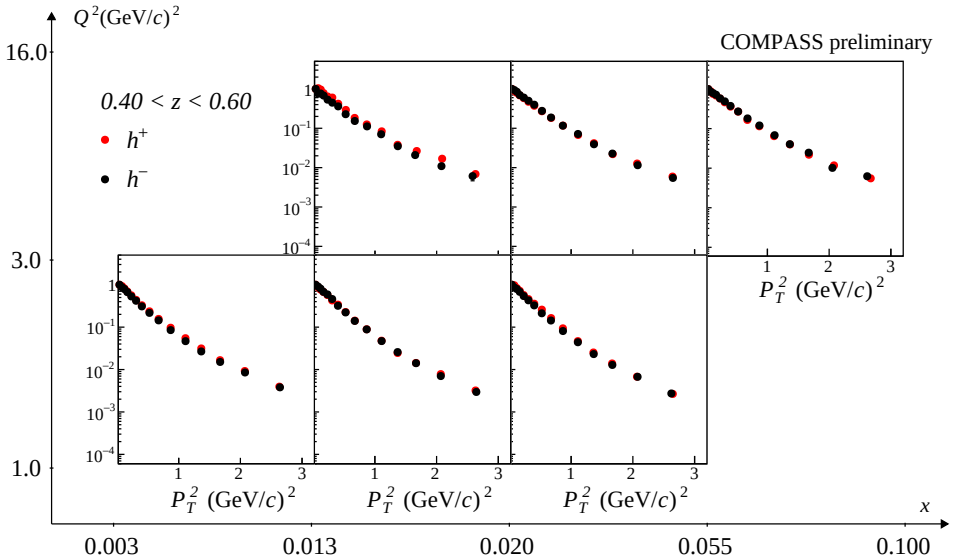
Measurement on LH_2: Exclusive VM decay subtraction



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

Measurement on LH_2: Results for the P_T-distributions





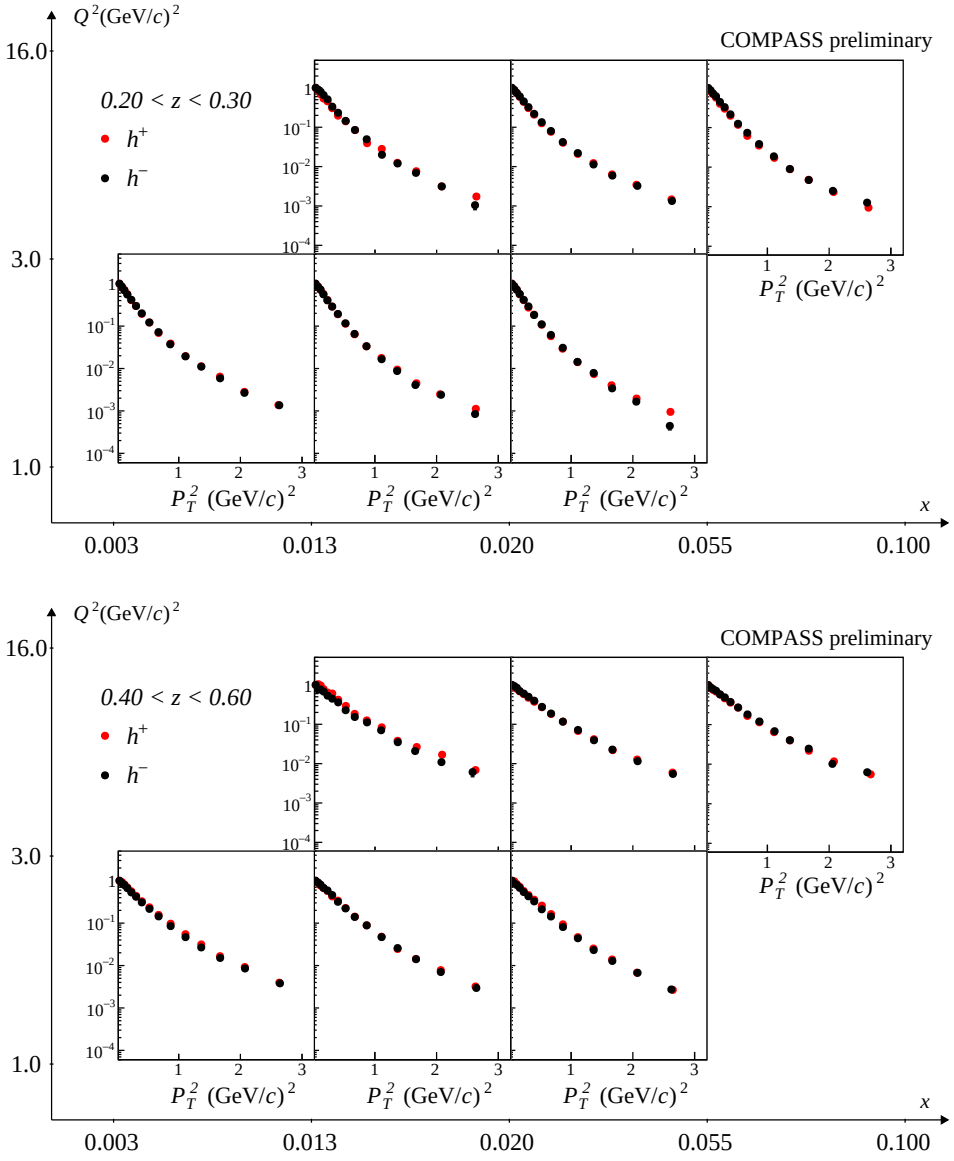
- Distributions normalised to the first bin.
- The shape almost the same for $h^{\pm}$ – no sign of flavour dependence of k_T, $p_\perp$.
- Clear z and Q^2 dependence.
- Gaussian model for f_1 and D_1:

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

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

- Deviation from the simple exponential visible at $P_T > 1$ (GeV/c)^2.

