COMPASS experiment: recent results from the spin-programme

Բակուր Պարսամյան

CERN, JINR,
University of Turin and INFN

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

on behalf of the COMPASS Collaboration

International Workshop on Correlations in Partonic and Hadronic Interactions

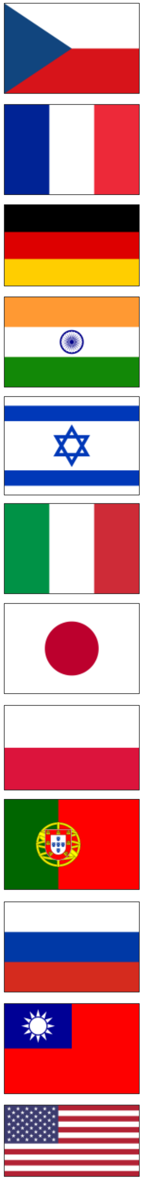
(CPHI-2018)

Yerevan, Armenia

September 24 – 28, 2018

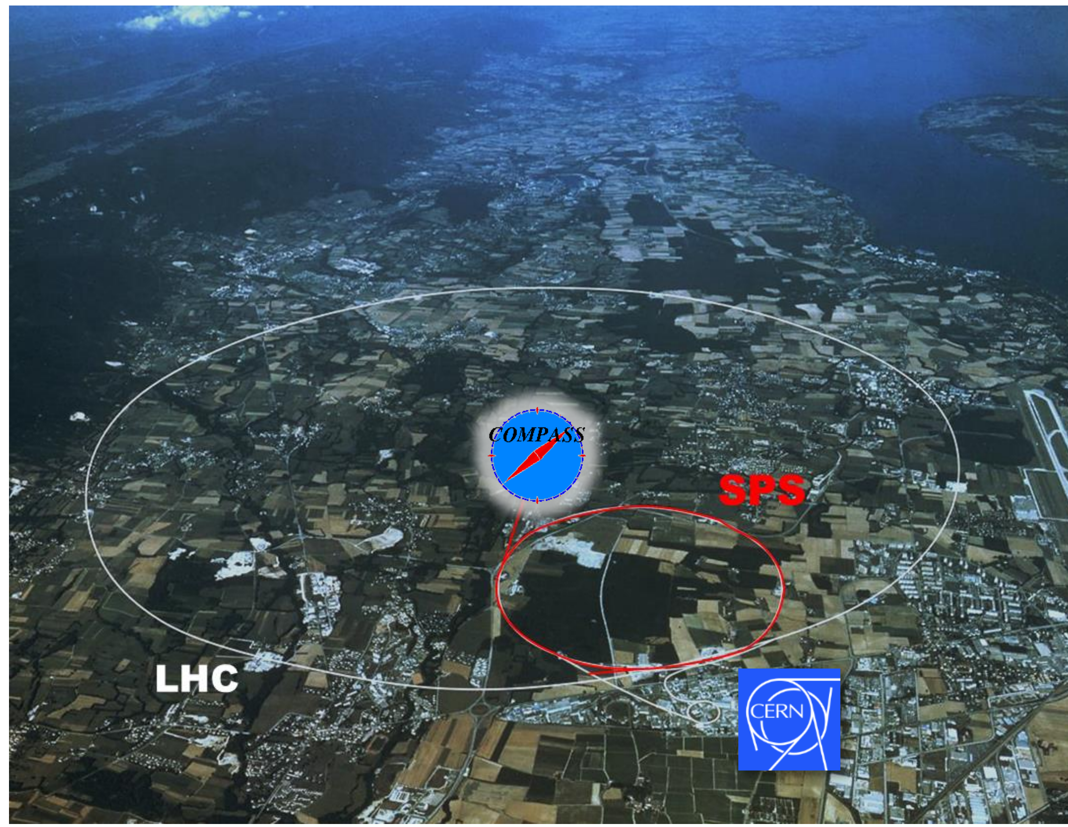
COMPASS collaboration

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



24 institutions from 13 countries
– nearly 250 physicists

- **CERN SPS north area**
- **Fixed target experiment**
- **Approved in 1997 (21 years)**
- **Taking data since 2002**



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

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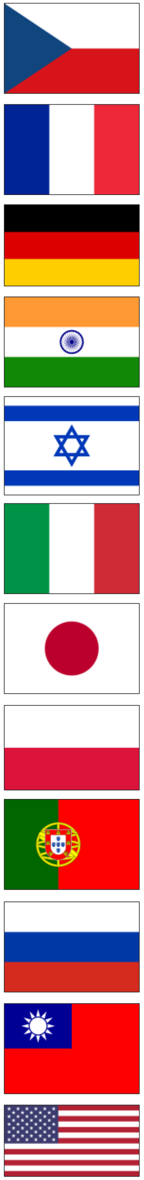

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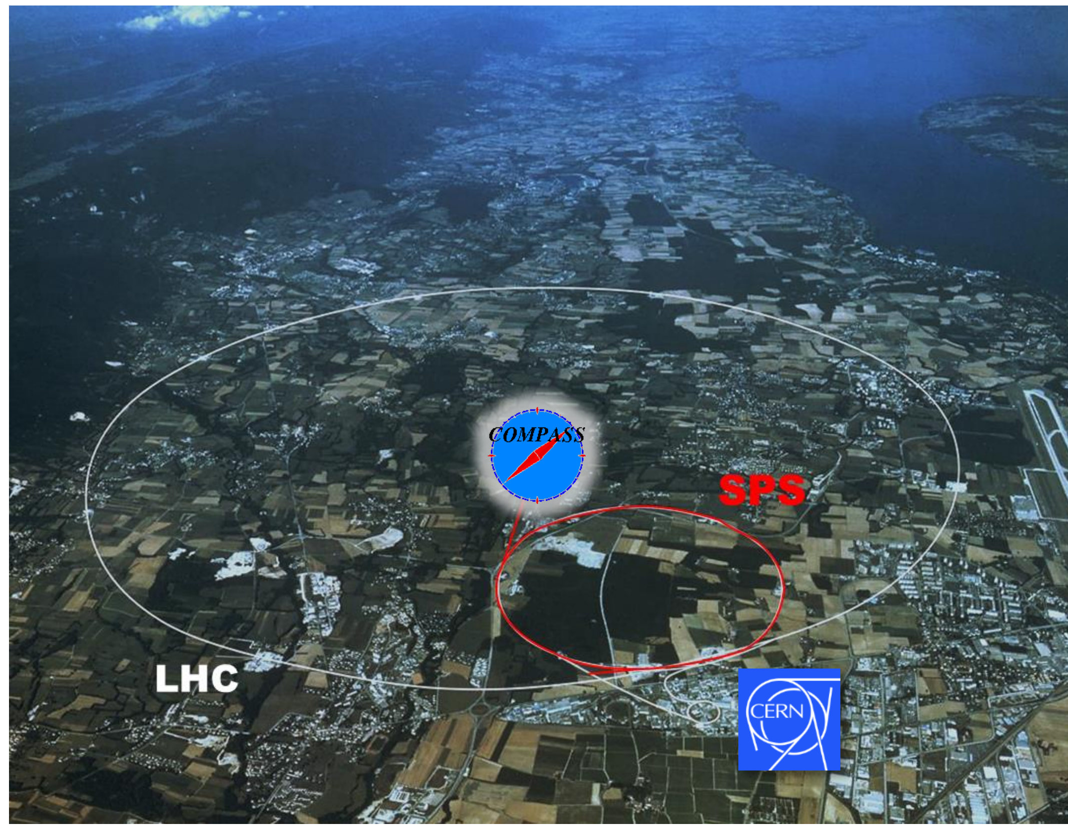
Wide physics program

COMPASS-I

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



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COMPASS-I

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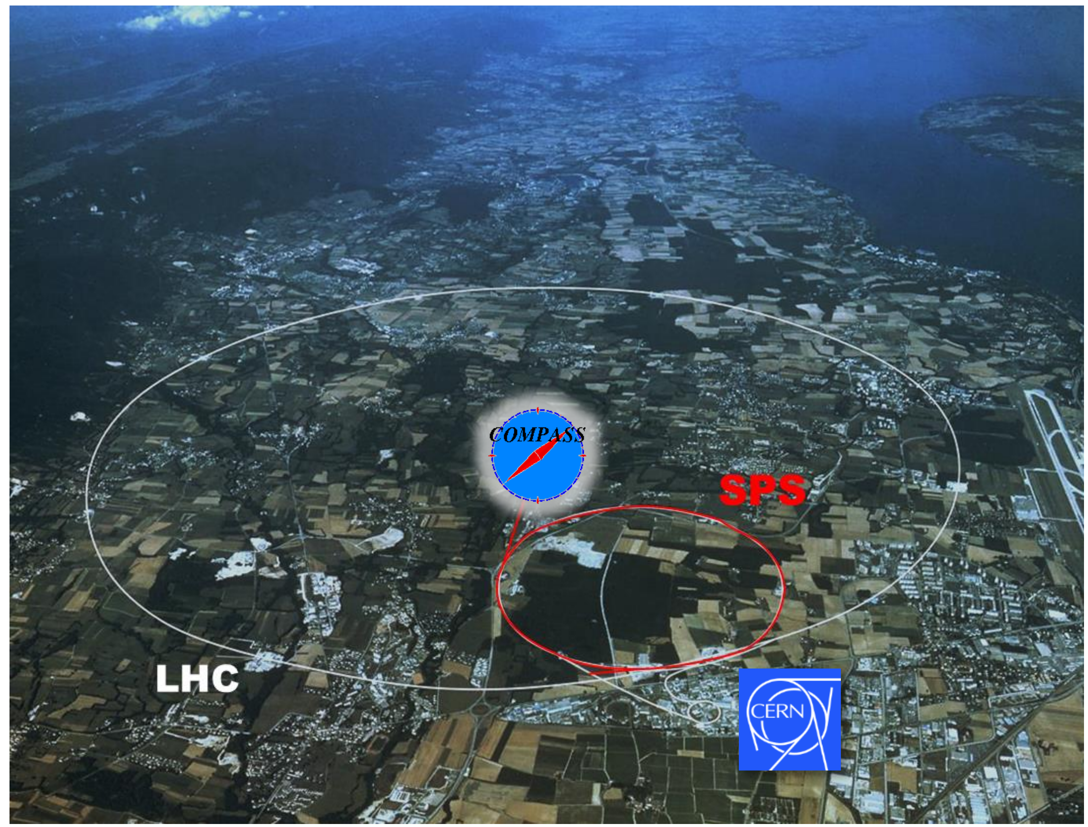
COMPASS-II

- **Data taking 2012-2018 (2021)**
- **Primakoff**
- **DVCS (GPD+SIDIS)**
- **Polarized Drell-Yan**
- **Transverse deuteron SIDIS**

Many "beyond 2021" ideas:
Proton-radius, Drell-Yan, spectroscopy… → NQF-M2



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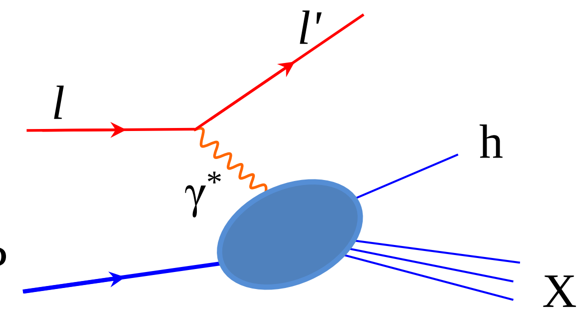
SIDIS x-section

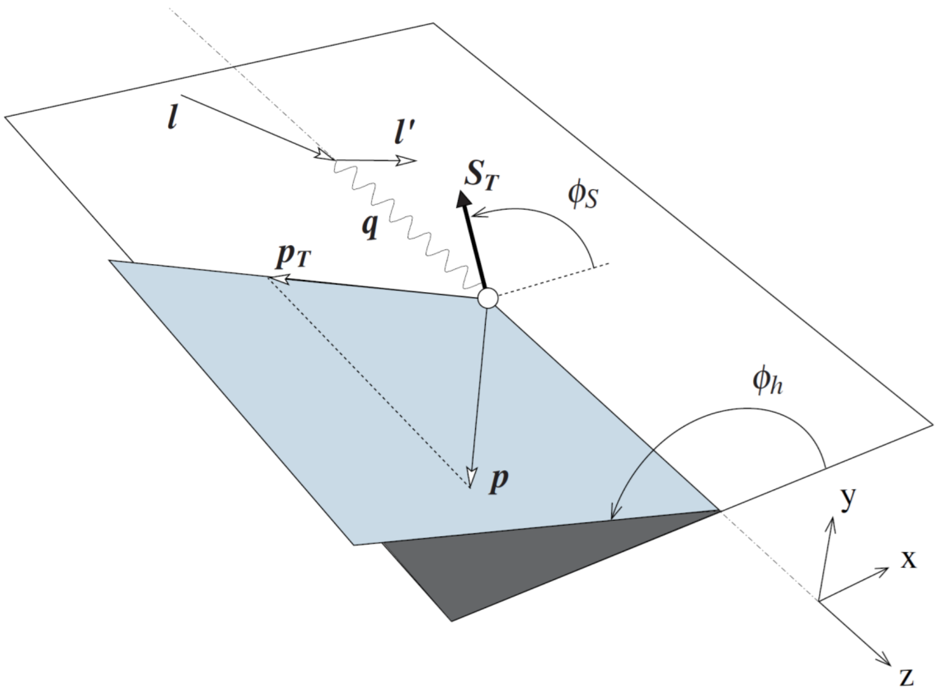
A.Kotzinian, Nucl. Phys. B441, 234 (1995).
Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel JHEP 0702:093 (2007).

All measured by COMPASS

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

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





$$A_{U(L),T}^{w(\varphi_h,\varphi_s)}=\frac{F_{U(L),T}^{w(\varphi_h,\varphi_s)}}{F_{UU,T}+\varepsilon F_{UU,L}};\quad \varepsilon=\frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2},\quad \gamma=\frac{2Mx}{Q}$$

SIDIS x-section

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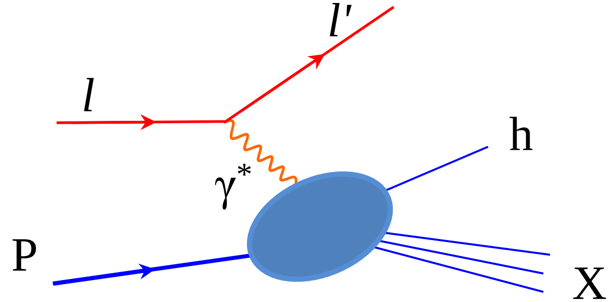
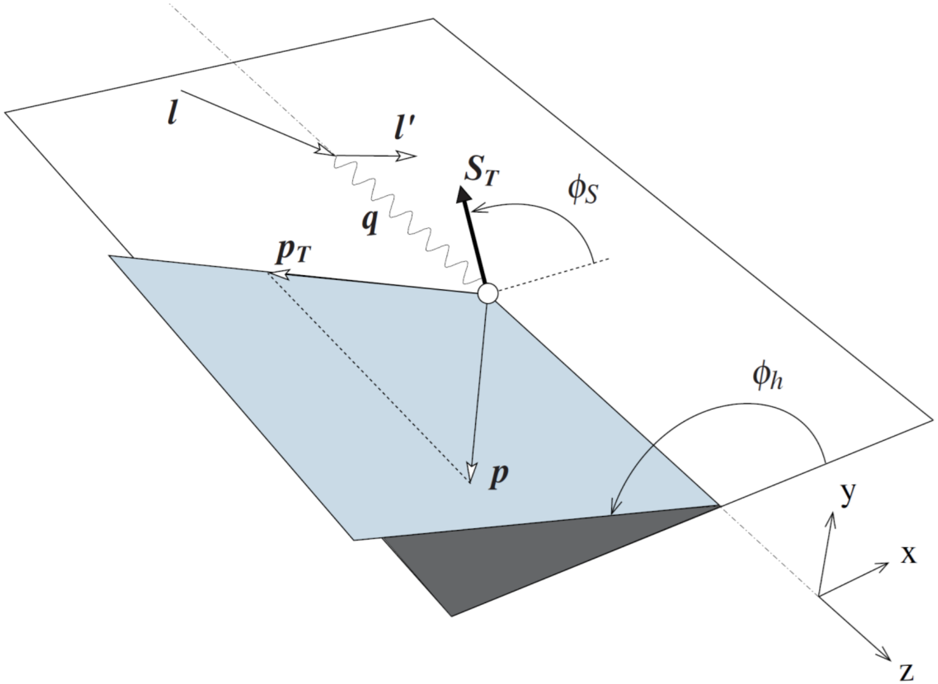
$$\times \left\{ \begin{array}{l} 1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\ + \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h \\ + S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h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





$$A_{U(L),T}^{w(\varphi_h,\varphi_s)} = \frac{F_{U(L),T}^{w(\varphi_h,\varphi_s)}}{F_{UU,T}+\varepsilon F_{UU,L}};\quad \varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2},\quad \gamma=\frac{2Mx}{Q}$$

SIDIS x-section and TMDs at twist-2

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

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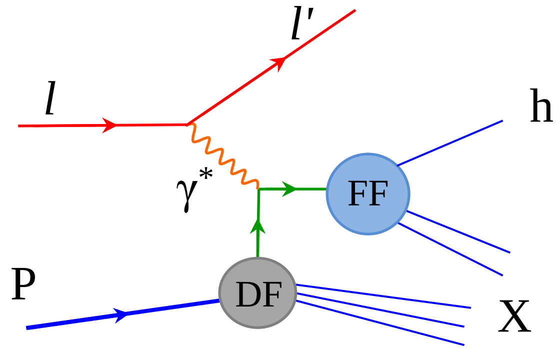
\end{aligned}$$

All measured by COMPASS



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 $H_{1q}^{\perp h}(z,P_\perp^2)$

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

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

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

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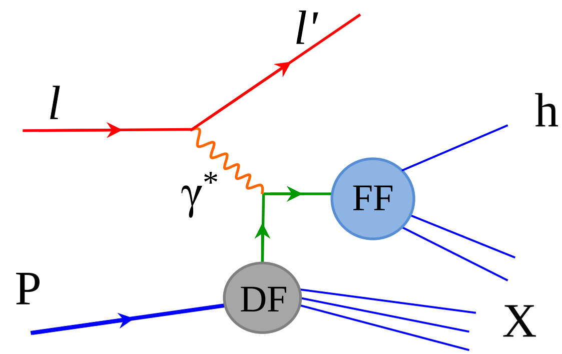
$$+ S_T\lambda\left[\begin{array}{l} \sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\ + \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\ + \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S) \end{array}\right]\Big\}$$



