Azimuthal asymmetries and transverse-momentum-dependent distributions of charged hadrons at COMPASS

Andrea Moretti

on behalf of the COMPASS Collaboration

Content of this talk

- Brief introduction on nucleon structure
- The COMPASS experiment
- Unpolarized SIDIS cross section and TMD observables
- Contribution from exclusive hadrons
- New preliminary results from COMPASS
- Conclusions

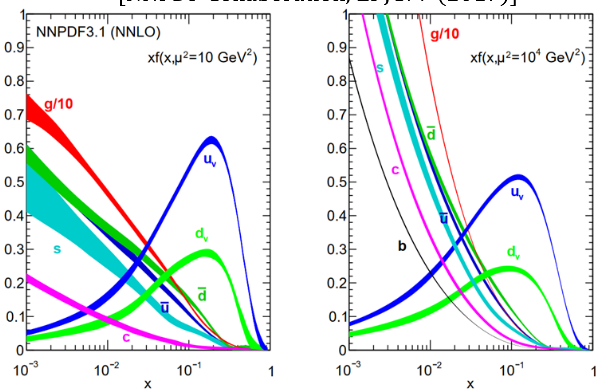
INTRODUCTION

Nucleon structure in collinear approximation

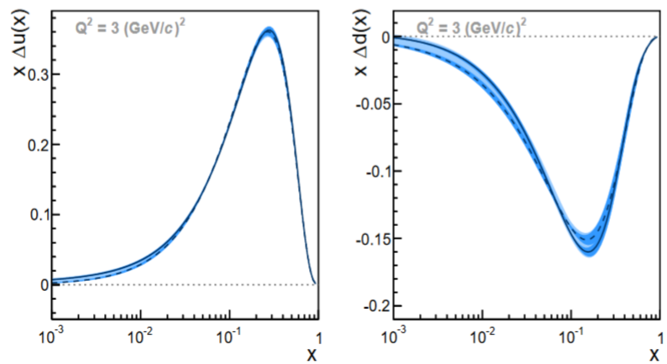
Parton Model and collinear QCD successful in explaining large amounts of data at high energies.

Such good description is based on three Parton Distribution Functions (PDFs):

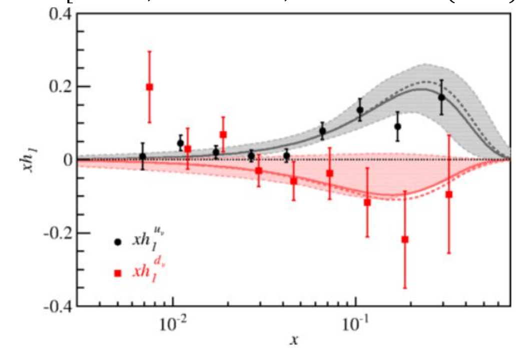
[NNPDF Collaboration, EPJC77 (2017)]



[COMPASS Collaboration, PLB769 (2017)]



[Barone, Bradamante, Martin PRD91 (2015)]



unpolarized PDF $f_1^q(x,Q^2)$

very well known

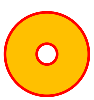
helicity $g_1^q(x,Q^2)$

well known

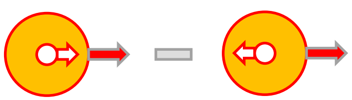
transversity $h_1^q(x,Q^2)$

first measurements in 2005

(HERMES, COMPASS)



unpolarized quark in unpolarized nucleon



difference of parallel and anti-parallel quark polarizations, when the nucleon has a fixed **longitudinal** polarization

difference of parallel and anti-parallel quark polarizations, when the nucleon has a fixed **transverse** polarization

Deep Inelastic Scattering (DIS)

Semi – Inclusive Deep Inelastic Scattering (SIDIS)

Beyond QCD collinear approximation

- However, collinear QCD not adequate to explain all measured phenomena
  (spin crisis, hyperon polarization, $pp \to \pi$ inclusive asymmetry …)

- Transverse degrees of freedom:
  parton transverse spin $\boldsymbol{s_T}$,
  its transverse momentum $\boldsymbol{k_T}$,
  their correlations,
  the correlation of each of them with the nucleon transverse spin $\boldsymbol{S_T}$.

- **From three collinear PDFs to 8 transverse-momentum-dependent (TMD) PDFs.**

Nucleon \ Quark	**U** unpolarized	**L** longitudinally polarized	**T** transversely polarized
U unpolarized	$f_1^q(x, \boldsymbol{k}_T^2)$ number density		$h_1^{q\perp}(x, \boldsymbol{k}_T^2)$ Boer-Mulders
L longitudinally polarized		$g_1^q(x, \boldsymbol{k}_T^2)$ helicity	$h_{1L}^{q\perp}(x, \boldsymbol{k}_T^2)$ worm-gear L
T transversely polarized	$f_{1\perp}^q(x, \boldsymbol{k}_T^2)$ Sivers	$g_{1T}^{q\perp}(x, \boldsymbol{k}_T^2)$ worm-gear T	$h_1^q(x, \boldsymbol{k}_T^2)$ transversity $h_{1T}^{q\perp}(x, \boldsymbol{k}_T^2)$ pretzelosity

Boer-Mulders function $h_1^{q\perp}$
one of the missing pieces
can be accessed in unpolarized SIDIS

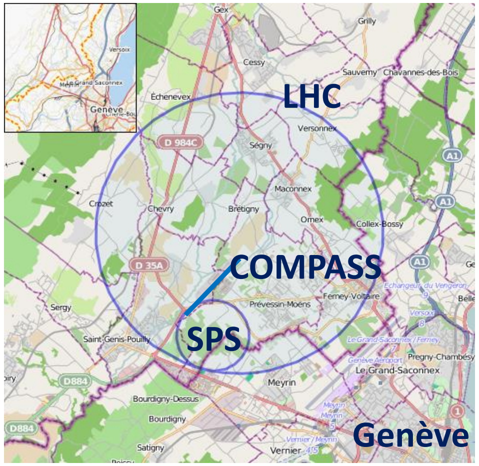
The COMPASS experiment

COMPASS contribution to the understanding of the nucleon structure

- via spin asymmetries (TSA, LSA with polarized target)
  important results on the extraction of transversity and Sivers functions
- via SIDIS with unpolarized target

COMPASS (COmmon Muon Proton Apparatus for Structure and Spectroscopy):

- 24 institutions from 13 countries (about 220 physicists)
- a fixed target experiment
- located in the CERN North Area, along the SPS M2 beamline



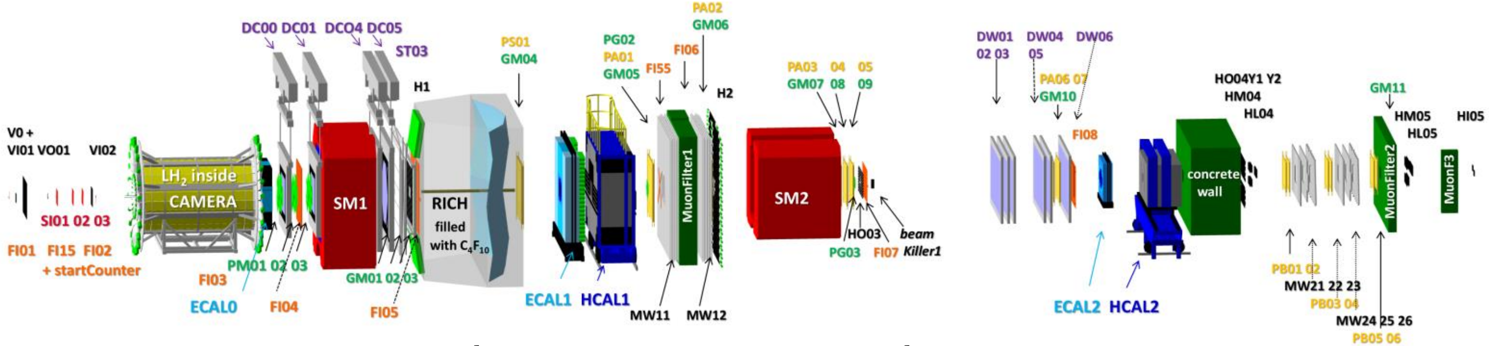
The COMPASS location at CERN

Broad research program:

- SIDIS with μ beam, with (un)polarized deuteron or proton target.
- Hadron spectroscopy with hadron beams and nuclear targets
- Drell-Yan measurement with π^- beam with polarized target
- Deeply Virtual Compton Scattering (DVCS)
- …

A multipurpose apparatus:

- Two-stage spectrometer, about 330 detector planes
- μ identification, RICH, calorimetry



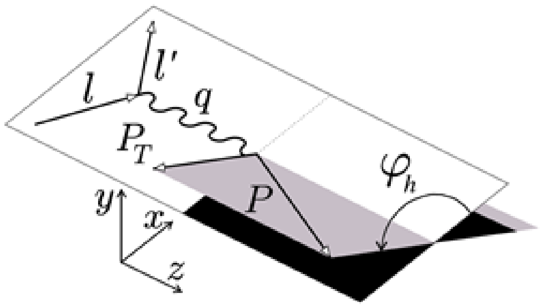
The 2016 COMPASS experimental setup

Cross section for unpolarized SIDIS

SIDIS cross section for the leptoproduction of a hadron h on an unpolarized nucleon target:

$$\frac{d\sigma}{dx\,dy\,dz\,d\varphi_h dP_T^2} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right) \cdot \left(\boldsymbol{F_{UU,T}} + \varepsilon \boldsymbol{F_{UU,L}} + \sqrt{2\varepsilon(1+\varepsilon)}\boldsymbol{F_{UU}^{\cos\varphi_h}}\cos\varphi_h + \varepsilon \boldsymbol{F_{UU}^{\cos 2\varphi_h}}\cos 2\varphi_h + \lambda_l\sqrt{2\varepsilon(1-\varepsilon)}\boldsymbol{F_{LU}^{\sin\varphi_h}}\sin\varphi_h\right)$$

- x is the Bjorken variable
- Q^2 the photon virtuality
- $y = 1 - \frac{E_{\ell'}}{E_\ell}$ the inelasticity with $E_{\ell(')}$ the energy of the incoming (scattered) lepton
- $\gamma = 2Mx/Q$ with M the target mass
- $\varepsilon(y)$ is a kinematic factor
- λ_l is the beam polarization.
- z is the fraction of photon energy carried by the hadron
- φ_h its azimuthal angle in the Gamma Nucleon System
- P_T its transverse momentum w.r.t. the photon



The Gamma Nucleon System (GNS)

Cross section for unpolarized SIDIS

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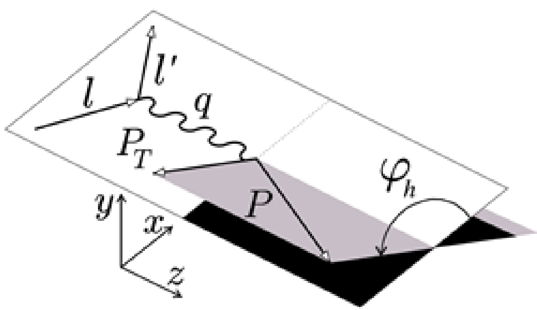


The Gamma Nucleon System (GNS)

The structure functions $\boldsymbol{F_{XY[,Z]}^{[f(\varphi_h)]}}$ can be written in terms of TMD PDFs and TMD FFs. Up to order $1/Q$:

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

Cahn effect

$$F_{UU}^{\cos\varphi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{(\hat{h}\cdot\vec{k}_T)}{M}\boldsymbol{f_1 D_1} - \frac{(\hat{h}\cdot\vec{p}_\perp)k_T^2}{M^2 M_h}\boldsymbol{h_1^\perp H_1^\perp} + \cdots\right]$$

$$F_{UU}^{\cos 2\varphi_h} = \mathcal{C}\left[-\frac{2(\hat{h}\cdot\vec{k}_T)(\hat{h}\cdot\vec{p}_\perp) - \vec{k}_T\cdot\vec{p}_\perp}{M\,M_h}\boldsymbol{h_1^\perp H_1^\perp}\right]$$

Two main observables:

→ *azimuthal asymmetries*

→ *transverse-momentum-dependent distributions*

$$\hat{h} = \vec{P}_T / |\vec{P}_T|$$

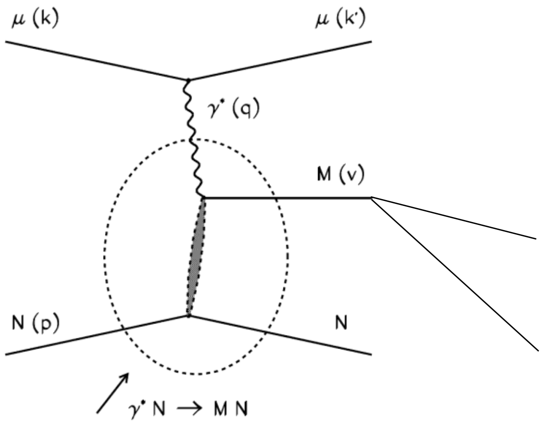
$$C[wfD] = x\sum_a e_a^2 \int d^2\vec{k}_T \int d^2\vec{p}_\perp \delta^2(\vec{P}_T - \vec{k}_T - \vec{p}_\perp) w(\vec{k}_T,\vec{p}_\perp) f^a(x,\vec{k}_T) D^a(z,\vec{p}_\perp)$$

