TMD observables in unpolarized Semi-Inclusive DIS at COMPASS

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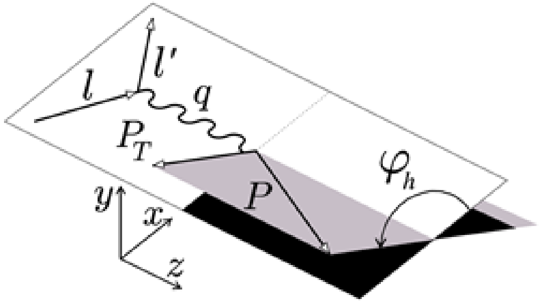
on behalf of the COMPASS Collaboration

XVIII International Workshop on Deep-Inelastic Scattering and Related Subjects – DIS 2021

Cross section for unpolarized SIDIS

In Semi-Inclusive Deep Inelastic Scattering (SIDIS) a high energy lepton scatters off a nucleon target and at least one hadron is observed in the final state.

→ a powerful tool to assess the Transverse-Momentum-Dependent (TMD) description of the nucleon structure.



The Gamma Nucleon System (GNS)

For an unpolarized nucleon target, the cross section reads:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}\varphi_h\mathrm{d}P_T^2} \approx \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}$$

$$\cdot\left(F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}F_{UU}^{\cos\varphi_h}\cos\varphi_h + \varepsilon F_{UU}^{\cos 2\varphi_h}\cos 2\varphi_h + \lambda_l\sqrt{2\varepsilon(1-\varepsilon)}F_{LU}^{\sin\varphi_h}\sin\varphi_h\right)$$

- x is the Bjorken variable
- Q^2 the photon virtuality
- $y = 1 - \frac{E_{\ell'}}{E_\ell}$ the inelasticity with $E_{\ell(\prime)}$ the energy of the incoming (scattered) lepton
- $\varepsilon(y)$ 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

Cross section for unpolarized SIDIS

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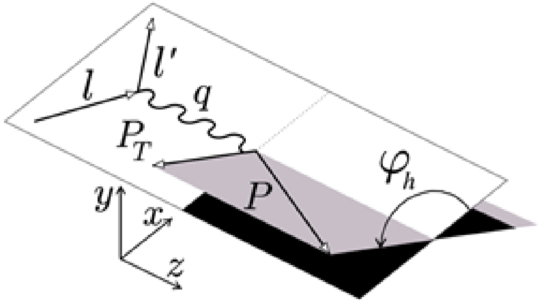

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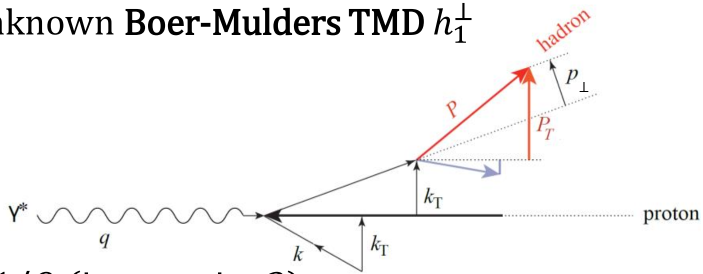
The structure functions $F_{XY[,Z]}^{[f(\varphi_h)]}$ can be written in terms of

- TMD Parton Distributions Functions (PDFs)
- TMD Fragmentation Functions (FFs).

Unpolarized structure functions

Unpolarized SIDIS → access to the **number density TMD** and to the still unknown **Boer-Mulders TMD** $h_1^{\perp}$



Quark / **Nucleon**	**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**	$h_{1L}^{q\perp}(x, \boldsymbol{k_T^2})$ **Kotzinian-Mulders worm-gear L**
T transversely polarized	$f_{1\perp}^q(x, \boldsymbol{k_T^2})$ **Sivers**	$g_{1T}^{q\perp}(x, \boldsymbol{k_T^2})$ **Kotzinian-Mulders worm-gear T**	$h_1^q(x, \boldsymbol{k_T^2})$ **transversity** $h_{1T}^{q\perp}(x, \boldsymbol{k_T^2})$ **pretzelosity**

Up to order $1/Q$ (i.e. at twist-3):

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

Cahn effect ***Boer-Mulders term***

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

Boer-Mulders term

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

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

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

Two main observables : the topics covered in this talk

1) Azimuthal asymmetries

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

2) Transverse-momentum distributions → $\boldsymbol{F_{UU,T}}$

The COMPASS experiment

New: Collins and Sivers asymmetries for inclusive ρ^0
Talk by A. Kerbizi

COMPASS contribution to the understanding of the nucleon structure

- spin asymmetries with transverse and longitudinal spin polarization
  important results on the extraction of transversity and Sivers functions
- SIDIS with unpolarized target
  azimuthal asymmetries and P_T^2-distributions on deuteron – NEW: ON PROTON

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

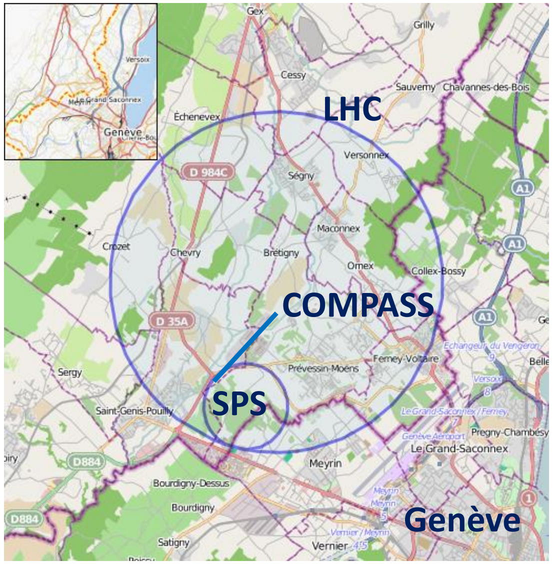
Broad research program:

- 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)
- …

New: COMPASS DY results
Talk by Y-H. Lien

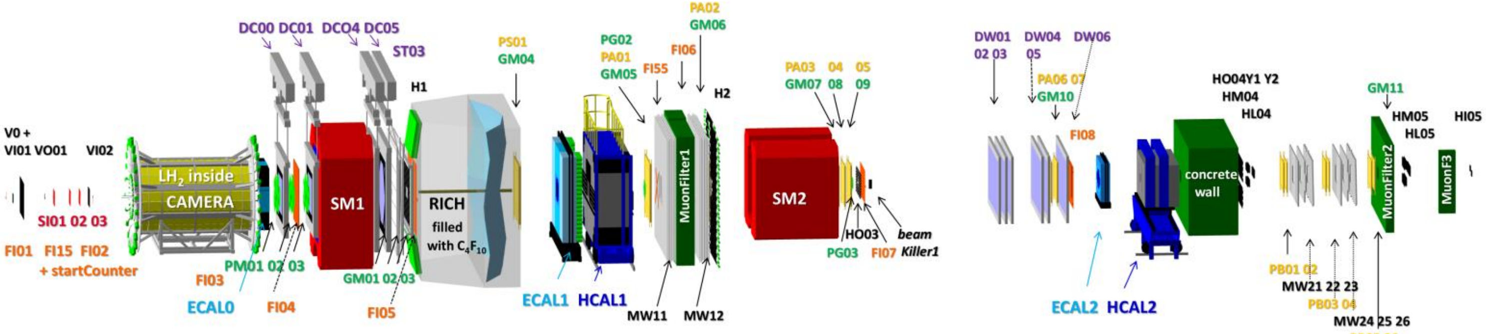
A multipurpose apparatus:

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



The COMPASS location at CERN

The 2016 COMPASS run



The 2016 COMPASS experimental setup

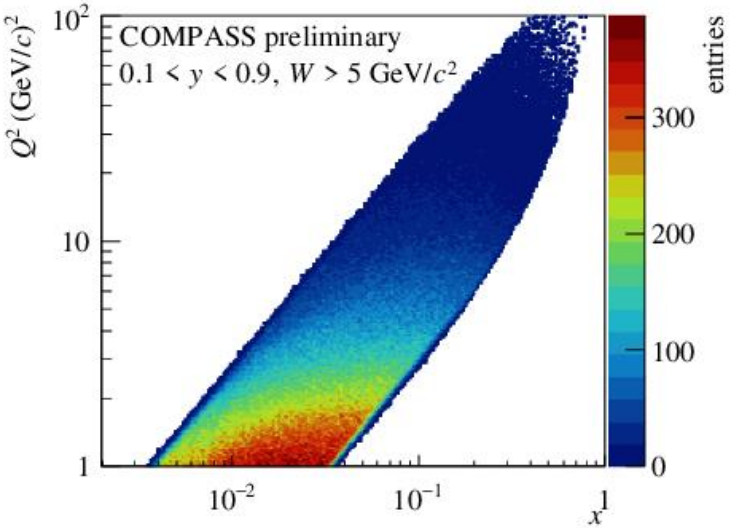
Talk by B. Ventura

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

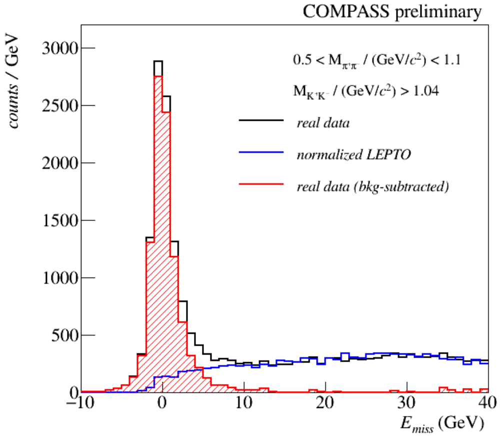
- the **acceptance correction** (LEPTO generator)
- the **subtraction of exclusive hadrons** (HEPGEN generator) → next slides

Contribution from exclusive hadrons

Hadrons from the decay of exclusive diffractive vector mesons *(exclusive hadrons)*, well visible in the data

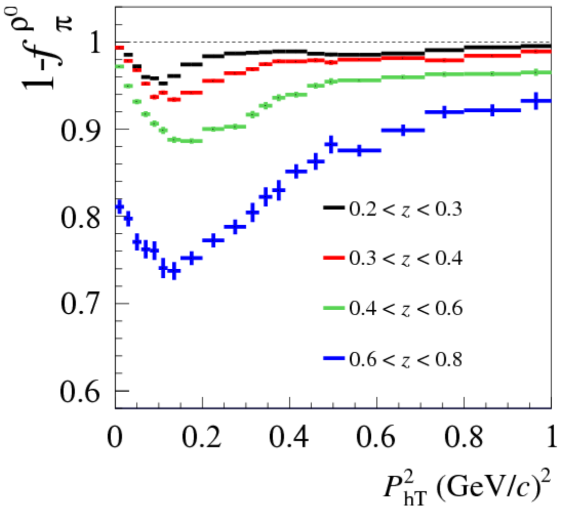
Talk by W. Augustiniak on ρ^0 SDMEs

- The two most important channels : $\rho^0 \to \pi^+\pi^-$ *and* $\phi \to K^+K^-$
- Their amount is strongly kinematic-dependent

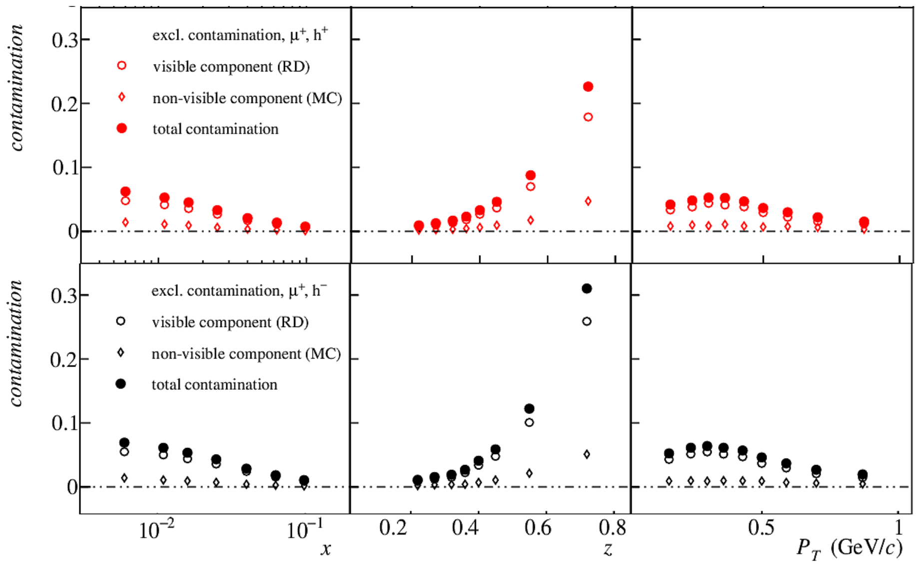


The exclusive peak as observed in the data

[COMPASS, PRD97 (2018) 032006]



Fraction of pions from SIDIS,
as a function of P_T^2 per z bin,
for $1.0 < Q^2/(\text{GeV}/c)^2 < 1.7$

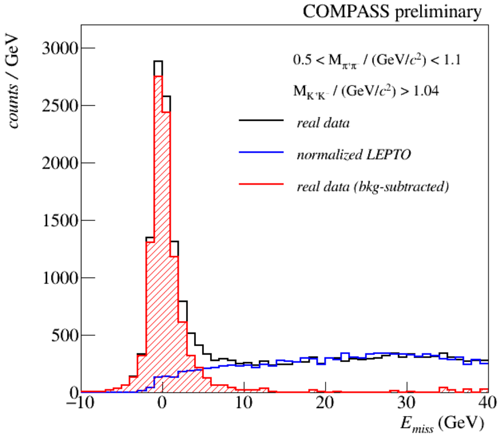


Estimated exclusive hadrons contaminations

Contribution from exclusive hadrons

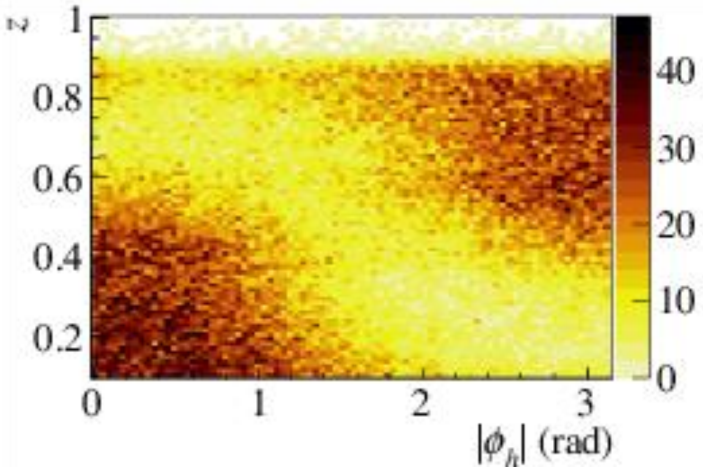
Hadrons from the decay of exclusive diffractive vector mesons *(exclusive hadrons)*, well visible in the data

- The two most important channels : $\rho^0 \rightarrow \pi^+\pi^-$ *and* $\phi \rightarrow K^+K^-$
- Their amount is strongly kinematic-dependent
- They show strong modulations in the azimuthal angle
  → they are estimated and discarded/subtracted

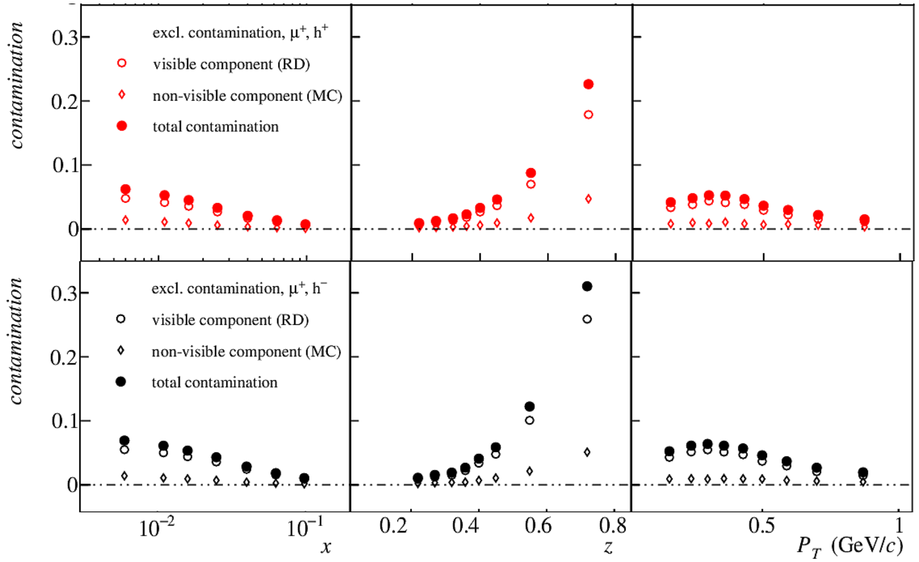


The exclusive peak as observed in the data

[COMPASS, NPB 956 (2020) 115039]



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



Estimated exclusive hadrons contaminations

Impact on the azimuthal asymmetries calculated for the deuteron data

[COMPASS, NPB 956 (2020) 115039]

Azimuthal asymmetries

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

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

Steps in the measurement:

1. Exclusive hadrons:
   - the visible component is *discarded*
   - the non-visible component is *subtracted*

   using the HEPGEN Monte Carlo
2. Acceptance correction
3. Fit of the **amplitude of the modulation in the azimuthal angle** of the hadrons
   - as a function of x, z or P_T (1D)
   - with a simultaneous binning (3D)

Azimuthal asymmetries – 1D

proton target

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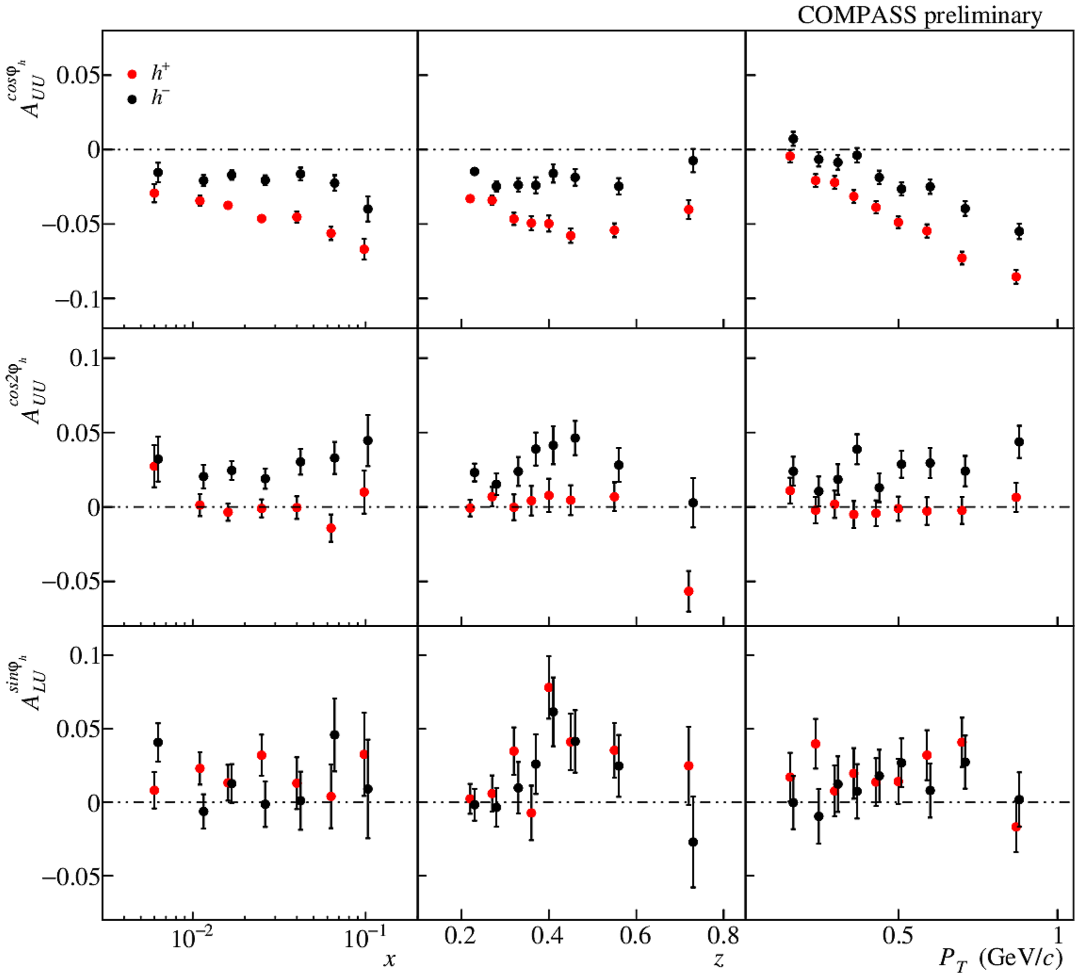


- Strong kinematic dependences
- interesting differences between positive and negative hadrons.