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

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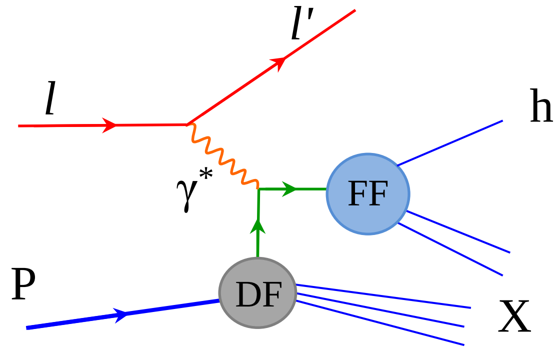

$$A_{UU}^{\cos\phi_h} \overset{WW}{\propto} Q^{-1}\left(f_1^q\otimes D_{1q}^h+h_1^{\perp q}\otimes H_{1q}^{\perp h}\ldots\right)$$

$$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q}\otimes H_{1q}^{\perp h}$$

$$A_{UL}^{\sin\phi_h} \overset{WW}{\propto} Q^{-1}\left(h_{1L}^{\perp q}\otimes H_{1q}^{\perp h}+\ldots\right)$$

$$A_{UL}^{\sin 2\phi_h} \propto h_{1L}^{\perp q}\otimes H_{1q}^{\perp h}$$

$$A_{LL} \propto g_{1L}^q\otimes D_{1q}^h$$

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

Twist-2

Twist-3

WW = Wandzura-Wilczek-type approximation"

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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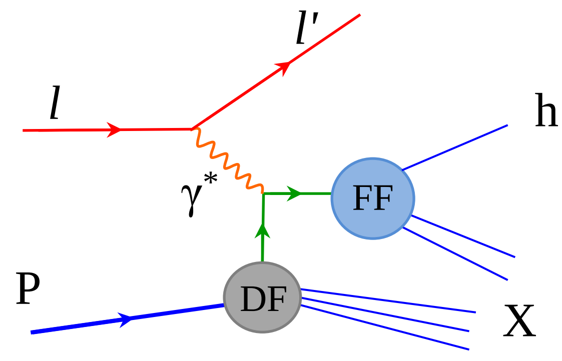
$$+ S_T\lambda\left[\begin{array}{l} \sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\ +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\ +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S) \end{array}\right]\Bigg\}$$



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

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

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

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

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

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

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

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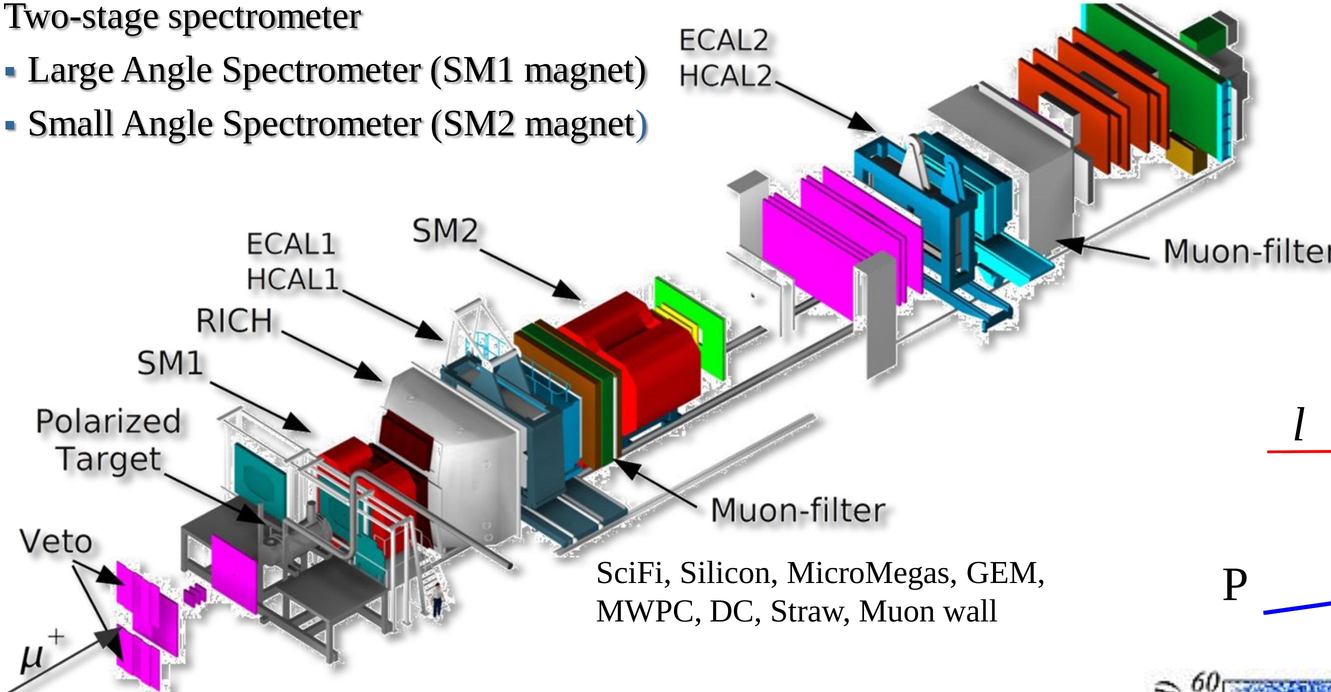
Twist-2

Twist-3

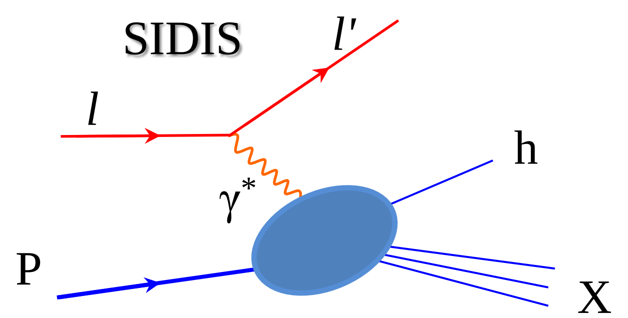
COMPASS experimental setup: Phase I (muon program)

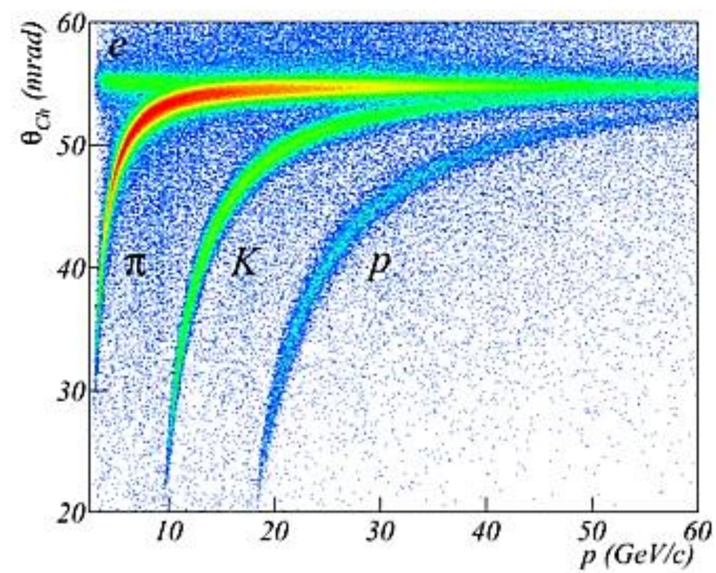
Two-stage spectrometer
- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)



SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon wall

- 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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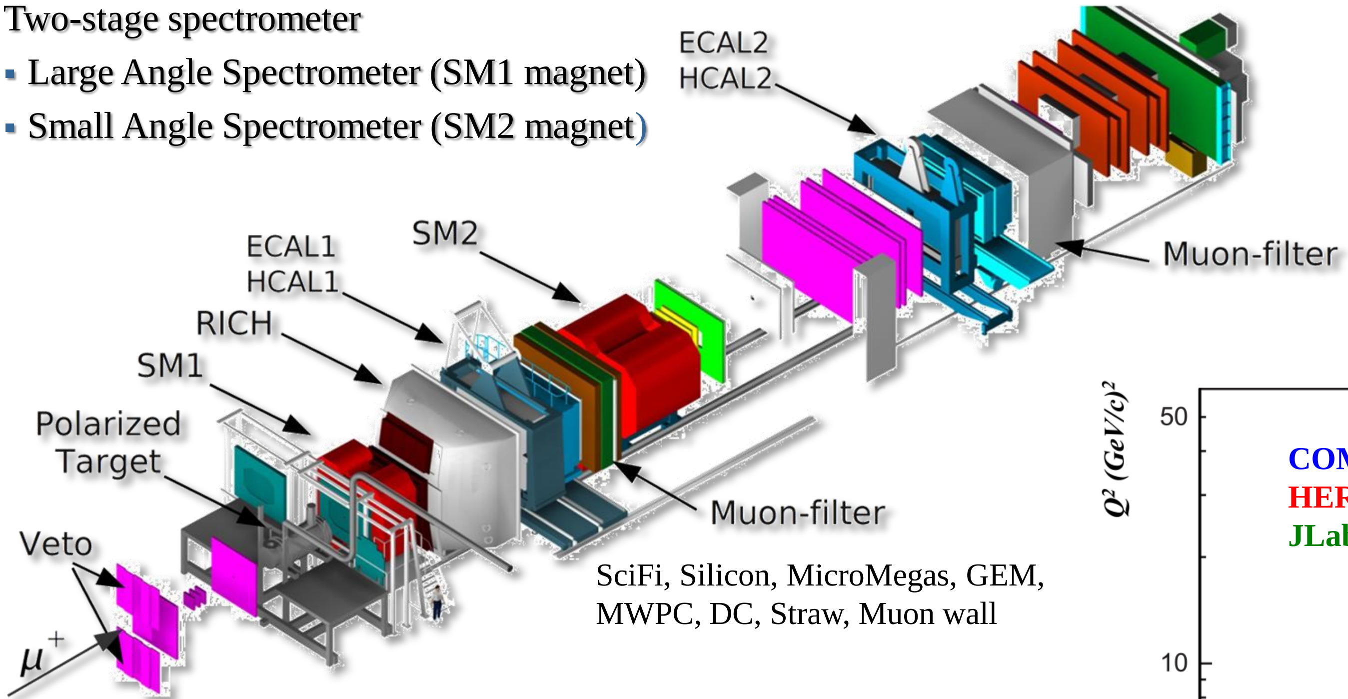

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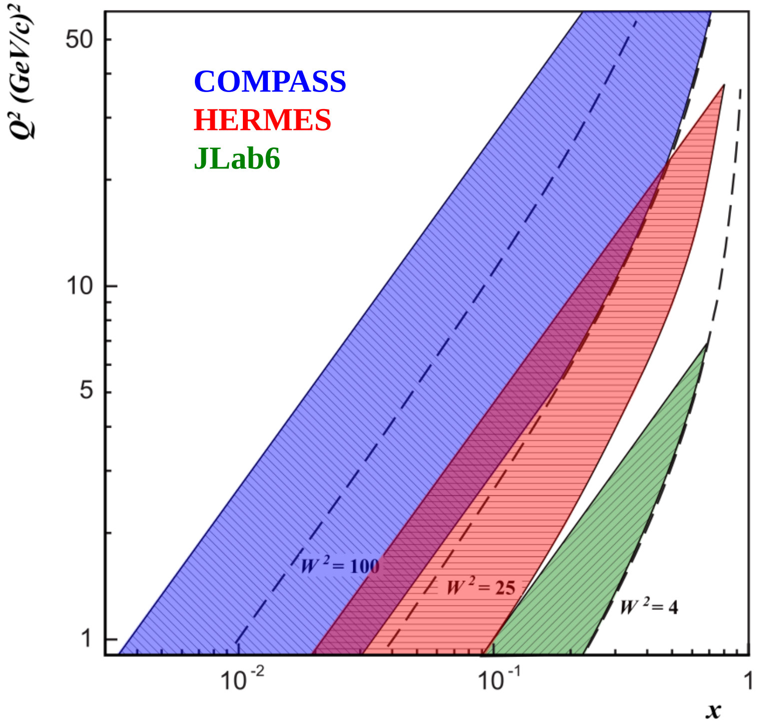

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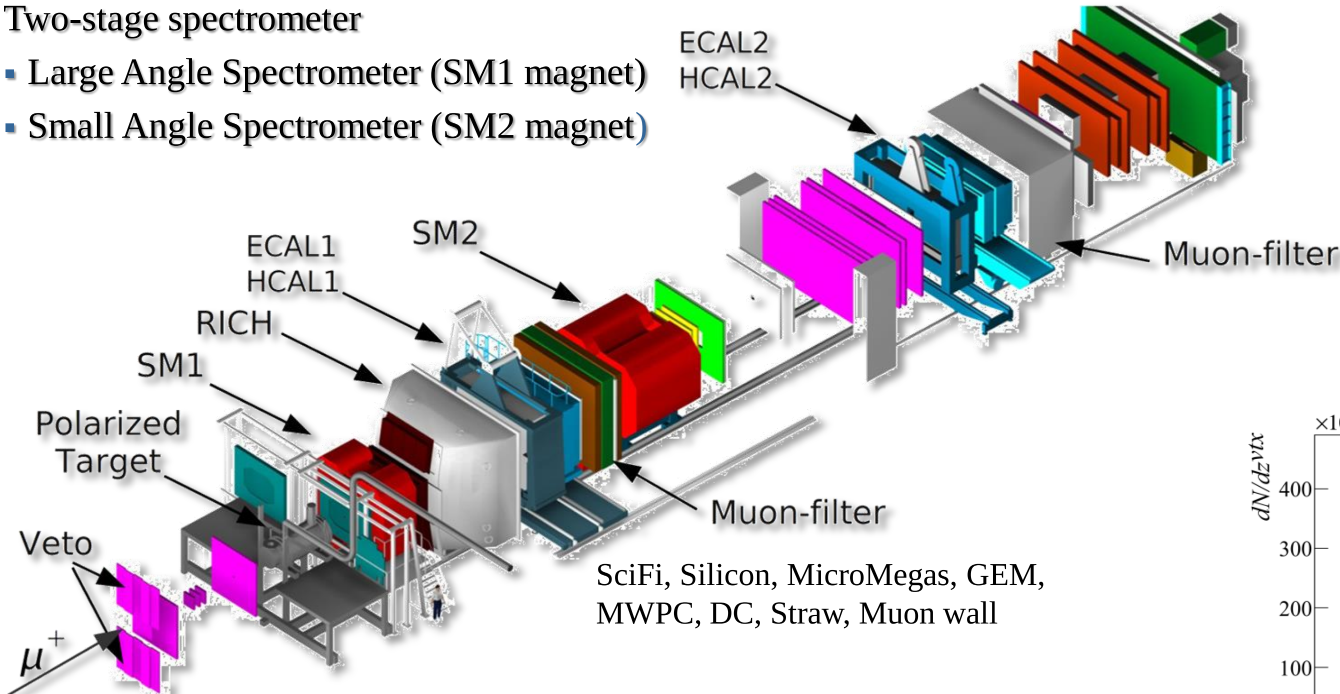

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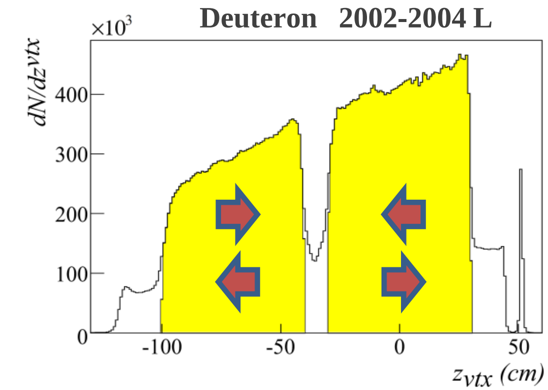
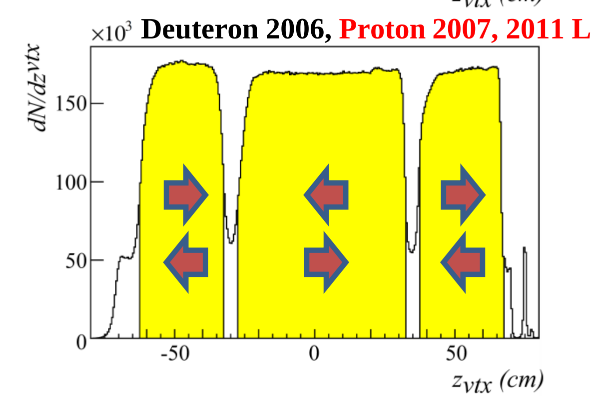
- Broad kinematical range
- Momentum, tracking and calorimetric measurements, PID





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 (*^{6}LiD 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
- Data is collected simultaneously with both target spin orientations. Periodic polarization reversal to minimize systematic effects

- Unpolarized azimuthal asymmetries (SIDIS)

SIDIS: Unpolarized azimuthal asymmetries

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

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

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

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xe^q H_{1q}^{\perp h} + \frac{M_h}{M} f_1^q \frac{\tilde{G}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xg^{\perp q} D_{1q}^h - \frac{M_h}{M} h_1^{\perp q}\frac{\tilde{E}_q^h}{z}\right)\right\}$$

SIDIS: Unpolarized azimuthal asymmetries

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

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

- Cahn-effect, R.N Cahn, PLB 78 (1978) - 40 years!
- Q-suppression, Various different “twist” ingredients
- Measurements at SLAC, CERN, DESY, JLab, Fermilab
- Large asymmetries for h^+, h^-
- Strong kinematic dependencies, multi-D extractions

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

- Boer-Mulders effect PRD 57 (1998) - 20years!
- Cahn-mechanism contributes at twist-4 level
- Sizable effect both for h^+, h^- production
- Strong kinematic dependencies, multi-D extractions

$$F_{LU}^{\sin\phi_h}=\frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xe^qH_{1q}^{\perp h}+\frac{M_h}{M}f_1^q\frac{\tilde{G}_q^{\perp h}}{z}\right)+\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xg^{\perp q}D_{1q}^h-\frac{M_h}{M}h_1^{\perp q}\frac{\tilde{E}_q^h}{z}\right)\right\}$$

