Recent COMPASS TMD results
- ongoing studies -

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on behalf of the COMPASS Collaboration

The COMPASS experiment

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

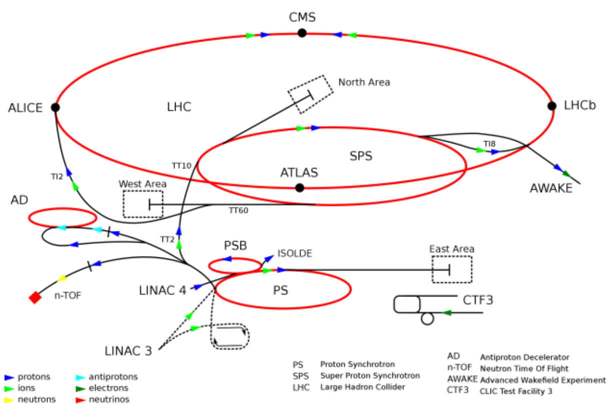
- 24 institutions from 13 countries (about 220 physicists)
- a fixed target experiment
- located in the CERN North Area, along the SPS M2 beamline

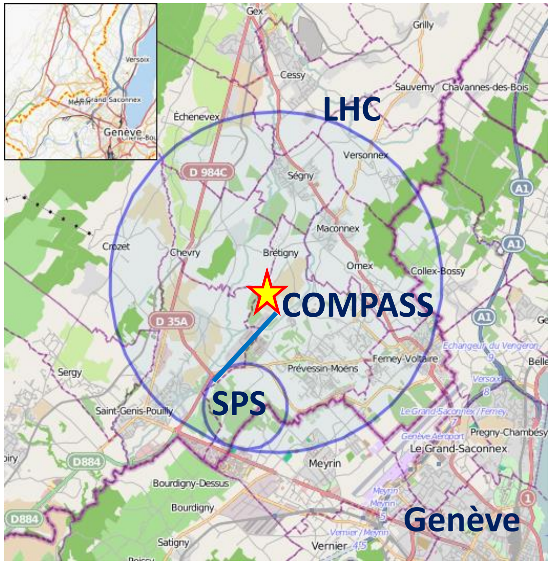
Broad research program:

- 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





Study of the nucleon structure

COMPASS contribution to the study of the nucleon structure (focus on SIDIS measurements)

- spin asymmetries with transversely polarized nucleons
  important results on the extraction of transversity and Sivers functions
- also, measurement in longitudinal configuration

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
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

Study of the nucleon structure

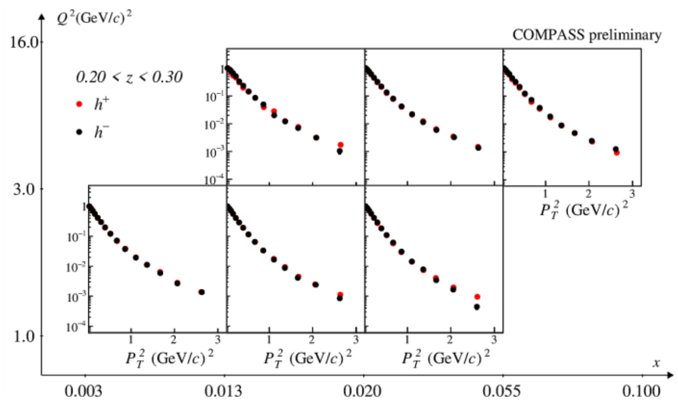
COMPASS contribution to the study of the nucleon structure (focus on SIDIS measurements)

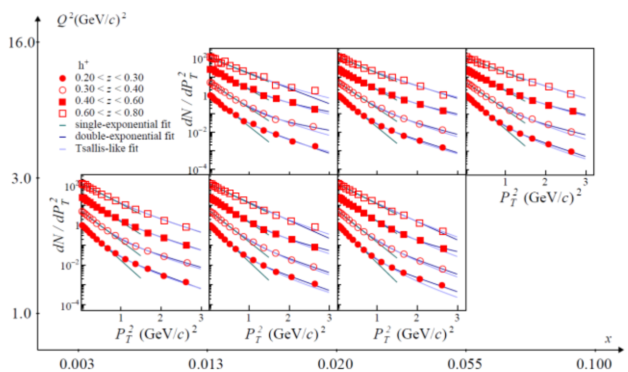
- spin asymmetries with transversely polarized nucleons
  important results on the extraction of transversity and Sivers functions
- also, measurement in longitudinal configuration
- SIDIS off unpolarized nucleons (deuteron, proton)
  P_T^2-distributions and azimuthal asymmetries

