Nucleon spin structure studies at COMPASS: Highlights from recent polarized measurements

BAKUR PARSAMYAN

INFN section of Turin and CERN

on behalf of the COMPASS Collaboration

International Hybrid Workshop on

"Opportunities with JLab Energy and Luminosity Upgrade"

ECT*, Trento, Italy

26-30 September, 2022

COMPASS collaboration

Common Muon and Proton Apparatus for Structure and Spectroscopy

25 institutions from 13 countries
– nearly 200 physicists

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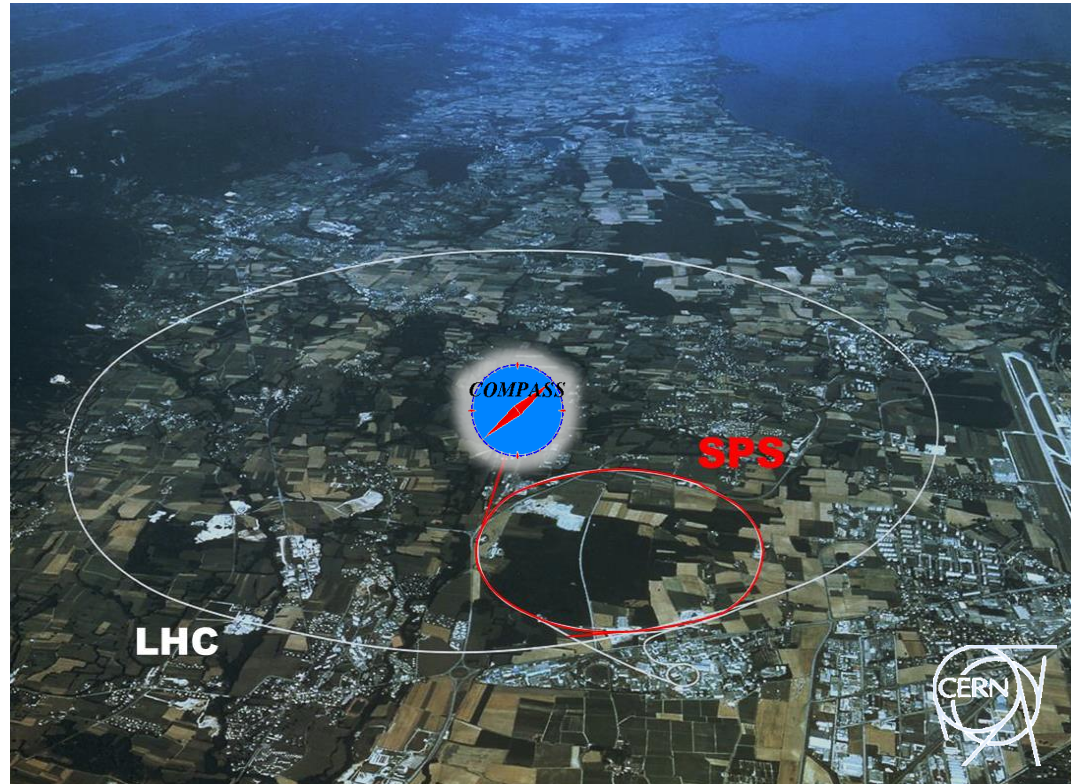- **Taking data since 2002 (20 years)**

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**

See also COMPASS talks by A.Martin, N. d'Hose and A.Moretti

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

COMPASS collaboration

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

COMPASS
25 years
1997 – 2022

25 institutions from 13 countries
– nearly 200 physicists

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International Workshop on Hadron Structure and Spectroscopy
IWHSS-2022 workshop (anniversary edition)
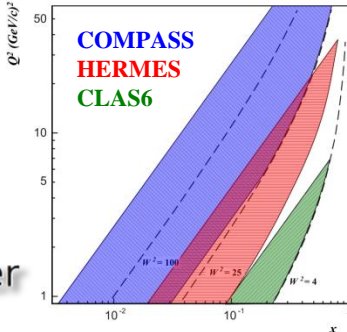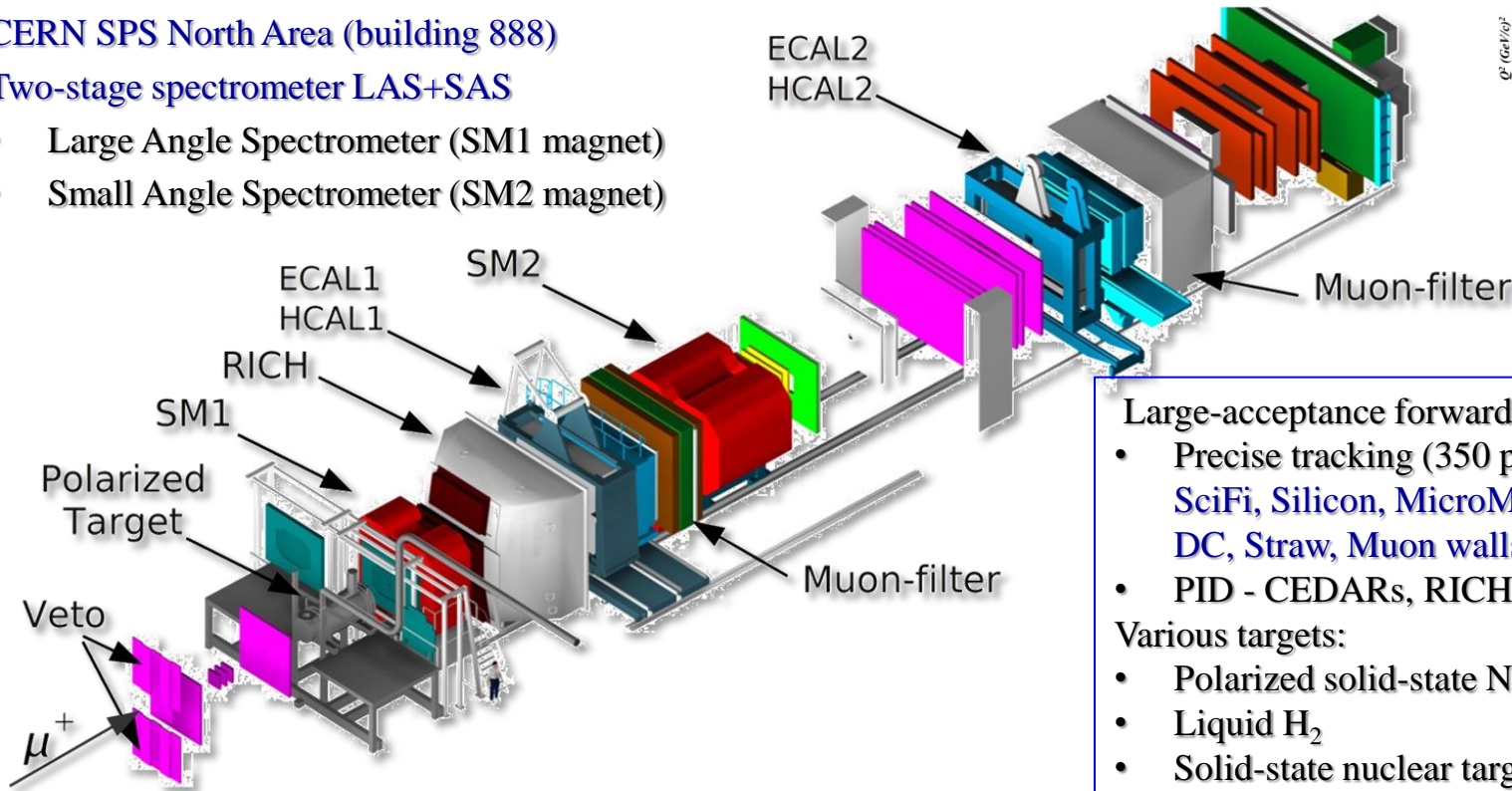CERN Globe, August 29-31, 2022

https://indico.cern.ch/e/IWHSS-2022
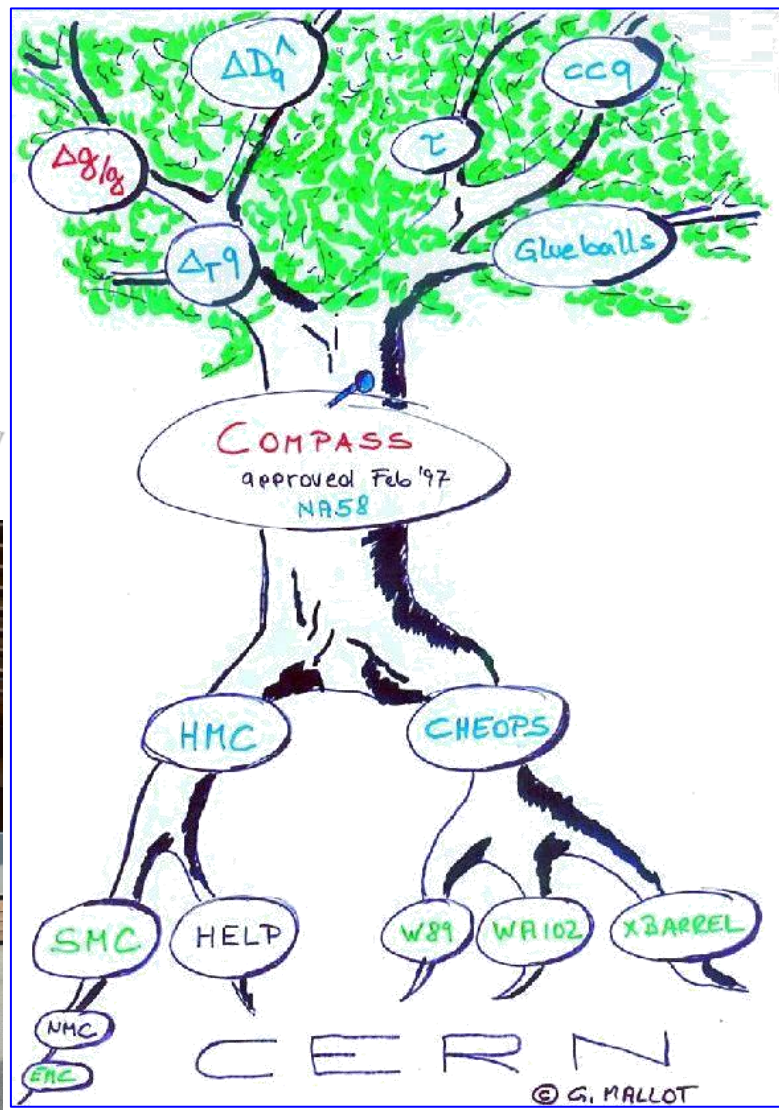
COMPASS experimental setup

COmmon Muon Proton Apparatus for Structure and Spectroscopy
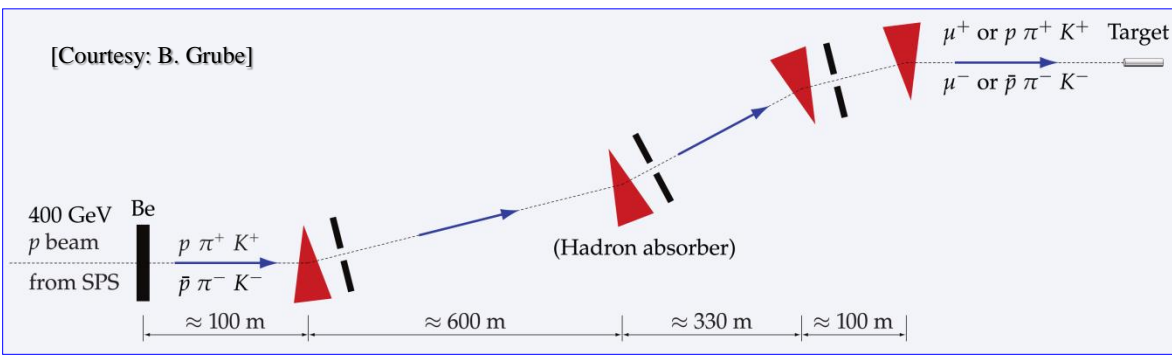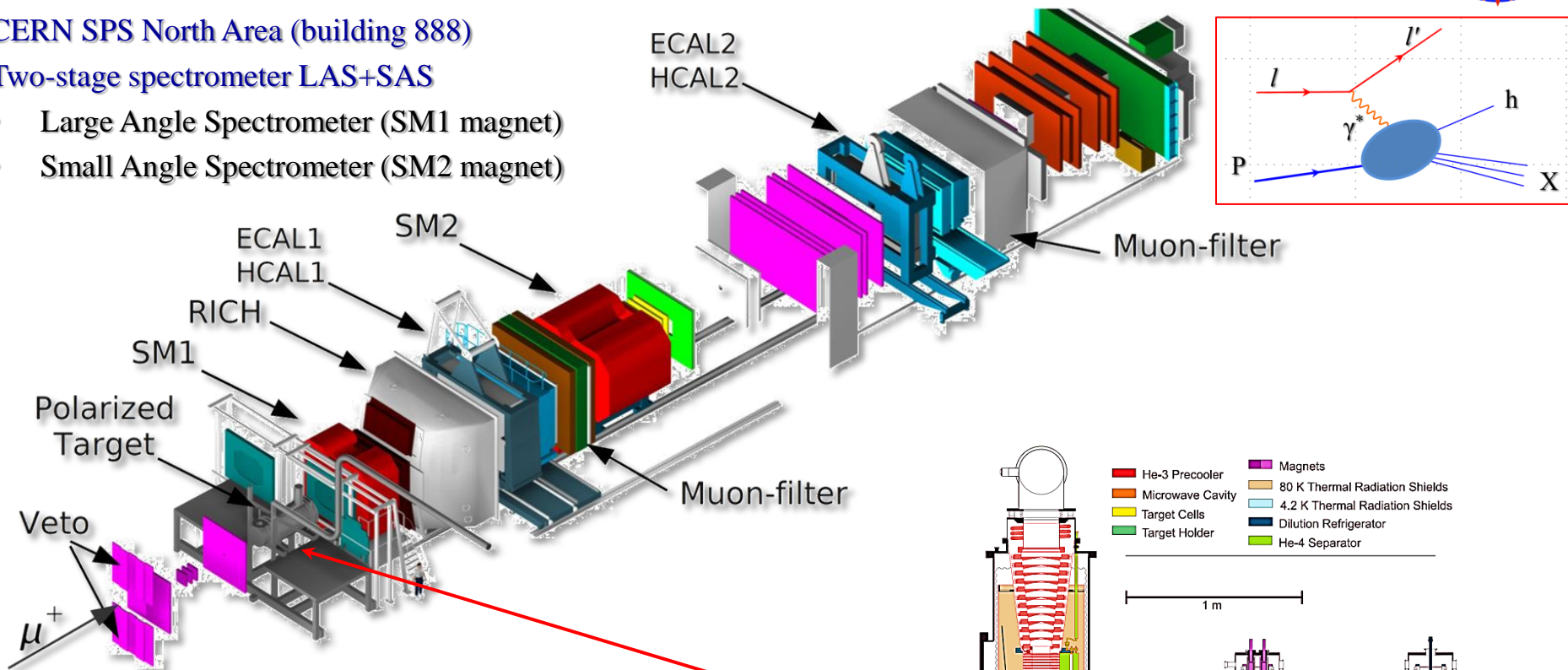
CERN SPS North Area (building 888)

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

[Courtesy: B. Grube]

400 GeV p beam from SPS — Be — $p\ \pi^+\ K^+$ / $\bar{p}\ \pi^-\ K^-$ — (Hadron absorber) — μ^+ or $p\ \pi^+\ K^+$ Target / μ^- or $\bar{p}\ \pi^-\ K^-$

≈ 100 m | ≈ 600 m | ≈ 330 m | ≈ 100 m

COMPASS experimental setup: Phase II (SIDIS programme)

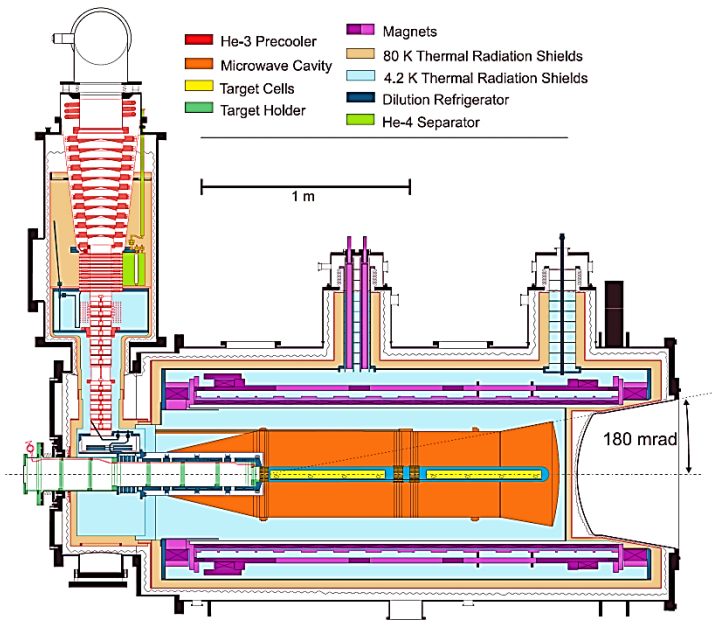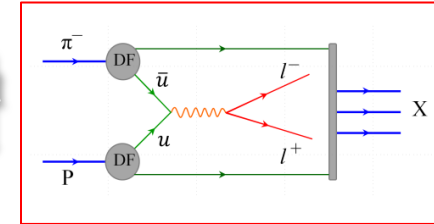## COmmon Muon Proton Apparatus for Structure and Spectroscopy

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
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  - h$^-$ beam: 97% π^-, 2% K^-, 1% p
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- 160 GeV tertiary muon beams
  - μ^+ longitudinally polarized

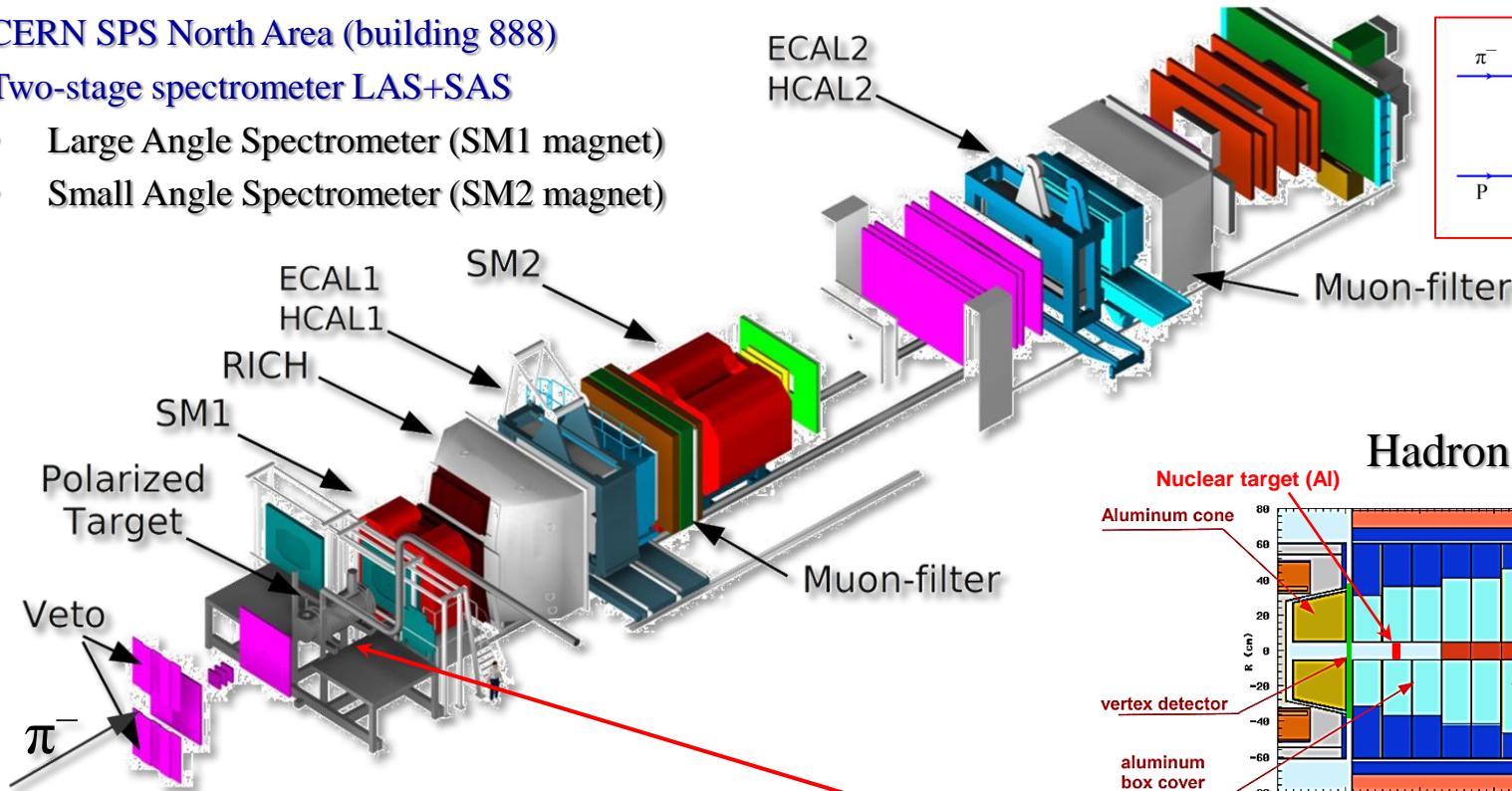# COMPASS experimental setup: Phase II (DY programme)

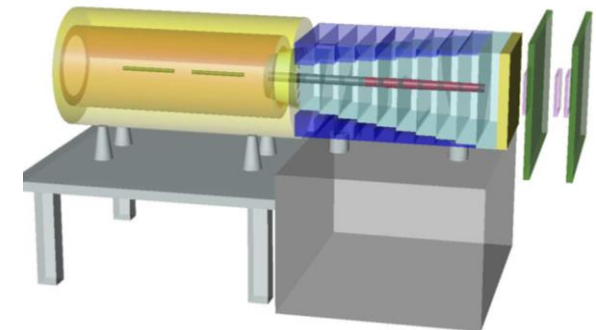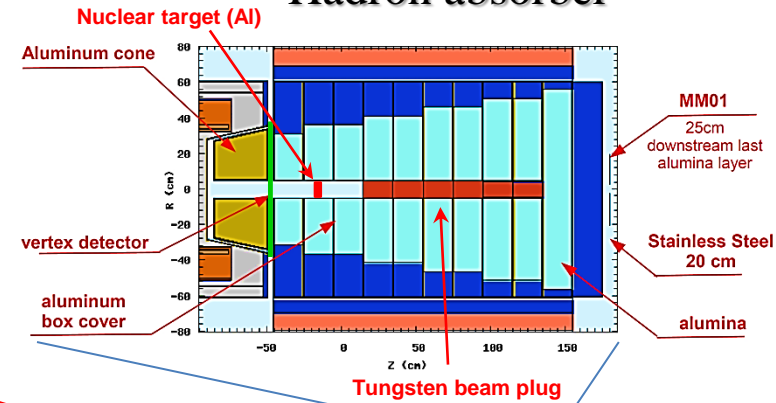## COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

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

ECAL2
HCAL2

ECAL1
HCAL1

SM2

RICH

SM1

Muon-filter

Polarized
Target

Veto

π^-

Muon-filter

Hadron absorber

Nuclear target (Al)

Aluminum cone

vertex detector

aluminum box cover

Tungsten beam plug

MM01
25cm downstream last alumina layer

Stainless Steel 20 cm

alumina

- 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
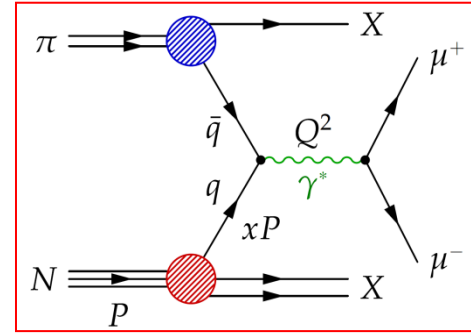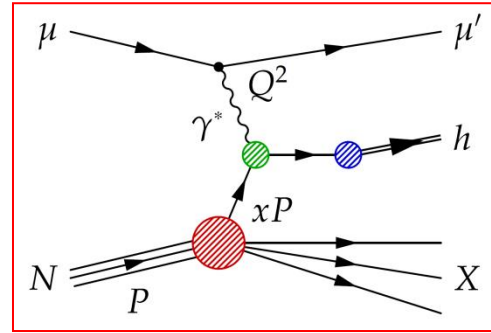 - h$^+$ beam: 75% p, 24% π^+, 1% K^+
- 160 GeV tertiary muon beams
  - $\mu^\pm$ longitudinally polarized

Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

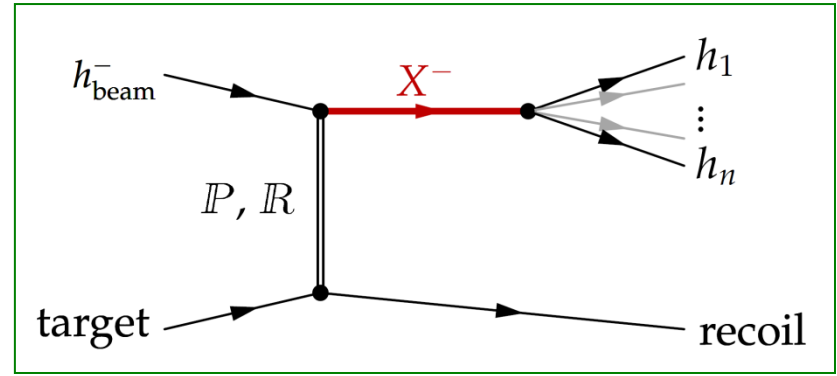**Increasing resolution scale (momentum transfer)**

Nucleon structure

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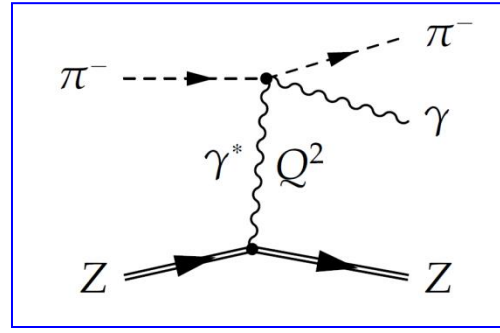- Parton distribution functions and fragmentation functions

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 $\pi(K)\,\gamma$ reactions
- $\pi^{\pm}$ and $K^{\pm}$ polarizabilities
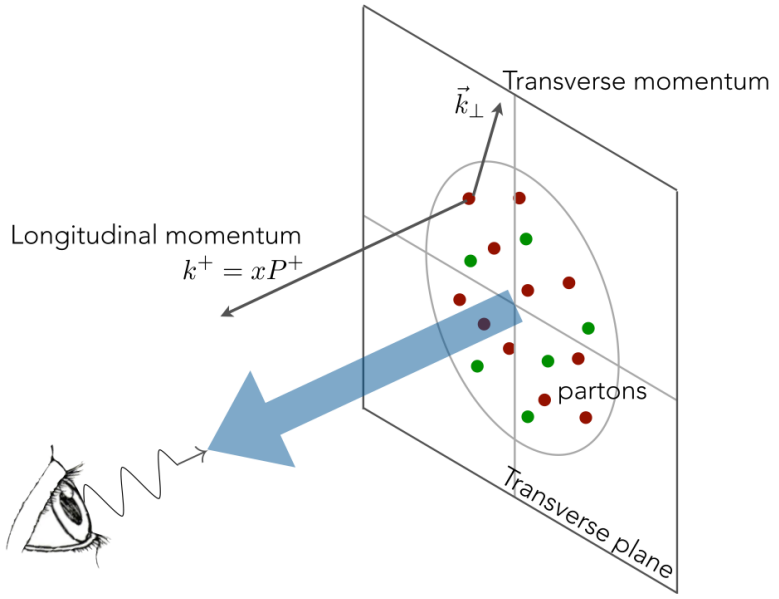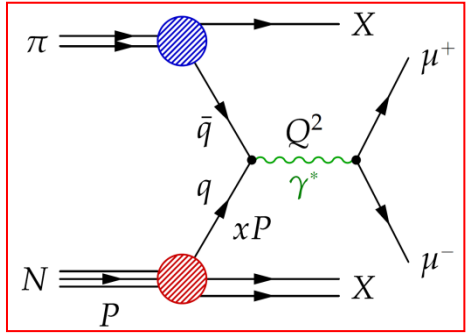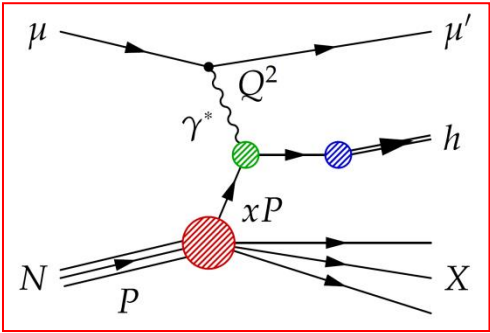- Chiral anomaly $F_{3\pi}$

The COMPASS Experiment at the CERN SPS

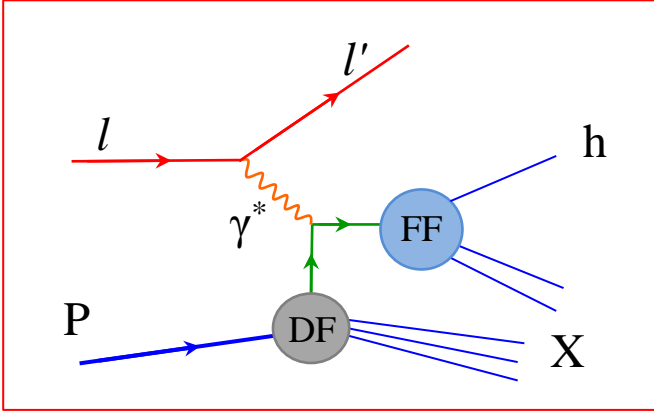## Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

Increasing resolution scale (momentum transfer)

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- Chiral anomaly $F_{3\pi}$

Transverse momentum $\vec{k}_\perp$

Longitudinal momentum $k^+ = xP^+$

partons

Transverse plane

Cahn effect in SIDIS

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

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

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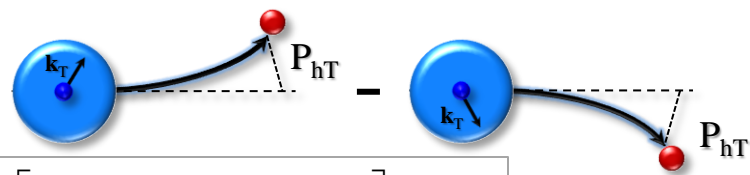

Cahn effect
R. N. Cahn, **PLB 78** (1978)

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;

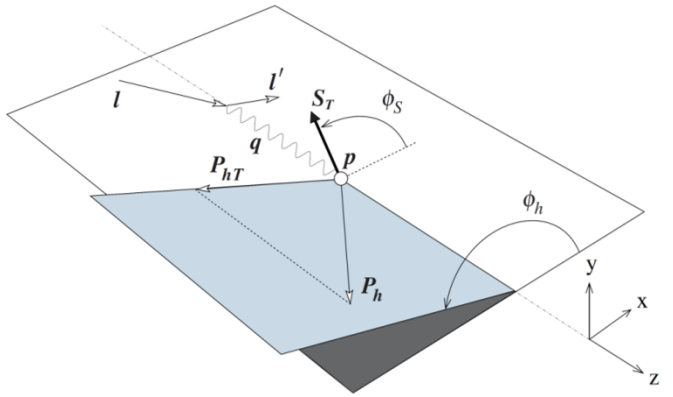$$k_T \rightarrow \cos\varphi_q \rightarrow \cos\varphi_h$$

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

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

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

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

Cahn effect in SIDIS

$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} =$$

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

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

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

k_T — P_{hT}

Significant non-zero effect observed by a number of experiments

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

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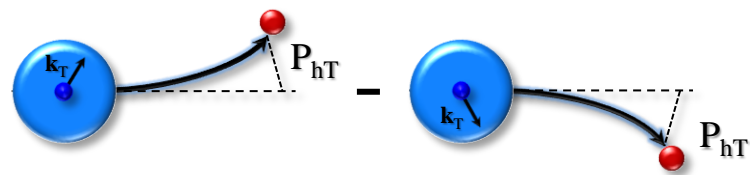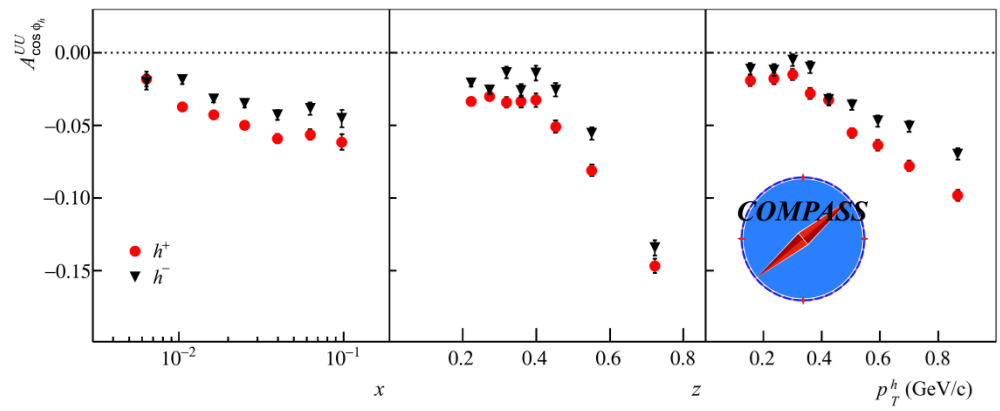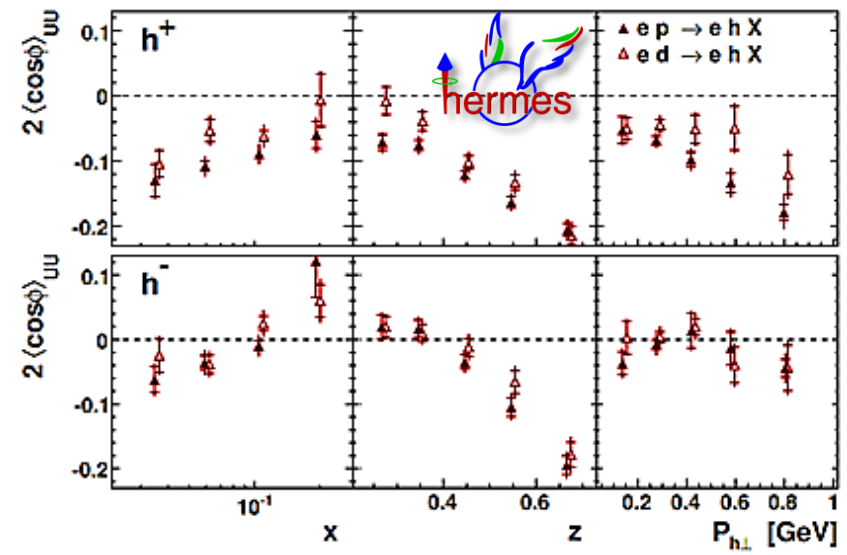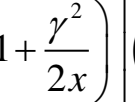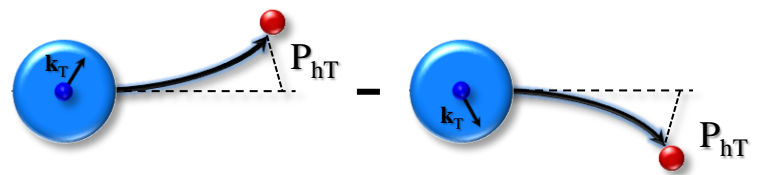
Cahn effect in SIDIS

