TMD observables in unpolarized SIDIS at COMPASS

Andrea Moretti

on behalf of the COMPASS Collaboration

Content of this talk

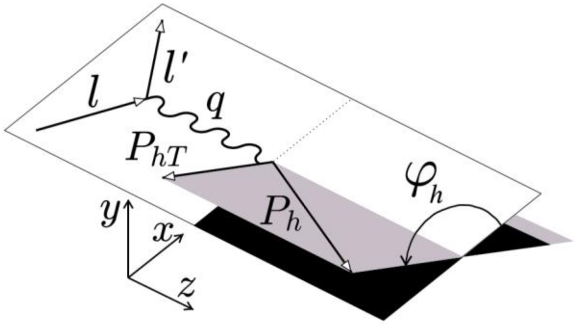
- Unpolarized SIDIS cross section
- TMD observables and COMPASS contributions
- Preliminary results from 2016 data taking
- Conclusions

Cross section for unpolarized SIDIS

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

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

- x, y and Q^2 are the usual DIS variables,
- $\gamma = 2Mx/Q$
- z is the fraction of photon energy carried by the hadron
- φ_h its azimuthal angle in the Gamma Nucleon System
- P_{hT}^2 its transverse momentum squared wrt the photon
- $\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}$ is a kinematic factor
- λ_l is the beam polarization.



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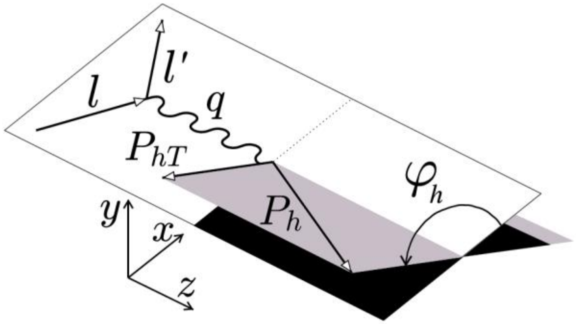


The Gamma Nucleon System

These structure functions have an expression in terms of TMDs.

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	$h_{1L}^{q\perp}(x, \boldsymbol{k}_T^2)$ 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

Structure functions and observables

Retaining the most interesting terms, in Wandzura-Wilczek approximation, up to $1/Q$:

- $F_{UU,T} = \mathcal{C}[f_1 D_1]$ ← Unpolarized PDF and FF

→ **Transverse momentum dependent multiplicities** relevant for the relation between $\vec{P}^2_{hT}$, $\vec{k}^2_T$ and $\vec{p}^2_T$.

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

  ($f_1 D_1$: Unpolarized PDF and FF, Cahn effect; $h_1^\perp H_1^\perp$: Boer-Mulders PDF, Collins FF)

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

  ($h_1^\perp H_1^\perp$: Boer-Mulders PDF, Collins FF)

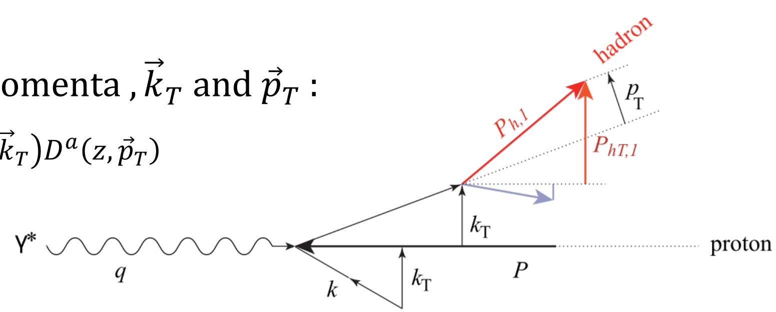
→ **Amplitudes of the azimuthal modulation** *(azimuthal asymmetries)* relevant for Boer-Mulders and $|\vec{k}_T|$.

Independent information on p_T from e^+e^- annihilation.

The symbol $\mathcal{C}$ denotes the convolution over the unobservable momenta , $\vec{k}_T$ and $\vec{p}_T$:

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

$$\hat{h} = \vec{P}_{hT} / |\vec{P}_{hT}|$$



Transverse momentum dependent multiplicities

Transverse momentum dependent multiplicities are defined as the ratio of the SIDIS - and the DIS cross sections:

$$\frac{d^2\mathcal{M}^h(x,Q^2;z,P_{hT}^2)}{dz\,dP_{hT}^2} = \frac{d^4\sigma^{\ell p\to\ell' h\,X}}{dx\,dQ^2 dz\,dP_{hT}^2} \Big/ \frac{d^2\sigma}{dx\,dQ^2} = \frac{\mathcal{C}[f_1 D_1]}{\sum_q e_q^2 f_1}$$

In gaussian approximation and for small values of P_{hT}, where $\langle P_{hT}^2\rangle = z^2\langle k_T^2\rangle + \langle p_T^2\rangle$ is expected to hold,

$$\frac{d^2\mathcal{M}^h(x,Q^2;z,P_{hT}^2)}{dz\,dP_{hT}^2} = \frac{N}{\langle P_{hT}^2\rangle}\exp\left(-\frac{P_{hT}^2}{\langle P_{hT}^2\rangle}\right)$$

P_{hT}^2-multiplicities on deuteron

data collected in 2004 and 2006 with a transversely polarized deuteron target

Just an example, from COMPASS:

Multiplicities as a function of P_{hT}^2,

in bins of x and Q^2,

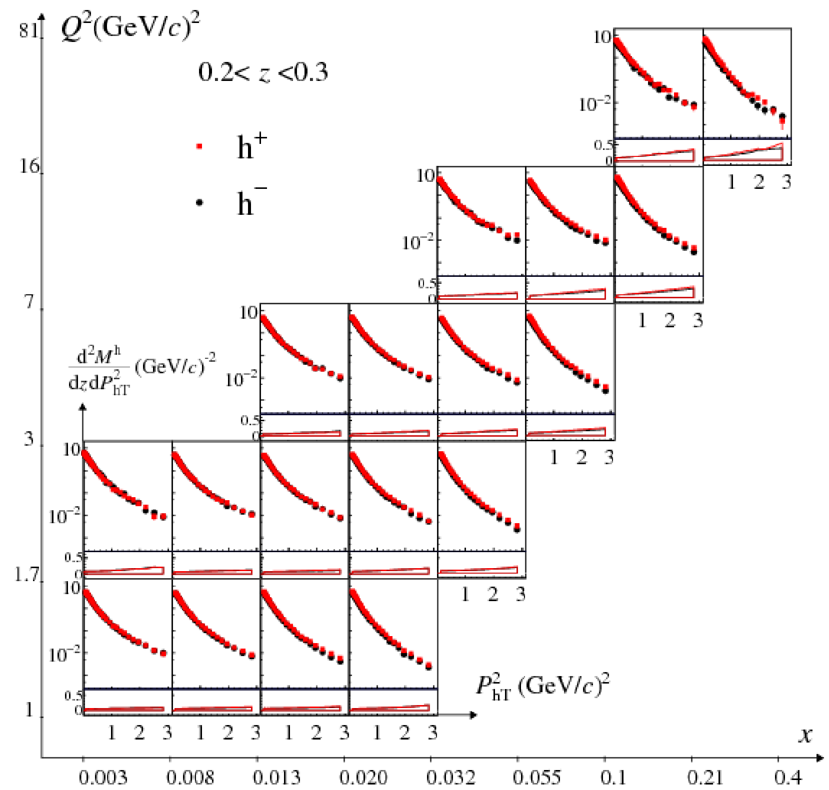
for a given z bin ($0.2 < z < 0.3$)

Systematic uncertainty mainly from:

acceptance correction

diffractive vector mesons contribution

Generally 5% to 7%



[COMPASS, Phys. Rev. D **97**, 032006 (2018)]

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P_{hT}^2-multiplicities on deuteron

data collected in 2004 and 2006 with a transversely polarized deuteron target

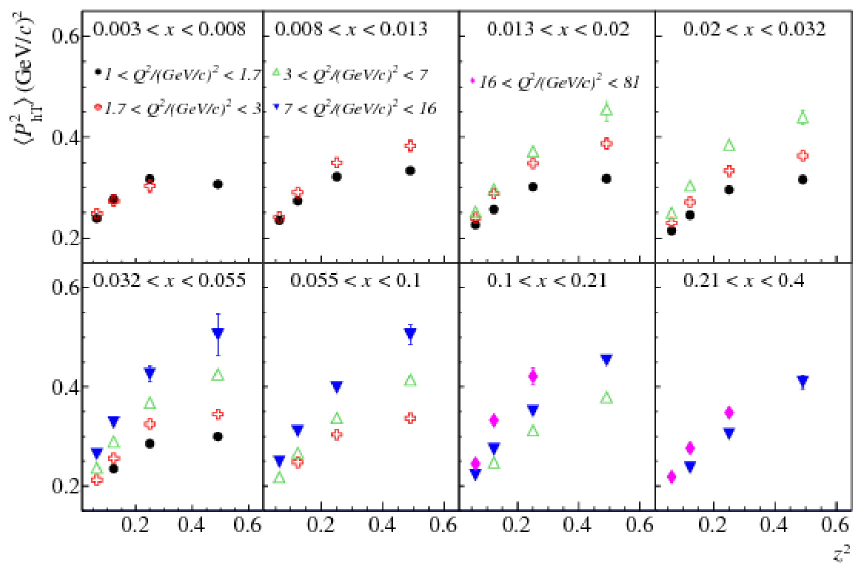
Test of the gaussian approximation

$\langle P_{hT}^2\rangle$ as obtained from the fit of the multiplicities with a single exponential, for $0.02 < P_{hT}^2 < 0.72$

Expected linear trend wrt z^2.

