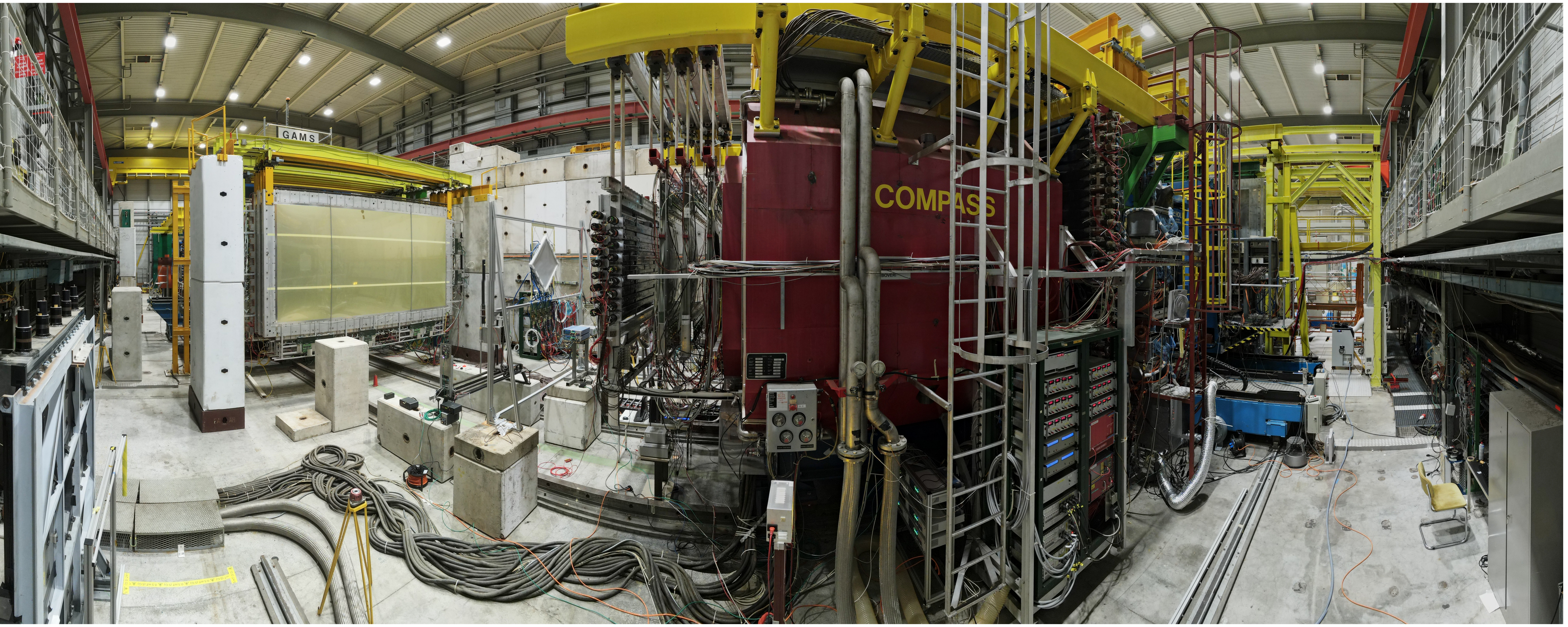
Study of the nucleon structure in Semi-Inclusive DIS off (un)polarized targets at COMPASS

Highlights



DIS23
MICHIGAN STATE UNIVERSITY

University of Illinois Urbana-Champaign

NSF

Caroline Riedl (UIUC)
on behalf of the COMPASS collaboration
March 30, 2023

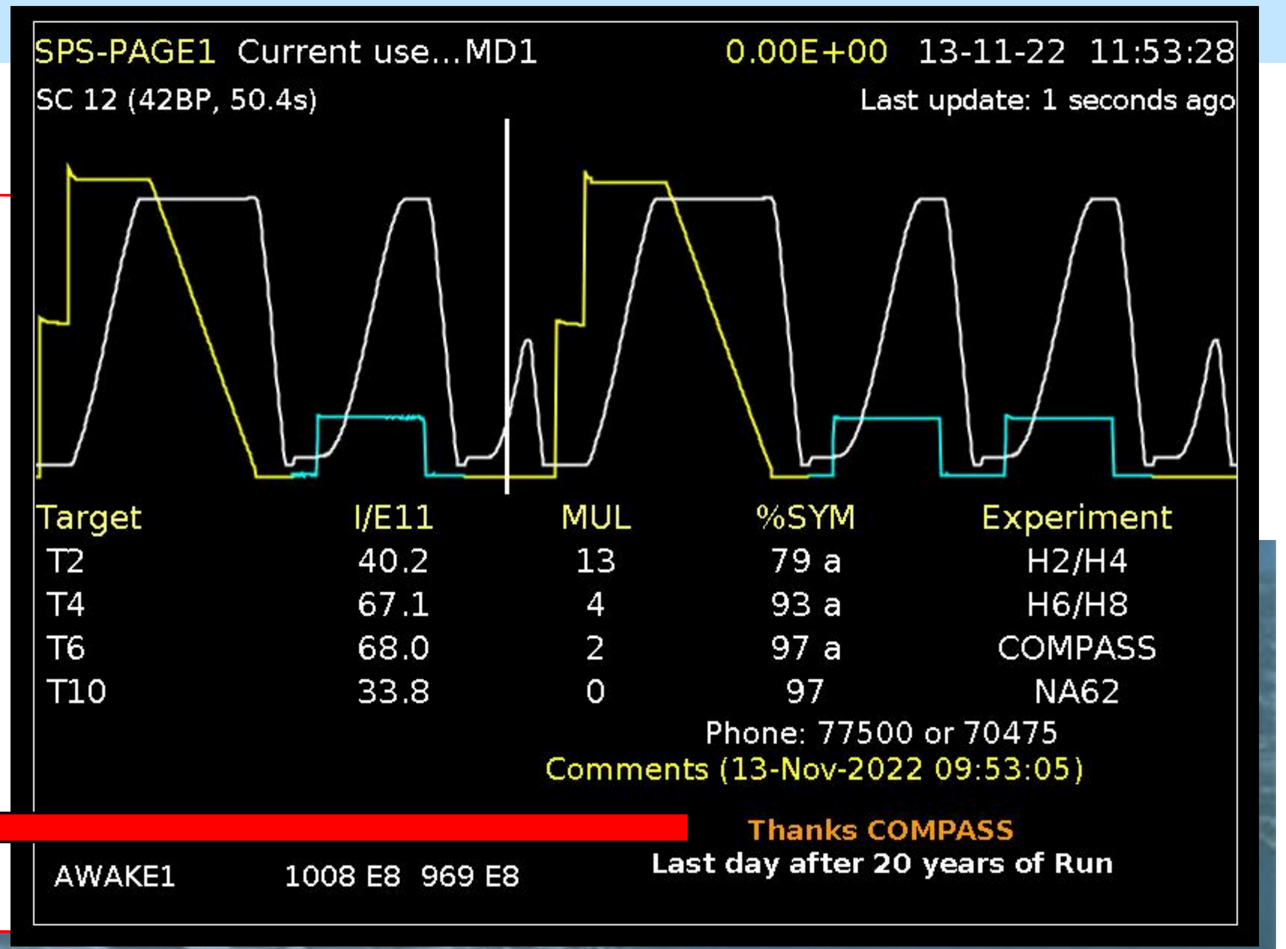
with material from Anna Martin, Bakur Parsamyan, Andrea Moretti, Andrea Bressan, …

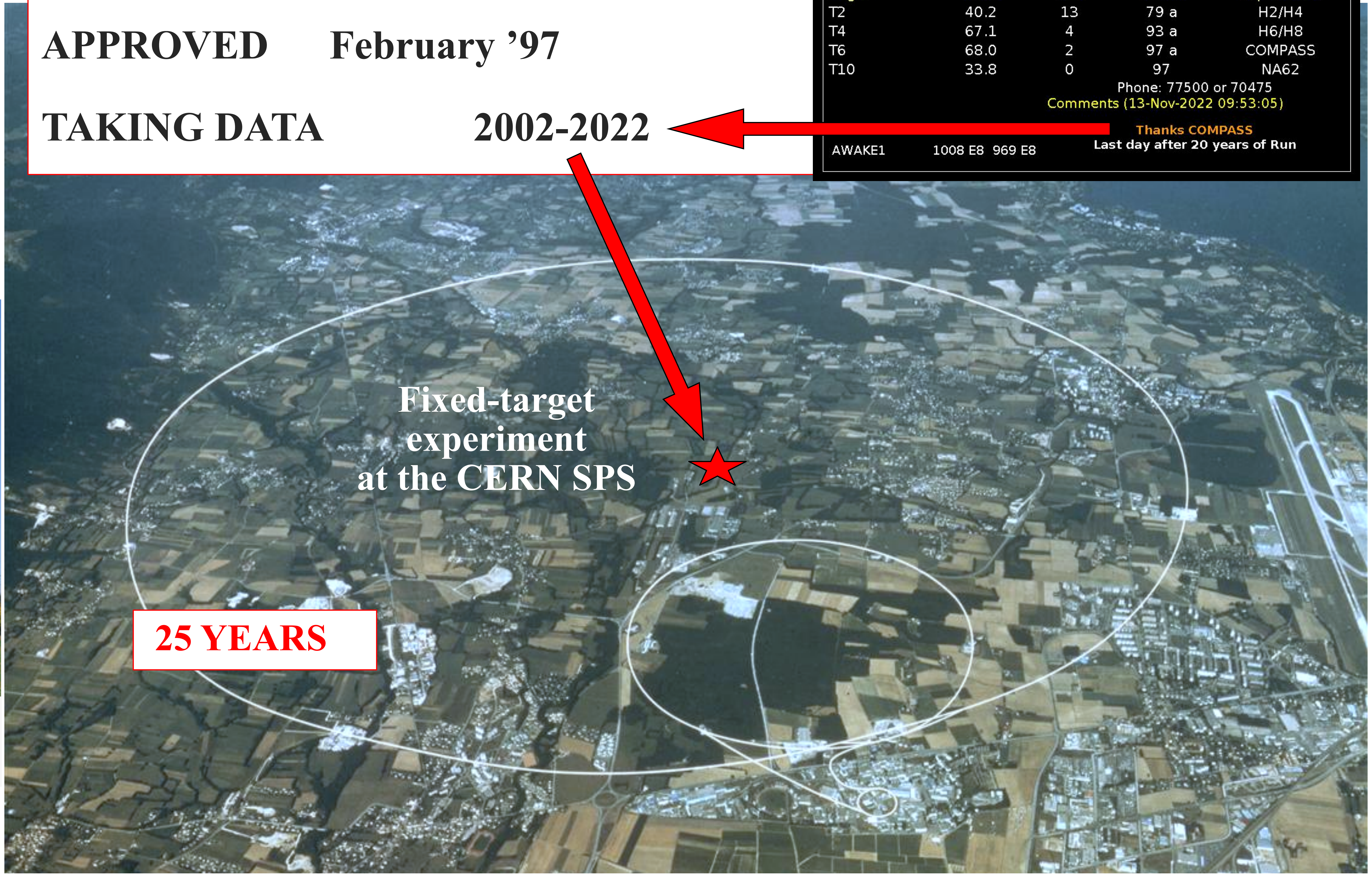
25 years of COMPASS

COMPASS

***CO**mmon*
***M**uon and*
***P**roton*
***A**pparatus for*
***S**tructure and*
***S**pectroscopy*

PROPOSAL	March ’96
RECOMMANDED	September ’96
APPROVED	February ’97
TAKING DATA	2002-2022





International Workshop on Hadron Structure and Spectroscopy - 2022

Aug 29 – 31, 2022
CERN

https://indico.cern.ch/event/1121975/

facebook https://www.facebook.com/compasscern

Broad spectrum of data-taking campaigns

COMPASS

Beam	Target	Year	Physics program
μ^+	Polarized deuteron (^{6}LiD)	2002 2003 2004	80% Longitudinal | 20% Transverse SIDIS
μ^+	Polarized deuteron (^{6}LiD)	2006	Longitudinal SIDIS
μ^+	Polarized proton (NH_3)	2007	50% Longitudinal | 50% Transverse SIDIS
π | K | p	LH_2, Ni, Pb, W	2008 2009	Spectroscopy
μ^+	Polarized proton (NH_3)	2010	Transverse SIDIS
μ^+	Polarized proton (NH_3)	2011	Longitudinal SIDIS
π | K | p	Ni	2012	Primakoff
$\mu^\pm$	LH_2	2012	Pilot DVCS & HEMP & unpolarized SIDIS
π^-	Polarized proton (NH_3)	2014	Pilot Drell-Yan
π^-	Polarized proton (NH_3)	2015 2018	Transverse Drell-Yan
$\mu^\pm$	LH_2	2016 2017	DVCS & HEMP & unpolarized SIDIS
μ^+	Polarized deuteron (^{6}LiD)	2021 2022	Transverse SIDIS

this talk:
SIDIS TMDs

see V. Andrieux's talk - Thursday 11:10

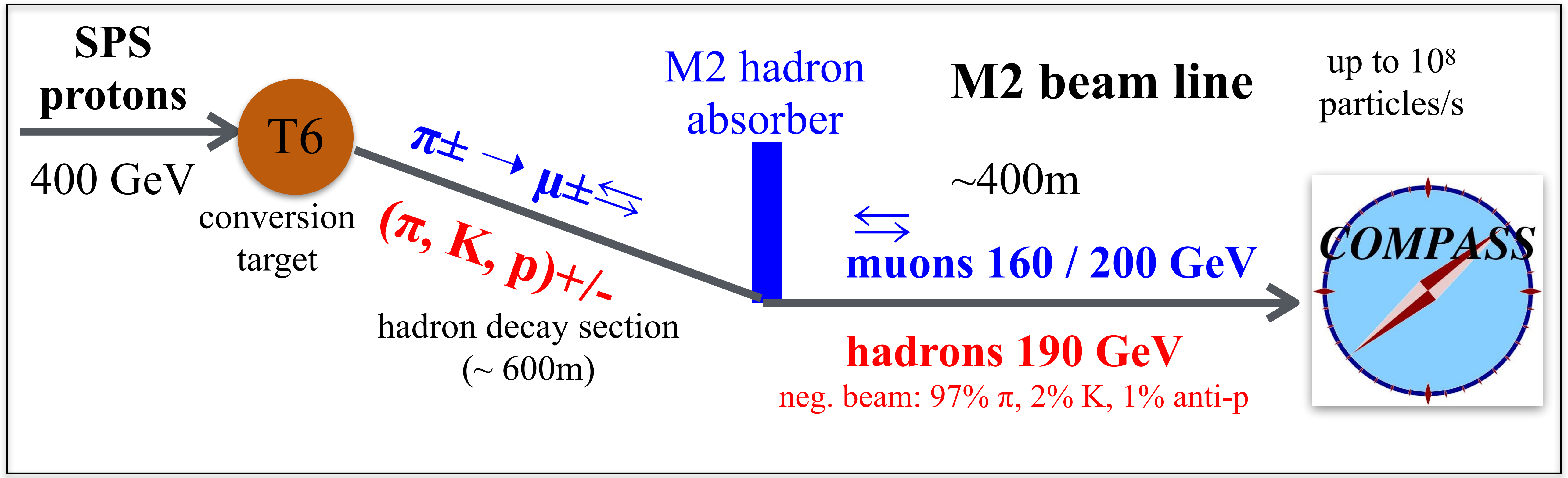
DY TMDs

see V. Andrieux's talk talk - Tuesday 9:00

→ **GPDs**

see A. Koval's talk - Tuesday 10:50

COMPASS experimental setup and future



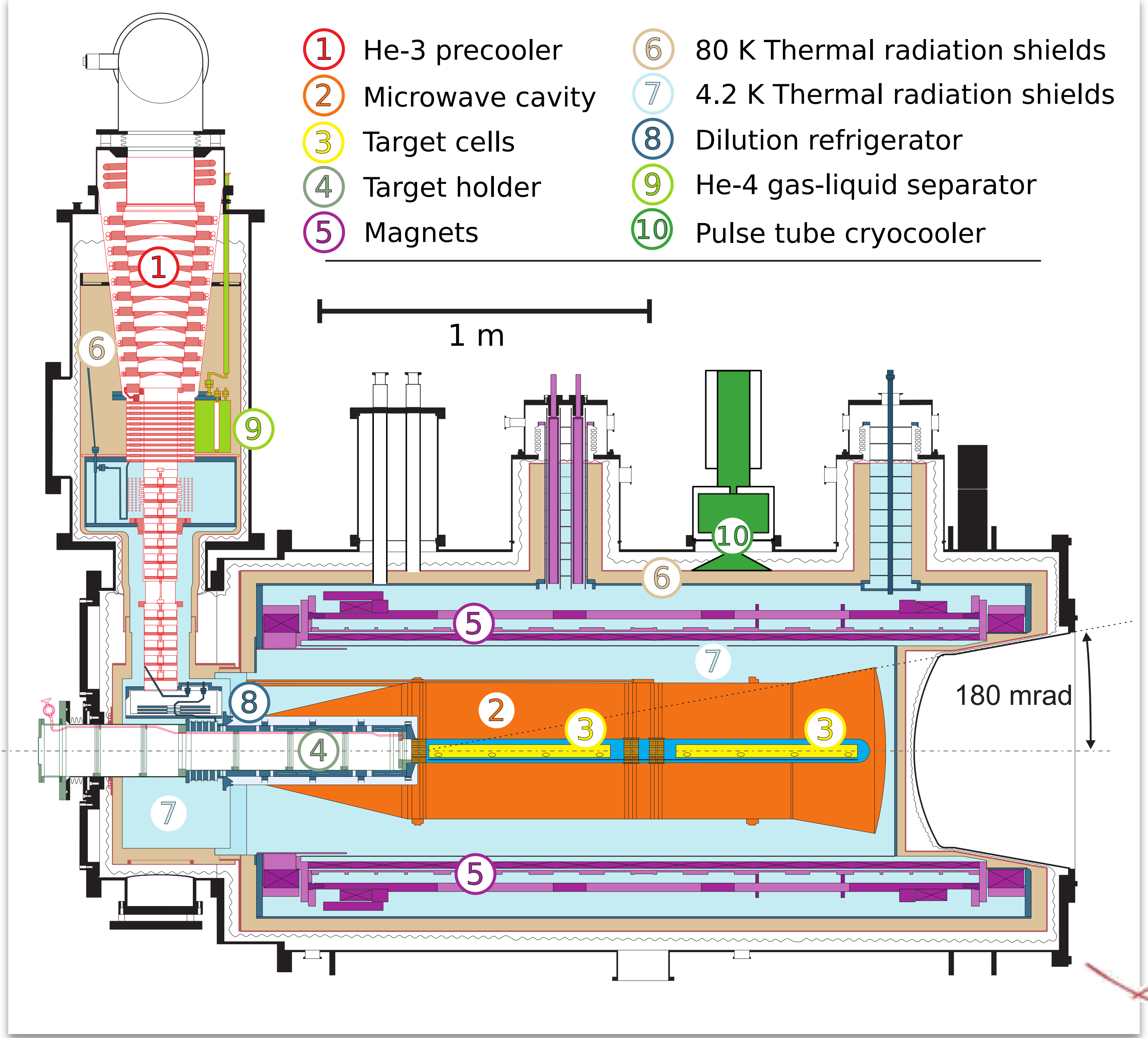
The 2022 data-taking campaign was the last run of the COMPASS experiment, and the last of the exploratory study of the nucleon structure

COMPASS changed from “data taking” to “data analysis” and will continue for several years

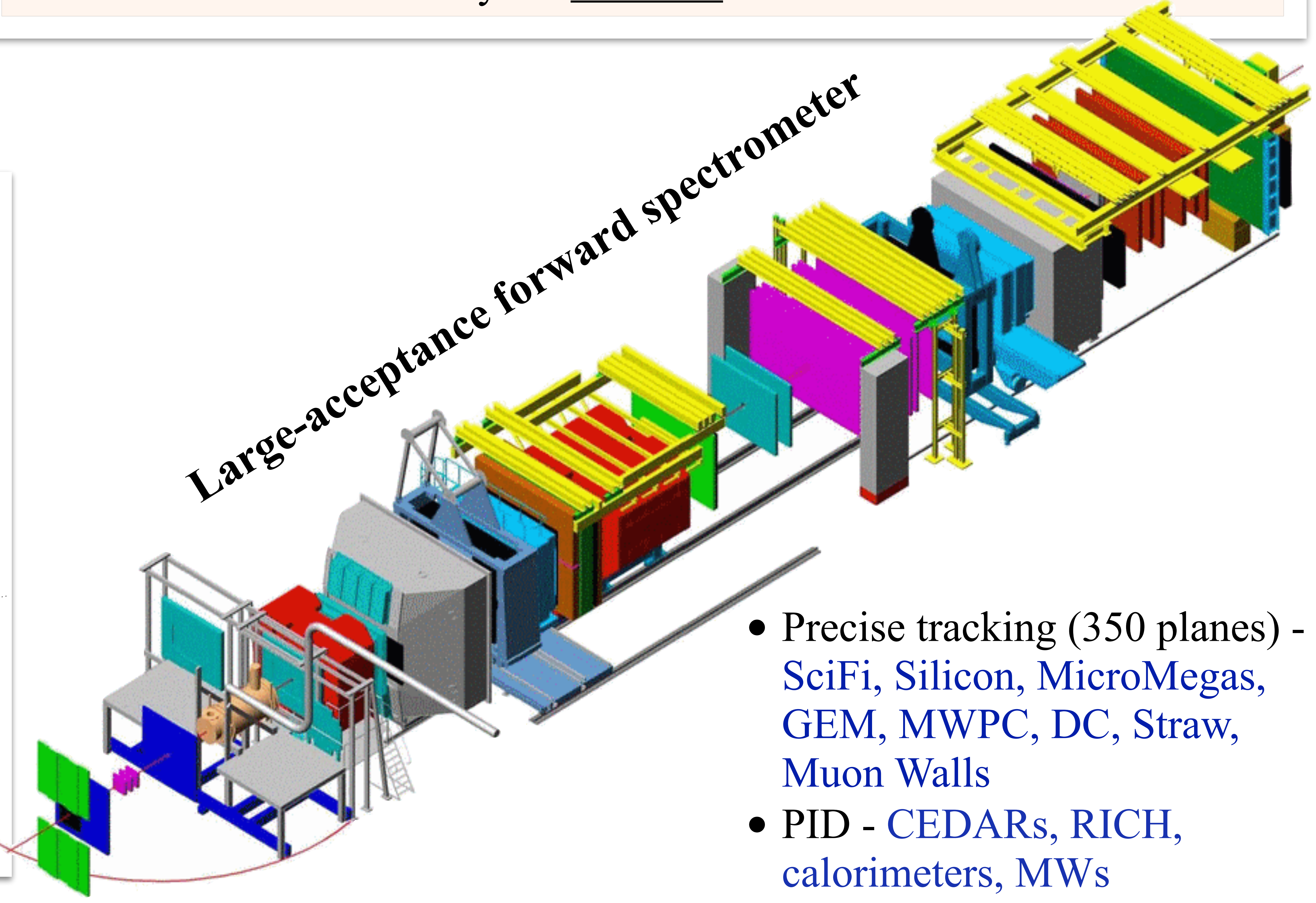
The spectrometer will stay in the experimental hall and is being upgraded and run by the AMBER Collaboration

COMPASS polarized solid-state target

- Polarization achieved by **Dynamic Nuclear Polarization (DNP)**
  - dilution refrigerator: ~60mK
  - dipole magnet (transverse): 0.5T
  - solenoid (longitudinal): 2.5T
  - microwave system
- Polarization determined with **Nuclear Magnetic Resonance (NMR)**

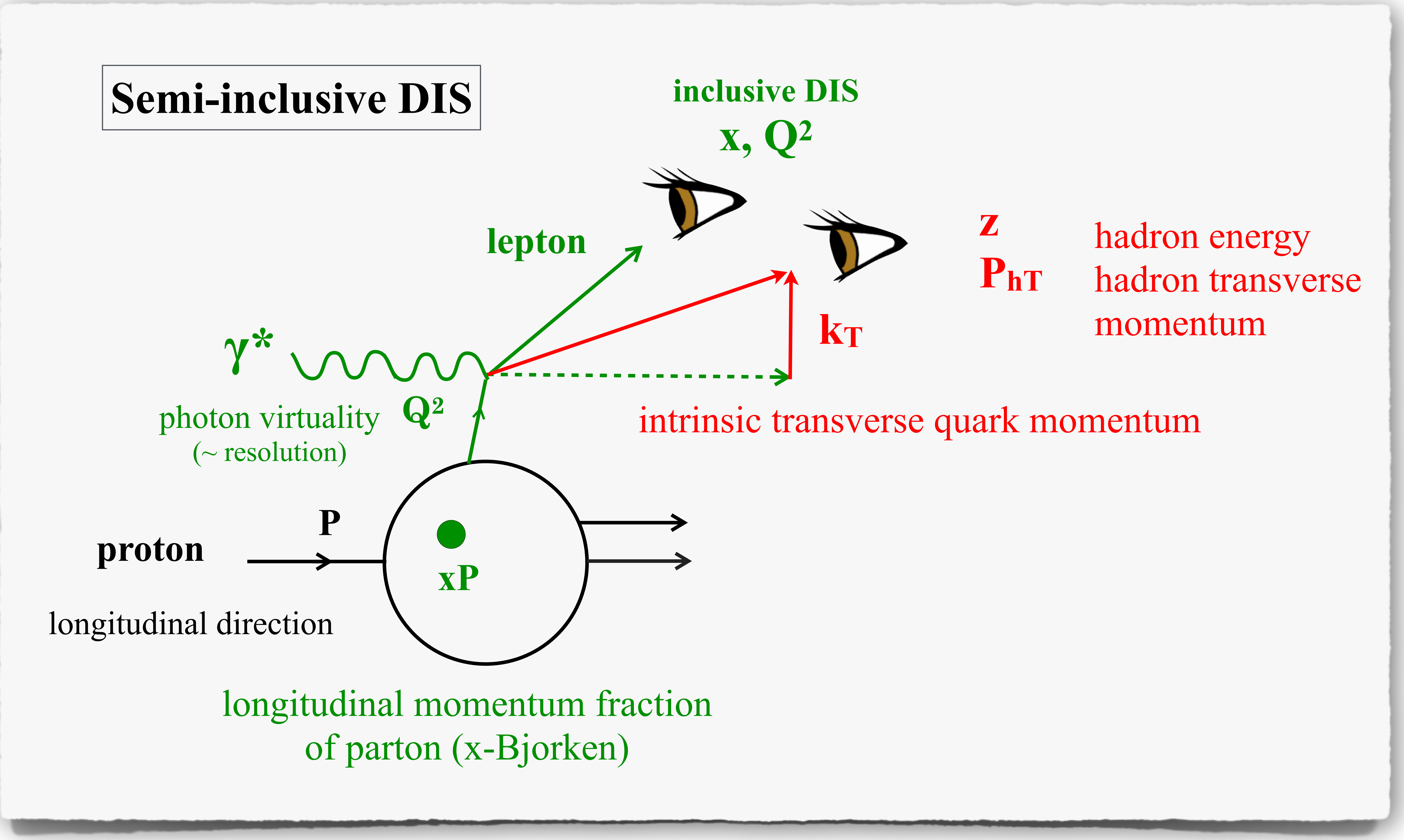


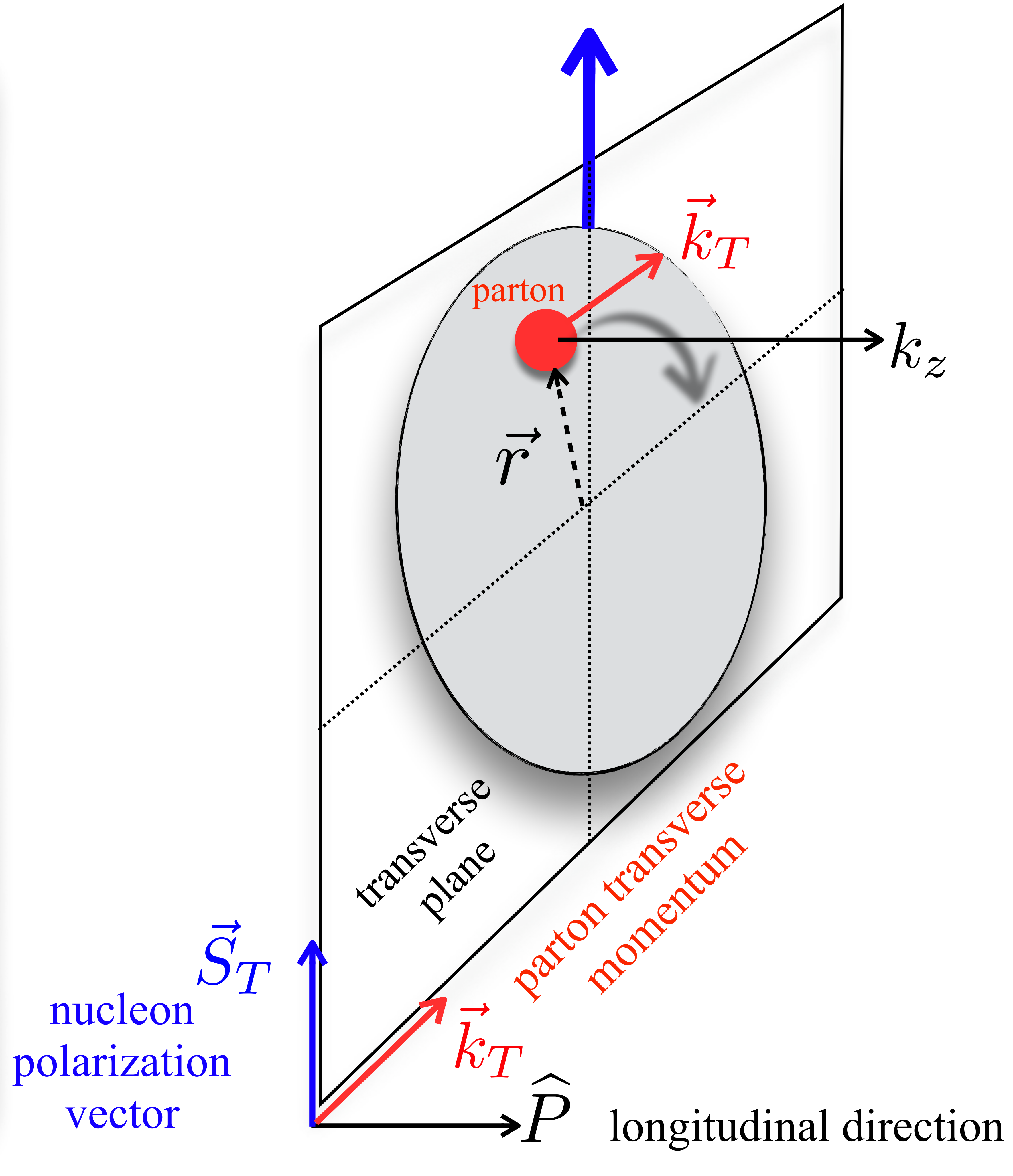
NH_3: ammonia beads, **^{6}LiD:** deuterated lithium
dilution factor ~ 0.22 (NH3), 0.5 (LiD)



- Precise tracking (350 planes) - SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon Walls
- PID - CEDARs, RICH, calorimeters, MWs

Transverse degrees of freedom





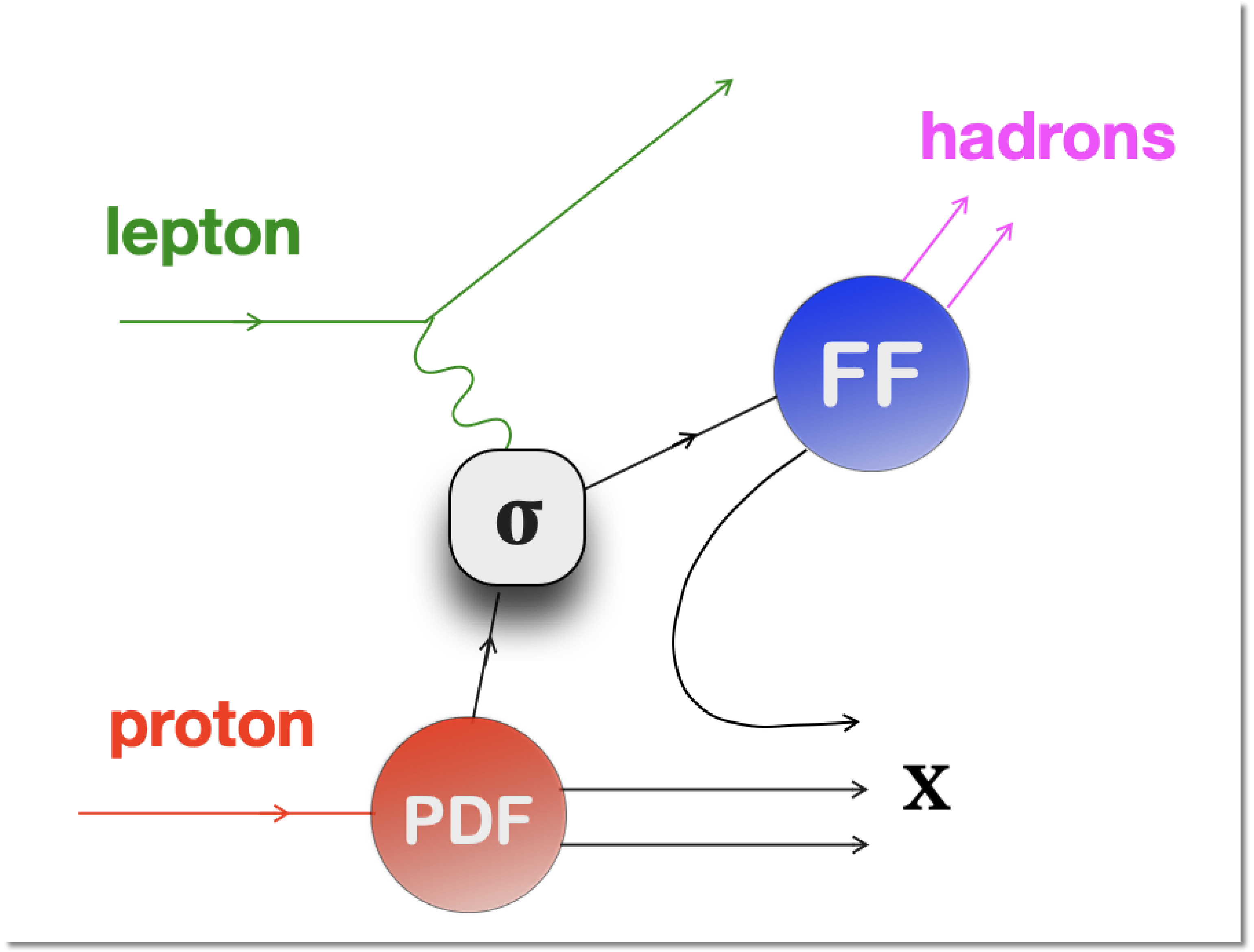
transverse momentum

$\Rightarrow \underline{r} \times \underline{k}_T \neq \underline{0}$

$\Rightarrow$ …**orbital angular momentum**…

The structure of the nucleon

- Taking into account the **quark intrinsic transverse momentum k_T**, at leading order **8 TMD PDFs** are needed for a full description of nucleon structure
- Correlations between parton transverse momentum, parton spin and nucleon spin (**spin-spin** and **spin-orbit correlations**)
- SIDIS gives access to all of them!



Collinear analysis

Naive time-reversal odd (spin-orbit)

chiral-odd

Table of TMD PDFs

N \ Q	U	L	T	
U	f_1 number density		$h_1^{\perp}$ Boer-Mulders	
L		g_1 helicity	$h_{1L}^{\perp}$ worm-gear	
T	$f_{1T}^{\perp}$ Sivers	$g_{1T}^{\perp}$ worm-gear	h_1 transversity	$h_{1T}^{\perp}$ pretzelosity

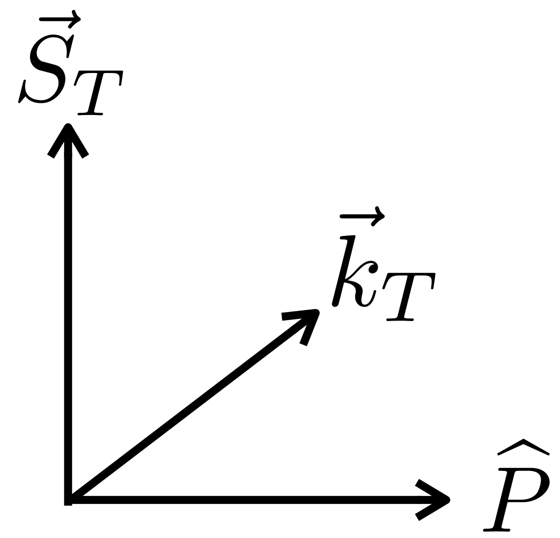
nucleon (N)

unpolarized parton (Q)

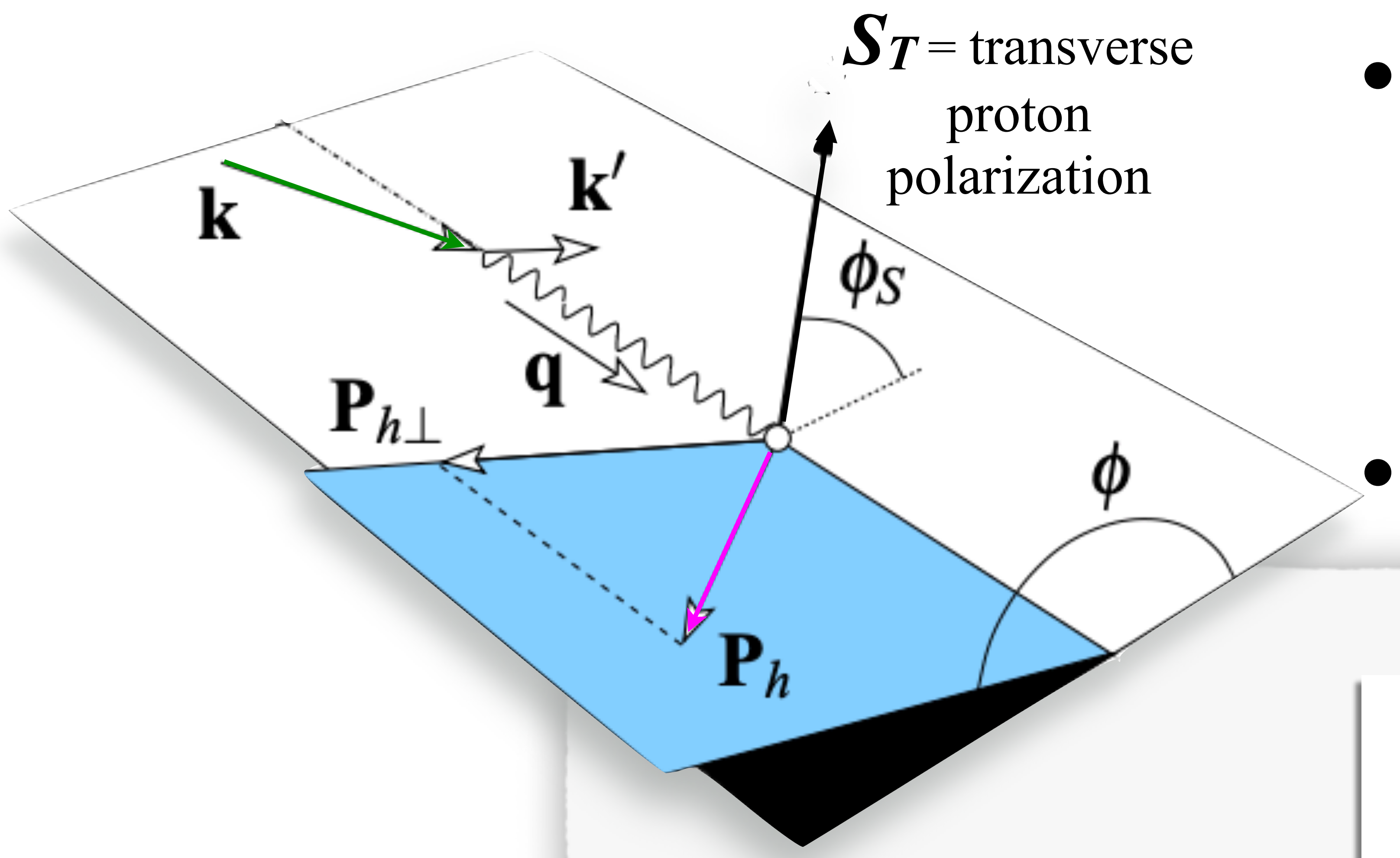
quark spin

parton transverse momentum

nucleon spin



Semi-inclusive deep-inelastic scattering cross section



- Cross section can be broken down in independent harmonic modulations ("azimuthal asymmetry amplitudes") times a PDF convoluted with a fragmentation function
- Experimental observable is of the type

"~ harmonic(ϕ, ϕ_S) · PDF ⊗ FF"

$$A_{UT}(\phi) = \frac{1}{f S_T} \frac{N^\uparrow(\phi) - N^\downarrow(\phi)}{N^\uparrow(\phi) + N^\downarrow(\phi)}$$

$$\sigma(\phi,\phi_S) \equiv \frac{d^6\sigma}{dx\,dy\,dz\,d\phi\,d\phi_S\,dP_{hT}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi\, F_{UU}^{\cos\phi} + \epsilon\cos(2\phi)\, F_{UU}^{\cos(2\phi)} + \lambda_e\left[\sqrt{2\epsilon(1-\epsilon)}\sin\phi\, F_{LU}^{\sin\phi}\right] +$$

$$+S_L\left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi\, F_{UL}^{\sin\phi} + \epsilon\sin(2\phi)\, F_{UL}^{\sin(2\phi)}\right] + S_L\lambda_e\left[\sqrt{1-\epsilon^2}\, F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos\phi\, F_{LL}^{\cos\phi}\right]$$

$$+|S_T|\left[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S)\, F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)\, F_{UT}^{\sin(3\phi-\phi_S)}\right.$$

$$\left. + \sqrt{2\epsilon(1+\epsilon)}\sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)\, F_{UT}^{\sin(2\phi-\phi_S)}\right]$$

$$+|S_T|\lambda_e\left[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)\, F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos\phi_S\, F_{LT}^{\cos\phi_S} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)\, F_{LT}^{\cos(2\phi-\phi_S)}\right]\Big\},$$

no proton polarization

longitudinal proton polarization

transverse proton polarization

Cahn-effect + BM ⊗ Collins

Worm-gear (Kotzinian-Mulders) ⊗ Collins

Sivers ⊗ D1

Worm-gear ⊗ D1

Transversity ⊗ Collins

Pretzelosity ⊗ Collins

BM ⊗ Collins

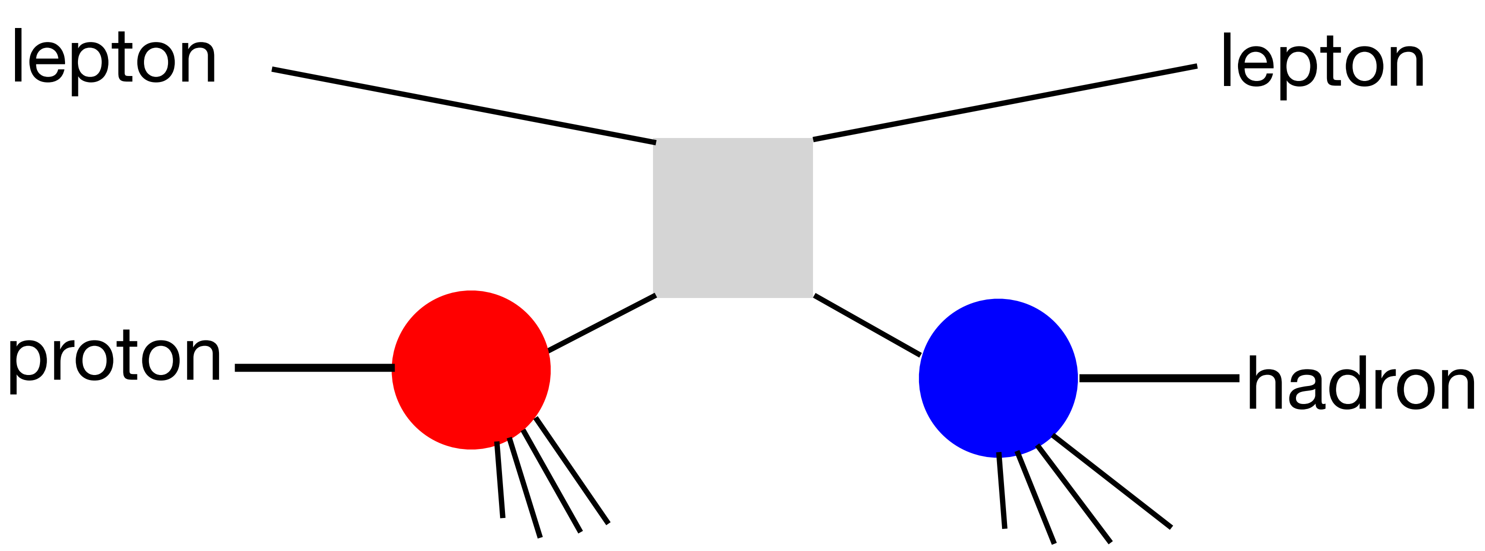
$F_{XY[Z]}$ = structure function. X=beam, Y= target polarization, [Z= virtual-photon polarization]. X, Y ∈ {U, L, T}. λ_e = helicity of the lepton beam. S_L and S_T = longitudinal and transverse target polarization. ϵ = ratio of longitudinal / transverse photon fluxes

