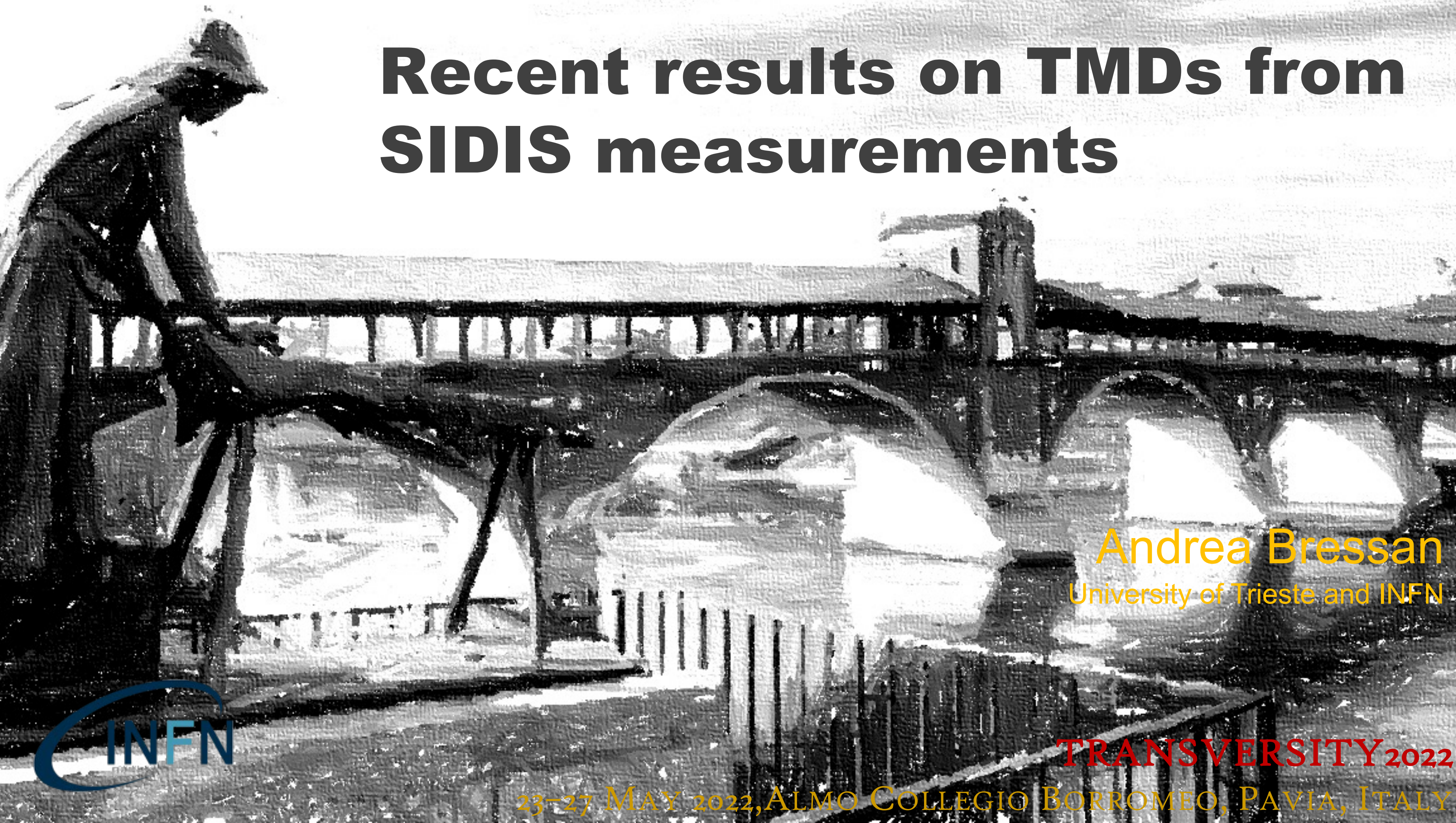


Recent results on TMDs from SIDIS measurements

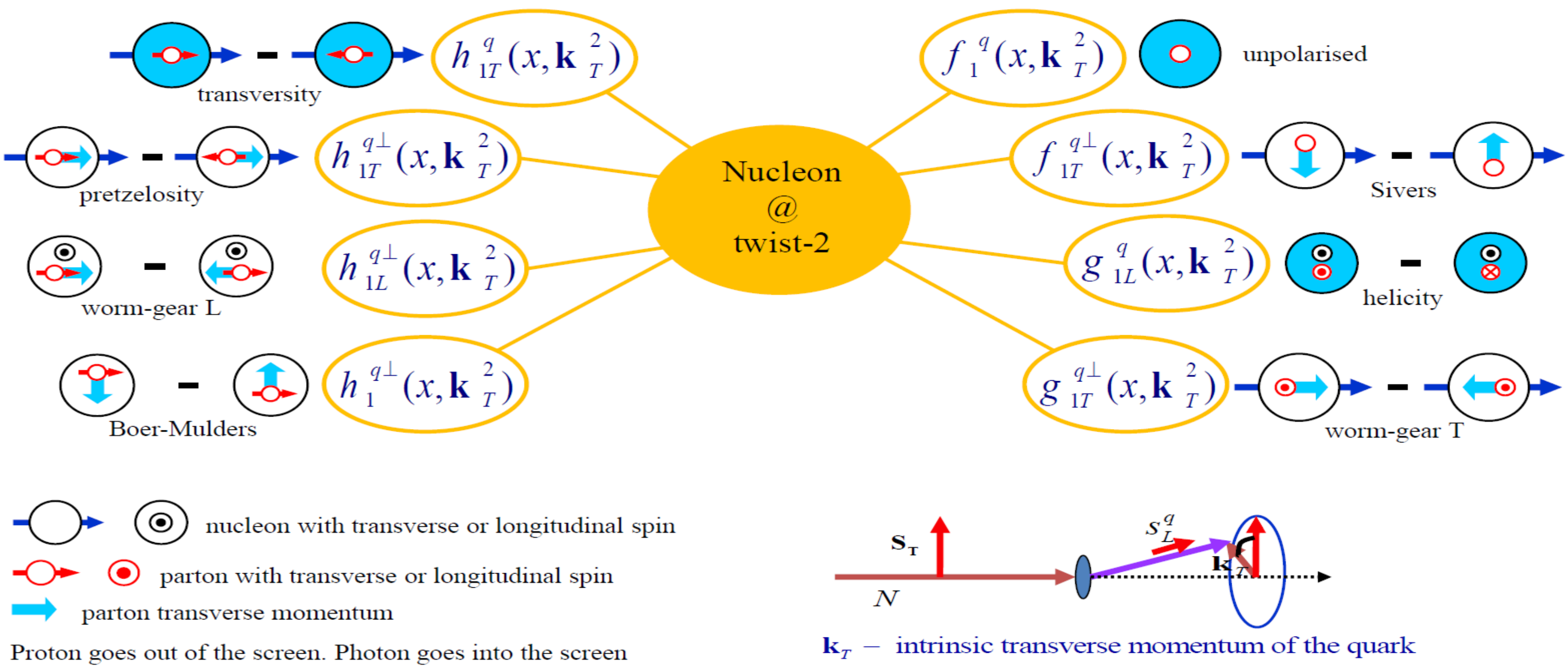
Andrea Bressan

University of Trieste and INFN

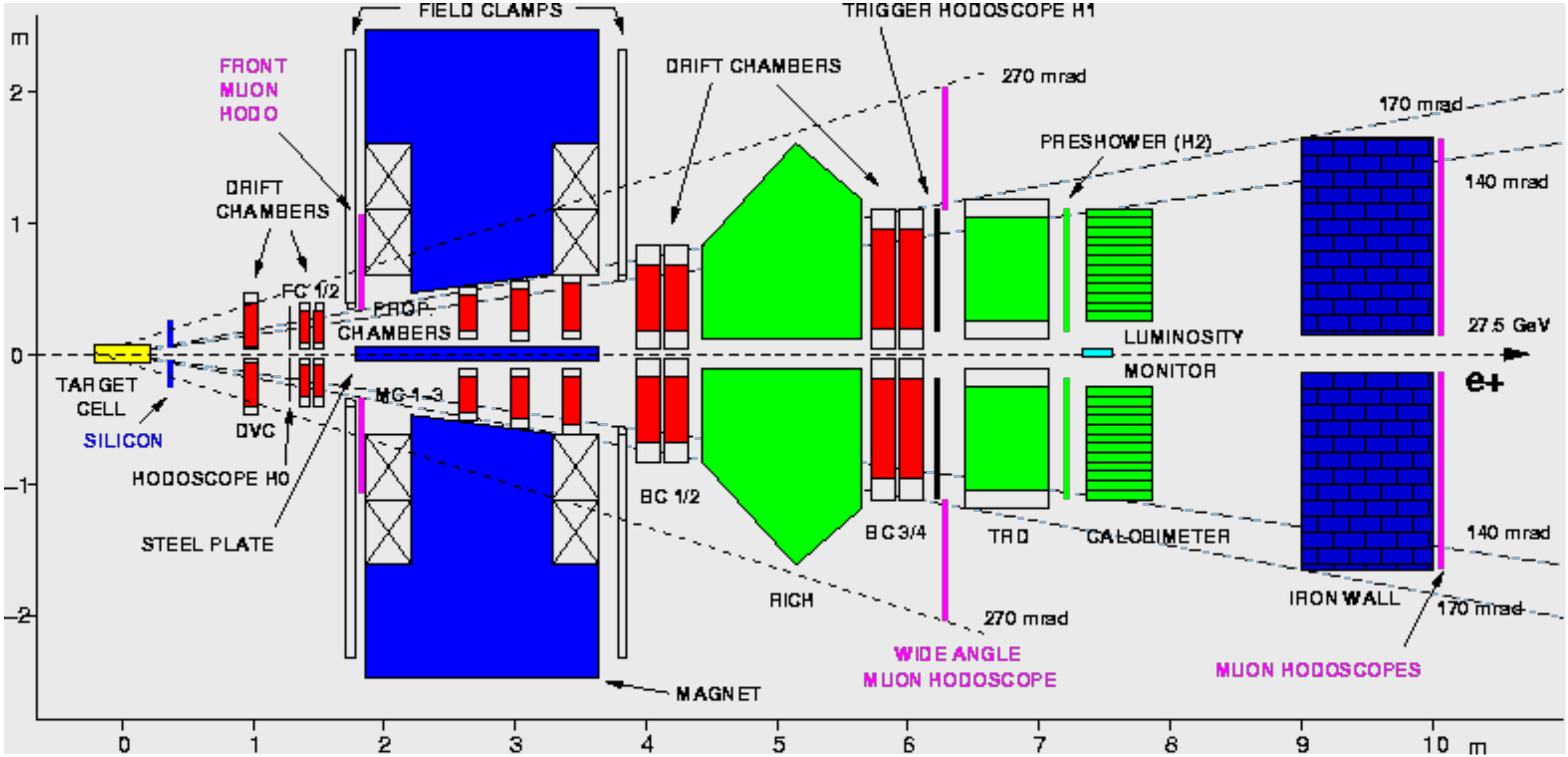
TRANSVERSITY2022

23–27 May 2022, Almo Collegio Borromeo, Pavia, Italy

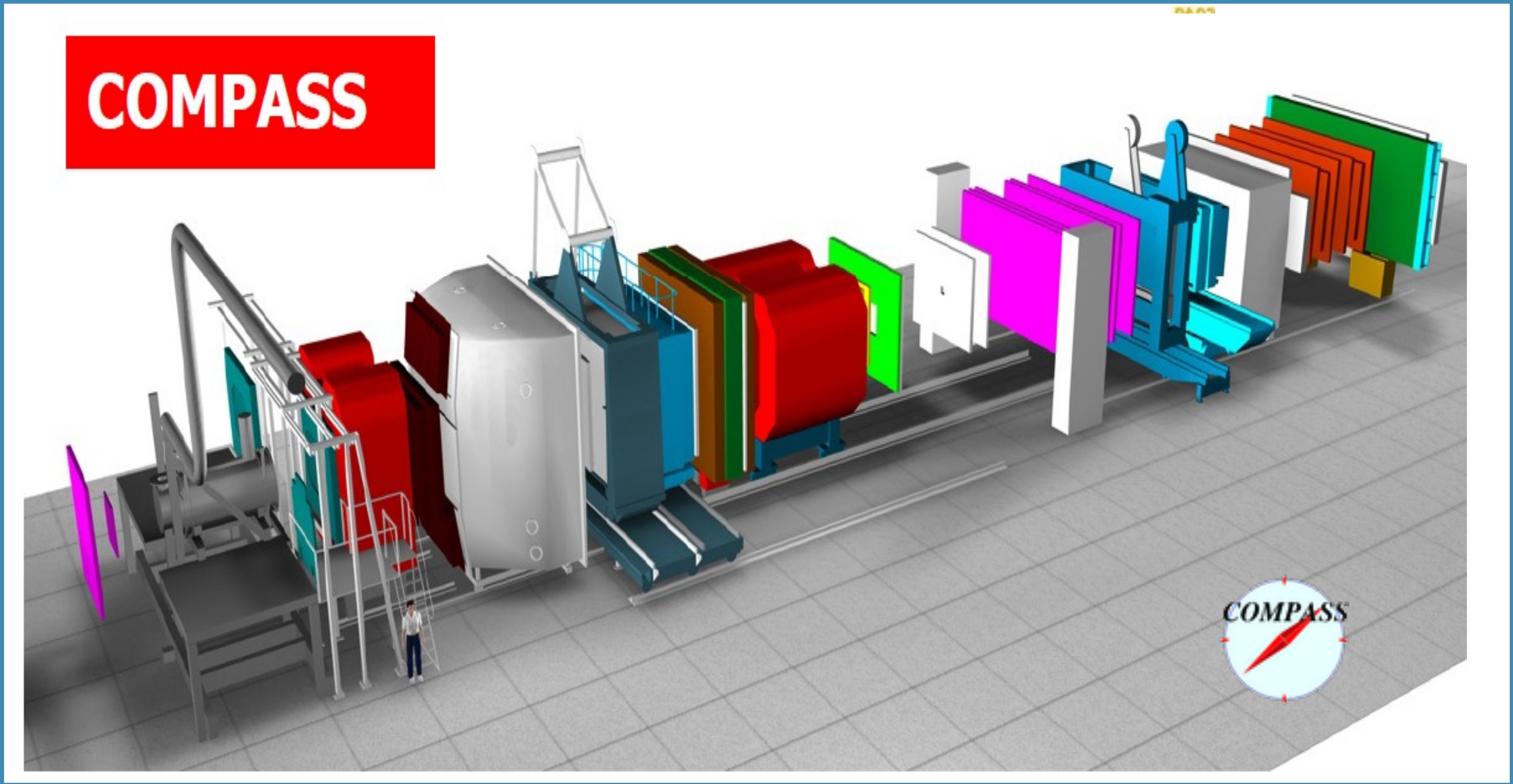
TMD Distribution Functions



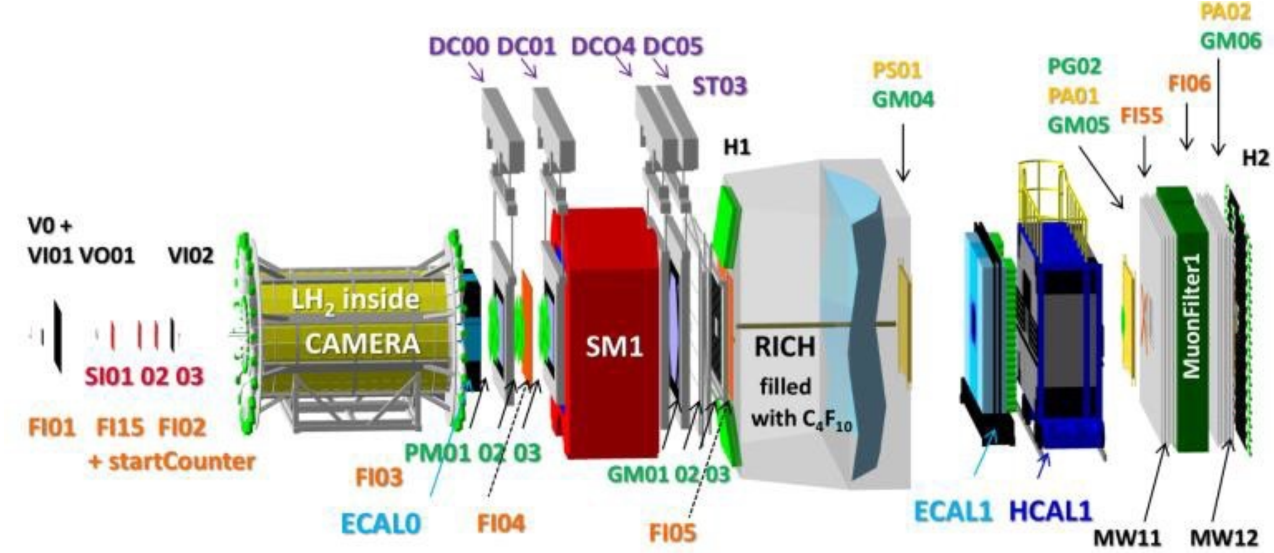
SIDIS @ HERMES

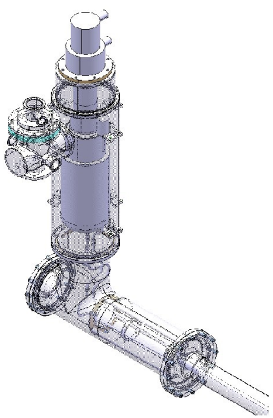


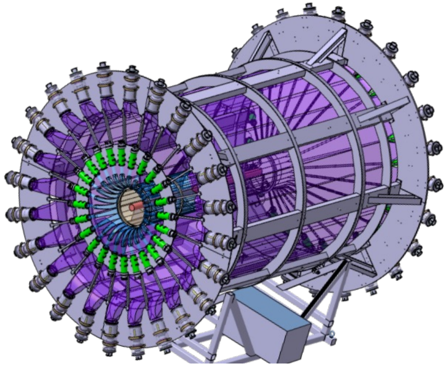
SIDIS @ COMPASS

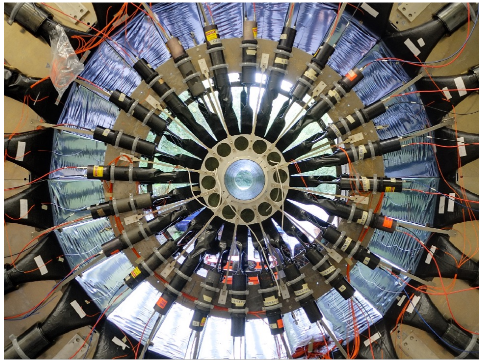


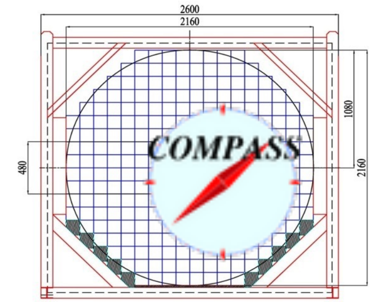
SIDIS @ COMPASS



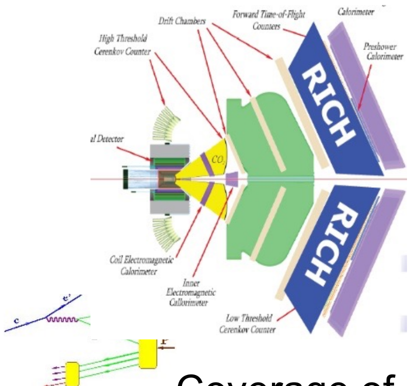








SIDIS at JLab12



Coverage of large Q^2 and large P_T

Proton

CLAS12

- E12-06-112: π^+,π^-,π^0 E12-09-008: K^+, K^-, K^0
- E12-07-107: π^+,π^-,π^0 E12-09-009: K^+,K^-,K^0
- C12-11-111: π^+,π^-,π^0 K^+, K^-

H_2, NH_3, HD

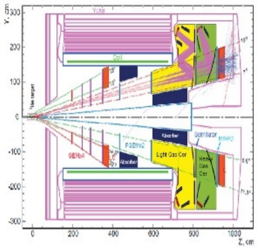
Quark spin polarization / Nucleon polarization

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Hall C | Hall A

- E12-09-017: π^+,π^-, K^+,K^- C12-11-102: π^0 — HMS SHMS
- C12-11-108: π^+,π^- — Solid