***X*, *Y*, *Z* indicate the beam, target and photon polarization states**

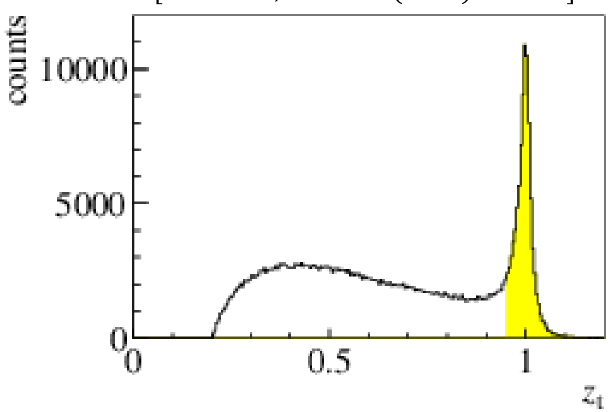
Contribution from exclusive hadrons

Hadrons from the decay of exclusive diffractive vector mesons *(exclusive hadrons)*

- The two most important channels : $\rho^0 \rightarrow \pi^+\pi^-$ *and* $\phi \rightarrow K^+K^-$
- observed in the data looking at their total energy fraction
- Their amount depends on kinematics
- **Show a modulation in the azimuthal angle**

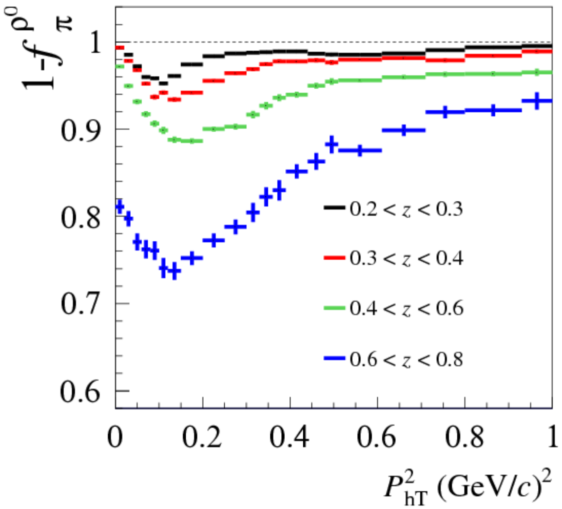


[COMPASS, NPB 956 (2020) 115039]



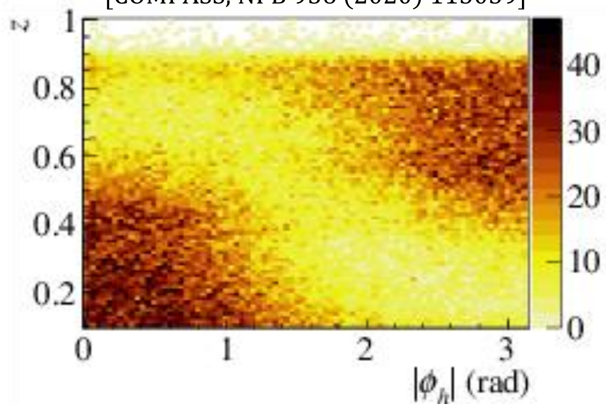
The $z_{h^+} + z_{h^-} = z_t$ distribution
(two hadrons with opposite charge)

[COMPASS, PRD97 (2018) 032006]



Fraction of pions from SIDIS,
as a function of P_T^2 per z bin

[COMPASS, NPB 956 (2020) 115039]



$|\varphi_h| - z$ correlation for
"exclusive" hadrons

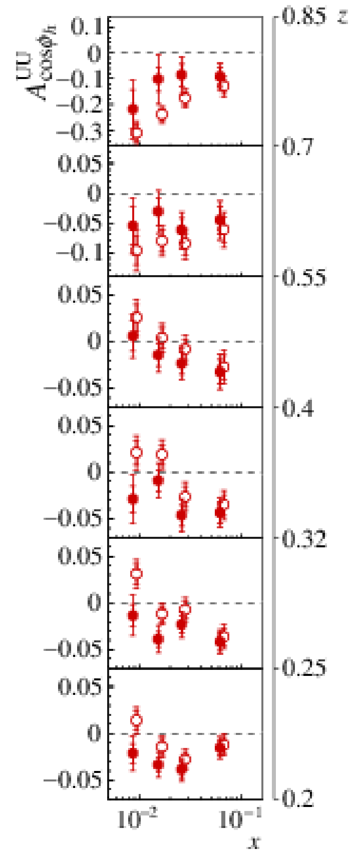
Contribution from exclusive hadrons

Impact on the azimuthal asymmetries calculated for the deuteron data

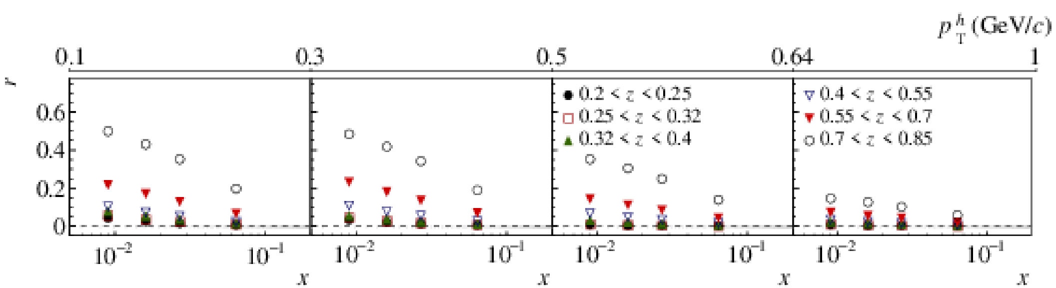
[COMPASS, NPB 886 (2014) 1046]
[COMPASS, NPB 956 (2020) 115039]

Example: $cos\ \varphi_h$ asymmetry
$0.1 < P_T\ /(\mathrm{GeV}/c) < 0.3$

- Comparison of not-subtracted (open points) and corrected (close points) asymmetries for positive hadrons.
- Correction applied at the asymmetry level



Fraction r of exclusive hadrons
as a function of x, in bins of z and P_T



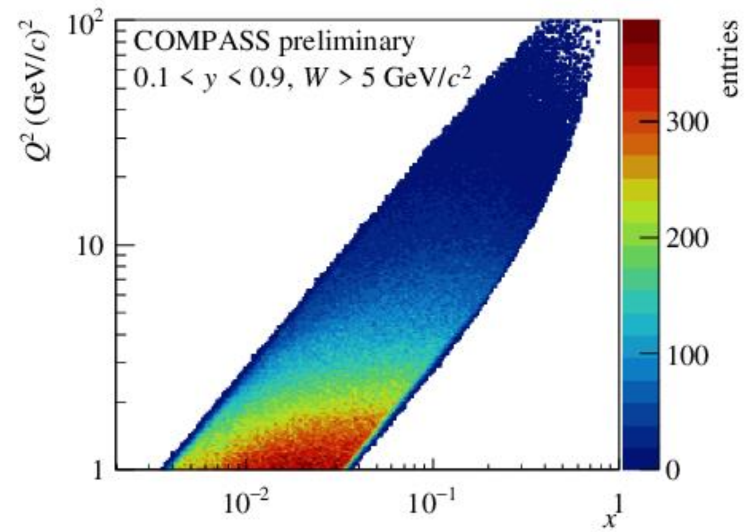
The 2016 COMPASS run

In 2016 (and 2017) the data-taking was dedicated to the measurement of Deeply Virtual Compton Scattering (DVCS).

In parallel, new SIDIS data have been collected in COMPASS, with:

- 160 GeV/c μ beam (μ^+ and μ^- with balanced statistics)
- Unpolarized, 2.5 m long liquid hydrogen target

Part of the data ($\sim$11% of the available statistics) have been analyzed to get preliminary results on SIDIS unpolarized observables.

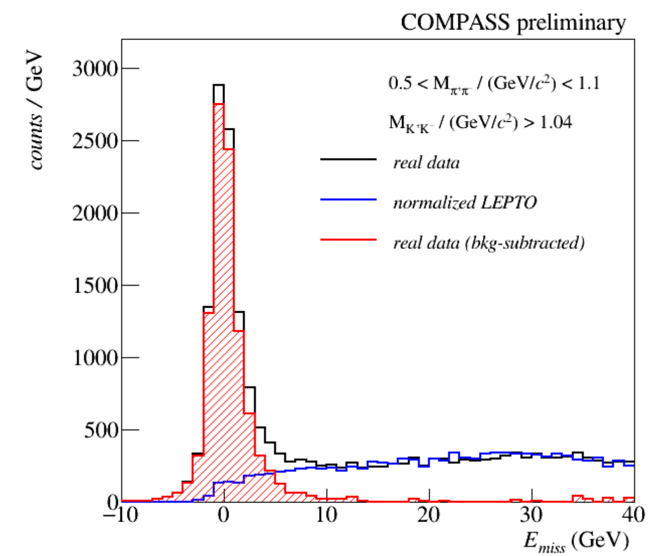


The $x - Q^2$ coverage

Both measurements of azimuthal asymmetries and P_T^2 distributions require Monte Carlo simulations for

- the **acceptance correction** (LEPTO generator) → **standard**
- the **subtraction of exclusive hadrons** (HEPGEN generator) → **NEW**

  to normalize the HEPGEN Monte Carlo to the data, the missing energy E_{miss} distribution is used



The exclusive peak as observed in the data

DIS events selected with standard cuts:

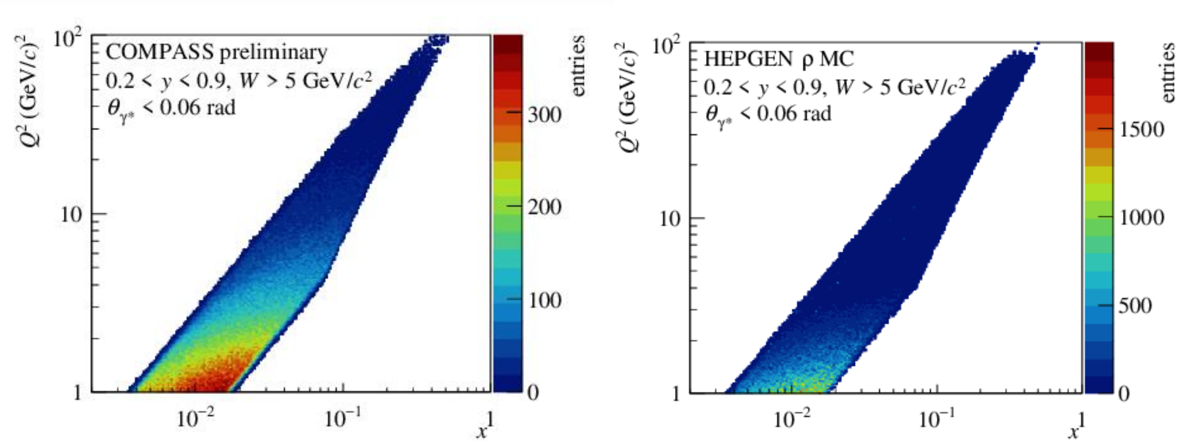
$Q^2 > 1\ (\mathrm{GeV}/c)^2$

$W\ > 5\ \mathrm{GeV}/c^2$

$0.003 < x < 0.130,$

$0.2 < y < 0.9$

$\theta_\gamma < 60$ mrad



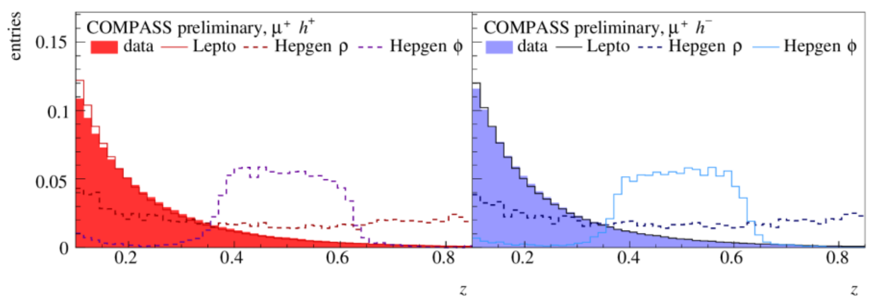
$x - Q^2$ correlation in the data (left) and for the exclusive ρ events (right) exclusive events concentrated at small x and Q^2.