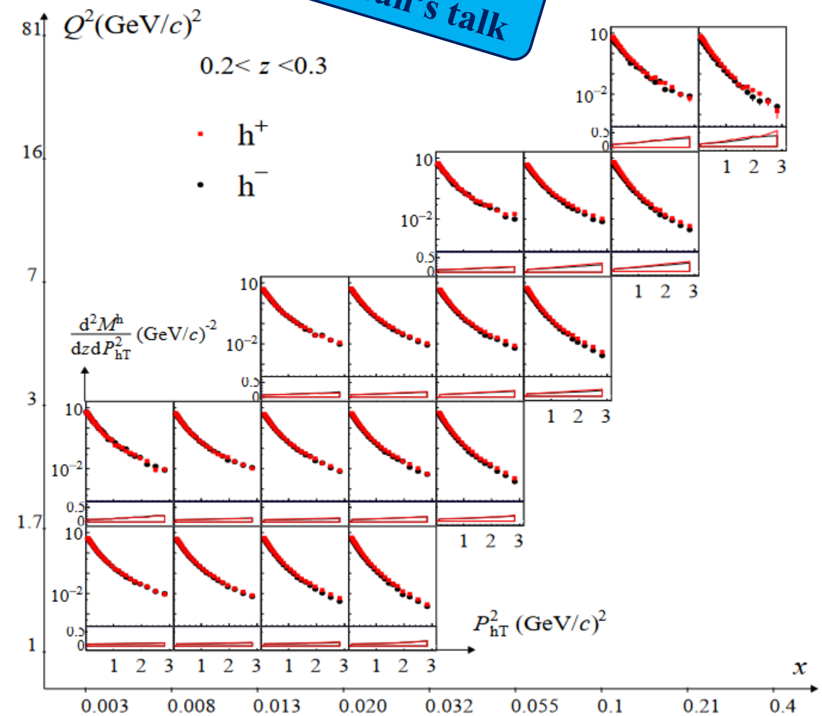
Nucleon \ Quark	U unpolarized	L longitudinally polarized	T transversely polarized
U unpolarized	$f_1^q(x, k_T^2)$ number density		$h_1^{\perp q}(x, k_T^2)$ Boer-Mulders