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

[COMPASS, NPB 886 (2014) 1046]

Azimuthal asymmetries – 1D – Q^2 dependence

proton target

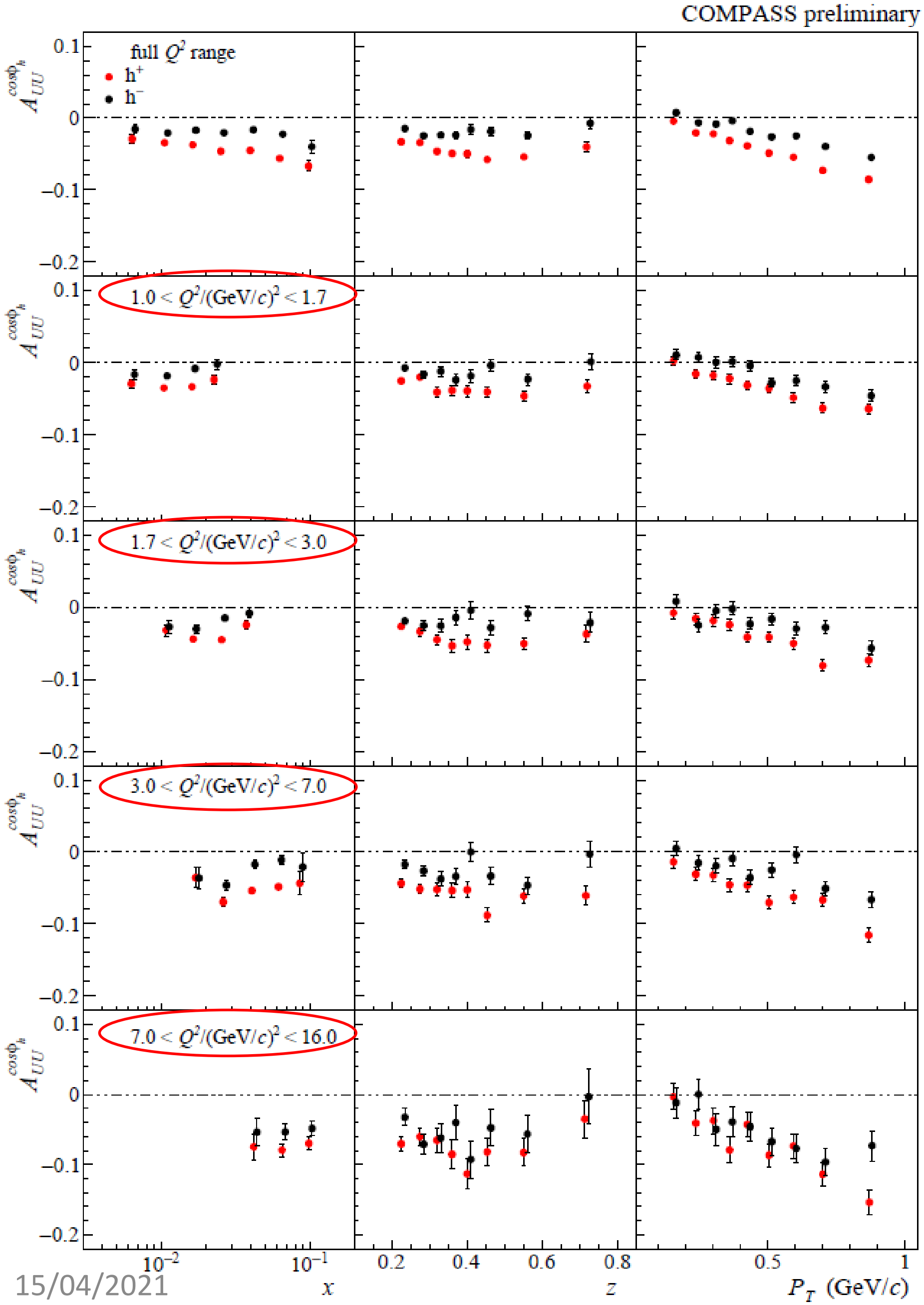
Binning in Q^2

- The $A_{UU}^{cos\phi_h}$ asymmetry is observed to increase with Q^2
- Flavor-independent expectation from the Cahn effect:

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

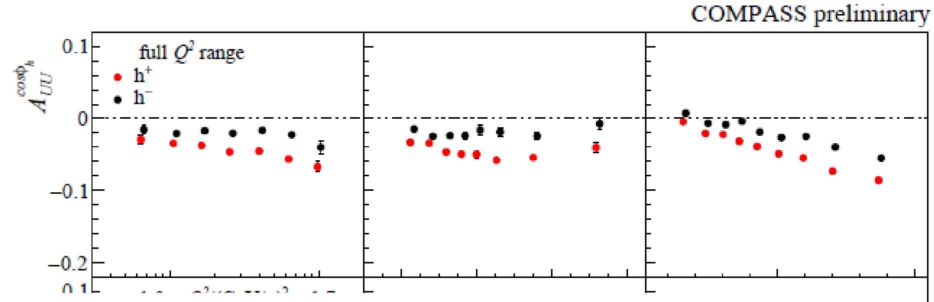
- → A strong dependence of $\langle k_T^2\rangle$ on Q^2, or the relevance of other terms in the asymmetry

- The difference between positive and negative hadrons decreases with Q^2.

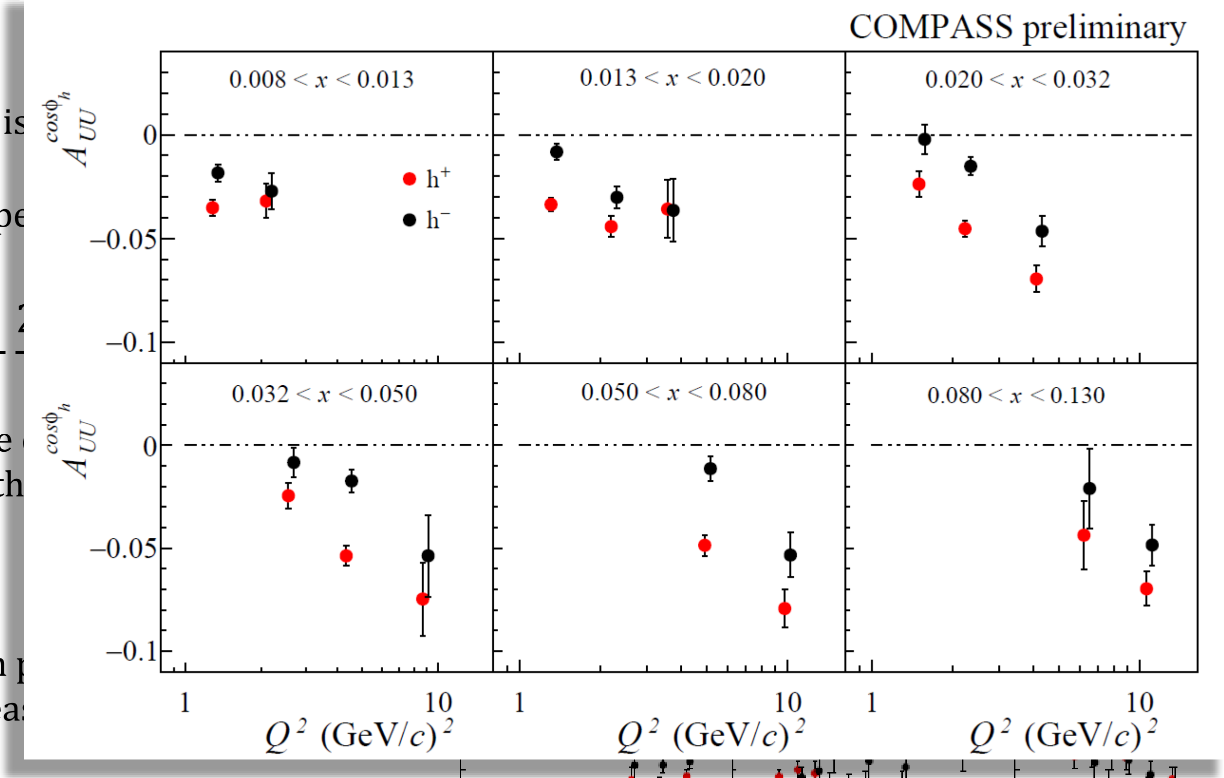


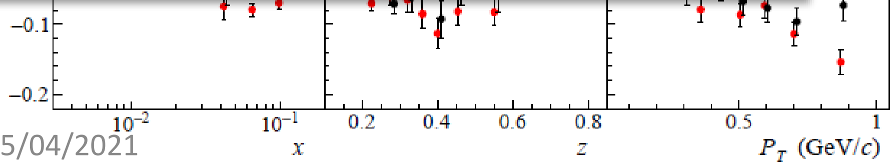
Azimuthal asymmetries – 1D – Q^2 dependence

proton target



Clear dependence on Q^2 also for fixed x $(0.2 < z < 0.8)$





Binning in Q^2

- The $A_{UU}^{cos\phi_h}$ asymmetry is increase with Q^2
- Flavor-independent expe Cahn effect:

$$A_{UU|Cahn}^{\cos\phi_h} = -$$

- → A strong dependence or the relevance of oth asymmetry

- The difference between negative hadrons decrea

Azimuthal asymmetries – 1D – W dependence

proton target

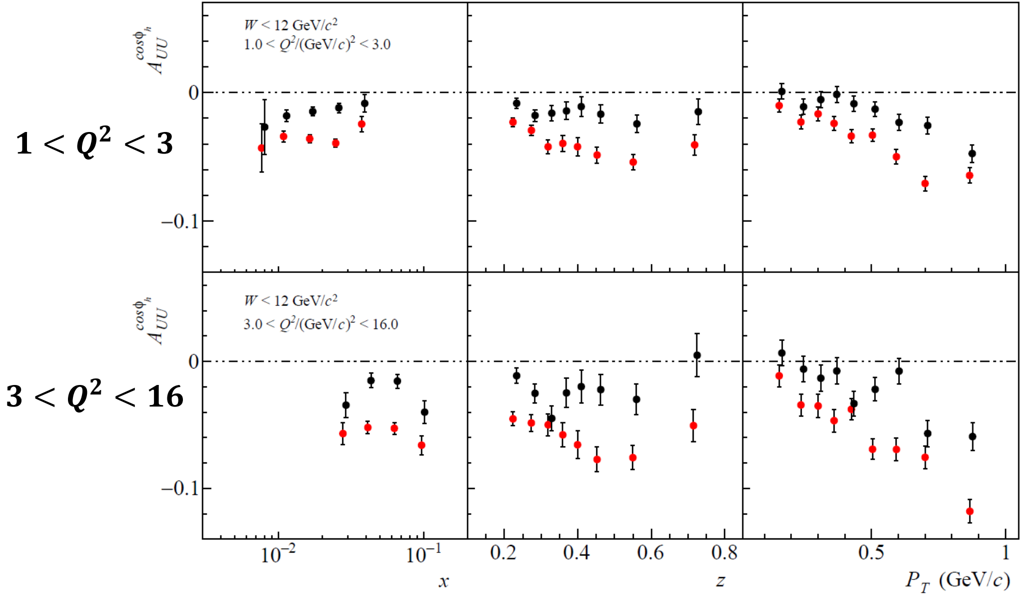
Correlated to the Q^2 dependence:
W dependence

$$W^2 = M_P^2 + Q^2 \frac{1-x}{x}$$

- The $A_{UU}^{cos\phi_h}$ asymmetry increases with Q^2 in both W bins.
- Better compatibility between positive and negative hadrons at larger W.
- Weaker dependence of $A_{UU}^{\cos 2\phi_h}$ on Q^2 and W

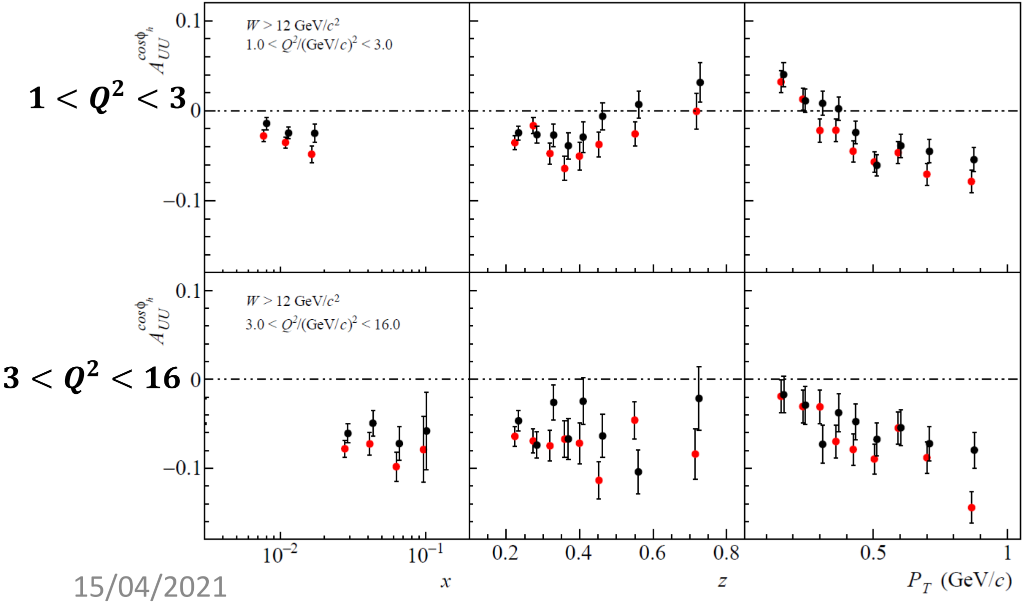
$A_{UU}^{cos\phi_h}$ for $W < 12$ GeV

COMPASS preliminary



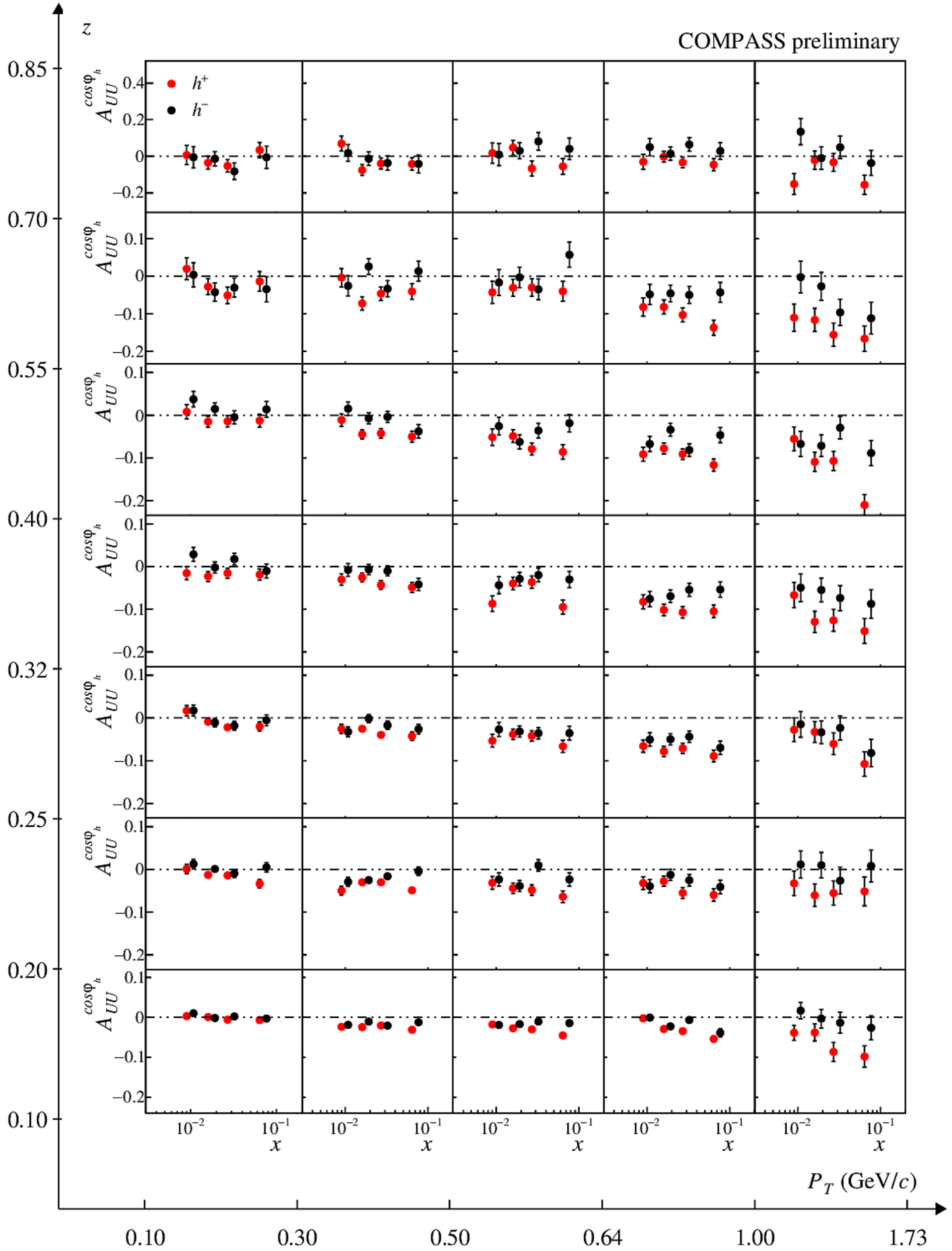
$A_{UU}^{cos\phi_h}$ for $W > 12$ GeV

COMPASS preliminary



Azimuthal asymmetries – 3D – $A_{UU}^{cos\phi_h}$

proton target



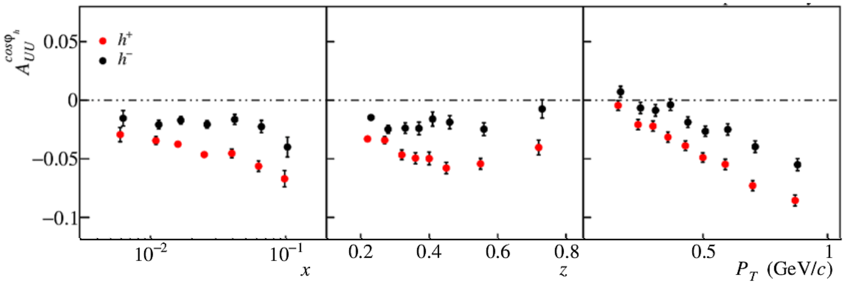
3D azimuthal asymmetries for positive and negative hadrons