Selection of hadrons:

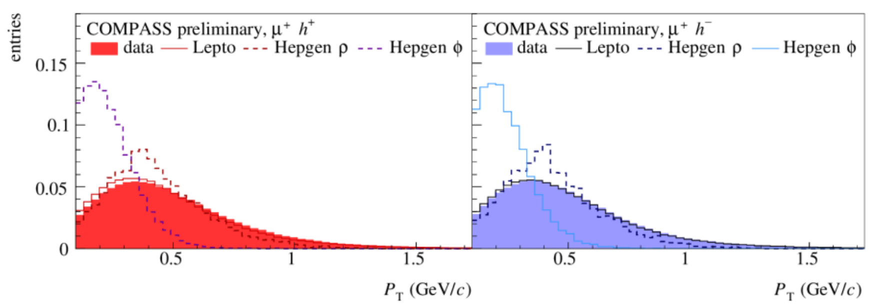
$z > 0.1$

$P_T > 0.1\ \mathrm{GeV}/c$

z



P_T



Distributions of z and P_T **normalized to their integral,**

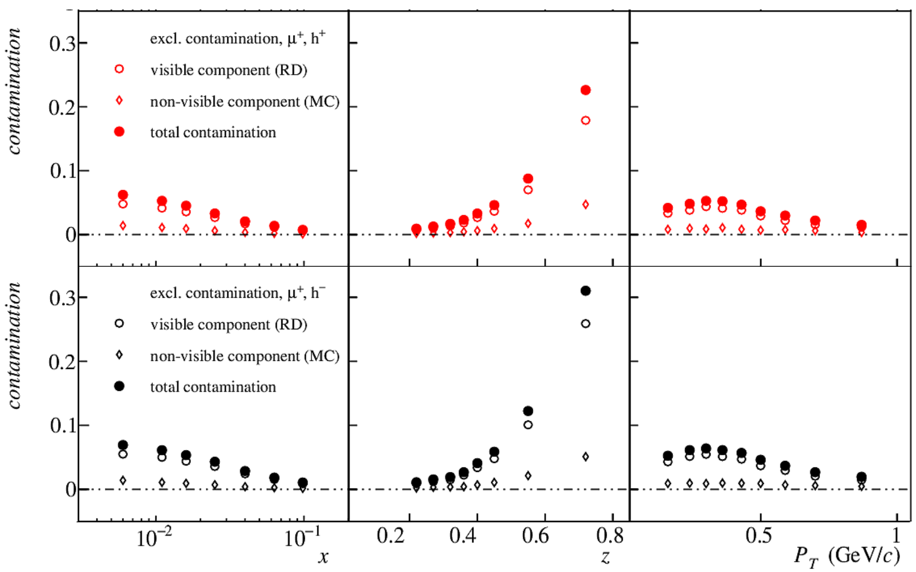
for the data, LEPTO, HEPGEN ρ and HEPGEN ϕ.

Azimuthal asymmetries

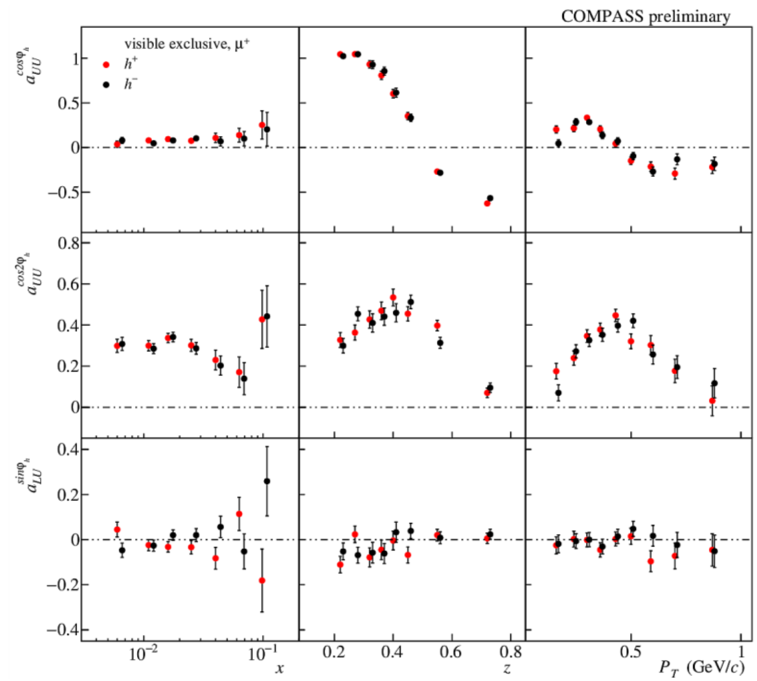
Azimuthal asymmetries: the ratio of the azimuthal-angle-dependent structure functions over the unpolarized

$$A_{UU}^{\cos\phi_h} = \frac{F_{UU}^{\cos\phi_h}}{F_{UU,T} + \varepsilon F_{UU,L}} \qquad A_{UU}^{\cos 2\phi_h} = \frac{F_{UU}^{\cos 2\phi_h}}{F_{UU,T} + \varepsilon F_{UU,L}} \qquad A_{LU}^{\sin\phi_h} = \frac{F_{LU}^{\sin\phi_h}}{F_{UU,T} + \varepsilon F_{UU,L}}$$

- Measured as the **amplitude of the modulation in the azimuthal angle** of the hadrons (fit) either as a function of x, z or P_T (1-dimensional analysis), or with a simultaneous binning (3D)
- After correcting for the contribution of the exclusive hadrons
- And for acceptance



Estimated exclusive hadrons contaminations



Raw asymmetries for the exclusive hadrons

Azimuthal asymmetries – 1D

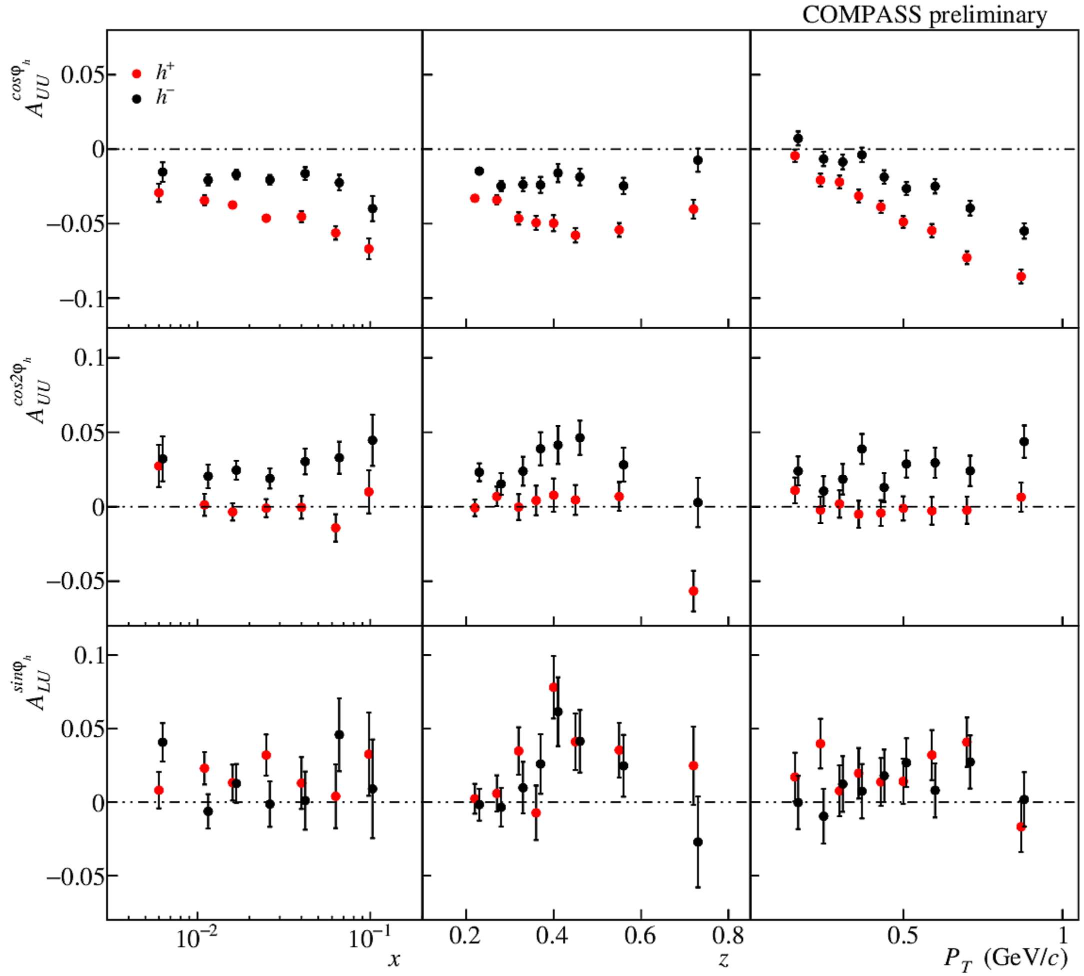
1D results: asymmetries shown as a function of x or z or P_T (integrating over the other two variables).

As observed with the previous measurements by COMPASS on deuteron and by HERMES:

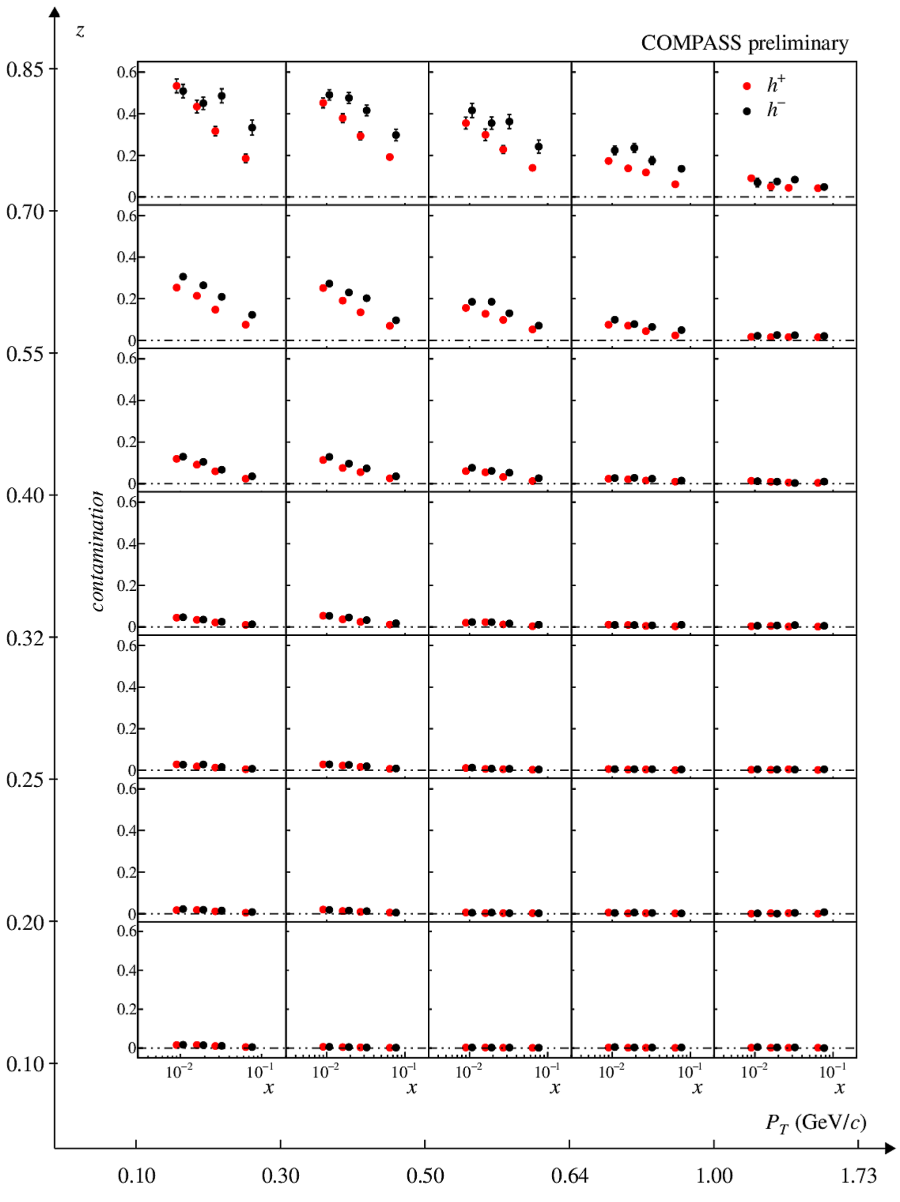
- Strong kinematic dependences
- interesting differences between positive and negative hadrons.

