Measurement of target transverse-spin-dependent azimuthal asymmetries in SIDIS at COMPASS

BAKUR PARSAMYAN

CERN, INFN section of Turin

on behalf of the COMPASS Collaboration

"XXIX International Workshop on Deep Inelastic Scattering and Related Subjects"

Santiago de Compostela, Spain

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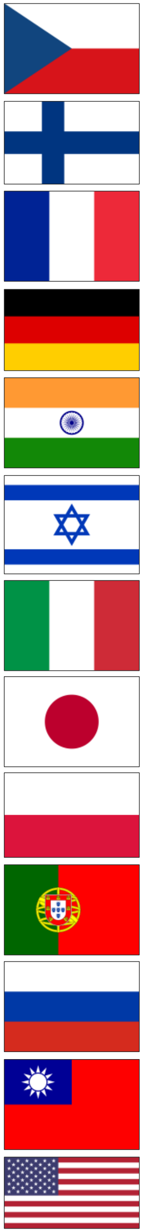
COMPASS collaboration



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

25 institutions from 13 countries
– nearly 200 physicists

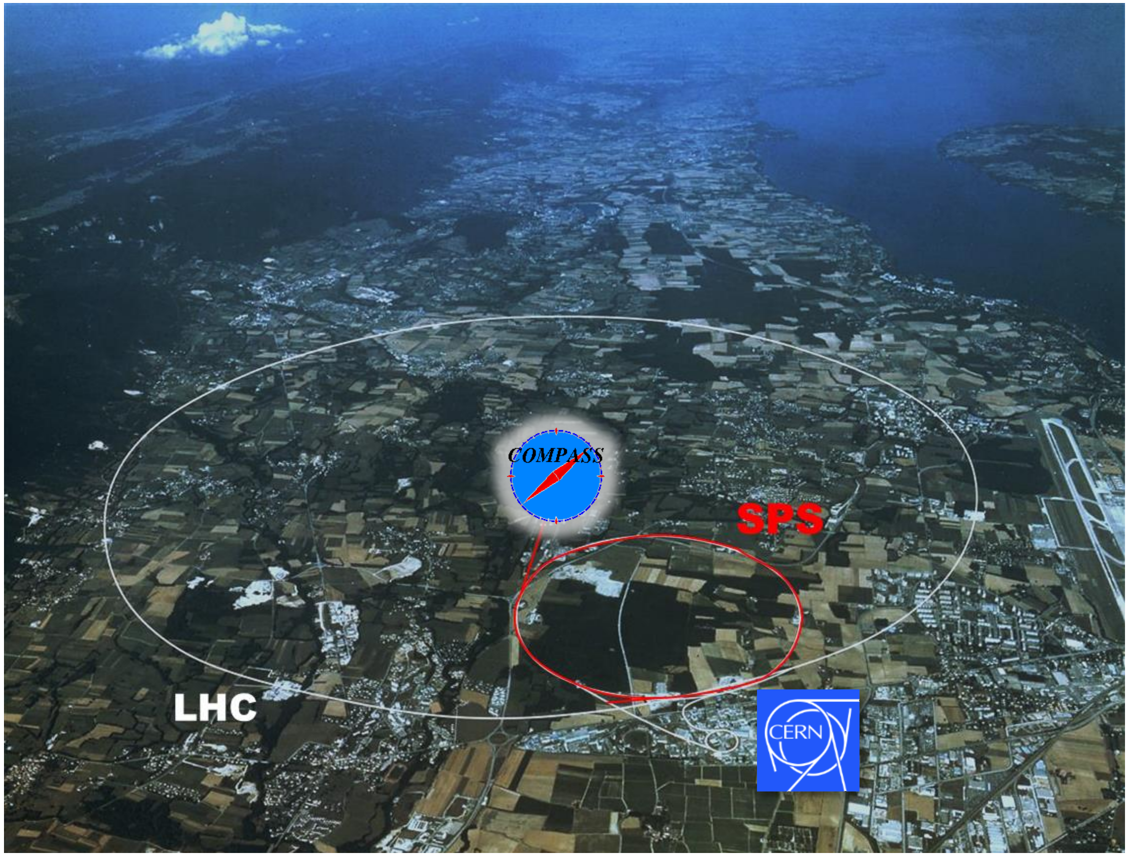
- **CERN SPS north area**
- **Fixed target experiment**
- **Approved in 1997**
- **Taking data since 2002**

See also COMPASS talks by J.Giarra (DVCS) and J.Matousek (SIDIS)

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**

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

COMPASS collaboration

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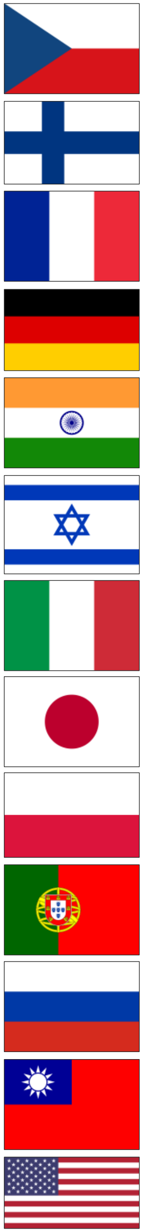

25 institutions from 13 countries
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- **Fixed target experiment**
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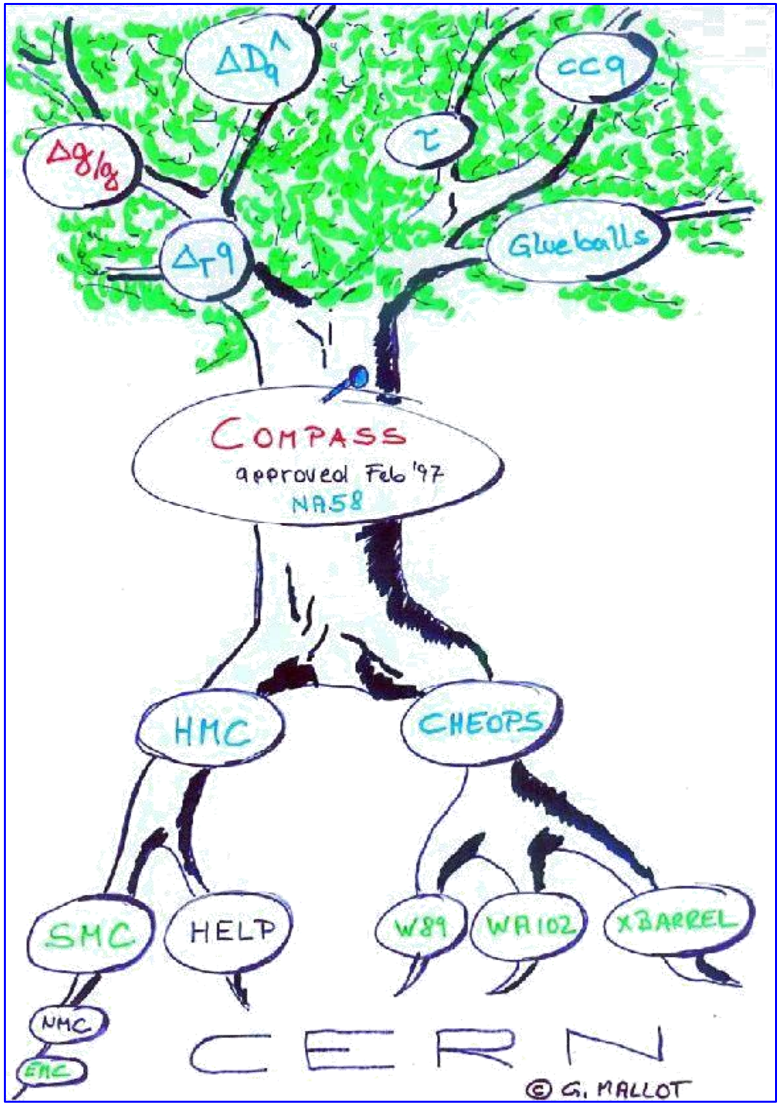
- **Taking data since 2002 (20 years)**

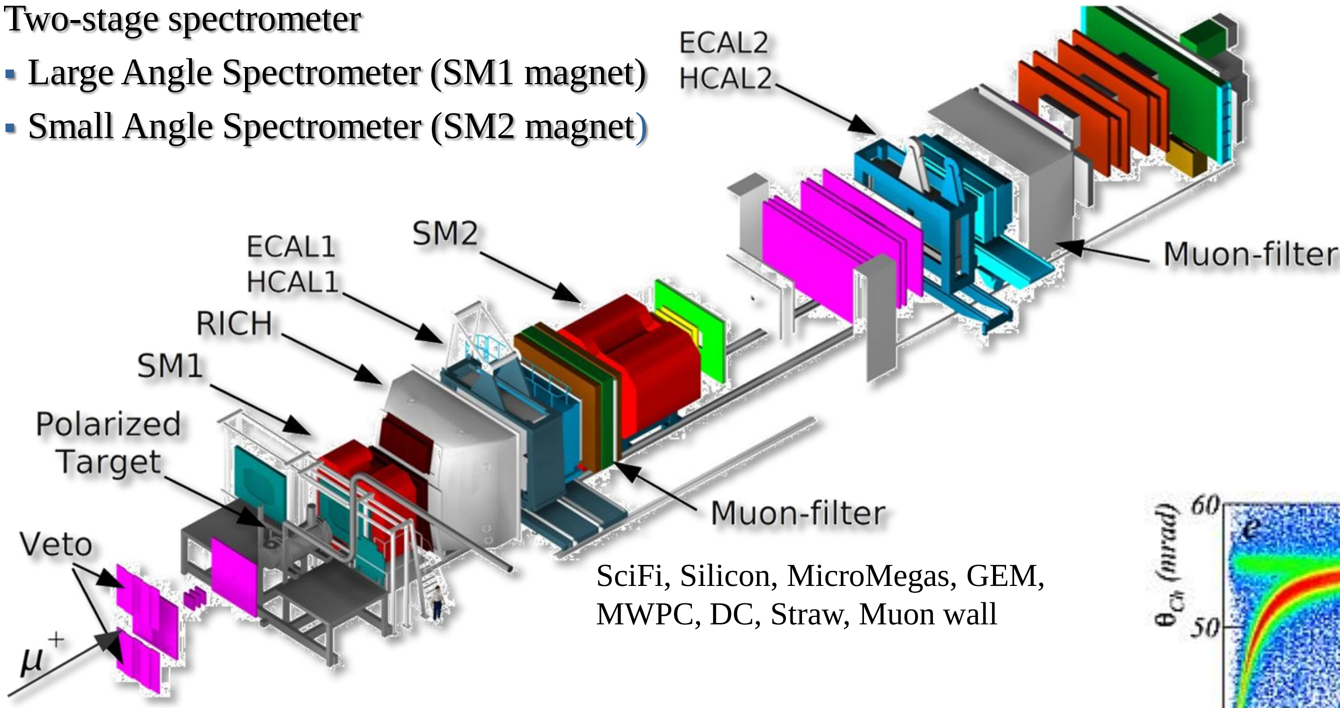
IWHSS-2022 workshop (anniversary edition)

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

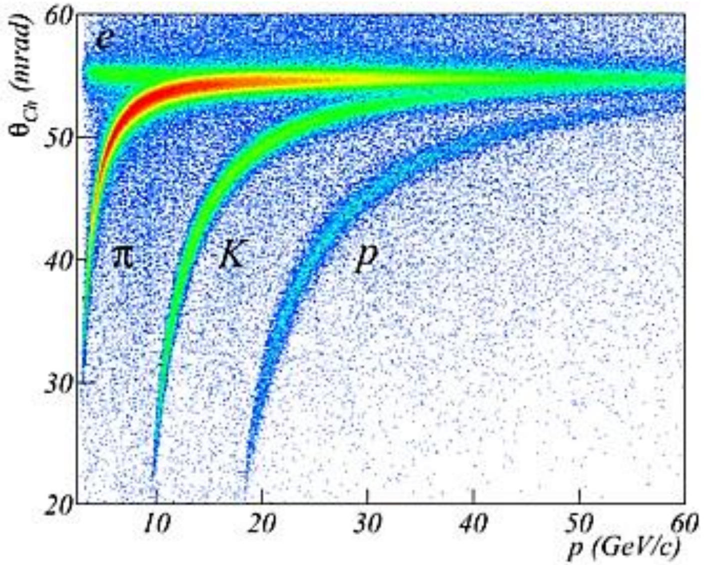


COMPASS experimental setup: Phase I (muon program)

Two-stage spectrometer
- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)



- High energy beam
- Large angular acceptance
- Broad kinematical range
- Momentum, tracking and calorimetric measurements, PID



Data-taking years: 2002-2011

Longitudinally polarized (80%) μ^+ beam:
Energy: 160/200 GeV/c, Intensity: $2{\cdot}10^8$ μ^+/spill (4.8s).

Target: Solid state *(^6LiD or NH_3)*

- ^{6}LiD 2-cell configuration. Polarization (L & T) ~ 50%, f ~ 0.38
- NH_3 3-cell configuration. Polarization (L & T) ~ 80%, f ~ 0.14

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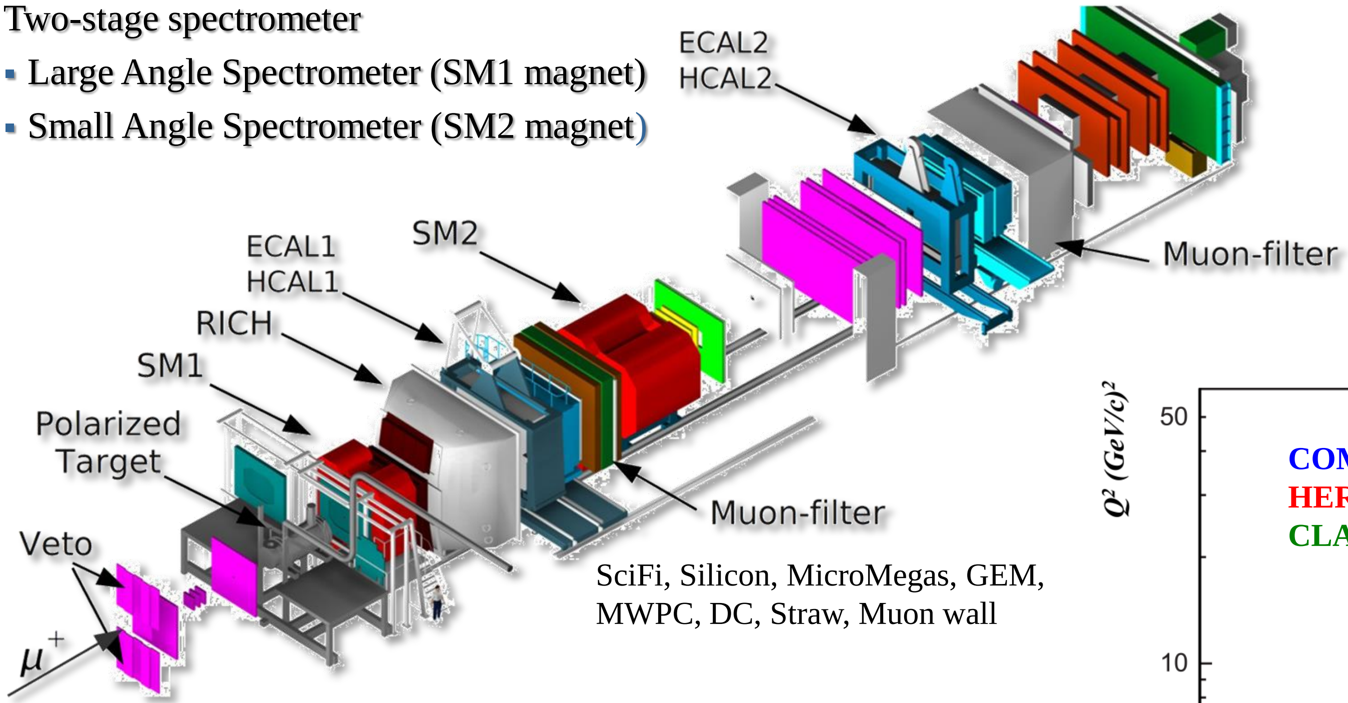