H_2 | NH_3



D_2

CLAS12

- E09-008: π^+,π^-,π^0 K^+, K^-,K^0
- E07-107: π^+,π^-,π^0 E09-009: K^+,K^-,K^0

D_2, ND_3

Quark spin polarization / Nucleon polarization

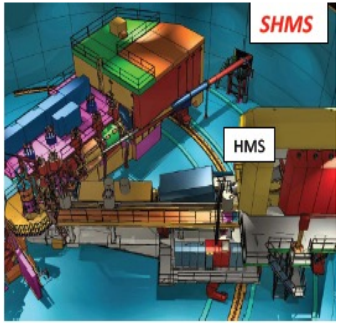
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Hall C

- E12-09-017: π^+,π^-, K^+,K^- C12-11-102: π^0 — HMS SHMS

D_2

Precision measurements of all SFs in a wide range



C12-20-002 π^+,π^-,π^0,K+

^3He

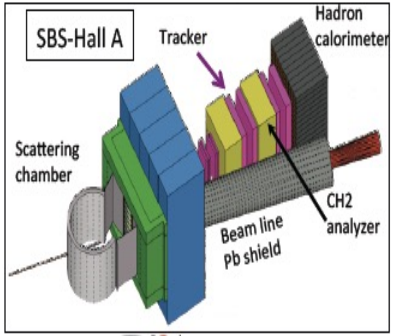
Quark spin polarization / Nucleon polarization

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

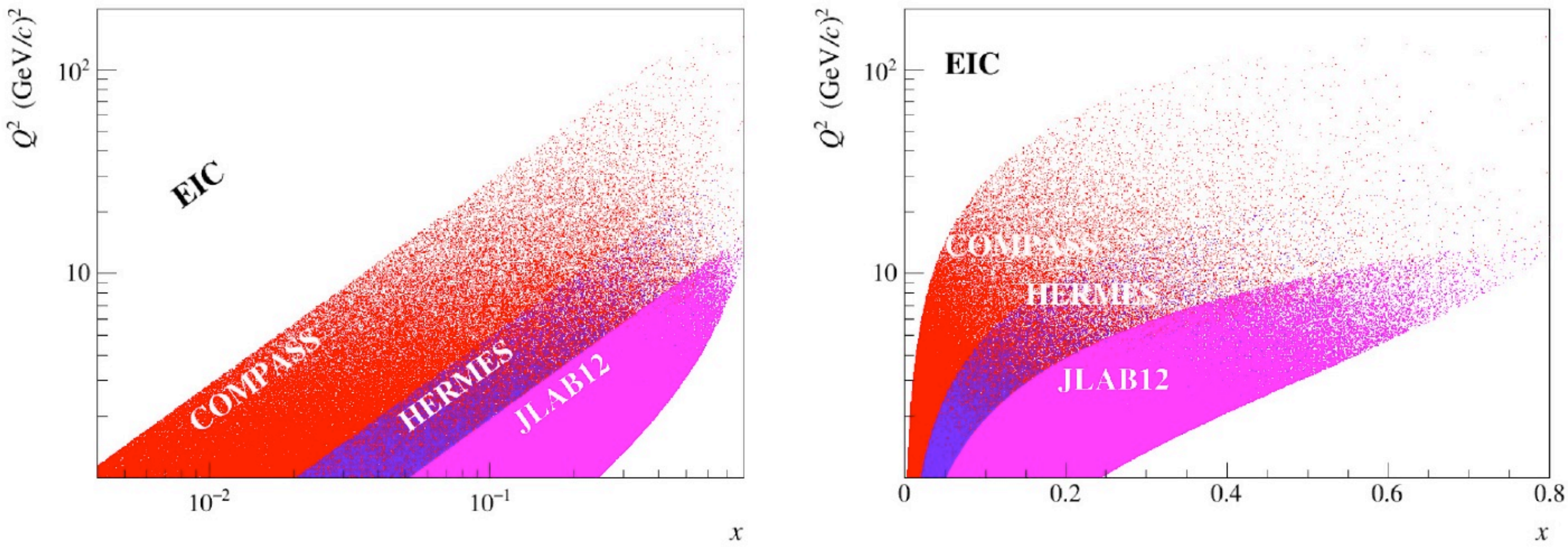
Hall A

- E12-07-007: π^+,π^- — Solid
- E10-006: π^+,π^- E12-09-018: π^+,π^-, K^+,K^- — Solid, SBS

^3He



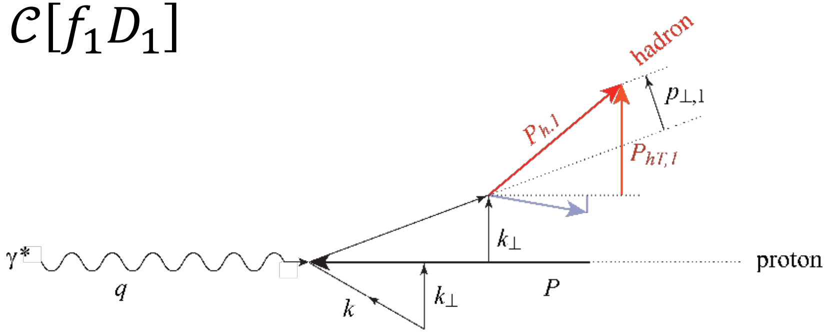
Kinematic coverage



UNPOLARIZED

Unpolarized SIDIS

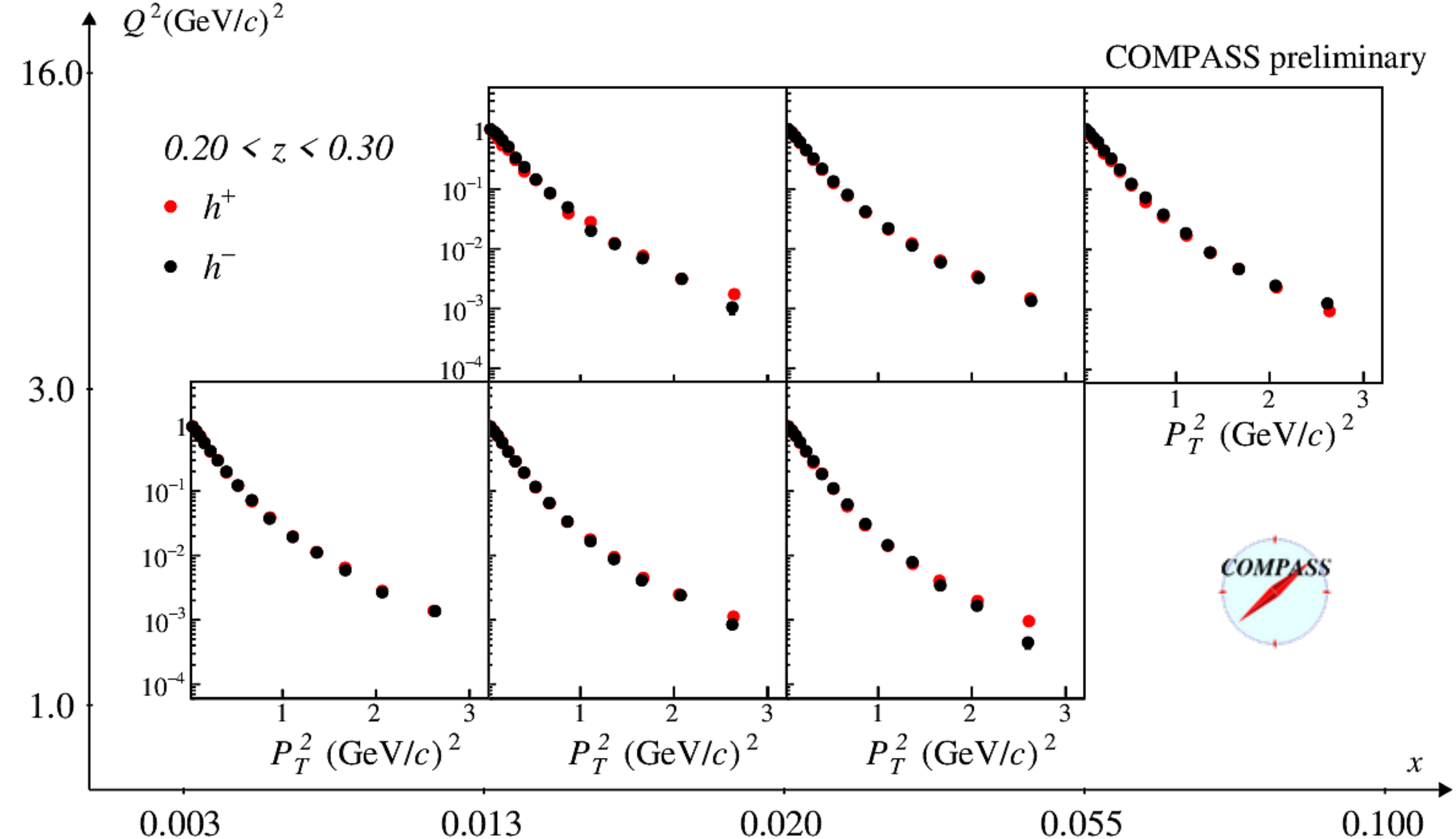
- The cross section is proportional to $\mathcal{C}[f_1 D_1]$
  - $f_1(x, k_\perp, Q^2)$
  - $D_1(z, p_\perp, Q^2)$



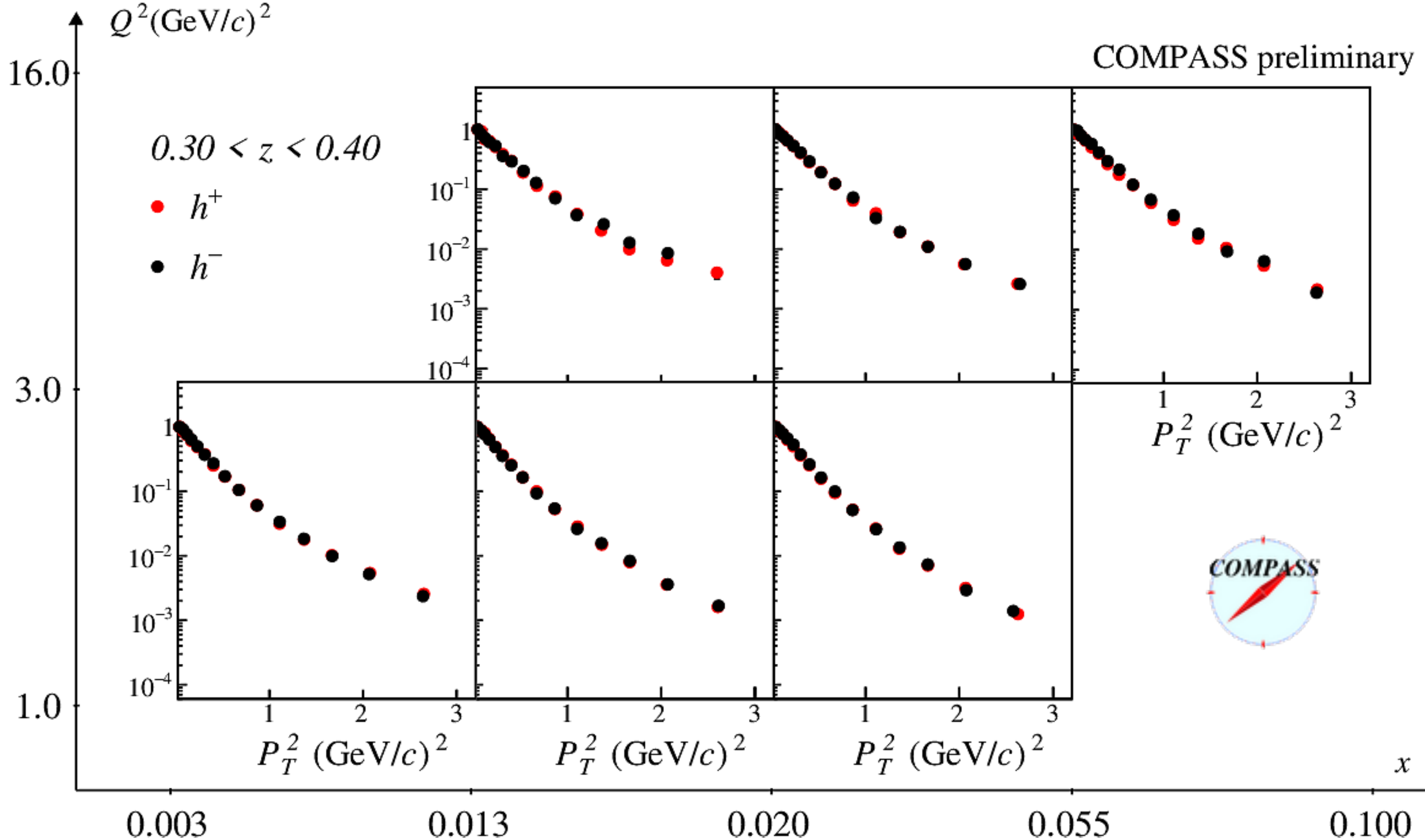
- The azimuthal modulations in the unpolarised cross sections comes from:
  - Intrinsic $k_\perp$ of the quarks
  - The Boer-Mulders PDF