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

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

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

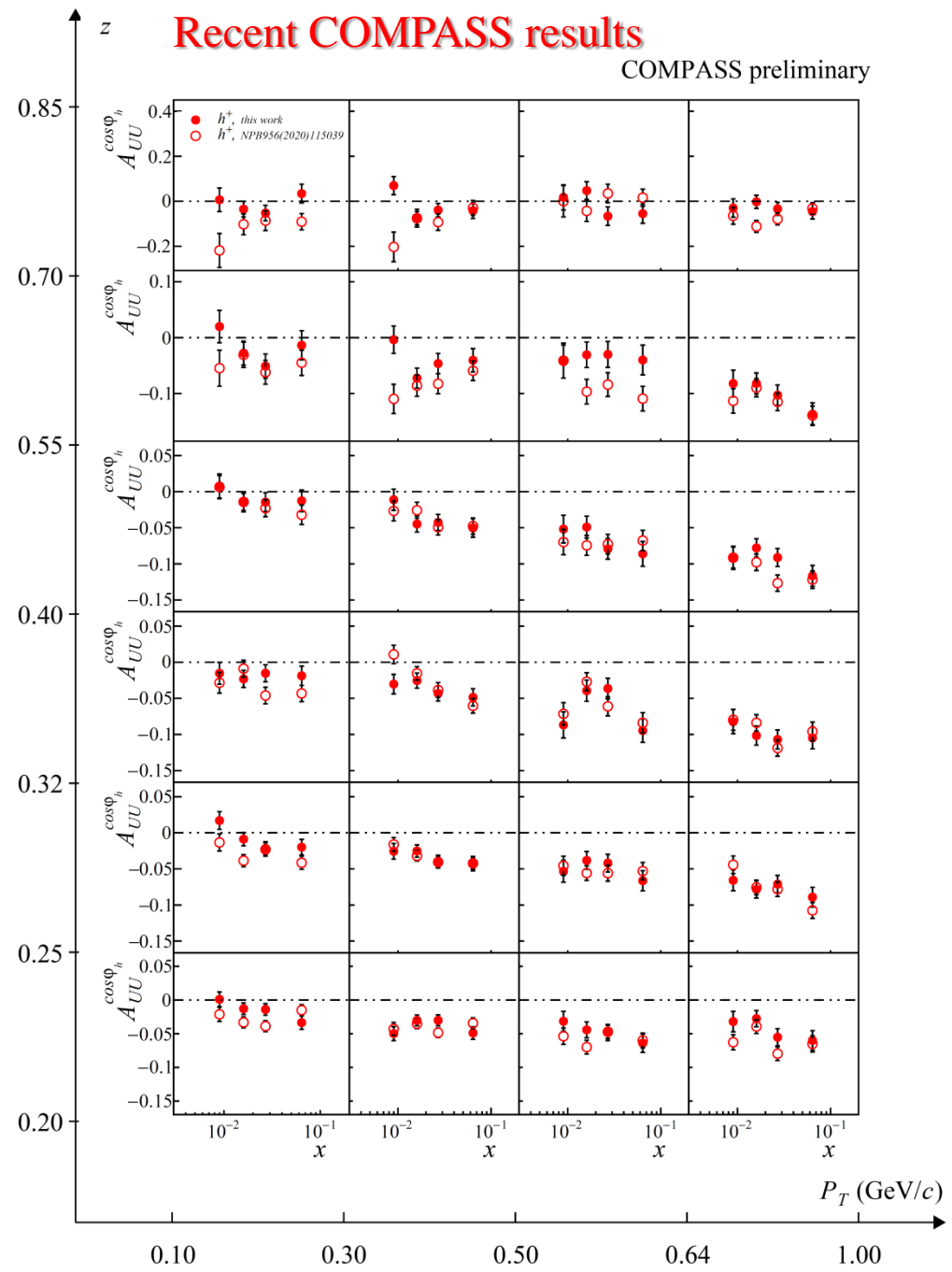| Quark Nucleon	U
U	$f_1^q(x, \boldsymbol{k}_T^2)$ **number density**

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

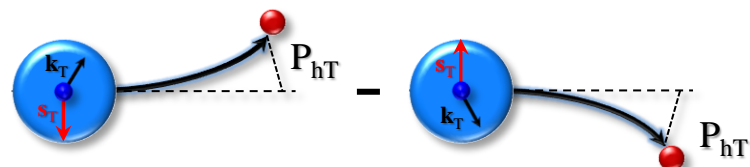See talk by A. Moretti

Recent COMPASS results

COMPASS preliminary

Boer-Mulders effect in SIDIS

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

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

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

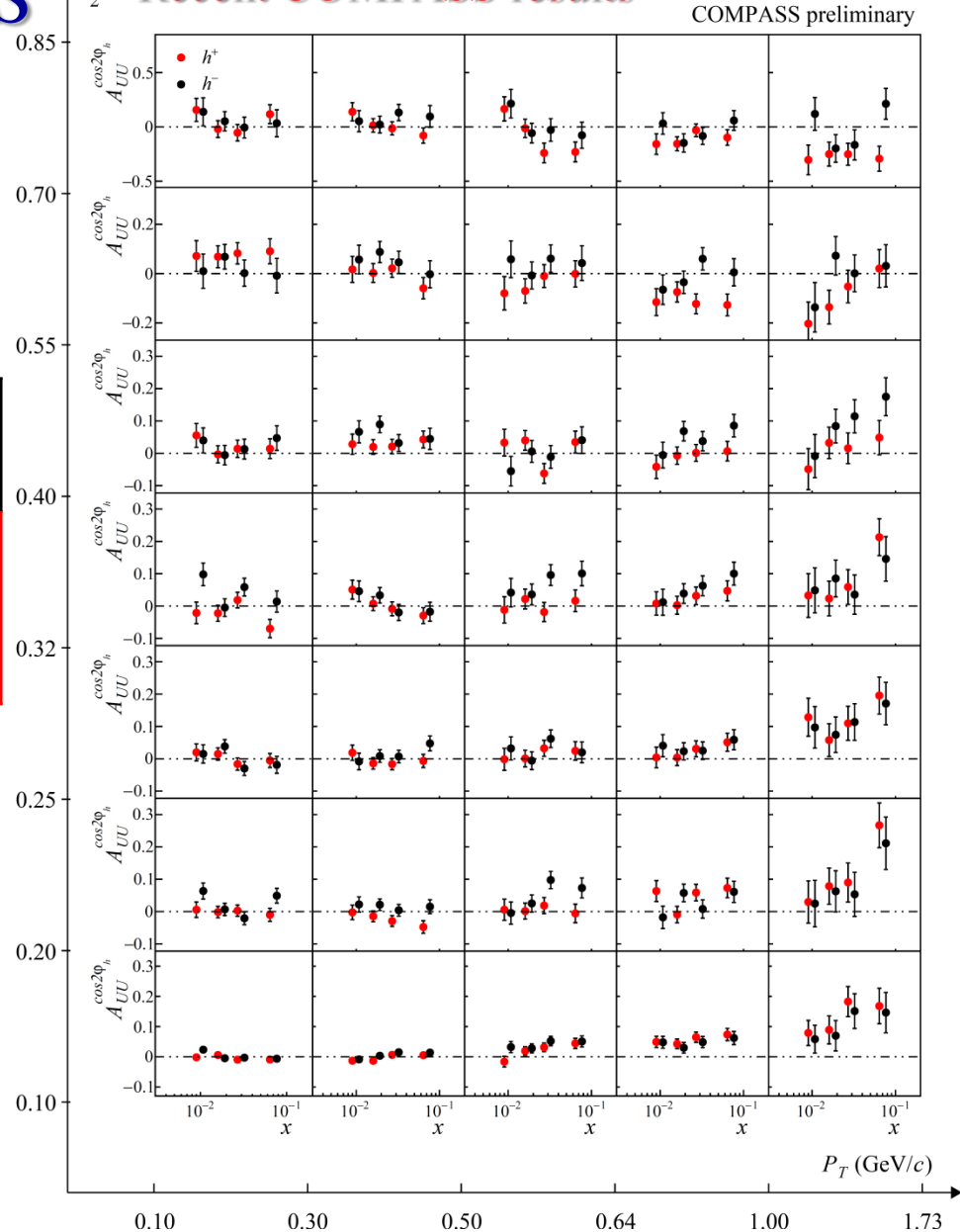| Quark / Nucleon	U		T
U	$f_1^q(x,\boldsymbol{k}_T^2)$ **number density**		$h_1^{\perp q}(x,\boldsymbol{k}_T^2)$ **Boer-Mulders**

Arises due to the correlation between quark transverse spin and intrinsic transverse momentum

$$F_{UU}^{\cos 2\phi_h}=C\left\{-\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)-\boldsymbol{p}_T\cdot\boldsymbol{k}_T}{MM_h}h_1^{\perp q}H_{1q}^{\perp h}\right\}$$

COMPASS preliminary

↑ **spin of the quark**   ↗ $\boldsymbol{k}_T$

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

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

$$\times \left\{ \begin{array}{l} 1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\[4pt] +\ \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h \\[6pt] +\ S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] \\[6pt] +\ S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\right] \end{array} \right\}$$

Nucleon \ Quark	U	L	T
U	number density		Boer-Mulders
L		helicity	worm-gear L

spin of the nucleon   spin of the quark k_T

SIDIS: target longitudinal spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\Bigg\{ \; 1 + ...$$

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

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

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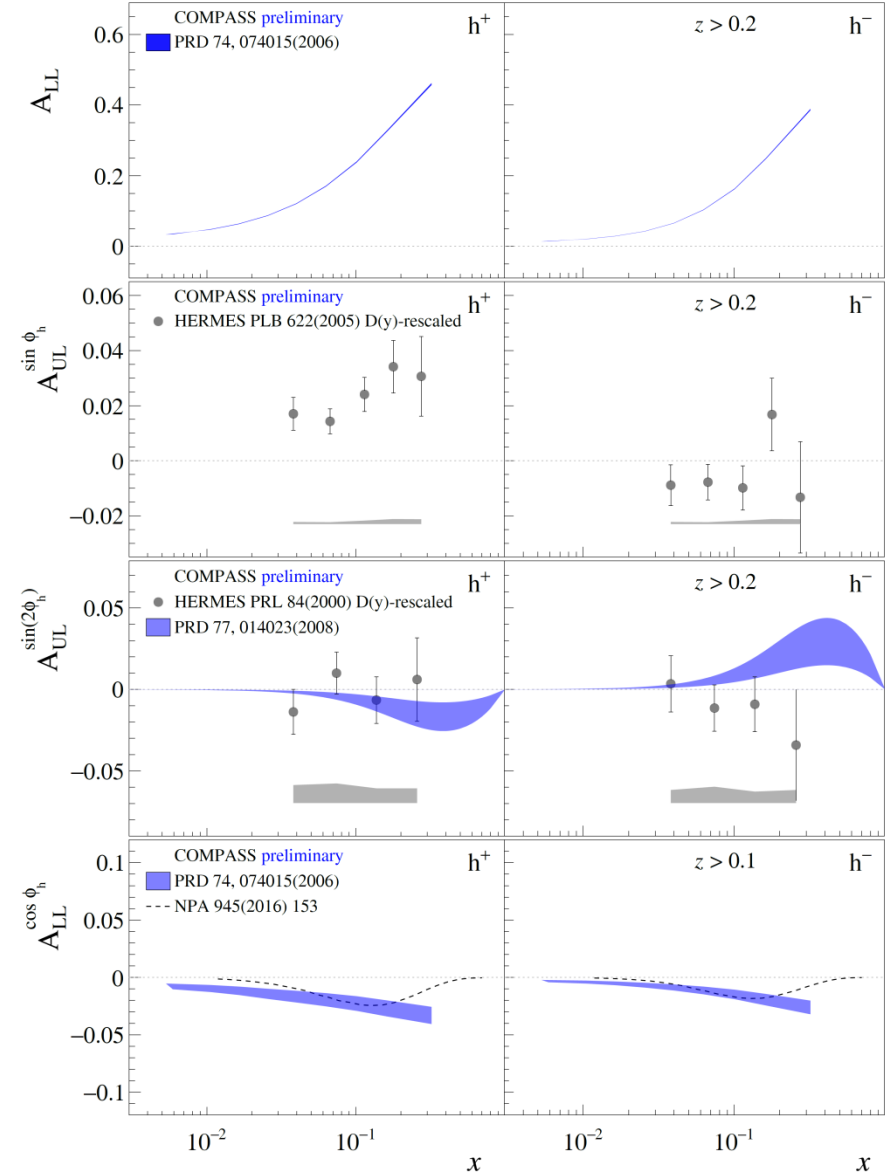
$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{ -\frac{\hat{h}\cdot p_T}{M_h}\left(xh_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z} \right)\right.$$
$$\left. + \frac{\hat{h}\cdot k_T}{M}\left(xf_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{H}_q^h}{z}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

$$F_{UL}^{\sin 2\phi_h} = \mathcal{C}\left\{ -\frac{2(\hat{h}\cdot p_T)(\hat{h}\cdot k_T) - p_T\cdot k_T}{MM_h} h_{1L}^{\perp q} H_{1q}^{\perp h} \right\}$$

$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{ -\frac{\hat{h}\cdot p_T}{M_h}\left(xe_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{D}_q^{\perp h}}{z} \right)\right.$$
$$\left. + \frac{\hat{h}\cdot k_T}{M}\left(xg_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{E}_q^h}{z} \right)\right\}$$

SIDIS: target longitudinal spin dependent asymmetries

$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L} \right) \Bigg\{ \ 1 + ...$$

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

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

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

COMPASS collected large amount of L-SIDIS data

Unprecedented precision for some amplitudes!

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

- Q-suppression, Various different "twist" ingredients
- Sizable TSA-mixing
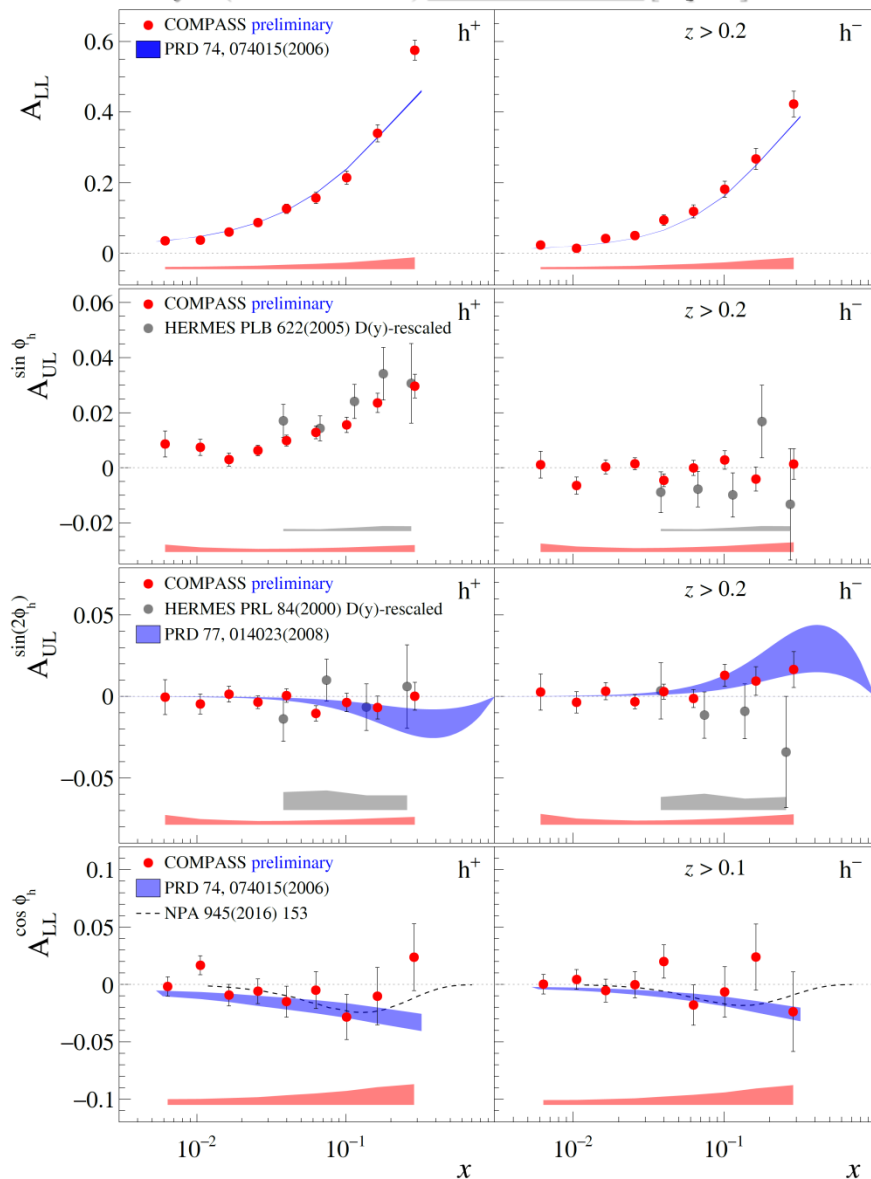- Significant h⁺ asymmetry, clear *z*-dependence
- h⁻ compatible with zero

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

- 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, Various different "twist" ingredients
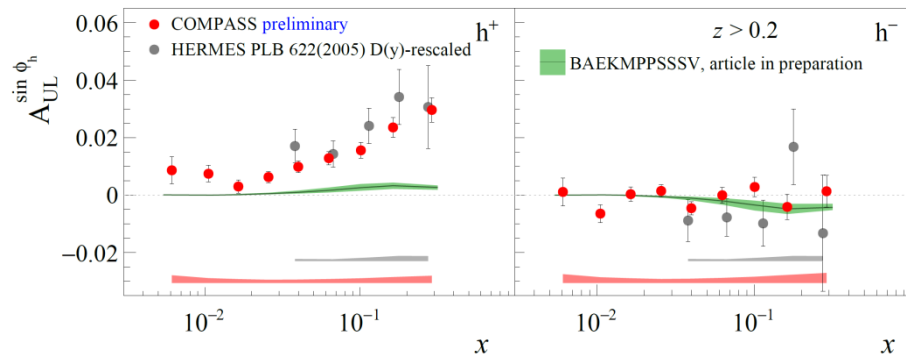- Compatible with zero, in agreement with models

SIDIS: target longitudinal spin dependent asymmetries

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

$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q} \mathbb{C} \left\{ -\frac{\hat{h} \cdot \boldsymbol{p}_T}{M_h} \left(x h_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) \right.$$
$$\left. + \frac{\hat{h} \cdot \boldsymbol{k}_T}{M} \left(x f_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{H}_q^h}{z} \right) \right\}$$
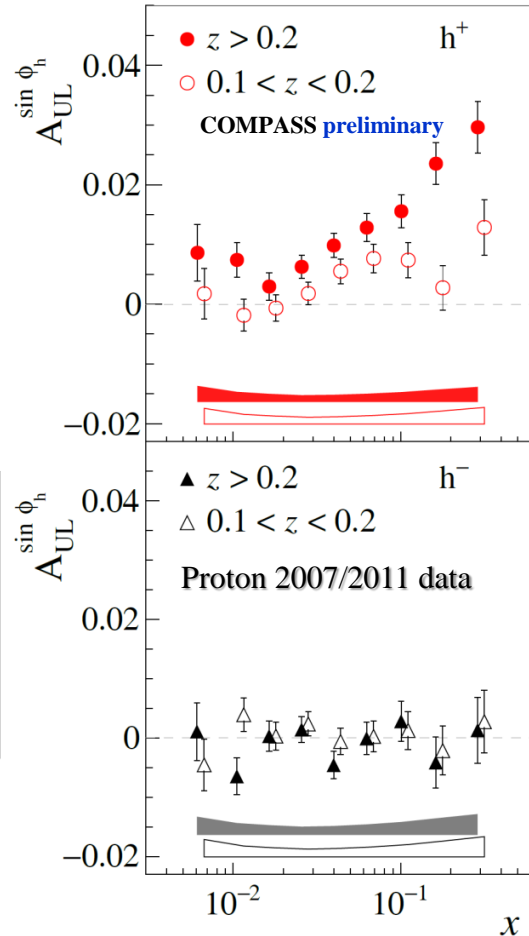
B. Parsamyan (for COMPASS)
arXiv:1801.01488 [hep-ex]

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

S. Bastami et al. JHEP 1906 (2019) 007:
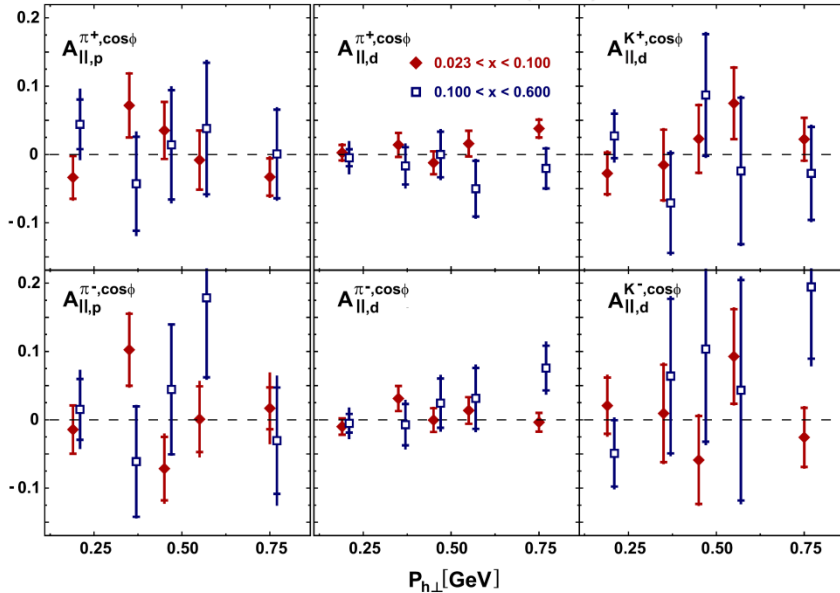"SIDIS in Wandzura-Wilczek-type approximation"
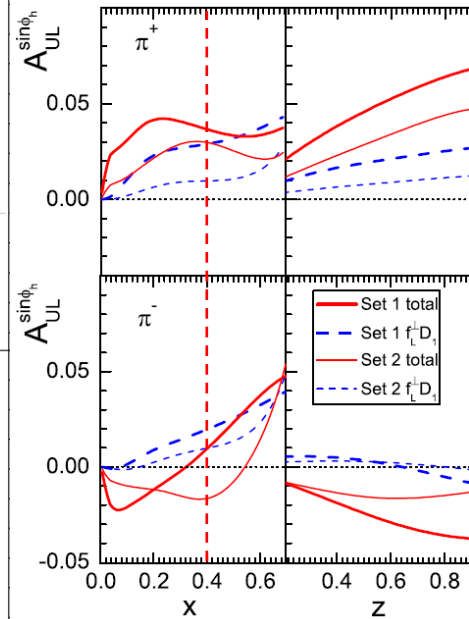
- Q-suppression, TSA-mixing
- Various different "twist" ingredients
- **Strong non-zero effect for h⁺, h⁻ compatible with zero, clear z-dependence**

COMPASS — 25 years 1997 – 2022

$$\frac{d\sigma}{dxdydzdp_T^2d\phi_hd\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L} \right)\left\{1+...+ S_L\lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h+...\right\}$$

$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q}\mathbb{C}\left\{-\frac{\hat{h}\cdot p_T}{M_h}\left(xe_L^q H_{1q}^{\perp h} + \frac{M_h}{M}g_{1L}^q\frac{\tilde{D}_q^{\perp h}}{z}\right)\right.$$
$$\left.+\frac{\hat{h}\cdot k_T}{M}\left(xg_L^{\perp q}D_{1q}^h - \frac{M_h}{M}h_{1L}^{\perp q}\frac{\tilde{E}_q^h}{z}\right)\right\}$$

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

HERMES: PRD 99, 112001 (2019) **NEW**

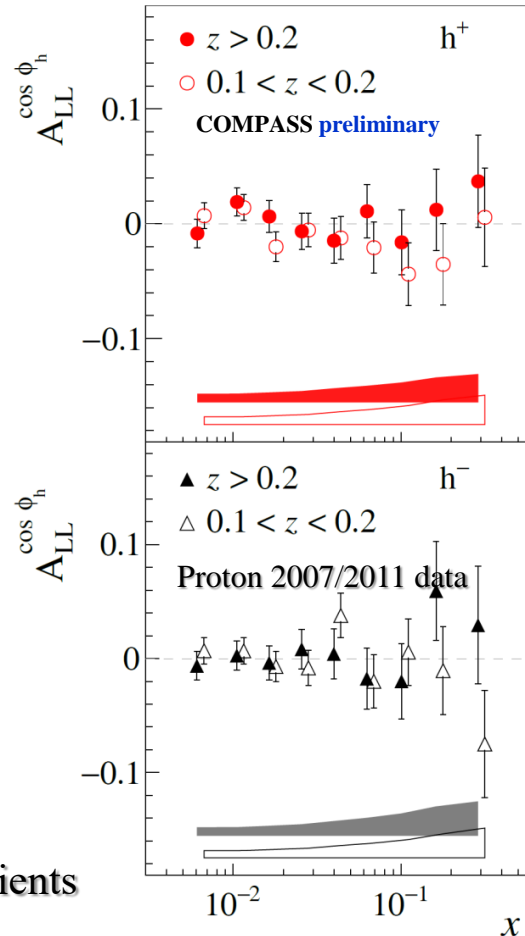

- Q-suppression, various different "twist" ingredients

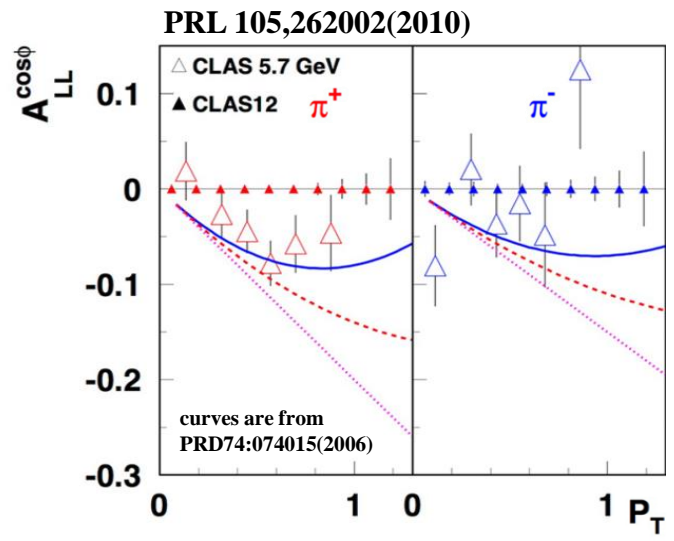- HERMES/COMPASS - small and compatible with zero, in agreement with model predictions

COMPASS
25 years
1997 – 2022

$$\frac{d\sigma}{dxdydzdp_T^2d\phi_hd\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1+...+ S_L\lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h+...\right\}$$

$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q}\mathbb{C}\left\{-\frac{\hat{h}\cdot p_T}{M_h}\left(xe_L^qH_{1q}^{\perp h} + \frac{M_h}{M}g_{1L}^q\frac{\tilde{D}_q^{\perp h}}{z}\right)\right.$$
$$\left.+\frac{\hat{h}\cdot k_T}{M}\left(xg_L^{\perp q}D_{1q}^h - \frac{M_h}{M}h_{1L}^{\perp q}\frac{\tilde{E}_q^h}{z}\right)\right\}$$

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

PRL 105,262002(2010)


curves are from
PRD74:074015(2006)

- Q-suppression, various different "twist" ingredients
- Measured to be non zero at JLab
- HERMES/COMPASS - small and compatible with zero, in agreement with model predictions

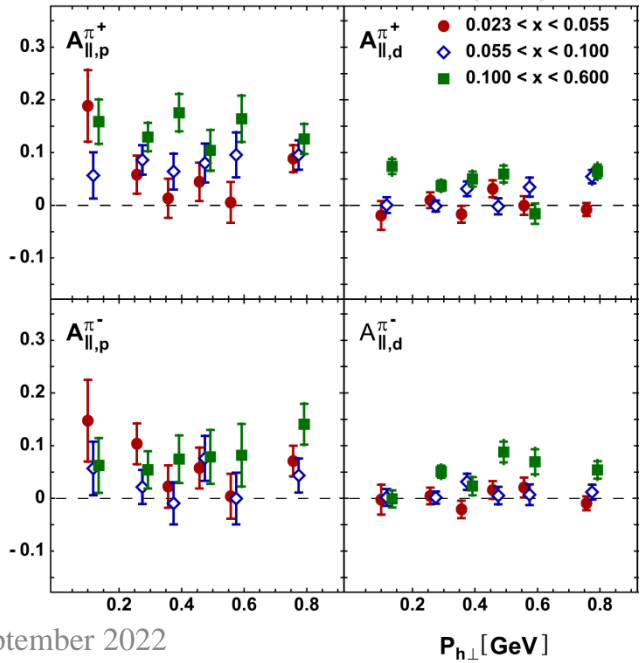# SIDIS: target longitudinal spin dependent asymmetries

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

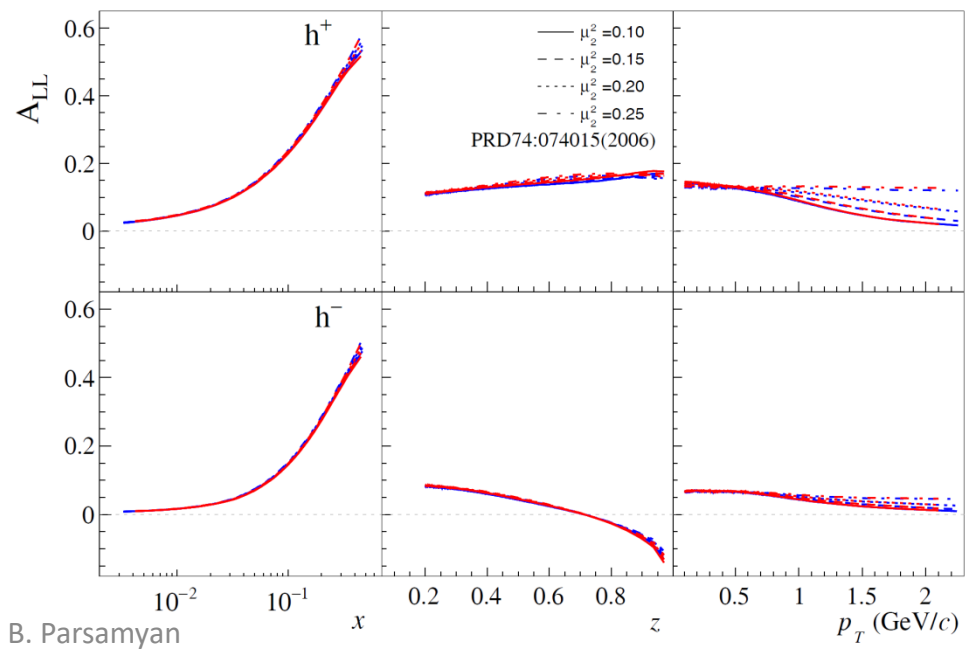$$F_{LL}^1 = \mathcal{C} \left\{ g_{1L}^q D_{1q}^h \right\}$$

- Measurement of (semi-)inclusive A_1(A_{LL}) is one of the key physics topics of HERMES/COMPASS
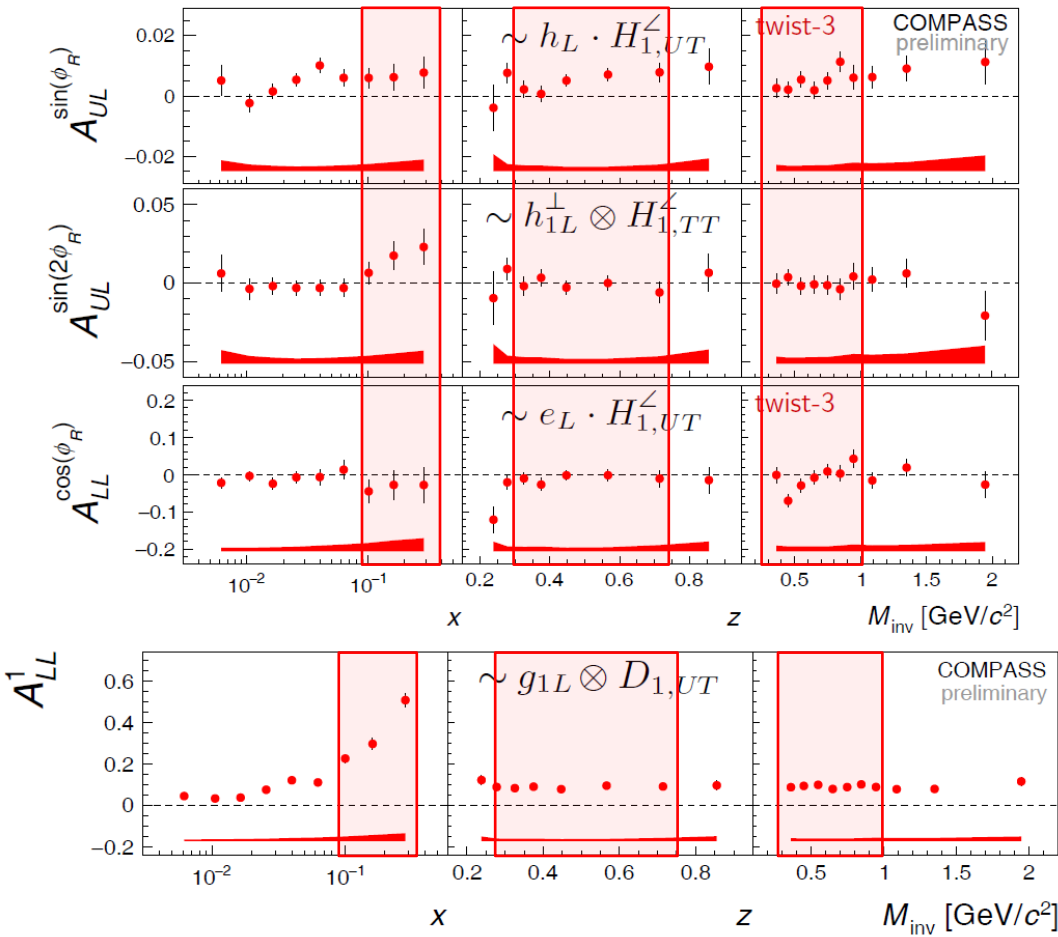- Large amount of P/D data
- No P_T-dependence observed

