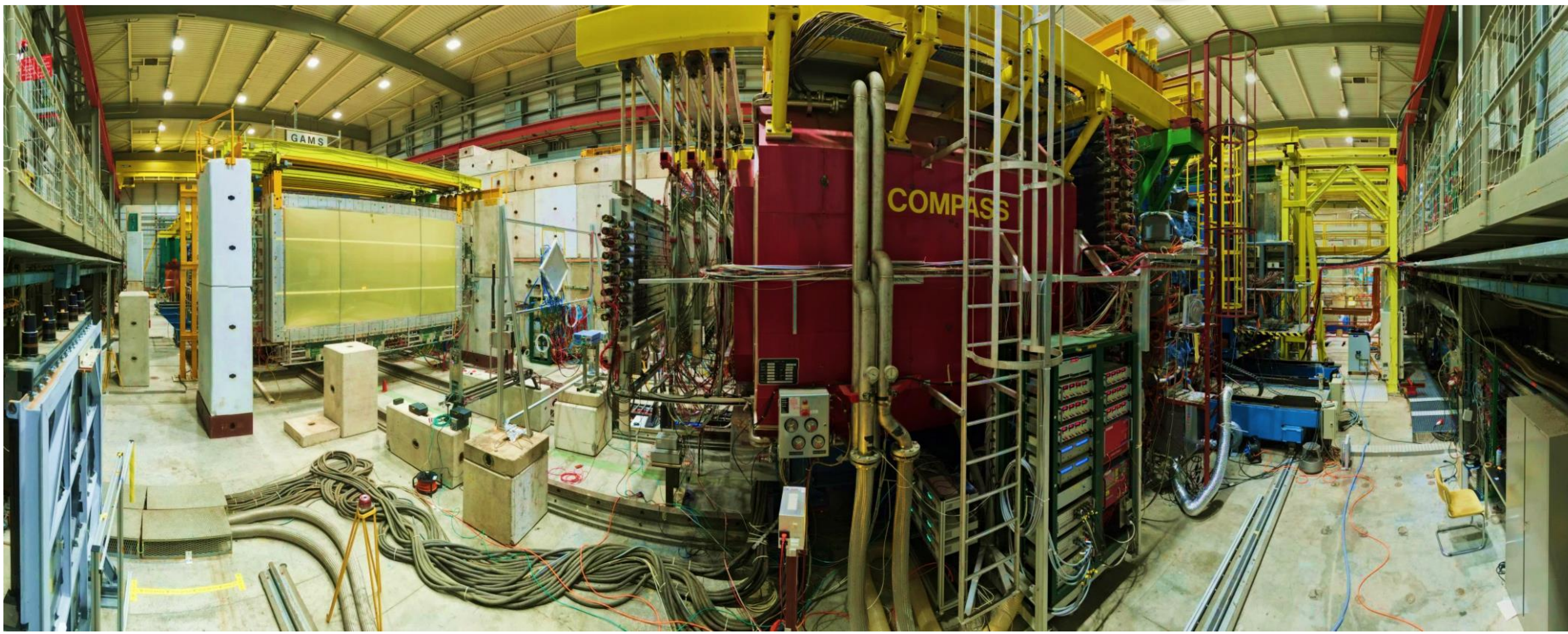
The relevance of multidimensional binning in SIDIS measurements: COMPASS experience

BAKUR PARSAMYAN

AANL, INFN section of Turin and CERN

on behalf of the COMPASS Collaboration

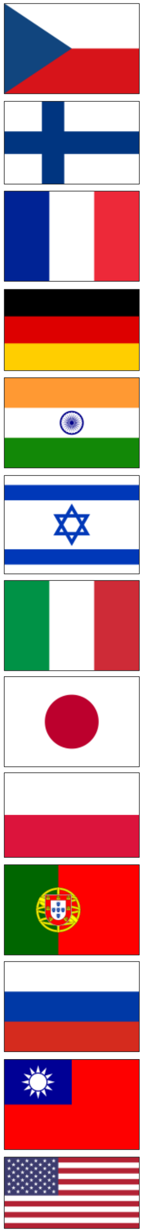


"Science at the Luminosity Frontier: Jefferson Lab at 22 GeV workshop"
23-26 January 2022, JLab, US

Introductory message

- For a better and more complex understanding of the TMD-spin-phenomena, it is important to carry out the extractions, analyses and various corrections in a multi-D approach
- It is also important to carefully confront experimental data from different experiments
- Different complex analysis techniques, Monte-Carlo simulations and various corrections (acceptance, VMs, radiative corrections) are being employed by different experimental collaborations
  - Closer collaboration between different experimental groups would be very beneficial for the field in general
  - Sharing the tools (MC, generators, analysis techniques), preliminary results, doing cross-analyses, etc.
- Close collaboration between experimentalists on one side and phenomenologists and theorists on the other would also be very beneficial
  - Flexibility in adapting on the analysis side (in a timely manner) the choice of the observables, phase-space limitations, etc.
  - Ideally a close collaborative work can be organized

COMPASS collaboration



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

25 institutions from 13 countries
– nearly 200 physicists

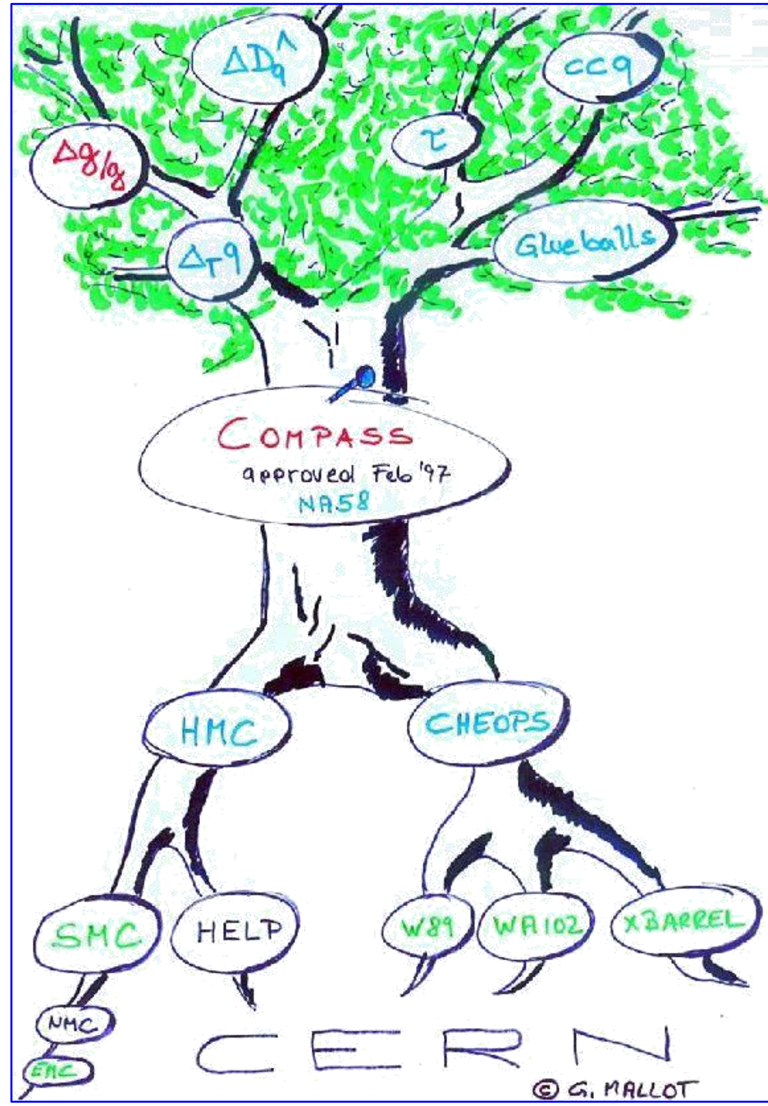
- **CERN SPS north area**
- **Fixed target experiment**
- **Approved in 1997 (25 years)**
- **Taking data since 2002 (20 years)**

International Workshop on Hadron Structure and Spectroscopy

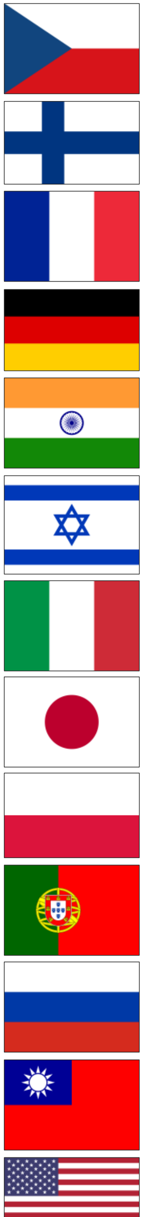
IWHSS-2022 workshop (anniversary edition)

CERN Globe, August 29-31, 2022

https://indico.cern.ch/e/IWHSS-2022



COMPASS collaboration



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

25 institutions from 13 countries
– nearly 200 physicists

- **CERN SPS north area**
- **Fixed target experiment**
- **Approved in 1997 (25 years)**
- **Taking data since 2002 (20 years)**

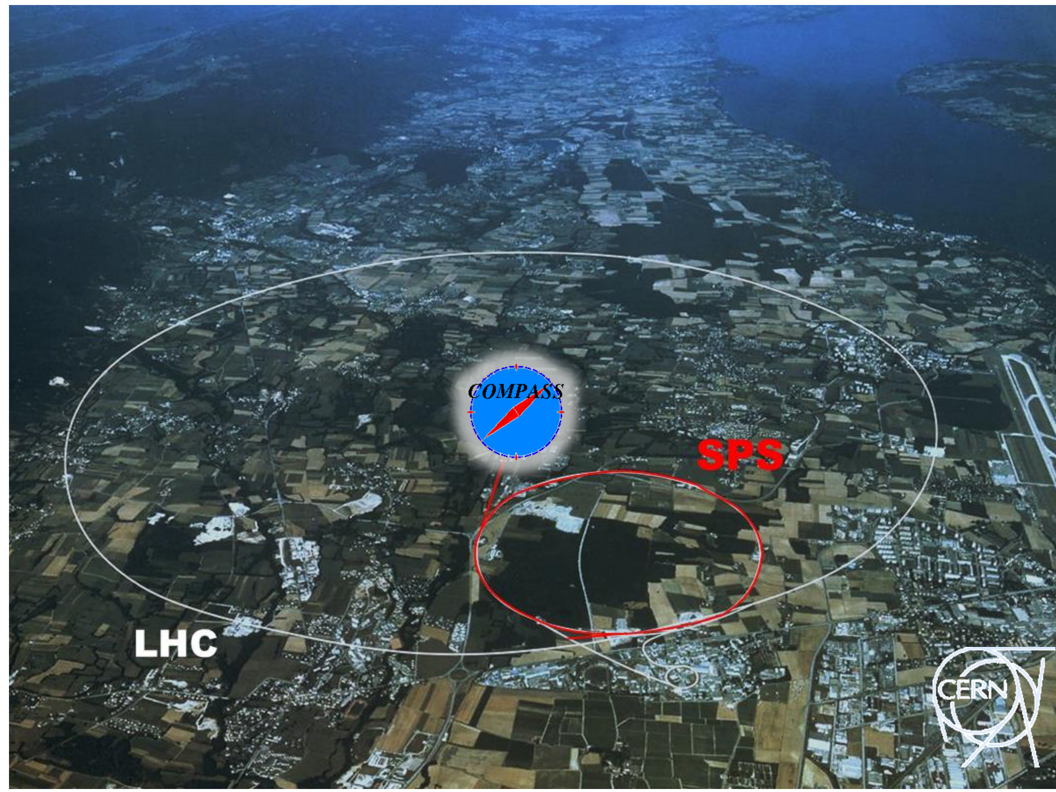
Wide physics program

COMPASS-I

- **Data taking 2002-2011**
- **Muon and hadron beams**
- **Nucleon spin structure**
- **Spectroscopy**

COMPASS-II

- **Data taking 2012-2022**
- **Primakoff**
- **DVCS (GPD+SIDIS)**
- **Polarized Drell-Yan**
- **Transverse deuteron SIDIS 2022**



COMPASS web page: http://wwwcompass.cern.ch

COMPASS data taking campaigns

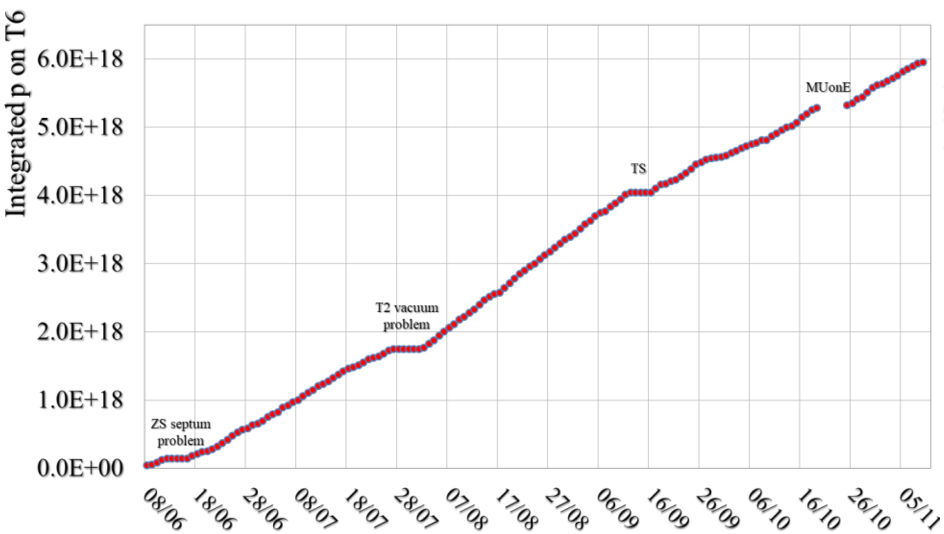
<table>
<tr><th>Beam</th><th>Target</th><th>year</th><th>Physics programme</th></tr>
<tr><td rowspan="3">μ^+</td><td rowspan="2">Polarized deuteron (^{6}LiD)</td><td>2002
2003
2004</td><td>80% Longitudinal | 20% Transverse SIDIS</td></tr>
<tr><td>2006</td><td>Longitudinal SIDIS</td></tr>
<tr><td>Polarized proton (NH_3)</td><td>2007</td><td>50% Longitudinal | 50% Transverse SIDIS</td></tr>
<tr><td>π | K | p</td><td>LH_2, Ni, Pb, W</td><td>2008
2009</td><td>Spectroscopy</td></tr>
<tr><td rowspan="2">μ^+</td><td rowspan="2">Polarized proton (NH_3)</td><td>2010</td><td>Transverse SIDIS</td></tr>
<tr><td>2011</td><td>Longitudinal SIDIS</td></tr>
<tr><td>π | K | p</td><td>Ni</td><td>2012</td><td>Primakoff</td></tr>
<tr><td>$\mu^\pm$</td><td>LH_2</td><td>2012</td><td>Pilot DVCS & HEMP & unpolarized SIDIS</td></tr>
<tr><td rowspan="2">π^-</td><td rowspan="2">Polarized proton (NH_3)</td><td>2014</td><td>Pilot Drell-Yan</td></tr>
<tr><td>2015
2018</td><td>Transverse Drell-Yan</td></tr>
<tr><td>$\mu^\pm$</td><td>LH_2</td><td>2016
2017</td><td>DVCS & HEMP & unpolarized SIDIS</td></tr>
<tr><td>μ^+</td><td>Polarized deuteron (^{6}LiD)</td><td>2021
2022</td><td>Transverse SIDIS</td></tr>
</table>

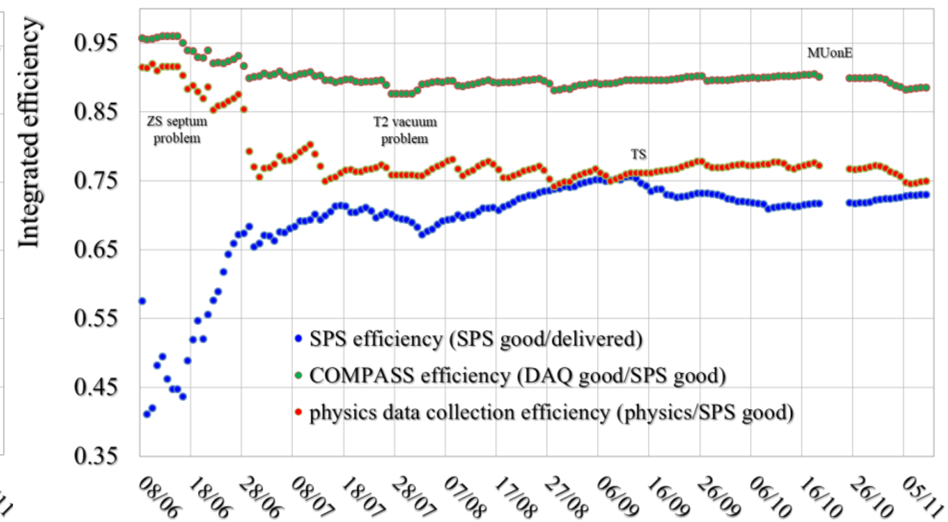
COMPASS data taking campaigns

Beam	Target	year	Physics programme
μ^+	Polarized deuteron (^{6}LiD)	2002 2003 2004	80% Longitudinal | 20% Transverse SIDIS

- Total number of protons delivered on T6: ~5.95×10^{18} (98%) in about 150 days

SPS efficiency: ~ 73%
Spectrometer efficiency: ~ 90%
Physics data collection efficiency: ~ 75%





Beam	Target	year	Physics programme
μ^+	Polarized deuteron (^{6}LiD)	2021 2022	Transverse SIDIS

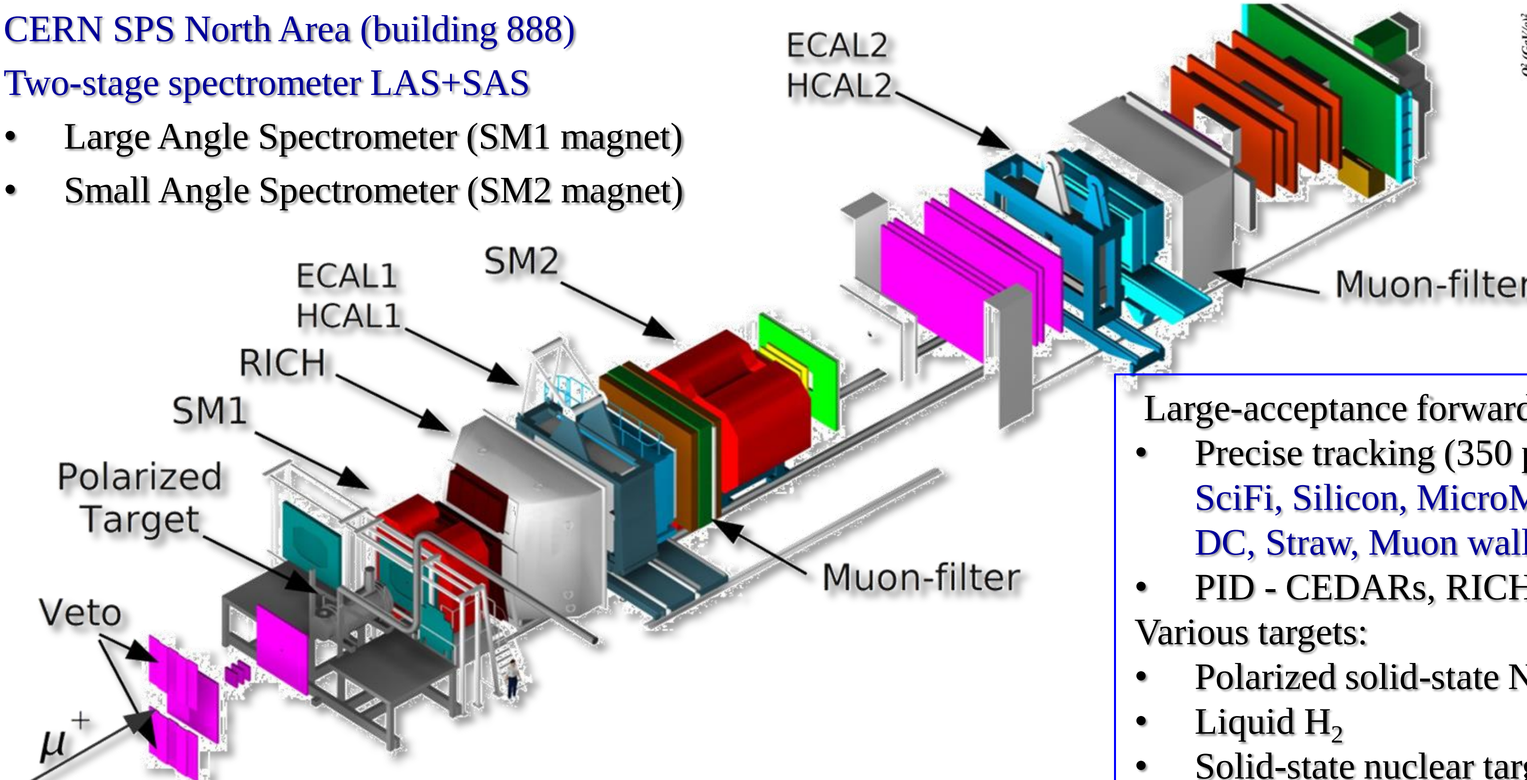
COMPASS experimental setup

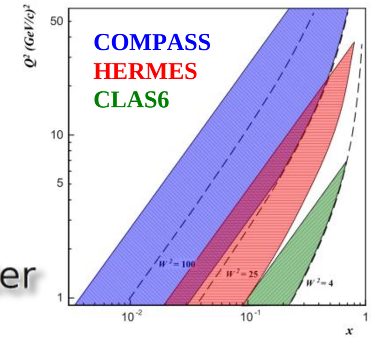
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)





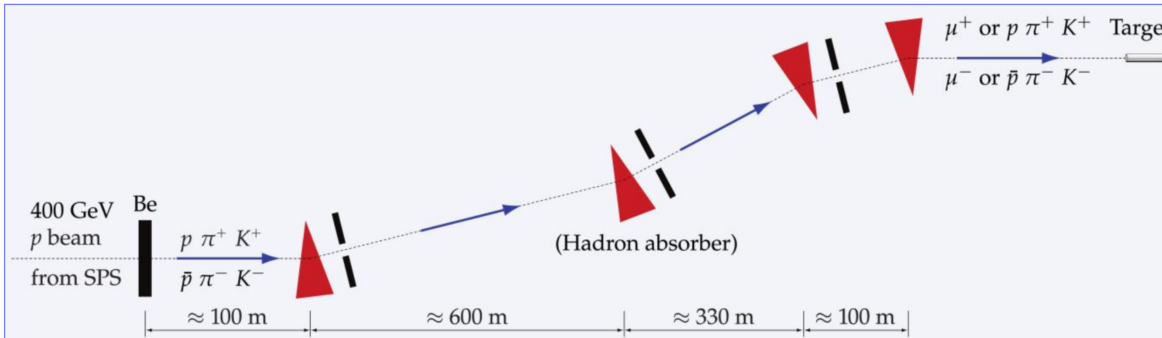
Large-acceptance forward spectrometer

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

Various targets:

- Polarized solid-state NH_3 or ^6LiD
- Liquid H_2
- Solid-state nuclear targets (e.g. Ni, W, Pb)

- Primary beam - 400 GeV p from SPS
  - impinging on Be production target (T6)
- 190 GeV secondary hadron beams
  - h^- beam: 97% π^-, 2% K^-, 1% p
  - h^+ beam: 75% p, 24% π^+, 1% K^+
- 160 GeV tertiary muon beams
  - $\mu^\pm$ longitudinally polarized