A lot of work

on both the experimental side and theoretical side to describe the data



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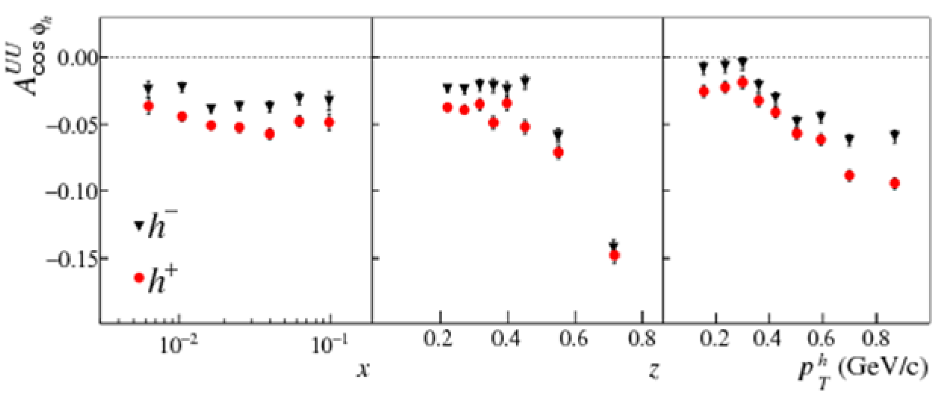
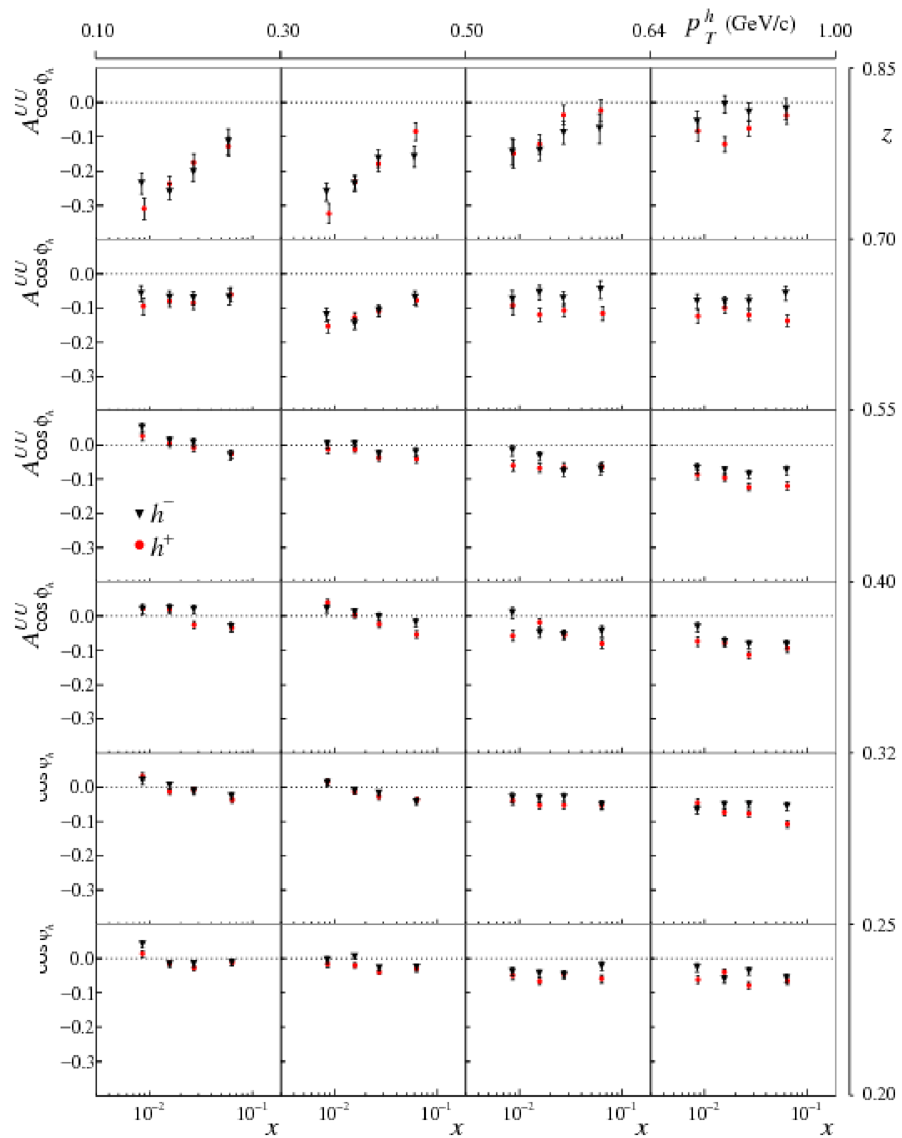
As for the azimuthal asymmetries of hadrons produced in SIDIS, recent results come from COMPASS, HERMES, JLAB

azimuthal asymmetries on deuteron

data collected in 2004 and 2006 with a transversely polarized deuteron target

Here, COMPASS results for the ***cos*** $\boldsymbol{\varphi_h}$ **asymmetry** as a function of x, z and P_{hT} (1D-analysis) + simultaneous binning in the three variables (3D-analysis)





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Azimuthal asymmetries

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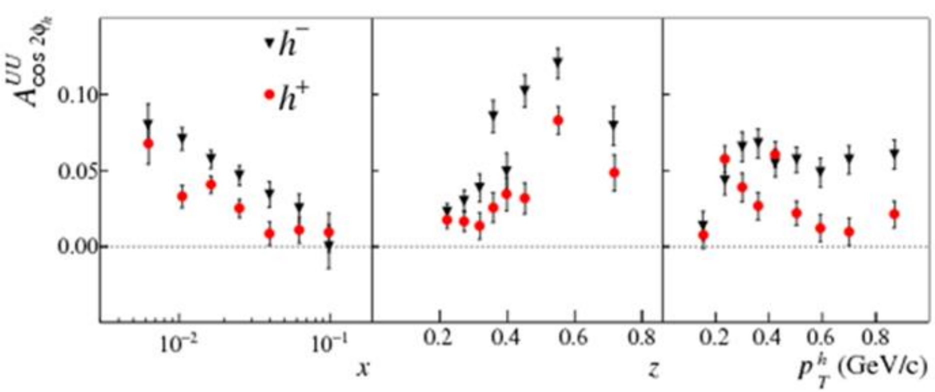
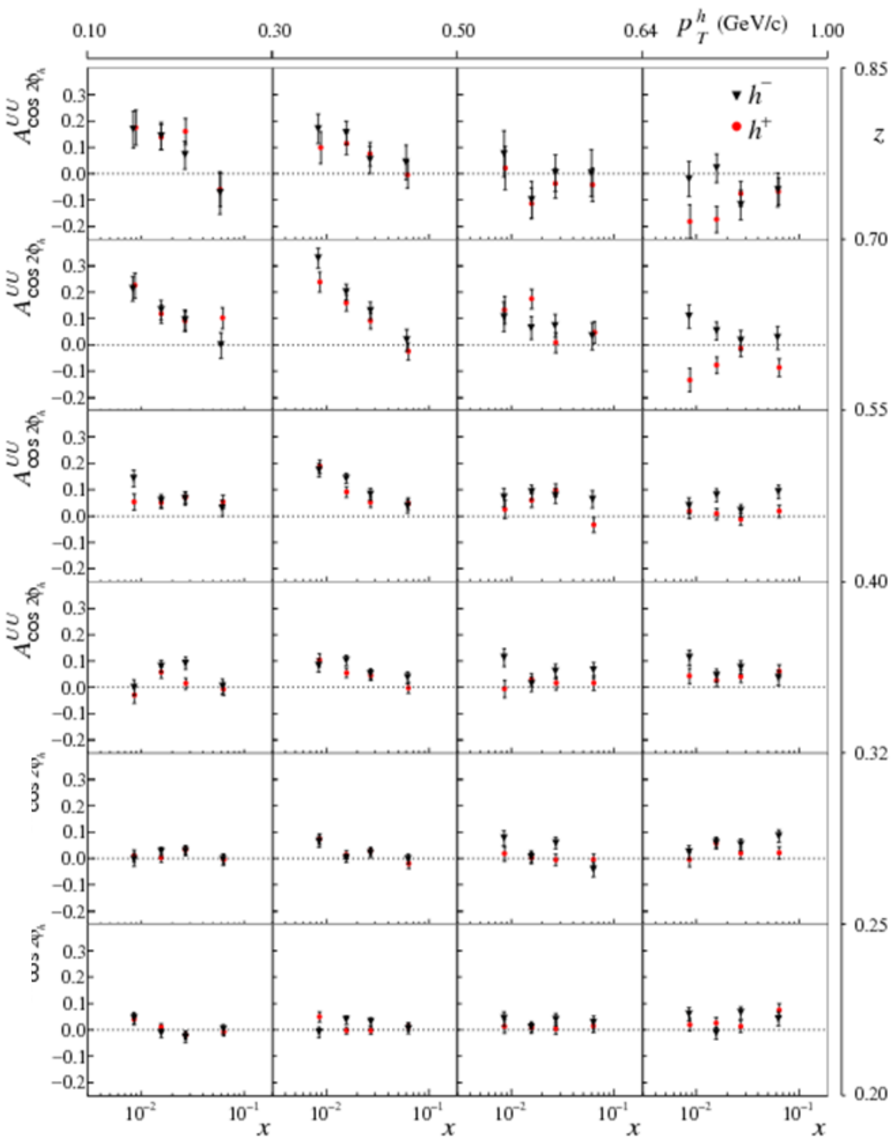
azimuthal asymmetries on deuteron

data collected in 2004 and 2006 with a transversely polarized deuteron target

Here, COMPASS results for the ***cos*** $\boldsymbol{2\varphi_h}$ **asymmetry** as a function of x, z and P_{hT} (1D-analysis) + simultaneous binning in the three variables (3D-analysis)

- Strong kinematic dependences: hard to describe
- Several attempts to extract $h_1^{\perp}$: not conclusive.