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

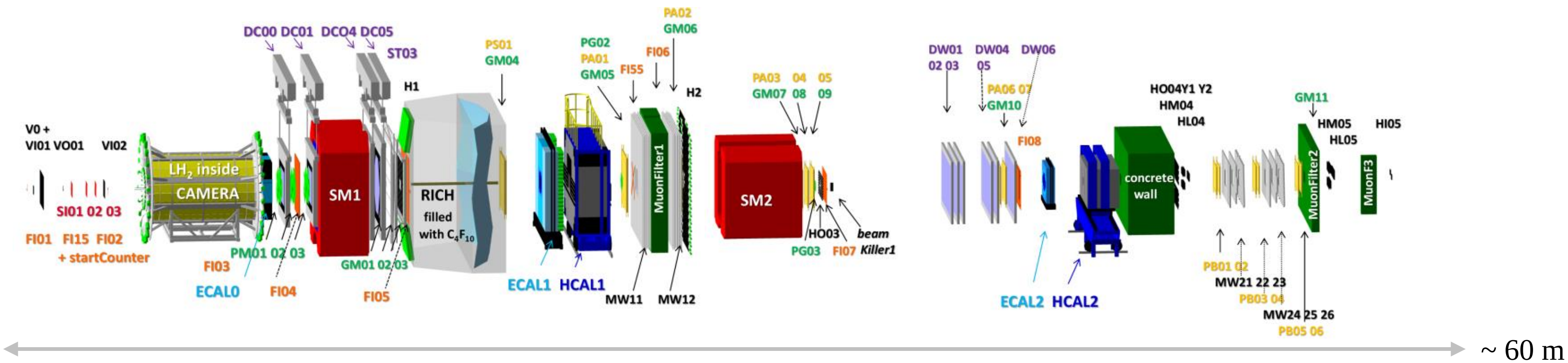
more in e.g. A. Bressan's talk







The 2016 COMPASS run



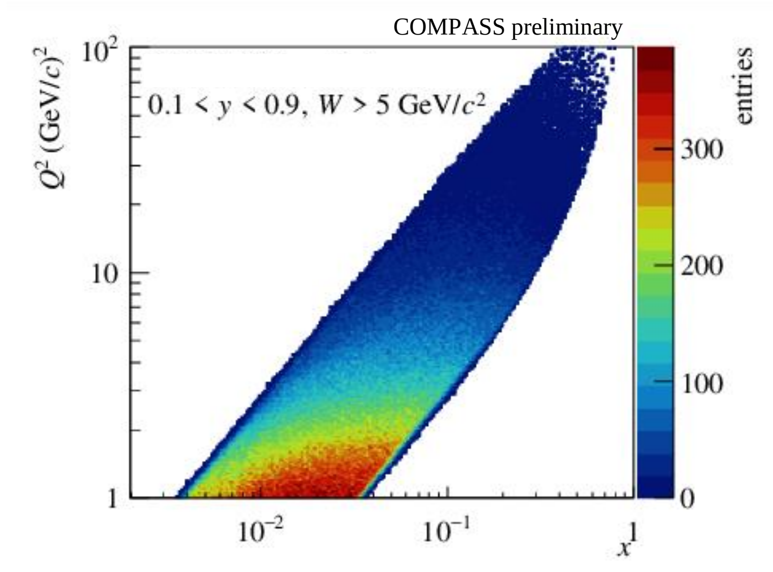
The 2016 COMPASS experimental setup

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

Unpolarized structure functions – 1h production

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 *:

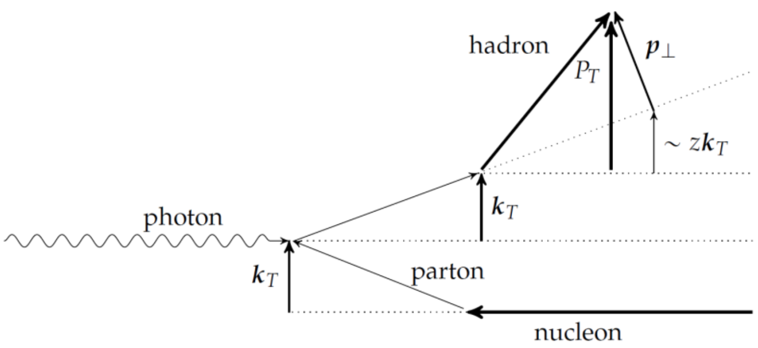
$$F_{UU,T} = \mathcal{C}[f_1 D_1]$$

Cahn effect — *Boer-Mulders term*

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

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

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

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.**

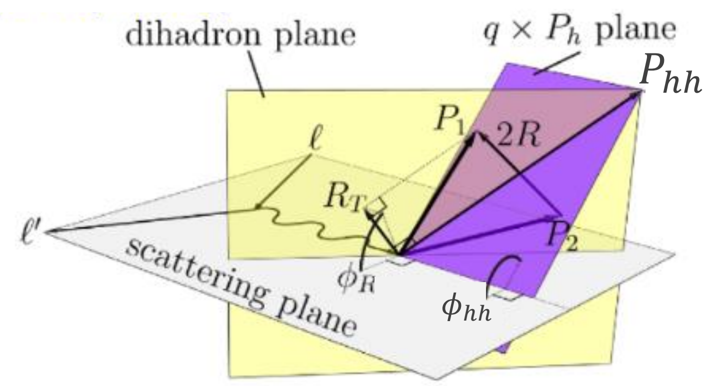
Bianconi, Boffi, Jakob, Radici **[PRD62, 034008, 2000]**

- leading twist formalism

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

- $\mathcal{F}$: 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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Additional information on the nucleon structure from the **azimuthal asymmetries for hadron pairs**.