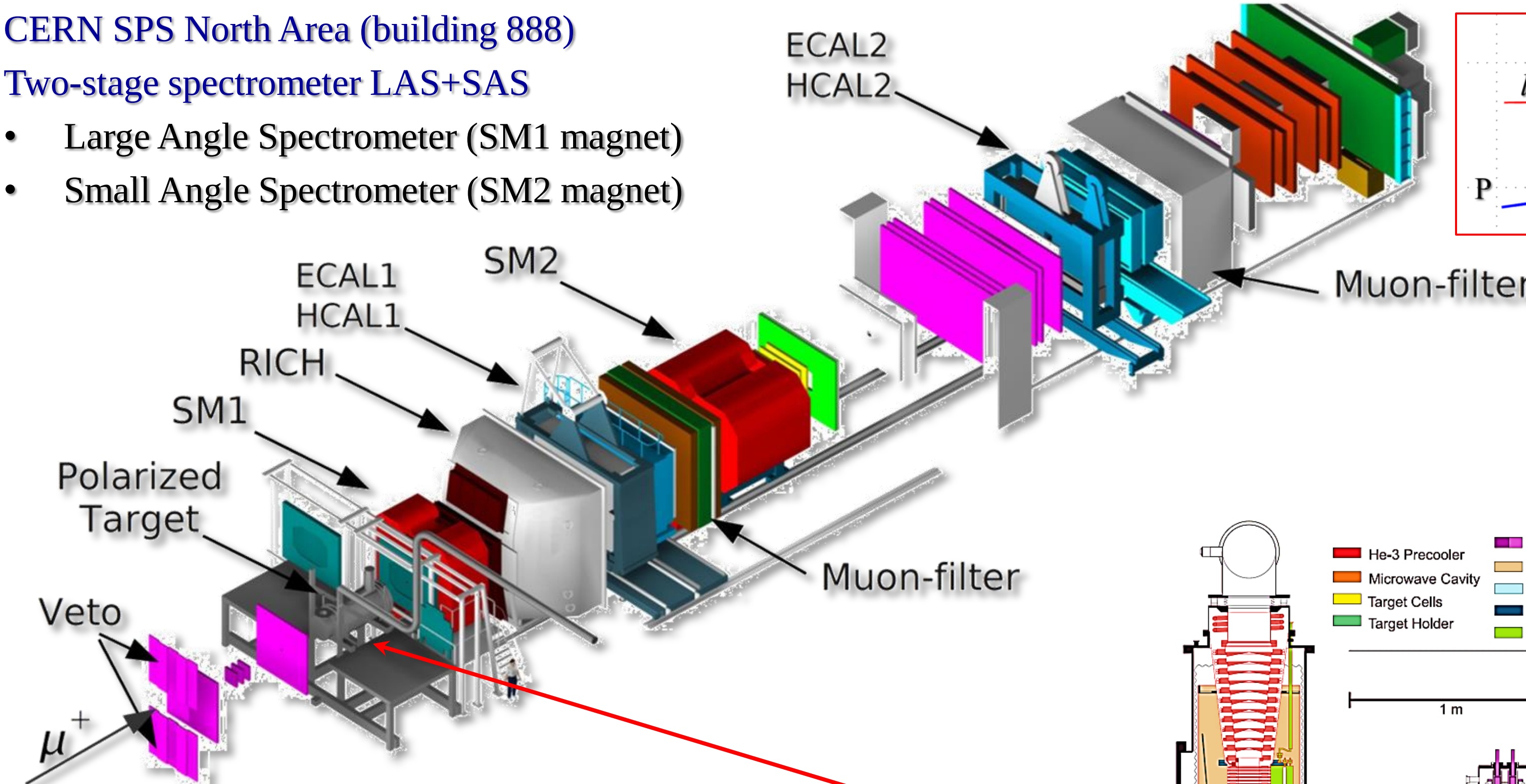
COMPASS experimental setup: Phase II (SIDIS programme)

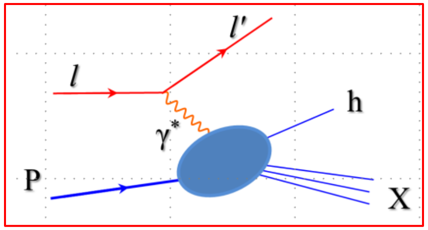
COmmon Muon Proton Apparatus for Structure and Spectroscopy

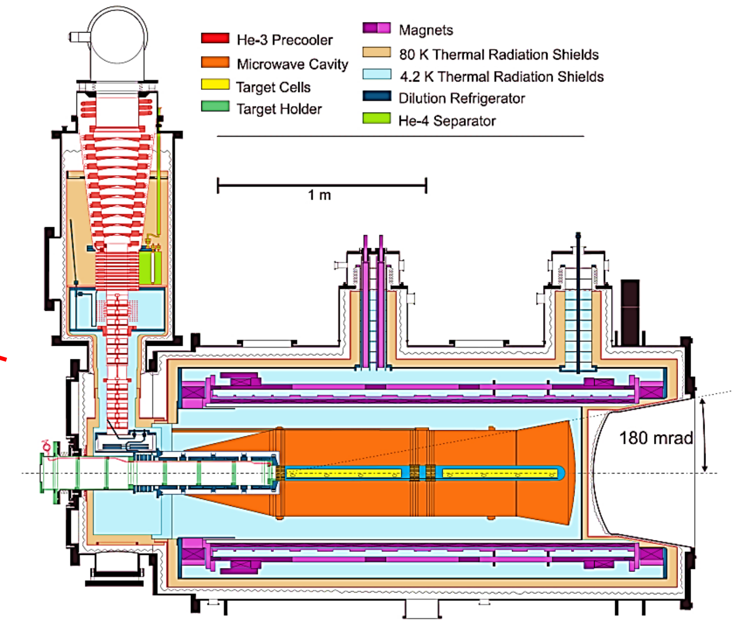
CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)







- Primary beam - 400 GeV p from SPS
  - impinging on Be production target (T6)
- 190 GeV secondary hadron beams
  - h⁻ beam: 97% π^-, 2% K^-, 1% p
  - h⁺ beam: 75% p, 24% π^+, 1% K^+
- 160 GeV tertiary muon beams
  - μ^+ longitudinally polarized

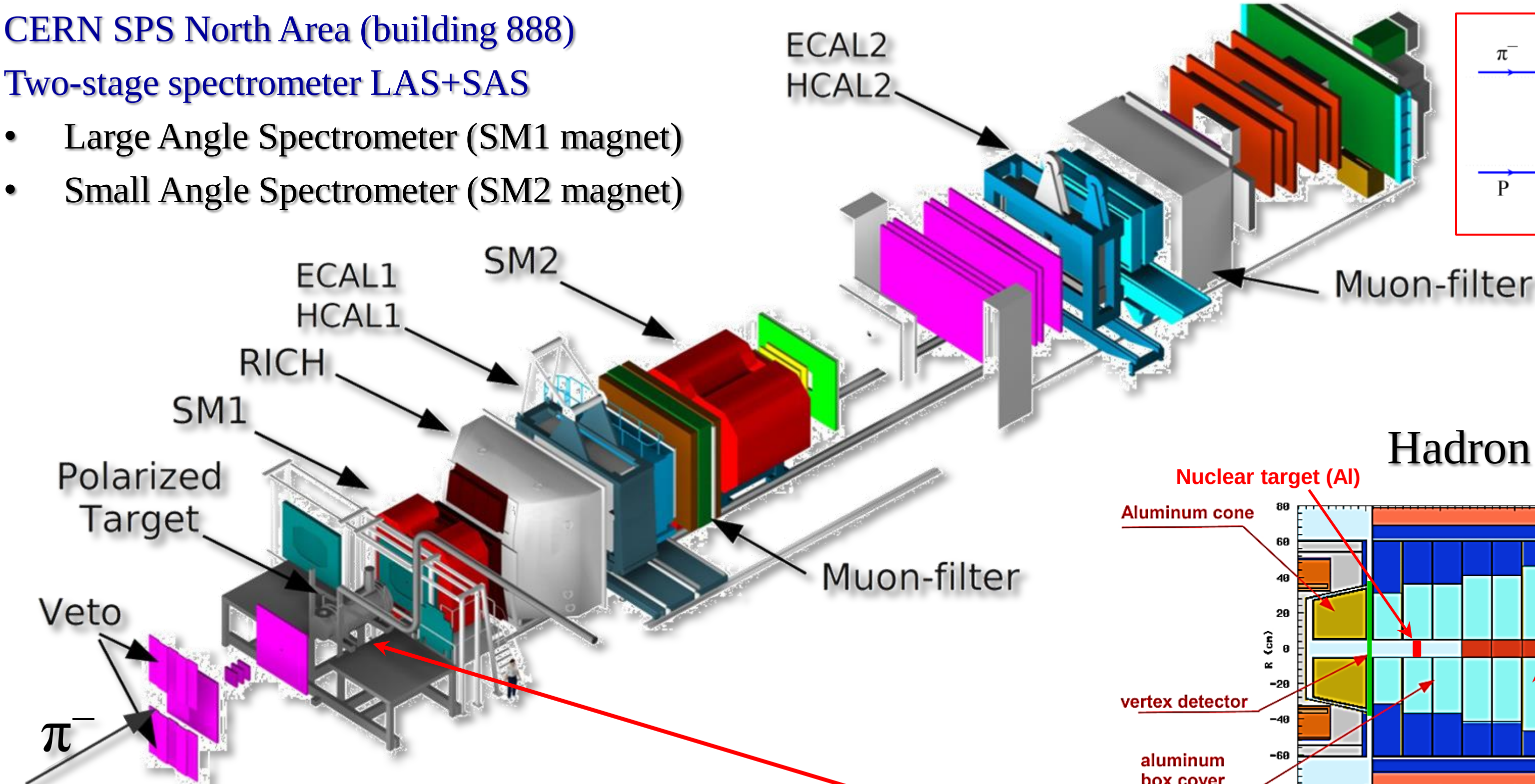
COMPASS experimental setup: Phase II (DY programme)

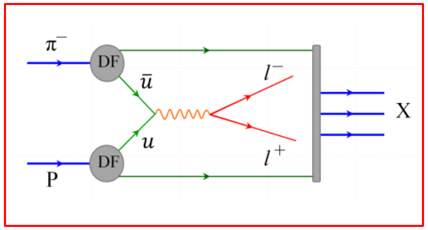
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

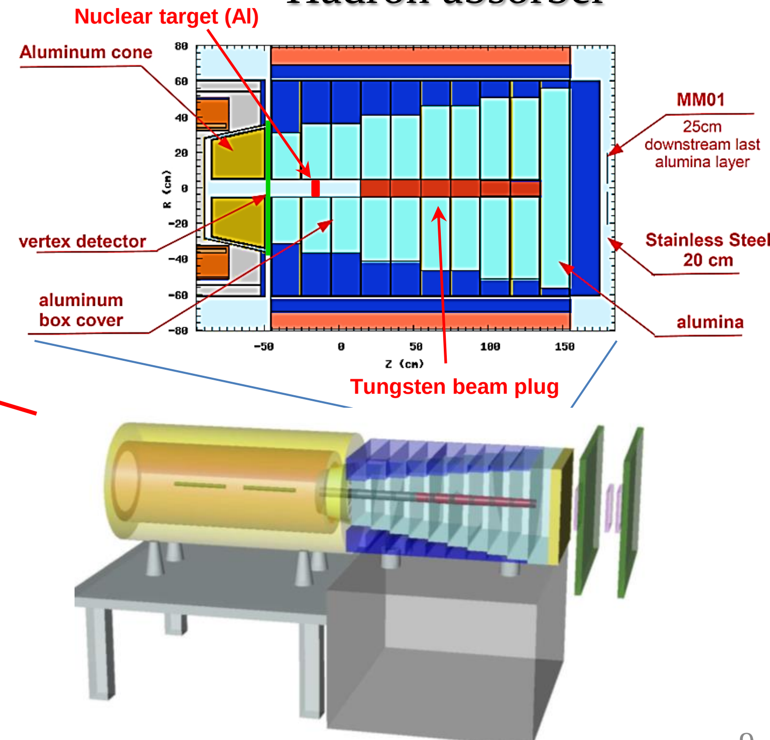
Two-stage spectrometer LAS+SAS

- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)





Hadron absorber



- Primary beam - 400 GeV p from SPS
  - impinging on Be production target (T6)
- 190 GeV secondary hadron beams
  - h⁻ beam: 97% π^-, 2% K^-, 1% p
  - h⁺ beam: 75% p, 24% π^+, 1% K^+
- 160 GeV tertiary muon beams
  - $\mu^\pm$ longitudinally polarized

The COMPASS Experiment at the CERN SPS

Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

Increasing resolution scale (momentum transfer)

Nucleon structure

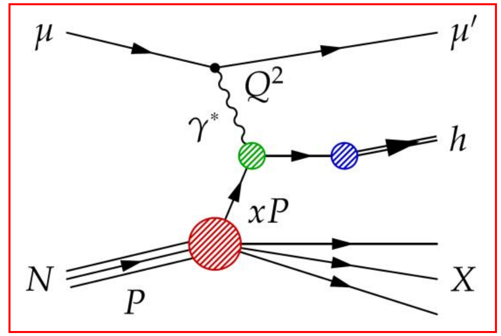
- Hard scattering of $\mu^{\pm}$ and π^{-} off (un)polarized P/D targets
- Study of nucleon spin structure
- Parton distribution functions and fragmentation functions

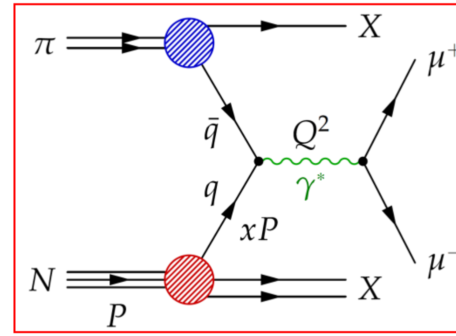
Hadron spectroscopy

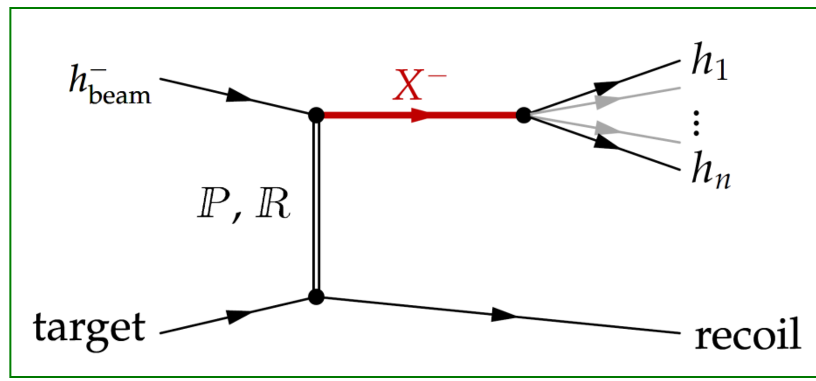
- Diffractive $\pi(K)$ dissociation reaction with proton target
- PWA technique employed
- High-precision measurement of light-meson excitation spectrum
- Search for exotic states

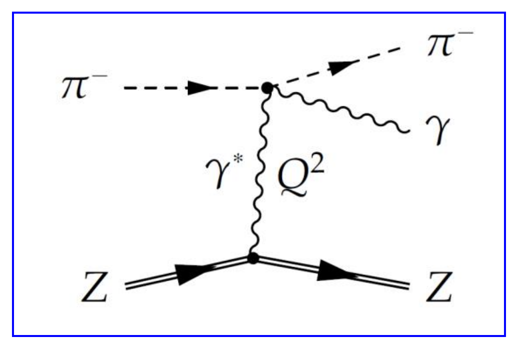
Chiral dynamics

- Test chiral perturbation theory in $\pi(K)$ γ reactions
- $\pi^{\pm}$ and $K^{\pm}$ polarizabilities
- Chiral anomaly $F_{3\pi}$









The COMPASS Experiment at the CERN SPS

Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

Increasing resolution scale (momentum transfer)

Nucleon structure

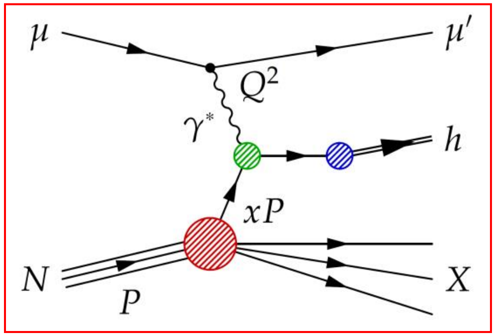
- Hard scattering of $\mu^{\pm}$ and π^{-} off (un)polarized P/D targets
- Study of nucleon spin structure
- Parton distribution functions and fragmentation functions

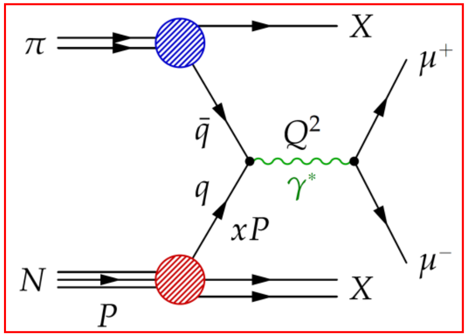
Hadron spectroscopy

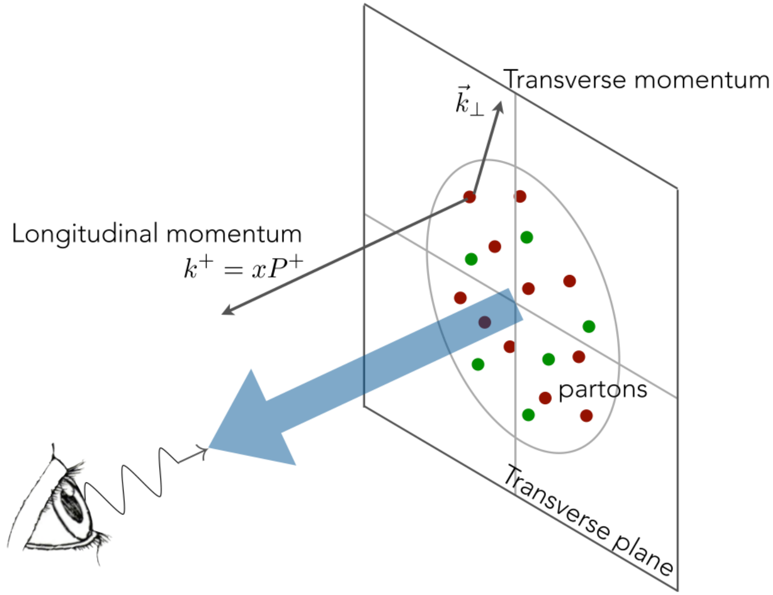
- Diffractive $\pi(K)$ dissociation reaction with proton target
- PWA technique employed
- High-precision measurement of light-meson excitation spectrum
- Search for exotic states

Chiral dynamics

- Test chiral perturbation theory in $\pi(K)$ γ reactions
- $\pi^{\pm}$ and $K^{\pm}$ polarizabilities
- Chiral anomaly $F_{3\pi}$



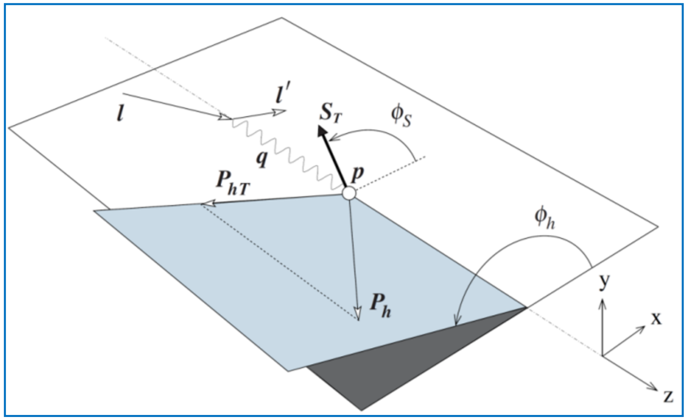




Cahn effect in SIDIS

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\ldots\right)$$



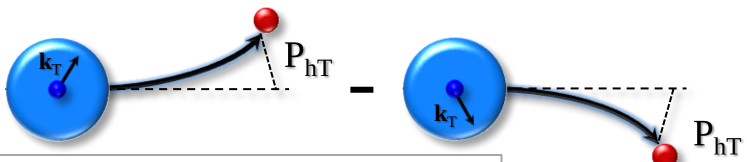
Cahn effect

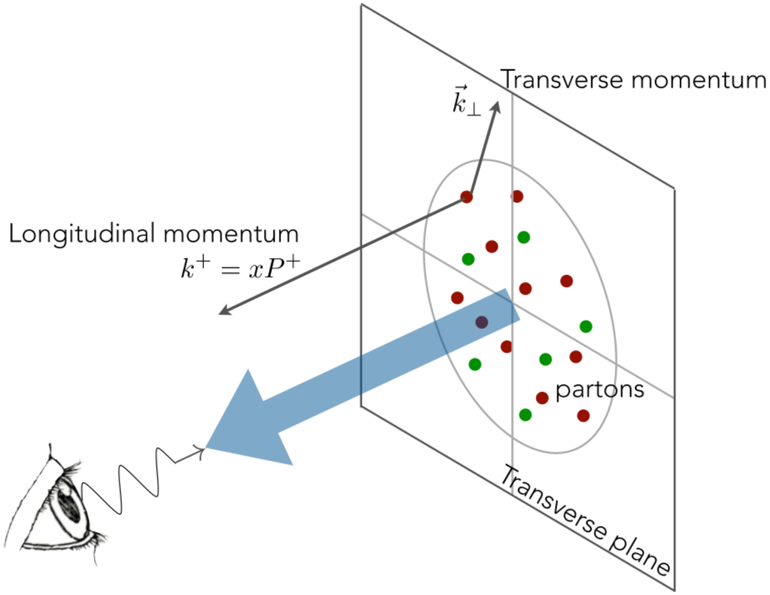
R. N. Cahn, **PLB 78** (1978)

The point that there are azimuthal dependences, which arise from the transverse momenta of the partons was clearly stated in this papers:

T.P. Cheng and A. Zee, **Phys. Rev. D6** (1972) 885;
F. Ravndal, **Phys. Lett. 43B** (1973) 301.
R.L. Kingsley, **Phys. Rev. D10** (1974) 1580;
A.M. Kotsinyan, **Teor. Mat. Fiz. 24** (1975) 206;

$$k_T \to \cos\varphi_q \to \cos\varphi_h$$





$$\hat{s} \simeq xs\left[1-2\sqrt{1-y}\,\frac{k_T}{Q}\cdot\cos\varphi_q\right]$$

$$\hat{u} \simeq -xs(1-y)\left[1-\frac{2k_T}{Q\sqrt{1-y}}\cdot\cos\varphi_q\right]$$

$$\hat{t} = -Q^2 = -xys, \quad where \quad s=(l+P)^2$$

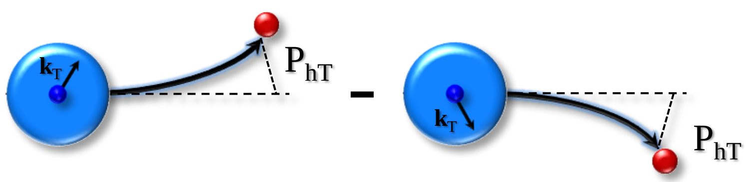
$$d\sigma^{lp\to l'hX} \propto d\sigma^{lq\to lq} \propto \frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$$