[Bacchetta, Diehl, Klaus Goeke, Metz, Mulders, Schlegel, JHEP 02 (2007) 093]

Experimental TMD probes

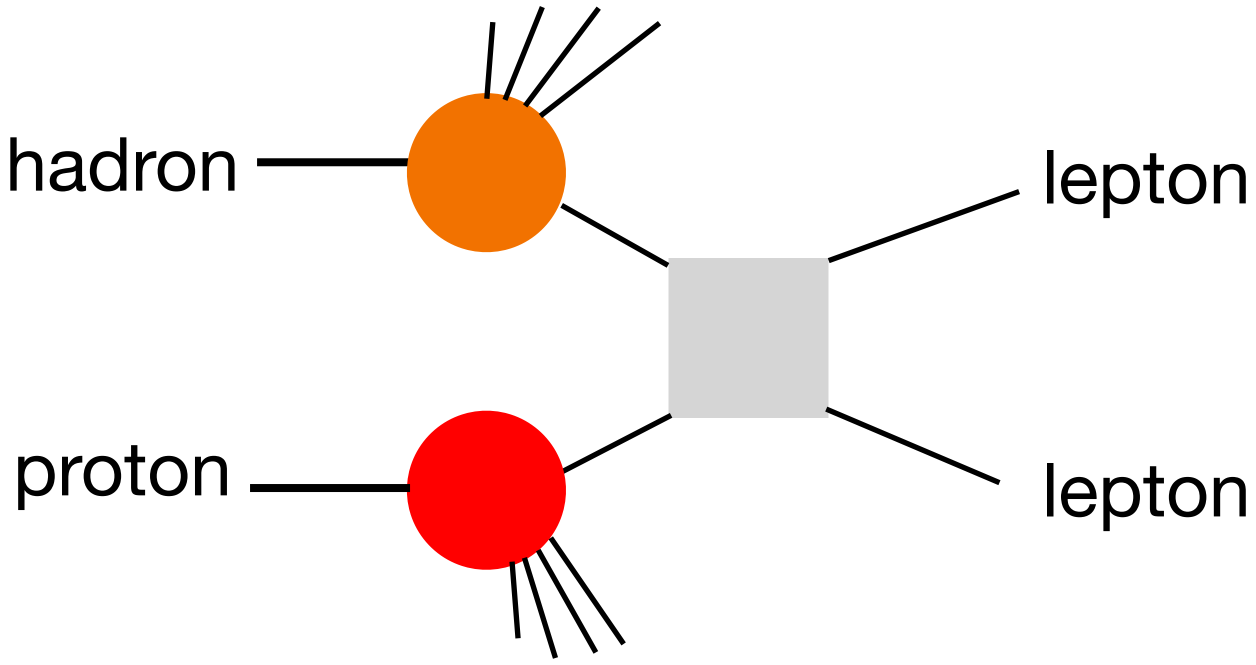
PDF FF

SIDIS



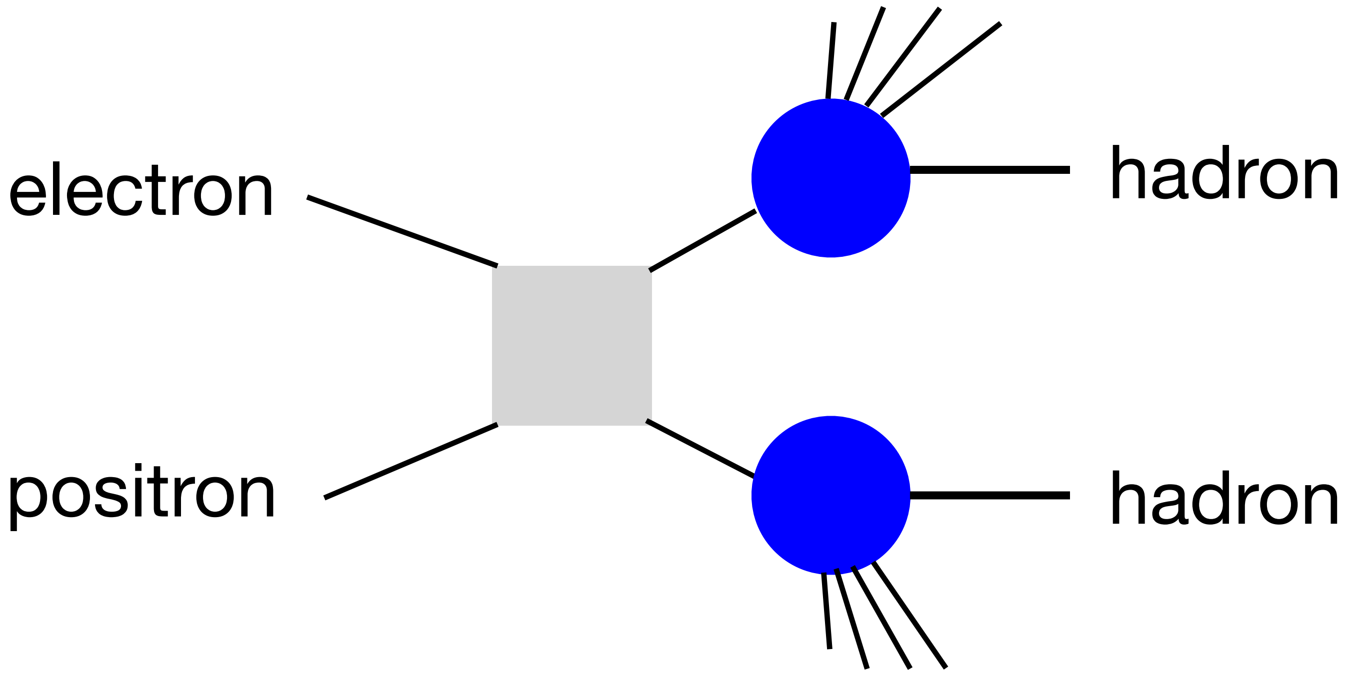
HERMES, COMPASS, JLab

Drell-Yan and W, Z



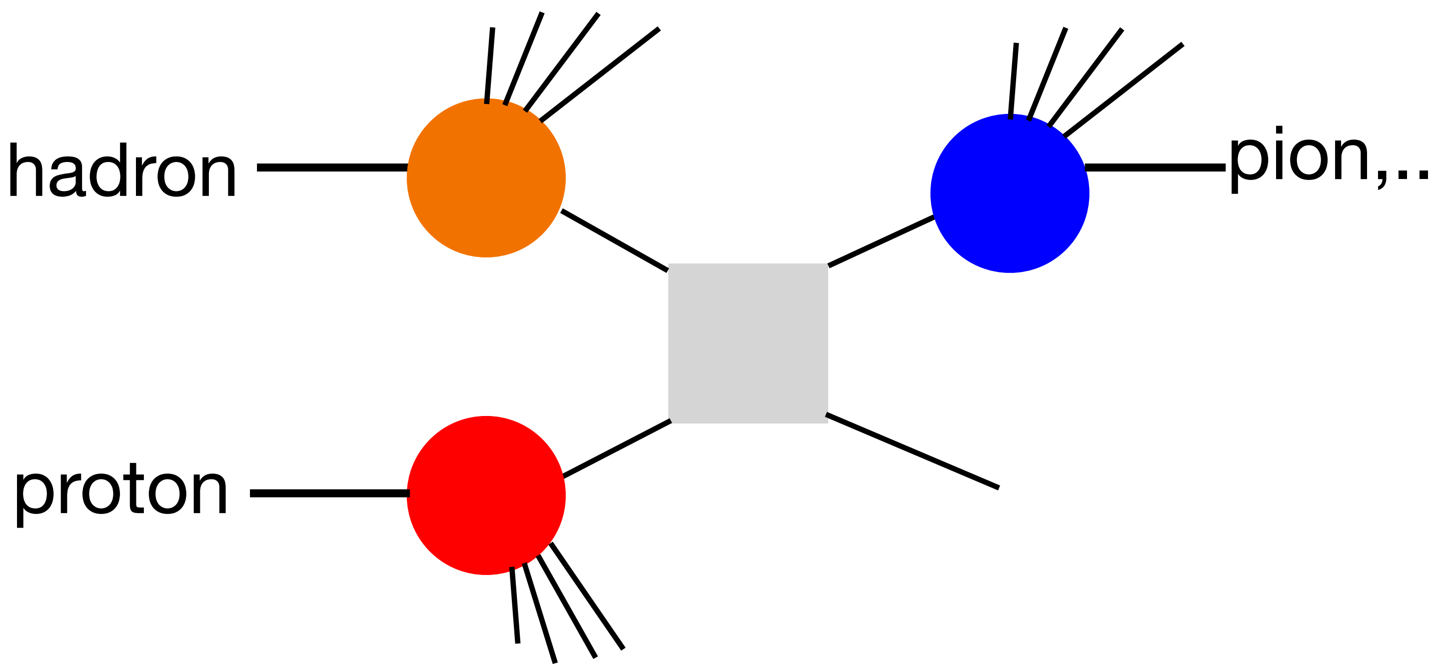
COMPASS, STAR, SpinQuest

e^+e^- annihilation



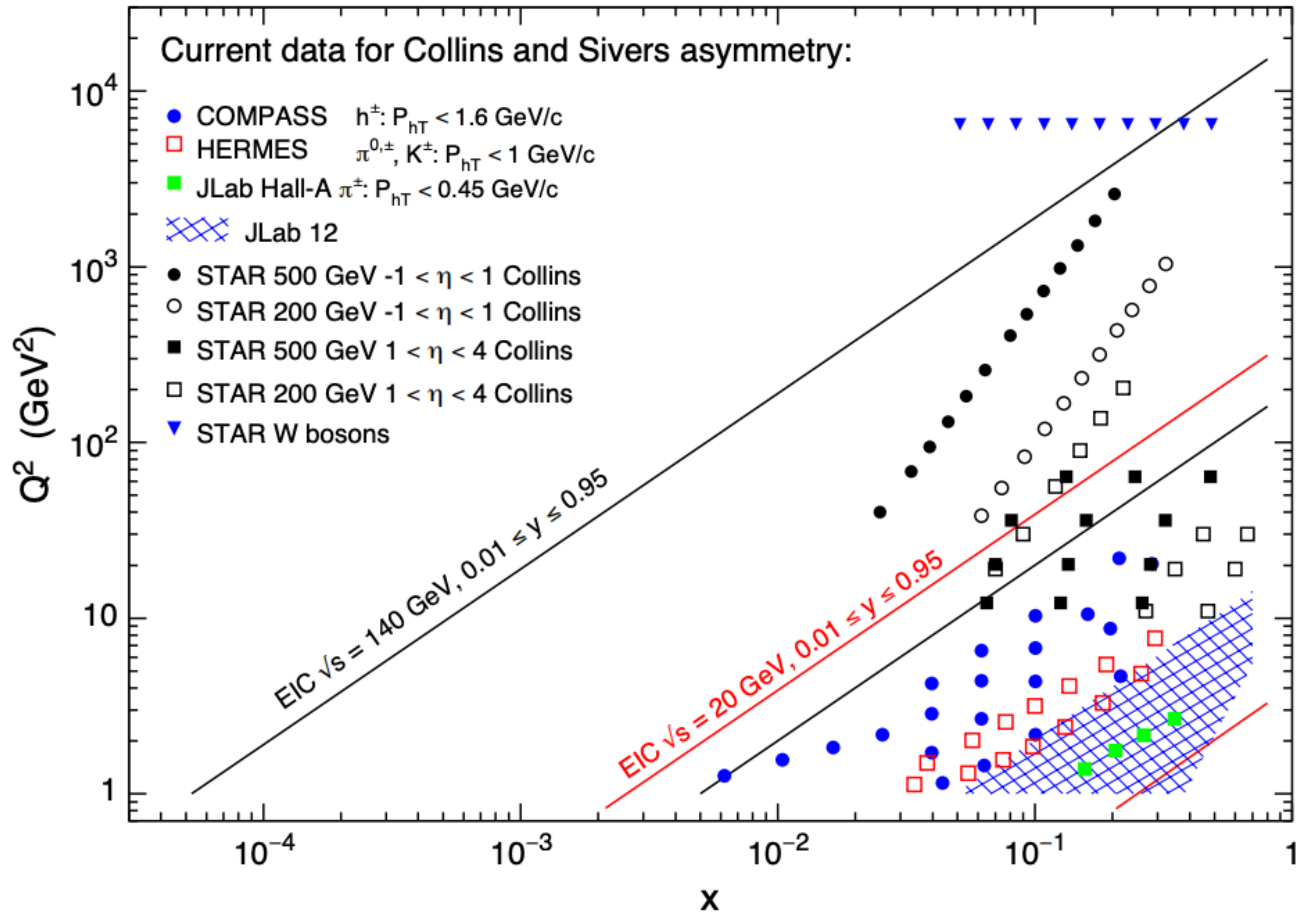
Belle, BaBar, BESIII

pp collisions



STAR, PHENIX, BRAHMS

A huge experimental effort



[EIC yellow report, arXiv:2103.05419]

Transverse-momentum distributions

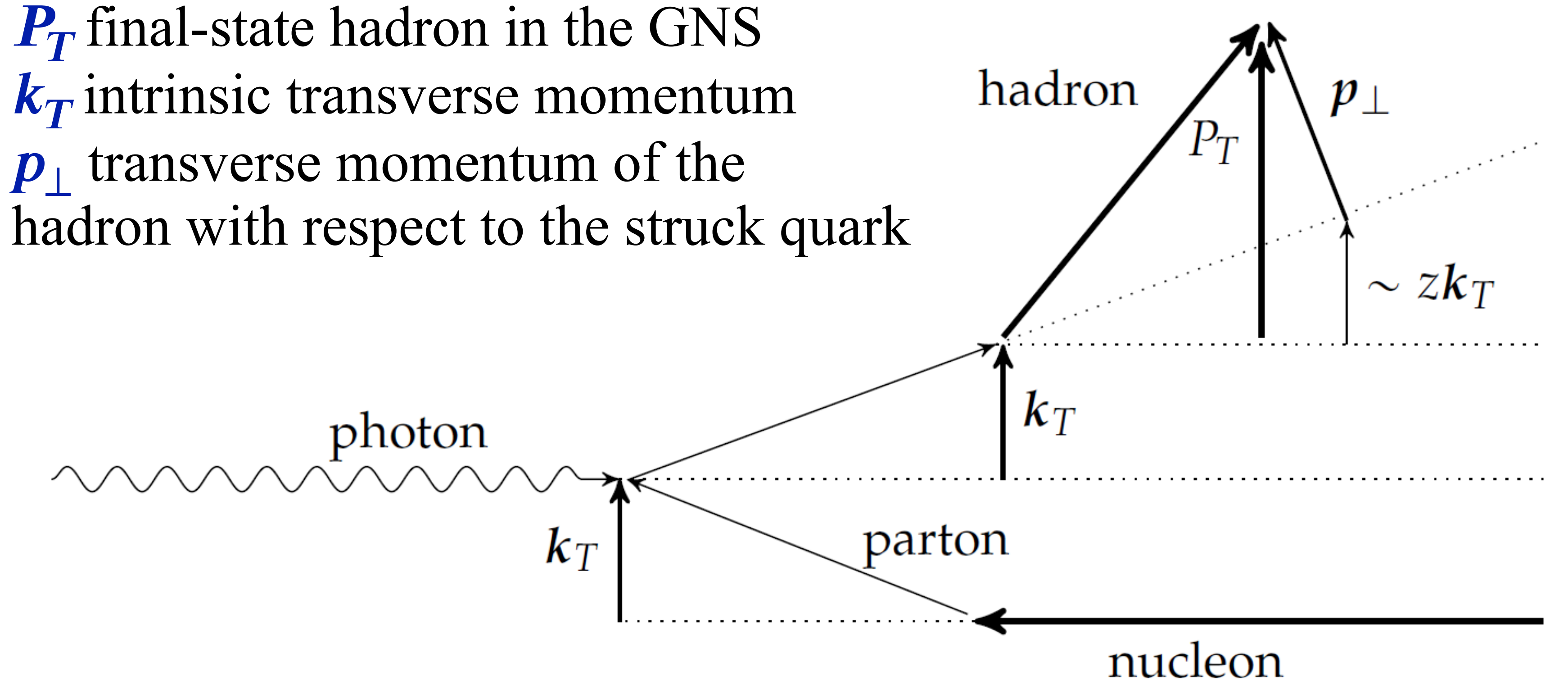
- Allow to gain information about **intrinsic quark momentum** k_T by measuring transverse momentum P_T of the produced hadron.
- Important for **TMD evolution studies & comparison between experiments.** Intense theoretical work ongoing to reproduce the experimental distributions over a wide energy range.
- In Gaussian approximation, at small values of P_T, the number of hadrons is expected to follow:

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

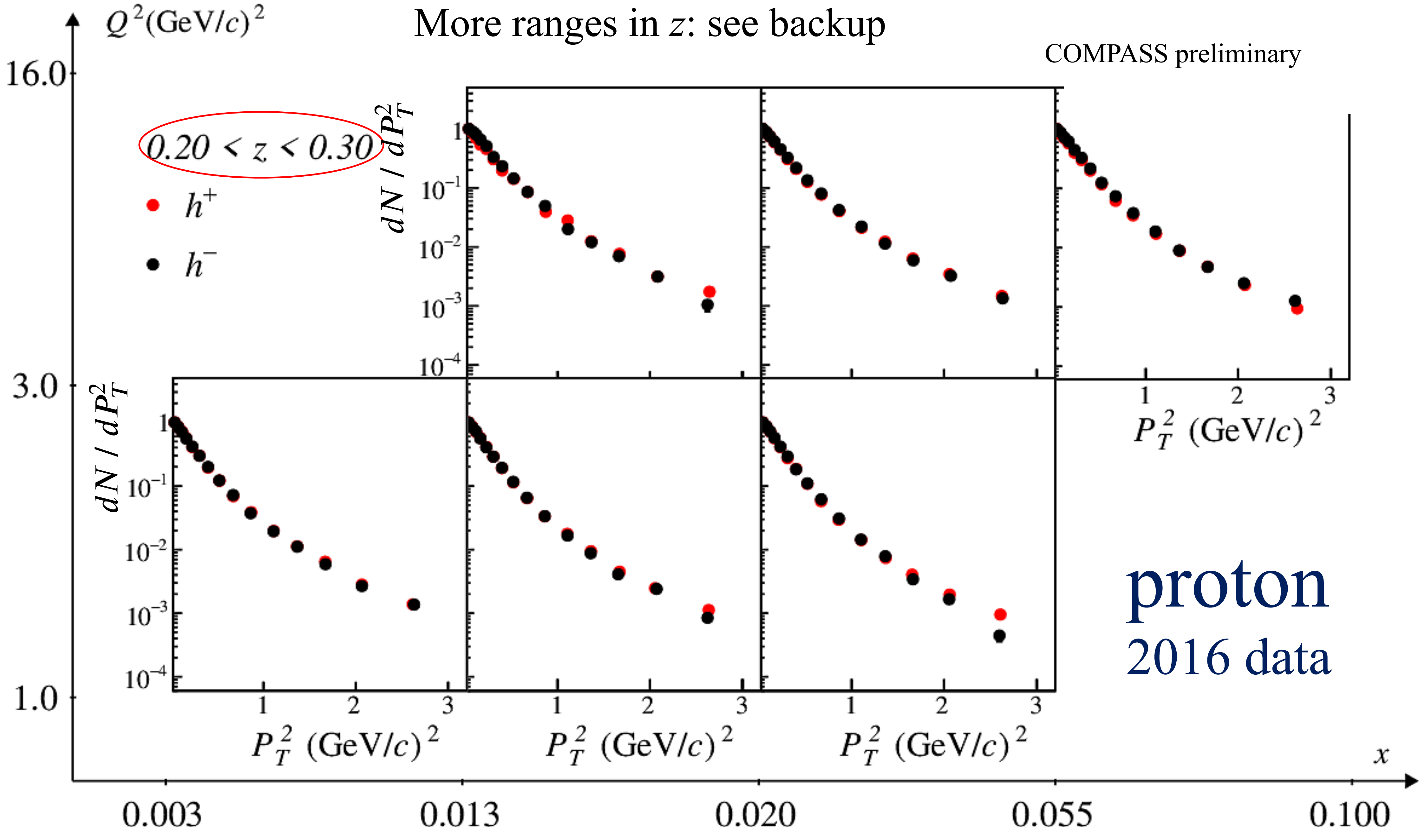
$$\langle P_T^2\rangle = z^2\langle k_T^2\rangle + \langle p_\perp^2\rangle$$

- Double Gauss structure in P_T spectrum separated at 1 GeV/c → 2 different slopes
  - Perturbative effects expected to contribute more at high P_T
  - Likely not sufficient to explain the high-P_T trend
    e.g. Gonzales-Hernandez et al., *Phys.Rev.D* 98 (2018) 11, 114005
- Hadron multiplicities (not shown)
  - p-/p+ and K-/K+ at high z PLB 807 (2020) 135600, K-/K+ at high z PLB 786 (2018) 390
  - h PRD 97 (2018) 032006, K isoscalar PLB 767 (2017) 133, π± and h± PLB 764 (2017) 001

P_T final-state hadron in the GNS
k_T intrinsic transverse momentum
$p_\perp$ transverse momentum of the hadron with respect to the struck quark



More ranges in z: see backup



- Normalization: first P_T^2 bin.
- Different normalization for each bin and charge
- Error bars correspond to the statistical uncertainty only. $\sigma_{syst} \sim 0.3\,\sigma_{stat}$

Azimuthal asymmetries - 1D (x or z or P_T)

unpolarized

Cahn effect + BM ⊗ Collins

- The **Boer-Mulders function** describes the strength of the spin-orbit correlation between quark spin s_T and intrinsic transverse momentum k_T:

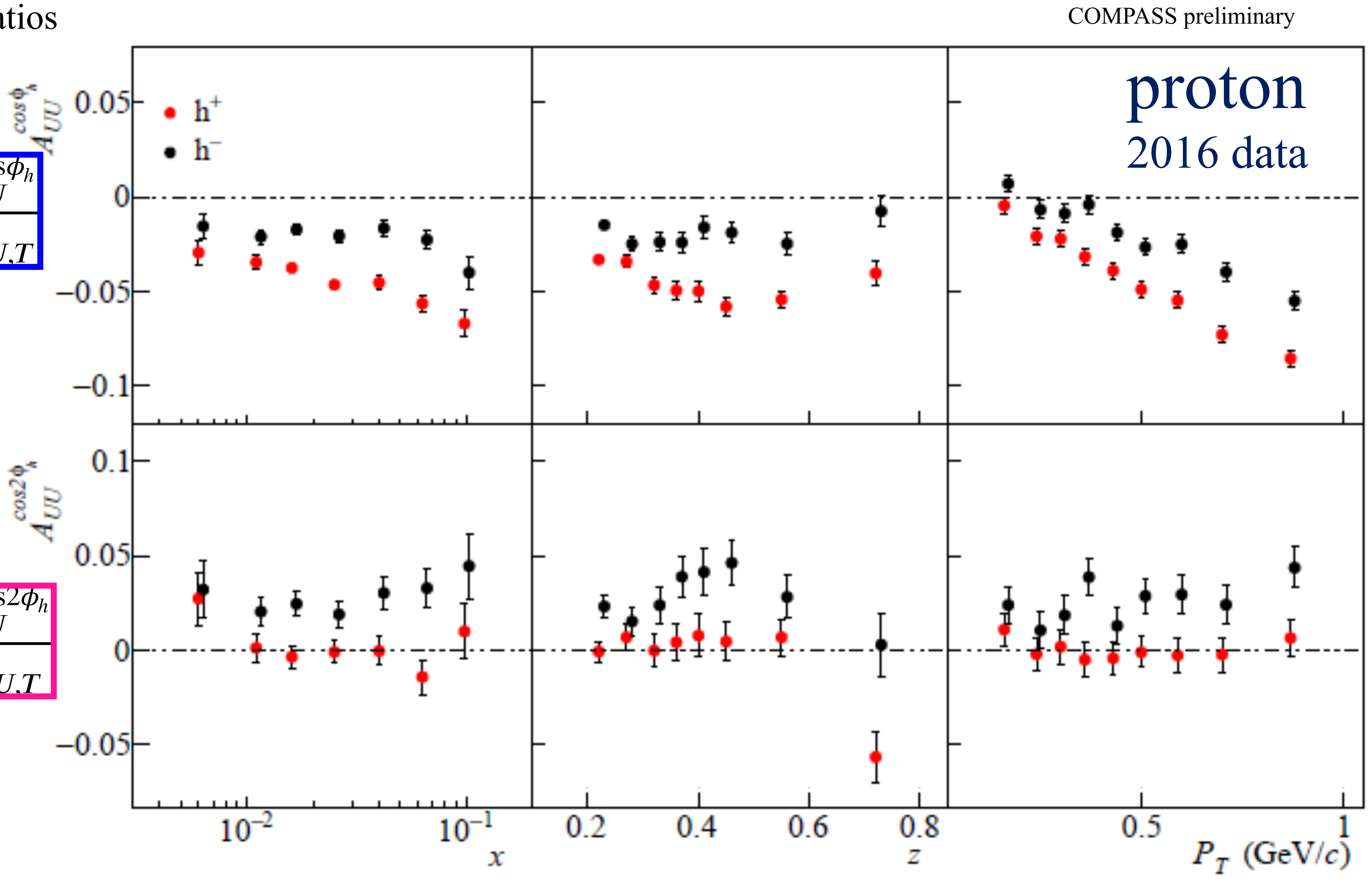
$$\vec{s}_T \cdot (\widehat{P} \times \vec{k}_T)$$

  - Contributes to **$\cos\phi_h$** and **$\cos(2\phi_h)$**
  - Strong kinematic dependences & interesting differences between positive and negative hadrons, as observed in previous measurements by COMPASS on deuteron and by HERMES (u-quark dominance, opposite signs of Collins FF into h+ and h-)
- **Cahn effect**
  - Contributes to **$\cos\phi_h$** only → next slide
- Higher-twist beam-spin asymmetry $A_{LU}^{\sin\phi_h} = \frac{F_{LU}^{\sin\phi_h}}{F_{UU,T}}$ (backup)
- Azimuthal asymmetries for **hadron pairs** on the unpolarized proton (backup)
  - Collins FF for 2 hadrons & interference fragmentation function

Azimuthal asymmetries
defined as the ratios

$$A_{UU}^{\cos\phi_h} = \frac{F_{UU}^{\cos\phi_h}}{F_{UU,T}}$$

$$A_{UU}^{\cos2\phi_h} = \frac{F_{UU}^{\cos2\phi_h}}{F_{UU,T}}$$



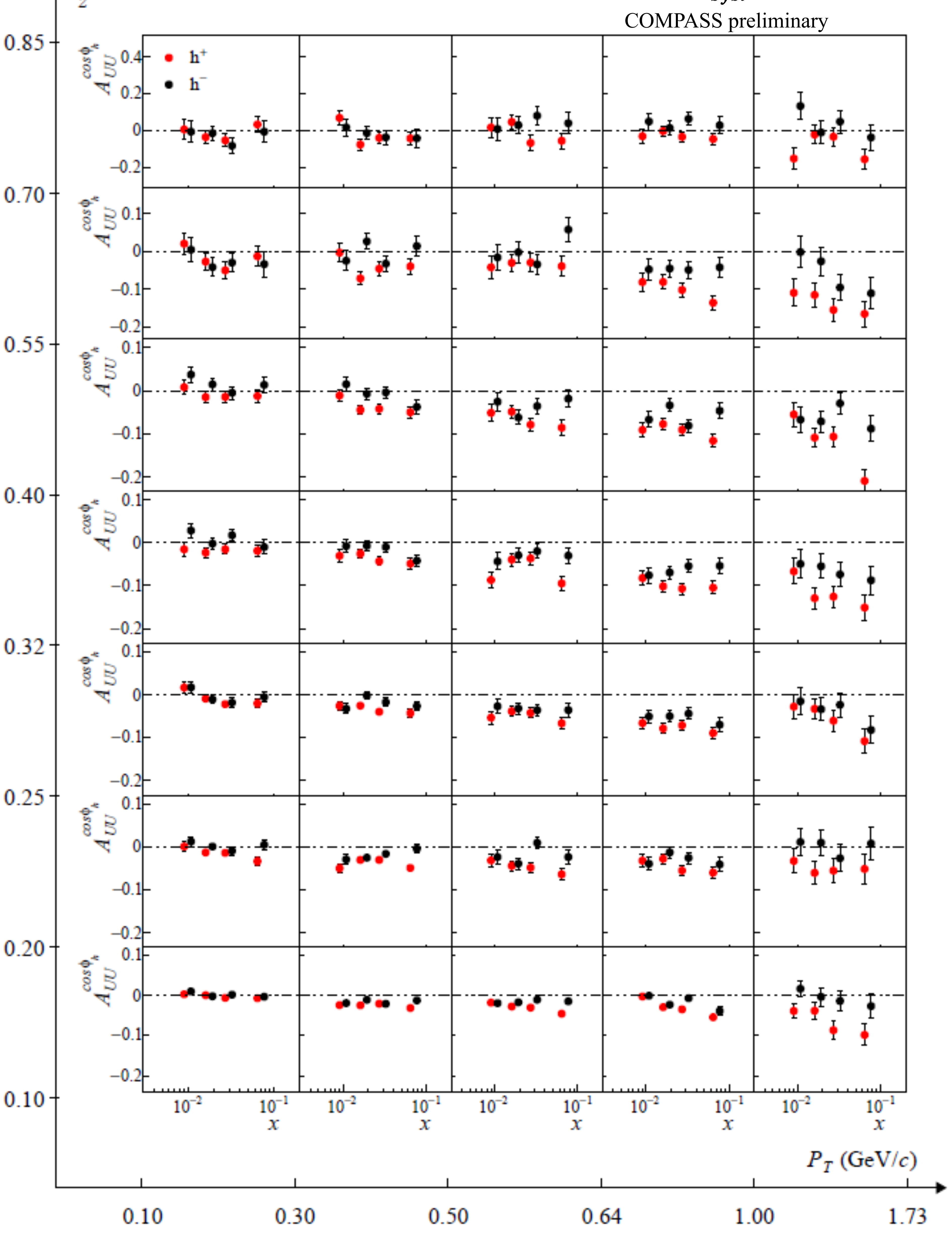
The error bars correspond to the statistical uncertainty only. $\sigma_{syst} \sim \sigma_{stat}$ (1D)

Azimuthal asymmetries - 3D (x, z, p_T)

unpolarized

Cahn-effect + BM ⊗ Collins

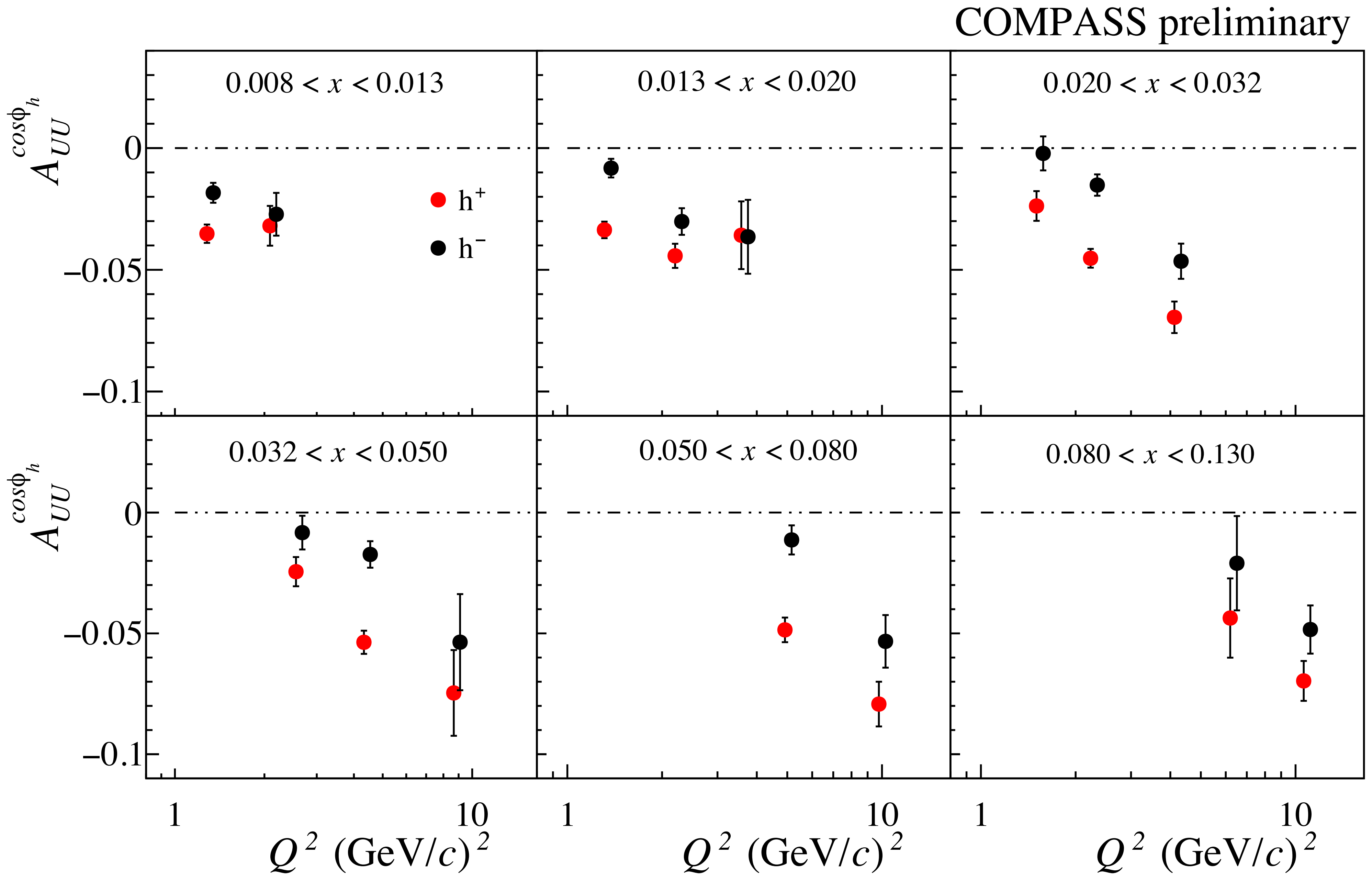
The error bars correspond to the statistical uncertainty only. $\sigma_{syst} \sim 0.5\,\sigma_{stat}$ (3D)



- **Cahn effect** - additional (to BM) cosϕ_h modulation purely due to the presence of intrinsic transverse momenta of unpolarized quarks in the unpolarized nucleon. No such modulation in the collinear case. Next-to-leading-order effect.
  - Clear signal, strong dependence on P_T .
    Compatible with zero at high z. In agreement with COMPASS deuteron results.
- Naive expectation

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

  - observed trend is however opposite (increase with Q^2)



- Complementary access to **quark intrinsic transverse momentum** + other PDFs & FFs contributions

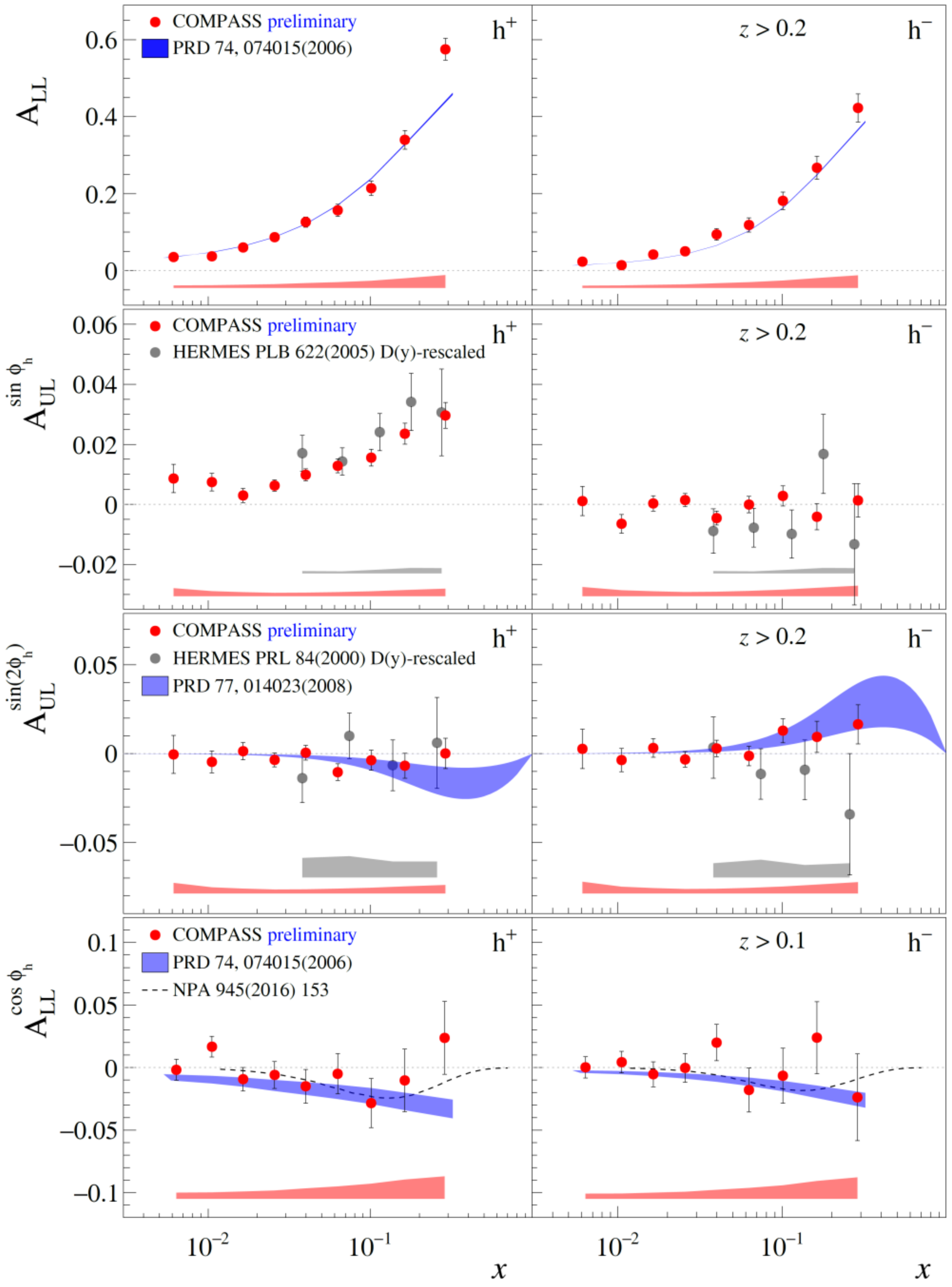
proton

2016 data

SIDIS off longitudinally polarized targets

L-polarized

B. Parsamyan (for COMPASS) arXiv:1801.01488 [hep-ex]



- COMPASS collected a large amount of L-SIDIS data with unprecedented precision for some amplitudes

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

  - Q-suppression, higher-twist subleading effects
  - Sizable TSA-mixing
  - Significant h+ asymmetry, clear z-dependence
  - h– compatible with zero

$A_{UL}^{\sin 2\phi_h}$

  - Only "twist-2" ingredients
  - Additional P_T-suppression
  - Compatible with zero, in agreement with models
  - Collins-like behavior?

$A_{LL}^{\cos\phi_h}$

  - Q-suppression, higher-twist subleading effects
  - Compatible with zero, in agreement with models

- Di-hadron asymmetries (not shown)

SIDIS off transversely polarized targets

T-polarized

COMPASS

A long list of measurements…

d & p	Collins and Sivers asymmetries (1D)	several papers
d & p	di-hadron asymmetries	several papers
d & p	other TSAs	
p	multiD measurements of TSAs $(x,\ Q^2,\ z,\ P_T)\ bins$	
p	Sivers asymmetry and other TSAs in Q^2 bins	PLB 770 (2017) 138
p	P_T - weighted Sivers asymmetries	NPB 940 (2019) 34
p	transversity induced $\Lambda /\ \bar{\Lambda}$ polarization	PLB 824 (2022) 136834
d & p	TSAs for high P_T pairs from PGF events	PLB 772 (2017) 85
p	J/Ψ Sivers asymmetry	
p	inclusive ρ^0 TSAs	submitted to PLB, hep-ex/2211.00093

…all to be done again using the 2022 data.