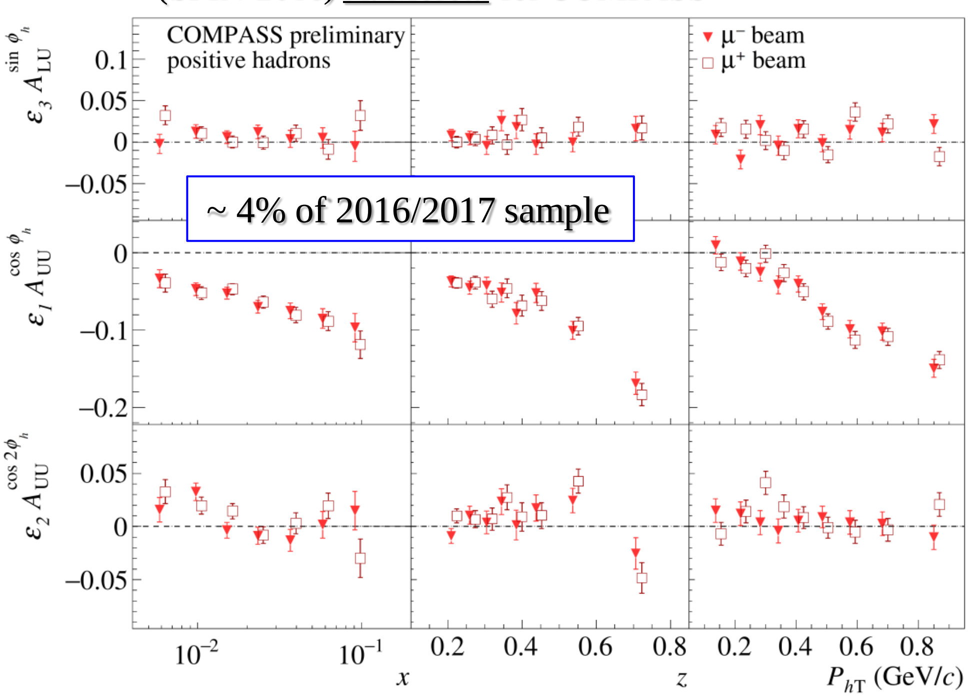
- Pure twist-3 effect, expected to be zero within WWA
- Measured by CLAS, HERMES, JLab, COMPASS
- Clear non zero effect

SIDIS: Unpolarized azimuthal asymmetries

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

- First preliminary proton results from COMPASS (2016-2017 DVCS-run) were presented at SPIN-2018
- Similarly strong kinematic dependences compared to published COMPASS-deuteron results

(SPIN-2018) A. Moretti for COMPASS

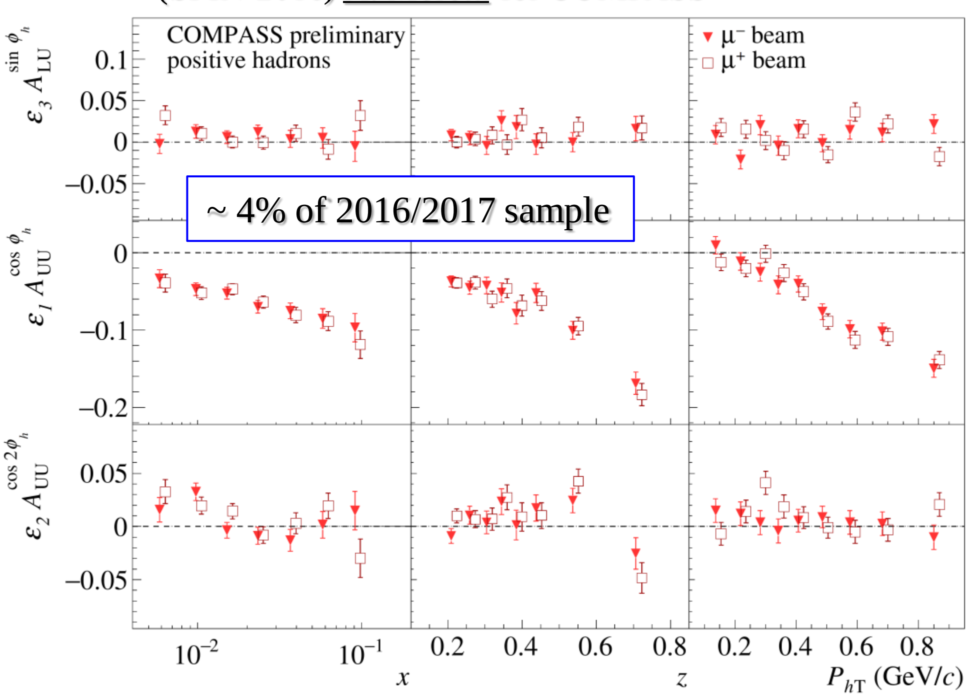


SIDIS: Unpolarized azimuthal asymmetries

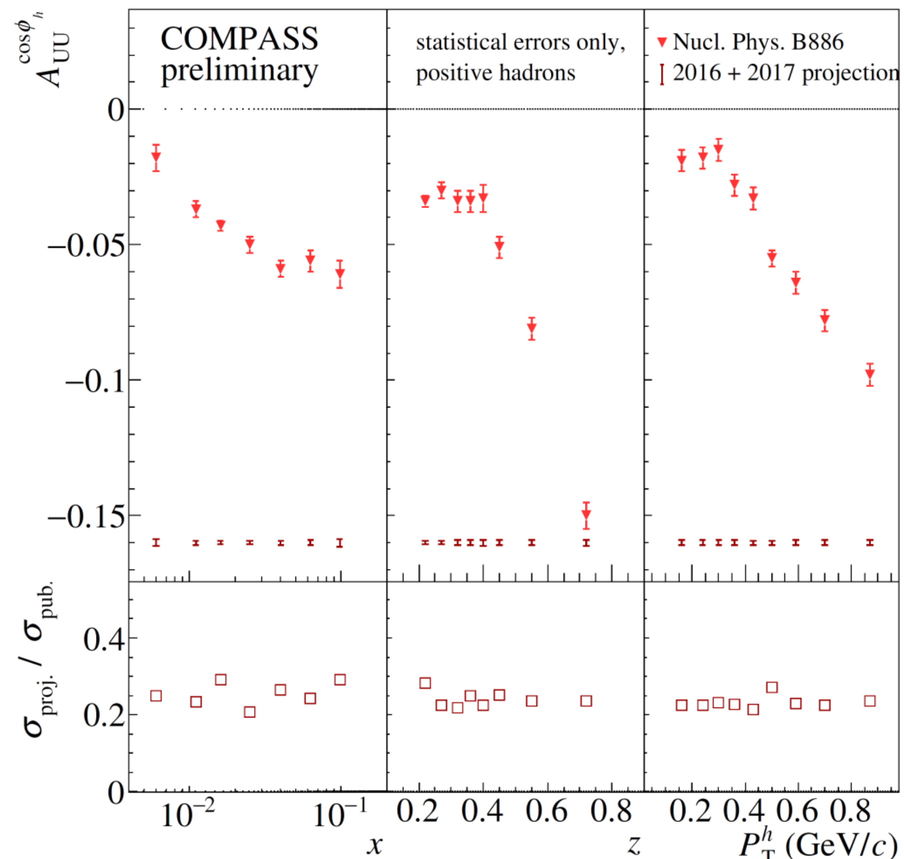
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + \lambda\sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h\right\}$$

- First preliminary proton results from COMPASS (2016-2017 DVCS-run) were presented at SPIN-2018
- Similarly strong kinematic dependences compared to published COMPASS-deuteron results
- Projected uncertainties for 2016+2017 sample are ~5 times smaller compared to published asymmetries
- Systematic errors are also expected to be considerably smaller

(SPIN-2018) A. Moretti for COMPASS



(SPIN-2018) A. Moretti for COMPASS

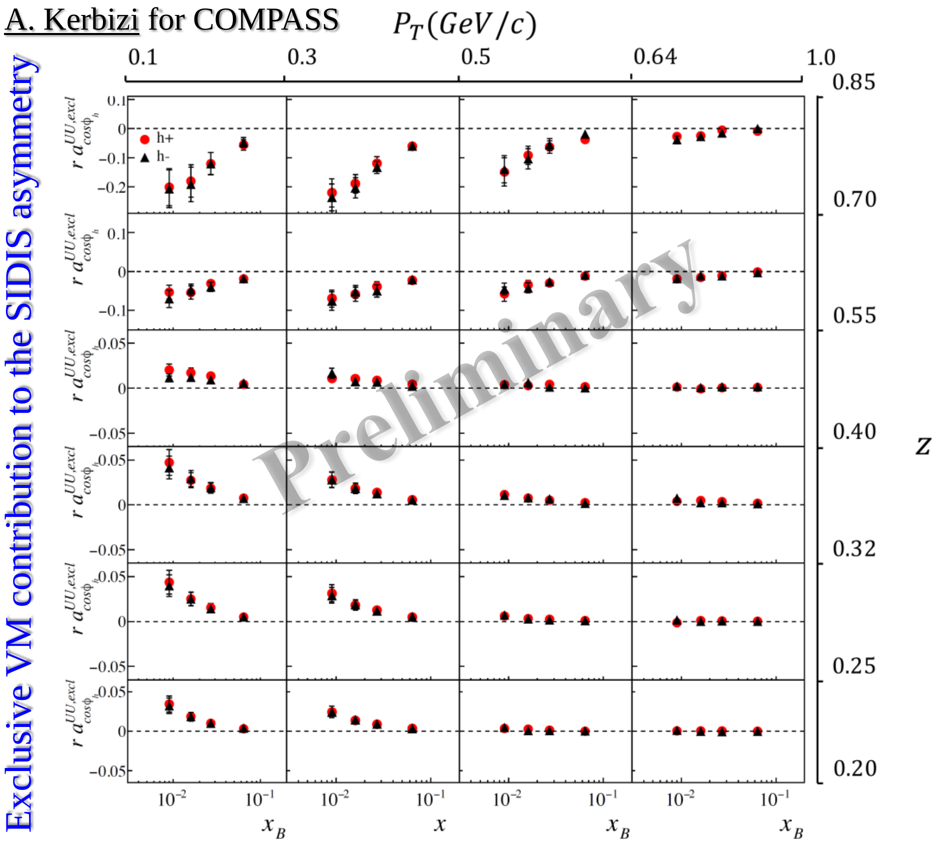


SIDIS: Unpolarized azimuthal asymmetries

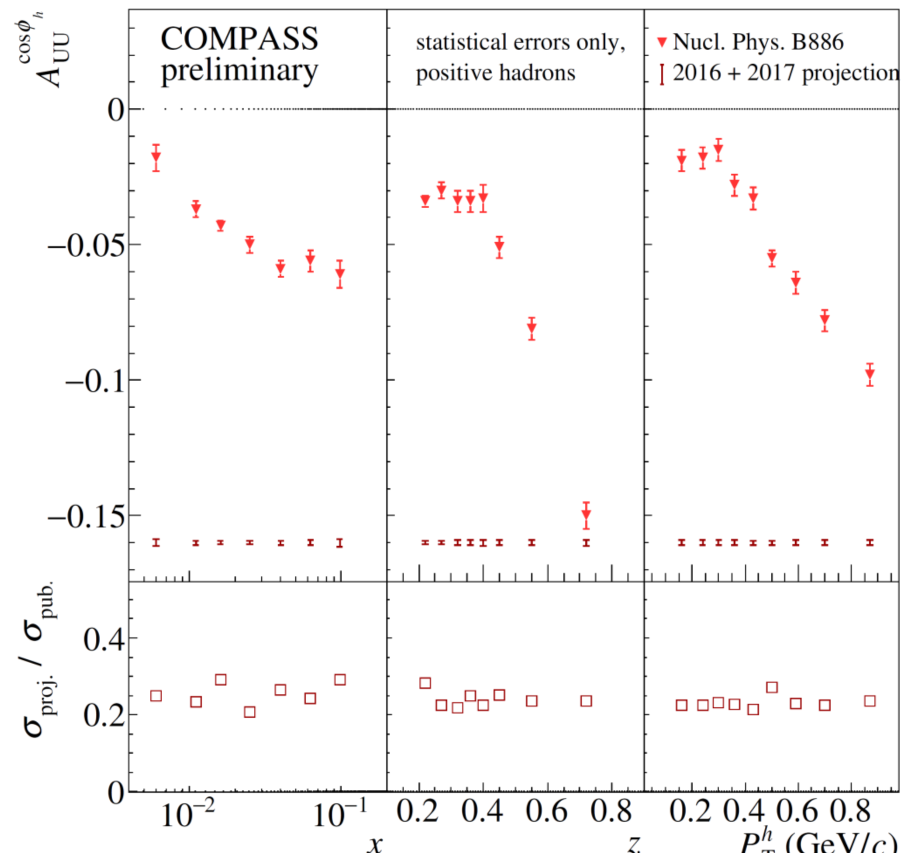
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + \lambda\sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h\right\}$$

- First preliminary proton results from COMPASS (2016-2017 DVCS-run) were presented at SPIN-2018
- Similarly strong kinematic dependences compared to published COMPASS-deuteron results
- Projected uncertainties for 2016+2017 sample are ~5 times smaller compared to published asymmetries
- Systematic errors are also expected to be considerably smaller
- Contribution from exclusive vector mesosns is sizably large (at small Q^2, large z and small P_T)

(SPIN-2018)
A. Kerbizi for COMPASS



(SPIN-2018) A. Moretti for COMPASS



- Longitudinal target spin dependent azimuthal asymmetries (SIDIS)

SIDIS: target longitudinal spin dependent asymmetries

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

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

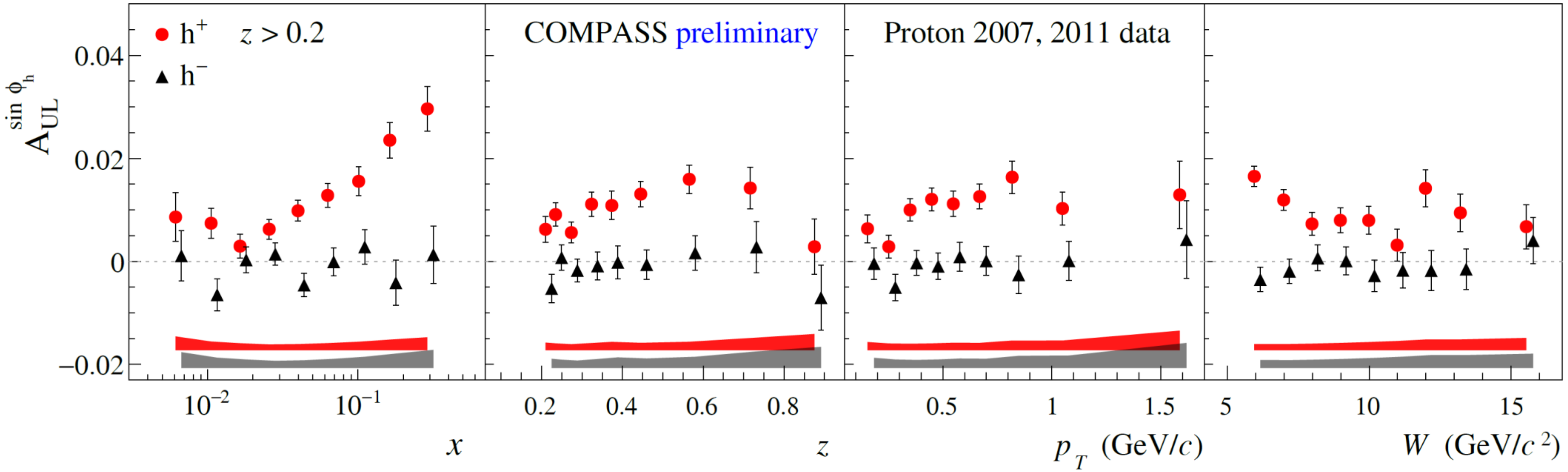
- Q-suppression, TSA-mixing
- Various different “twist” ingredients

SIDIS: target longitudinal spin dependent asymmetries

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

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

B.Parsamyan (for COMPASS) arXiv:1801.01488 [hep-ex] (DIS-2017)



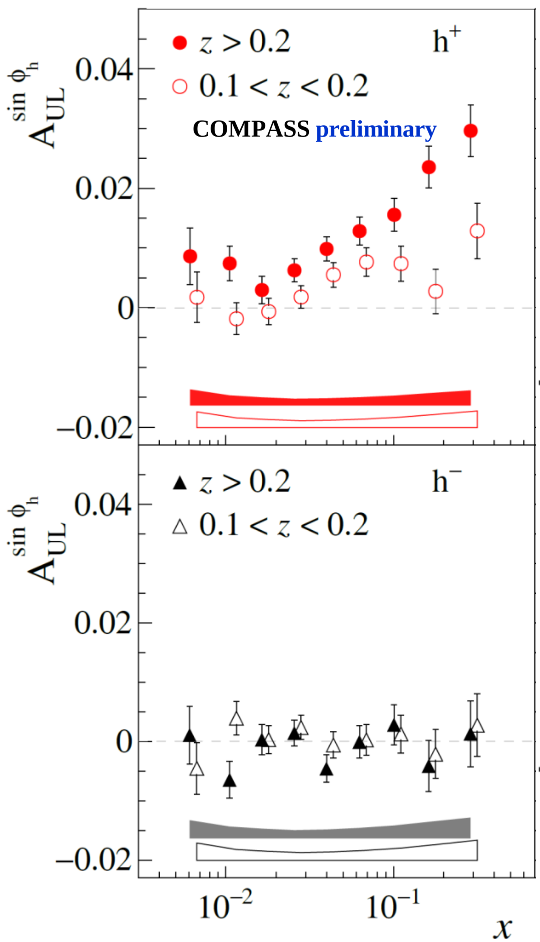
- Q-suppression, TSA-mixing
- Various different "twist" ingredients
- **Non-zero trend for h^+, h^- compatible with zero**

SIDIS: target longitudinal spin dependent asymmetries

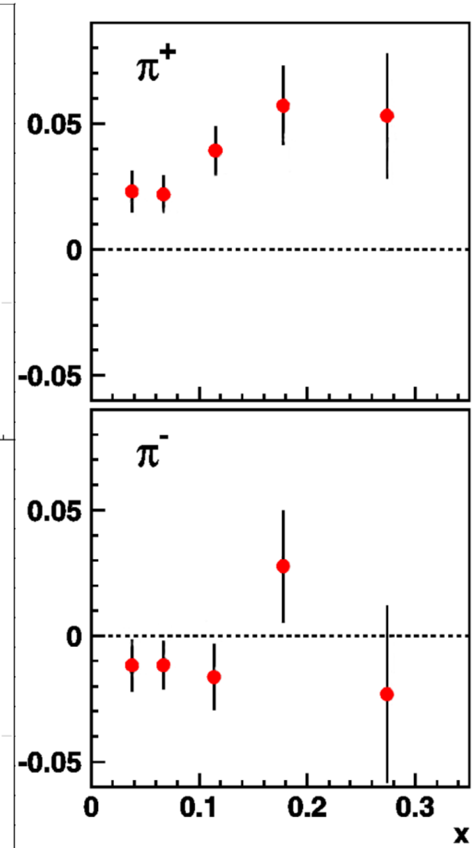
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \sqrt{2\varepsilon(1+\varepsilon)}\,A_{UL}^{\sin\phi_h} \sin\phi_h + \ldots\right\}$$