Cahn effect in SIDIS

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h + \dots\right)$$

Quark / Nucleon	U
U	$f_1^q(x, \boldsymbol{k}_T^2)$ number density



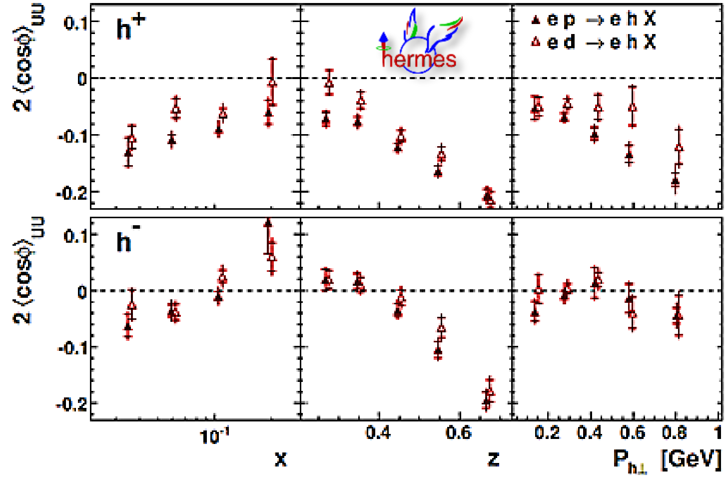
As of 1978 – simplistic kinematic effect:

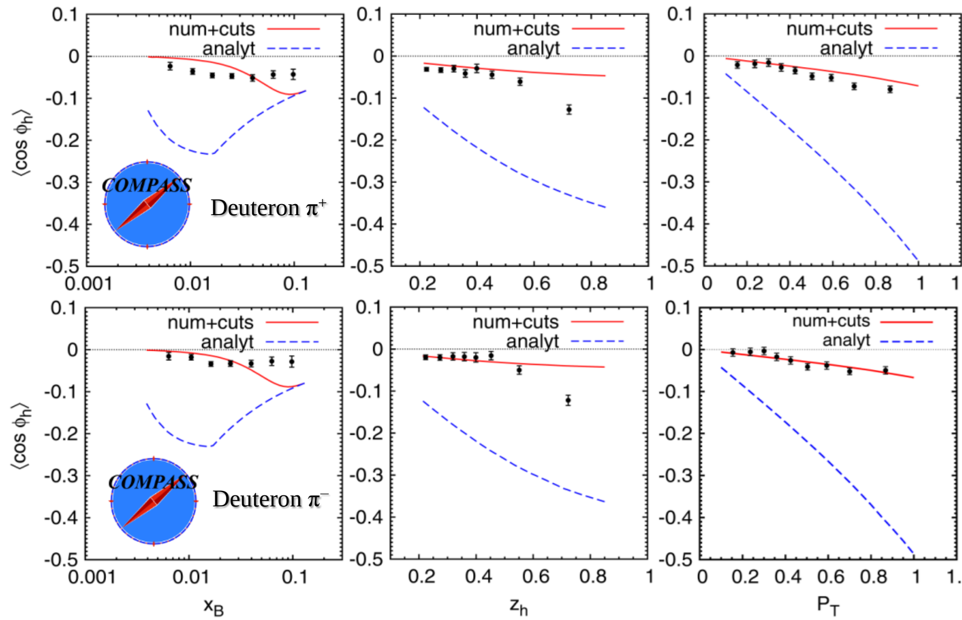
- non-zero k_T induces an azimuthal modulation

As of 2022 – complex SF (twist-2/3 functions)

- Measurements by different experiments

Significant non-zero effect observed by a number of experiments





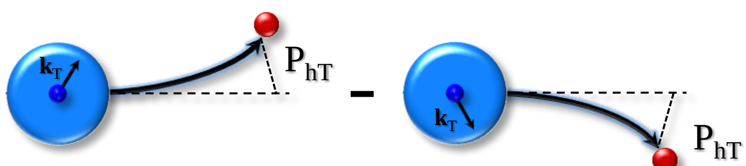
$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}C\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h}\left(xhH_{1q}^{\perp h}+\frac{M_h}{M}f_1^q\frac{\tilde{D}_q^{\perp h}}{z}\right)-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\left(xf^{\perp q}D_{1q}^h+\frac{M_h}{M}h_1^{\perp q}\frac{\tilde{H}_q^h}{z}\right)\right\}$$

Cahn effect in SIDIS

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h + \ldots\right)$$

Nucleon \ Quark	U
U	$f_1^q(x, \boldsymbol{k}_T^2)$ number density



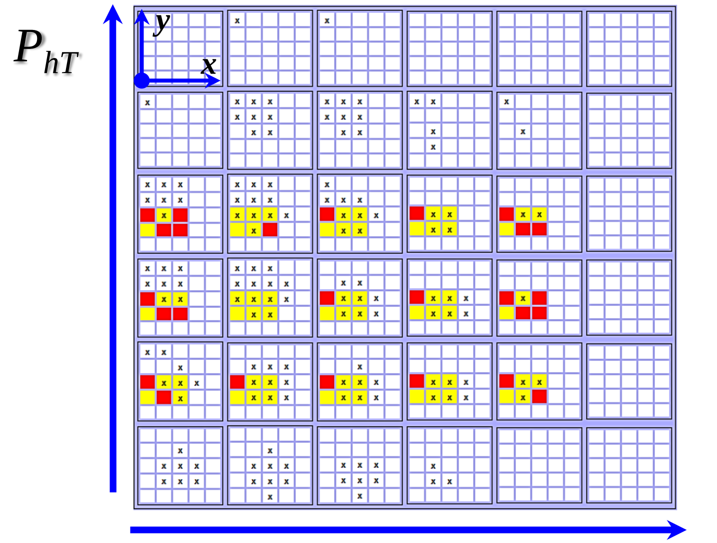
As of 1978 – simplistic kinematic effect:

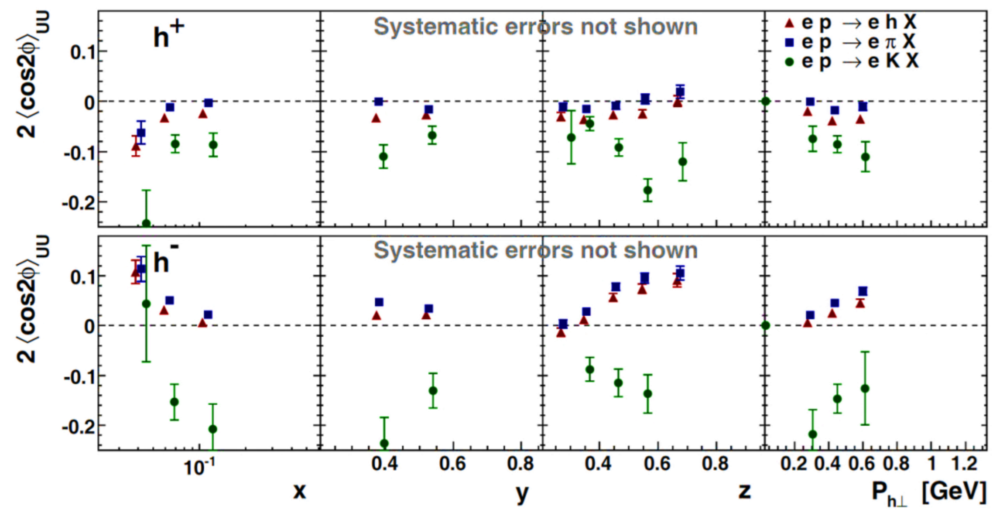
- non-zero k_T induces an azimuthal modulation

As of 2022 – complex SF (twist-2/3 functions)

- Measurements by different experiments

Significant non-zero effect observed by a number of experiments





$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q} C\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h}\left(xhH_{1q}^{\perp h}+\frac{M_h}{M}f_1^q\frac{\tilde{D}_q^{\perp h}}{z}\right)-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\left(xf^{\perp q}D_{1q}^h+\frac{M_h}{M}h_1^{\perp q}\frac{\tilde{H}_q^h}{z}\right)\right\}$$

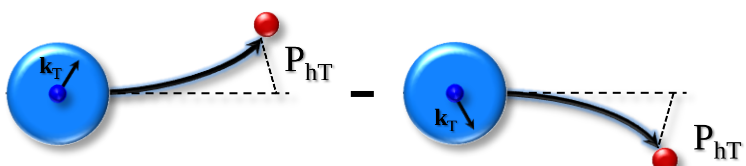
Cahn effect in SIDIS

$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} =$$

$$\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h + \ldots\right)$$

Quark / Nucleon	U
U	$f_1^q(x, \boldsymbol{k}_T^2)$ **number density**



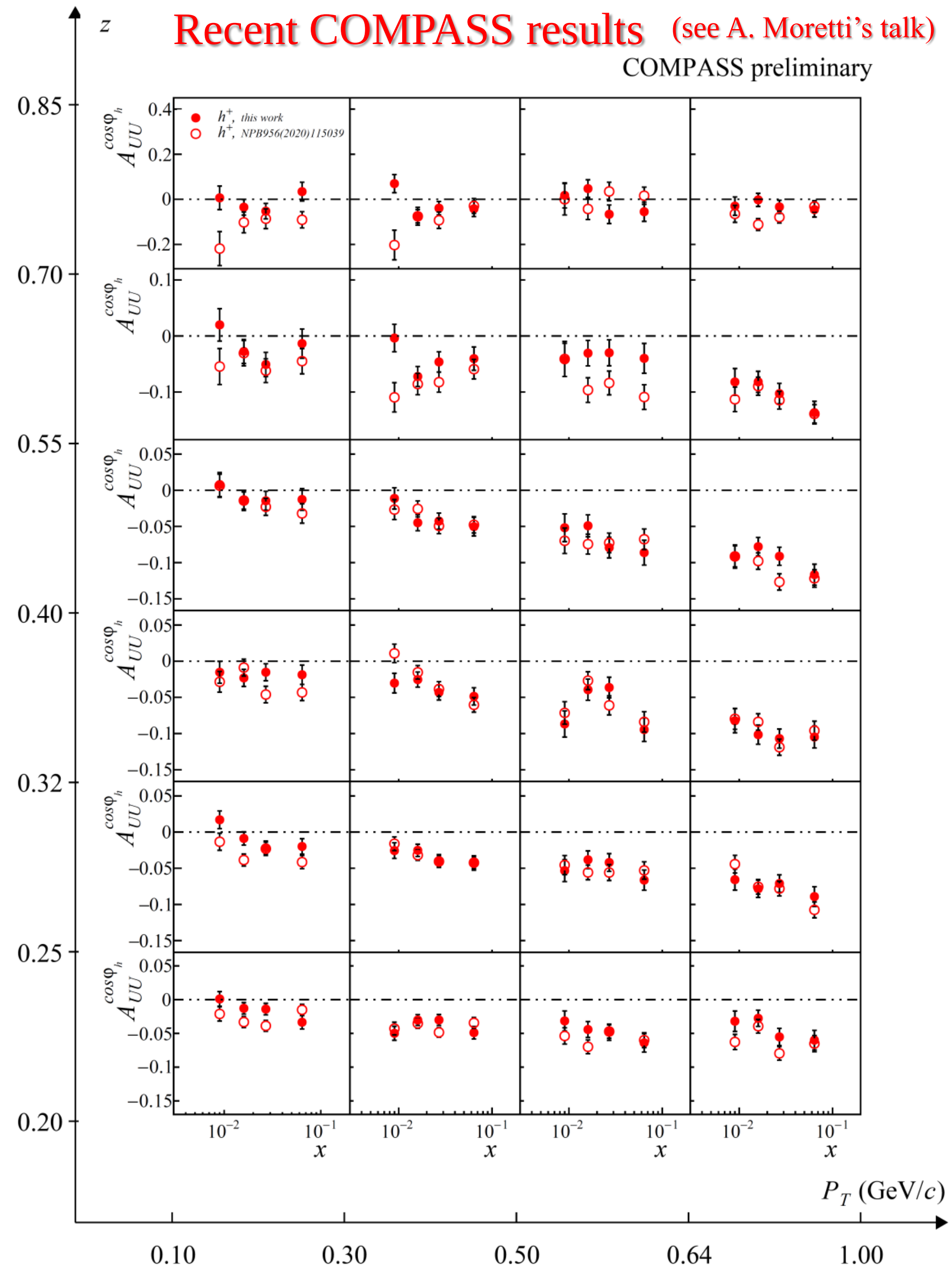
As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

As of 2022 – complex SF (twist-2/3 functions)

- Measurements by different experiments
- Complex multi-D kinematic dependences
  - So far, no clear interpretation

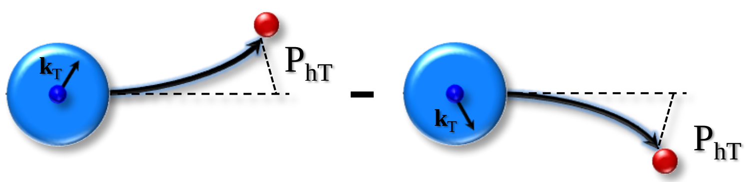
Recent COMPASS results (see A. Moretti's talk)



Cahn effect in SIDIS

$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right) \times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}\,A_{UU}^{\cos\phi_h}\cos\phi_h + \ldots\right)$$

Quark / Nucleon	U
U	$f_1^q(x,\boldsymbol{k}_T^2)$ **number density**



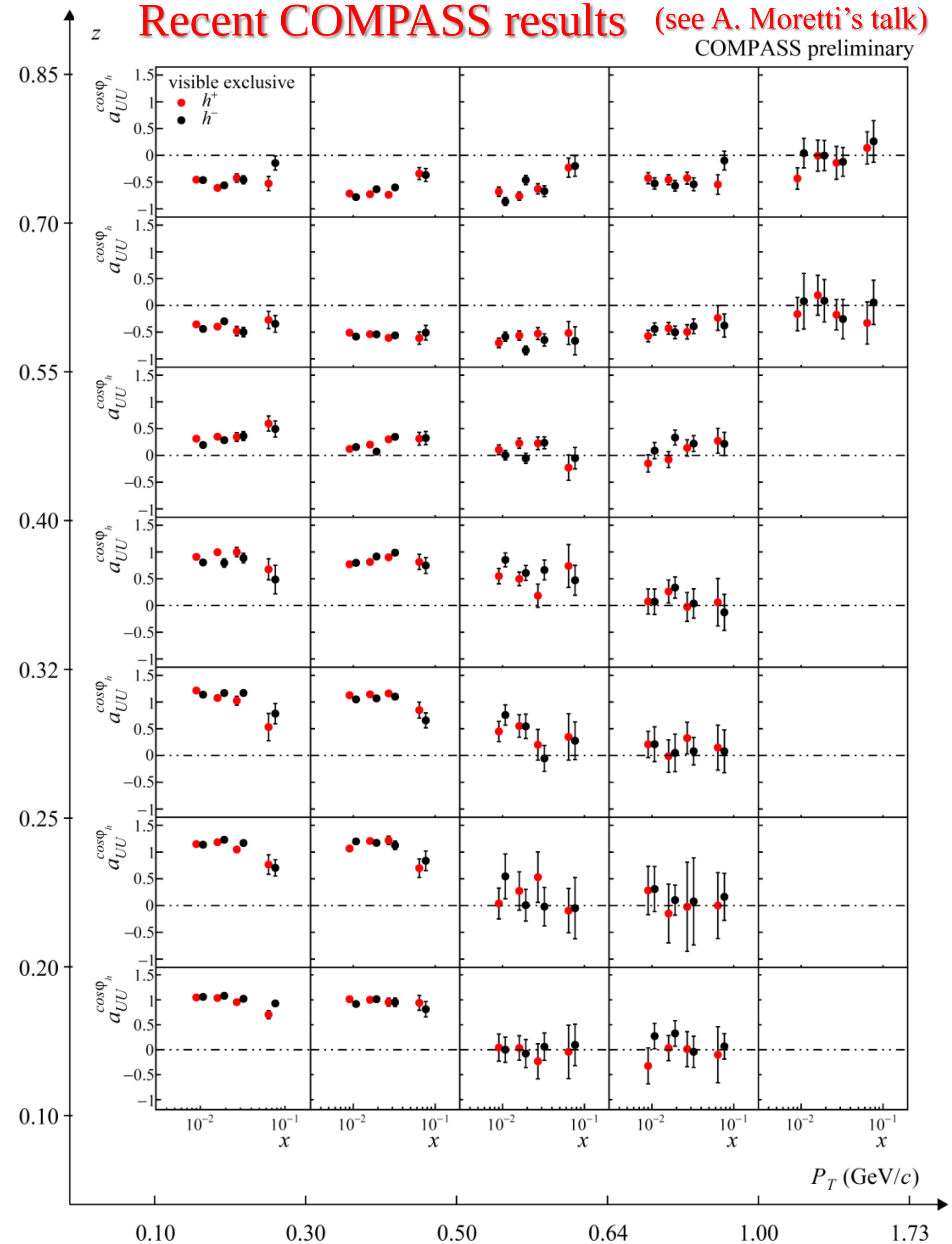
As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

As of 2022 – complex SF (twist-2/3 functions)

- Measurements by different experiments
- Complex multi-D kinematic dependences
  - So far, no clear interpretation

Recent COMPASS results (see A. Moretti's talk)



- A set of complex corrections: Acceptance, diffractively produced VMs, radiative corrections, etc.

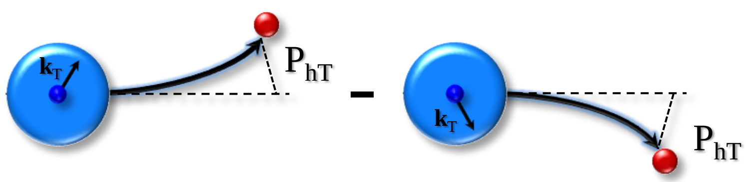
Cahn effect in SIDIS

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} =$$

$$\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\ldots\right)$$

Quark / Nucleon	U
U	$f_1^q(x,\boldsymbol{k}_T^2)$ **number density** 



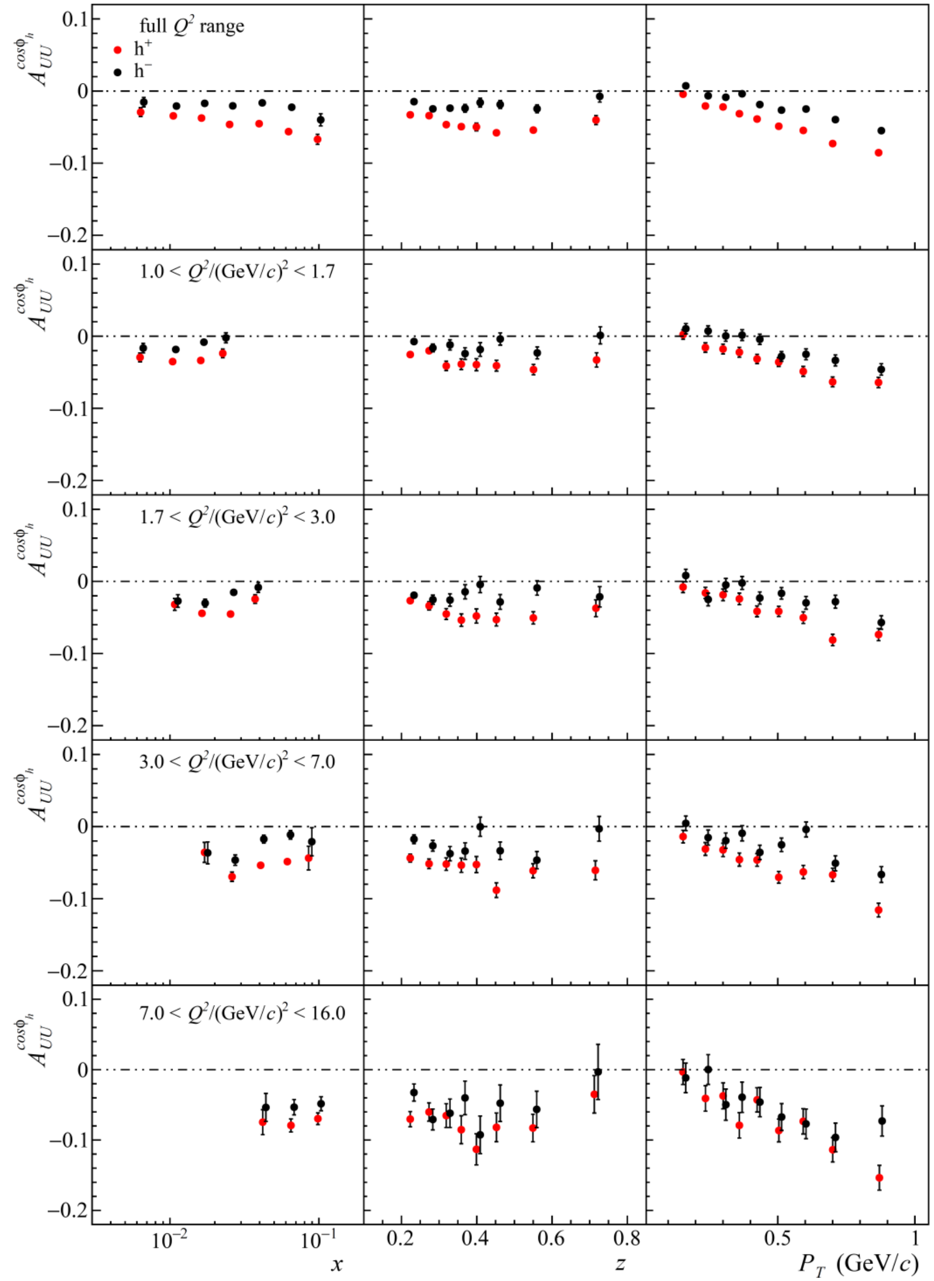
As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

As of 2022 – complex SF (twist-2/3 functions)

- Measurements by different experiments
- Complex multi-D kinematic dependences
  - So far, no clear interpretation

Recent COMPASS results (see A. Moretti's talk)



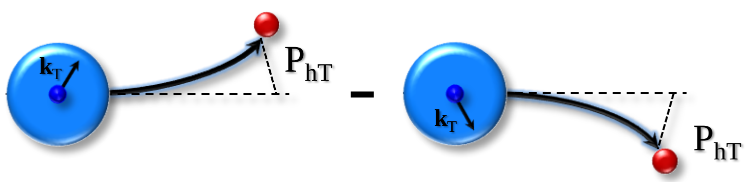
- Strong Q^2 dependence

Cahn effect in SIDIS

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h + \ldots\right)$$

Quark / Nucleon	U
U	$f_1^q(x, \boldsymbol{k}_T^2)$ **number density**



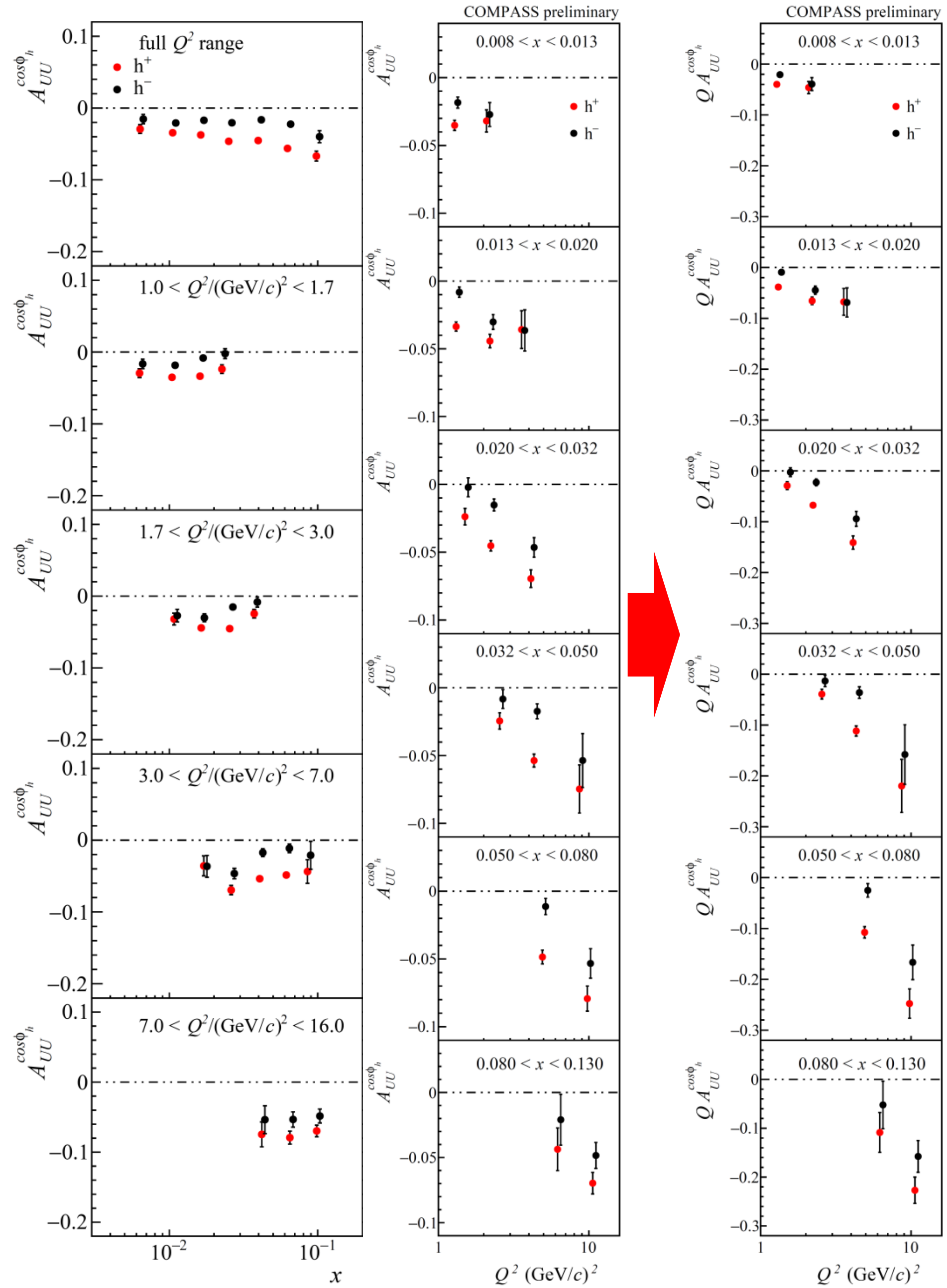
As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

