Azimuthal asymmetries in unpolarized SIDIS at COMPASS

Andrea Moretti

on behalf of the COMPASS Collaboration

Introduction

Semi-Inclusive Deep Inelastic Scattering (SIDIS) is a powerful tool to access the rich and complex structure of the nucleon.

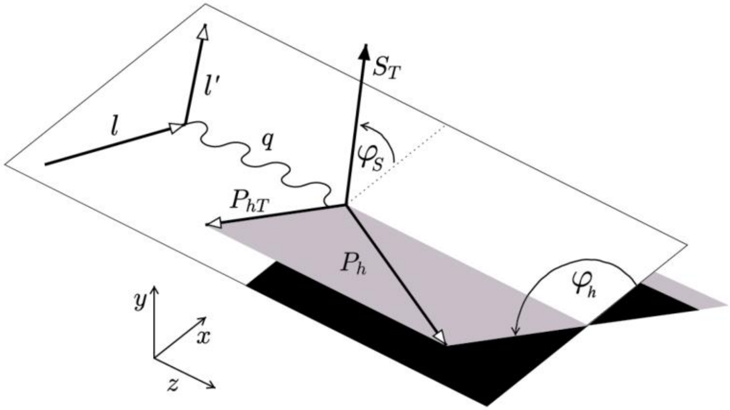
Depending on the nucleon polarization, several (TMD)-PDFs can be accessed

In this talk: focus on the SIDIS off unpolarized nucleons

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

Cross section for unpolarized SIDIS

In SIDIS, a high energy lepton scatters off a nucleon target and at least one hadron is observed in the final state.



The Gamma Nucleon System (GNS)

For an unpolarized nucleon target, at high Q^2 and in the one-photon exchange approximation **the fully-differential cross-section** reads:

Bacchetta et al., *JHEP* 02 (2007) 093

$$\frac{\mathrm{d}^5\sigma}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}\varphi_h\mathrm{d}P_T^2} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

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

- x is the Bjorken variable
- Q^2 the photon virtuality
- $\gamma = \frac{2Mx}{Q}$ (small in COMPASS kinematics)
- $y = 1 - \frac{E_{\ell'}}{E_\ell}$ the inelasticity with $E_{\ell(\prime)}$ the energy of the incoming (scattered) lepton in the target rest frame
- $\varepsilon(y) = \frac{1-y-\frac{1}{4}\gamma^2 y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2 y^2}$
- 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

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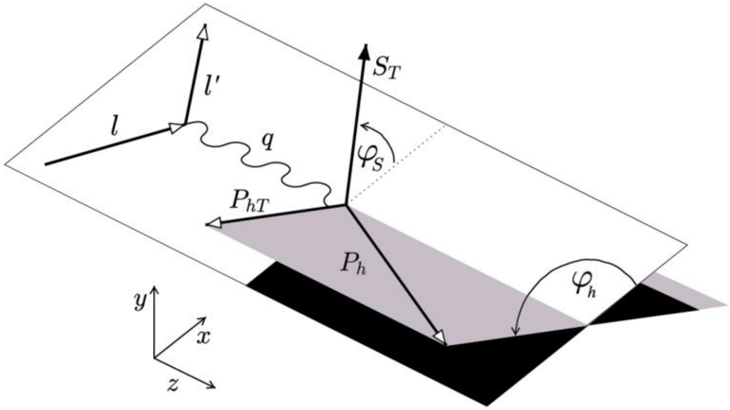

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The structure functions $F_{XY[,Z]}^{[f(\varphi_h)]}$ can be written in terms of

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

Unpolarized structure functions

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

Quark / Nucleon	**U** unpolarized	**L** longitudinally polarized	**T** transversely polarized
U unpolarized	$f_1^q(x,k_T^2)$ number density		$h_1^{\perp q}(x,k_T^2)$ Boer-Mulders

The correlation between $\boldsymbol{k_T}$ and $\boldsymbol{s_T}$ *generates* a neat transverse polarization

Boer-Mulders function $\boldsymbol{h_1^\perp}$ couples to the **Collins FF** $\boldsymbol{H_1^\perp}$: fragmentation of a transversely polarized quarks into hadron

Up to order $1/Q$ (i.e. at twist-3) in Wandzura-Wilczek approximation *:

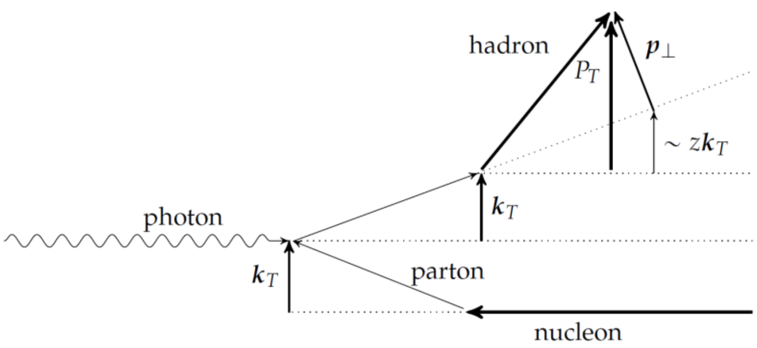
$$F_{UU,T} = \mathcal{C}[f_1 D_1]$$

Cahn effect *Boer-Mulders term*

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

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

Boer-Mulders term



where $\mathcal{C}[wfD]$ is the convolution over the unobservable transverse momenta:

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

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

* possible further contributions at high z from the *Berger-Brodsky* mechanism
Brandenburg et al., *Phys.Lett.B* 347 (1995) 413-418

The COMPASS experiment

COMPASS contribution to the understanding of the nucleon structure

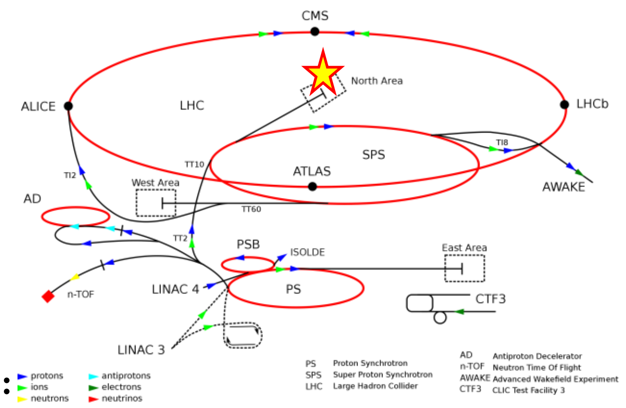
- spin asymmetries with transverse and longitudinal spin polarization

  important results on the extraction of transversity and Sivers functions

- SIDIS with unpolarized target

  azimuthal asymmetries and P_T^2-distributions on deuteron

  EPJC 73 (2013) 2531 NPB 886 (2014) 1046
  PRD 97(2018) 032006 NPB 956 (2020) 115039



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

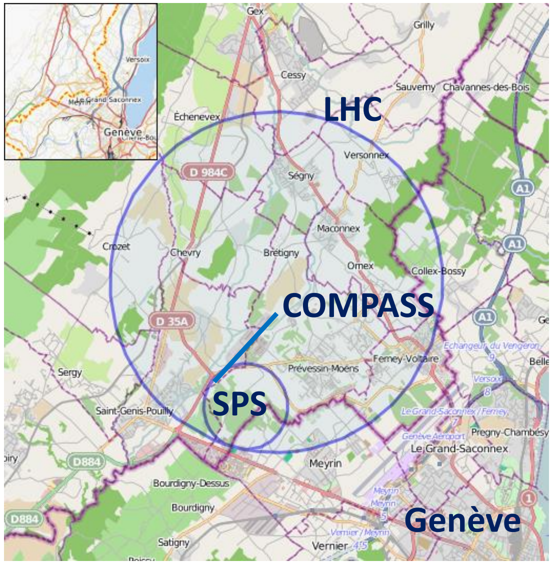
- 24 institutions from 13 countries (about 220 physicists)
- a fixed target experiment
- located in the CERN North Area, along the SPS M2 beamline

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)
- …

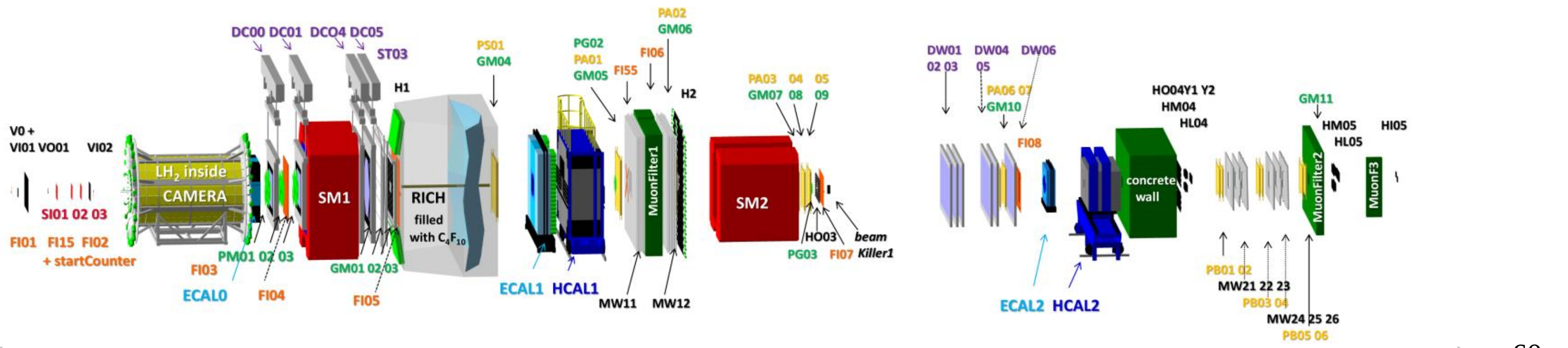
A multipurpose apparatus:

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



The COMPASS location at CERN

The 2016 COMPASS run



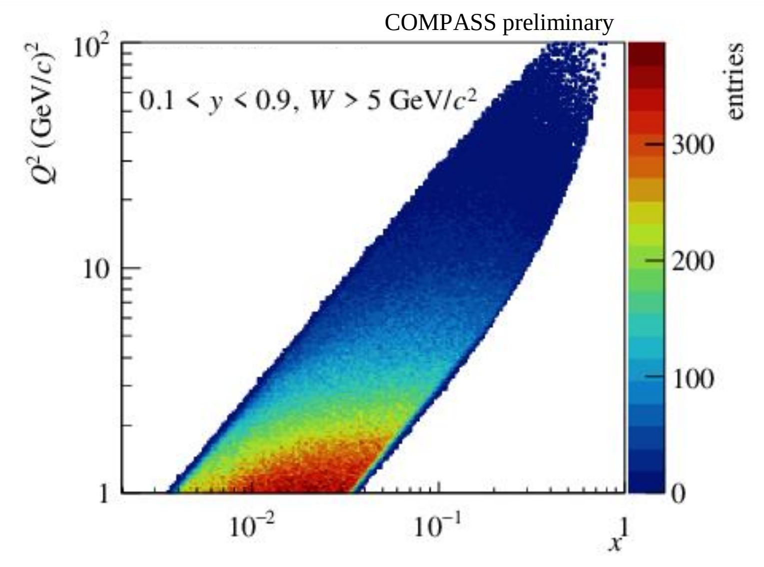
The 2016 COMPASS experimental setup

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 (~11% of the available statistics) have been analyzed to measure unpolarized SIDIS observables → ~ 6.5 million hadrons



The $x - Q^2$ coverage

Contribution from exclusive hadrons

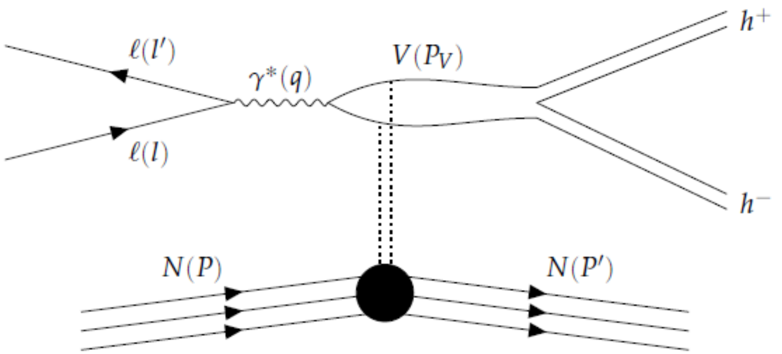
Hadrons from the decay of exclusive diffractive vector mesons *(exclusive hadrons)*, very interesting per se, constitute a relevant source of background for the SIDIS measurement.