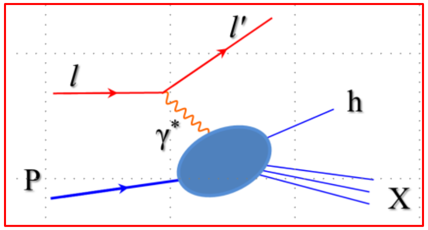

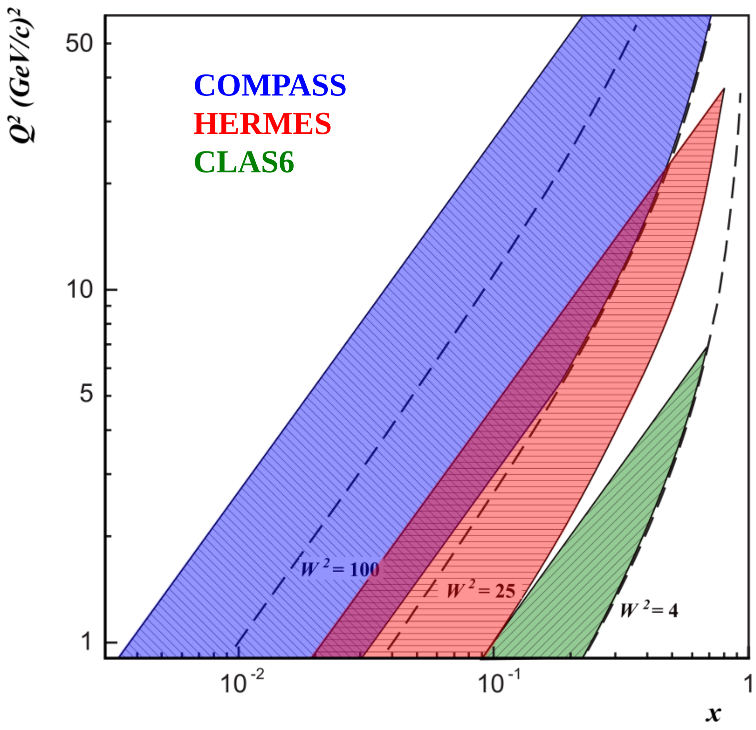

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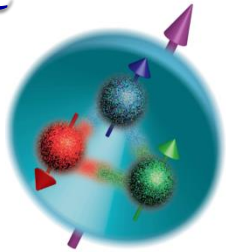
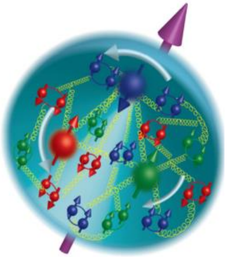
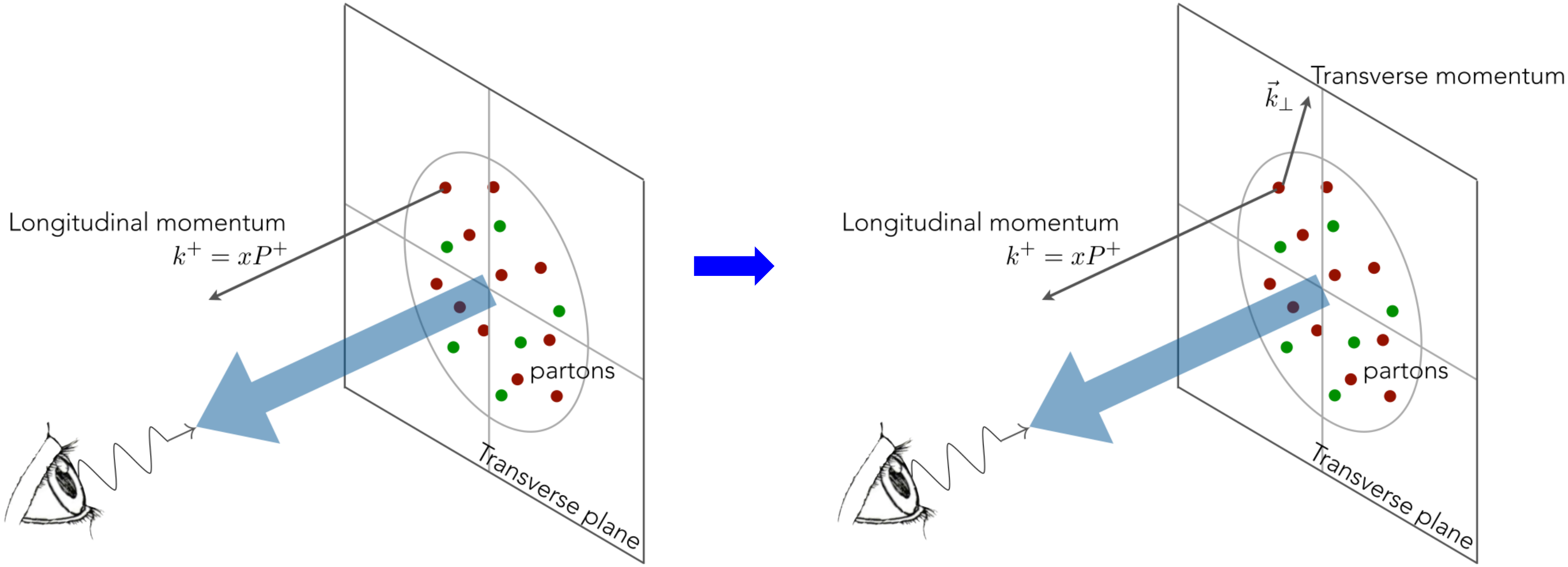
Nucleon transverse structure

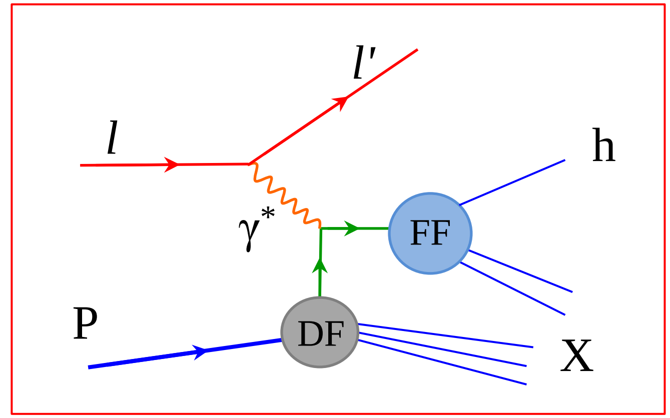


- 1964 Quark model 
- 1969 Parton model 
- 1973 asymptotic freedom and QCD 
- 1978 intrinsic transverse motion of quarks and azimuthal asymmetries 





Cahn effect in SIDIS



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

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

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

Cahn effect

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

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

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

A. Kotzinian On behalf of:
T.P. Cheng, A. Zee,
F. Ravndal, R.L. Kingsley
and himself

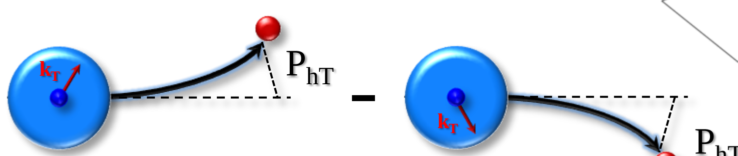
$$\hat{s} \simeq xs\left[1-2\sqrt{1-y}\,\frac{k_T}{Q}\cdot\cos\varphi_q\right]$$

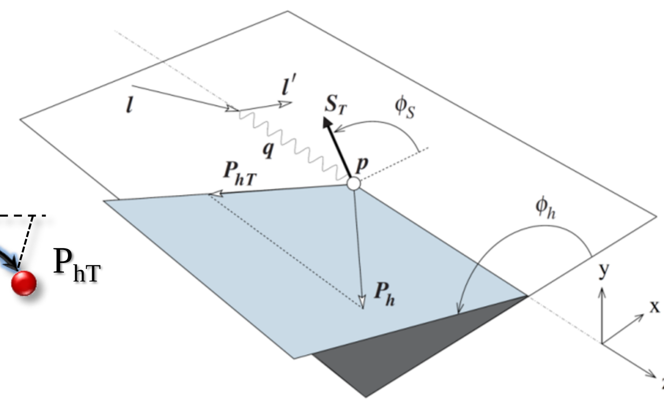
$$\hat{u} \simeq -xs(1-y)\left[1-\frac{2k_T}{Q\sqrt{1-y}}\cdot\cos\varphi_q\right]$$

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

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

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





As of 1978 – simplistic kinematic effect:

non-zero k_T induces an azimuthal modulation

Cahn effect in SIDIS

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

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

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

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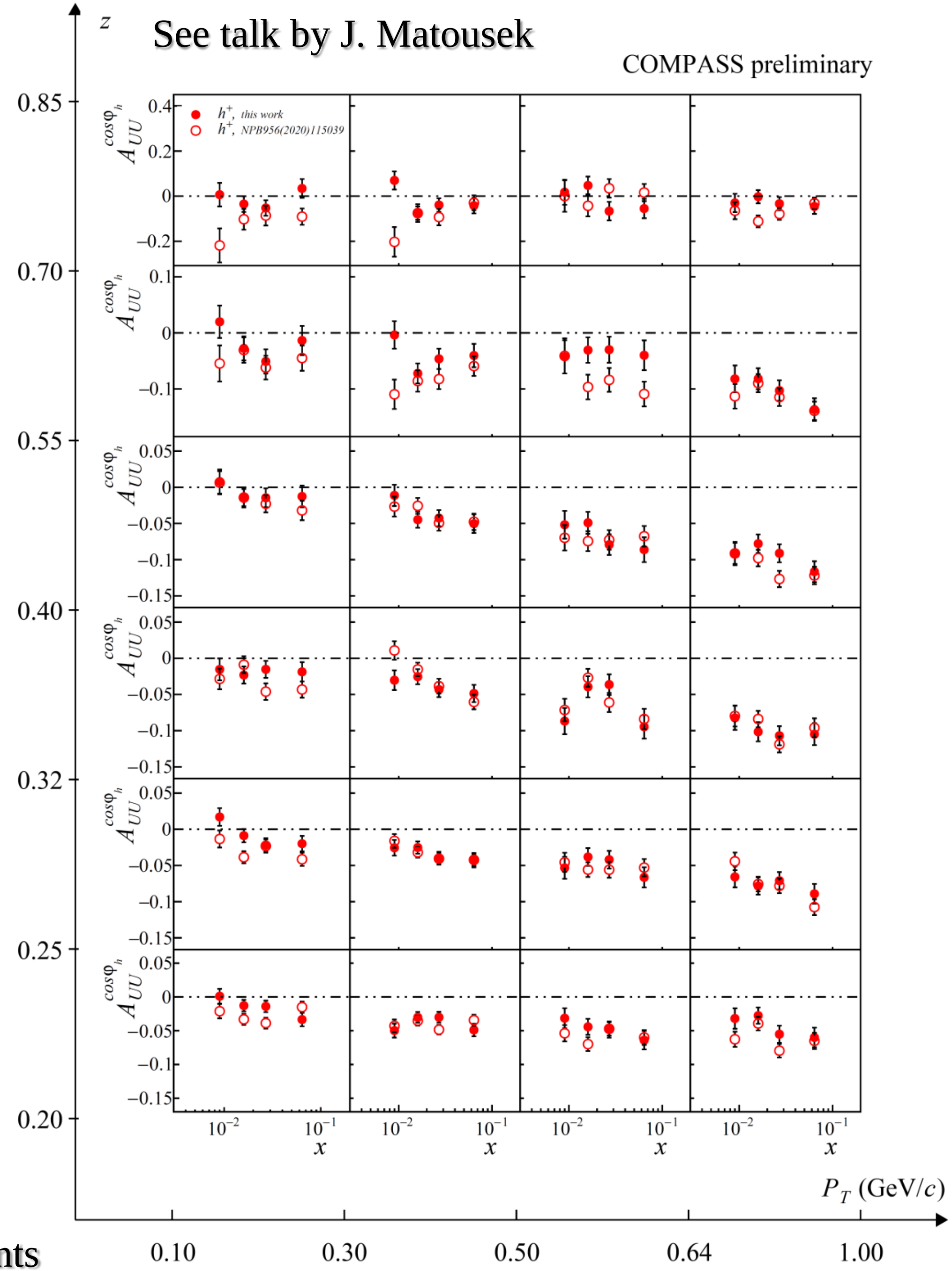
See talk by J. Matousek



As of 1978 – simplistic kinematic effect:

non-zero k_T induces an azimuthal modulation

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

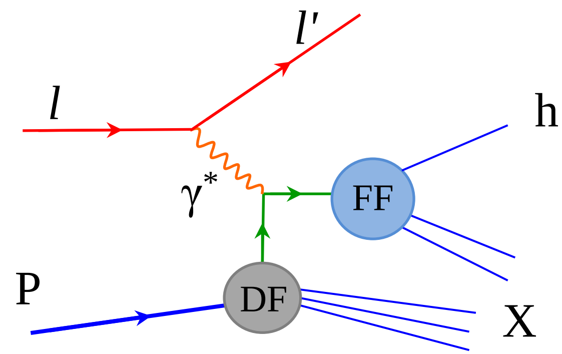
A number of measurements by different experiments

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

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



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

spin of the nucleon — spin of the quark — k_T

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

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+\ 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] \\
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\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 \\
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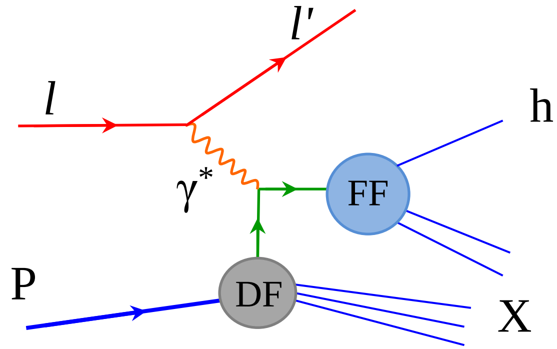
\end{array}\right]
\end{array}\right\}$$



Nucleon \ **Quark**	**U**	**L**	**T**
U	$f_1^q(x, \boldsymbol{k}_T^2)$ **number density**		$h_1^{\perp q}(x, \boldsymbol{k}_T^2)$ **Boer-Mulders**
L		$g_1^q(x, \boldsymbol{k}_T^2)$ **helicity**	$h_{1L}^{\perp q}(x, \boldsymbol{k}_T^2)$ **worm-gear L**
T	$f_{1T}^{\perp q}(x, \boldsymbol{k}_T^2)$ **Sivers**	$g_{1T}^q(x, \boldsymbol{k}_T^2)$ **Kotzinian-Mulders worm-gear T**	$h_1^q(x, \boldsymbol{k}_T^2)$ **transversity** $h_{1T}^{\perp q}(x, \boldsymbol{k}_T^2)$ **pretzelosity**