Results in qualitative agreement with the COMPASS measurement on deuteron

[COMPASS, NPB 886 (2014) 1046]

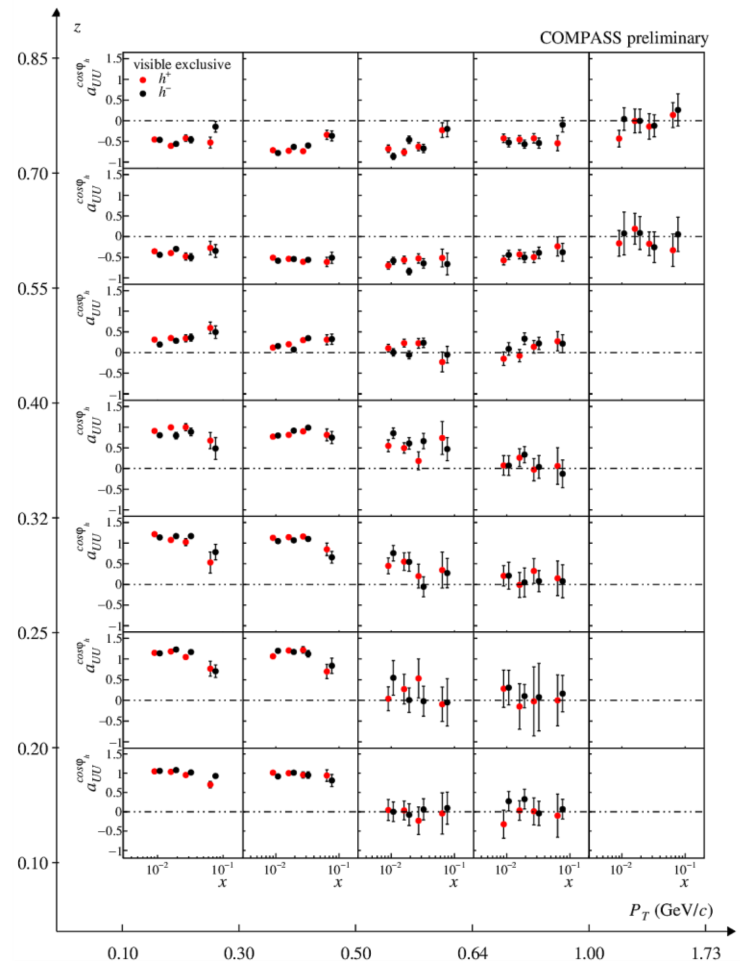


Azimuthal asymmetries – 3D

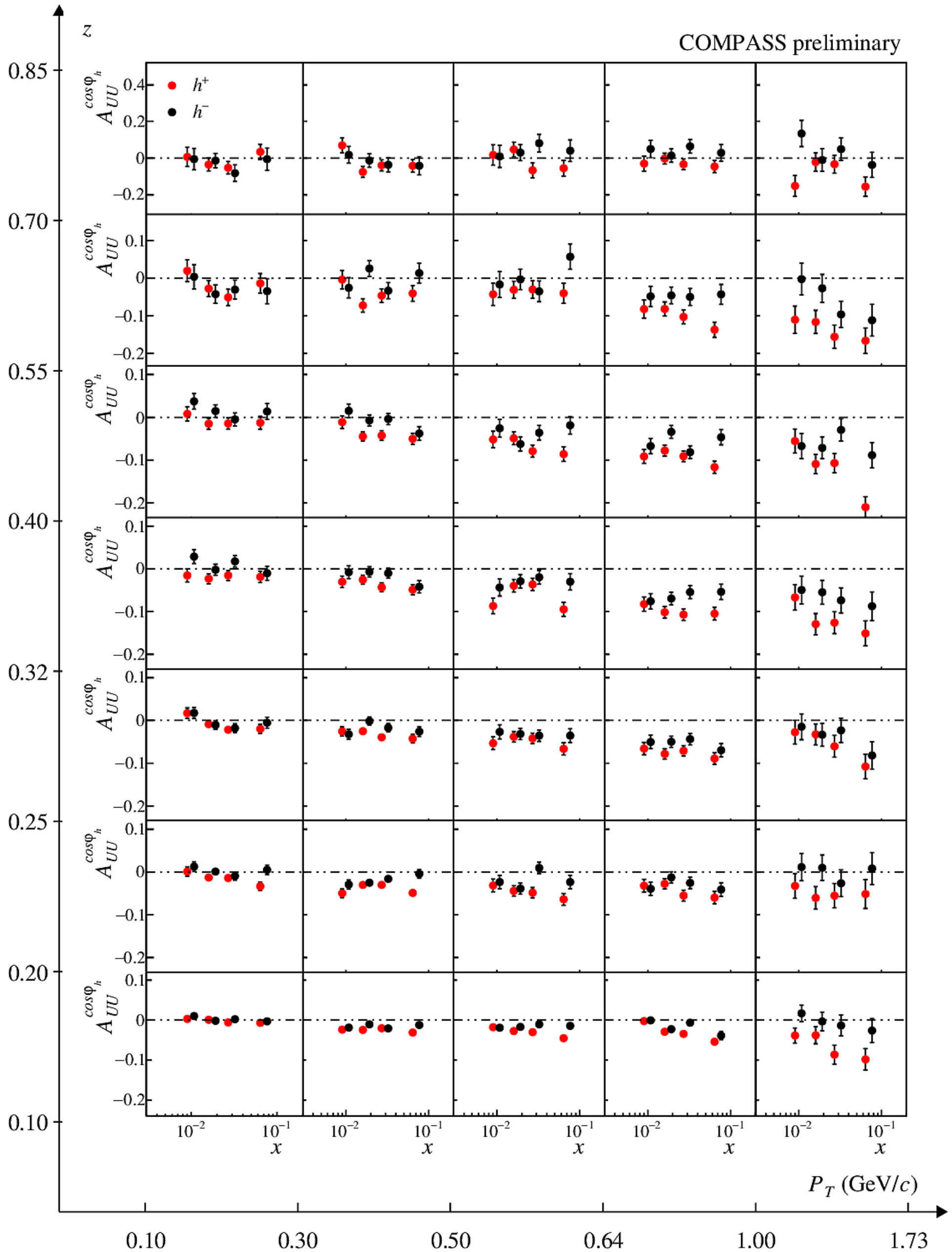


← **Total contamination** of exclusive hadrons:
increases with z and decreases along x and P_T.
80% reduction after discarding exclusive events in the data

↓ **Raw asymmetry in $\cos\phi_h$** for exclusive hadrons:
almost no dependence on x, mild on P_T, strong on z



Azimuthal asymmetries – 3D



3D azimuthal asymmetries for positive and negative hadrons

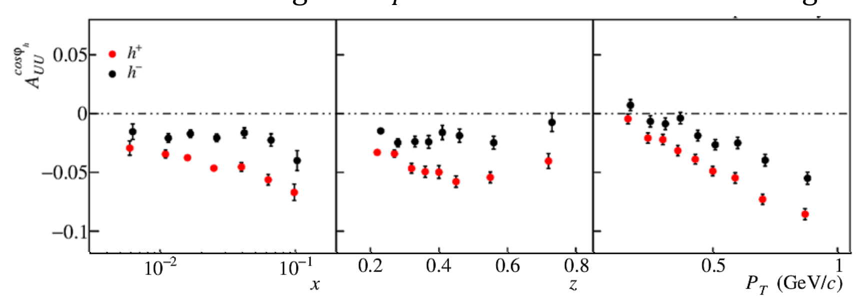
$A_{UU}^{\cos\phi_h}$ as a function of x, in bins of z (rows) and P_T (columns).

Clear signal, strong dependence on P_T; compatible with zero at high z.
In agreement with COMPASS deuteron results.

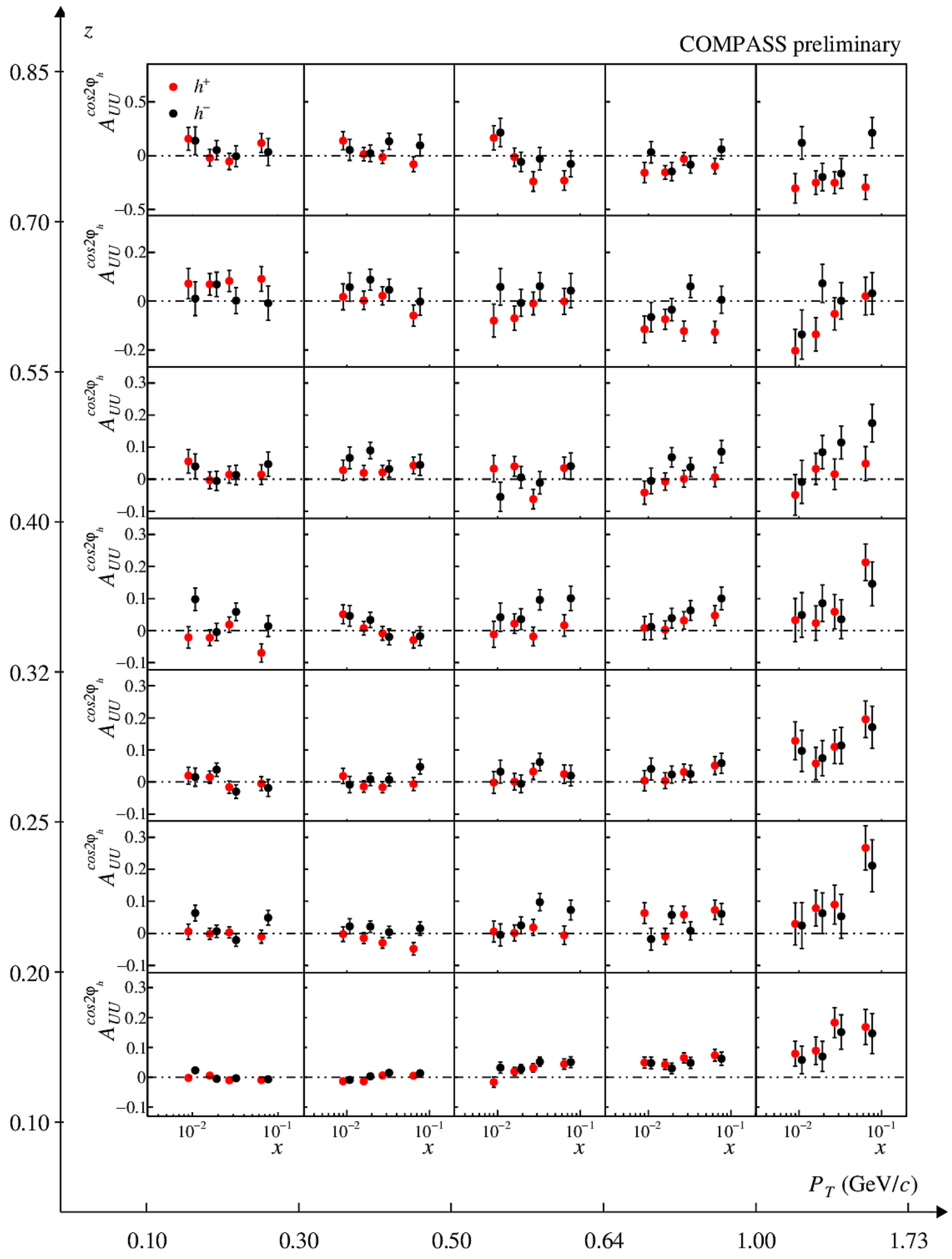
Expectation from Cahn effect:

$$A_{UU}^{\cos\phi_h} \propto -zP_T$$

Comparison with the 1D case:
lowest z and highest P_T bin not included in the average



Azimuthal asymmetries – 3D



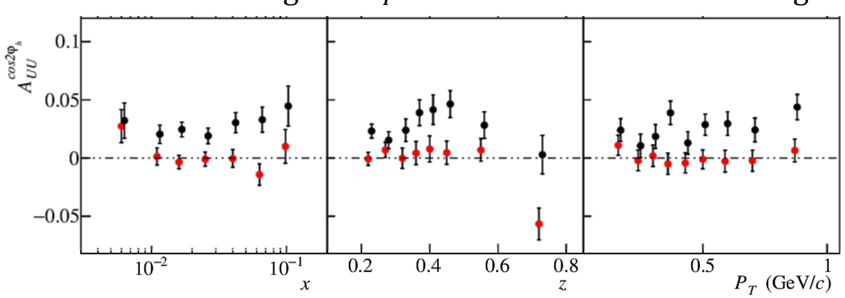
3D azimuthal asymmetries for positive and negative hadrons

$A_{UU}^{\cos 2\phi_h}$ as a function of x,
in bins of z (rows) and P_T (columns).