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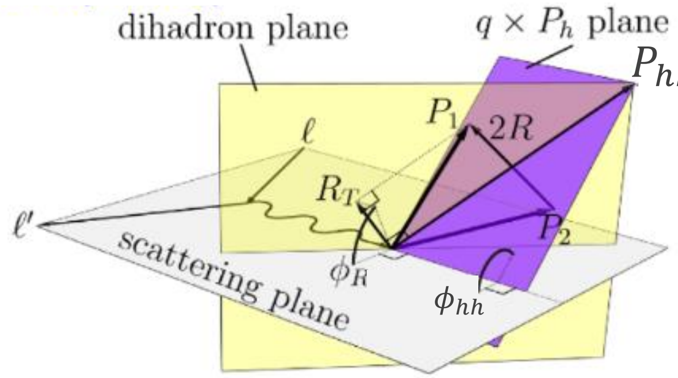
***Bacchetta, Radici* [PRD69, 074026, 2004]**

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

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

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

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



Events, hadrons and pairs selection

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

$z > 0.1$

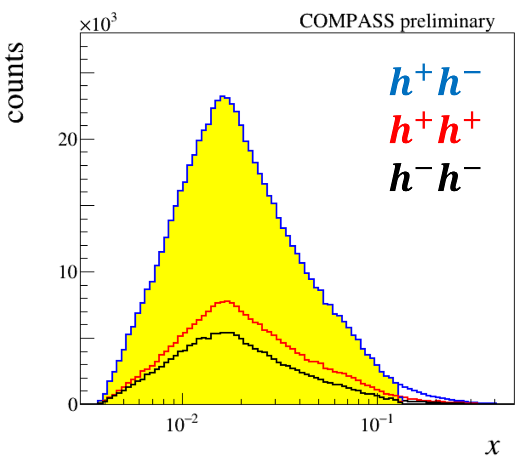
$P_T > 0.1\ \mathrm{GeV}/c$

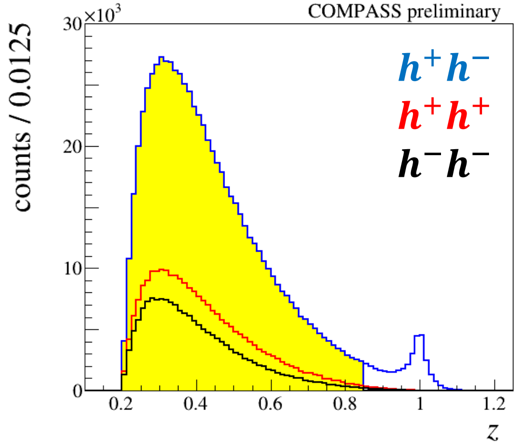
Size of the hadron sample: ~ 6.5 M hadrons