+ two FFs: $D_{1q}^h(z, P_\perp^2)$ and $H_{1q}^{\perp h}(z, P_\perp^2)$

- Longitudinal spin asymmetries

SIDIS: target longitudinal spin dependent asymmetries

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

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

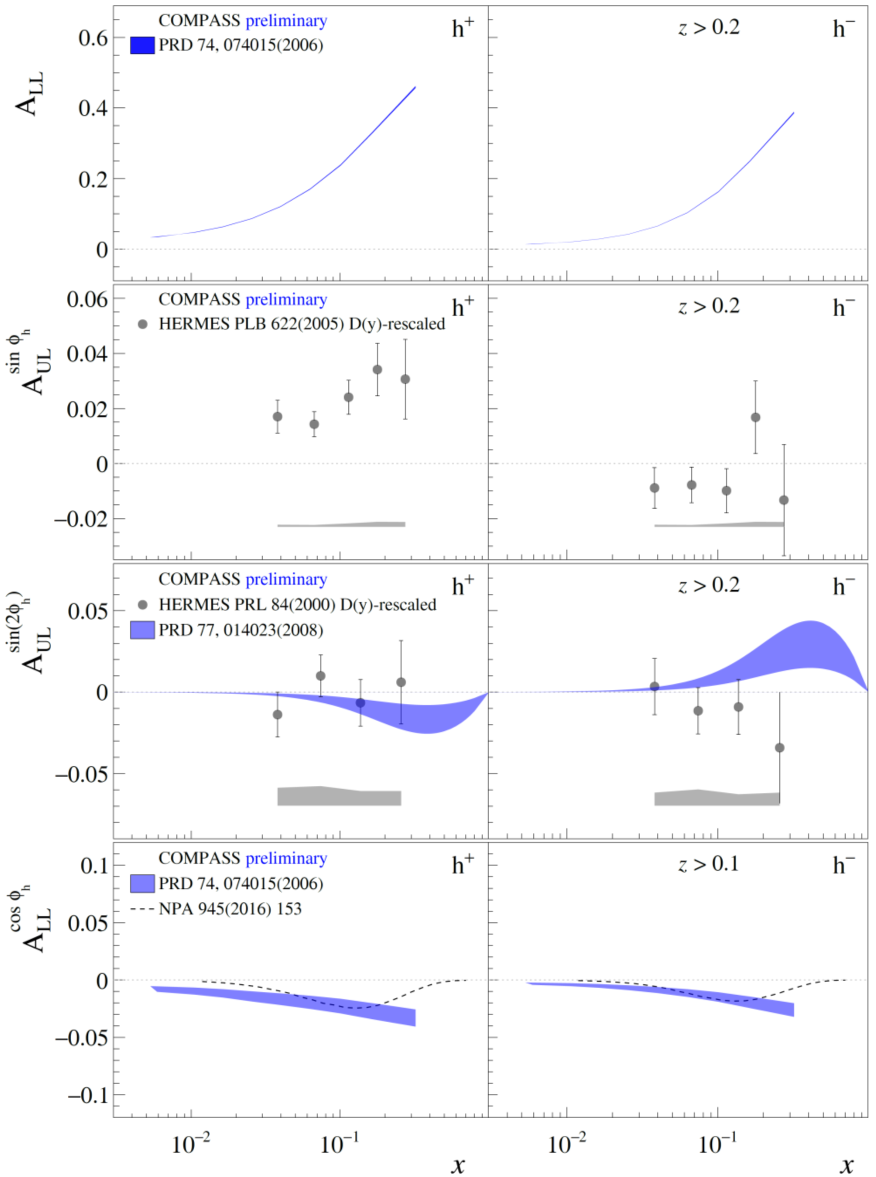
$$\left. + S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right] \right\}$$

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

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

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

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



SIDIS: target longitudinal spin dependent asymmetries

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

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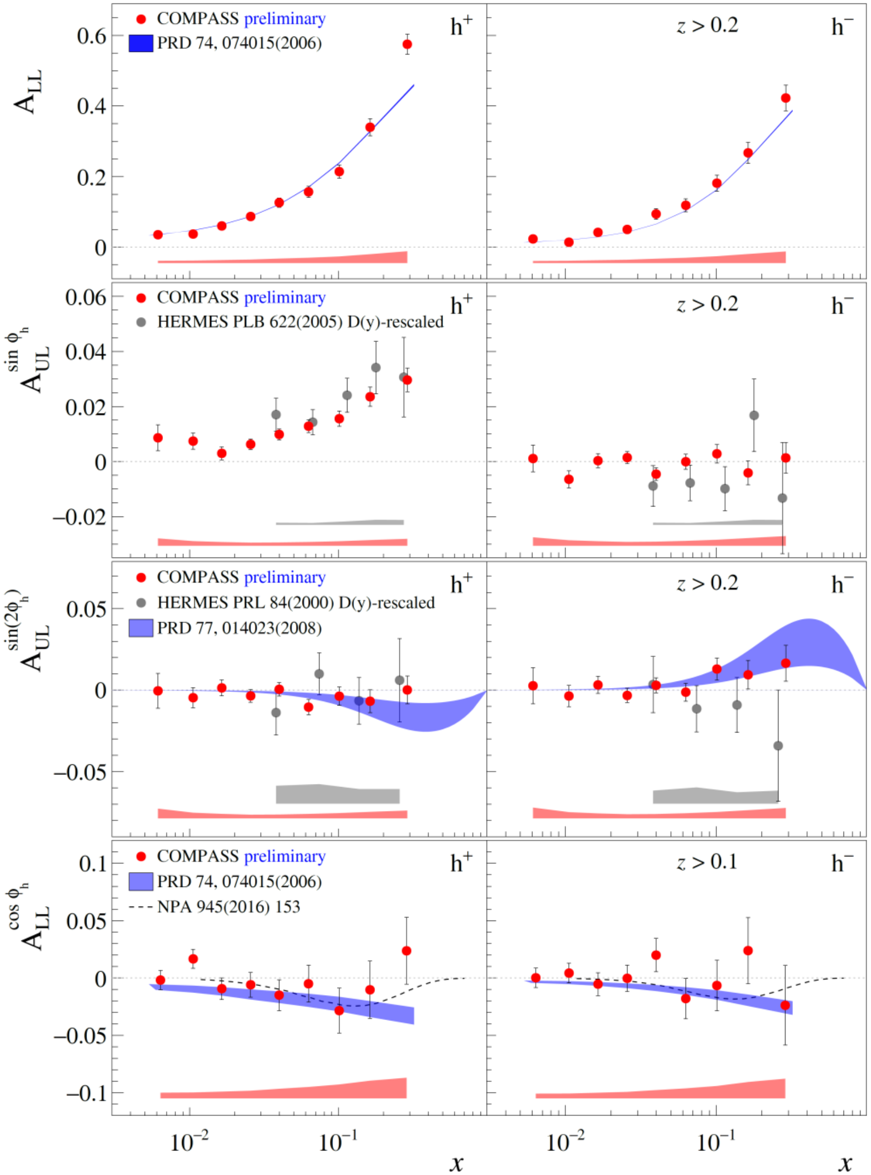
$$\left. + S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right] \right\}$$

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

- Transverse spin asymmetries

SIDIS x-section: transverse spin dependent part

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

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

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

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

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

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

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

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

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

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

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

Twist-2

Twist-3

Eight transverse-spin-dependent azimuthal asymmetries (TSA) appear in SIDIS x-section

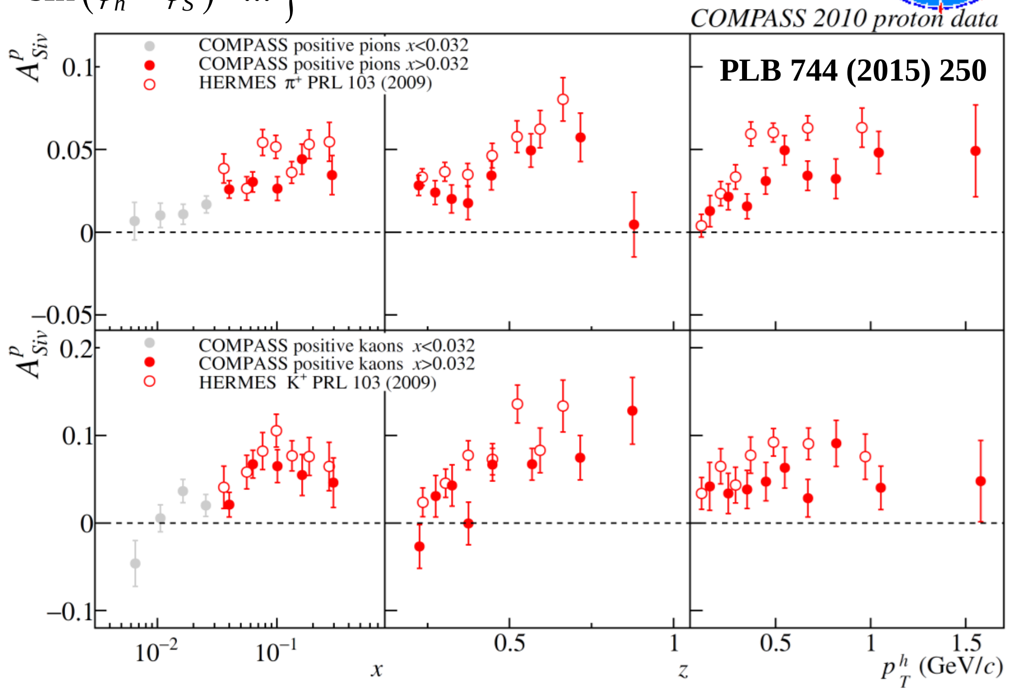
- Four "twist-2" TSAs
  (Sivers, Collins, pretzelosity, Kotzinian-Mulders)
- Four "higher-twist"
- All measured at COMPASS (P/D)

SIDIS TSAs: Sivers effect

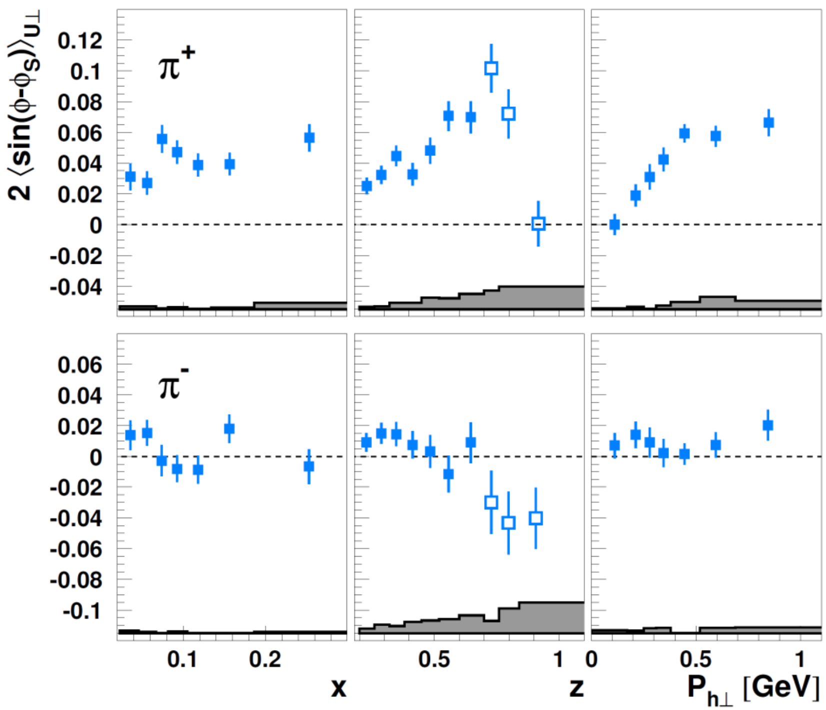
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \ldots\right\}$$

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

- Measured on proton and deuteron
- Recently - gluon Sivers paper PLB 772 (2017) 854



HERMES, JHEP 12 (2020) 010



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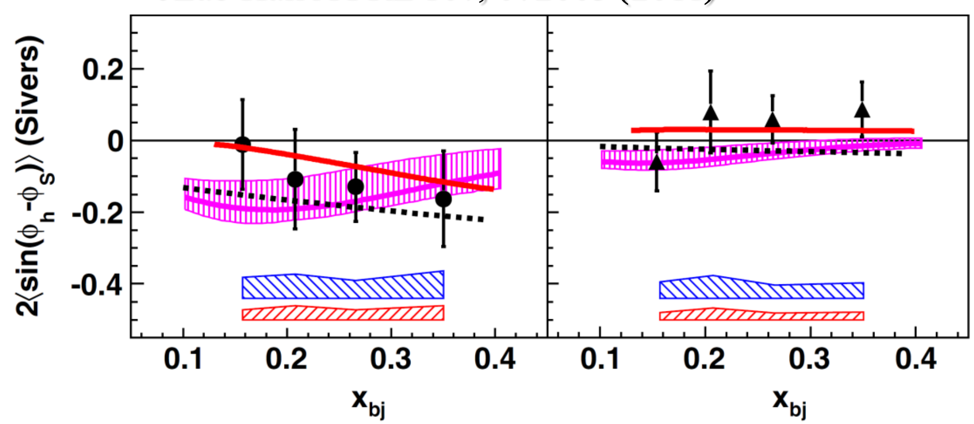


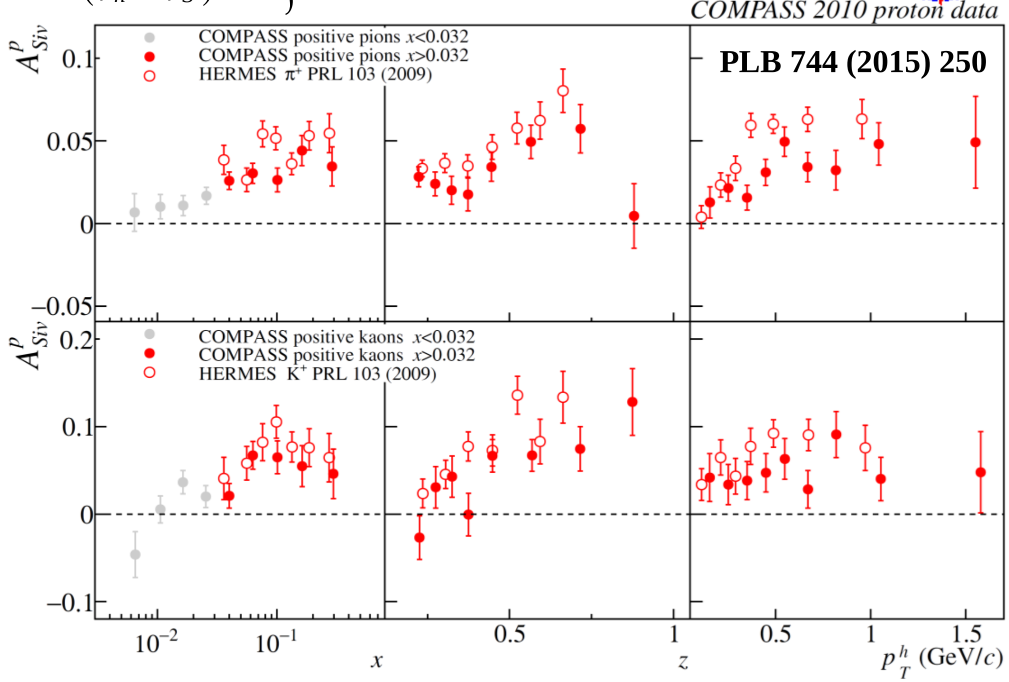
SIDIS TSAs: Sivers effect

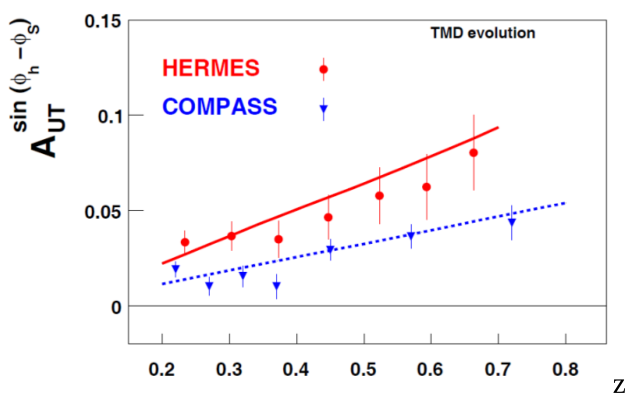
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \ldots\right\}$$