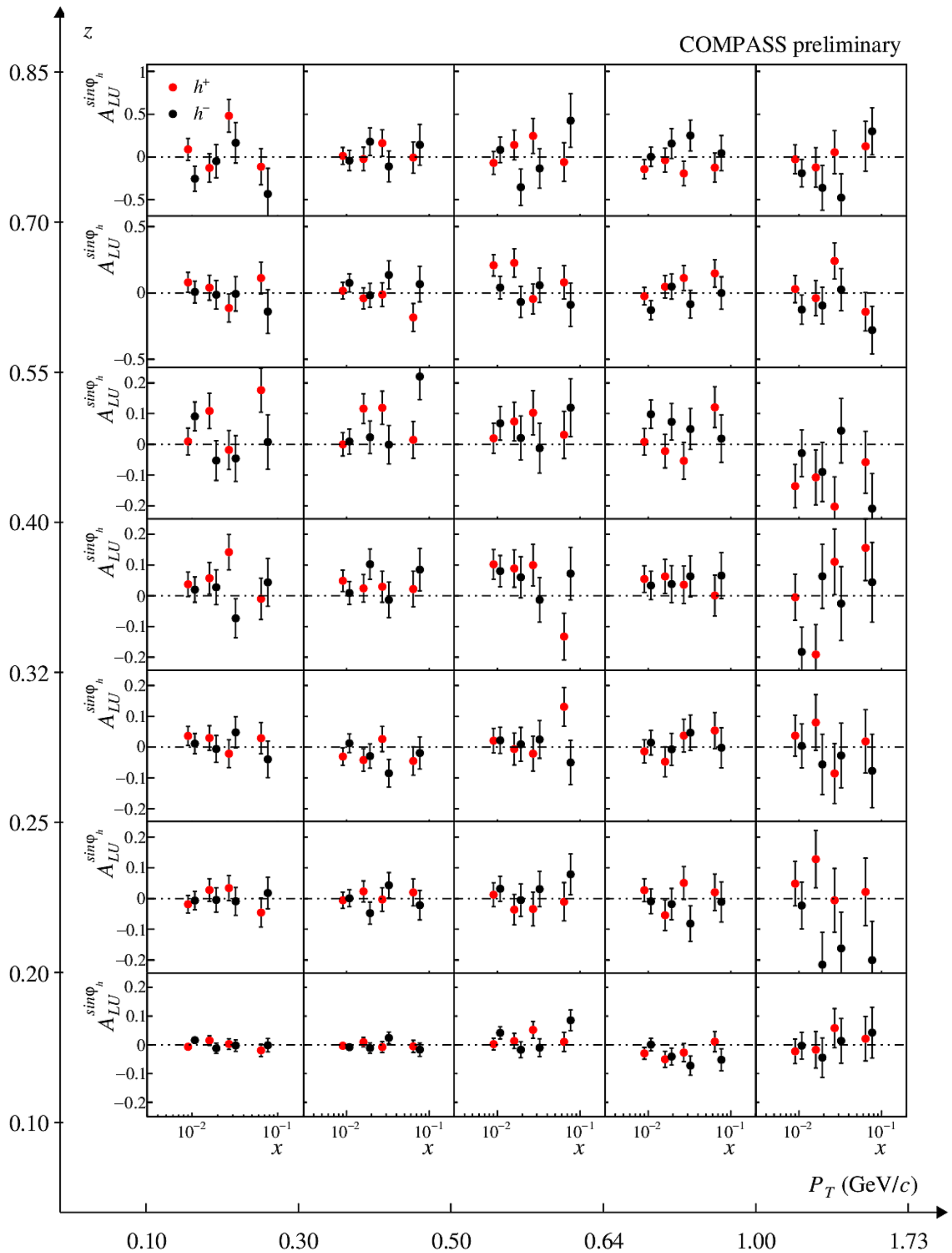
Clear signal, strong dependence on x and P_T;
interesting change of sign along z at high P_T.

The larger contribution from the $h_1^\perp H_1^\perp$ convolution
$\rightarrow$ direct information on $h_1^\perp$ may be extracted

Comparison with the 1D case:
lowest z and highest P_T bin not included in the average



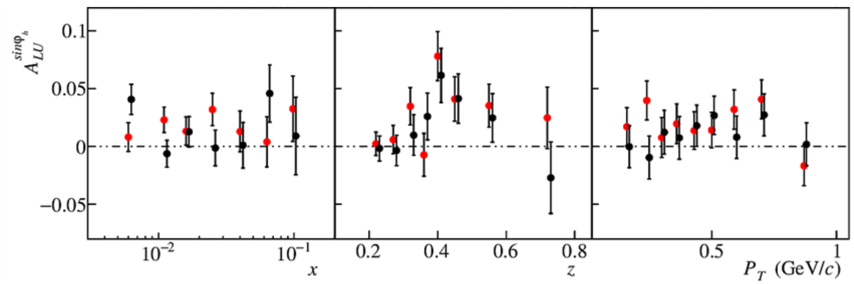
Azimuthal asymmetries – 3D



3D azimuthal asymmetries for positive and negative hadrons

$A_{LU}^{sin\phi_h}$ as a function of x,
in bins of z (rows) and P_T (columns).

Comparison with the 1D case:
lowest z and highest P_T bin not included in the average



P_T^2 - dependent distributions

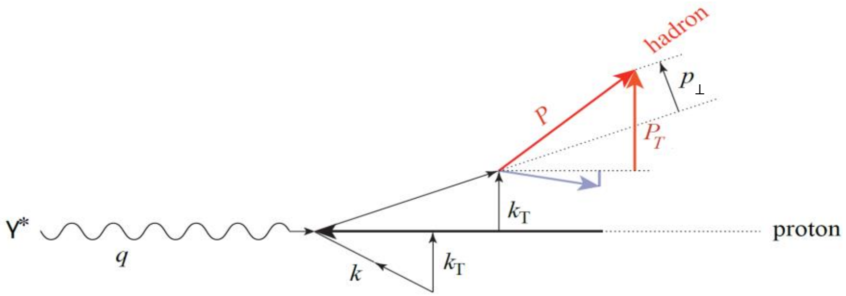
Transverse-momentum-dependent distributions

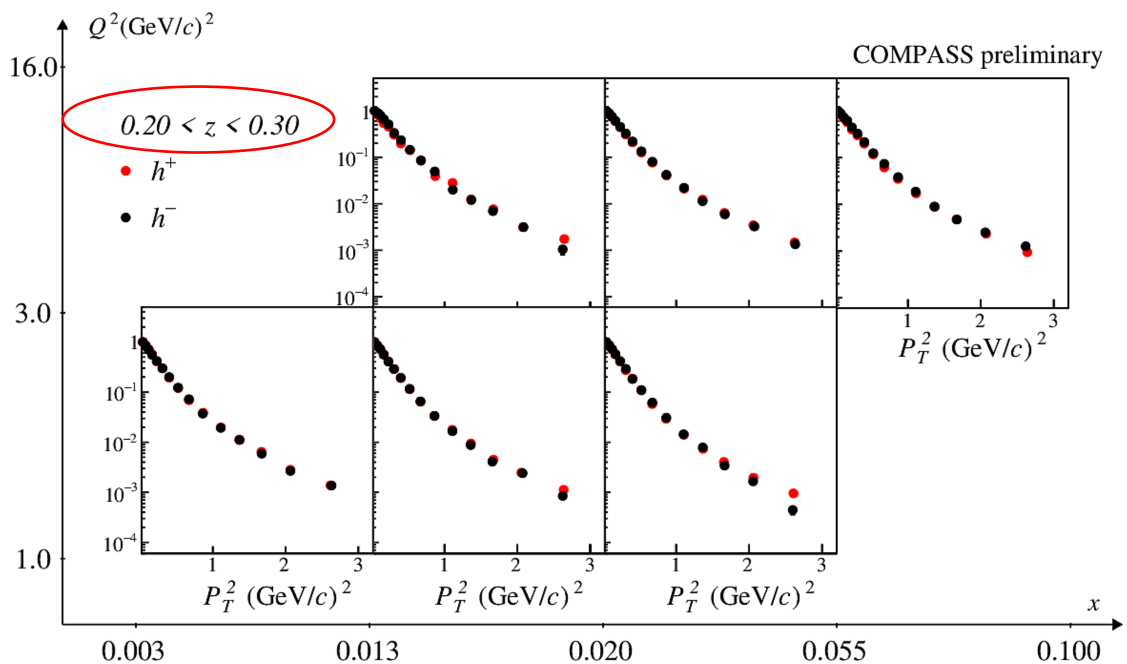
- give complementary information on k_T and $p_\perp$ w.r.t. azimuthal asymmetries
- are interesting for the TMD evolution studies:
  a lot of theoretical work to reproduce the experimental distributions over large energy range

In gaussian approximation, at small values of P_T, the number of hadrons is expected to follow:

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

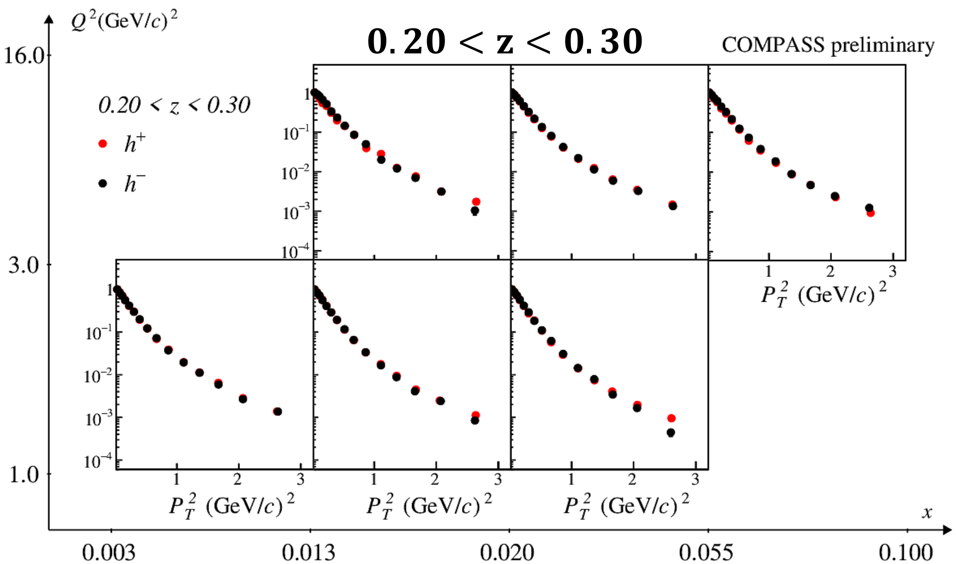
$$\langle P_T^2\rangle = z^2\langle k_T^2\rangle + \langle p_\perp^2\rangle$$