The two most important channels: $\rho^0 \rightarrow \pi^+\pi^-$ *and* $\phi \rightarrow K^+K^-$

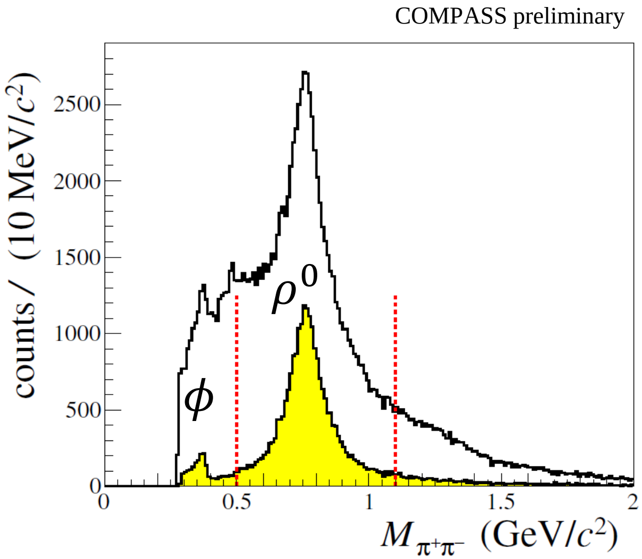
- Well visible in the data at vanishing missing energy

$$E_{miss} = \frac{M_X^2 - M_p^2}{2M_p}$$

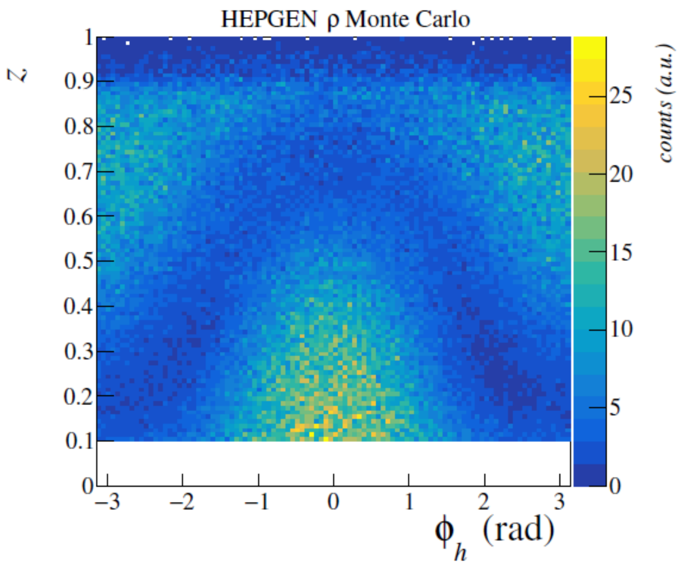
- Strong modulations in the azimuthal angle
- Contamination as high as 30% at high z



The diffractive production of a vector meson V and its decay into a hadron pair



Invariant mass distribution in the data, before and after cutting in missing energy



$\phi_h - z$ correlation for exclusive hadrons

Impact on the azimuthal asymmetries measured on a deuteron target: COMPASS, *Nucl.Phys.B* 956 (2020) 115039

Azimuthal asymmetries – 1D

Azimuthal asymmetries: defined as the following ratios

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

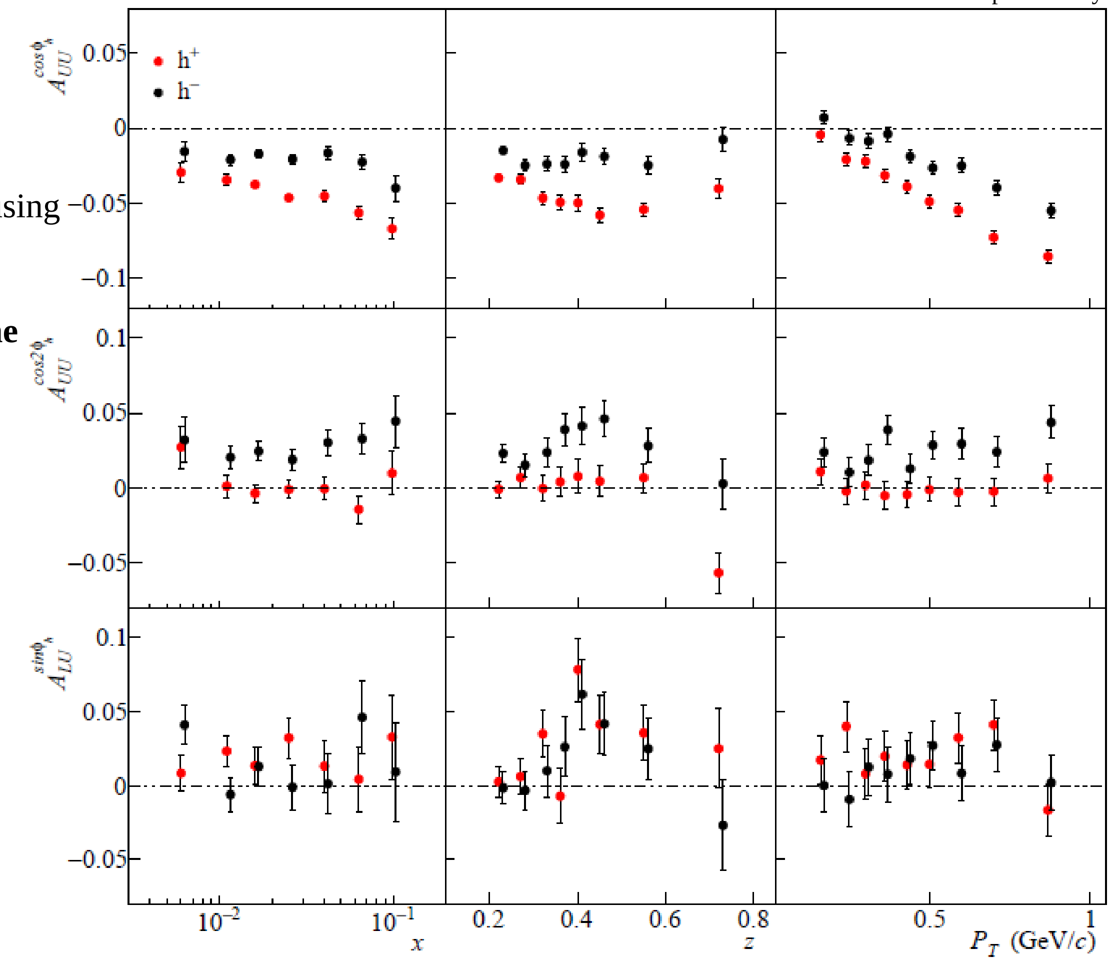
Steps in the measurement:

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)

- **Strong kinematic dependences**
- **Interesting differences** between positive and negative hadrons, as observed in previous measurements by COMPASS on deuteron and by HERMES

- Results not corrected for radiative effects

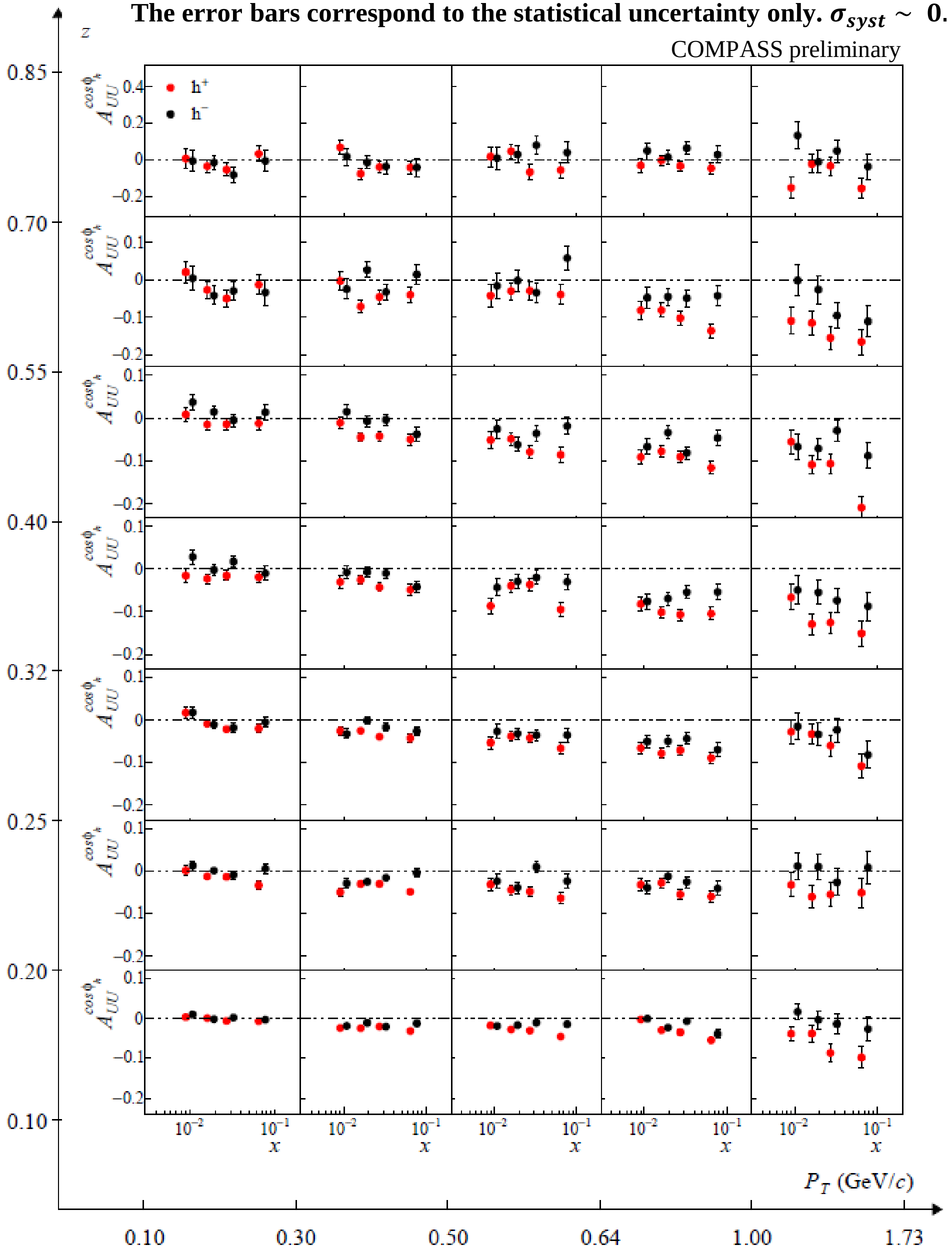
COMPASS preliminary



The error bars correspond to the statistical uncertainty only. $\sigma_{syst} \sim \sigma_{stat}$ (1D)

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

The error bars correspond to the statistical uncertainty only. $\sigma_{syst} \sim 0.5\,\sigma_{stat}$ (3D)



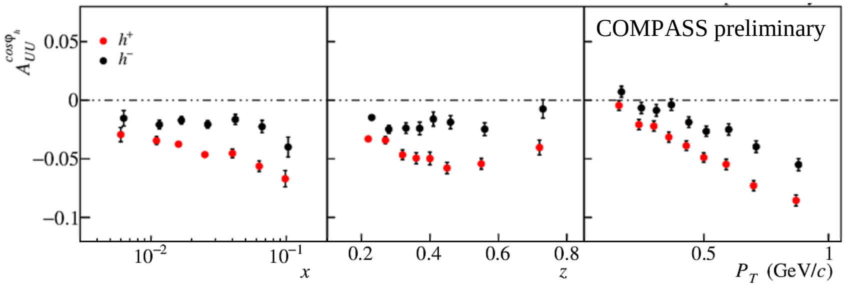
3D azimuthal asymmetries for positive and negative hadrons

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

Expectation from Cahn effect:

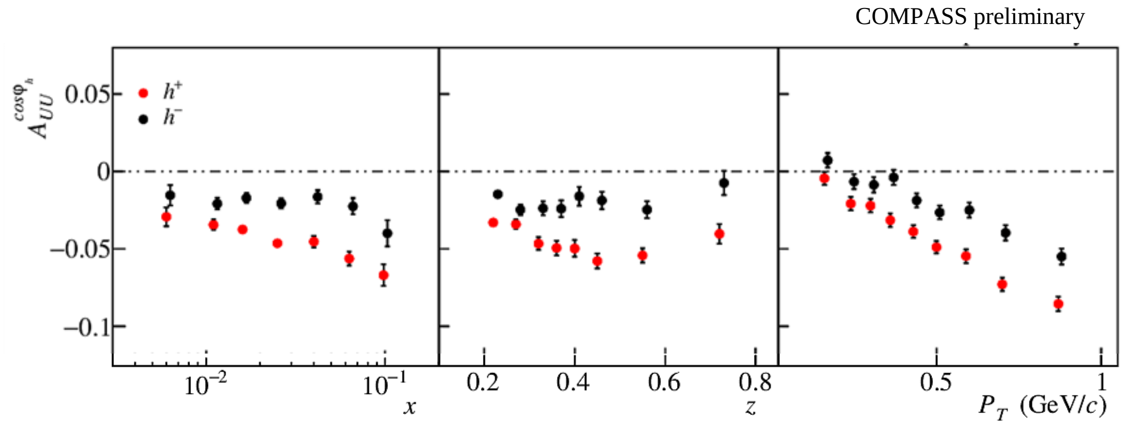
$$A_{UU|Cahn}^{\cos\phi_h} = -\frac{2zP_T\langle k_T^2\rangle}{Q\,\langle P_T^2\rangle}$$

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



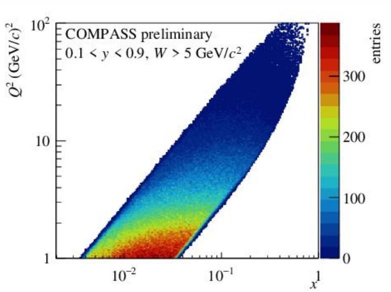
Extraction of $\langle k_T^2 \rangle$ from $A_{UU}^{\cos\phi_h}$

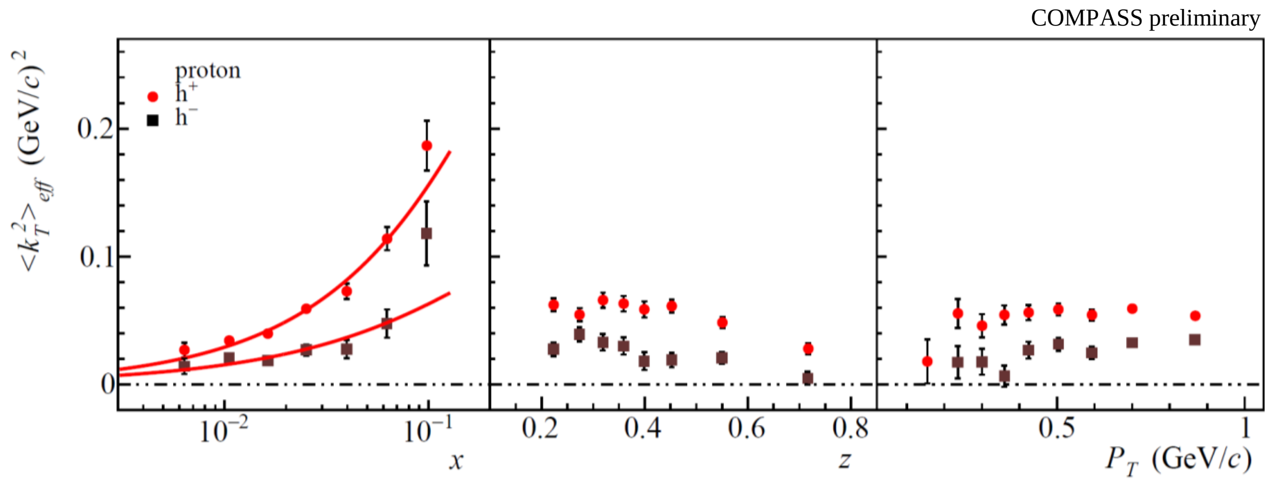
Extraction of $\langle k_T^2 \rangle$
from the 1D – asymmetry
assuming only Cahn effect
at work



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

Power-law fit of $\langle k_T^2 \rangle(x)$





Is it an x – or Q^2 – dependence (or both)?