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

Expectation from Cahn effect:

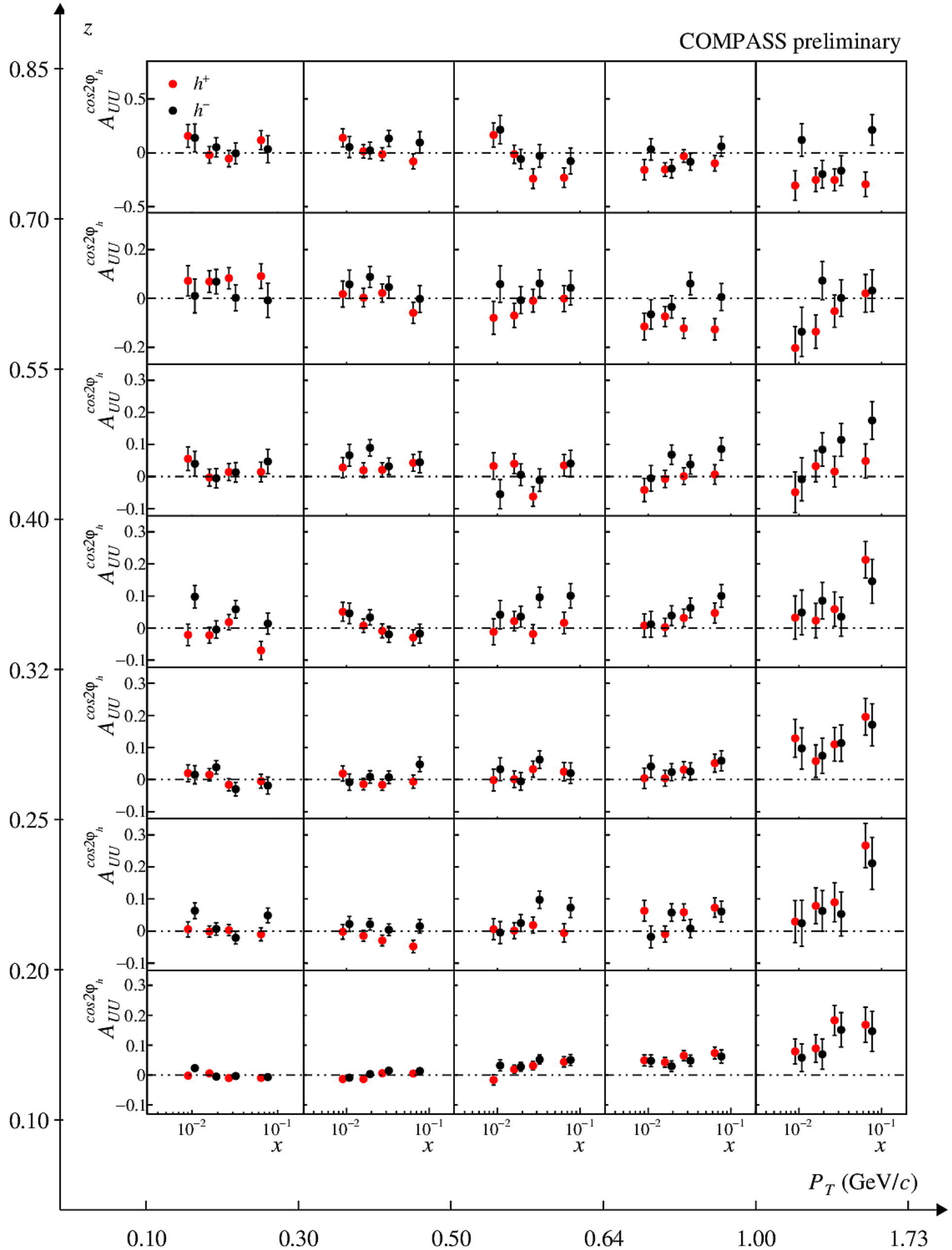
$$A_{UU|Cahn}^{\cos\phi_h} = -\frac{2zP_T\langle k_T^2\rangle}{Q\ \langle P_T^2\rangle}$$

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



Azimuthal asymmetries – 3D – $A_{UU}^{\cos 2\phi_h}$

proton target

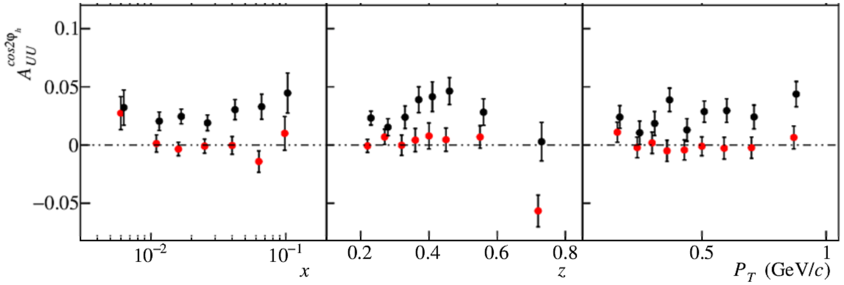


3D azimuthal asymmetries for positive and negative hadrons

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 → 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



Transverse momentum distributions

proton target

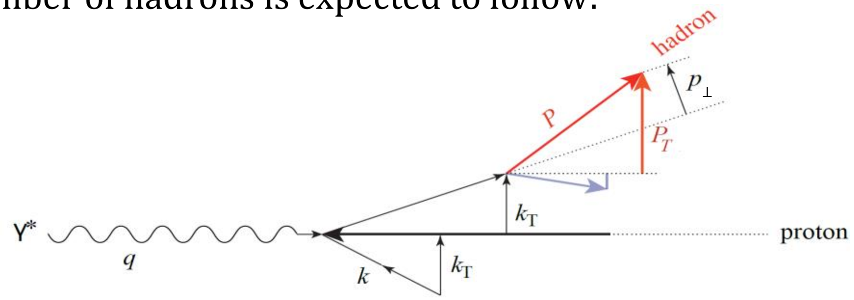
Transverse-momentum distributions

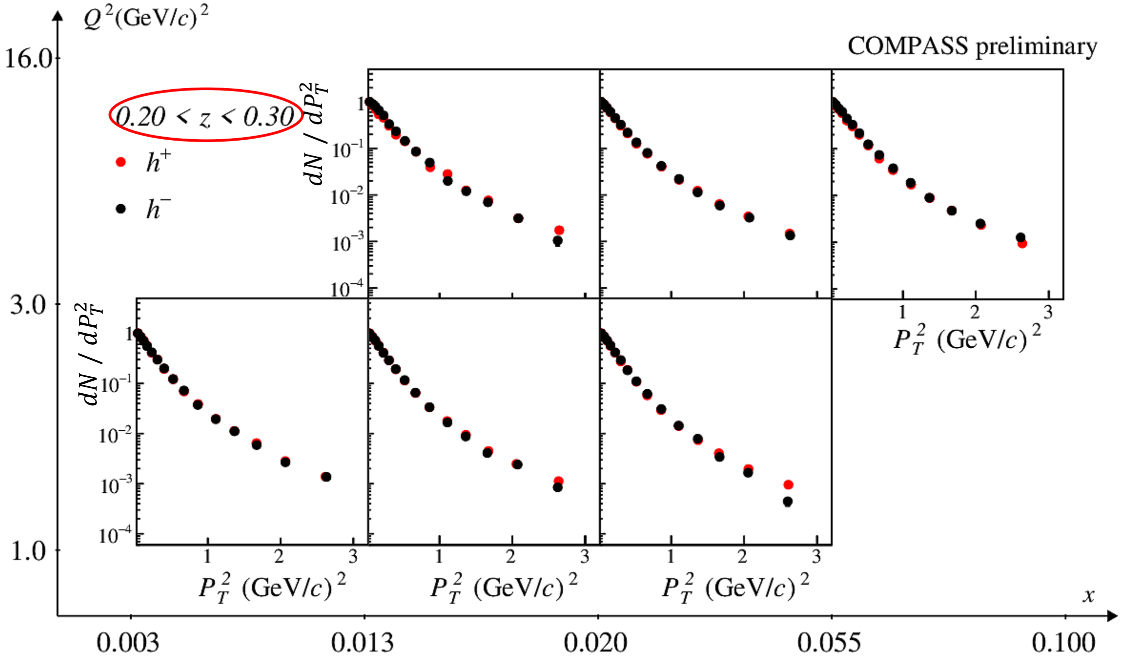
- give complementary information on k_T and $p_\perp$ w.r.t. azimuthal asymmetries
- are interesting for the TMD evolution studies:
  a lot of theoretical work to reproduce the experimental distributions over large energy range
- cross section gives more information: the work is ongoing

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

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

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

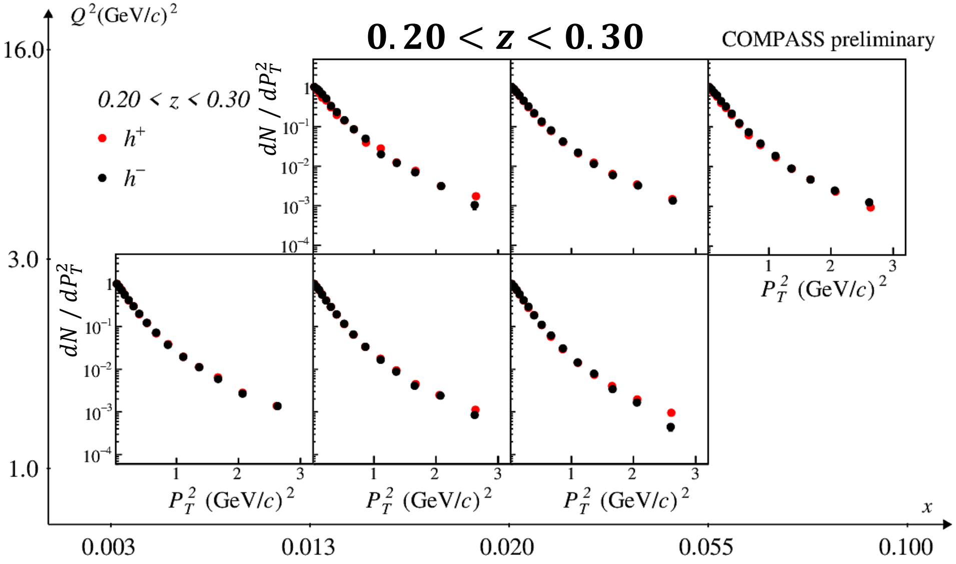


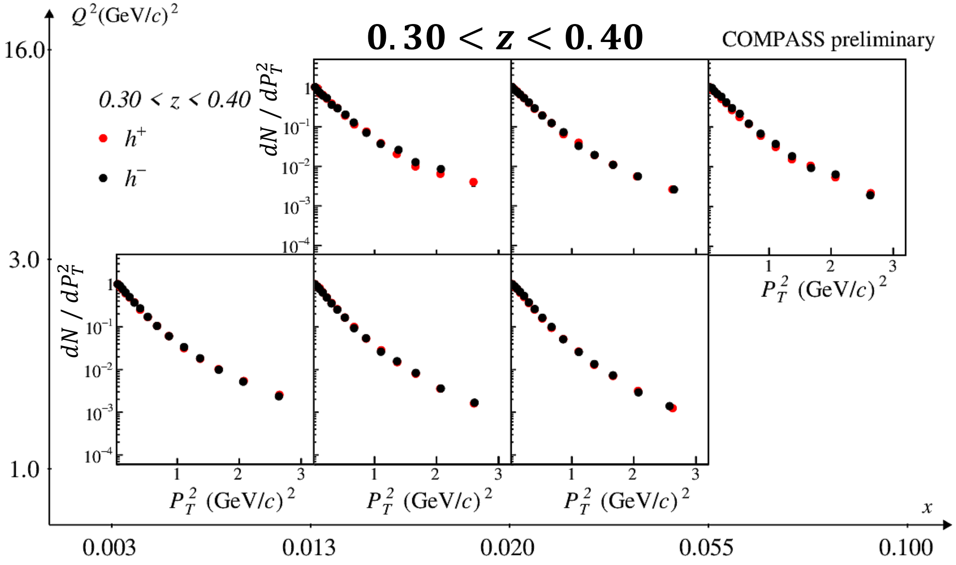


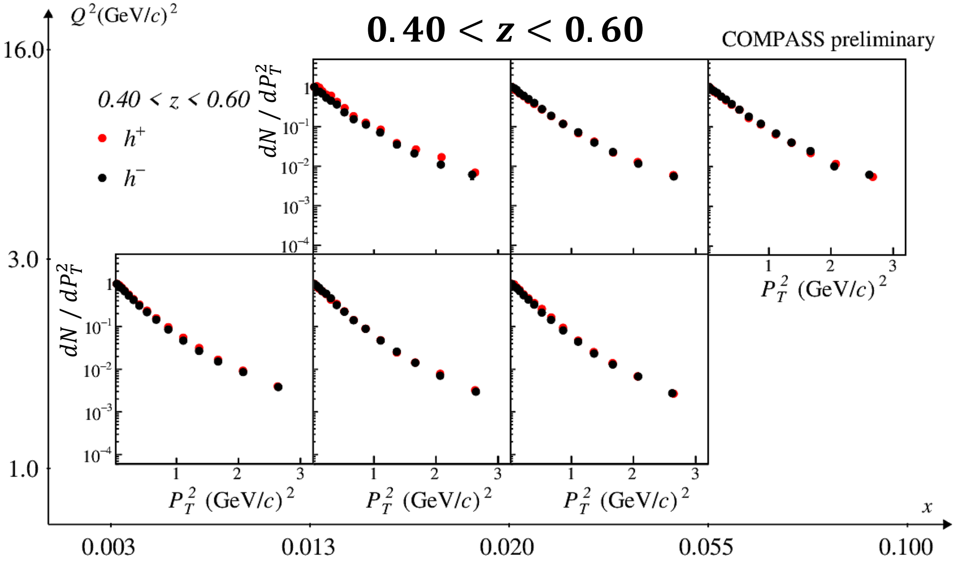
Normalization: first P_T^2 bin.