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

Proton 2007+2011 data



HERMES PLB 622 (2005) 14

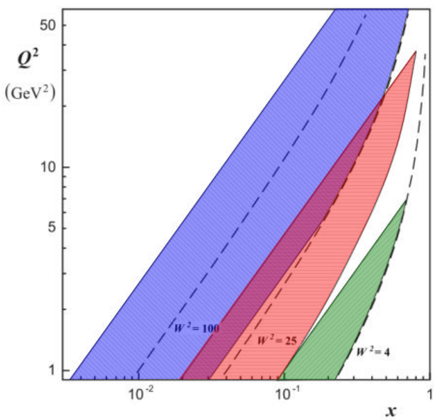


- Q-suppression, TSA-mixing
- Various different "twist" ingredients
- **Non-zero trend for h^+, h^- compatible with zero, clear *z*-dependence**

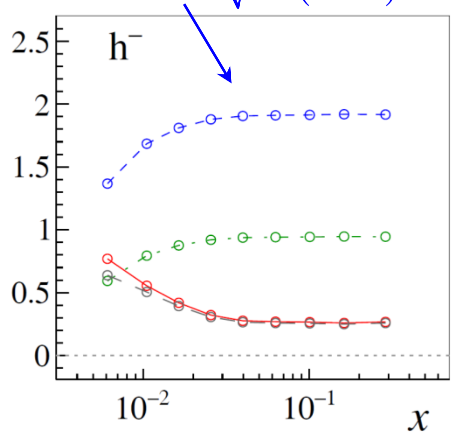
SIDIS: target longitudinal spin dependent asymmetries

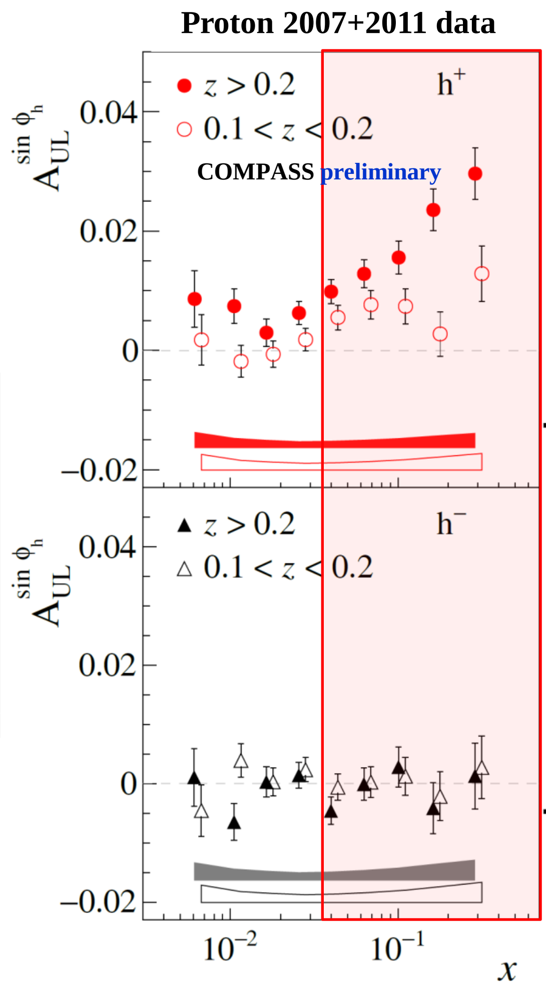
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \ldots\right\}$$

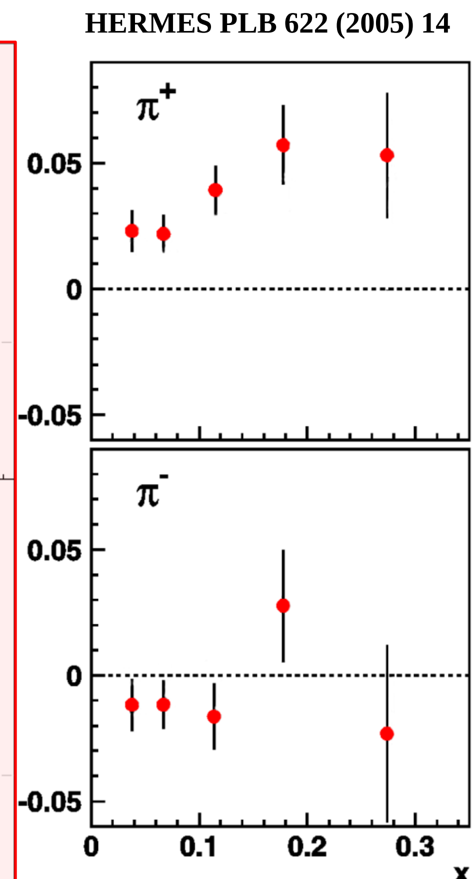
$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(x h_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(x f_L^{\perp q} D_{1q}^h - \frac{M_h}{M}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



$$D^{\sin(\phi_h)} = \sqrt{2\varepsilon(1+\varepsilon)}$$







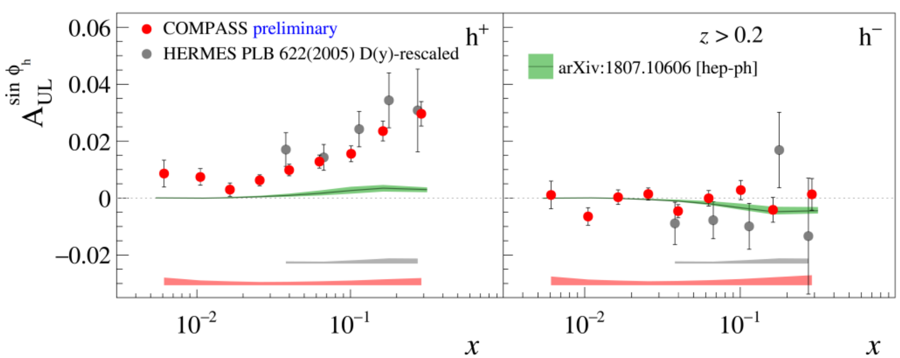
- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- **Non-zero trend for h⁺, h⁻ compatible with zero, clear z-dependence**

SIDIS: target longitudinal spin dependent asymmetries

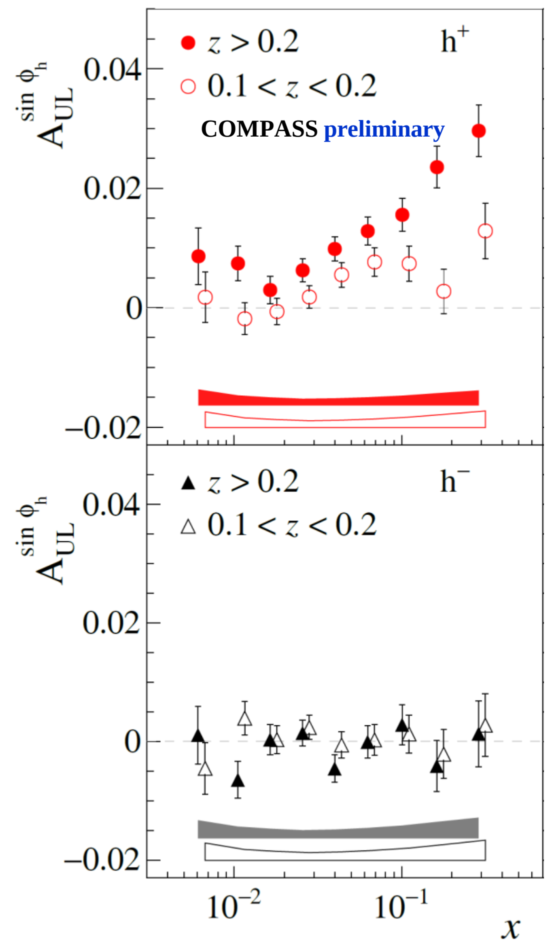
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \sqrt{2\varepsilon(1+\varepsilon)}\,A_{UL}^{\sin\phi_h} \sin\phi_h + \ldots\right\}$$

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

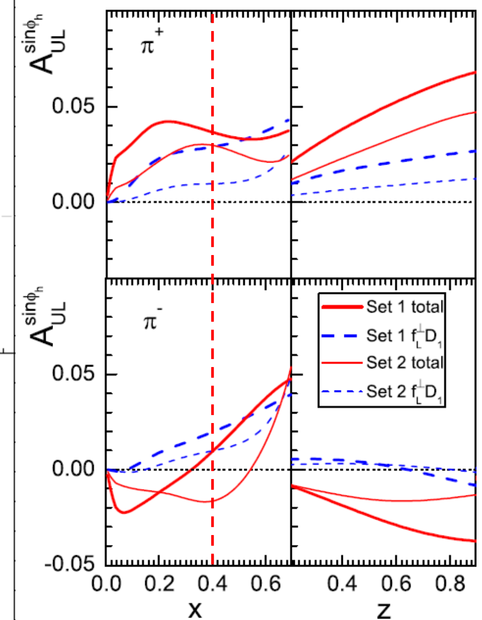
S. Bastami, H. Avakian, A. V. Efremov, A. Kotzinian, B. U. Musch, B. Parsamyan, A. Prokudin, M. Schlegel, G. Schnell, P. Schweitzer, W. Vogelsang *"SIDIS in Wandzura-Wilczek-type approximation"* - arXiv:1807.10606 [hep-ph]



Proton 2007+2011 data



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

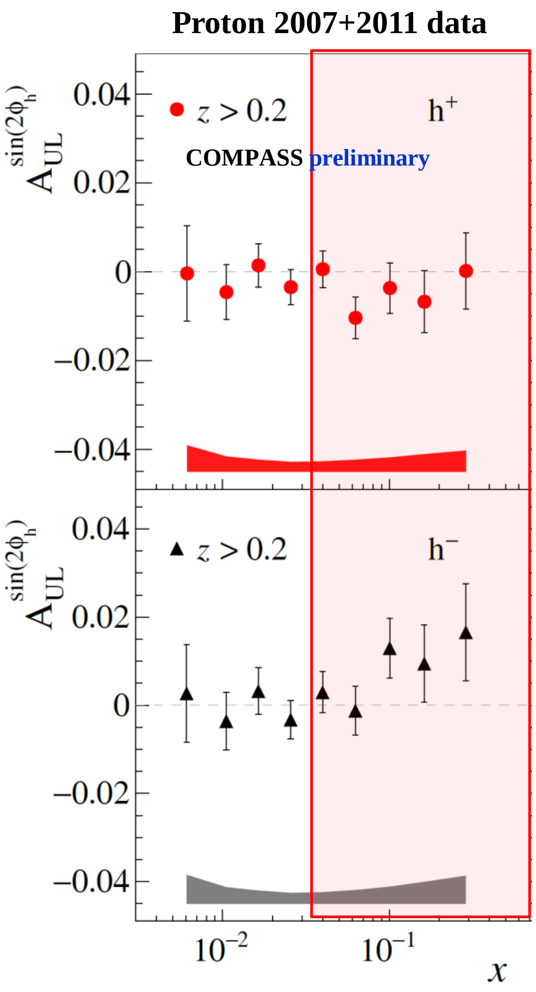


- Q-suppression, TSA-mixing
- Various different "twist" ingredients
- **Non-zero trend for h^+, h^- compatible with zero, clear z-dependence**

SIDIS: target longitudinal spin dependent asymmetries

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

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

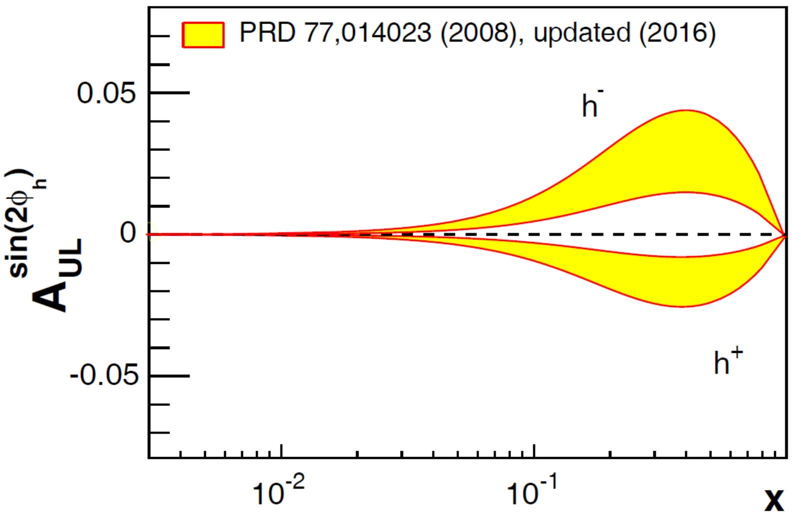


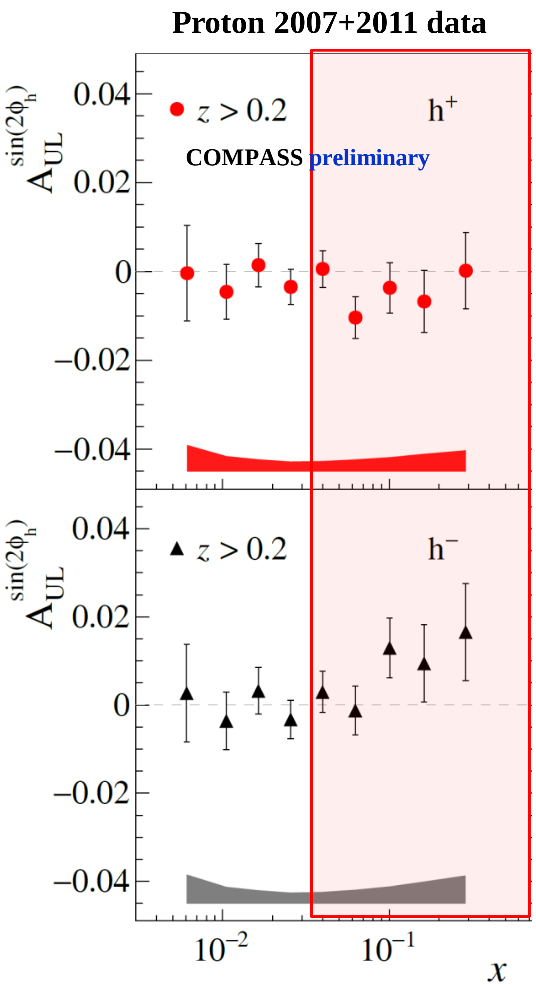
- Only “twist-2” ingredients
- Additional p_T-suppression
- **Collins-like behavior?**
- **In agreement with model predictions**

SIDIS: target longitudinal spin dependent asymmetries

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

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



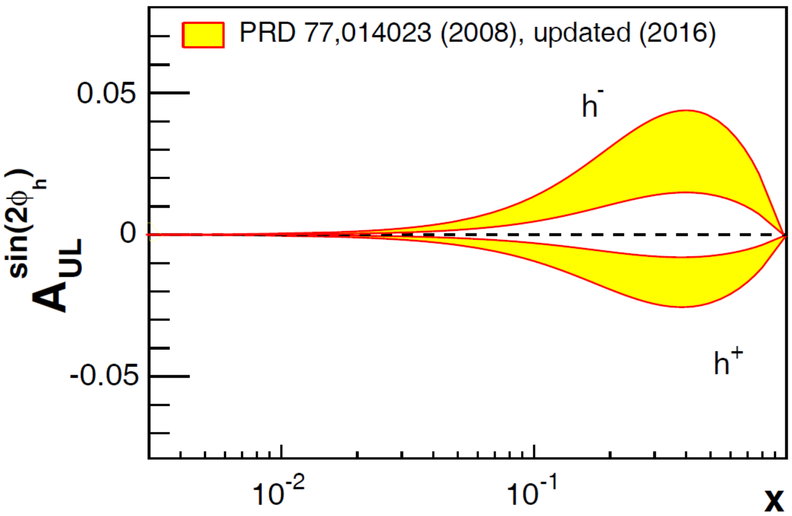


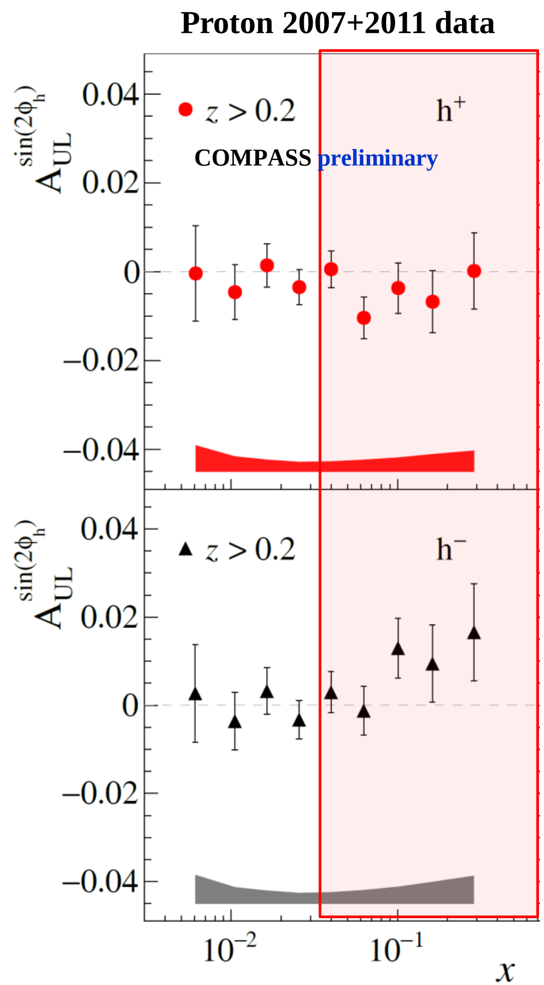
- Only "twist-2" ingredients
- Additional p_T-suppression
- **Collins-like behavior?**
- **In agreement with model predictions**

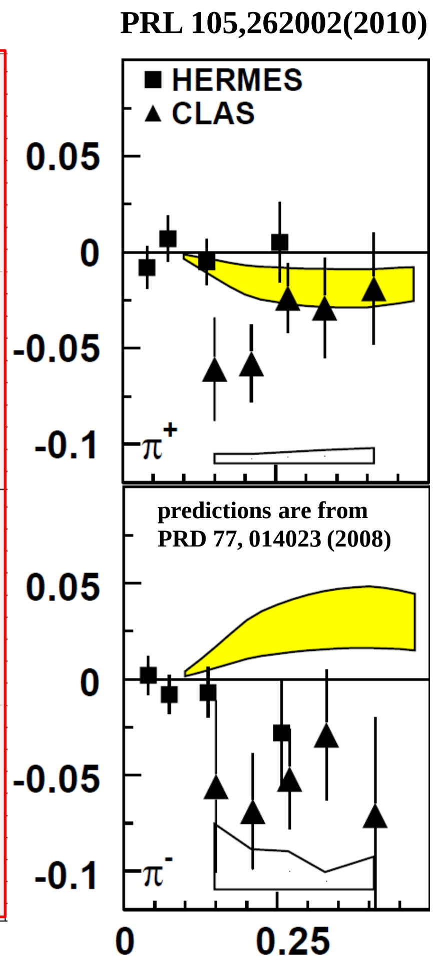
SIDIS: target longitudinal spin dependent asymmetries