Azimuthal asymmetries – 1D – Q^2 dependence

Binning in Q^2

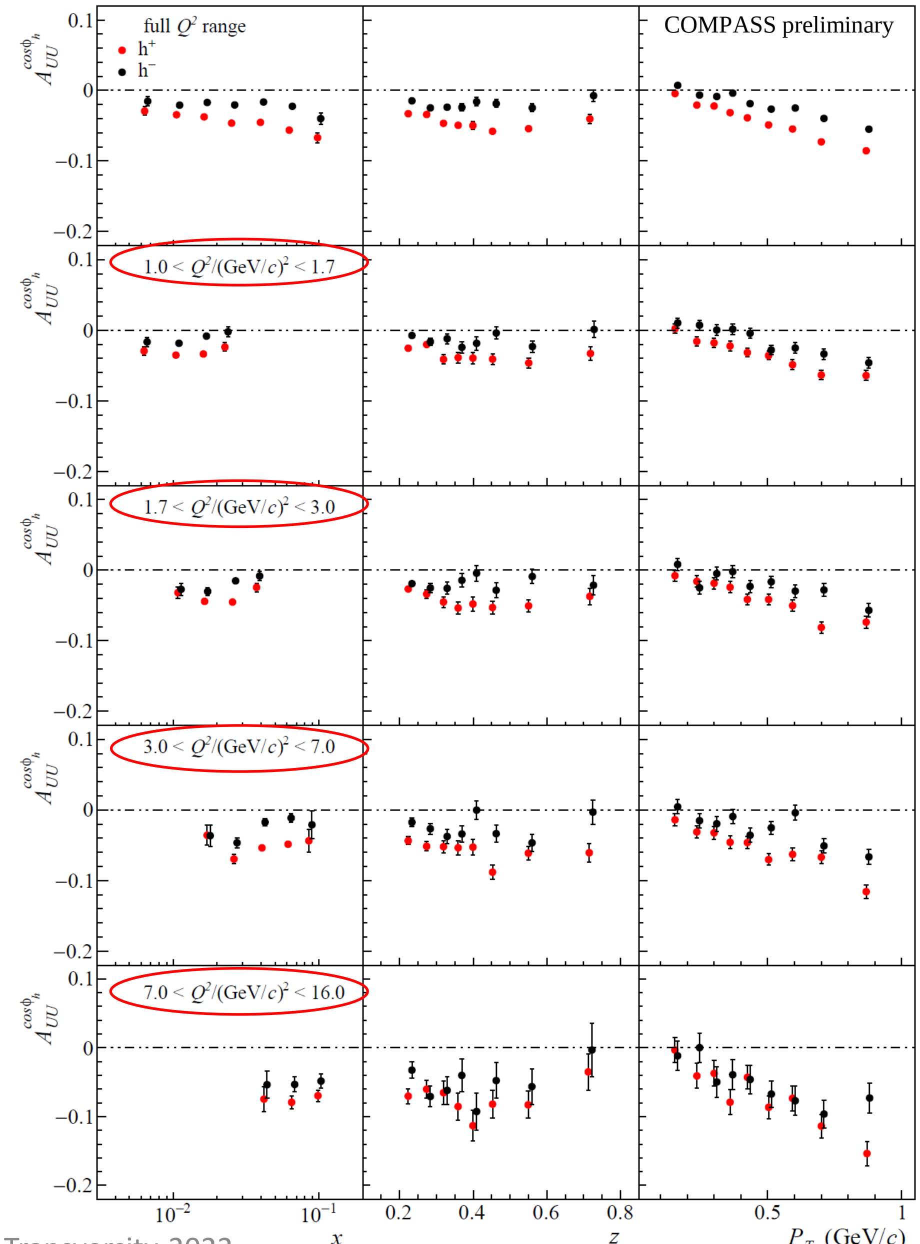
- The $A_{UU}^{cos\phi_h}$ asymmetry is observed to increase with Q^2
- Flavor-independent expectation from the Cahn effect:

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

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

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

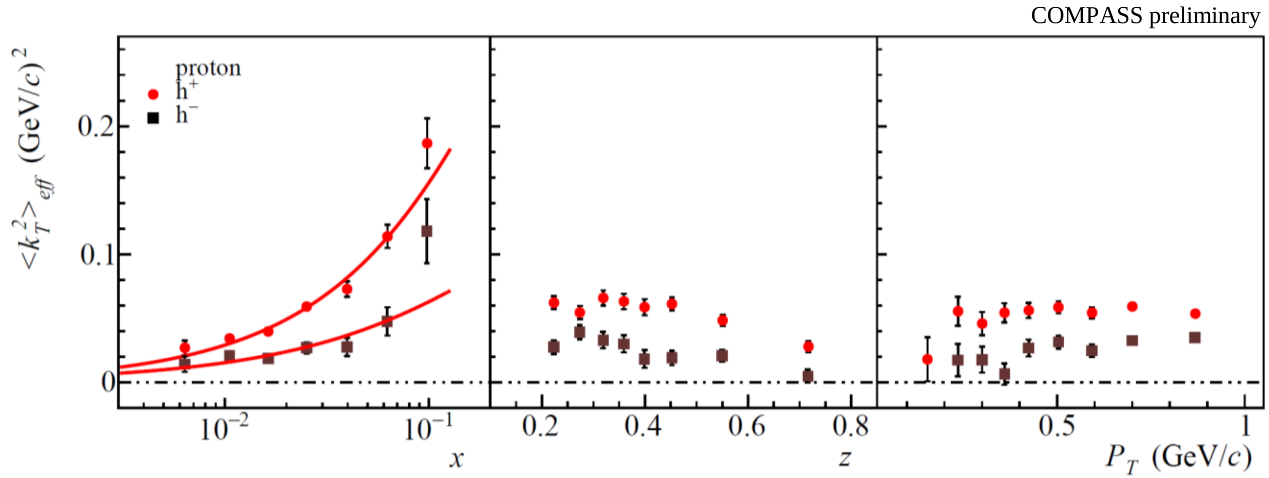
- Almost no Q^2 dependence for $A_{UU}^{cos2\phi_h}$



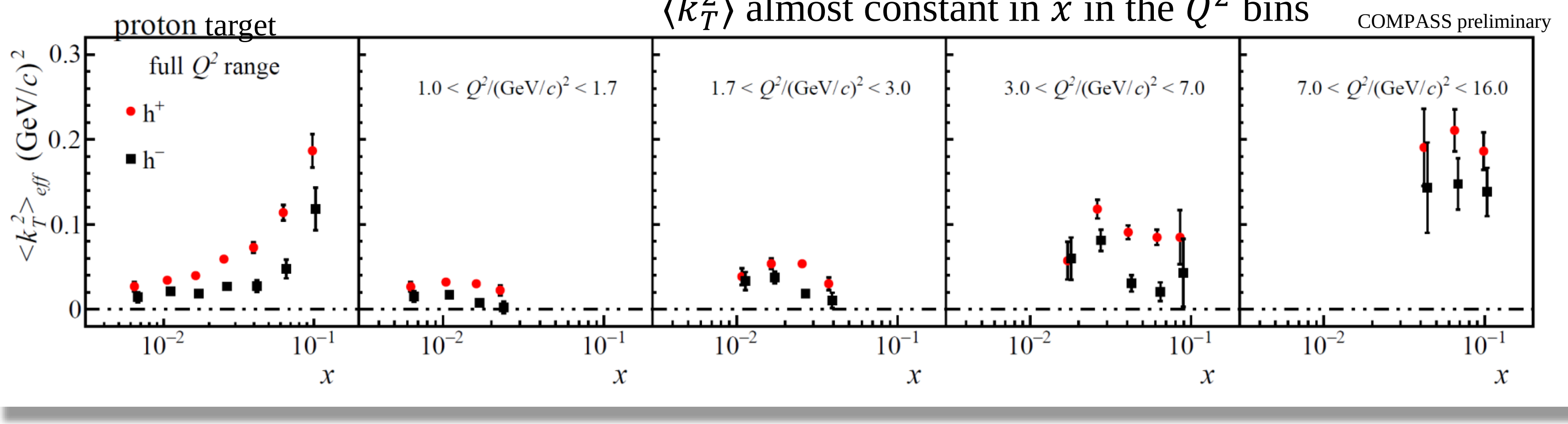
Extraction of $\langle k_T^2 \rangle$ from $A_{UU}^{\cos\phi_h}$

Extraction of $\langle k_T^2 \rangle$ *assuming only Cahn effect at work*

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



$\langle k_T^2 \rangle$ almost constant in x in the Q^2 bins



Extraction of $\langle k_T^2 \rangle$ from $A_{UU}^{\cos\phi_h}$

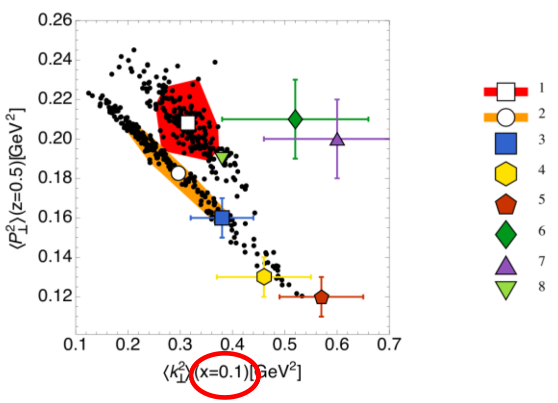
For comparison:

Bacchetta et al JHEP 06 (2017) 081

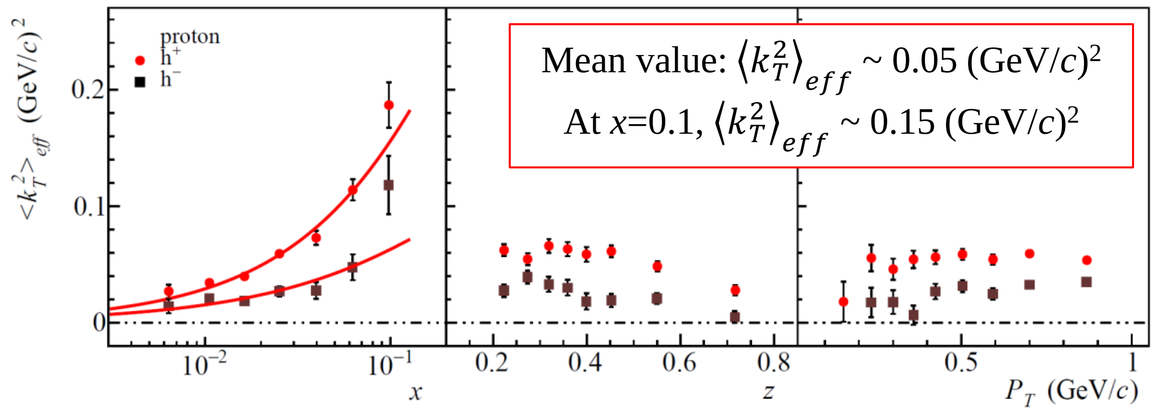
Analysis of SIDIS d- multiplicities (HERMES, COMPASS)

+ Drell-Yan (E288, E605 Tevatron)

and Z-boson production(CDF, D0)



COMPASS preliminary



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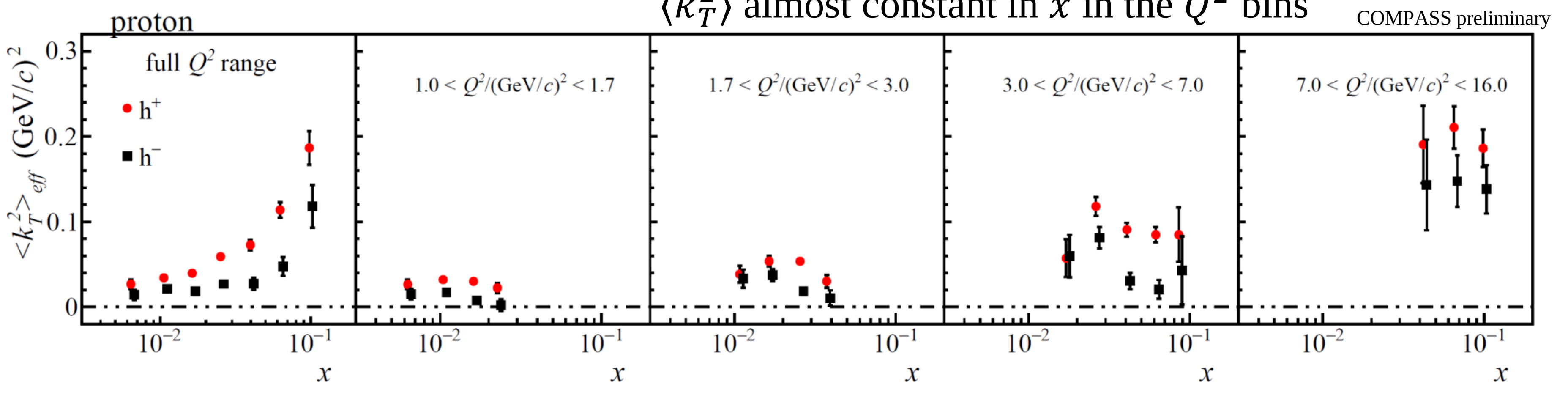