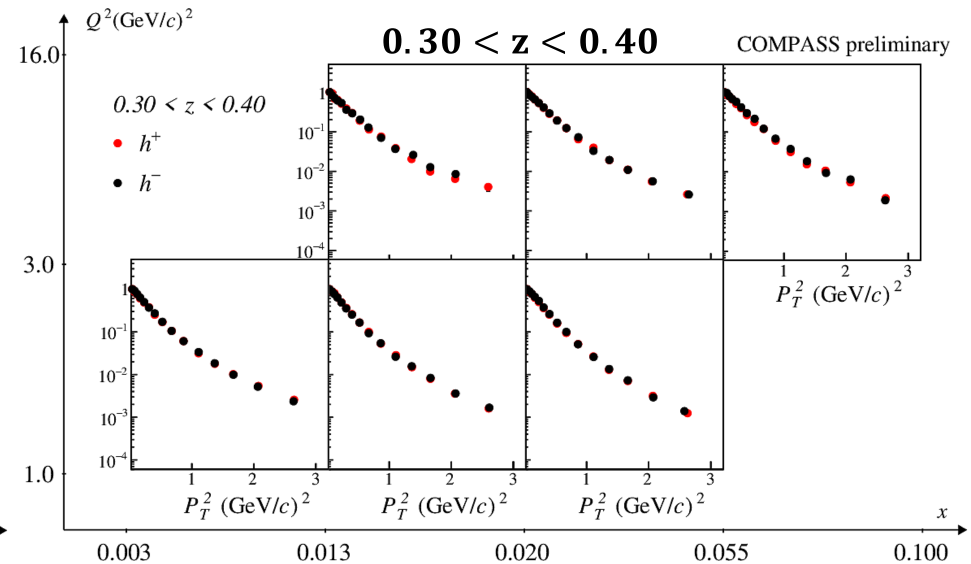


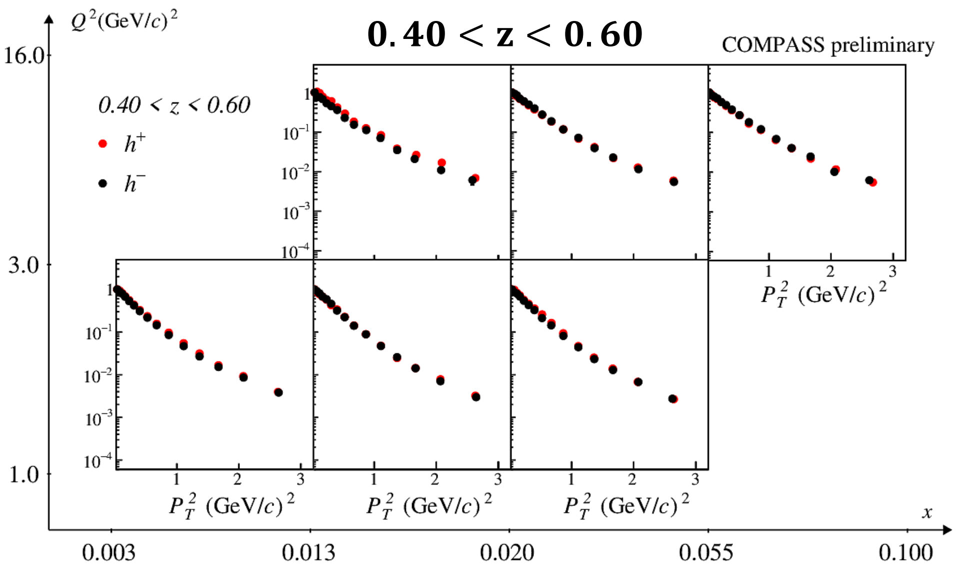


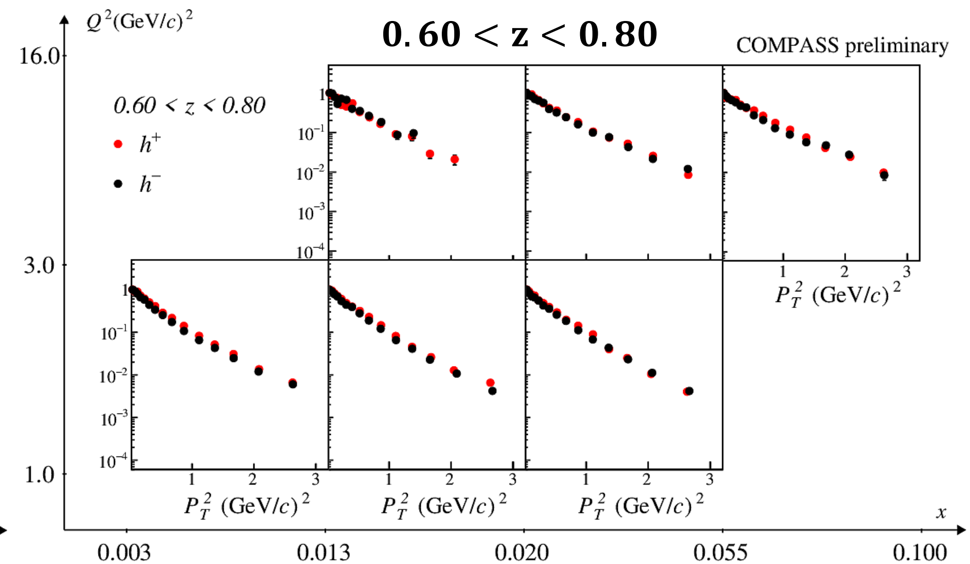
Normalization: first P_T^2 bin.

P_T^2 - dependent distributions



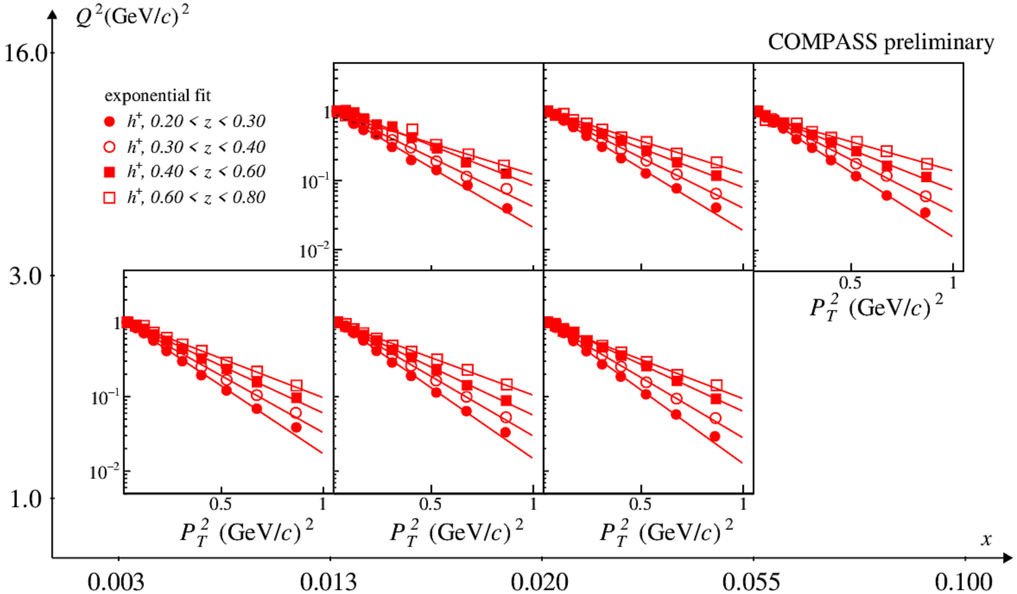


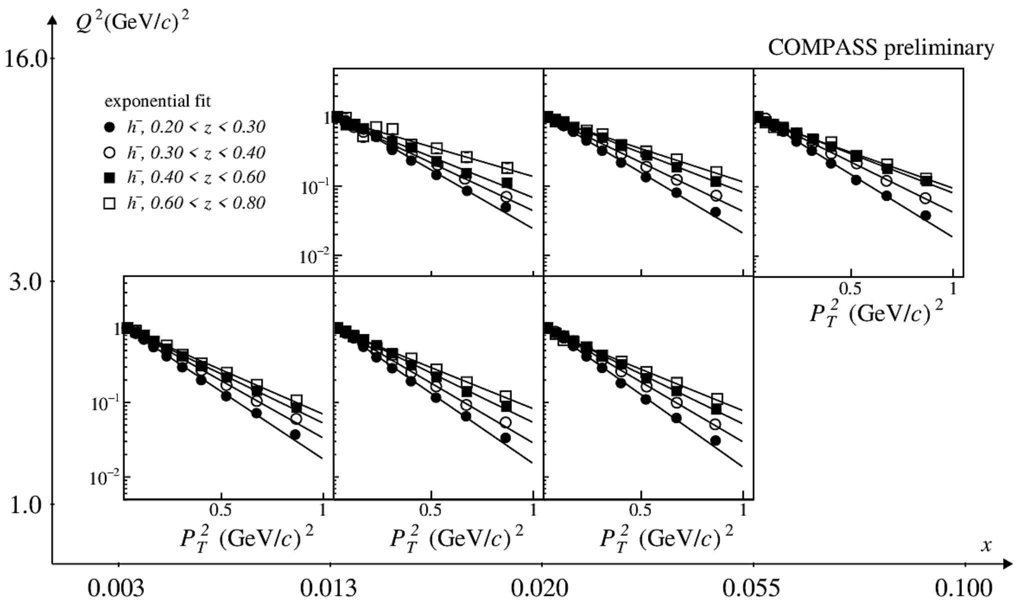




In good agreement with previous deuteron results [COMPASS, PRD97 (2018) 032006]

P_T^2 - dependent distributions

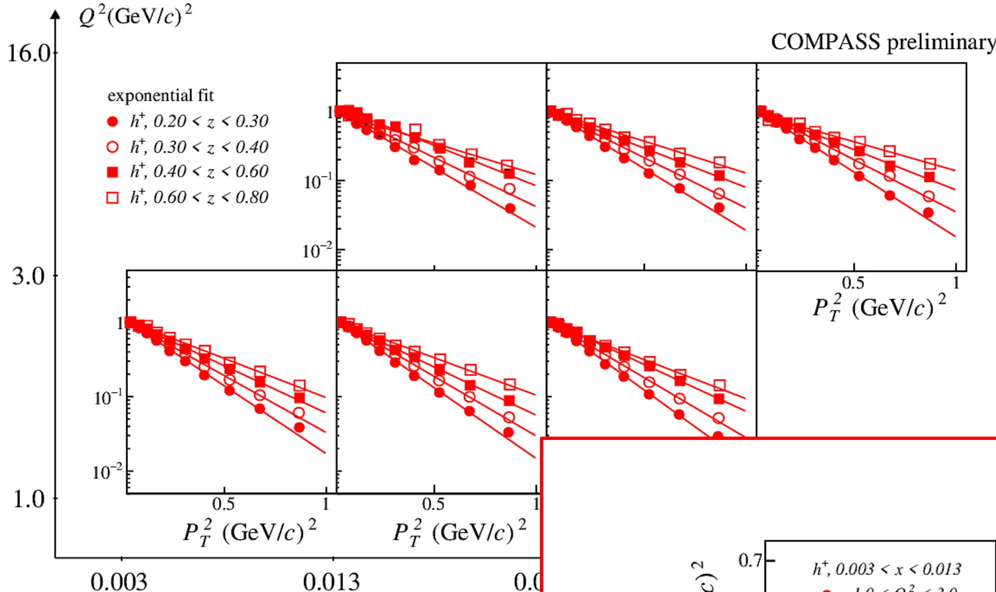




Distributions fitted with an exponential function up to $P_T = 1\ (\mathrm{GeV}/c)^2$

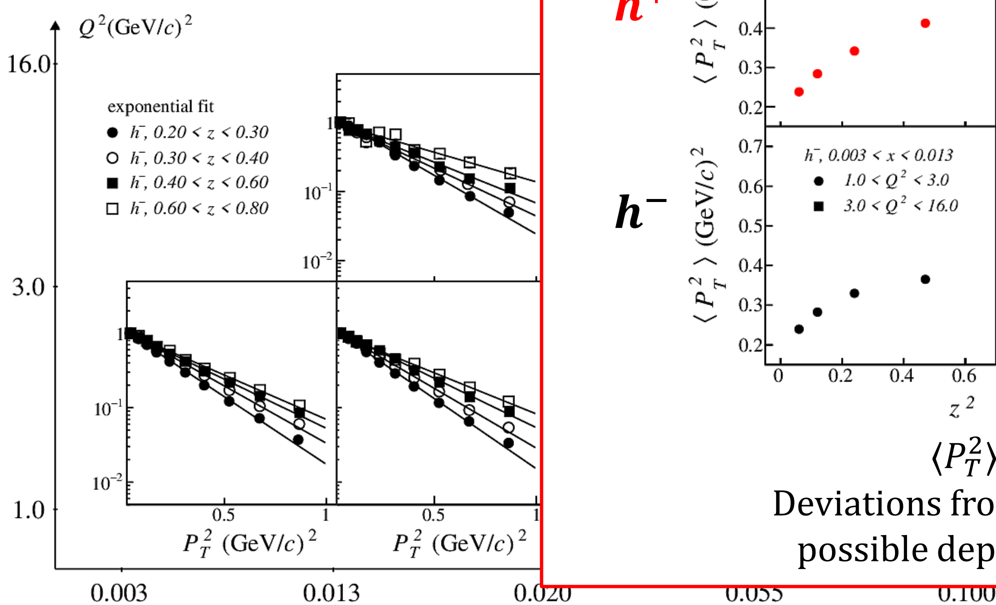
Evolution of the slope with z

P_T^2 - dependent distributions



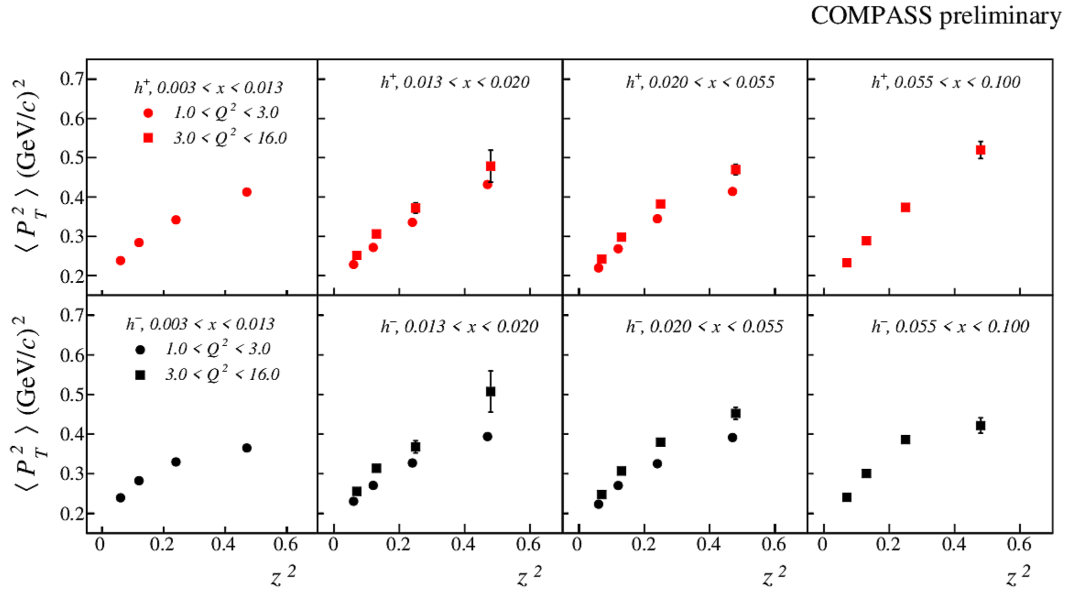
Distributions fitted with an exponential function up to $P_T = 1\ (\mathrm{GeV}/c)^2$

Evolution of the slope with z



h^+

h^-



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

Deviations from the linear trend $\boldsymbol{\langle P_T^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_\perp^2 \rangle}$

possible dependences of $\langle p_\perp^2 \rangle$ on z and of $\langle k_T^2 \rangle$ on x.