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

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





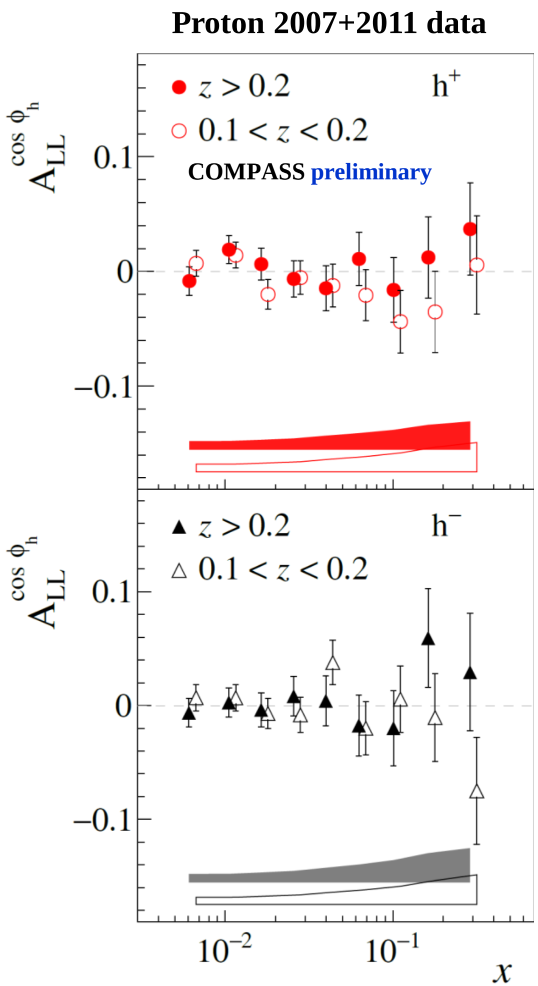


- Only “twist-2” ingredients
- Additional p_T-suppression
- **Collins-like behavior?**
- **In agreement with model predictions**
- **Discrepancy with HERMES and JLab?**

SIDIS: target longitudinal spin dependent asymmetries

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

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



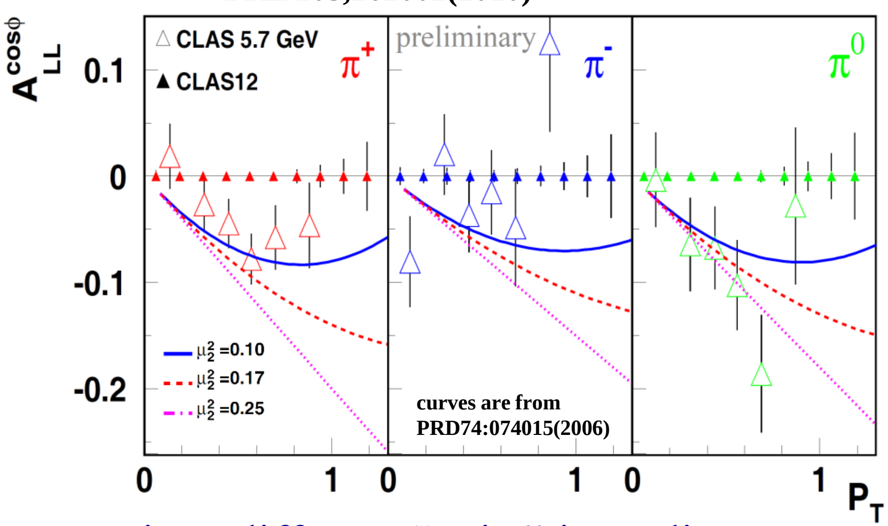
- Various different “twist” ingredients,
- Q-suppression

SIDIS: target longitudinal spin dependent asymmetries

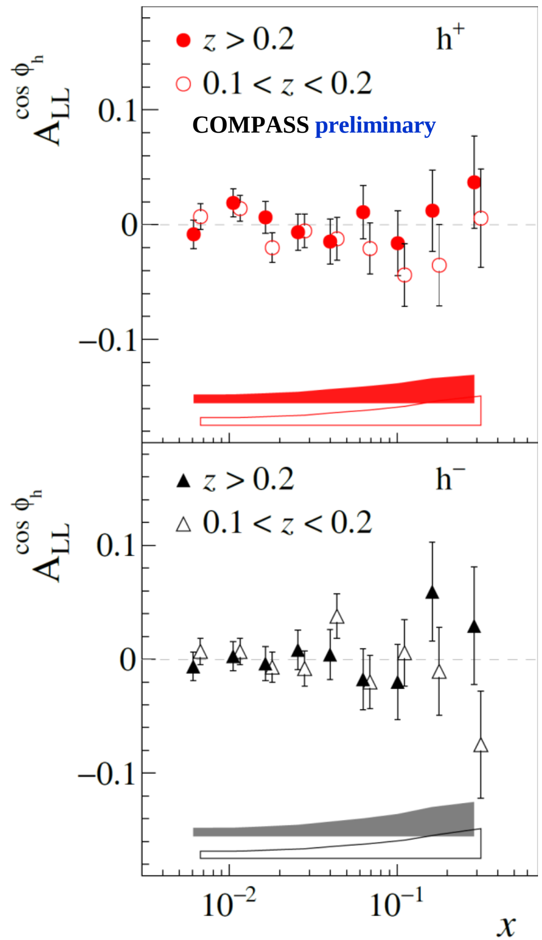
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \lambda \sqrt{2\varepsilon(1-\varepsilon)}\, A_{LL}^{\cos\phi_h} \cos\phi_h + \ldots \right\}$$

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

PRL 105,262002(2010)



Proton 2007+2011 data



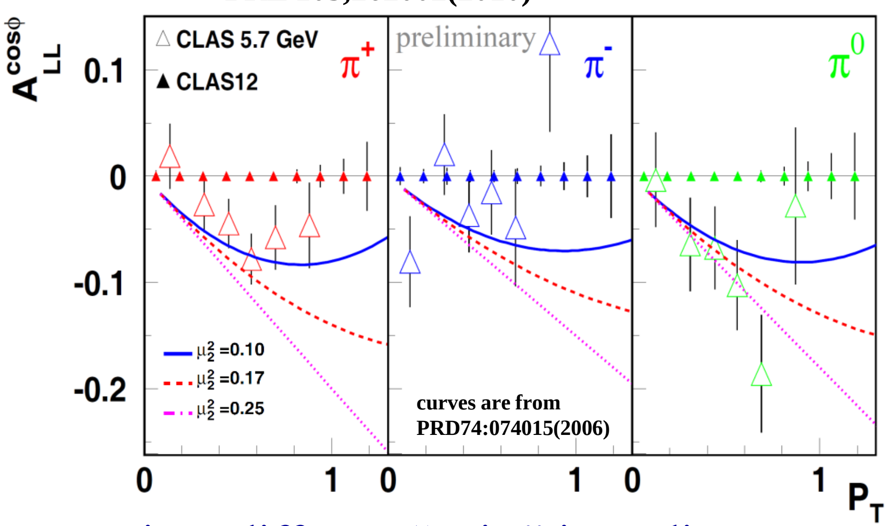
- Various different “twist” ingredients,
- Q-suppression
- Non zero at JLab

SIDIS: target longitudinal spin dependent asymmetries

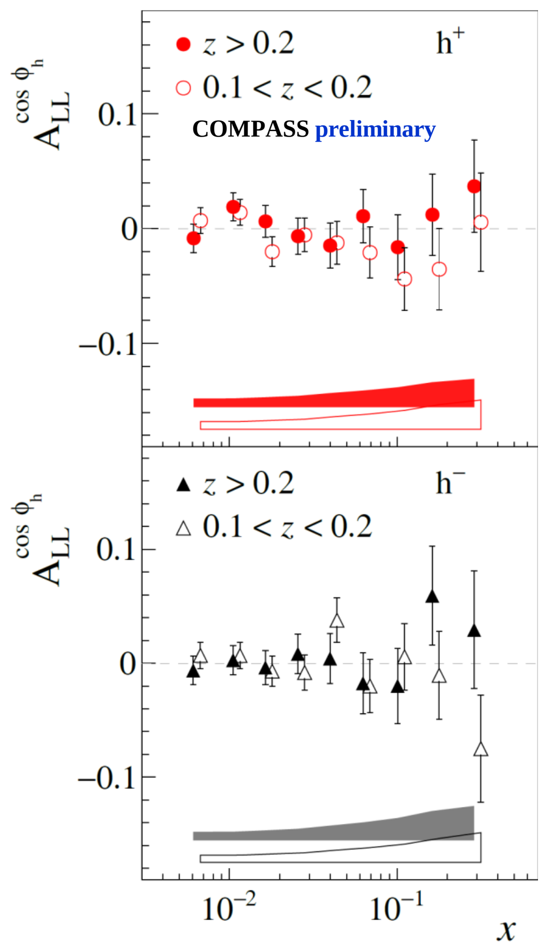
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1+\ldots+ S_L \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h + \ldots\right\}$$

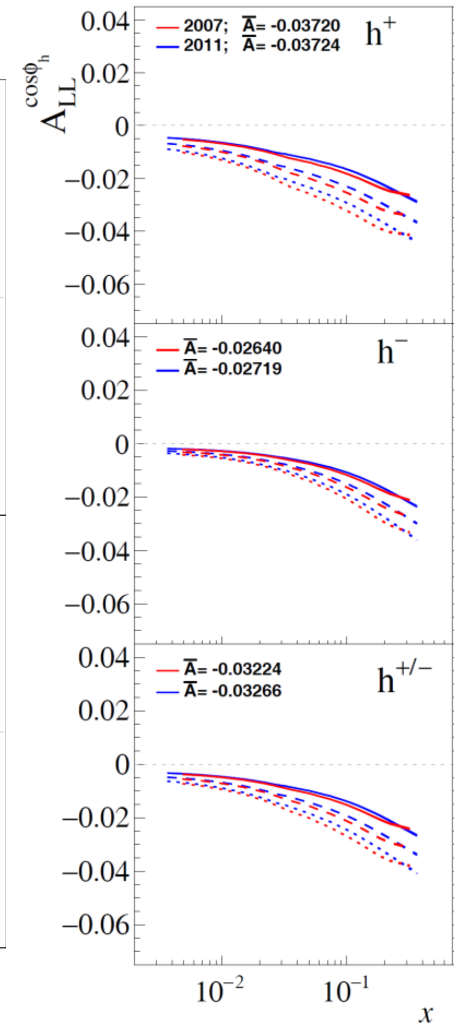
$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h}\left(xe_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{D}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\left(xg_L^{\perp q} D_{1q}^h - \frac{M_h}{M}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

PRL 105,262002(2010)



Proton 2007+2011 data



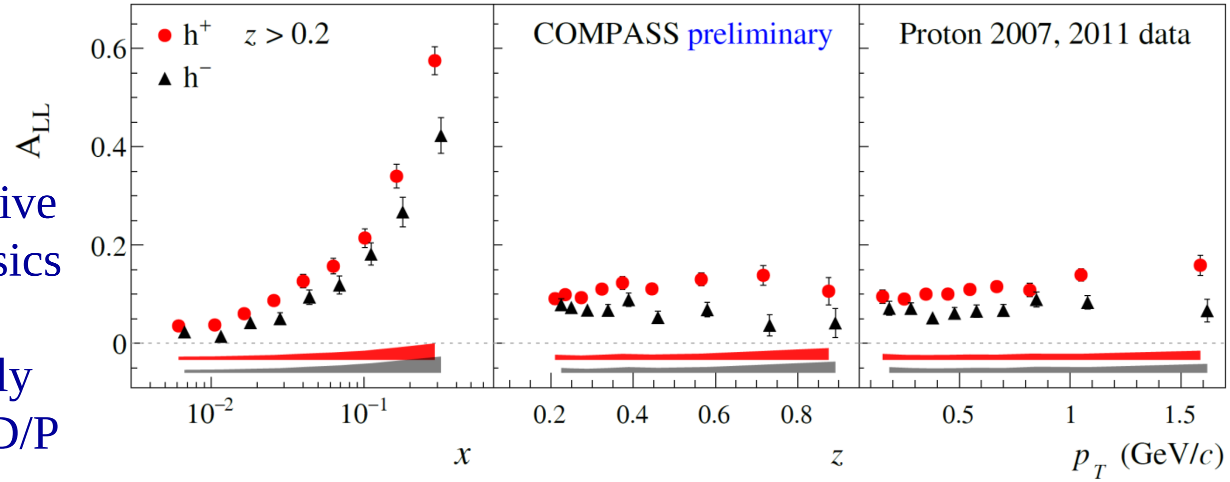


- Various different “twist” ingredients,
- Q-suppression
- Non zero at JLab
- **Small and compatible with zero, in agreement with model predictions**

SIDIS: target longitudinal spin dependent asymmetries

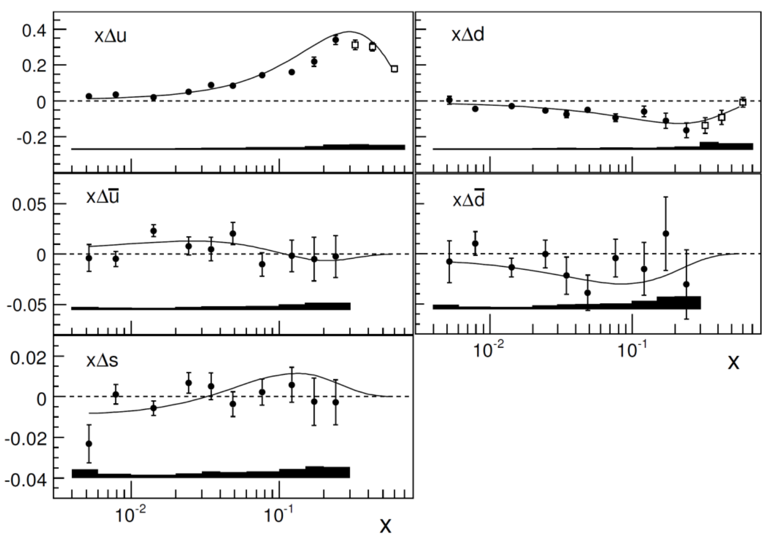
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL} + \ldots\right\}$$

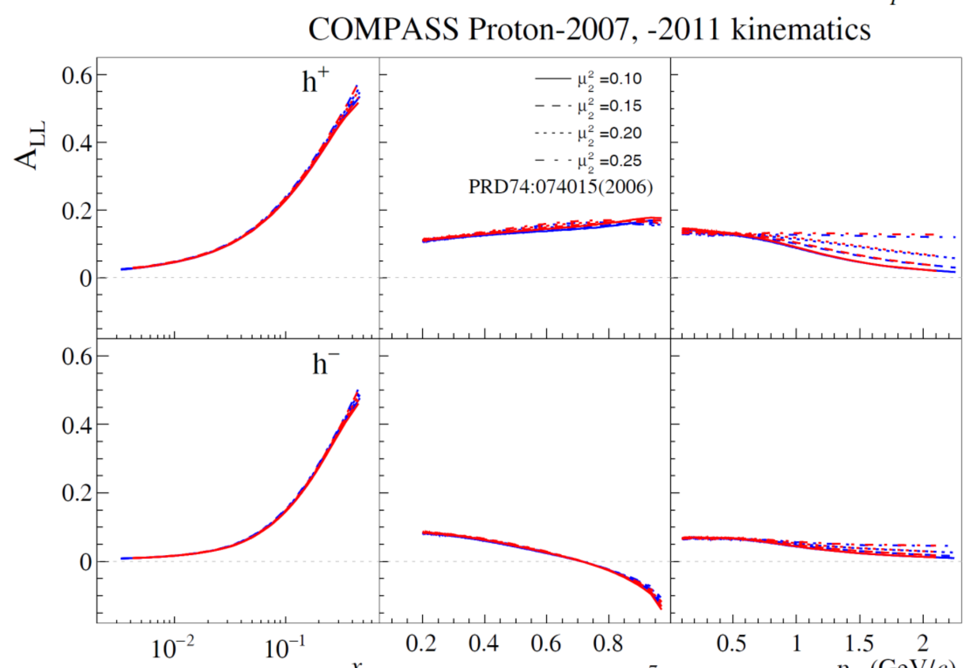
$$F_{LL}^{1} = \mathcal{C}\left\{g_{1L}^{q} D_{1q}^{h}\right\}$$



- Measurement of (semi-)inclusive $A_1(A_{LL})$ is one of the key physics topics of COMPASS
- Large amount of longitudinally polarized data collected with D/P targets (2002-2011)

PLB 693 (2010) 227–235





SIDIS: target longitudinal spin dependent asymmetries

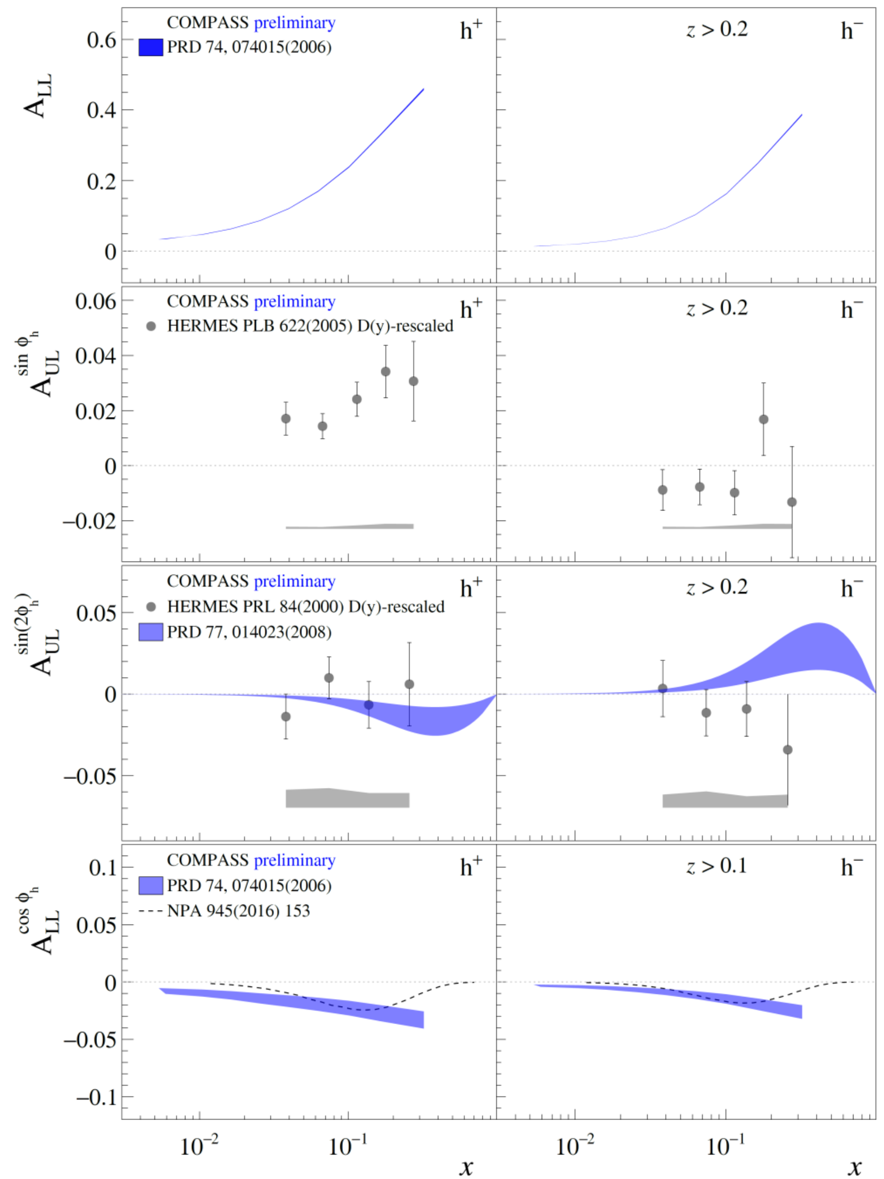
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\Bigg\{ 1+\ldots + S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] + S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\right]\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

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

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

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

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



SIDIS: target longitudinal spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{ 1+\ldots \right.$$
$$+\ S_L \left[\begin{array}{l} \sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h \\ +\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h \end{array}\right]$$
$$\left. +\ S_L\lambda \left[\begin{array}{l} \sqrt{1-\varepsilon^2}A_{LL} \\ +\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h \end{array}\right] \right\}$$

COMPASS collected large amount of L-SIDIS data

Unprecedented precision!