Measurement on LH_2: Results for the P_T-distributions



- Distributions normalised to the first bin.
- The shape almost the same for $h^{\pm}$ – no sign of flavour dependence of k_T, $p_\perp$.
- Clear z and Q^2 dependence.
- Gaussian model for f_1 and D_1:

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

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

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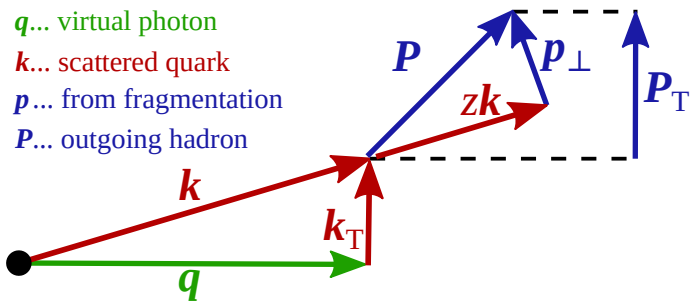

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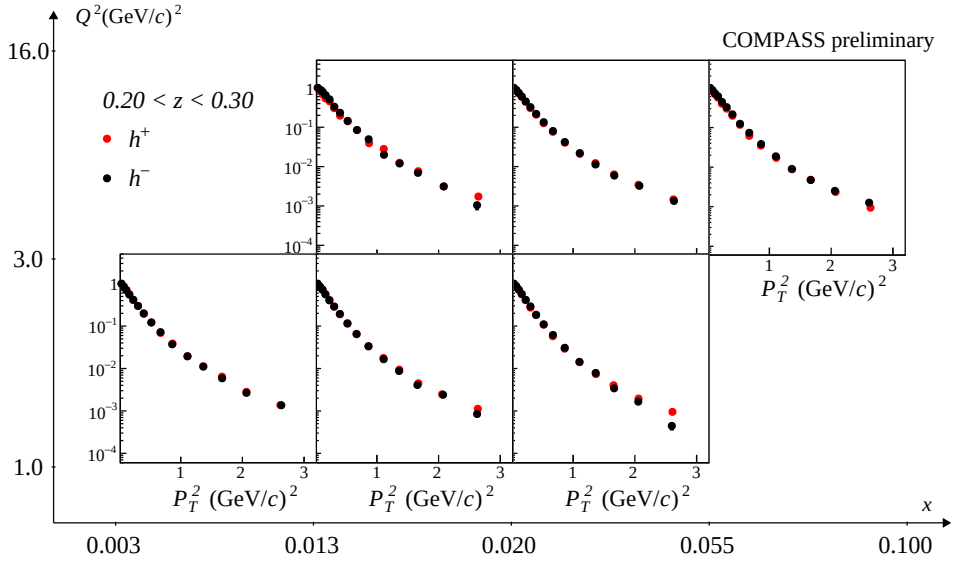