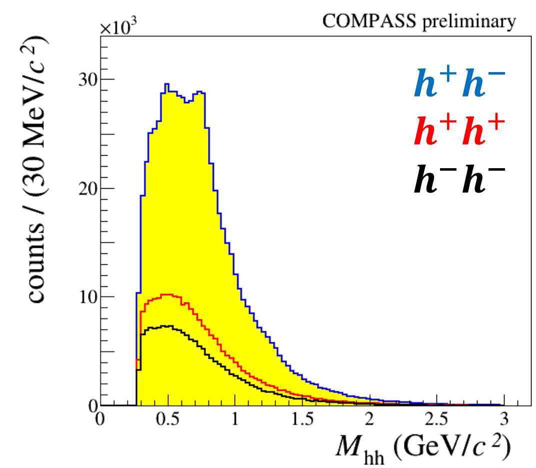
Additional cuts on the hadron pairs

$0.2 < z = (z_1 + z_2) < 0.85$
$M_{hh} < 3.0\ \mathrm{GeV}/c^2$

~ 3.5 M hadron pairs
65% h^+h^-,
20% h^+h^+, 15% h^-h^-





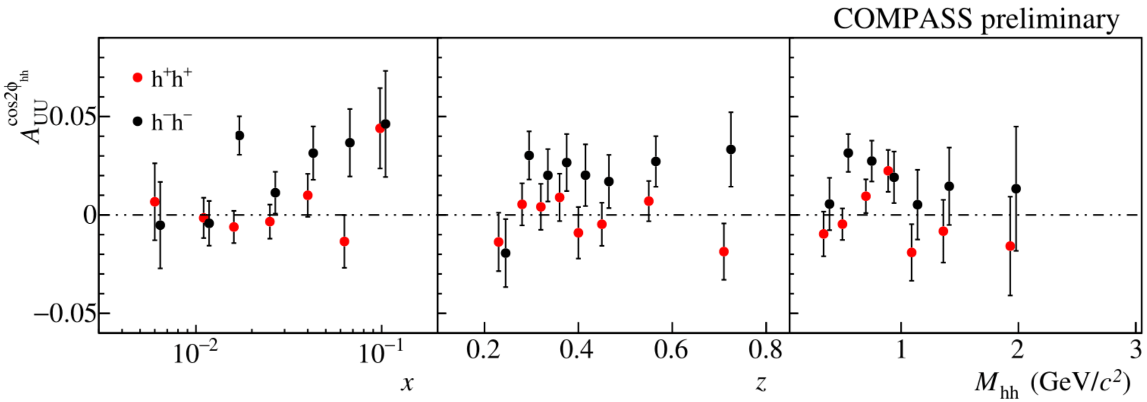


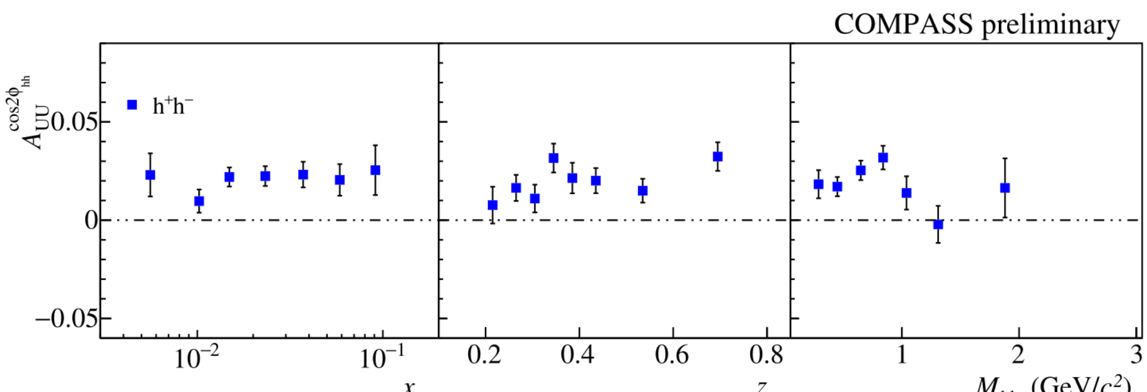
Azimuthal asymmetries for hadron pairs - $A_{UU}^{\cos 2\phi_{hh}}$

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

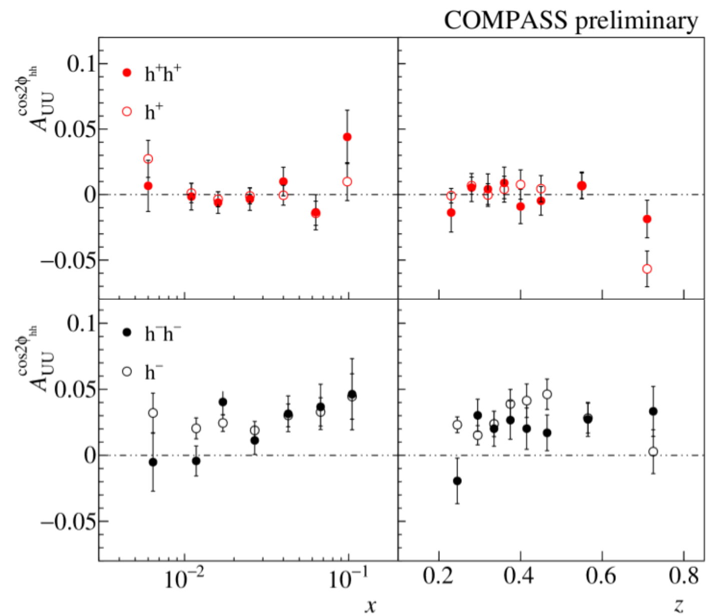
- Asymmetry $A_{UU}^{cos2\phi_{hh}}$ for same-sign pairs (h^+h^+, h^-h^-) and opposite-sign pairs h^+h^-