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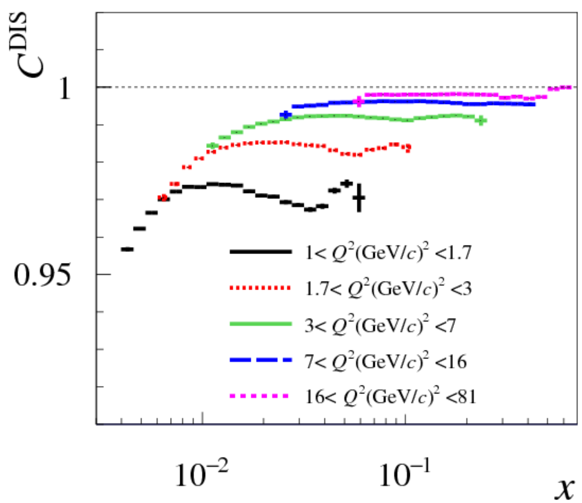
Contribution from exclusive events

A fraction of the hadrons selected for the SIDIS analyses comes from the decay of **diffractively produced vector mesons (DVM).** The two most important channels are:

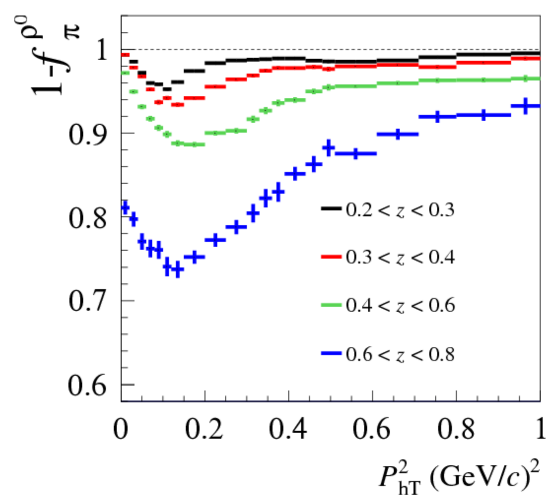
$$\rho^0 \to \pi^+\pi^-$$
$$\phi \to K^+K^-$$

Such exclusive events/hadrons contribute to the measured multiplicities.
Estimation done in COMPASS based on Monte Carlo (LEPTO for SIDIS, HEPGEN for DVM).

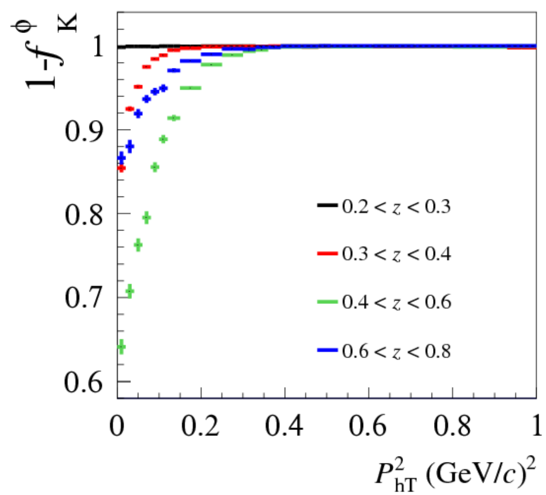
[COMPASS, Phys. Rev. D **97**, 032006 (2018)]



Correction to the number of reconstructed DIS events, as a function of x, per Q^2 bin



Fraction of pions from SIDIS, as a function of P^2_{hT} per z bin



Fraction of kaons from SIDIS, as a function of P^2_{hT} per z bin

$$C^{DIS} = \frac{N^{DIS}}{N^{DIS} + N^{DVM}}$$

$$f_\pi^{\rho^0} = \frac{N_\pi^{\rho^0}}{N_\pi^{SIDIS} + N_\pi^{\rho^0}}$$

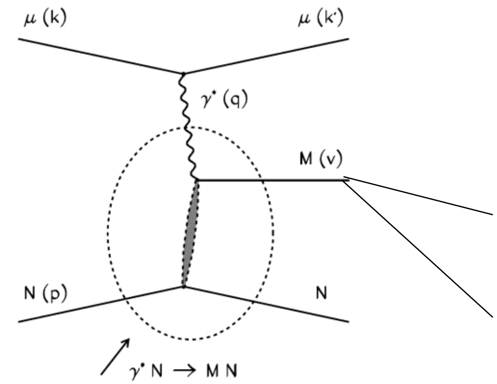
$$f_K^{\phi} = \frac{N_K^{\phi}}{N_K^{SIDIS} + N_K^{\phi}}$$

Contribution from exclusive events

Recently, it has been demonstrated that such diffractive production mechanism has a **sizable impact on the measured azimuthal asymmetries** as well. [COMPASS, arXiv:1912.10322)]

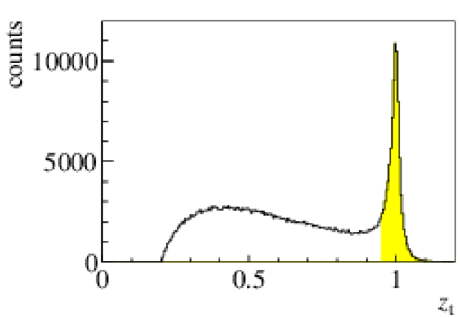
- The spin density matrix of the virtual photon is “transferred” to the vector meson, and then to the final state hadron.
- This can induce a modulation in φ_h.
- The target proton is almost kept intact: the process is exclusive

- **Analysis performed on 2006 deuteron data**
  Same conditions as for published results, Monte Carlo available
- Selection of exclusive events with
  - exactly 2 hadrons
  - with opposite charge
  - $z_{h^+} + z_{h^-} = z_t > 0.95$
- Subtraction of asymmetries.

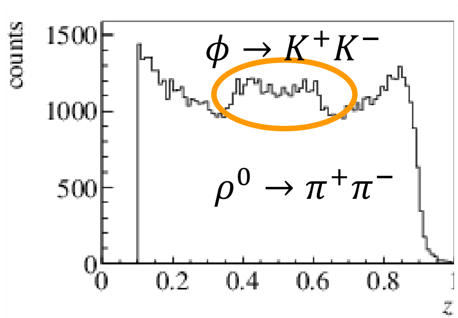


Diffractive production of vector mesons and subsequent decay into two hadrons (sketch)

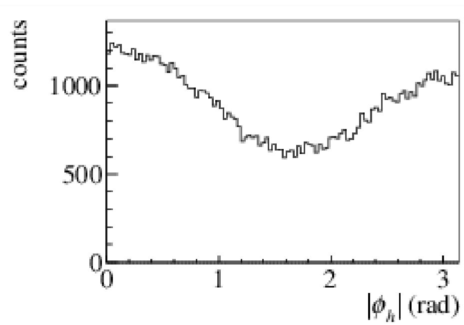
The $z_{h^+} + z_{h^-} = z_t$ distribution (2h with opposite charge)



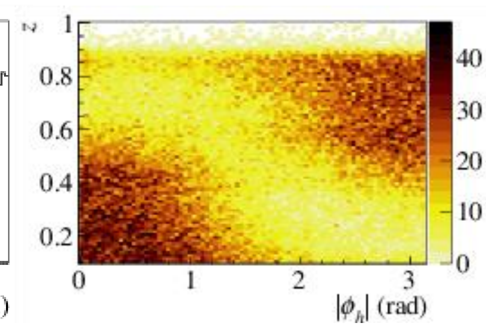
z for “exclusive” hadrons



$|\varphi_h|$ for “exclusive” hadrons



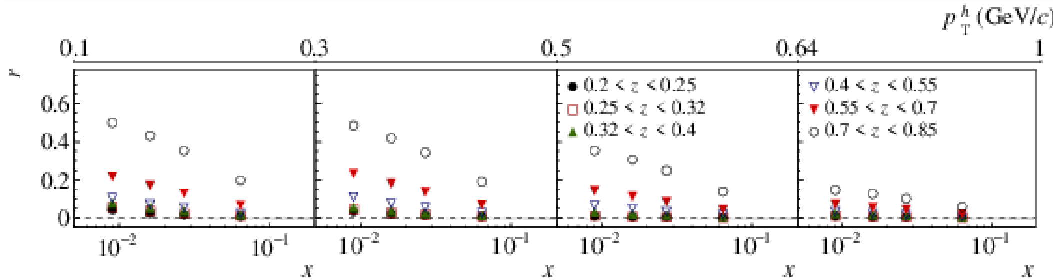
$|\varphi_h| - z$ correlation for “exclusive” hadrons



[COMPASS, arXiv:1912.10322)]

Contribution from exclusive events

Fraction r of exclusive hadrons
in the same 3D binning and using the same Monte Carlo results as for published results.