As of 2022 – complex SF (twist-2/3 functions)

- Measurements by different experiments
- Complex multi-D kinematic dependences
  - So far, no clear interpretation

Recent COMPASS results (see A. Moretti's talk)



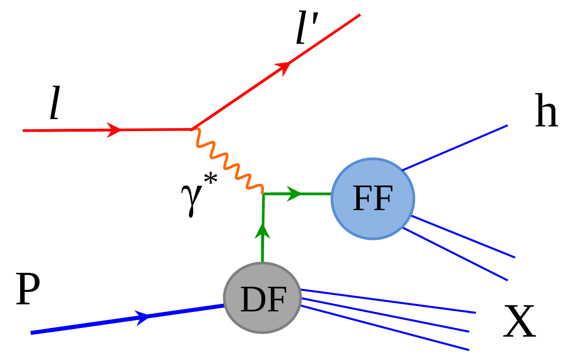
- Strong Q^2 dependence

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times \left\{ \begin{array}{l}
1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos2\phi_h}\cos2\phi_h \\
+\lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h \\
+S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin2\phi_h}\sin2\phi_h\right] \\
+S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\right] \\
+S_T\left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ +\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ +\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\ +\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\ +\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S) \end{array}\right] \\
+S_T\lambda\left[\begin{array}{l} \sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\ +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\ +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S) \end{array}\right]
\end{array}\right\}$$



Nucleon \ Quark	U	L	T
U	number density		Boer-Mulders
L		helicity	worm-gear L
T	Sivers	Kotzinian-Mulders worm-gear T	transversity pretzelosity

spin of the nucleon — spin of the quark — k_T

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times \Bigg\{ 1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h$$

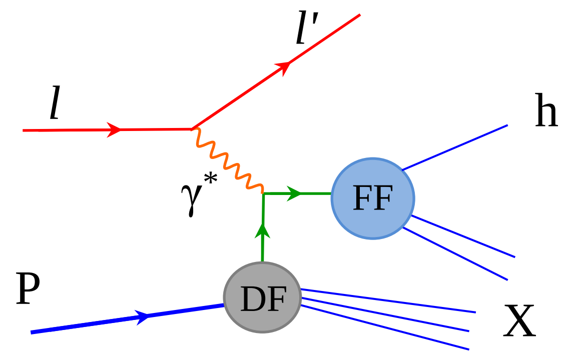
$$+\lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h$$

$$+S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right]$$

$$+S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\right]$$

$$+S_T\begin{bmatrix} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ +\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ +\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\ +\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\ +\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\end{bmatrix}$$

$$+S_T\lambda\begin{bmatrix} \sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\ +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\ +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\end{bmatrix}\Bigg\}$$



$$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q}\otimes D_{1q}^h$$

$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q\otimes H_{1q}^{\perp h}$$

$$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q}\otimes H_{1q}^{\perp h}$$

$$A_{UT}^{\sin(\phi_s)} \overset{WW}{\propto} Q^{-1}\left(h_1^q\otimes H_{1q}^{\perp h}+f_{1T}^{\perp q}\otimes D_{1q}^h+\ldots\right)$$

$$A_{UT}^{\sin(2\phi_h-\phi_s)} \overset{WW}{\propto} Q^{-1}\left(h_{1T}^{\perp q}\otimes H_{1q}^{\perp h}+f_{1T}^{\perp q}\otimes D_{1q}^h+\ldots\right)$$

$$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q\otimes D_{1q}^h$$

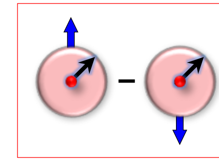
$$A_{LT}^{\cos(\phi_s)} \overset{WW}{\propto} Q^{-1}\left(g_{1T}^q\otimes D_{1q}^h+\ldots\right)$$

$$A_{LT}^{\cos(2\phi_h-\phi_s)} \overset{WW}{\propto} Q^{-1}\left(g_{1T}^q\otimes D_{1q}^h+\ldots\right)$$

Twist-2

Twist-3

SIDIS TSAs: Sivers effect



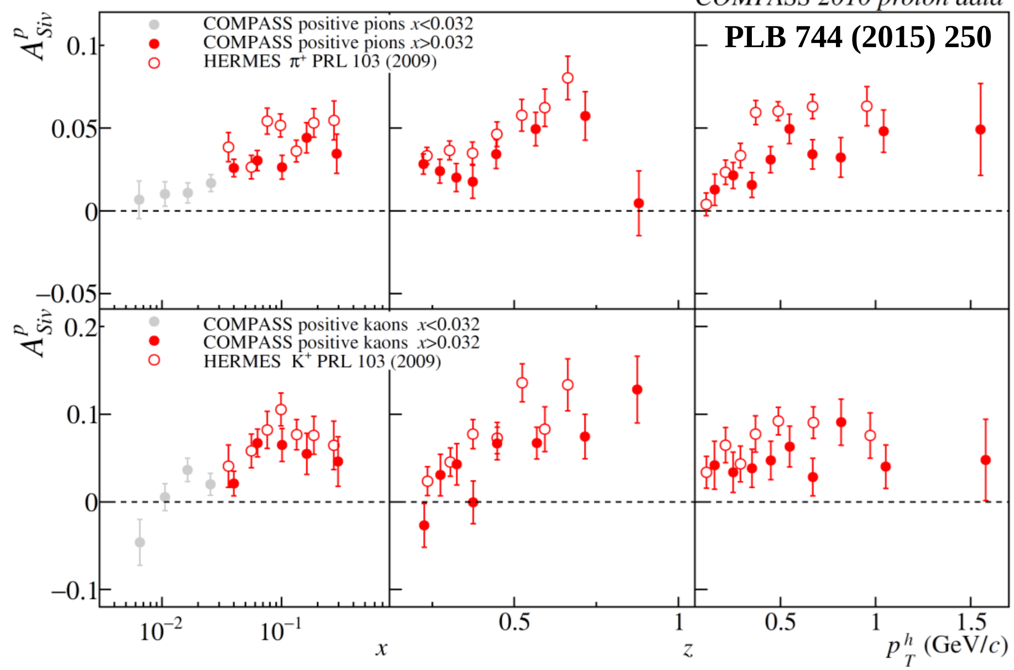
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin\left(\phi_h - \phi_S\right) + \ldots\right\}$$

$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}} \cdot \boldsymbol{k_T}}{M} f_{1T}^{\perp q} D_{1q}^h\right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$

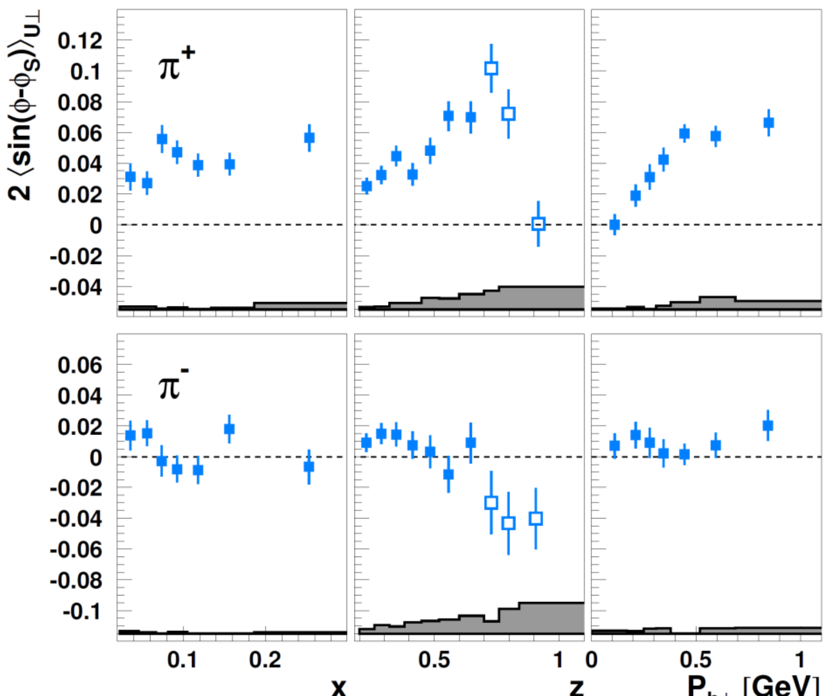
- Measured on proton and deuteron
- Expected to change sign between SIDIS and Drell-Yan

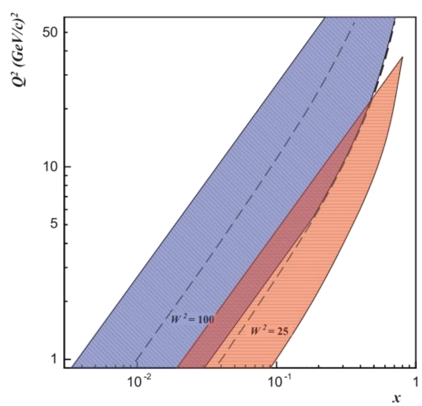
COMPASS 2010 proton data

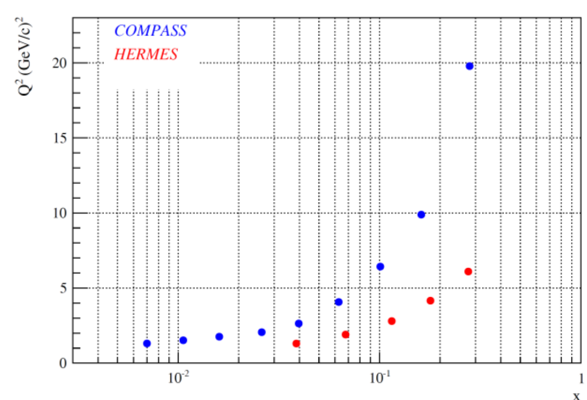
PLB 744 (2015) 250



HERMES, JHEP 12 (2020) 010







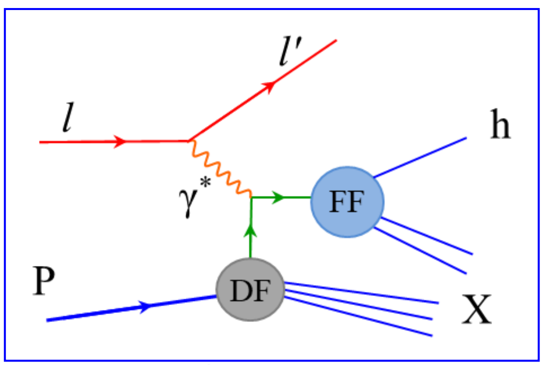
SIDIS and single-polarized DY x-sections at twist-2 (LO)

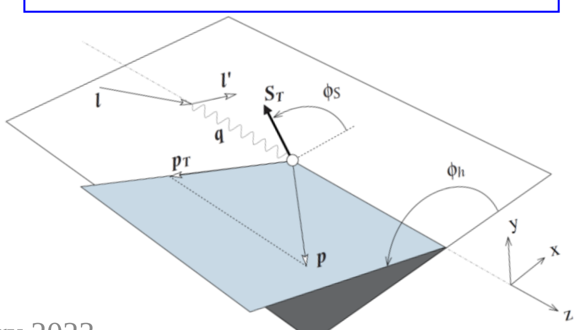
COMPASS 25 years 1997 - 2022

SIDIS

$$\frac{d\sigma^{LO}}{dxdydzdp_T^2d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)$$

$$\times \left\{ \begin{array}{l} 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + S_L\, \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL} \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) \end{array} \right] \\ + S_T \lambda \left[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h-\phi_S) \right] \end{array} \right\}$$



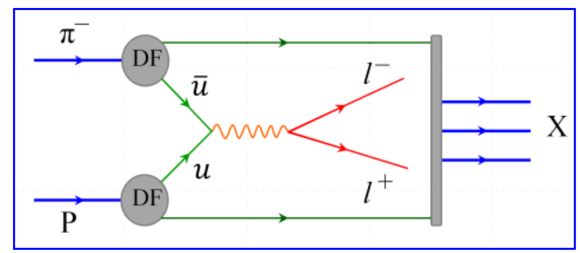


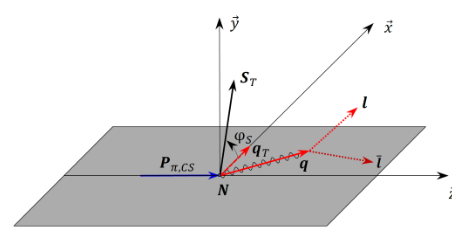
DY

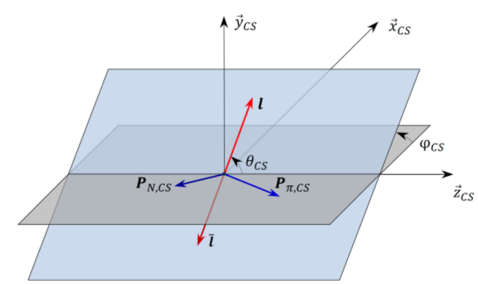
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right)$$

$$\times \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S} \sin\varphi_S \\ + D_{[\sin^2\theta_{CS}]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \\ + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) \end{array} \right) \end{array} \right] \end{array} \right\}$$

where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1+\cos^2\theta_{CS}\right)$

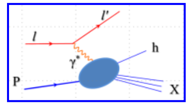






SIDIS and single-polarized DY x-sections at twist-2 (LO)

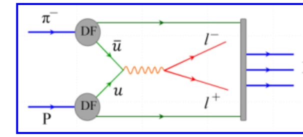
$$\frac{d\sigma^{LO}}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$



$$\times\left\{\begin{aligned}
&1+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\
&+S_L\,\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h + S_L\lambda\sqrt{1-\varepsilon^2}\,A_{LL} \\
&+S_T\left[\begin{aligned}&A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S)\\ &+\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S)\\ &+\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)\end{aligned}\right] \\
&+S_T\lambda\left[\sqrt{(1-\varepsilon^2)}\,A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)\right]
\end{aligned}\right\}$$

SIDIS-DY bridge

$$\frac{d\sigma^{LO}}{dq^4\,d\Omega} \propto F_U^1\left(1+\cos^2\theta_{CS}\right)$$



$$\times\left\{\begin{aligned}
&1+D_{[\sin^2\theta_{CS}]}\,A_U^{\cos 2\varphi_{CS}}\cos 2\varphi_{CS} \\
&+S_L\sin^2\theta_{CS}\,A_L^{\sin 2\varphi_{CS}}\sin 2\varphi_{CS} \\
&+S_T\left[\begin{aligned}&A_T^{\sin\varphi_S}\sin\varphi_S\\ &+D_{[\sin^2\theta_{CS}]}\left(\begin{aligned}&A_T^{\sin(2\varphi_{CS}-\varphi_S)}\sin(2\varphi_{CS}-\varphi_S)\\ &+A_T^{\sin(2\varphi_{CS}+\varphi_S)}\sin(2\varphi_{CS}+\varphi_S)\end{aligned}\right)\end{aligned}\right]
\end{aligned}\right\}$$

where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS}/\left(1+\cos^2\theta_{CS}\right)$

SIDIS		DY
$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + \dots$	← Boer-Mulders →	$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$	← Sivers →	$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$	← Transversity →	$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^q$
$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$	← Pretzelosity →	$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$

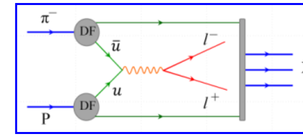
Complementary information from two different channels :

- SIDIS-DY bridging of nucleon TMD PDFs; Universality studies;
- Sign-change of T-odd Sivers and Boer-Mulders TMD PDFs;
- Multiple access to Collins FF $H_{1q}^{\perp h}$ and pion Boer-Mulders PDF $h_{1,\pi}^{\perp q}$

Single-polarized DY measurements at COMPASS

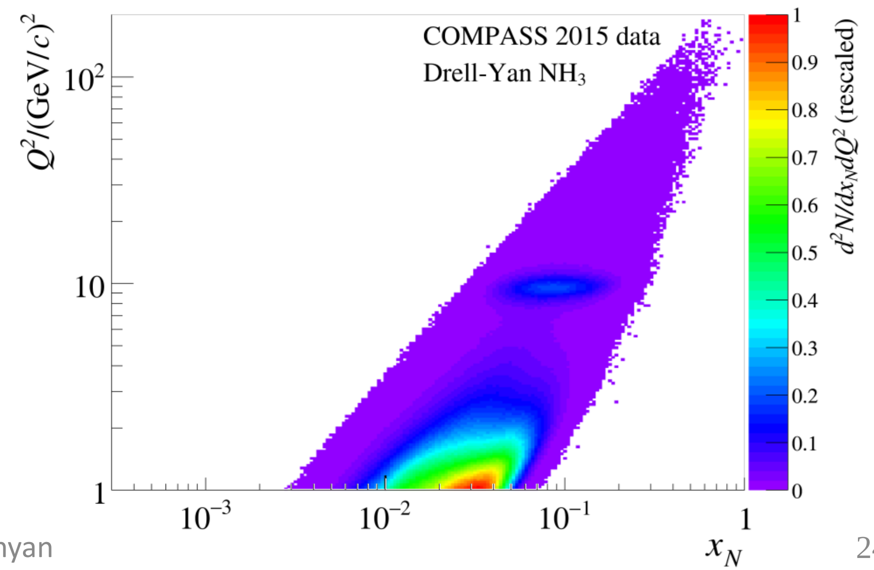
- $1.0 < M/(\text{GeV}/c^2) < 2.0$ "Low mass"
  - Large background contamination, combinatorial, Open-charm (B) $D\bar{D}$, $B\bar{B}$, π, K decays
- $2.0 < M/(\text{GeV}/c^2) < 2.5$ "Intermediate mass"
  - High DY-cross section
  - Still low DY-signal/background ratio
- $2.5 < M/(\text{GeV}/c^2) < 4.3$ "Charmonia mass"
  - Strong J/ψ-signal → study of J/ψ physics
  - Good signal/background
- $4.3 < M/(\text{GeV}/c^2) < 8.5$ "High mass"
  - Low DY cross-section
  - Beyond charmonium region, background < 3%
  - Valence region → largest asymmetries

$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right) \times \left\{ 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} + S_T \left[A_T^{\sin\varphi_S} \sin\varphi_S + D_{[\sin^2\theta_{CS}]} \left(A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) \right) \right] \right\}$$

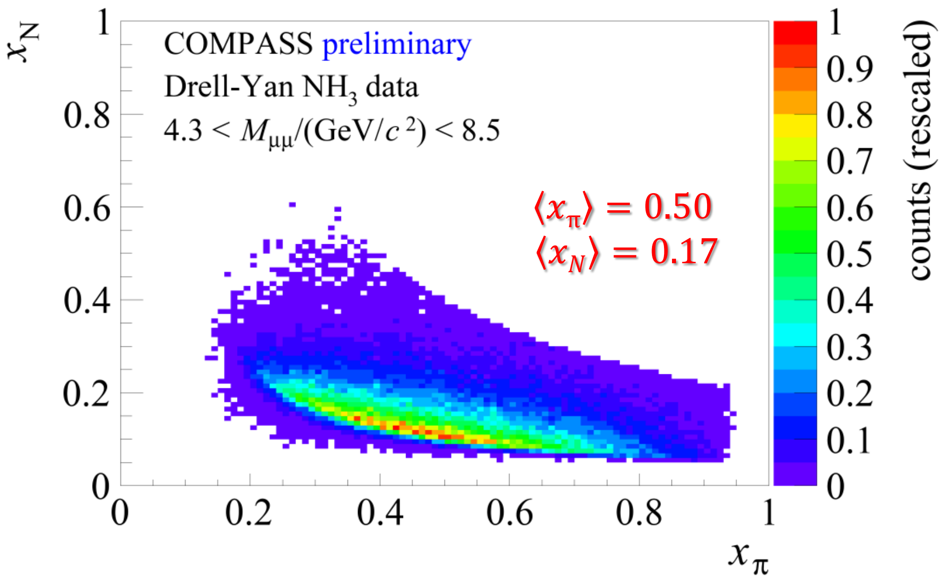


$$D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1+\cos^2\theta_{CS}\right)$$

COMPASS x:Q² phase space

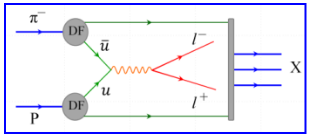


Single-polarized DY measurements at COMPASS



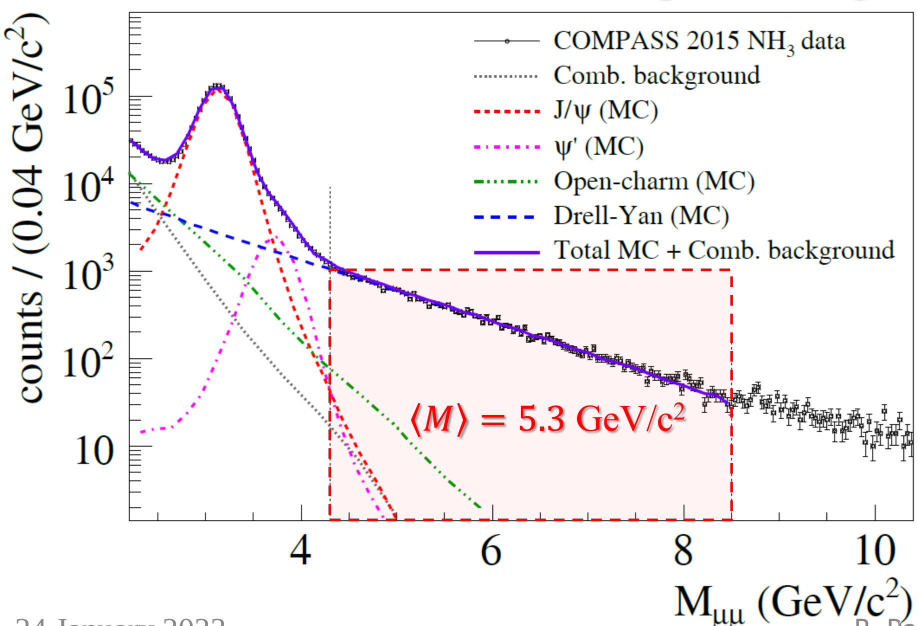
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right)$$

$$\times \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S} \sin\varphi_S \\ + D_{[\sin^2\theta_{CS}]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \\ + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) \end{array} \right) \end{array} \right] \end{array} \right\}$$