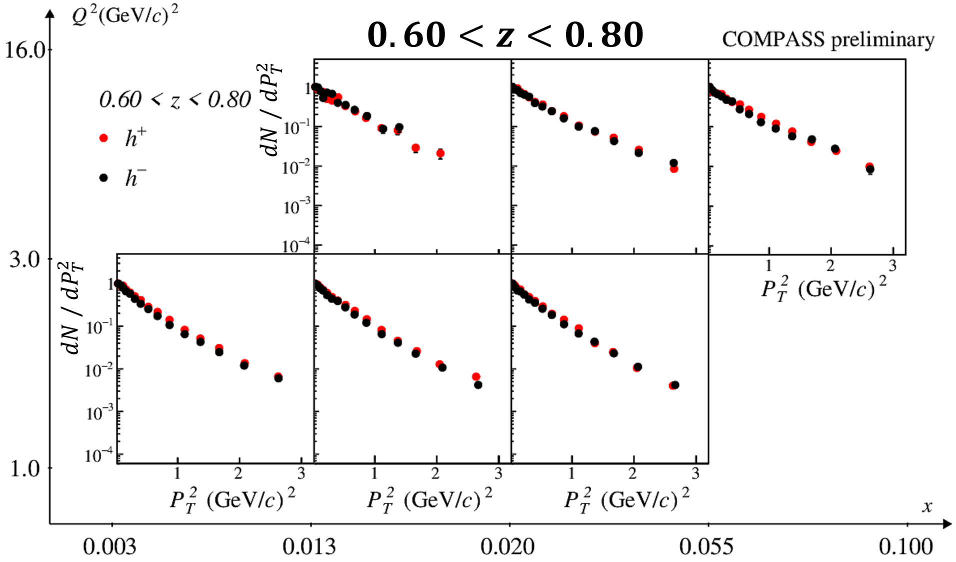
Transverse momentum distributions

proton target





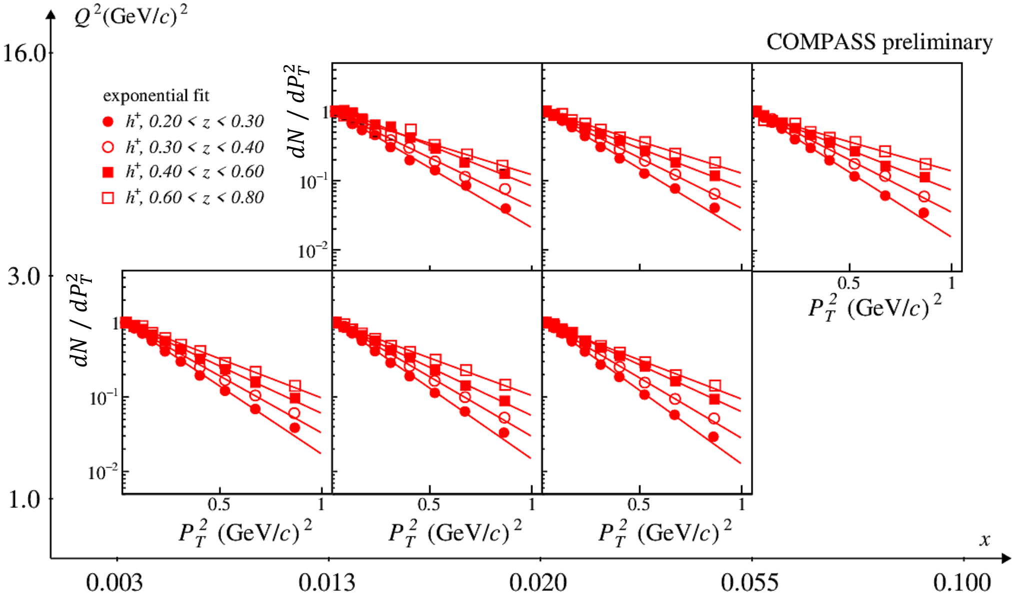


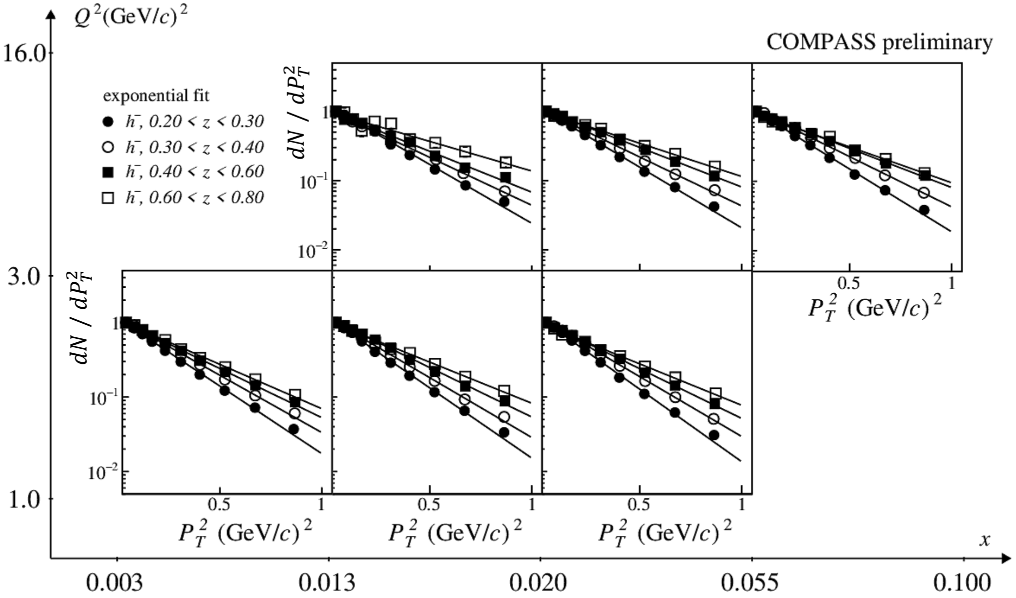


<u>In good agreement with previous deuteron results</u> [COMPASS, PRD97 (2018) 032006]

Transverse momentum distributions – exponential fit

proton target





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

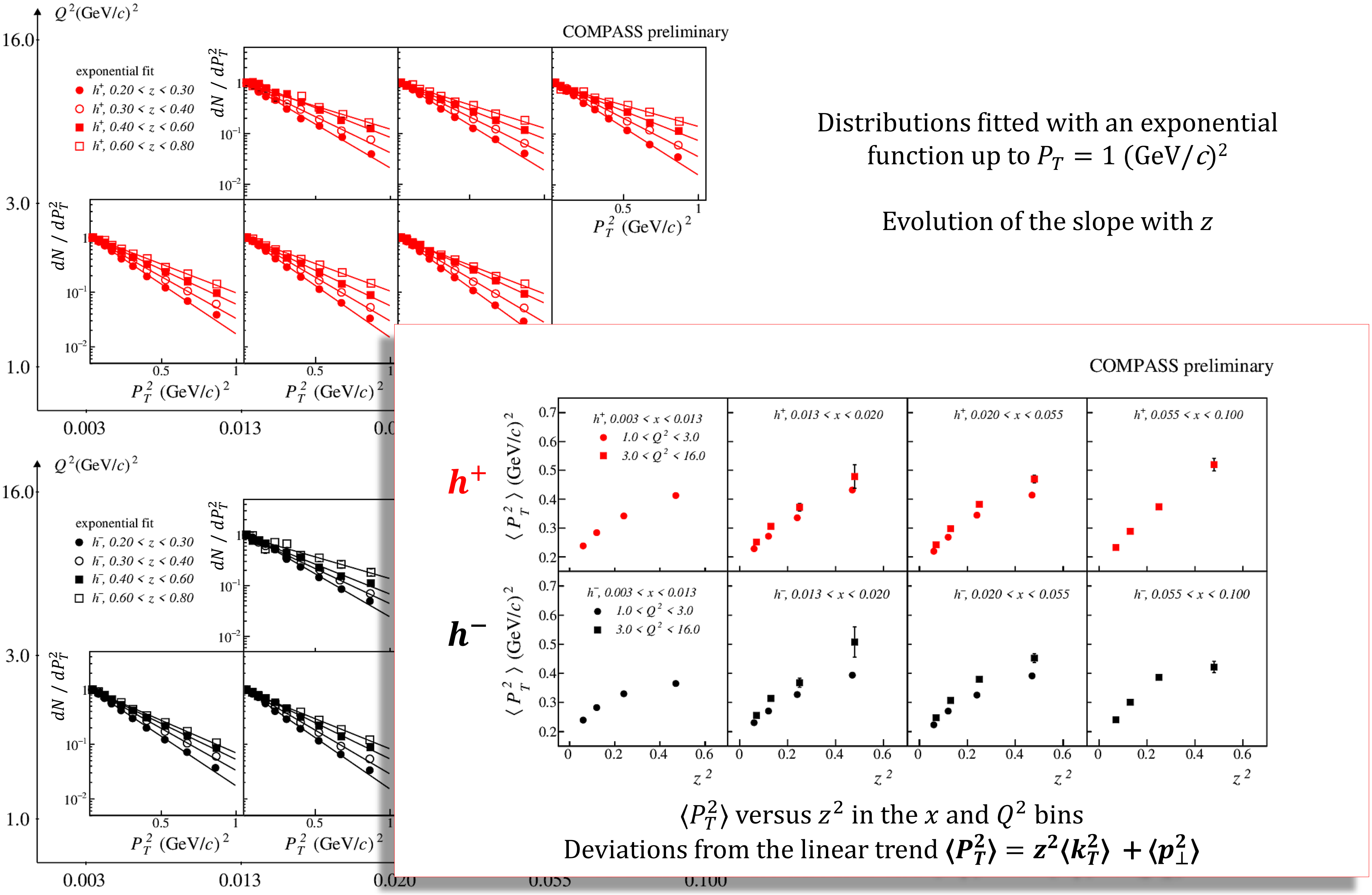
Evolution of the slope with z

Transverse momentum distributions – exponential fit

proton target

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

Evolution of the slope with z

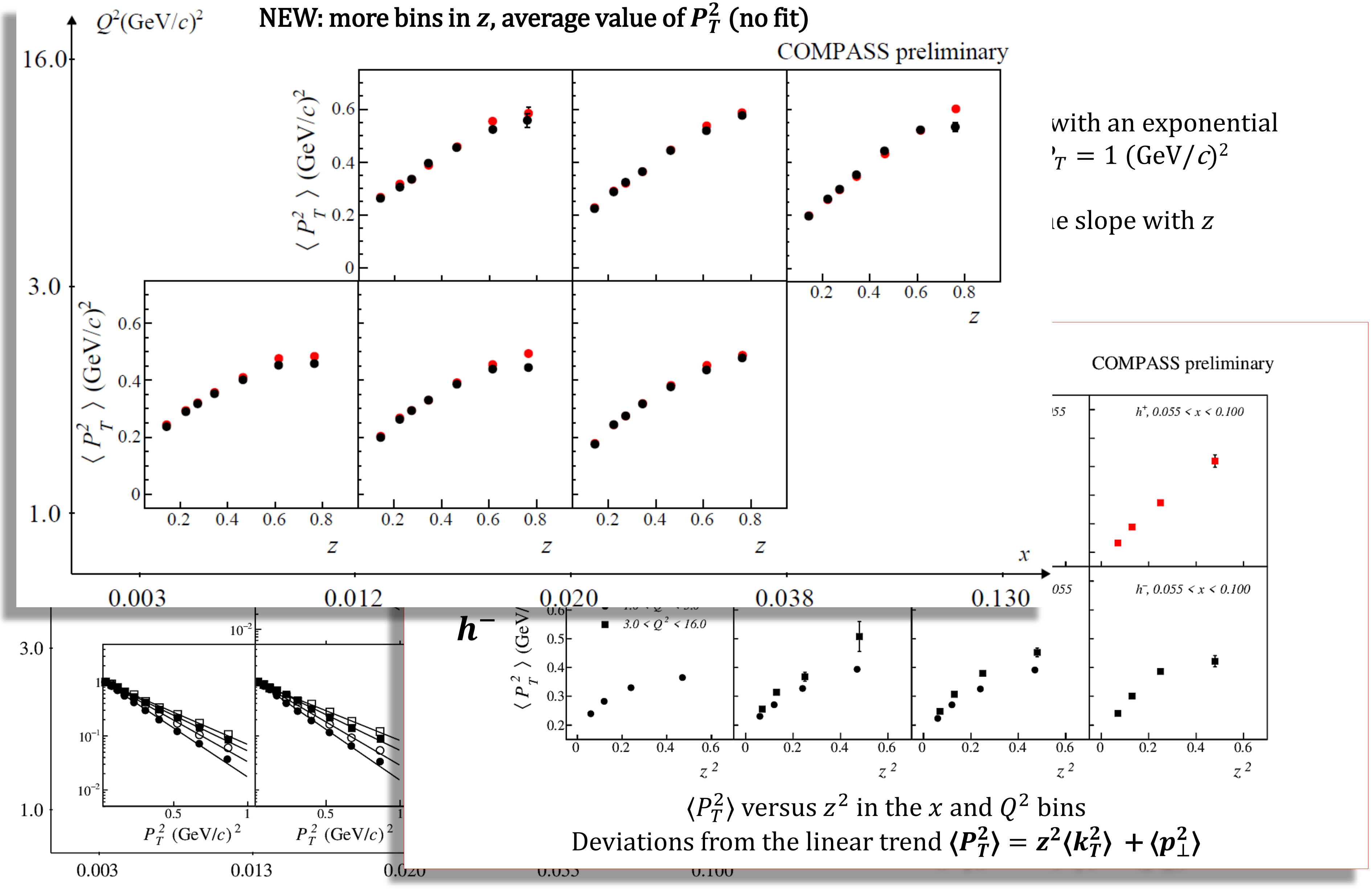


$\langle P_T^2 \rangle$ versus z^2 in the x and Q^2 bins

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

Transverse momentum distributions

proton target



NEW: more bins in z, average value of P_T^2 (no fit)

with an exponential

$_T = 1$ (GeV/c)^2

e slope with z

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

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

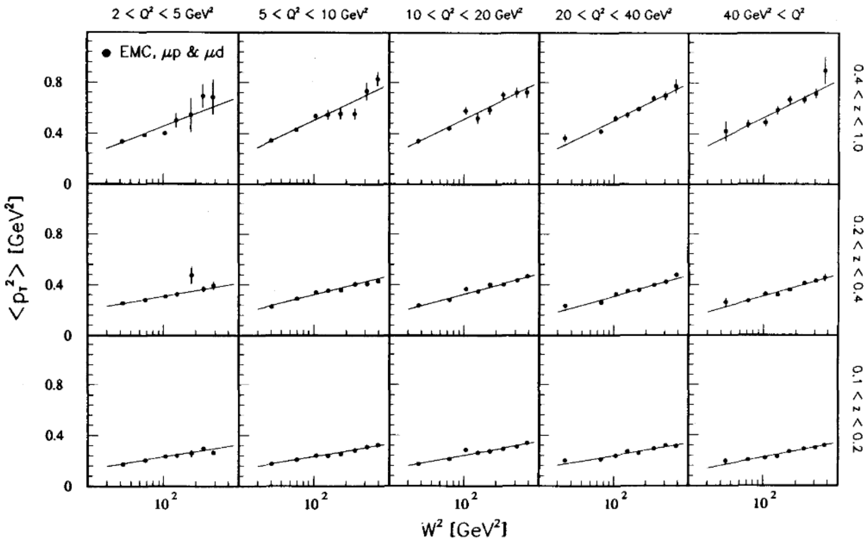
Transverse momentum distributions - W dependence

proton target

Characterization of the kinematic dependences

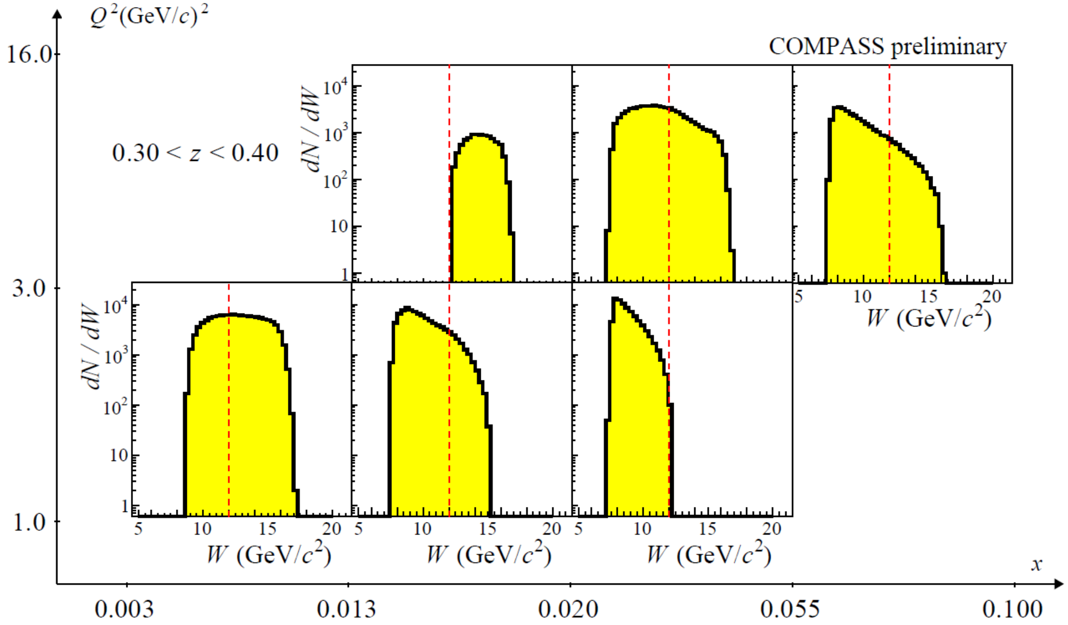
- Q^2 dependence: expected from TMD formalism
- W dependence: also interesting and present

→ EMC: $\langle P_T^2 \rangle$ vs W^2



[EMC, Z. Phys. C 52, 361 (1991)]

- P_T^2 distributions in two bins of W, cut at $W = 12$ GeV/c.