- Difficult measurements were one has to correct for the apparatus acceptance

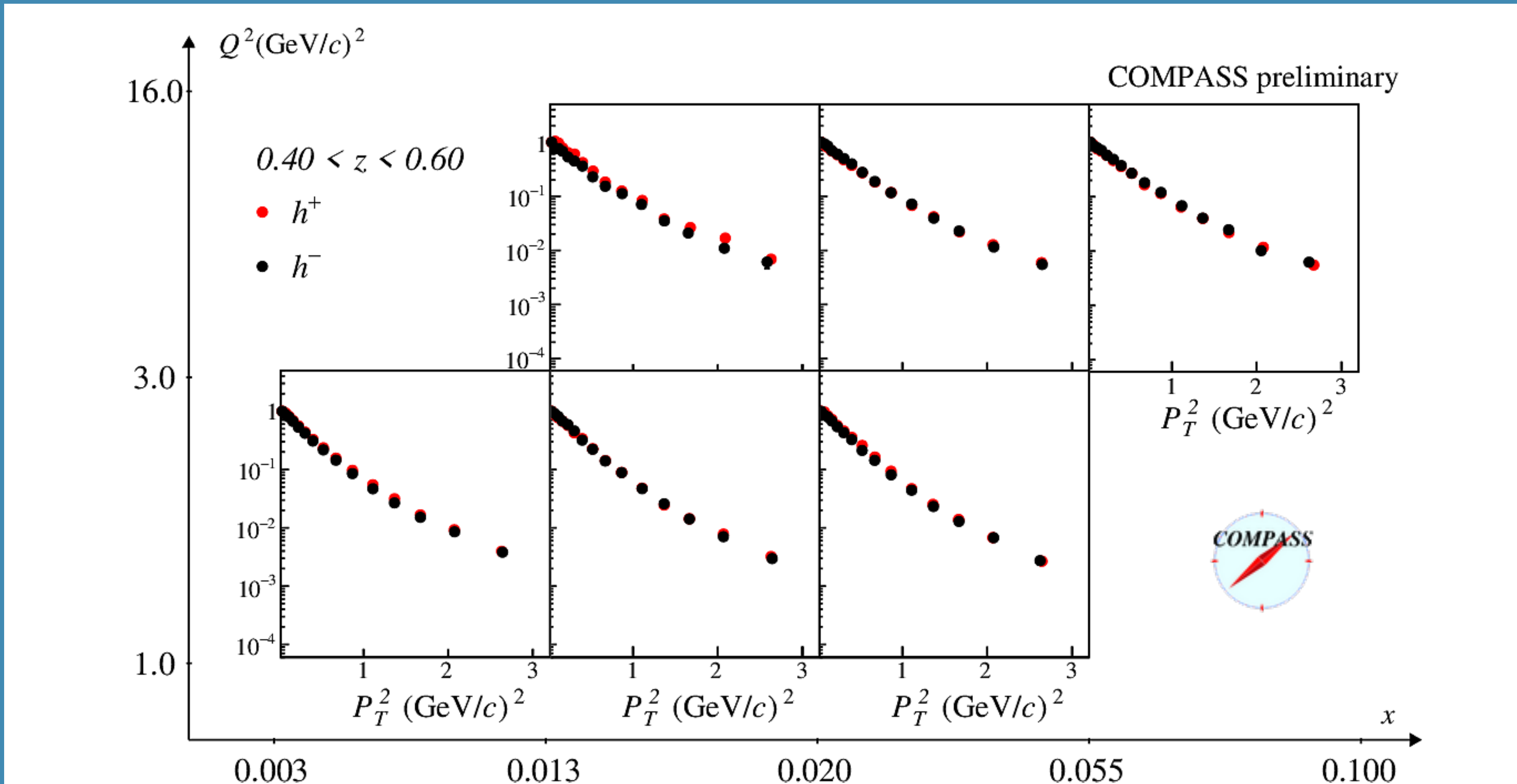
Unpolarized P_T^2 distributions



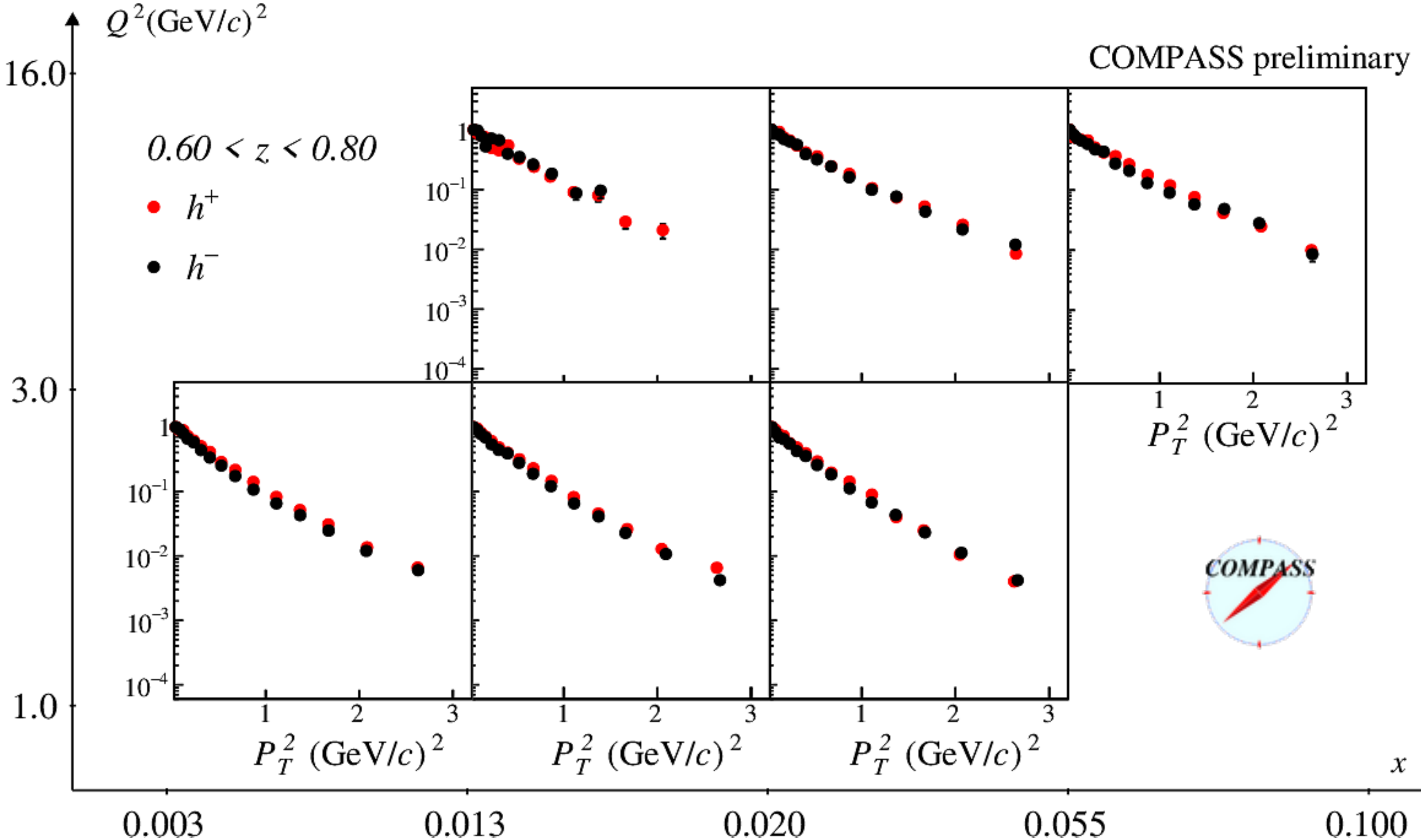
Unpolarized P_T^2 distributions



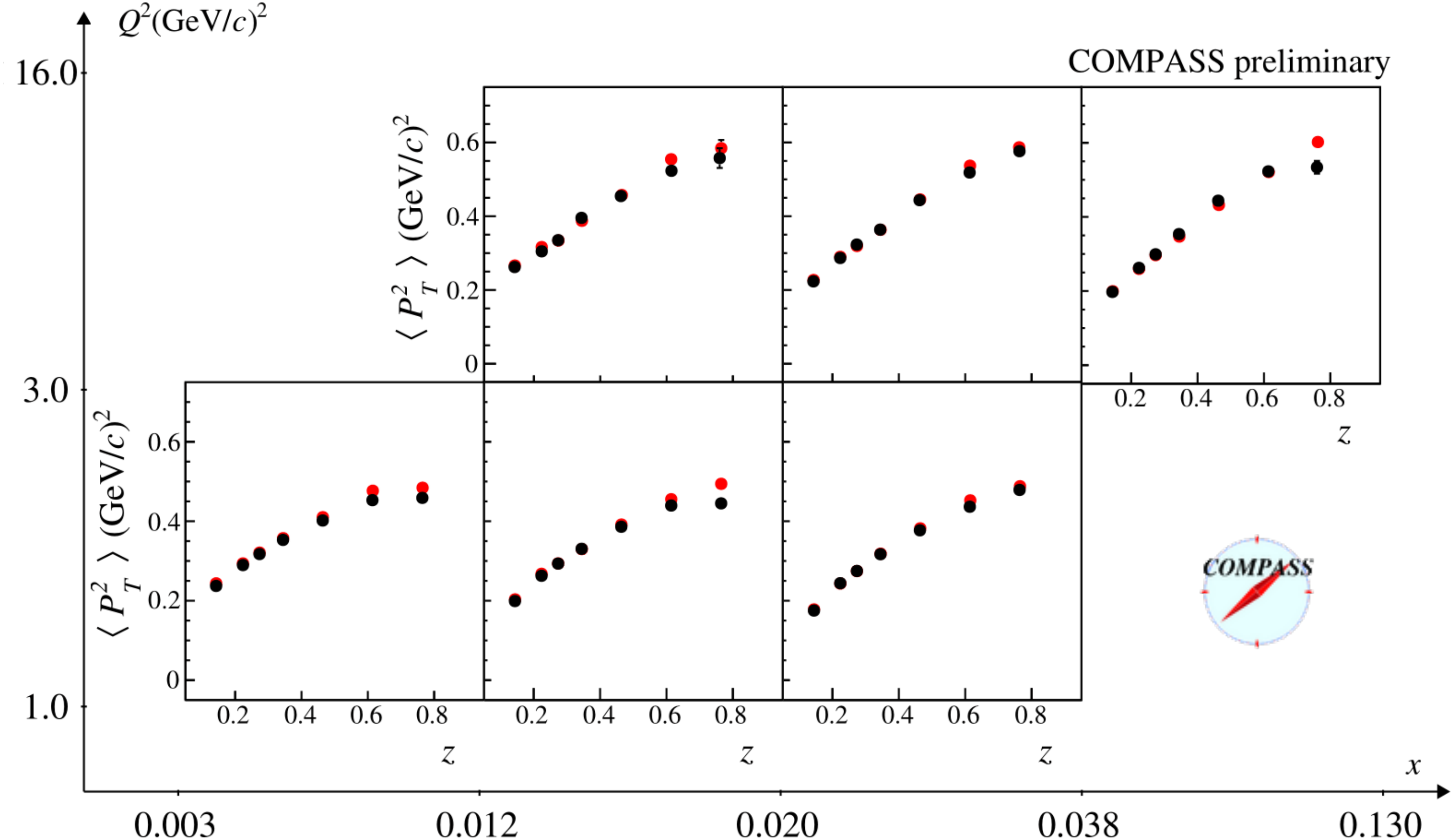
Unpolarized P_T^2 distributions



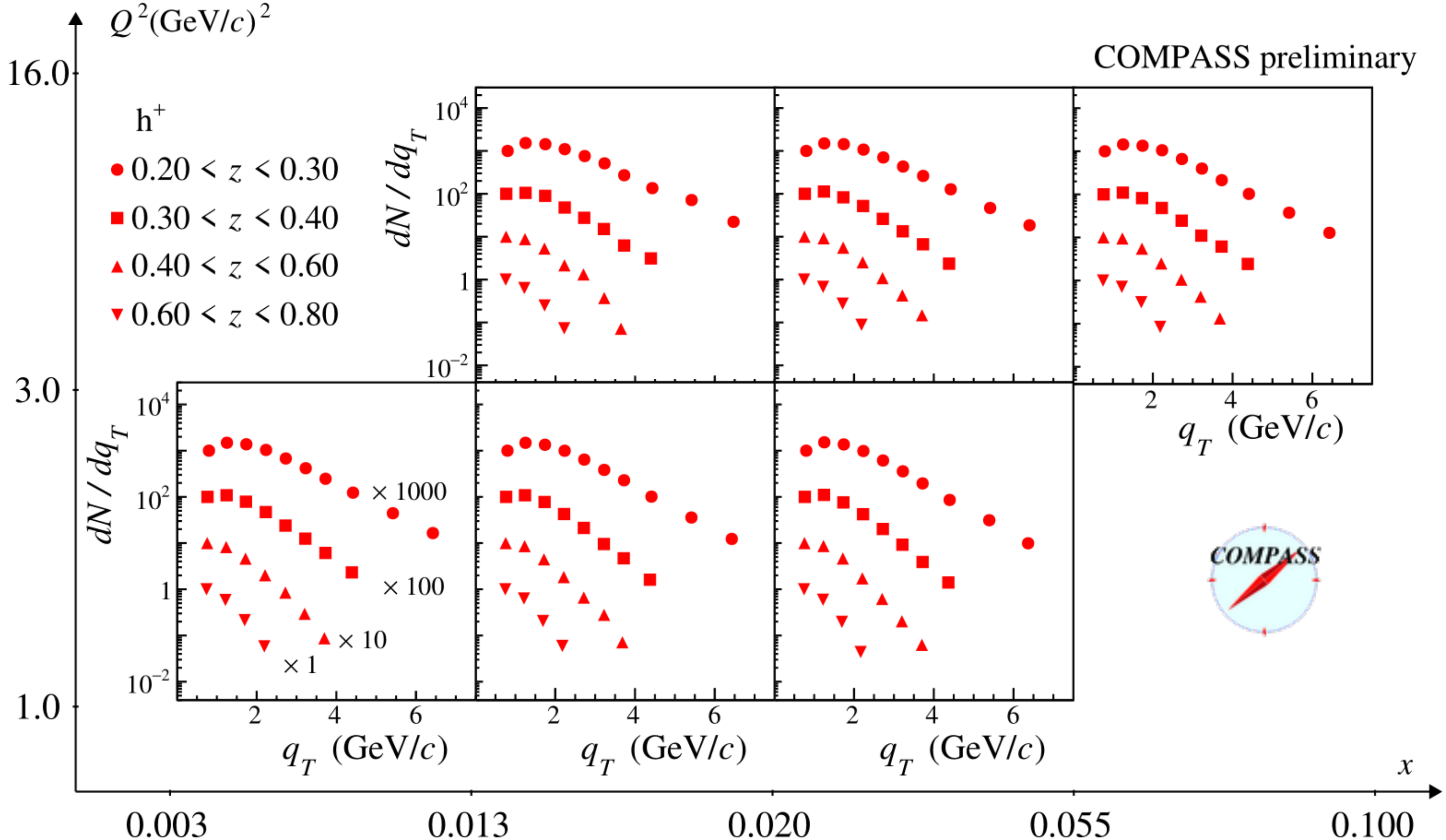
Unpolarized P_T^2 distributions



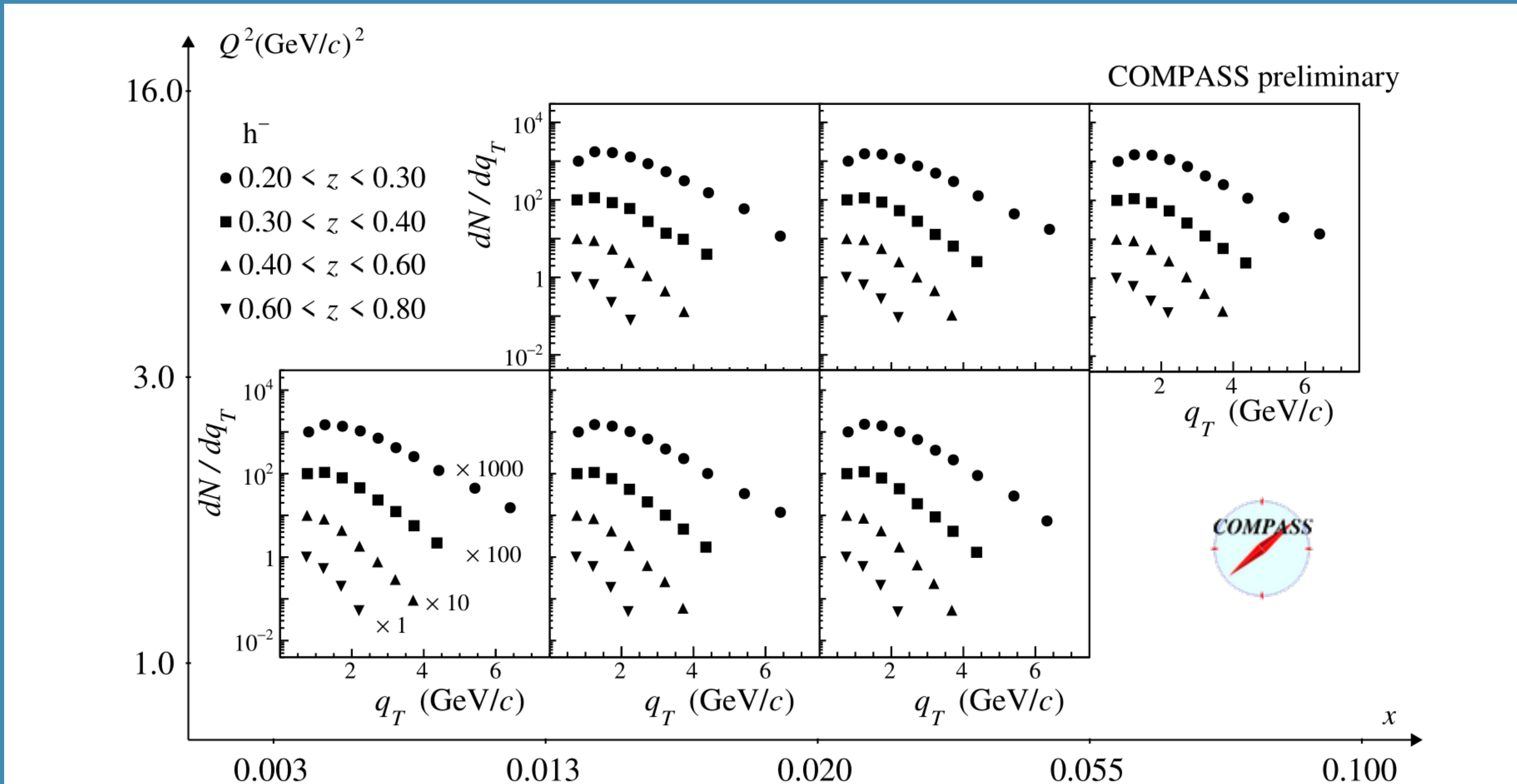
Unpolarized P_T^2 distributions



Unpolarized q_T distributions



Unpolarized q_T distributions



Unpolarised Azimuthal Modulation

When looking at the content of the structure functions/modulations in terms of TMD PDFs for the $\cos\phi_h$ and $\cos 2\phi_h$ we can write:

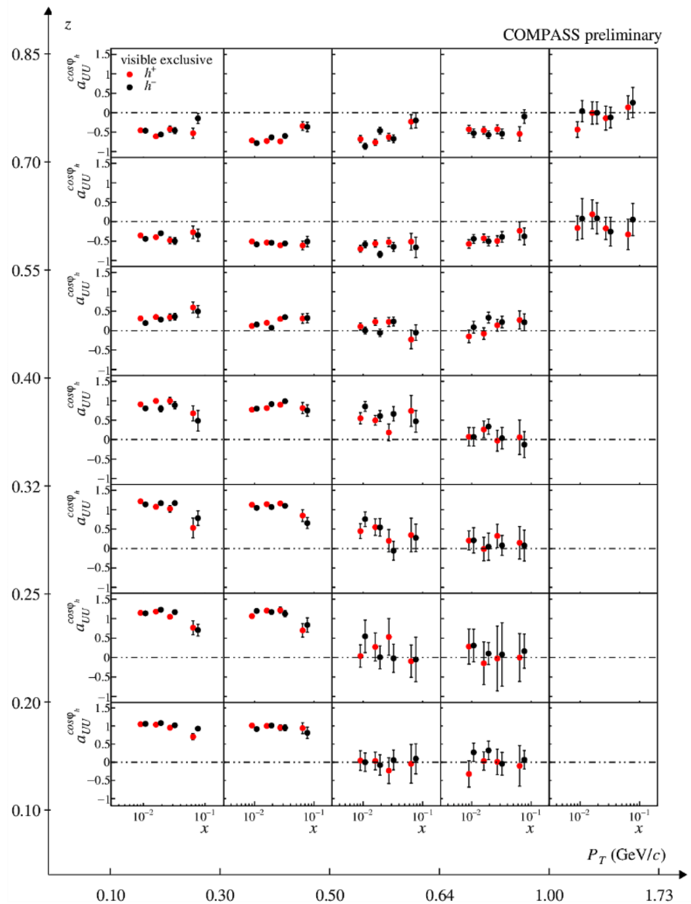
$$F_{UU}^{\cos\phi_h} = -\frac{2M}{Q} C\left[\frac{\hat{h}\cdot\vec{k}_\perp}{M} f_1 D_1 - \frac{p_\perp k_\perp}{M}\frac{\vec{P}_{hT} - z\left(\hat{h}\cdot\vec{k}_\perp\right)}{zM_h M} h_1^\perp H_1^\perp\right] + \text{twists} > 3$$

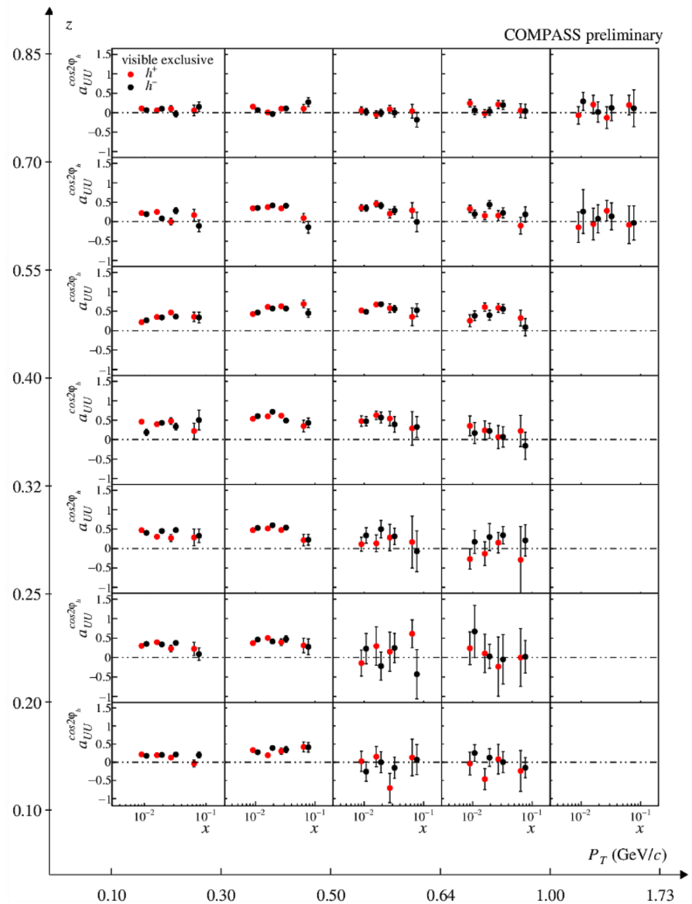
$$F_{UU}^{\cos 2\phi_h} = C\left[\frac{\left(\hat{h}\cdot\vec{k}_\perp\right)\left(\hat{h}\cdot\vec{p}_\perp\right) - \vec{p}_\perp\cdot\vec{k}_\perp}{MM_h} h_1^\perp H_1^\perp\right] + \text{twists} > 3$$

In the $\cos 2\phi_h$ Cahn effects enters only at twist4

$$F_{\text{Cahn}}^{\cos 2\phi_h} \approx \frac{2}{Q^2} C\left[\left\{2\left(\hat{h}\cdot\vec{k}_\perp\right)^2 - k_\perp^2\right\} f_1 D_1\right]$$