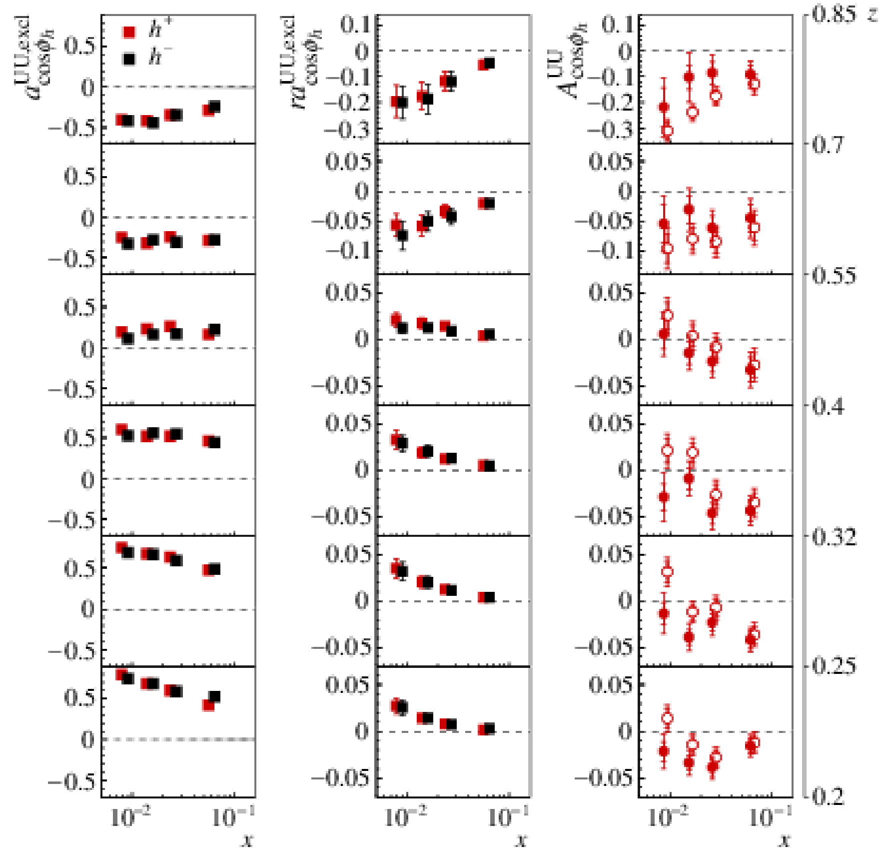
Summary plot
from left to right, for $0.1 < p_T^h/(\mathrm{GeV}/c) < 0.3$
and for the $\cos\varphi_h$ asymmetry,

1. Amplitude $a_{\cos\varphi_h}^{UU,excl}$ of the azimuthal modulation for exclusive hadrons

2. Size of the correction to the published asymmetries $ra_{\cos\varphi_h}^{UU,excl}$

3. Comparison of published (open points) and corrected (close points) asymmetries for positive hadrons.

$$A_{\cos\varphi_h}^{UU} = \frac{A_{\cos\varphi_h}^{UU,publ} - ra_{\cos\varphi_h}^{UU,excl}}{1-r}$$



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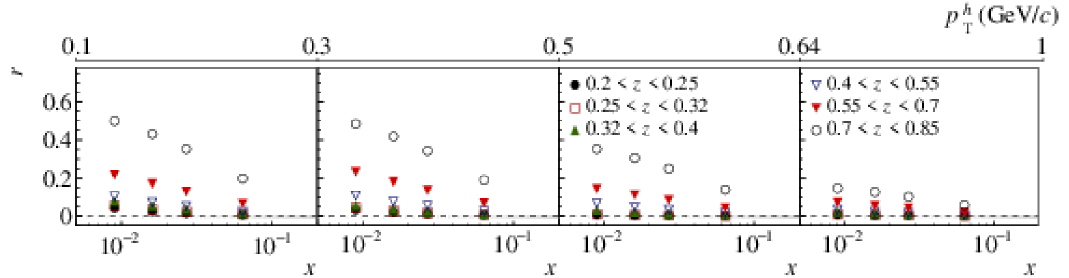
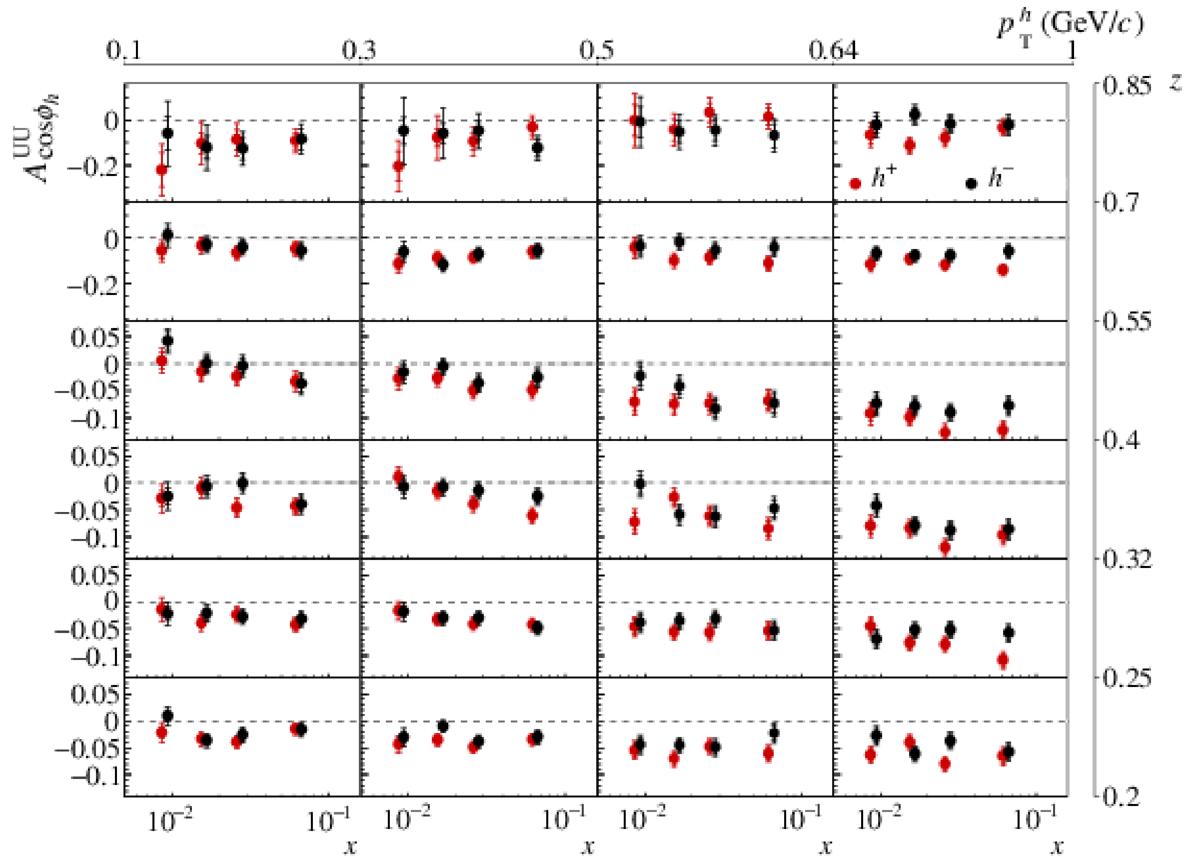


3D azimuthal asymmetries after subtraction of the exclusive contribution

$$A^{UU}_{\cos\varphi_h} = \frac{A^{UU,publ}_{\cos\varphi_h} - r a^{UU,excl}_{\cos\varphi_h}}{1 - r}$$



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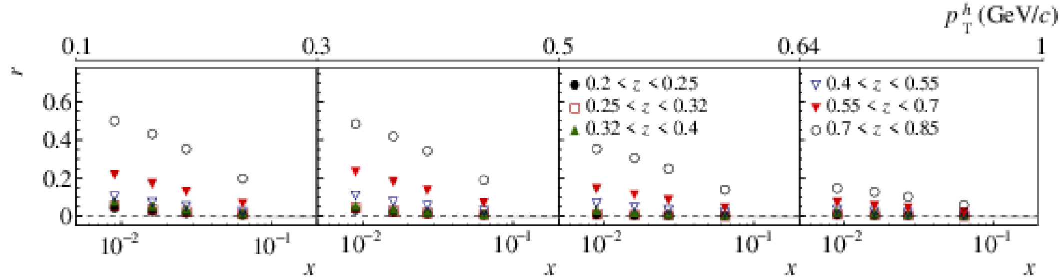
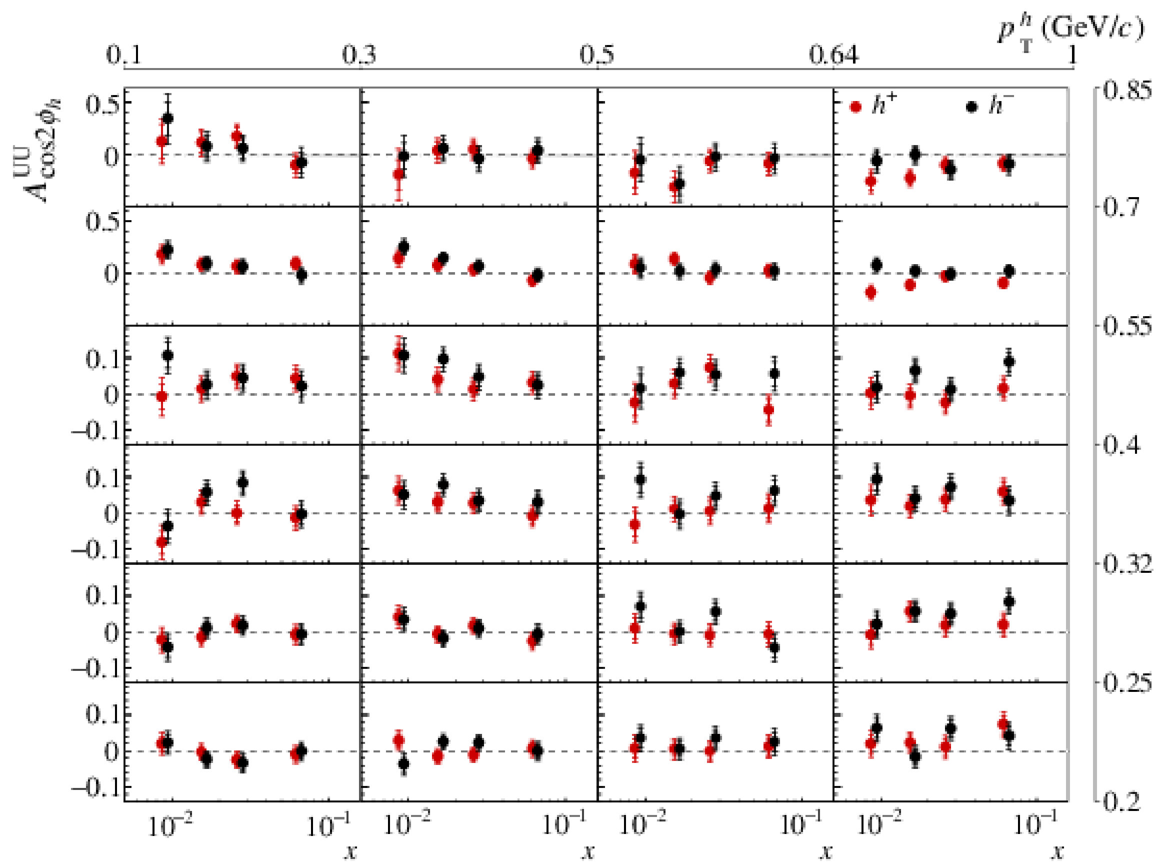