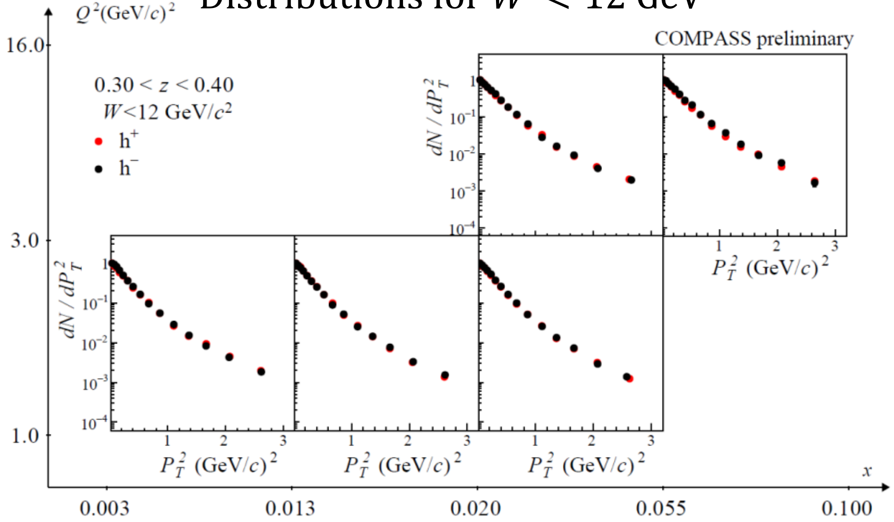


Transverse momentum distributions - W dependence

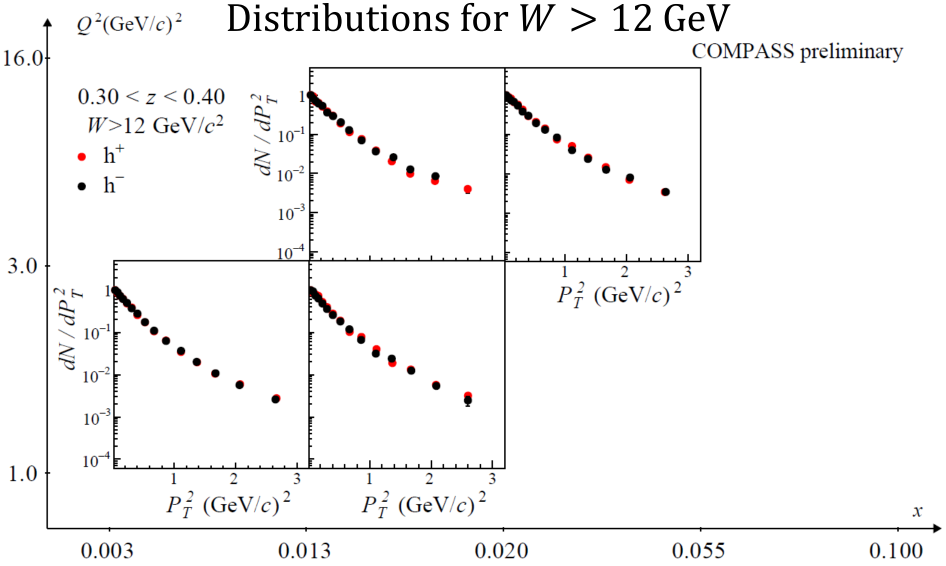
proton target

Characterization of the kinematic dependences: some examples

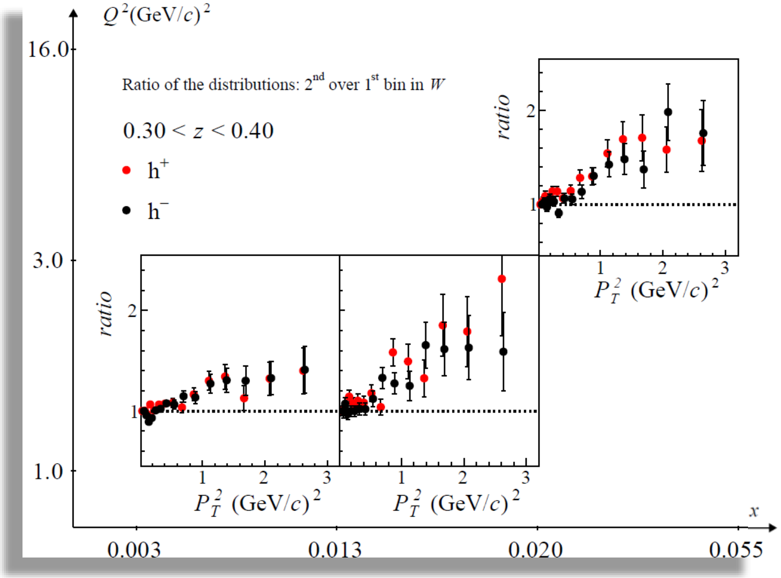
Distributions for $W < 12$ GeV



Distributions for $W > 12$ GeV



Their ratio in the common x, Q^2 bins



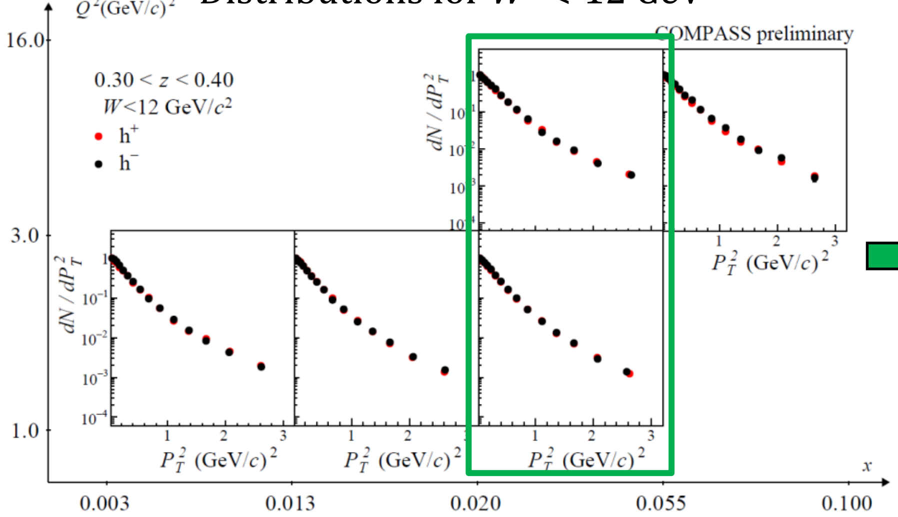
Linear trend: expected from the ratio of two exponential distributions with (slightly) different slope

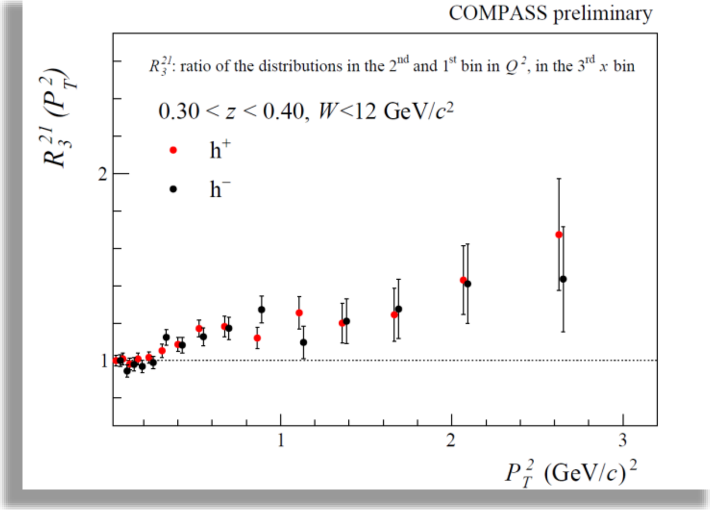
Transverse momentum distributions - W dependence

proton target

Characterization of the kinematic dependences: some examples

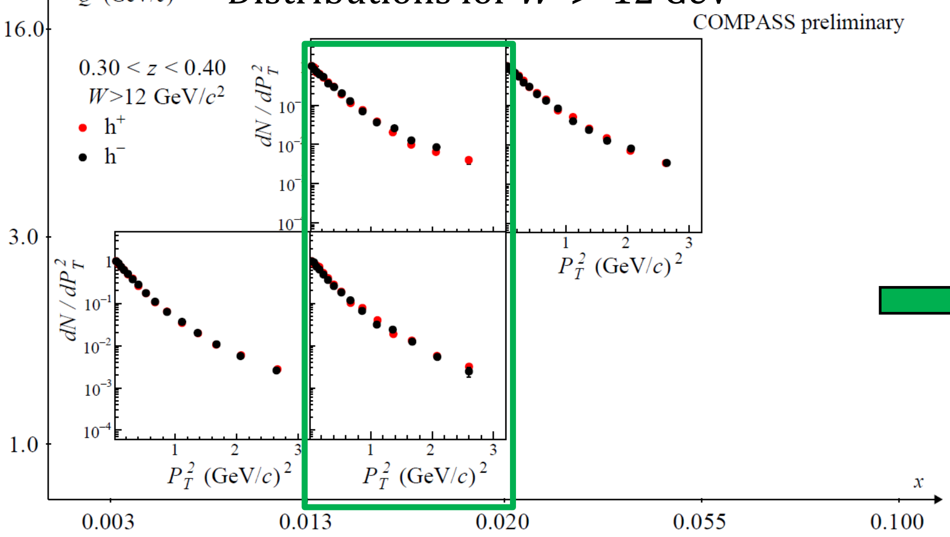
Distributions for $W < 12$ GeV

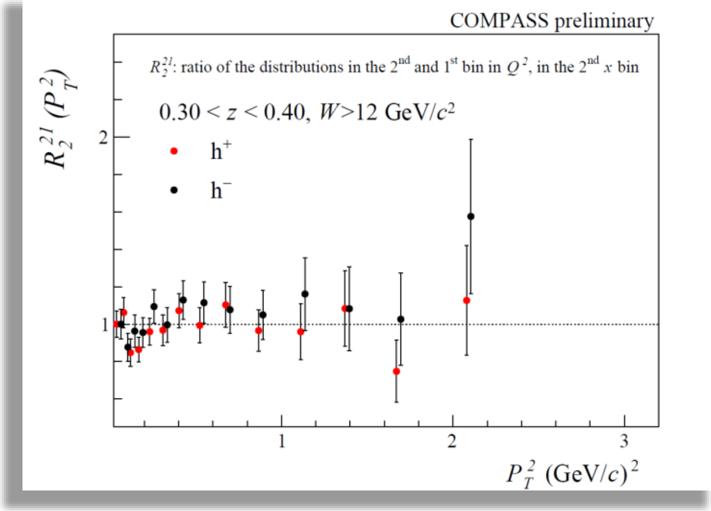




Their ratio for higher and lower Q^2

Distributions for $W > 12$ GeV

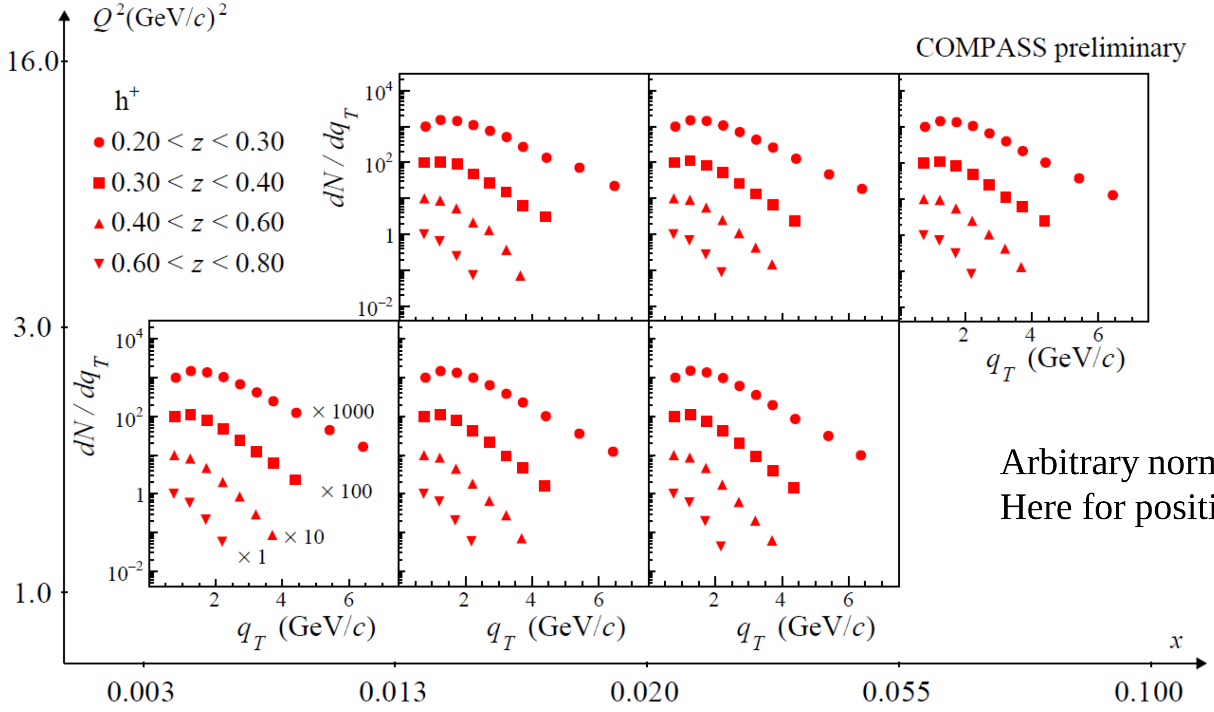




q_T distributions

proton target

- $q_T = P_T \,/\, z$, often indicated to set the limits of applicability of the TMD formalism
  (expected to hold at low q_T/Q)
- q_T distributions measured using the same hadron sample selected for the standard P_T^2 distributions



Arbitrary normalization and scaling
Here for positive hadrons, similar for negative

q_T distributions

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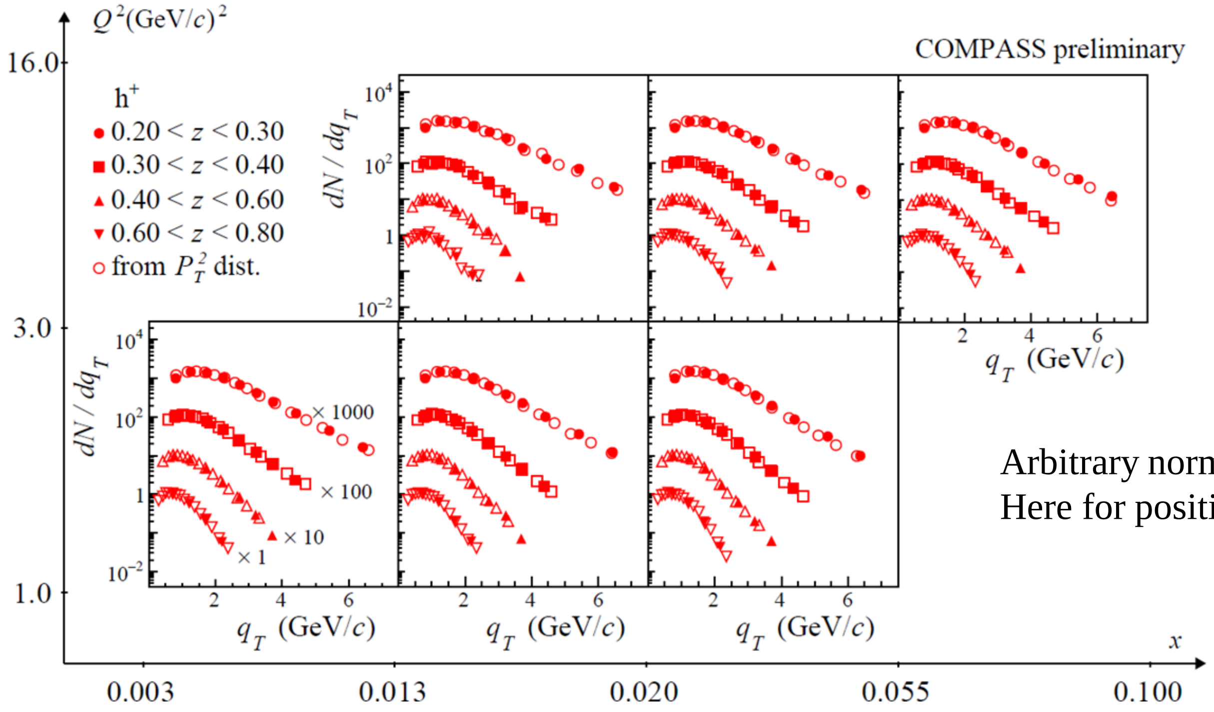
- q_T distributions measured using the same hadron sample selected for the standard P_T^2 distributions
- Comparison with the approximated formula:

$$\frac{dN_h}{dz\, dP_T^2} = \frac{dN_h}{dz\, 2P_T dP_T} = \frac{dN_h}{dz\, dP_T/z}\frac{1}{2zP_T} \approx \frac{dN_h}{dz\, dq_T}\frac{1}{2zP_T}$$



Arbitrary normalization and scaling
Here for positive hadrons, similar for negative

Conclusions

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

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

- Both observables look interesting with rich kinematic dependences.

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

Conclusions

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

- Both observables look interesting with rich kinematic dependences.

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

Thank you

backup

The 2016 COMPASS run

DIS events selected with standard cuts:

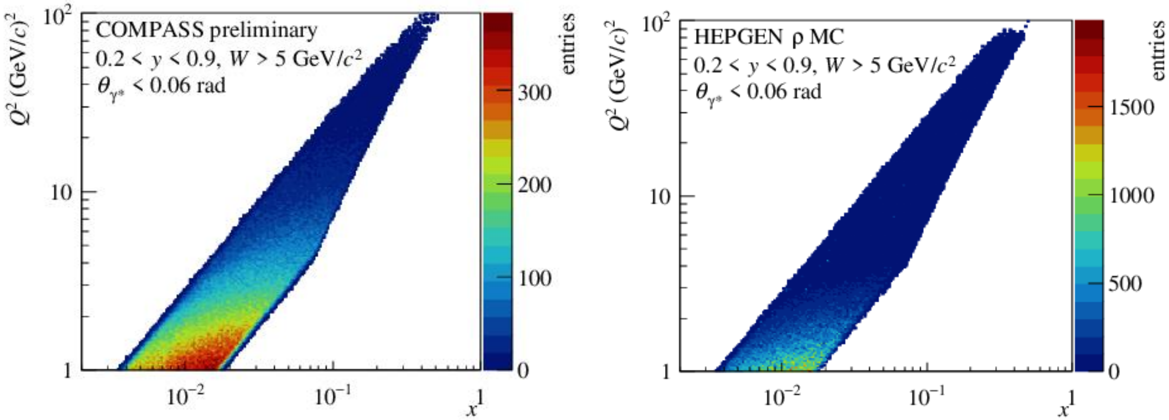
$Q^2 > 1\ (\mathrm{GeV}/c)^2$

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

$0.003 < x < 0.130,$

$0.2 < y < 0.9$

$\theta_\gamma < 60\ \mathrm{mrad}$



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

Selection of hadrons:

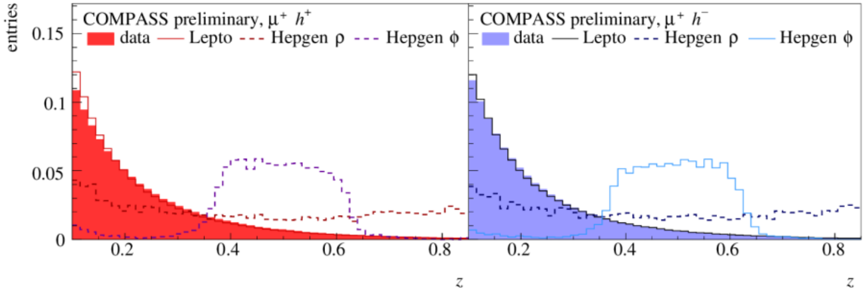
$z > 0.1$

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

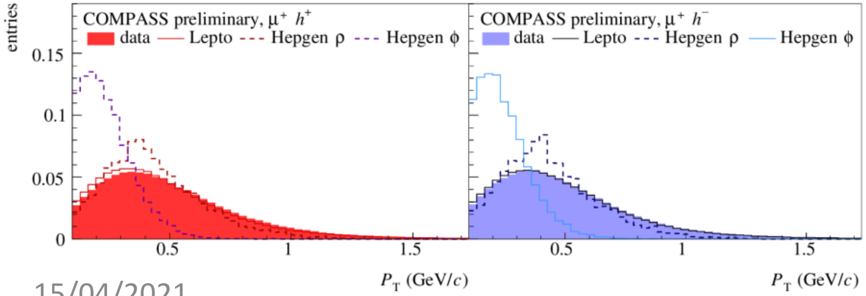
Distributions of z and P_T
normalized to their integral,