Cahn $\cos\phi_h$ and Boer-Mulders $\cos 2\phi_h$ Asyms

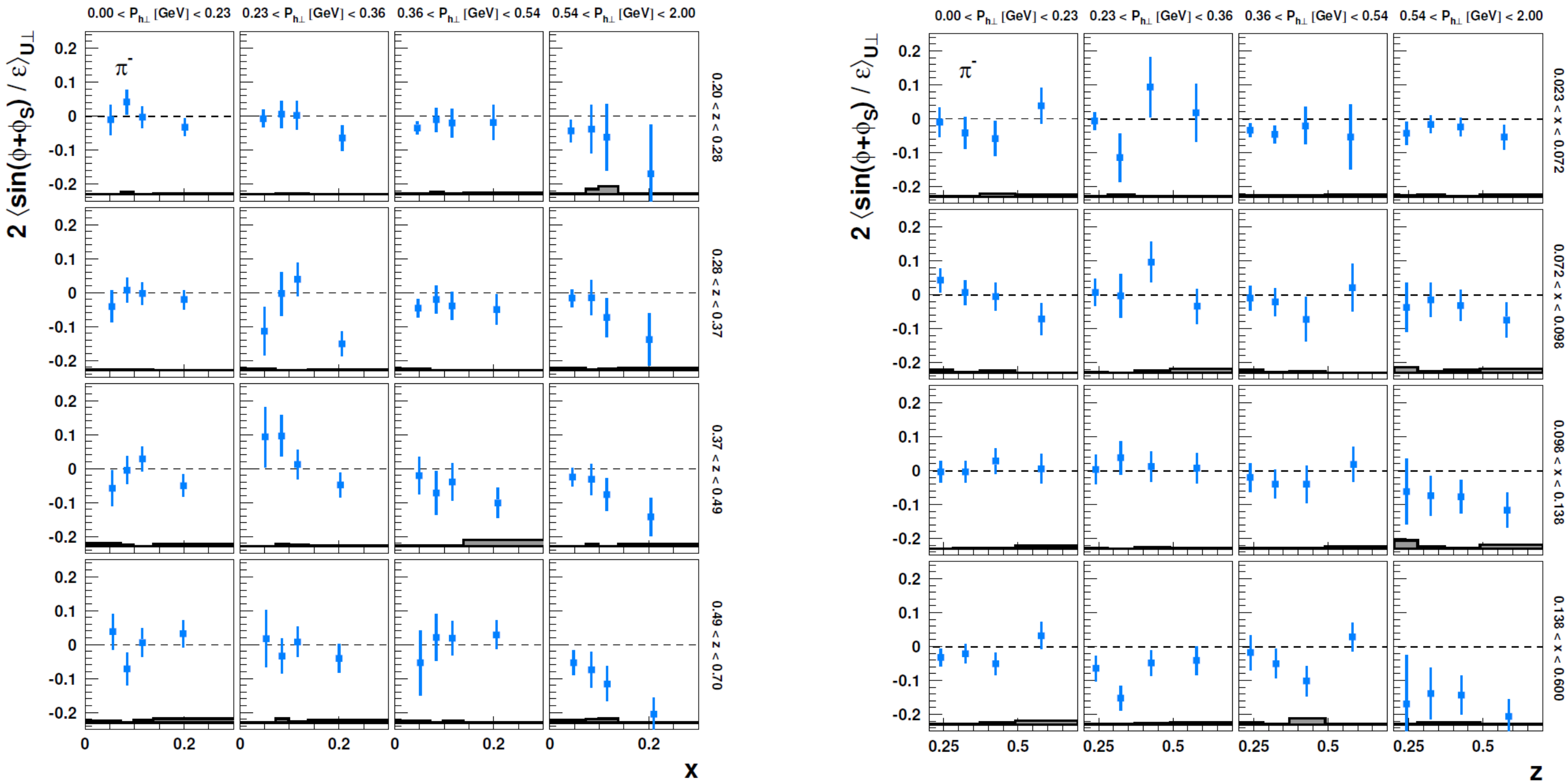




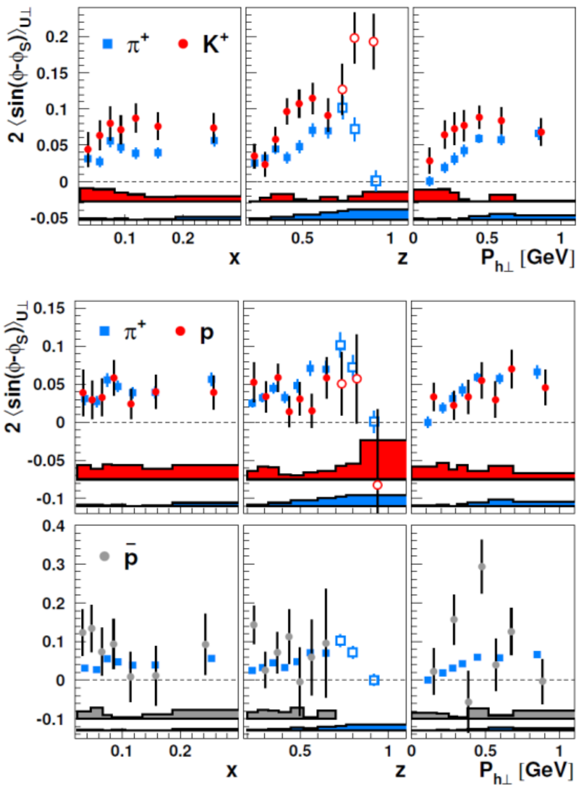
CAROSELLO

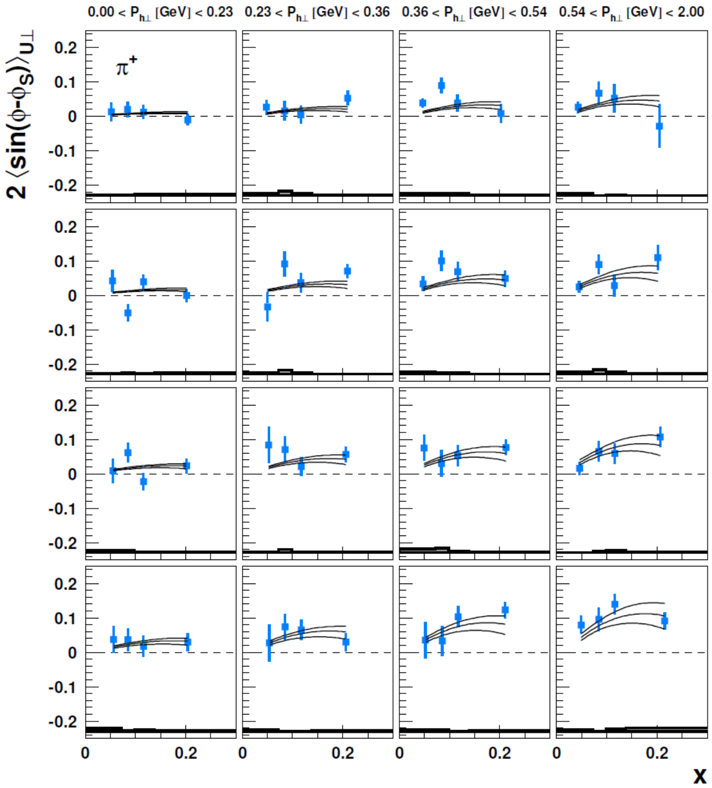
SINGLE SPIN ASYMMETRIES

HERMES 3D ssa - COLLINS

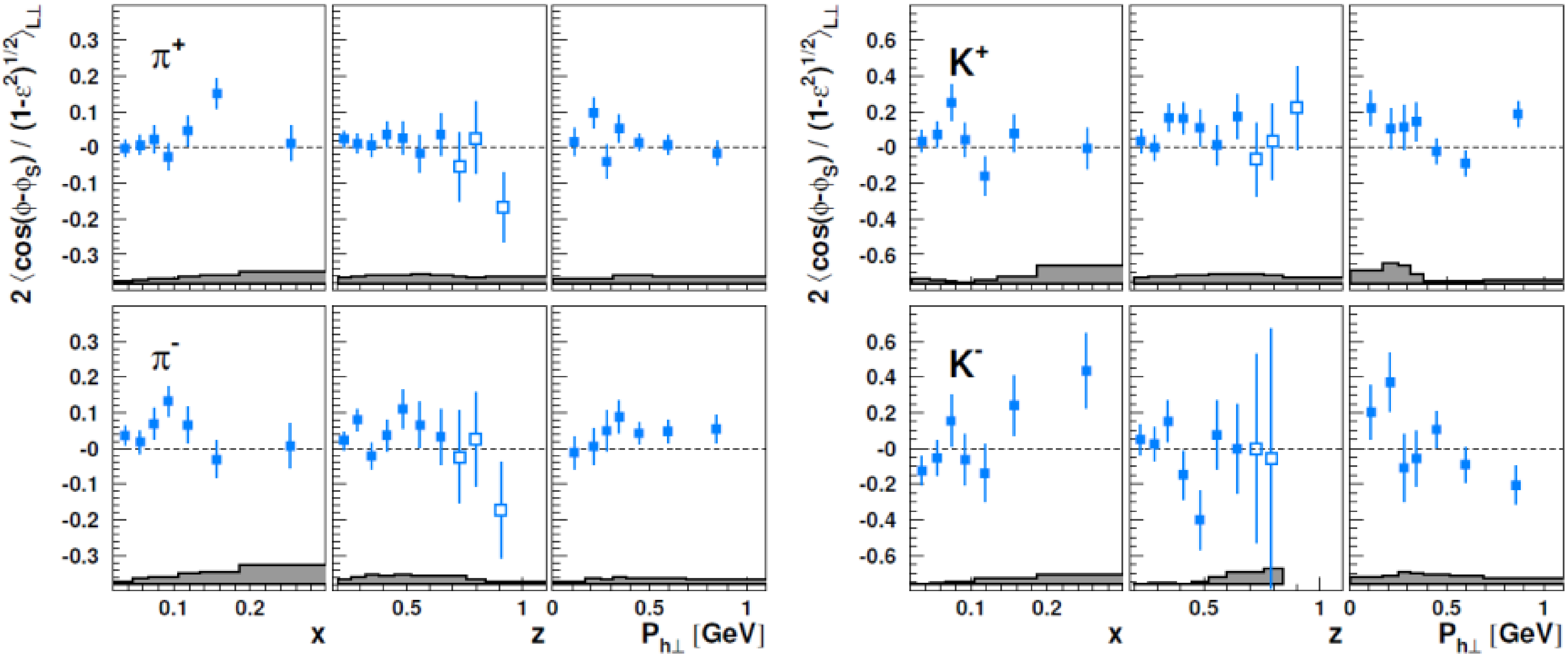


HERMES 3D ssa - SIVERS

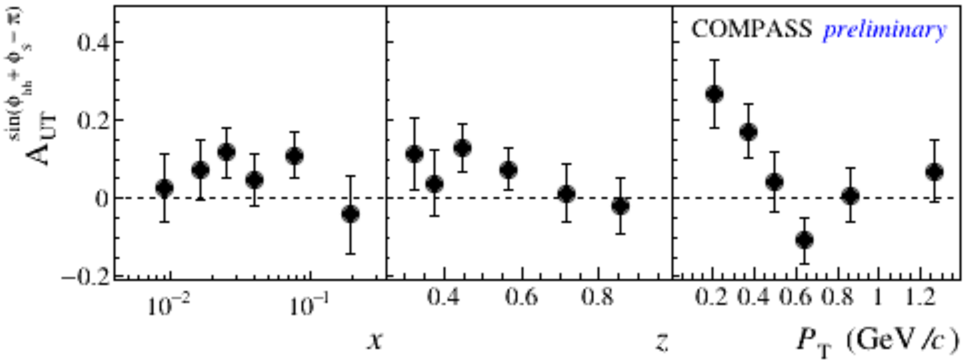




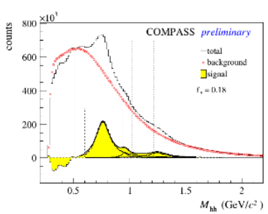
HERMES 3D ssa – WORM GEAR (II)



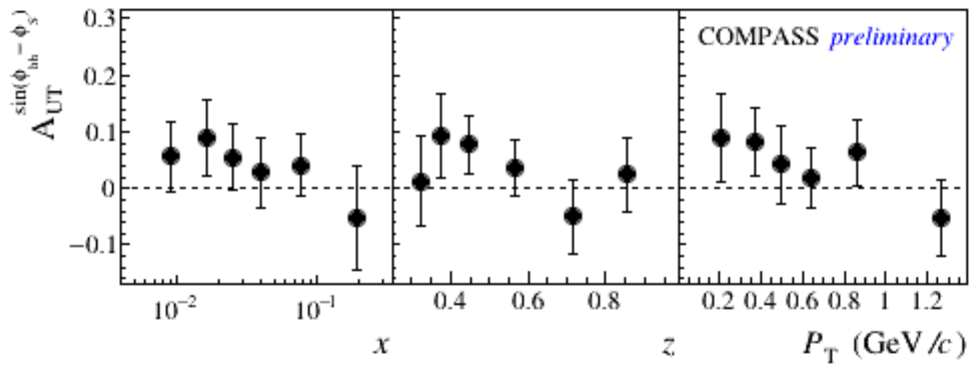
Collins/Sivers for ρ^0



- indication for a positive asymmetry
- opposite to π^+ and π^0 as predicted by the models
- Large effect at small P_T



- indication for a positive asymmetry
- similar to π^0 as expected from the models

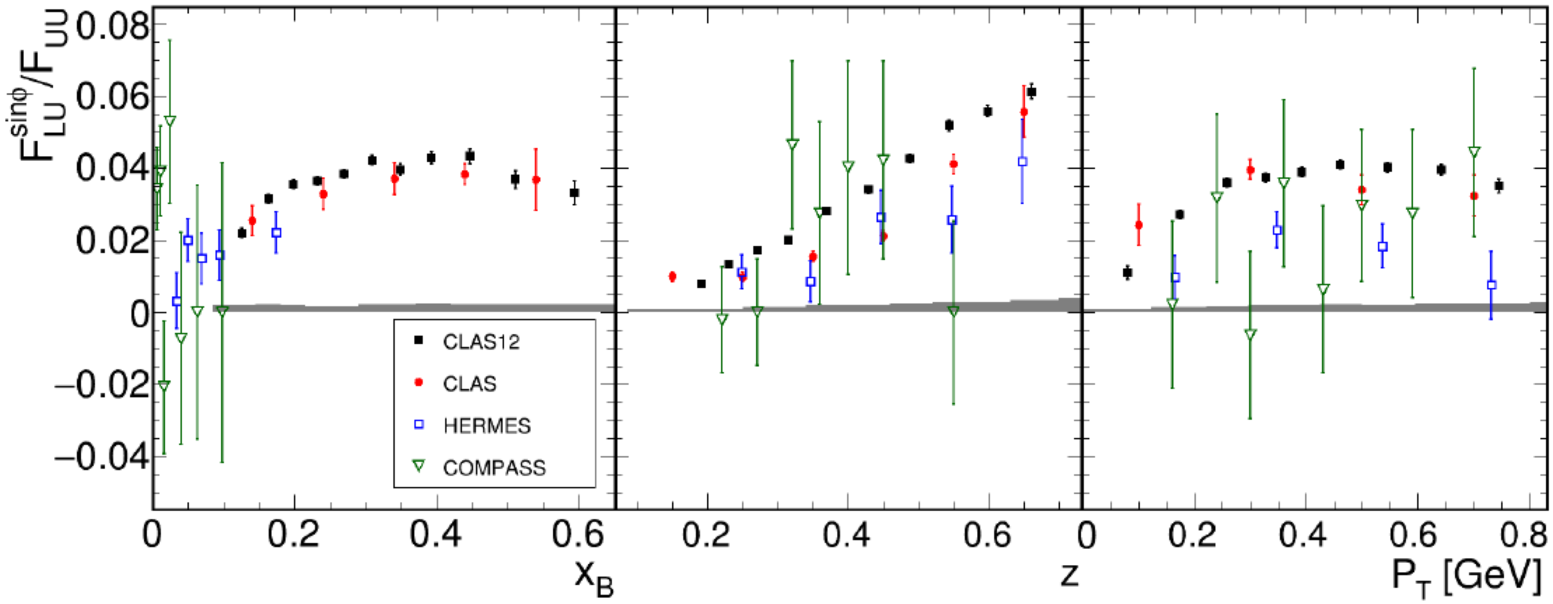


Higher twists

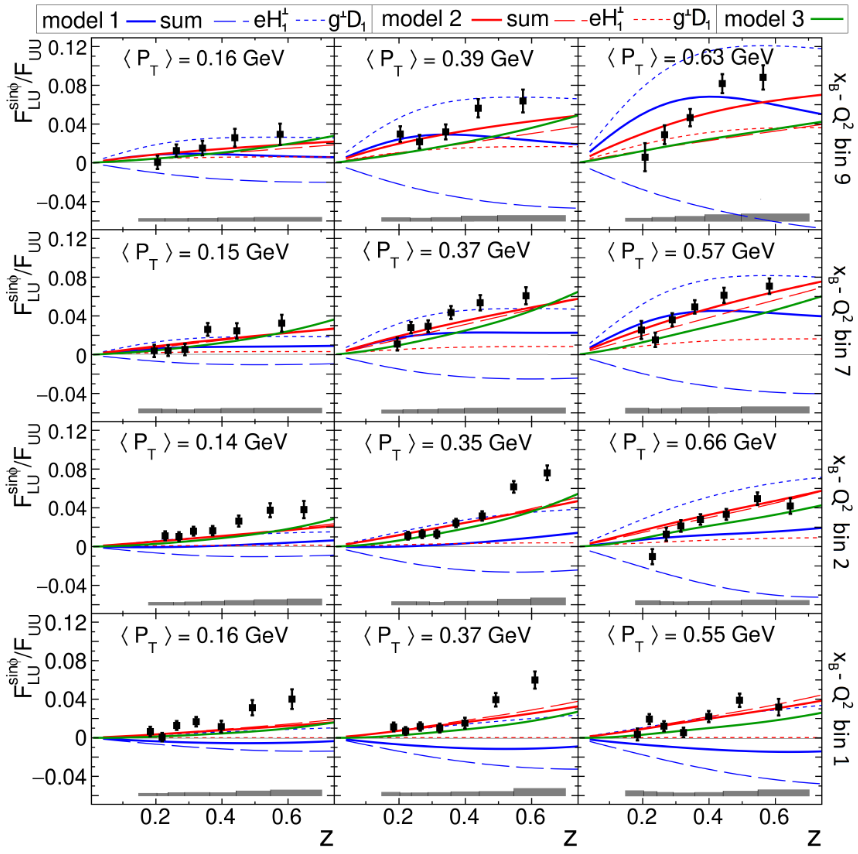
Beam Spin Asymmetry Measurements

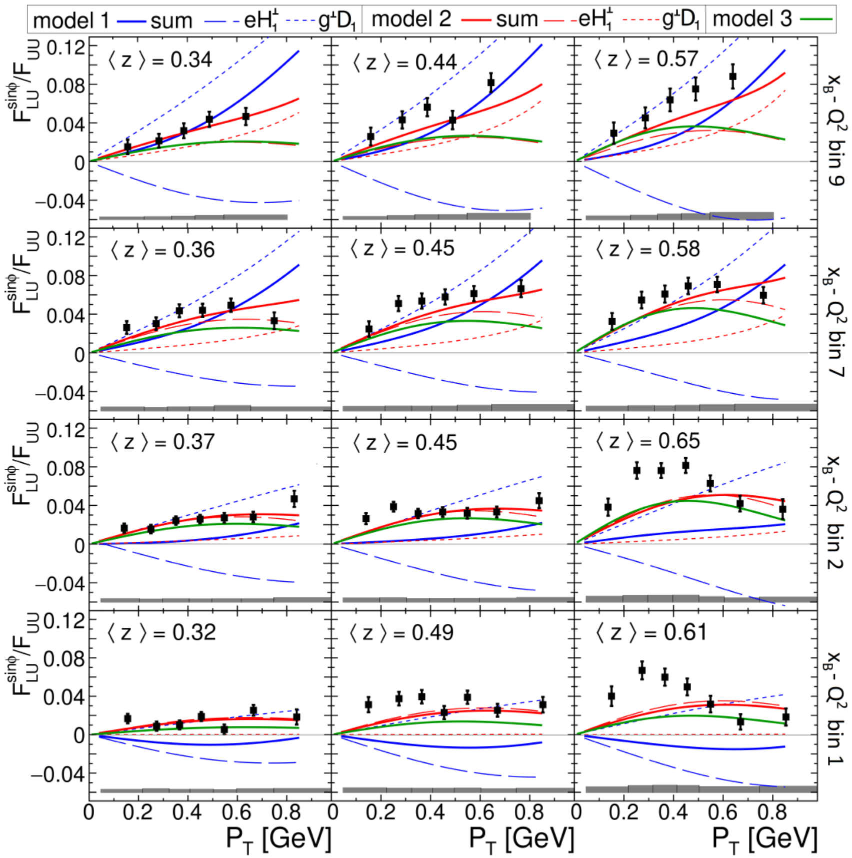
$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{h}\cdot\vec{k}_T}{M_h}\left(xeH_1^{\perp} + \frac{M_h}{M} f_1 \frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{h}\cdot\vec{p}_{\perp}}{M}\left(xg^{\perp}D_1 + \frac{M_h}{M} h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