3D azimuthal asymmetries after subtraction of the exclusive contribution

$$A^{UU}_{\cos 2\varphi_h} = \frac{A^{UU,publ}_{\cos 2\varphi_h} - r a^{UU,excl}_{\cos 2\varphi_h}}{1-r}$$



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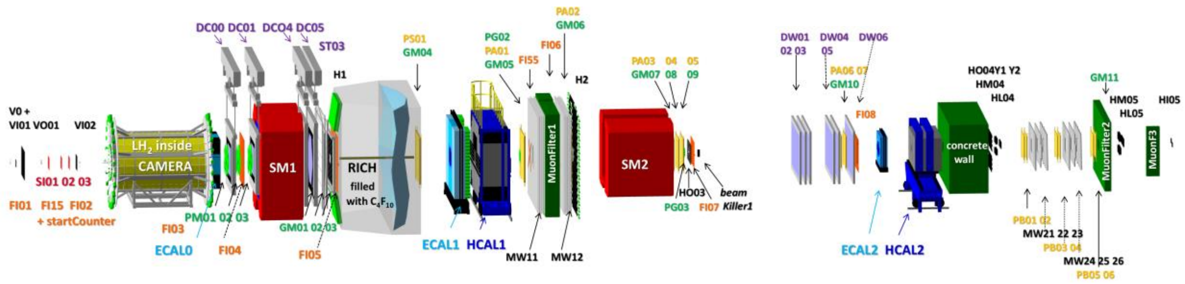
The 2016/2017 COMPASS runs

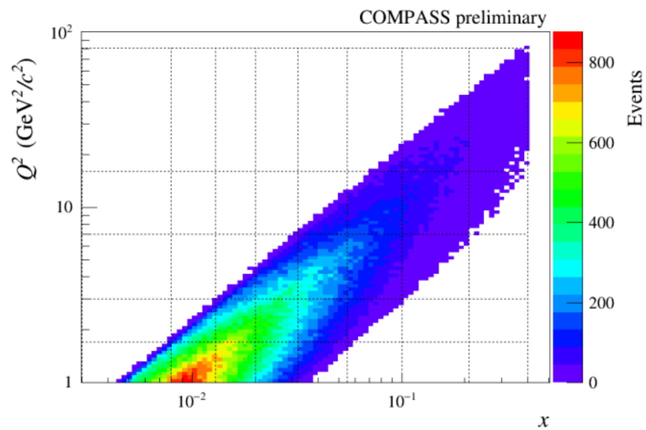


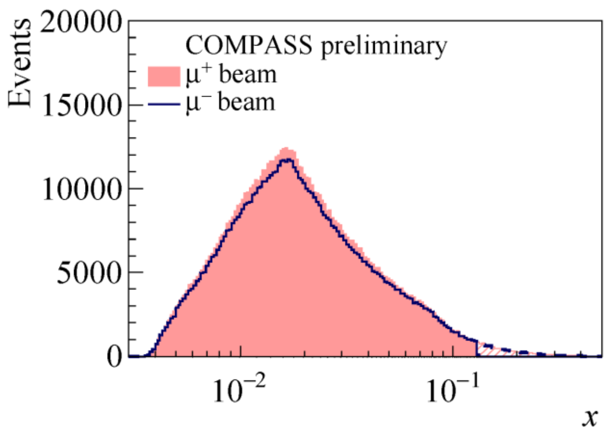
In 2016/2017 new SIDIS data have been collected in COMPASS, with:

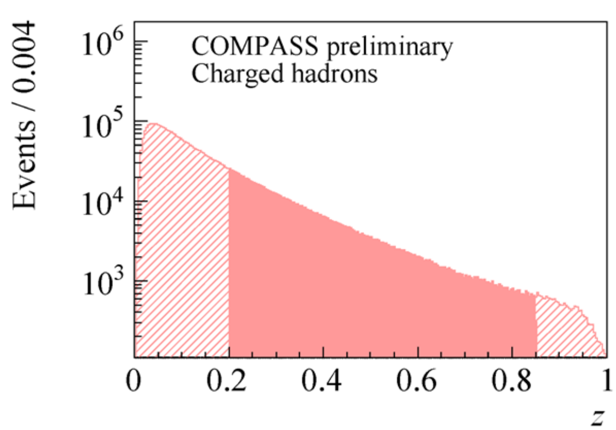
- 160 GeV/c μ beam (μ^+ and μ^- with balanced statistics)
- Unpolarized, liquid hydrogen target

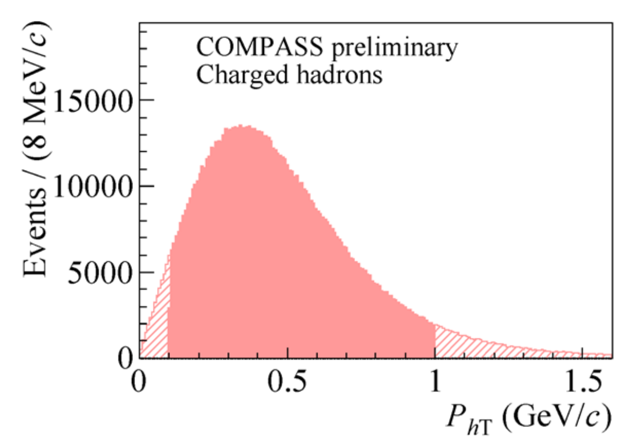
In this talk: preliminary results for TMD observables

Here: a selection of kinematic distributions ($x - Q^2$ coverage, x, z, P_{hT})



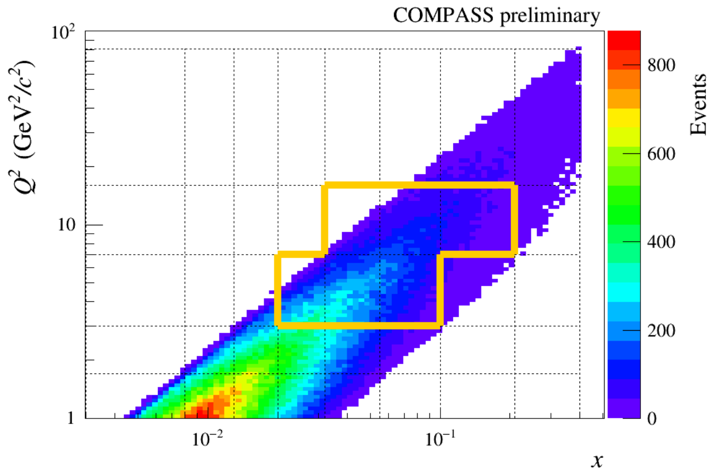






P_{hT}^2-dependent multiplicities ~10% of the available statistics.

COMPASS



KINEMATIC RANGE

$3 < Q^2\ /\ (\mathrm{GeV}/c)^2 < 16$

$0.02 < x < 0.21$

$0.1 < y < 0.9$

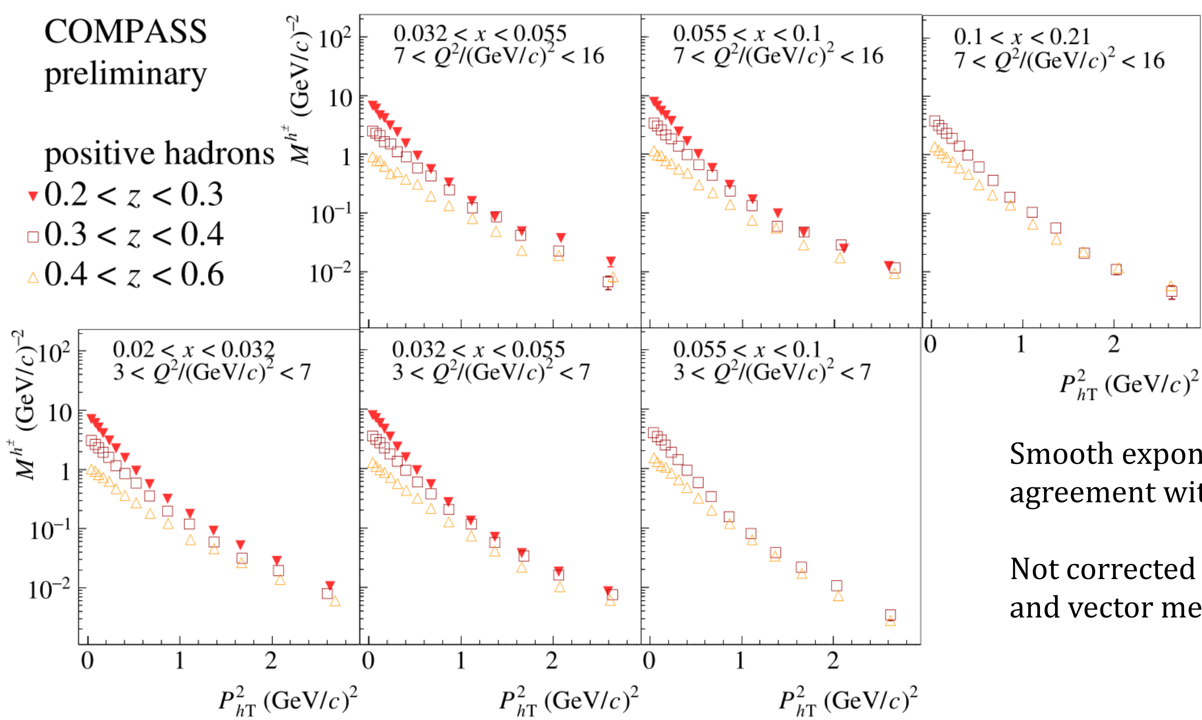
$0.2 < z < 0.6$

$0.02 < P_{hT}^2\ /\ (\mathrm{GeV}/c)^2 < 3$

optimized to have high and flat acceptance, avoiding:

- dependence on P_{hT}^2
- modulations in φ_h

also, avoiding the regions where corrections due to DVM are estimated larger than 2%.