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

z



P_T

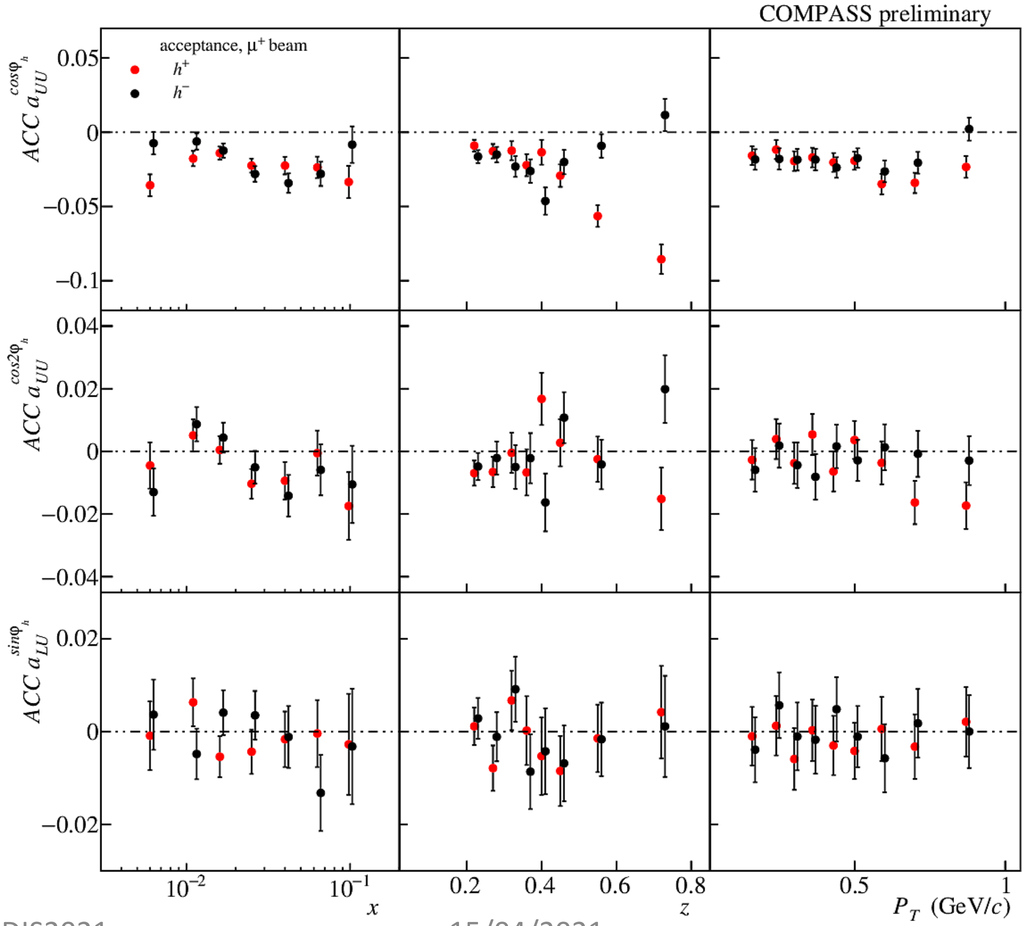


Acceptance modulations

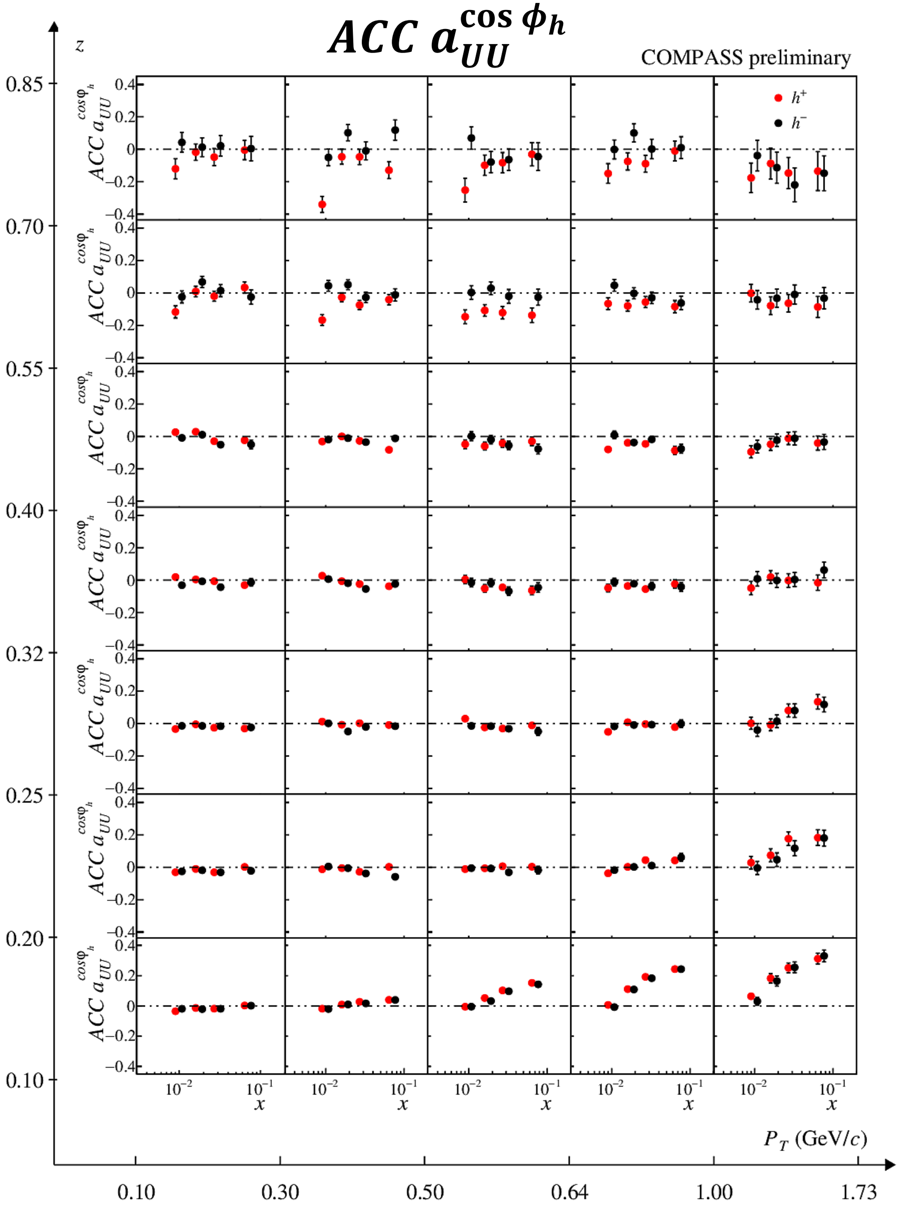
Correction for acceptance applied to each ϕ bin, taken as the ratio of reconstructed and generated hadrons:

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

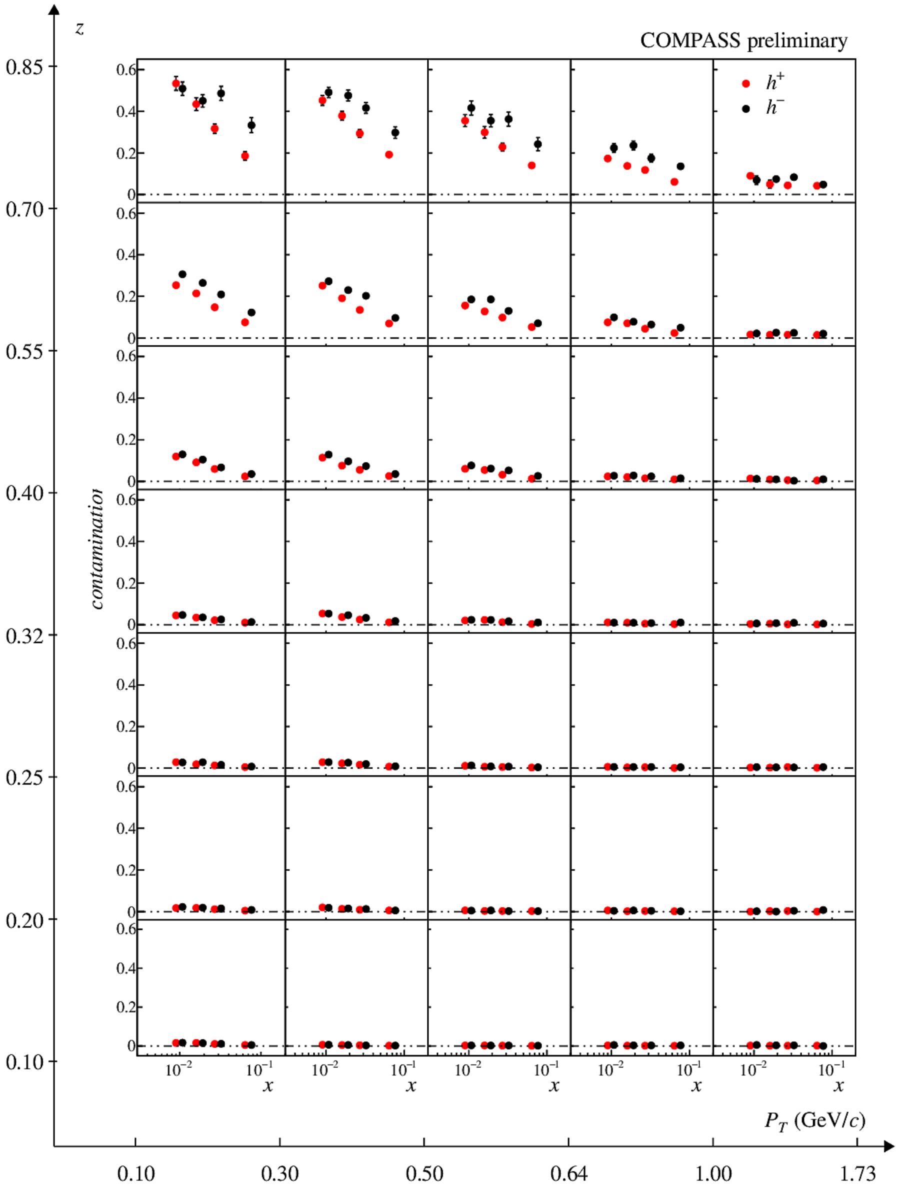
Azimuthal modulations of the acceptance in 1D binning, for μ^+ beam and positive (red) and negative hadrons (black).



Acceptance modulations

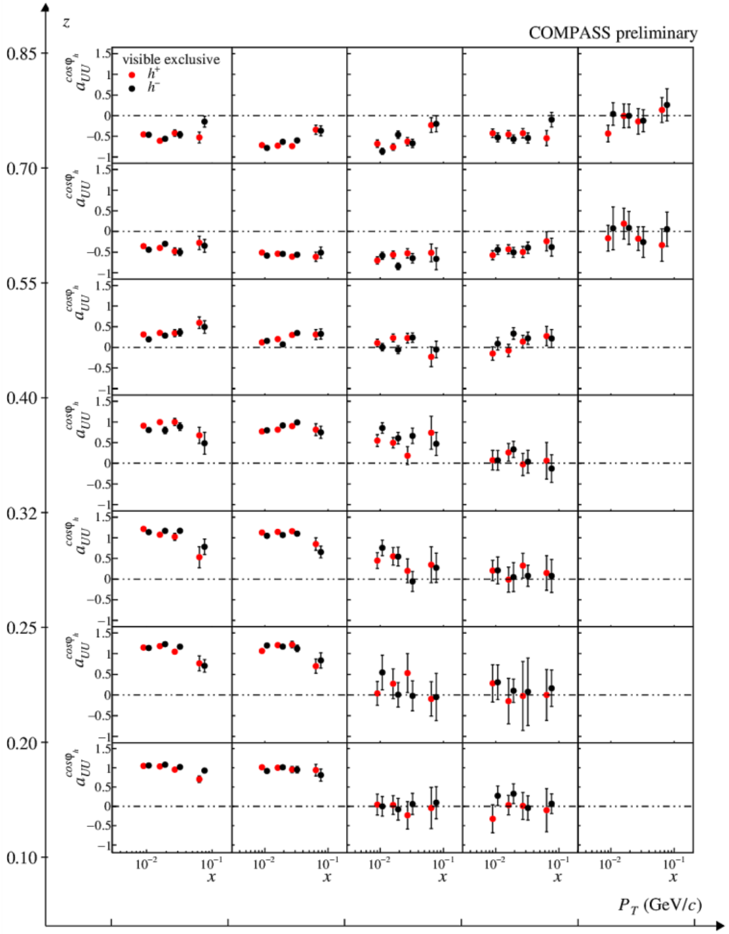


Azimuthal asymmetries – 3D



← **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 ϕ_h** for exclusive hadrons:
almost no dependence on x, mild on P_T, strong on z



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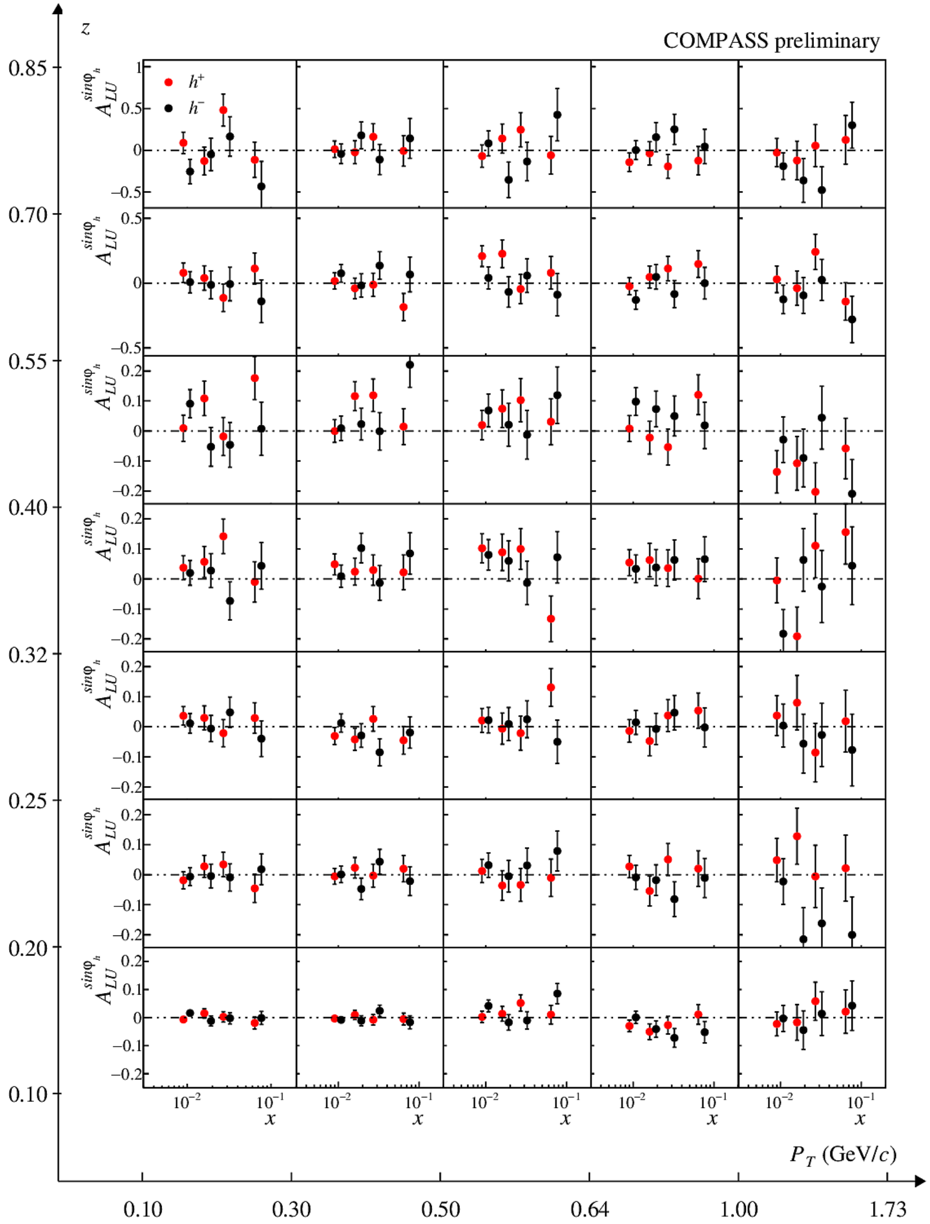
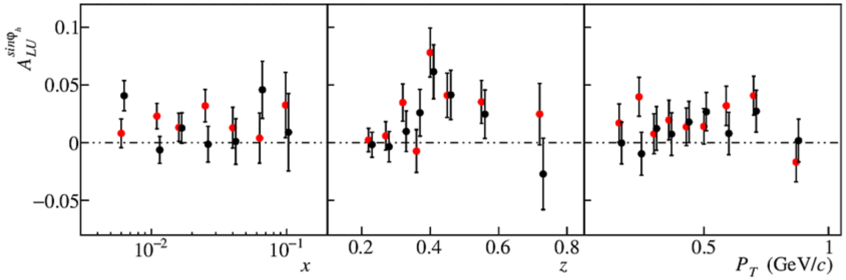


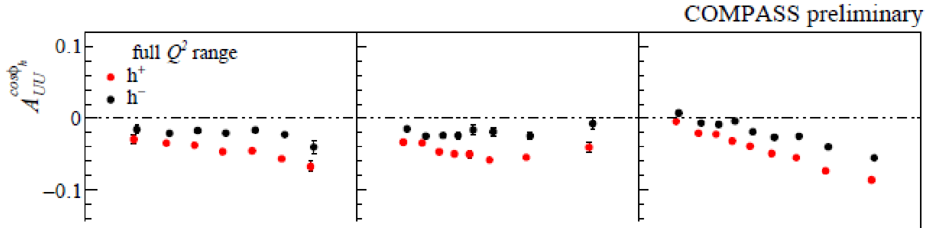
3D azimuthal asymmetries for positive and negative hadrons