Beam Spin Asymmetry Measurements

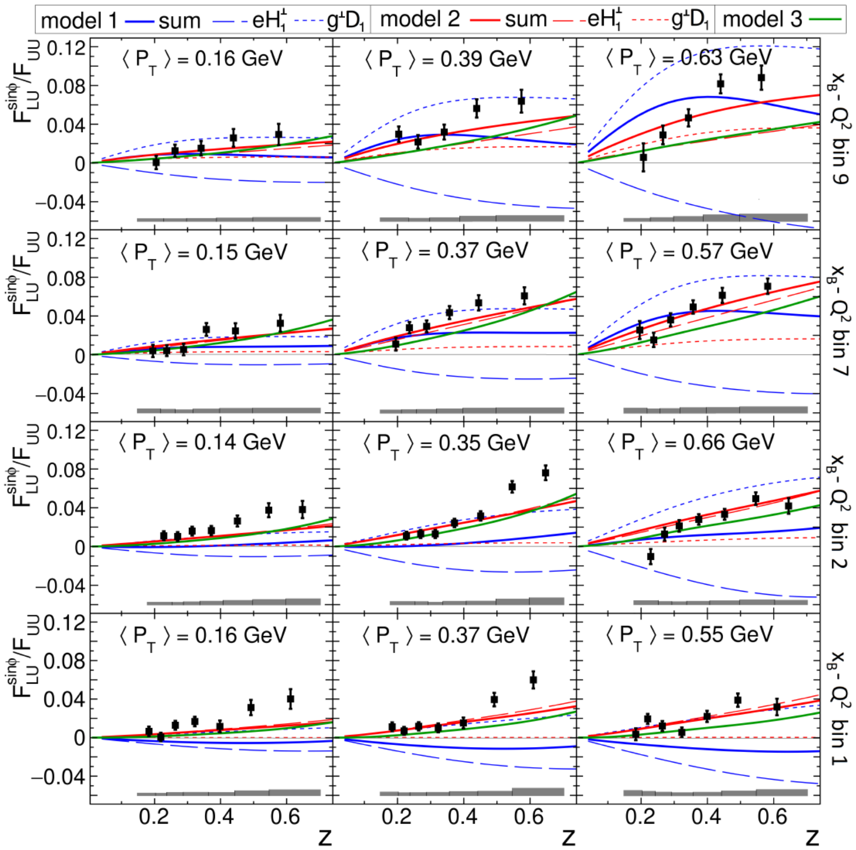


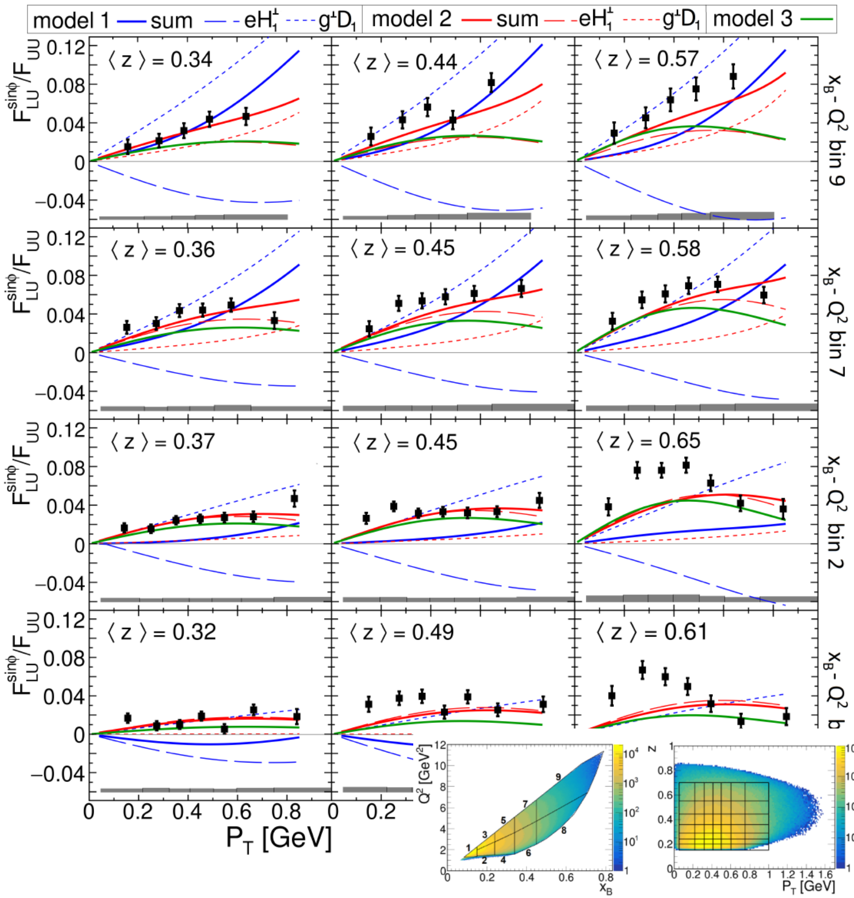
Beam Spin Asymmetry Measurements



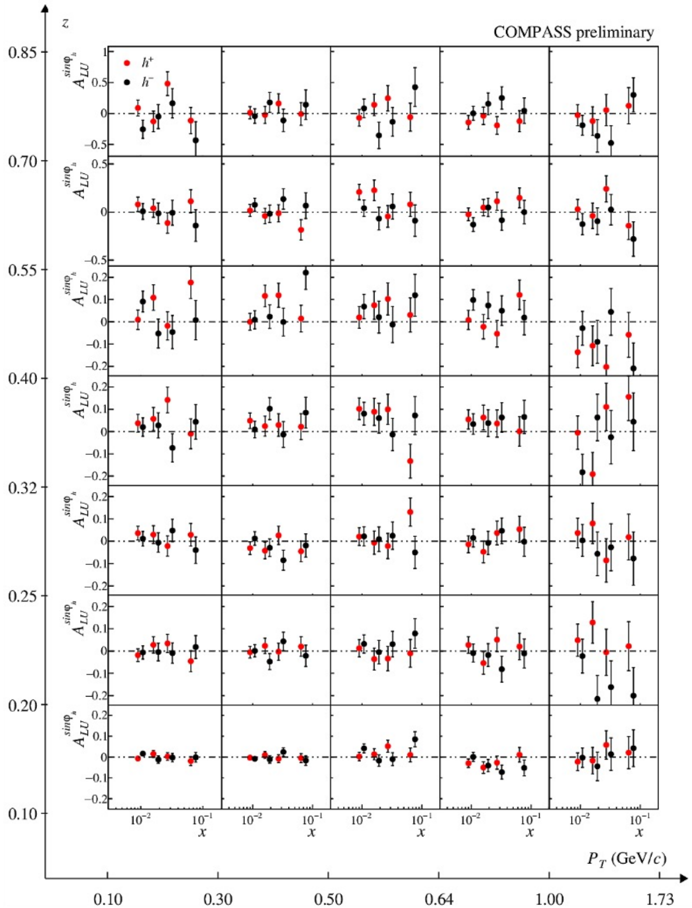


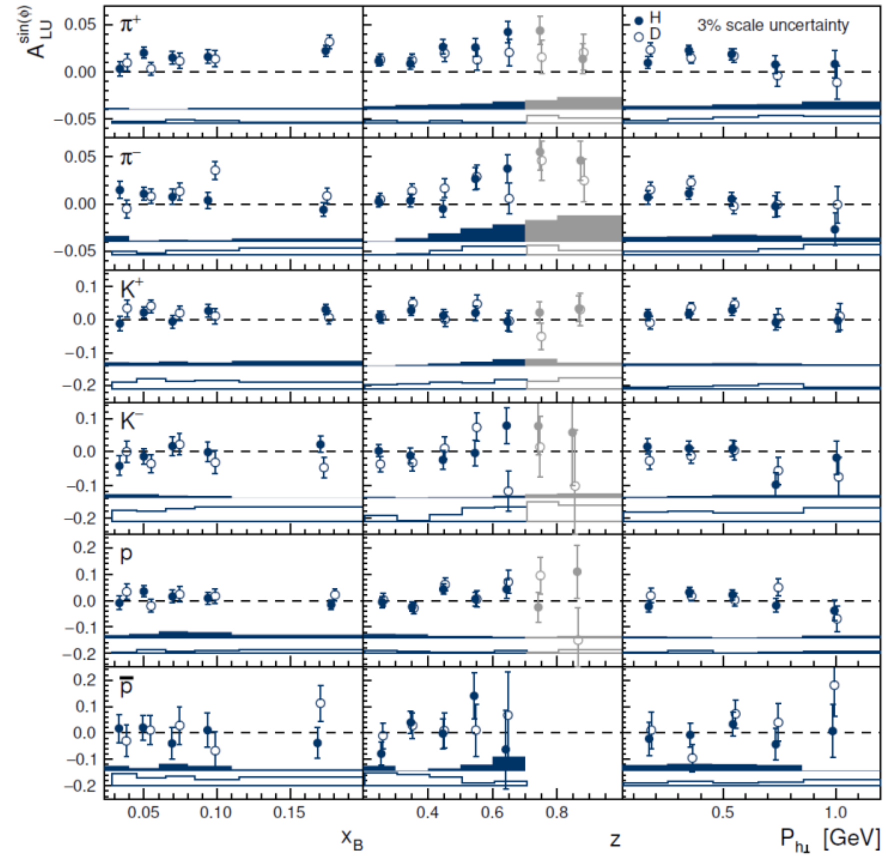
Beam Spin Asymmetry Measurements



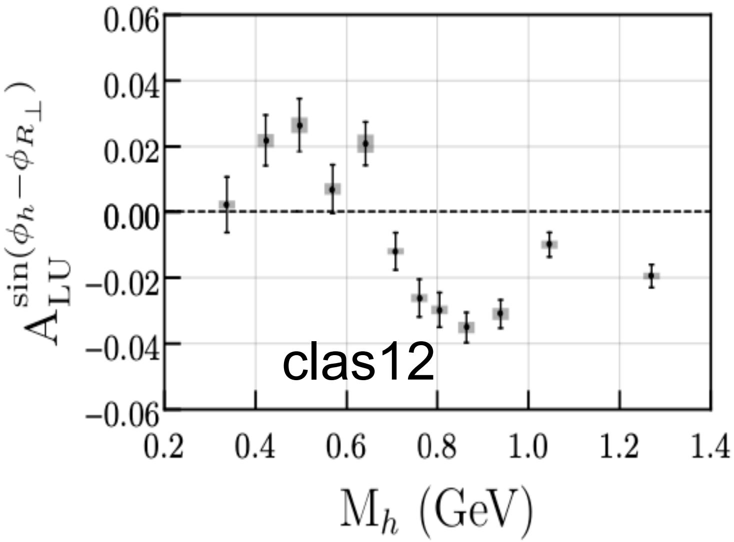


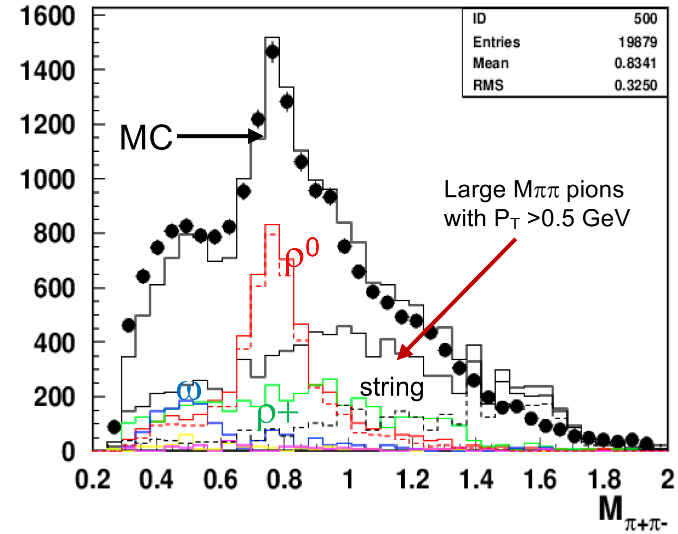
Beam Spin Asymmetry Measurements





2 hadron correlations in CFR $ep \to e'\pi^+\pi^- X$

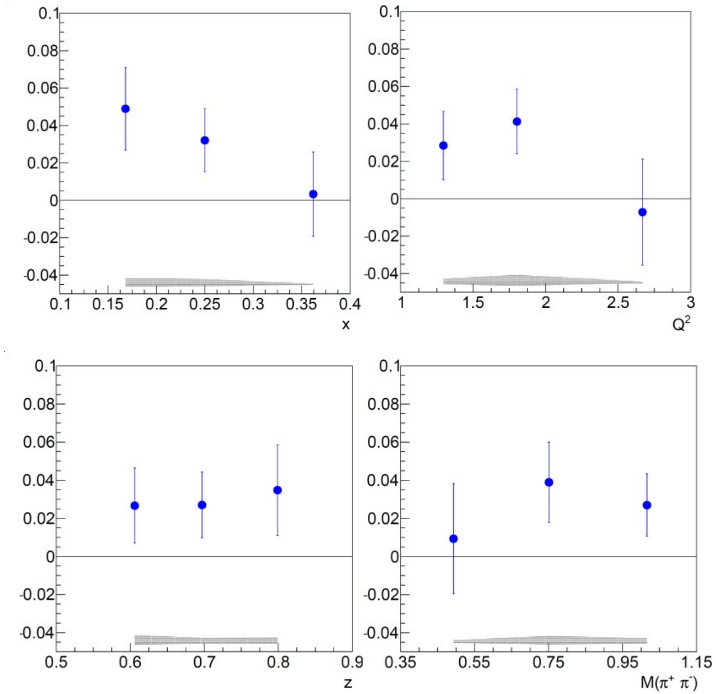




- Spin-azimuthal correlations in hadron pair production are very significant
- Hadron pairs in SIDIS (true from JLab to LHC) are dominated by VM decays (therefore single hadron channel too)
- Direct pions dominate only at relatively high P_T, (P_T >0.6-0.7 GeV)

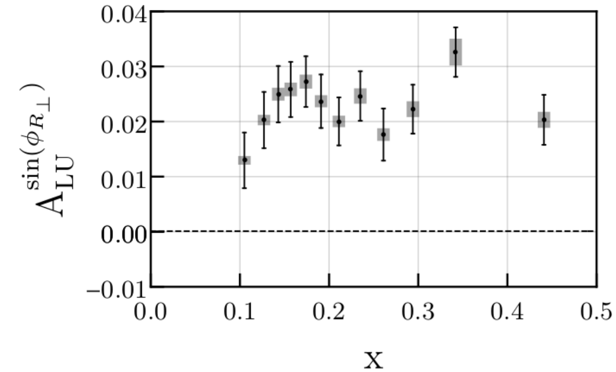
Beam Spin Asymmetry Measurements

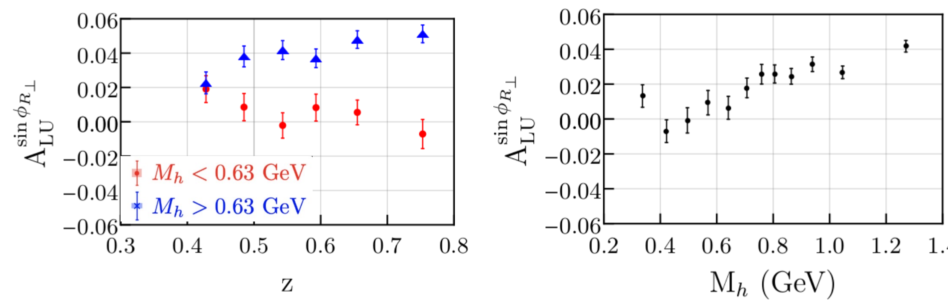
Updated CLAS6 $\pi^+\pi^-$ $A_{LU}^{\sin\phi_R}$



[Phys.Rev.Lett. 126 (2021) 6, 062002](#)

CLAS12 $\pi^+\pi^-$ $A_{LU}^{\sin\phi_R}$





[Phys.Rev.Lett. 126 (2021) 152501](#)

$$d\sigma_{LU} \propto W\lambda_e \sin\phi_{R_\perp}\left[xeH_1^{\sphericalangle} + \frac{1}{z} f_1 \tilde{G}\right]$$

FUTURE MEASUREMENTS/RESULTS

Already on tape

- COMPASS @ CERN:
  - 2016-17 DVCS and SIDIS on $\mathrm{LH_2}$
- Jlab 12 – proton/deuteron unpolarised