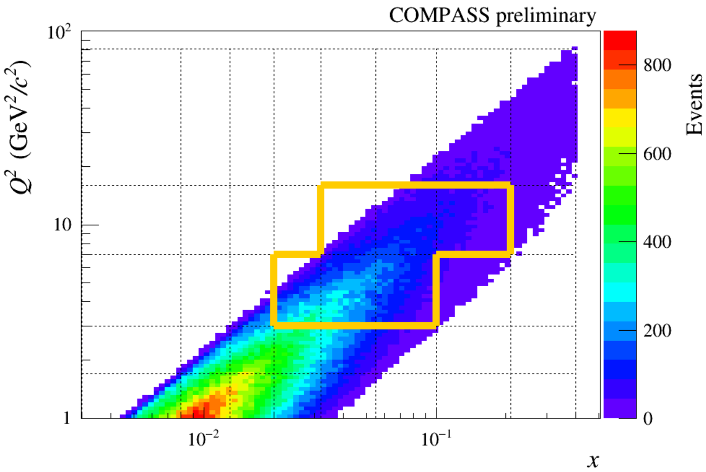


Smooth exponential trend, in qualitative agreement with the published results.

Not corrected for radiative effects and vector mesons contamination.

PRELIMINARY RESULTS FROM THE 2016 RUN

P_{hT}^2-dependent multiplicities ~10% of the available statistics.



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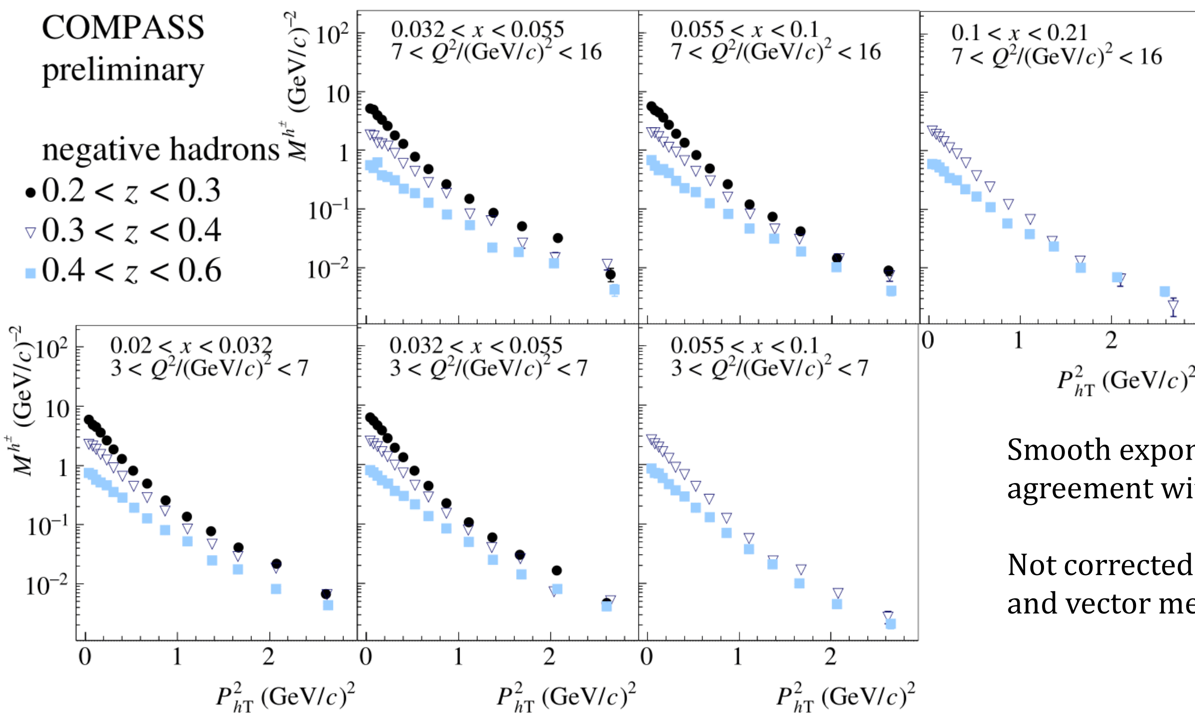
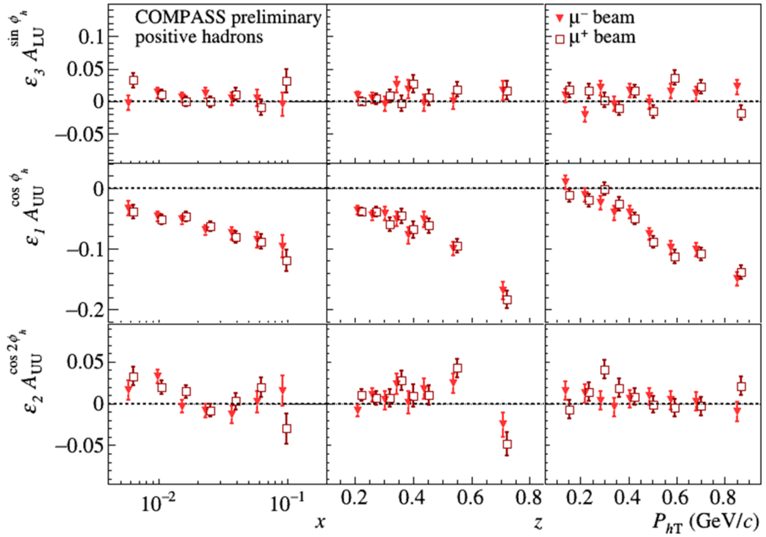


Smooth exponential trend, in qualitative agreement with the published results.

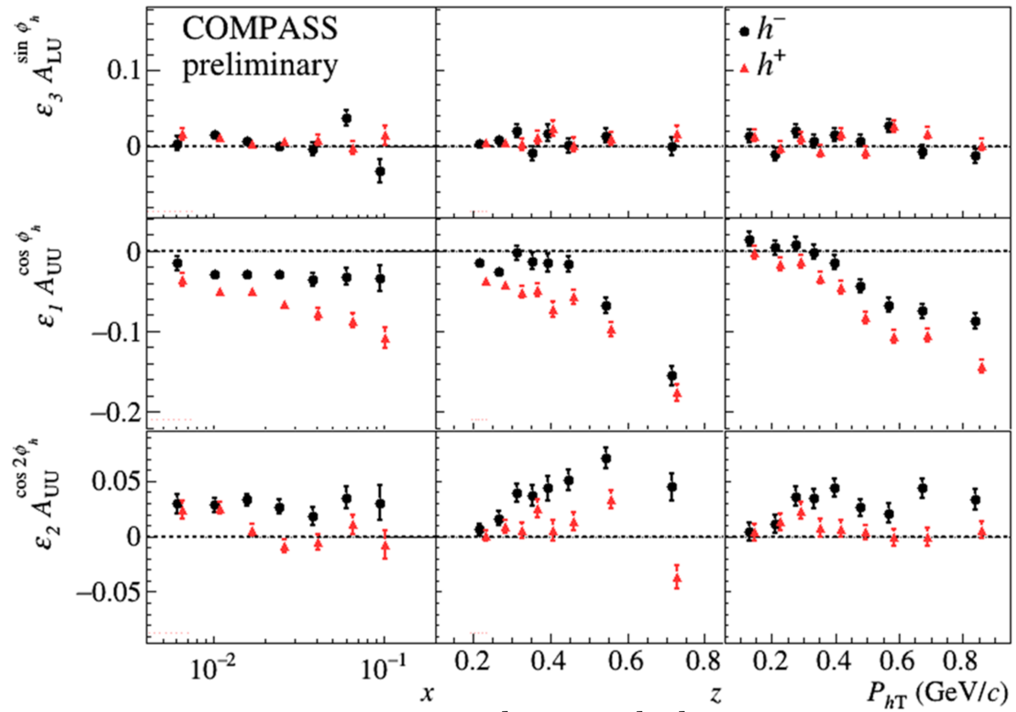
Not corrected for radiative effects and vector mesons contamination.