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

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

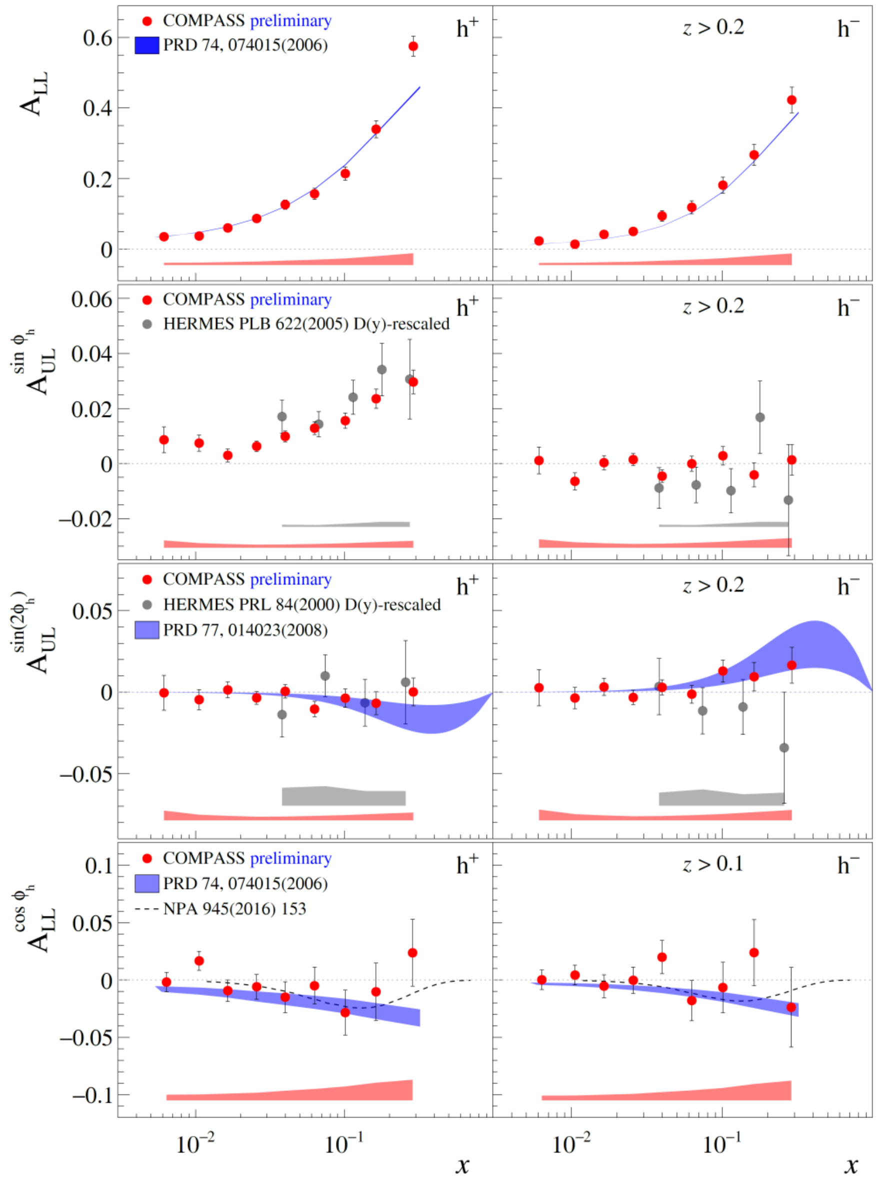
$A_{UL}^{\sin2\phi_h}$

- 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**

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

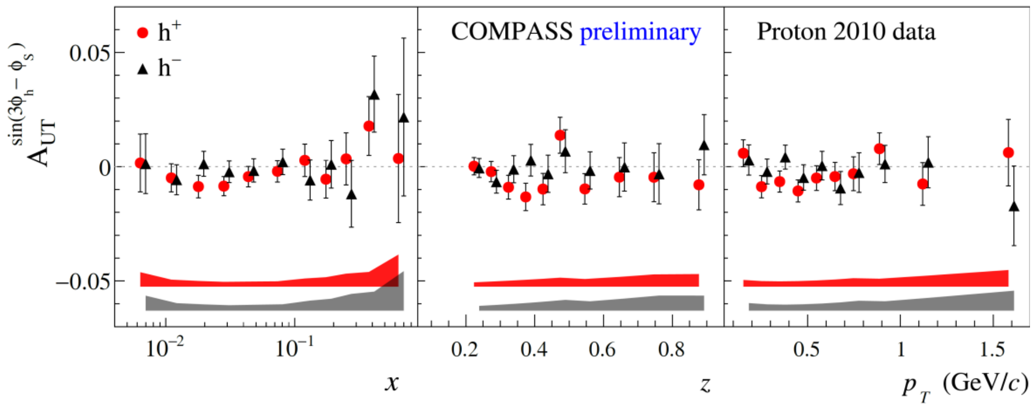


- Transverse target spin dependent azimuthal asymmetries (SIDIS)

SIDIS: target transverse spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{ 1+\ldots \right.$$
$$+ S_T\left[\begin{array}{l} +\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\ +\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\ +\ldots \end{array}\right]$$
$$\left. + S_T\lambda\left[\begin{array}{l} \sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\ +\ldots \end{array}\right]\right\}$$

B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



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

COMPASS results

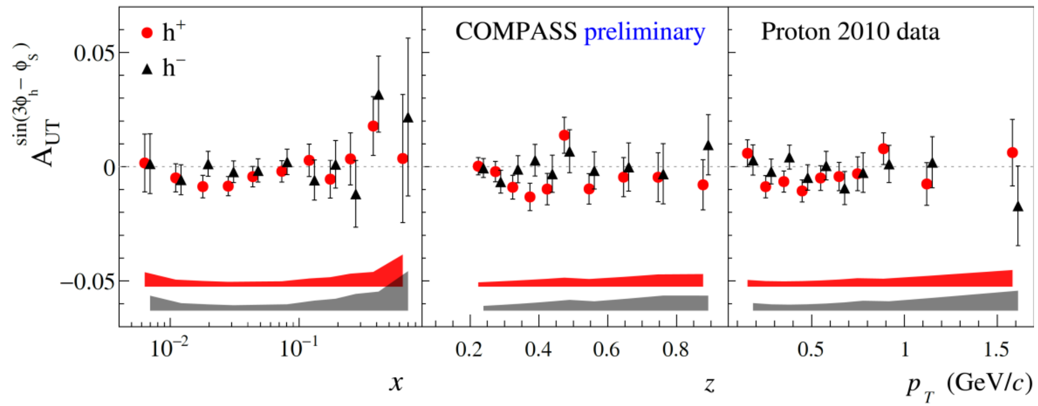
$A_{UT}^{\sin(3\phi_h-\phi_S)}$

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

SIDIS: target transverse spin dependent asymmetries

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

B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



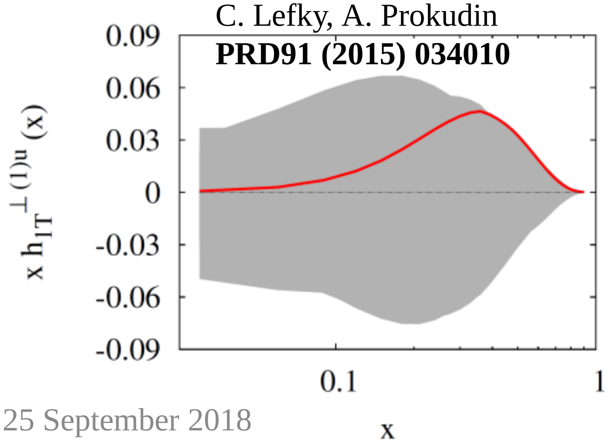
$$F_{UT}^{\sin(3\phi_h-\phi_S)} = C\left[\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)(\boldsymbol{k}_T\cdot\boldsymbol{p}_T) + \boldsymbol{k}_T^2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T) - 4(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)^2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)}{2M^2 M_h} h_{1T}^{\perp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

COMPASS results

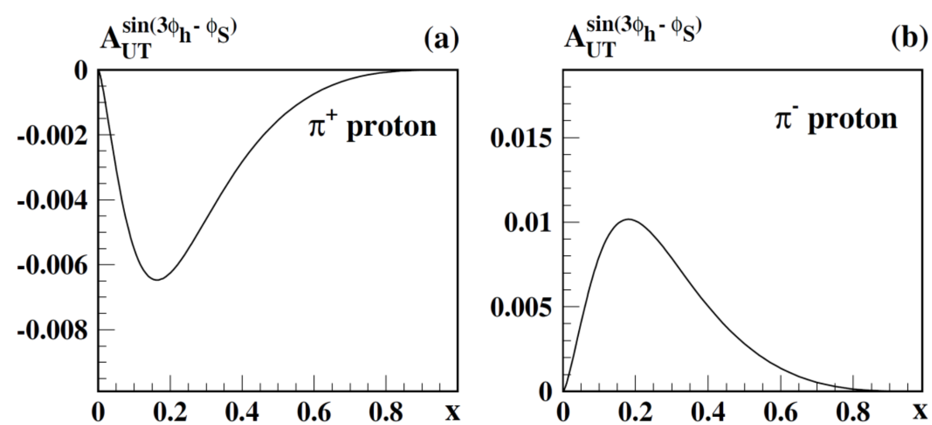
$A_{UT}^{\sin(3\phi_h-\phi_S)}$

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

C. Lefky, A. Prokudin
PRD91 (2015) 034010



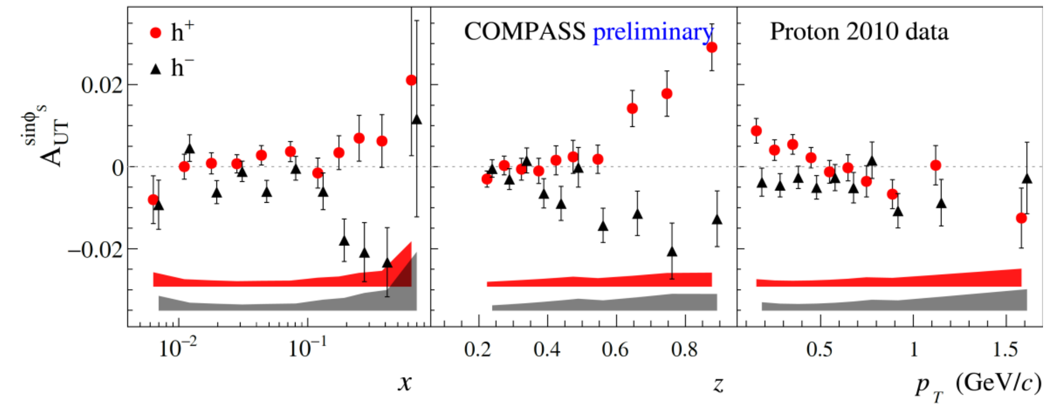
B. Pasquini, S. Boffi, A.V. Efremov, P. Schweitzer
arXiv:0912.1761 [hep-ph]



SIDIS: target transverse spin dependent asymmetries

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

B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042

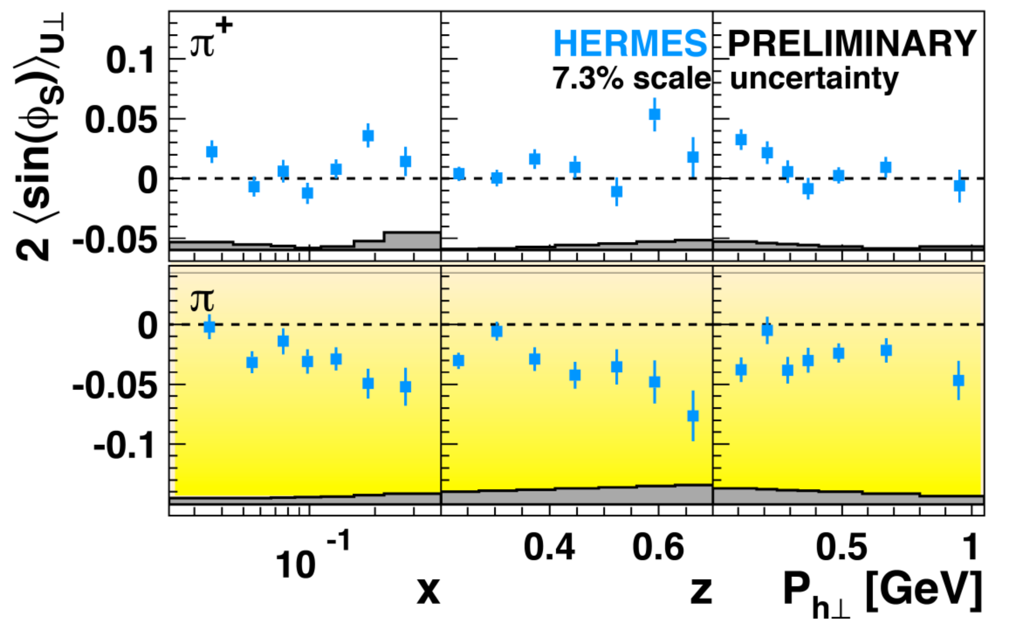


COMPASS results

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

- Q-suppression
- Various different "twist" ingredients
- Within WW is related to Sivers and Collins
- **Small asymmetry, non-zero signal for h⁻ ?**

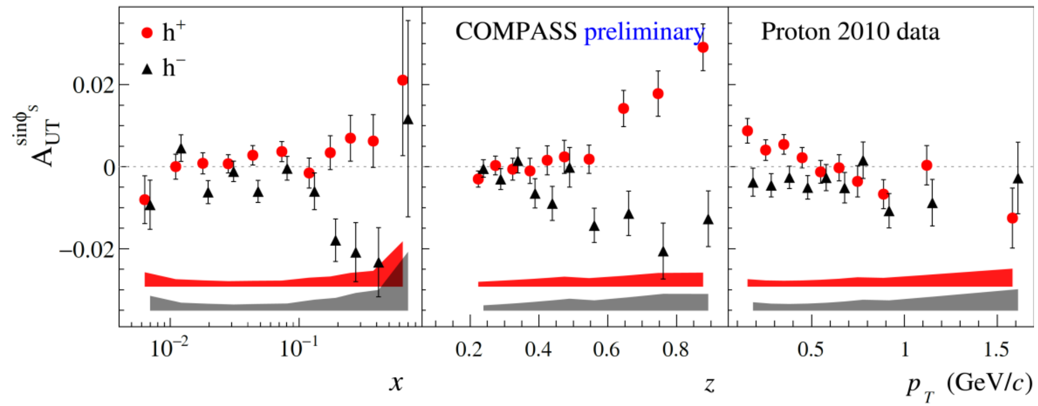
$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q} C \left\{ \left(x f_T^q D_{1q}^h - \frac{M_h}{M} h_1^q \frac{\tilde{H}_q^h}{z} \right) - \frac{\boldsymbol{p_T} \cdot \boldsymbol{k_T}}{2MM_h} \left[\left(x h_T^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1T}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) - \left(x h_T^{\perp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



SIDIS: target transverse spin dependent asymmetries

$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{ 1+\ldots \right.$$
$$+ S_T \left[+\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) + \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S + \ldots \right]$$
$$\left. + S_T\lambda \left[\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) + \ldots \right] \right\}$$

B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



COMPASS results

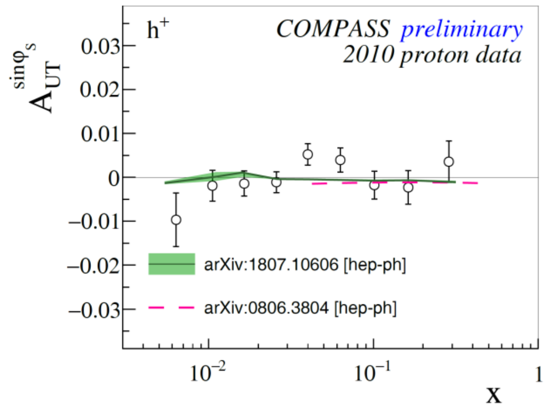
$A_{UT}^{\sin\phi_S}$

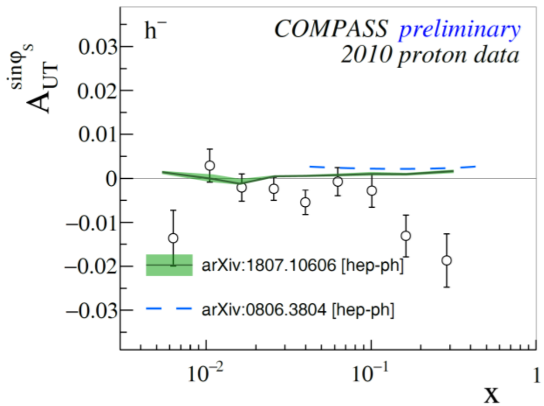
- Q-suppression
- Various different "twist" ingredients
- Within WW is related to Sivers and Collins
- **Small asymmetry, non-zero signal for h⁻?**