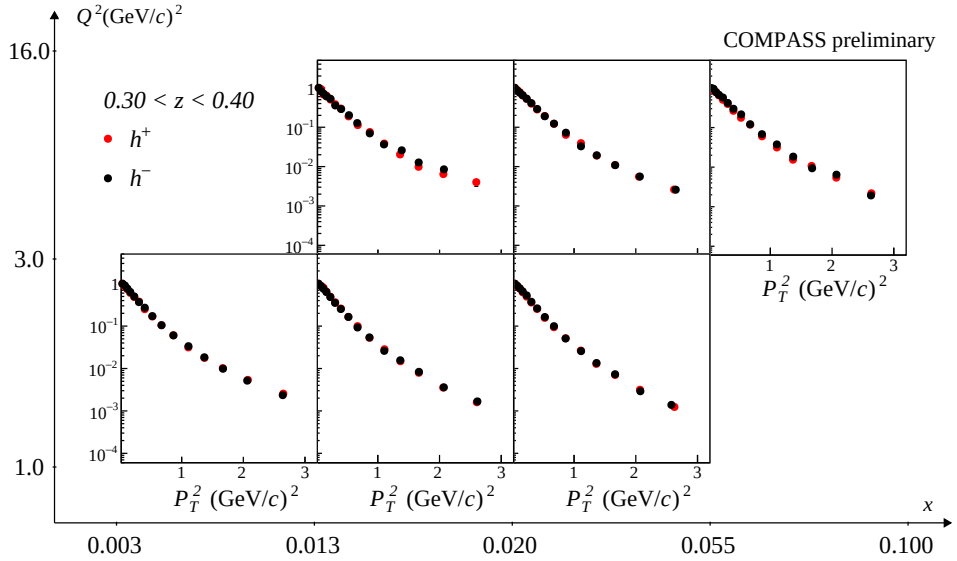

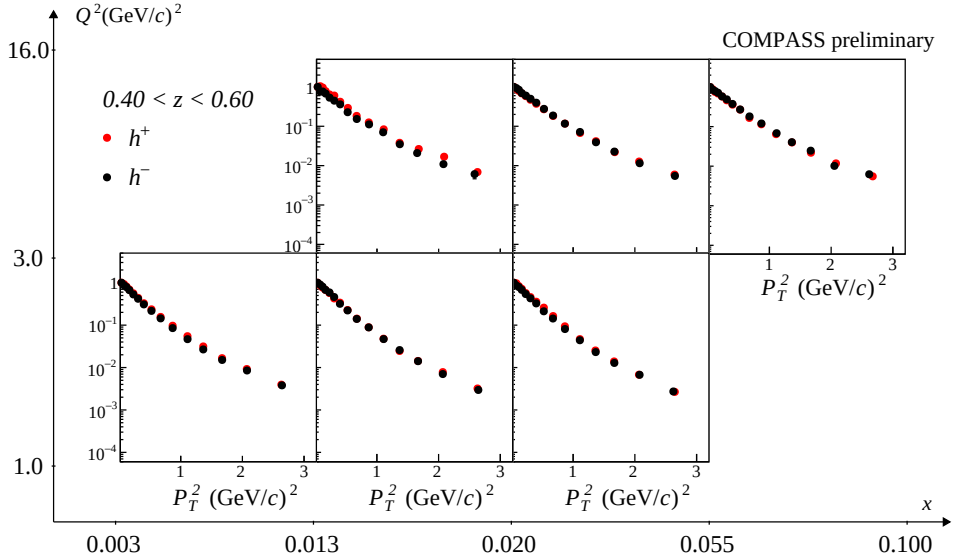

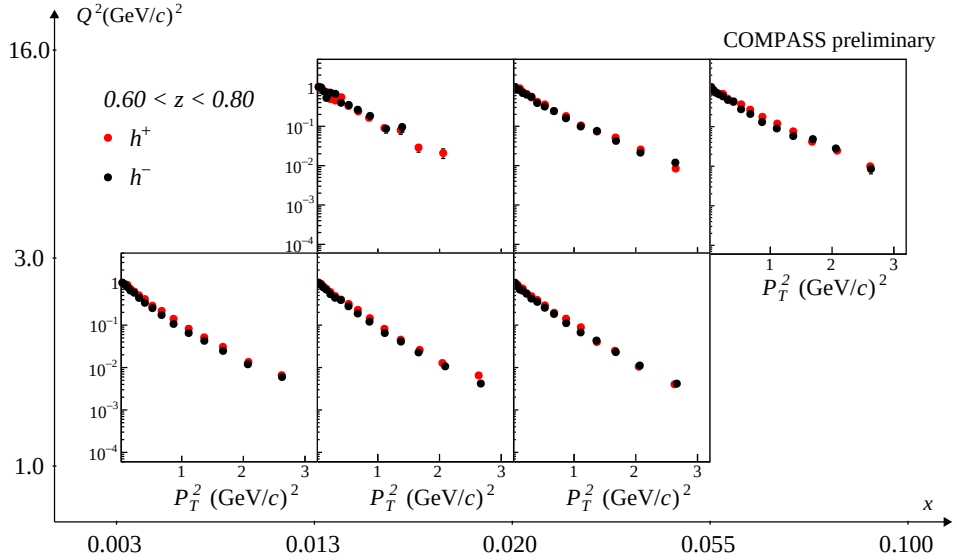

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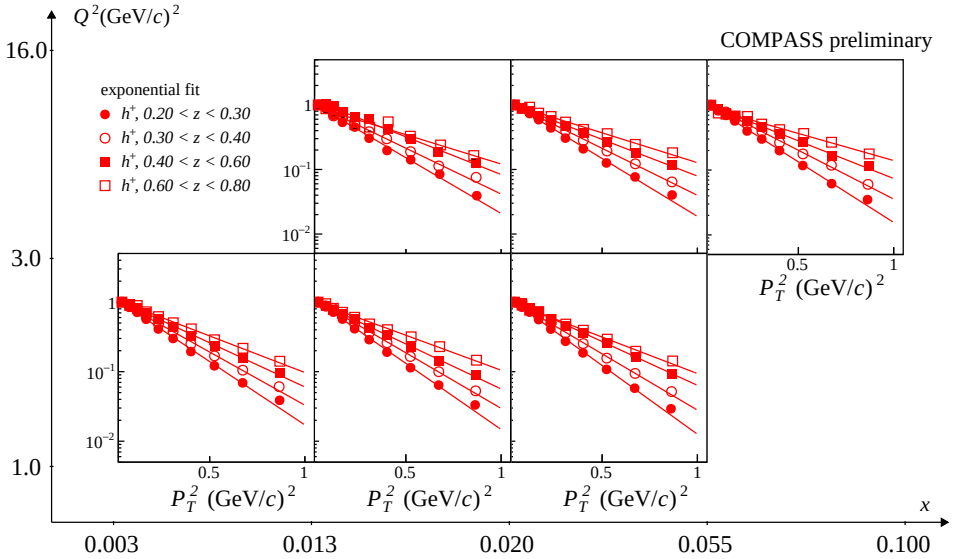

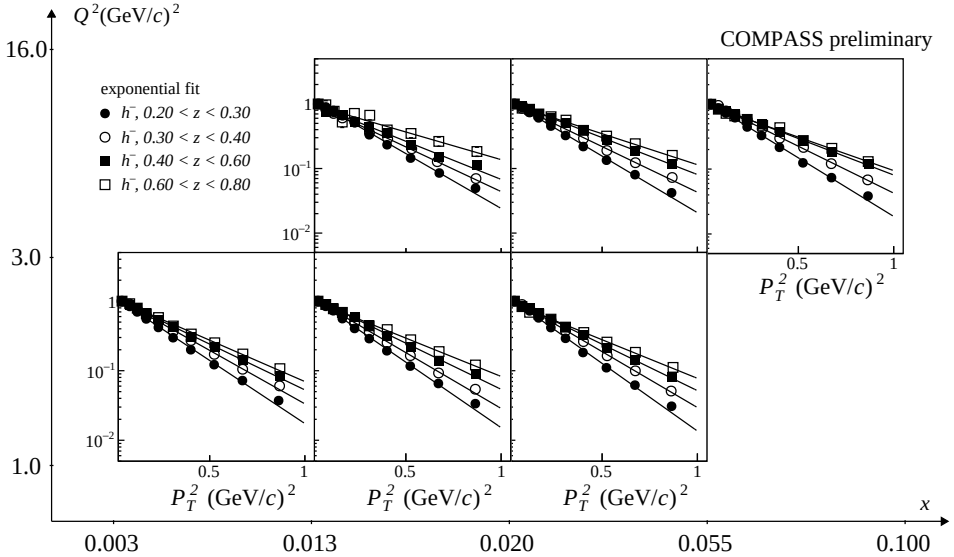

Exponential fit in $P_\mathrm{T} < 1\ (\mathrm{GeV}/c)^2$ range.