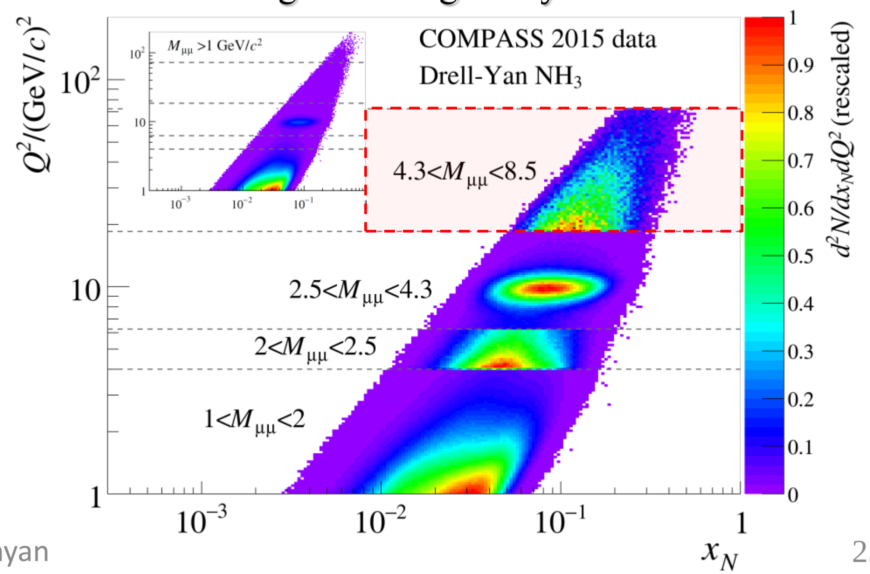


$$D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1+\cos^2\theta_{CS}\right)$$

HM events are in the valence quark range



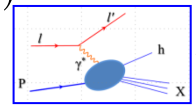
$4.3 < M/(\mathrm{GeV}/c^2) < 8.5$ “High mass” range
Beyond charmonium region, background < 3%
Valence region → largest asymmetries



SIDIS and single-polarized DY x-sections at twist-2 (LO)

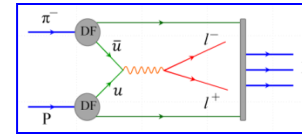
SIDIS

$$\frac{d\sigma^{LO}}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right) \times \left\{ \begin{array}{l} 1+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\ + S_L\,\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h + S_L\lambda\sqrt{1-\varepsilon^2}A_{LL} \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \end{array} \right] \\ + S_T\lambda\left[\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)\right] \end{array} \right\}$$



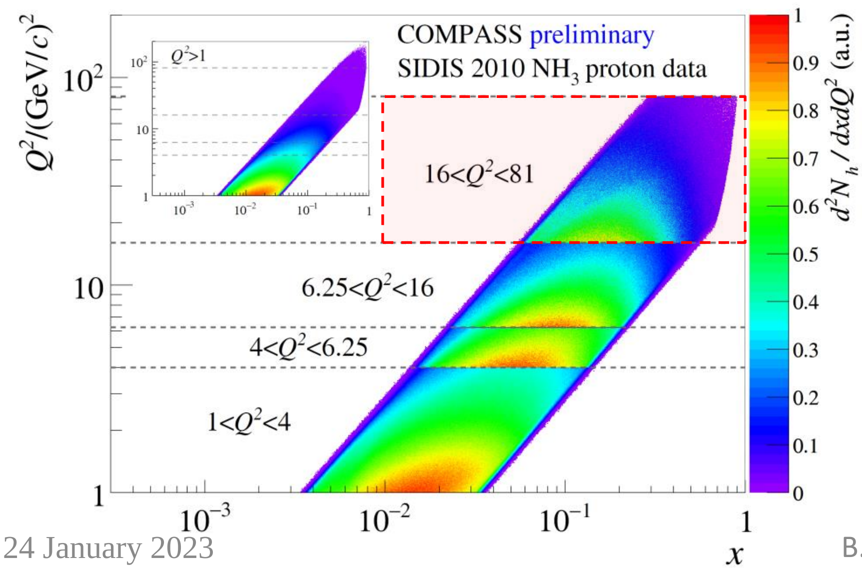
DY

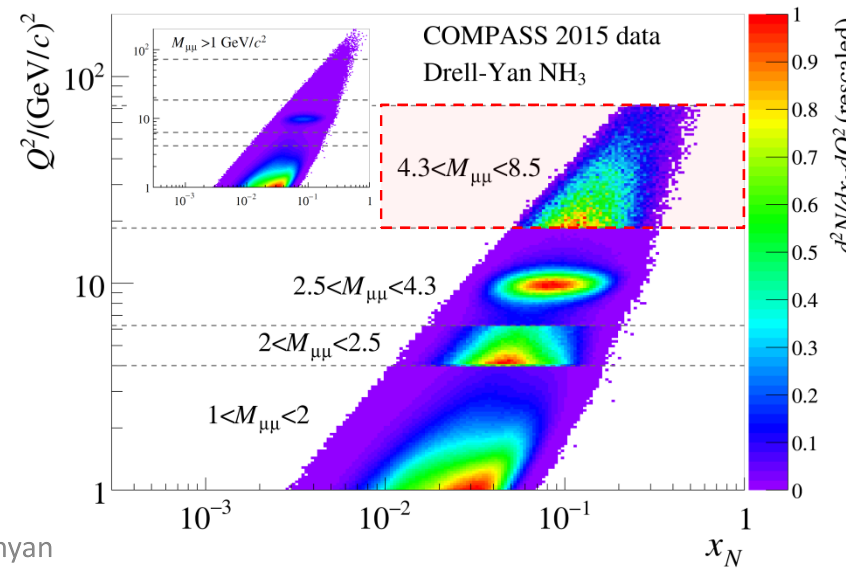
$$\frac{d\sigma^{LO}}{dq^4\,d\Omega} \propto F_U^1\left(1+\cos^2\theta_{CS}\right) \times \left\{ \begin{array}{l} 1+D_{[\sin^2\theta_{CS}]}A_U^{\cos 2\varphi_{CS}}\cos 2\varphi_{CS} \\ + S_L\sin^2\theta_{CS}A_L^{\sin 2\varphi_{CS}}\sin 2\varphi_{CS} \\ + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S}\sin\varphi_S \\ + D_{[\sin^2\theta_{CS}]}\left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)}\sin(2\varphi_{CS}-\varphi_S) \\ + A_T^{\sin(2\varphi_{CS}+\varphi_S)}\sin(2\varphi_{CS}+\varphi_S) \end{array} \right) \end{array} \right] \end{array} \right\}$$



where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS}/\left(1+\cos^2\theta_{CS}\right)$

Comparable x:Q² coverage – minimization of possible Q²-evolution effects



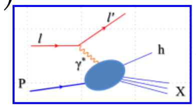


SIDIS and single-polarized DY x-sections at twist-2 (LO)

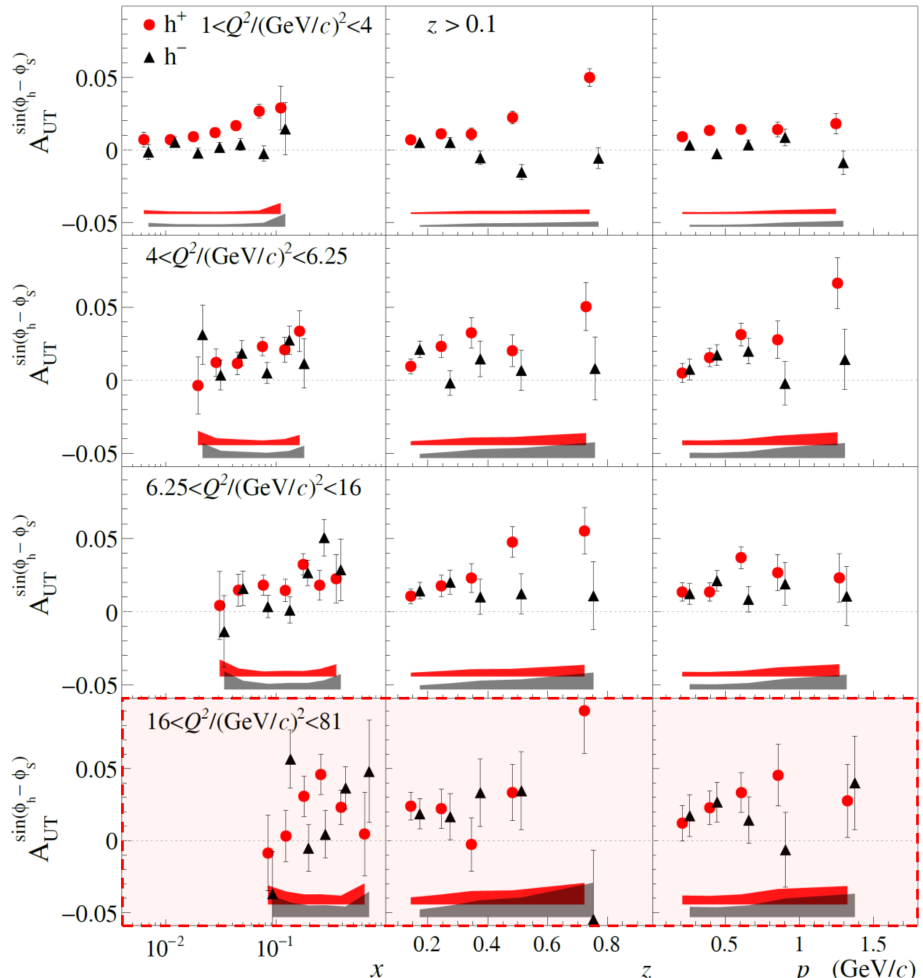
SIDIS

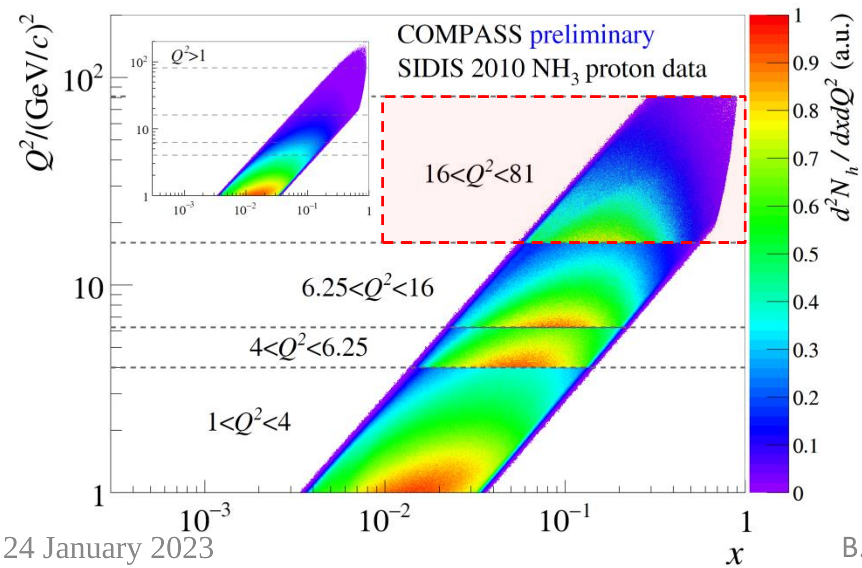
$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)$$

$$\times \left\{ \begin{array}{l} 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + S_L\, \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL} \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h - \phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h + \phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h - \phi_S) \end{array} \right] \\ + S_T \lambda \left[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h - \phi_S) \right] \end{array} \right\}$$



COMPASS PLB 770 (2017) 138





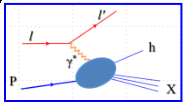
1[st] COMPASS multi-D fit done for all eight TSAs

SIDIS and single-polarized DY x-sections at twist-2 (LO)

SIDIS

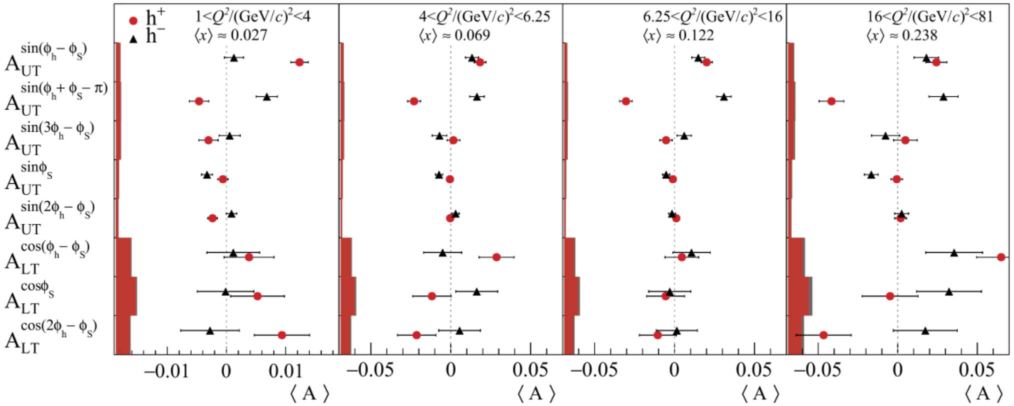
$$\frac{d\sigma^{LO}}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

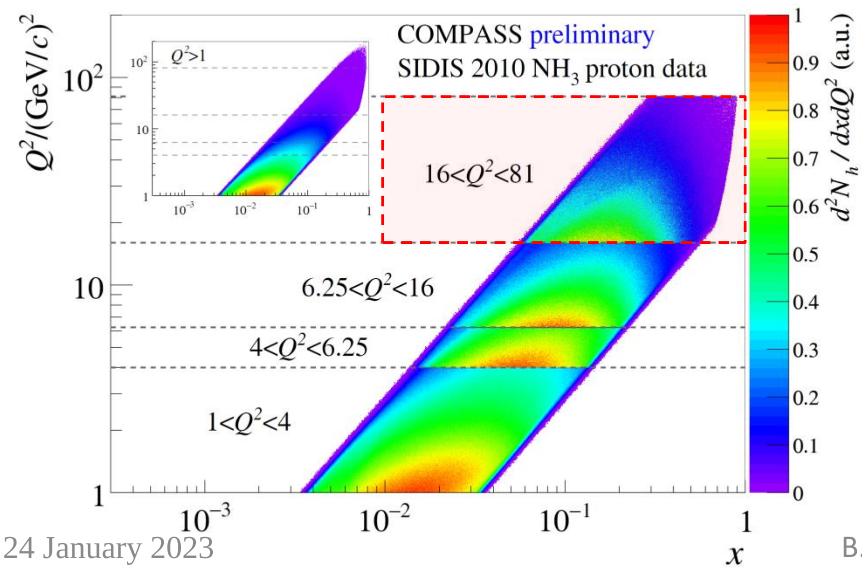
$$\times \left\{ \begin{array}{l} 1+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\ + S_L\, \varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2}\, A_{LL} \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \end{array} \right] \\ + S_T \lambda \left[\sqrt{(1-\varepsilon^2)}\, A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)\right] \end{array} \right\}$$

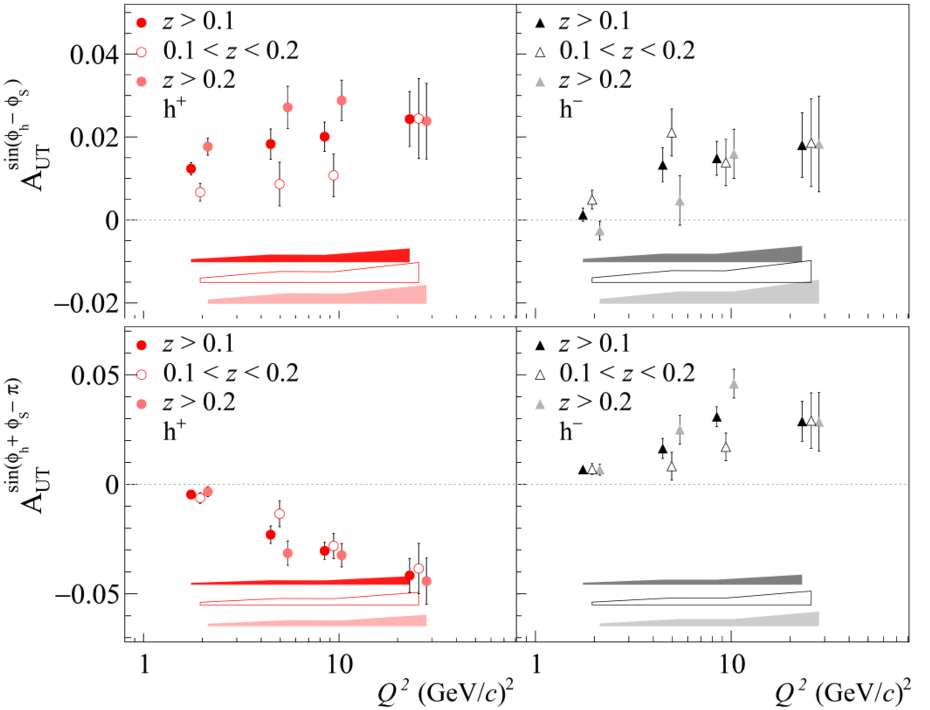


COMPASS PLB 770 (2017) 138

1st COMPASS multi-D fit done for all eight TSAs

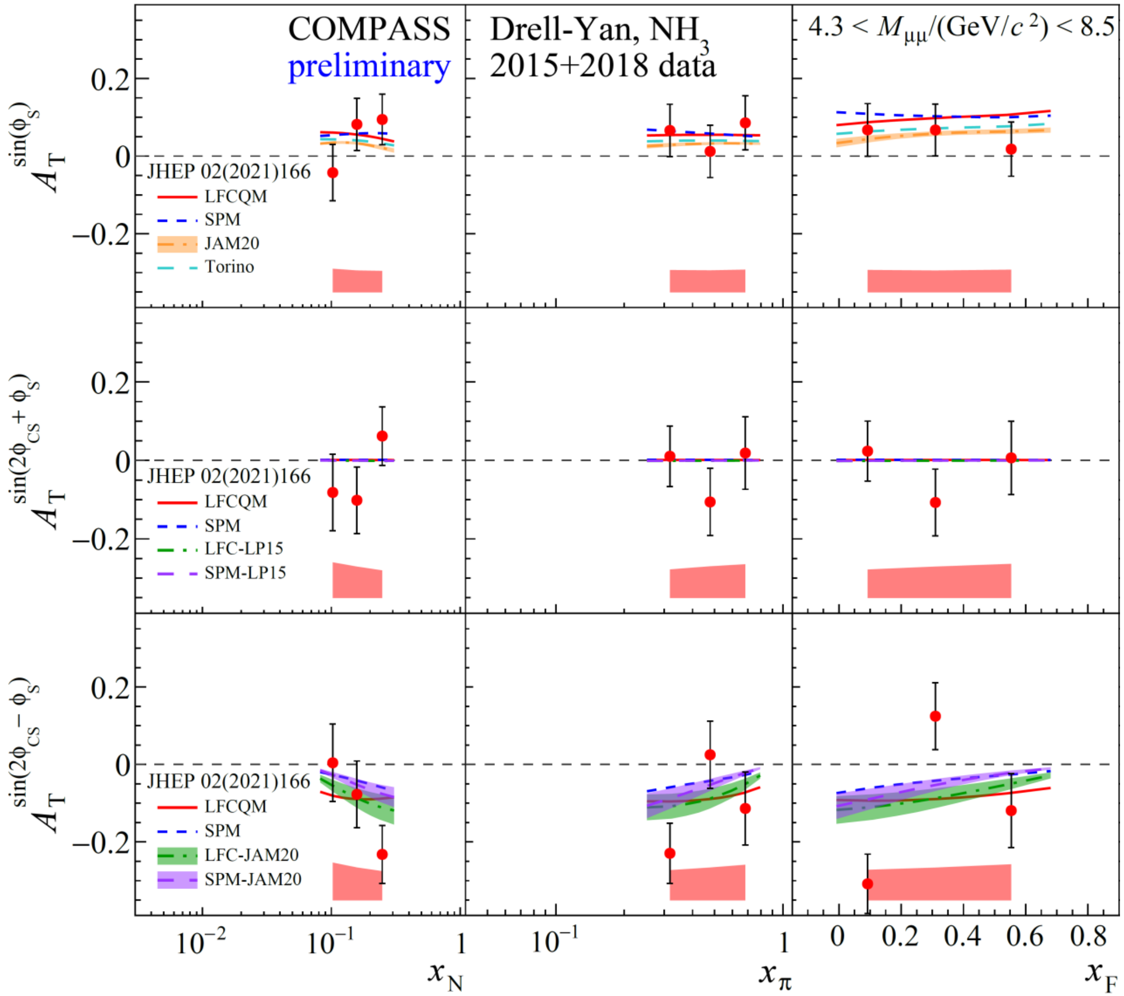


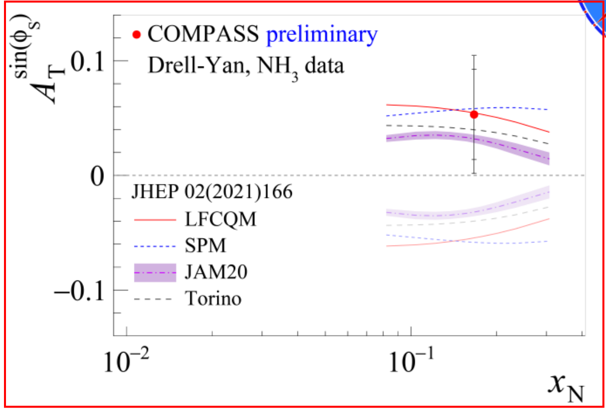


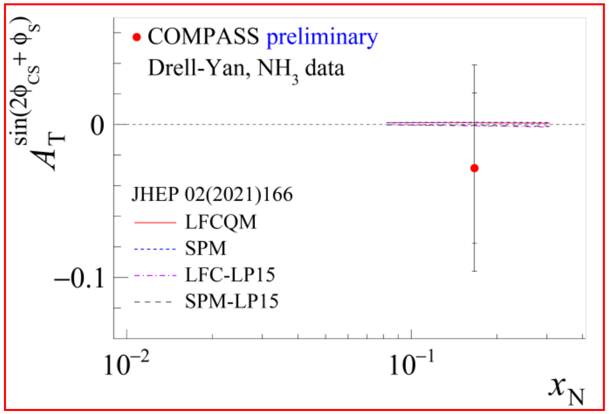


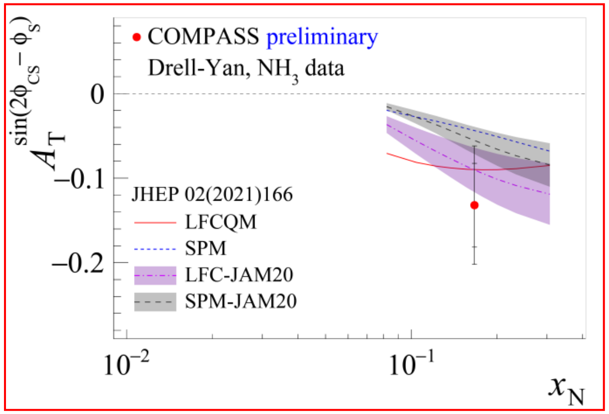
DY TSAs at COMPASS (high-mass range)