Sivers asymmetry in SIDIS

T-polarized

Sivers ⊗ D1

- Sivers effect: spin-orbit correlation between the nucleon transverse spin and parton transverse momentum in the transversely polarized nucleon

$$\vec{S}_T \cdot (\widehat{P} \times \vec{k}_T)$$

- Sivers function describes strength of distortion in transverse momentum space from the symmetric unpolarized distribution f_1

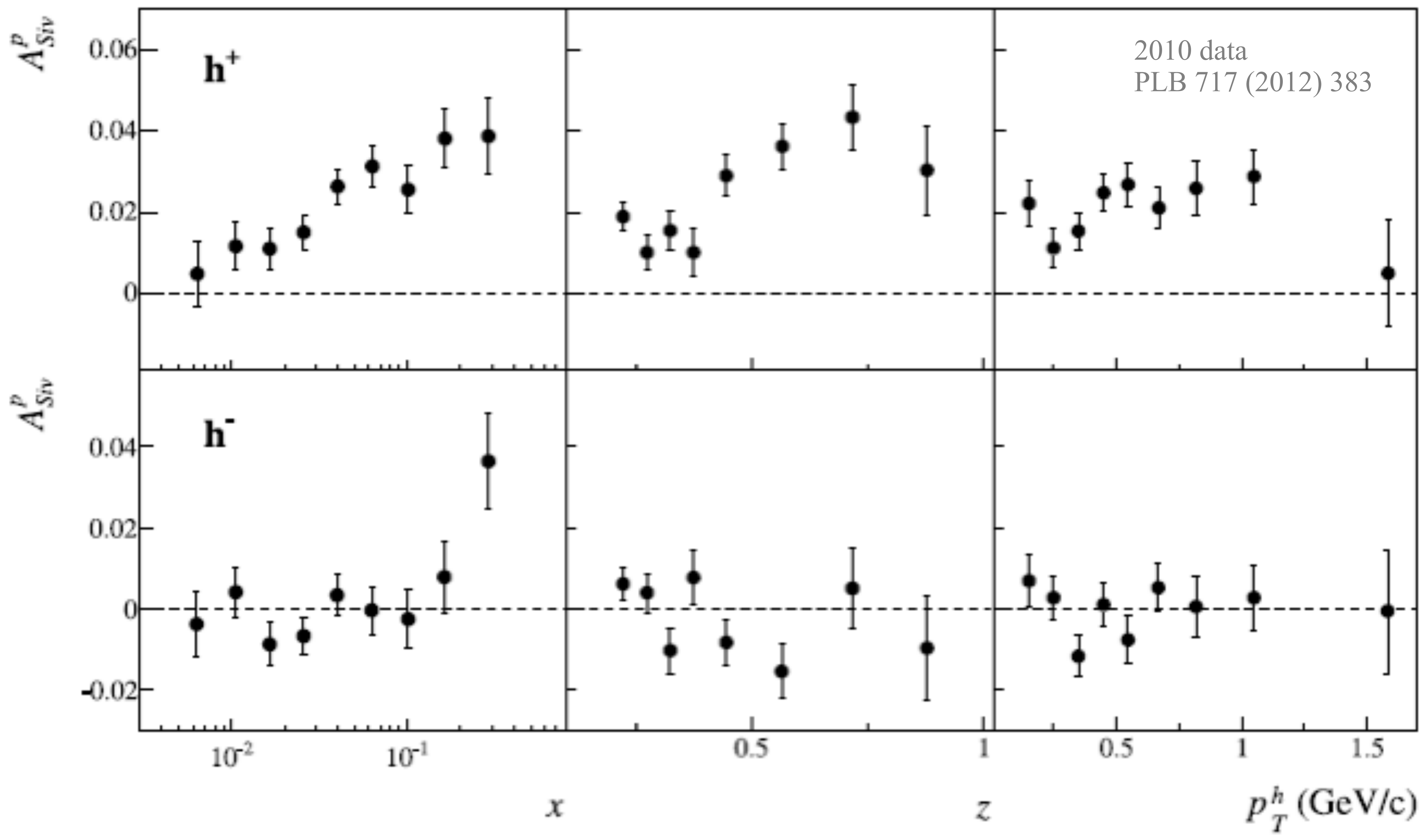
$$f_{q/p^\uparrow}(x, \boldsymbol{k}_T) = f_1^q(x, \boldsymbol{k}_T^2)$$

$$- f_{1T}^{\perp q}(x, \boldsymbol{k}_T^2)\, \boldsymbol{S} \cdot \left(\frac{\hat{\boldsymbol{P}}}{M} \times \boldsymbol{k}_T \right)$$

proton results

clearly positive for h^+

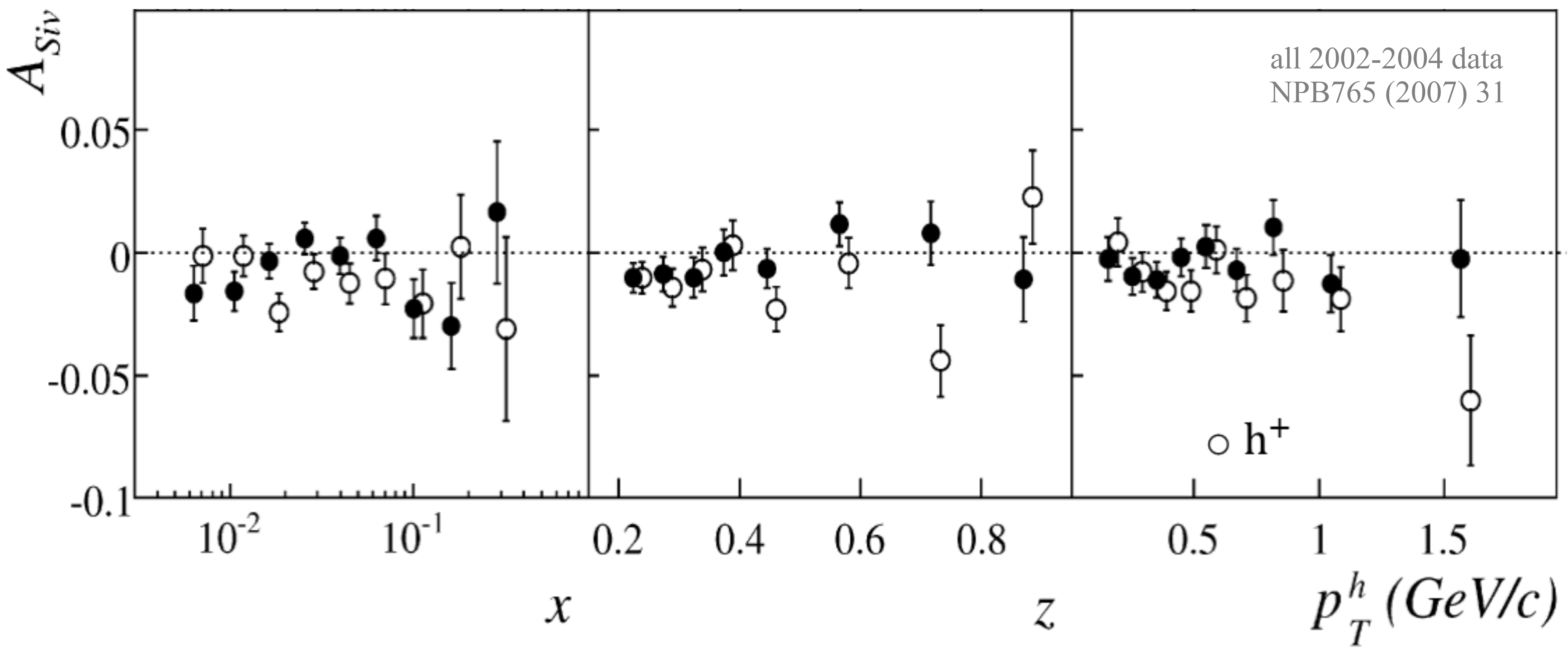
compatible with zero (but last x point) for h^-



deuteron results

close to zero with large statistical uncertainties

attributed to u/d-quark cancellation effects

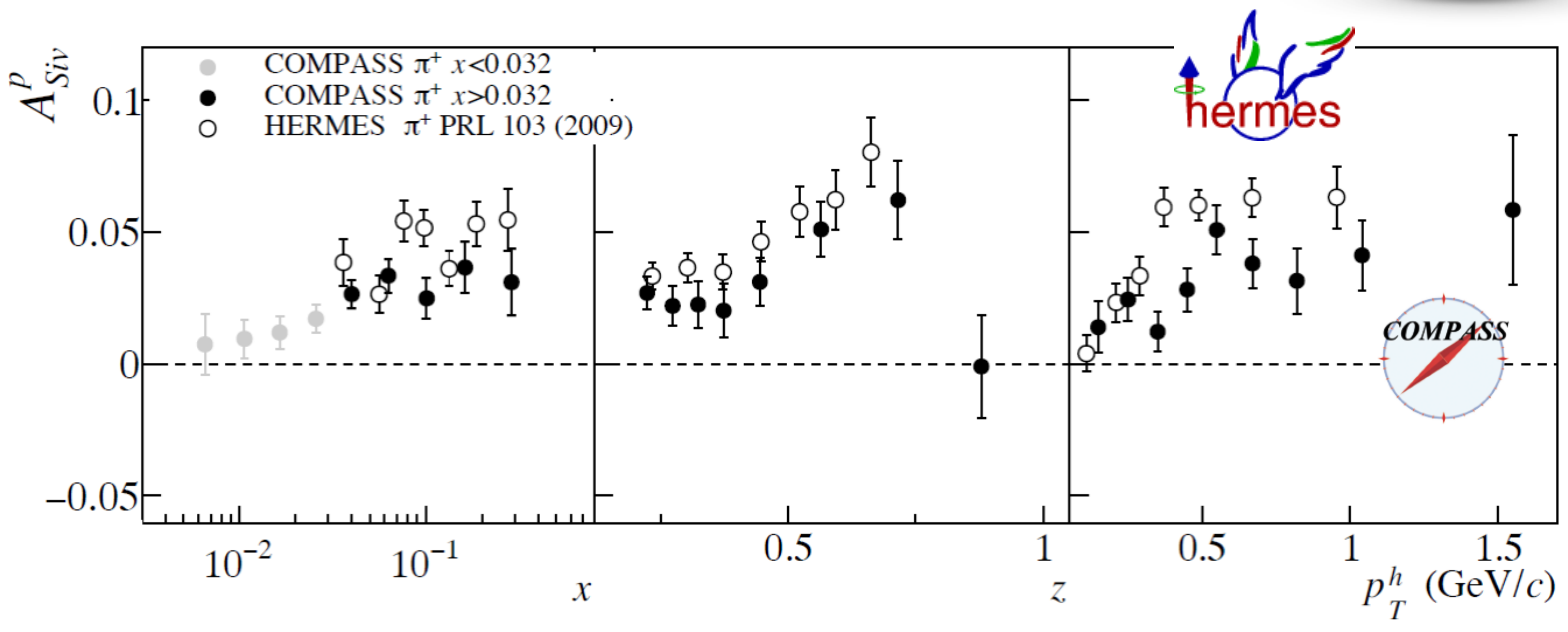


Sivers asymmetry in SIDIS - a first global look

T-polarized

Sivers ⊗ D1

COMPASS



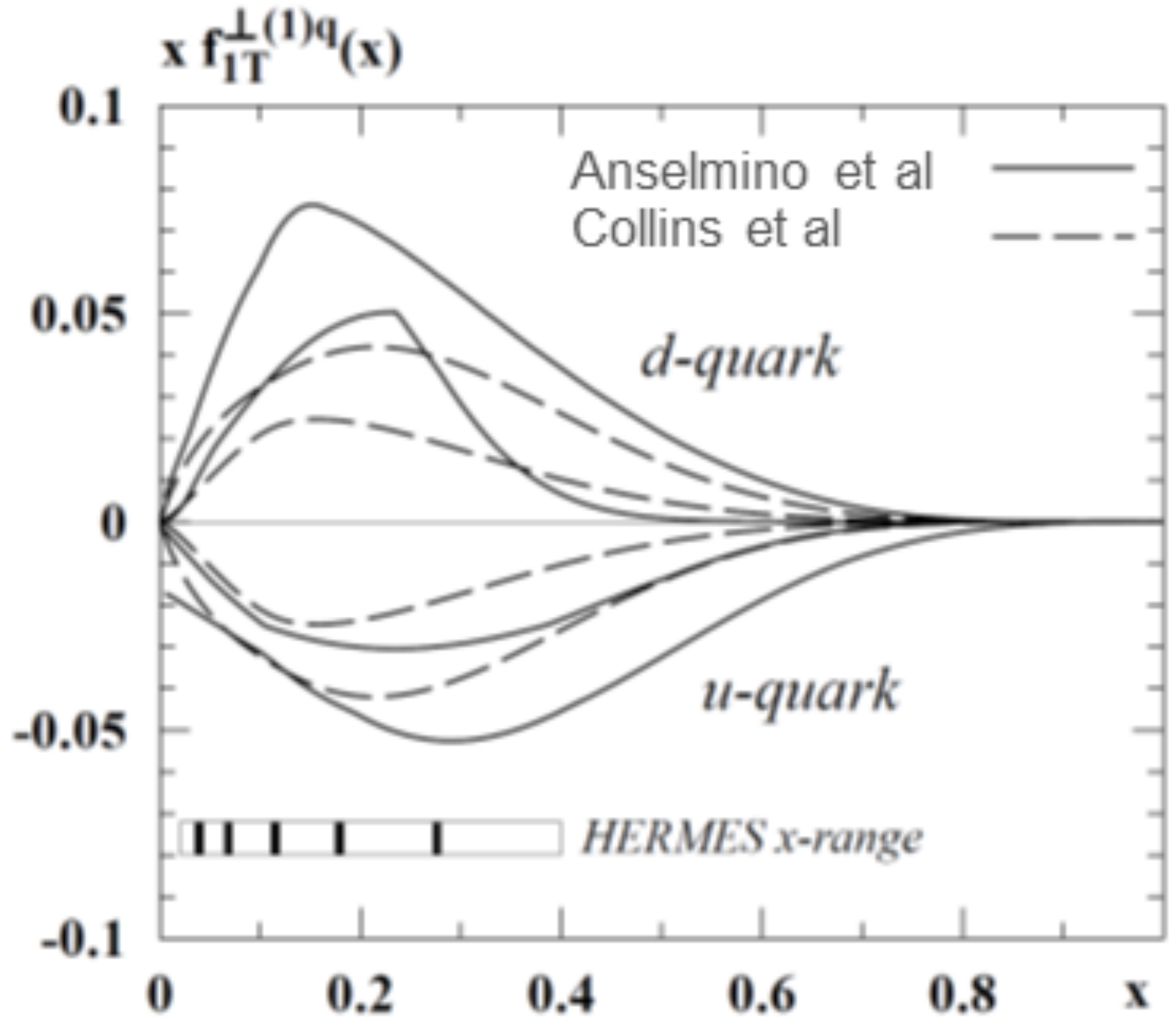
- Comparison with HERMES - smaller values of the Sivers asymmetry amplitude at COMPASS: may be attributed to TMD evolution …

  lepton beam energies:
  HERMES: 27.6 GeV
  COMPASS: 160 GeV

- The first extractions of the **Sivers TMD PDFs** from these Sivers asymmetries on the proton and the deuteron **in the TMD framework** followed very soon, in 2005, the publication of the first HERMES p results and COMPASS d results.

  Both the HERMES and COMPASS data could be well described.

- A success of the then new TMD framework. Various global extractions with additional data followed.
- u- and d-quark Sivers functions have different signs.



proceedings of ***Transversity 2005***

P_T-weighted Sivers asymmetry in SIDIS

T-polarized

Sivers P_T-weighted ⊗ D1

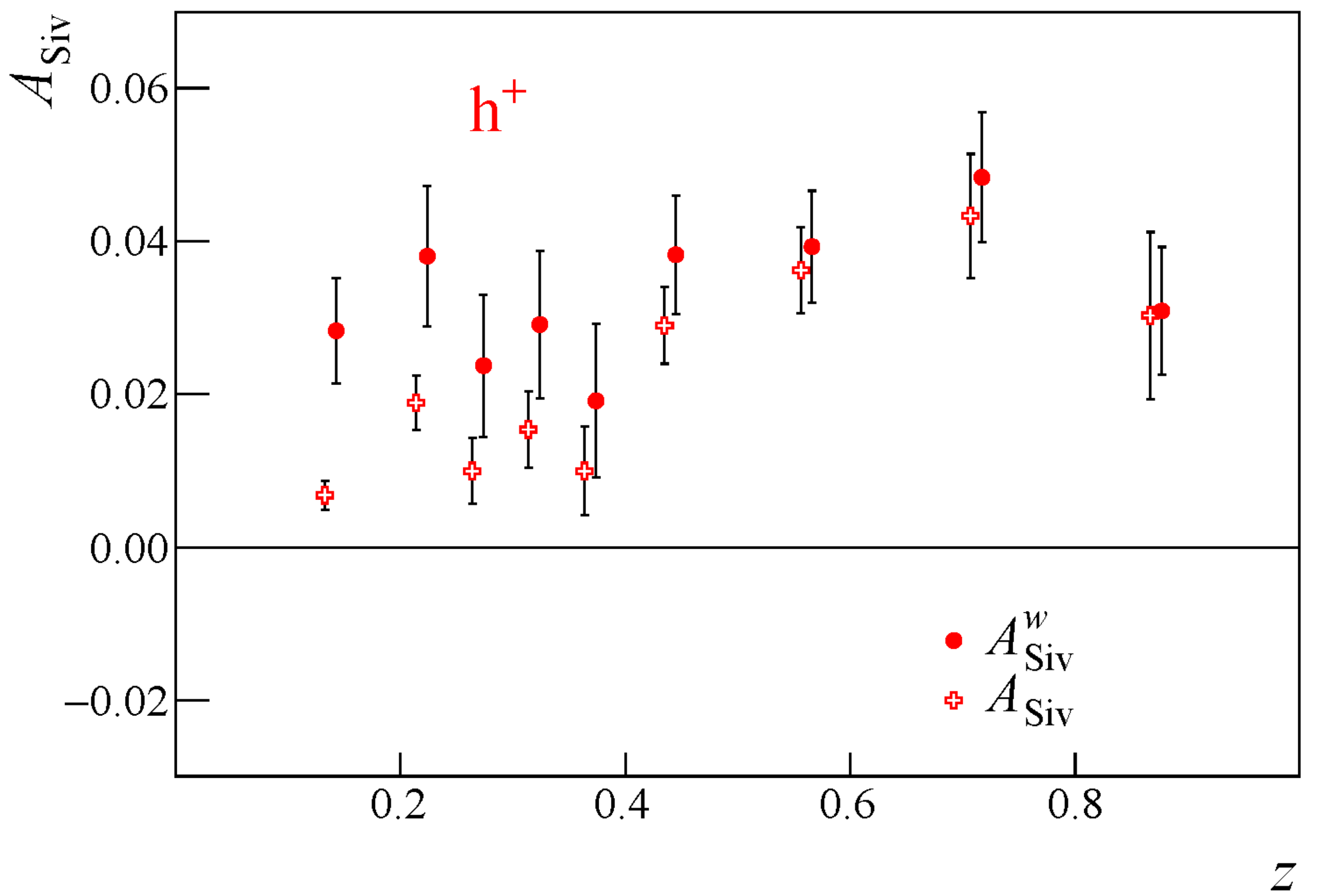
COMPASS

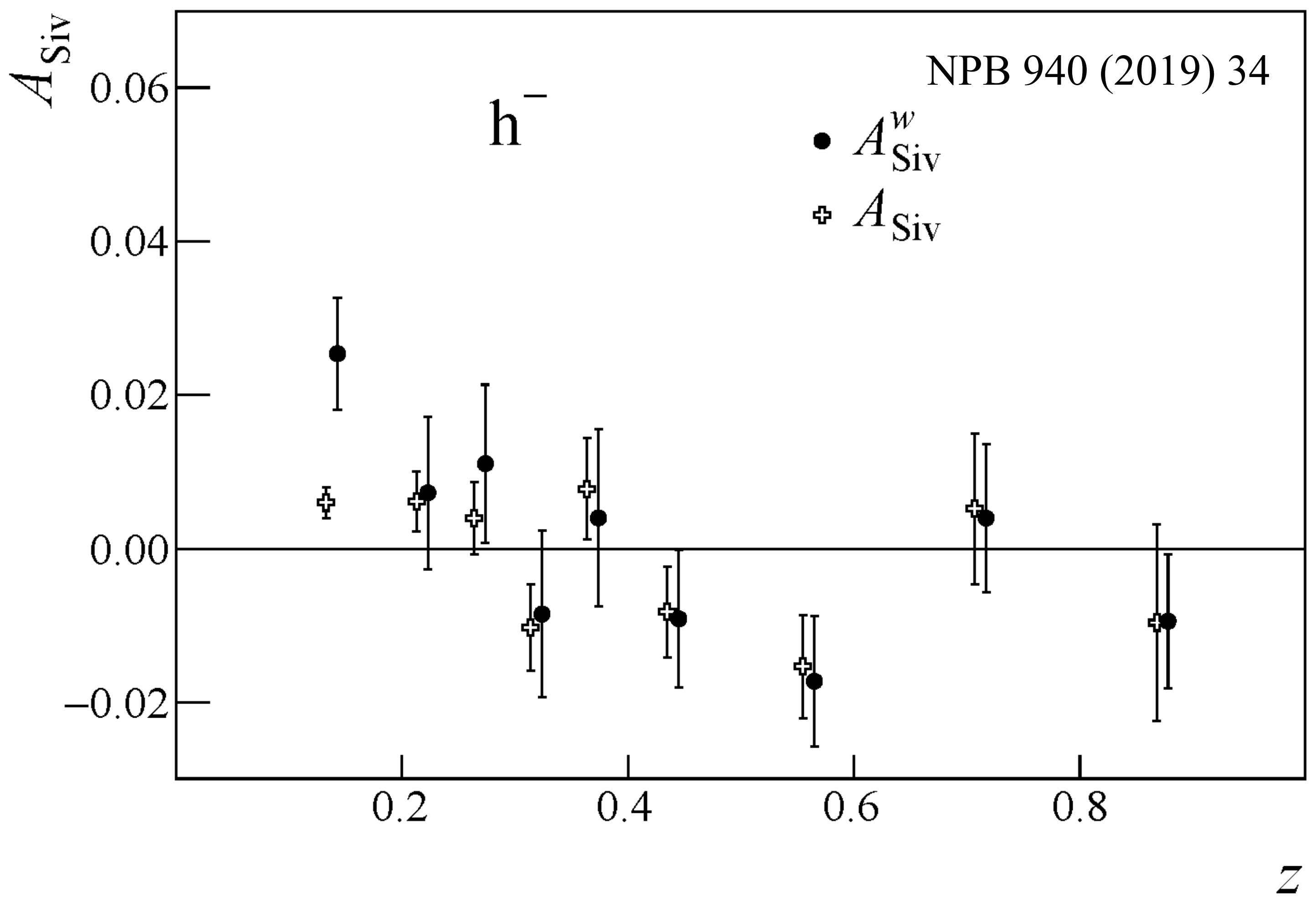
$$A_{Siv}(x,z,P_T) = \frac{\sum_q e_q^2 x \mathcal{C}\left[\frac{\boldsymbol{P}_T\cdot \boldsymbol{k}_T}{MP_T} f_{1T}^{\perp q}(x,k_T^2)\; D_1^q(z,p_\perp^2)\right]}{\sum_q e_q^2 x \mathcal{C}\left[f_1^q(x,k_T^2)\; D_1^q(z,p_T^2)\right]} \quad \Rightarrow \quad A_{Siv}^{w,\pm}(x) = 2\frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x)\tilde{D}_1^{q,\pm}}{\sum_q e_q^2 x f_1^q(x)\tilde{D}_1^{q,\pm}}$$

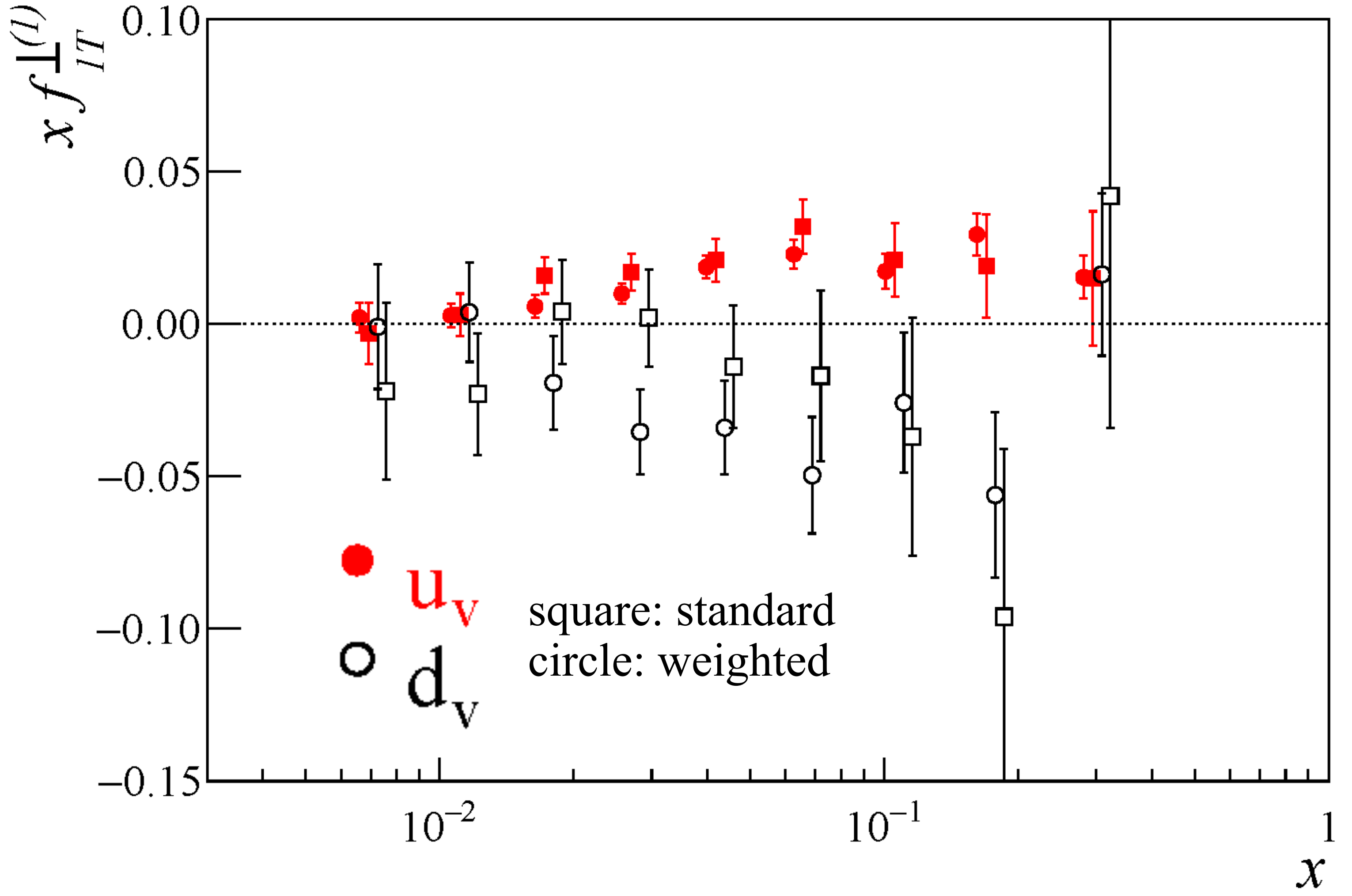
ω=P_T/zM weighted asymmetries

2010 proton data

- ***P_T*-weighted asymmetries**: direct measurement of TMD k_T^2 moments that avoids assumptions on shape of k_T. Products instead of convolutions of TMDs (as in the "standard" extraction).
- Extraction of $f_{1T}^{\perp(1)}(x)$
  - Neglecting sea quark Sivers distribution (proton data only) → deviation from standard extraction not unexpected for d-quarks
  - u-quark distributions for P_T-weighted and standard in good agreement
  - Indication that TMD factorization applies; that the TMD framework in general "is operational"; and that the Gaussian ansatz is not so bad after all.







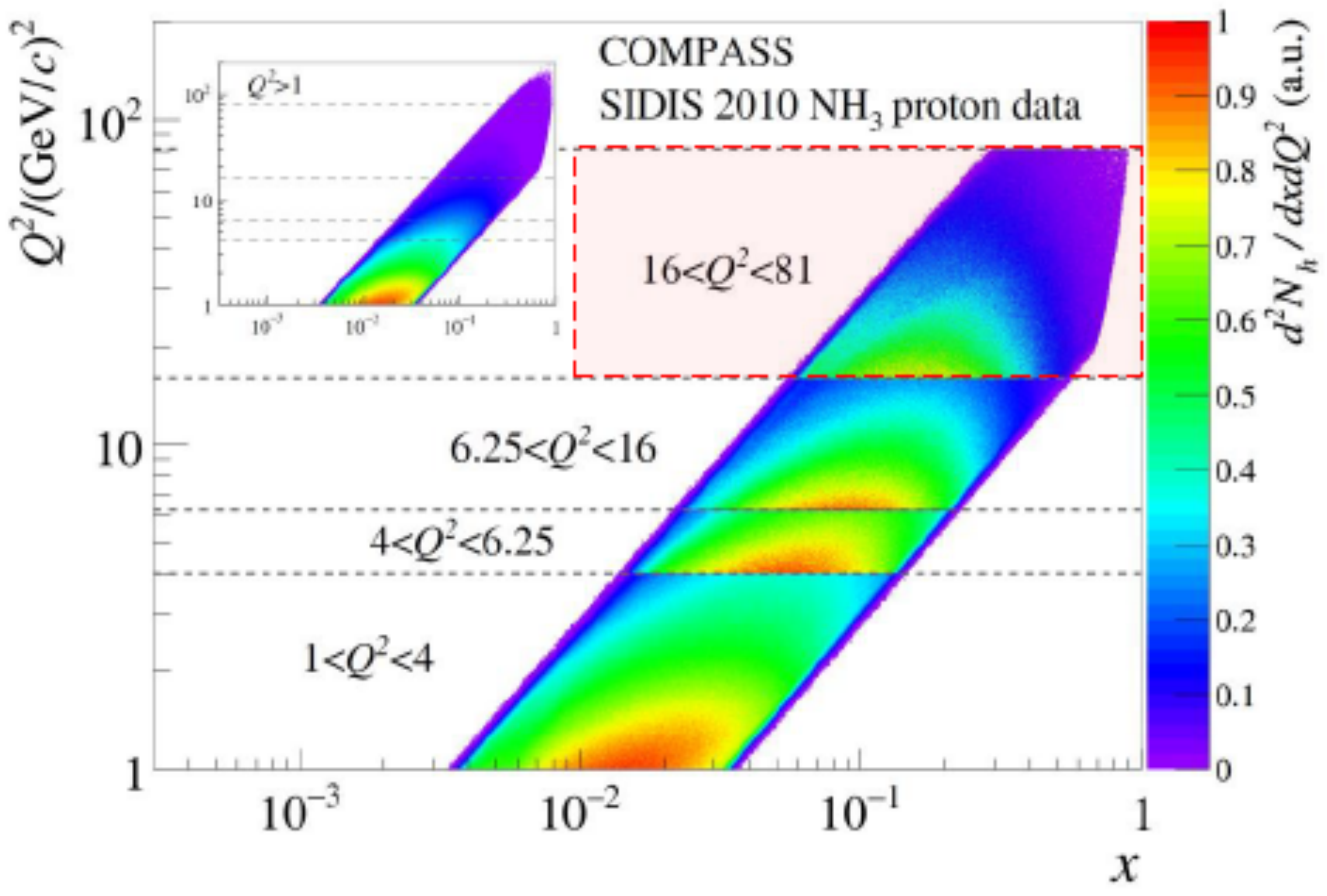
f_1^q, $\tilde{D}_1^{q,\pm}$ from parameterizations (CTEQ5D and DSS)

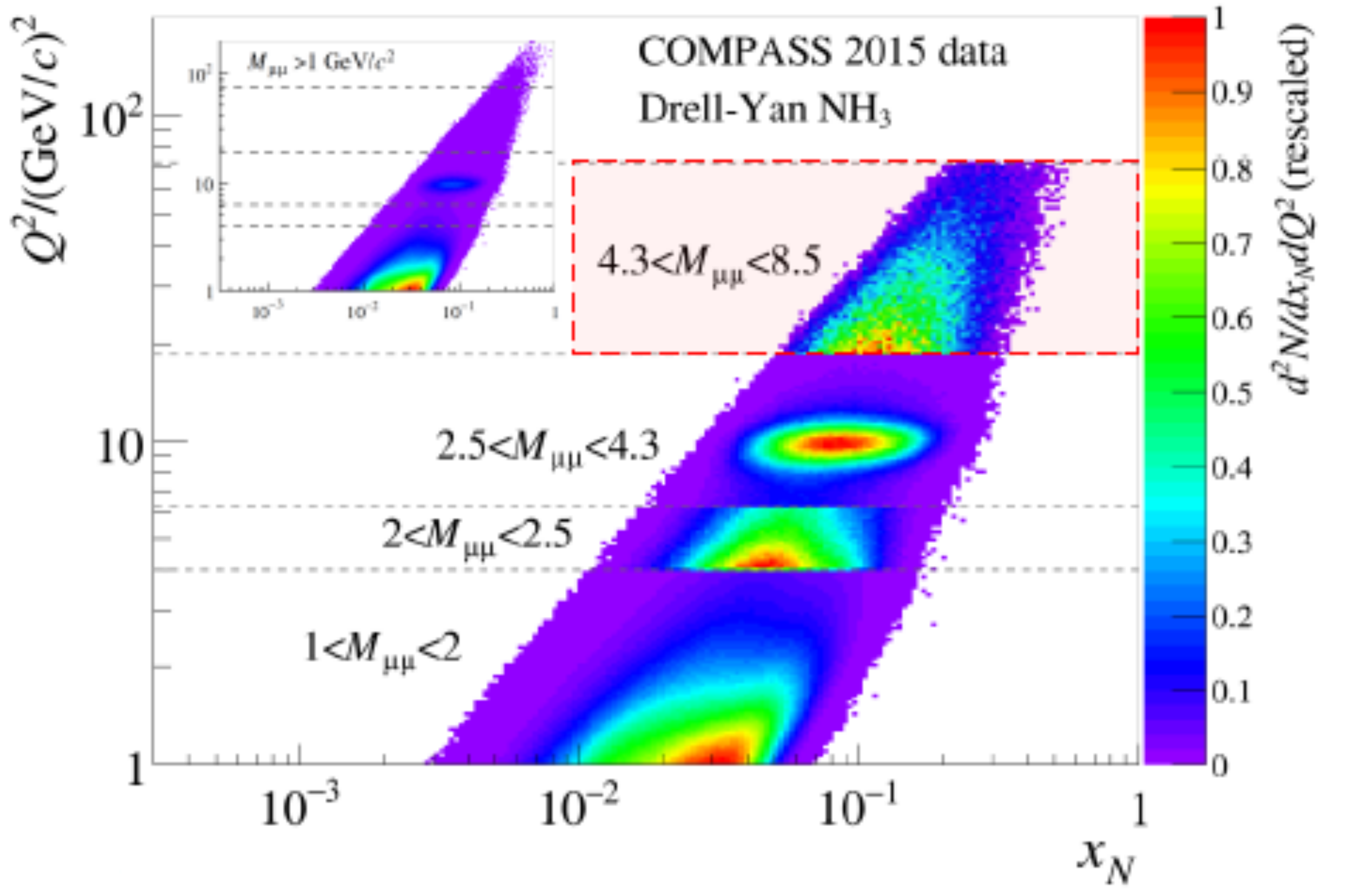
Sivers in SIDIS at the scale of the DY measurement

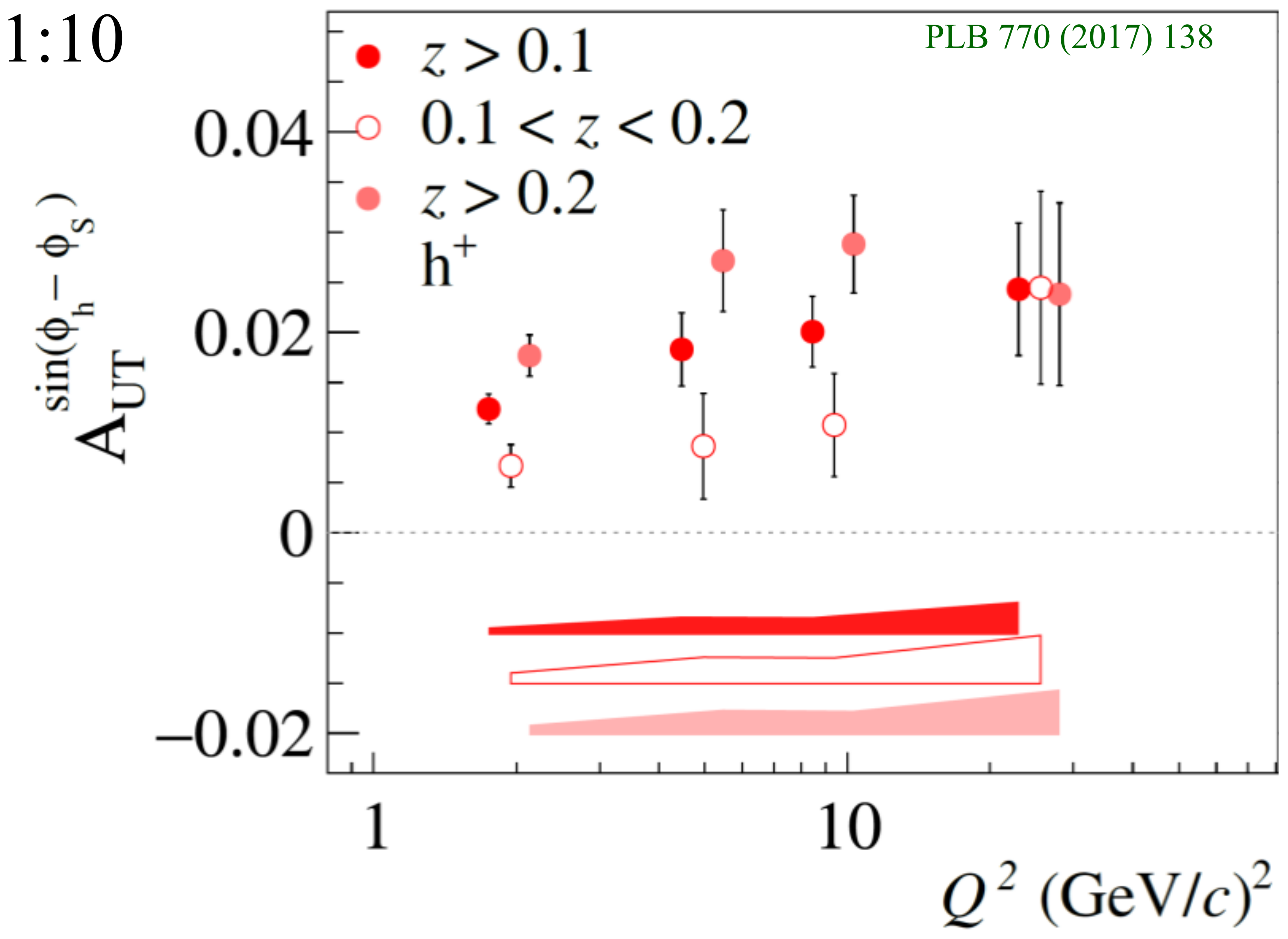
T-polarized

Sivers ⊗ D1

- To ease the comparison with the COMPASS 2015 + 2018 Drell-Yan measurement ($\pi^- p\uparrow \rightarrow \mu^+\mu^- X$), and to circumvent the complication of TMD evolution effects:
  - COMPASS extracted the Sivers SIDIS asymmetry in the kinematic phase space of the DY experiment.
  - See also V. Andrieux's talk - Thursday 11:10
- Different Q^2 bins
- No strong Q^2-dependence





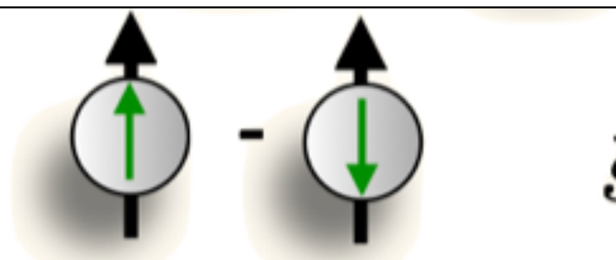


Collins asymmetry in SIDIS

T-polarized

Transversity ⊗ Collins

- **Collins effect: azimuthal modulations** of the produced hadron transverse momentum in a transversely-polarized quark fragmentation
- Is generated by the coupling of the **Collins FF** to the **transversity TMD PDF**:



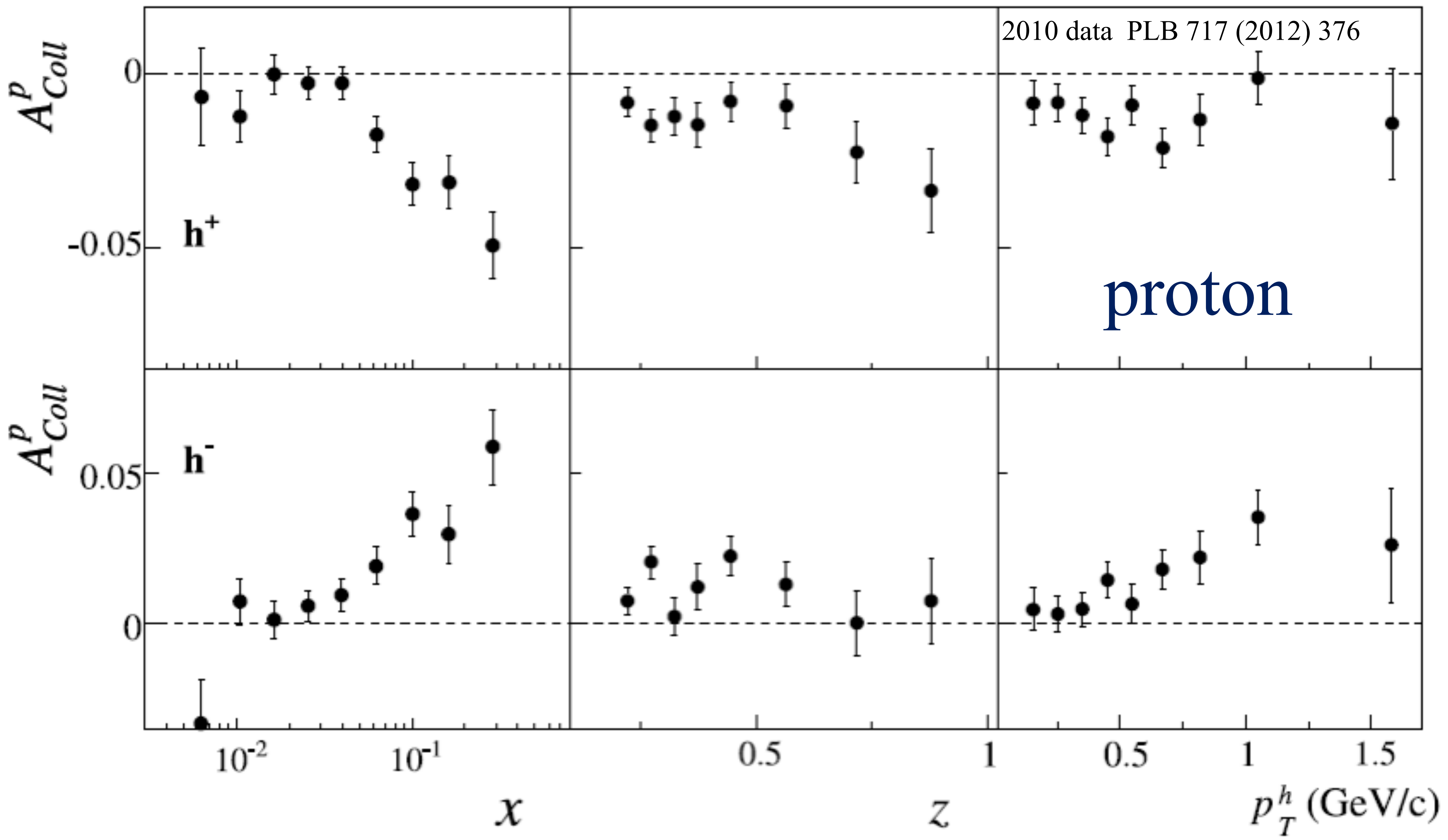
$\vec{s}_T \cdot (\hat{k} \times \vec{P}_{hT})$

Collins asymmetry ~ Transversity ⊗ Collins function

chiral-odd PDF — chiral-odd FF

TMD PDF (x, k_T, Q^2) — FF (z, κ_T, Q^2)

- Transversity describes the spin-spin correlation of a transversely polarized parton in a transversely polarized hadron.
- It is **chiral-odd** since it corresponds to a **spin flip** of the involved parton.