COMPASS preliminary — Proton 2007, 2011 data
B. Parsamyan (for COMPASS)
arXiv:1801.01488 [hep-ex]
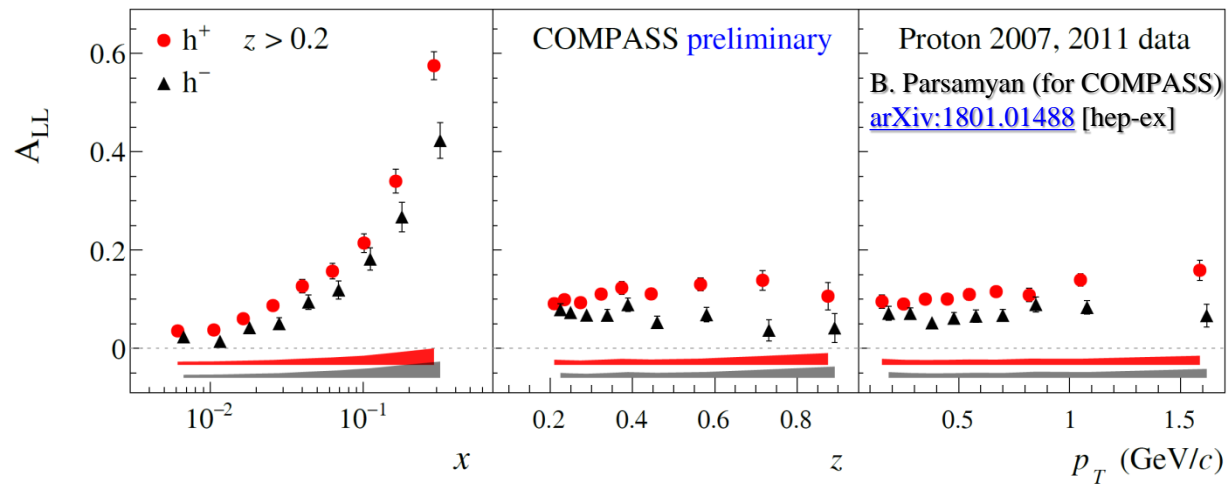
HERMES: PRD 99, 112001 (2019)

COMPASS Proton-2007, -2011 kinematics

PRD74:074015(2006)

Selected results for di-hadron asymmetries

COMPASS (NH_3) 2007+2011 data

CLAS 6 GeV (NH_3)
S. A. Pereira: PoS (DIS 2014) 231

$$\sim h_L \cdot H_{1,UT}^\angle$$

$$\sim h_{1L}^\perp \otimes H_{1,TT}^\angle$$

$$\sim e_L \cdot H_{1,UT}^\angle$$

$$\sim g_{1L} \otimes D_{1,UT}$$

COMPASS preliminary — twist-3

$$Q^2 > 1\,(\text{GeV}/c)^2$$
$$0.0025 < x < 0.7$$
$$0.1 < y < 0.9$$
$$W > 5\,\text{GeV}/c^2$$
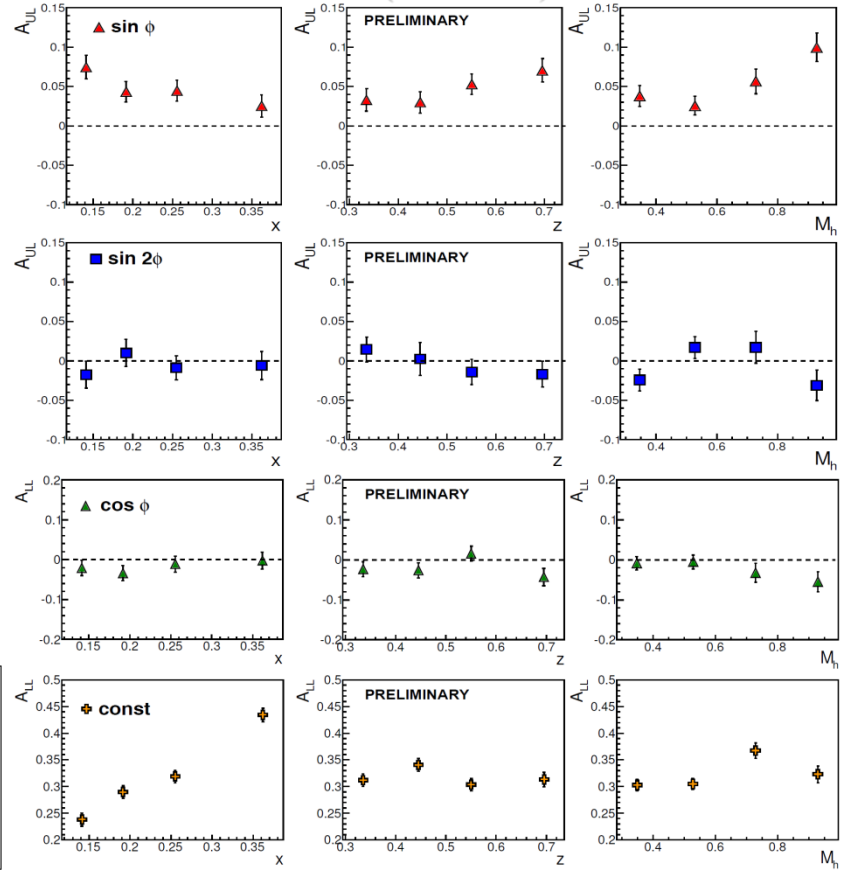
- Alternative way to access various twist-2/-3 distributions
- Non zero signal for $A_{UL}^{\sin\phi_R}$ and A_{LL}^1
- CLAS-COMPASS: different behavior for $A_{UL}^{\sin 2\phi_R}$ at large x?
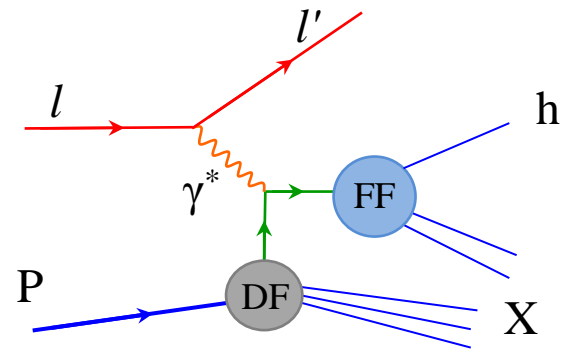
SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

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

$\times$
$$\left\{\begin{array}{l}
1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\[4pt]
+\;\lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h
\end{array}\right.$$

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

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

$$+\,S_T\left[\begin{array}{l}
A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\[4pt]
+\;\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\[4pt]
+\;\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\[4pt]
+\;\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\[4pt]
+\;\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)
\end{array}\right]$$

$$+\,S_T\lambda\left[\begin{array}{l}
\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\[4pt]
+\;\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\[4pt]
+\;\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)
\end{array}\right]$$

Quark / Nucleon	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

All measured by COMPASS

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

$$\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$
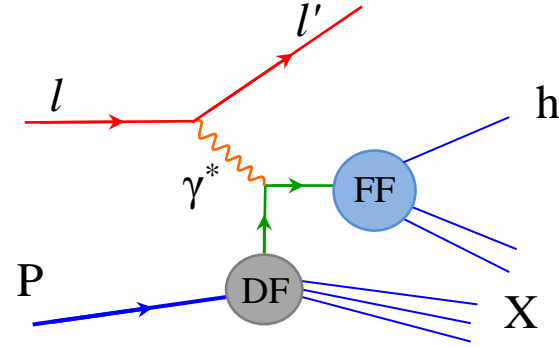
$$\times \left\{ \begin{array}{l} 1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\ + \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h \end{array} \right.$$

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

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

$$+ S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\ + \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\ + \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S) \end{array} \right]$$

$$+ S_T\lambda \left[\begin{array}{l} \sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\ + \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\ + \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S) \end{array} \right]$$

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

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

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

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

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

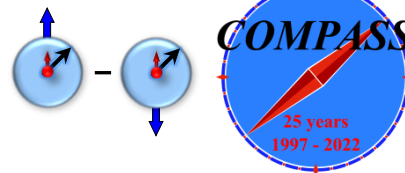$$A_{LT}^{\cos(\phi_h-\phi_S)} \propto g_{1T}^q\otimes D_{1q}^{h}$$

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

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

Twist-2

Twist-3

l, l', h, γ^*, FF, P, DF, X

COMPASS
25 years
1997 – 2022

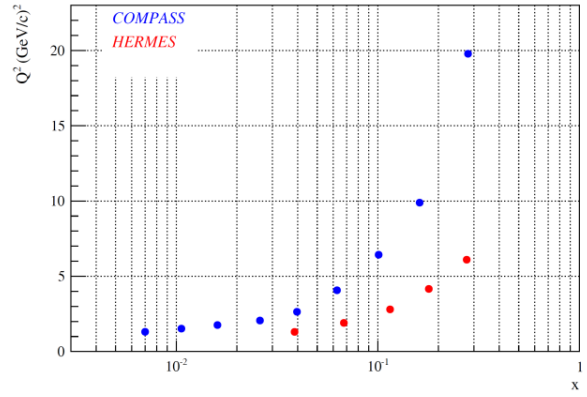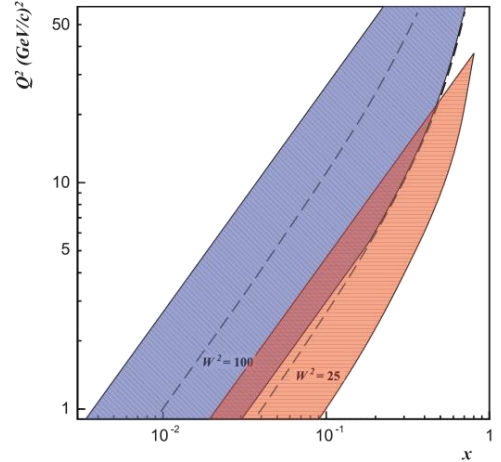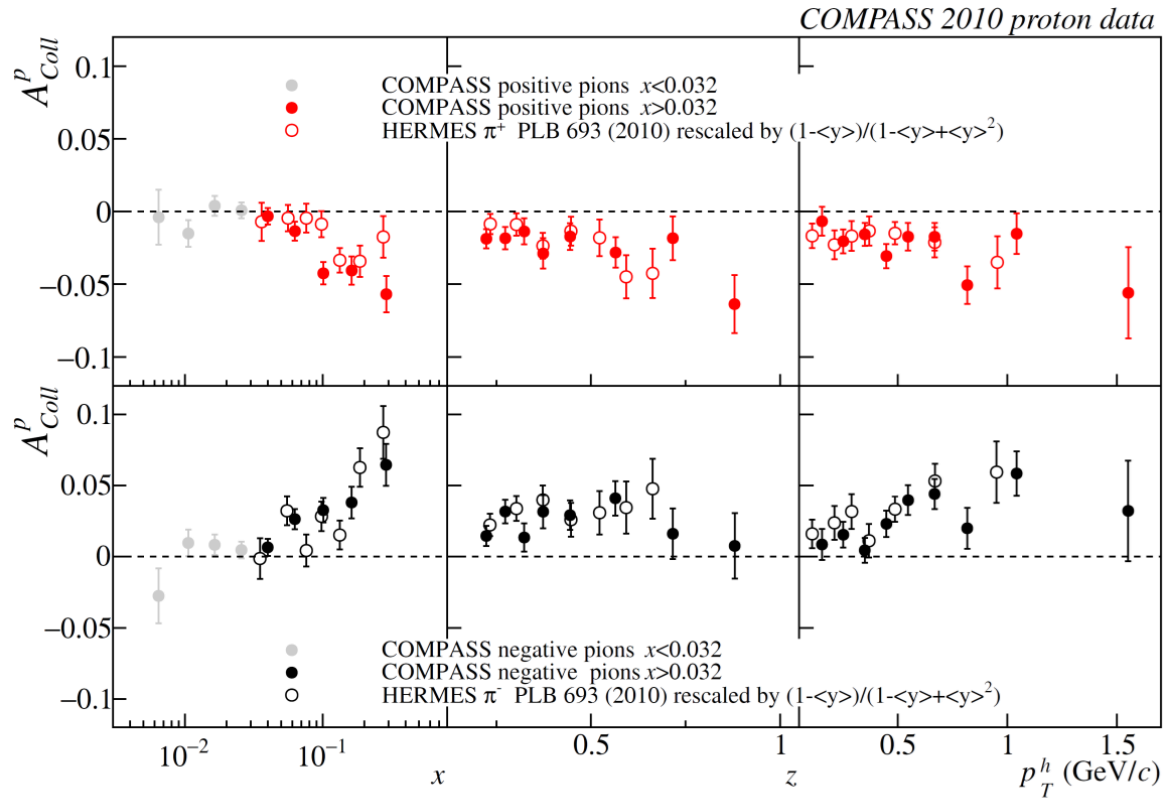# SIDIS TSAs: Collins effect and Transversity

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

$$F_{UT}^{\sin(\phi_h + \phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}} \cdot \boldsymbol{p}_T}{M_h} h_1^q H_{1q}^{\perp h} \right]$$
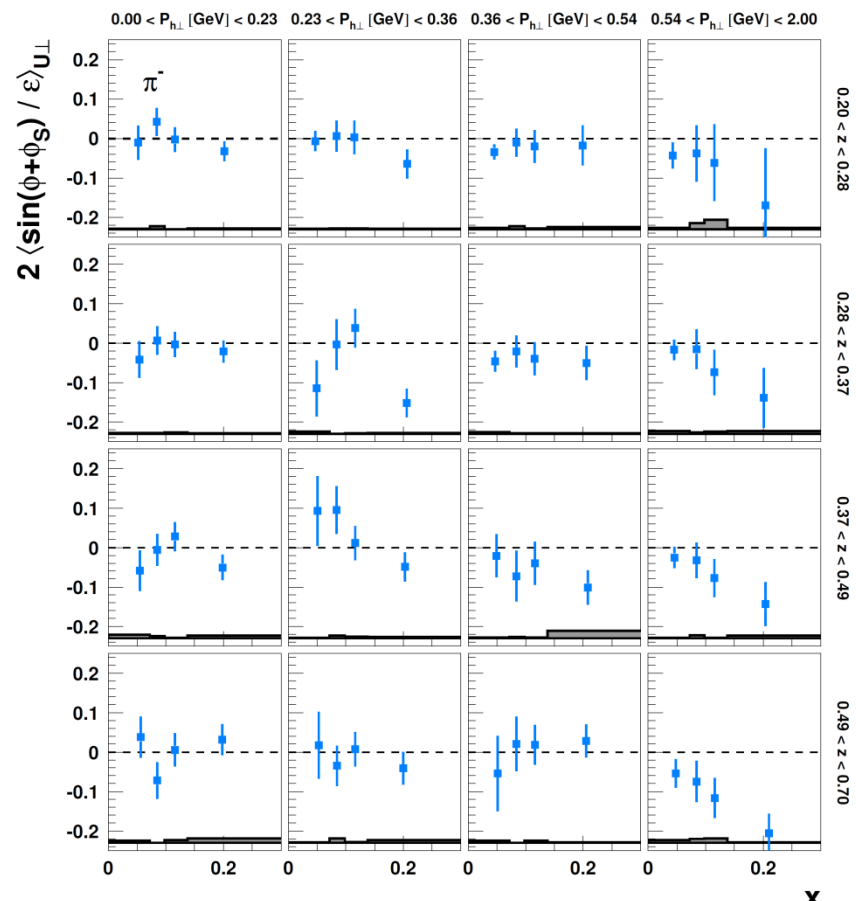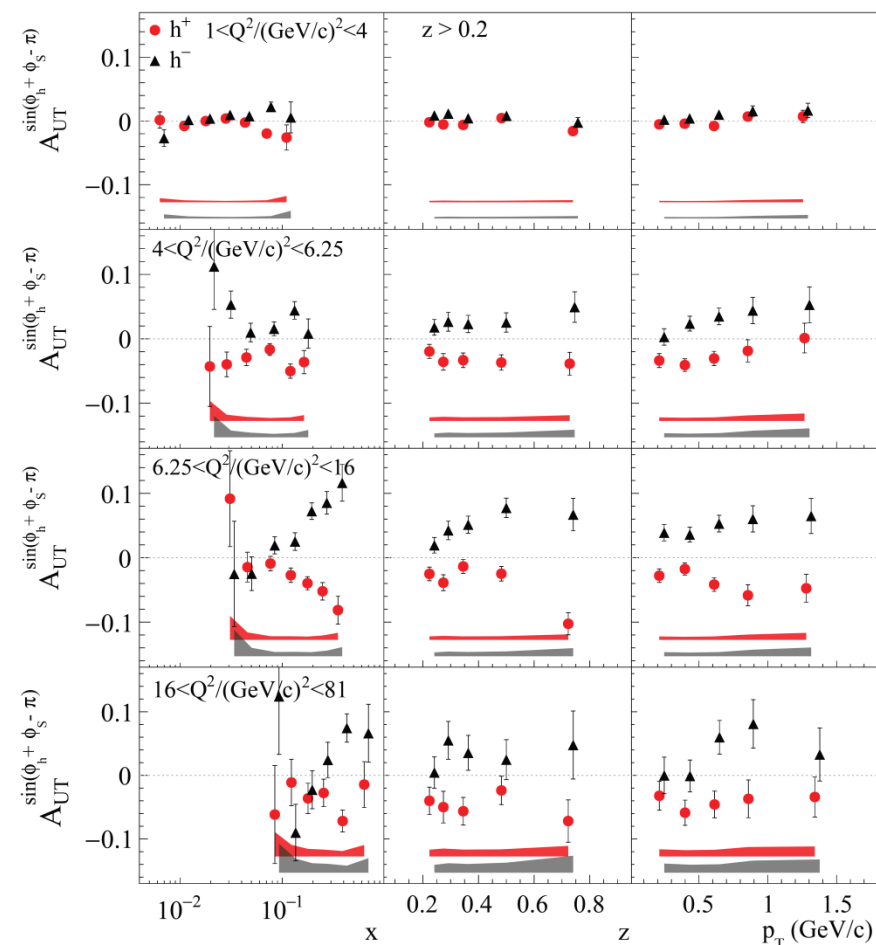
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES
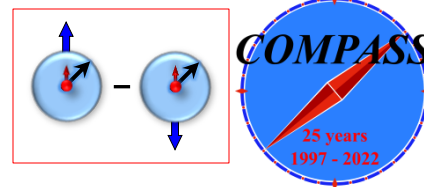 (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?

COMPASS PLB 744 (2015) 250
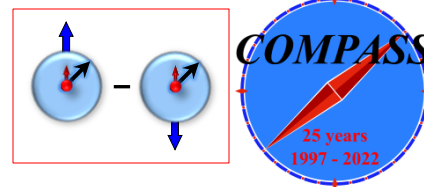
COMPASS 2010 proton data

COMPASS positive pions $x<0.032$
COMPASS positive pions $x>0.032$
HERMES π^+ PLB 693 (2010) rescaled by $(1-\langle y \rangle)/(1-\langle y \rangle + \langle y \rangle^2)$

COMPASS negative pions $x<0.032$
COMPASS negative pions $x>0.032$
HERMES π^- PLB 693 (2010) rescaled by $(1-\langle y \rangle)/(1-\langle y \rangle + \langle y \rangle^2)$

SIDIS TSAs: Collins effect and Transversity

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

$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h}\,h_1^q\,H_{1q}^{\perp h}\right]$$
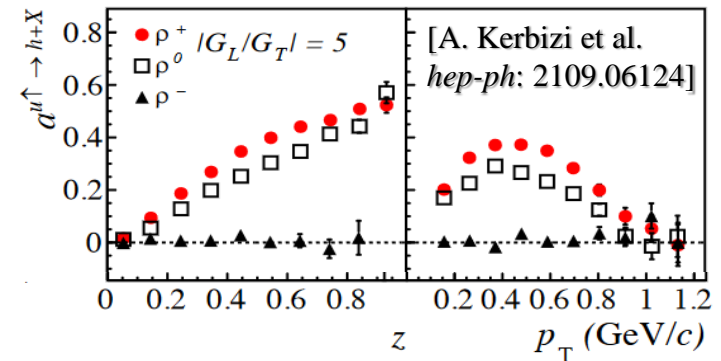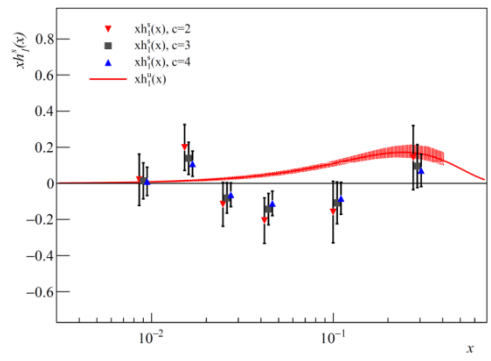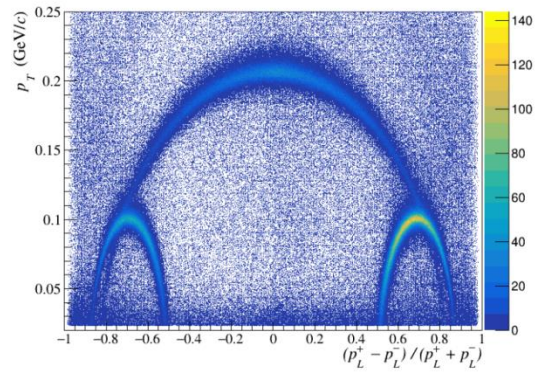
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?

HERMES, JHEP 12 (2020) 010

COMPASS, PBL 770 (2017) 138

SIDIS TSAs: Collins effect and Transversity

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

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

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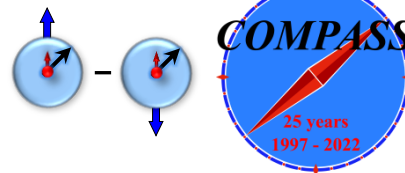- No impact from Q^2-evolution?

PLB 824 (2022) 136834 - NEW

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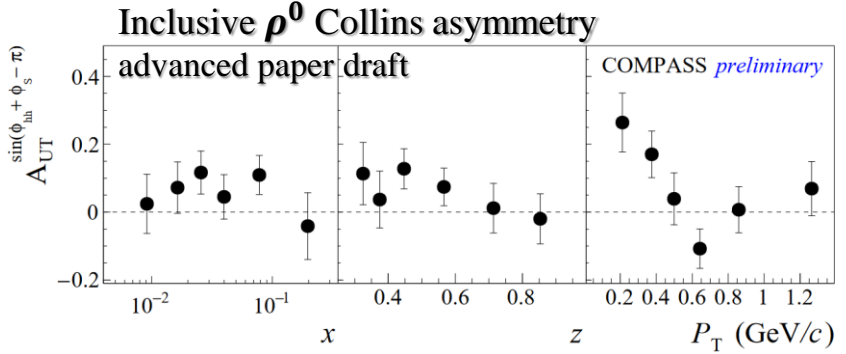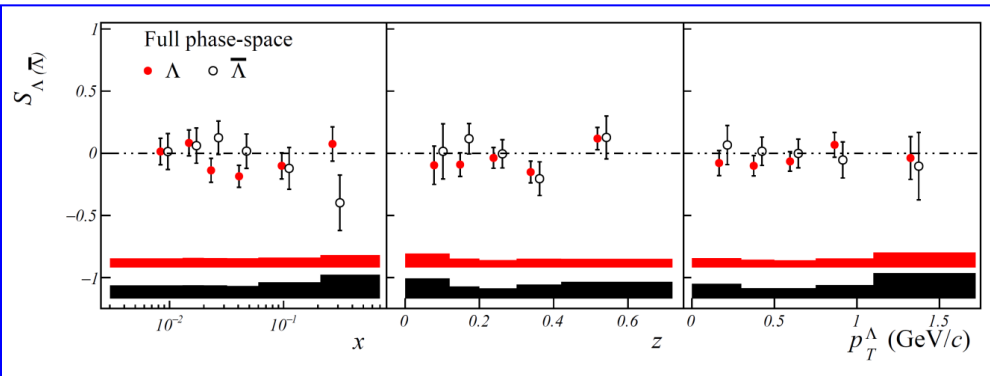
- indication for a positive asymmetry
- opposite to π^+ and π^0 as predicted by the models
- Large effect at small P_T

[A. Kerbizi et al. hep-ph: 2109.06124]
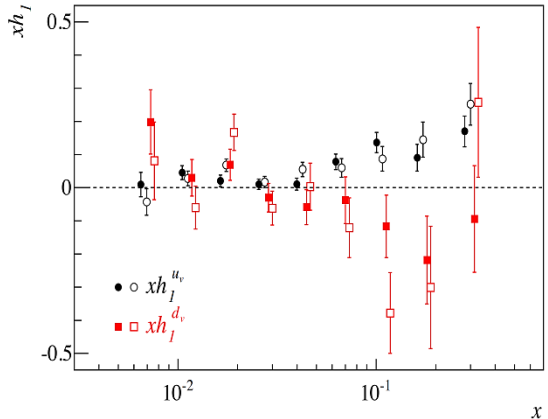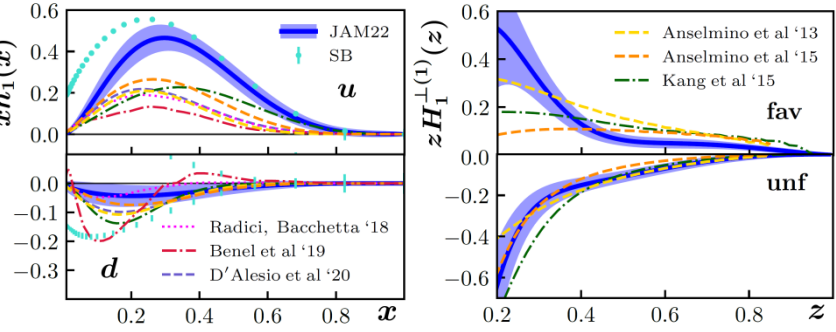
SIDIS TSAs: Collins effect and Transversity

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

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

- 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?
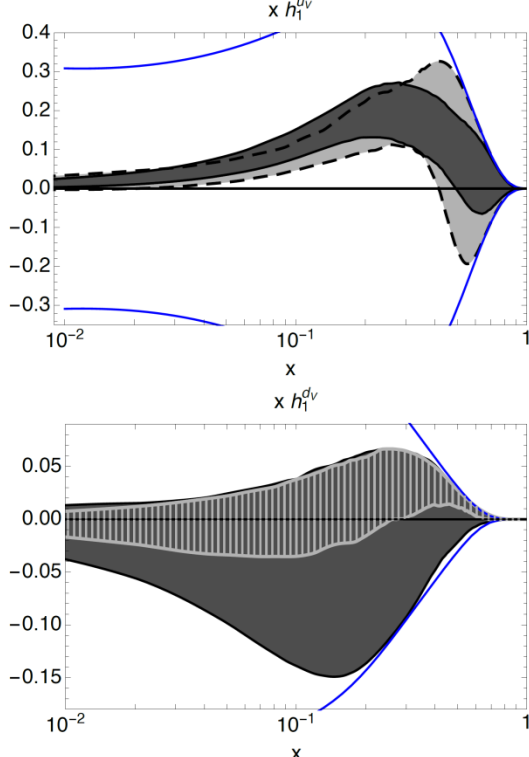- Extensive phenomenological studies and various global fits by different groups

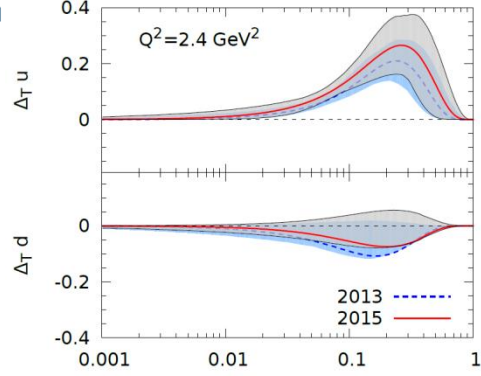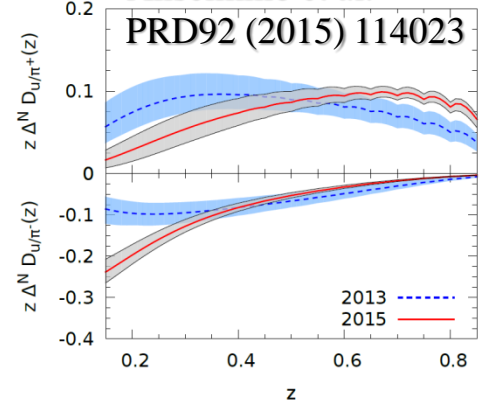A. Martin, F. Bradamante, V. Barone
PRD91 (2015) no.1, 014034

M. Radici and A. Bacchetta
PRL 120 (2018) no.19, 192001

Anselmino et al.
PRD92 (2015) 114023
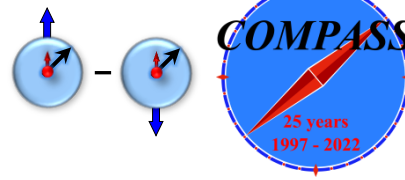
JAM Collaboration, hep-ph > arXiv:2205.00999

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]
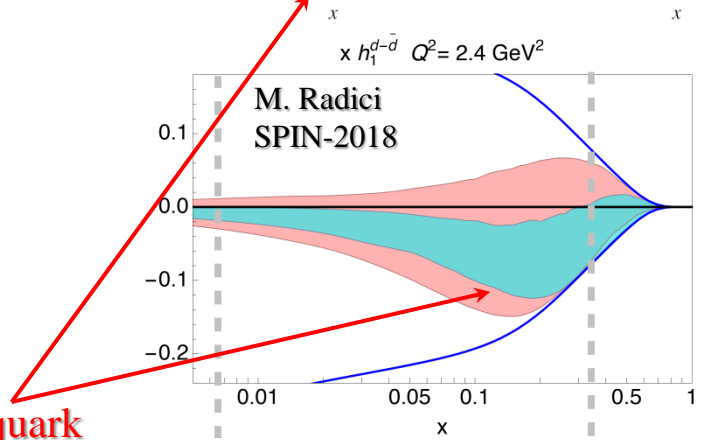Projected uncertainties for Collins asymmetry
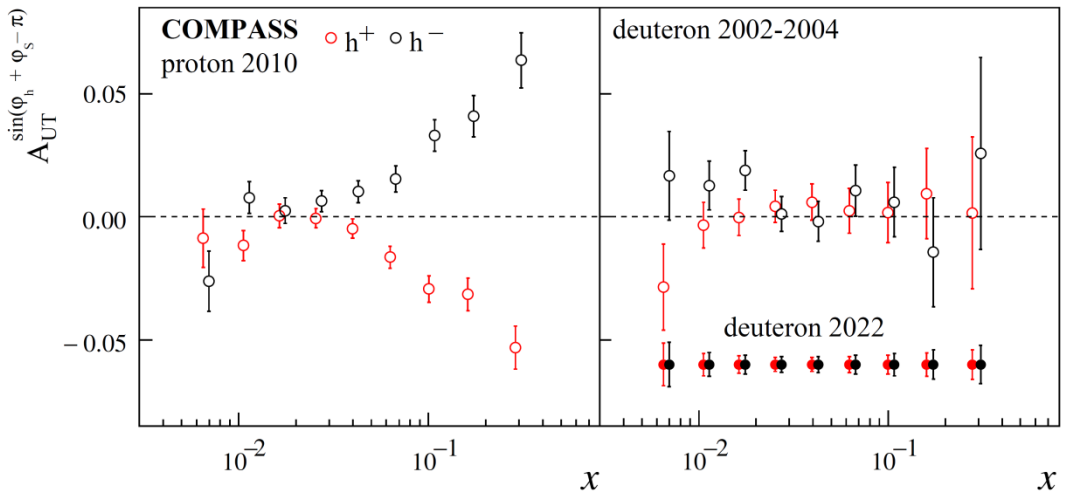
Projected uncertainties for transversity PDF