Theory curves based on S. Bastami et al. JHEP 02, (2021),166









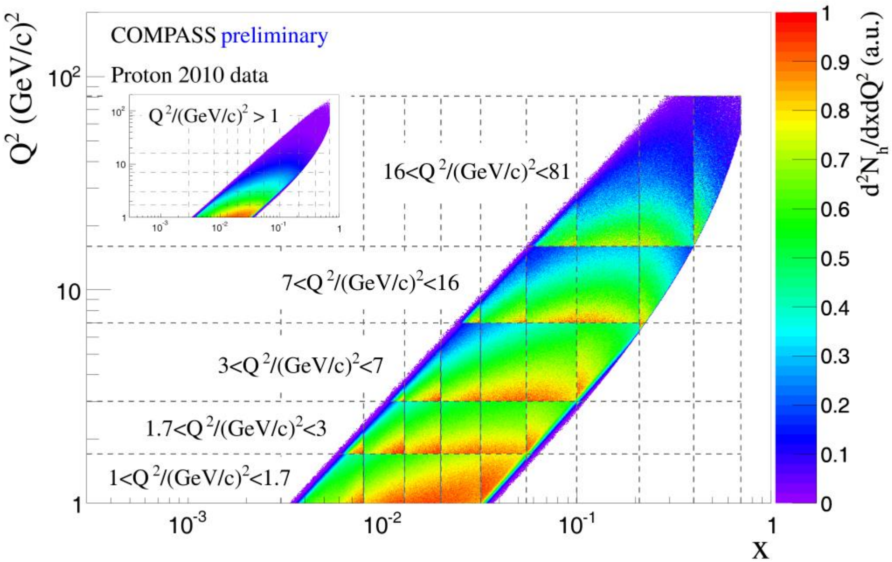
- General agreement with available theory predictions

COMPASS Multi-D TSA analyses

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

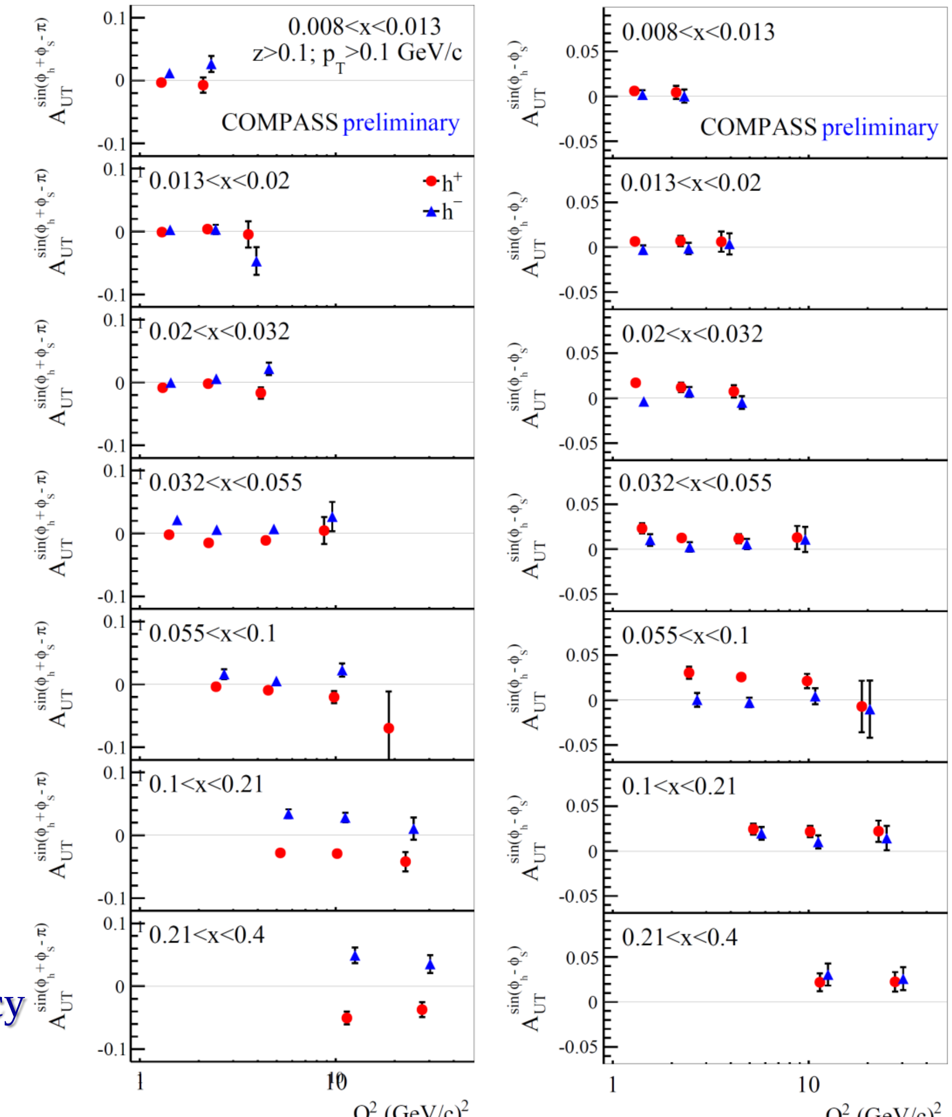
$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{h}\cdot k_T}{M} f_{1T}^{\perp q} D_{1q}^h\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0$$

$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{h}\cdot p_T}{M_h} h_1^q H_{1q}^{\perp h}\right]$$



3D x:Q^2:z or x:Q^2:p_T x:z:p_T

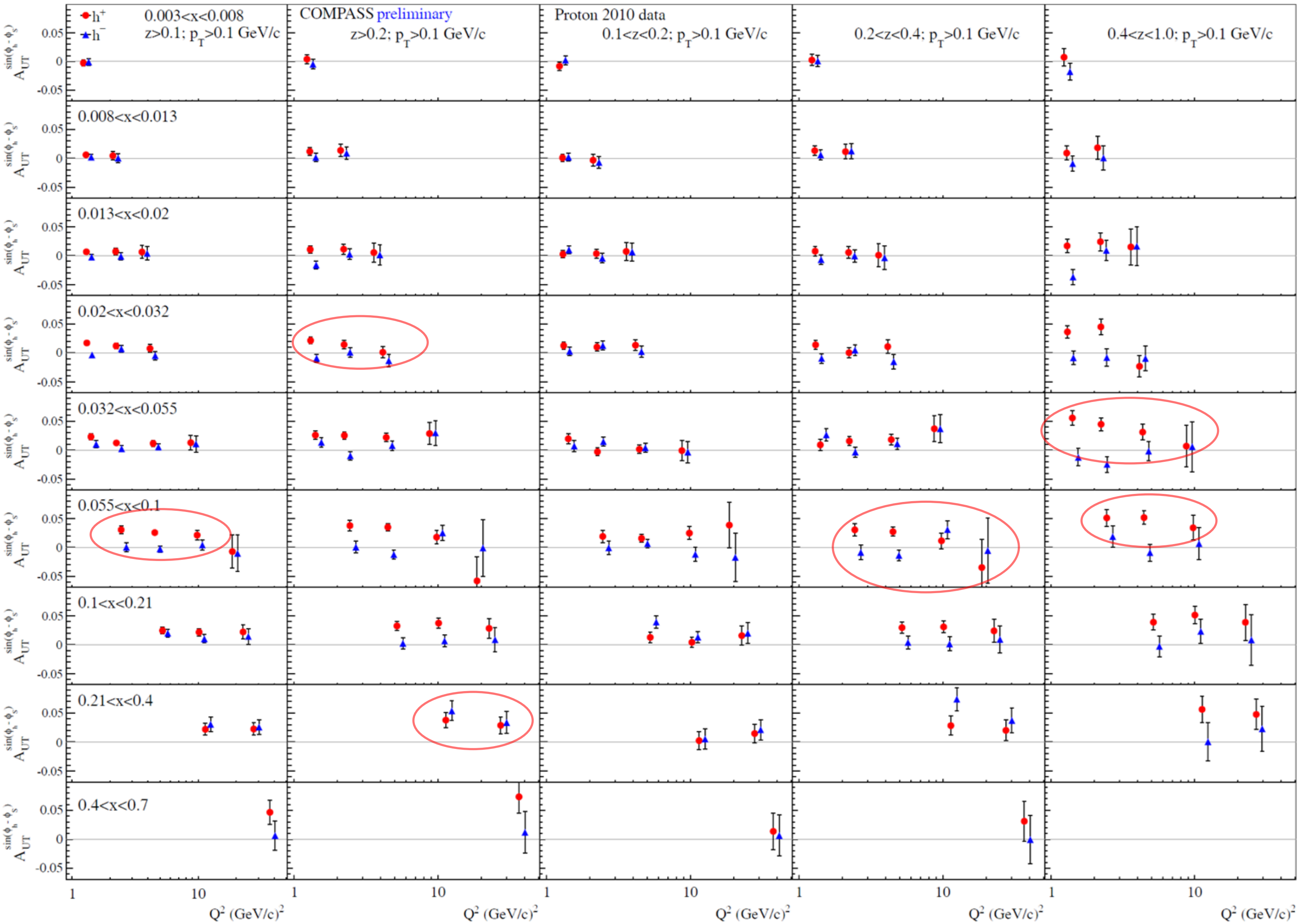
B.Parsamyan (for COMPASS) arXiv:1504.01599 [hep-ex] (SPIN-2014)



- No clear Q^2-dependence within statistical accuracy
- Possible decreasing trend for Sivers TSA?

Sivers asymmetry: 3D x-z-Q^2 dependence

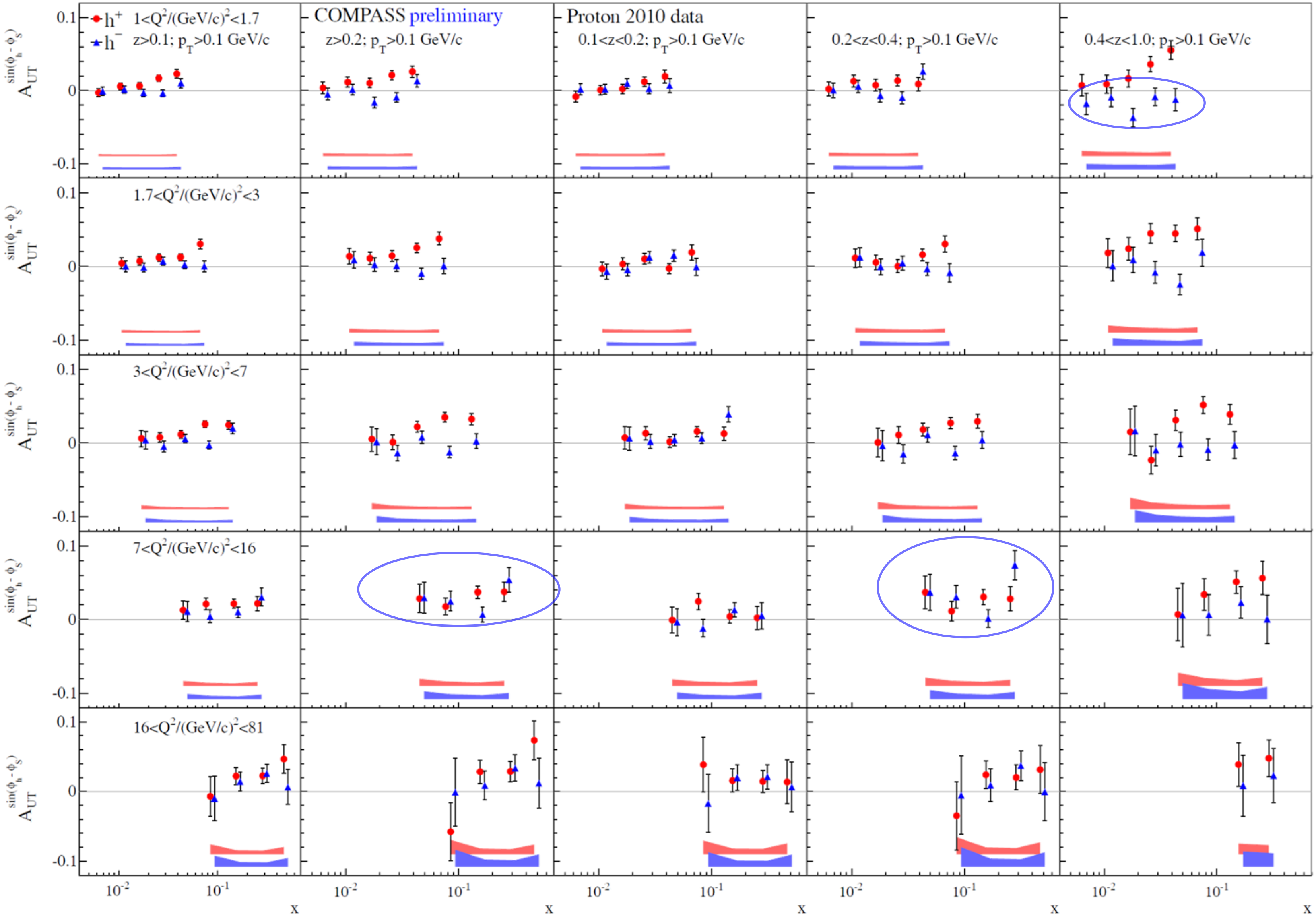
COMPASS 25 years 1997 - 2022



3D

- In several x-bins some hints for possible Q^2-dependence for positive hadrons (decrease) more evident at large z
- At low z effect for h^+ is smaller in general
- No clear picture for negative hadrons

Sivers asymmetry: 3D Q^2-z-x dependence



3D

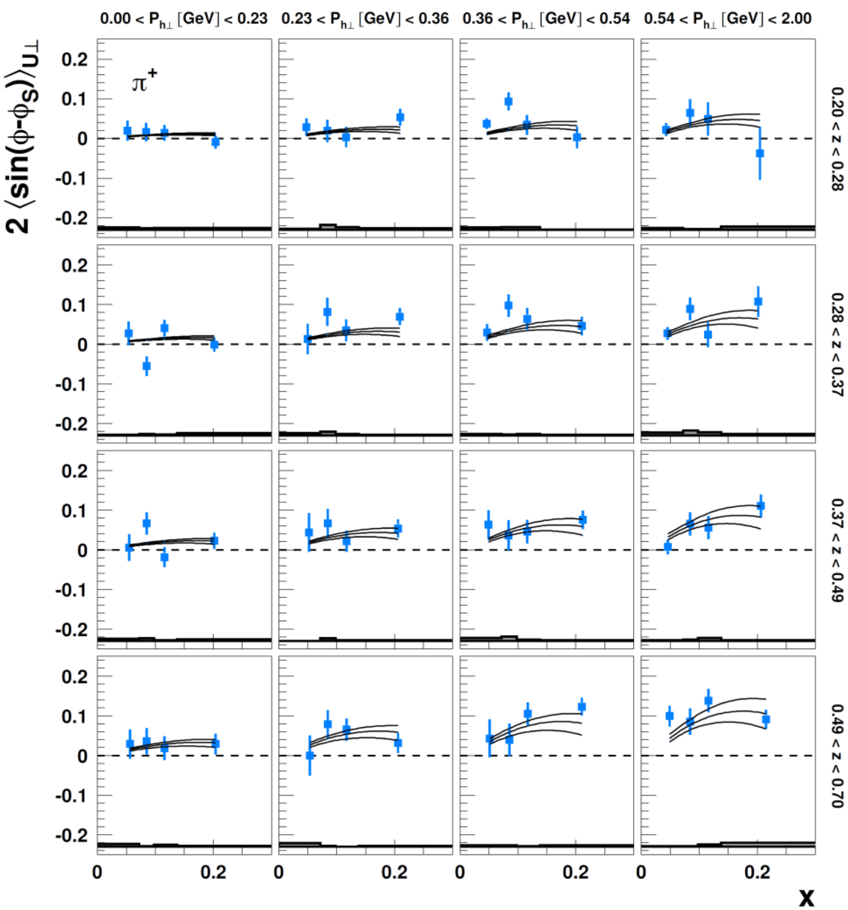
- Positive amplitude for h^+ (increasing with x and z)
- Positive h^- amplitude at relatively large x (>0.032) and Q^2 (>7) at intermediate and large z
- Some hint for a possible negative h^- amplitude at low x (<0.032) and Q^2 (<7)) at intermediate and large z

COMPASS Multi-D TSA analyses

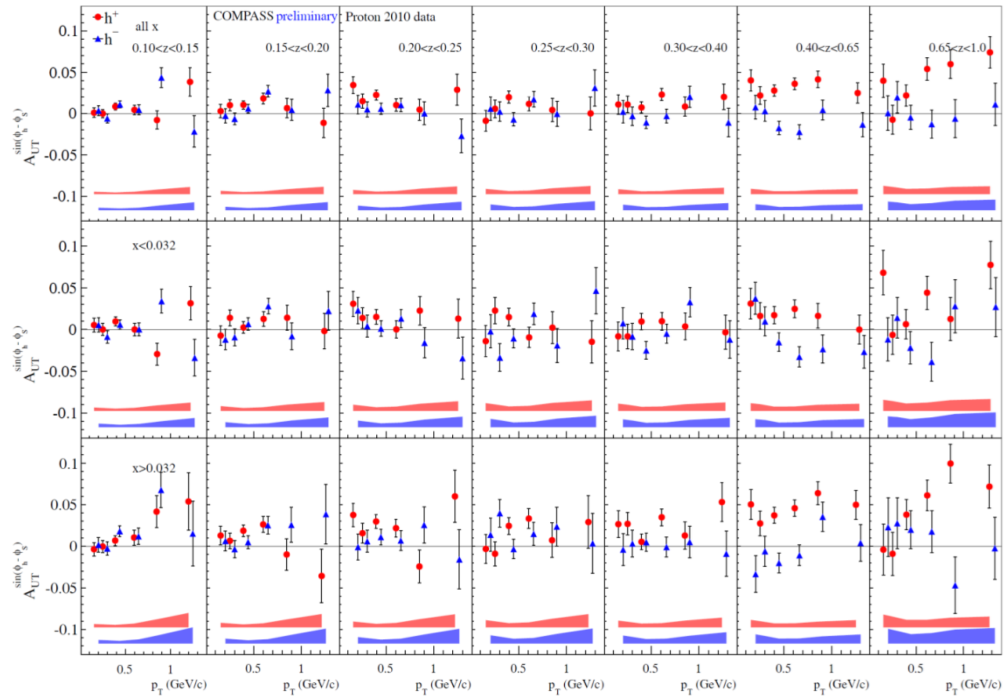
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h - \phi_S) + \ldots\right\}$$

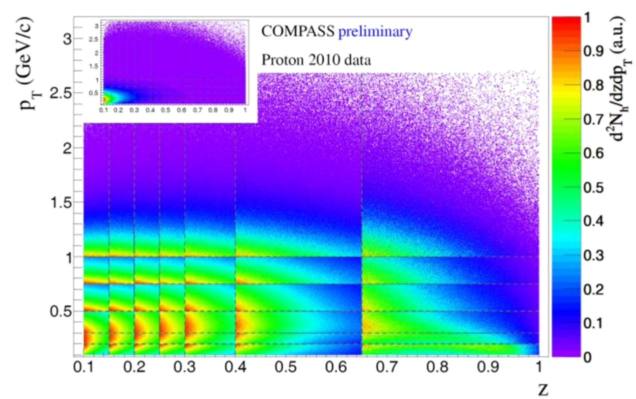
$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M} f_{1T}^{\perp q} D_{1q}^{h}\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0$$

HERMES, JHEP 12 (2020) 010

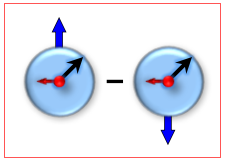


B.Parsamyan (for COMPASS) arXiv:1504.01599 [hep-ex] (SPIN-2014)





SIDIS TSAs: Kotzinian-Mulders asymmetry



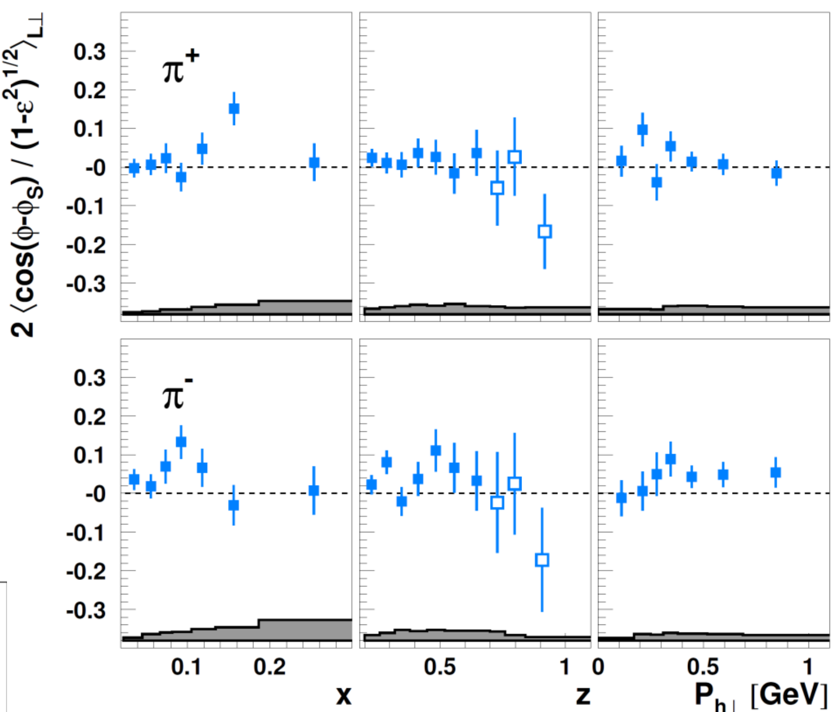
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\lambda S_T\sqrt{\left(1-\varepsilon^2\right)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos\left(\phi_h-\phi_S\right)+\ldots\right\}$$

$$F_{LT}^{\cos(\phi_h-\phi_S)} = C\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}g_{1T}^q D_{1q}^h\right]$$

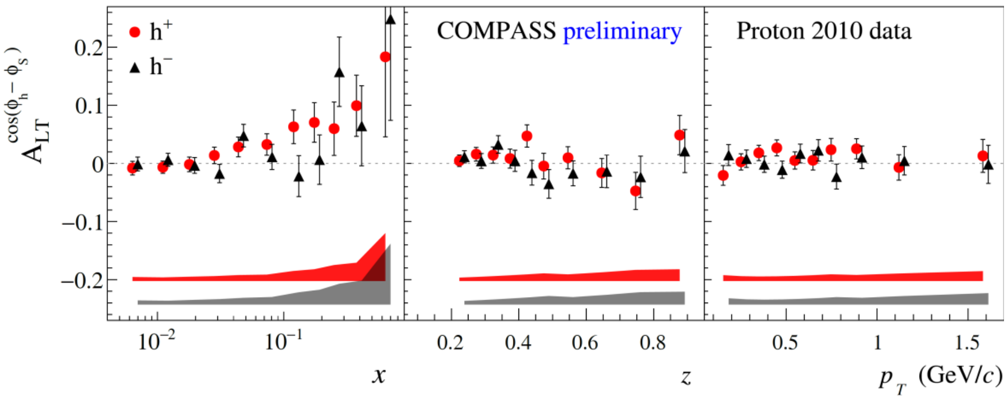
COMPASS/HERMES/CLAS6 results $A_{LT}^{\cos(\phi_h-\phi_S)}$

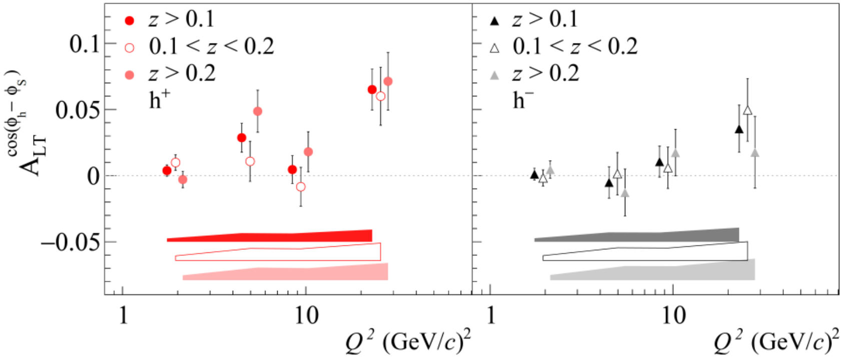
- Only “twist-2” ingredients
- Sizable non-zero effect for h^+ !
- Similar effect at HERMES