- Very clear signal in the valence region (proton target)
- Opposite sign for h^+ and h^-, mirror symmetry vs x
- Very good agreement with HERMES data (backup)
- COMPASS Collins asymmetries on the deuteron compatible with zero (backup) ☞ u- and d-quark cancellations

Large experimental uncertainties ☞ motivation for the 2022 run

Di-hadron asymmetry μp↑→μh⁺h⁻X

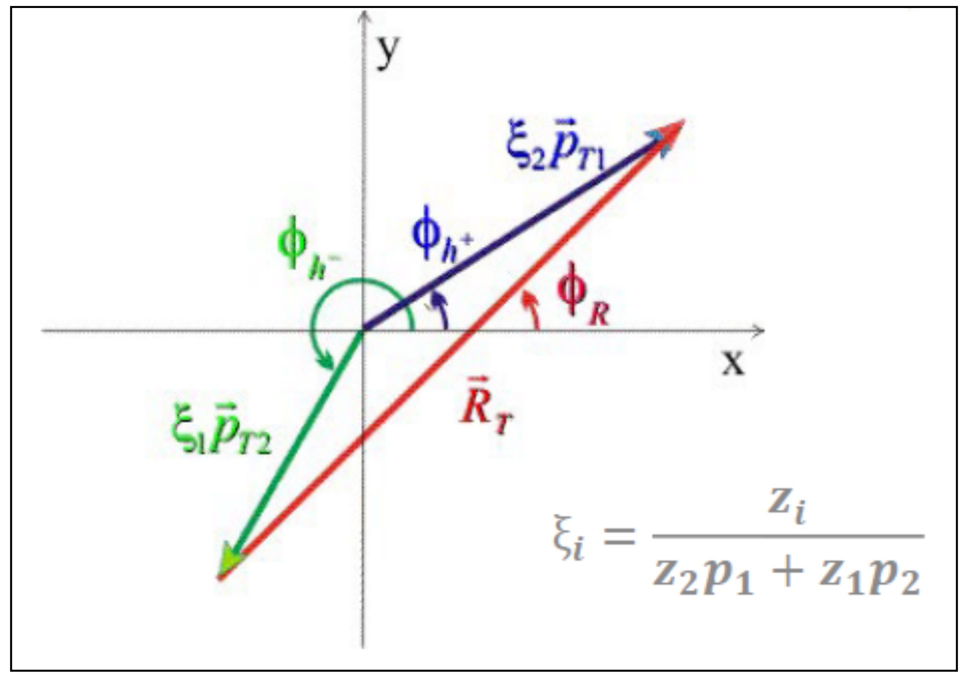
T-polarized

Transversity ⊗ IFF

COMPASS

$$A_{hh} \sim \frac{\sum_q e_q^2\, h_1^q \cdot H_{1q}^{\angle}}{\sum_q e_q^2\, f_1^q \cdot D_{1q}}$$

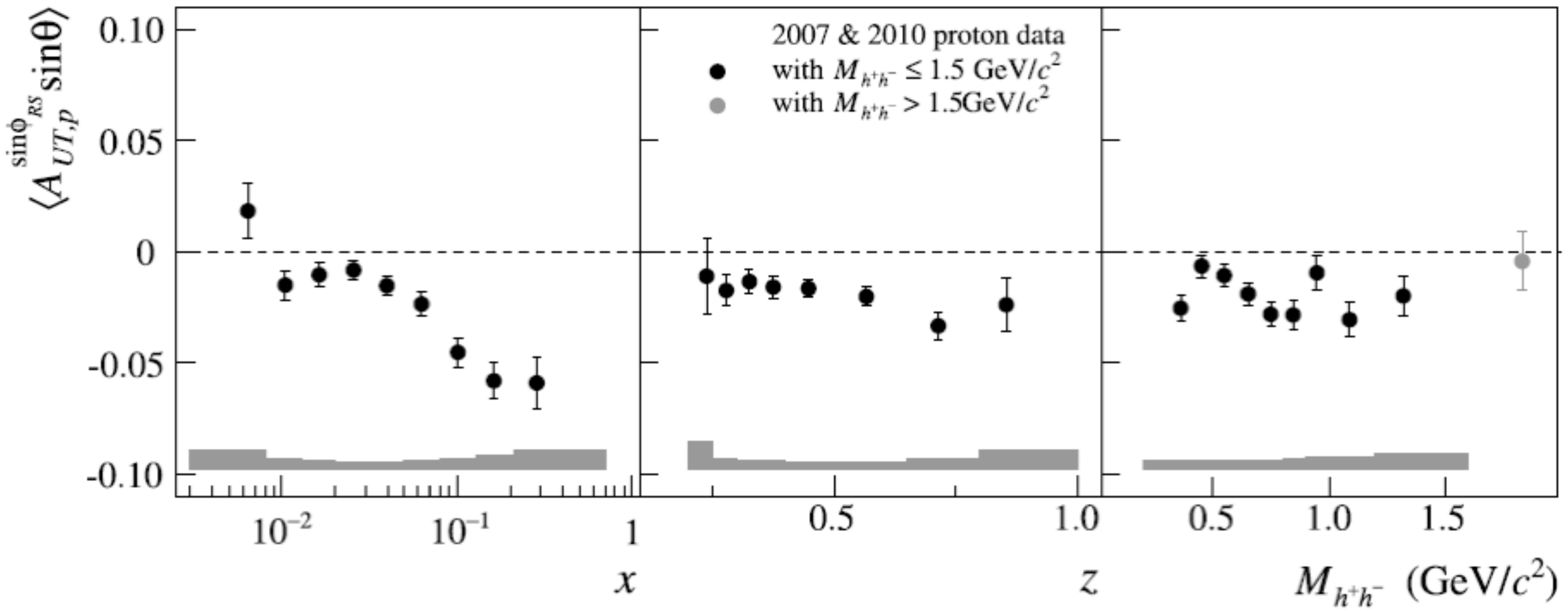
- Transversity TMD PDF coupled to **interference fragmentation function IFF** from the interference of different channels of the fragmentation process into the two-hadron system.
- Amplitude of the sin modulation in the distribution of the azimuthal angle (ϕ_R+ϕ_S)

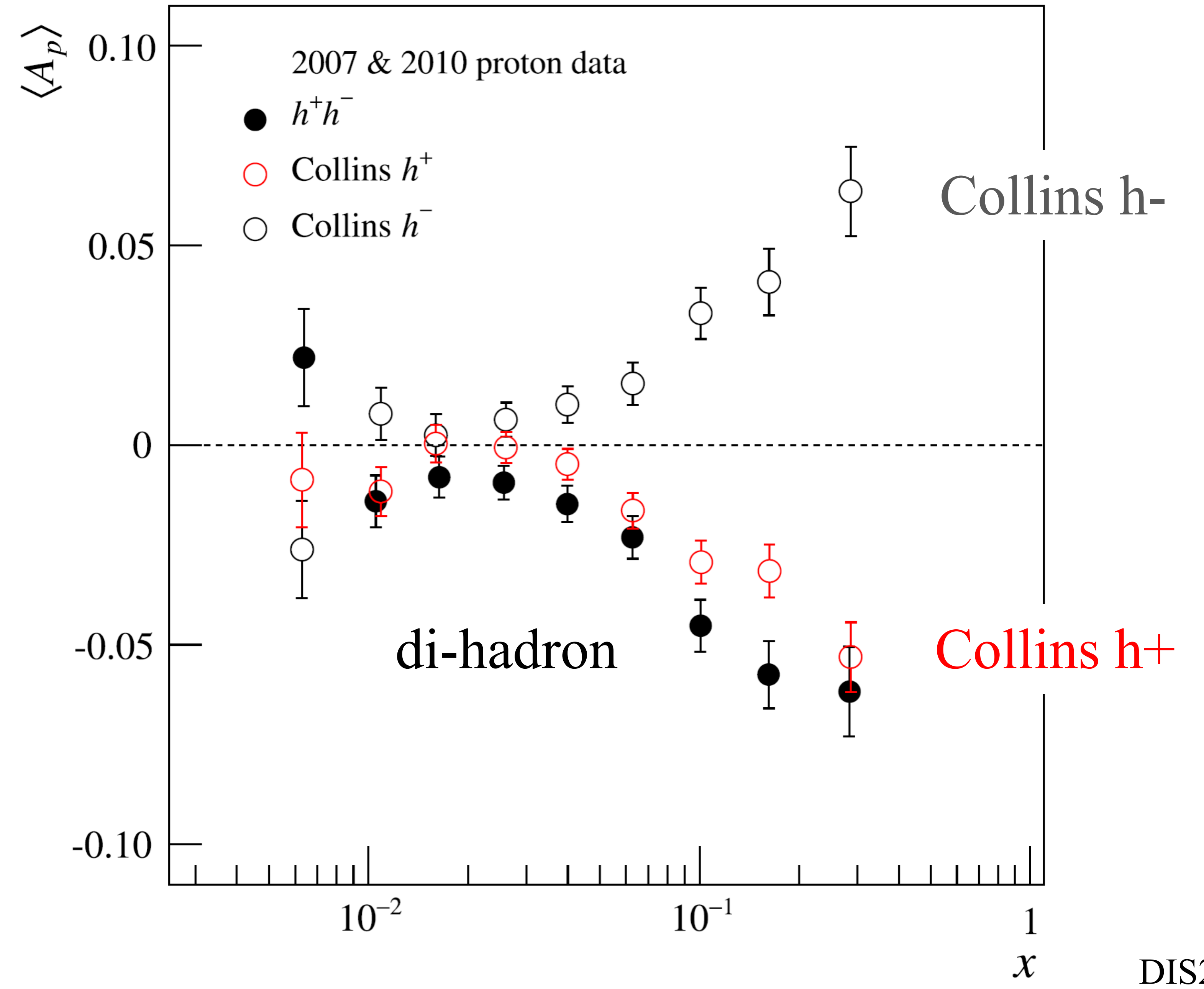


- Interference FF ≈
  ½·(Collins[h+] + (-1)·Collins[h−])
  ☞ Hint at a common physical origin for Collins & IFF
- Results on the deuteron compatible with zero (backup).

di-hadron asymmetry proton

PLB 736 (2014) 124





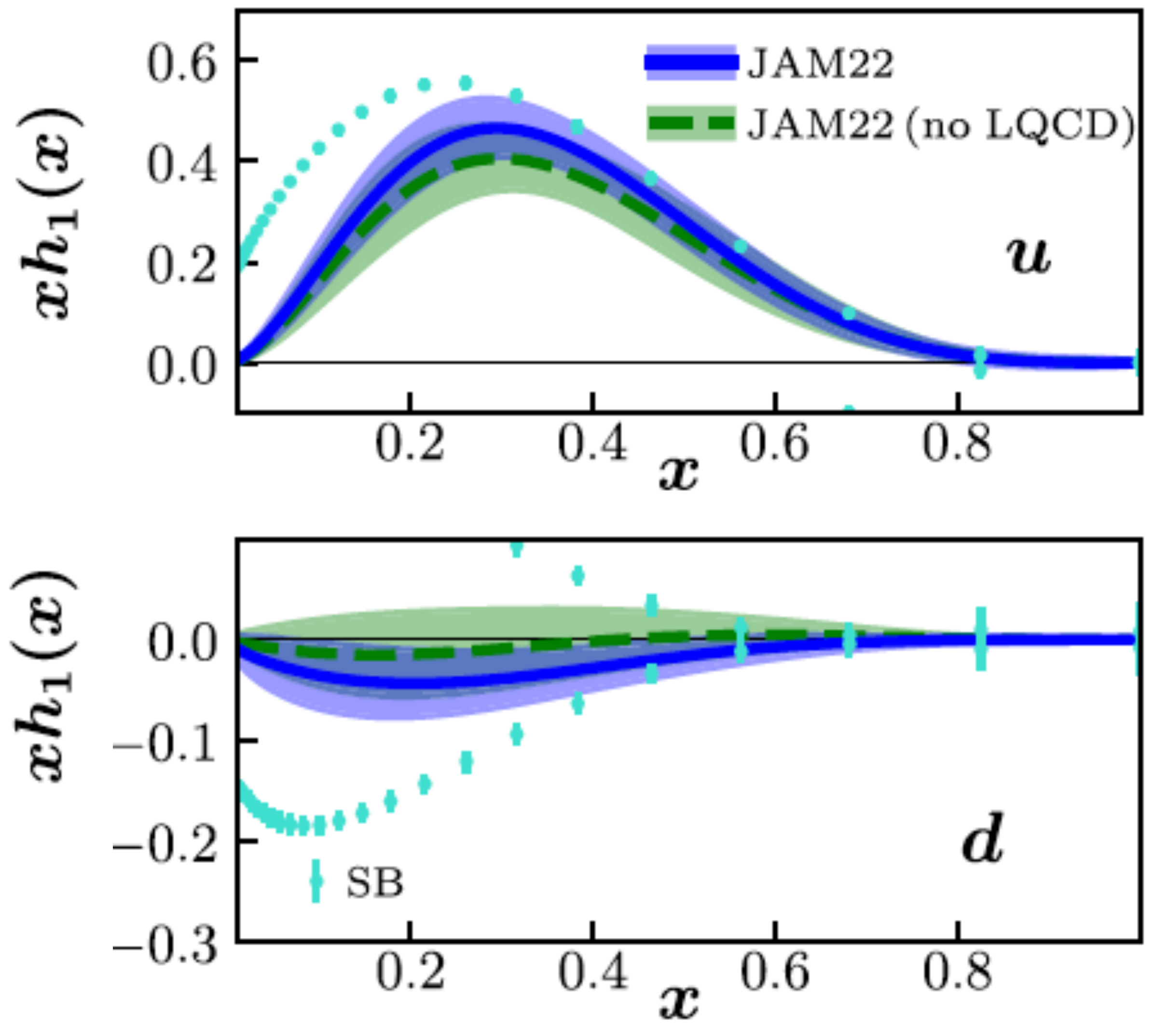
interplay
PLB 736 (2014) 124

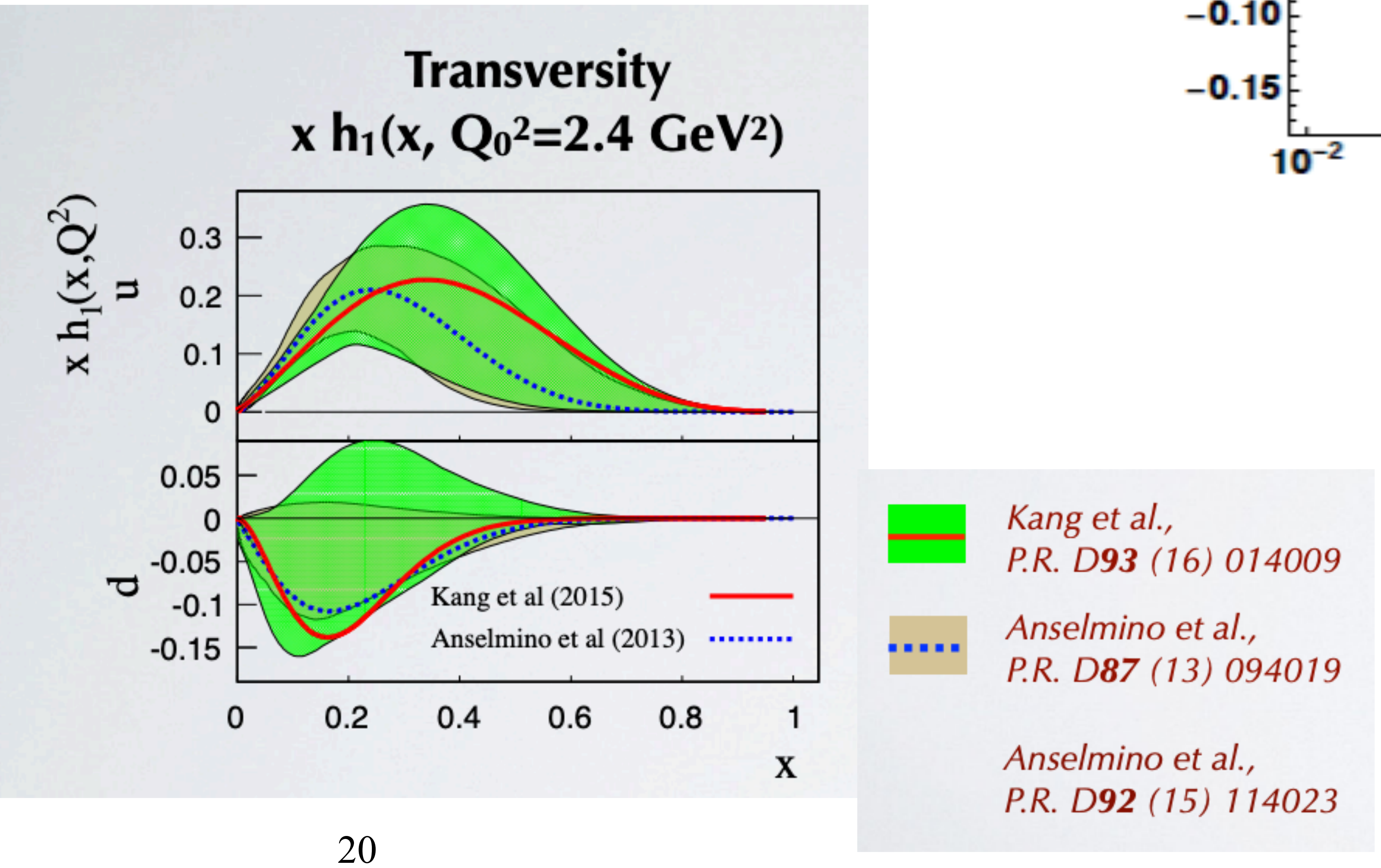
Accessing transversity

- Fits to global data (including also TMD-sensitive processes other than SIDIS) to extract the transversity PDF and the corresponding spin-dependent FFs.
- Very important results: the TMD framework allows to describe all data well.
- Work ongoing…
- From the existing SIDIS data it is clear that
  - u- and d-quark transversity PDFs have opposite sign
  - d-quark PDF much worse determined than u-quark PDF because of the scarcity of deuteron (neutron) data

fits of **Collins asymmetries**

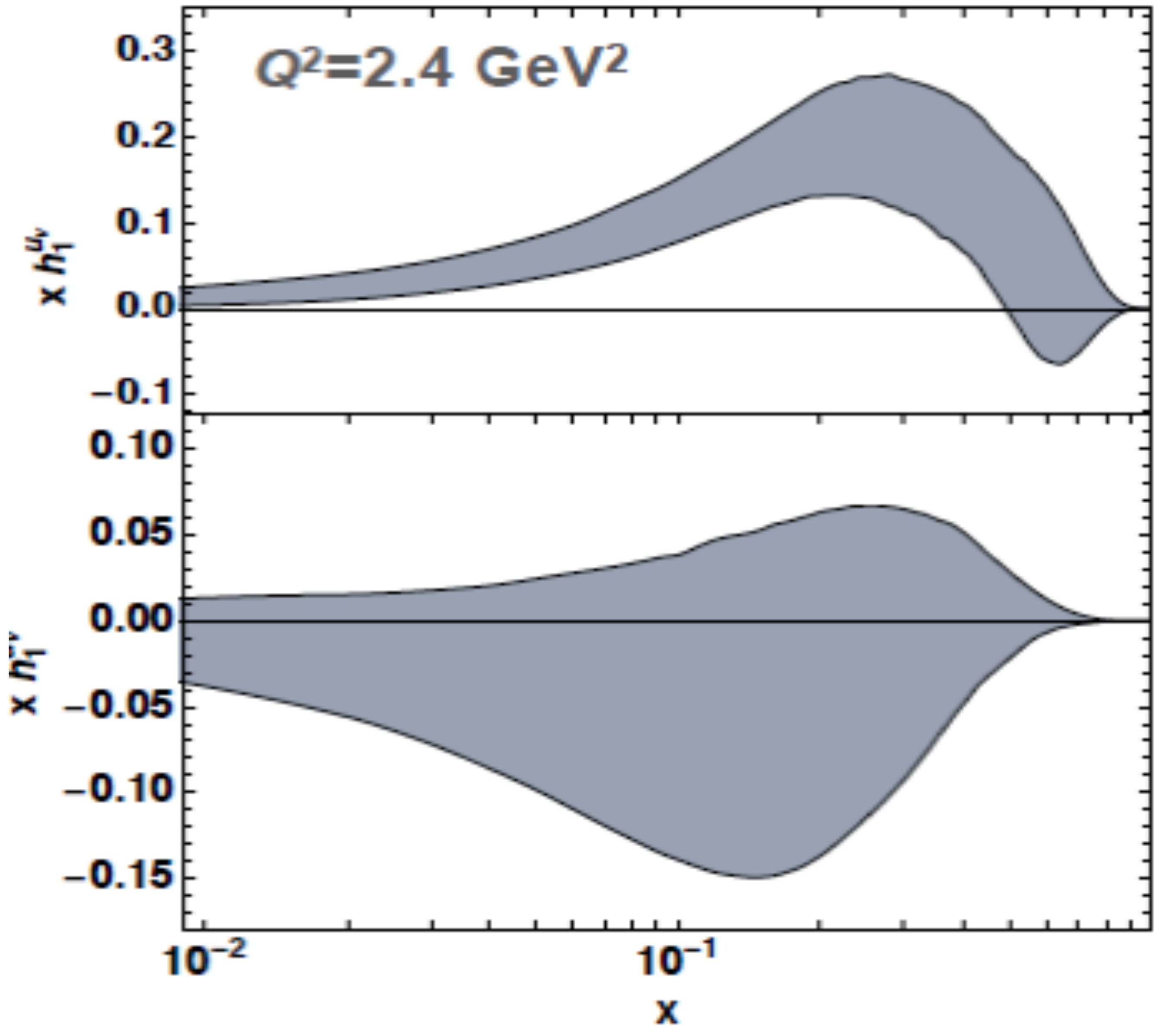
JAM PRD 106, 034014 (2022)





fits of **di-hadron asymmetries**

Radici Bacchetta PRL **2018**

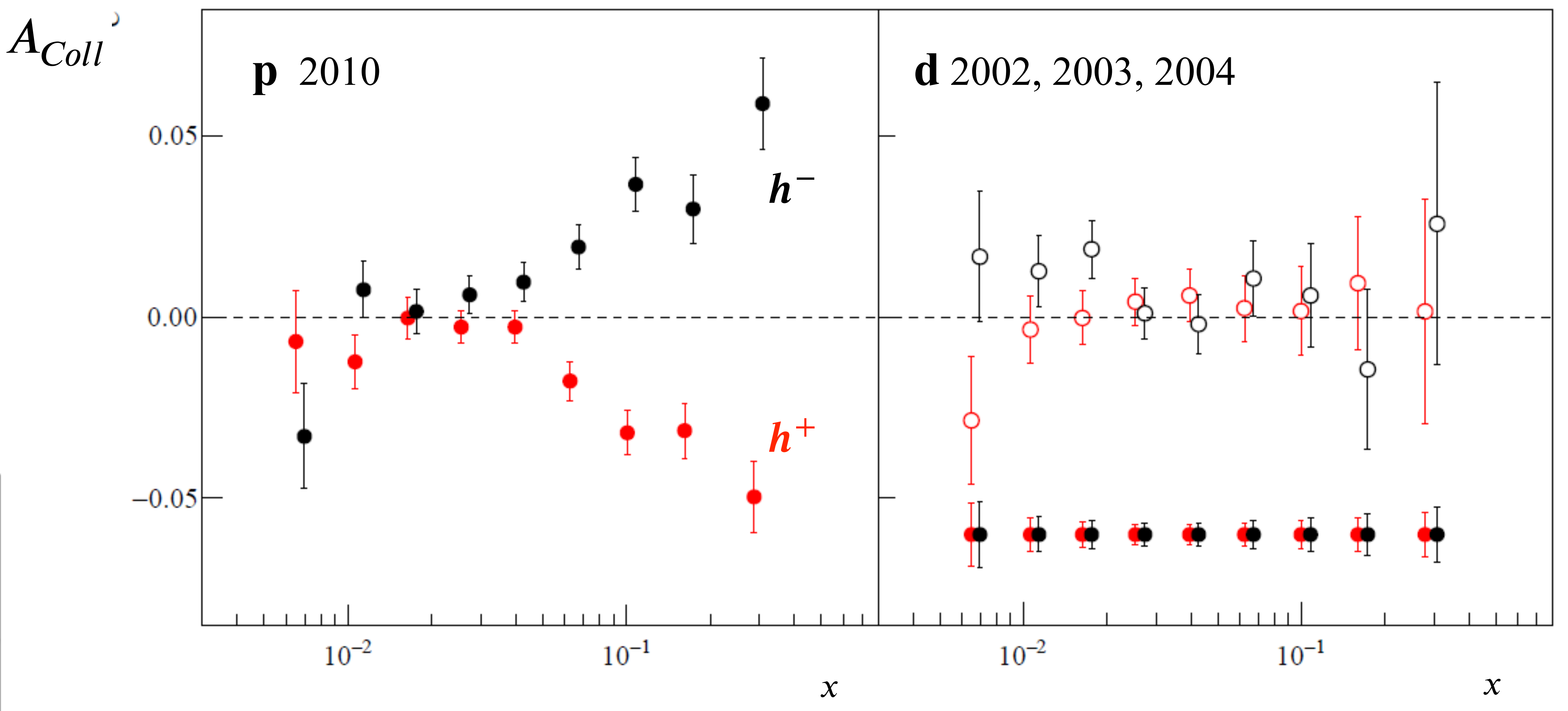


The 2022 COMPASS run: μd↑→hX

T-polarized

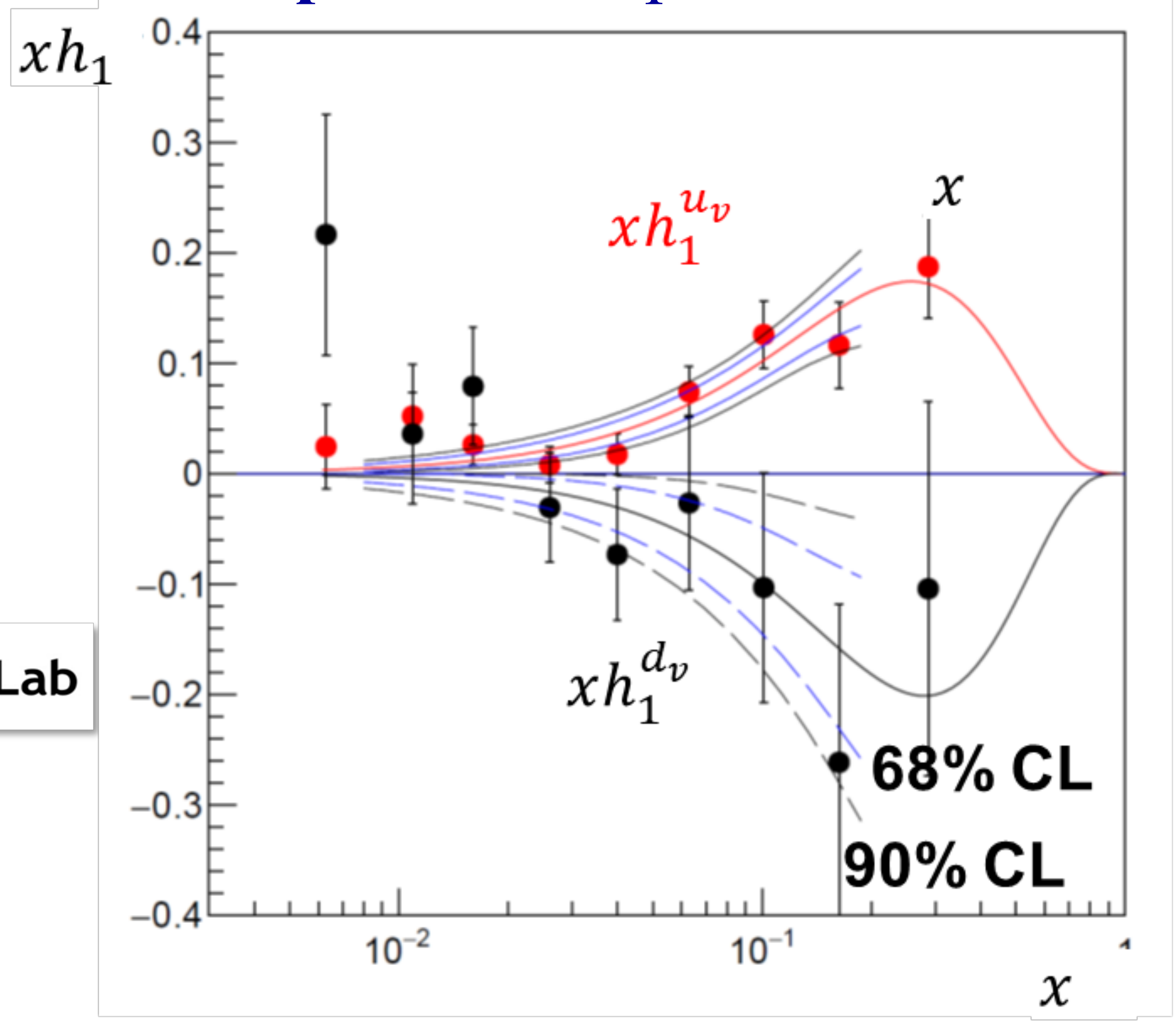
Transversity ⊗ Collins

- June - November 2022 with transversely polarized deuteron (^{6}LiD) target with almost the same conditions as 2010 proton run.
- Impact on the deuteron **SIDIS Collins asymmetry** - the 2022 uncertainties are expected to be a factor 2 to 5 smaller.
- Impact on **transversity TMD PDF** and on **tensor charge**

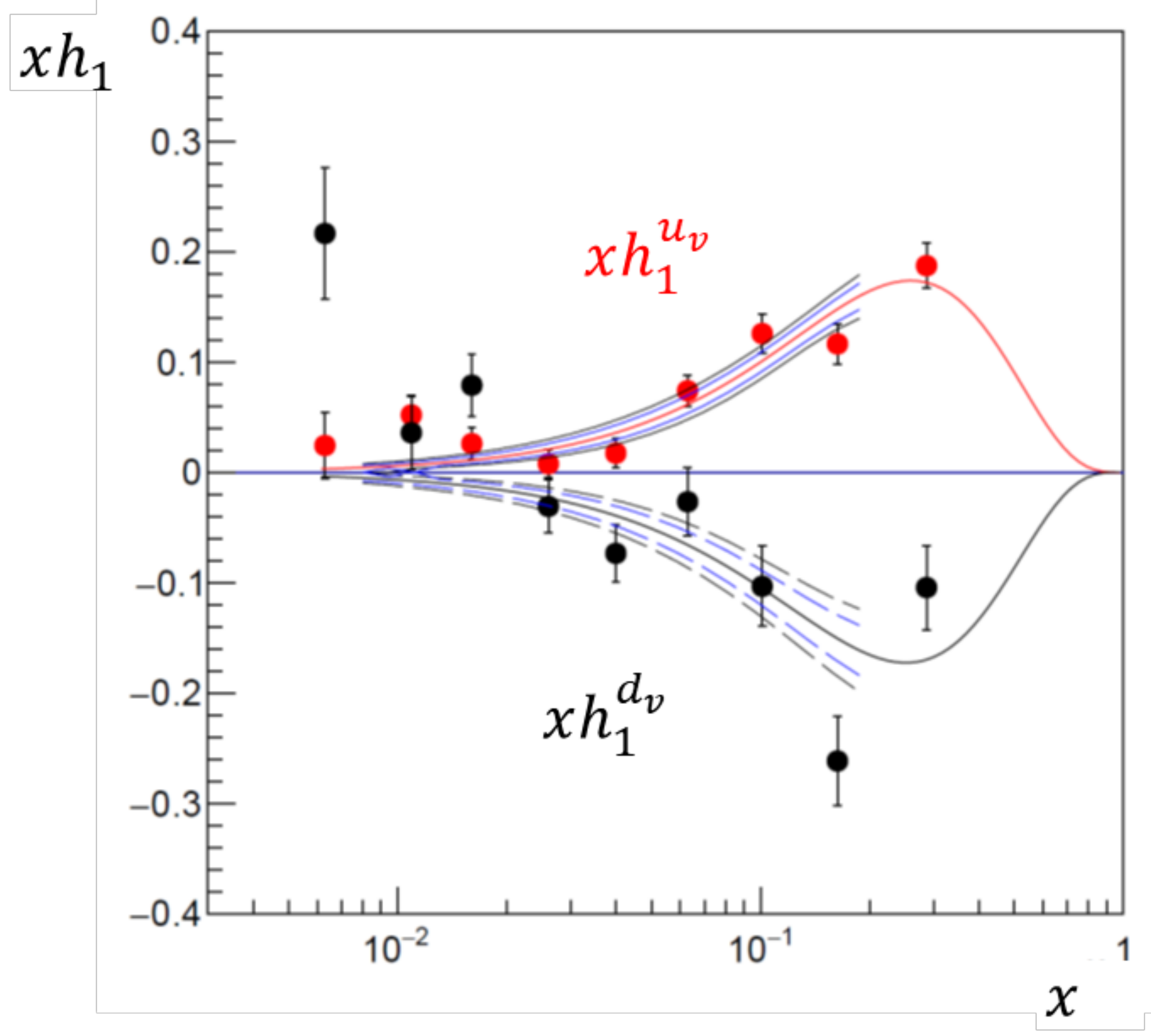


Ω_x: 0.008 ÷ 0.210	$\delta_u = \int_{\Omega_x} dx h_1^{u_v}(x)$	$\delta_d = \int_{\Omega_x} dx h_1^{d}(x)$	$g_T = \delta_u - \delta_d$
present	$0.201 \pm \mathbf{0.032}$	$-0.189 \pm \mathbf{0.108}$	$0.390 \pm \mathbf{0.087}$
projected	$0.201 \pm \mathbf{0.019}$	$-0.189 \pm \mathbf{0.040}$	$0.390 \pm \mathbf{0.044}$

present: all p and d data

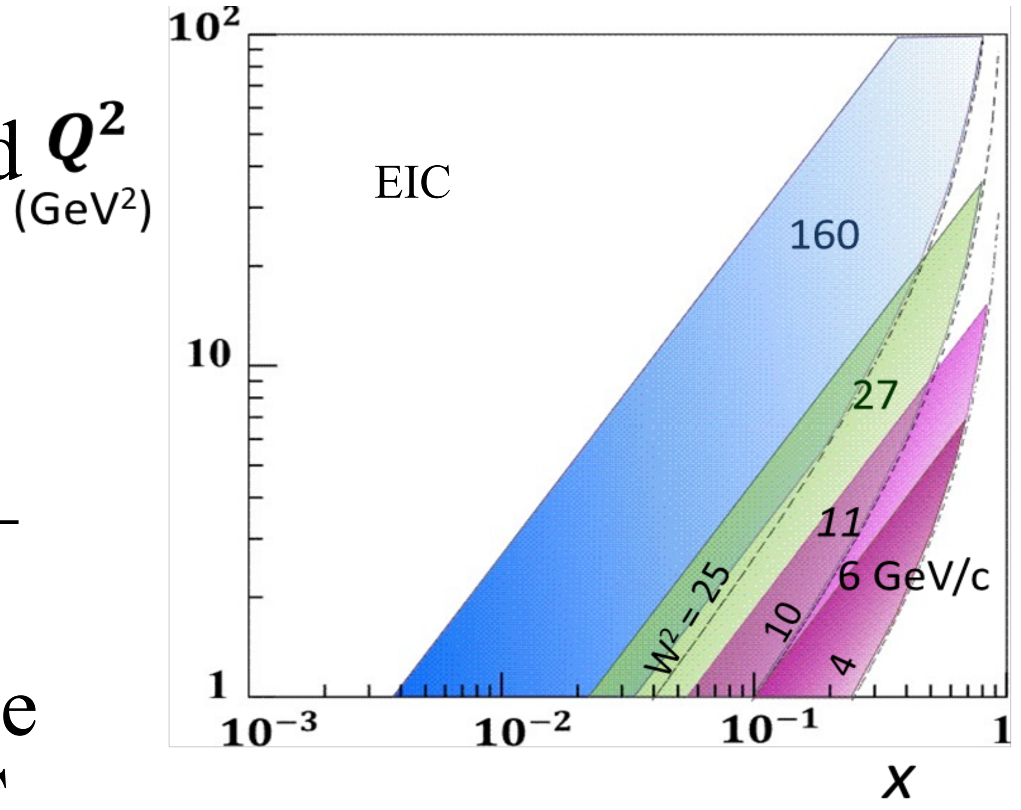


projected: all p and 2022 d data

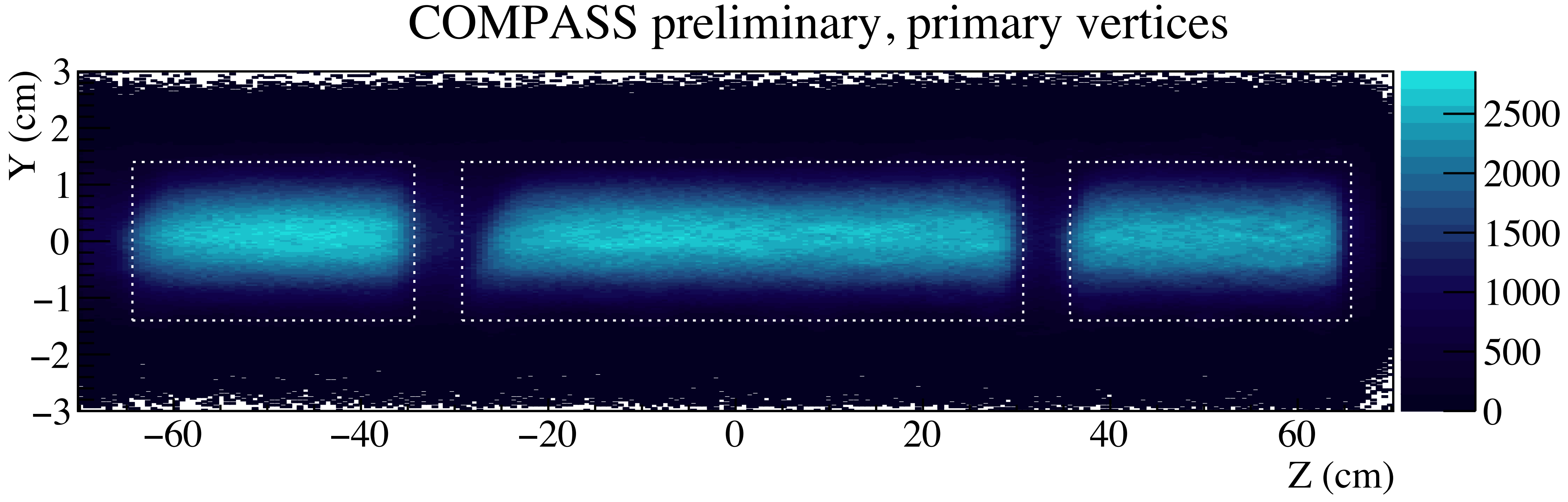


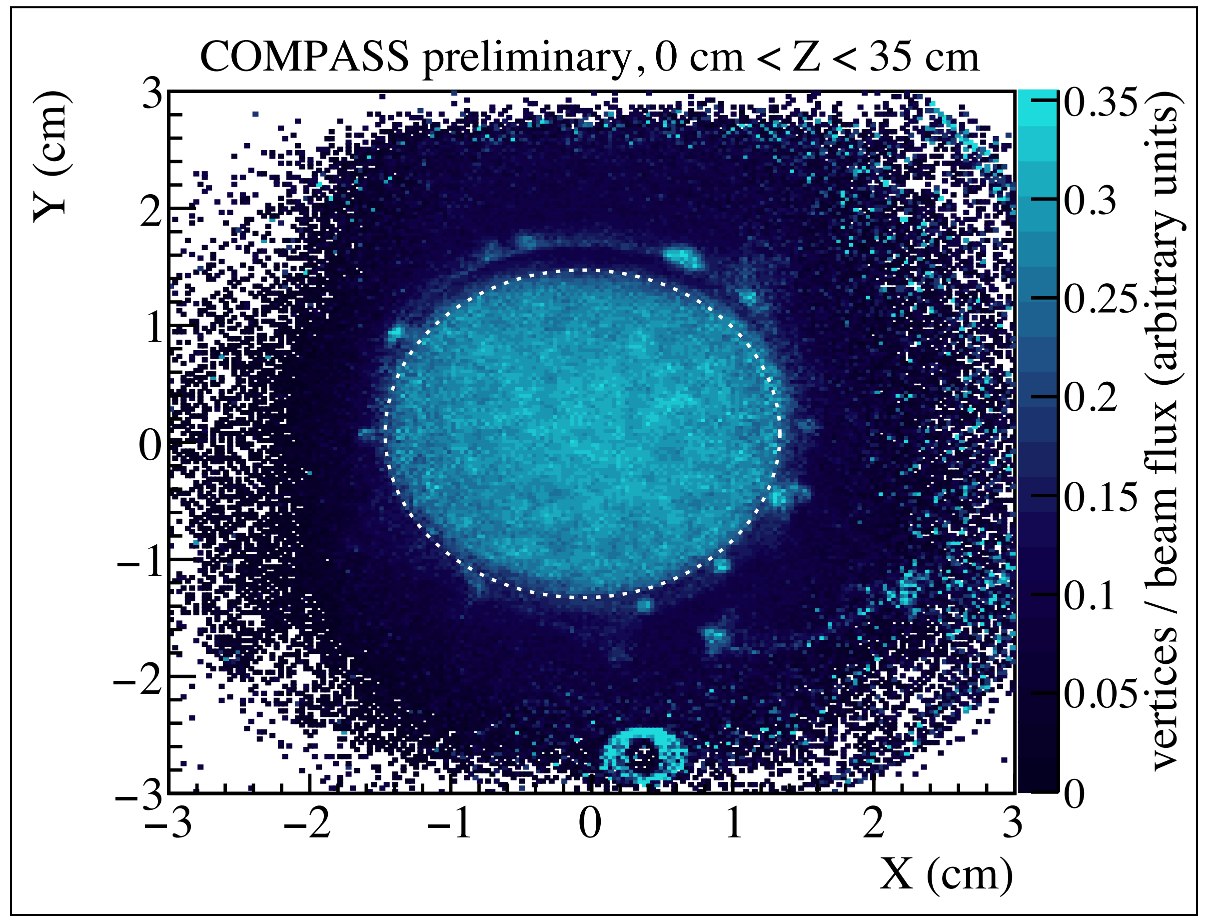
The work will not be over with the COMPASS measurements - precise measurements are needed asap, in particular at larger x.