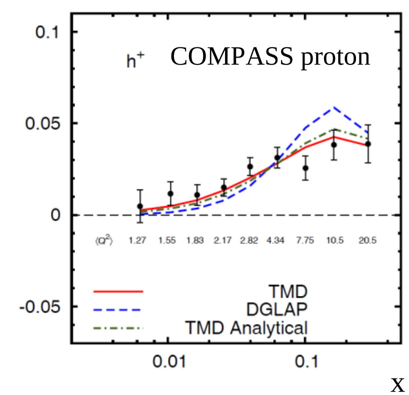
$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}} \cdot \boldsymbol{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h\right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$

- Measured on proton and deuteron
- Recently - gluon Sivers paper PLB 772 (2017) 854

- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results (Q^2 is different by a factor of ~2-3)
- **Q²-evolution? Intriguing result!**





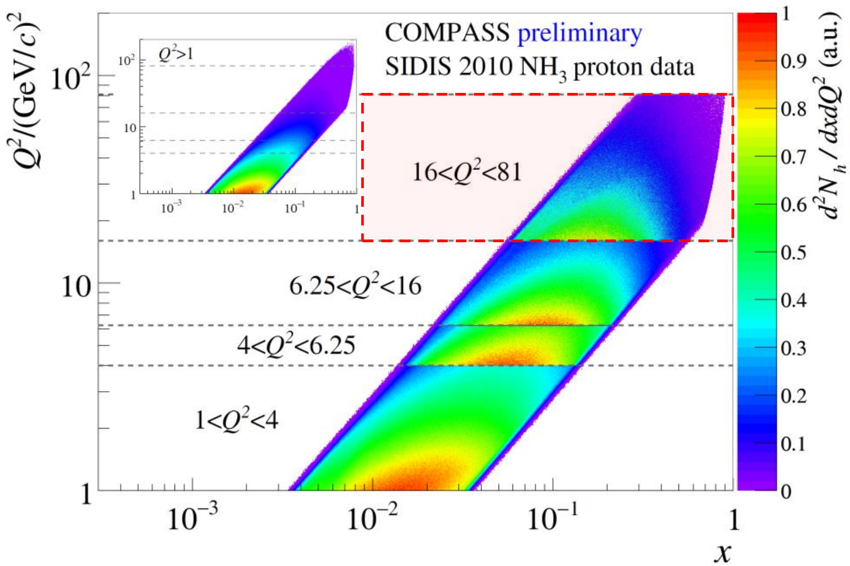


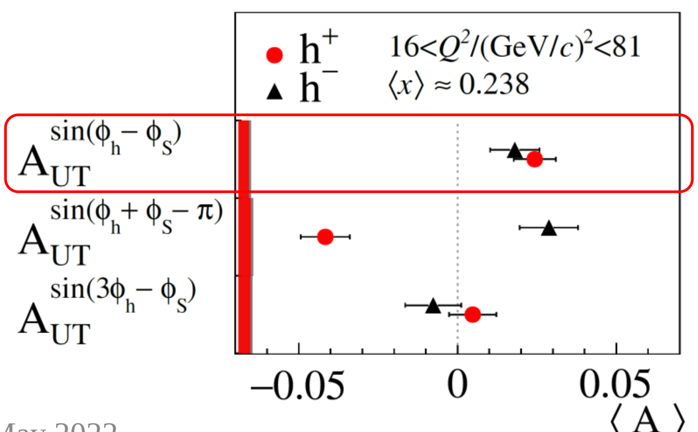
S. M. Aybat, A. Prokudin, T. C. Rogers **PRL 108 (2012) 242003**
M. Anselmino, M. Boglione, S. Melis **PRD 86 (2012) 014028**

SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

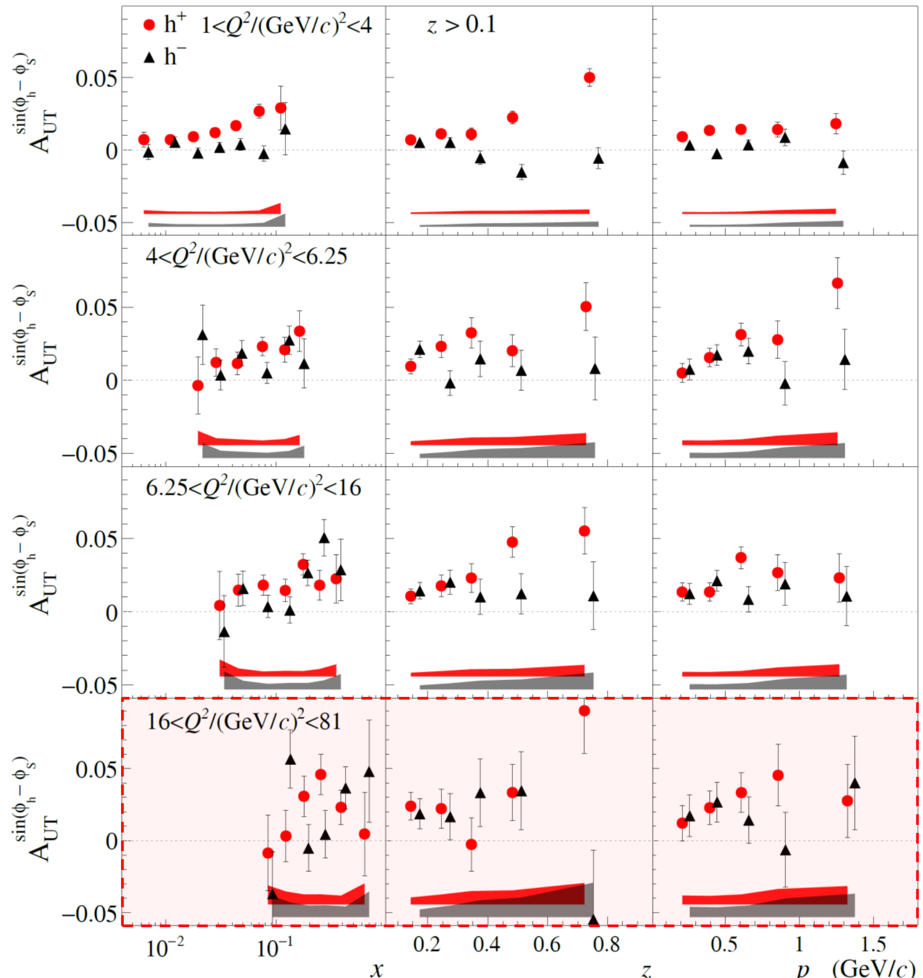
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h - \phi_S) + \ldots\right\}$$

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





COMPASS PLB 770 (2017) 138



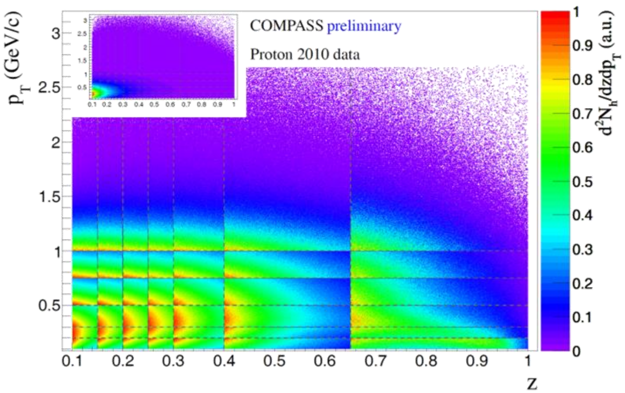
1st COMPASS multi-D fit done for all eight TSAs

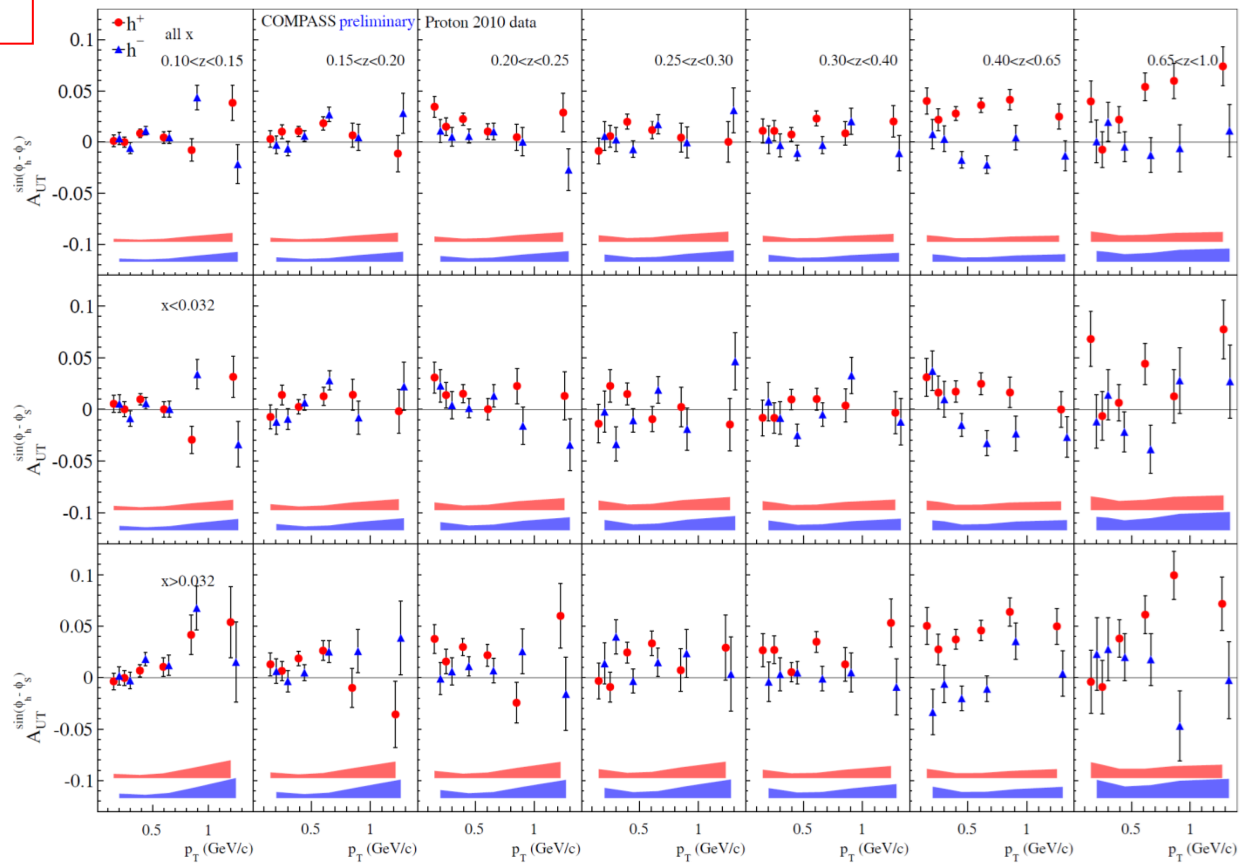
COMPASS Multi-D TSA analyses

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

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

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

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

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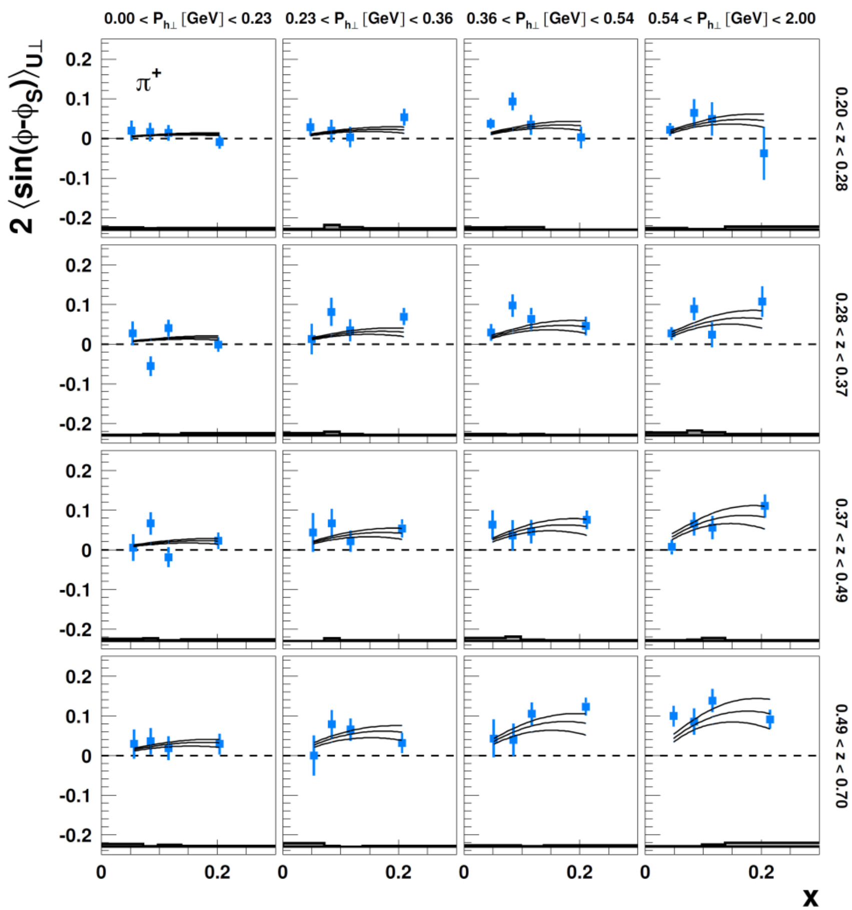
HERMES, JHEP 12 (2020) 010



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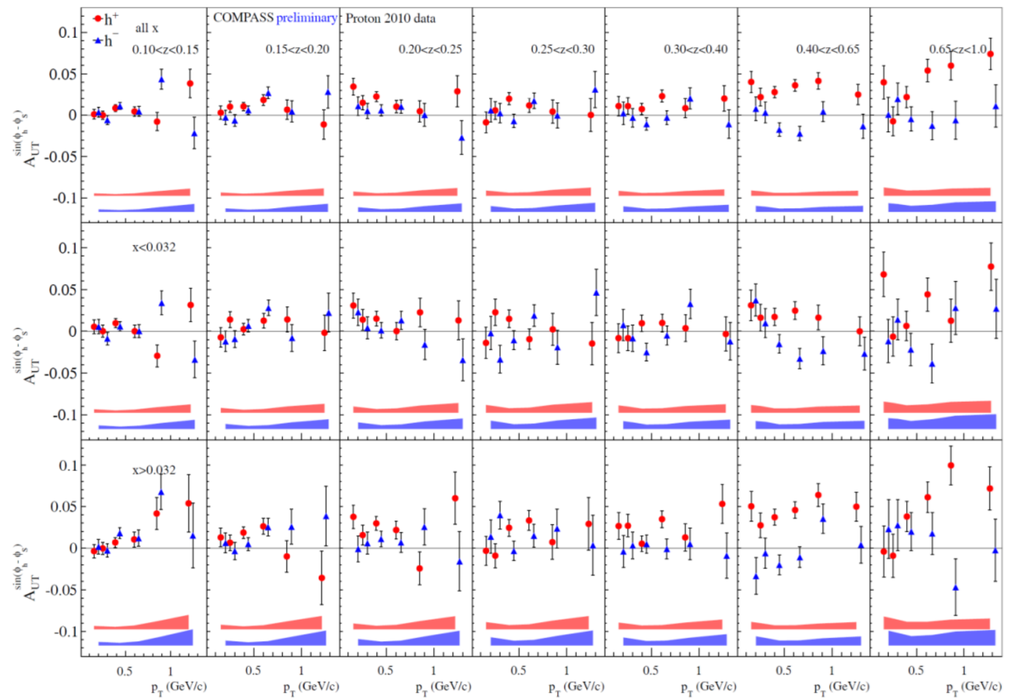