Conclusions

- Two observables in unpolarized SIDIS are particularly interesting for the TMD physics: **transverse momentum dependent distributions** and **azimuthal asymmetries.**

- After the first measurements on a deuteron target, COMPASS has produced new preliminary results for both of them, using a proton target.

- Both the P_T^2 distributions and the azimuthal asymmetries look interesting with rich kinematic dependences.

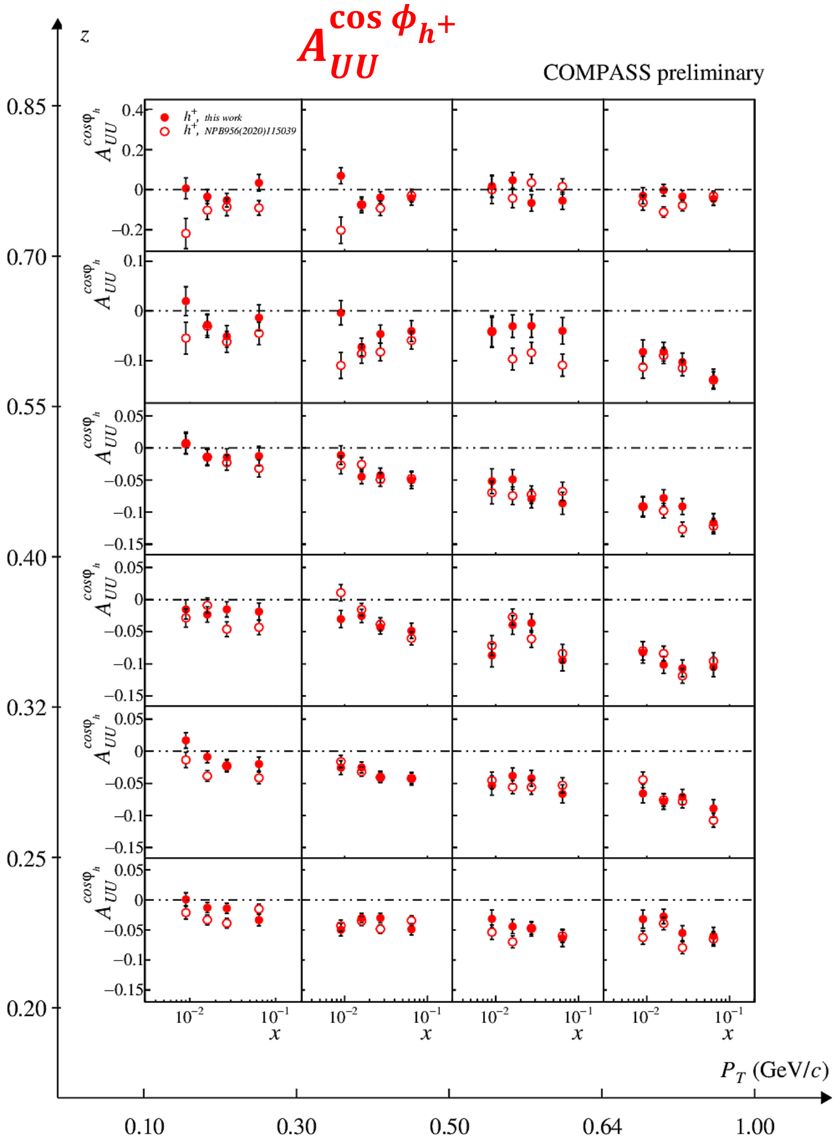
- A new step forward in our understanding of the nucleon structure.

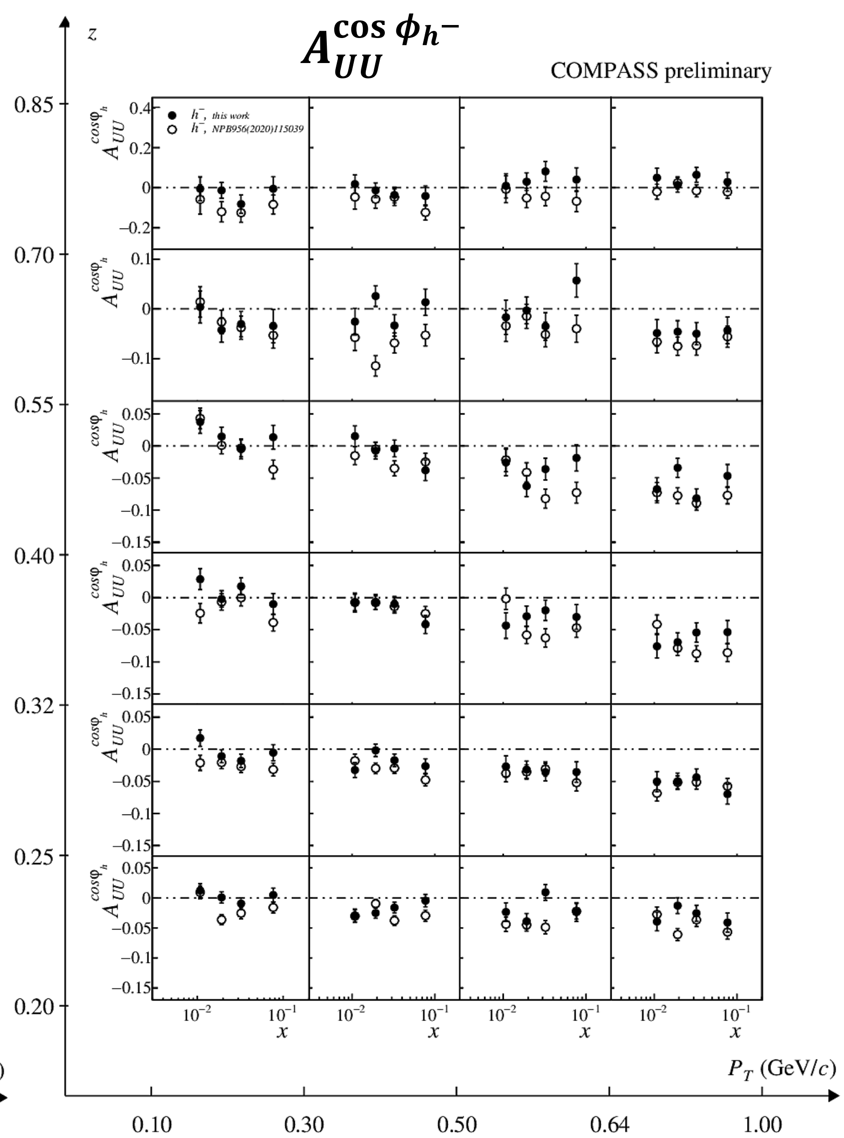
backup

Comparison with deuteron results

Current results (full points) compared to published results on deuteron **[COMPASS, NPB 956 (2020) 115039].**

Proton and deuteron results are in good agreement, as observed in other experiments (HERMES).





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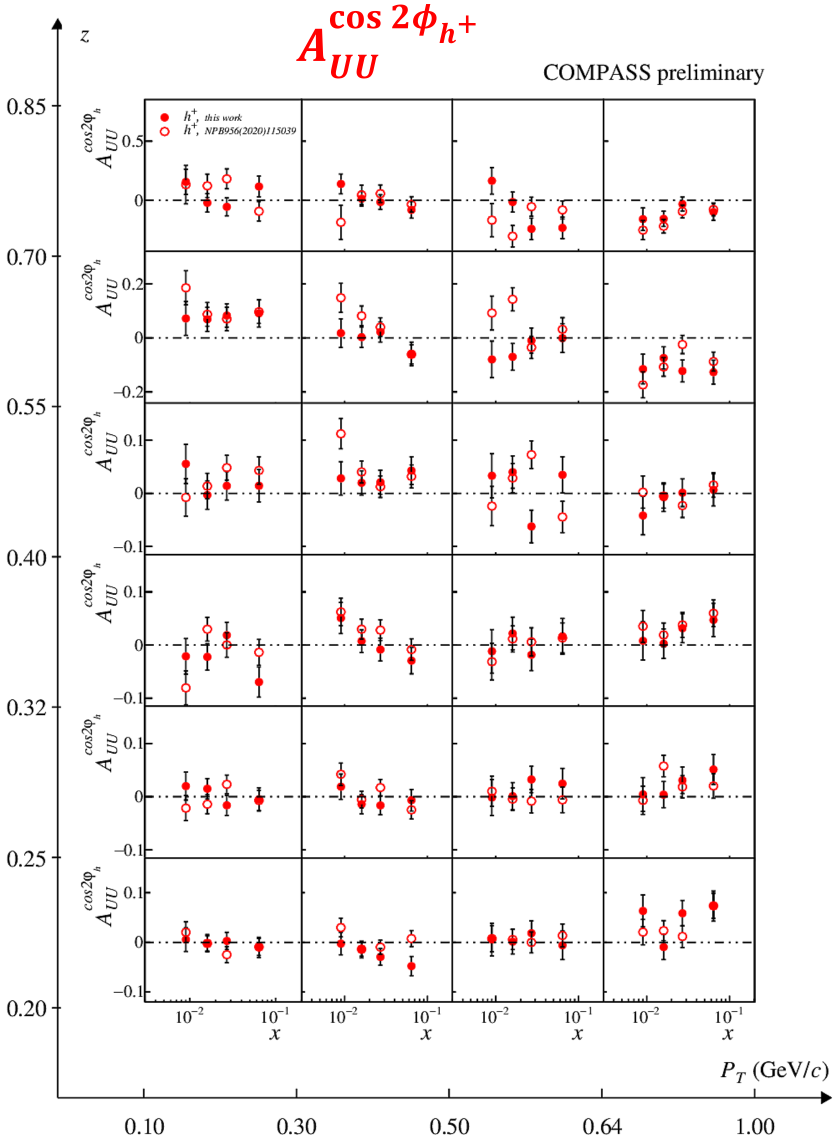
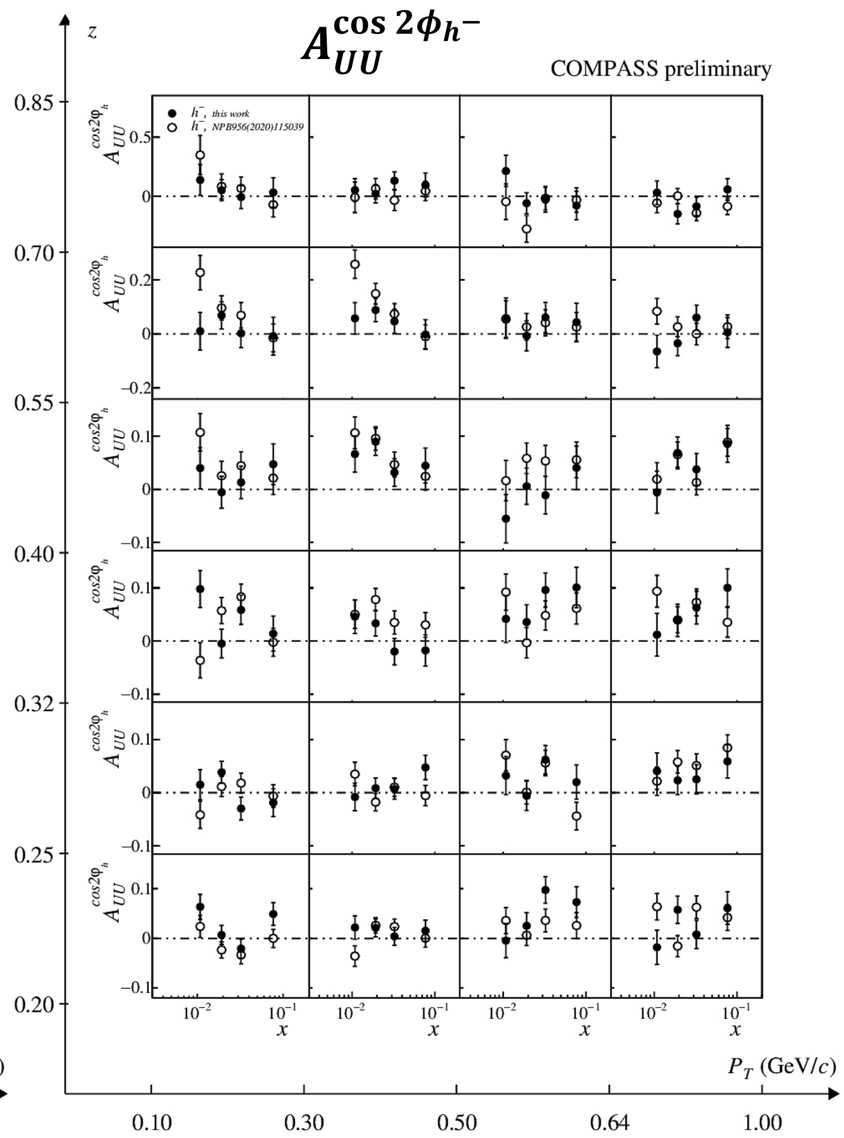