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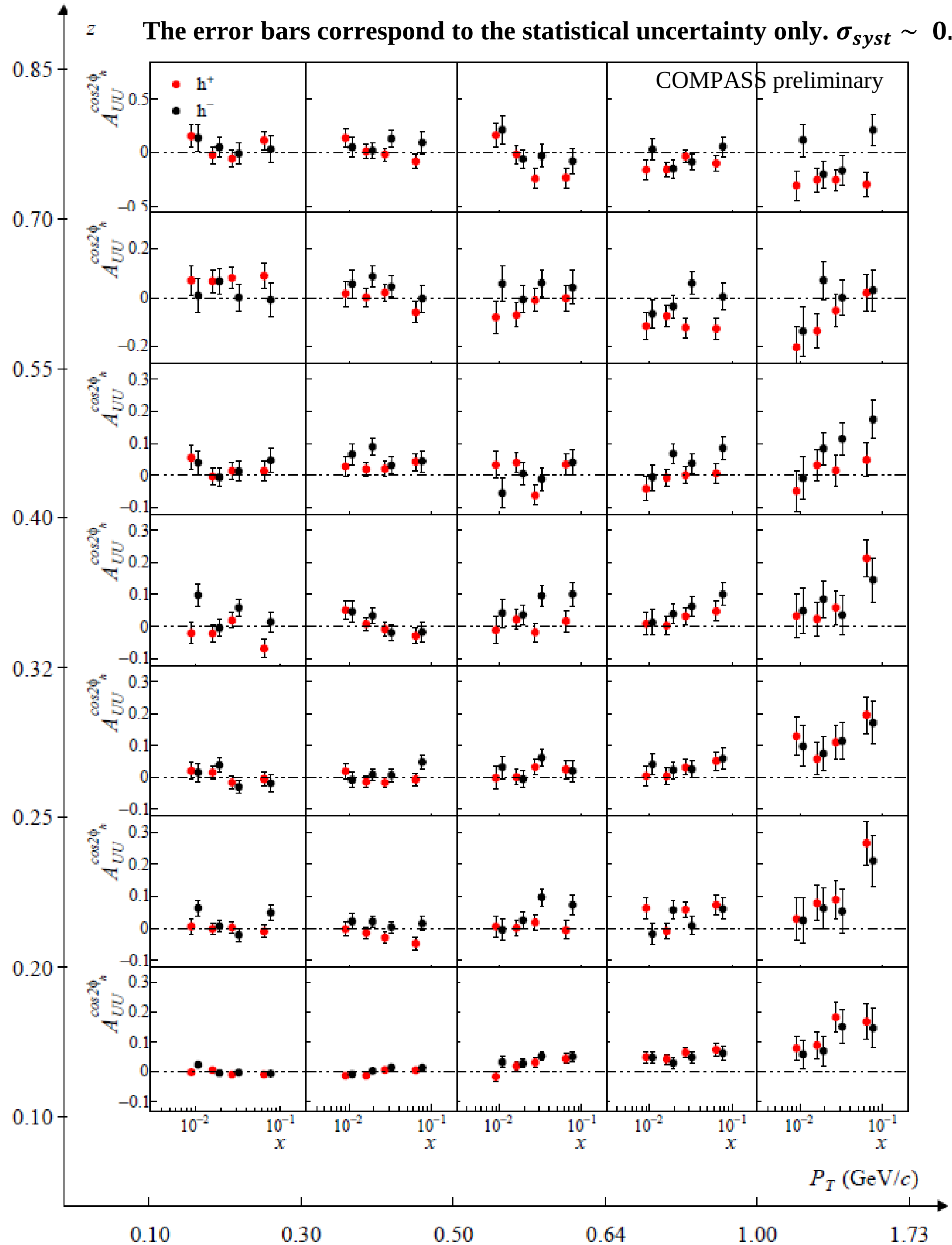
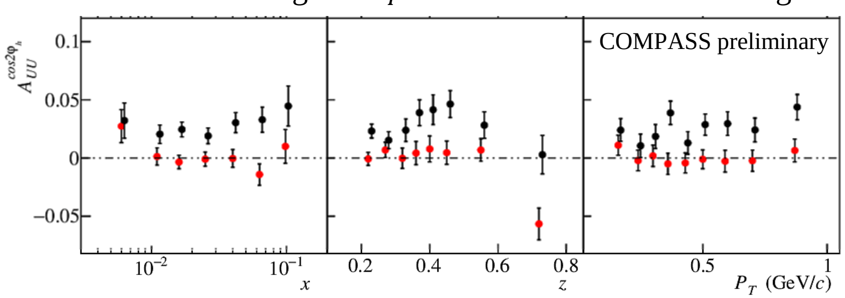


3D azimuthal asymmetries for positive and negative hadrons

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

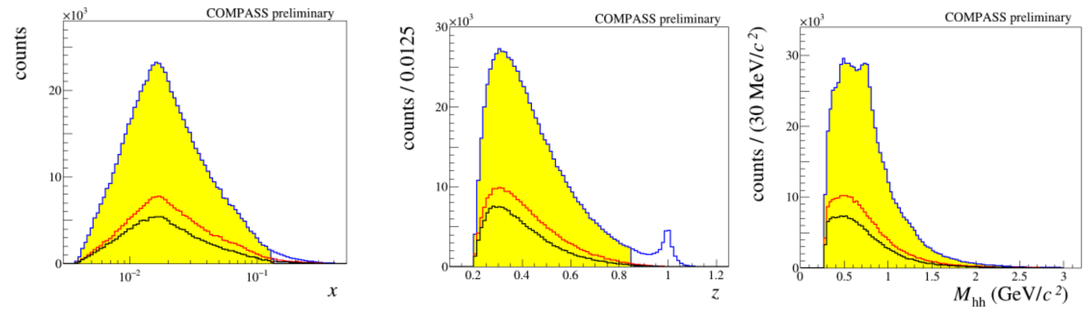
Comparison with the 1D case:
lowest z and highest P_T bin not included in the average



Azimuthal asymmetries for hadron pairs

Additional information on the nucleon structure from the **azimuthal asymmetries for hadron pairs**.

In particular, we focus here on the asymmetries related to the Boer-Mulders TMD PDF.



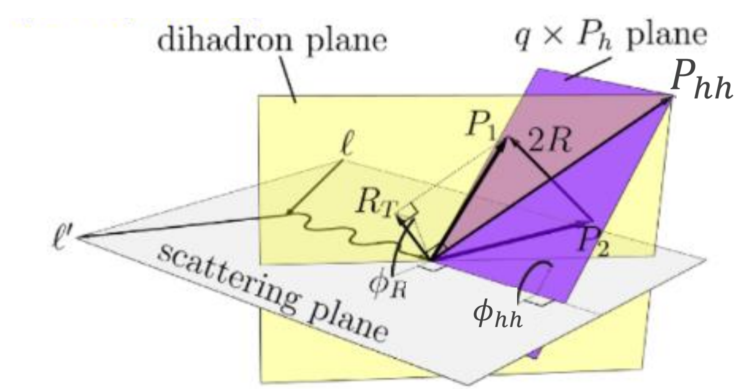
Bianconi, Boffi, Jakob, Radici [PRD62, 034008, 2000]

- leading twist formalism

$$\sigma_{UU} \propto A(y)\mathcal{F}[f_1 D_1] - |\vec{R}_T| B(y) \cos(\phi_{hh} + \phi_R) \mathcal{F}\left[w_1 \frac{h_1^\perp H_1^\angle}{M(M_1+M_2)}\right] - B(y) \cos(2\phi_{hh}) \mathcal{F}\left[w_2 \frac{h_1^\perp H_1^\perp}{M(M_1+M_2)}\right]$$

- $\mathcal{F}$: convolution over intrinsic transverse momentum k_T and the one acquired during the fragmentation $p_\perp$
- $w_1 (w_2)$: functions of $k_T, p_\perp$.
- D_1: unpolarized FF in two hadrons
- $H_1^\angle$: interference FF
- $H_1^\perp$: Collins FF for two hadrons (same as in 2h-TSAs)
- M, M_1, M_2: mass of the nucleon and of the first (second) hadron

- **ϕ_{hh}: azimuthal angle of the pair**
- **ϕ_R: azimuthal angle of the vector $\vec{R} = \frac{z_2\vec{P}_1 - z_1\vec{P}_2}{z_1+z_2} \approx \frac{\vec{P}_1 - \vec{P}_2}{2}$**



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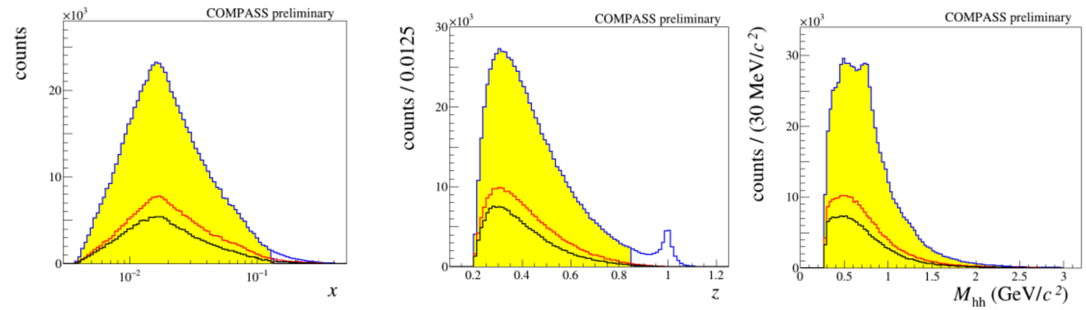


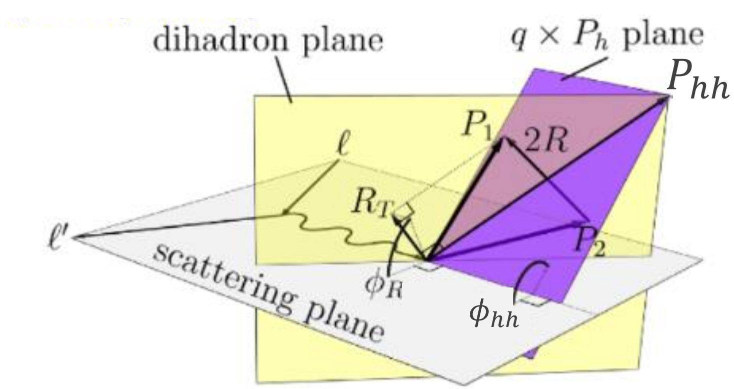
Bacchetta, Radici [PRD69, 074026, 2004]

- subleading twist formalism (twist-3)
- cross section integrated over $\vec{P}_{hhT}$

$$\sigma_{UU} \propto A(y) f_1 D_1 - V(y)\, \textcolor{red}{\cos(\phi_R)}\, \frac{|\vec{R}_T|}{Q}\left[\frac{1}{z} f_1 \widetilde{D}^{\angle} + \frac{M}{M_h} x h H_1^{\angle}\right]$$

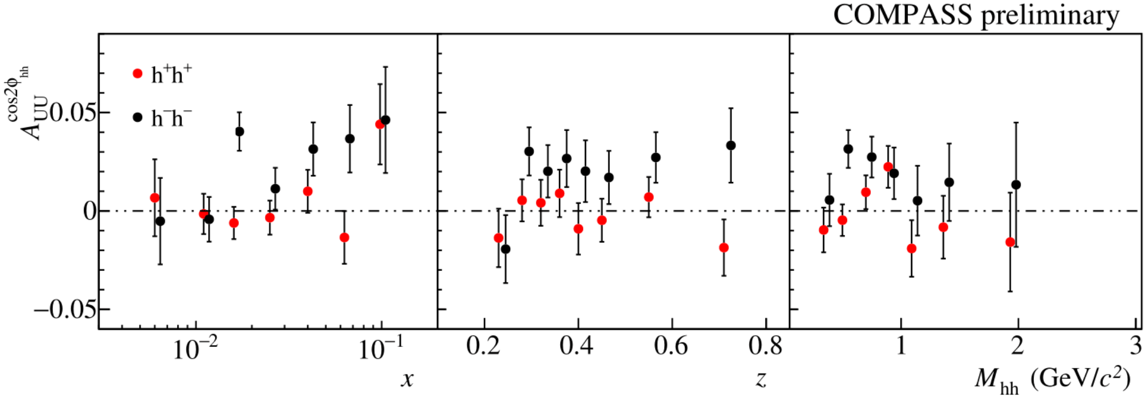
- $\boldsymbol{xh = x\,\widetilde{h} + \frac{k_T^2}{M^2} h_1^{\perp}}$
- $\widetilde{D}^{\angle}$: pure twist-3 FF, vanishing in Wandzura-Wilczek approximation