PRELIMINARY RESULTS FROM THE 2016 RUN

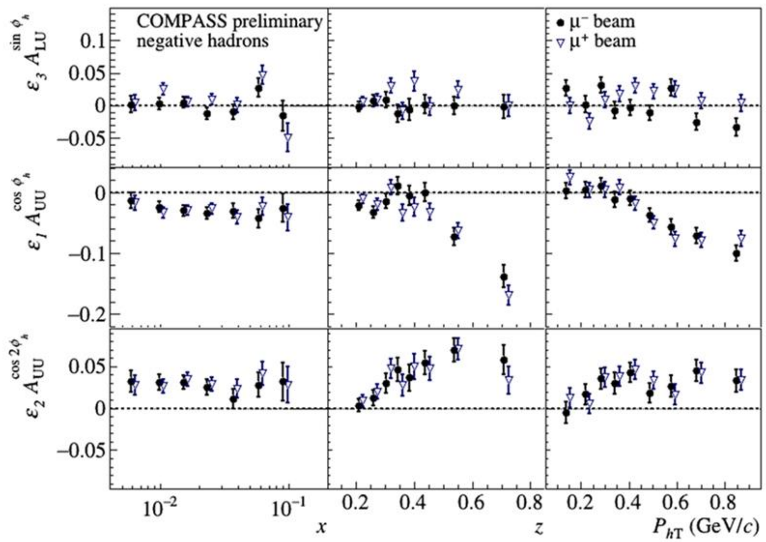
Azimuthal asymmetries ~4% of the available statistics.



Positive hadrons, μ^+ and μ^- beams compared



Positive and negative hadrons, average



Negative hadrons, μ^+ and μ^- beams compared

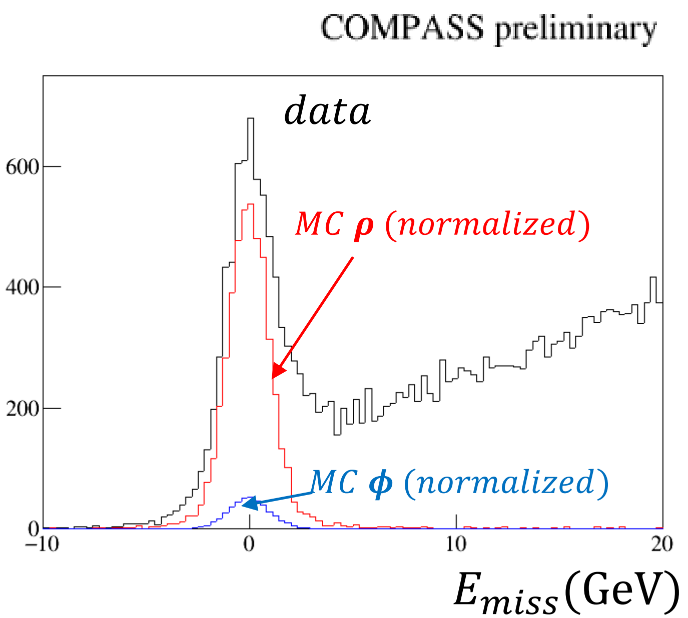
- The strong kinematic dependences, already observed on deuteron, are confirmed
- Small statistical uncertainties
- Systematics expected at the level of statistical uncertainty

Diffractive vector mesons contamination

We are working on a **refined method** to estimate – and subtract the contribution to the hadron sample coming from the decay of diffractive vector mesons.

- The method does not require a precise knowledge of the diffractive cross section.
- It is based on the exclusive events observed in data.

- Here, for example, the missing energy peak for all the events where exactly **2 hadrons with opposite charge** were reconstructed.
    1. The 2h - E_{miss} peak is used to normalize the HEPGEN Monte Carlo to the data
    2. **If both hadrons are reconstructed in the data**, the exclusive event can be removed with kinematic cuts
    3. **If only one hadron is reconstructed in the** data, the leftover contamination can be obtained from Monte Carlo.



Diffractive vector mesons contamination

We are working on a **refined method** to estimate – and subtract the contribution to the hadron sample coming from the decay of diffractive vector mesons.

- The method does not require a precise knowledge of the diffractive cross section,
- It is based on the exclusive events observed in data

- Here, for example, the missing energy peak for all the events where exactly **2 hadrons with opposite charge** were reconstructed.
    1. The 2h - E_{miss} peak is used to normalize the HEPGEN Monte Carlo to the data
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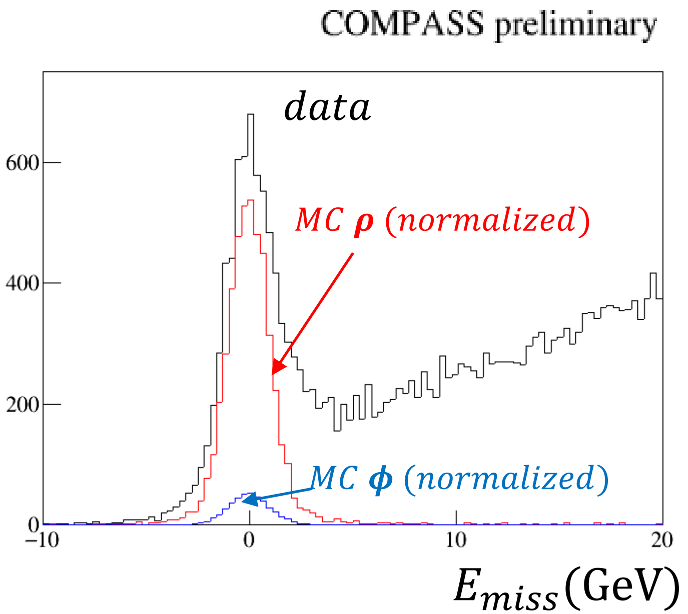
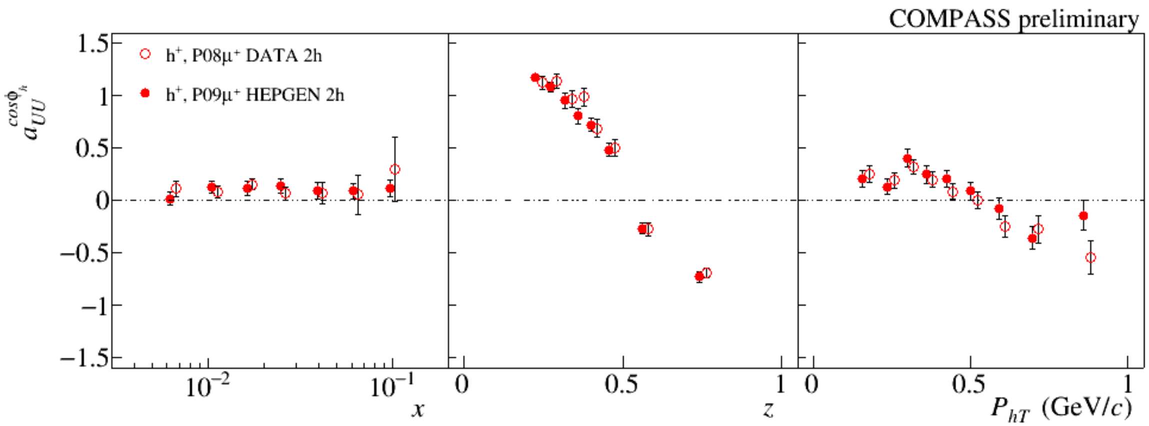


SDME's in HEPGEN Monte Carlo

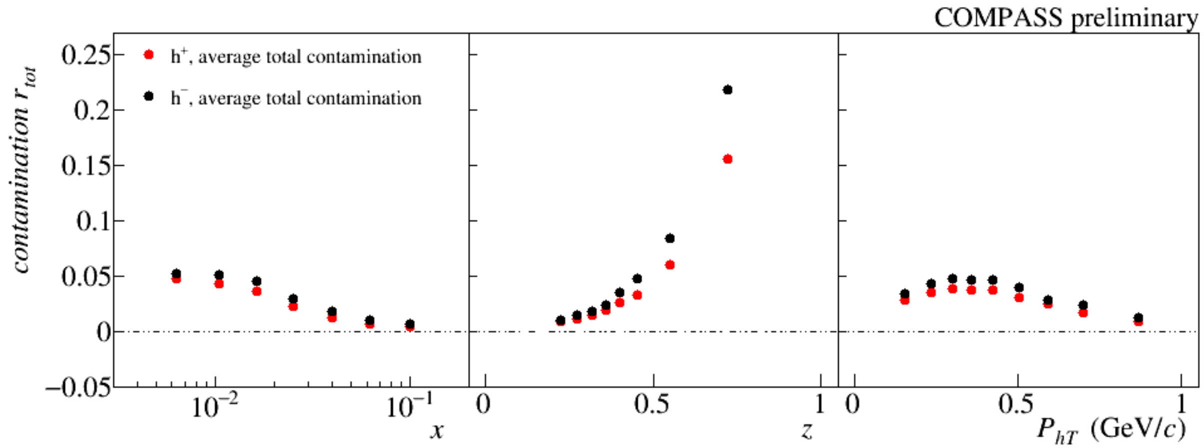
- The azimuthal modulations of decay hadrons are implemented in the Monte Carlo via the *Spin Density Matrix Elements* (SDME's), measured in COMPASS
- The data – Monte Carlo agreement for raw 2h "asymmetries" is satisfactory.