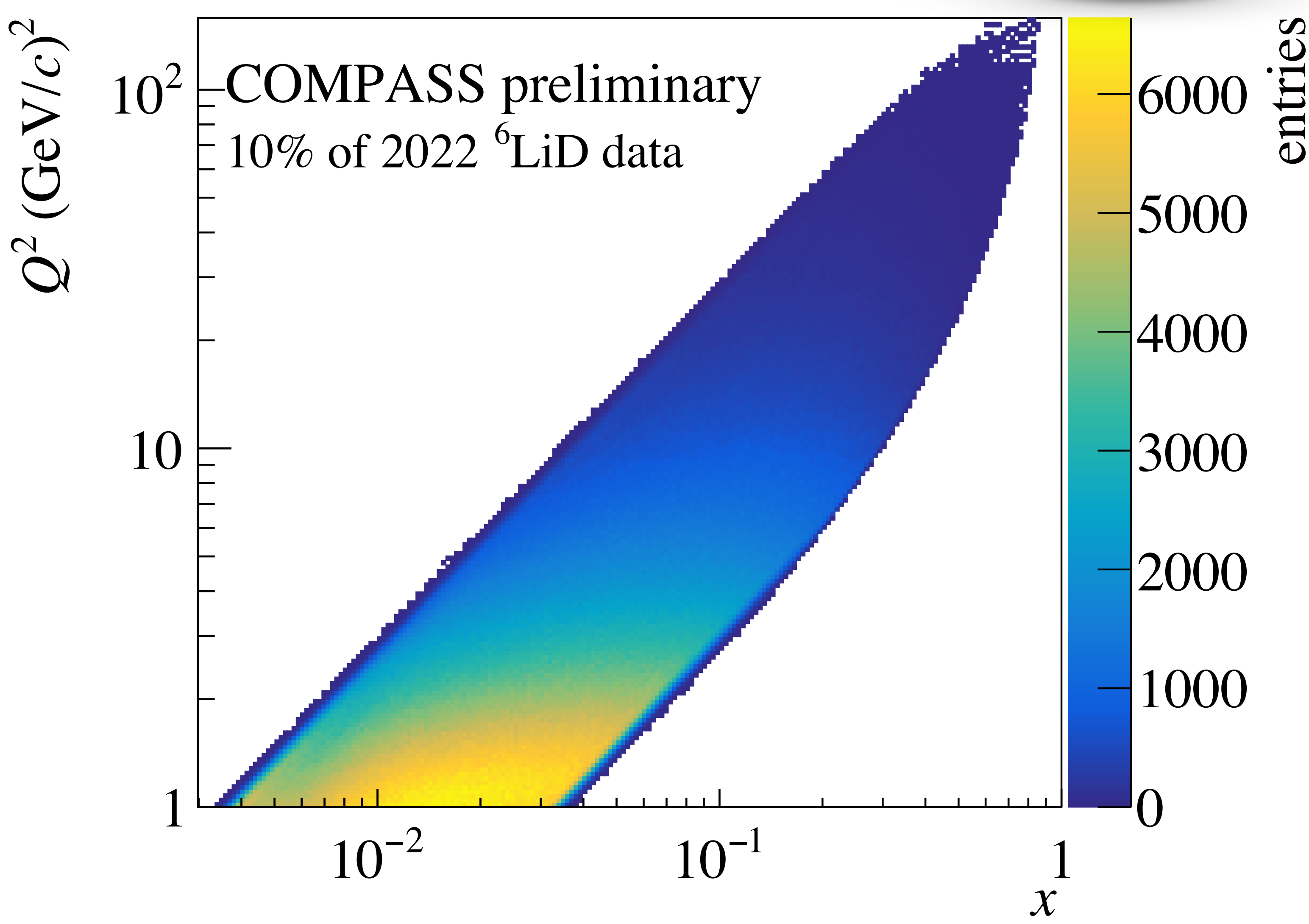
The complementary measurements at Jlab 12 and 20+ will allow for a more precise measurement of the tensor charge and, in the farther future, the EIC.

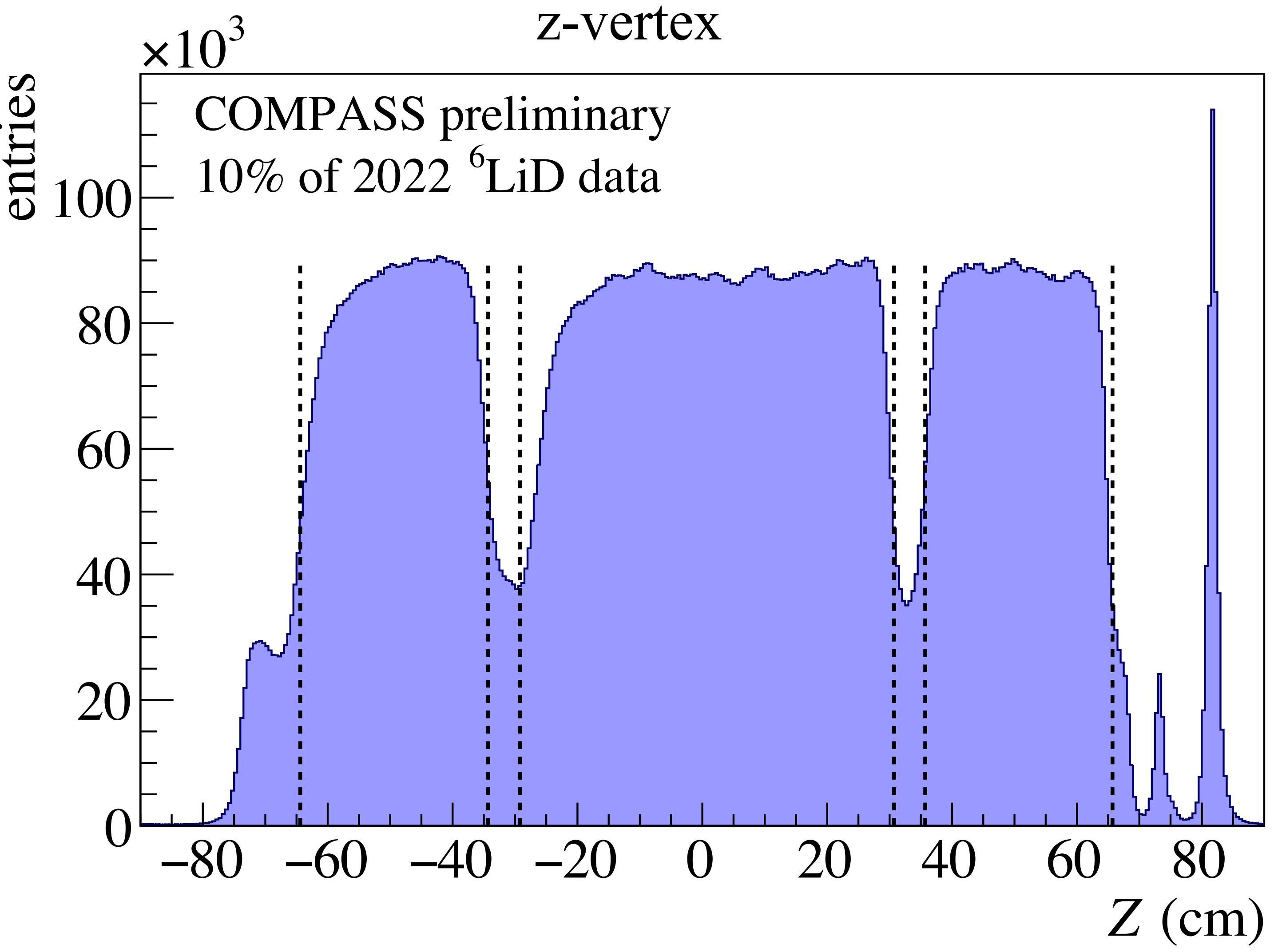


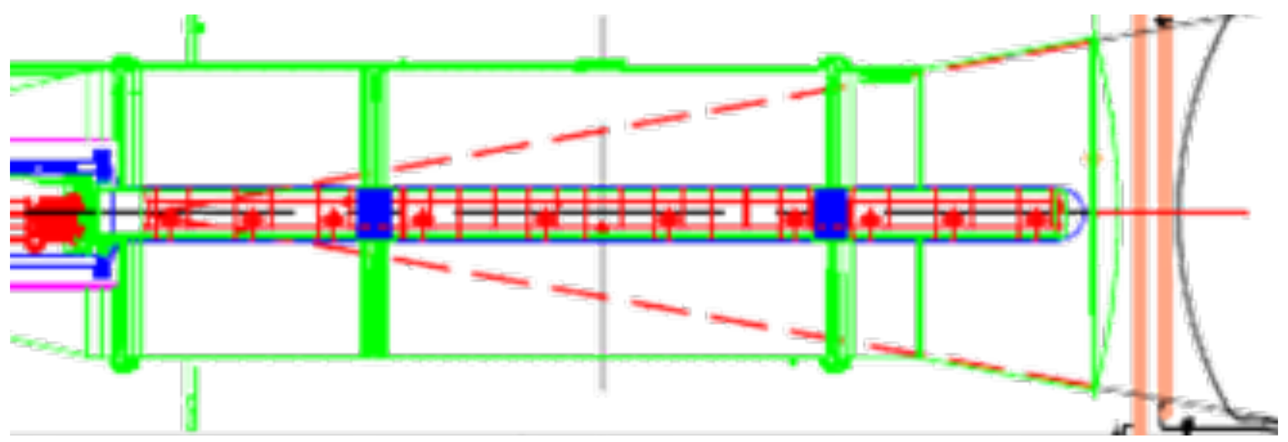
First look at the COMPASS 2022 data (about 10%)

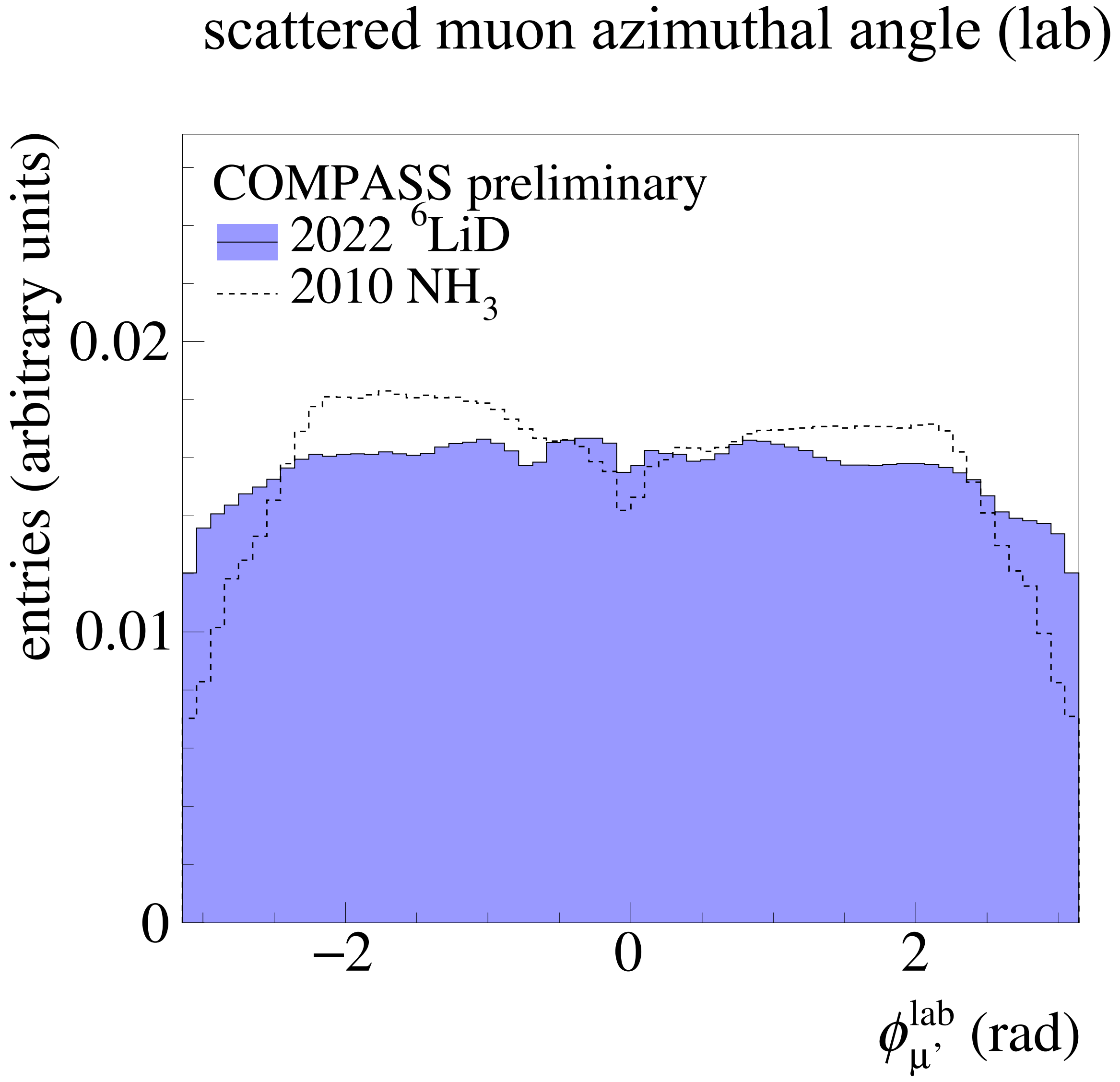


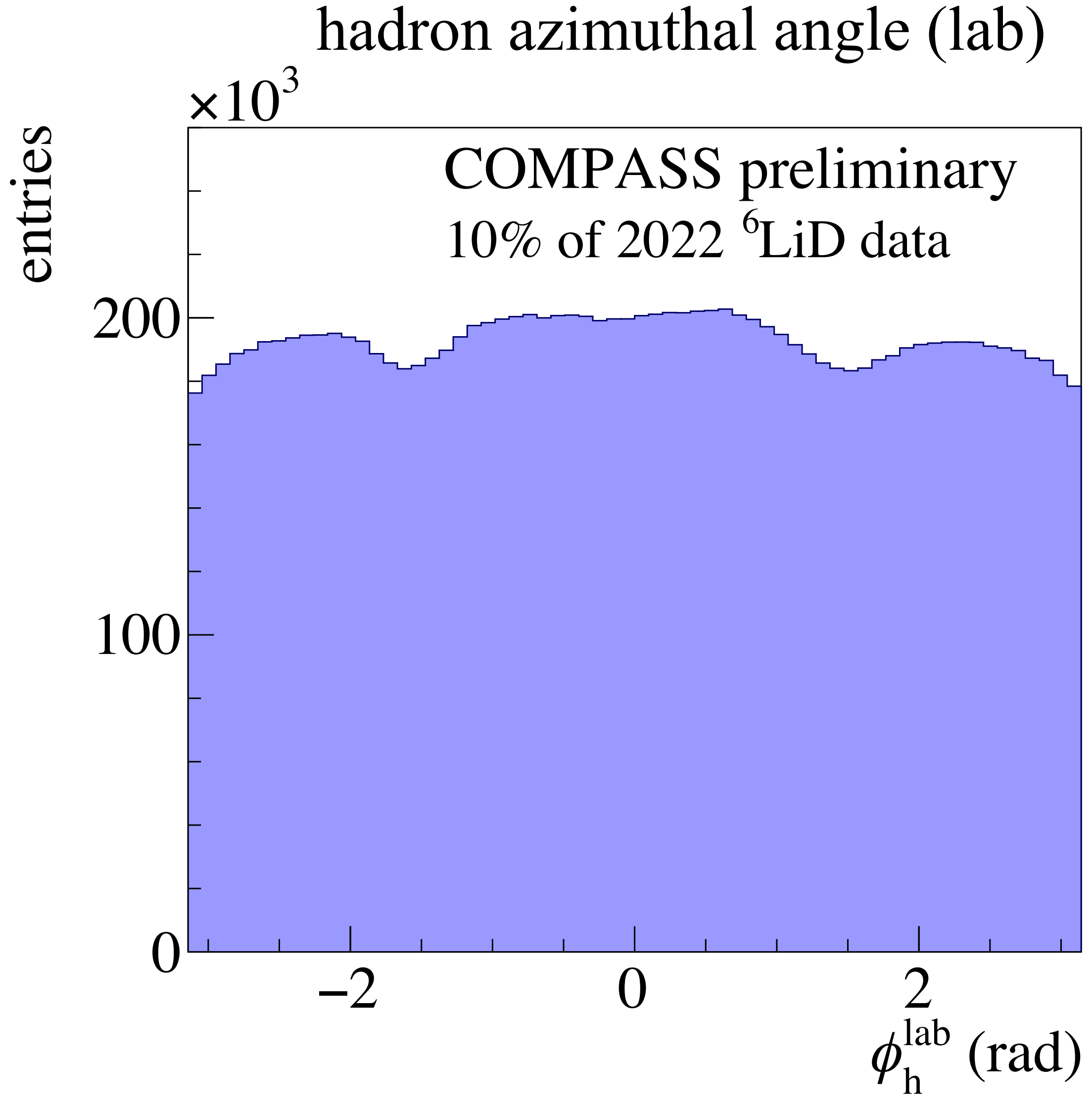




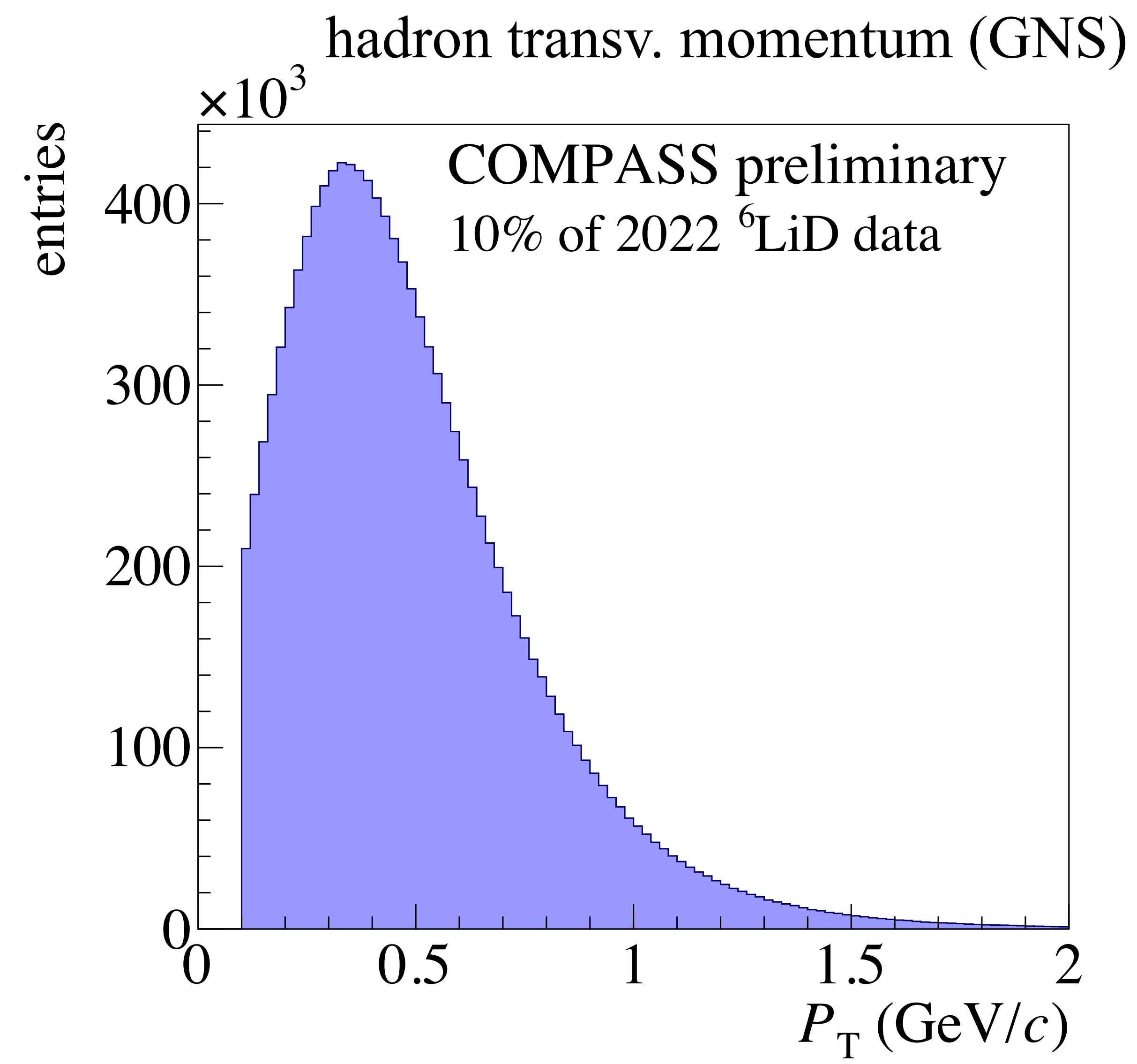






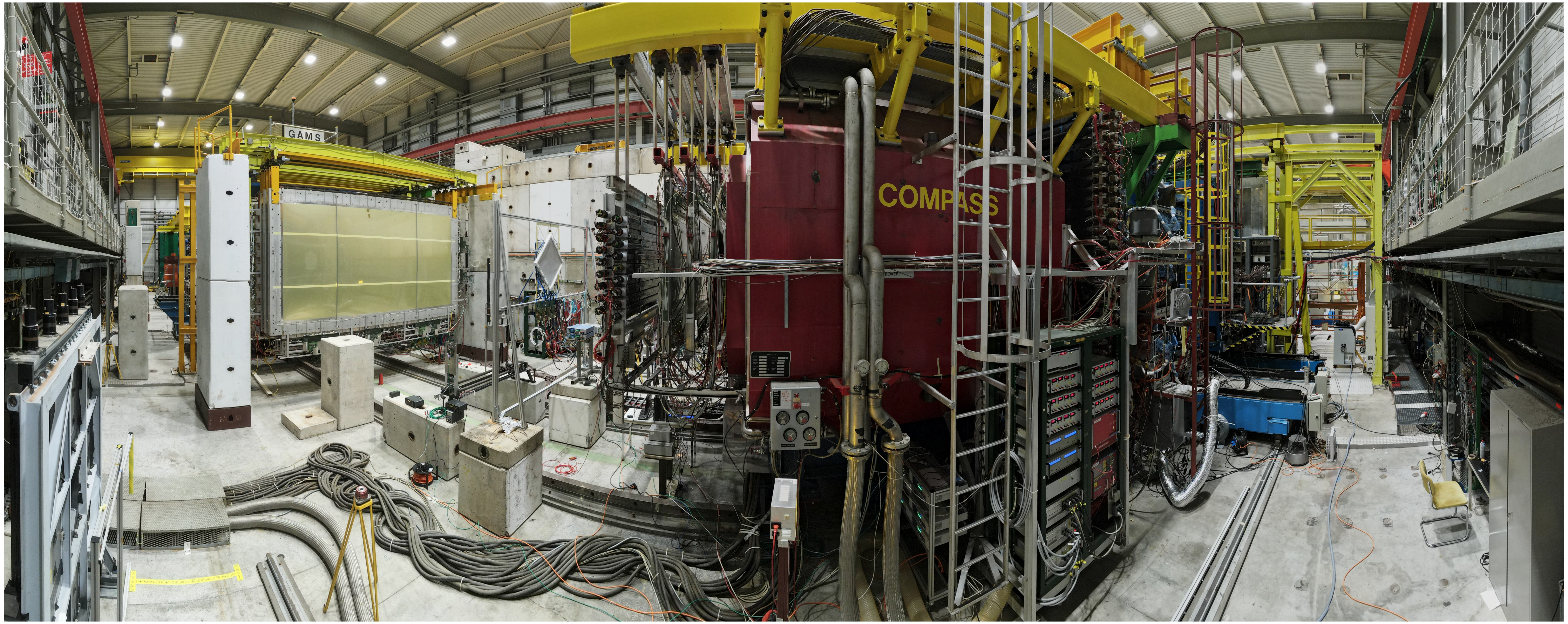


DIS events



Summary: COMPASS SIDIS TMDs

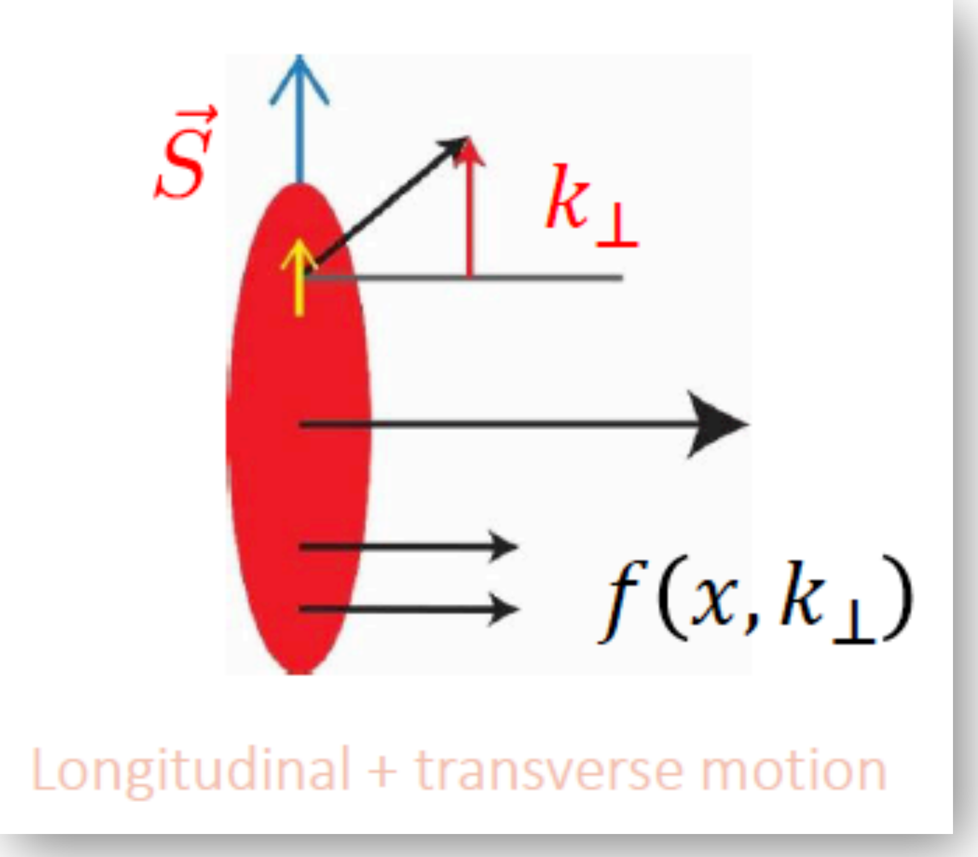
- **Unpolarized** - P_T distributions, hadron multiplicities, Boer-Mulders TMD PDF and Cahn effect
- **Longitudinally polarized** - various azimuthal modulations of unprecedented precision
- **Transversely polarized** - Sivers TMD PDF, Collins FF and IFF, FF for vector mesons
- Multi-dimensional binnings
- Access to intrinsic transverse parton momentum, input for studies of TMD universality, factorization, & evolution
- **2022 run** - **SIDIS** measurements with **transversely polarized deuteron target**
  - Unique input for d-quark transversity and many other studies



Backup

SIDIS off unpolarized targets

unpolarized



P_T^2 distributions from give access to k_T distributions

- 2004 and 2006 deuteron (^{6}LiD) data - published EPJC 73 (2013) 2531 PRD 97 (2018) 032006
- 2016 proton (LH) data - paper in preparation

smooth dependencies on the kinematic variables

azimuthal asymmetries from $\langle k_T^2 \rangle$, Boer-Mulders function, higher twist

- 2004 deuteron (^{6}LiD) data - published NPB 886 (2014) 1046 NPB 956 (2020) 115039
- 2016 proton (LH) data - preliminary results

strong dependencies on the kinematic variables,
sometimes at variance with naive expectations

The BM function describes the strength of the spin-orbit correlation between quark spin s_T and transverse momentum k_T:

$$\vec{s}_T \cdot (\hat{P} \times \vec{k}_T)$$

azimuthal asymmetries for hadron pairs from Boer-Mulders function, higher twist

- 2016 proton (LH) data - preliminary results

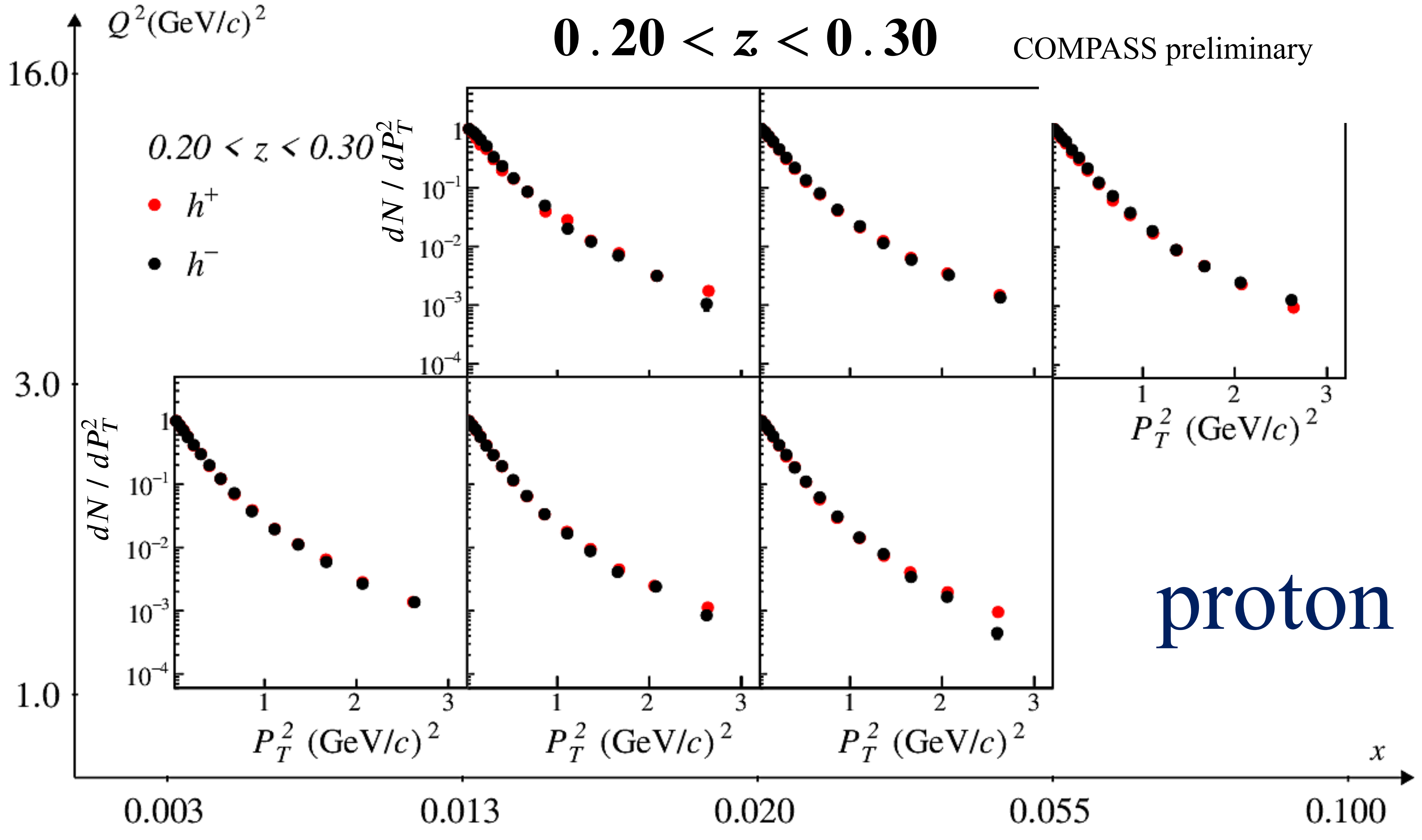
new

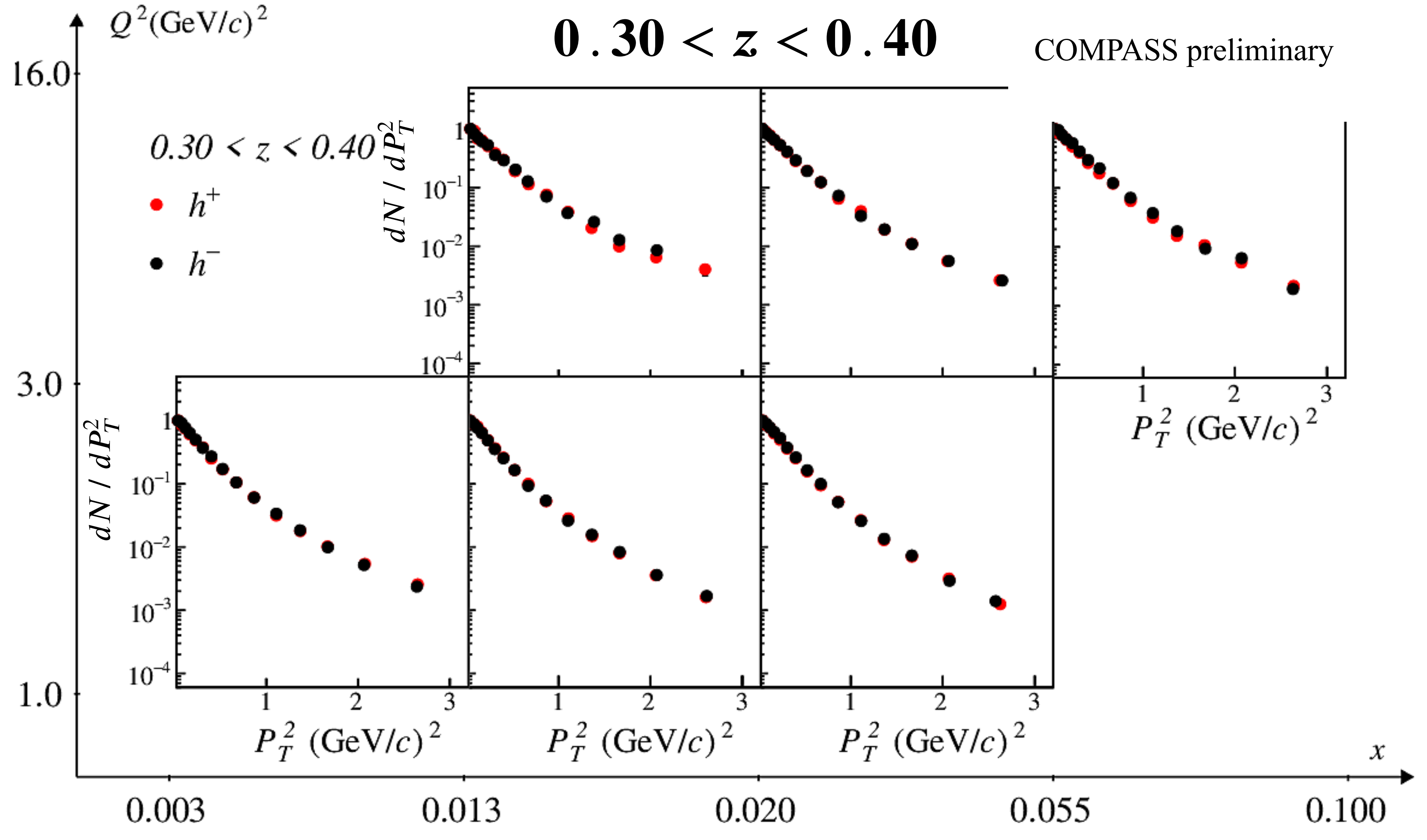
Transverse-momentum distributions

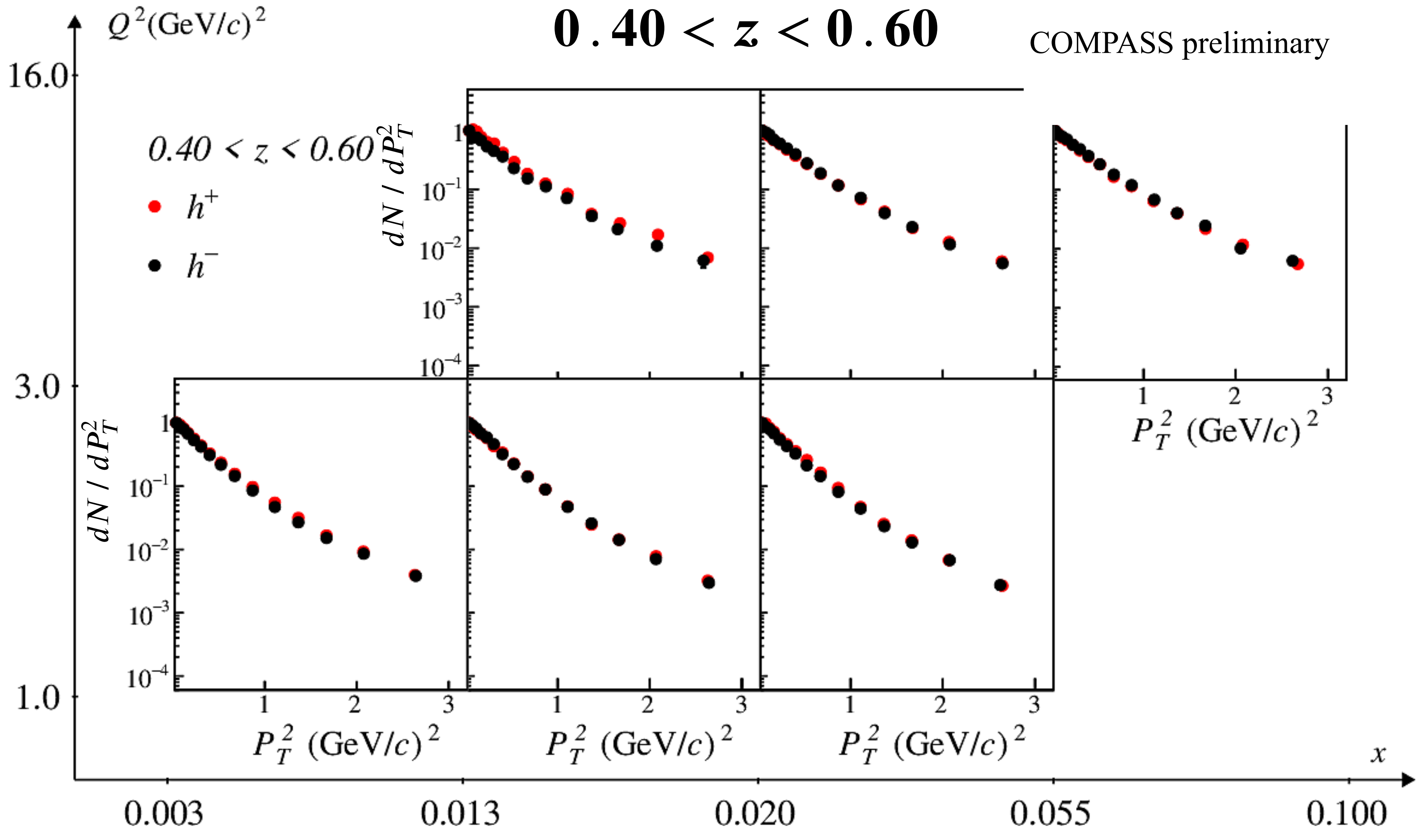
unpolarized

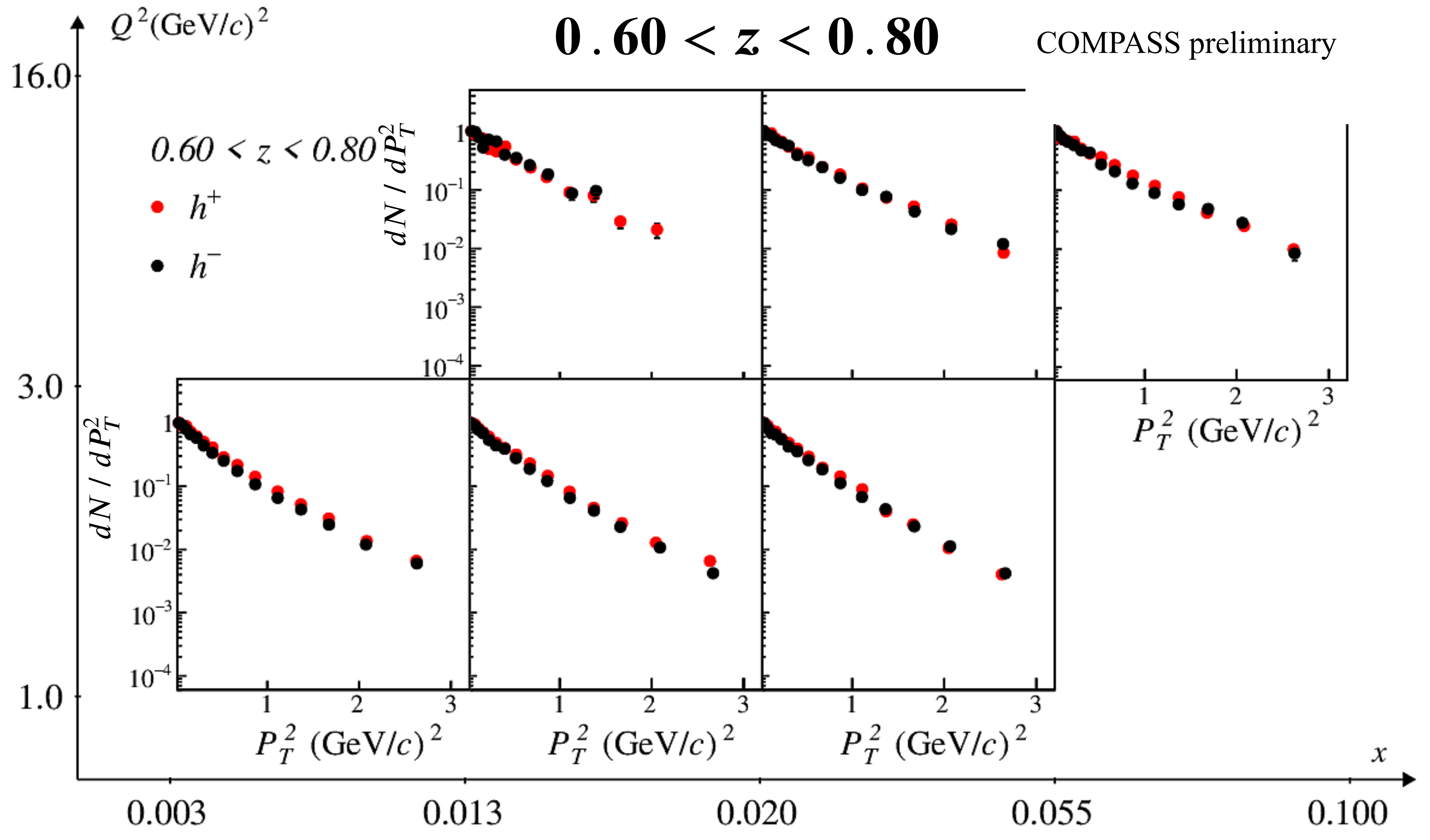
COMPASS

The error bars correspond to the statistical uncertainty only. $\sigma_{syst} \sim 0.3\,\sigma_{stat}$









Azimuthal asymmetries – 1D – Q^2 dependence & analysis method

Binning in Q^2

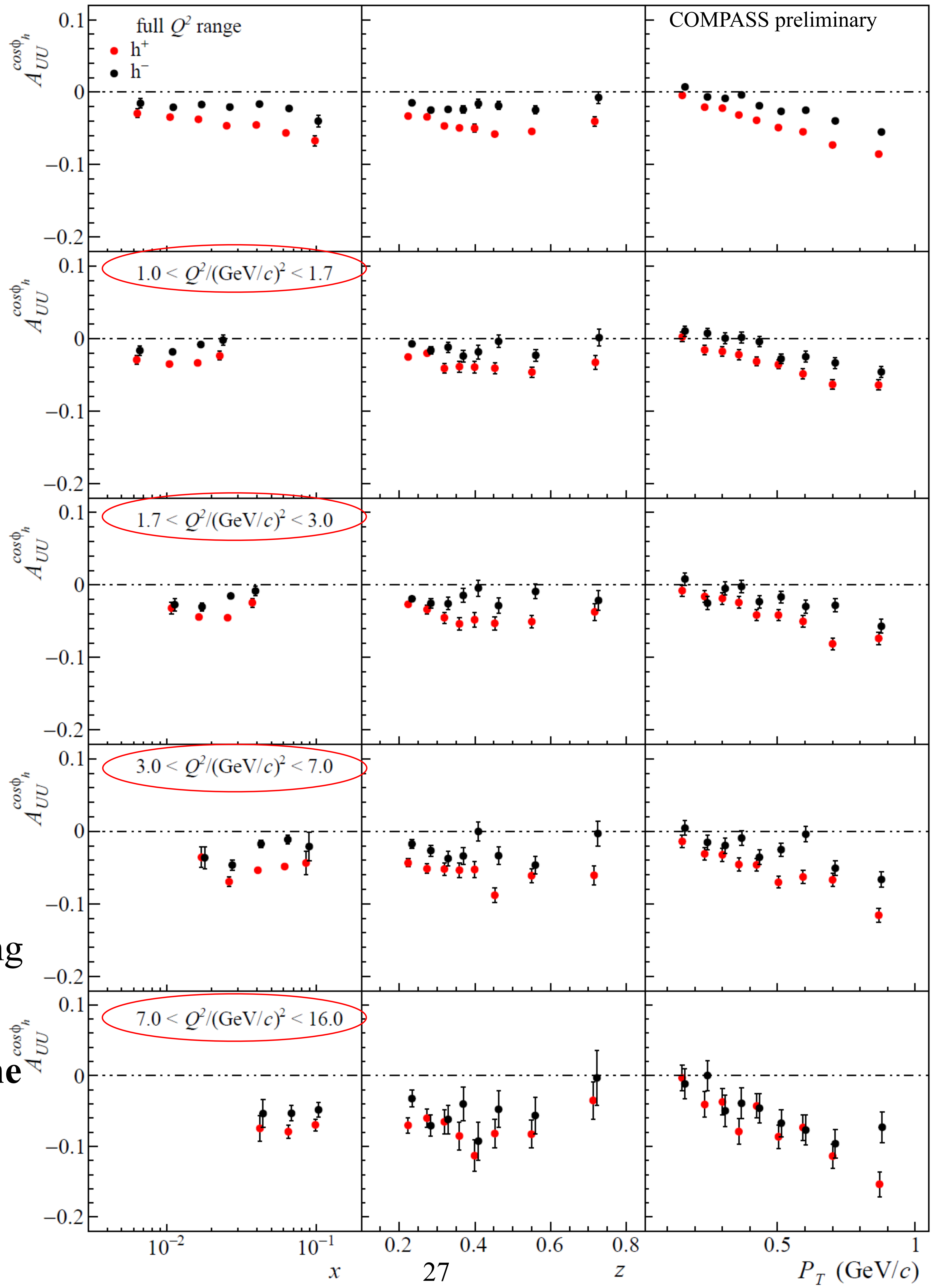
- Flavor-independent expectation from the Cahn effect:

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

- **The $A_{UU}^{\cos\phi_h}$ asymmetry is observed to increase with Q^2 *unexpected!***
- The difference between positive and negative hadrons decreases with Q^2.
- **Almost no Q^2 dependence for $A_{UU}^{\cos 2\phi_h}$**

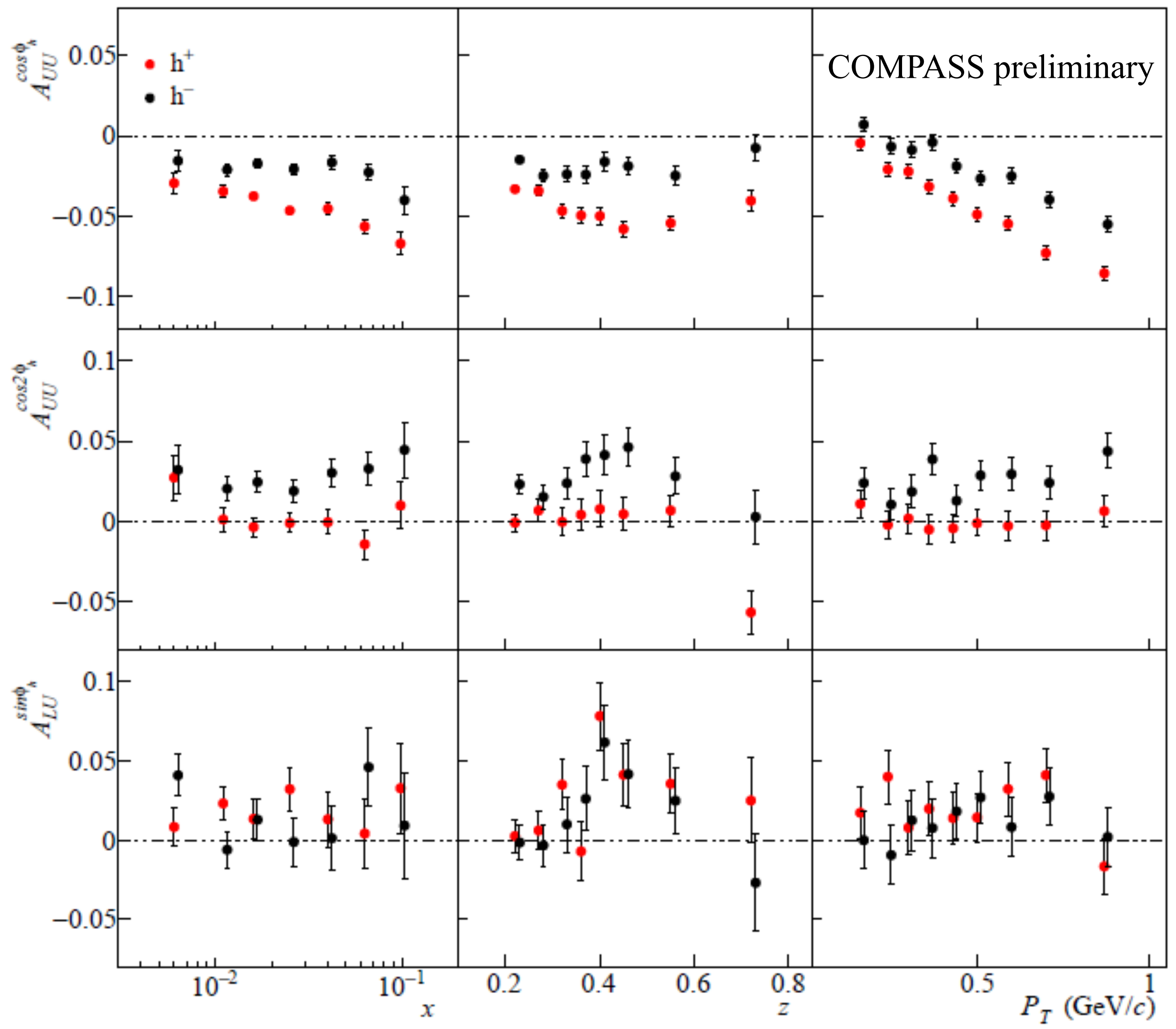
Steps in the measurement:

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)

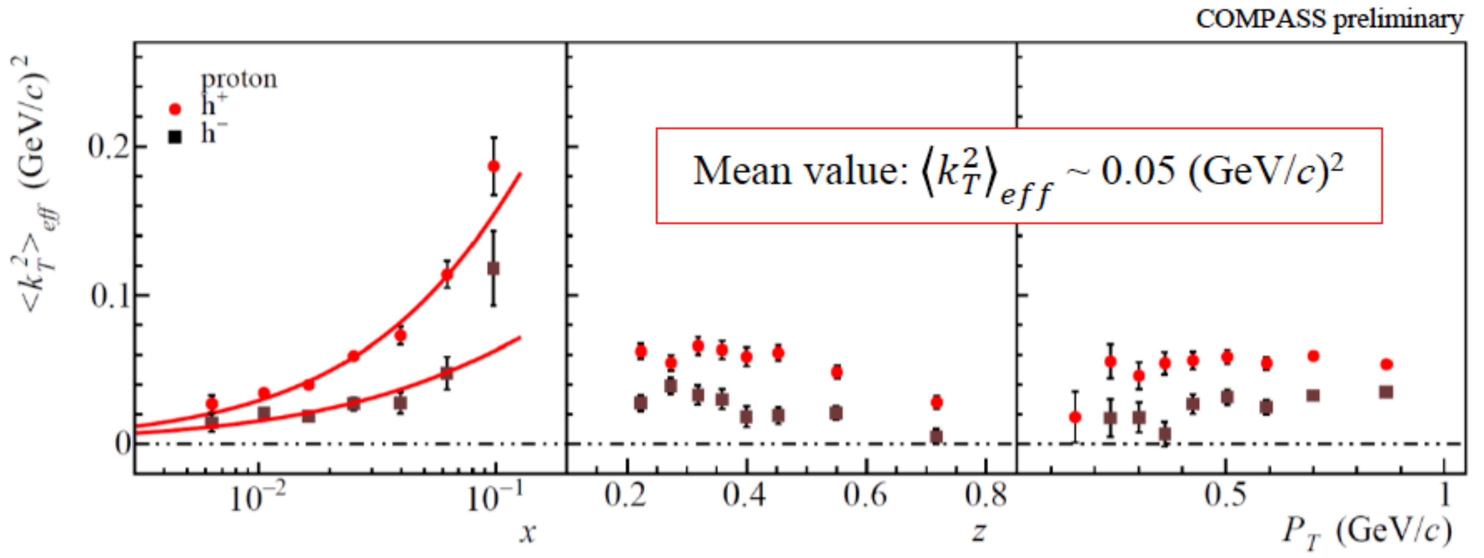


proton
2016 data

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



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



Azimuthal asymmetries for hadron pairs

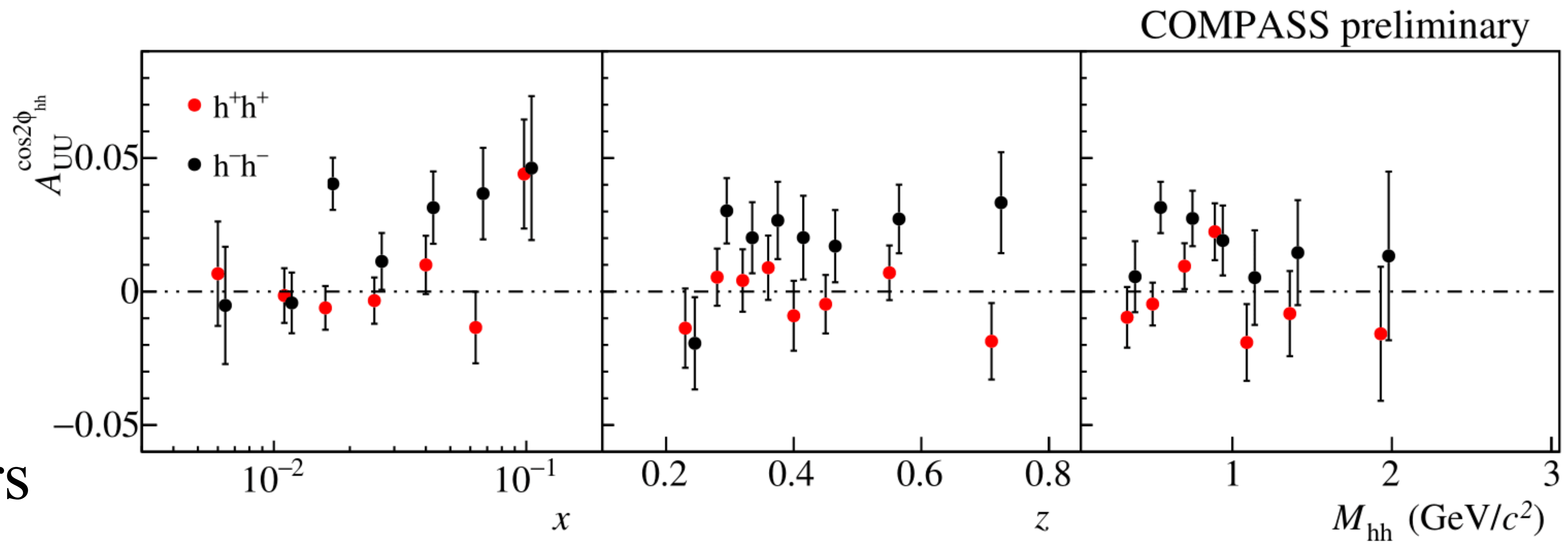
unpolarized

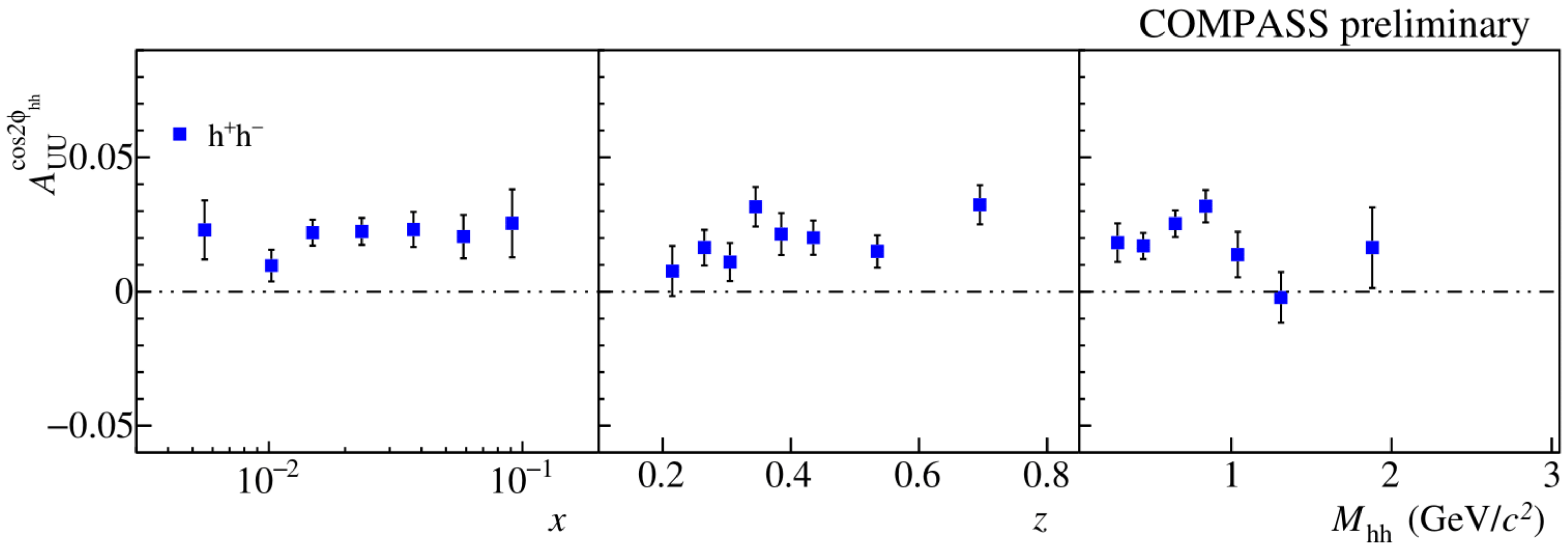
BM ⊗ Collins / IFF

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

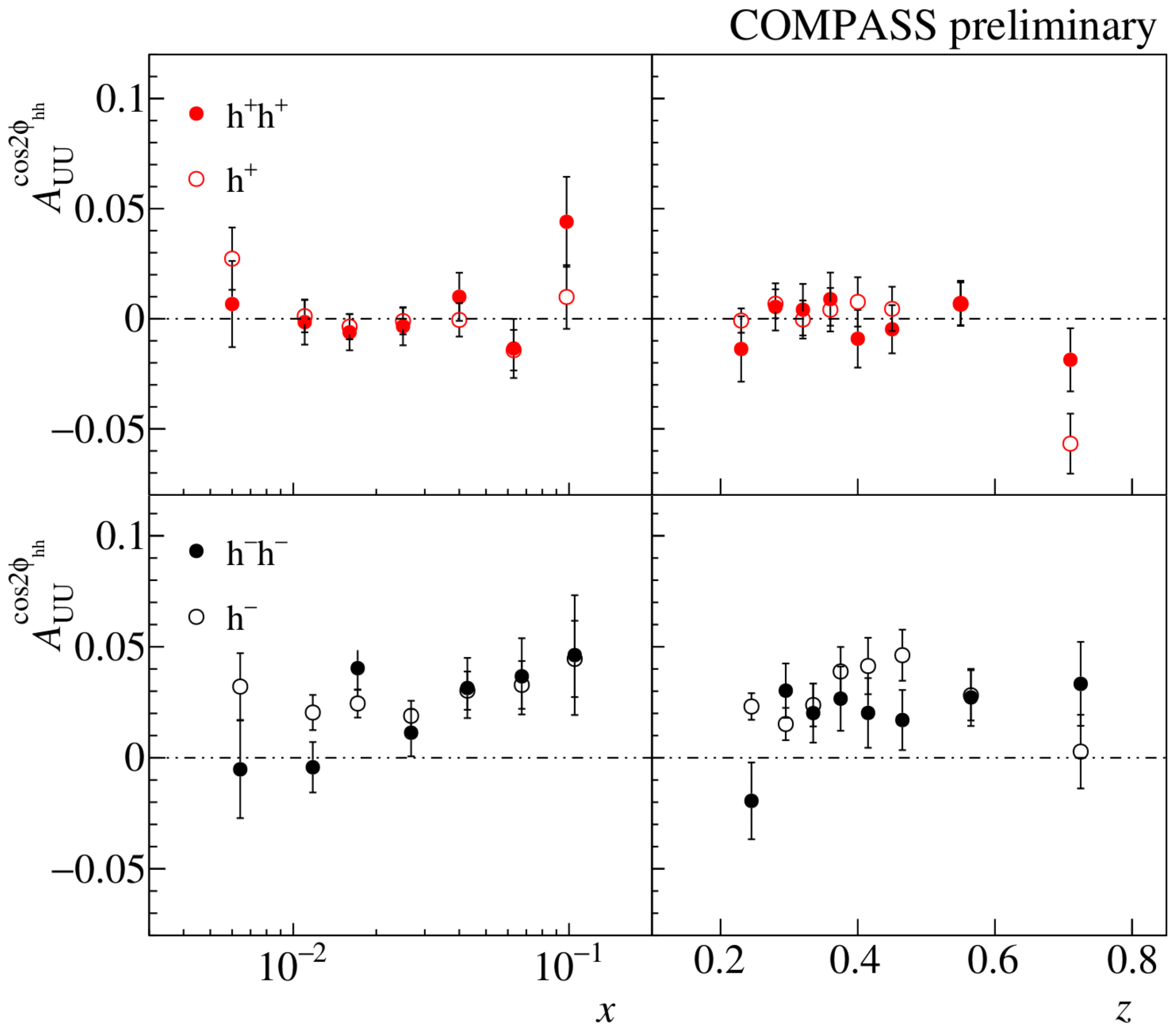
proton
2016 data

- Interference fragmentation function (IFF) and Collins FF in 2 hadrons
- 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

unpolarized

BM ⊗ Collins / IFF

Additional information on the nucleon structure from the **azimuthal asymmetries for hadron pairs**. (detailed info)

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

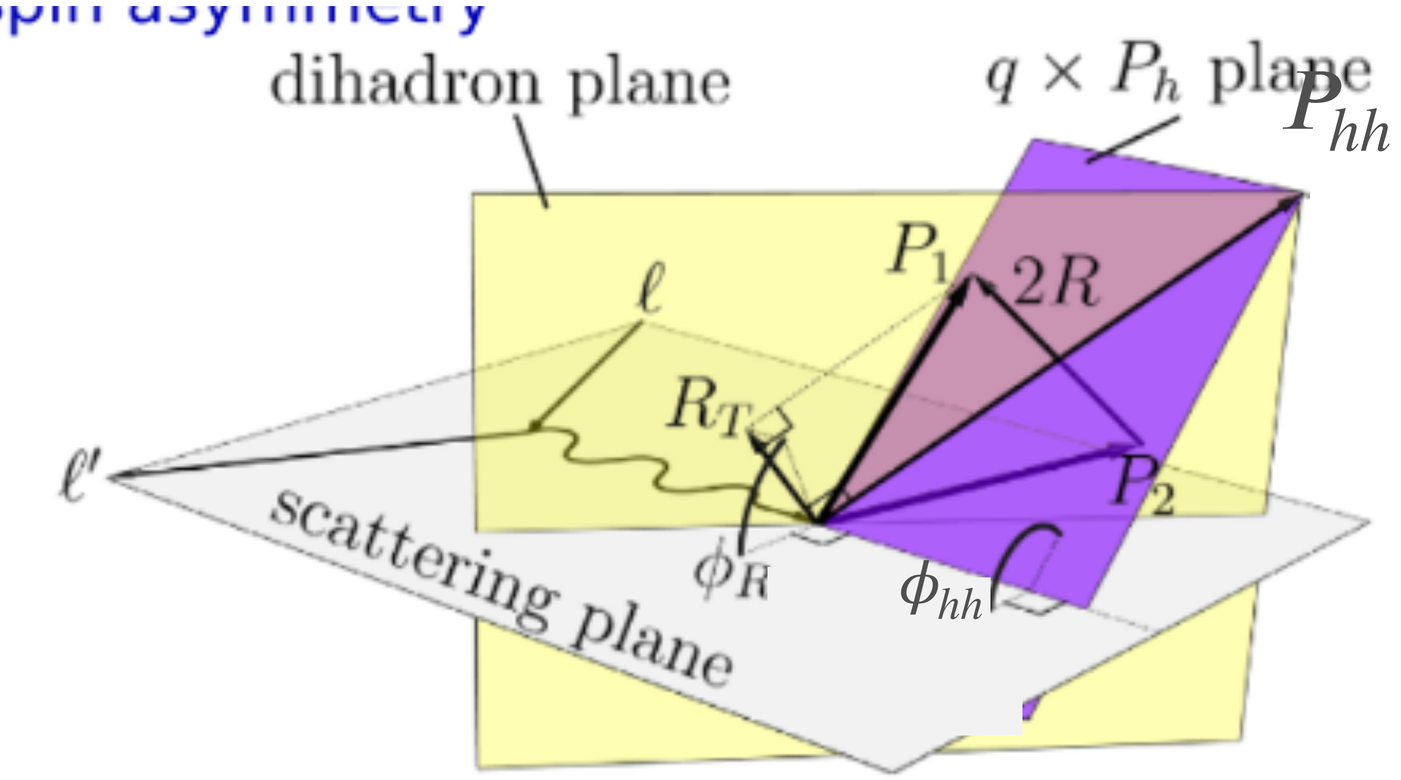
***Bianconi, Boffi, Jakob, Radici* [PRD62, 034008, 2000]**

- leading twist formalism

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

- $\mathscr{F}$: 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 $\vec{R} = \frac{z_2\vec{P}_1 - z_1\vec{P}_2}{z_1+z_2} \approx \frac{\vec{P}_1 - \vec{P}_2}{2}$**



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

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

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

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

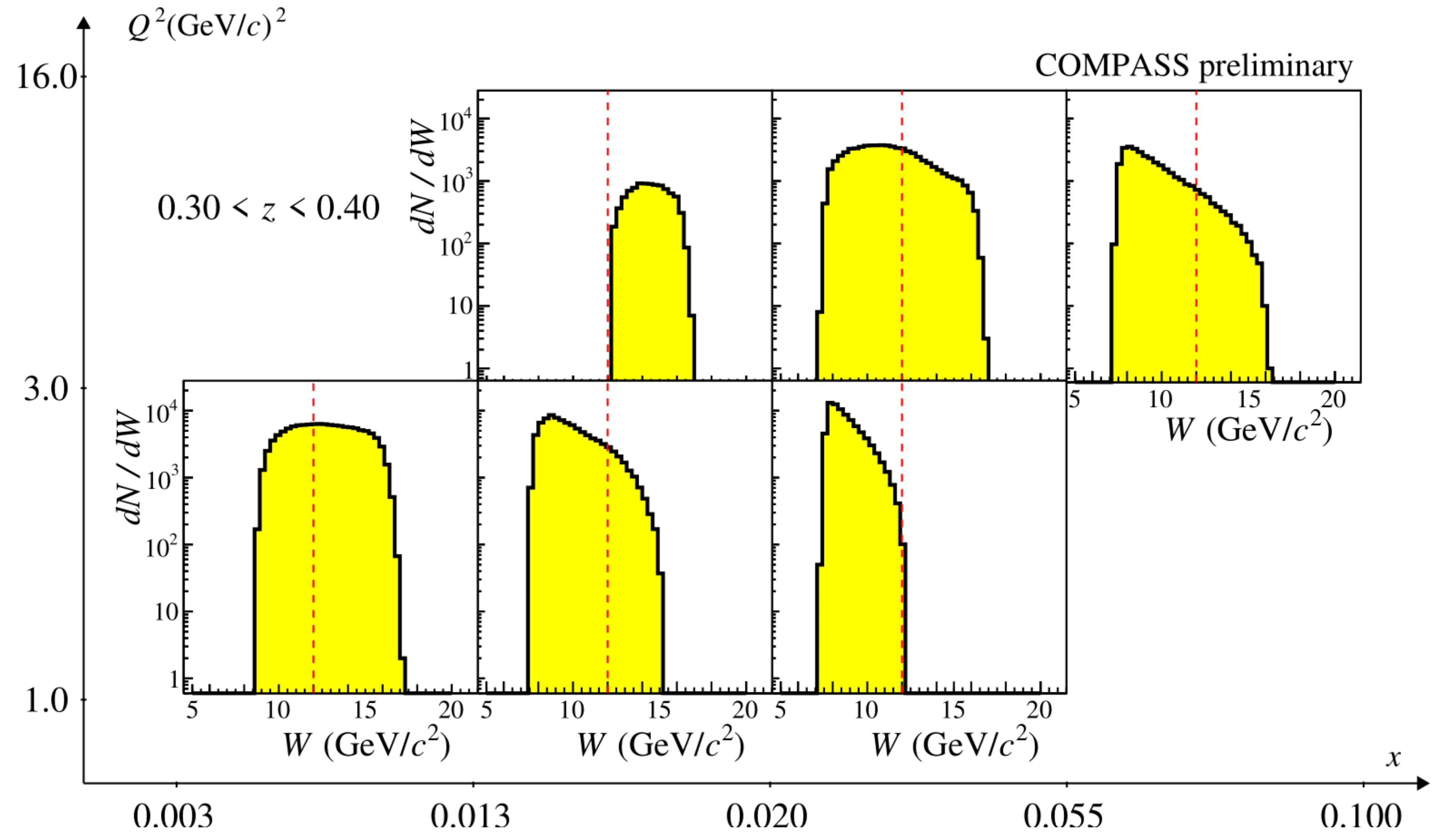
- $A(y) = 1 - y + \frac{y^2}{2}$ $\quad B(y) = 1 - y$ $\quad V(y) = 2(2-y)\sqrt{1-y}$

Transverse momentum distributions - kinematic dependences

proton

Investigation of kinematic dependences on Q^2, W

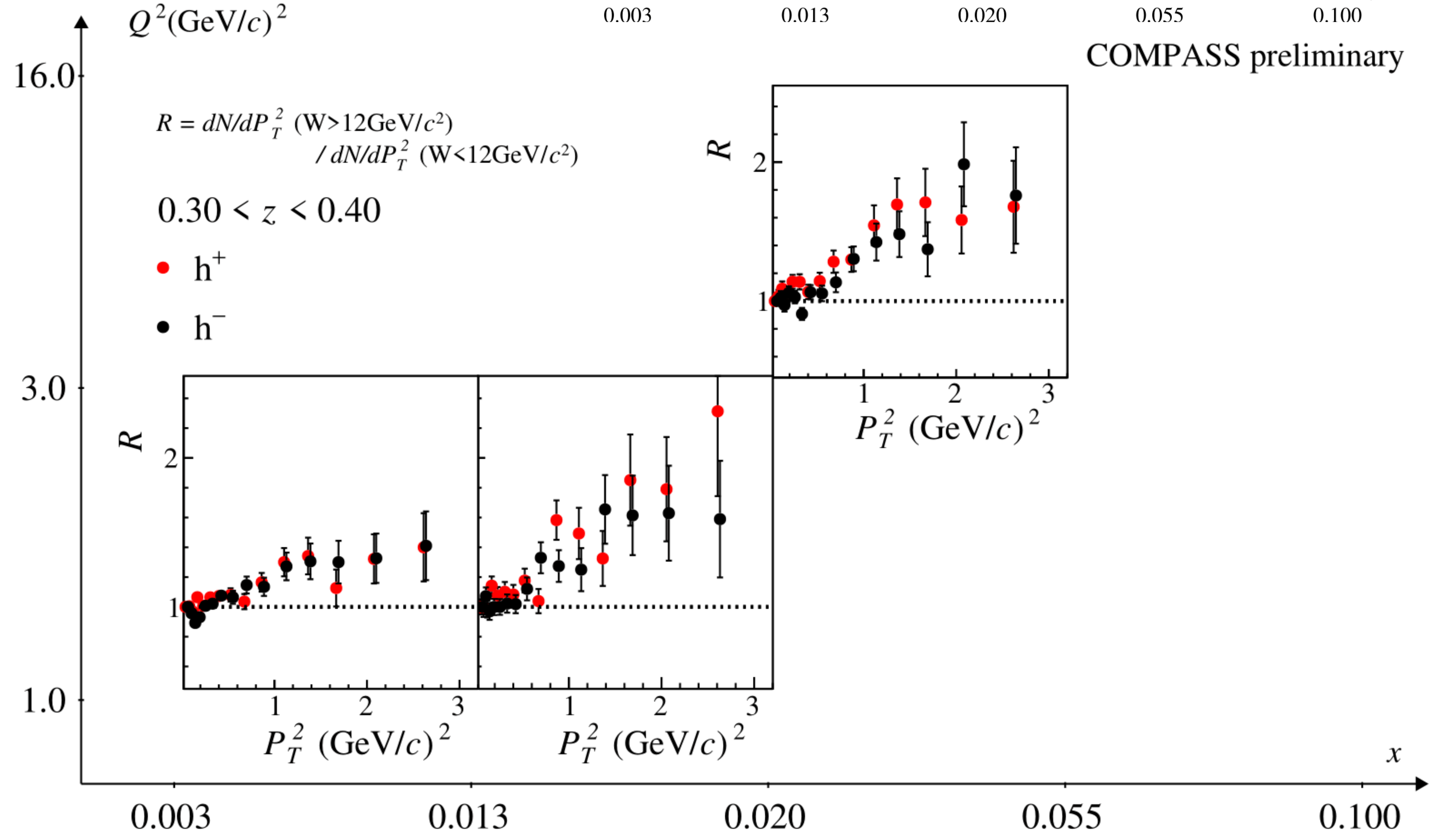
- *Distributions in 2 W bins + ratio high-over-low Q^2 + ratio high-over-low W*
- *Distributions in 4 Q^2 bins*
- *…*



COMPASS preliminary

Interesting observation: increase of $\langle P_T^2 \rangle$ with W

Phase-space effect



Azimuthal asymmetries for hadron pairs - 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

$z > 0.1$

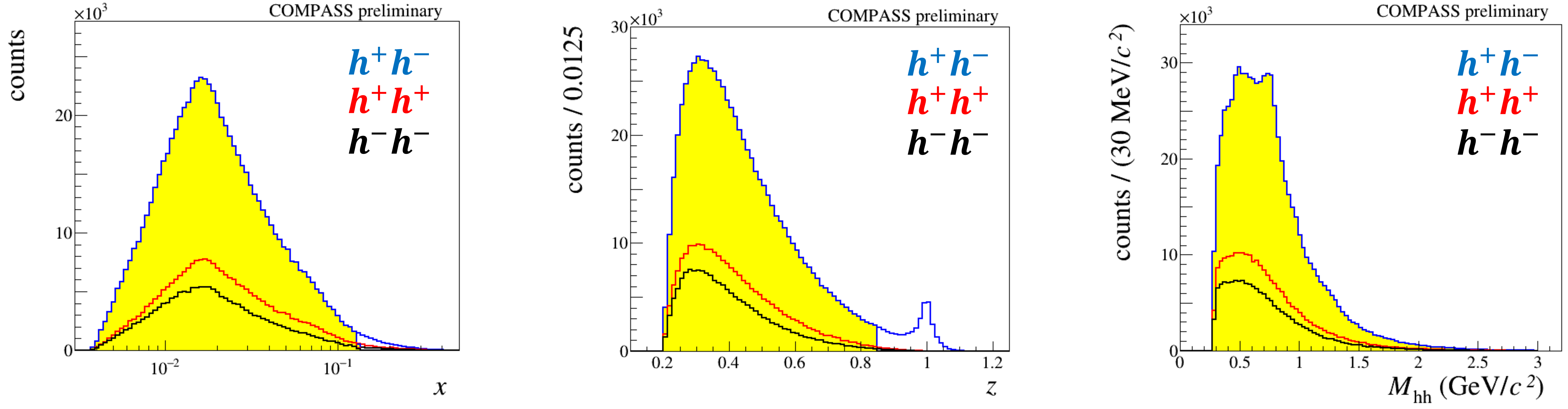
$P_T > 0.1\ \mathrm{GeV}/c$

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^-



P_T-weighted Sivers asymmetry in SIDIS

T-polarized

This more explicit slide for the backup

Sivers P_T-weighted ⊗ D1

COMPASS

At leading twist and leading order in QCD:

$$A_{Siv}(x,z,P_T) = \frac{\sum_q e_q^2 x \mathcal{C}\left[\frac{\boldsymbol{P_T}\cdot\boldsymbol{k_T}}{MP_T} f_{1T}^{\perp q}(x,k_T^2)\ D_1^q(z,p_\perp^2)\right]}{\sum_q e_q^2 x \mathcal{C}\left[f_1^q(x,k_T^2)\ D_1^q(z,p_T^2)\right]}$$

This convolution cannot be analytically evaluated in the general case: to disentangle $f_{1T}^{\perp}$ and D_1, and to extract the Sivers function, **assumptions** for the transverse-momentum dependence of the distribution and fragmentation functions have to be made.

For example, assuming the usual Gaussian dependence and integrating over $\boldsymbol{P_T}$:

$$A_{Siv,G}(x,z) = \frac{a_G \sum_q e_q^2\ x f_{1T}^{\perp(1)q}(x)\ z D_1^q(z)}{\sum_q e_q^2\ x f_1^q(x)\ D_1^q(z)}$$

$$f_{1T}^{\perp(1)q}(x) = \int d^2\boldsymbol{k}_T \frac{k_T^2}{2M^2} f_{1T}^{\perp q}(x,k_T^2)$$

$$a_G = \frac{\sqrt{\pi}M}{\sqrt{\langle p_T^2\rangle + z^2\langle k_T^2\rangle_S}} \simeq \frac{\pi M}{2\langle P_T\rangle}$$

($a_G \cong 1$ for the Collins asymmetry)

but the assumption can introduce a bias into the extraction of the Sivers function.

The problem can be avoided measuring P_T−weighted asymmetries:

$$w = P_T/zM$$

$$A_{Siv}^{w}(x,z) = \frac{\sum_q e_q^2 x \int d^2\boldsymbol{P_T}\frac{P_T}{zM}\mathcal{C}\left[\frac{\boldsymbol{P_T}\cdot\boldsymbol{k_T}}{MP_T} f_{1T}^{\perp q}(x,k_T^2)\ D_1^q(z,p_T^2)\right]}{\sum_q e_q^2\ x f_1^q(x)\ D_1^q(z)}$$

$$= 2\frac{\sum_q e_q^2\ x f_{1T}^{\perp(1)q}(x)\ D_1^q(z)}{\sum_q e_q^2\ x f_1^q(x)\ D_1^q(z)}$$

$$w' = P_T/M$$

$$A_{Siv}^{w'}(x,z) = 2\frac{\sum_q e_q^2\ x f_{1T}^{\perp(1)q}(x)\ z D_1^q(z)}{\sum_q e_q^2\ x f_1^q(x)\ D_1^q(z)}$$

$$\frac{A_{Siv}^{w'}(x,z)}{A_{Siv,G}(x,z)} = \frac{4\langle P_T\rangle}{\pi M}$$

$$A_{Siv}^{w}(z) = 2\frac{\sum_q e_q^2 D_{1q}(z)\int C(x) f_{1T}^{\perp(1)q}(x)dx}{\sum_q e_q^2 D_{1q}(z)\int C(x) f_1^q(x)dx}$$

P_T-weighted Sivers - details of extraction

extraction of $f_{1T}^{\perp(1)}(x)$

P_T/zM weighted asymmetries for positive e negative hadrons:

$$A_{Siv}^{w,\pm}(x) = 2\frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x)\widetilde{D}_1^{q,\pm}}{\sum_q e_q^2 x f_1^q(x)\widetilde{D}_1^{q,\pm}}$$

$$\widetilde{D}_1^{q,\pm} = \int_{z_{min}}^{z_{max}} dz D_1^{q,\pm}(z)$$

f_1^q, $\widetilde{D}_1^{q,\pm}$ from parametrisations (CTEQ5D and DSS)

having only the proton data, we had to neglect the **sea-quark** Sivers distributions, it is

$$A_{Siv}^{w,\pm} = 2\frac{4x f_{1T}^{\perp(1)u_v}\widetilde{D}_1^{u,\pm} + x f_{1T}^{\perp(1)d_v}\widetilde{D}_1^{d,\pm}}{\delta^\pm}$$

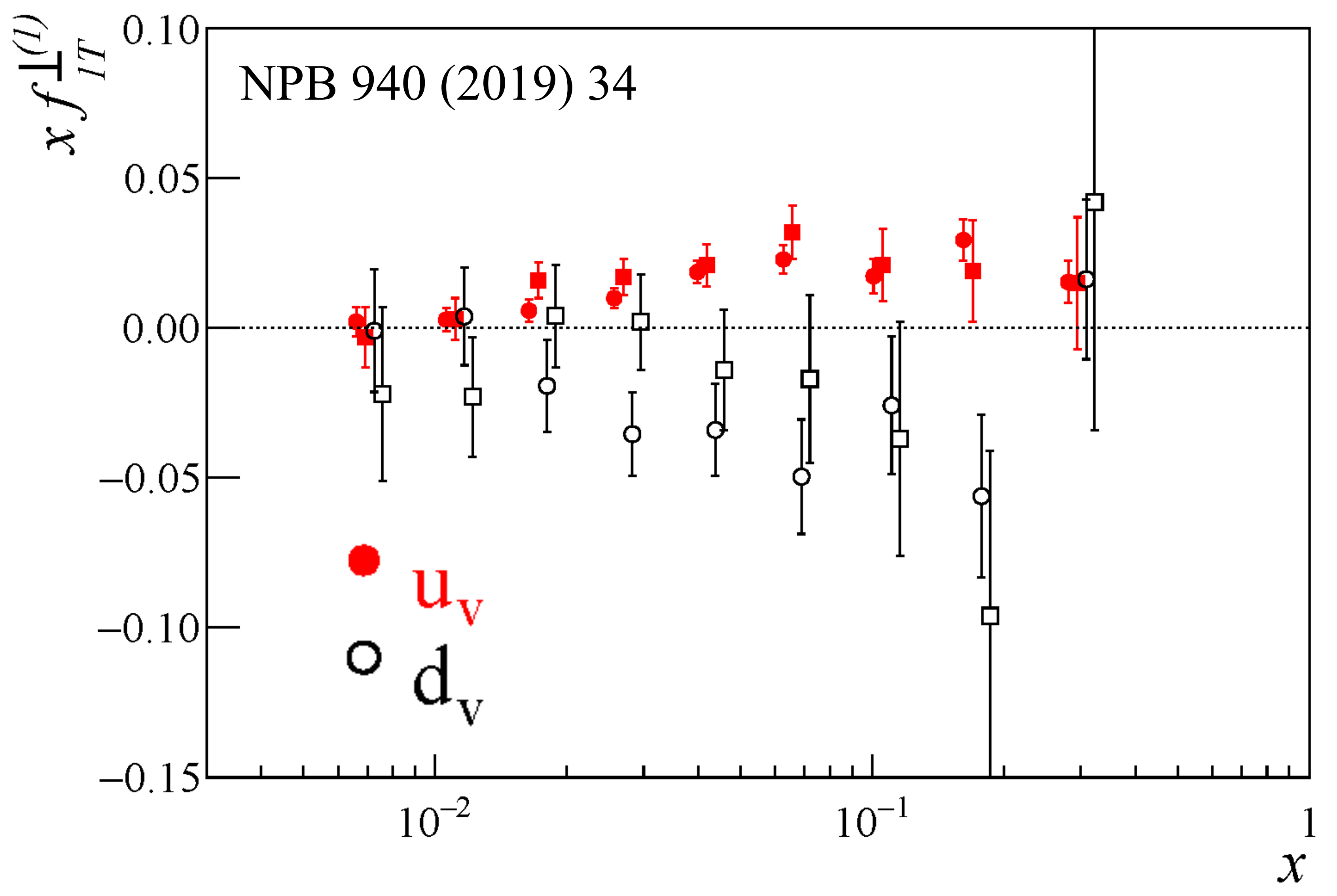
$$\delta^\pm = 9\,\Sigma_q e_q^2 x f_1^q \widetilde{D}_1^q$$

and

$$x f_{1T}^{\perp(1)u_v} = \frac{1}{8}\frac{\delta^+ A_{Siv}^{w,+}\widetilde{D}_1^{d,-} - \delta^- A_{Siv}^{w,-}\widetilde{D}_1^{d,+}}{\widetilde{D}_1^{u,+}\widetilde{D}_1^{d,-} - \widetilde{D}_1^{d,+}\widetilde{D}_1^{u,-}}$$

$$x f_{1T}^{\perp(1)d_v} = \frac{1}{2}\frac{\delta^- A_{Siv}^{w,-}\widetilde{D}_1^{u,+} - \delta^+ A_{Siv}^{w,+}\widetilde{D}_1^{u,-}}{\widetilde{D}_1^{u,+}\widetilde{D}_1^{d,-} - \widetilde{D}_1^{d,+}\widetilde{D}_1^{u,-}}$$

Extraction of pT-weighted Sivers function



previous point-by-point extraction [A.M., F.Bradamante, V.Barone, PRD95, 2017]

using pion Sivers asymmetries from the COMPASS p and d data,

(no assumptions on the Sivers function of the sea quarks, Gaussian ansatz)

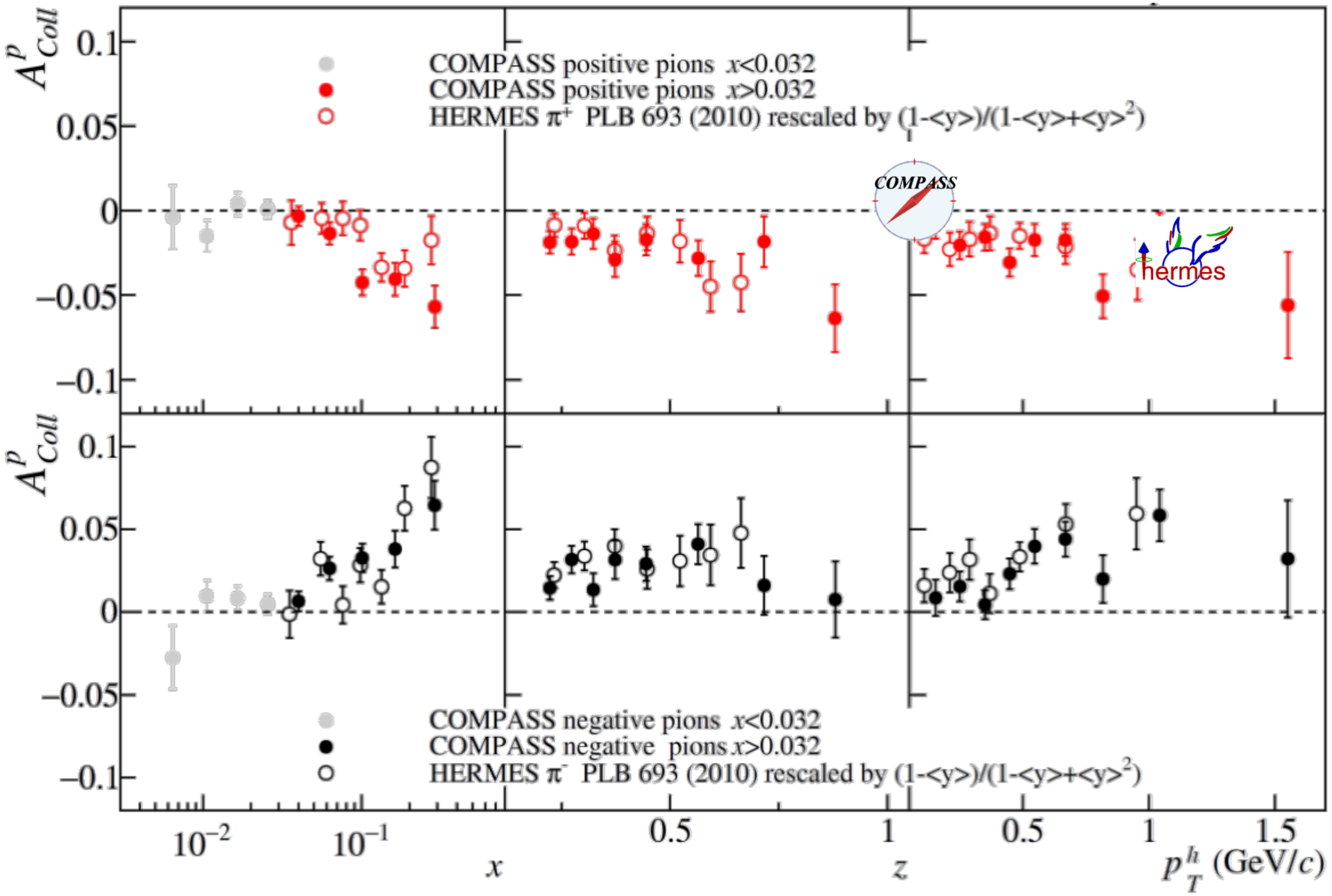
slightly different trend for $f_{1T}^{\perp(1)d_v}$

we checked that the difference is only due to the fact that here we had to neglect the sea-quark contribution

using the p data only and imposing the sea-quark Sivers functions to be zero, both the central values and the uncertainties become very similar to the present ones

Collins SIDIS - COMPASS vs. HERMES

proton



2007 and 2010 data PLB 744 (2015) 250

very good agreement with the 2010 **HERMES** results

Collins & 2-hadron asymmetries in d SIDIS

T-polarized

Transversity ⊗ Collins

COMPASS

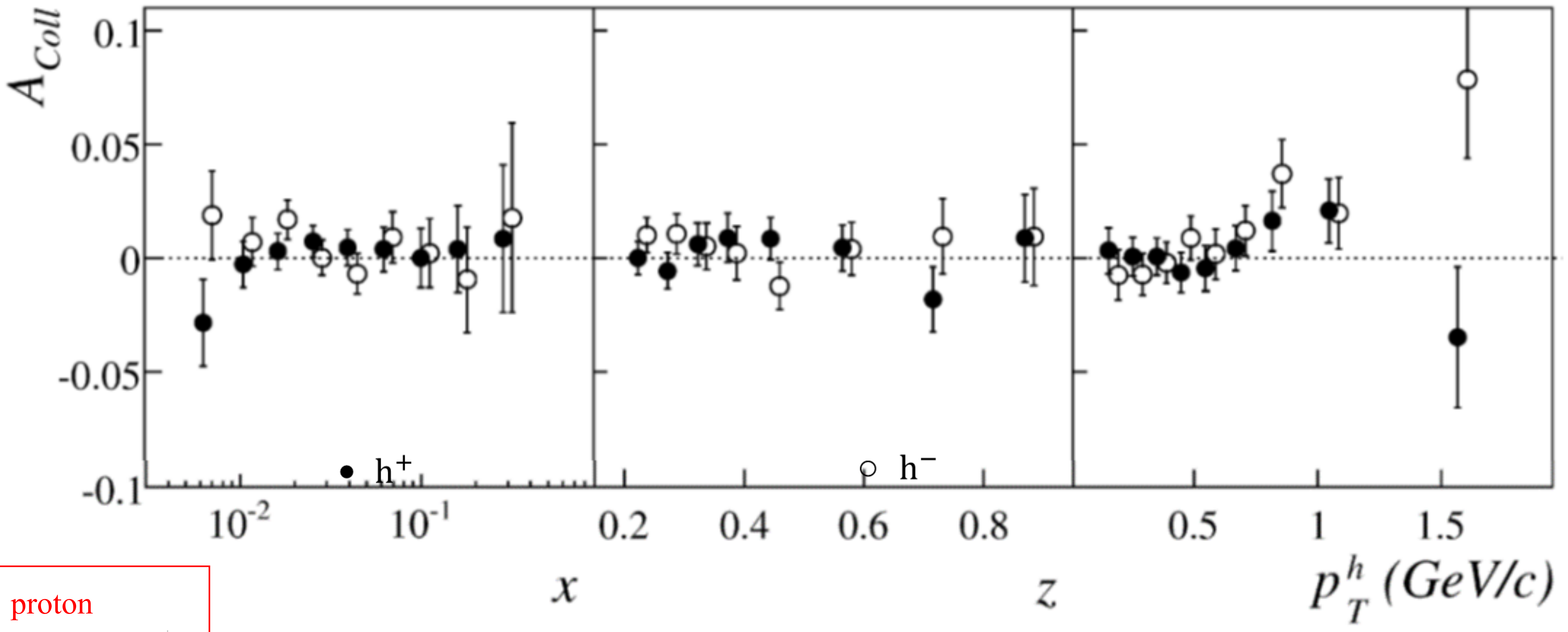
compatible with zero

some signal at $P_T^h \simeq 1$ GeV/c ?