- For same-sign pairs: similar trends w.r.t. single-hadron case
  compatible with zero for positive pairs, positive for negative pairs





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

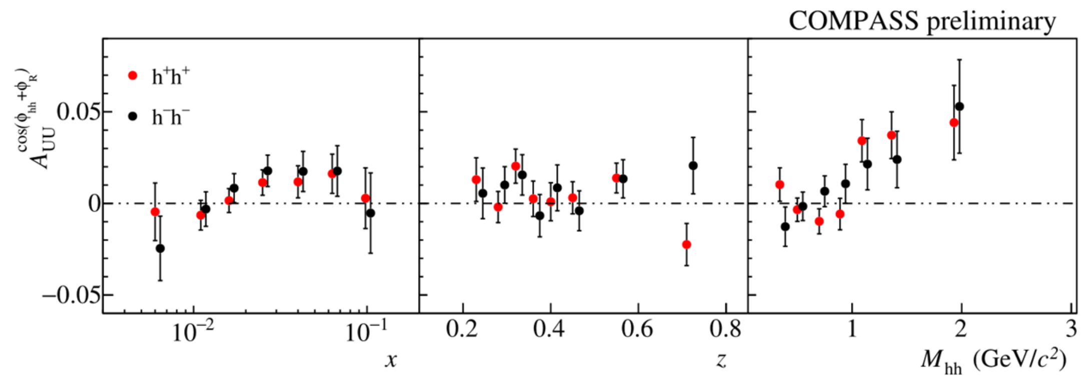


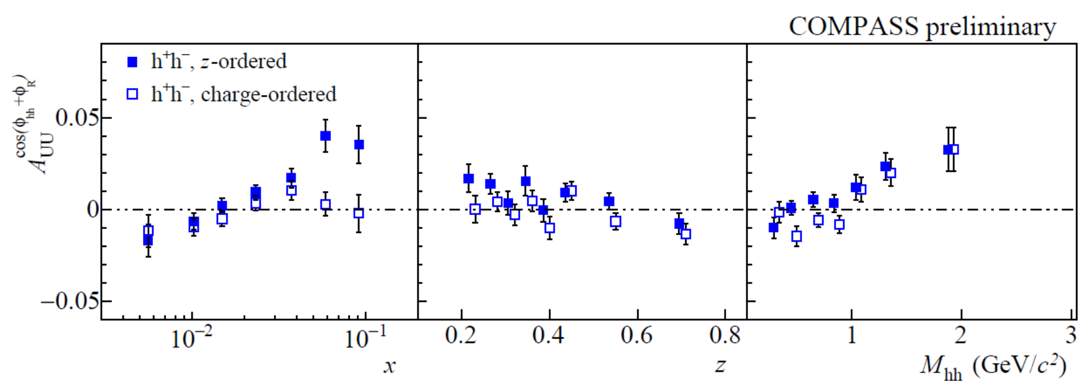
Azimuthal asymmetries for hadron pairs- $A_{UU}^{\cos(\phi_{hh}+\phi_R)}$

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

- Asymmetry $\boldsymbol{A_{UU}^{cos(\phi_{hh}+\phi_R)}}$ 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.
- Interesting comparison of the two ordering schemes for h^+h^- : difference at high x