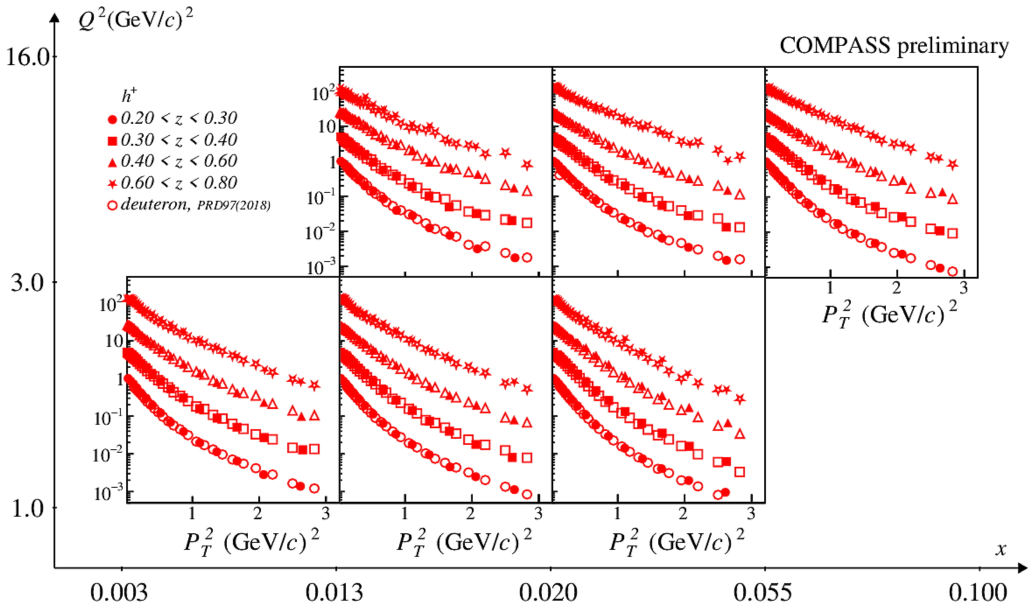


Comparison with deuteron results

The new preliminary results are compared to published results on a deuteron target **[COMPASS, PRD97(2018) 032006]**

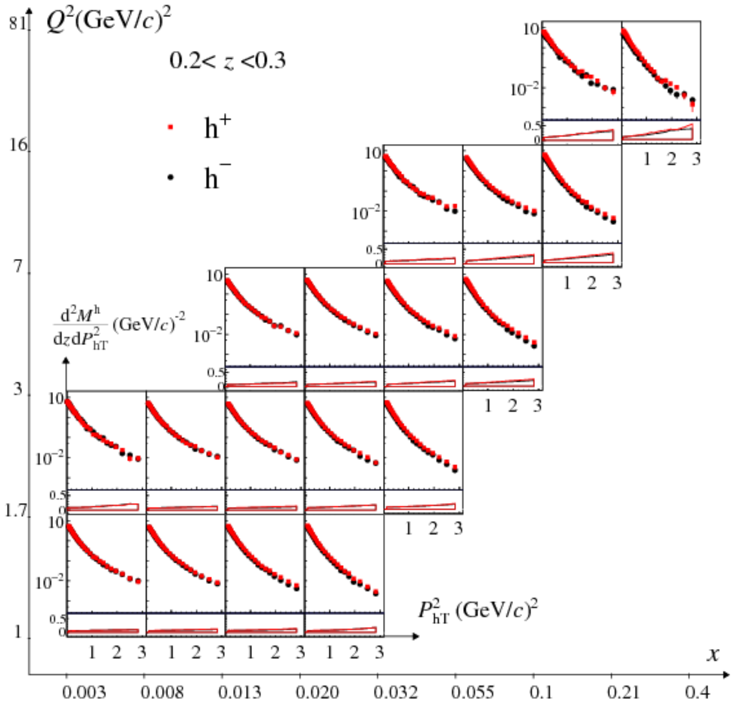
The old results (an example in the right plot) have been renormalized over the first point and averaged over x and Q^2 in order to match the current binning, while the z and P_T^2 binning has not been modified.

The agreement between new proton results and old deuteron ones is good.



New preliminary results (closed markers) compared to renormalized published results on deuteron (empty markers).

The binning for the current analysis has been chosen to be easily compared to the punlished one (an example on the right).

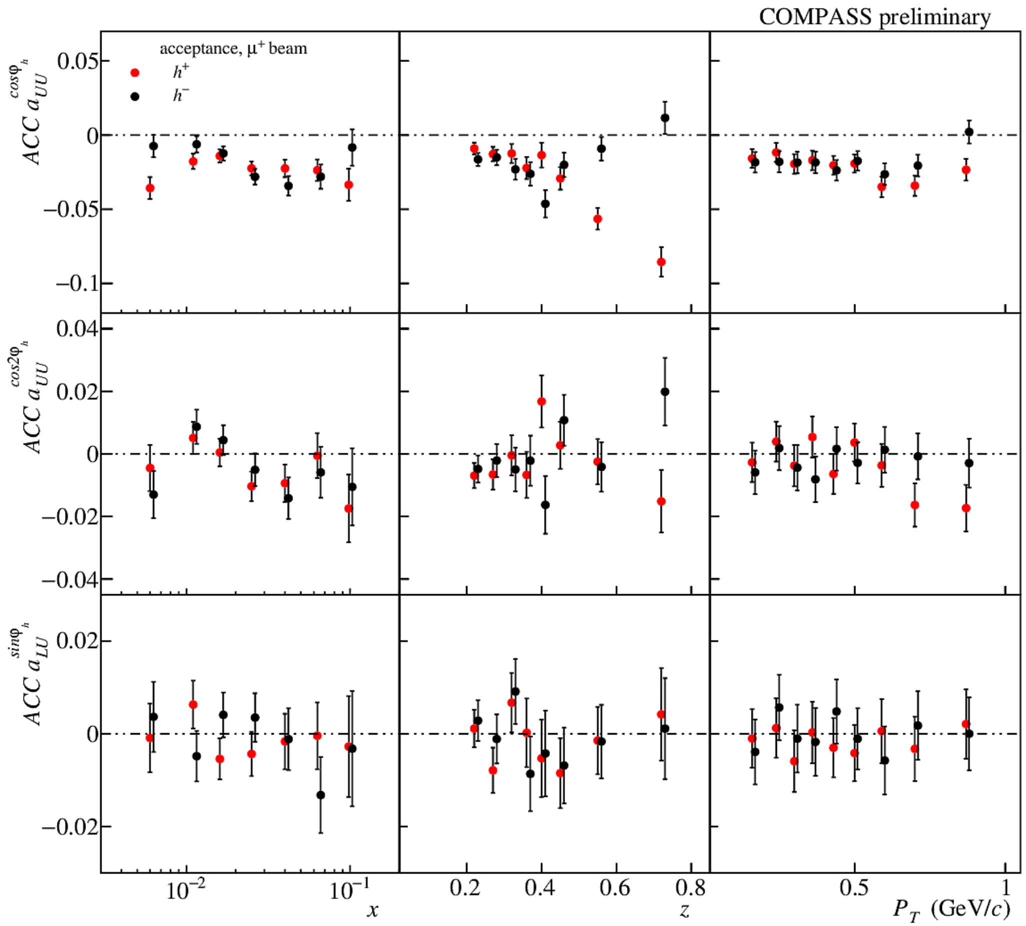


Acceptance modulations

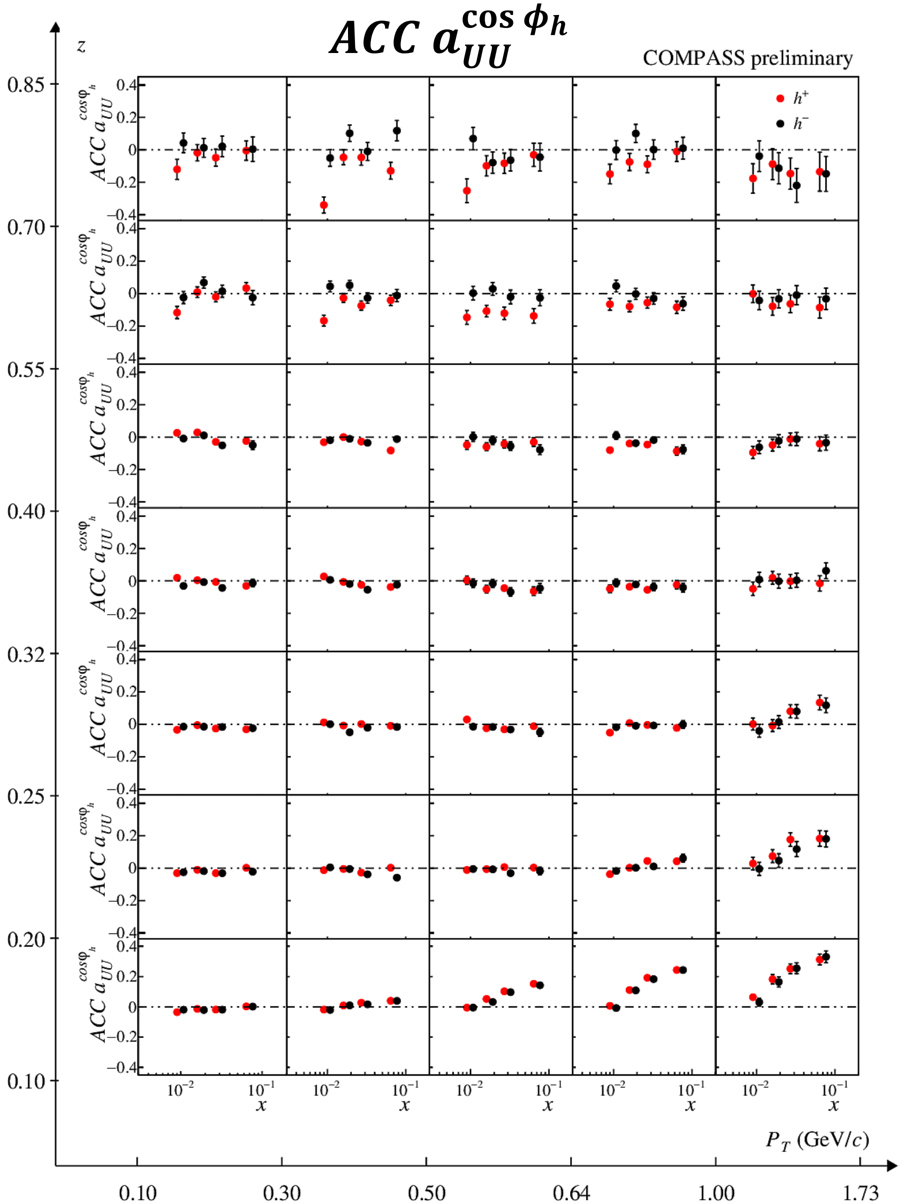
Correction for acceptance applied to each ϕ bin, taken as the ratio of reconstructed and generated hadrons:

$$c_{acc}(\phi) = \frac{N_h^{rec}(\phi)}{N_h^{gen}(\phi)}$$

Azimuthal modulations of the acceptance in 1D binning, for μ^+ beam and positive (red) and negative hadrons (black).



Acceptance modulations



Acceptance

$$c_{acc}(P_T^2) = \frac{N_h^{rec}(P_T^2)}{N_h^{gen}(P_T^2)}$$

The acceptance is shown here in the first z bin, for positive and negative hadrons.
A flat plateau at values larger than 50% and, in some bins, a decrease at large P_T^2.