$x\, h_1^{d-\bar{d}}$ $Q^2 = 2.4$ GeV^2

M. Radici
SPIN-2018
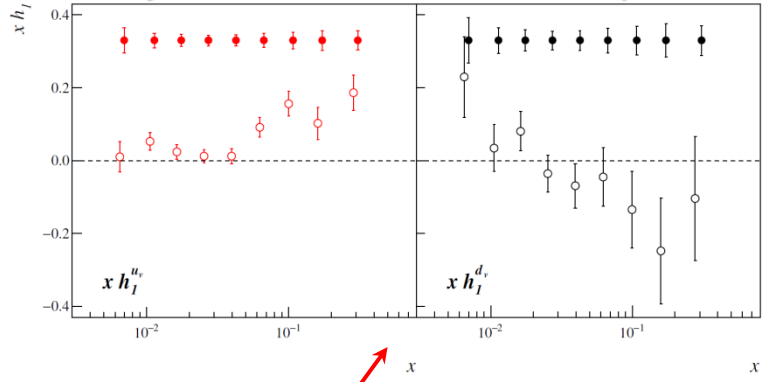
COMPASS-II (2022)
- Deuteron measurement being repeated
- Will be crucial to constrain the transversity TMD PDF for the d-quark
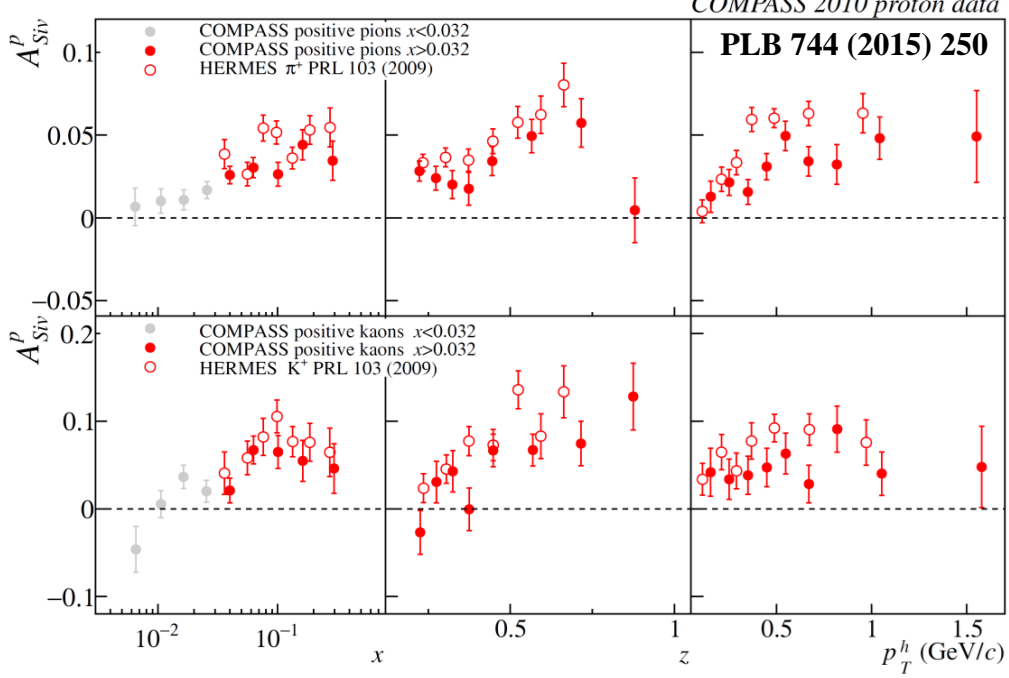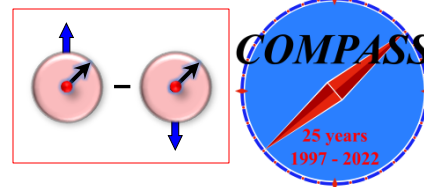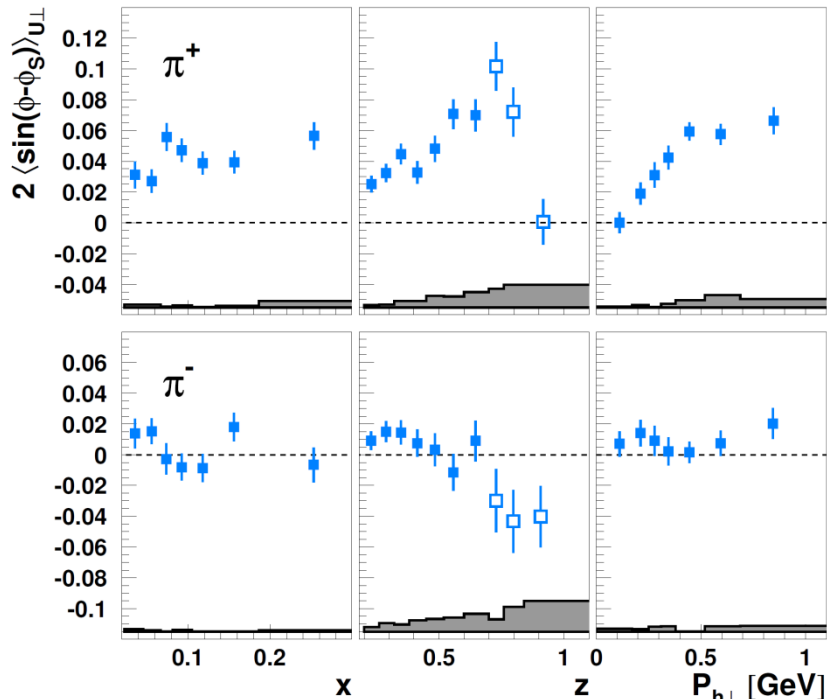
SIDIS TSAs: Sivers effect

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

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

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

HERMES, JHEP 12 (2020) 010

COMPASS 2010 proton data

PLB 744 (2015) 250

JLab Hall A PRL 107, 072003 (2011)

SIDIS TSAs: Sivers effect

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

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

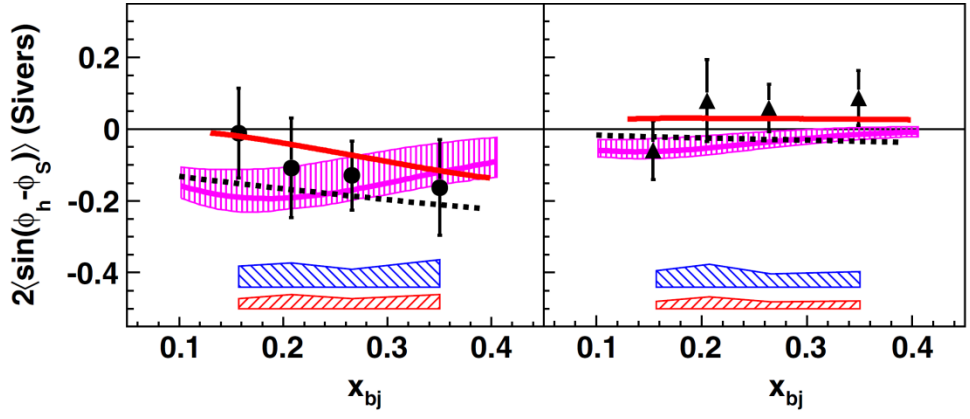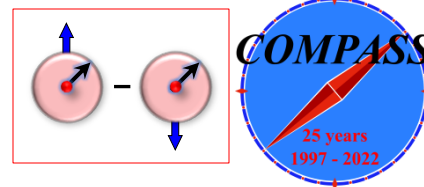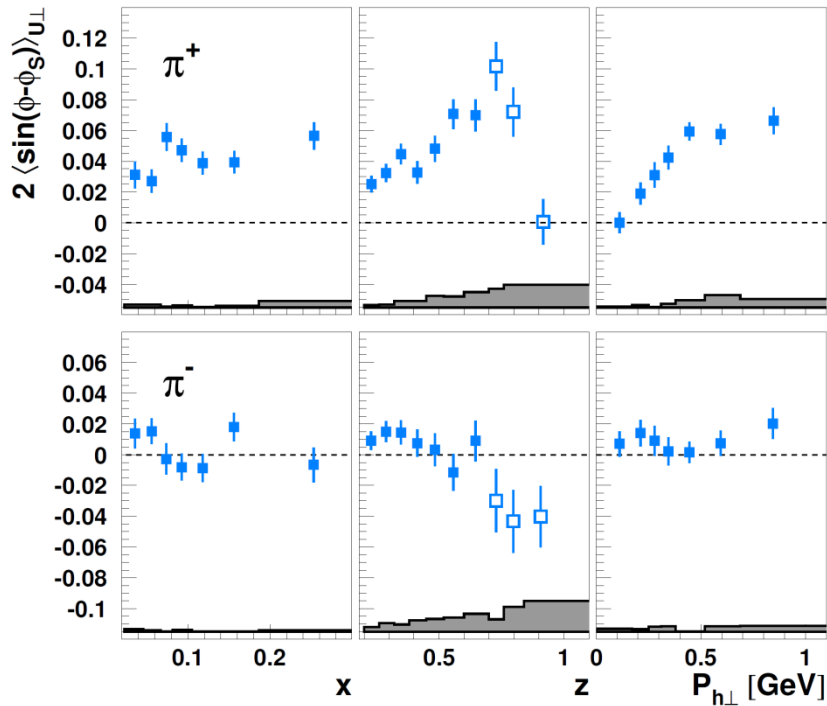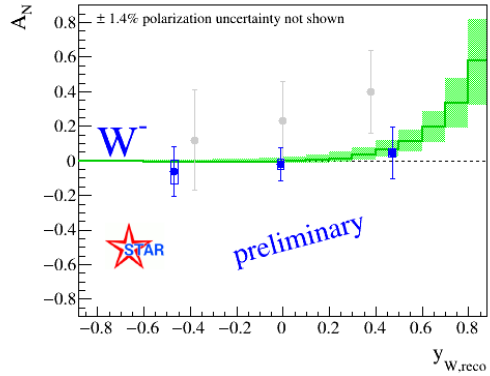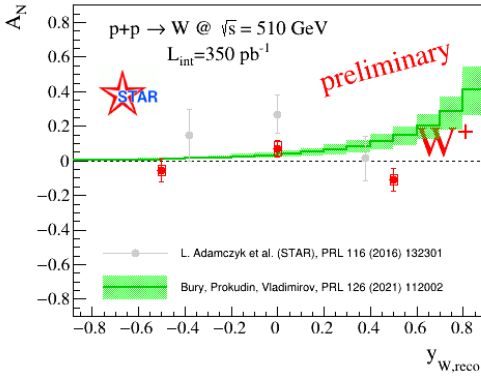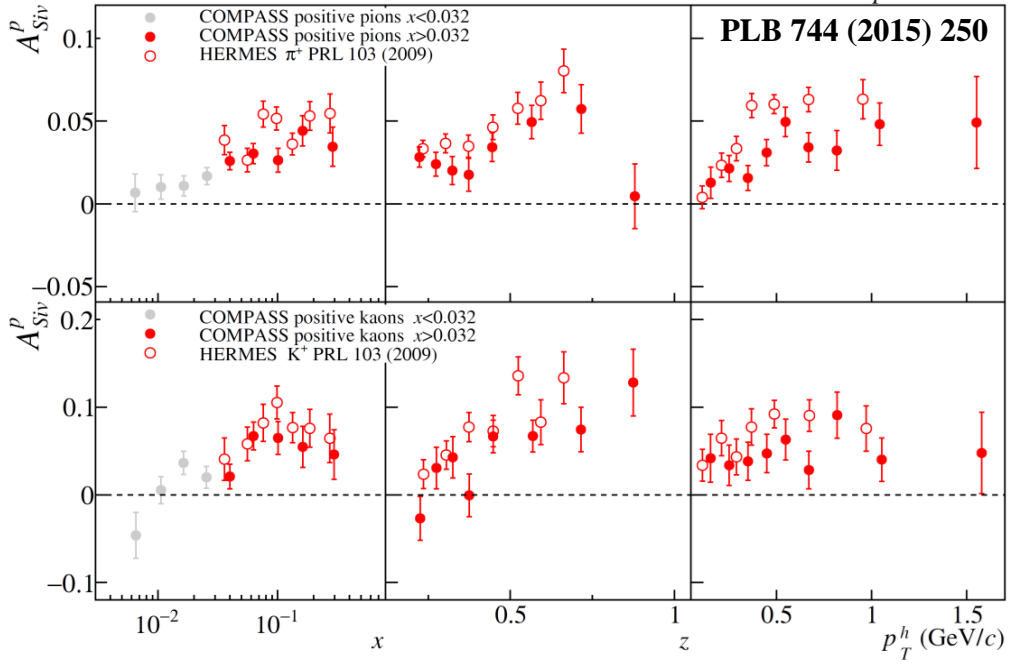- Measured on proton and deuteron
- Expected to change sign between SIDIS and Drell-Yan

HERMES, JHEP 12 (2020) 010

COMPASS 2010 proton data

PLB 744 (2015) 250

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

SIDIS

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

$$\times \left\{ 1 + \boxed{\varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h} \right.$$

$$+ S_L \, \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2} \, A_{LL}$$

$$+ S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h - \phi_S)} \sin\left(\phi_h - \phi_S\right) \\[4pt] + \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin\left(\phi_h + \phi_S\right) \\[4pt] + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin\left(3\phi_h - \phi_S\right) \end{array} \right]$$

$$\left. + S_T \lambda \left[\sqrt{\left(1-\varepsilon^2\right)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos\left(\phi_h - \phi_S\right) \right] \right\}$$

DY

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

$$\times \left\{ 1 + D_{\left[\sin^2 \theta_{CS}\right]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \right.$$

$$+ S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS}$$

$$+ S_T \left[\begin{array}{l} A_T^{\sin\varphi_S} \sin \varphi_S \\[4pt] + D_{\left[\sin^2 \theta_{CS}\right]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin\left(2\varphi_{CS} - \varphi_S\right) \\[4pt] + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin\left(2\varphi_{CS} + \varphi_S\right) \end{array} \right) \end{array} \right] \right\}$$

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

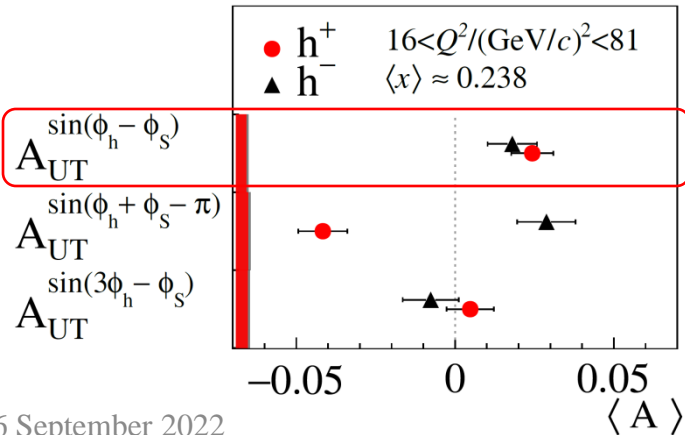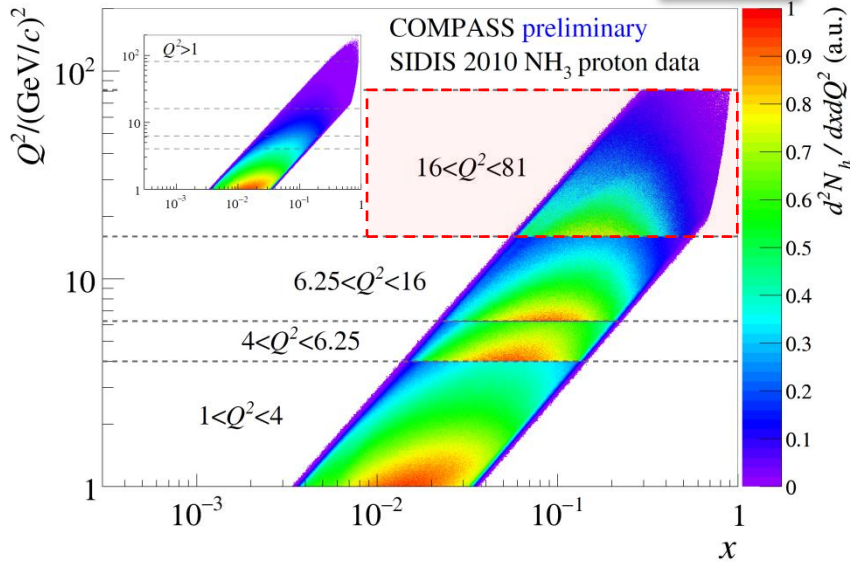## Comparable x:Q² coverage – minimization of possible Q²-evolution effects
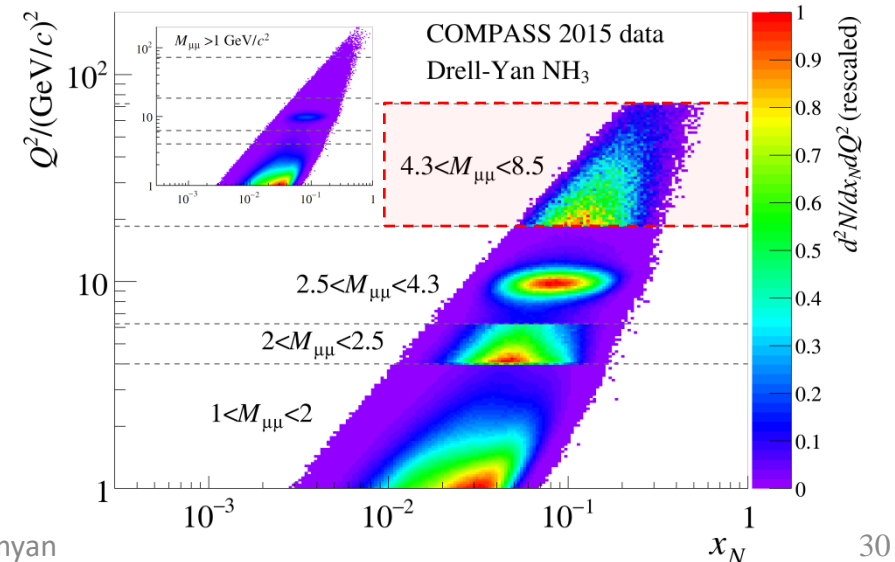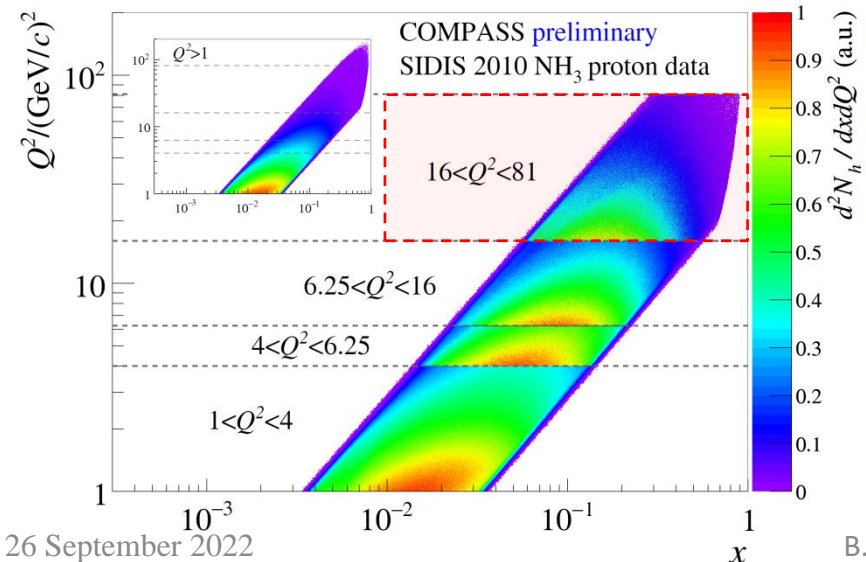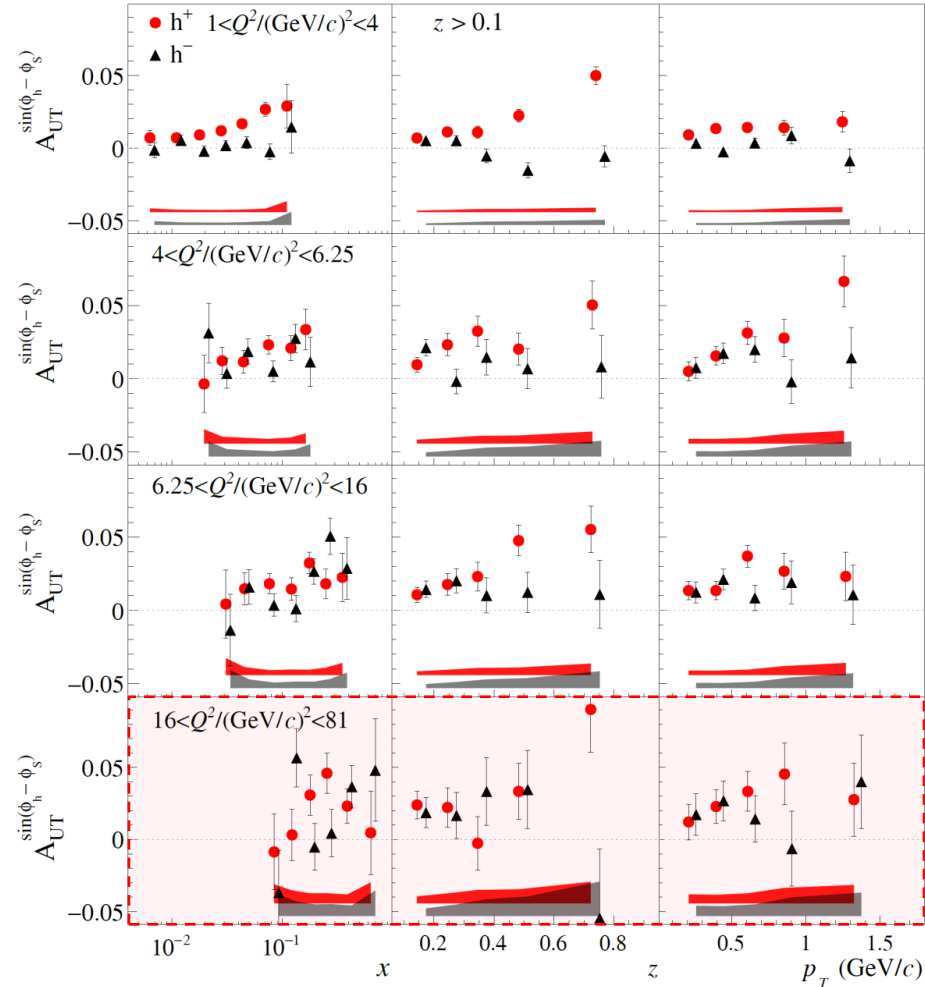
SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

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

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

COMPASS PLB 770 (2017) 138

COMPASS preliminary
SIDIS 2010 NH$_3$ proton data

$16 < Q^2 < 81$

$6.25 < Q^2 < 16$

$4 < Q^2 < 6.25$

$1 < Q^2 < 4$

$\bullet$ h$^+$ $16 < Q^2/(\text{GeV}/c)^2 < 81$
$\blacktriangle$ h$^-$ $\langle x \rangle \approx 0.238$

$A_{UT}^{\sin(\phi_h - \phi_S)}$

$A_{UT}^{\sin(\phi_h + \phi_S - \pi)}$

$A_{UT}^{\sin(3\phi_h - \phi_S)}$

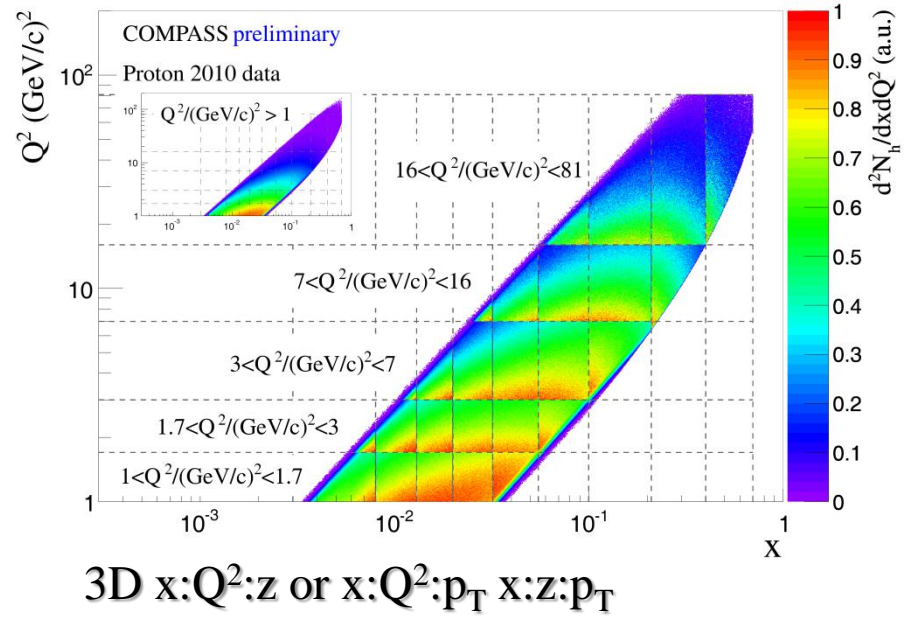**1$^{\text{st}}$ COMPASS multi-D fit done for all eight TSAs**

COMPASS Multi-D TSA analyses

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

$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C \left[-\frac{\hat{h} \cdot \mathbf{k_T}}{M} f_{1T}^{\perp q} D_{1q}^h \right], \quad F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$
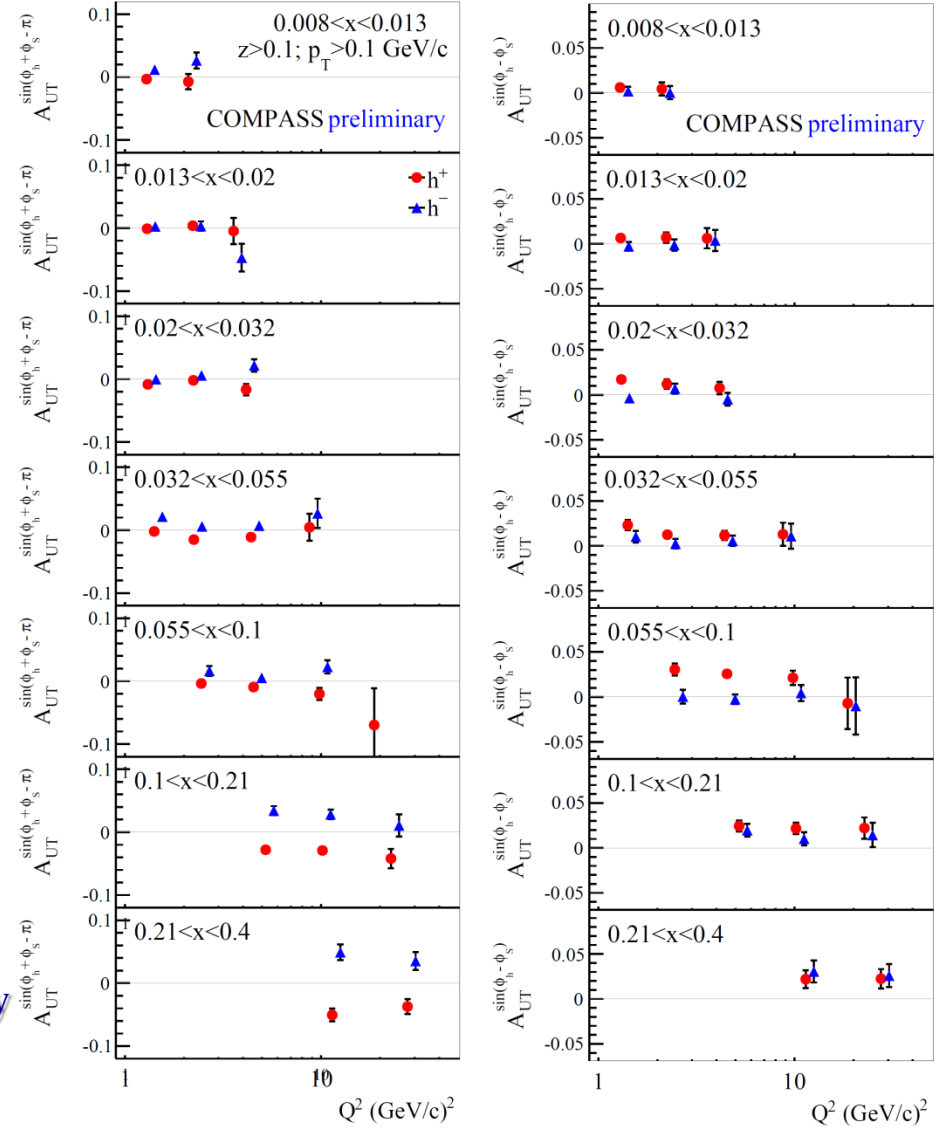
$$F_{UT}^{\sin(\phi_h + \phi_S)} = C \left[-\frac{\hat{h} \cdot \mathbf{p_T}}{M_h} h_1^q H_{1q}^{\perp h} \right]$$

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

3D x:Q²:z or x:Q²:p_T x:z:p_T

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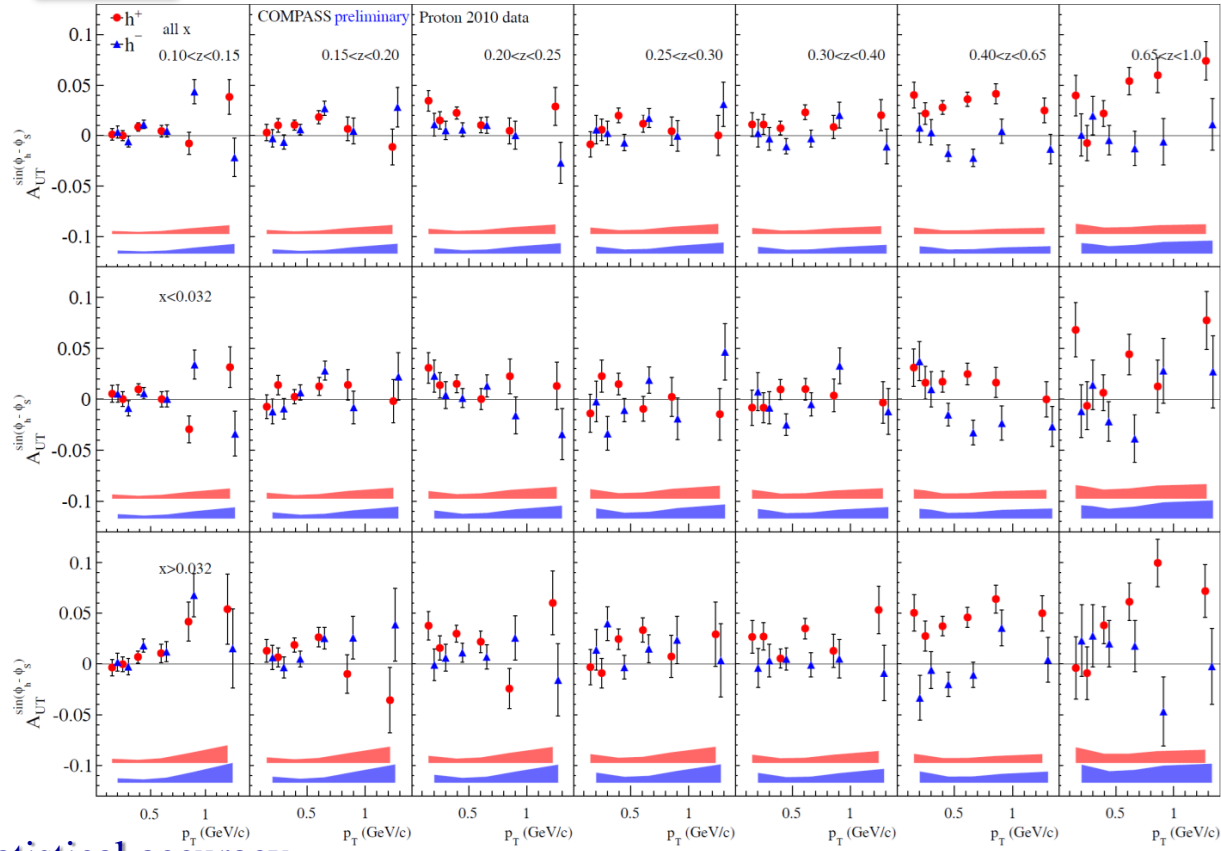- Possible decreasing trend for Sivers TSA?