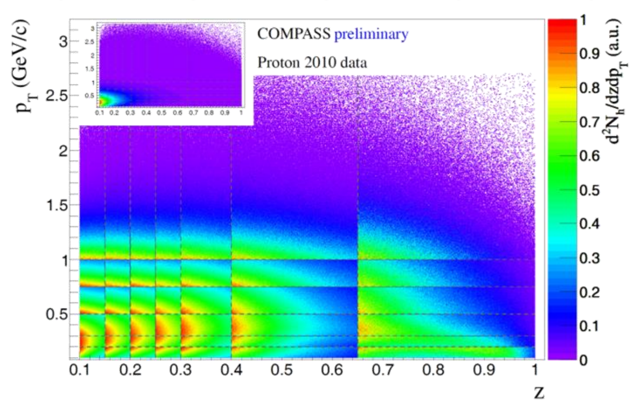

COMPASS Multi-D TSA analyses

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

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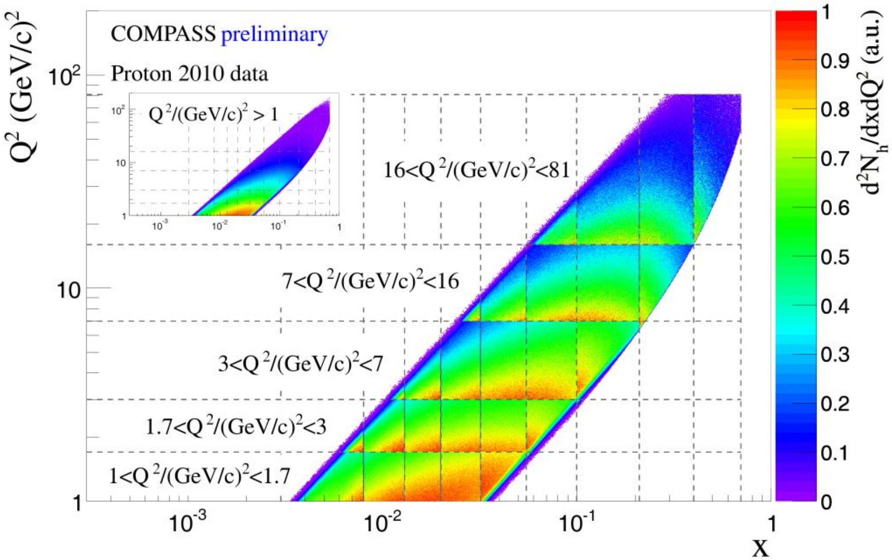

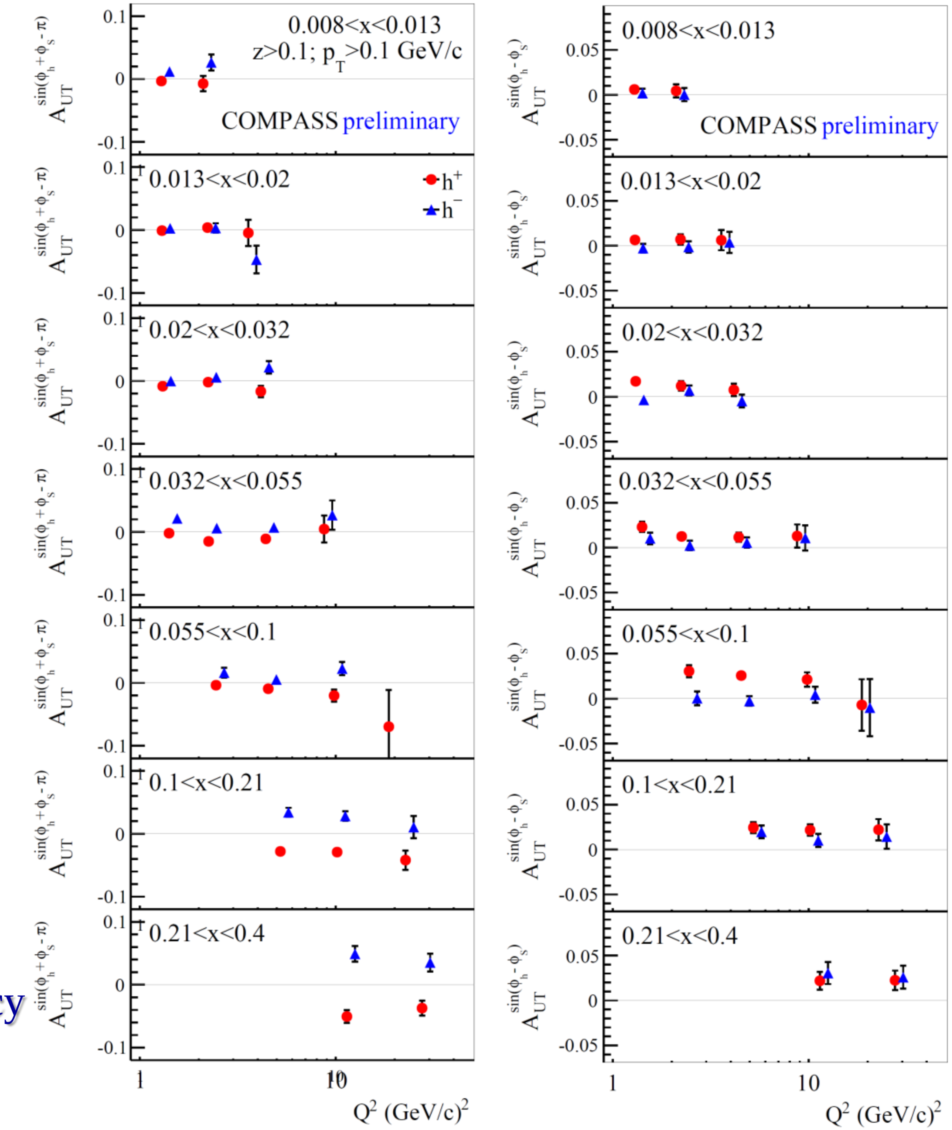

3D x:Q^2:z or x:Q^2:p_T x:z:p_T

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SIDIS TSAs: Collins effect and Transversity

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- Measured on P/D/N in SIDIS and in dihadron SIDIS

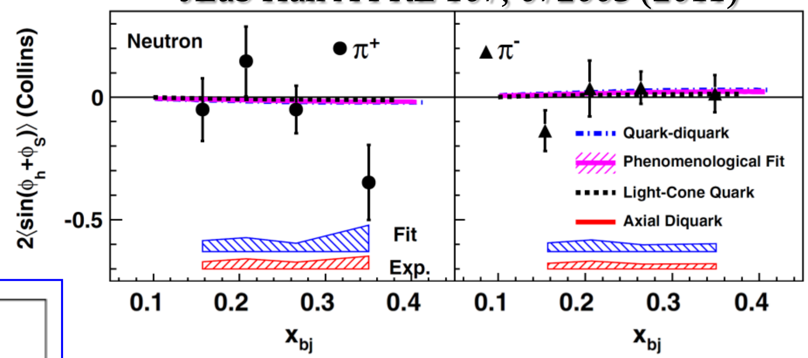
First measurement of the transverse spin asymmetries of the deuteron in semi-inclusive deep inelastic scattering #116

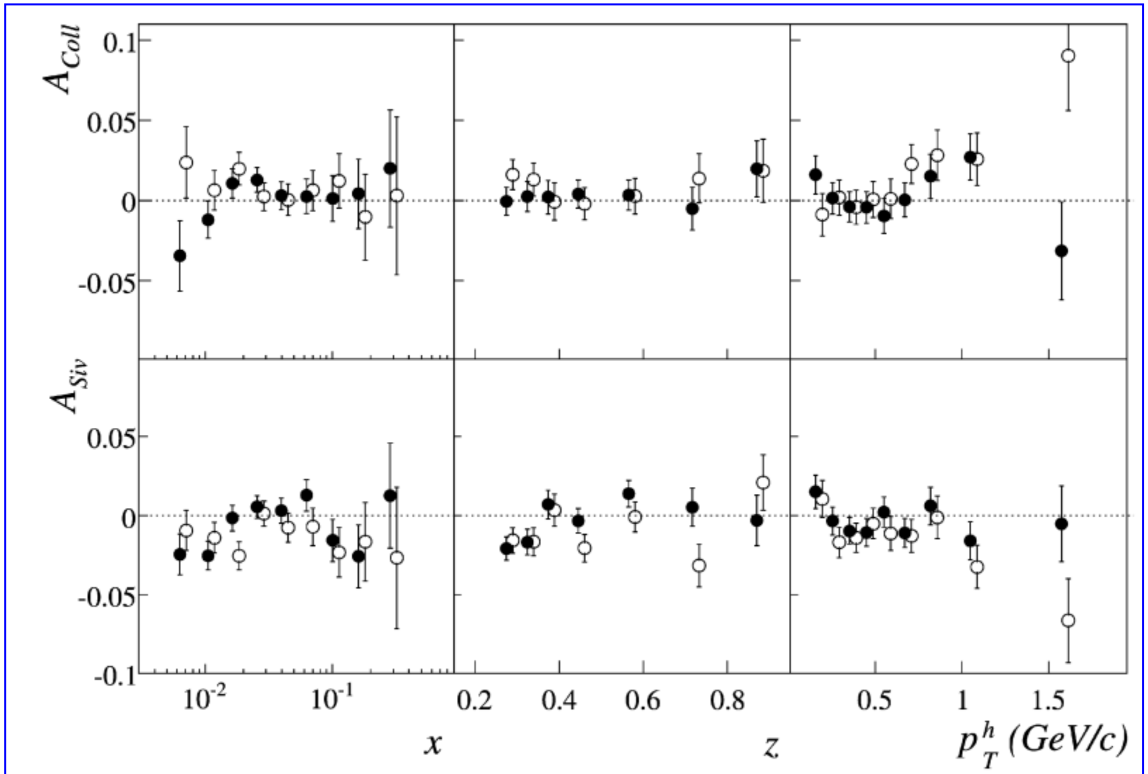
COMPASS Collaboration • V.Yu. Alexakhin (Dubna, JINR) et al. (Feb, 2005)

Published in: *Phys.Rev.Lett.* 94 (2005) 202002 • e-Print: hep-ex/0503002 [hep-ex]

pdf links DOI cite datasets 407 citations

JLab Hall A PRL 107, 072003 (2011)





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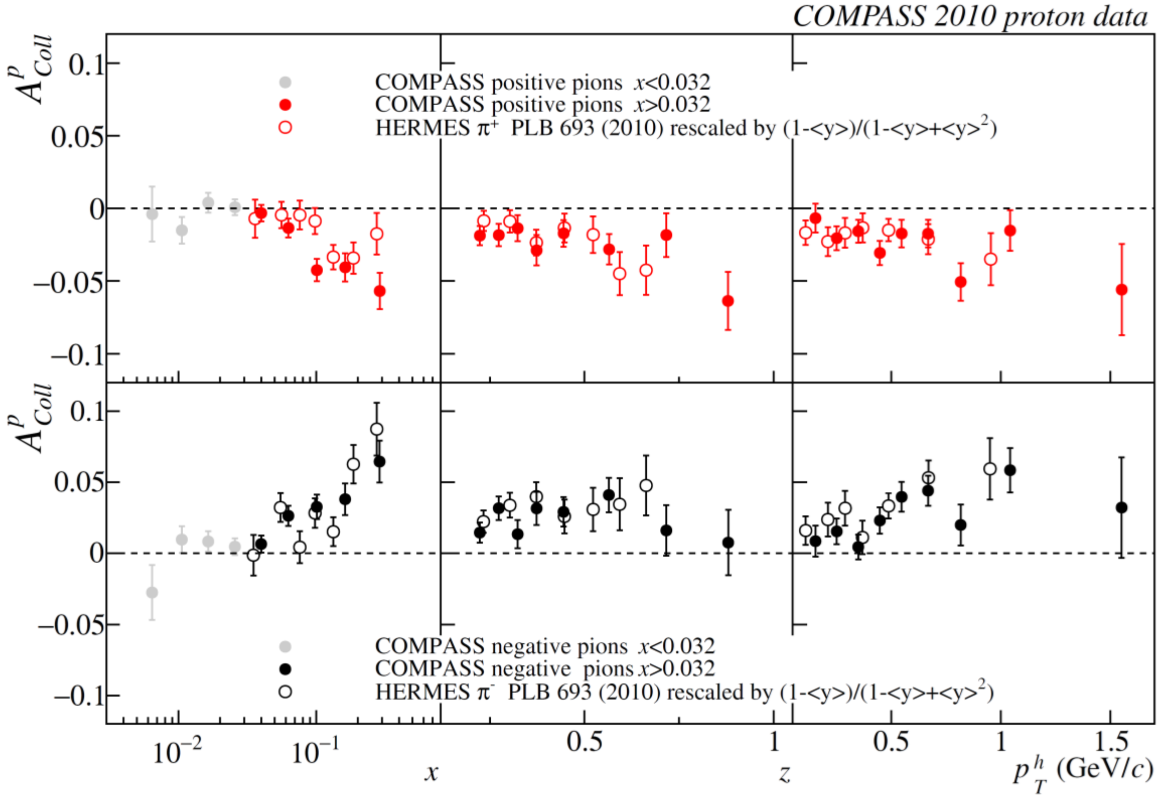
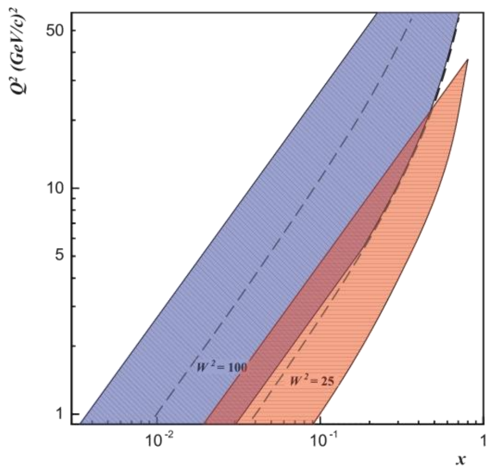
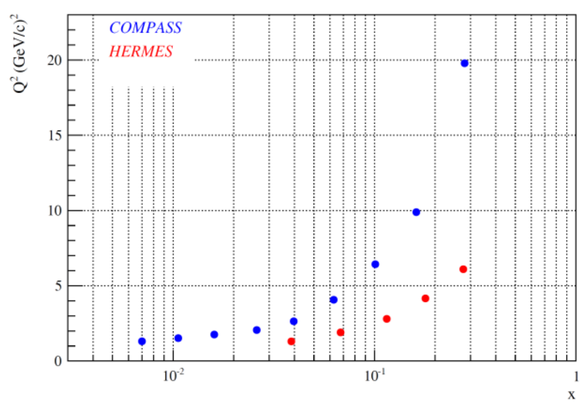
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
- **No Q^2-evolution?**