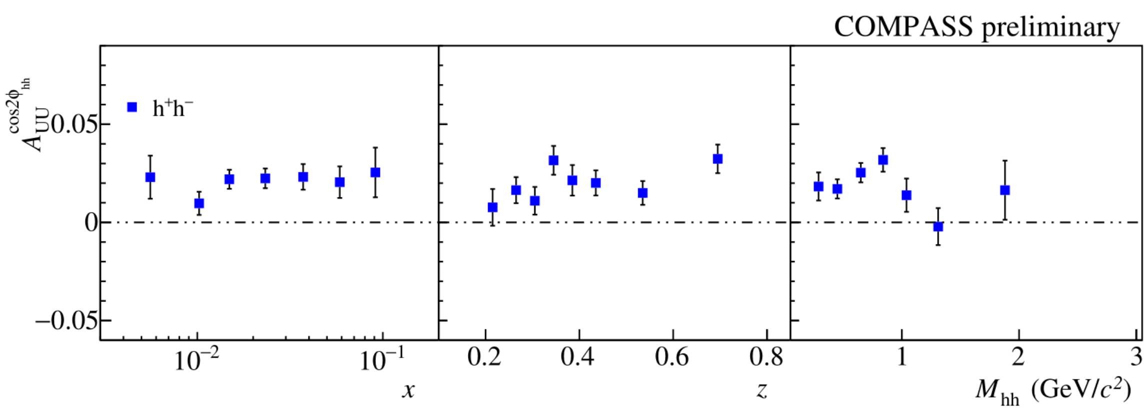
- $A(y) = 1 - y + \frac{y^2}{2}$
- $B(y) = 1 - y$
- $V(y) = 2(2-y)\sqrt{1-y}$

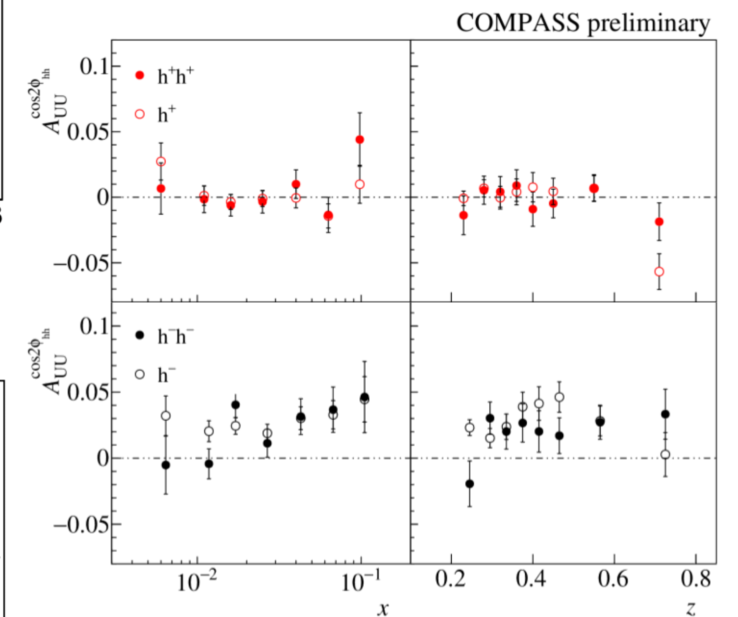


Azimuthal asymmetries for hadron pairs - $A_{UU}^{\cos 2\phi_{hh}}$

- Asymmetry $\boldsymbol{A_{UU}^{cos2\phi_{hh}}}$ for same-sign pairs (h^+h^+, h^-h^-) and opposite-sign pairs h^+h^-
- For same-sign pairs: similar trends w.r.t. single-hadron case
  compatible with zero for positive pairs, positive for negative pairs

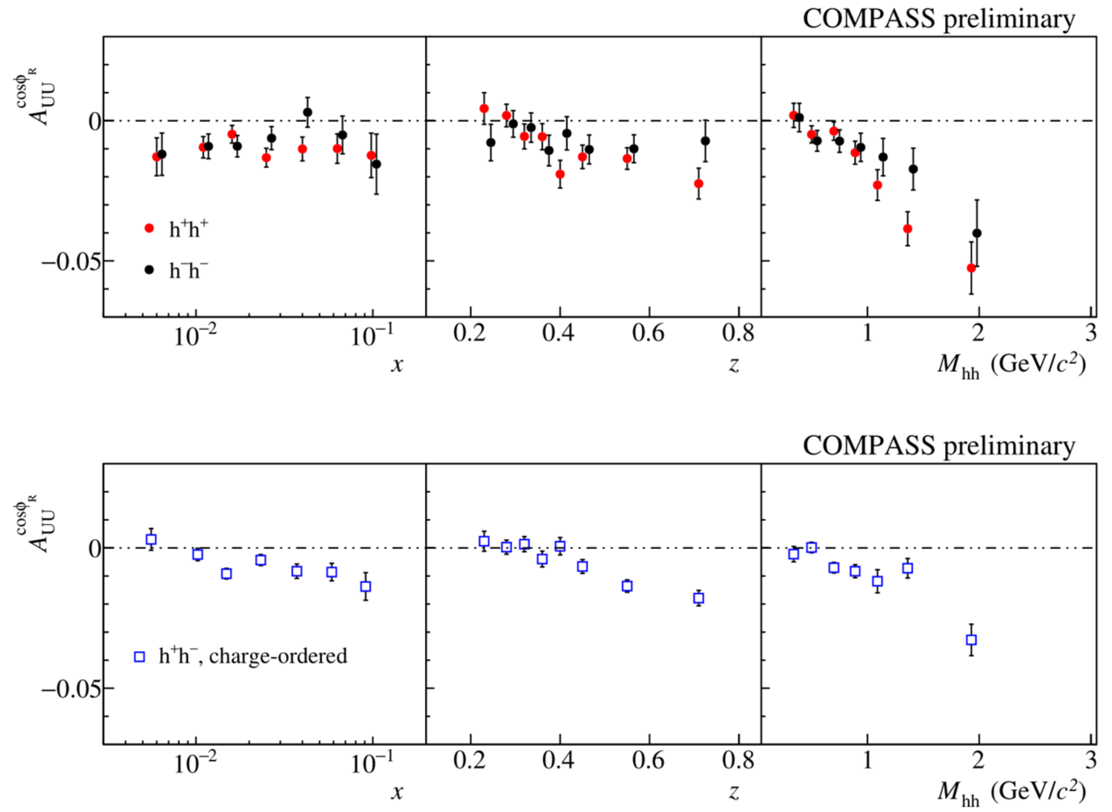






Azimuthal asymmetries for hadron pairs - $A_{UU}^{\cos\phi_R}$

- Asymmetry $A_{UU}^{\cos\phi_R}$ for same-sign pairs (h^+h^+, h^-h^-) and opposite-sign pairs h^+h^-
- Ordering scheme:
  - same-sign: h_1 is the hadron with highest z
  - opposite-sign: h_1 is the positive hadron
- Strong kinematic dependence, particularly as a function of the invariant mass
- Similar trend for same-sign and opposite charge pairs.



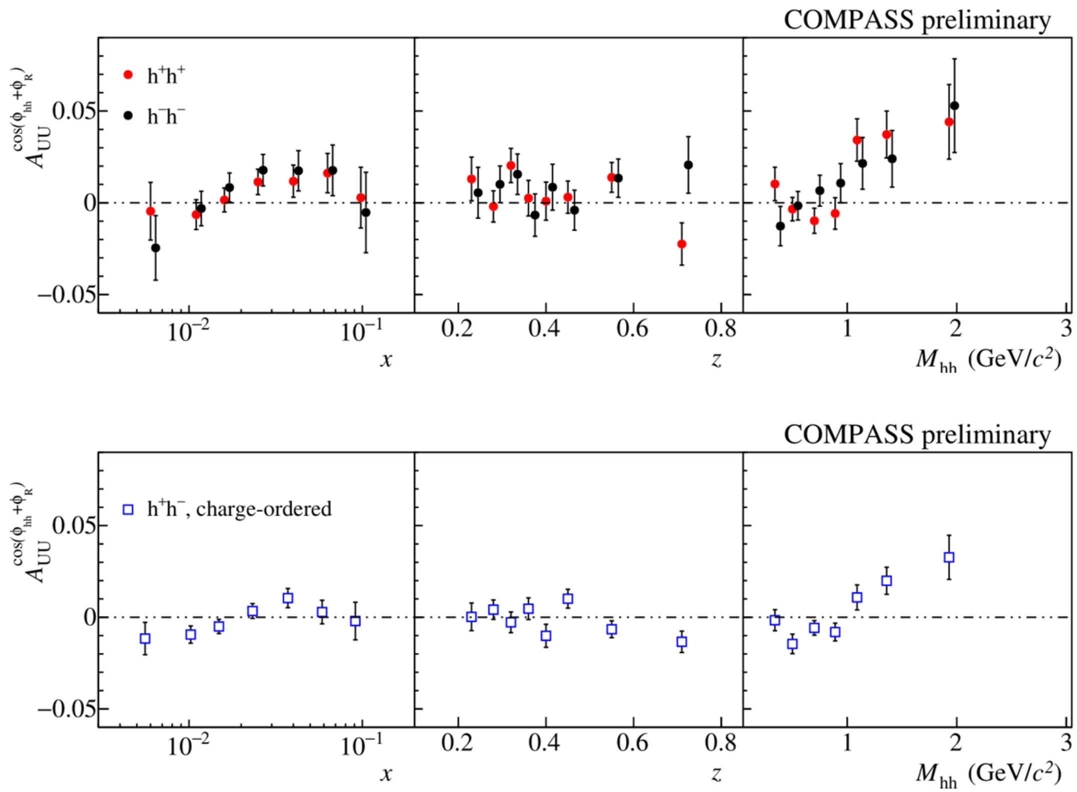
Azimuthal asymmetries for hadron pairs

- Asymmetry $A_{UU}^{cos(\phi_{hh}+\phi_R)}$ for same-sign pairs (h^+h^+, h^-h^-) and opposite-sign pairs h^+h^-

- Ordering scheme:
  - same-sign: h_1 is the hadron with highest z
  - opposite-sign: h_1 is the positive hadron

- Strong kinematic dependence, particularly as a function of the invariant mass

- Similar trend for same-sign and opposite charge pairs.



Conclusions and Perspectives

- Azimuthal asymmetries in unpolarized SIDIS: particularly interesting for the TMD physics
- After the first measurements on a deuteron target (1h), **COMPASS** has produced new results for both single hadron and hadron pairs (NEW!)
- The rich kinematic dependences and the $h^+ - h^-$ difference for single hadrons are intriguing
- Interesting additional information from the azimuthal asymmetries from hadron pairs
  (here: focus on the Boer-Mulders related asymmetries)
- Very interesting! Deeper studied are deserved.

Thank you

backup

The 2016 COMPASS run

Events and hadron selection – standard

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

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

$0.003 < x < 0.130$

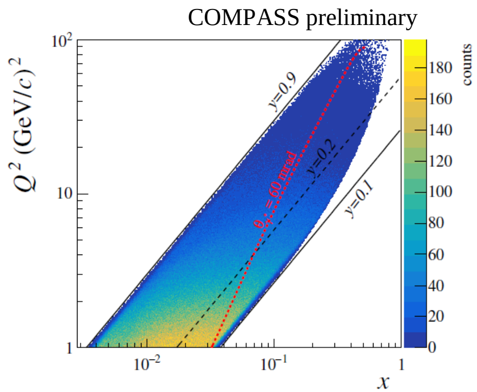
$0.2 < y < 0.9$

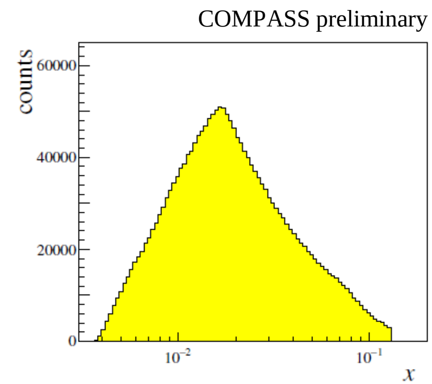
$\theta_\gamma < 60$ mrad

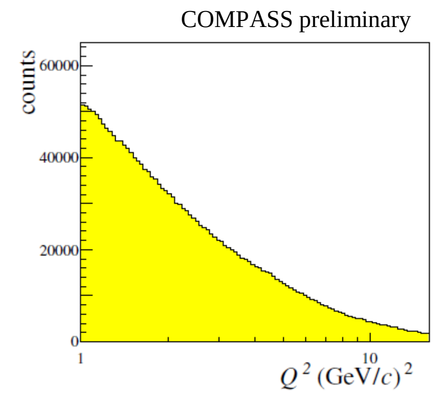
$z > 0.1$

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

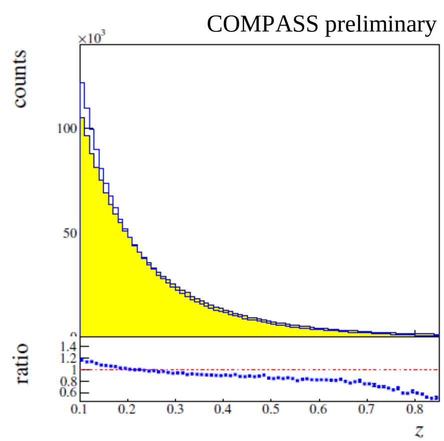
Size of the hadron sample: ~ 6.5 M hadrons