COMPASS Multi-D TSA analyses

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

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

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

Multi-D extraction
3D x:Q^2:z or x:Q^2:p$_T$ x:z:p$_T$

- No clear Q^2-dependence within statistical accuracy
- Possible decreasing trend for Sivers TSA?
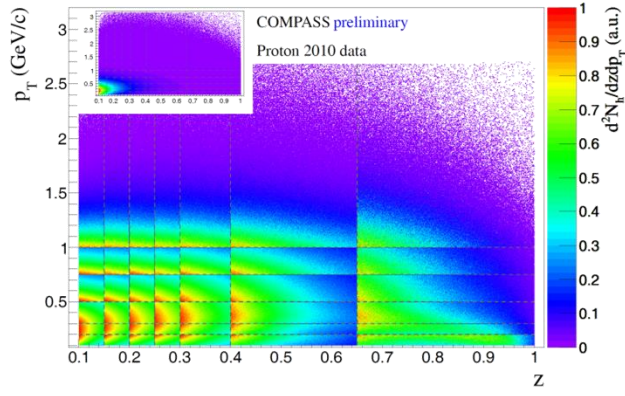- Negative amplitude for h$^-$ at large z?
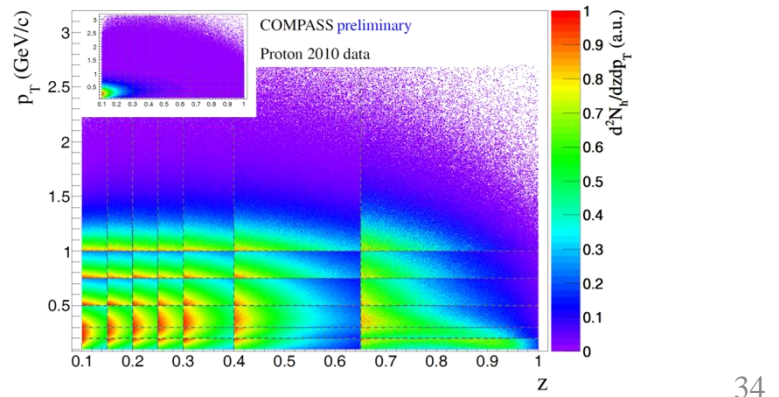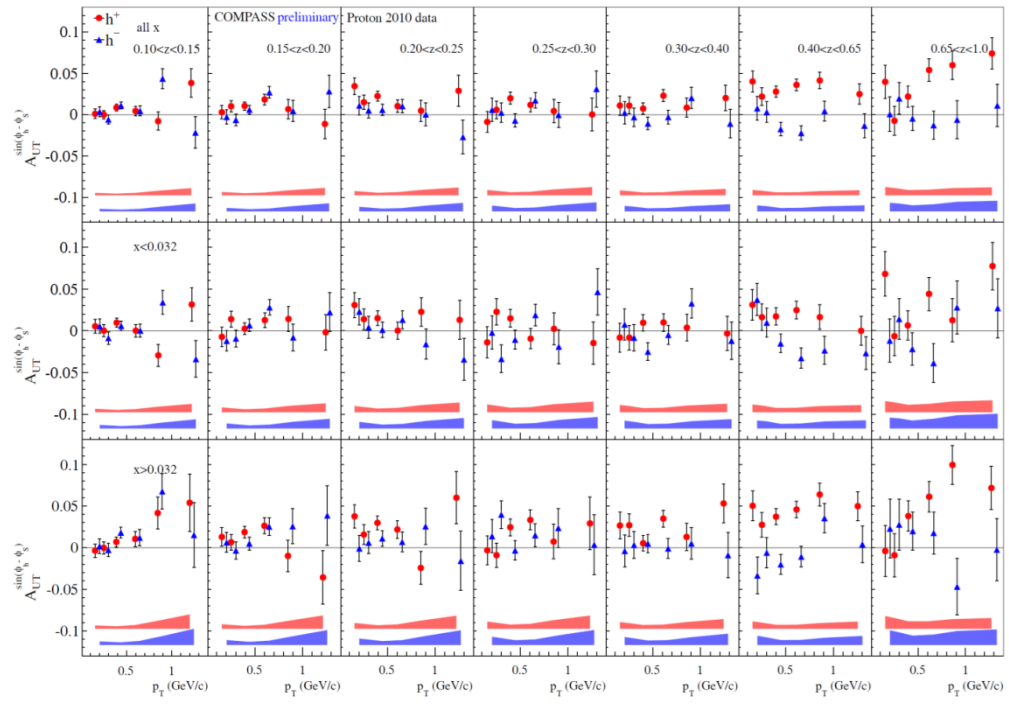
COMPASS Multi-D TSA analyses

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

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

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

HERMES, JHEP 12 (2020) 010

Raphael "Madonna del Prato"

Salvador Dali "Maximum Speed of Raphael's Madonna"

"Nature"   *"multi-D" with available statistics*

Raphael "Madonna del Prato"

Raphael "Madonna del Prato" (poor resolution)
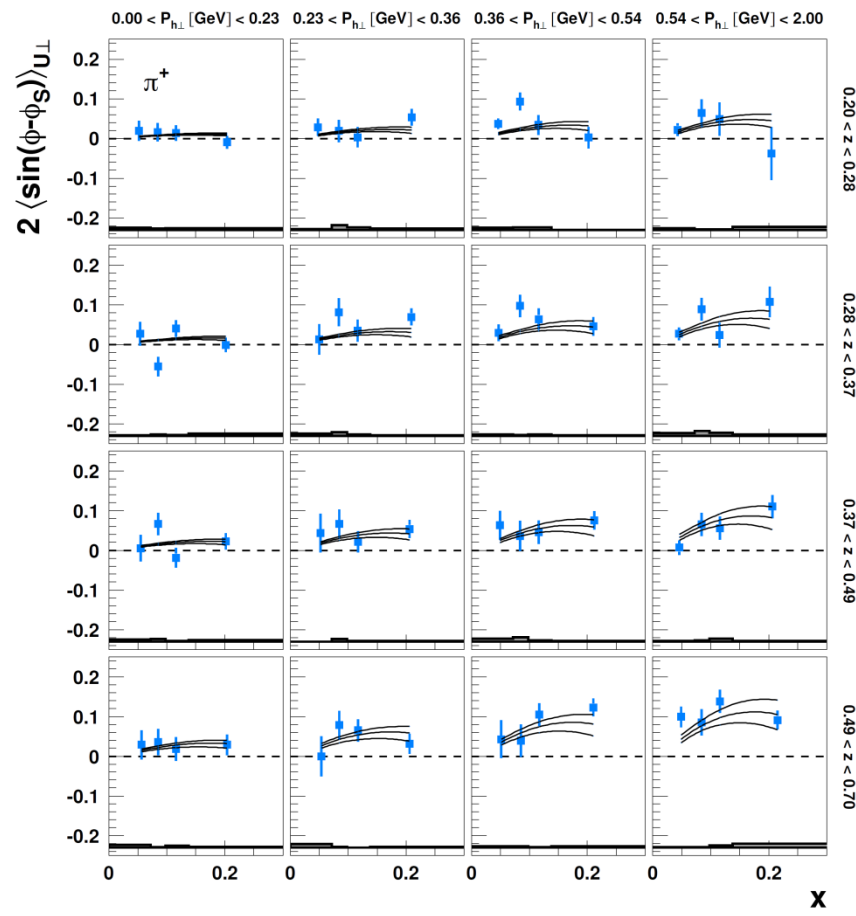
"Nature"

Raphael "Madonna del Prato"

"multi-D" with available statistics
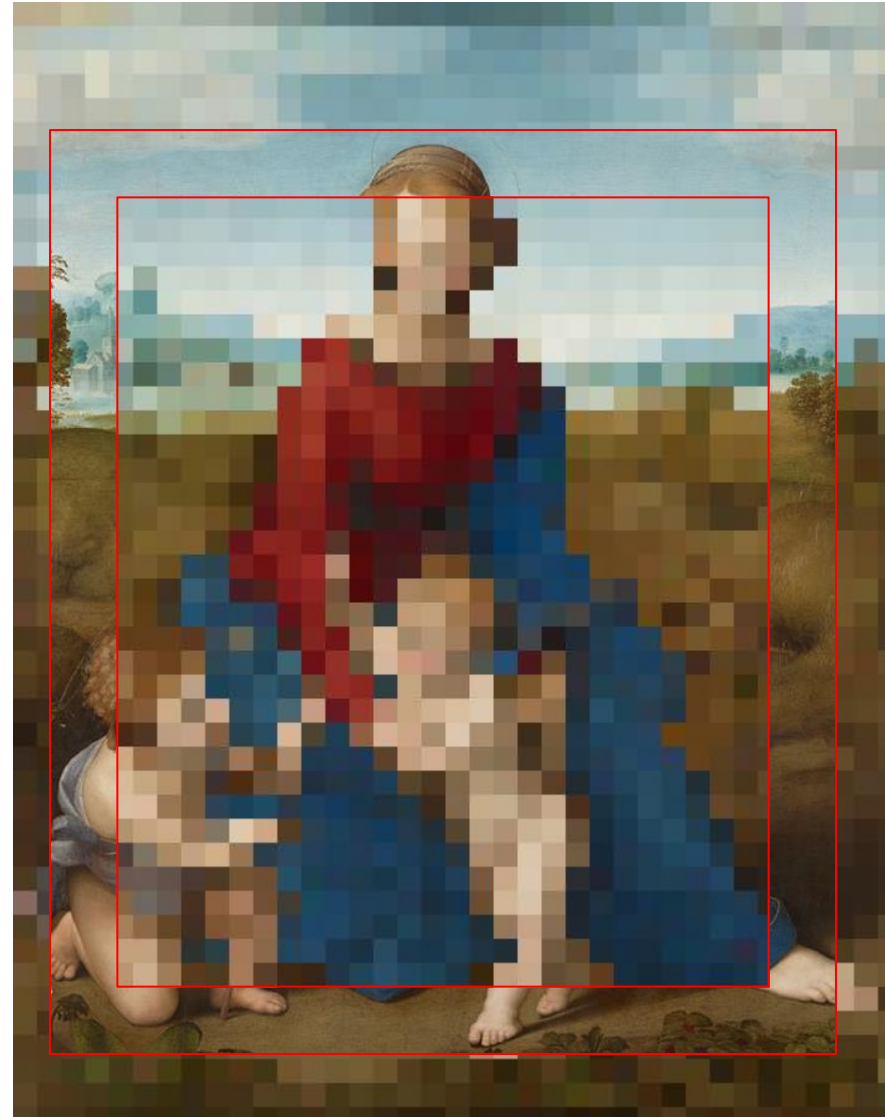
Raphael "Madonna del Prato" (poor resolution)

SIDIS TSAs: Kotzinian-Mulders asymmetry

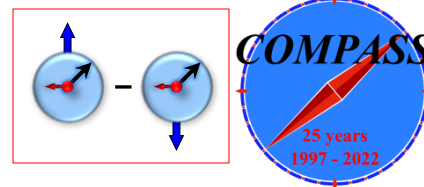$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + ... + \lambda S_T \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h-\phi_S) + ...\right\}$$

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

COMPASS, PBL 770 (2017) 138; PoS QCDEV2017 (2018) 042
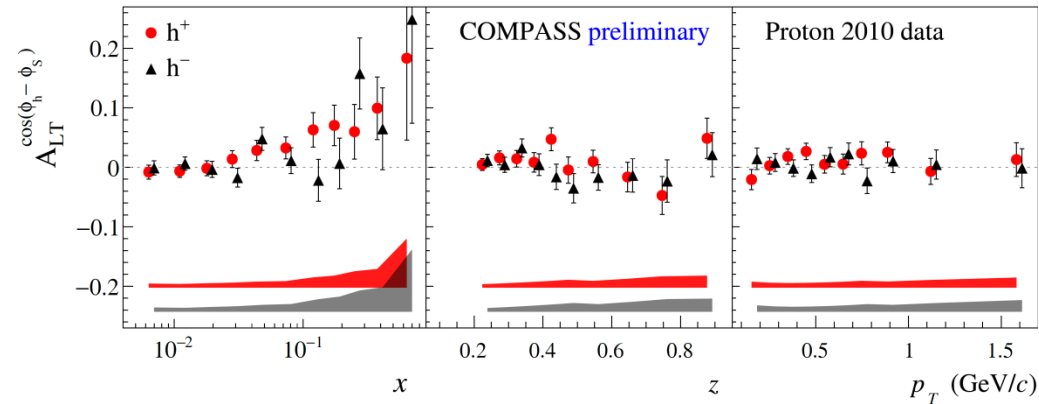
COMPASS/HERMES/CLAS6 results
$A_{LT}^{\cos(\phi_h-\phi_S)}$

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

First global QCD analysis of the g_{1T} TMD PDF using SIDIS data
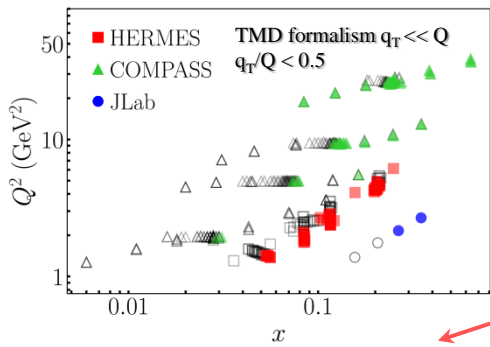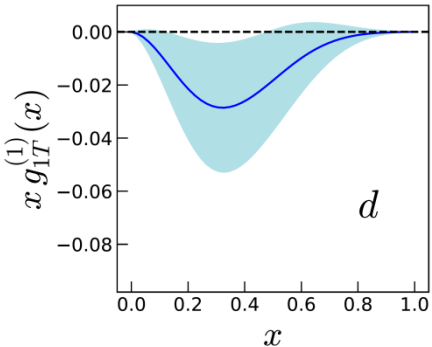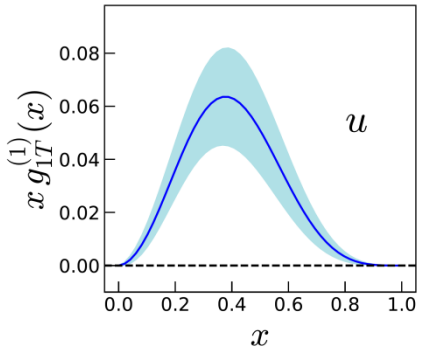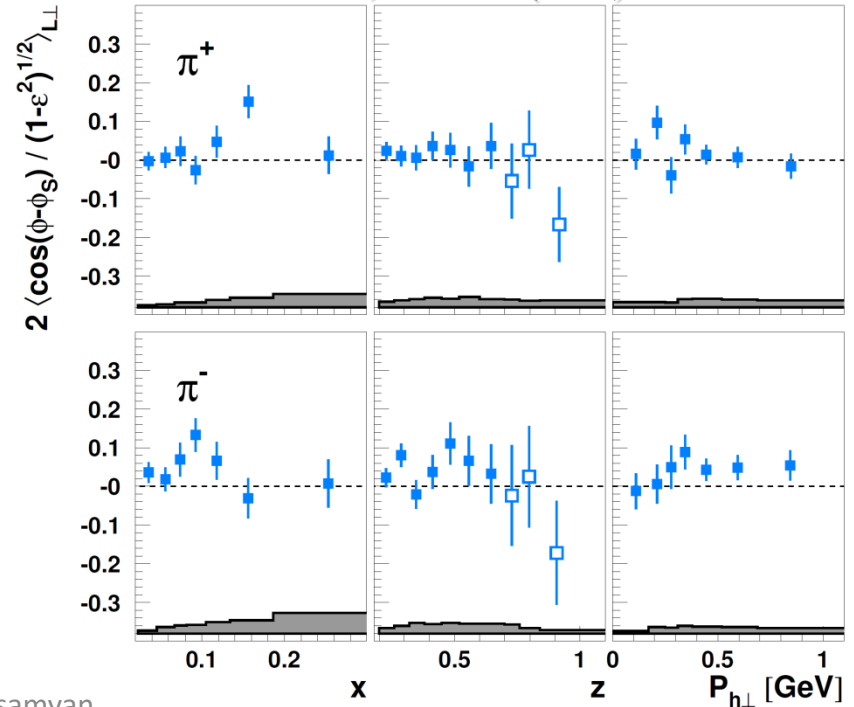
HERMES, JHEP 12 (2020) 010

SIDIS TSAs: subleading twist effects

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

$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q}C\left\{\left(xf_T^q D_{1q}^h - \frac{M_h}{M}h_1^q \frac{\tilde{H}_q^h}{z}\right)\right.$$

$$\left.-\frac{\boldsymbol{p}_T \cdot \boldsymbol{k}_T}{2MM_h}\left[\left(xh_T^q H_{1q}^{\perp h} + \frac{M_h}{M}g_{1T}^q \frac{\tilde{G}_q^{\perp h}}{z}\right)\right.\right.$$

$$\left.\left.-\left(xh_T^{\perp q}H_{1q}^{\perp h} - \frac{M_h}{M}f_{1T}^{\perp q}\frac{\tilde{D}_q^{\perp h}}{z}\right)\right]\right\}$$

COMPASS, PBL 770 (2017) 138; PoS QCDEV2017 (2018) 042
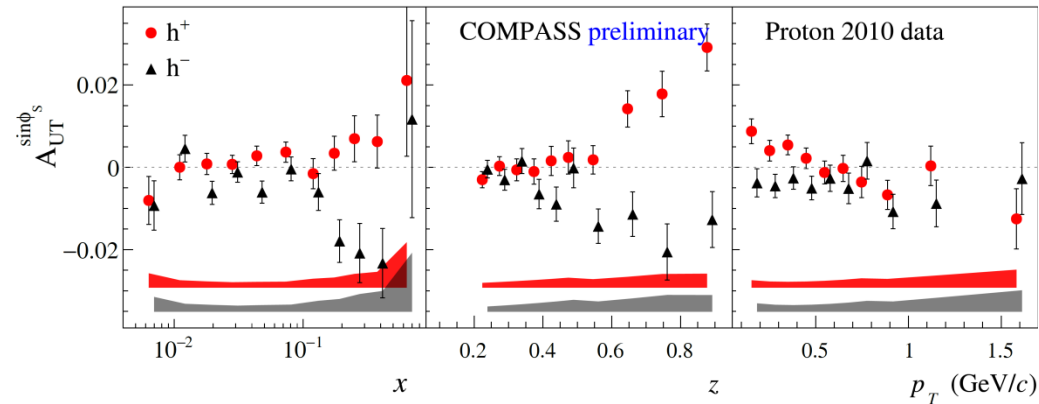
COMPASS/HERMES results $A_{UT}^{\sin\phi_S}$

- Q-suppression
- various "twist-2/3" ingredients
- non-zero signal for h± at large z?

HERMES, JHEP 12 (2020) 010
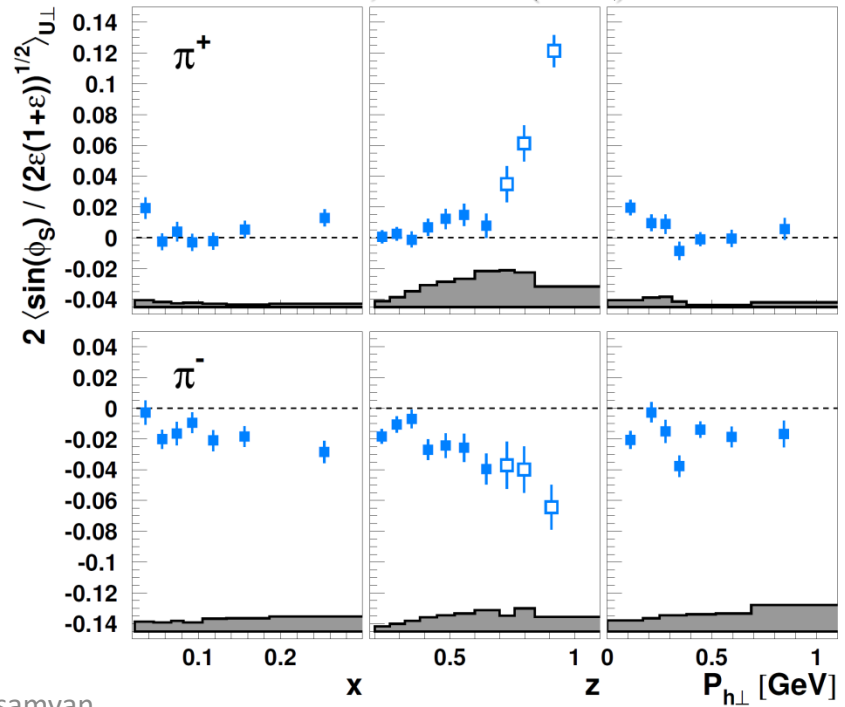
S. Bastami et al.
JHEP 1906 (2019) 007

W. Mao et al.
PRD 90 (2014) 014048

COMPASS 2022 run: new unique deuteron data to come

See talk by A. Martin

proton [H]
hermes
95 data points
Airapetian et al.,
P.R.L. **103** (09) 152002

neutron [³He]
Jefferson Lab
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

Pavia group fits

Bacchetta, Delcarro, Pisano, Radici,
in preparation

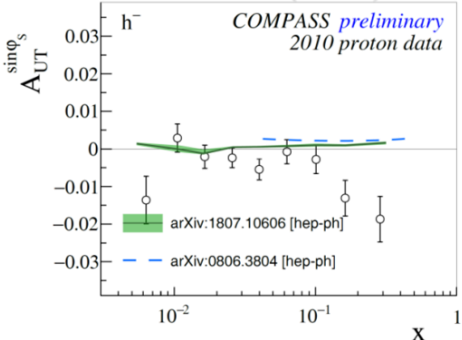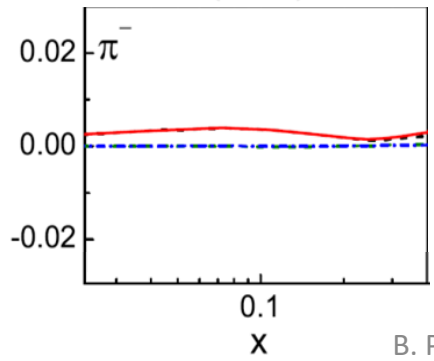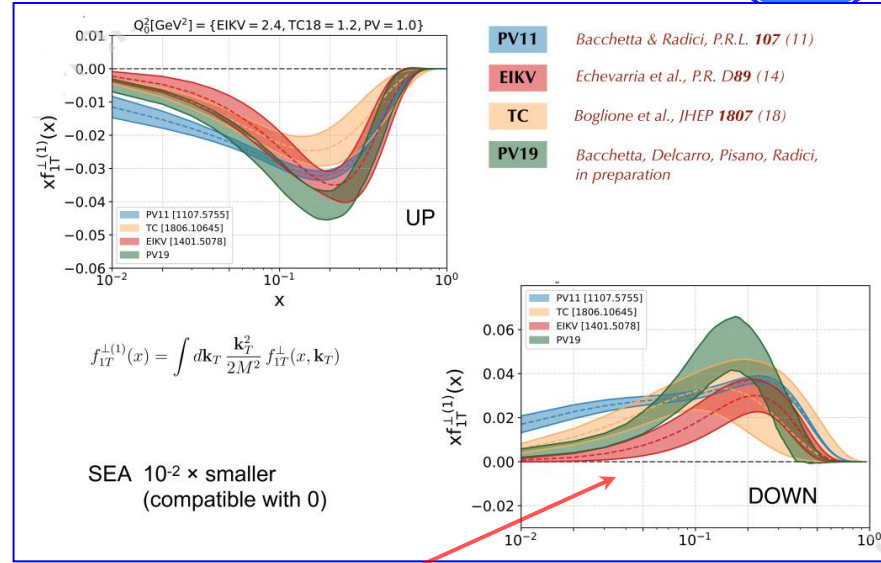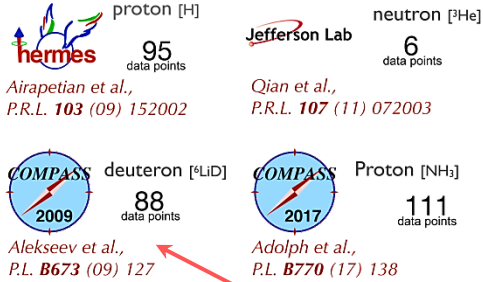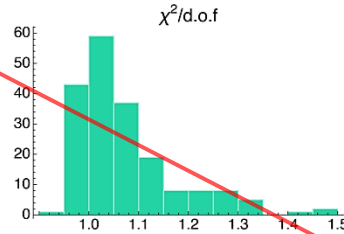analysis of statistical error
with replica method (200)
68% confidence level

Same kinematic cuts applied to unpolarized

x, z, P_{hT} data projections

$Q^2 \geq 1.4$ GeV² $\quad 0.2 \leq z \leq 0.7$
$P_{hT} < \min[0.2Q, 0.7Qz] + 0.5$ GeV

χ^2/d.o.f

300 data points → **118** data fitted
14 free parameters
χ^2/d.o.f. = **1.06 ± 0.10**

$Q_0^2[\text{GeV}^2] = \{\text{EIKV} = 2.4, \text{TC18} = 1.2, \text{PV} = 1.0\}$

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

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

PV11 [1107.5755]
TC [1806.10645]
EIKV [1401.5078]
PV19

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

SEA $10^{-2} \times$ smaller
(compatible with 0)

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

COMPASS 2022 deuteron run

JAM Collaboration, [hep-ph](#) > arXiv:2205.00999

$x h_1(x)$
JAM22
SB
u
d
Radici, Bacchetta '18
Benel et al '19
D'Alesio et al '20

$x f_{1T}^{\perp(1)}(x)$
u
d
Echevarria et al '20
Anselmino et al '17
Bacchetta et al '21

$z H_1^{\perp(1)}(z)$
fav
unf
Anselmino et al '13
Anselmino et al '15
Kang et al '15
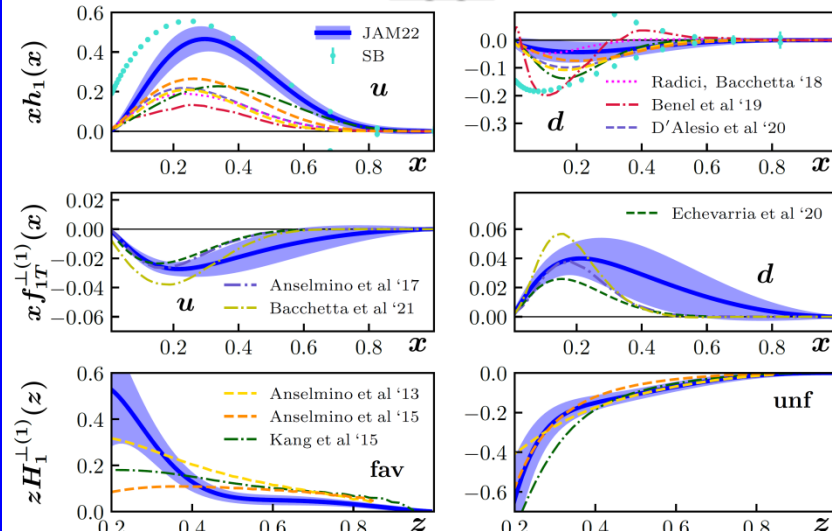
S. Bhattacharya, Z. B. Kang, A. Metz, G. Penn and D. Pitonyak
PRD 105 (2022) 3, 034007

$x g_{1T}^{(1)}(x)$ u

$x g_{1T}^{(1)}(x)$ d
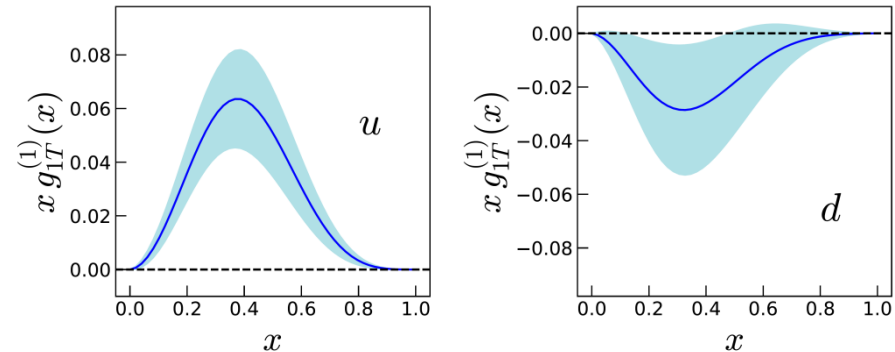
Conclusions-SIDIS

- During phase I COMPASS has measured all SIDIS TSAs (P/D)
  - Deuteron TSAs are all compatible with zero
  - Non-zero Sivers and Collins asymmetries with proton target
  - Apart from Sivers and Collins effects non-zero signal was observed for *twist-2* $A_{LT}^{cos(\phi_h - \phi_S)}$ and *subleading-twist* $A_{UT}^{sin\phi_S}$ TSAs
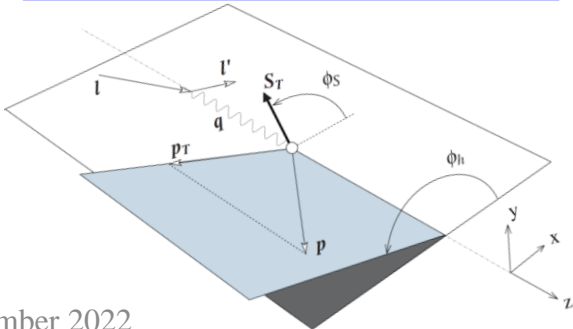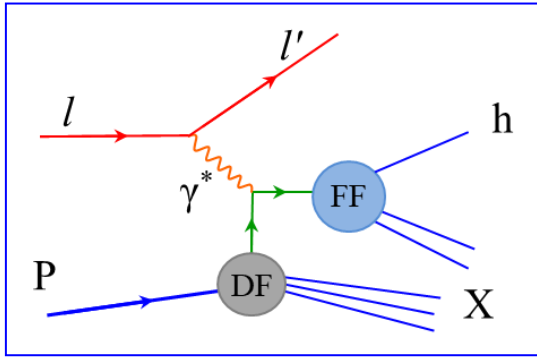 - First multi-D results for all TSAs - PLB 770 (2017) 138
    - No hints for significant Q^2-dependences of Sivers and Collins TSAs
- COMPASS has measured all SIDIS LSAs (P/D)
  - Deuteron azimuthal LSAs are compatible with zero
  - Interesting proton results, non-zero asymmetries
  - *twist-2* $A_{UL}^{sin2\phi_h}$ asymmetry seem to exhibit a Collins-like behavior
  - Significant effect was observed for *subleading-twist* $A_{UL}^{sin\phi_h}$ LSA

- SIDIS measurements with transversely polarized deuteron target in 2022
  - Unique input for d-quark transversity and many other studies

SIDIS

$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L} \right)$$
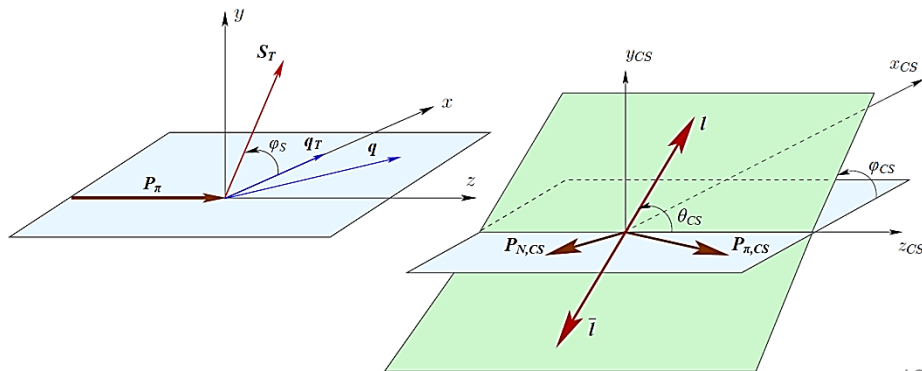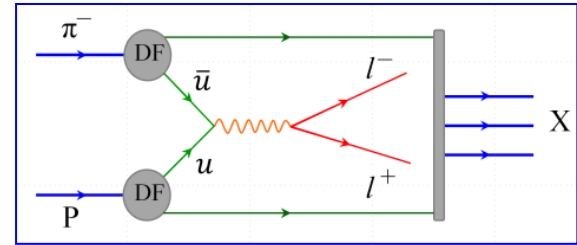
$$\times \left\{
\begin{array}{l}
1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\[4pt]
+ \; S_L \; \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + \; S_L \lambda \sqrt{1-\varepsilon^2}\, A_{LL} \\[6pt]
+ \; S_T \left[
\begin{array}{l}
A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) \\[4pt]
+ \; \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \\[4pt]
+ \; \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S)
\end{array}
\right] \\[6pt]
+ \; S_T \lambda \left[\sqrt{(1-\varepsilon^2)}\, A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) \right]
\end{array}
\right\}$$

DY

$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1 + \cos^2 \theta_{CS} \right)$$
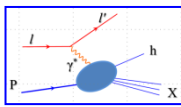
$$\times \left\{
\begin{array}{l}
1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\[4pt]
+ \; S_L \sin^2 \theta_{CS}\, A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\[6pt]
+ \; S_T \left[
\begin{array}{l}
A_T^{\sin \varphi_S} \sin \varphi_S \\[4pt]
+ D_{[\sin^2 \theta_{CS}]} \left(
\begin{array}{l}
A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \\[4pt]
+ \; A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S)
\end{array}
\right)
\end{array}
\right]
\end{array}
\right\}$$

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

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

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

COMPASS
25 years
1997 – 2022

$$\left[1 + \boxed{\varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h} \right.$$
$$+ \ S_L \ \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + \ S_L \lambda \sqrt{1-\varepsilon^2} A_{LL}$$

$$\times \left\{ + \ S_T \begin{bmatrix} A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h - \phi_S) \\ + \ \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h + \phi_S) \\ + \ \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h - \phi_S) \end{bmatrix} \right.$$

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

COMPASS
SIDIS-DY bridge

$$\left[1 + \boxed{D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}} \right.$$
$$+ \ S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS}$$

$$\times \left\{ + \ S_T \begin{bmatrix} A_T^{\sin\varphi_S} \sin\varphi_S \\ + D_{[\sin^2\theta_{CS}]} \begin{pmatrix} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \\ + \ A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \end{pmatrix} \end{bmatrix} \right. \right\}$$

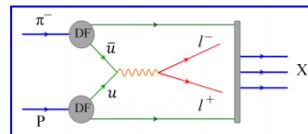where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1 + \cos^2\theta_{CS} \right)$

$$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots \quad \xleftarrow{\text{Boer-Mulders}} \quad A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$$

$$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h \quad \xleftarrow{\text{Sivers}} \quad A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$$

$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h} \quad \xleftarrow{\text{Transversity}} \quad A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^q$$

$$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} \quad \xleftarrow{\text{Pretzelosity}} \quad A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$$

Complementary information from two different channels :
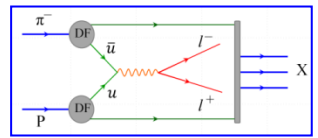
- SIDIS-DY bridging of nucleon TMD PDFs; Universality studies;

- 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 /(GeV/c²) < 2.0** "Low mass"
  - Large background contamination, combinatorial, Open-charm (B) $D\bar{D}$, $B\bar{B}$, π, K decays
- **2.0 < M /(GeV/c²) < 2.5** "Intermediate mass"
  - High DY-cross section
  - Still low DY-signal/background ratio
- **2.5 < M /(GeV/c²) < 4.3** "Charmonia mass"
  - Strong J/ψ-signal → study of J/ψ physics
  - Good signal/background
- **4.3 < M /(GeV/c²) < 8.5** "High mass"
  - Low DY cross-section
  - Beyond charmonium region, background < 3%
  - Valence region → largest asymmetries

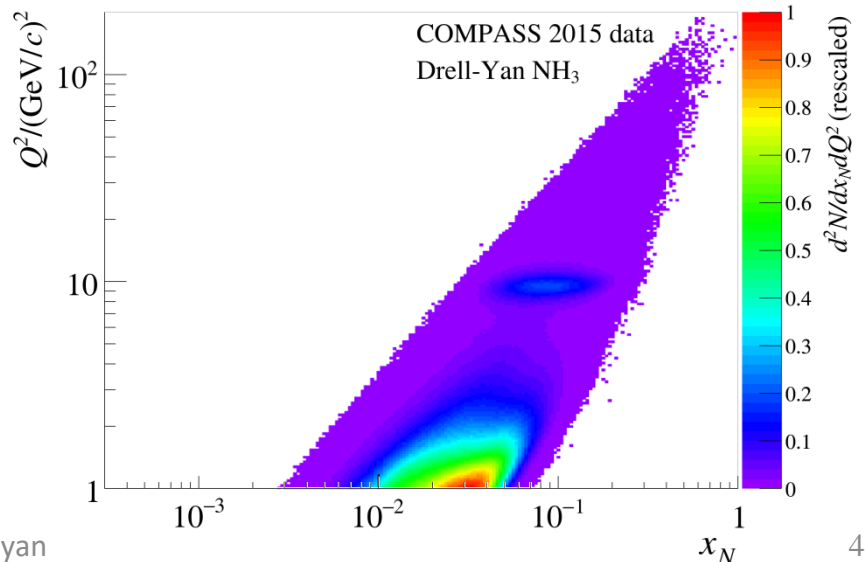$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1 + \cos^2 \theta_{CS}\right)$$

$$\times \left\{ \begin{array}{l} 1 + D_{\left[\sin^2 \theta_{CS}\right]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\[6pt] + S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\[6pt] + S_T \left[\begin{array}{l} A_T^{\sin \varphi_S} \sin \varphi_S \\[4pt] + D_{\left[\sin^2 \theta_{CS}\right]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \\[4pt] + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) \end{array} \right) \end{array} \right] \end{array} \right\}$$