HERMES, JHEP 12 (2020) 010

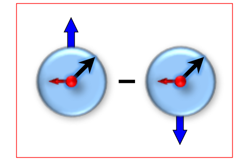


COMPASS, PBL 770 (2017) 138; PoS QCDEV2017 (2018) 042



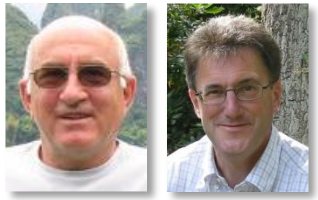


SIDIS TSAs: Kotzinian-Mulders asymmetry

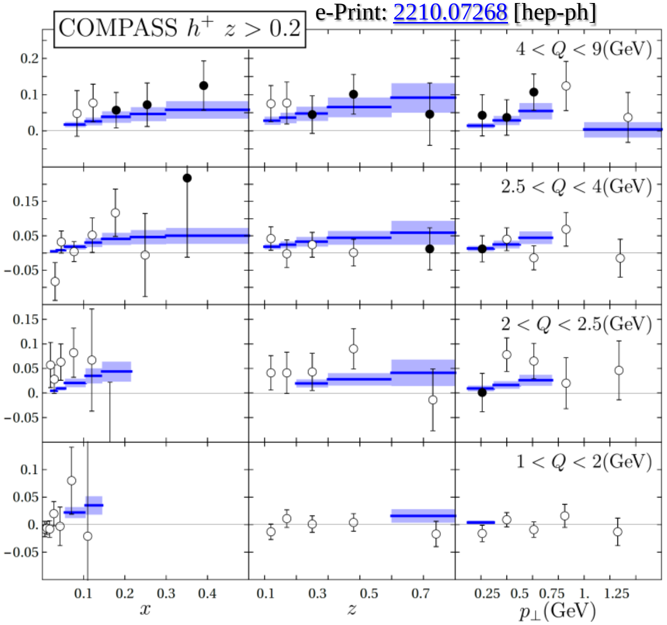


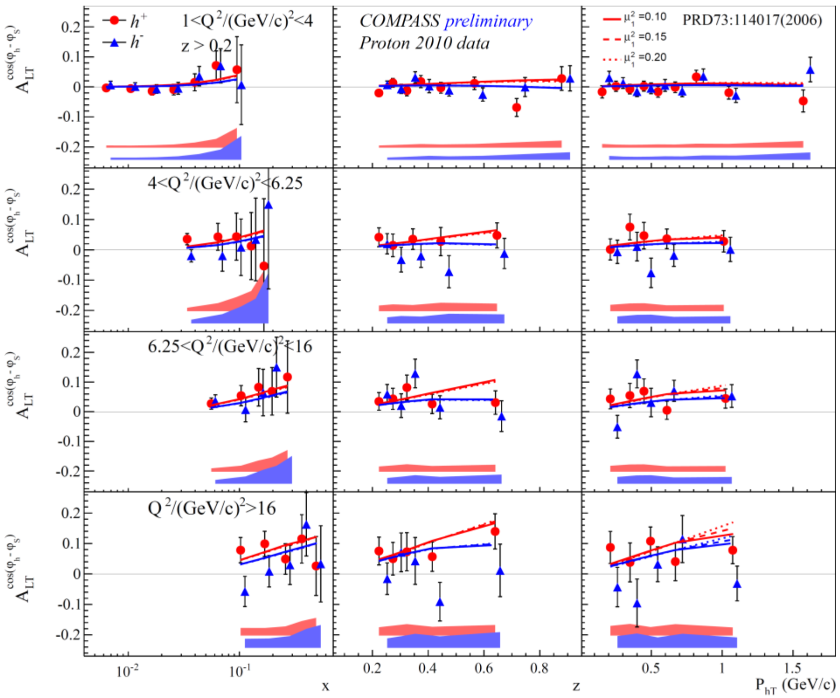
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + \lambda S_T \sqrt{\left(1-\varepsilon^2\right)}\, A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h - \phi_S) + \ldots\right\}$$

$$F_{LT}^{\cos(\phi_h-\phi_S)} = C\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\, g_{1T}^{q} D_{1q}^{h}\right]$$

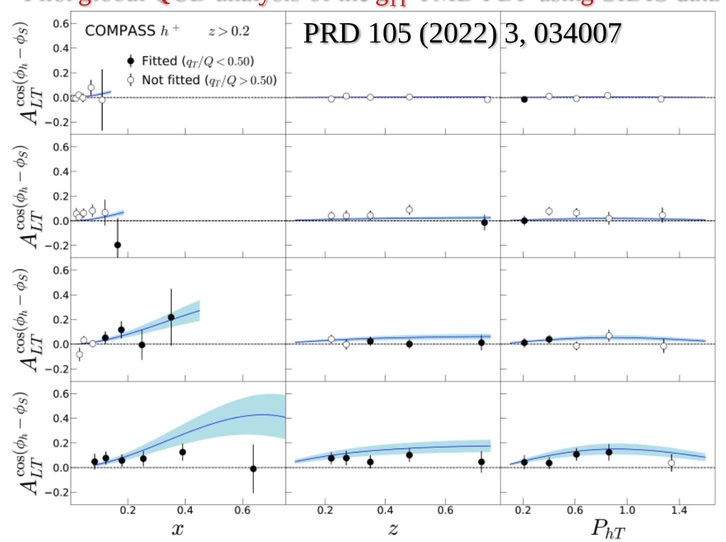


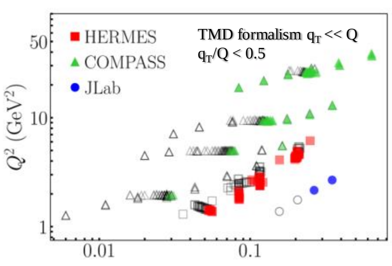
M. Horstmann, A. Schafer and A. Vladimirov
e-Print: 2210.07268 [hep-ph]

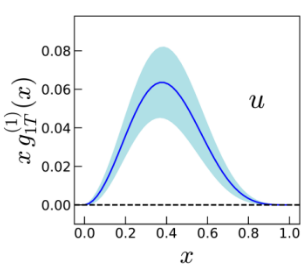


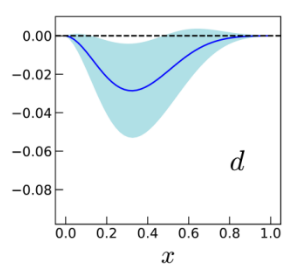


First global QCD analysis of the g_{1T} TMD PDF using SIDIS data









COMPASS 2022 run: new unique deuteron data to come

Pavia group fits

- hermes, proton [H], 95 data points — *Airapetian et al., P.R.L.* ***103*** *(09) 152002*
- Jefferson Lab, neutron [³He], 6 data points — *Qian et al., P.R.L.* ***107*** *(11) 072003*
- COMPASS 2009, deuteron [⁶LiD], 88 data points — *Alekseev et al., P.L.* ***B673*** *(09) 127*
- COMPASS 2017, Proton [NH₃], 111 data points — *Adolph et al., P.L.* ***B770*** *(17) 138*

Bacchetta, Delcarro, Pisano, Radici, in preparation

analysis of statistical error with replica method (200)
68% confidence level

Same kinematic cuts applied to unpolarized

x, z, P_{hT} data projections

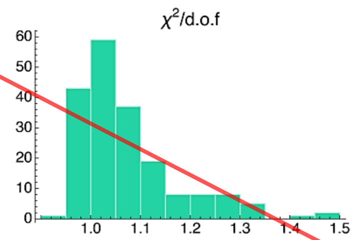
$Q^2 \geq 1.4\ \mathrm{GeV}^2$ $\quad 0.2 \leq z \leq 0.7$

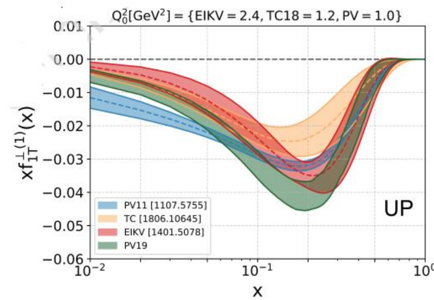
$P_{hT} < \min[0.2Q,\ 0.7Qz] + 0.5\ \mathrm{GeV}$

300 data points → **118** data fitted

14 free parameters

χ^2/d.o.f. = 1.06 ± 0.10

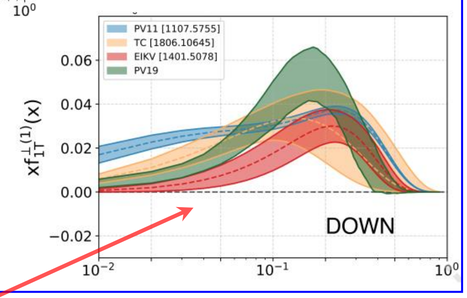




PV11	*Bacchetta & Radici, P.R.L.* ***107*** *(11)*
EIKV	*Echevarria et al., P.R. D****89*** *(14)*
TC	*Boglione et al., JHEP* ***1807*** *(18)*
PV19	*Bacchetta, Delcarro, Pisano, Radici, in preparation*

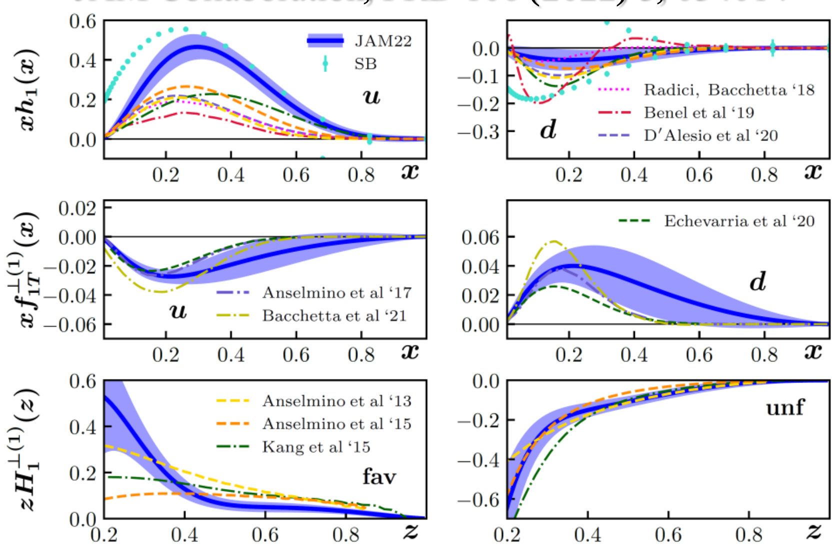
$$f_{1T}^{\perp(1)}(x) = \int d\mathbf{k}_T \,\frac{\mathbf{k}_T^2}{2M^2}\, f_{1T}^{\perp}(x, \mathbf{k}_T)$$

SEA 10^{-2} × smaller
(compatible with 0)

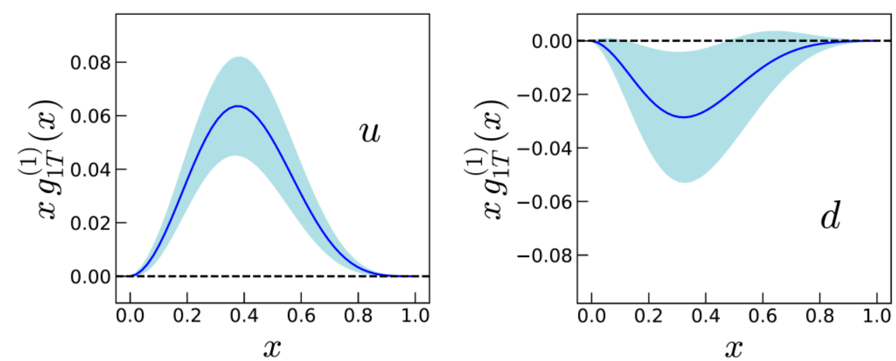


COMPASS 2022 deuteron run

JAM Collaboration, PRD 106 (2022) 3, 034014



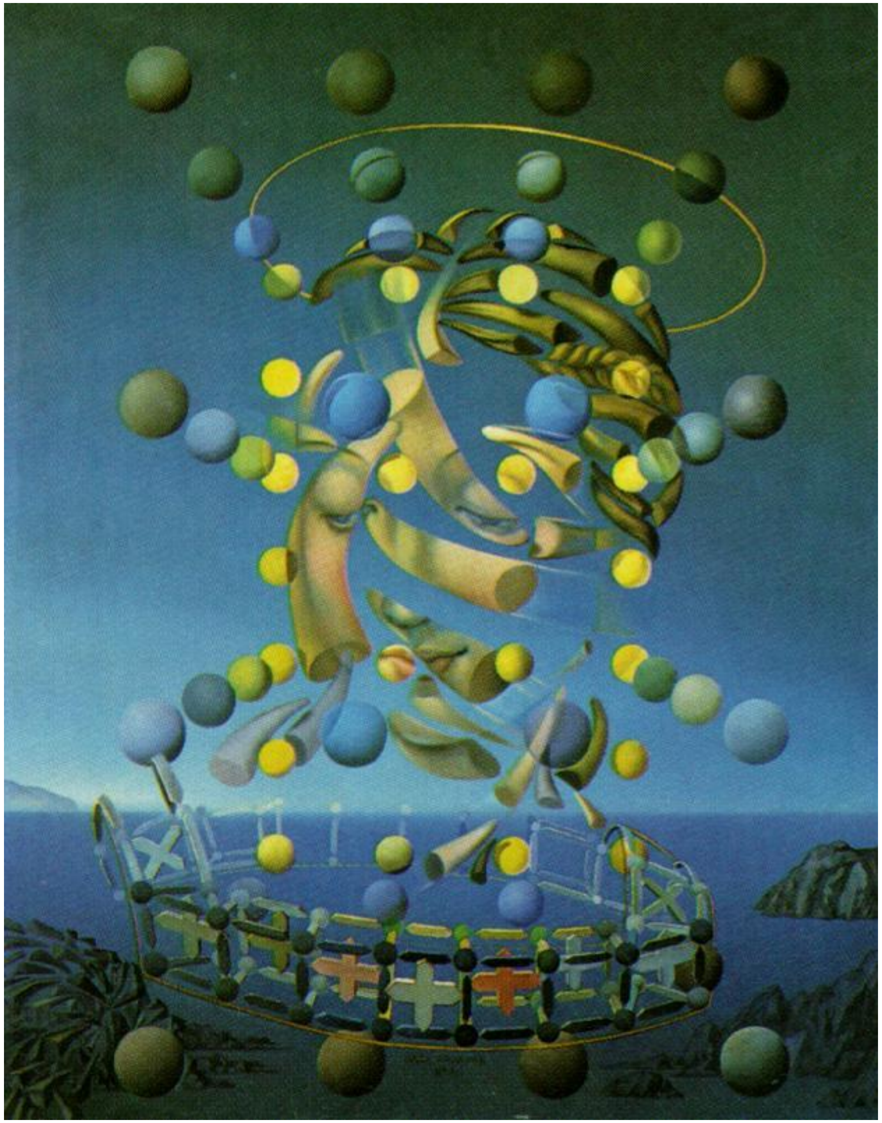
S. Bhattacharya, Z. B. Kang, A. Metz, G. Penn and D.Pitonyak PRD 105 (2022) 3, 034007



“Nature”

Raphael “Madonna del Prato”

“1D”

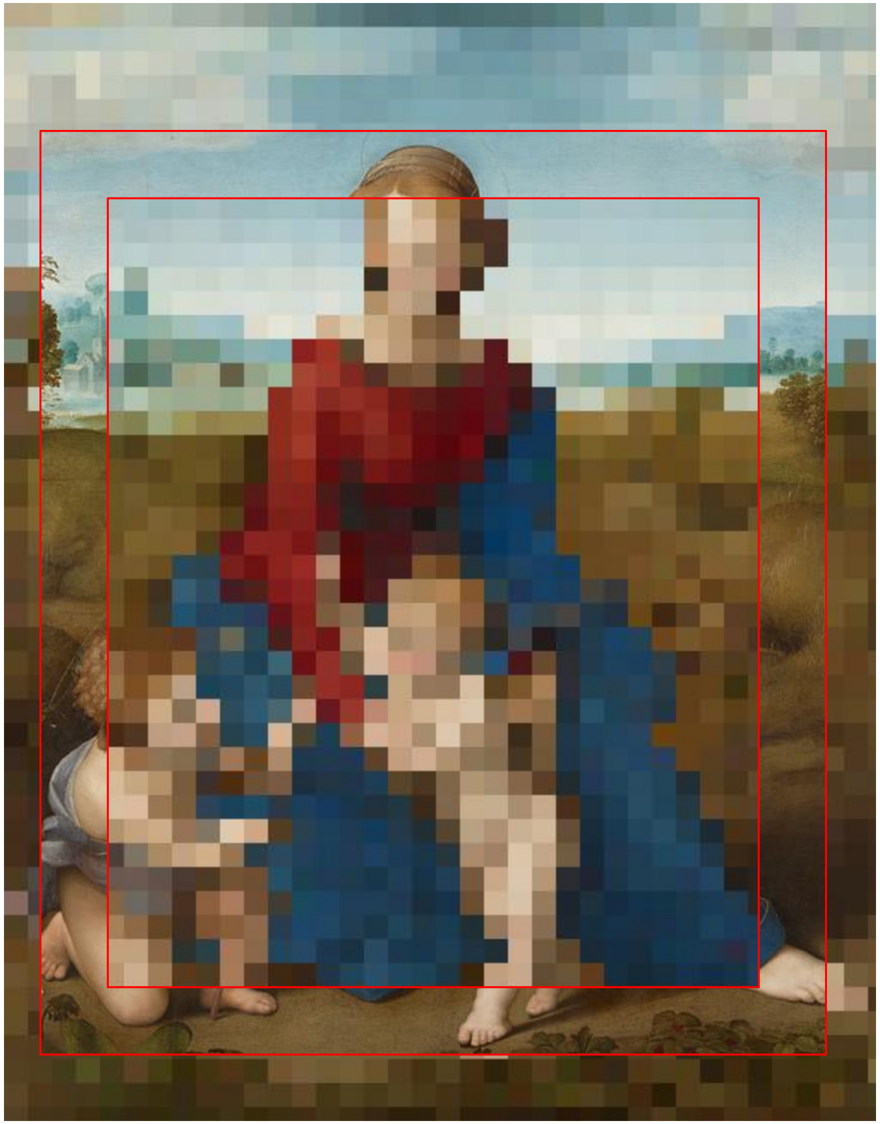


Salvador Dali “Maximum Speed of Raphael's Madonna”

“Nature”

Raphael “Madonna del Prato”

“multi-D” with available statistics



Raphael “Madonna del Prato” (poor resolution)

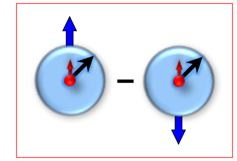
Conclusions

- For a better and more complex understanding of the TMD-spin-phenomena, it is important to carry out the extractions, analyses and various corrections in a multi-D approach
- It is also important to carefully confront experimental data from different experiments
- Different complex analysis techniques, Monte-Carlo simulations and various corrections (acceptance, VMs, radiative corrections) are being employed by different experimental collaborations
  - Closer collaboration between different experimental groups would be very beneficial for the field in general
  - Sharing the tools (MC, generators, analysis techniques), preliminary results, doing cross-analyses, etc.
- Close collaboration between experimentalists on one side and phenomenologists and theorists on the other would also be very beneficial
  - Flexibility in adapting on the analysis side (in a timely manner) the choice of the observables, phase-space limitations, etc.
  - Ideally a close collaborative work can be organized

Thank You!

- Spare slides

SIDIS TSAs: Collins effect and Transversity



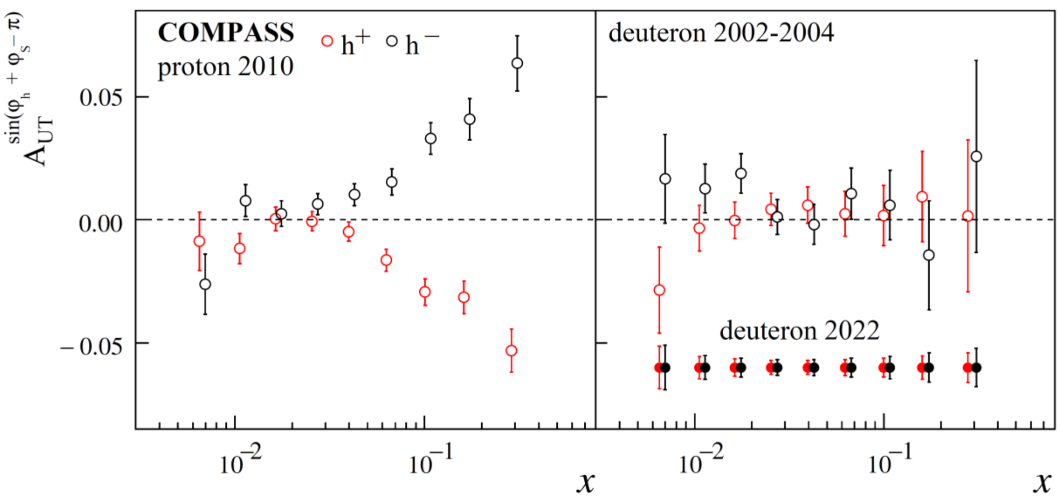
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h + \phi_S) + \ldots\right\}$$

$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}} \cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

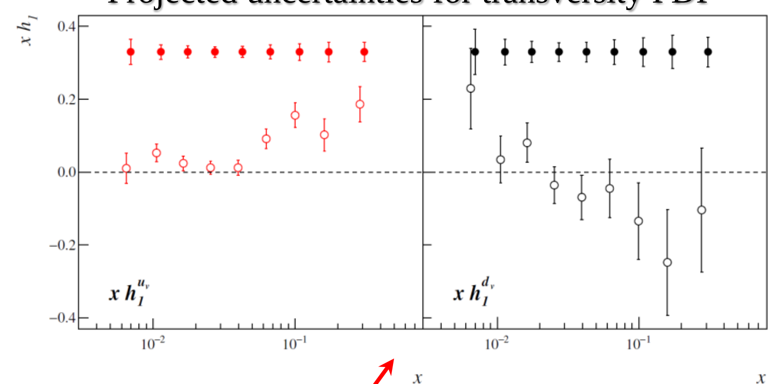
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?
- Extensive phenomenological studies and various global fits by different groups

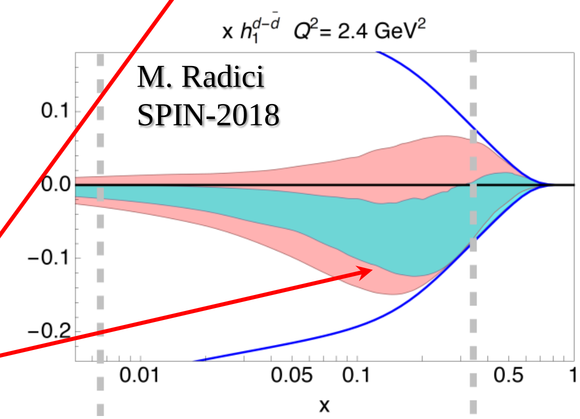
[Addendum to the COMPASS-II Proposal]