COMPASS PLB 744 (2015) 250







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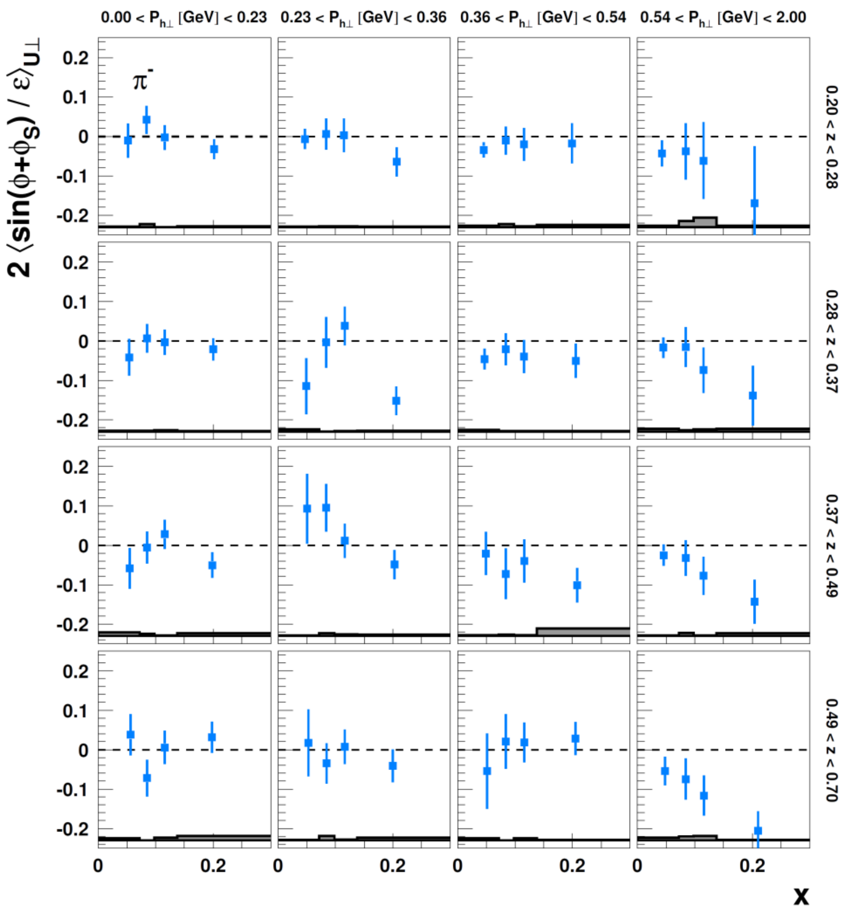
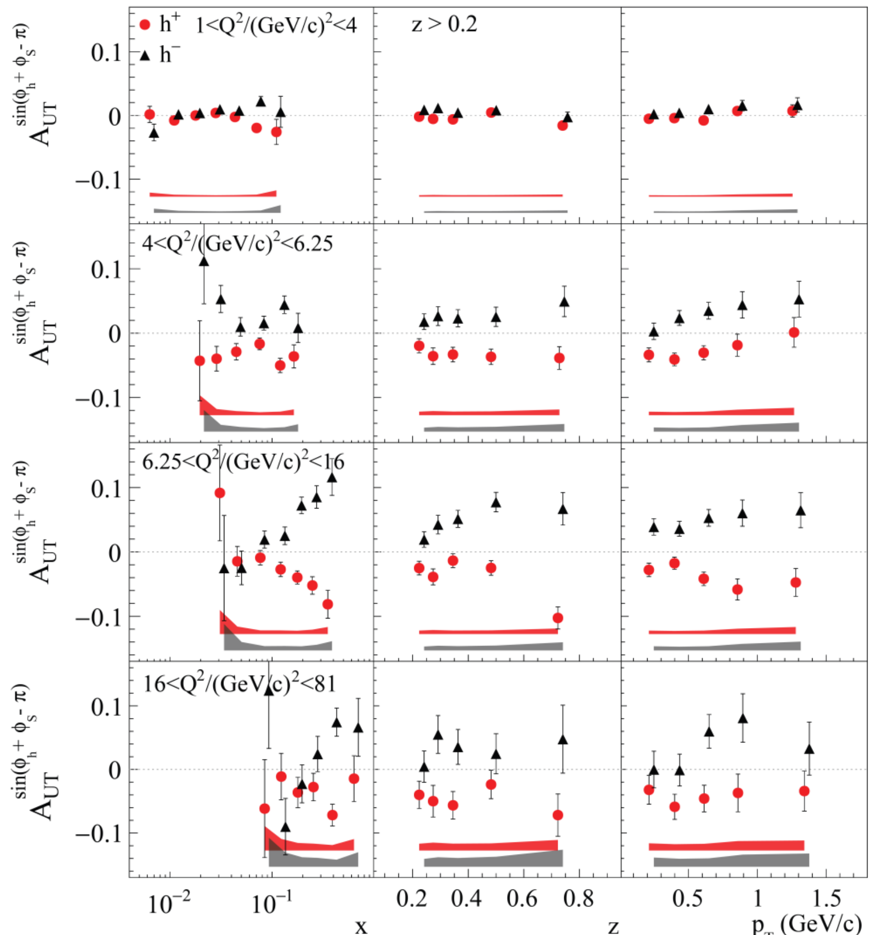
HERMES, JHEP 12 (2020) 010



COMPASS, PBL 770 (2017) 138



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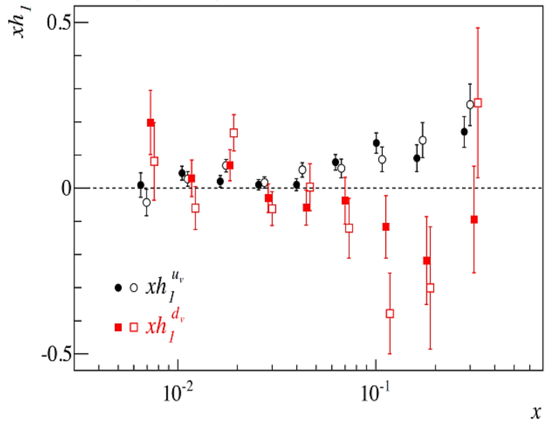
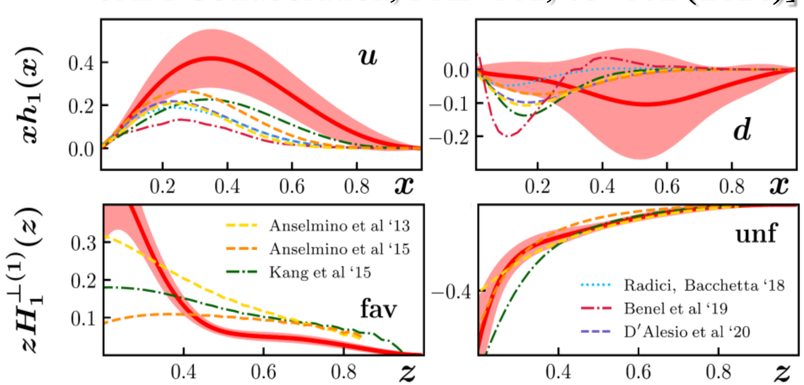
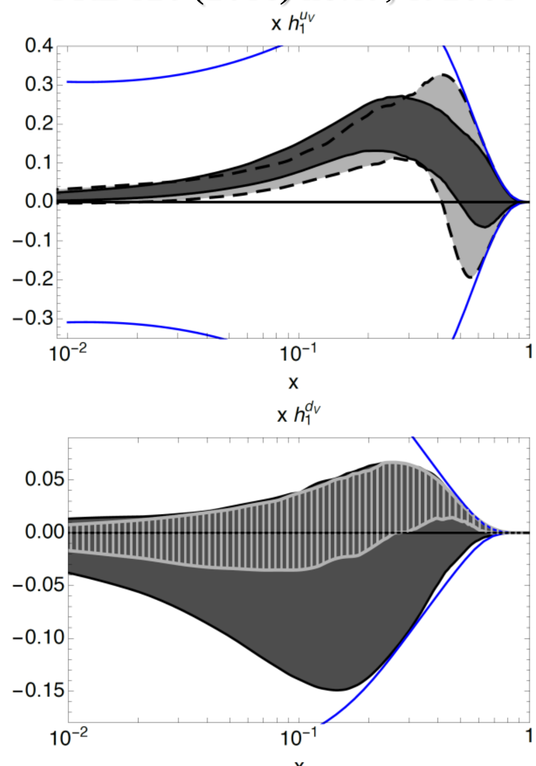
A. Martin, F. Bradamante, V. Barone PRD91 (2015) no.1, 014034



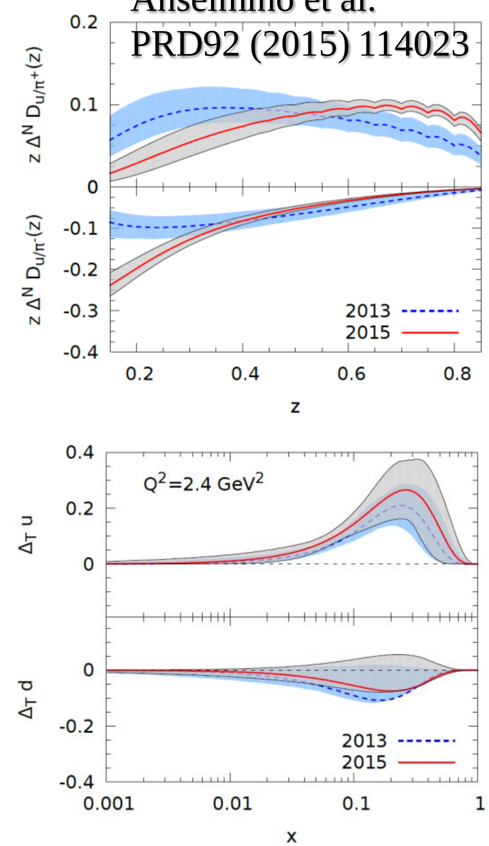
JAM Collaboration, PRD 102, 054002 (2020)]



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



Anselmino et al. PRD92 (2015) 114023



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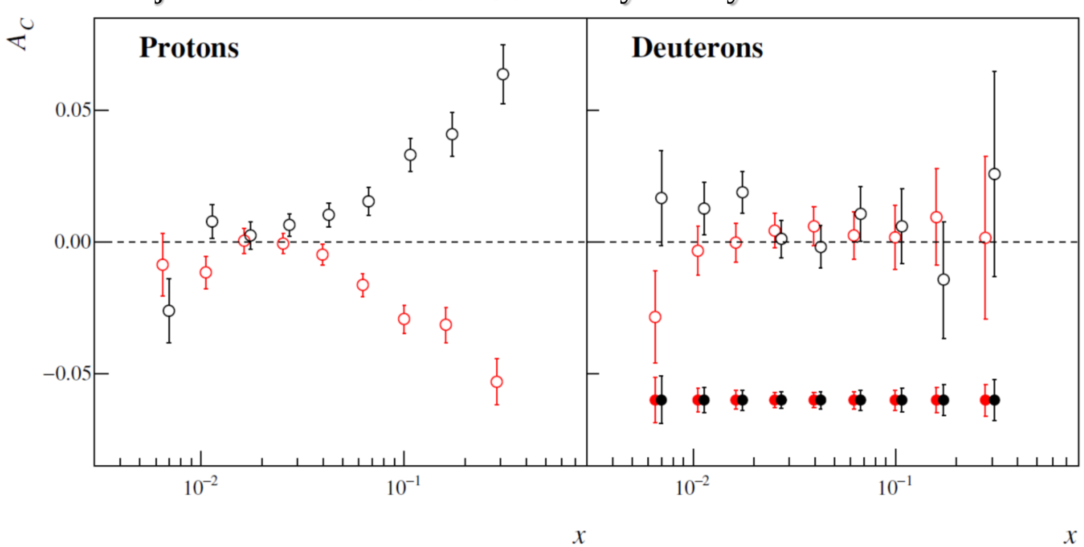
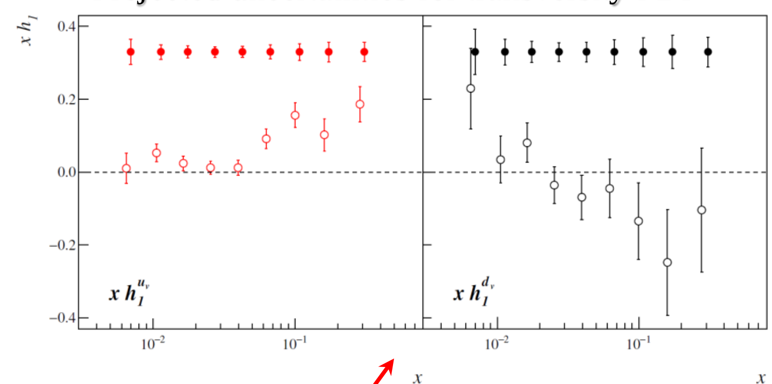
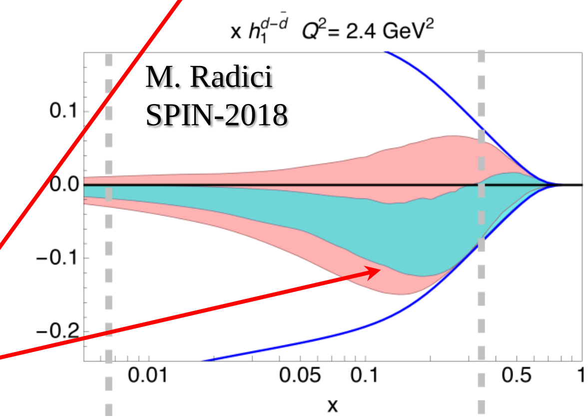
Addendum to the COMPASS-II Proposal
Projected uncertainties for Collins asymmetry



Addendum to the COMPASS-II Proposal
Projected uncertainties for transversity PDF





COMPASS-II (2022 run)

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

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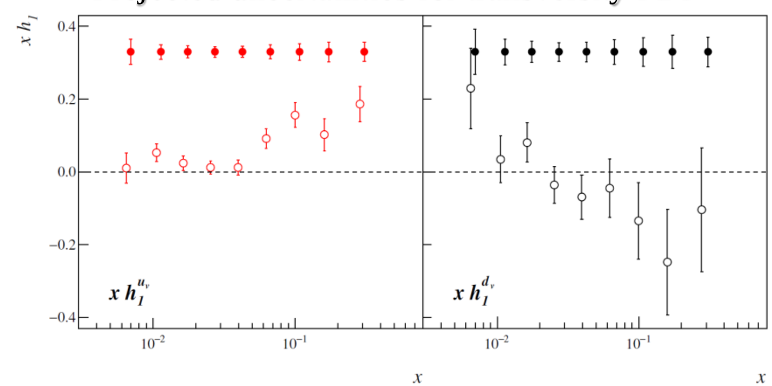

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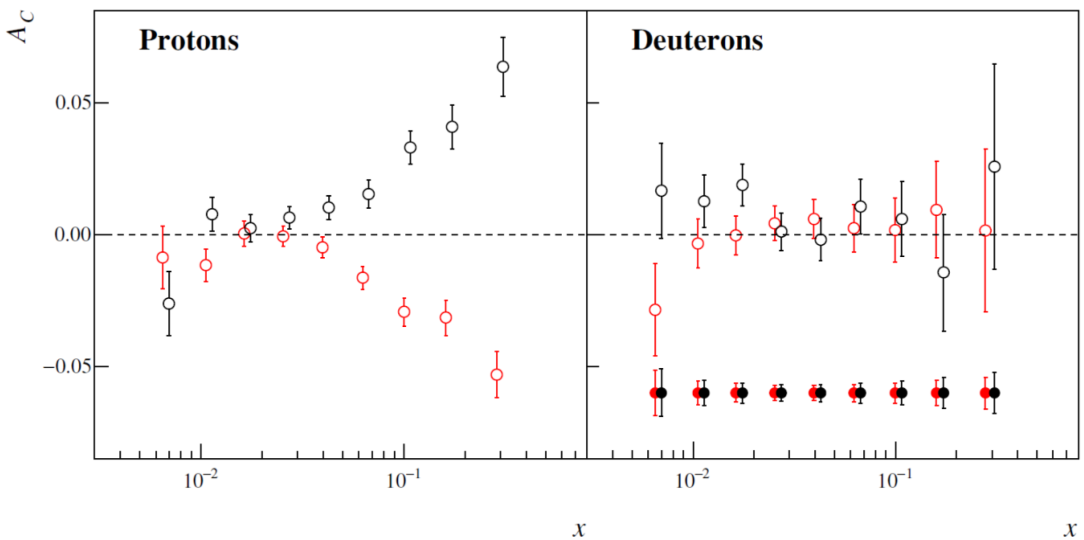