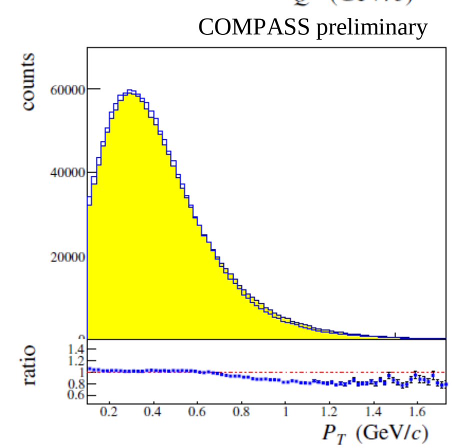






Comparison with the LEPTO Monte Carlo simulation.
Exclusive contribution at high *z* in the data

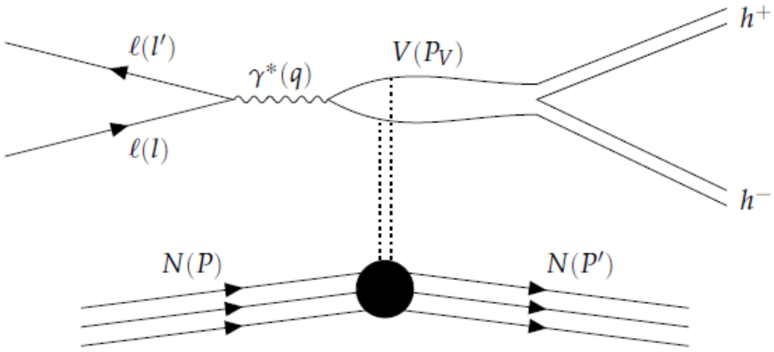




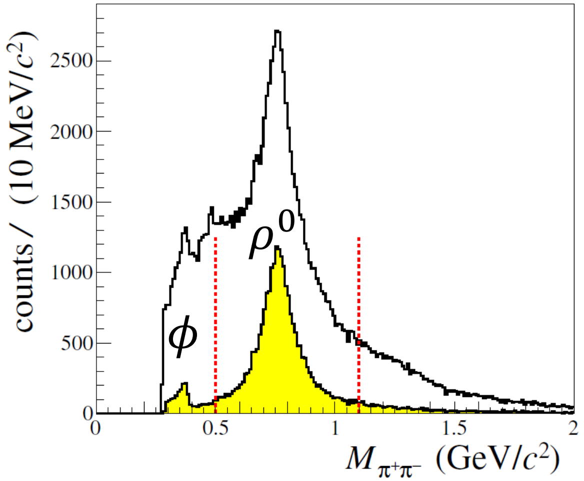
Contribution from exclusive hadrons

- The exclusive events fully reconstructed in the data are
  1) selected by cutting in missing energy E_{miss}
  2) used to normalized the HEPGEN Monte Carlo, needed to take into account the non-reconstructed part
  3) discarded
- The exclusive events non-fully reconstructed are subtracted using the normalized HEPGEN Monte Carlo

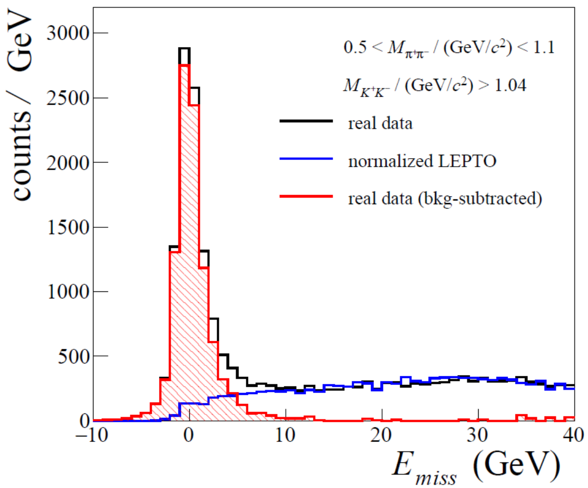
- This procedure does not require the knowledge of the absolute cross-section for the diffractive production, not well known (~ 30% relative uncertainty)



The diffractive production of a vector meson V and its decay into a hadron pair



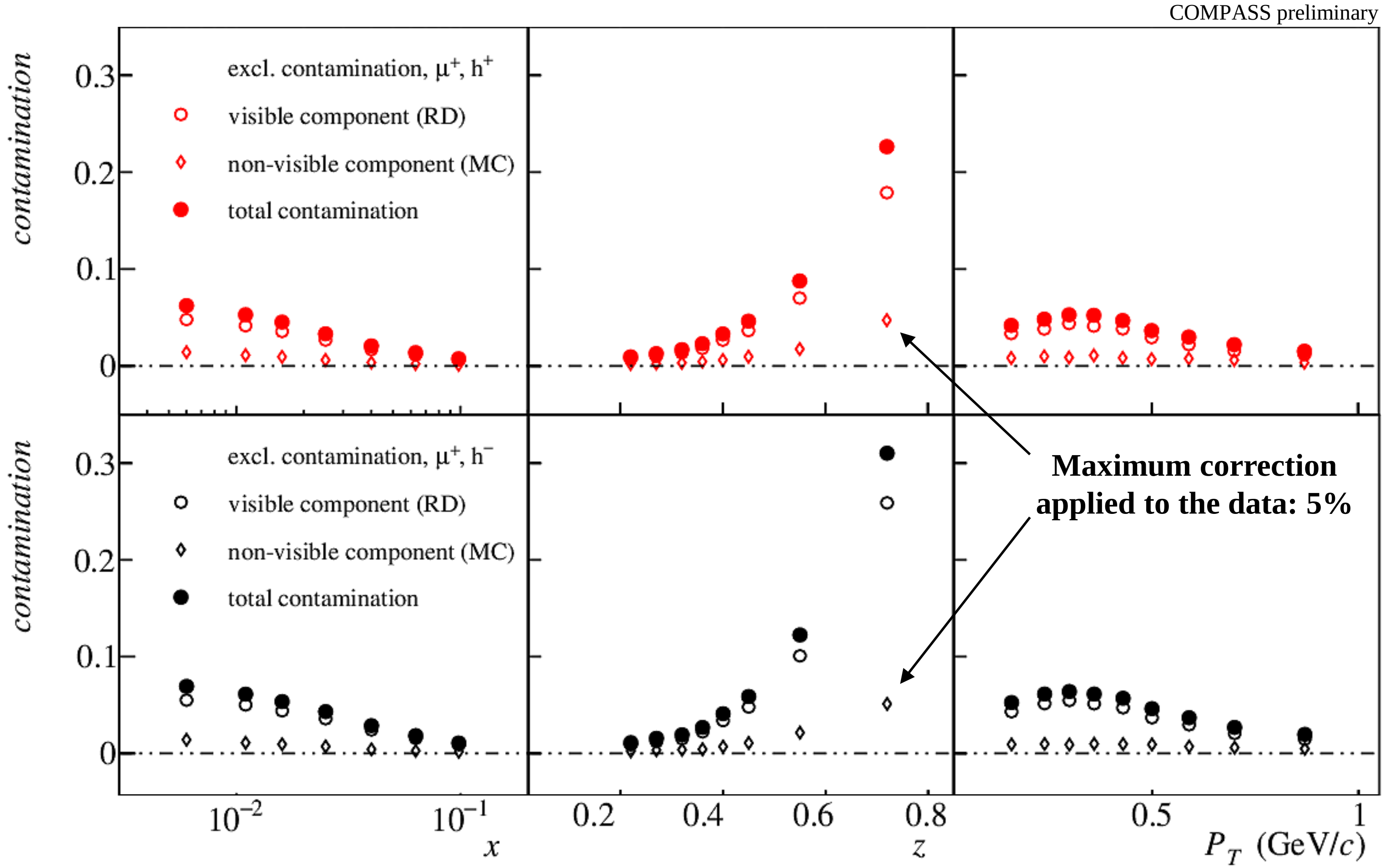
Invariant mass distribution in the data, before and after cutting in missing energy



The exclusive peak as observed in the data

Contribution from exclusive hadrons

Estimated exclusive hadrons contaminations in the data:
~80% is fully reconstructed

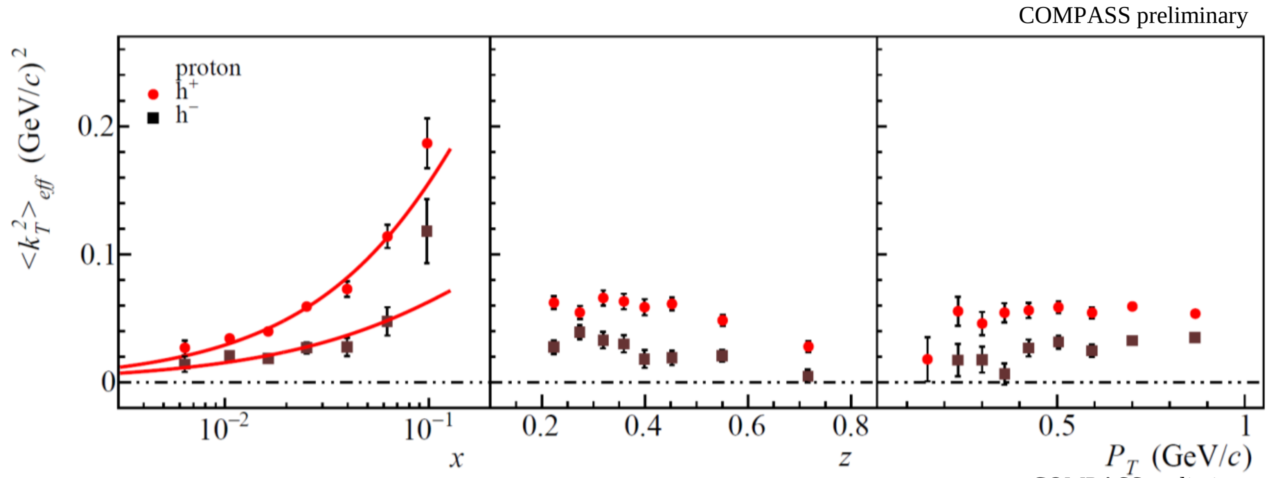


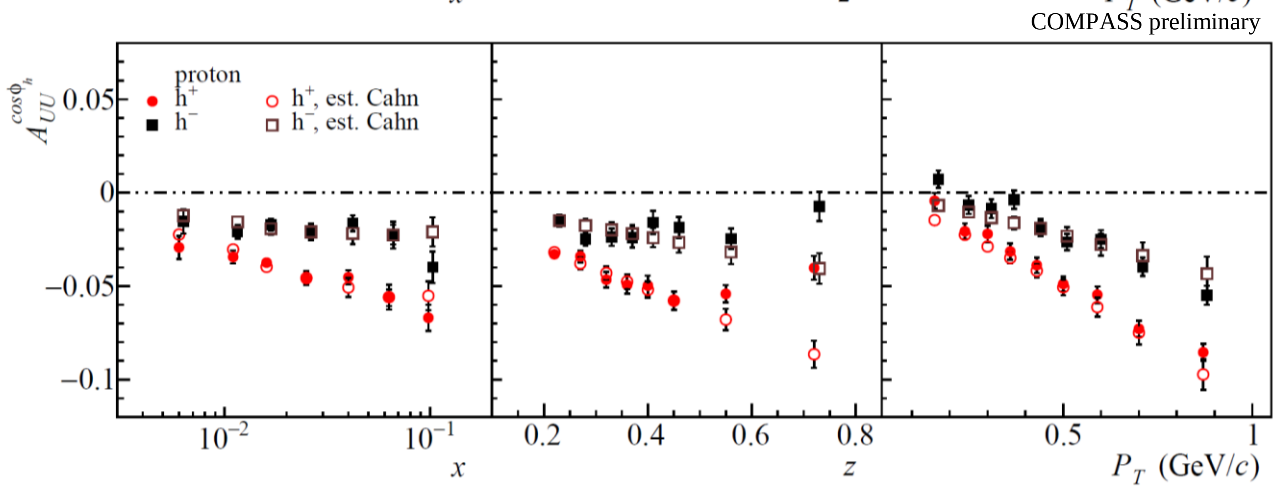
Extraction of $\langle k_T^2 \rangle$ from $A_{UU}^{\cos\phi_h}$

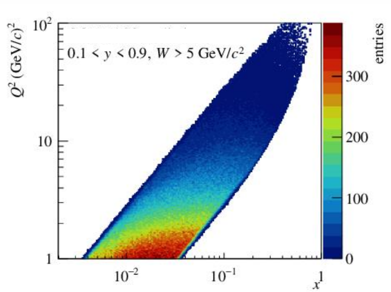
Extraction of $\langle k_T^2 \rangle$ *assuming only Cahn effect at work*

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

Power-law fit of $\langle k_T^2 \rangle(x)$
Rather satisfactory description also vs z (below 0.5) and P_T