Year	Period	Run	Target	Polarization	Beam
2018	Spring-Fall	RGA	Proton	-	10.6 GeV
	Fall	RGK	Proton	-	6.5-7.5 GeV
2019	Spring	RGA	Proton	-	10.6 GeV
2019	Spring-Fall	RGB	Deuteron	-	10.6 GeV
2020	Spring-Fall	RGF	Deuteron	-	10.6 GeV
2021	Fall	RGM	Nuclear	-	Several GeV

Almost on tape

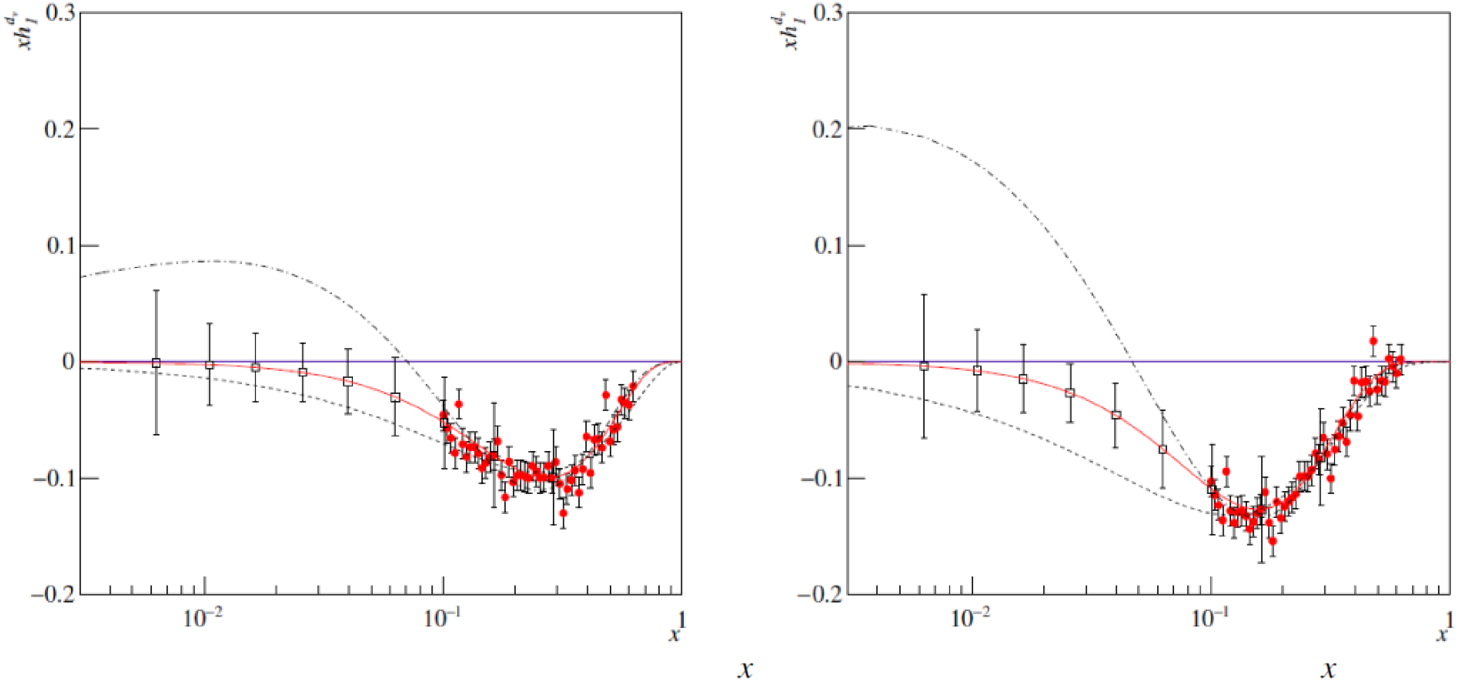
- COMPASS @ CERN:
  - 2022 on transversely polarized $^{6}\mathrm{LiD}$
- Jlab 12 – polarized
  - CLAS12

Year	Period	Run	Target	Polarization	Beam
2022	Spring-Fall	RGC	NH_3-ND_3	Longitudinal	10.6 GeV
> 2022		RGH	HDice, NH_3-ND_3	Transverse	10.6 GeV
> 2022			^{3}He	Longitudinal	10.6 GeV
> 2022		RGG	^{7}LiD, ^{6}LiH	Longiudinal	10.6 GeV

  - Hall A - E12-09-018 Neutron transverse SSAs

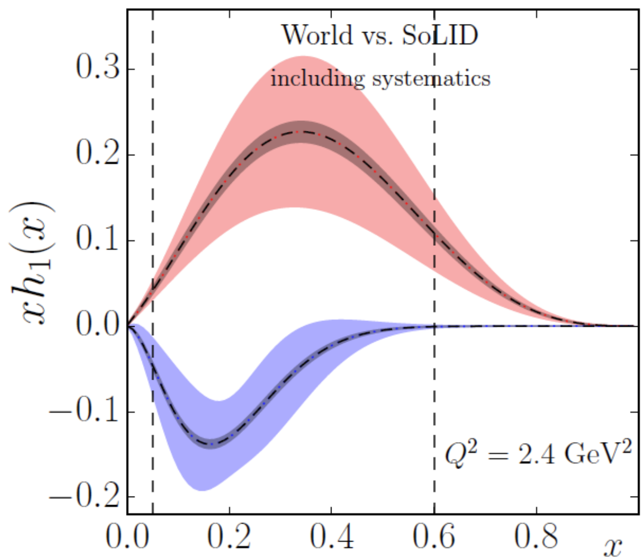
COMPASS deuteron data in 2022

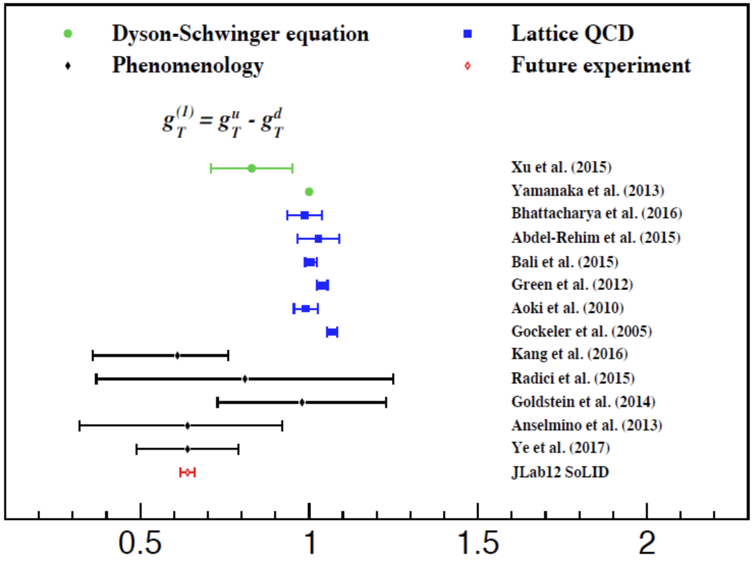
- Expected gain in precision on u- and d-quark transversity



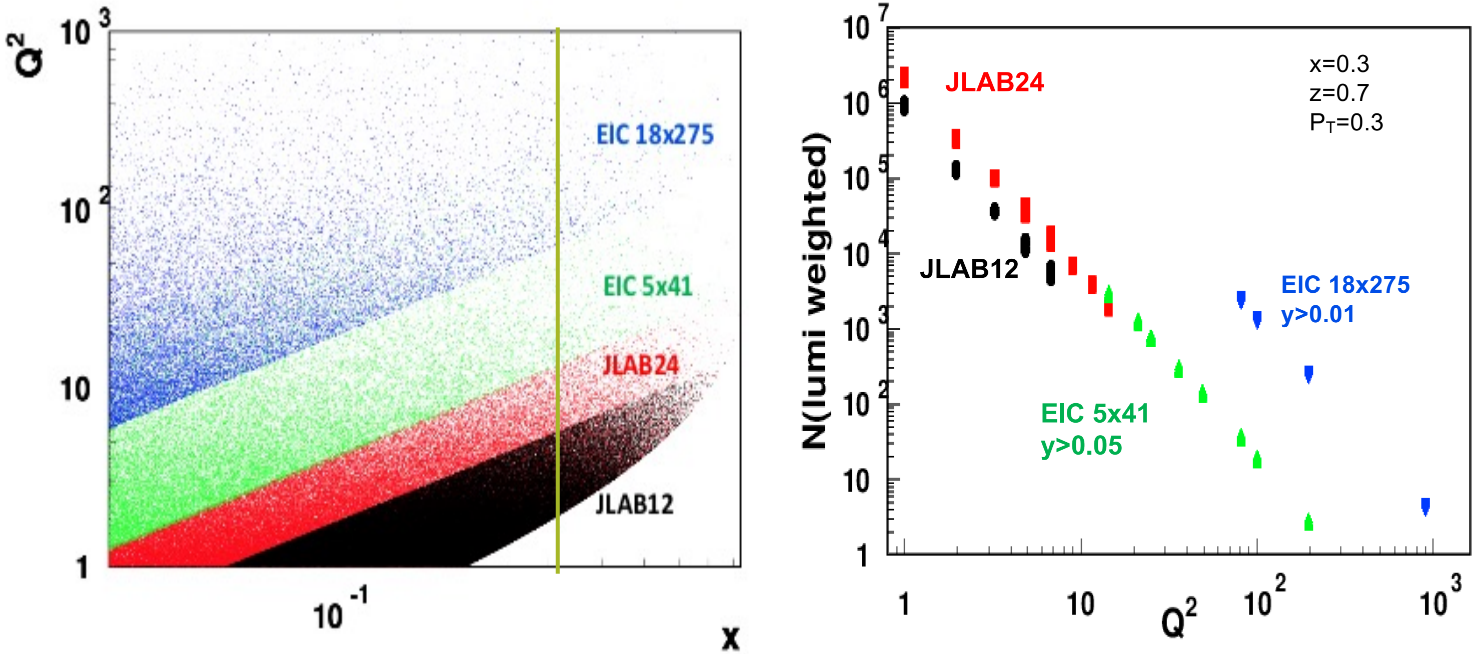
JLAB12 More in the feauture

- CLAS12 and SOLID





From JLab to EIC: complementarity

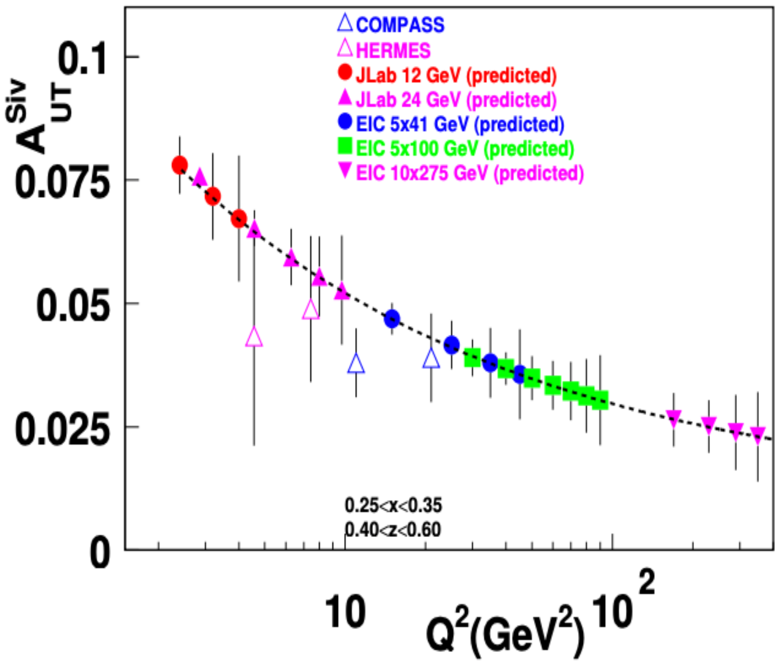


- JLab at 24 GeV will provide critical input in evolution studies of TMDs, increase the P_T coverage
- Higher Q^2-coverage of “Low s” EIC running will provide validation of evolution studies at JLab at large x (will require high luminosity)

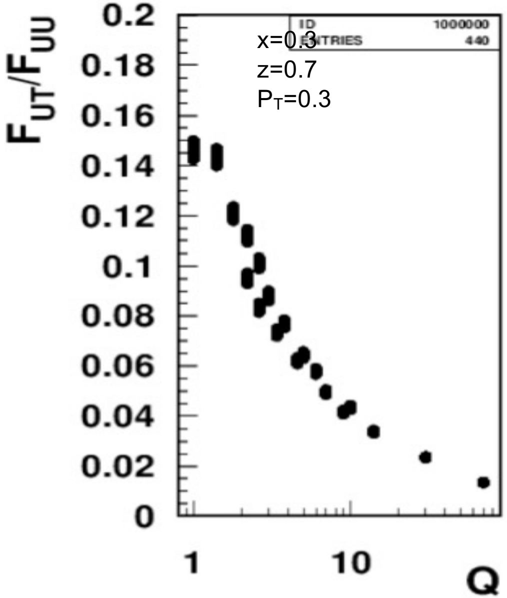
Contributions for 3D structure studies: Sivers

y>0.05,100 days (corrected for EIC official lumi)

H.A./C.Pecar/A.Vossen



Pavia grids

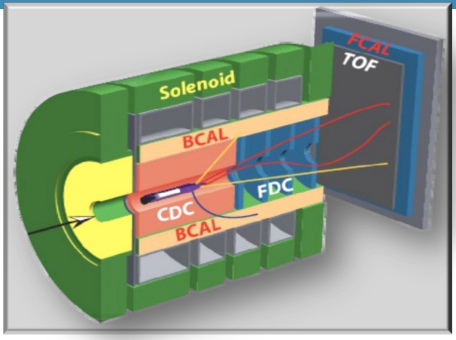


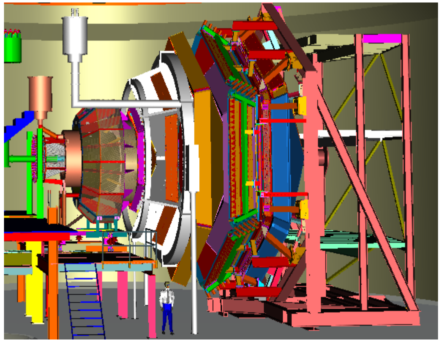
- Measurements of Q^2-dependence of SSAs will be crucial in validation of the theory
- JLab24 will be crucial to bridge the TMD studies between JLab12 and EIC in the valence region


Thank you

12 GeV Upgrade Physics Instrumentation

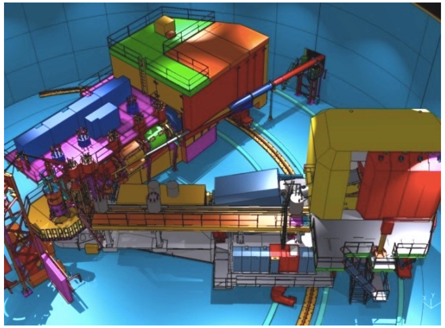
GLUEx (Hall D): **exploring origin of confinement by studying hybrid mesons**

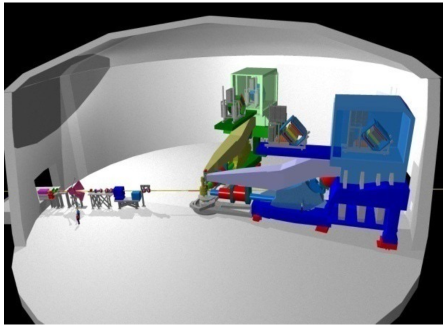




CLAS12 (Hall B): **understanding nucleon structure via generalized parton distributions**

SHMS (Hall C): **precision determination of valence quark properties in nucleons and nuclei**