$$\vec{R} = \frac{z_2\vec{P}_1 - z_1\vec{P}_2}{z_1+z_2}$$





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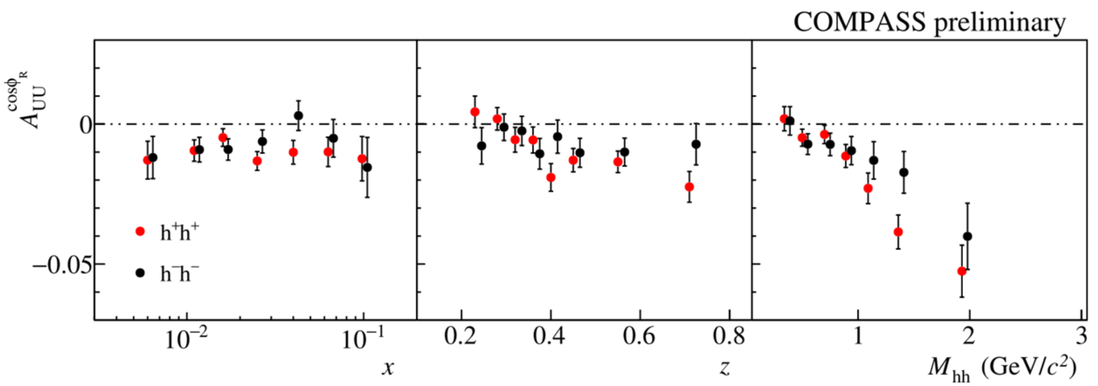
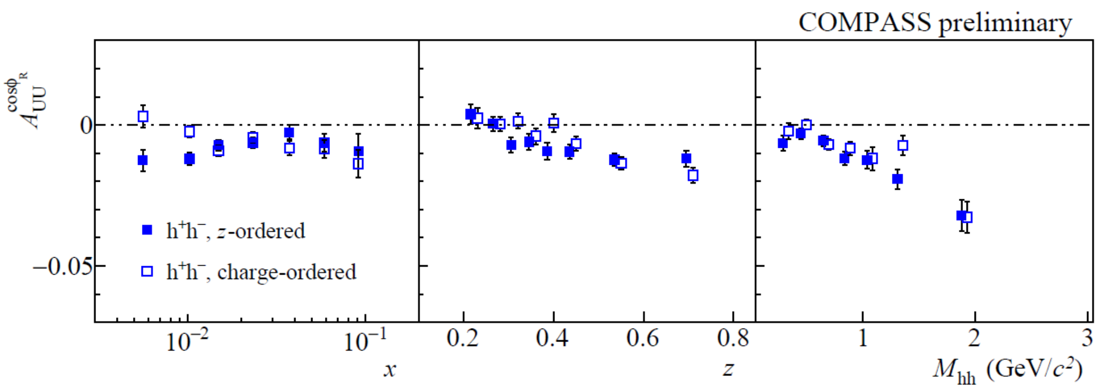
Azimuthal asymmetries for hadron pairs - $A_{UU}^{\cos\phi_R}$

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

- 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.
- Interesting comparison of the two ordering schemes for h^+h^- : difference at low x and intermediate invariant mass





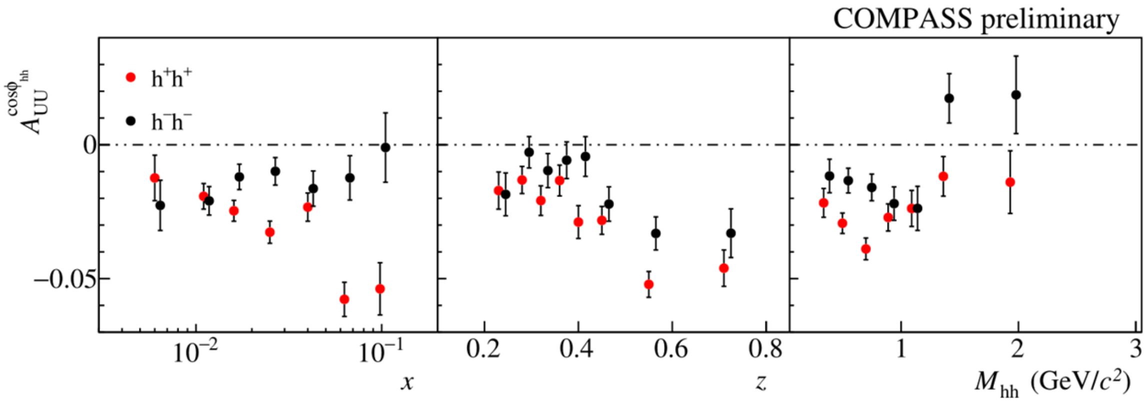
$$\vec{R} = \frac{z_2\vec{P}_1 - z_1\vec{P}_2}{z_1 + z_2}$$