$A_{LU}^{sin\phi_h}$ 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



Azimuthal asymmetries – 1D – Q^2 dependence



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

Fine binning in Q^2

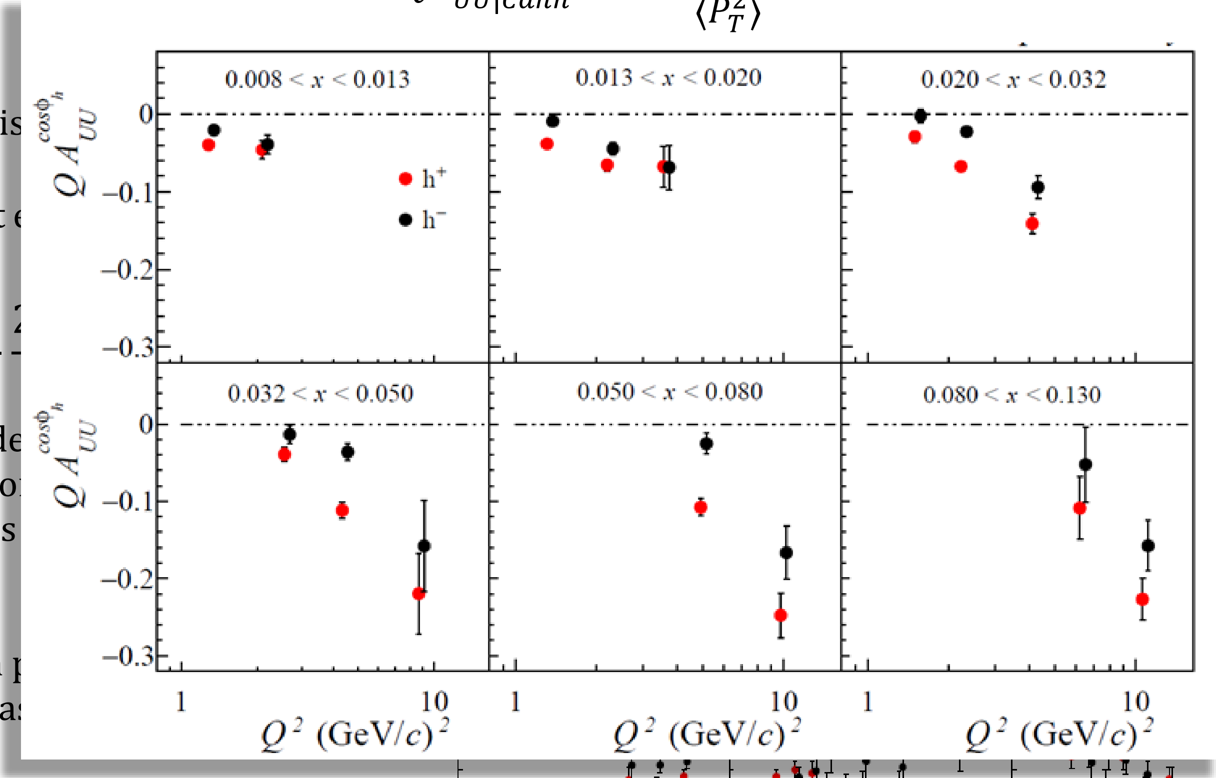
- The $A_{UU}^{cos\phi_h}$ asymmetry is
  increase with Q^2
- The flavor-independent
  the Cahn effect is:

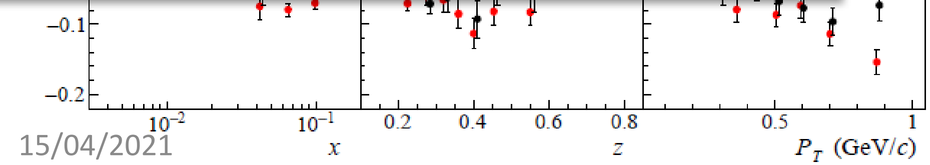
$$A^{\cos\phi_h}_{UU|Cahn} = -$$

- This suggests a strong de
  transverse momentum o
  relevance of other terms
- The difference between p
  negative hadrons decrea

Clear dependence on Q^2 also for fixed x $(0.2 < z < 0.8)$

$$QA^{\cos\phi_h}_{UU|Cahn} = -\frac{2zP_T\langle k_T^2\rangle}{\langle P_T^2\rangle}$$





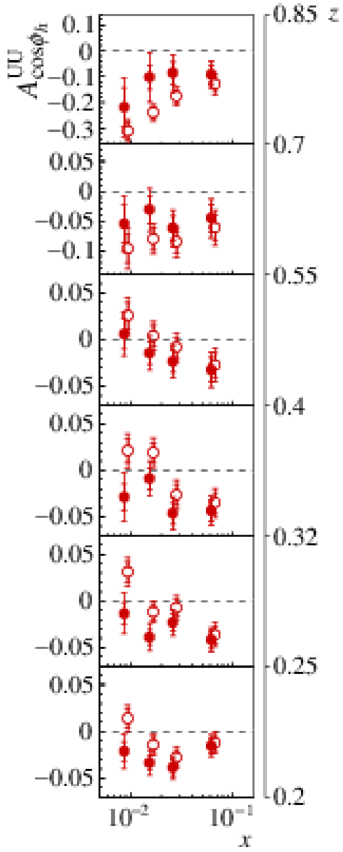
Contribution from exclusive hadrons

[COMPASS, NPB 886 (2014) 1046]

[COMPASS, NPB 956 (2020) 115039]

Example: $\cos\varphi_h$ asymmetry

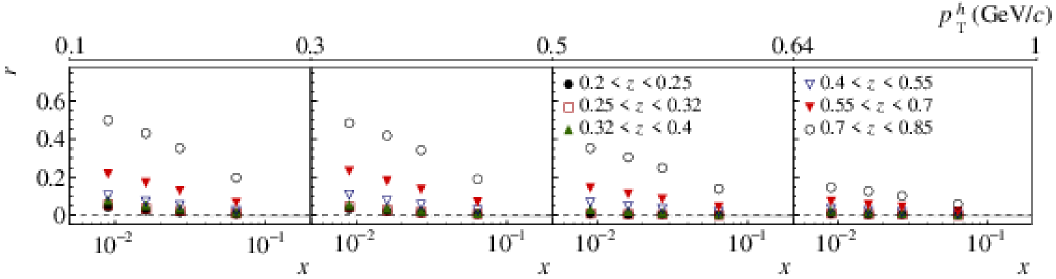
$0.1 < P_T\,/(\mathrm{GeV}/c) < 0.3$



- 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

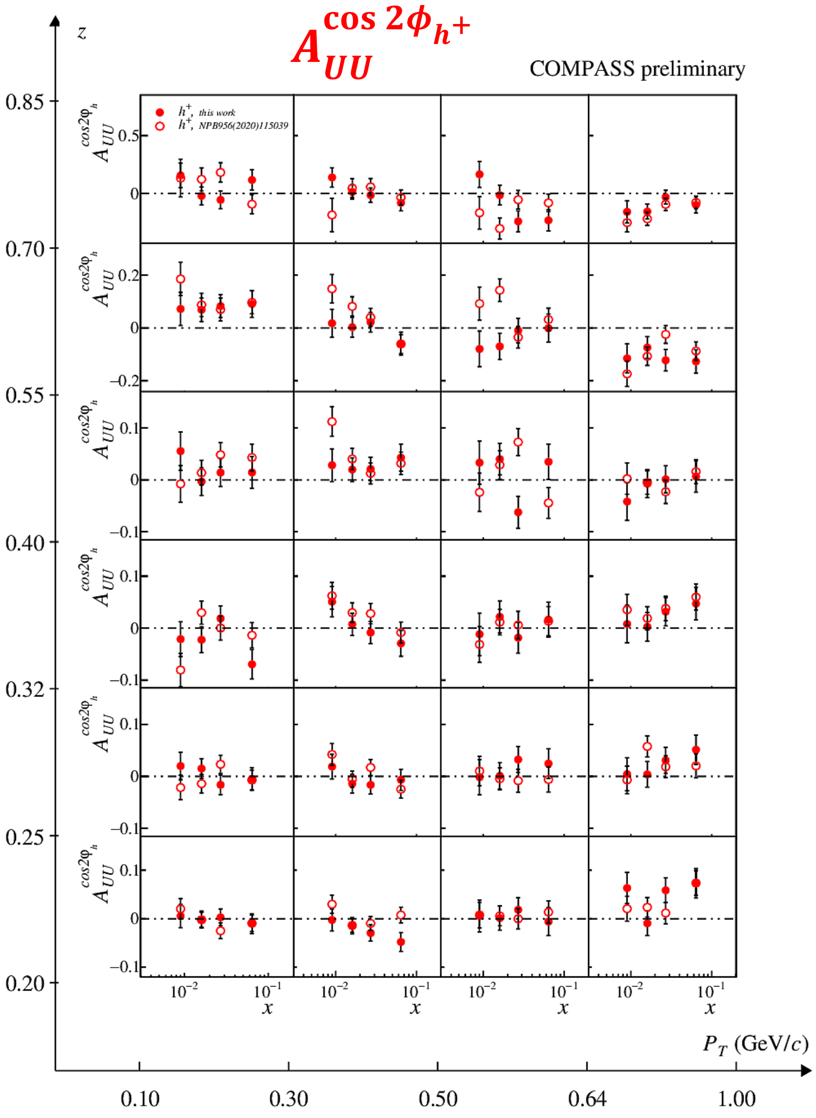


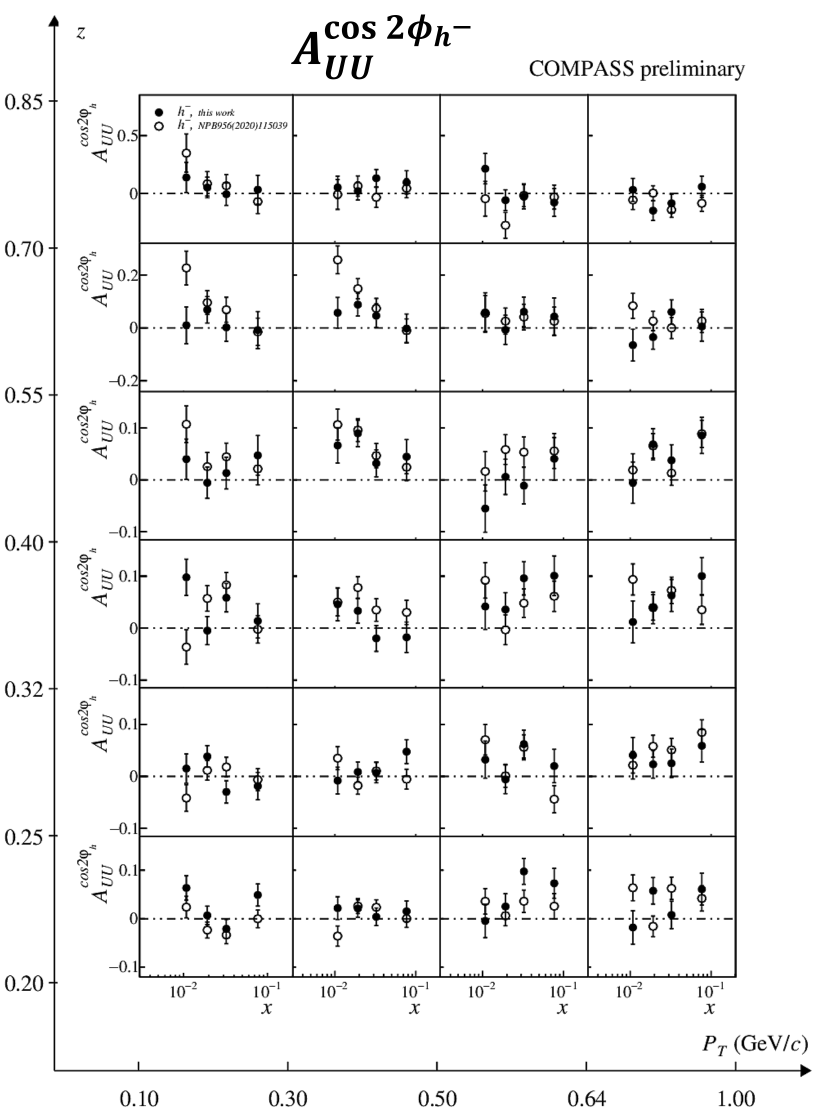
AZIMUTHAL ASYMMETRIES 3D

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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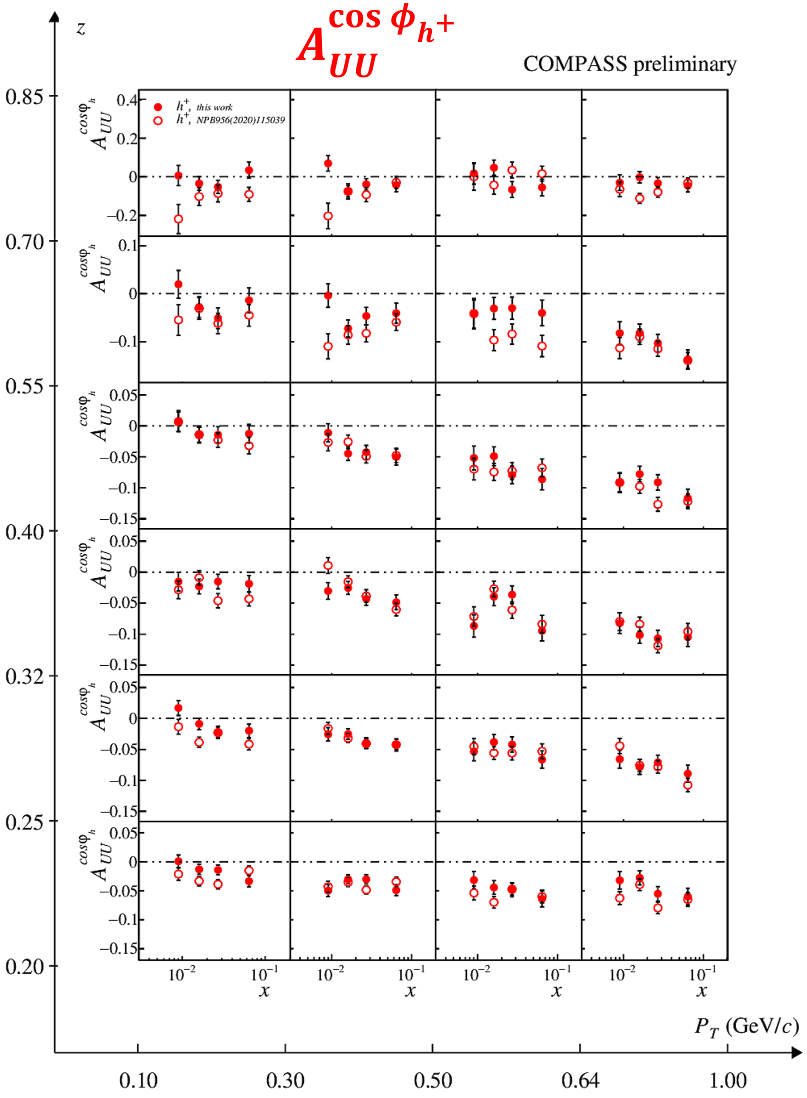
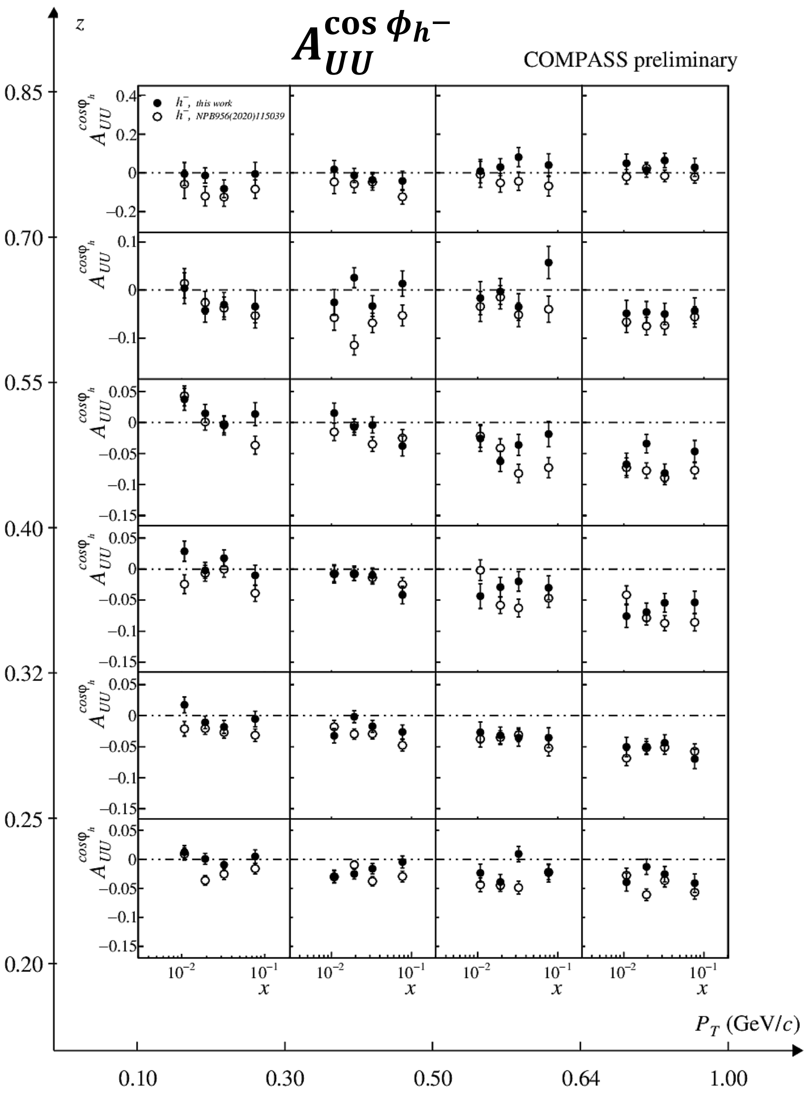


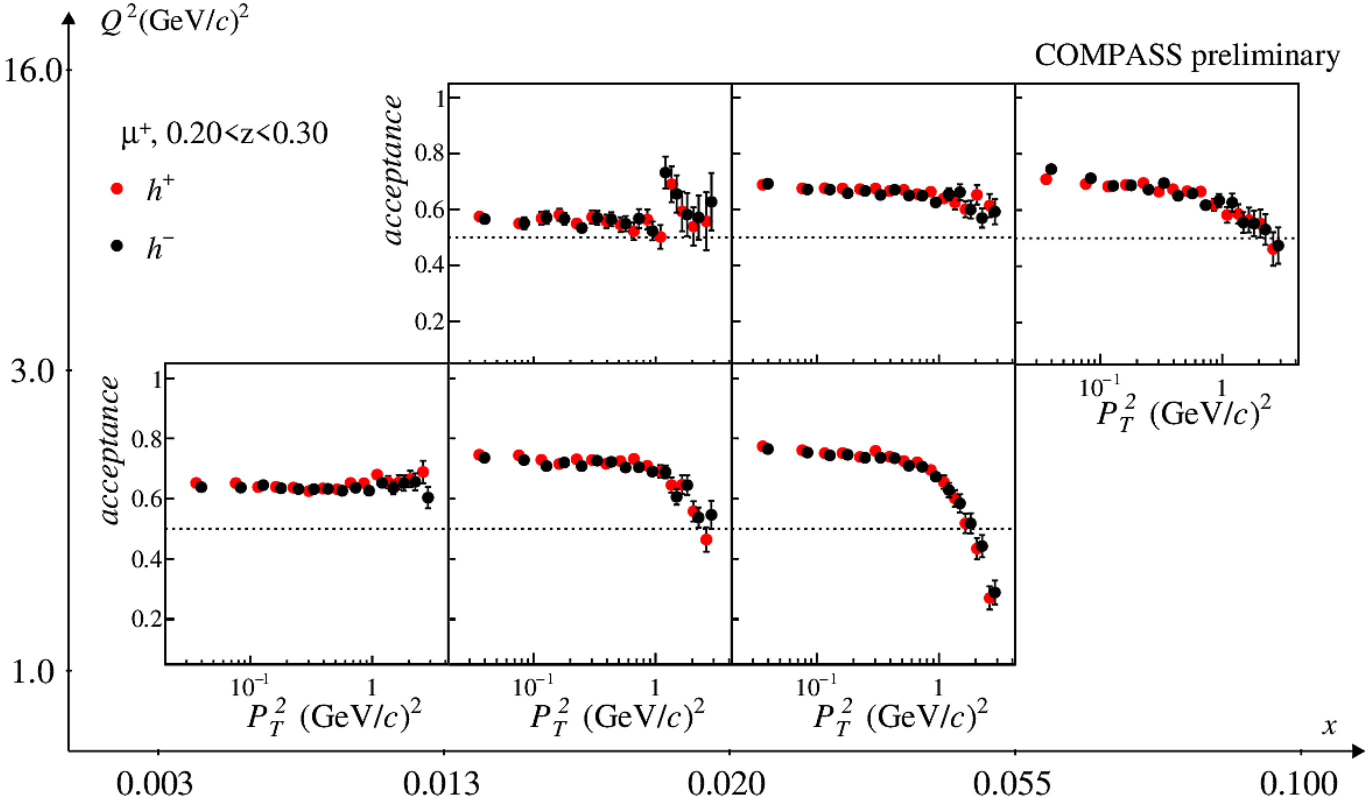


P_T^2 - DEPENDENT DISTRIBUTIONS

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.