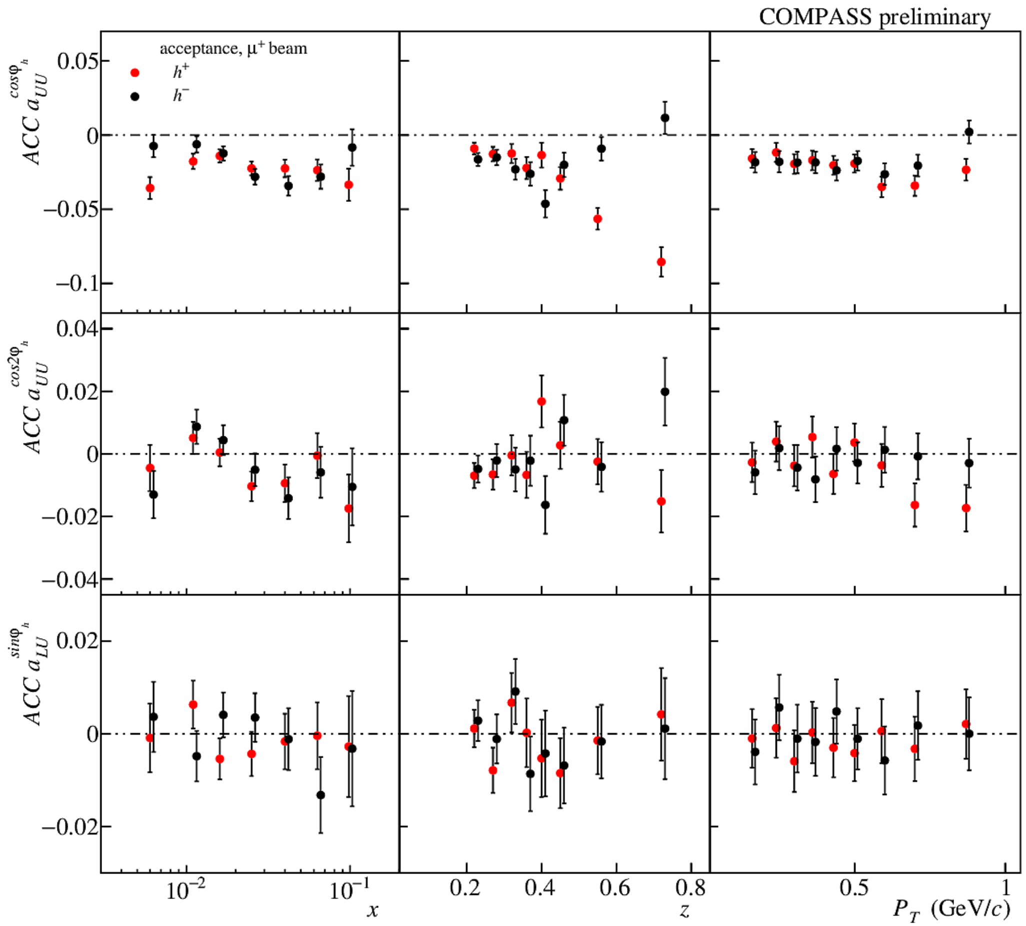
Is it an $x-$ or Q^2- dependence (or both)?

Acceptance modulations

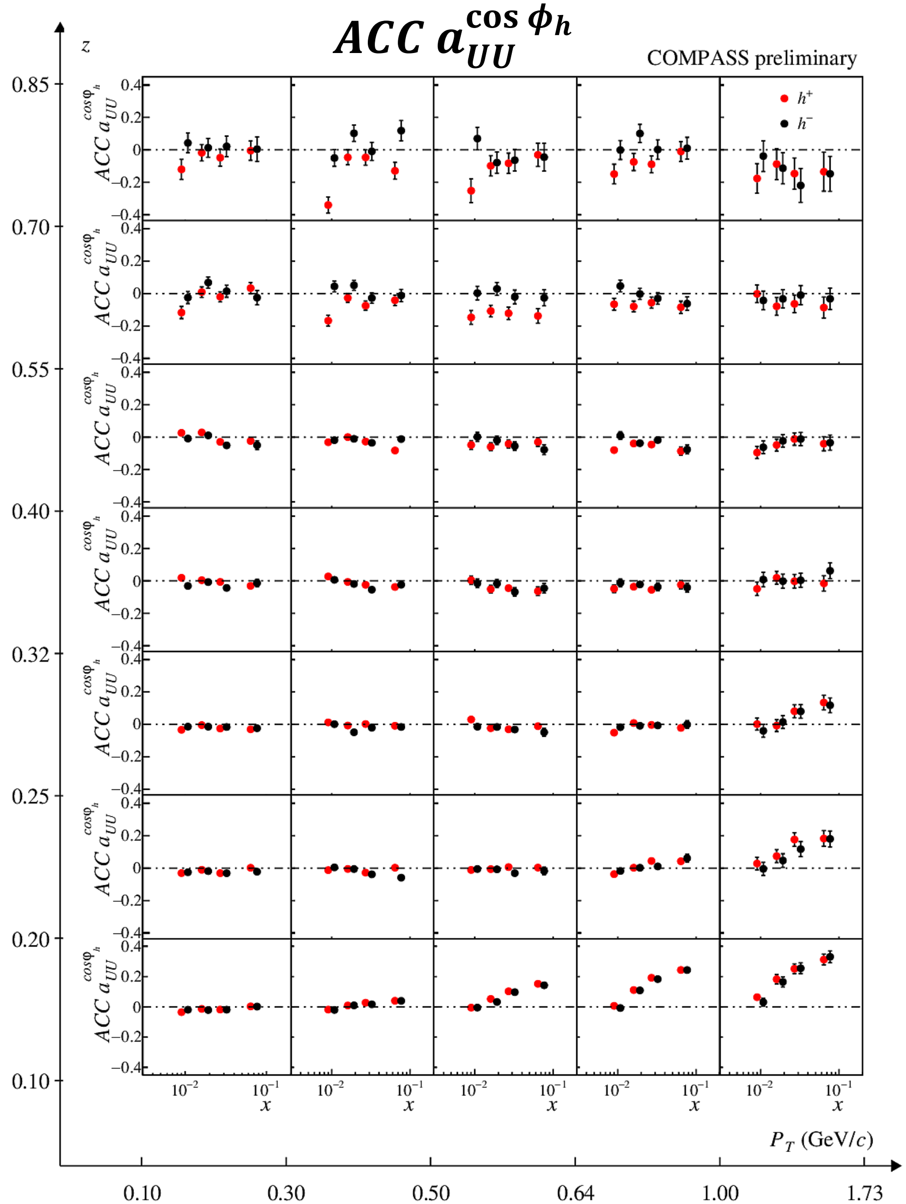
Correction for acceptance applied to each ϕ bin, taken as the ratio of reconstructed and generated hadrons:

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

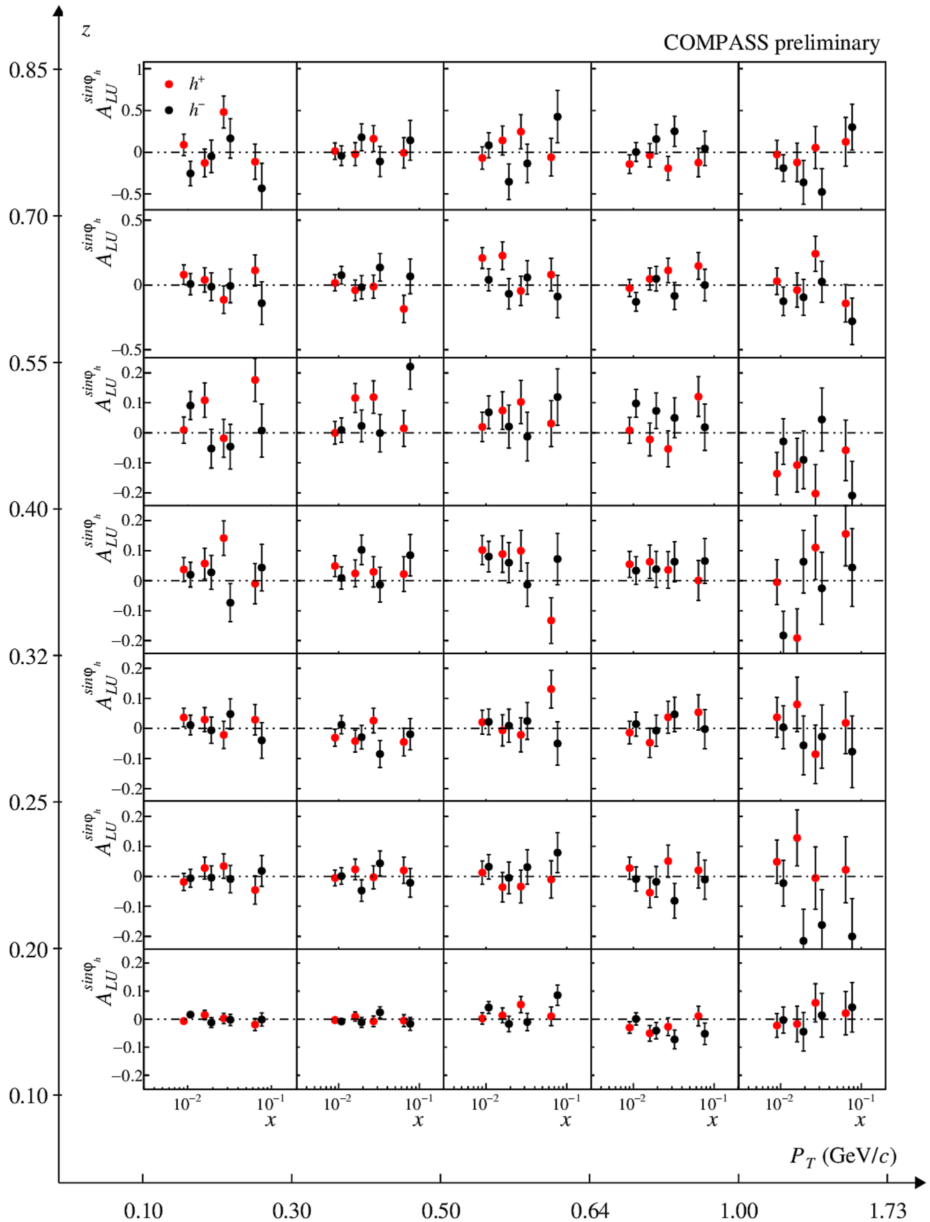
Azimuthal modulations of the acceptance in 1D binning, for μ^+ beam and positive (red) and negative hadrons (black).



Acceptance modulations



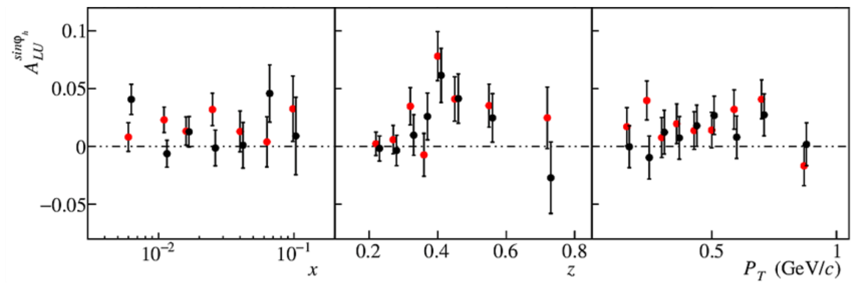
Azimuthal asymmetries – 3D



3D azimuthal asymmetries for positive and negative hadrons

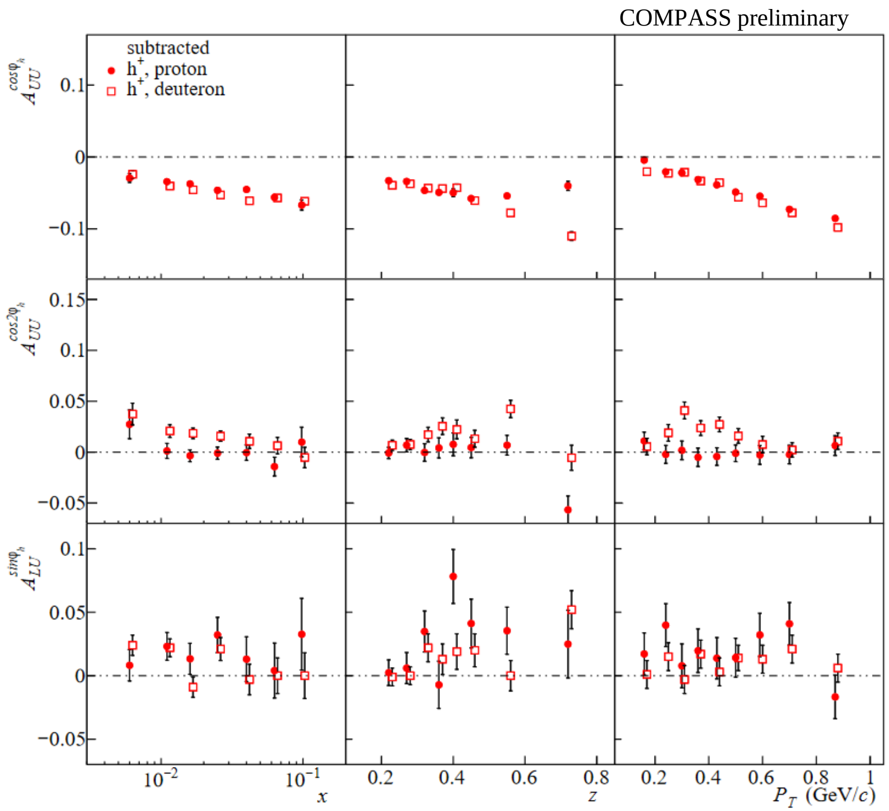
$A_{LU}^{sin\phi_h}$ as a function of x,
in bins of z (rows) and P_T (columns).