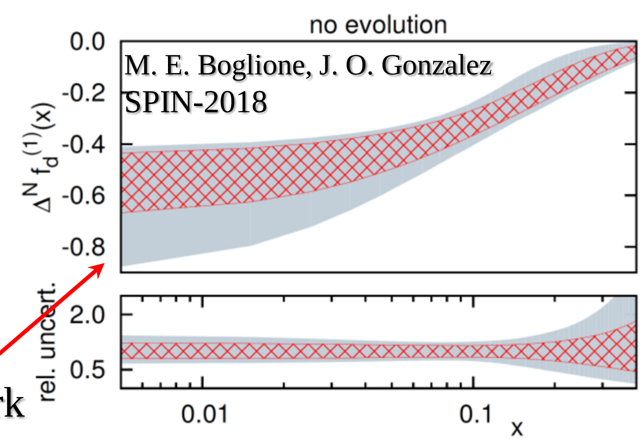

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SIDIS: target transverse spin dependent asymmetries

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

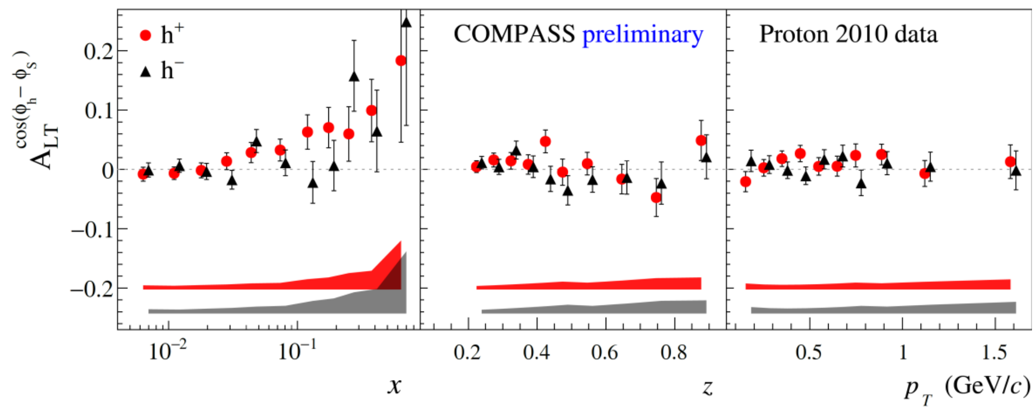
$$F_{LT}^{\cos(\phi_h-\phi_S)} = C\left[\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{k}_T}{M}\, g_{1T}^q D_{1q}^h\right]$$

COMPASS/HERMES/CLAS6 results

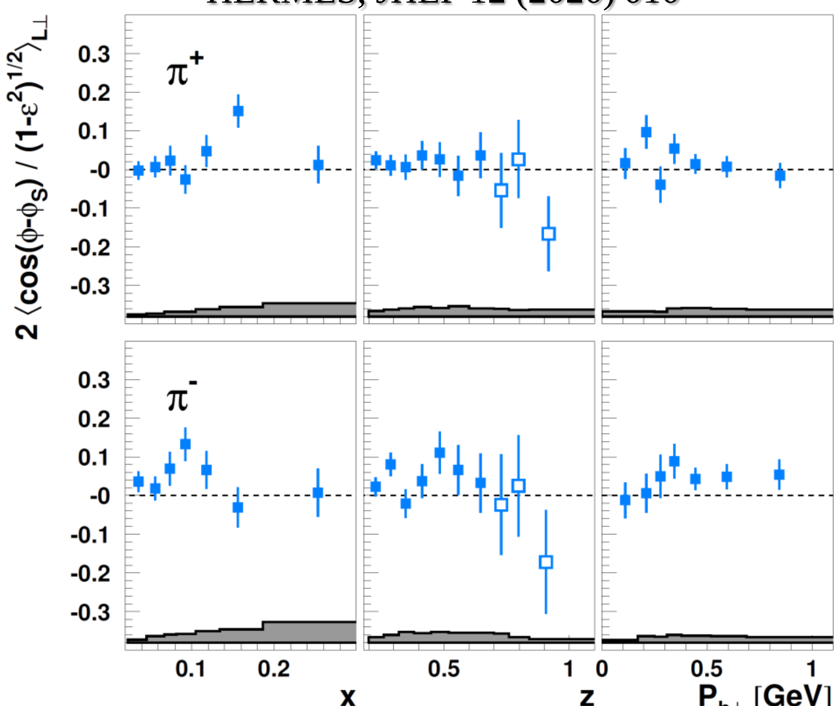
$A_{LT}^{\cos(\phi_h-\phi_S)}$

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

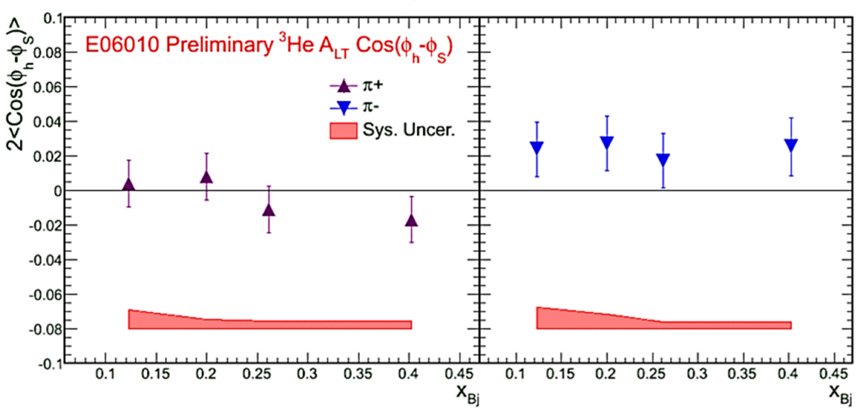
COMPASS, PBL 770 (2017) 138; PoS QCDEV2017 (2018) 042



HERMES, JHEP 12 (2020) 010



CLAS6, neutron target



SIDIS: target transverse spin dependent asymmetries

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

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

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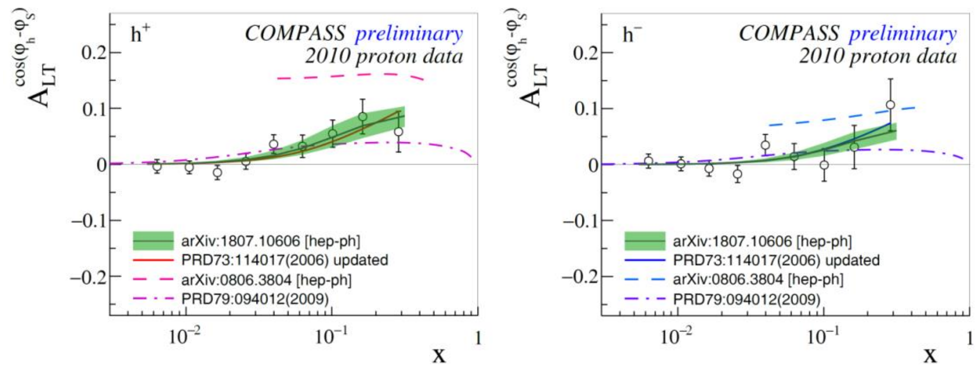
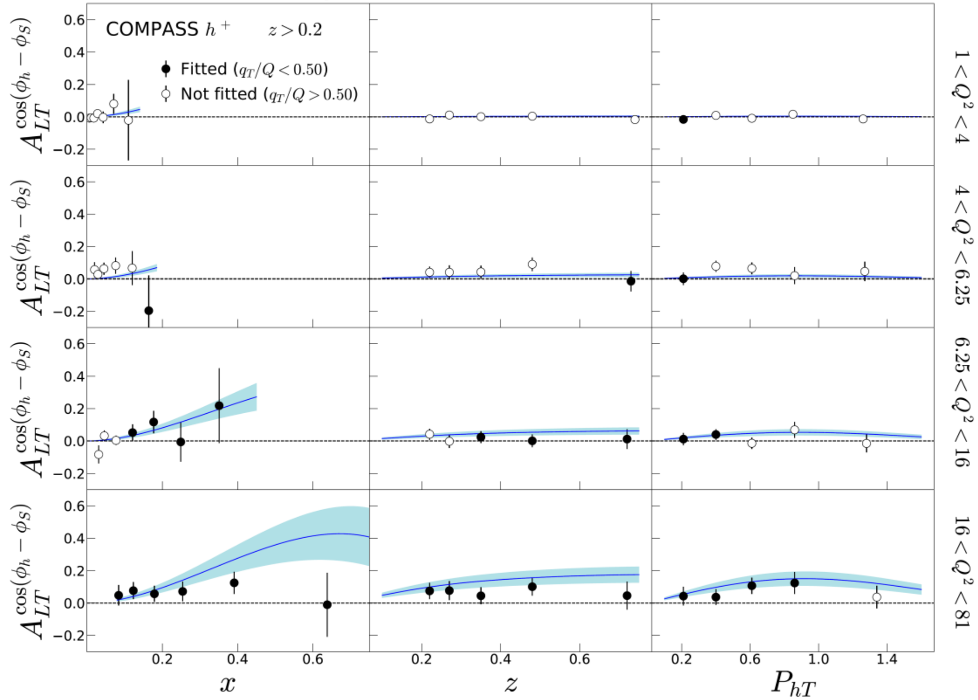
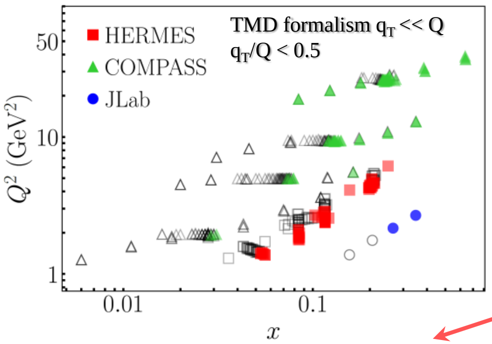
S. Bastami et al. JHEP 1906 (2019) 007



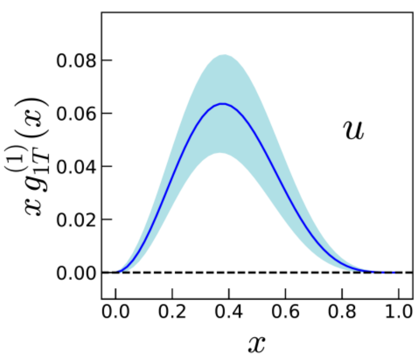
S. Bhattacharya et al. PRD 105 (2022) 3, 034007

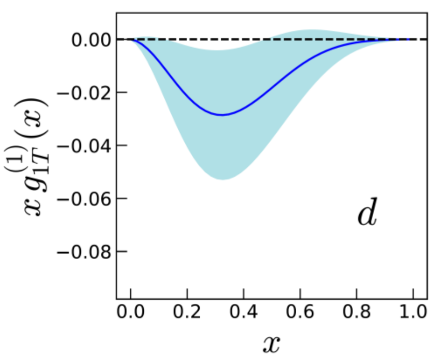




First global QCD analysis of the g_{1T} TMD PDF using SIDIS data

See Shohini's talk





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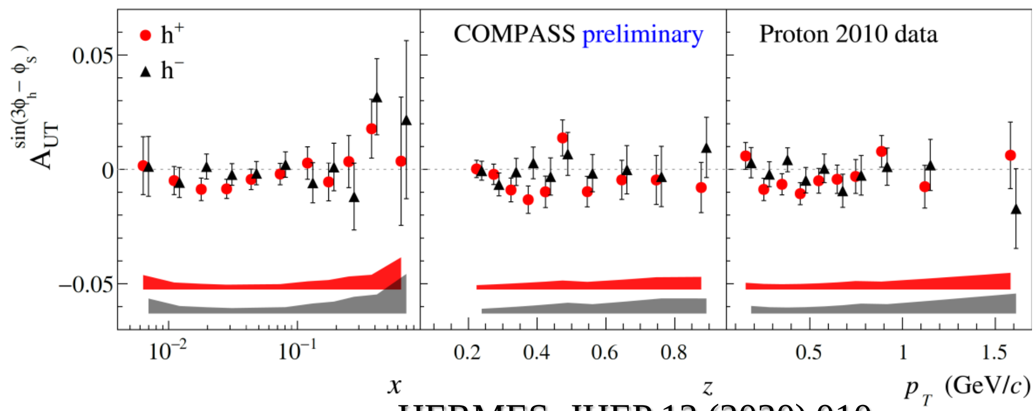
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) + \ldots\right\}$$

COMPASS/HERMES results

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

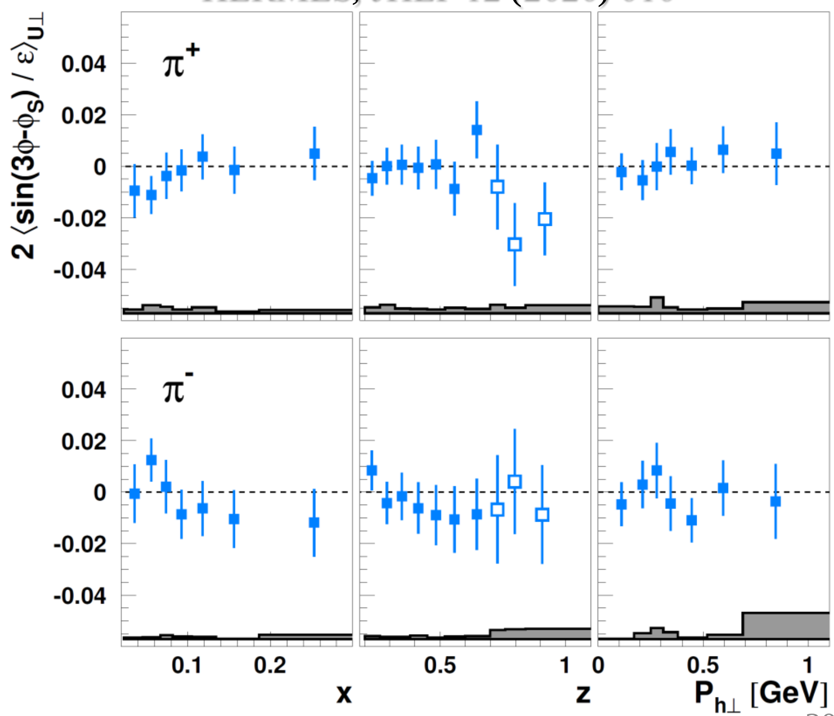
- Only "twist-2" ingredients,
- $\sim p_T^2$-suppression
- $h_{1T}^{\perp q}$ is expected to be small (see e.g. PLB769 (2017) 84-89)
- **Small, compatible with zero asymmetry**
- **In agreement with models**

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

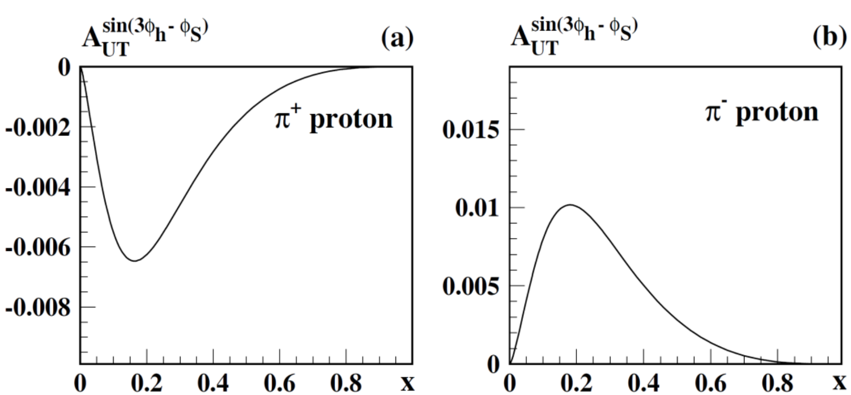


$$F_{UT}^{\sin(3\phi_h-\phi_S)} = C\left[\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\boldsymbol{k}_T\cdot\boldsymbol{p}_T\right) + \boldsymbol{k}_T^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right) - 4\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)}{2M^2 M_h} h_{1T}^{\perp q} H_{1q}^{\perp h}\right]$$