Projected uncertainties for Collins asymmetry



Projected uncertainties for transversity PDF

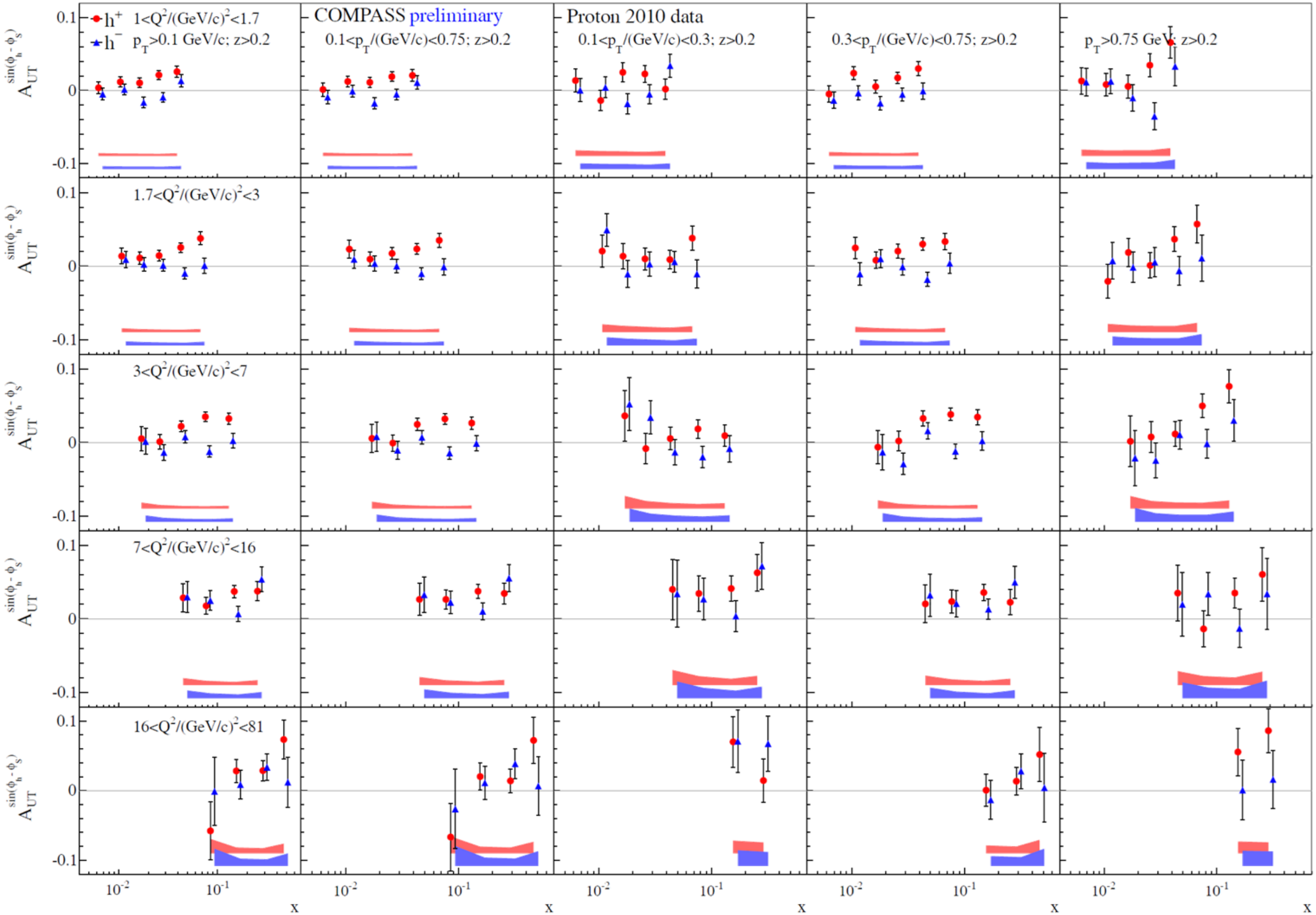




COMPASS-II (2022)

- Deuteron measurement being repeated
- Will be crucial to constrain the transversity TMD PDF for the d-quark

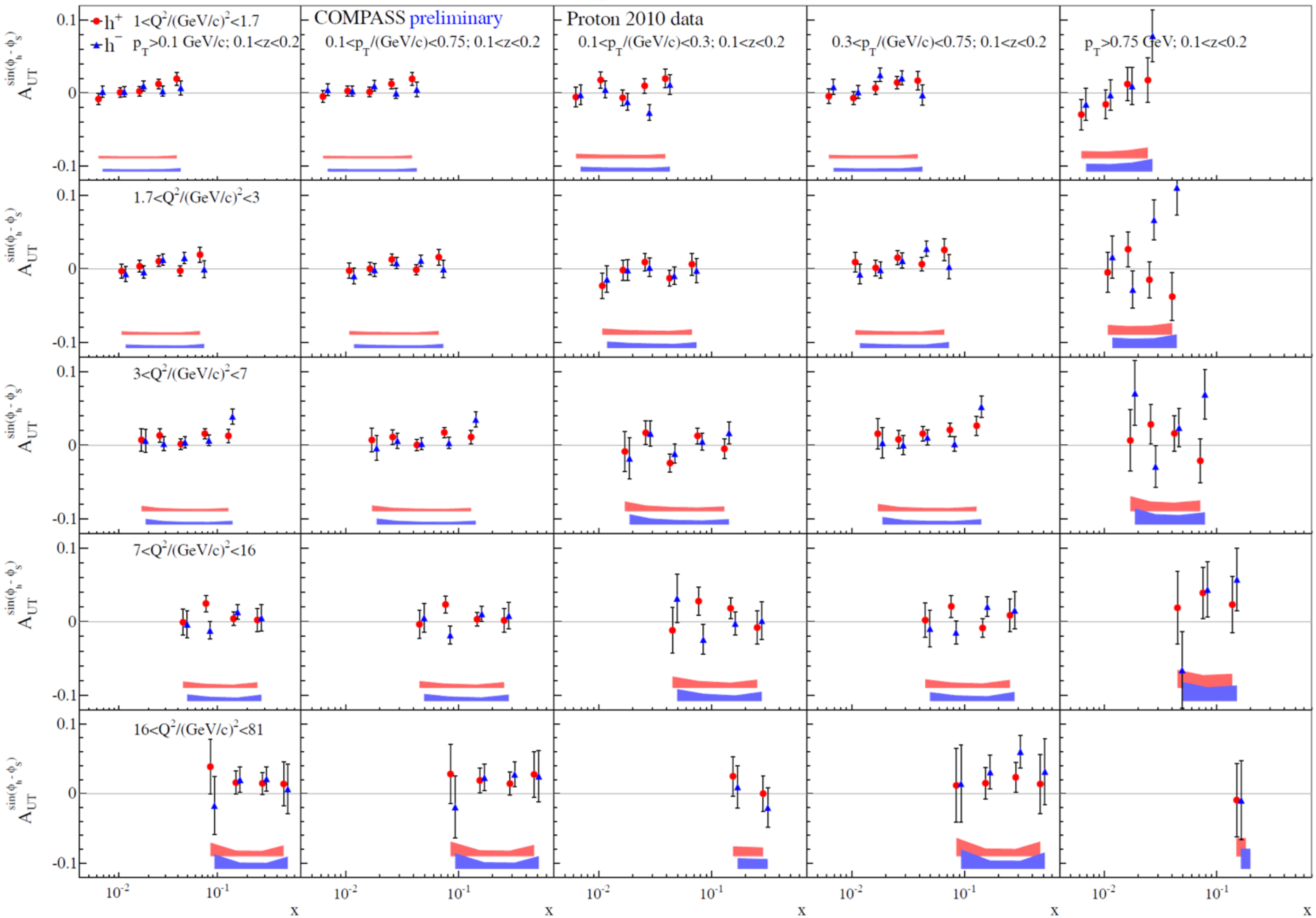
Sivers asymmetry: 4D Q^2-p_T-x dependence at z>0.2



4D

- Positive amplitude for h^+ (increasing with x and z and p_T)
- Positive h^- amplitude at relatively large x (>0.032) and Q^2 (>7) at intermediate and large z (all p_T)
- Some hint for a possible negative h^- amplitude at low x (<0.032) and Q^2 (<7)) at intermediate and large z (all p_T)

Sivers asymmetry: 4D Q^2-p_T-x dependence at 0.1<z<0.2



4D

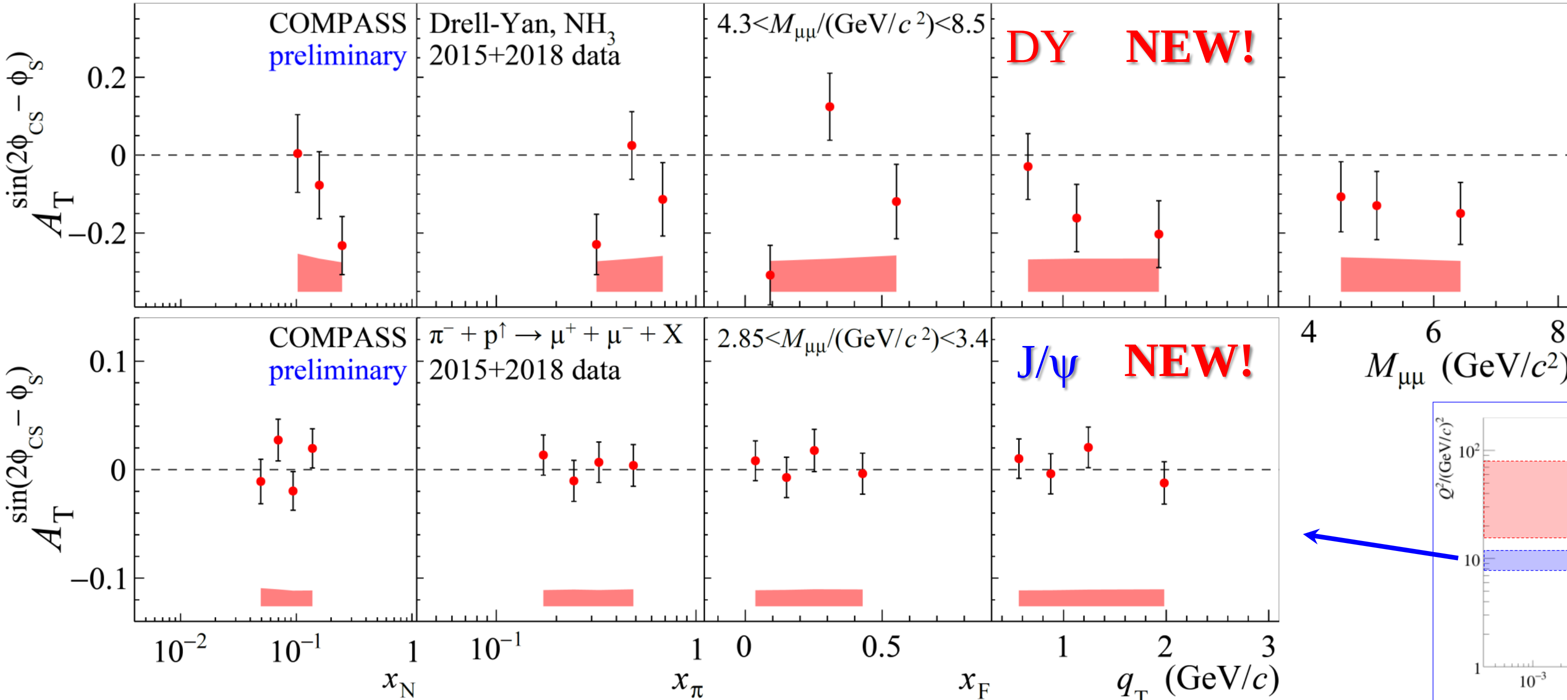
- Positive amplitude for h^+ (increasing with x and z and p_T)
- Positive h^- amplitude at relatively large x (>0.032) and Q^2 (>7) at intermediate and large z (all p_T)
- Some hint for a possible negative h^- amplitude at low x (<0.032) and Q^2 (<7)) at intermediate and large z (all p_T)

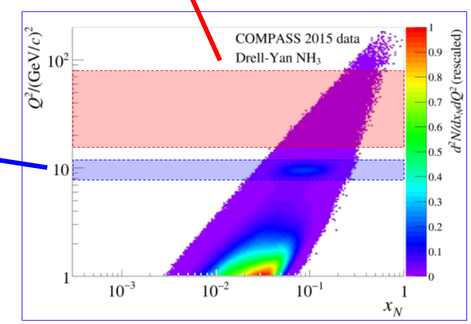
Drell-Yan TSAs – Transversity

$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \ldots + S_T \left[D_{[\sin^2\theta_{CS}]} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) + \ldots \right]$$

Transversity DY TSA

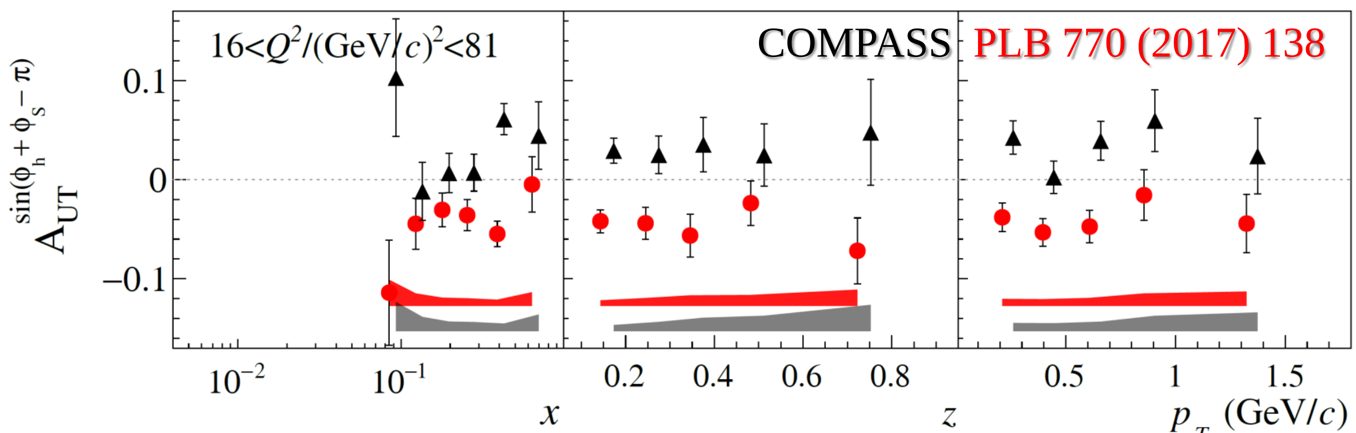
$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$$





Collins SIDIS TSA

$$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1^q \otimes H_{1q}^{\perp h}$$

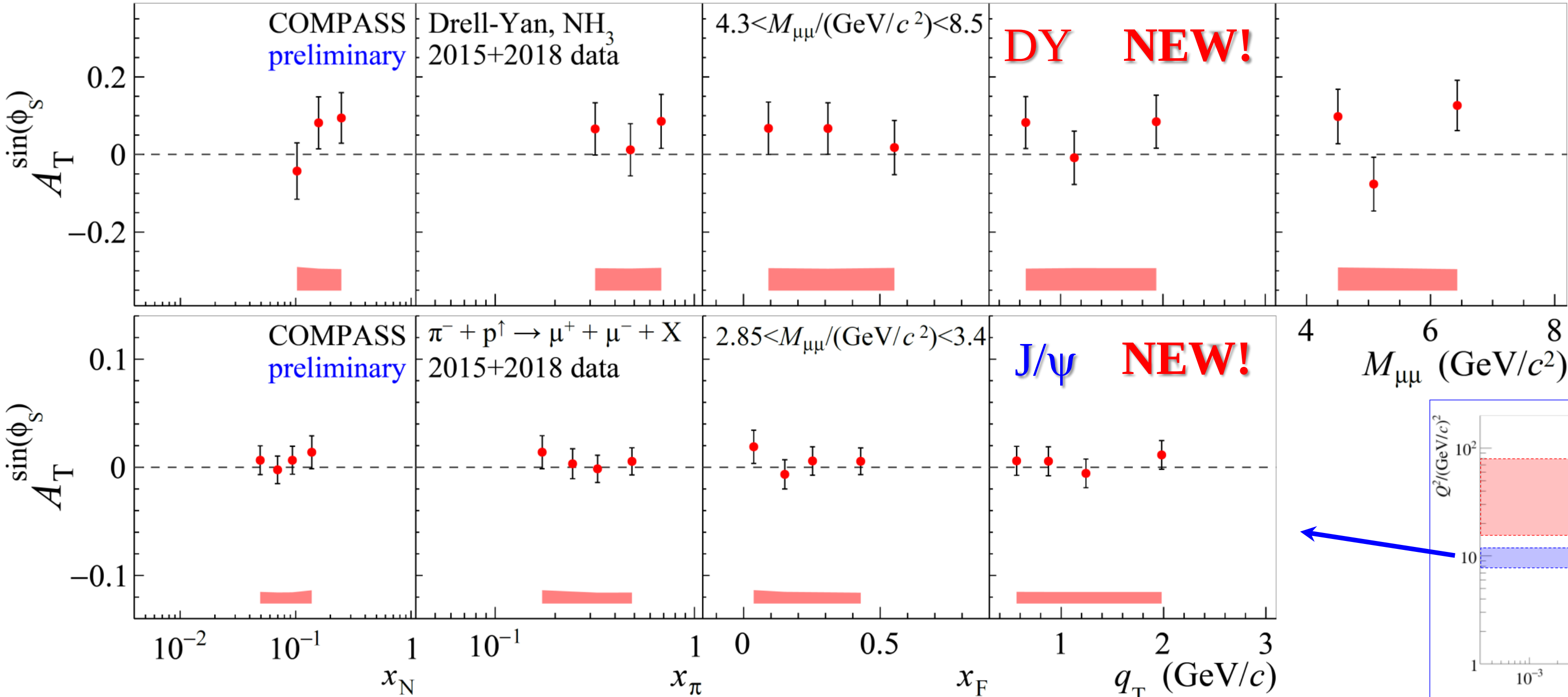


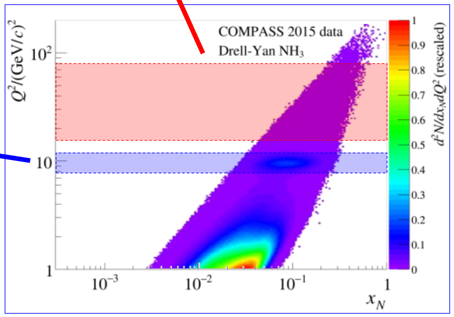
Drell-Yan TSAs – Sivers

$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \ldots + S_T \left[A_T^{\sin\varphi_S} \sin\varphi_S + \ldots \right]$$

Sivers DY TSA

$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$$

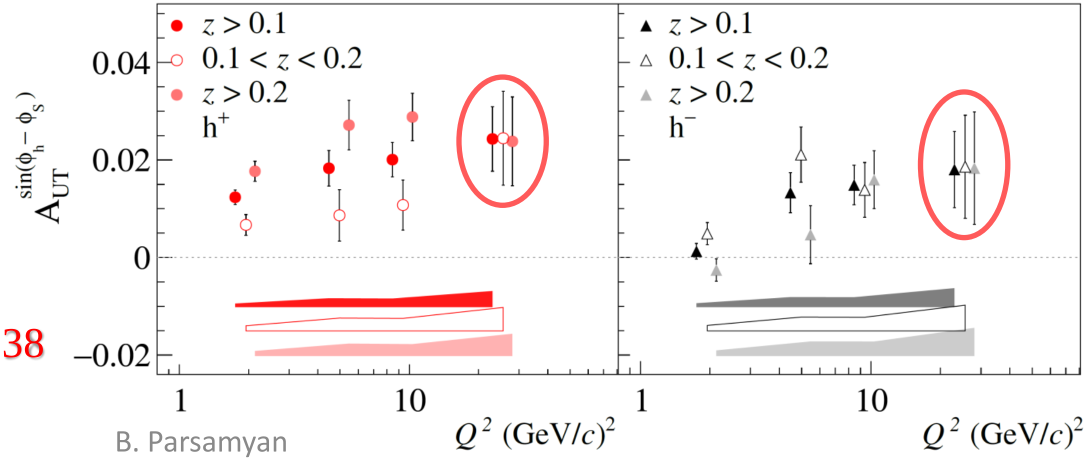




Sivers SIDIS TSA

$$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$

COMPASS
PLB 770 (2017) 138

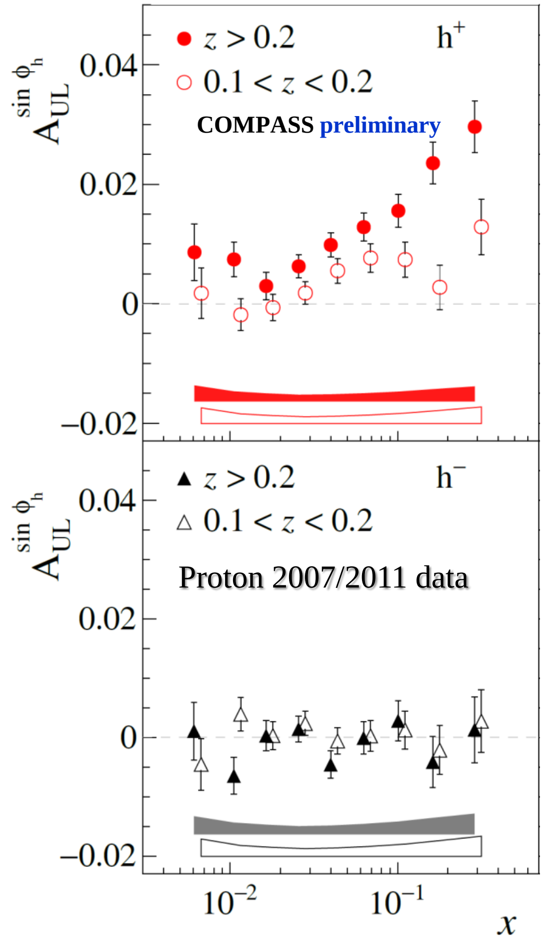


SIDIS: target longitudinal spin dependent asymmetries

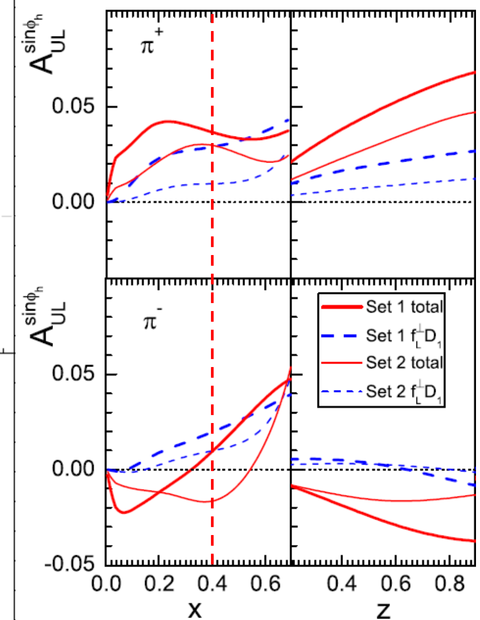
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \ldots\right\}$$

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

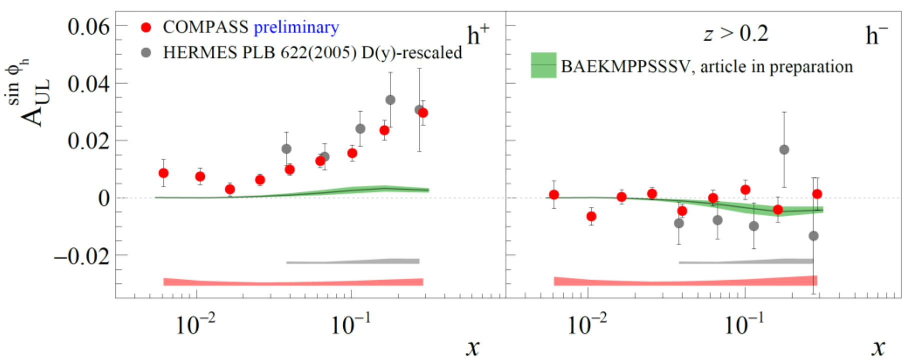
B. Parsamyan (for COMPASS)
arXiv:1801.01488 [hep-ex]



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**