- Linear trend in z^2 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.
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Measurement on LH_2: Results for the P_T-distributions

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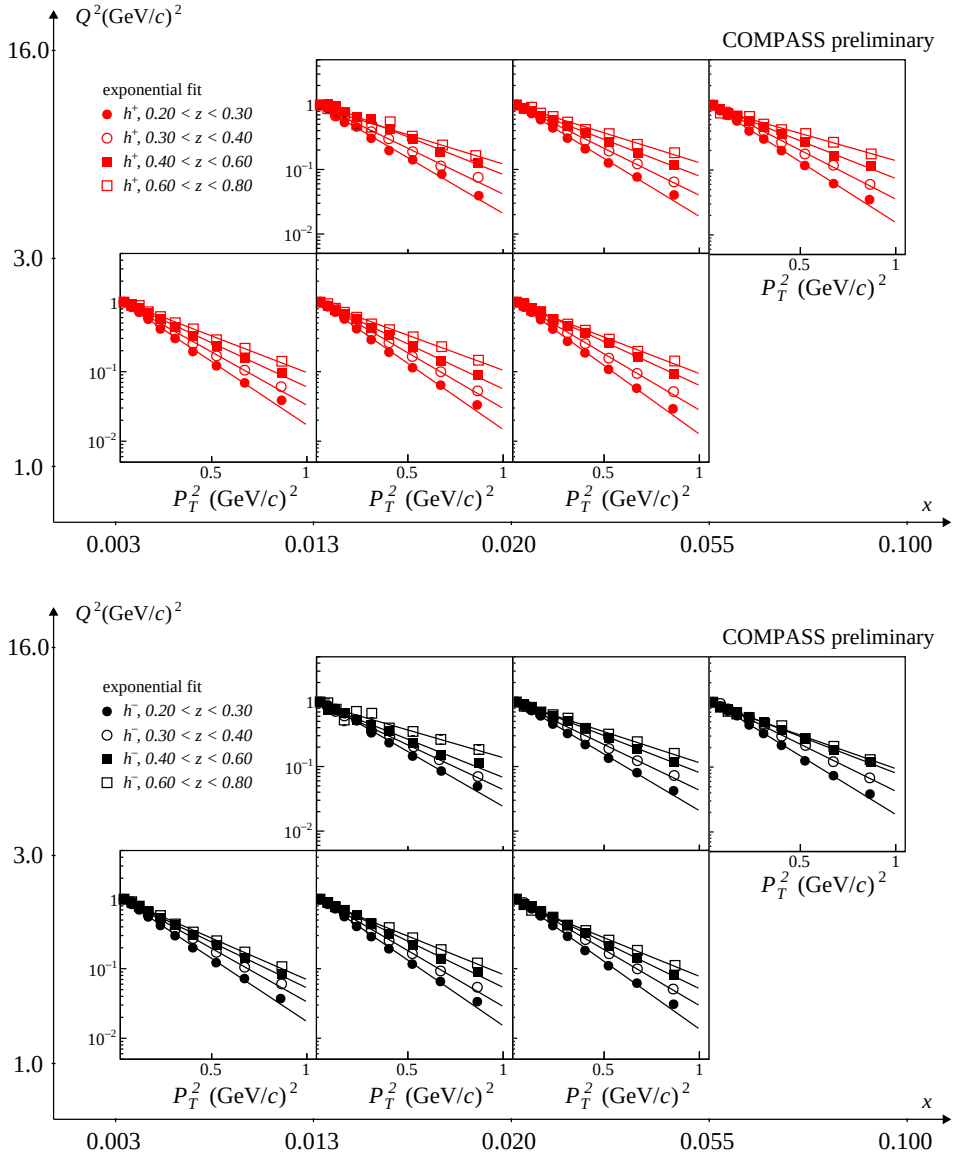

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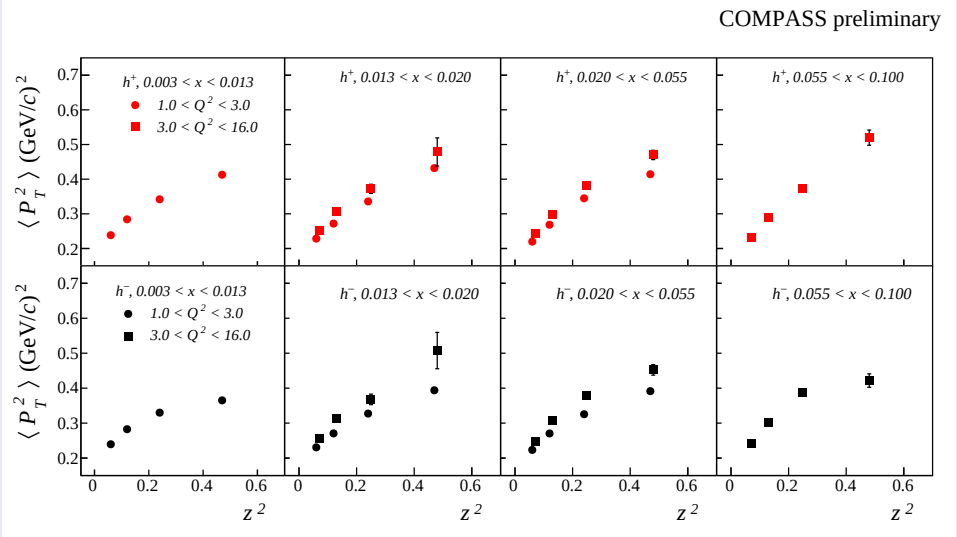

The fitted $\langle P_\mathrm{T}^2 \rangle$ versus z^2 in the x and Q^2 bins.