HERMES, JHEP 12 (2020) 010



B. Pasquini, S. Boffi, A.V. Efremov, P. Schweitzer
arXiv:0912.1761 [hep-ph]

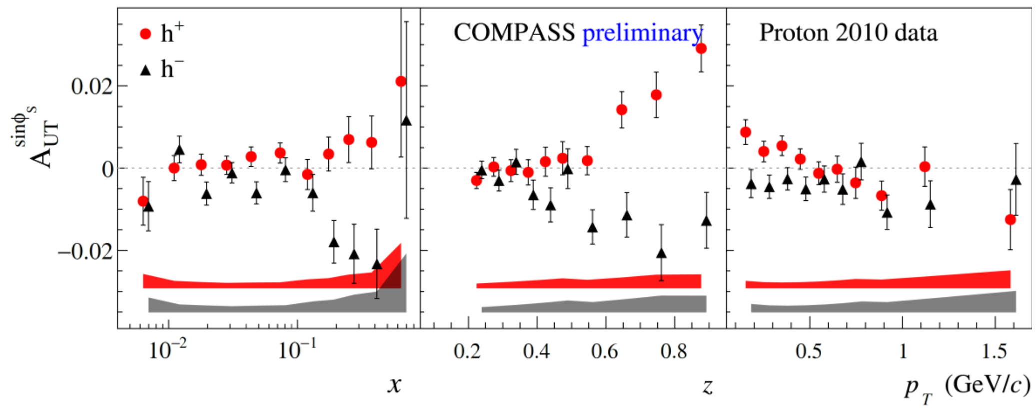


SIDIS: target transverse spin dependent asymmetries

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

$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q} C\left\{\left(x f_T^q D_{1q}^h - \frac{M_h}{M} h_1^q \frac{\tilde{H}_q^h}{z}\right) - \frac{\boldsymbol{p_T}\cdot\boldsymbol{k_T}}{2MM_h}\left[\left(x h_T^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1T}^q \frac{\tilde{G}_q^{\perp h}}{z}\right) - \left(x h_T^{\perp q} H_{1q}^{\perp h} - \frac{M_h}{M} f_{1T}^{\perp q} \frac{\tilde{D}_q^{\perp h}}{z}\right)\right]\right\}$$

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

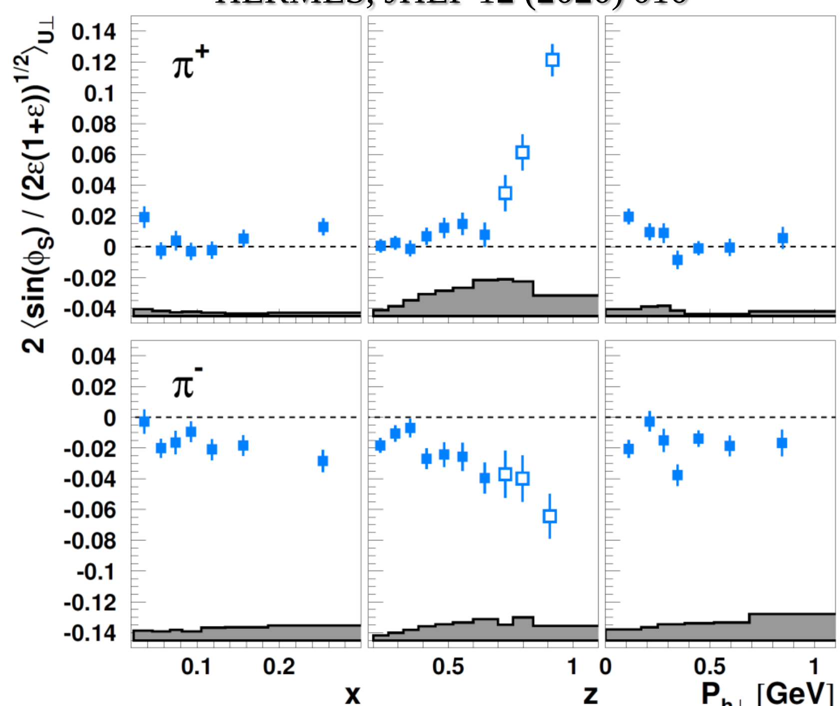


COMPASS/HERMES results

$A_{UT}^{\sin\phi_S}$

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

HERMES, JHEP 12 (2020) 010



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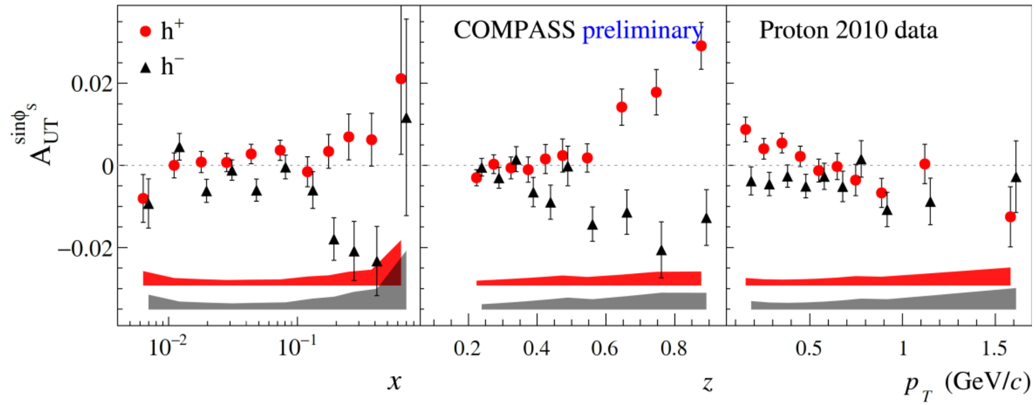
$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q} C \left\{ \left(x f_T^q D_{1q}^h - \frac{M_h}{M} h_1^q \frac{\tilde{H}_q^h}{z} \right) - \frac{\boldsymbol{p_T} \cdot \boldsymbol{k_T}}{2MM_h} \left[\left(x h_T^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1T}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) - \left(x h_T^{\perp q} H_{1q}^{\perp h} - \frac{M_h}{M} f_{1T}^{\perp q} \frac{\tilde{D}_q^{\perp h}}{z} \right) \right] \right\}$$

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



COMPASS/HERMES results

$A_{UT}^{\sin\phi_S}$

- Q-suppression
- various “twist-2/3” ingredients
- **Small asymmetry**
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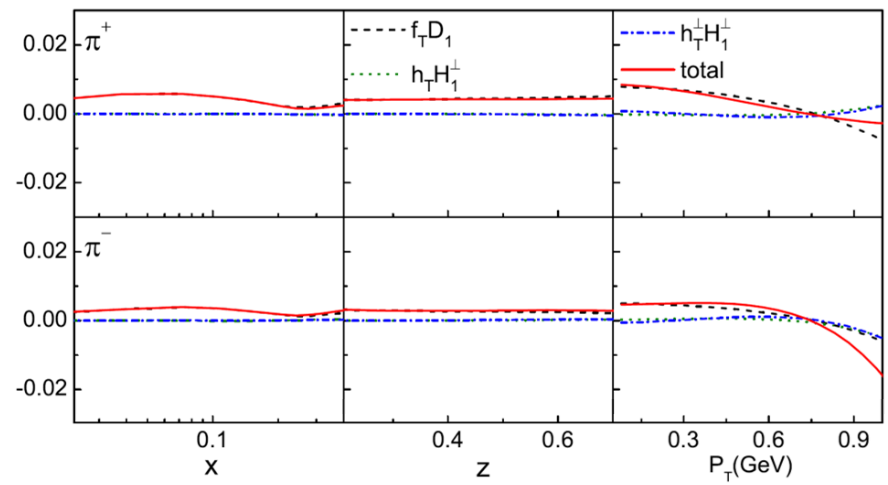
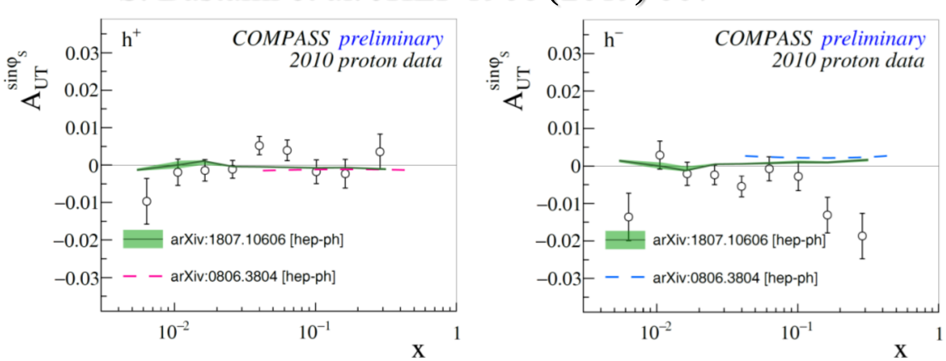
W. Mao, Z. Lu and B.Q. Ma Phys.Rev. D 90 (2014) 014048



S. Bastami et al. JHEP 1906 (2019) 007



COMPASS 2022 run: new unique deuteron data to come

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

Jefferson Lab — neutron [³He] — 6 data points
*Qian et al., P.R.L. **107** (11) 072003*

COMPASS 2009 — deuteron [⁶LiD] — 88 data points
*Alekseev et al., P.L. **B673** (09) 127*

COMPASS 2017 — Proton [NH₃] — 111 data points
*Adolph et al., P.L. **B770** (17) 138*

Same kinematic cuts applied to unpolarized

x, z, P_{hT} data projections

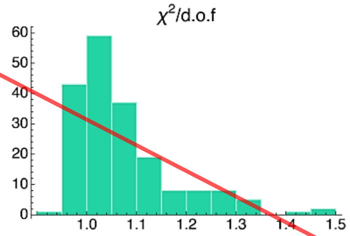
$Q^2 \geq 1.4$ GeV² $0.2 \leq z \leq 0.7$
$P_{hT} < \min[0.2Q, 0.7Qz] + 0.5$ GeV

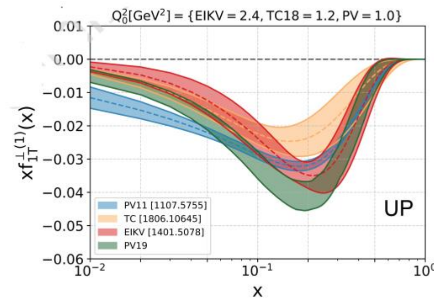
300 data points → **118** data fitted
14 free parameters
χ^2/d.o.f. = 1.06 ± 0.10

Pavia group fits

Bacchetta, Delcarro, Pisano, Radici, in preparation

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

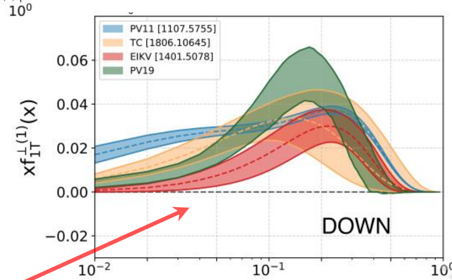




PV11	*Bacchetta & Radici, P.R.L. **107** (11)*
EIKV	*Echevarria et al., P.R. D**89** (14)*
TC	*Boglione et al., JHEP **1807** (18)*
PV19	*Bacchetta, Delcarro, Pisano, Radici, in preparation*

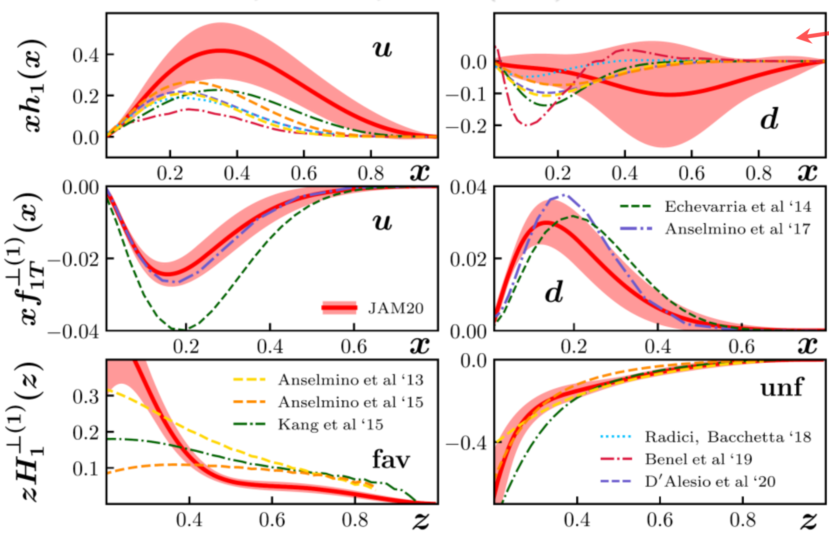
$$f_{1T}^{\perp(1)}(x) = \int d\mathbf{k}_T \frac{\mathbf{k}_T^2}{2M^2} f_{1T}^{\perp}(x, \mathbf{k}_T)$$

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

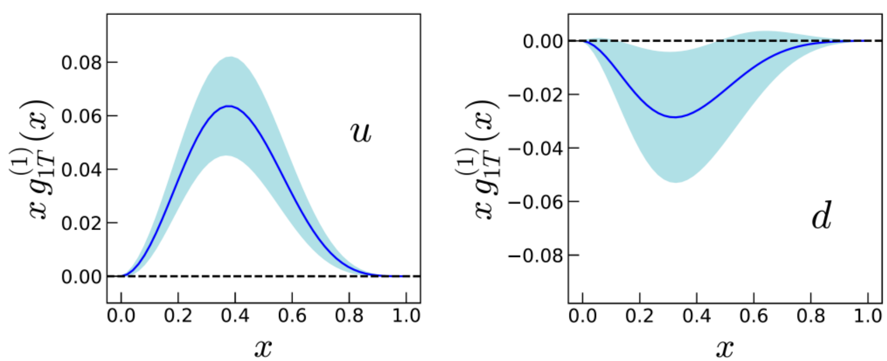


COMPASS 2022 deuteron run

JAM Collaboration, PRD 102, 054002 (2020)



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



Conclusions

- 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

COMPASS data taking campaigns

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

Transversity (s-quark) and Λ polarization

Transversity and Λ polarisation in polarised SIDIS at COMPASS

The COMPASS Collaboration

Abstract

Based on the observation of target-transverse-spin asymmetries in single-hadron and hadron-pair production in Semi-Inclusive measurements of Deep Inelastic Scattering (SIDIS), the existence of the chiral-odd transversity quark distribution function $h_1^q(x)$ is nowadays well established. Several possible channels to access transversity have been discussed. One major candidate is the measurement of the polarisation of Λ hyperons produced in SIDIS off transversely polarised nucleons, where the transverse polarisation of the struck quark can be transferred to the final-state hyperon. In this article, we present the COMPASS results on the transversity-induced polarisation of Λ and $\bar{\Lambda}$ hyperons produced in SIDIS off transversely polarised protons. Within the experimental uncertainties, no significant deviations from zero could be observed in these data. The results are discussed taking into account the known transversity functions and some models.

COMPASS
PLB 824 (2022) 136834