Diffractive vector mesons contamination

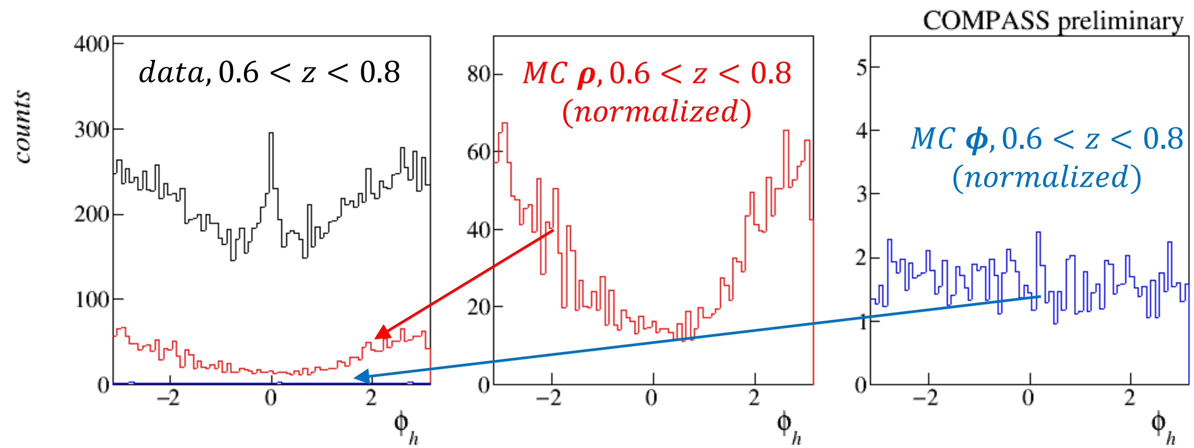
Estimated contamination

$$r_{tot} = \frac{N_h^{excl}}{N_h^{tot}} = \frac{N_h^{excl,1h} + N_h^{excl,2h}}{N_h^{tot}}$$



Example
Subtraction of azimuthal spectra

azimuthal spectra for diffractively produced ρ and ϕ (Monte Carlo) subtracted from the data



Conclusions

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

- Both have seen and are seeing a deep investigation both experimentally and theoretically.

- After addressing these topics with a deuteron target, the COMPASS Collaboration is working on the analysis of the proton data collected in 2016 and 2017.

- Promising preliminary results have been shown for both the considered observables.

- A new method for the subtraction of events from diffractive production of vector mesons is used

- Analysis in a multi dimensional space of variables (including q_T, rapidity …) ongoing

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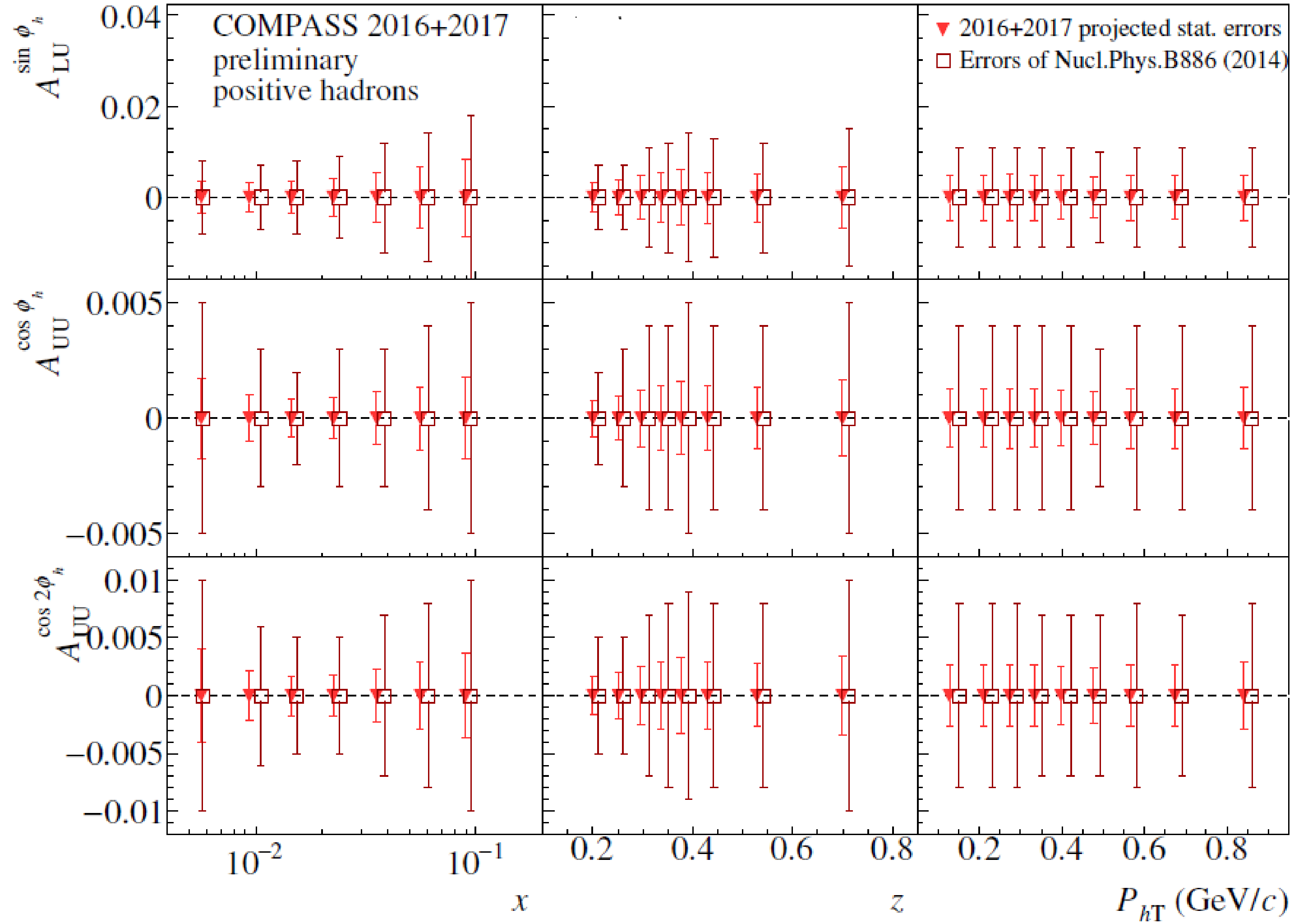
- A challenging analysis, but – we think – of great impact for the TMD physics.

backup

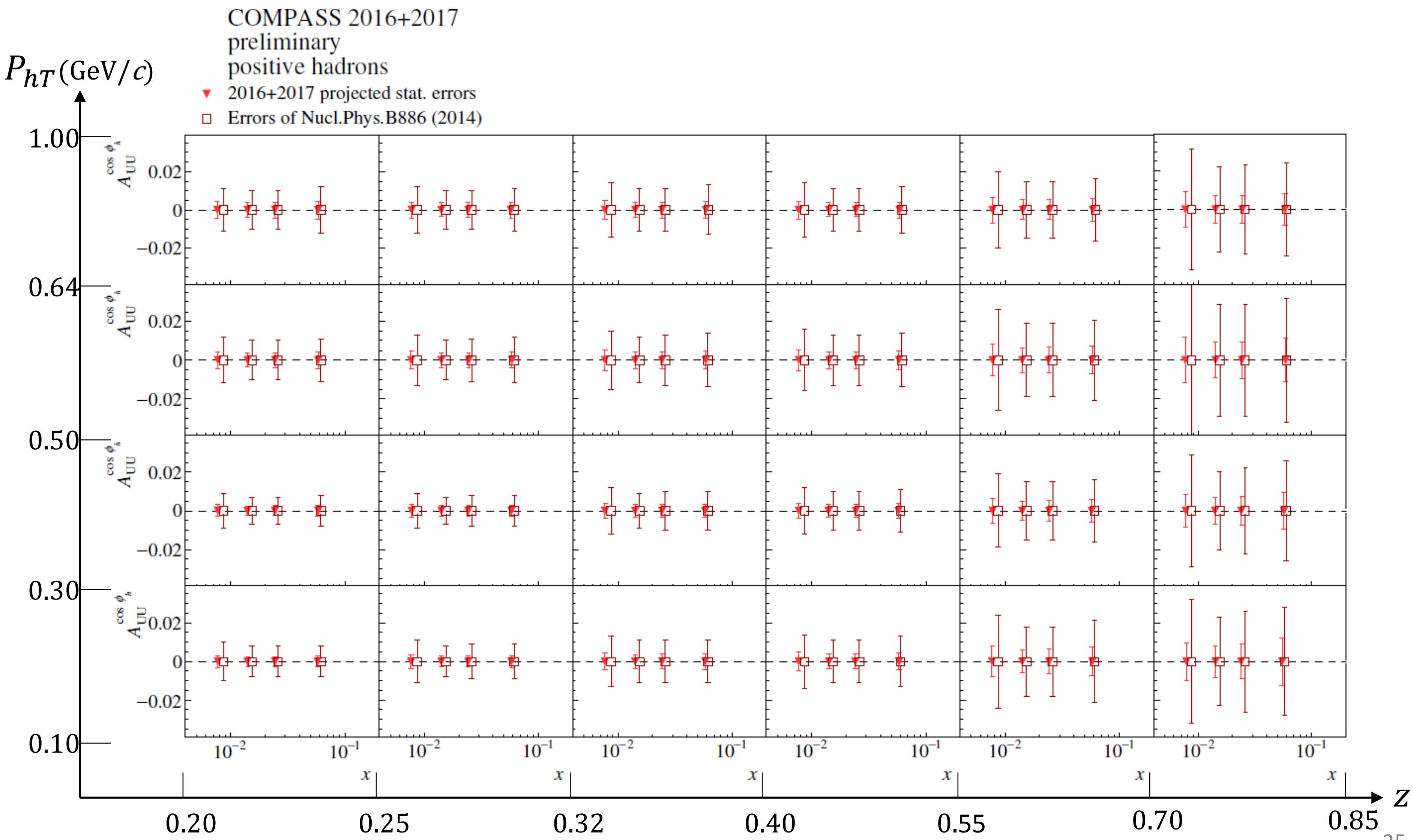
Projection for the 1D asymmetries (full target length)

Systematic uncertainties on the published results: **~2** x statistical uncertainty
expected for the new results: **~1** x statistical uncertainty



Projection for the 3D asymmetries (full target length)

- **COMPARISON WITH PUBLISHED DEUTERON for the $cos\ \phi_h$ asymmetry**



Projection for the 4D asymmetries (full target length)

- $\cos\phi_h$ asymmetry in the first z bin $(0.2 < z < 0.3)$