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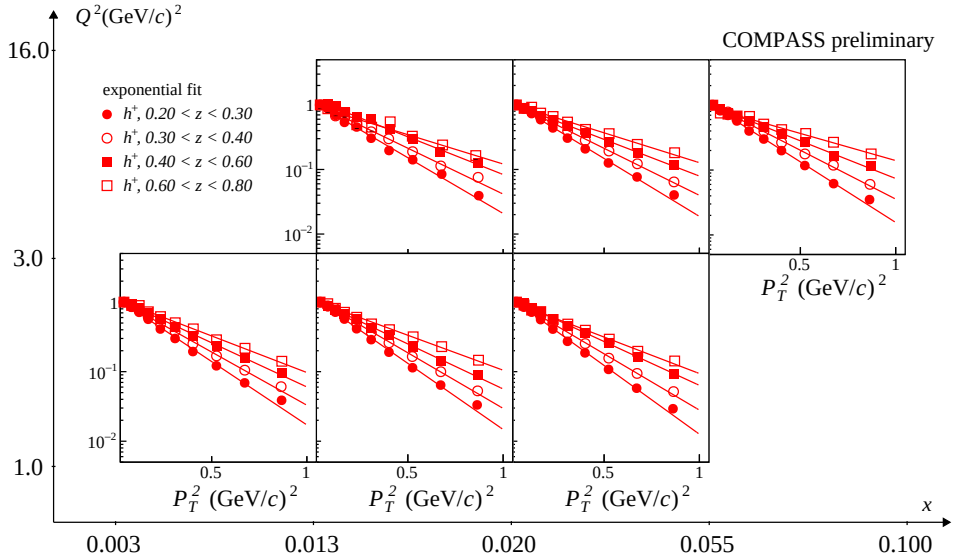

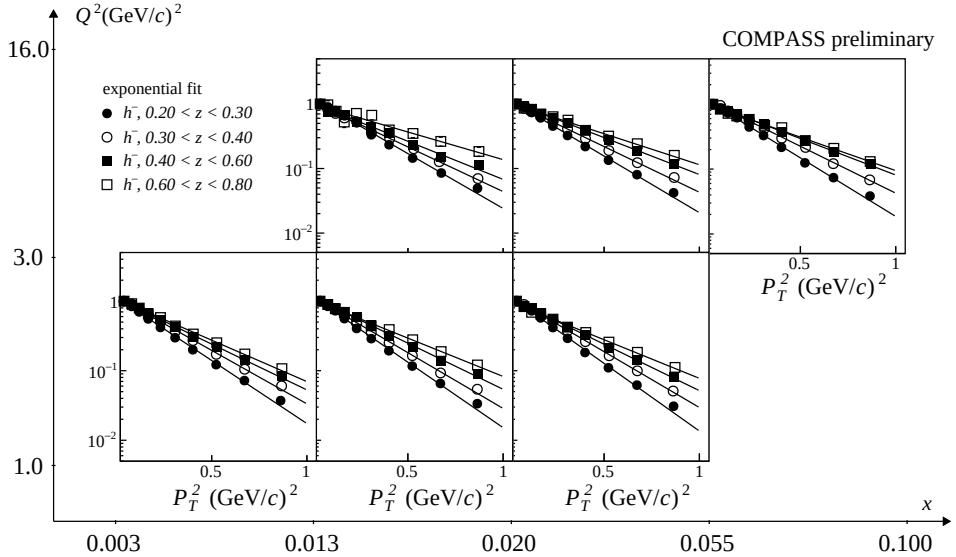

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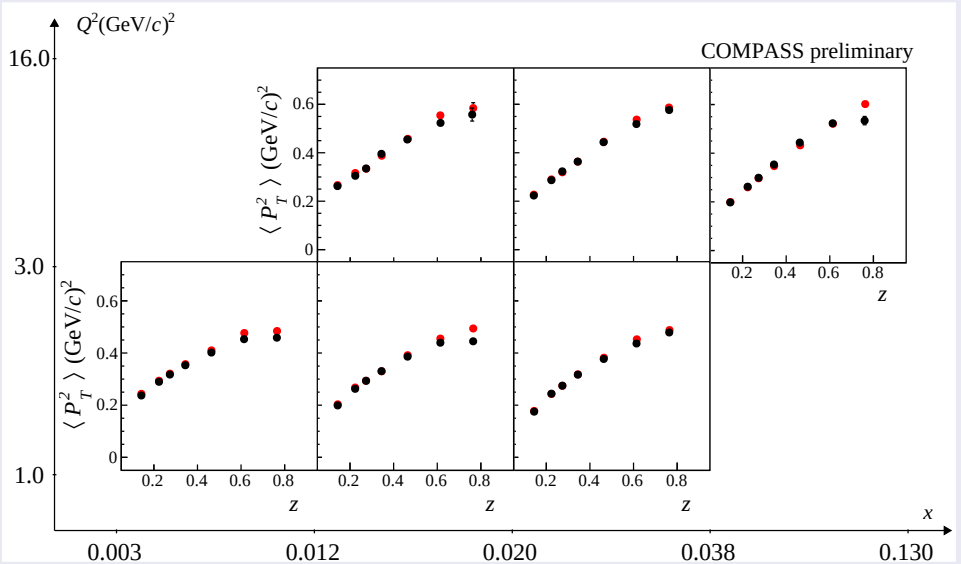

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Comparison with Pavia 2017 fit [A. Bacchetta *et al.*, JHEP 06 (2017) 081]

- SIDIS ep(D)→eπ±(K±)X (HERMES)
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- Drell–Yan (E228, E605)
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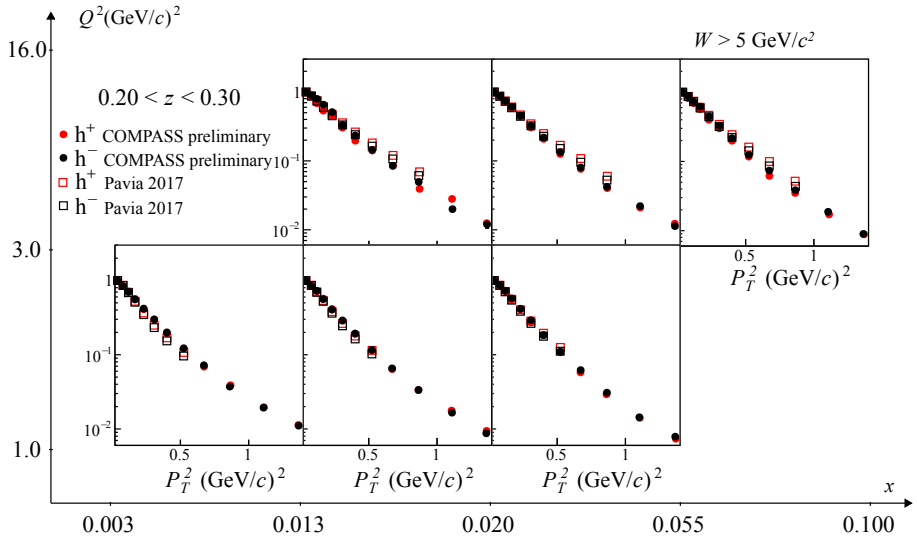