Collins asymmetry

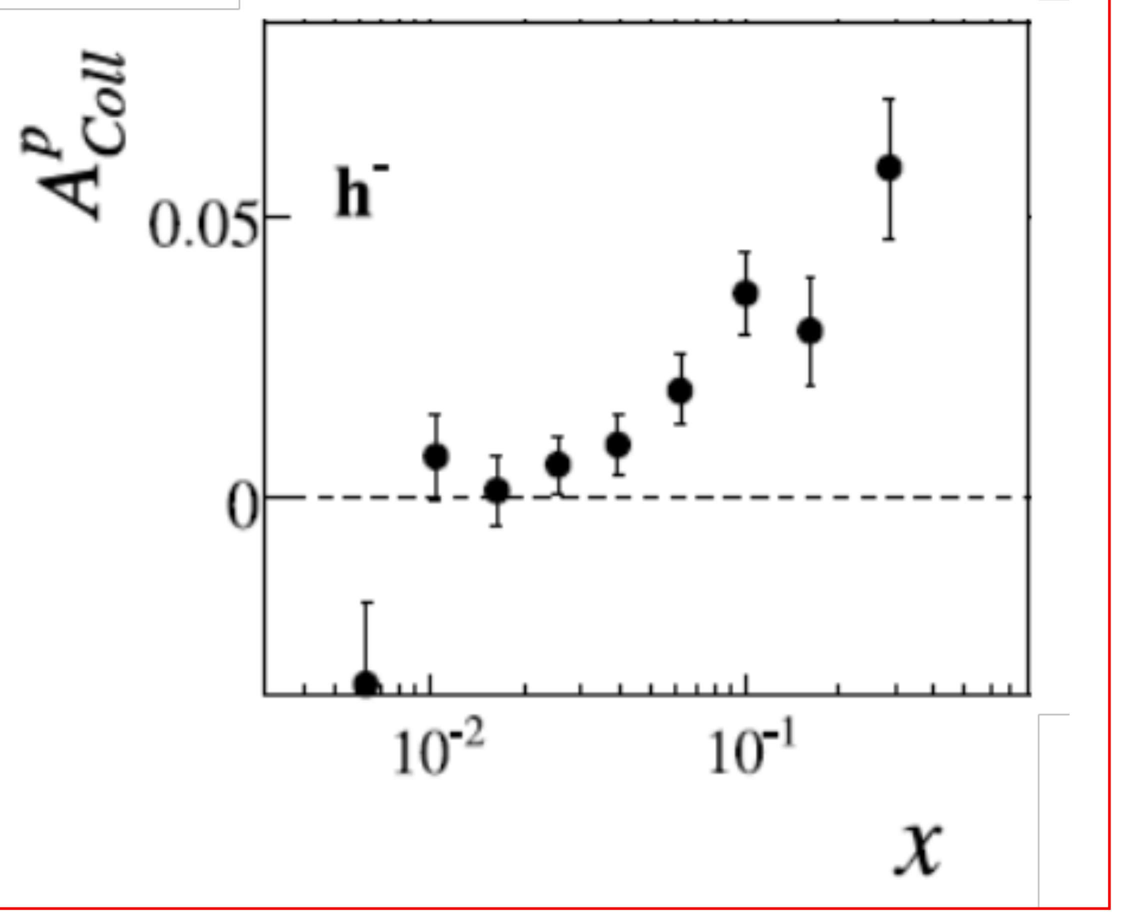
all deuteron 2002-2004 data NPB765 (2007) 31

deuteron



interpreted as cancellation between u and d quark contributions

proton



large statistical errors, as compared to the proton data

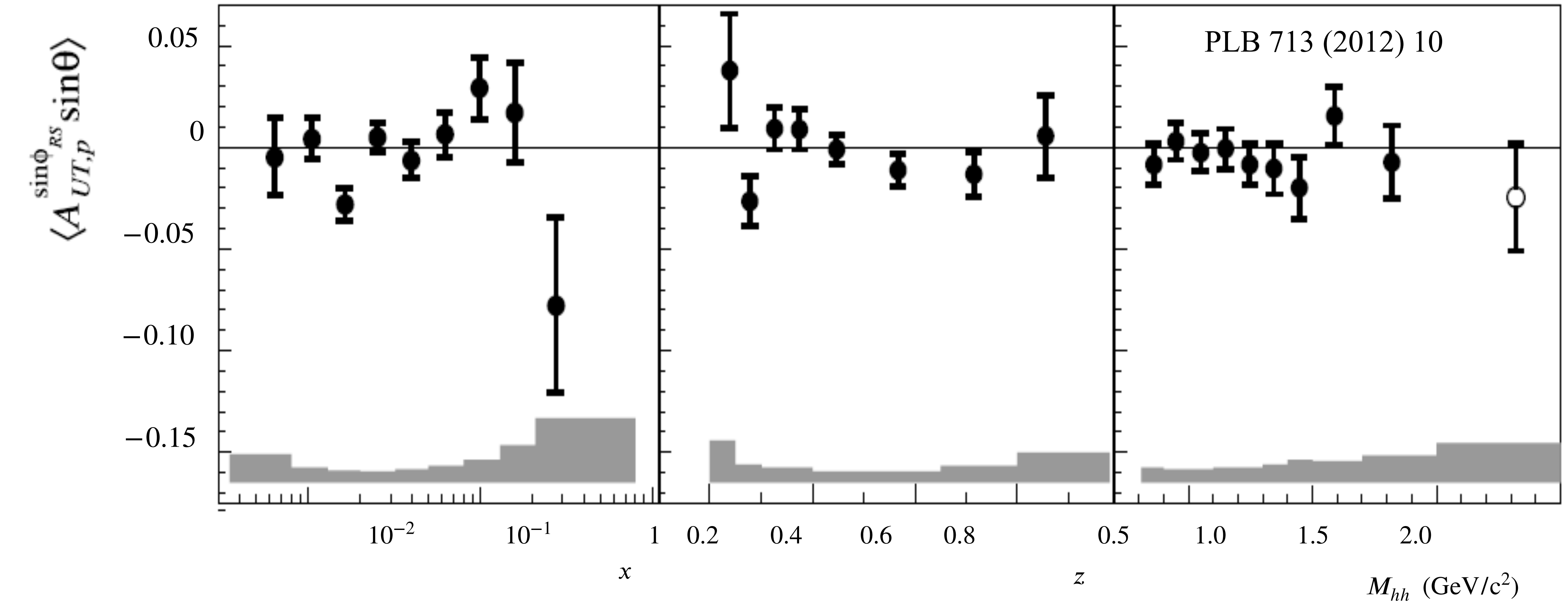
only existing d data

(low statistics He3 measurement at Jlab)

motivation for the 2022 COMPASS run

di-hadron asymmetry

deuteron



My extra slides (to be deleted from official talk)

Input from Anna et al. & notes (delete when talk is complete)

Unpolarized TMDs - Andrea Bressan's talk at IWHSS 2022
https://indico.cern.ch/event/1121975/contributions/5011546/attachments/2499261/4292722/Unpolxs_Bressan.pdf

Transverse TMDs - Franco Bradamante's talk at IWHSS 2022
https://indico.cern.ch/event/1121975/contributions/5011569/attachments/2498313/4290865/Bradamante_IWHSS2022.pdf

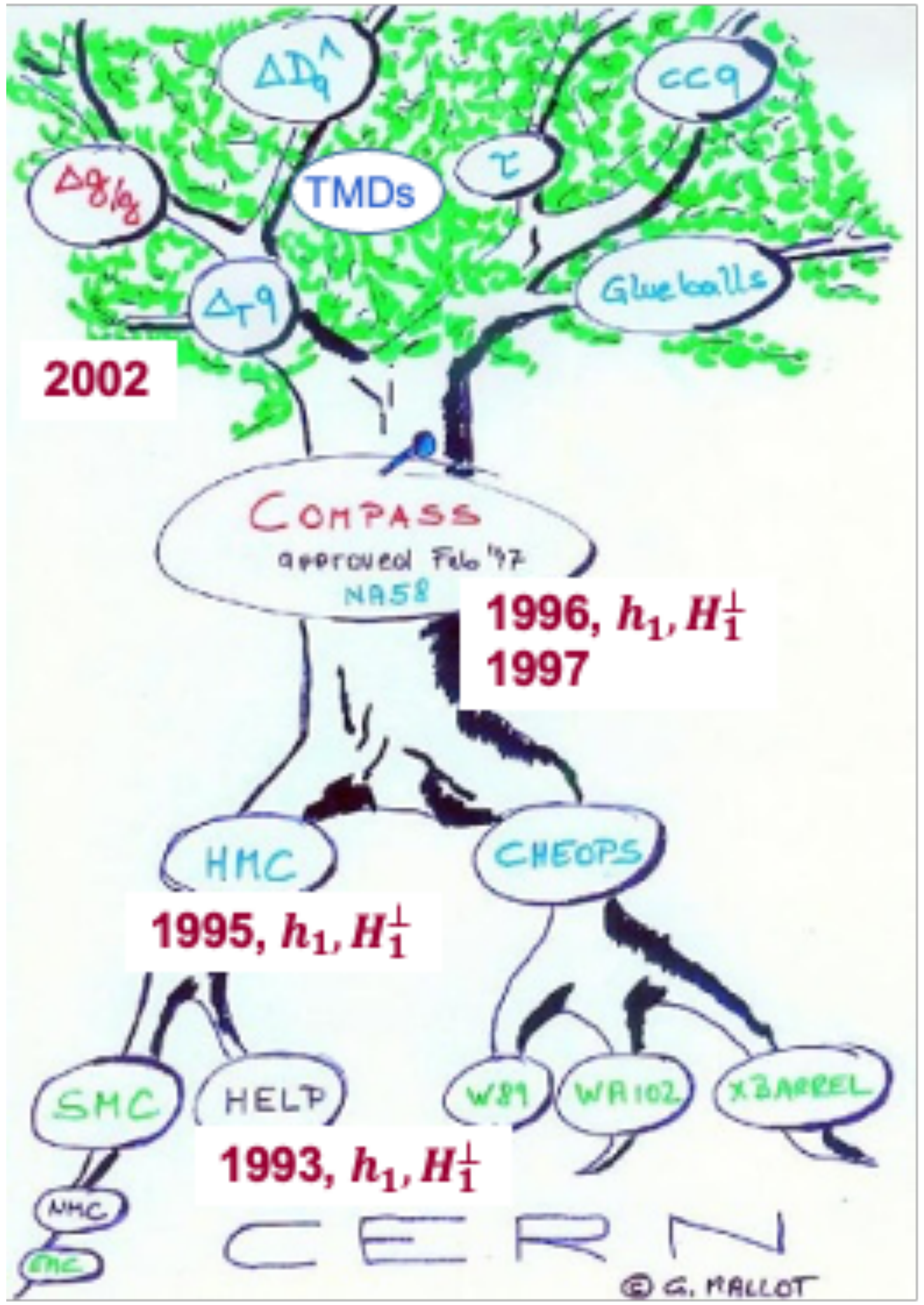
Other recent talks were given at this ECT workshop:
https://indico.ectstar.eu/event/152/timetable/#all.detailed

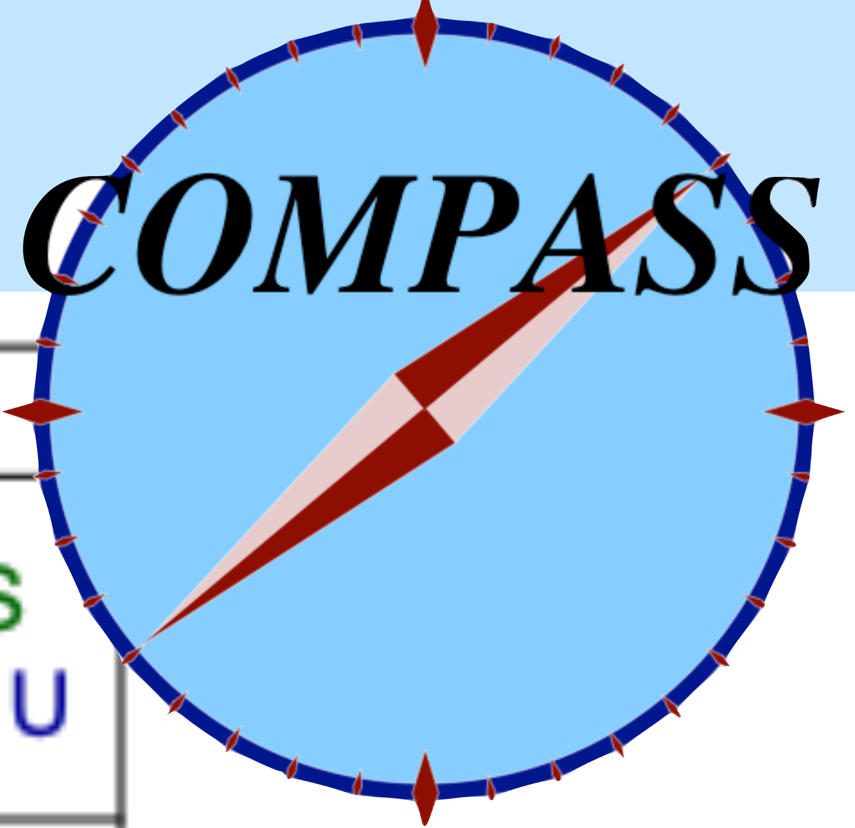
by Bakur Parsamyan, Andrea Moretti, and Anna Martin.

In operation since 2002, COMPASS is a fixed-target experiment located along the M2 beamline of the CERN SPS. One of the key measurements of its broad physics programme is the investigation of the transverse-momentum and transverse-spin structure of the nucleon, which has been pursued e.g. via measurements of Semi-Inclusive Deep Inelastic Scattering using a 160 GeV/c muon beam and transversely polarized and unpolarized proton and deuteron targets.

Data have been collected with a transversely polarized deuteron target first in 2002-2004; together with those collected in 2007 and 2010 on a transversely polarized proton target, they allowed extracting unique and very important information on the transversity and Sivers distribution functions. The unbalance in the statistics collected on deuteron and on proton target, reflected in a large uncertainty on the transversity PDF for the d-quark compared to the u-quark, is one of the main reasons behind the 2022 data taking with a transversely polarized deuteron target. In this talk, along with a review of the major results obtained from the previous measurements on polarized and unpolarized targets, projections of the statistical uncertainties of the freshly collected 2022 data sample will be presented for the first time.

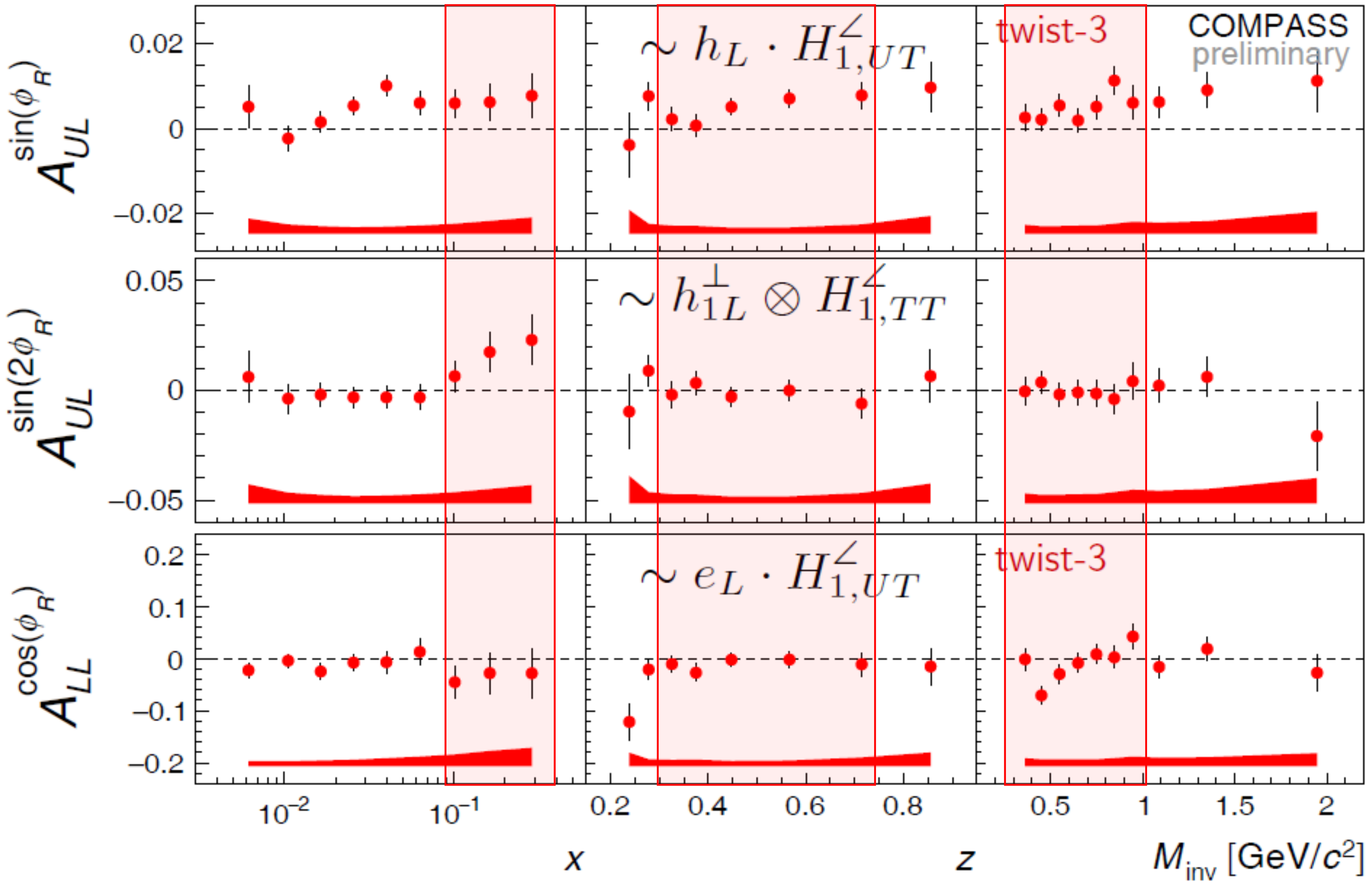
Some history - 21 years on the floor

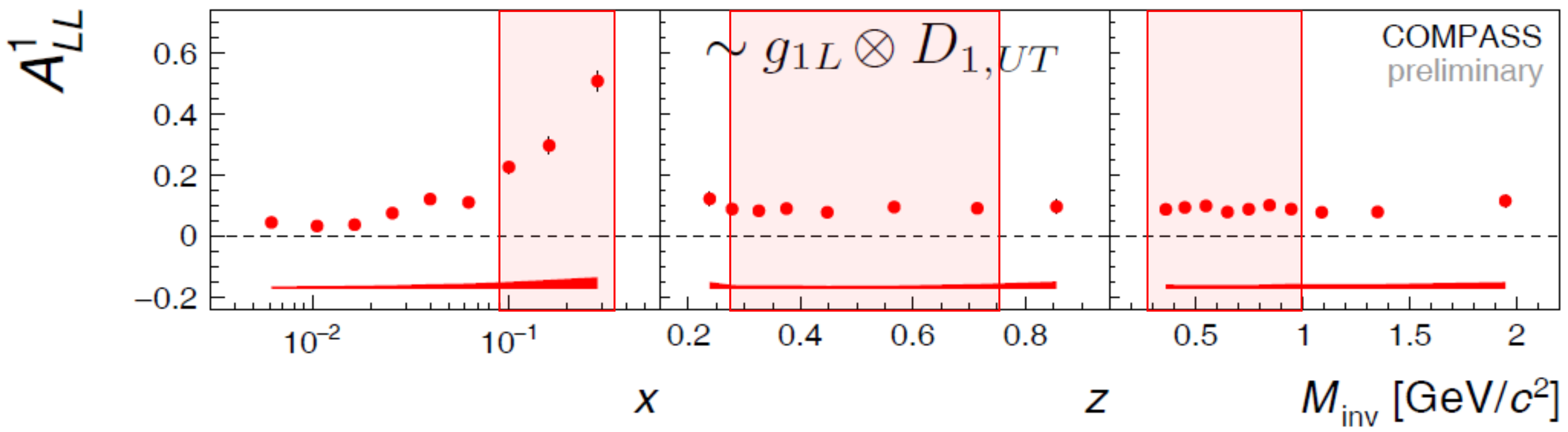




year	beam	target	physics
2002 2003 2004	μ,160 GeV	P deuteron (^{6}LiD)	80% L polarization SIDIS 20% T → U
2005			acc. shut down / upgrade
2006	μ,160 GeV	P deuteron	100% L, SIDIS → U
2007	μ,160 GeV	P proton (NH_3)	50% L 50% T, SIDIS
2008/09	hadron	LH_2	spectroscopy, Primakoff
2010	μ,160 GeV	P proton	100% T, SIDIS
2011	μ, 200 GeV	P proton	100% L, SIDIS
2012	hadron	Ni target	Primakoff & pilot DVCS
2013			acc. shut down
2014	π	proton	pilot Drell-Yan
2015	π	P proton	100% T, Drell-Yan
2016/17	μ , 160 GeV	LH_2	DVCS, unpol. SIDIS
2018	pion beam	P proton	100% T, Drell-Yan
2019/20			acc. shut down
2021	μ,160 GeV	deuteron	running in, SIDIS
2022	μ,160 GeV	P deuteron	100% T , SIDIS → U

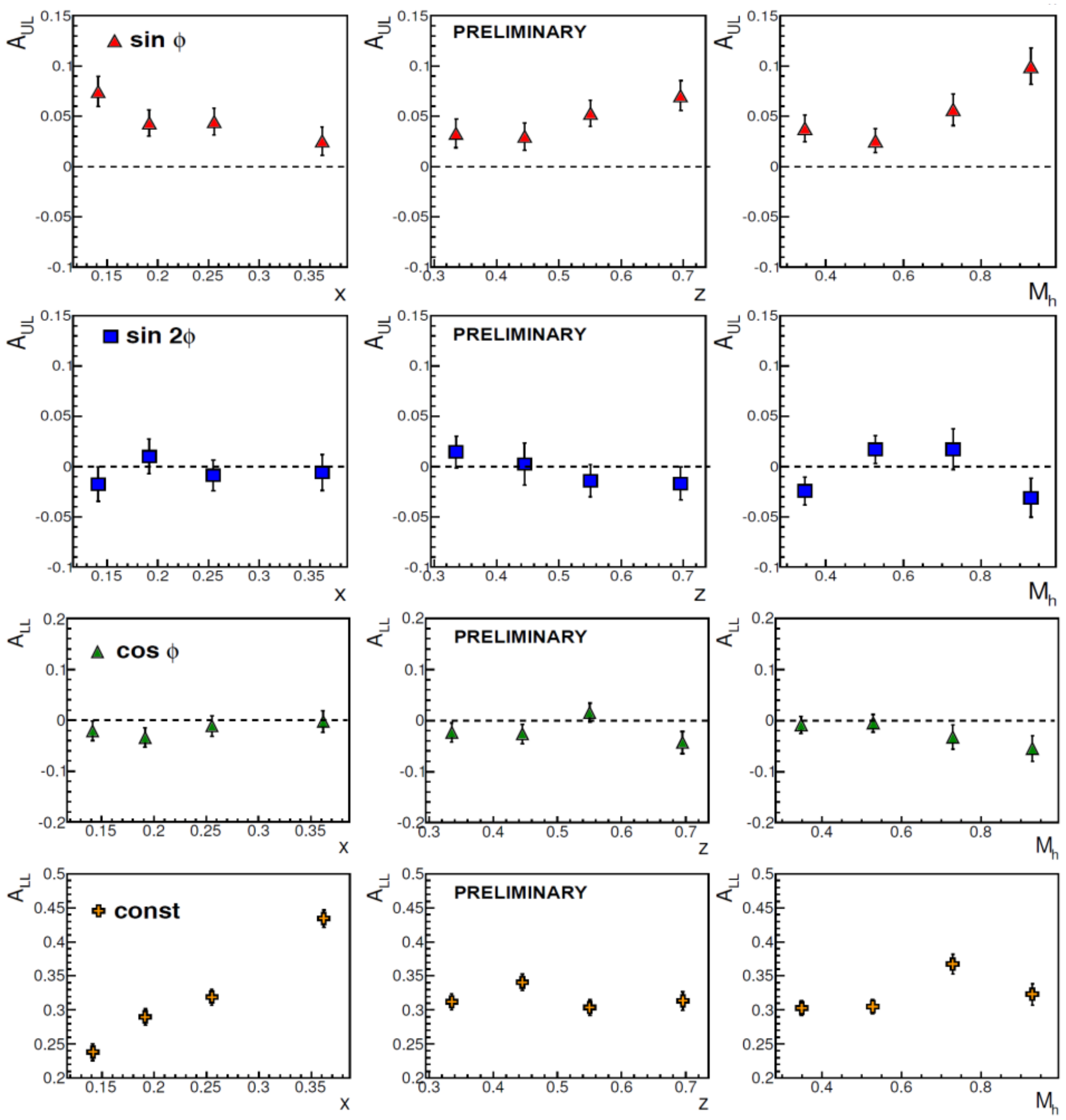
COMPASS (NH_3) 2007+2011 data



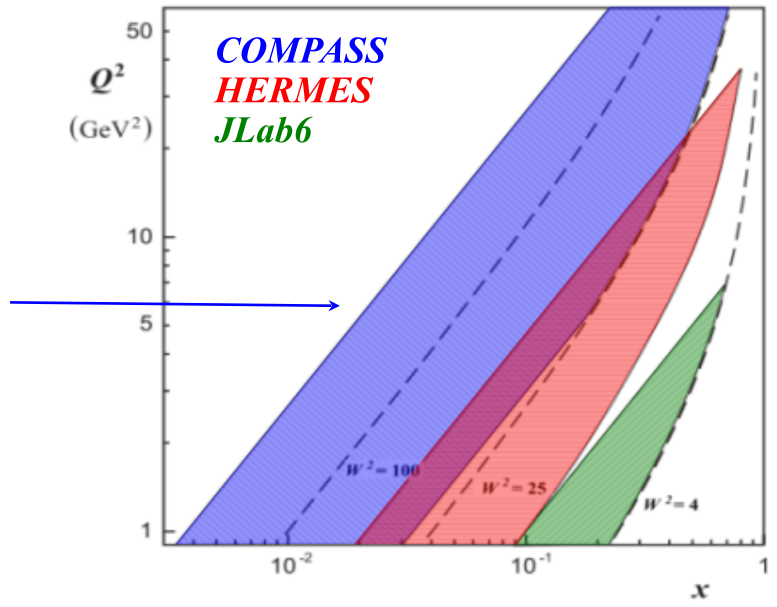


CLAS 6 GeV (NH_3)

S. A. Pereira: PoS (DIS 2014) 231



$Q^2 > 1\,(\mathrm{GeV/c})^2$
$0.0025 < x < 0.7$
$0.1 < y < 0.9$
$W > 5\,\mathrm{GeV/c}^2$



- Alternative way to access various twist-2/-3 distributions
- Non zero signal for $A_{UL}^{\sin\phi_R}$ and A_{LL}^{1}
- CLAS-COMPASS: different behavior for $A_{UL}^{\sin 2\phi_R}$ at large x?

SIDIS

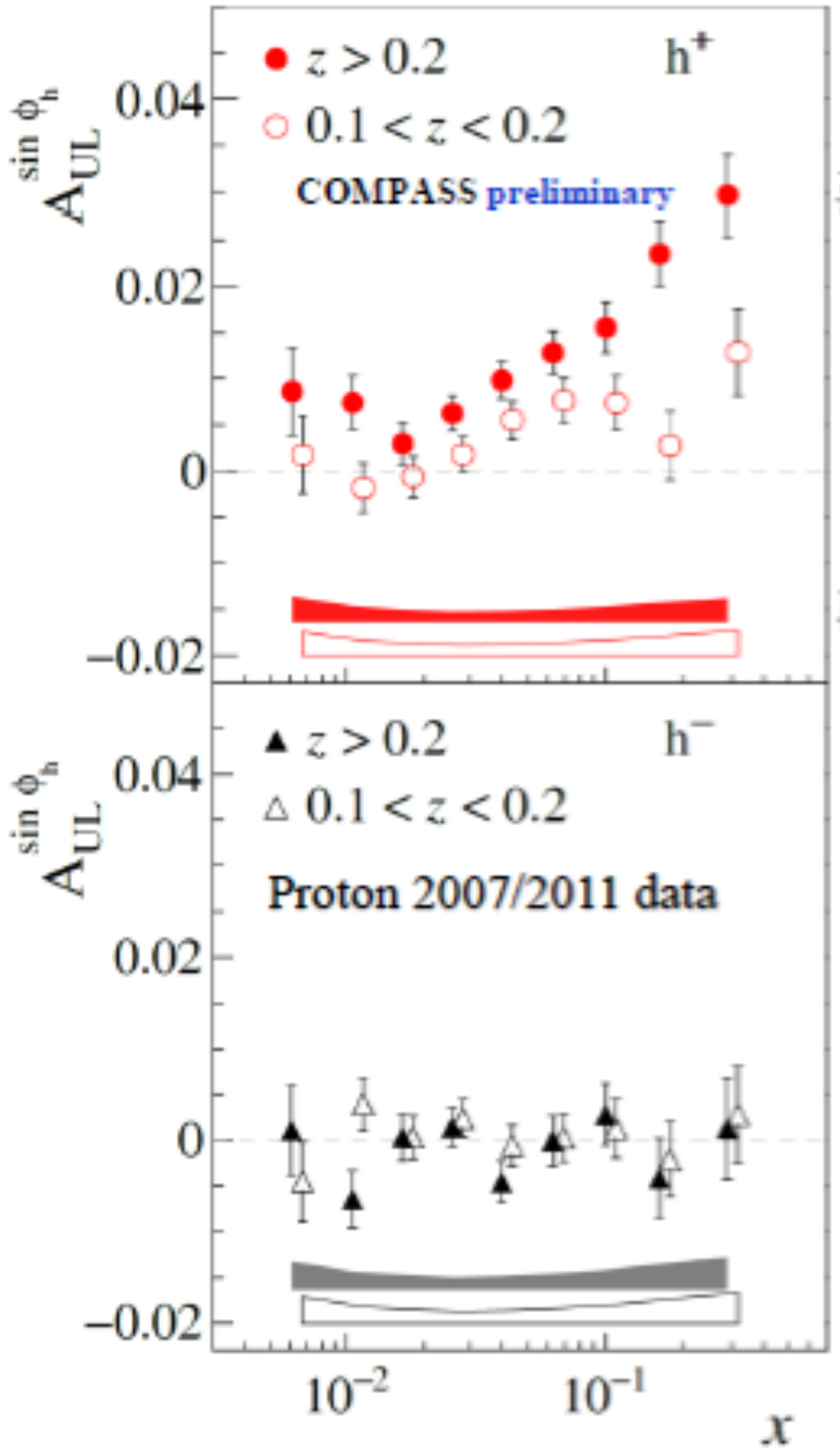
off longitudinally polarised targets (d and p?)

SIDIS: target longitudinal spin dependent asymmetries

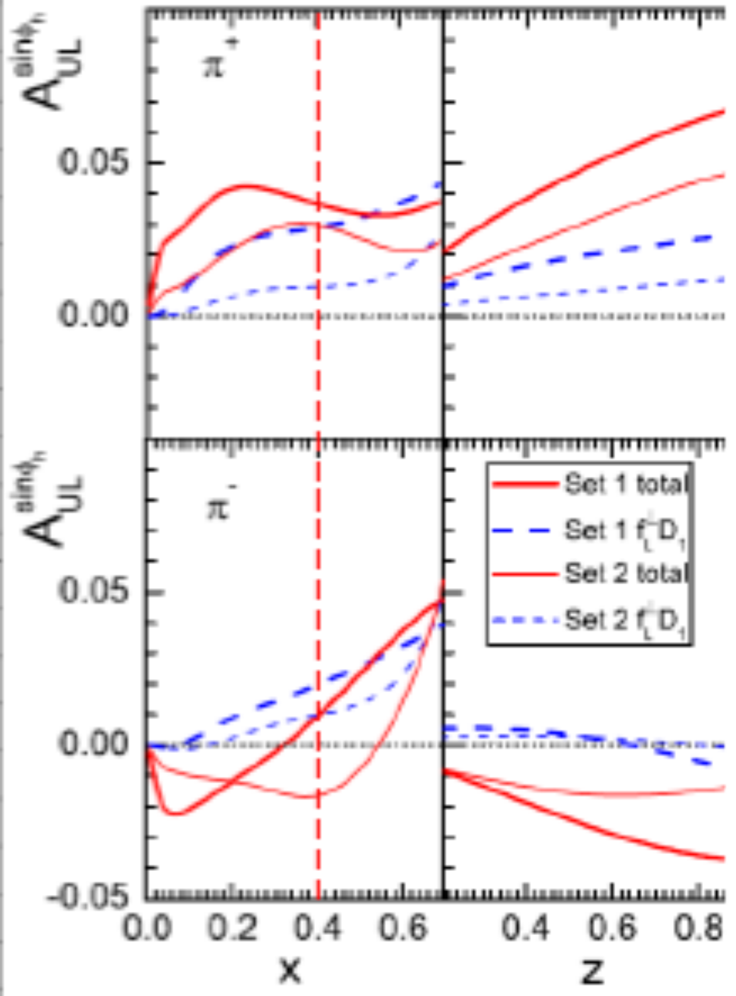
$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \ldots\right\}$$

$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{h}\cdot p_T}{M_h}\left(xh_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z}\right) + \frac{\hat{h}\cdot k_T}{M}\left(xf_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{H}_q^h}{z}\right)\right\}$$

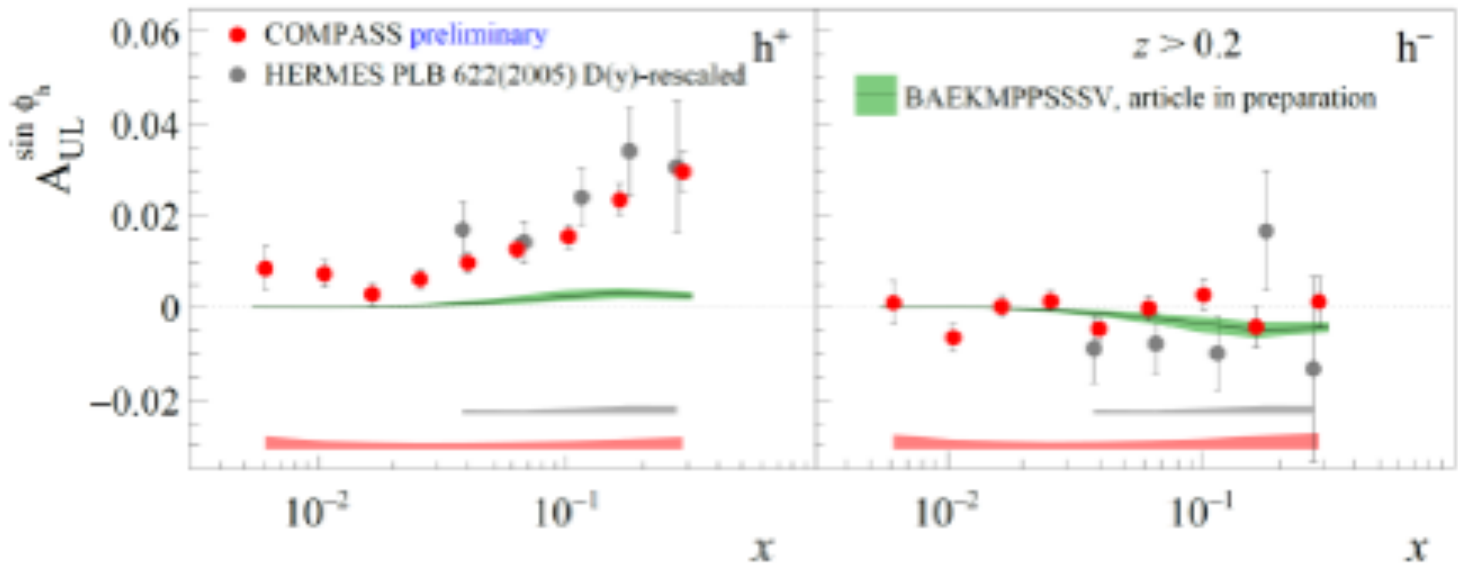
B. Parsamyan (for COMPASS)
arXiv:1801.01488 [hep-ex]



Zhun Lu
Phys. Rev. D 90, 014037(2014)



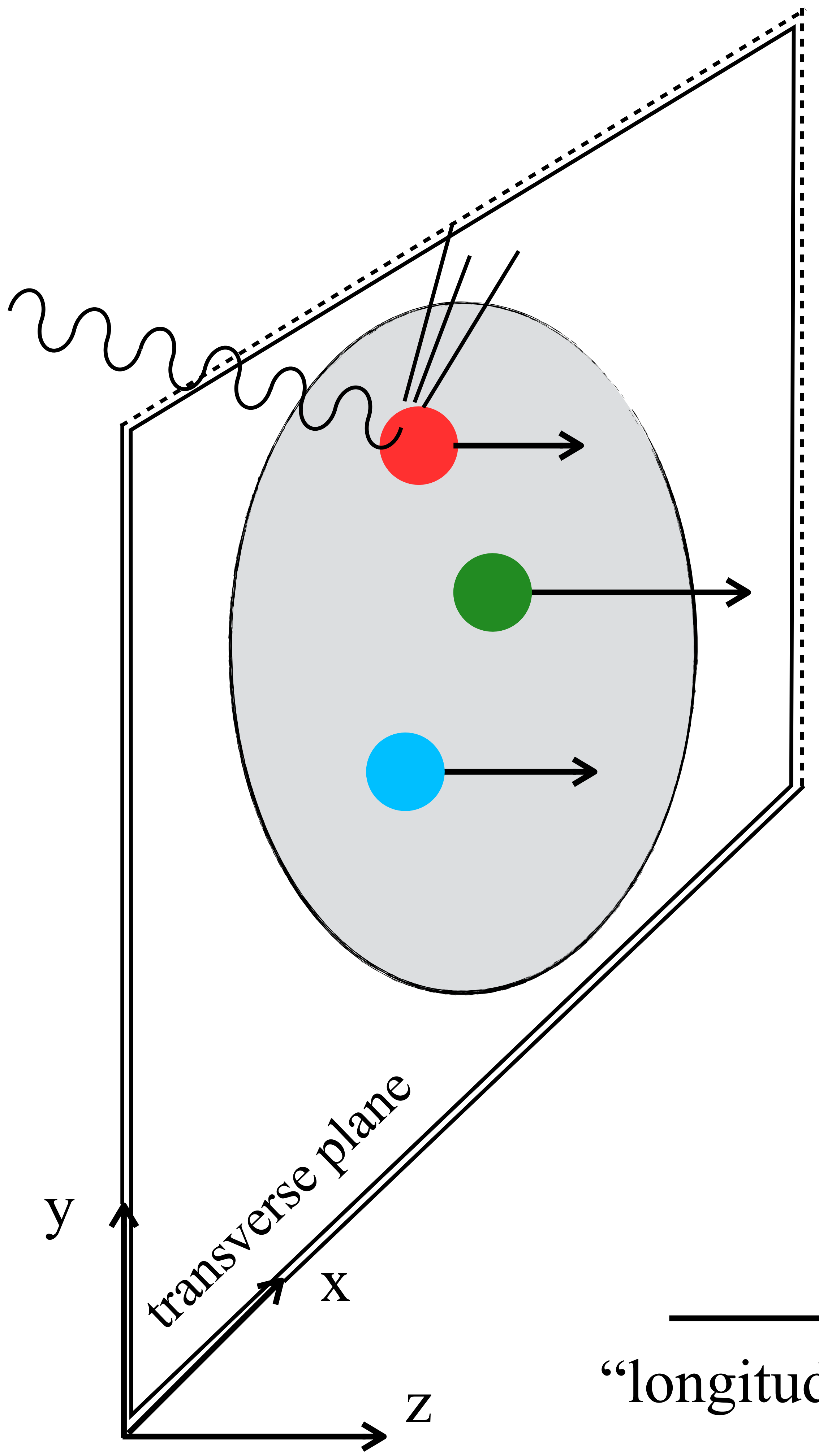
S. Bastami et al. JHEP 1906 (2019) 007:
"SIDIS in Wandzura-Wilczek-type approximation"