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

COMPASS x:Q² phase space

COMPASS 2015 data
Drell-Yan NH₃

Single-polarized DY measurements at COMPASS

- **2.5 < M /(GeV/c²) < 4.3** "Charmonia mass"
  - Strong J/ψ-signal → study of J/ψ physics
  - Good signal/background
- 4.3 < M /(GeV/c²) < 8.5 "High mass"
  - Low DY cross-section
  - Beyond charmonium region, background < 3%
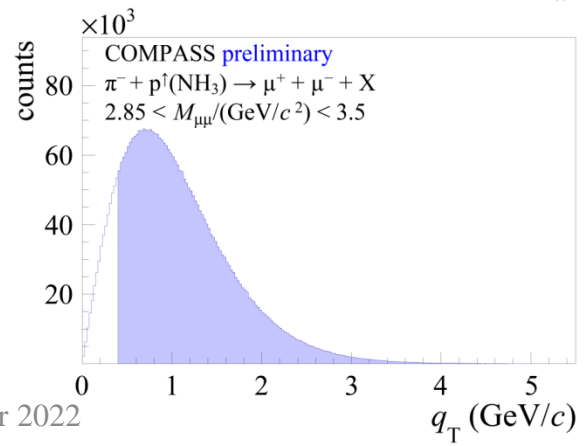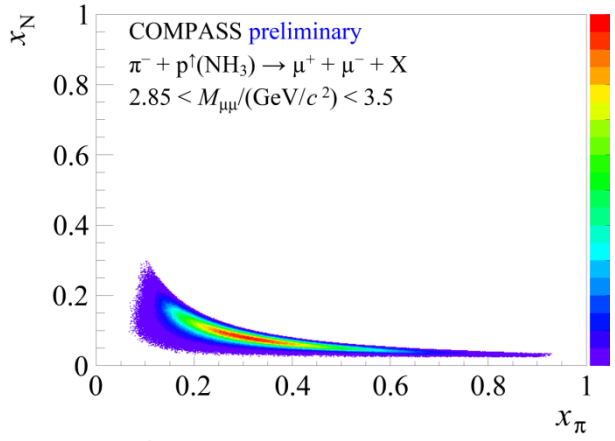 - Valence region → largest asymmetries

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

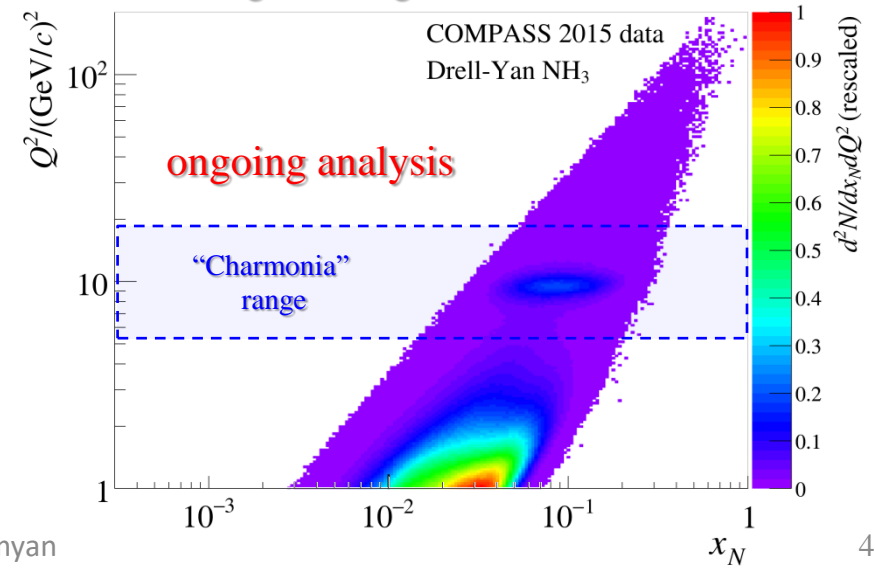$$\times \left\{ \begin{array}{l} 1 + D_{\left[\sin^2\theta_{CS}\right]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\[1mm] + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\[1mm] + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S} \sin\varphi_S \\[1mm] + D_{\left[\sin^2\theta_{CS}\right]}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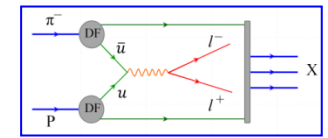
$$D_{\left[\sin^2\theta_{CS}\right]} = \sin^2\theta_{CS} / \left(1 + \cos^2\theta_{CS}\right)$$

$$\langle x_\pi \rangle = 0.31, \langle x_N \rangle = 0.09, \ \langle x_F \rangle = 0.22, \ \langle q_T \rangle = 1.1 \text{ GeV/c}$$
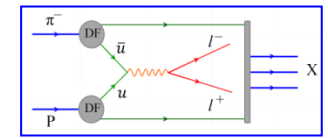
2.5 < M /(GeV/c2) < 4.3 "Charmonia mass"
Strong J/ψ-signal → study of J/ψ physics
Good signal/background

COMPASS preliminary
$\pi^- + p^\uparrow(NH_3) \rightarrow \mu^+ + \mu^- + X$
$2.85 < M_{\mu\mu}/(GeV/c^2) < 3.5$

COMPASS preliminary
$\pi^- + p^\uparrow(NH_3) \rightarrow \mu^+ + \mu^- + X$
$2.85 < M_{\mu\mu}/(GeV/c^2) < 3.5$

COMPASS 2015 data
Drell-Yan NH₃

ongoing analysis

"Charmonia" range

Single-polarized DY measurements at COMPASS

- $2.5 < M\,/(\text{GeV}/c^2) < 4.3$ "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%
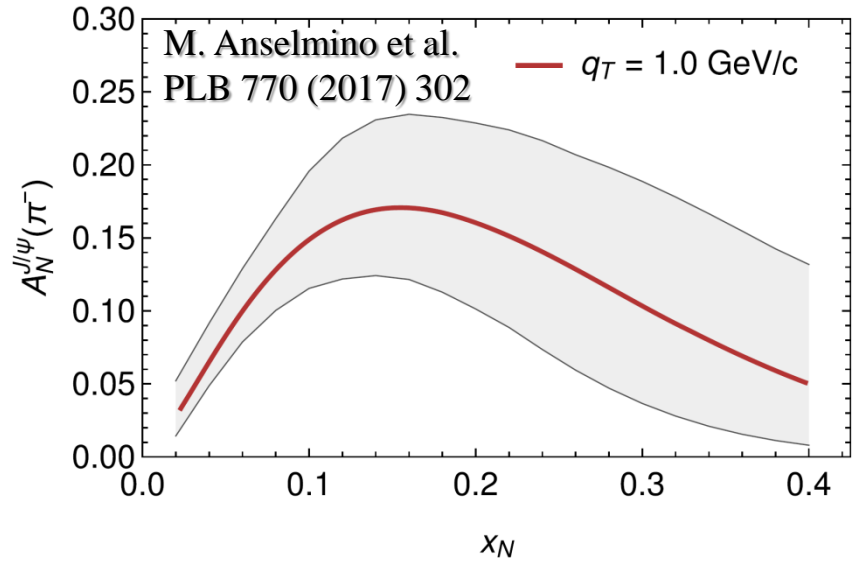 - Valence region → largest asymmetries

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

$$\times \left\{ \begin{array}{c} 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\[4pt] + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\[8pt] + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S} \sin\varphi_S \\[4pt] + D_{[\sin^2\theta_{CS}]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \\[4pt] + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) \end{array} \right) \end{array} \right] \end{array} \right\}$$
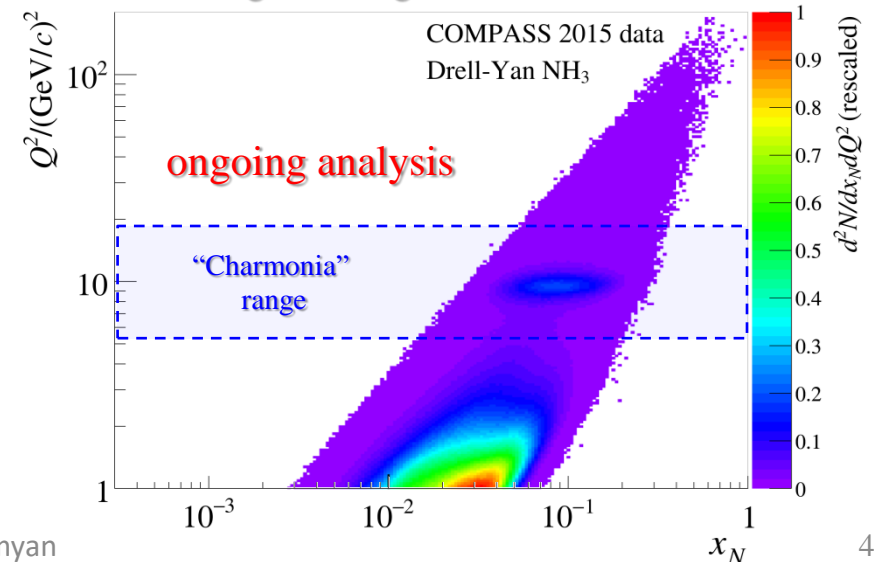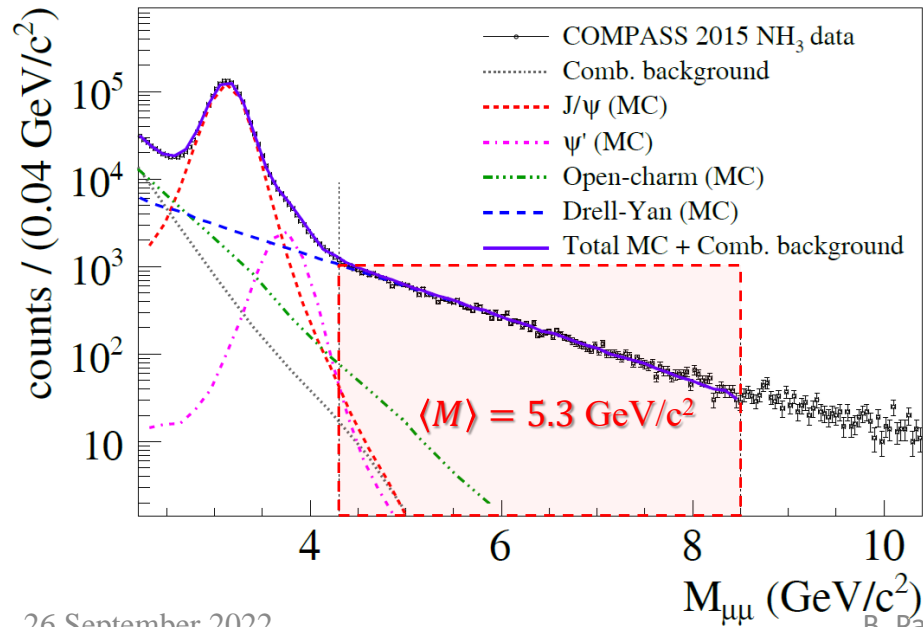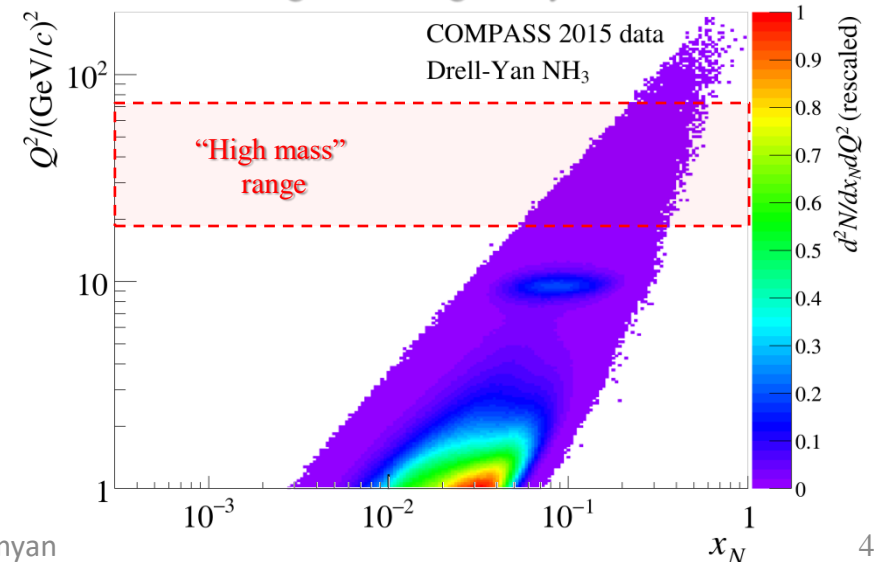
$$D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1 + \cos^2\theta_{CS}\right)$$

$\langle x_\pi \rangle = 0.31, \langle x_N \rangle = 0.09,\ \langle x_F \rangle = 0.22,\ \langle q_T \rangle = 1.1$ GeV/c

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$q_T = 1.0$ GeV/c

$A_N^{J/\psi}(\pi^-)$ x_N

$2.5 < M\,/(\text{GeV}/c2) < 4.3$ "Charmonia mass"
Strong J/ψ-signal → study of J/ψ physics
Good signal/background

COMPASS 2015 data
Drell-Yan NH$_3$

ongoing analysis

"Charmonia" range

$Q^2/(\text{GeV}/c)^2$ x_N $d^2N/dx_N dQ^2$ (rescaled)

- Assuming $q\bar{q}$-annihilation as dominant channel for J/ψ production at COMPASS
- Neglecting gluon fusion contribution and the role of feed-down J/ψ mesons

Single-polarized DY measurements at COMPASS

- 2.5 < M /(GeV/c^2) < 4.3   "Charmonia mass"
  - Strong J/ψ-signal → study of J/ψ physics
  - Good signal/background
- **4.3 < M /(GeV/c^2) < 8.5   "High mass"**
  - Low DY cross-section
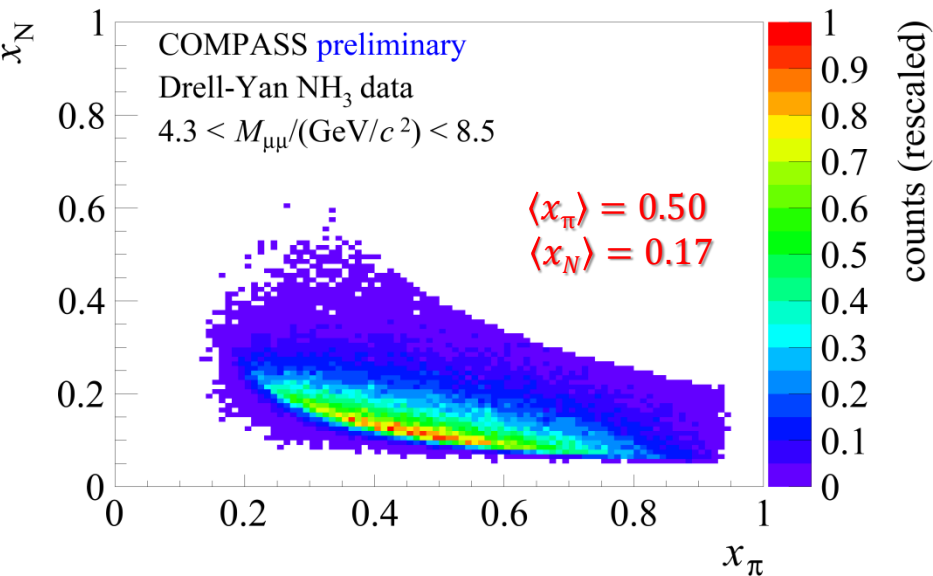 - Beyond charmonium region, background < 3%
  - Valence region → largest asymmetries

$\langle x_\pi \rangle = 0.50, \langle x_N \rangle = 0.17, \langle x_F \rangle = 0.33, \langle q_T \rangle = 1.2$ GeV/c

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

$$\times \left\{ \begin{array}{l} 1 + D_{\left[\sin^2 \theta_{CS}\right]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\[4pt] + S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\[4pt] + S_T \left[A_T^{\sin \varphi_S} \sin \varphi_S + D_{\left[\sin^2 \theta_{CS}\right]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \\[4pt] + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \end{array} \right) \right] \end{array} \right\}$$

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

4.3 < M /(GeV/c^2) < 8.5 "High mass" range
Beyond charmonium region, background < 3%
Valence region → largest asymmetries

Single-polarized DY measurements at COMPASS

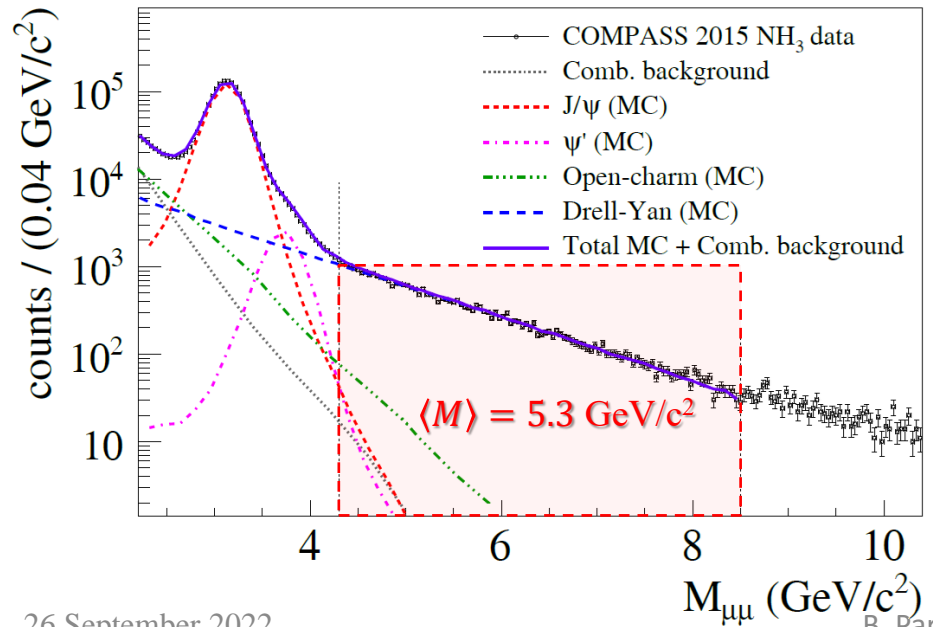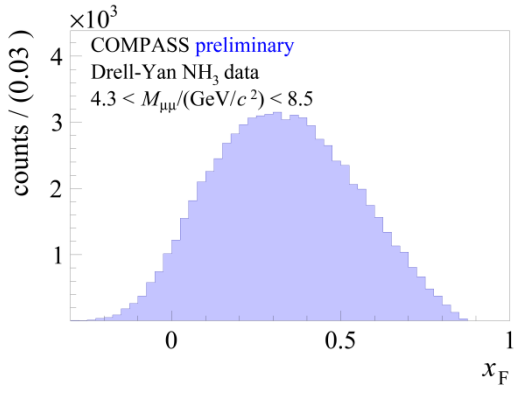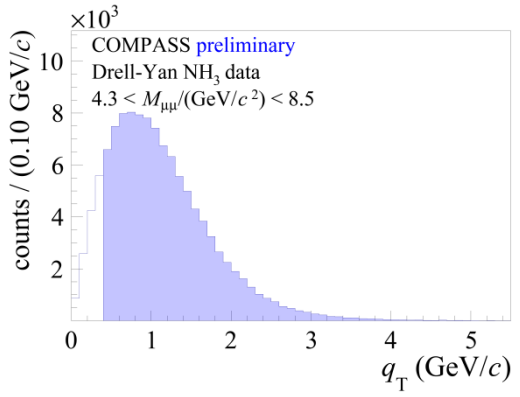COMPASS preliminary
Drell-Yan NH$_3$ data
$4.3 < M_{\mu\mu}/(\text{GeV}/c^2) < 8.5$

$\langle x_\pi \rangle = 0.50$
$\langle x_N \rangle = 0.17$

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

$$\times \left\{ \begin{array}{l} 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\[4pt] + S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\[4pt] + S_T \left[\begin{array}{l} A_T^{\sin \varphi_S} \sin \varphi_S \\[4pt] + D_{[\sin^2 \theta_{CS}]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \\[4pt] + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \end{array} \right) \end{array} \right] \end{array} \right\}$$

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

HM events are in the valence quark range

COMPASS 2015 NH$_3$ data
Comb. background
J/ψ (MC)
ψ' (MC)
Open-charm (MC)
Drell-Yan (MC)
Total MC + Comb. background

$\langle M \rangle = 5.3$ GeV/c^2

$4.3 < M /(\text{GeV}/c^2) < 8.5$ "High mass" range

Beyond charmonium region, background < 3%
Valence region → largest asymmetries

COMPASS 2015 data
Drell-Yan NH$_3$

$4.3 < M_{\mu\mu} < 8.5$

$2.5 < M_{\mu\mu} < 4.3$

$2 < M_{\mu\mu} < 2.5$

$1 < M_{\mu\mu} < 2$

$M_{\mu\mu} > 1$ GeV/c^2
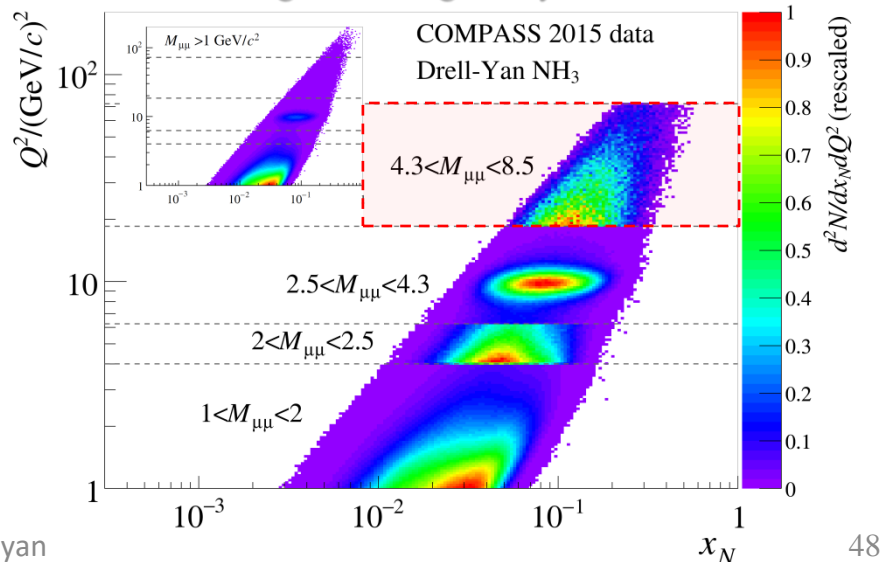
Single-polarized DY measurements at COMPASS

Dimuon transverse momentum $q_T > 0.4$ GeV/c

$\langle x_F \rangle = 0.33$, $\langle q_T \rangle = 1.2$ GeV/c

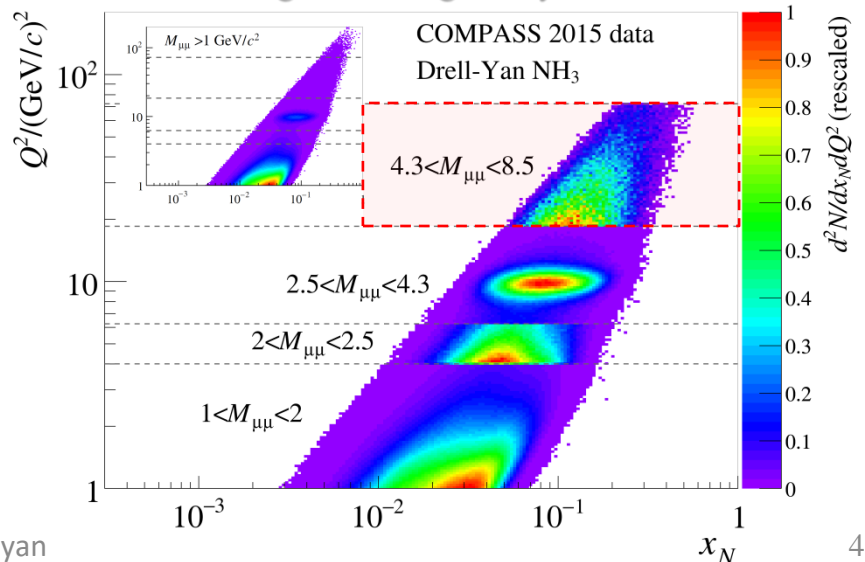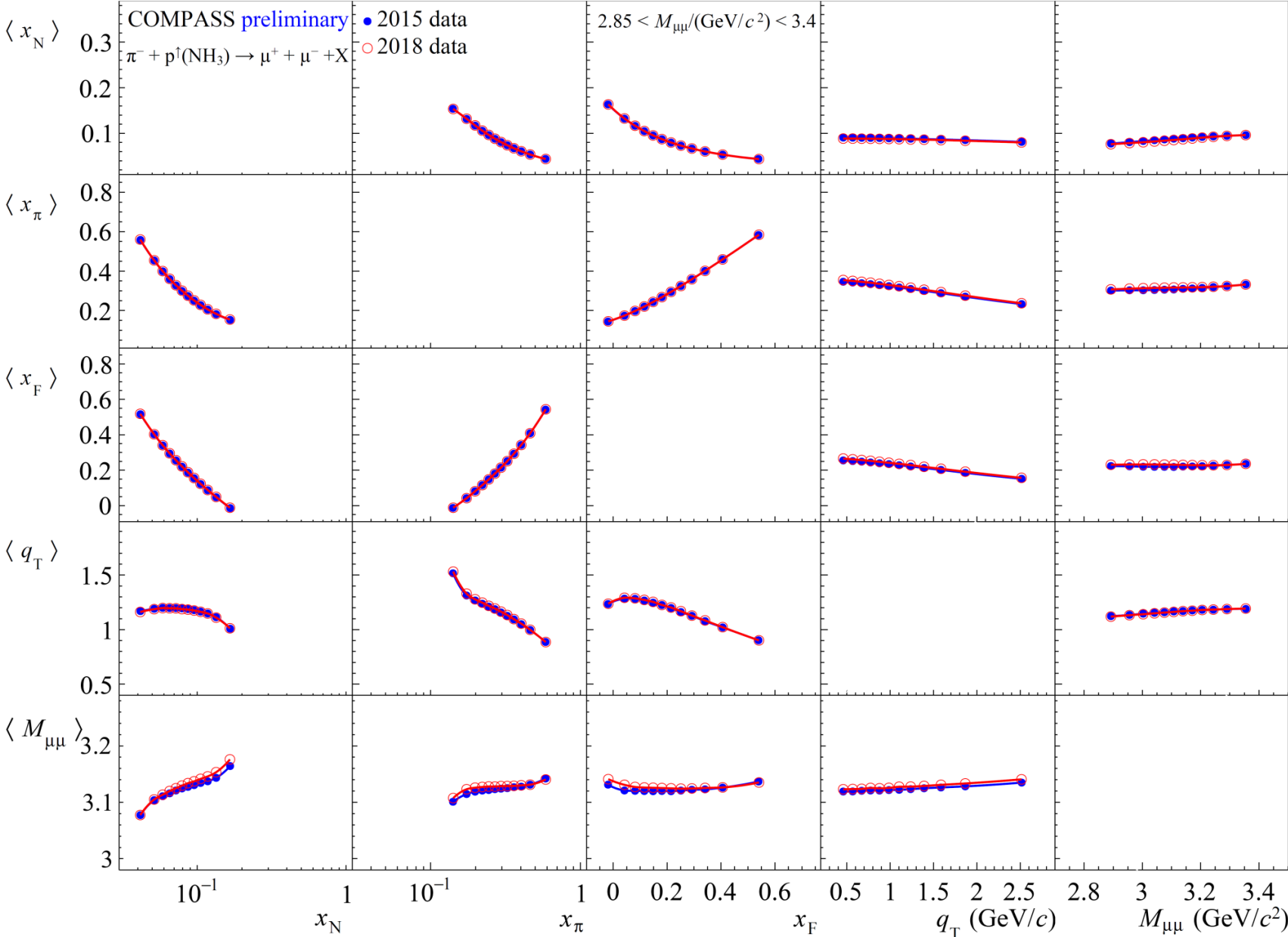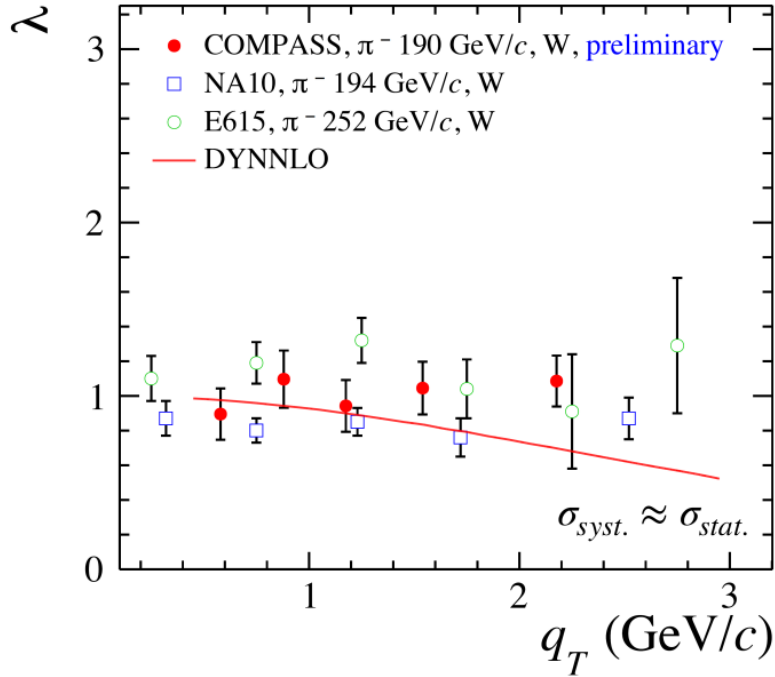$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1 + \cos^2 \theta_{CS} \right)$$

$$\left\{ 1 + D_{\left[\sin^2 \theta_{CS}\right]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \right.$$

$$+ S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS}$$

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

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

$4.3 < M/(GeV/c^2) < 8.5$ "High mass" range

Beyond charmonium region, background < 3%
Valence region → largest asymmetries

$\langle M \rangle = 5.3$ GeV/c^2

Kinematic map: J/ψ mass range

COMPASS Drell-Yan NH$_3$ data preliminary
● 2015 data
○ 2018 data
$4.3 < M_{\mu\mu}/(GeV/c^2) < 8.5$

Single-polarized DY x-section: transverse part

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

$$\times \left\{ \begin{array}{l} 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + D_{[\sin 2\theta_{CS}]} A_U^{\cos \varphi_{CS}} \cos \varphi_{CS} \\[6pt] + S_T \left[\begin{array}{l} A_T^{\sin \varphi_S} \sin \varphi_S \\[4pt] + D_{[\sin 2\theta_{CS}]} \left(\begin{array}{l} A_T^{\sin(\varphi_{CS}-\varphi_S)} \sin(\varphi_{CS}-\varphi_S) \\ + A_T^{\sin(\varphi_{CS}+\varphi_S)} \sin(\varphi_{CS}+\varphi_S) \end{array} \right) \\[10pt] + D_{[\sin^2 \theta_{CS}]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \\ + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) \end{array} \right) \end{array} \right] \end{array} \right.$$

$$D_{[f(\theta_{CS})]} = f(\theta_{CS}) / \left(1 + A_U^1 \cos^2 \theta_{CS} \right)$$
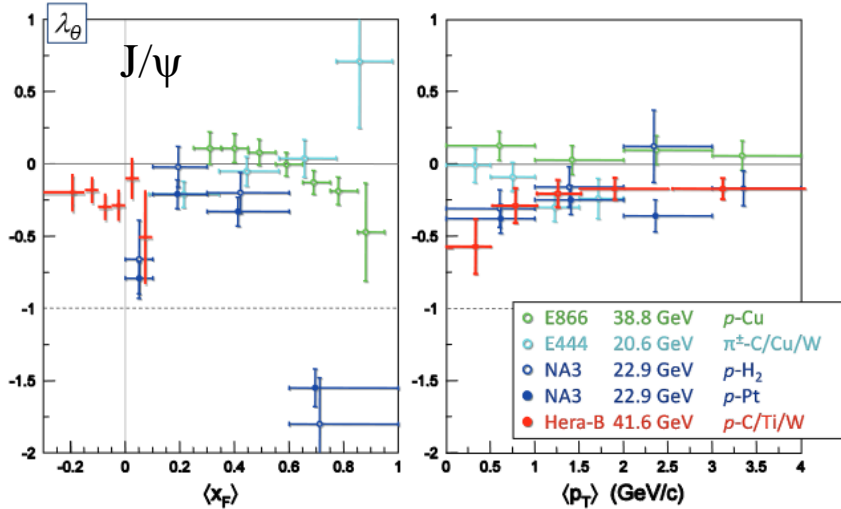
- All five Drell-Yan TSAs are extracted simultaneously using extended unbinned Maximum likelihood estimator.
- Depolarization factors are evaluated under assumption $A_U^1=1$ (DY) and $A_U^1=1$ (J/ψ)
- Possible impact of other scenarios leads to a normalization uncertainty of ~5%.