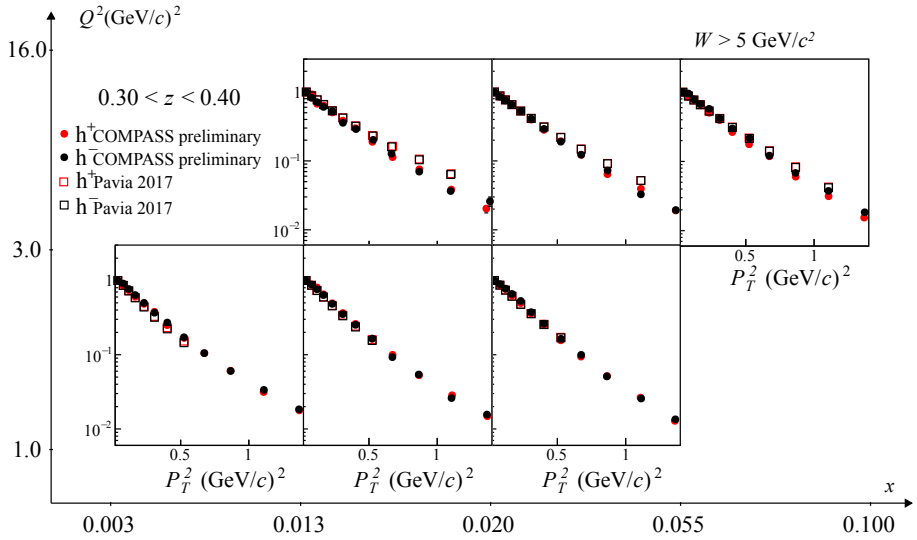

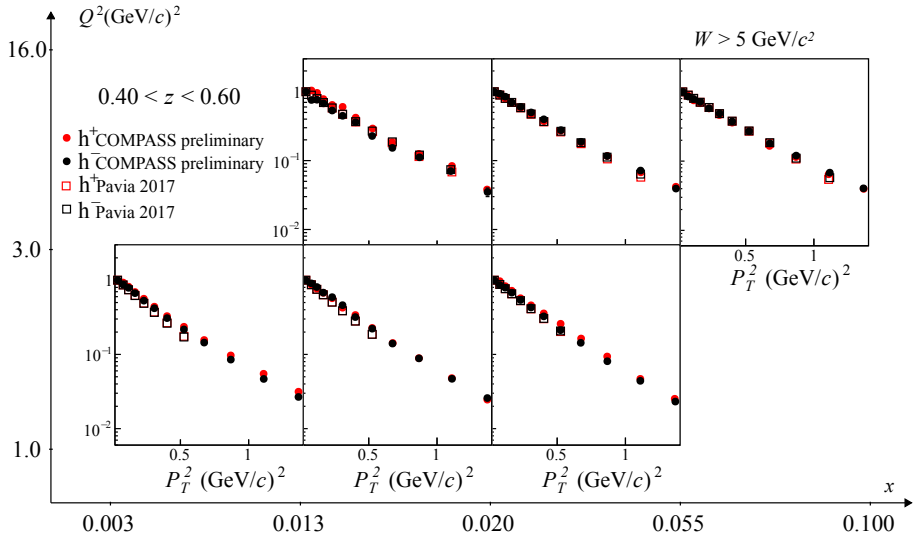

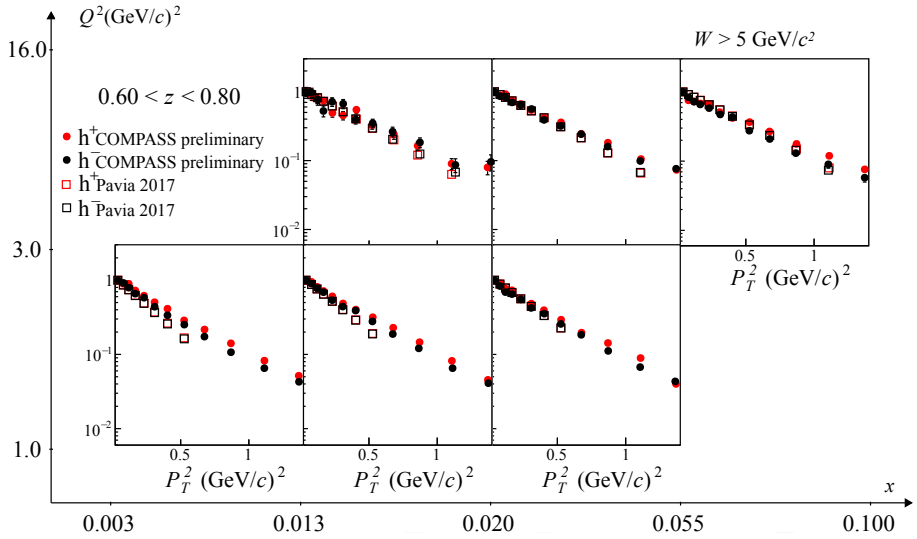

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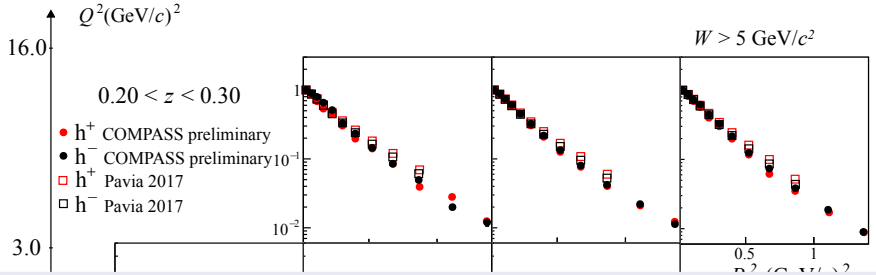
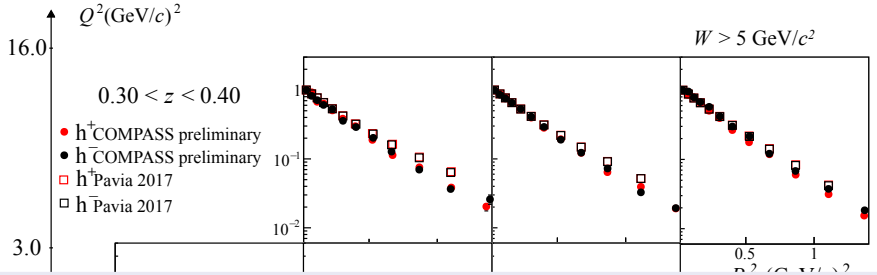
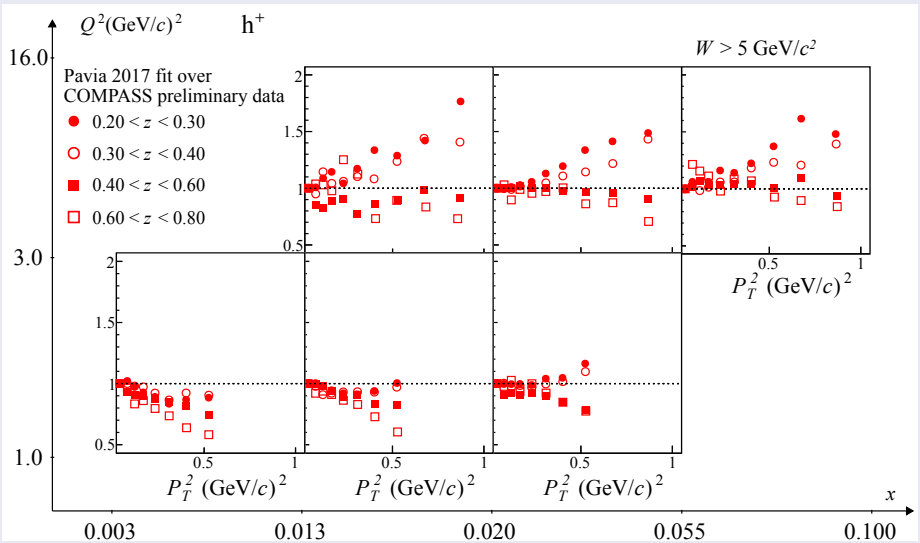
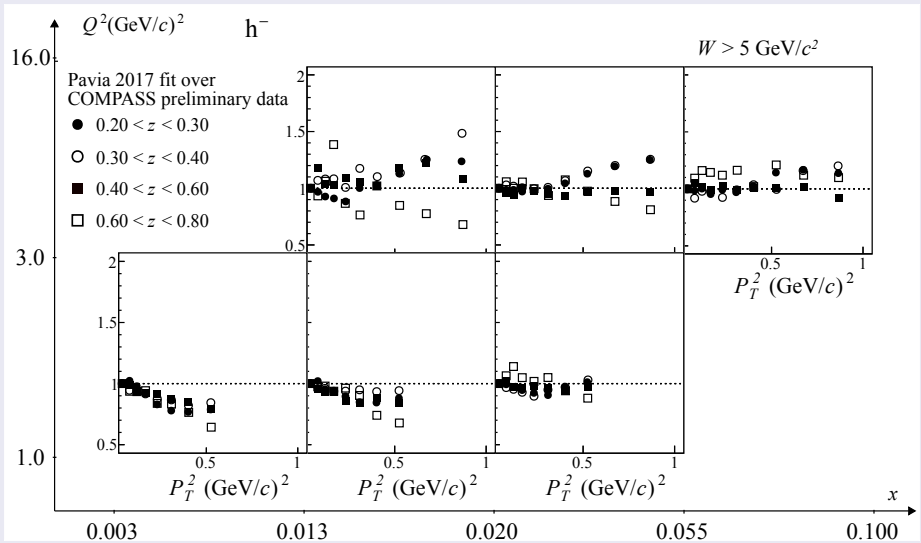




The ratio of the prediction from the fit over the preliminary data:





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 – an important role in some regions.

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.
  - Two-exponential shape, the same for $h^\pm$.
  - More results will come.
- 2022 measurement with (transversely polarised) ^{6}LiD target just about to start.