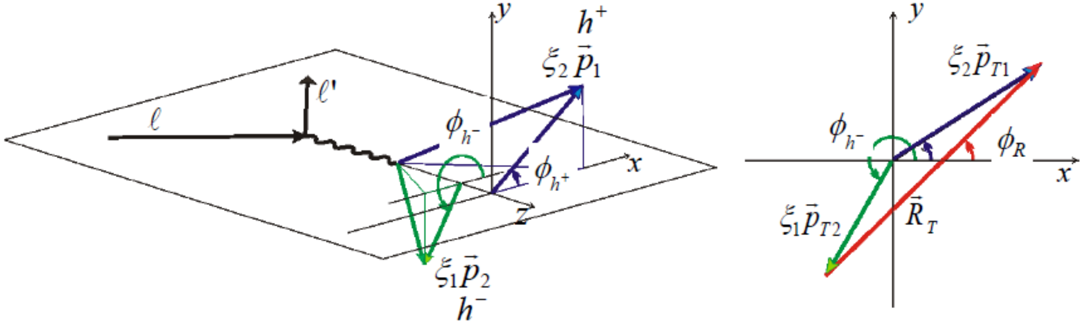
Hall A: **nucleon form factors**

& future new experiments like Moller & SOLID

The asymmetries

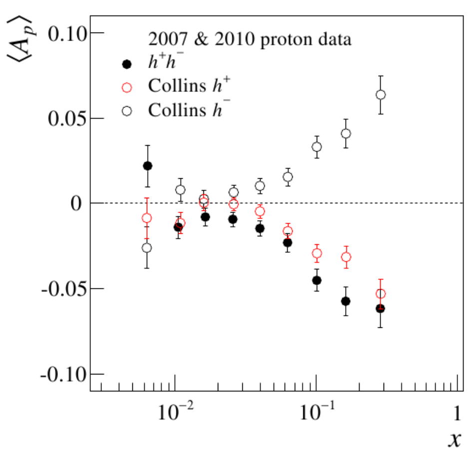
- The asymmetries are:
- $$A_{U(L),T}^{w(\phi_h,\phi_S)}(x,z,p_T;Q^2) = \frac{F_{U(L),T}^{w(\phi_h,\phi_S)}}{F_{UU,T}+\varepsilon F_{UU,L}}$$
- When we measure on 1D
- $$A_{U(L),T}^{w(\phi_h,\phi_S)}(x) = \frac{\int_{Q^2_{min}}^{Q^2_{max}} dQ^2 \int_{z_{min}}^{z_{max}} dz \int_{p_{T,min}}^{p_{T,max}} d^2\vec{p}_T F_{U(L),T}^{w(\phi_h,\phi_S)}}{\int_{Q^2_{min}}^{Q^2_{max}} dQ^2 \int_{z_{min}}^{z_{max}} dz \int_{p_{T,min}}^{p_{T,max}} d^2\vec{p}_T \left(F_{UU,T}+\varepsilon F_{UU,L}\right)}$$

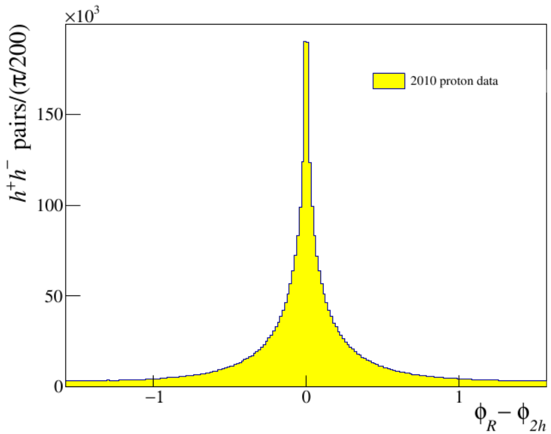
Hadron correlations

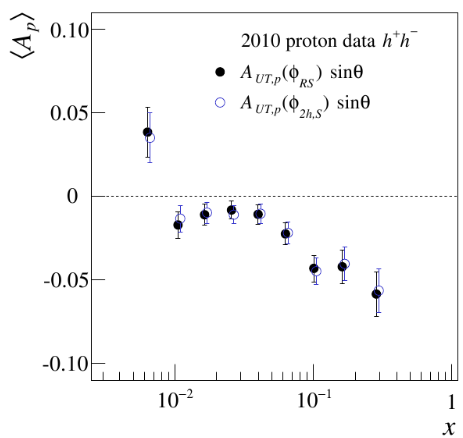


Interplay between Collins and IFF asymmetries

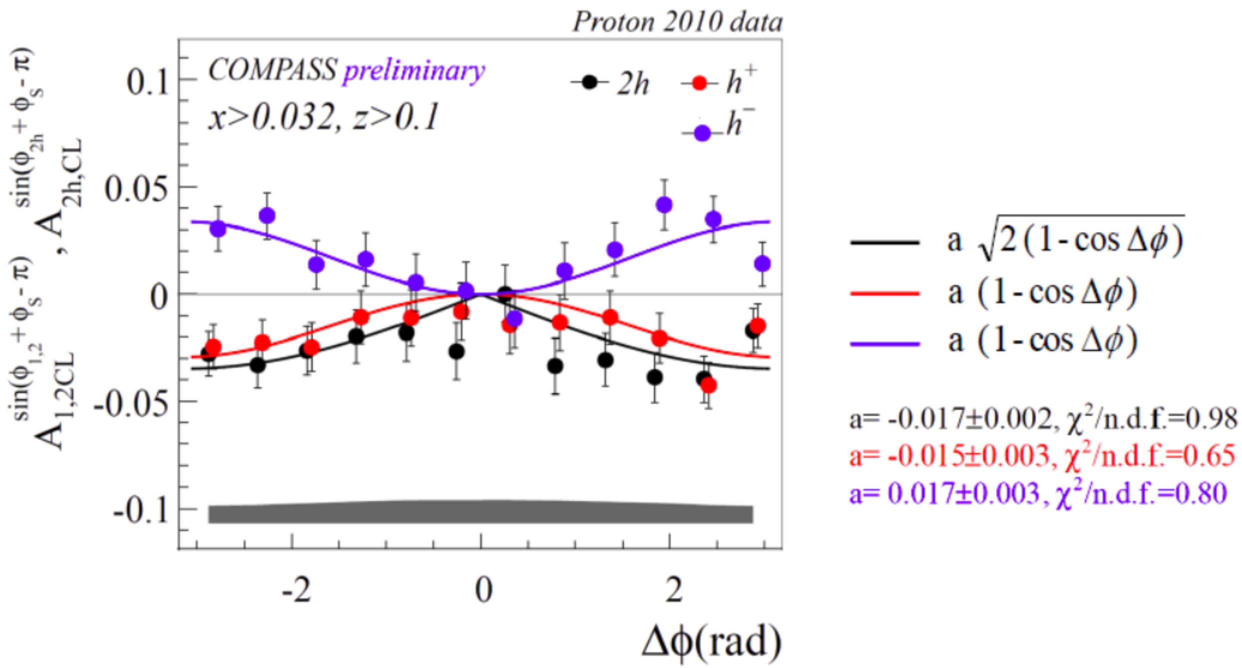
common hadron sample for Collins and 2h analysis







Asymmetries for $x > 0.032$ vs $\Delta\phi = \phi_{h^+} - \phi_{h^-}$



$$a = \frac{\sigma_{1C}^{h^+h^-}(\Delta\phi)}{\sigma_U(\Delta\phi)}$$

$$= -\frac{\sigma_{2C}^{h^+h^-}(\Delta\phi)}{\sigma_U(\Delta\phi)}$$

ratio of the integrals compatible with $4/\pi$

Hints for a common origin of 1h and 2h mechanisms

From Collins asymmetries to transversity

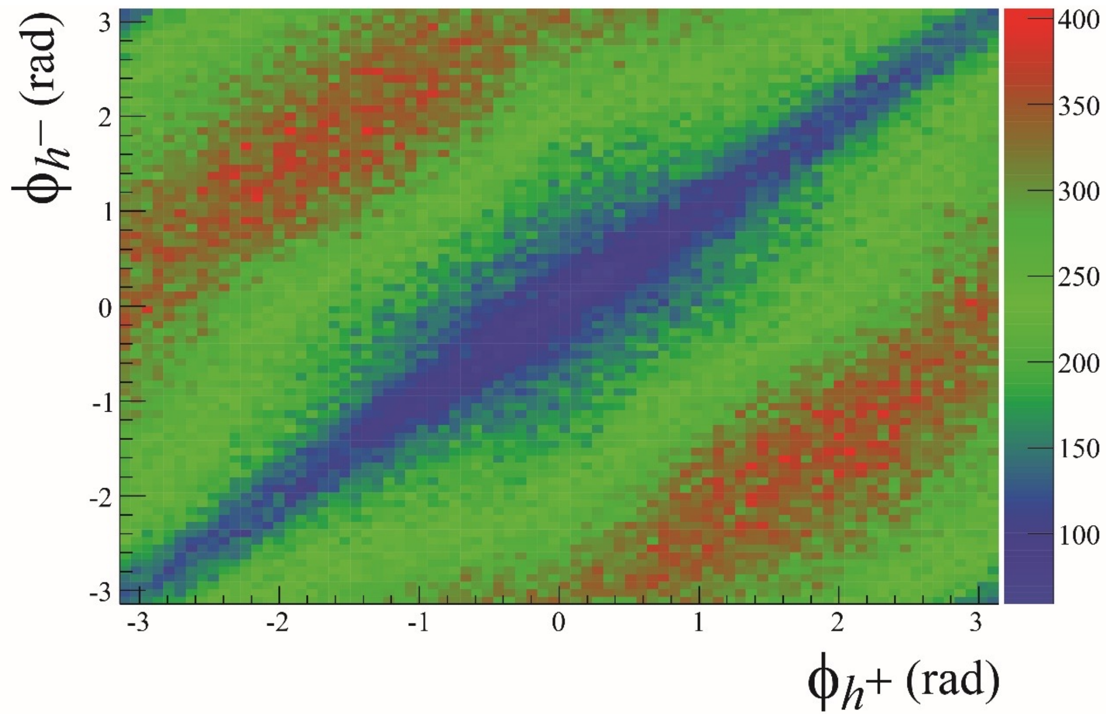
- Following Physical Review D 91, 014034 (2015), in the valence region

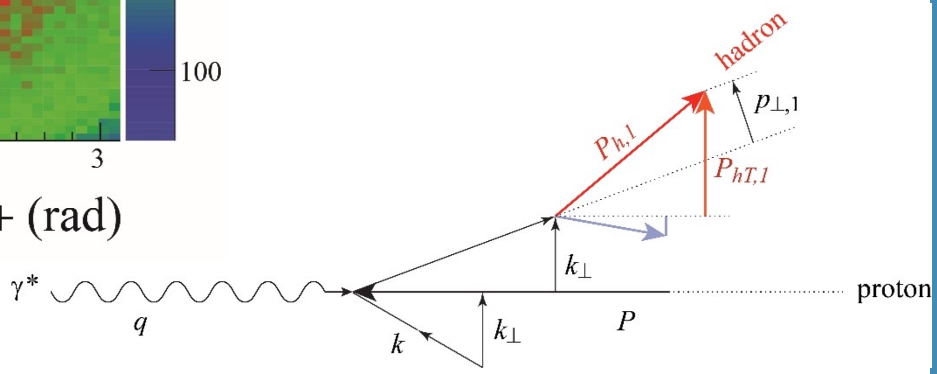
$$x h_1^u = \frac{1}{5}\frac{1}{\tilde{a}_P^h(1-\tilde{\alpha})}\left[\left(x f_p^+ A_p^+ - x f_p^- A_p^-\right) + \frac{1}{3}\left(x f_d^+ A_d^+ - x f_d^- A_d^-\right)\right]$$

$$x h_1^d = \frac{1}{5}\frac{1}{\tilde{a}_P^h(1-\tilde{\alpha})}\left[\frac{4}{3}\left(x f_d^+ A_d^+ - x f_d^- A_d^-\right) - \left(x f_p^+ A_p^+ - x f_p^- A_p^-\right)\right]$$

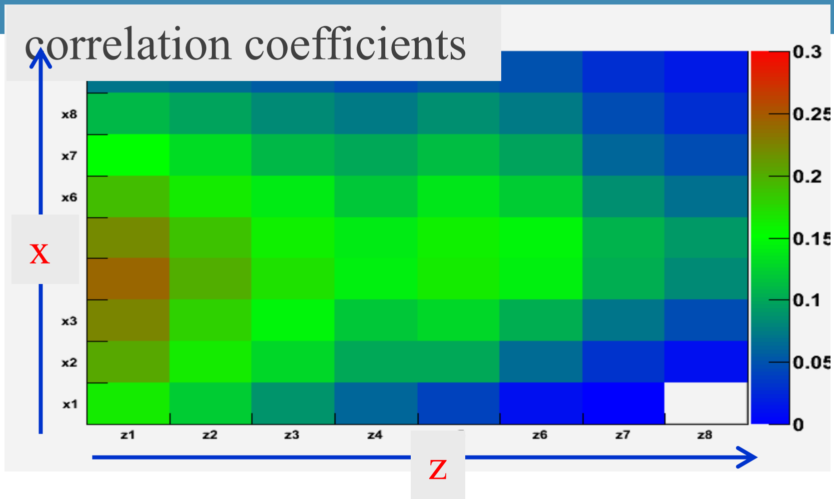
With $\tilde{a}_P^h$ and $\tilde{\alpha}$ constants

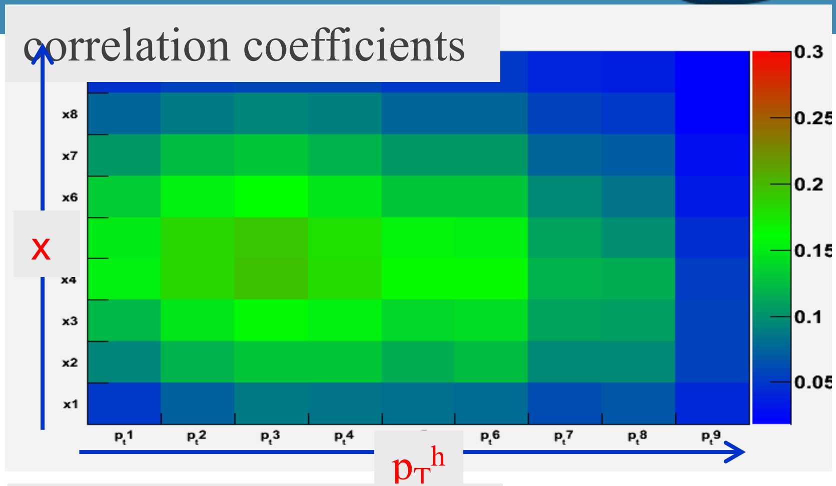
Is correlation having an impact?

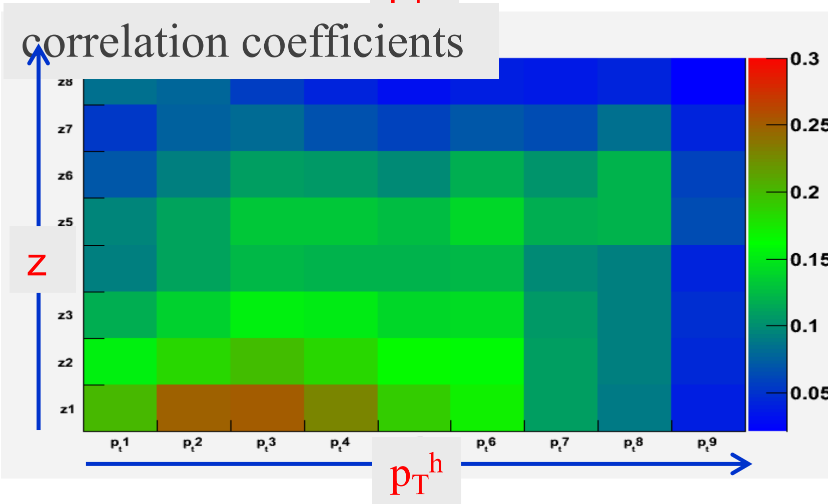




Statistical correlations







charged pions

also available for

charged hadrons

charged kaons

have to be taken into account