Unpolarized Drell-Yan results (high-mass range)

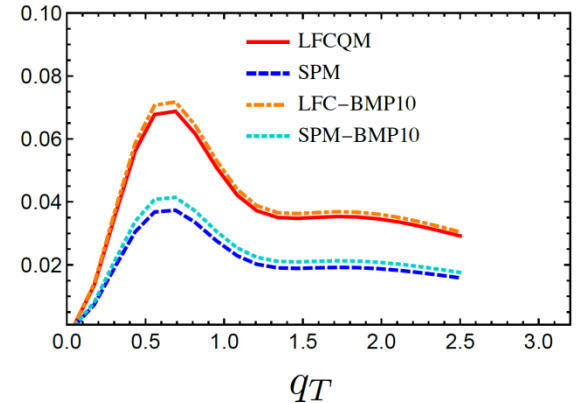M. Lambertsen, W. Vogelsang **PRD93, 114013 (2016)**
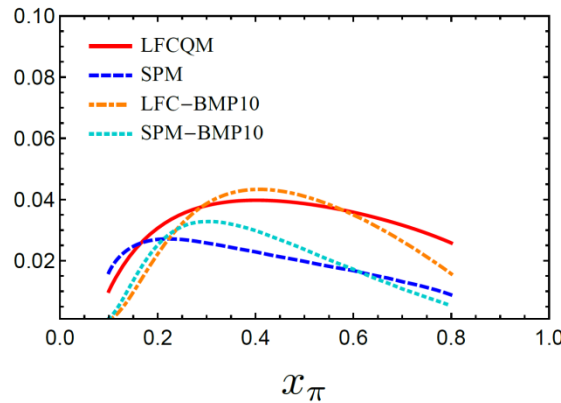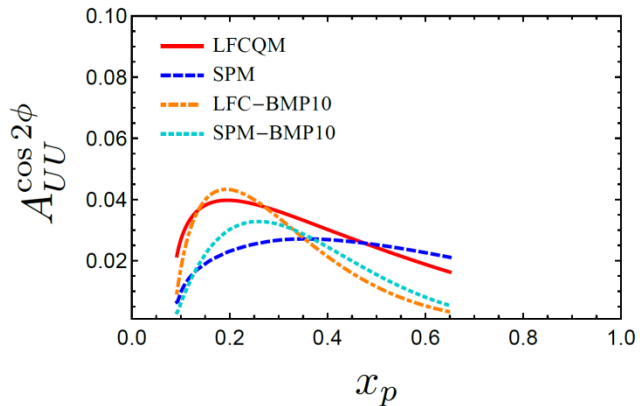
DIS-2021
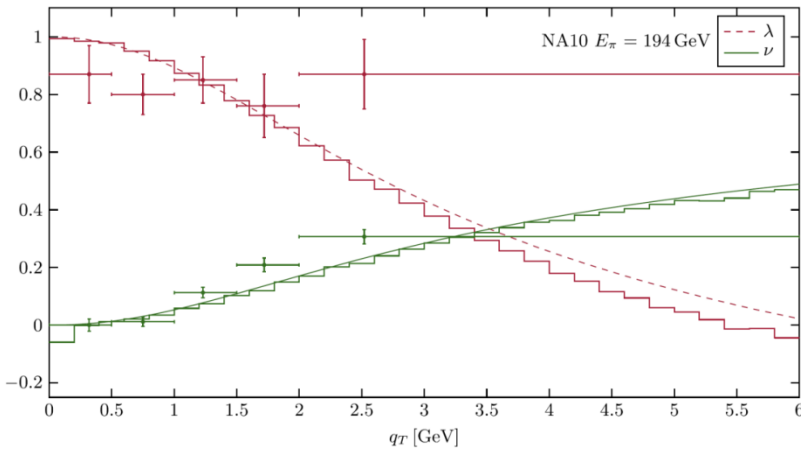
NA10 data **Z.Phys.C 37,545(1988)**
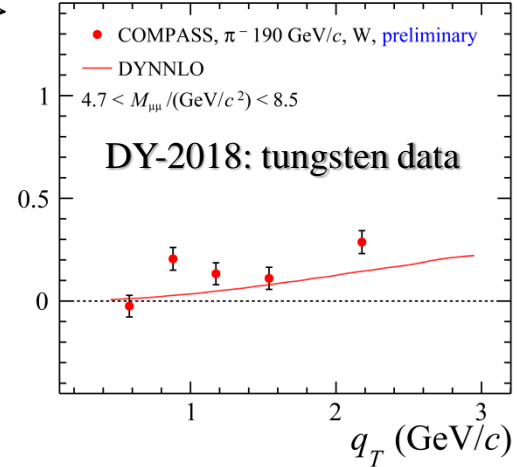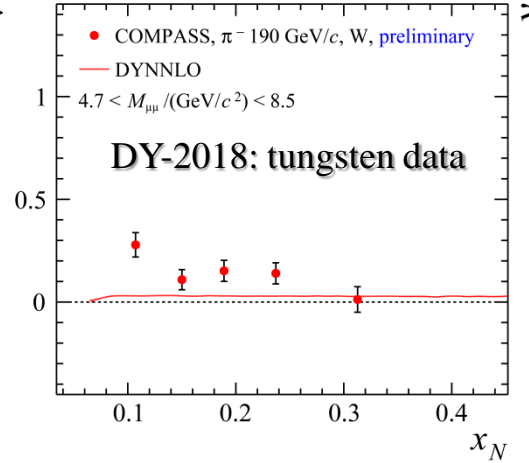
DY-2018 NH_3 data: ongoing analysis

S. Bastami et al. JHEP 02, (2021),166

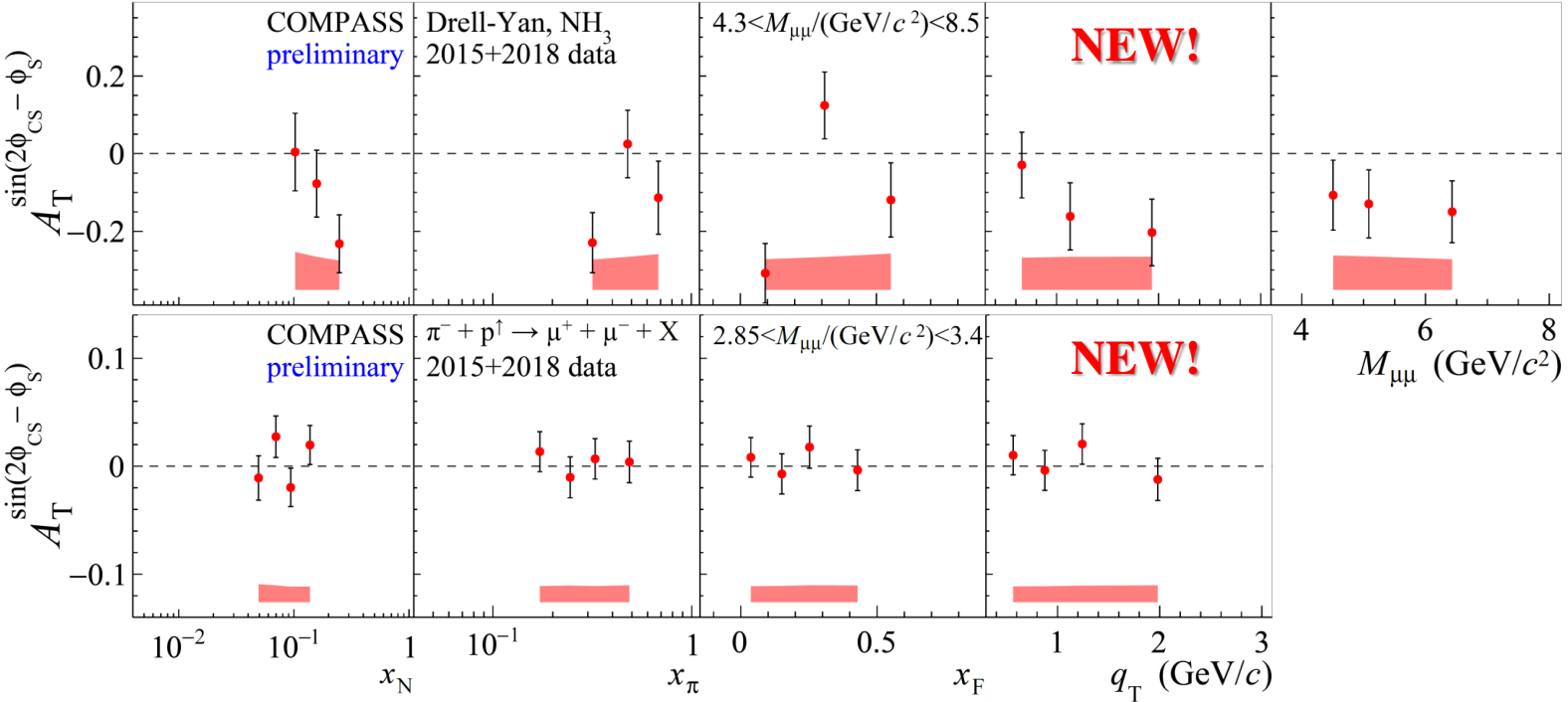**Is there a room for BM at low (COMPASS) q_T?**
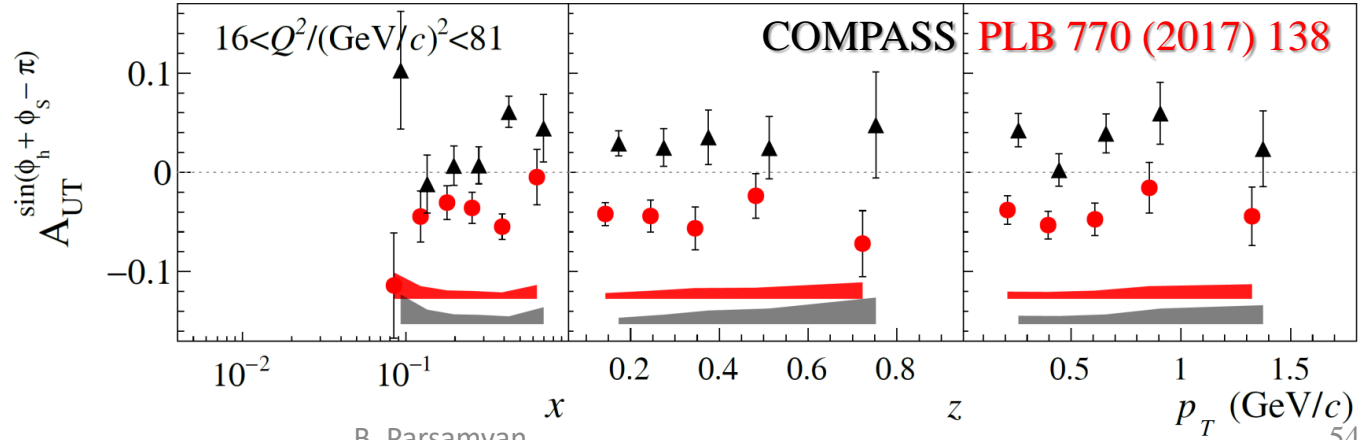
Drell-Yan TSAs – Transversity

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

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

COMPASS
25 years
1997 – 2022

COMPASS
preliminary
Drell-Yan, NH$_3$
2015+2018 data

$4.3 < M_{\mu\mu}/(\text{GeV}/c^2) < 8.5$

NEW!

COMPASS
preliminary
$\pi^- + p^\uparrow \rightarrow \mu^+ + \mu^- + X$
2015+2018 data

$2.85 < M_{\mu\mu}/(\text{GeV}/c^2) < 3.4$

NEW!

Collins SIDIS TSA

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

$16 < Q^2/(\text{GeV}/c)^2 < 81$

COMPASS   PLB 770 (2017) 138

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

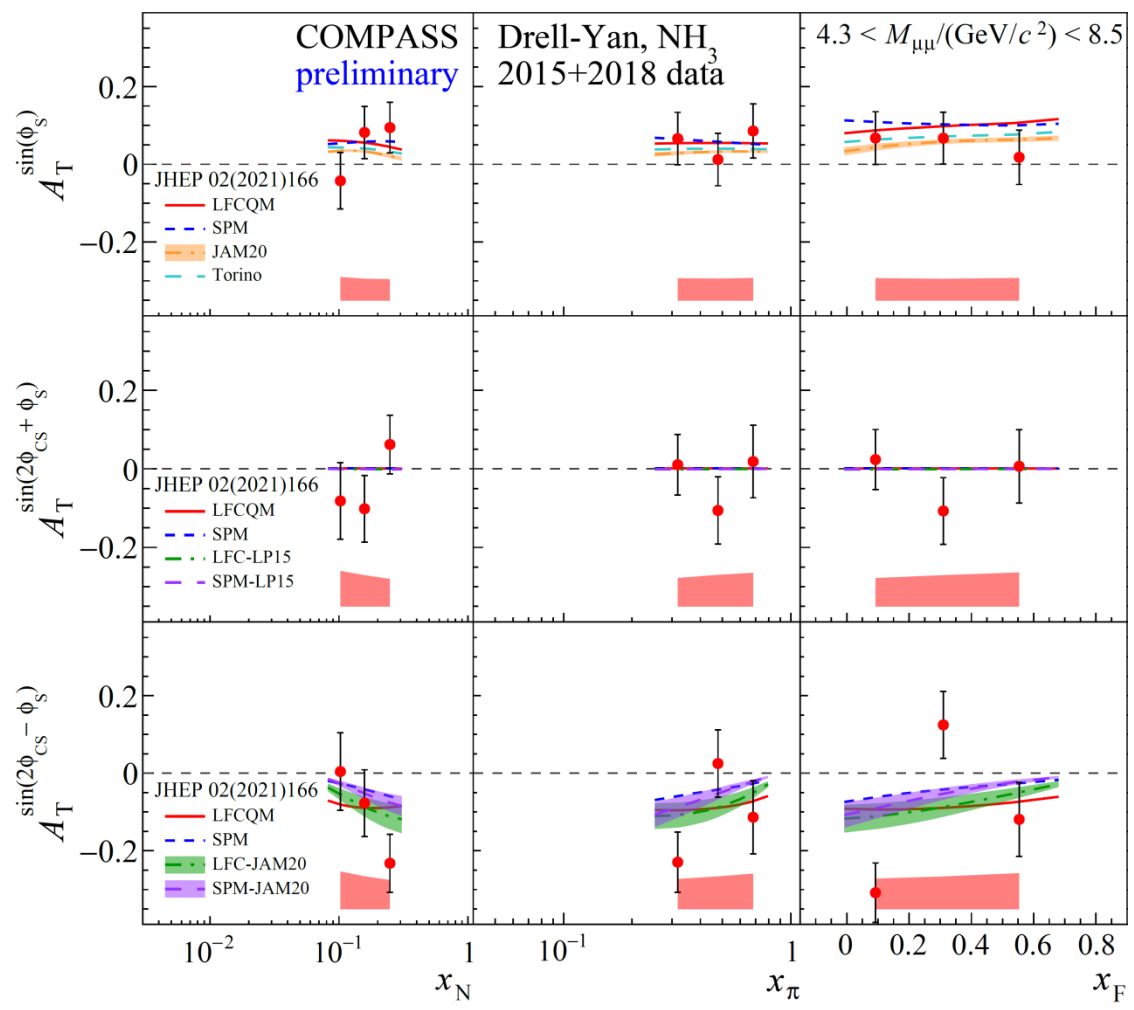$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$$

COMPASS

25 years
1997 – 2022

COMPASS preliminary, Drell-Yan, NH$_3$, 2015+2018 data, $4.3 < M_{\mu\mu}/(GeV/c^2) < 8.5$, NEW!

COMPASS preliminary, $\pi^- + p^\uparrow \to \mu^+ + \mu^- + X$, 2015+2018 data, $2.85 < M_{\mu\mu}/(GeV/c^2) < 3.4$, NEW!
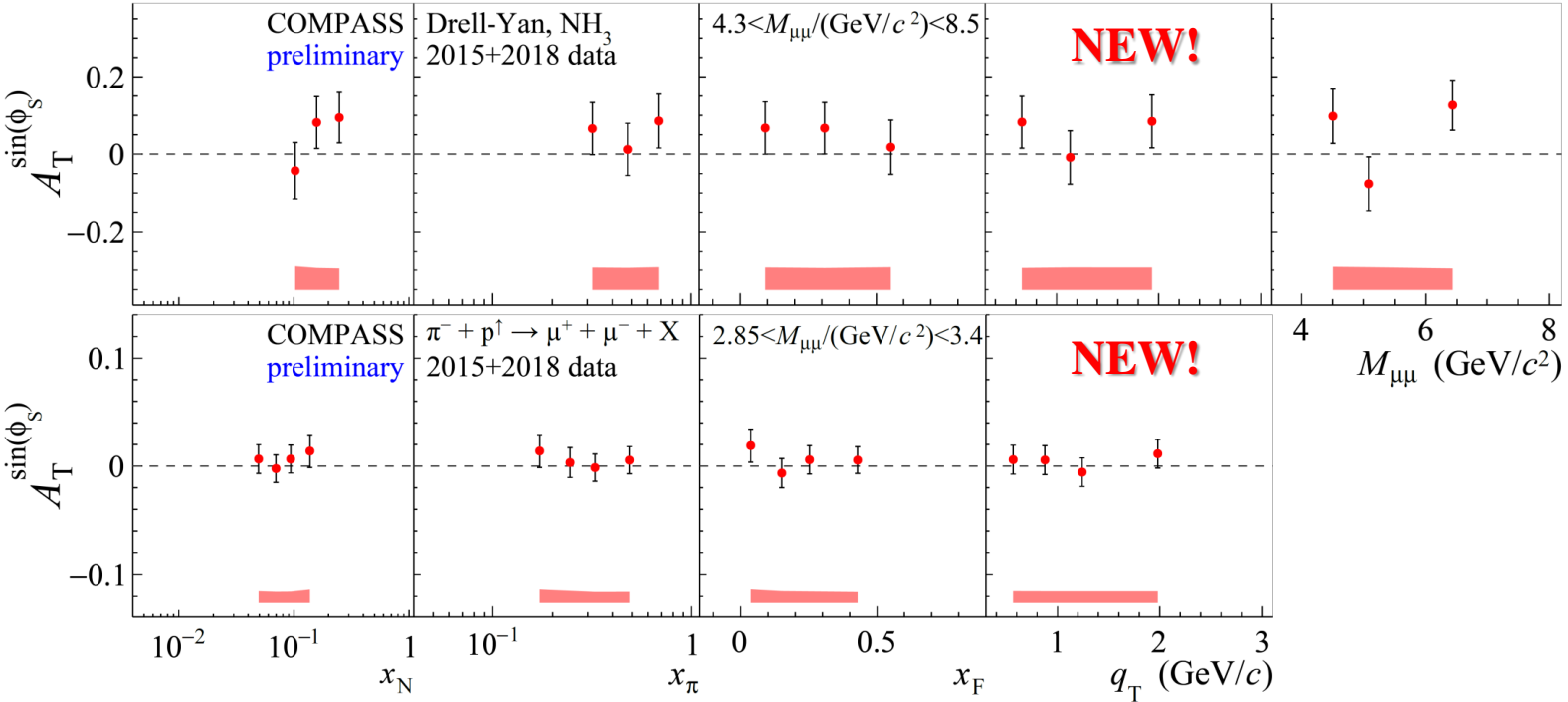
Sivers SIDIS TSA

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

COMPASS
PLB 770 (2017) 138
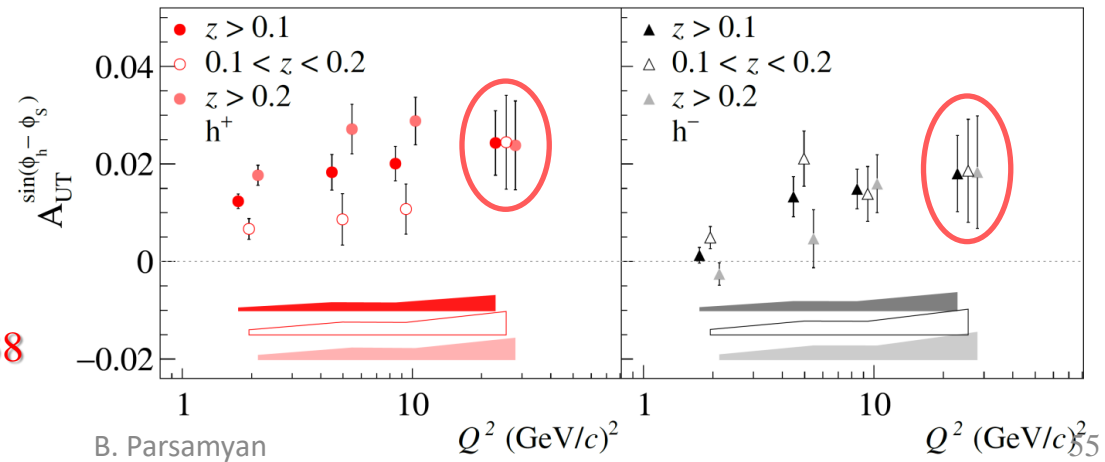
Theory curves based on S. Bastami et al. JHEP 02, (2021),166
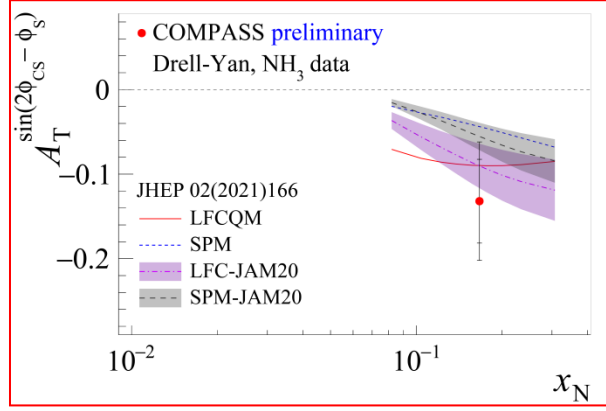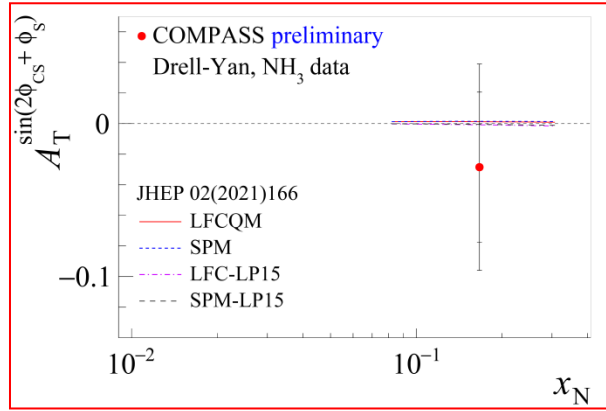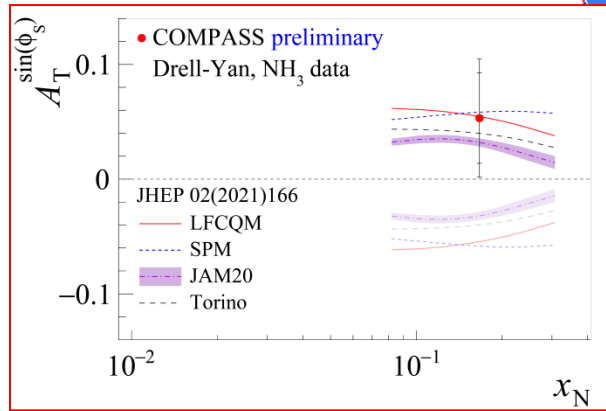
- General agreement with available theory predictions

Conclusions - DY TSAs at COMPASS

- During phase I COMPASS has measured all possible SIDIS TSAs.
  - Non-zero Sivers and Collins SIDIS-TSAs in the Drell-Yan "high-mass range": PLB 770 (2017) 138

- In 2017 COMPASS has published the results for the first polarized DY measurements: PRL 119, 112002 (2017)

- The second year of polarized DY data-taking was performed in 2018

- Re-production and re-analysis of both 2015 2018 data is over

- Final results have been presented at DIS-2022 and other conferences: the paper is in preparation

- COMPASS data favors the sign-change of Sivers TMD PDF

- J/ψ TSAs are consistent with zero

- DY x-section and unpolarized asymmetry studies are ongoing

Thank you!

COMPASS preliminary
Drell-Yan, NH_3 data

$A_T^{\sin(\phi_S)}$

JHEP 02(2021)166
— LFCQM
---- SPM
—·— JAM20
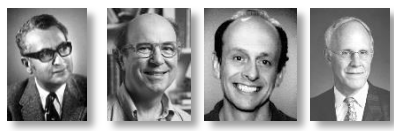---- Torino
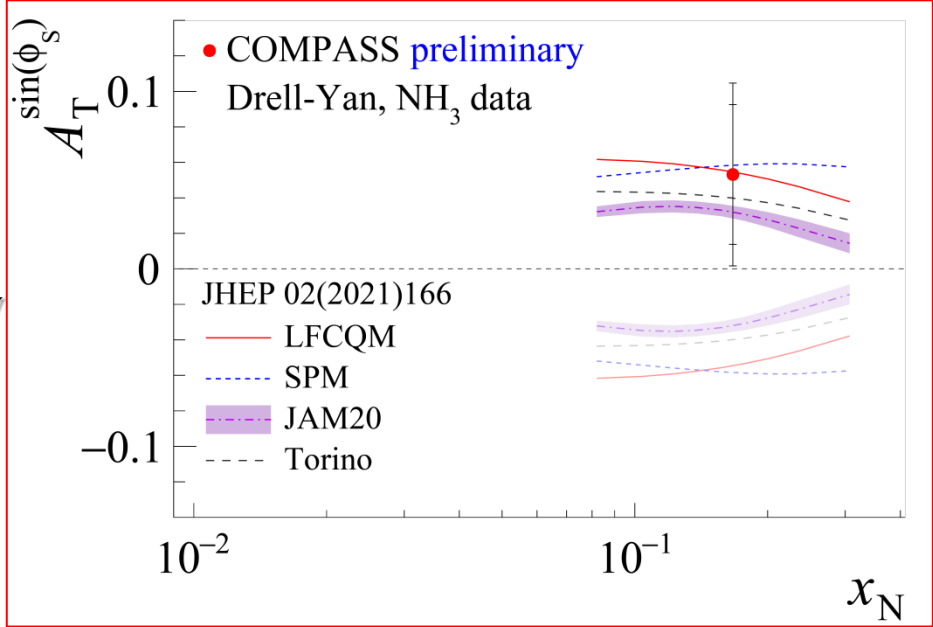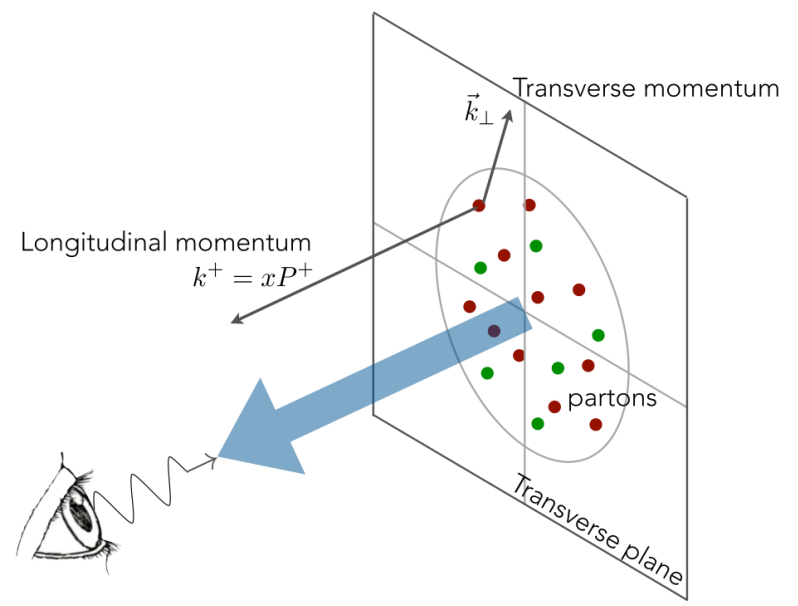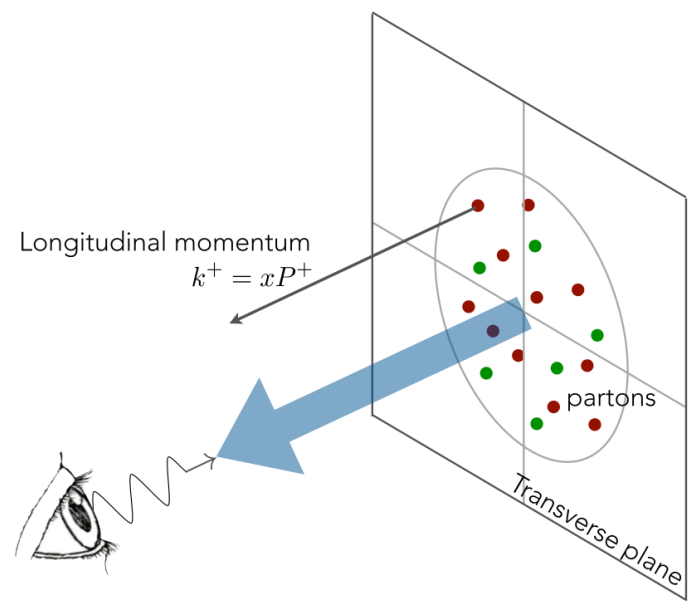
- Spare slides

Nucleon transverse structure

- 1964 Quark model
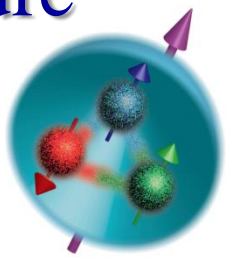
- 1969 Parton model

- 1973 asymptotic freedom and QCD
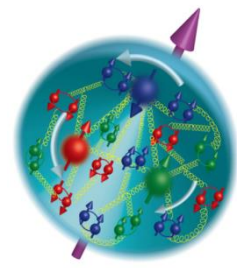
- 1978 intrinsic transverse motion of quarks and azimuthal asymmetries

Longitudinal momentum
$k^+ = xP^+$

partons

Transverse plane

Transverse momentum
$\vec{k}_\perp$

Longitudinal momentum
$k^+ = xP^+$

partons

Transverse plane

The COMPASS Experiment at the CERN SPS

Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

Increasing resolution scale (momentum transfer)

Measurement of the Charged-Pion Polarizability

(COMPASS Collaboration)

The COMPASS collaboration at CERN has investigated pion Compton scattering, $\pi^-\gamma \to \pi^-\gamma$, at center-of-mass energy below 3.5 pion masses. The process is embedded in the reaction $\pi^-\mathrm{Ni} \to \pi^-\gamma\mathrm{Ni}$, which is initiated by 190 GeV pions impinging on a nickel target. The exchange of quasireal photons is selected by isolating the sharp Coulomb peak observed at smallest momentum transfers, $Q^2 < 0.0015$ $(\mathrm{GeV}/c)^2$. From a sample of 63 000 events, the pion electric polarizability is determined to be $\alpha_\pi = (2.0 \pm 0.6_{\mathrm{stat}} \pm 0.7_{\mathrm{syst}}) \times 10^{-4}$ fm^3 under the assumption $\alpha_\pi = -\beta_\pi$, which relates the electric and magnetic dipole polarizabilities. It is the most precise measurement of this fundamental low-energy parameter of strong interaction that has been addressed since long by various methods with conflicting outcomes. While this result is in tension with previous dedicated measurements, it is found in agreement with the expectation from chiral perturbation theory. An additional measurement replacing pions by muons, for which the cross-section behavior is unambiguously known, was performed for an independent estimate of the systematic uncertainty.

$$\alpha_\pi = (2.0 \pm 0.6_{\mathrm{stat}} \pm 0.7_{\mathrm{syst}}) \times 10^{-4} \text{ fm}^3$$
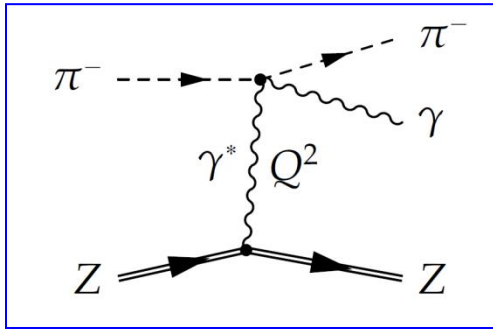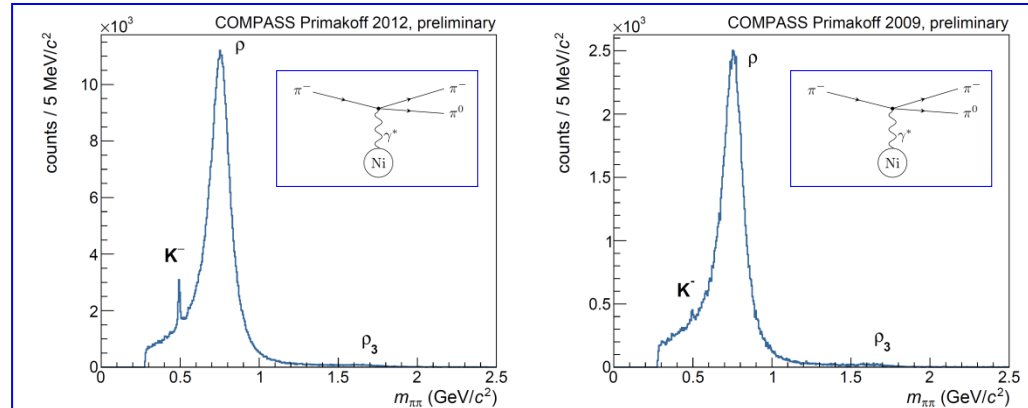
ongoing analysis:

study of chiral anomaly in $\pi^-\gamma \to \pi^-\pi^0$

Chiral dynamics

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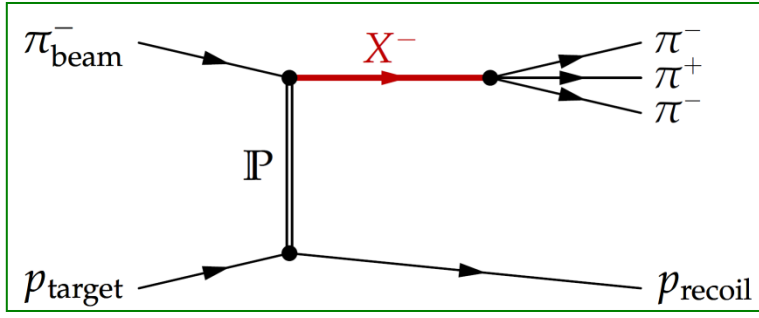- $\pi^\pm$ and $K^\pm$ polarizabilities
- Chiral anomaly $F_{3\pi}$

Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

COMPASS
25 years
1997 – 2022

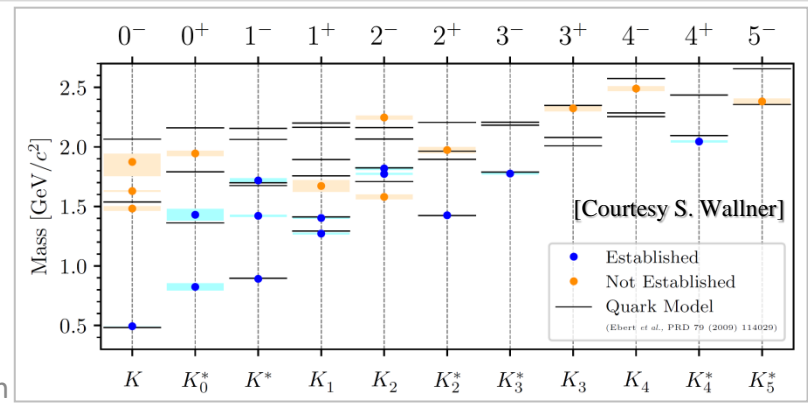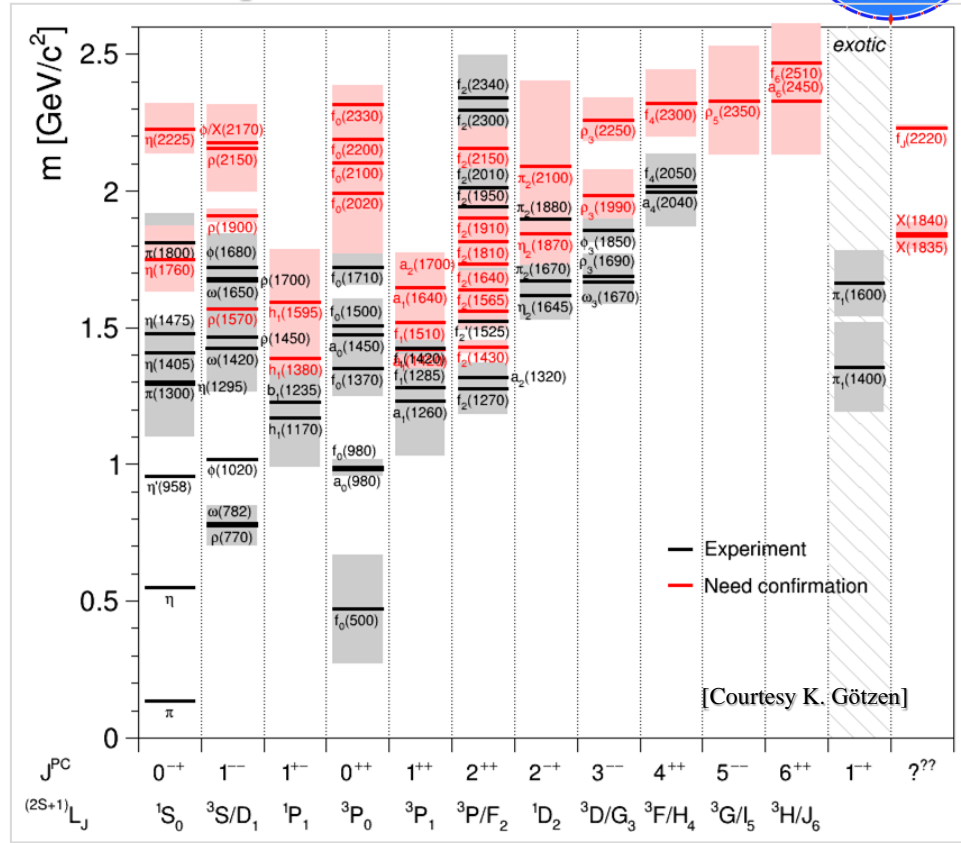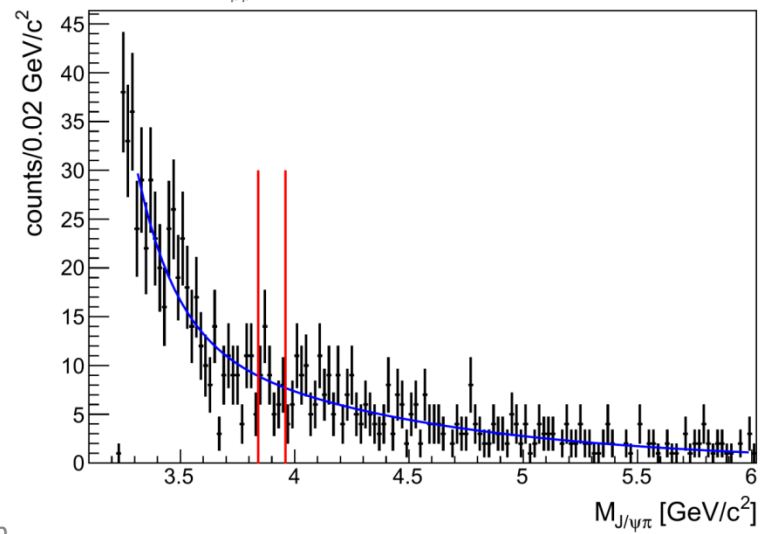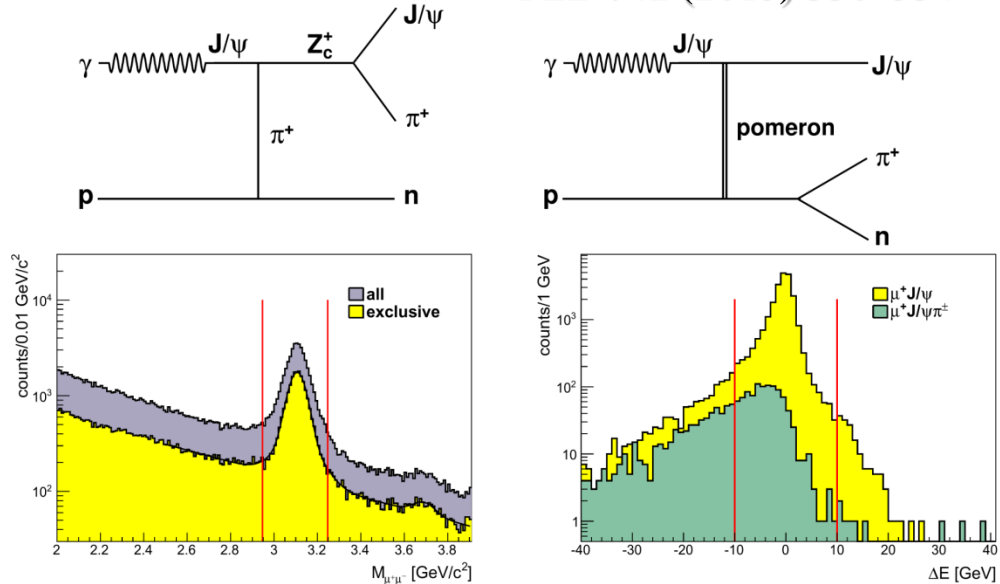Increasing resolution scale (momentum transfer)

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 $\pi(K)\,\gamma$ reactions
- $\pi^{\pm}$ and $K^{\pm}$ polarizabilities
- Chiral anomaly $F_{3\pi}$

[Courtesy K. Götzen]

[Courtesy S. Wallner]

Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

COMPASS
25 years
1997 – 2022

Search for exclusive photoproduction of $Z_c^{\pm}$ (3900)

PLB 742 (2015) 330–334

Increasing resolution scale (momentum transfer)

Hadron spectroscopy

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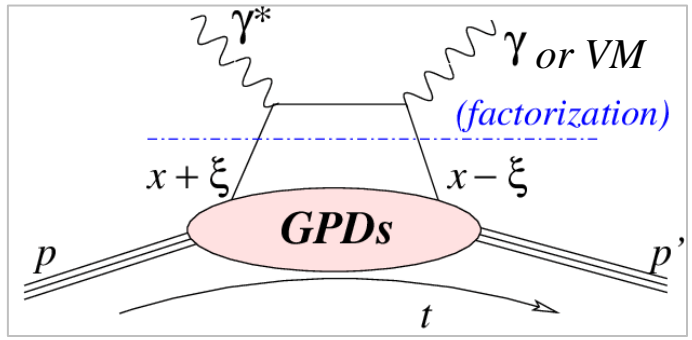- **Search for exotic states**

Chiral dynamics

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

Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

COMPASS
25 years
1997 – 2022

Search for exclusive muoproduction of $X(3872)$, observation of $\tilde{X}(3872)$ PLB 783 (2018) 334–340

Increasing resolution scale (momentum transfer)

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 $\pi(K)\,\gamma$ reactions
- $\pi^{\pm}$ and $K^{\pm}$ polarizabilities
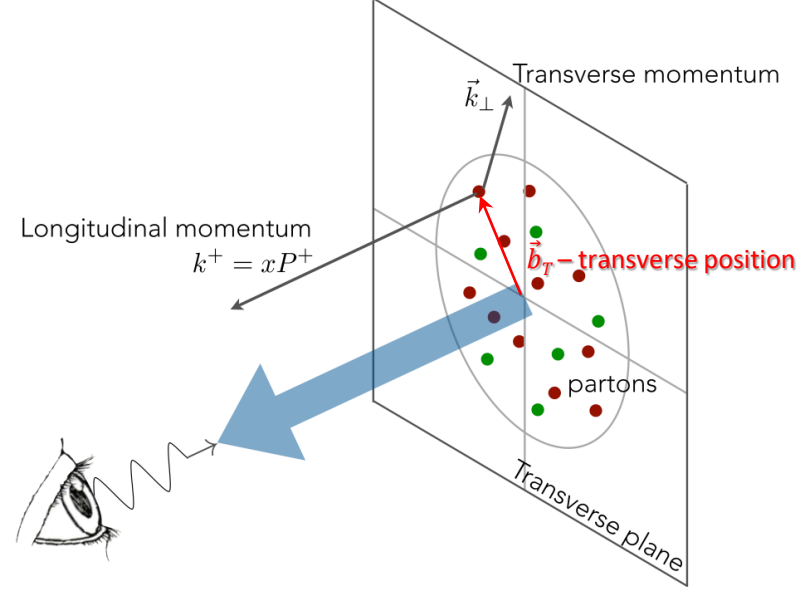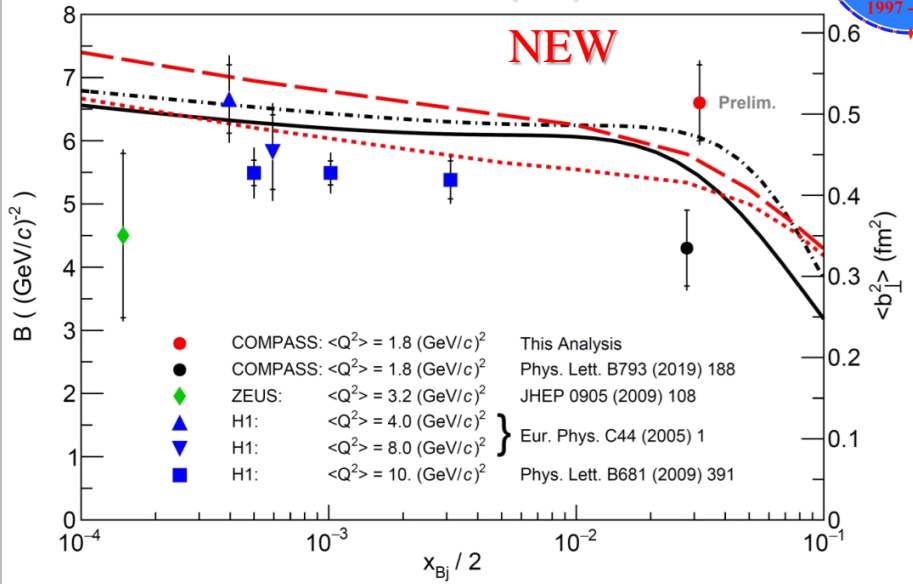- Chiral anomaly $F_{3\pi}$
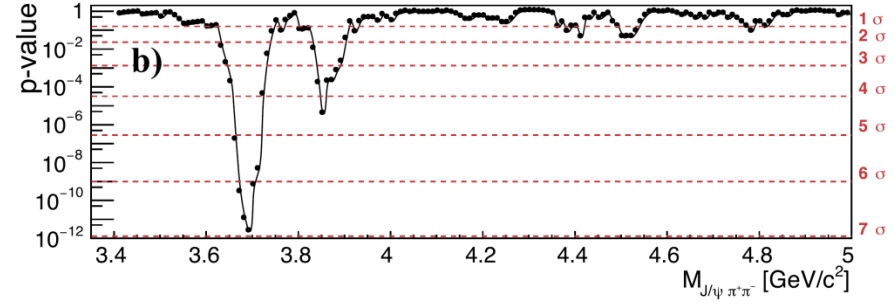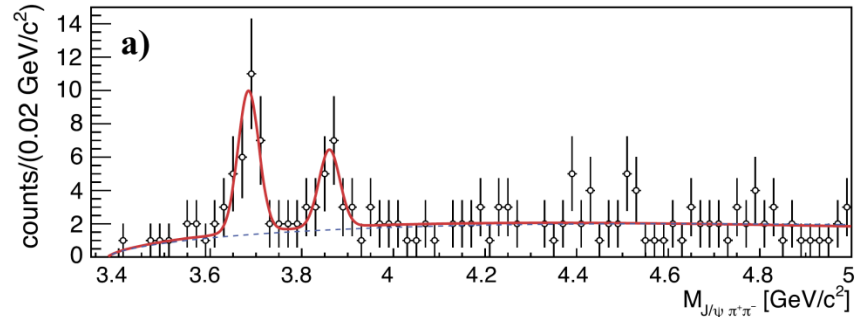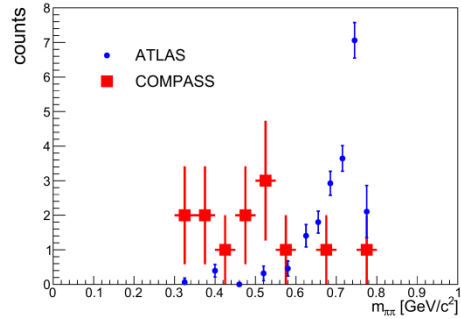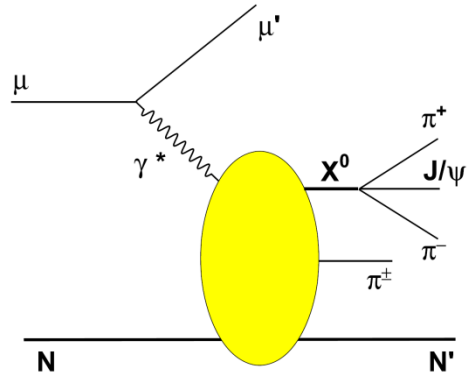
Nucleon transverse structure

- Transverse position $\vec{b}_T$ of partons
  - Correlation between $\vec{b}_T$ and x
  - Complementary to TMD PDFs
- 8 generalized parton distribution functions (GPDs)
  - Contain information about parton orbital angular momentum
  - Mostly unknown
- Measured in exclusive processes:
  - Deeply virtual Compton scattering (DVCS): $\mu + N \rightarrow \mu + \gamma + N$
  - Hard exclusive meson production (HEMP): $\mu + N \rightarrow \mu + VM + N$ with $VM = \pi^0, \rho(770), \omega(782),..$

COMPASS 2016 data (2/3)

NEW

Legend:
- COMPASS: $\langle Q^2 \rangle = 1.8\ (GeV/c)^2$ This Analysis
- COMPASS: $\langle Q^2 \rangle = 1.8\ (GeV/c)^2$ Phys. Lett. B793 (2019) 188
- ZEUS: $\langle Q^2 \rangle = 3.2\ (GeV/c)^2$ JHEP 0905 (2009) 108
- H1: $\langle Q^2 \rangle = 4.0\ (GeV/c)^2$ $\Big\}$ Eur. Phys. C44 (2005) 1
- H1: $\langle Q^2 \rangle = 8.0\ (GeV/c)^2$
- H1: $\langle Q^2 \rangle = 10.\ (GeV/c)^2$ Phys. Lett. B681 (2009) 391

Axes: $B\ ((GeV/c)^{-2})$ vs $x_{Bj}/2$; $\langle b_\perp^2 \rangle\ (fm^2)$

γ^* ; γ or VM

(factorization)

$x + \xi$; $x - \xi$

GPDs

p ; p' ; t

Transverse momentum $\vec{k}_\perp$

Longitudinal momentum $k^+ = xP^+$

$\vec{b}_T$ – transverse position
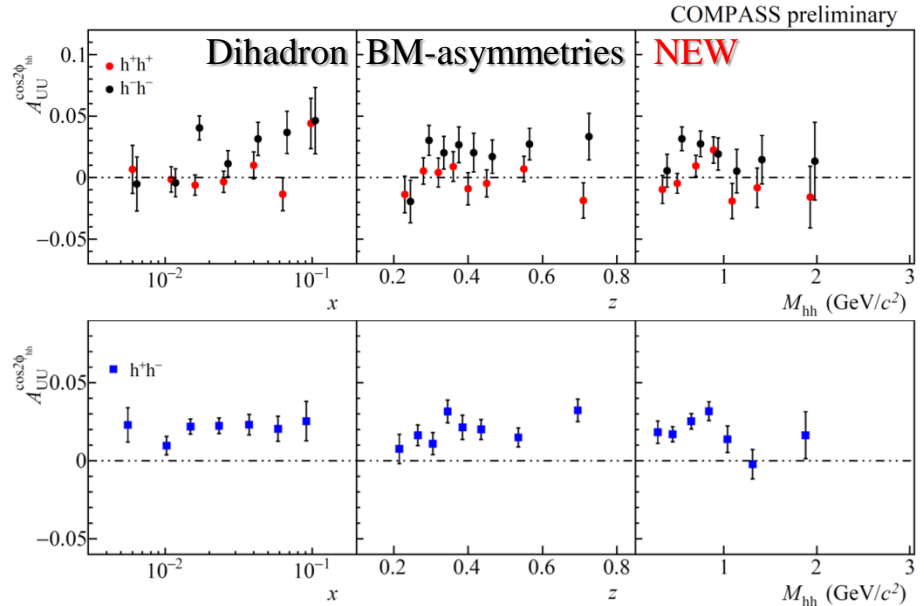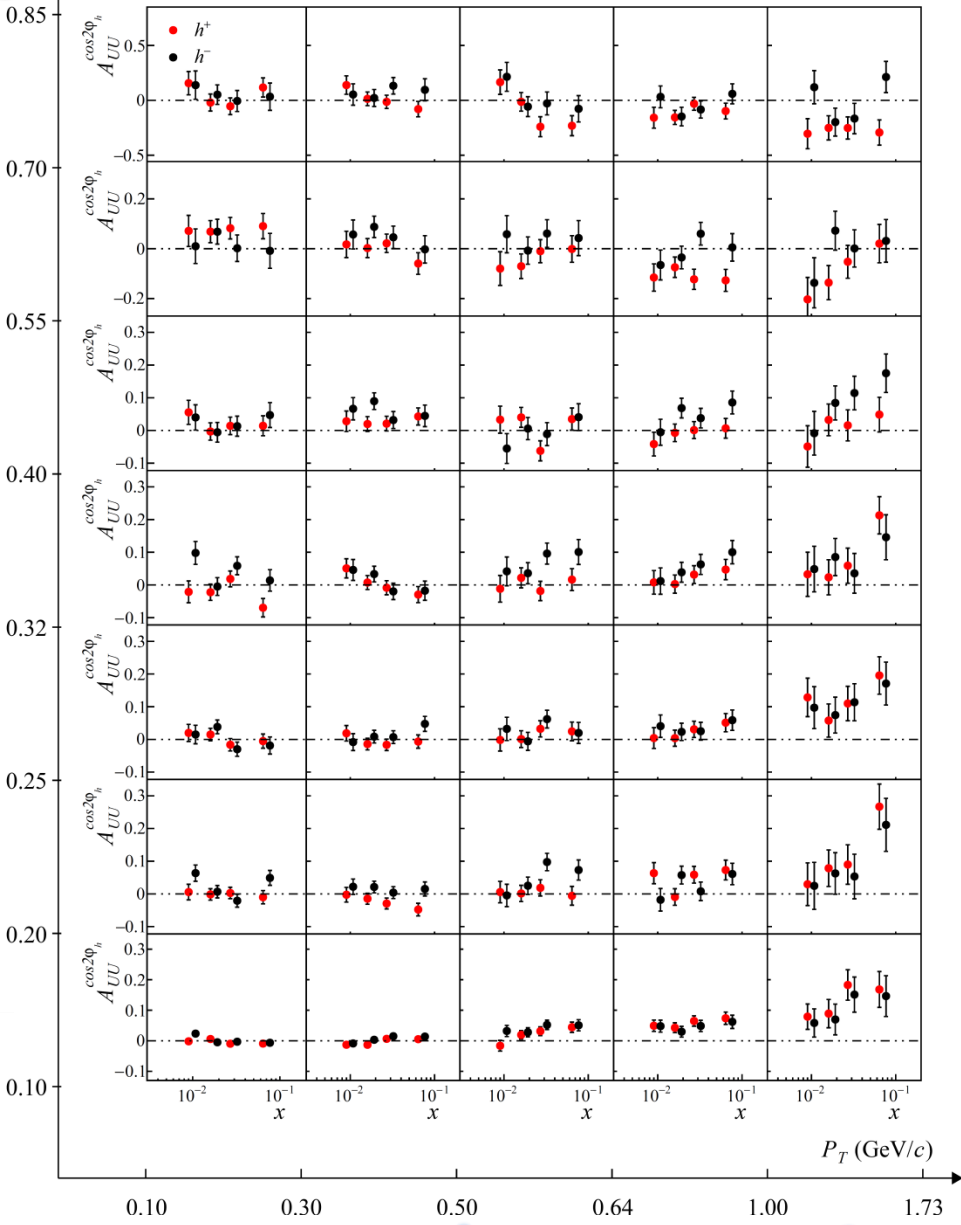
partons

Transverse plane

Boer-Mulders effect in SIDIS

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

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

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

Quark / Nucleon	U		T
U	$f_1^q(x, \mathbf{k}_T^2)$ **number density**		$h_1^{\perp q}(x, \mathbf{k}_T^2)$ **Boer-Mulders**

COMPASS preliminary

Dihadron BM-asymmetries NEW

COMPASS preliminary

spin of the quark k_T

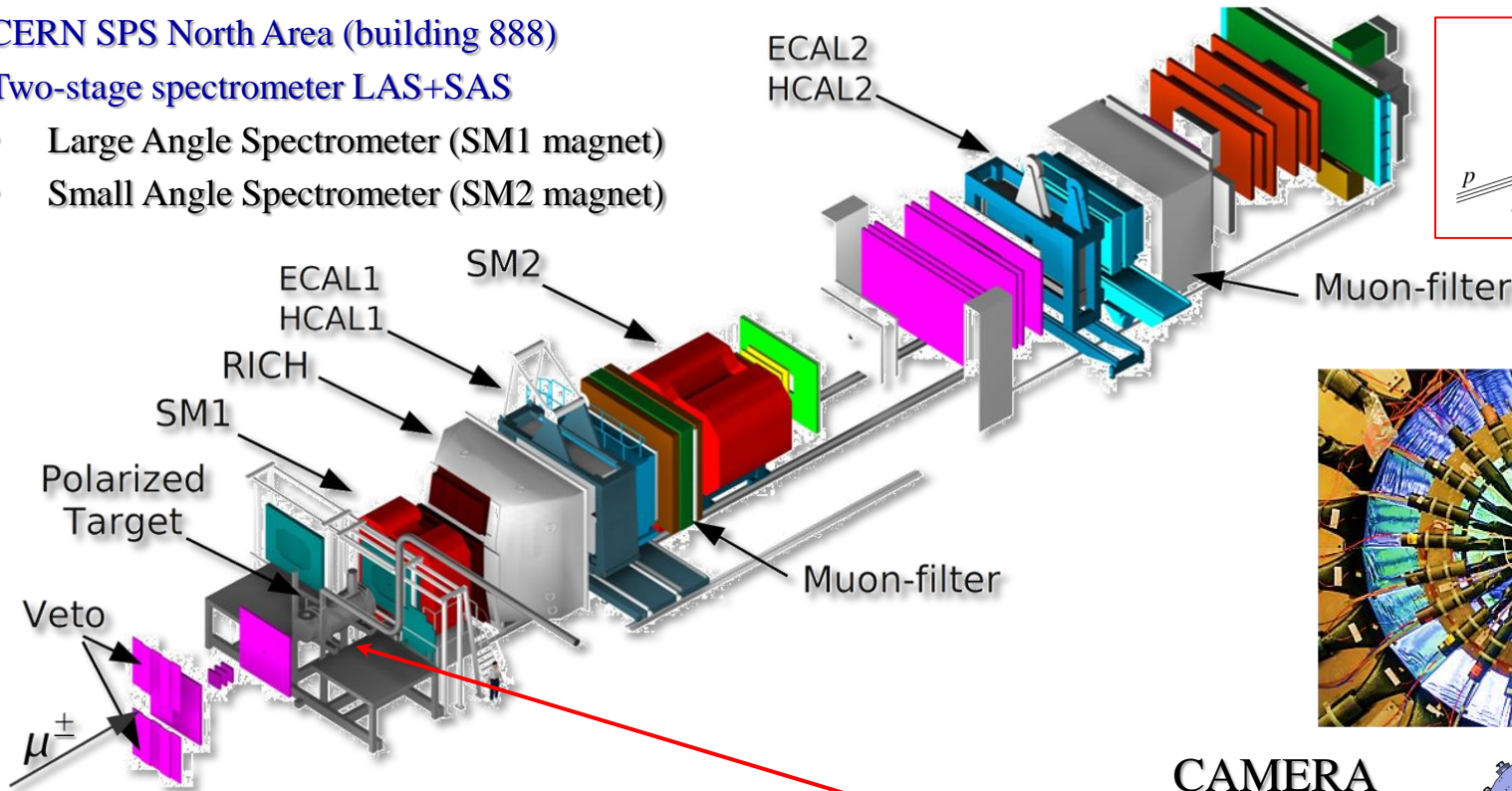# COMPASS experimental setup: Phase II (DVCS programme)

COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

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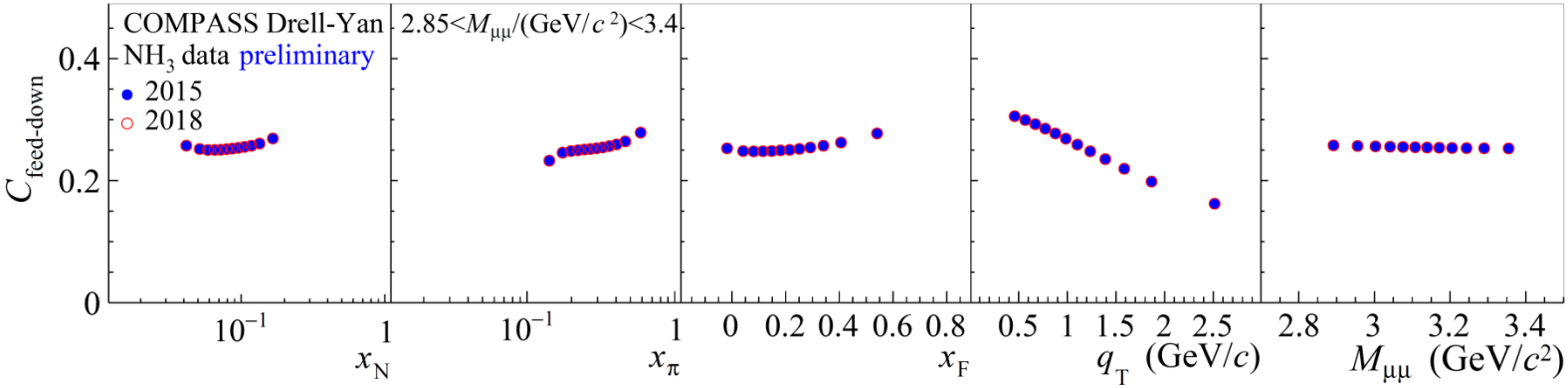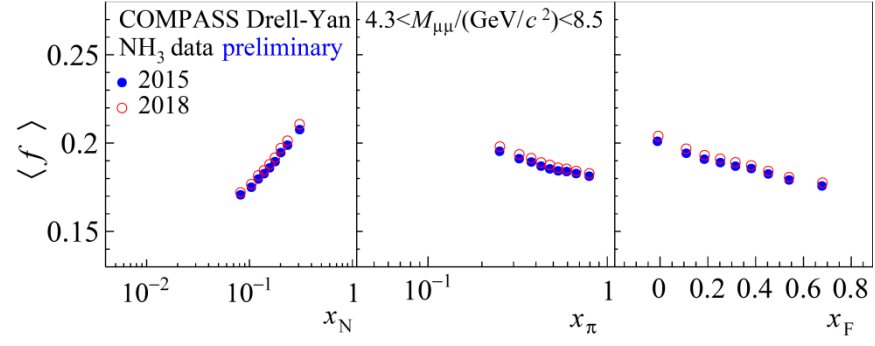- Small Angle Spectrometer (SM2 magnet)

ECAL2
HCAL2
ECAL1
HCAL1
RICH
SM1
SM2
Polarized Target
Veto
$\mu^{\pm}$
Muon-filter
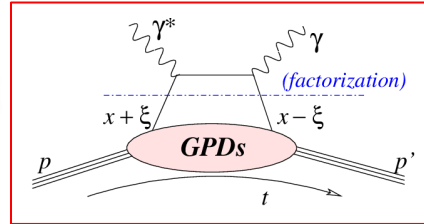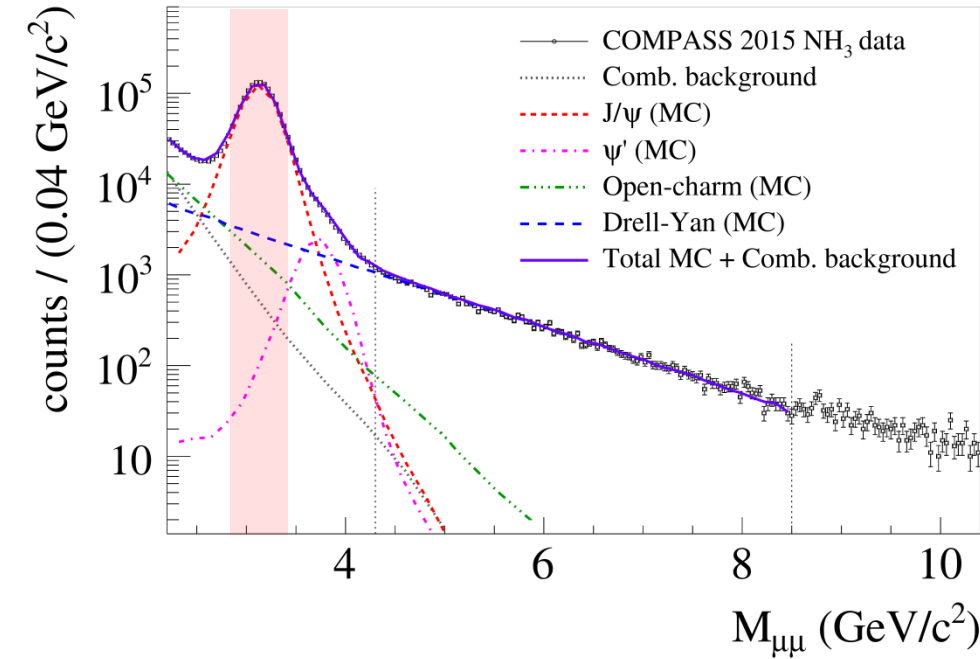

CAMERA detector

- 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
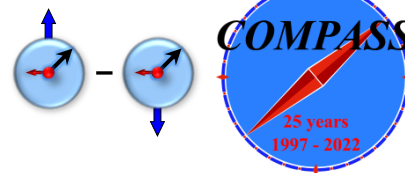 - h^+ beam: 75% p, 24% π^+, 1% K^+
- 160 GeV tertiary muon beams
  - $\mu^{\pm}$ longitudinally polarized
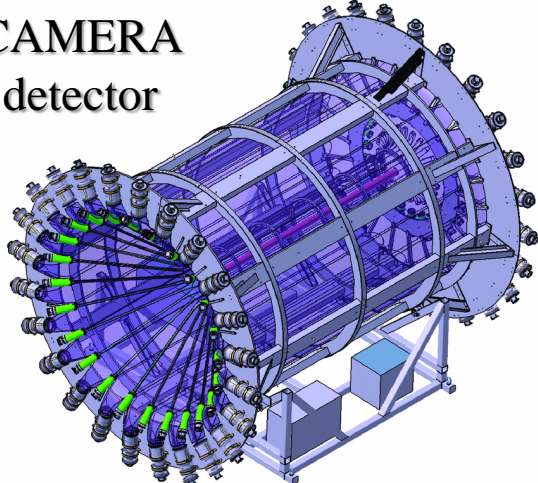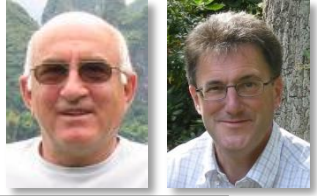
- **Dilution factor and feed down contribution**

Parton Reggeization approach
A.V. Karpishkov, M.A. Nefedov, V.A. Saleev
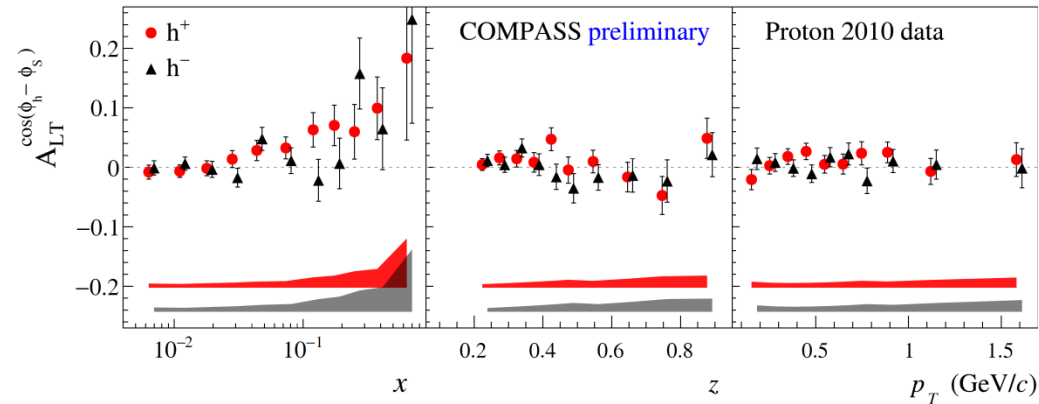
SIDIS TSAs: Kotzinian-Mulders asymmetry

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

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

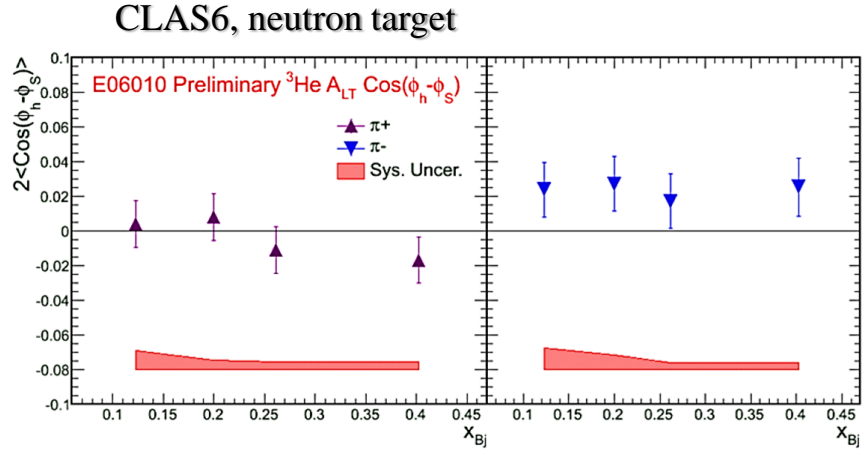**COMPASS/HERMES/CLAS6 results**
$A_{LT}^{\cos(\phi_h - \phi_S)}$

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

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

CLAS6, neutron target

HERMES, JHEP 12 (2020) 010