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

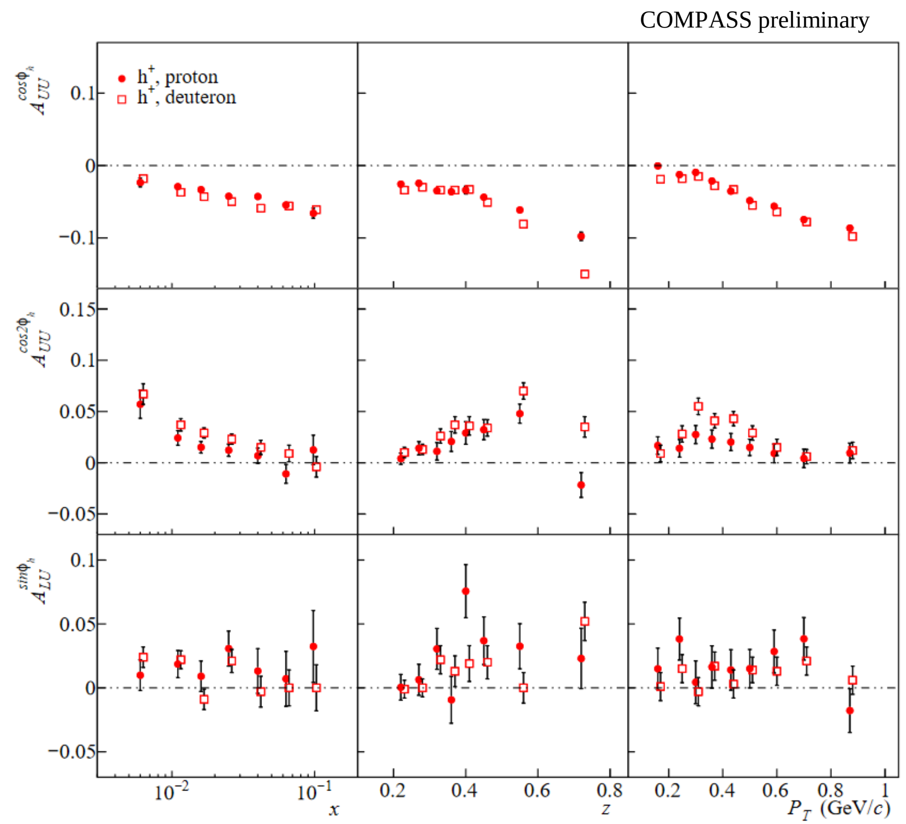


Comparison with deuteron results

Exclusive hadrons discarded / subtracted



Exclusive hadrons ***not*** *discarded / subtracted*

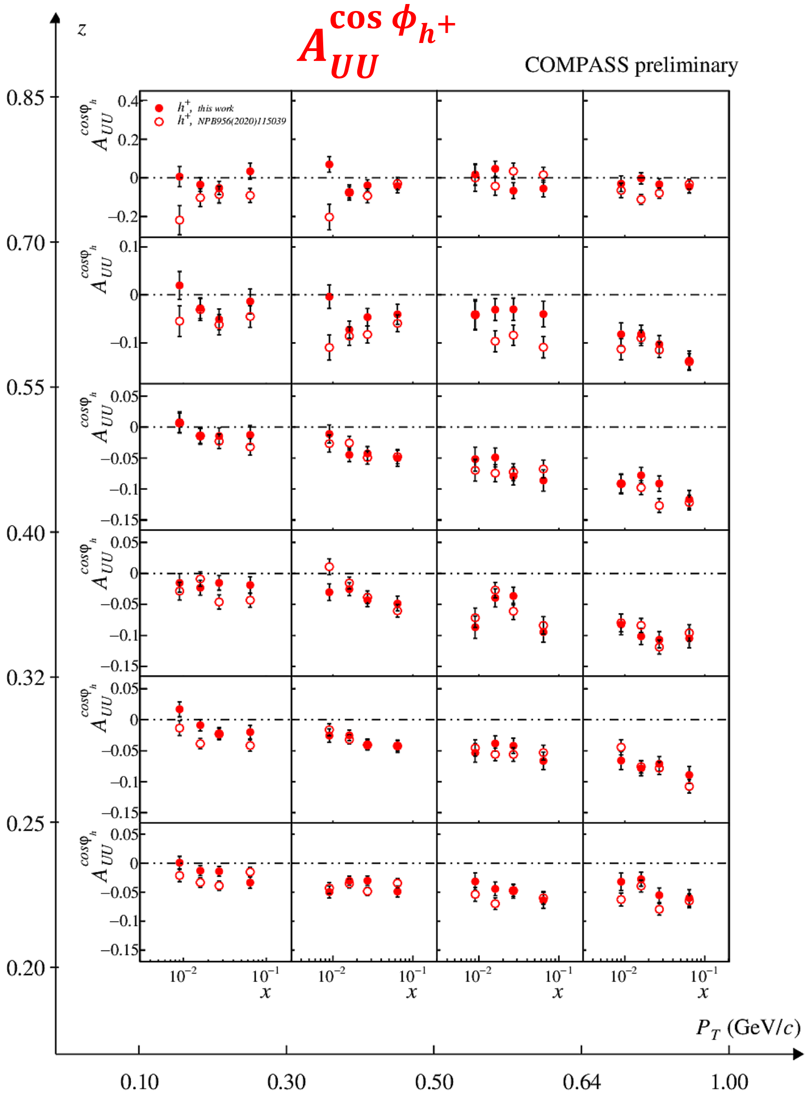


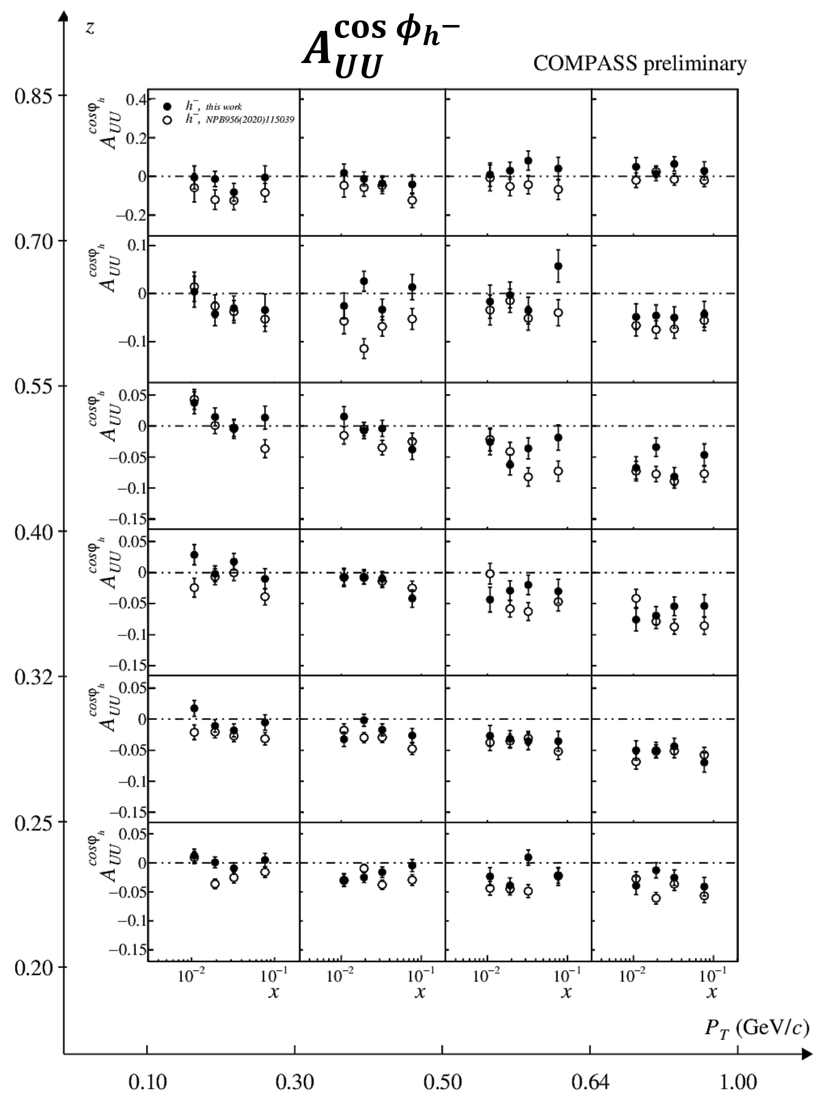
Difference visible also *before* the DVM subtraction / correction

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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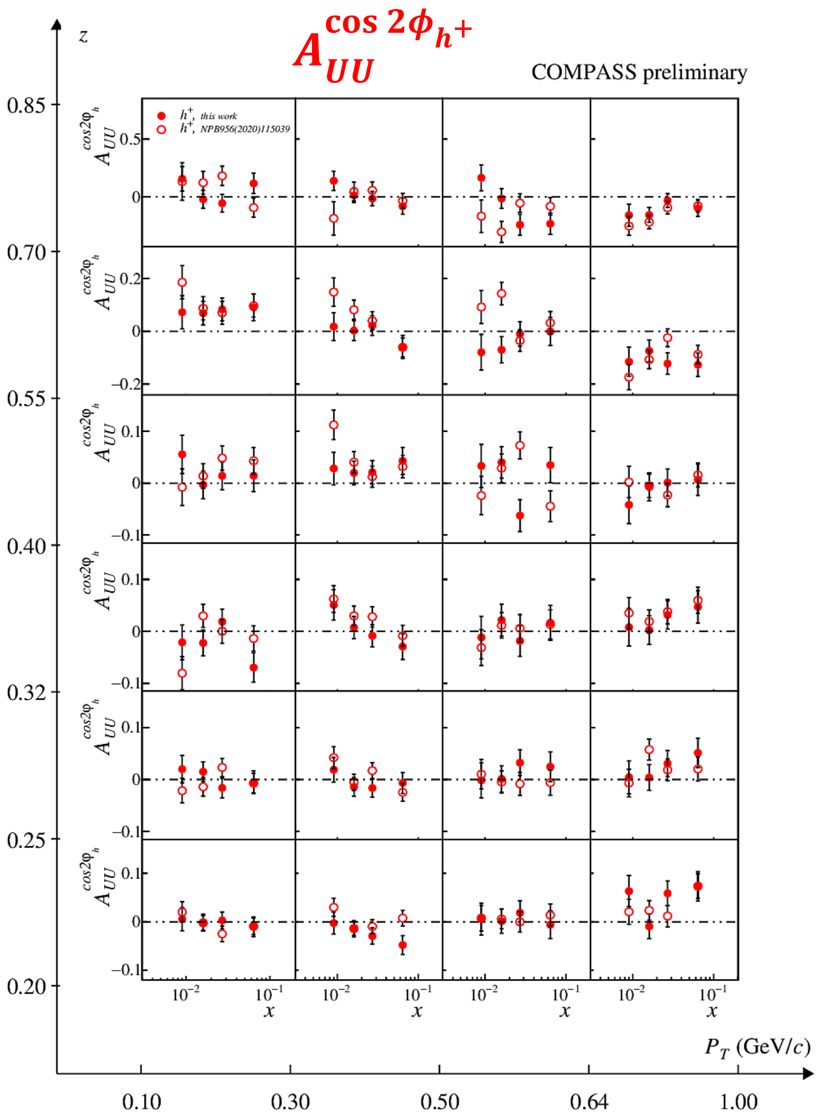

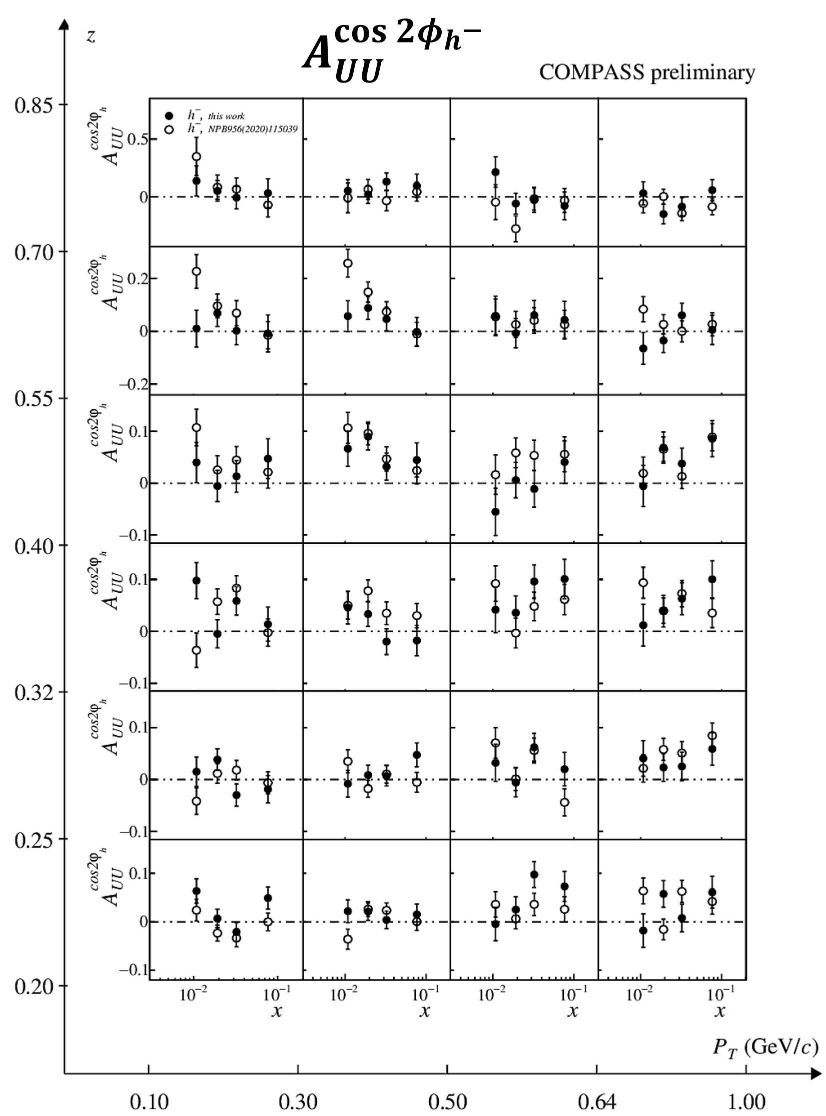

Azimuthal asymmetries for hadron pairs - $A_{UU}^{\cos\phi_{hh}}$

- Asymmetry $A_{UU}^{cos\phi_{hh}}$ for same-sign pairs (h^+h^+, h^-h^-) and opposite-sign pairs h^+h^-