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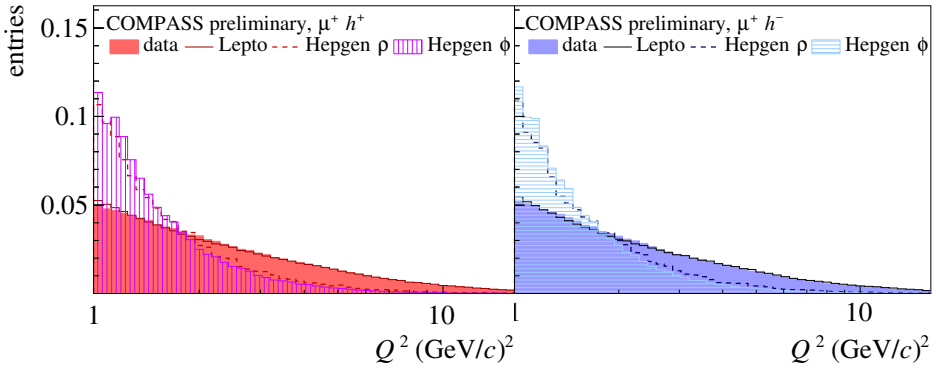
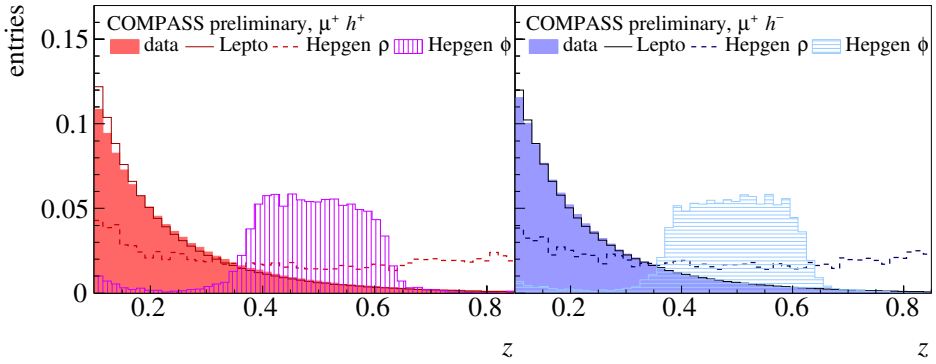
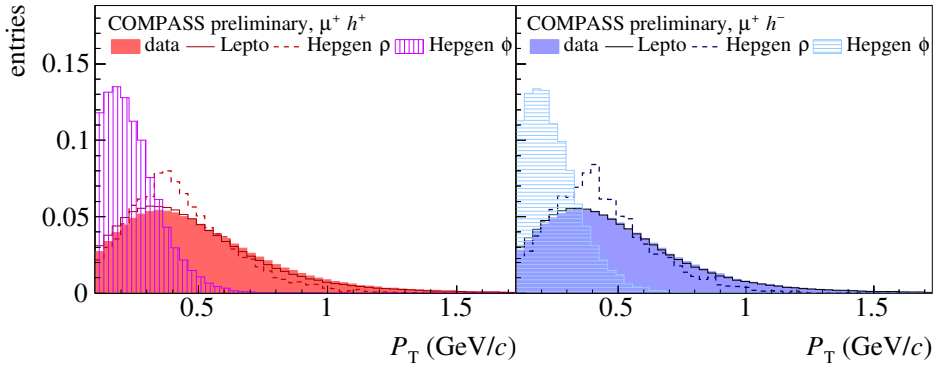
Thank you for your attention!

Backup: Kinematic distributions on LH_2

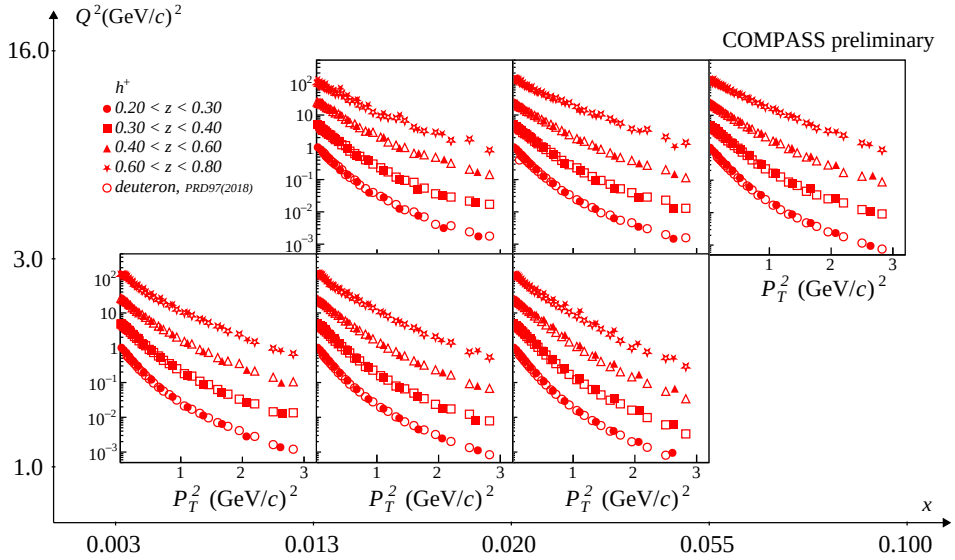


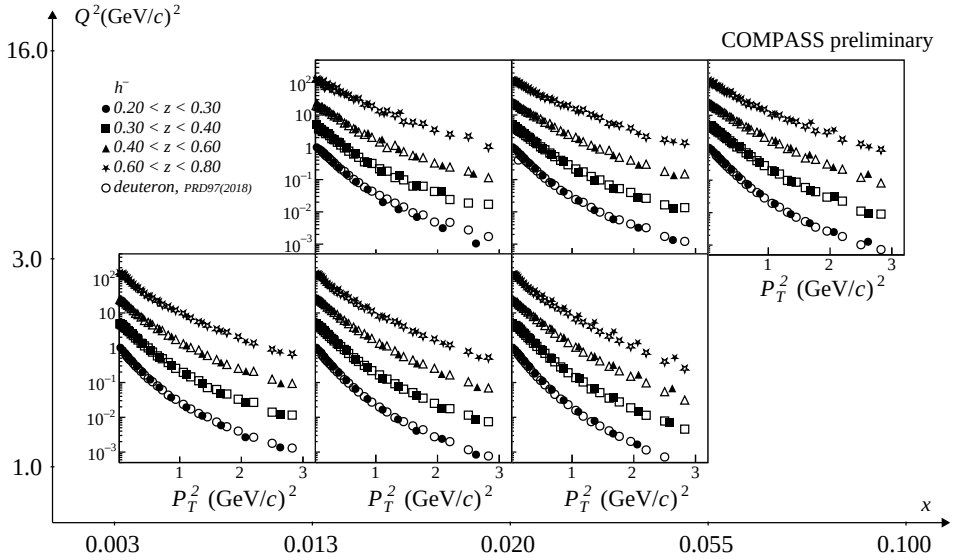




Normalised kinematic distributions: real data, LEPTO, HEPGEN ρ^0 and HEPGEN ϕ.

Backup: Comparison of the P_{T}-distributions with deuteron





Backup: Distributions of q_{T} and q_{T}^2

$q_{\mathrm{T}} = P_{\mathrm{T}}/z$