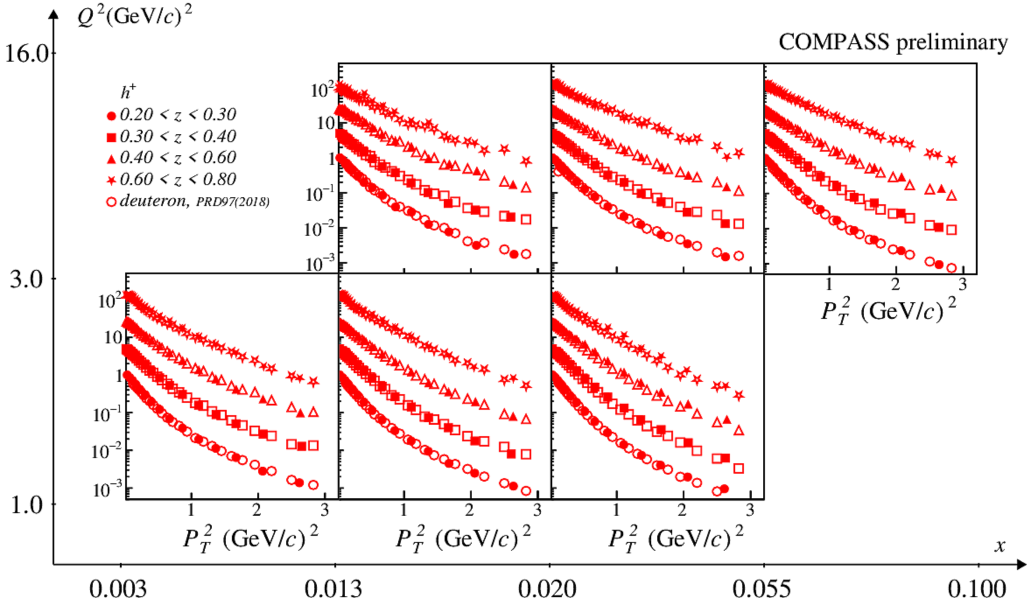
P_T^2 - DEPENDENT DISTRIBUTIONS

Comparison with deuteron results

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

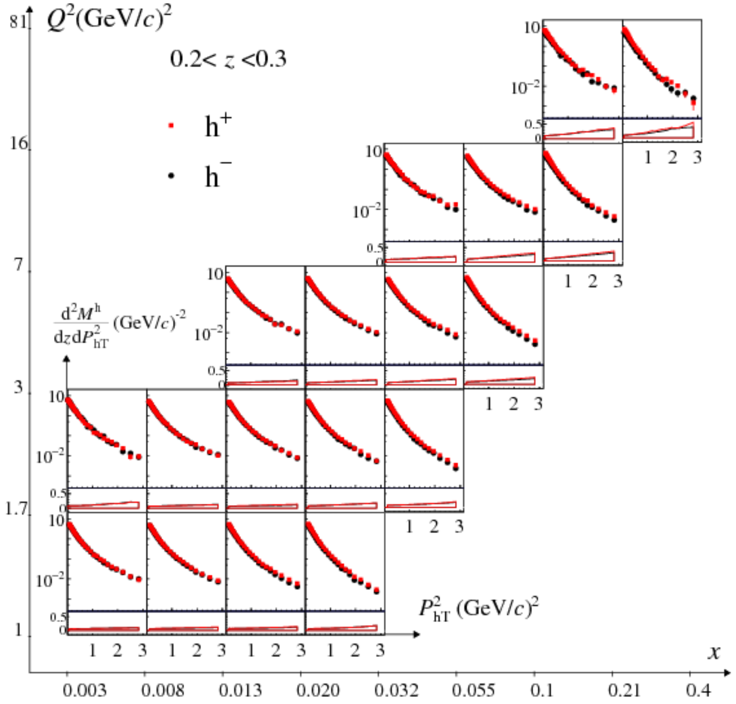
The old results (an example in the right plot) have been renormalized over the first point and averaged over x and Q^2 in order to match the current binning, while the z and P_T^2 binning has not been modified.

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).

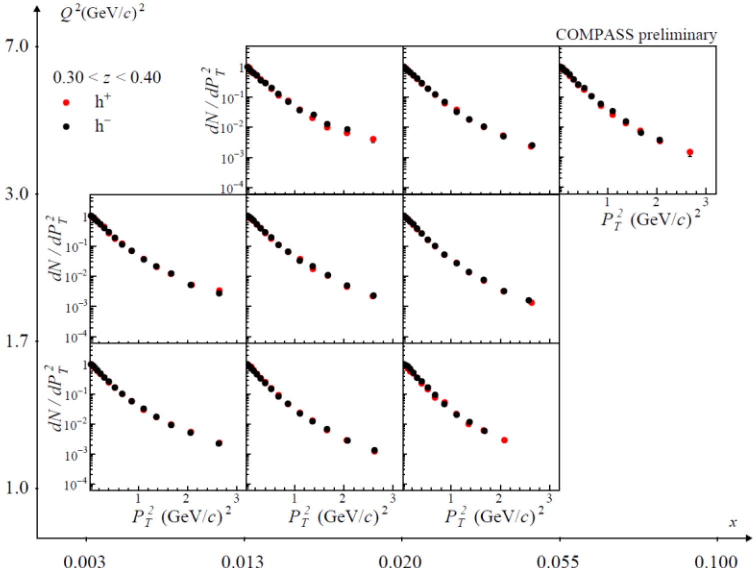
The binning for the current analysis has been chosen to be easily compared to the published one (an example on the right).

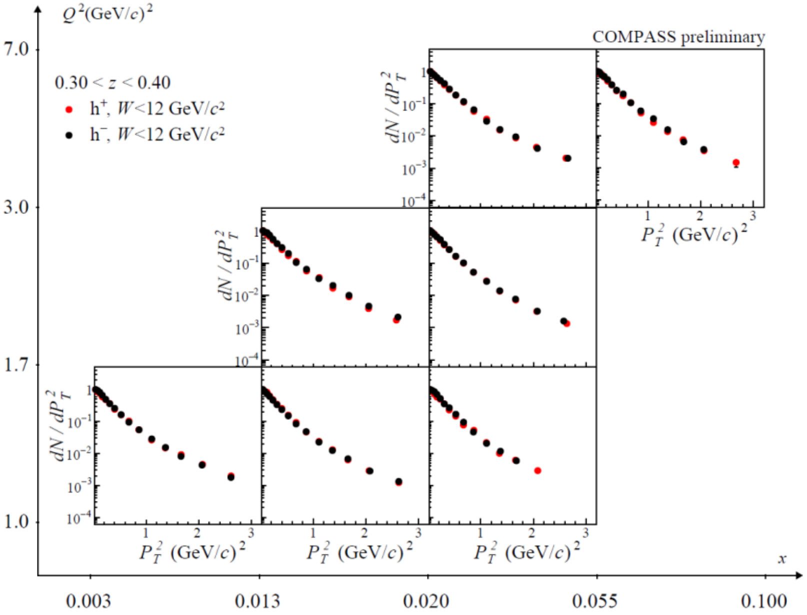


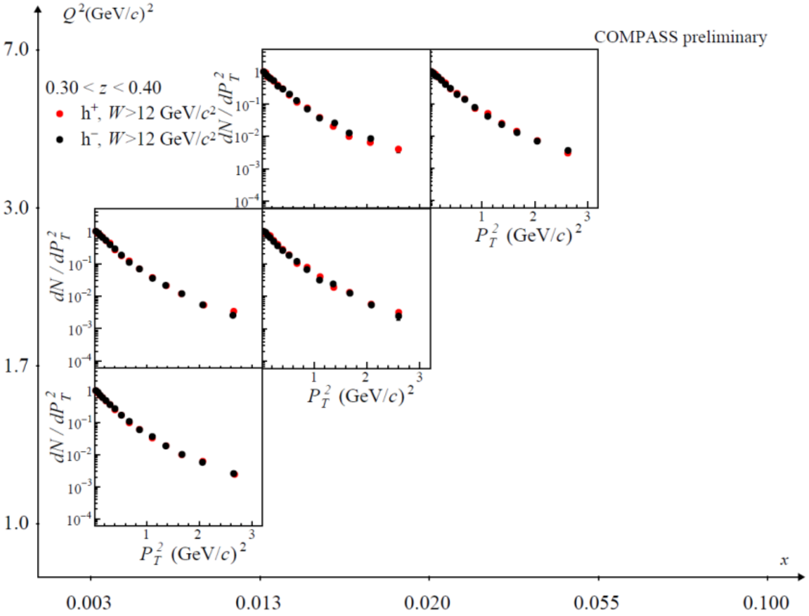
P_T^2 - dependent distributions

$0.30 < z < 0.40$

Distributions also inspected in more bins of Q2 and in 2 bins of W to characterize the kinematic dependences







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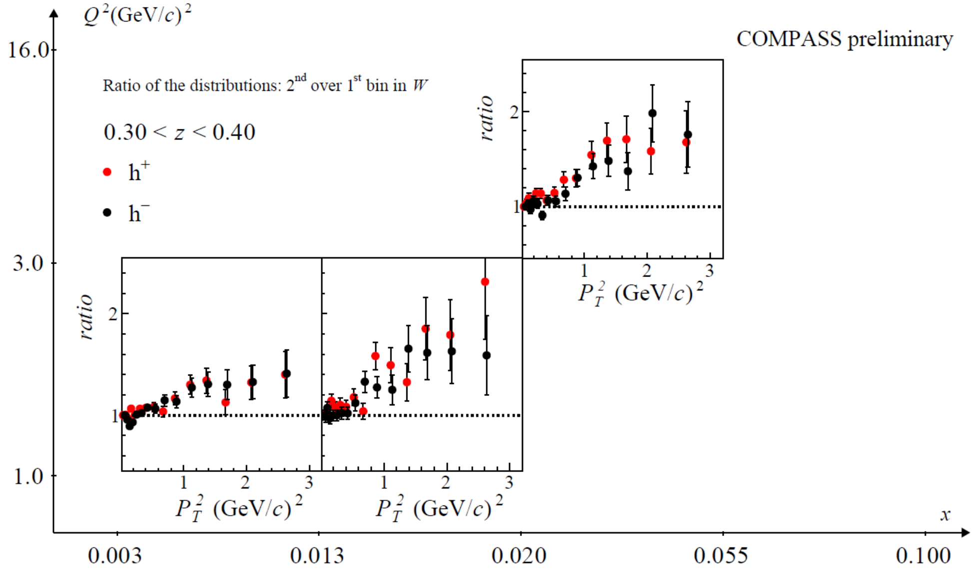

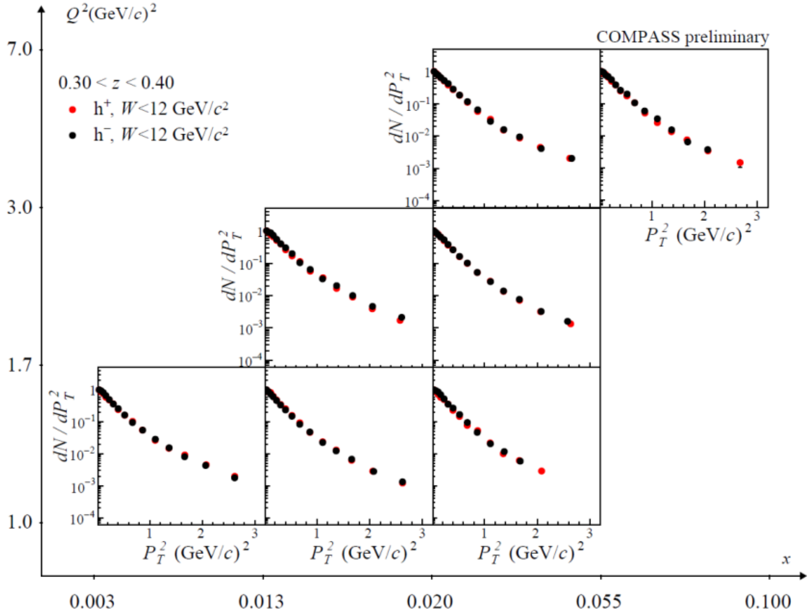

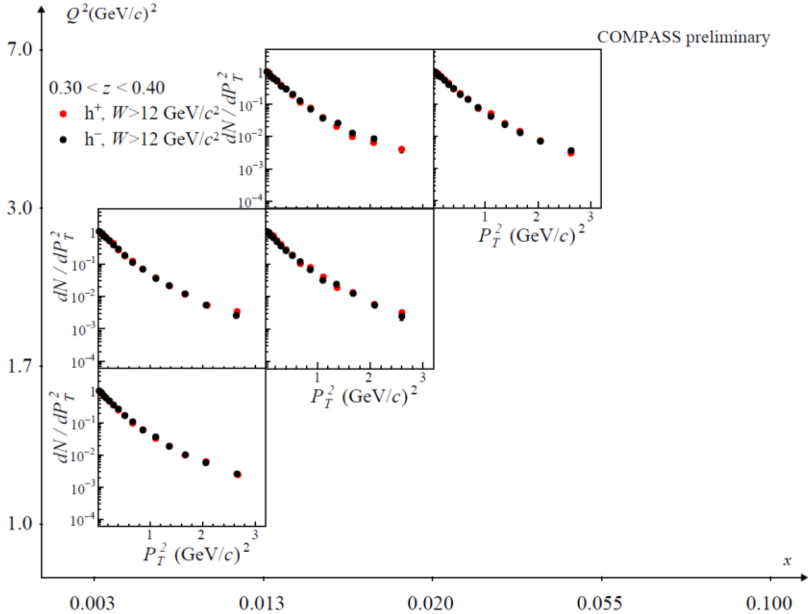

q_T^2 distributions

proton target

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- q_T distributions measured using the same hadron sample selected for the standard P_T^2 distributions
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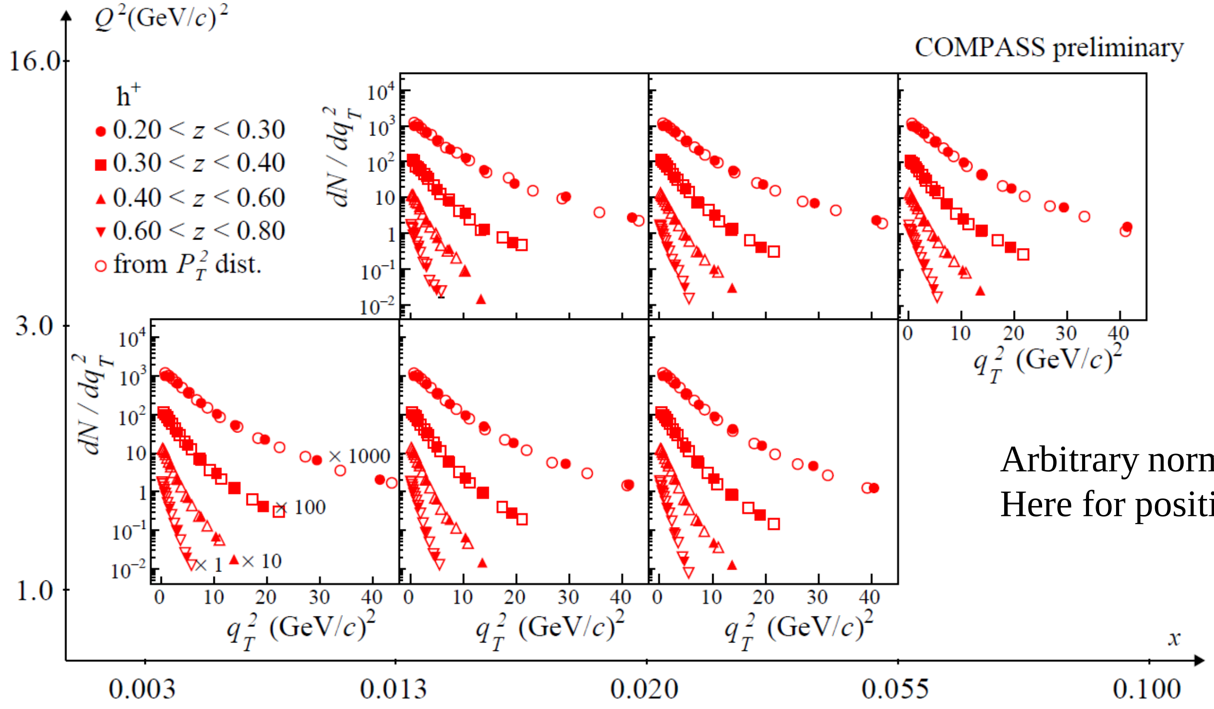

Arbitrary normalization and scaling
Here for positive hadrons, similar for negative