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

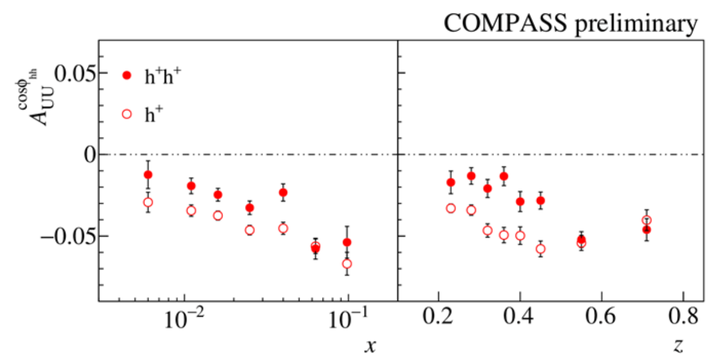
Azimuthal asymmetries for hadron pairs - $A_{UU}^{\cos\phi_{hh}}$

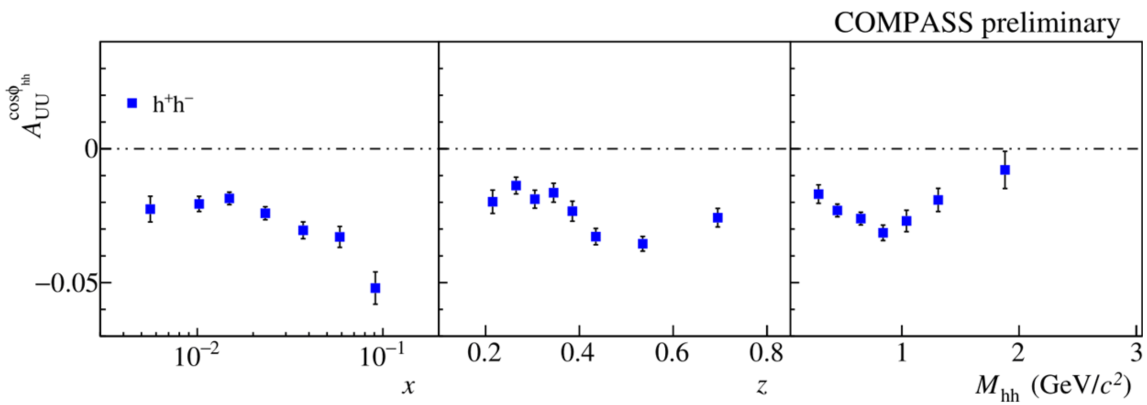
By-product of the analysis: $A_{UU}^{cos\phi_{hh}}$ (higher twist, as in the 1h case)
In the 1h case, asymmetry generated by Cahn + Boer-Mulders effects.

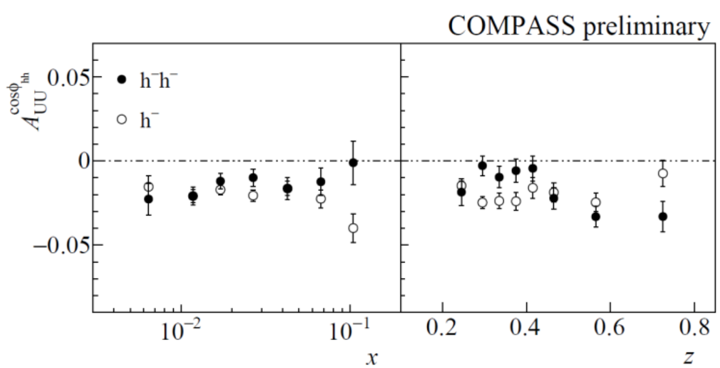
- Asymmetry $\boldsymbol{A_{UU}^{cos\phi_{hh}}}$ for same-sign pairs (h^+h^+, h^-h^-) and opposite-sign pairs h^+h^-
- A clear and strong signal



Similar trends compared to the 1h cases







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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 the **azimuthal asymmetries** for single hadrons and **(NEW!) hadron pairs.**
- Interesting additional information on the nucleon structure (here: focus on the **Boer-Mulders** related asymmetries)
- Deeper studies are deserved are foreseen.

Thank you

Backup