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

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

S. Bastami, H. Avakian, A. V. Efremov, A. Kotzinian, B. U. Musch, B. Parsamyan, A. Prokudin, M. Schlegel, G. Schnell, P. Schweitzer, W. Vogelsang
"SIDIS in Wandzura-Wilczek-type approximation" - arXiv:1807.10606 [hep-ph]

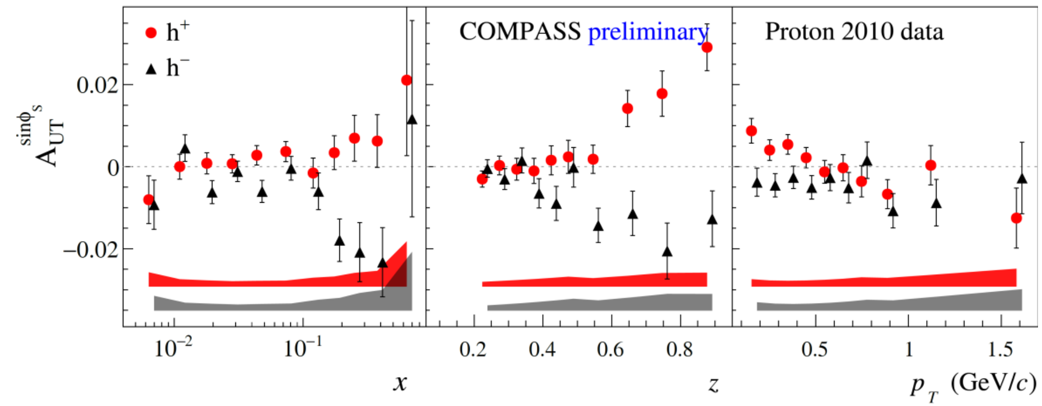




SIDIS: target transverse spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{ 1 + \dots \right.$$
$$+ S_T \left[\begin{array}{l} + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S \\ + \dots \end{array} \right]$$
$$\left. + S_T \lambda \left[\begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) \\ + \dots \end{array} \right] \right\}$$

B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042

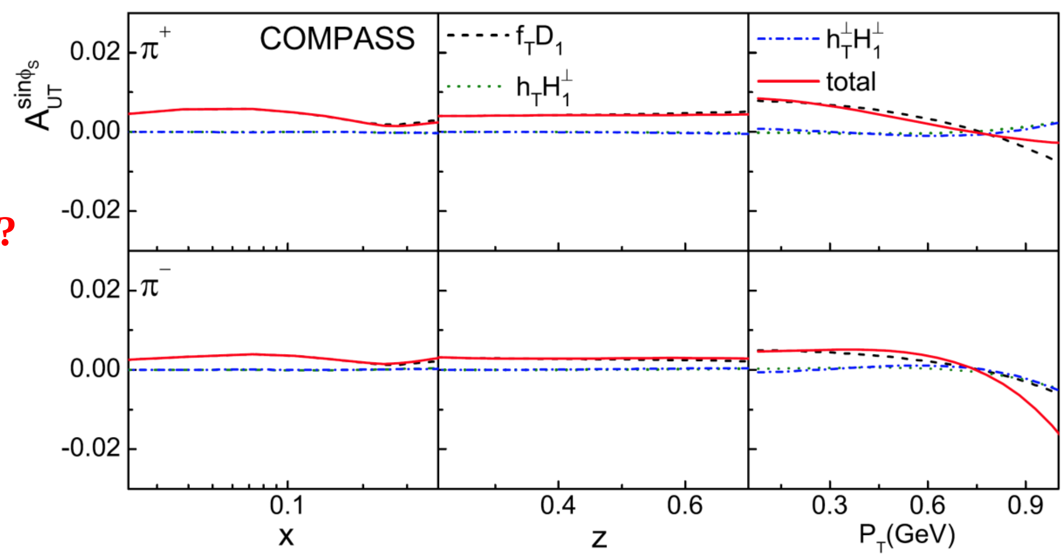


COMPASS results

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

- Q-suppression
- Various different "twist" ingredients
- Within WW is related to Sivers and Collins
- **Small asymmetry, non-zero signal for h⁻ ?**

W. Mao, Z. Lu and B.Q. Ma **Phys.Rev. D 90 (2014) 014048**



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

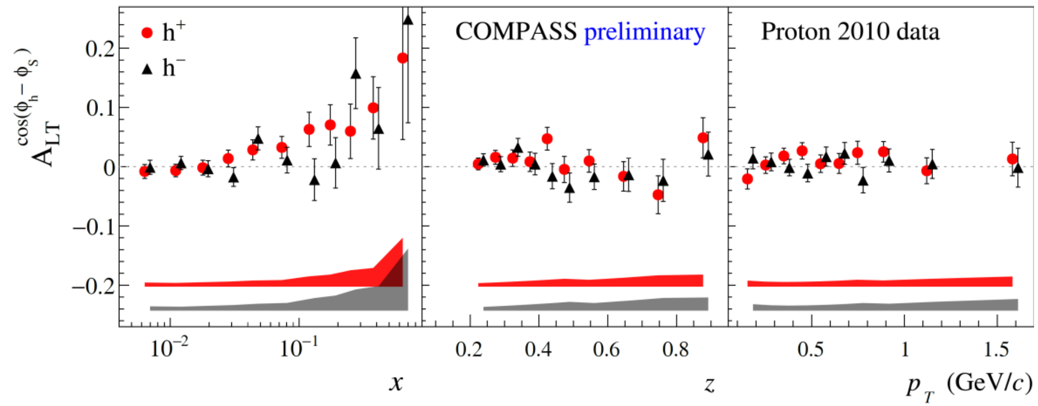
SIDIS: target transverse spin dependent asymmetries

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

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

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

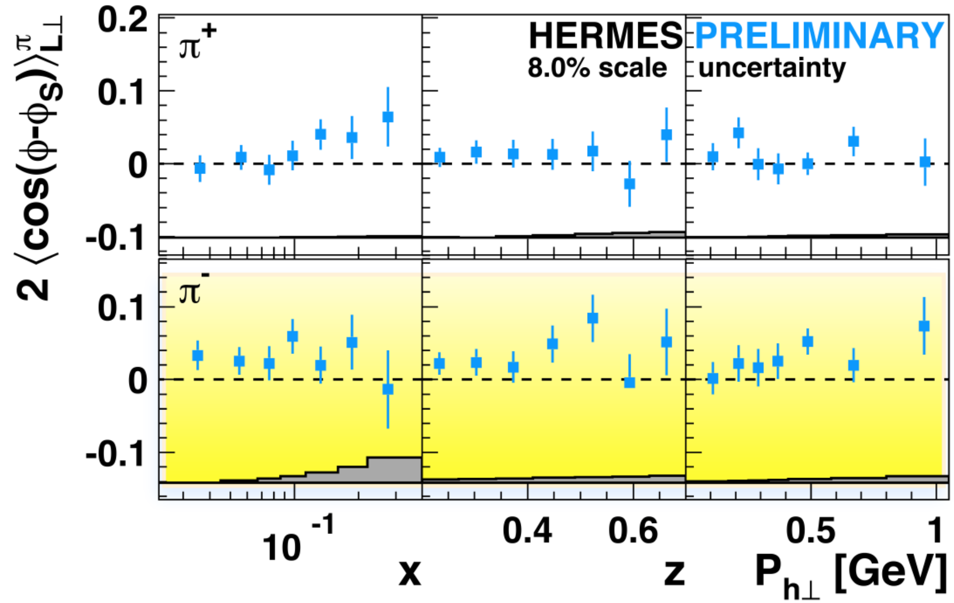
B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



COMPASS results

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

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



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

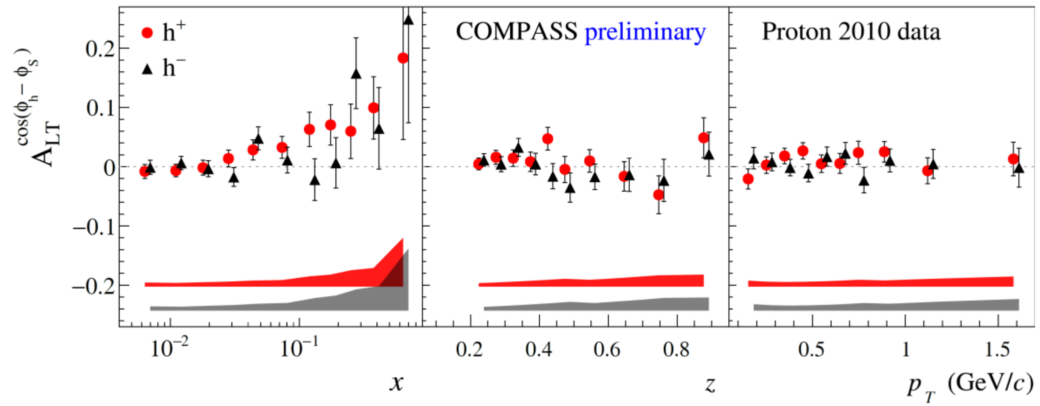
SIDIS: target transverse spin dependent asymmetries

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

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

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

B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



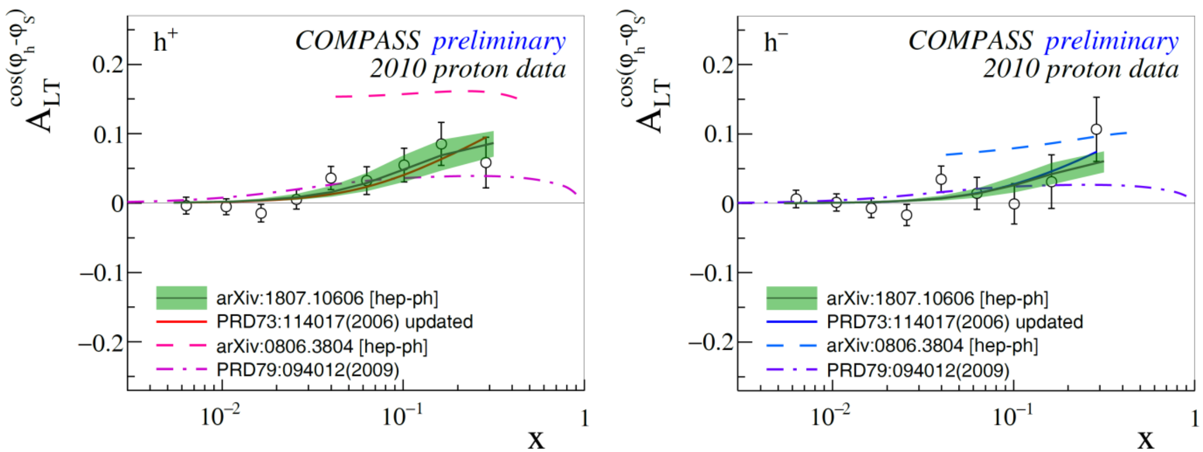
COMPASS results

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

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

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

S. Bastami, H. Avakian, A. V. Efremov, A. Kotzinian, B. U. Musch, B. Parsamyan, A. Prokudin, M. Schlegel, G. Schnell, P. Schweitzer, W. Vogelsang
"SIDIS in Wandzura-Wilczek-type approximation" - arXiv:1807.10606 [hep-ph]



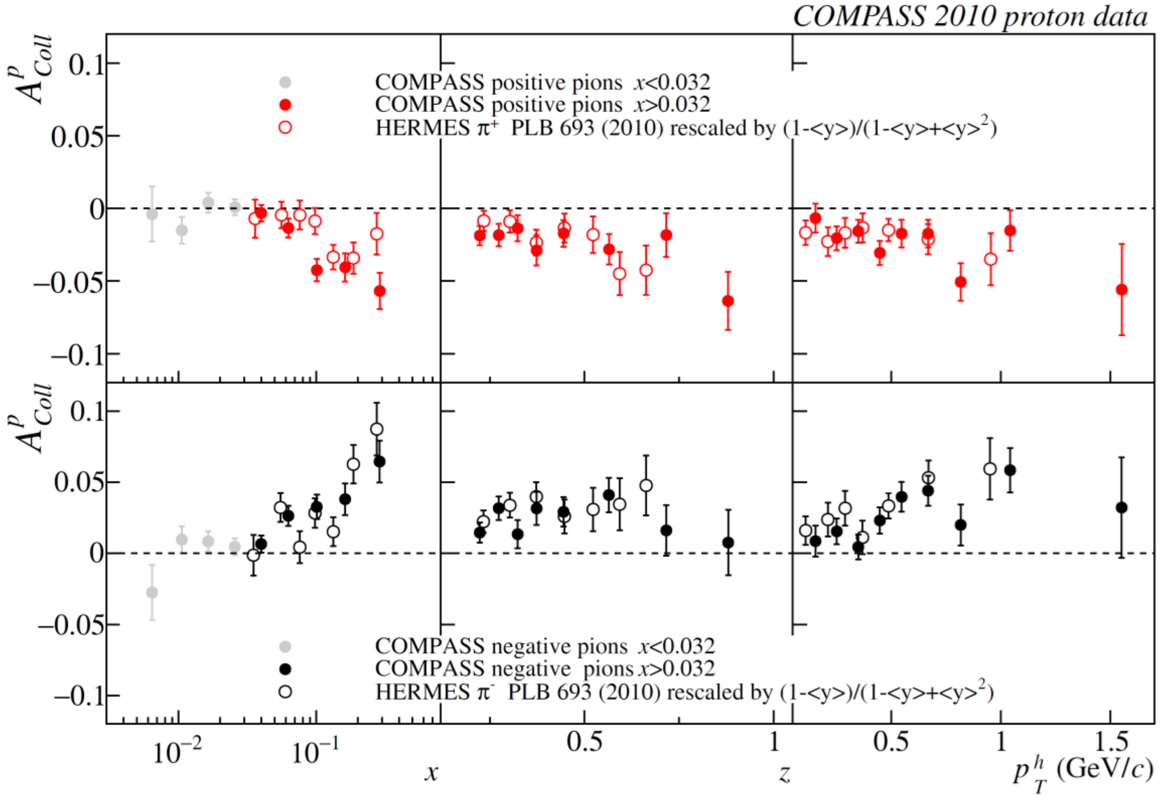
SIDIS TSAs (Collins)

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

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

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

COMPASS PLB 744 (2015) 250



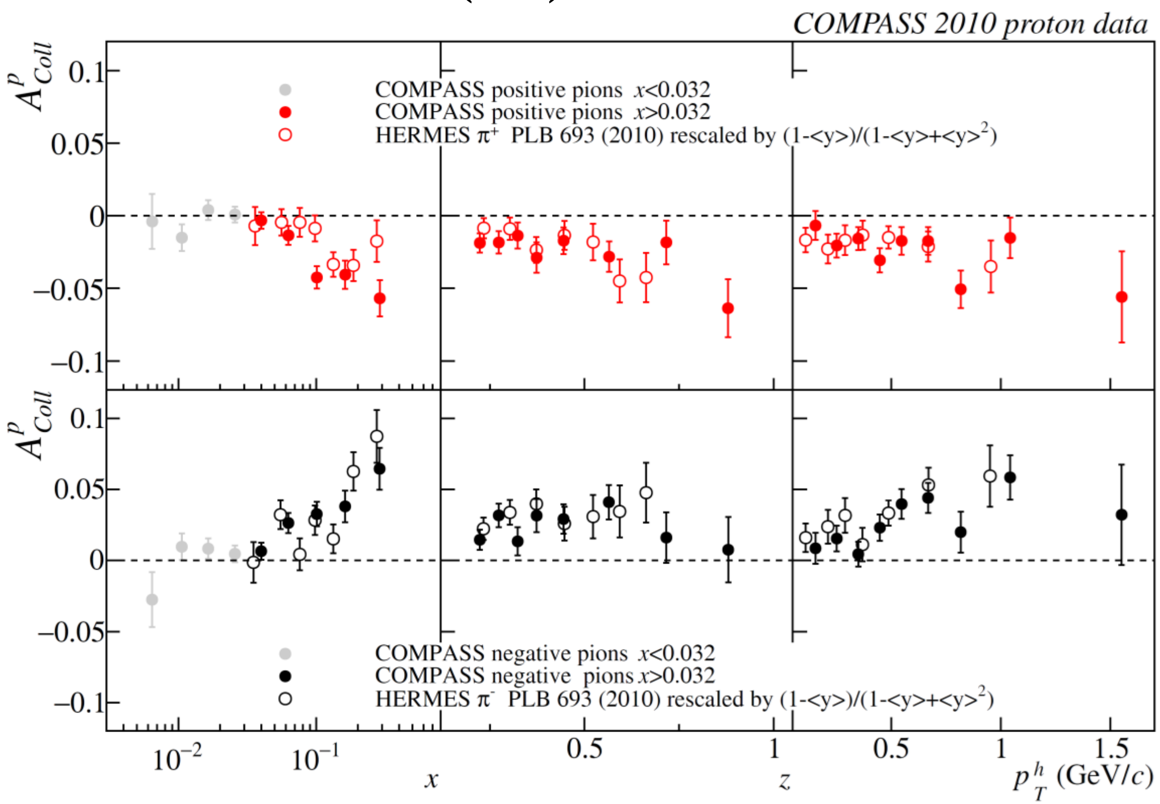
SIDIS TSAs (Collins)

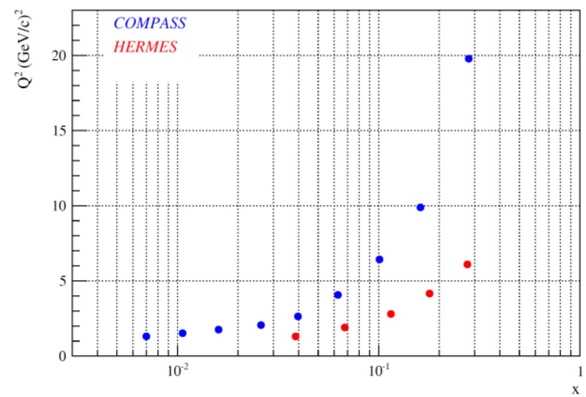
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + \ S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h + \phi_S\right) + \ldots\ \right\}$$

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

- 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 Q^2-evolution? Intriguing result!**