- Q-suppression, TSA-mixing
- Various different "twist" ingredients
- **Strong non-zero effect for h+, h− compatible with zero, clear z-dependence**

26 September 2022 B. Parsamyan 16

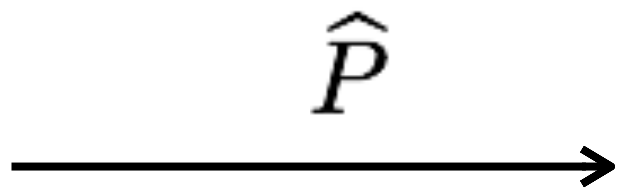
Introducing the transverse plane



deep-inelastic scattering with transverse plane - an infinitesimally thin disc

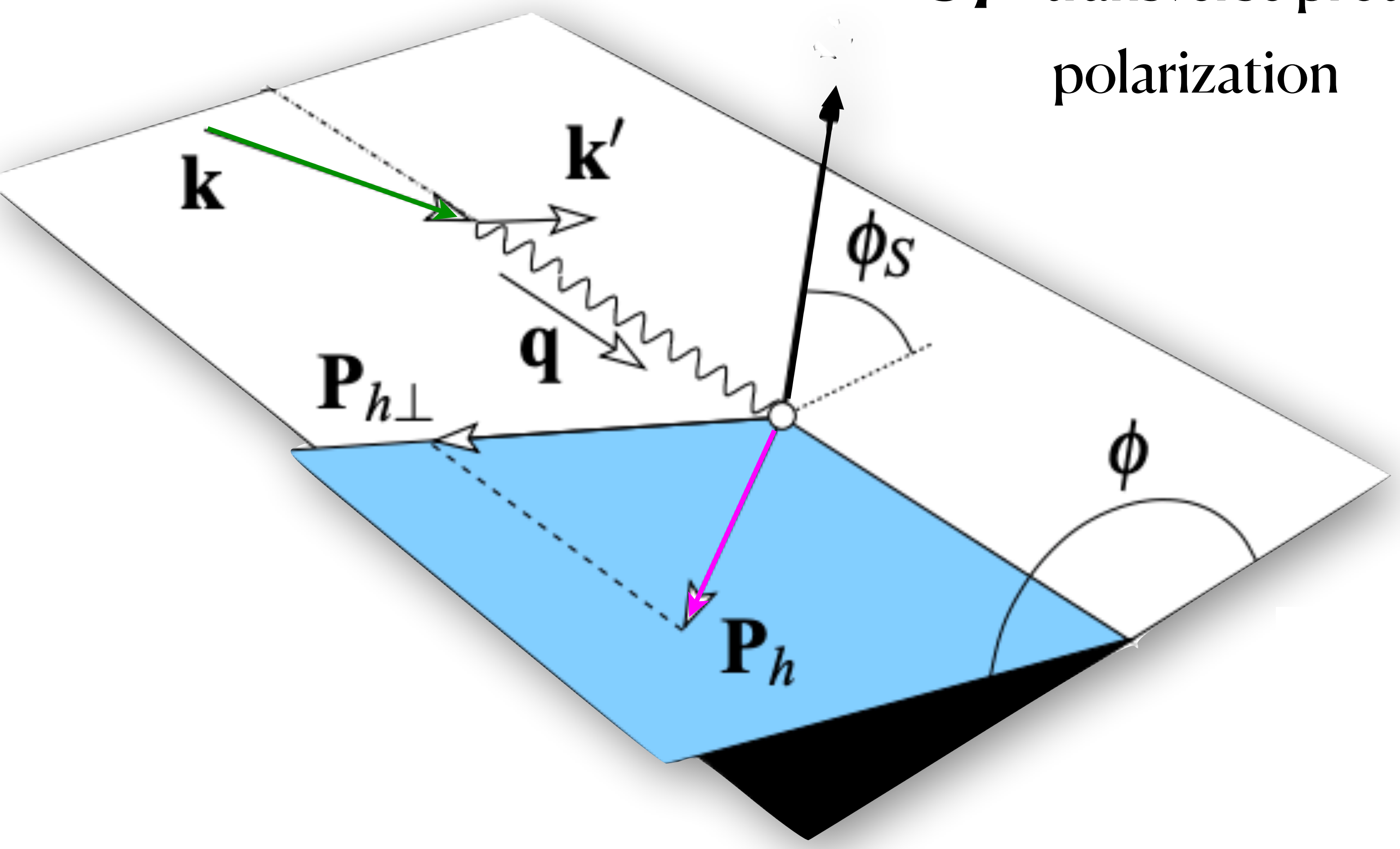
only longitudinal quark momenta $k_z = x|\vec{P}|$ with x-Bjorken

no transverse quark momenta $\vec{k_T} = (k_x, k_y) = (0, 0)$



“longitudinal” direction

SIDIS cross section on unpol, L-pol, or T-pol protons

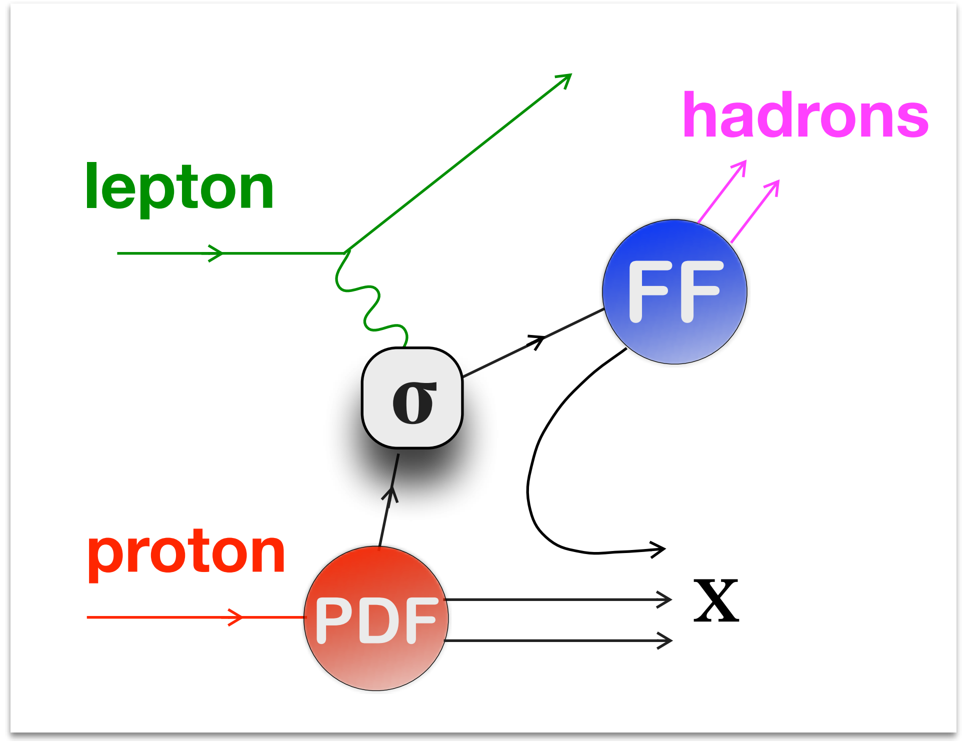


S_T = transverse proton polarization

"~ harmonic(ϕ, ϕ_S) · PDF ⊗ FF"

type of experimental observable:

$$A_{UT}(\phi) = \frac{1}{f S_T} \frac{N^{\uparrow}(\phi) - N^{\downarrow}(\phi)}{N^{\uparrow}(\phi) + N^{\downarrow}(\phi)}$$



Cahn-effect + BM ⊗ Collins

Worm-gear (Kotzinian-Mulders) ⊗ Collins

BM ⊗ Collins

$$\sigma(\phi, \phi_S) \equiv \frac{d^6\sigma}{dx\,dy\,dz\,d\phi\,d\phi_S\,dP_{hT}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\epsilon)} \left(1 + \frac{\gamma^2}{2x}\right)$$

no proton polarization

$$\Big\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\,\cos\phi\, F_{UU}^{\cos\phi} + \epsilon\cos(2\phi)\, F_{UU}^{\cos(2\phi)} + \lambda_e \left[\sqrt{2\epsilon(1-\epsilon)}\,\sin\phi\, F_{LU}^{\sin\phi}\right] +$$

longitudinal proton polarization

$$+ S_L \left[\sqrt{2\epsilon(1+\epsilon)}\,\sin\phi\, F_{UL}^{\sin\phi} + \epsilon\sin(2\phi)\, F_{UL}^{\sin(2\phi)}\right] + S_L\lambda_e \left[\sqrt{1-\epsilon^2}\, F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\,\cos\phi\, F_{LL}^{\cos\phi}\right]$$

transverse proton polarization

$$+ |S_T| \Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S)\, F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)\, F_{UT}^{\sin(3\phi-\phi_S)}$$

$$+ \sqrt{2\epsilon(1+\epsilon)}\,\sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\epsilon(1+\epsilon)}\,\sin(2\phi-\phi_S)\, F_{UT}^{\sin(2\phi-\phi_S)} \Big]$$

$$+ |S_T|\lambda_e \left[\sqrt{1-\epsilon^2}\,\cos(\phi-\phi_S)\, F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\,\cos\phi_S\, F_{LT}^{\cos\phi_S} + \sqrt{2\epsilon(1-\epsilon)}\,\cos(2\phi-\phi_S)\, F_{LT}^{\cos(2\phi-\phi_S)}\right] \Big\},$$

Sivers ⊗ D1

Worm-gear ⊗ D1

Transversity ⊗ Collins

Pretzelosity ⊗ Collins

- $F_{XY[Z]}$ = structure function. X=beam, Y= target polarization, [Z= virtual-photon polarization]. X, Y ∈ {U, L, T}. λ_e = helicity of the lepton beam. S_L and S_T = longitudinal and transverse target polarization. ε = ratio of longitudinal and transverse photon fluxes

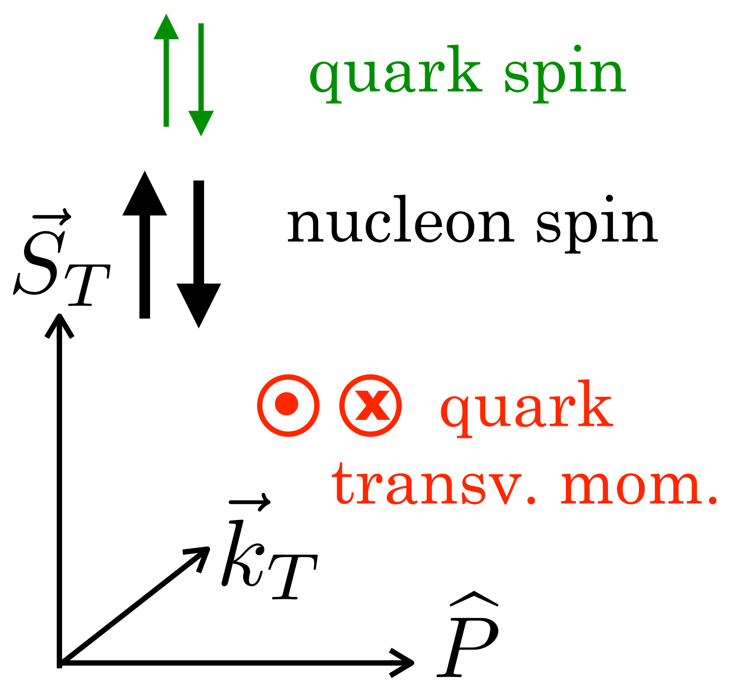
[Bacchetta, Diehl, Klaus Goeke, Metz, Mulders, Schlegel, JHEP 02 (2007) 093]

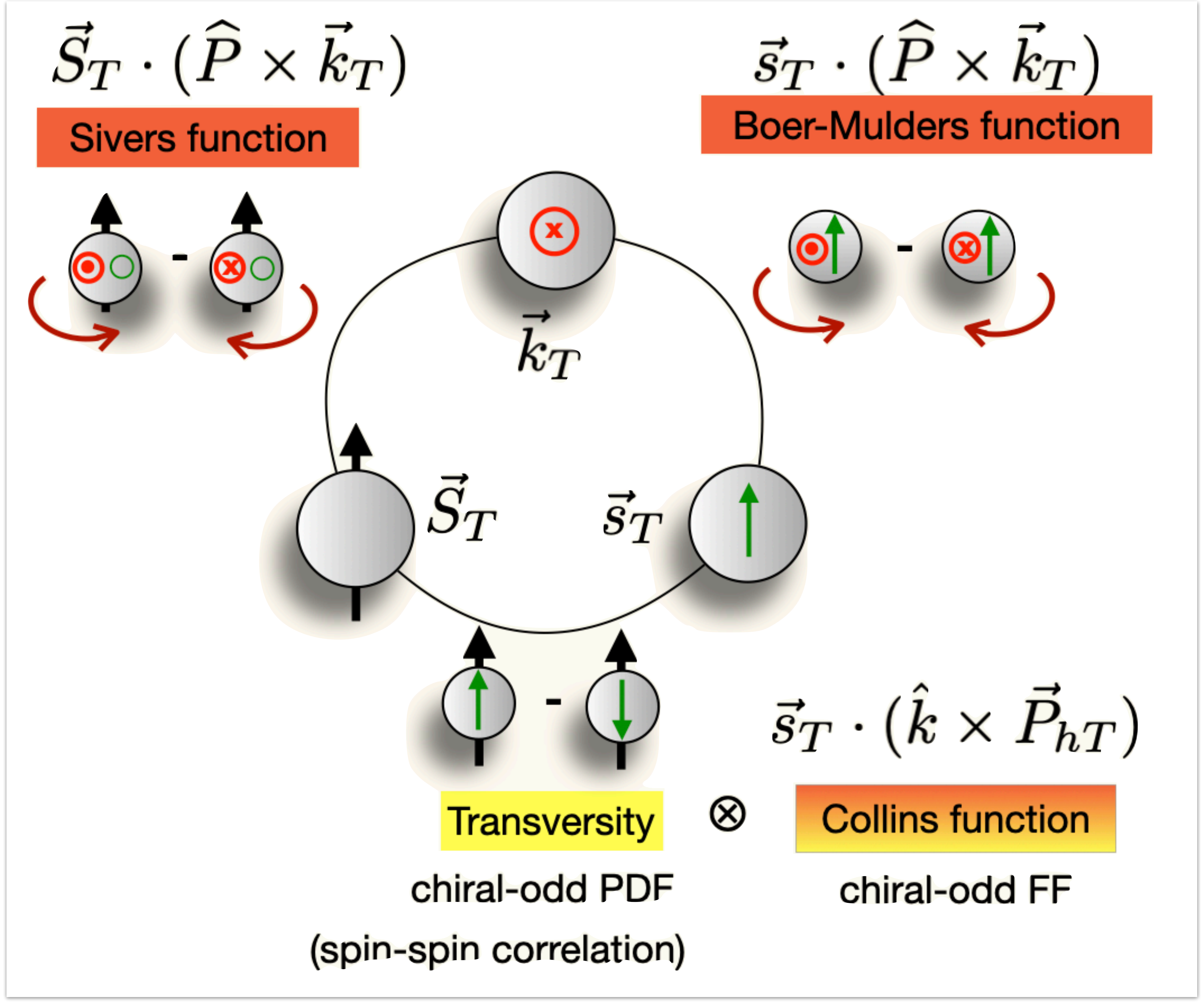
$\vec{S} \cdot (\vec{p_1} \times \vec{p_2})$

Spin-orbit correlations in the proton

Non-zero TMDs describing the strength of **spin-orbit correlations** indicate parton orbital angular momentum (OAM).

No quantitative relation between TMDs & OAM identified yet.

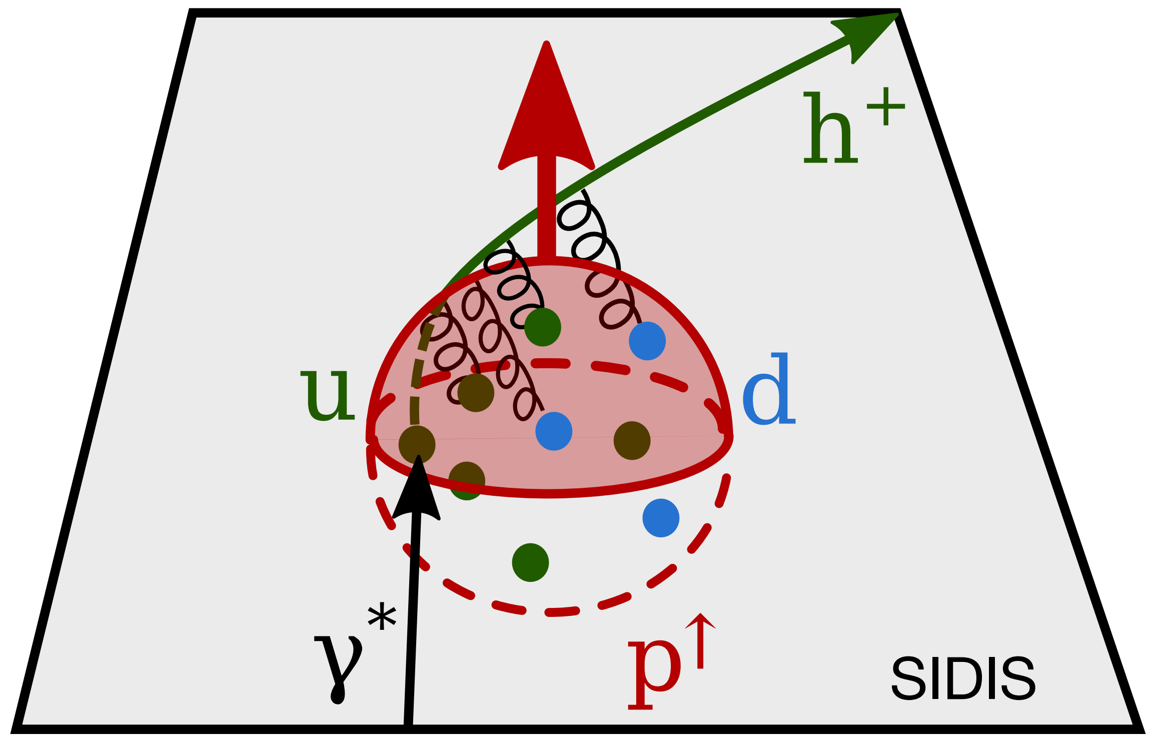




"Collinear analysis"

Collins effect: fragmentation of a transversely polarized parton into a final-state hadron

Sivers effect: correlations between the nucleon transverse spin direction & parton transverse momentum in the polarized nucleon



The Sivers function was originally thought to vanish (*).

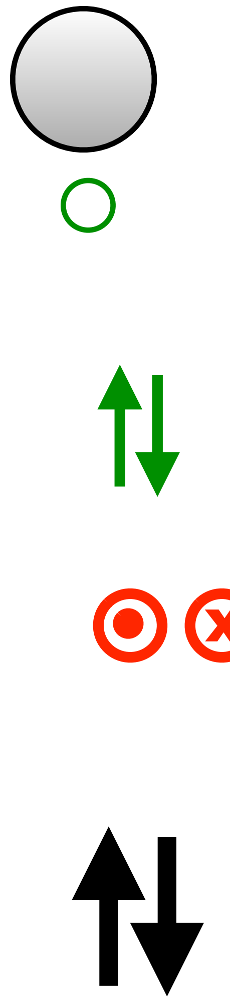
A nonzero Sivers function was then shown to be allowed due to **QCD final state interactions** (soft gluon exchange) in SIDIS between the outgoing quark and the target remnant (**).

(*) [J. C. Collins, Nucl. Phys. B396, 161 (1993)]
(**) [S. J. Brodsky et al., Phys. Lett. B530, 99 (2002)]

sketch courtesy Jan Matoušek / COMPASS

bin from Cracow proceedings

N \ Q	U	L	T
U	f_1 number density		$h_1^\perp$ Boer-Mulders
L		g_1 helicity	$h_{1L}^\perp$ worm-gear
T	$f_{1T}^\perp$ Sivers	g_{1T} worm-gear	h_1 transversity / $h_{1T}^\perp$ pretzelosity



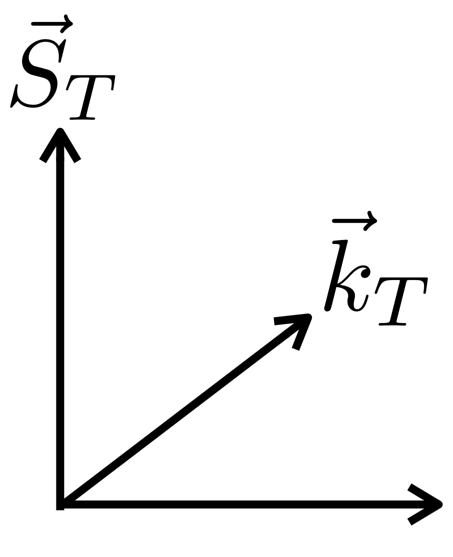
nucleon (**N**)

unpolarized parton (**Q**)

quark spin

parton transverse momentum

nucleon spin



(longitudinal direction = movement of nucleon)

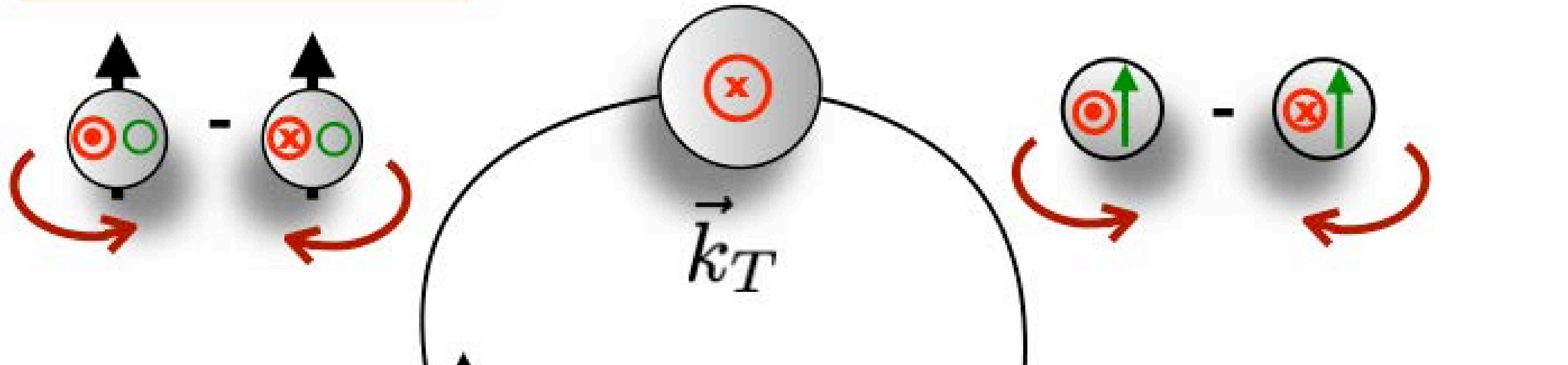
TMDs surviving integration over k_T. "Collinear analysis"

Naive time-reversal odd TMDs describing strength of **spin-orbit correlations.**

chiral odd TMDs
Exist because of **chiral symmetry breaking** of the QCD nucleon wave function

$\vec{S}_T \cdot (\widehat{P} \times \vec{k}_T)$ Sivers function

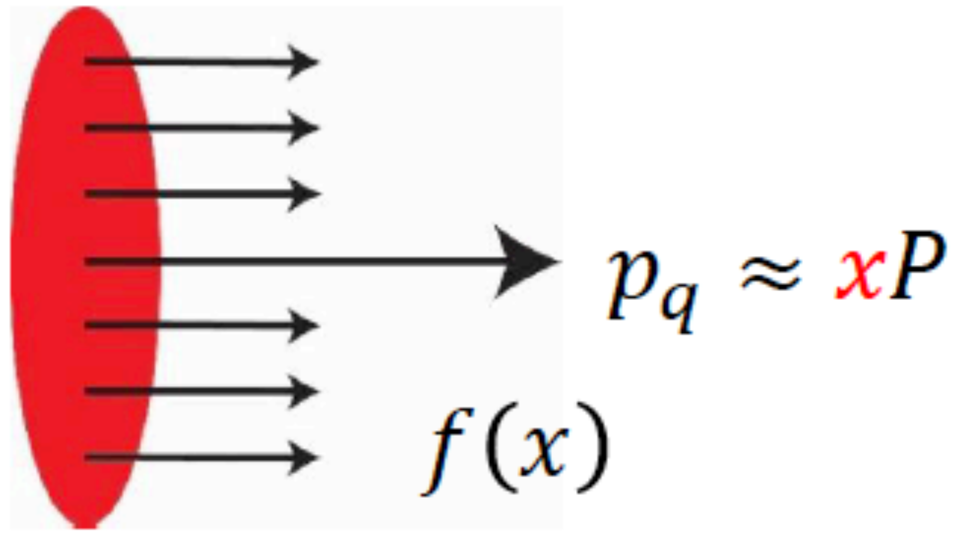
$\vec{s}_T \cdot (\widehat{P} \times \vec{k}_T)$ Boer-Mulders function



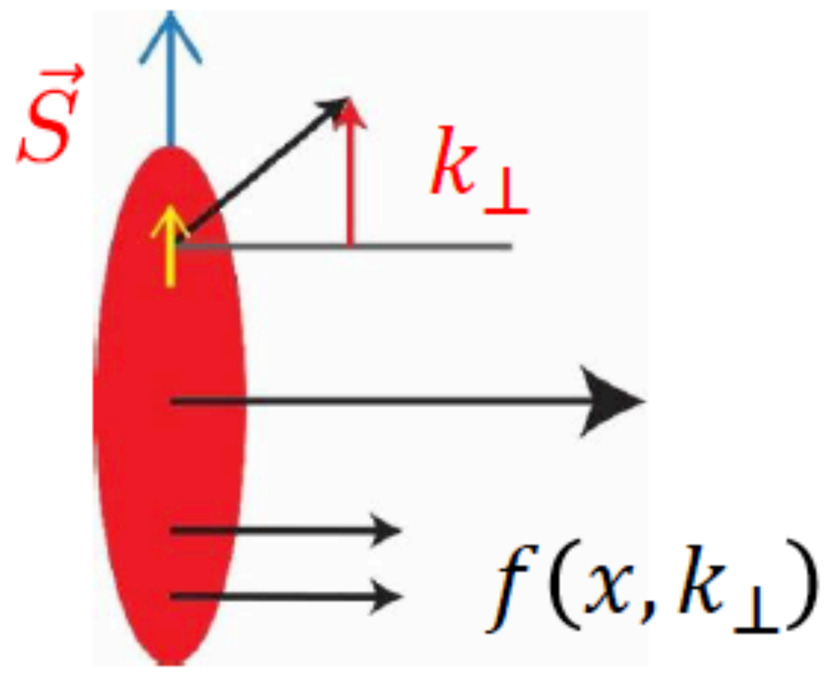
Bressan talk for unpol

Unpolarised Transverse Momentum dependent PDFs

- When we consider the transverse momentum of the quark in the calculation of the cross section Transverse Momentum Dependent parton distribution (TMDs)



Longitudinal motion only



Longitudinal + transverse motion

- The unpolarised number density of the quarks gains a dependence from the intrinsic transverse momentum $k_\perp$

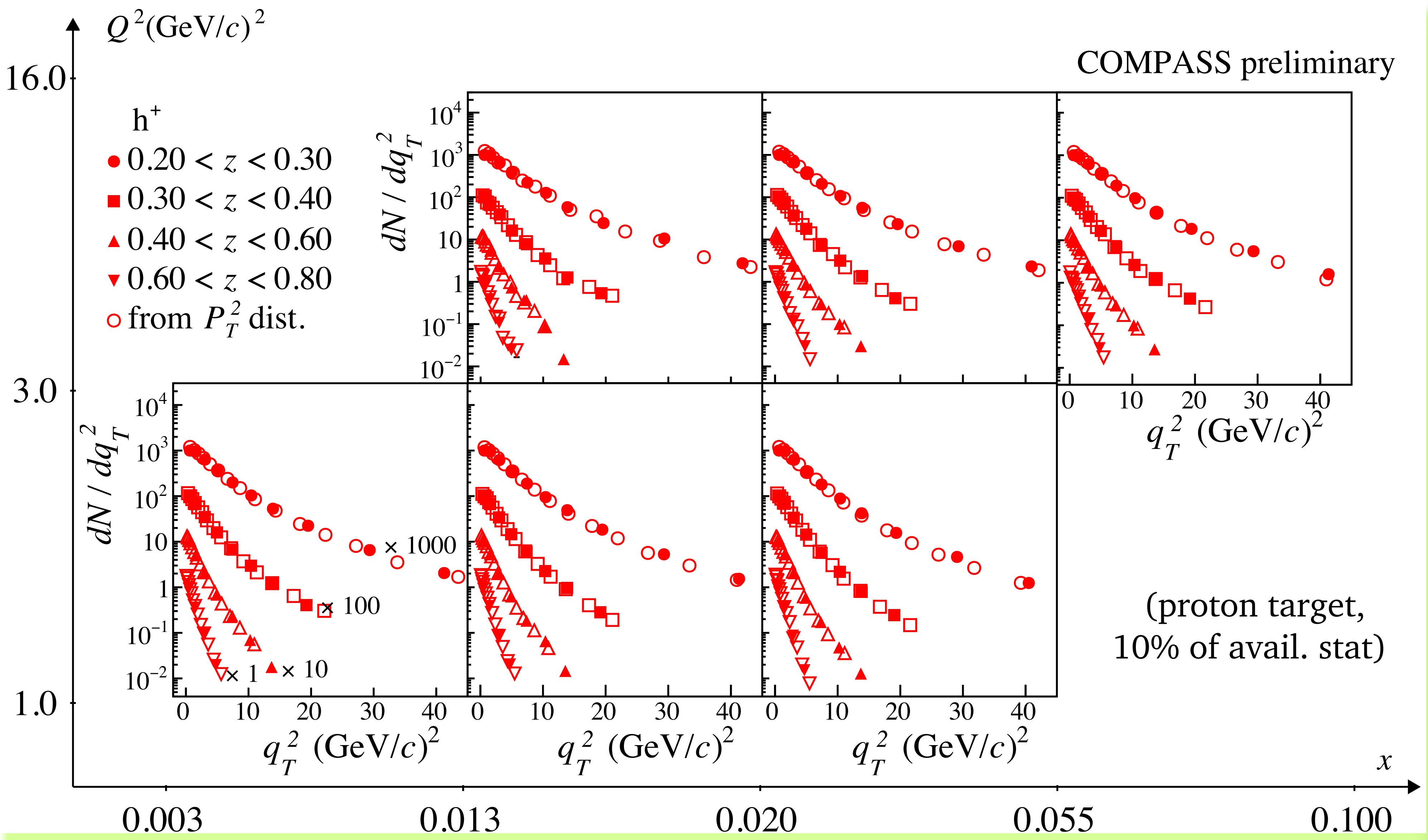
$$f_1^q(x, k_\perp)$$

- New parton densities arise: the Boer-Mulders functions $h_1^{\perp,q}(x, k_\perp)$, describing the correlation between the intrinsic quark transverse momentum and the spin of the quark in an unpolarised nucleon

$$f_{q\uparrow}(x, k_\perp, \vec{s}) = f_1^q(x, k_\perp) - \frac{1}{M} h_1^{\perp,q}(x, k_\perp)\vec{s} \cdot (\hat{p} \times \vec{k}_\perp)$$

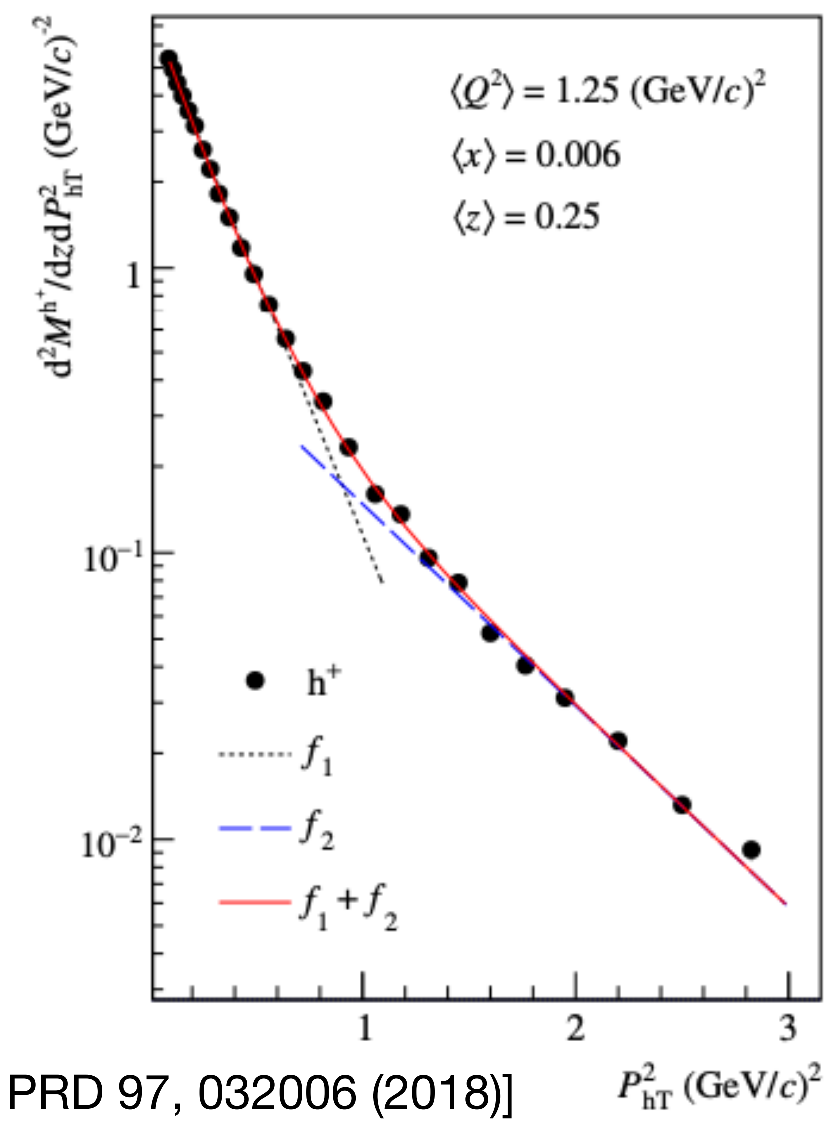
TMD effects in unpolarized SIDIS

New prelim COMPASS p_T dependences & azimuthal asymmetries



see talk by A. Moretti, Thursday, 12:35

- p_T distributions provide complementary information to cos(ϕ) Boer-Mulders & Cahn and cos(2ϕ) Boer-Mulders azimuthal asymmetries (not shown)



[COMPASS PRD 97, 032006 (2018)]

Modern multi-dimensional binnings in p_T, Q^2, x, z, W allow for TMD evolution studies & comparison between experiments

New data will help to clarify the double-Gauss structures in p_T

- Real $\langle k_T^2 \rangle$ underestimated
- Importance of vector-meson decays (CLAS12)

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

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

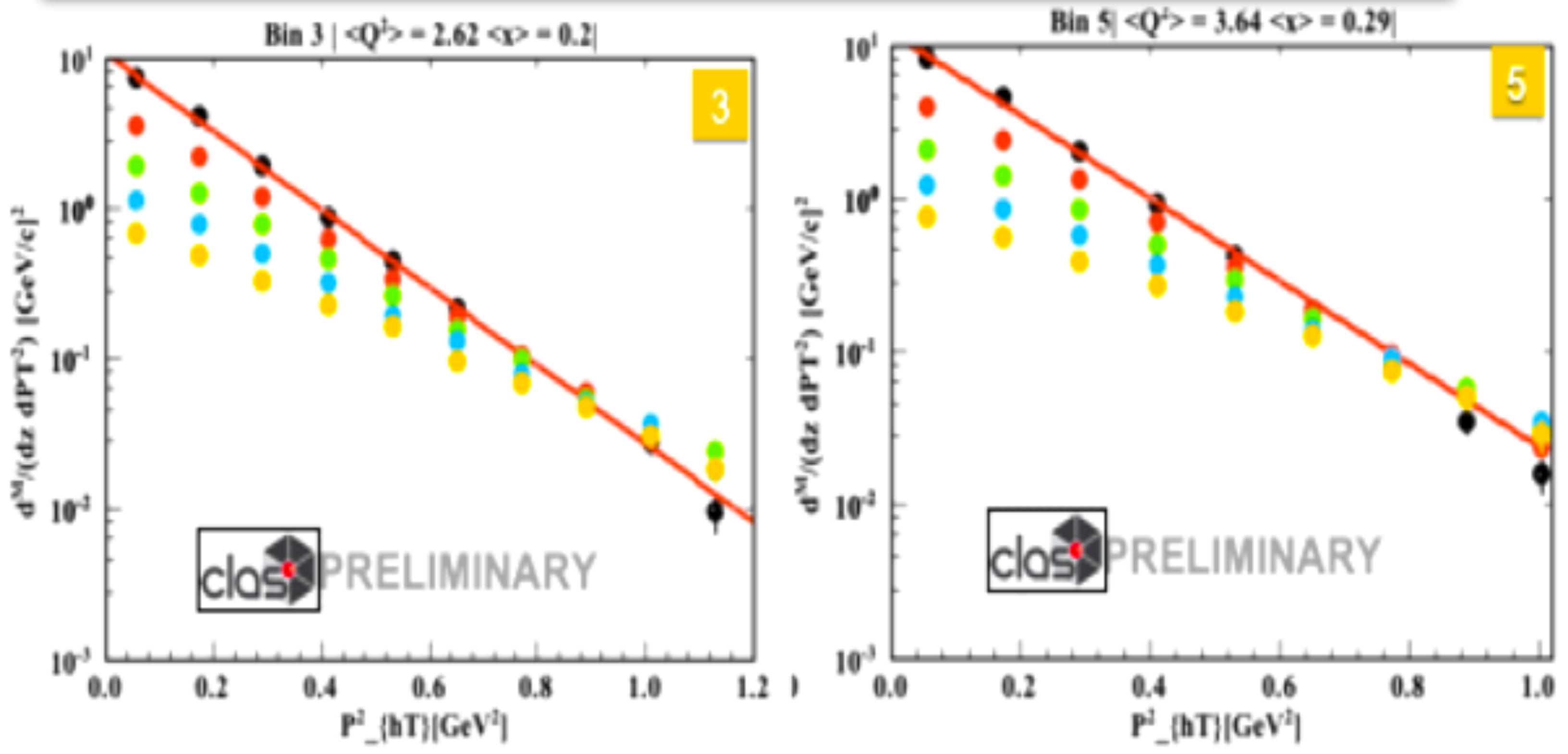
Towards a more complete mapping of the SIDIS landscape - current vs. target fragmentation

Phenomenological approximation for q_T works well for new COMPASS data.

$q_T = P_T/z$ to validate region of TMD formalism

[Boglione *et al.*, JHEP10 (2019) 122]

Prelim CLAS12 pion multiplicities



courtesy G. Angelini / H. Avakian

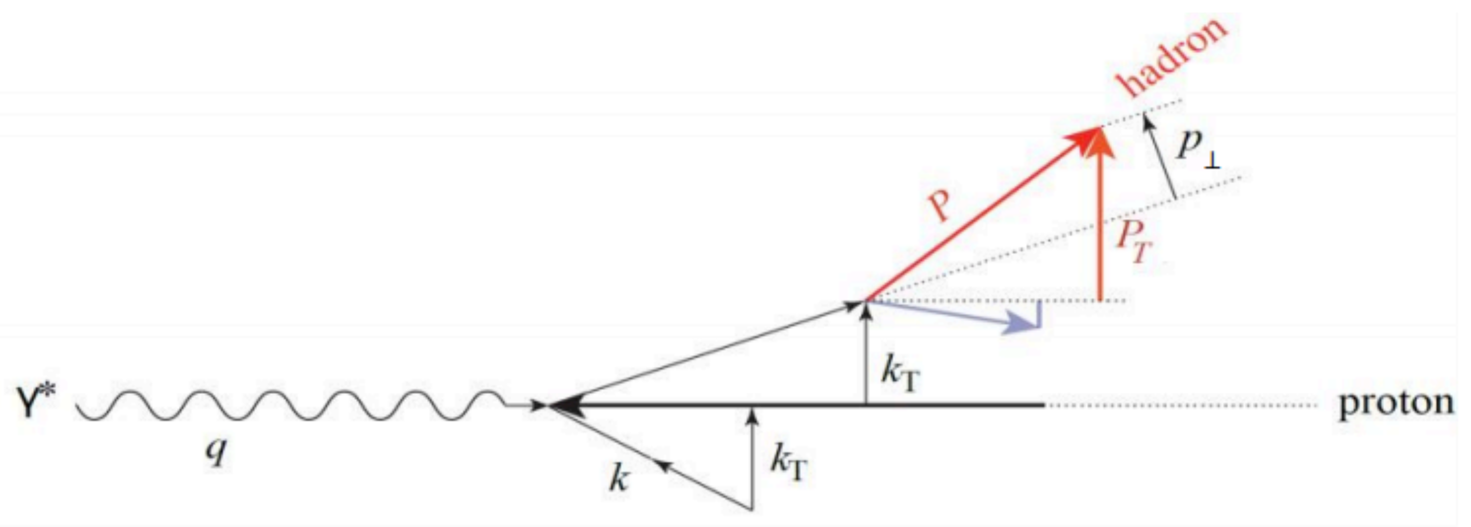
π^+ multiplicities in example (x, Q^2) bins, for various z

- 0.2<z<0.3
- 0.3<z<0.4
- 0.4<z<0.5
- 0.5<z<0.6
- 0.6<z<0.7

quark-to-hadron FF

$$\frac{dM^h(x, Q^2, z)}{dz} = \frac{\sum_a e_a^2 f_a(x, Q^2) D_a^h(z, Q^2)}{\sum_a e_a^2 f_a(x, Q^2)}$$

quark PDF



h+ ≈ π+ dominated by u-quark scattering:

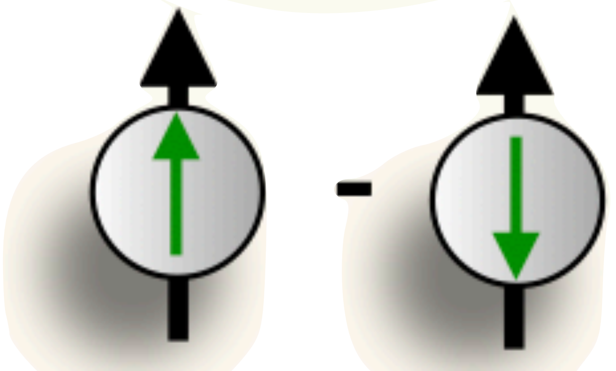
$$2\langle \sin(\phi - \phi_S)\rangle_{UT}$$

$$\simeq -f_{1T}^{\perp}(x, p_T^2) \otimes D_1^{u\to\pi^+}(z, k_T^2)$$

PDF **FF**

u-quark Sivers function < 0

d-quark Sivers function > 0
(cancellation effects for π-)



$\vec{s}_T \cdot (\hat{k} \times \vec{P}_{hT})$

Collins asymmetry ~ Transversity ⊗ Collins function

chiral-odd PDF chiral-odd FF

TMD PDF (x, k_T, Q^2) FF (z, κ_T, Q^2)