COMPASS PLB 744 (2015) 250





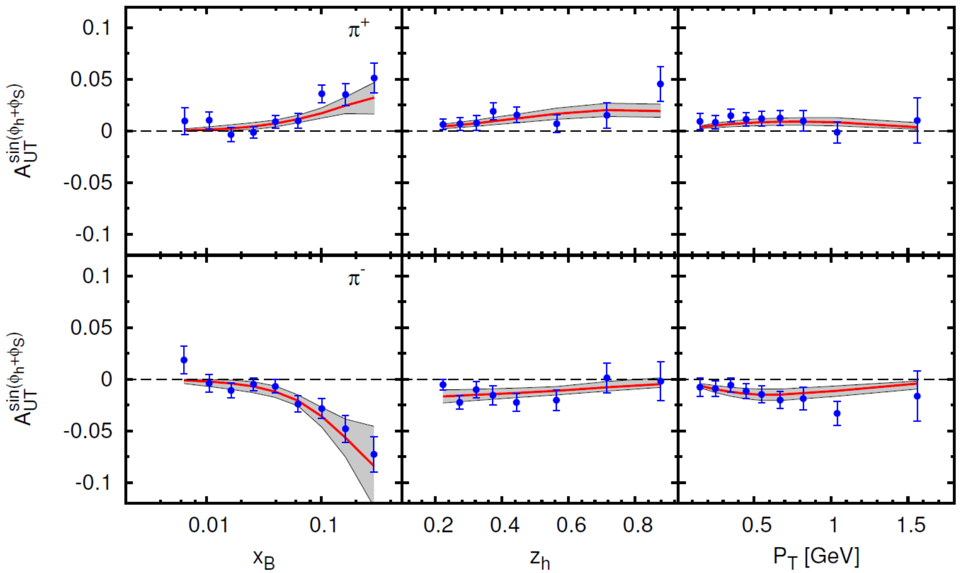
SIDIS TSAs (Collins)

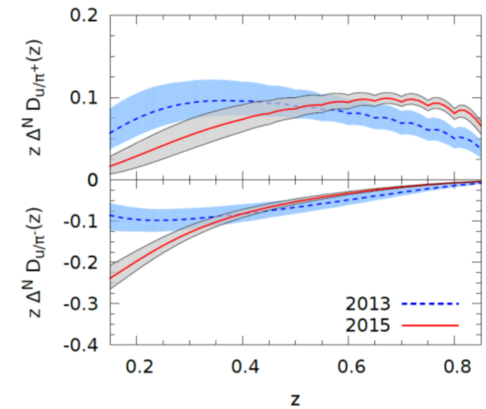
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h + \phi_S) + \ldots\right\}$$

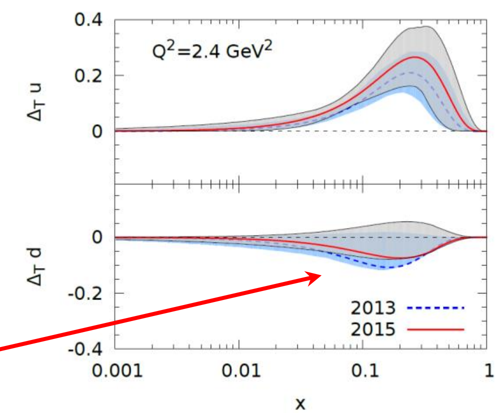
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

- 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 Q^2-evolution? Intriguing result!**
- Extensive phenomenological studies and various global fits by different groups

Global fit HERMES-COMPASS-BELLE data
Anselmino et al. **Phys.Rev. D92 (2015) 114023**







COMPASS-II (2021)

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

SIDIS TSAs (Collins)

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

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

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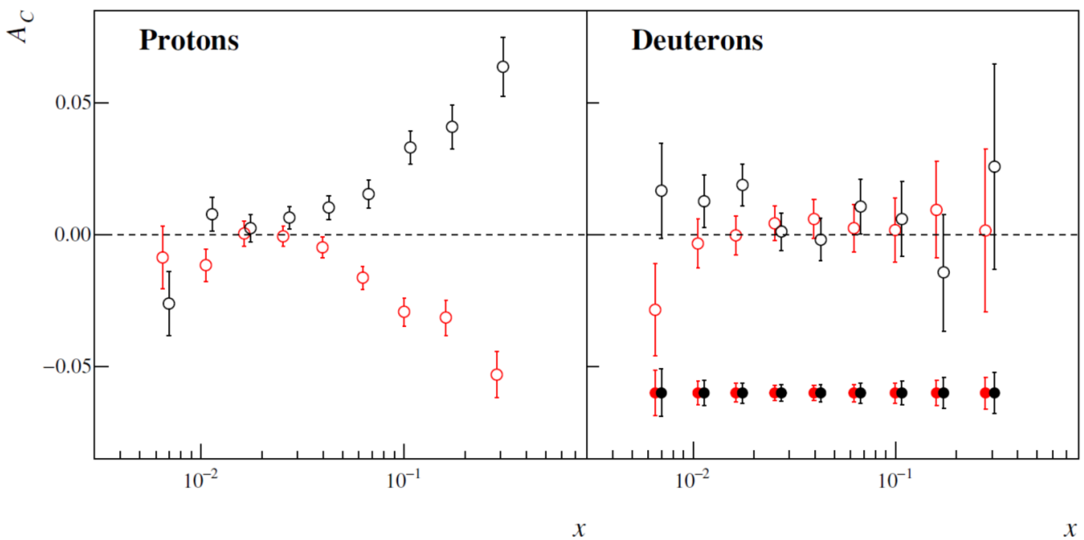
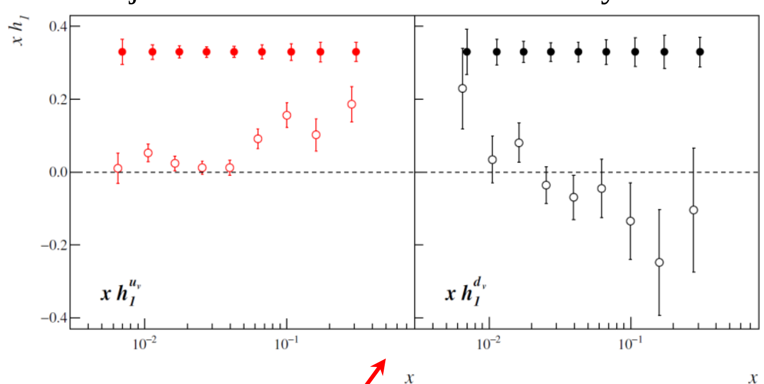
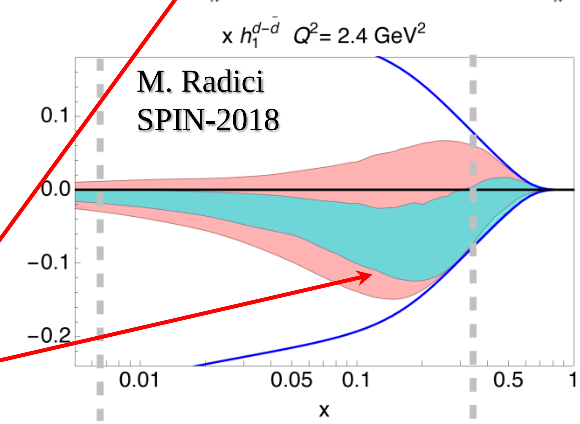
Addendum to the COMPASS-II Proposal
Projected uncertainties for Collins asymmetry



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





COMPASS-II (2021 run – approved!)

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

SIDIS TSAs (Collins)

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

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

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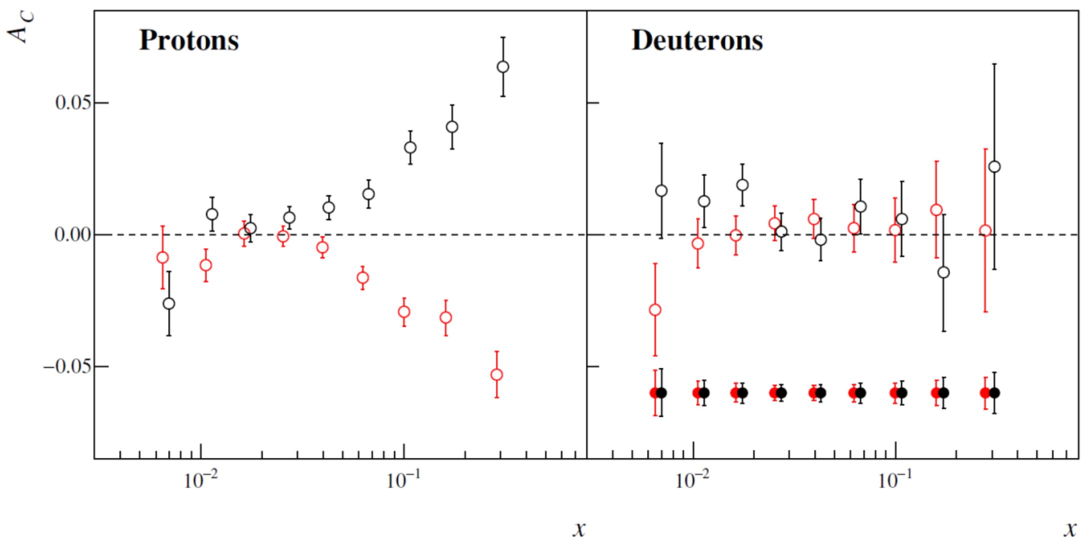
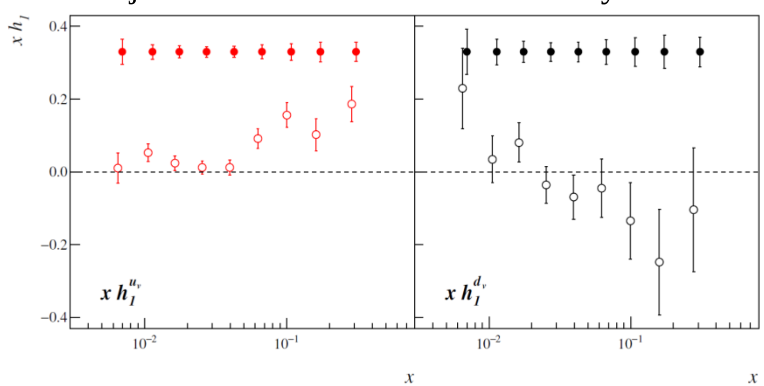
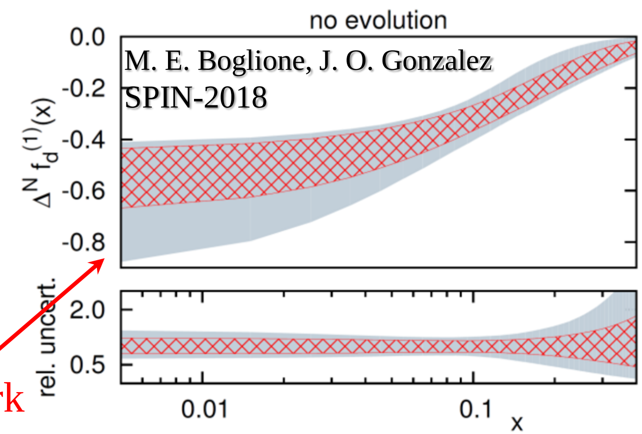


Addendum to the COMPASS-II Proposal
Projected uncertainties for transversity PDF





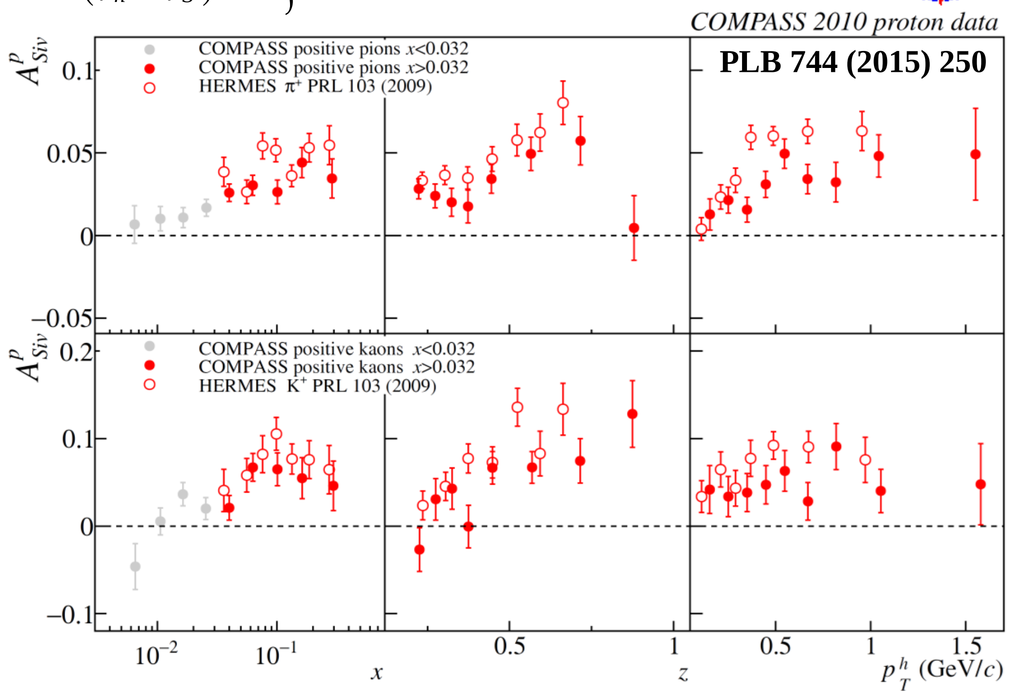
COMPASS-II (2021 run – approved!)

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

SIDIS TSAs (Sivers)

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

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



- 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)
- **Q^2-evolution? Intriguing result!**

SIDIS TSAs (Sivers)

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

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

- Measured on proton and deuteron
- Recently - gluon Sivers paper PLB 772 (2017) 854
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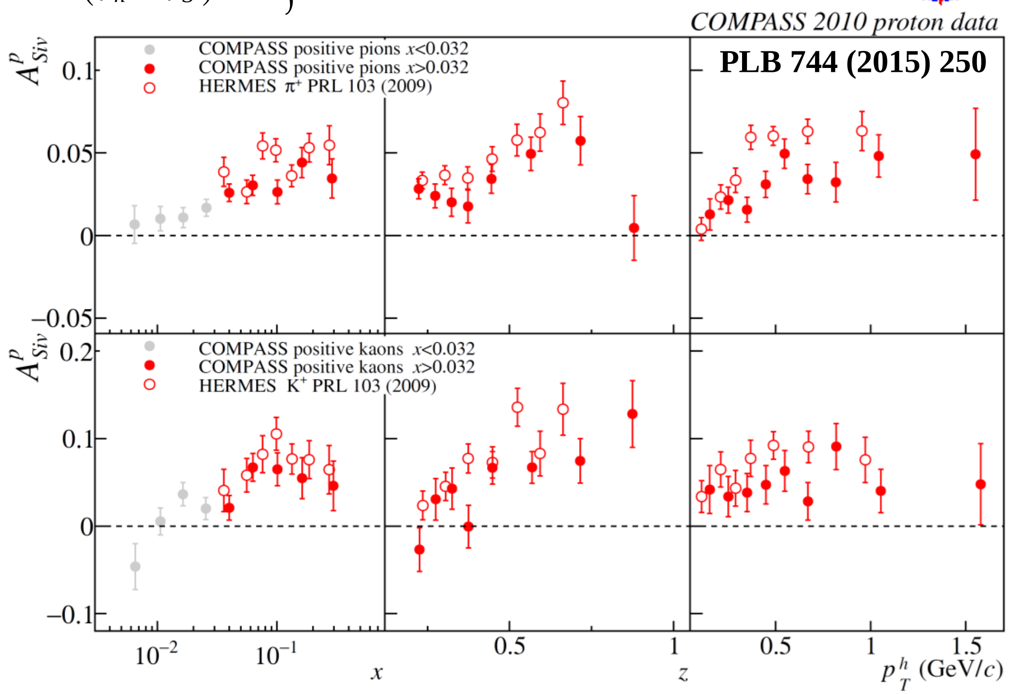
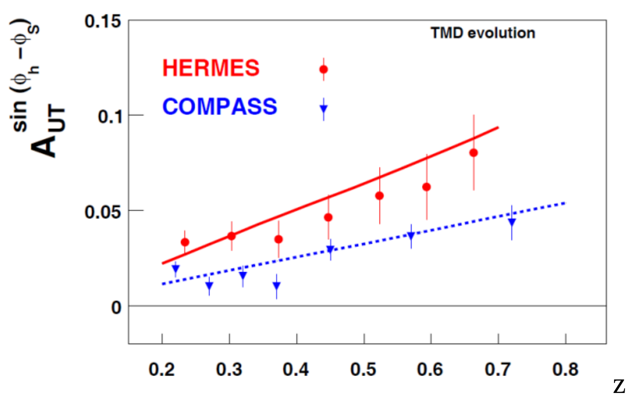
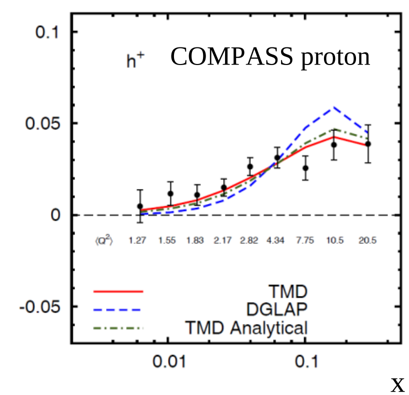
- **Q^2-evolution? Intriguing result!**
- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan
- Sivers TMD PDF is predicted to change the sign between SIDIS and DY







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

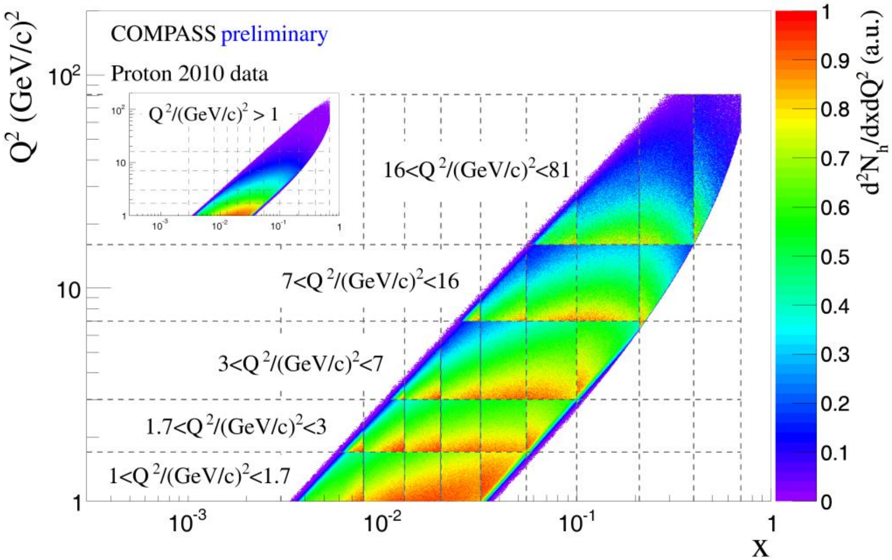
Multi-D TSA analysis

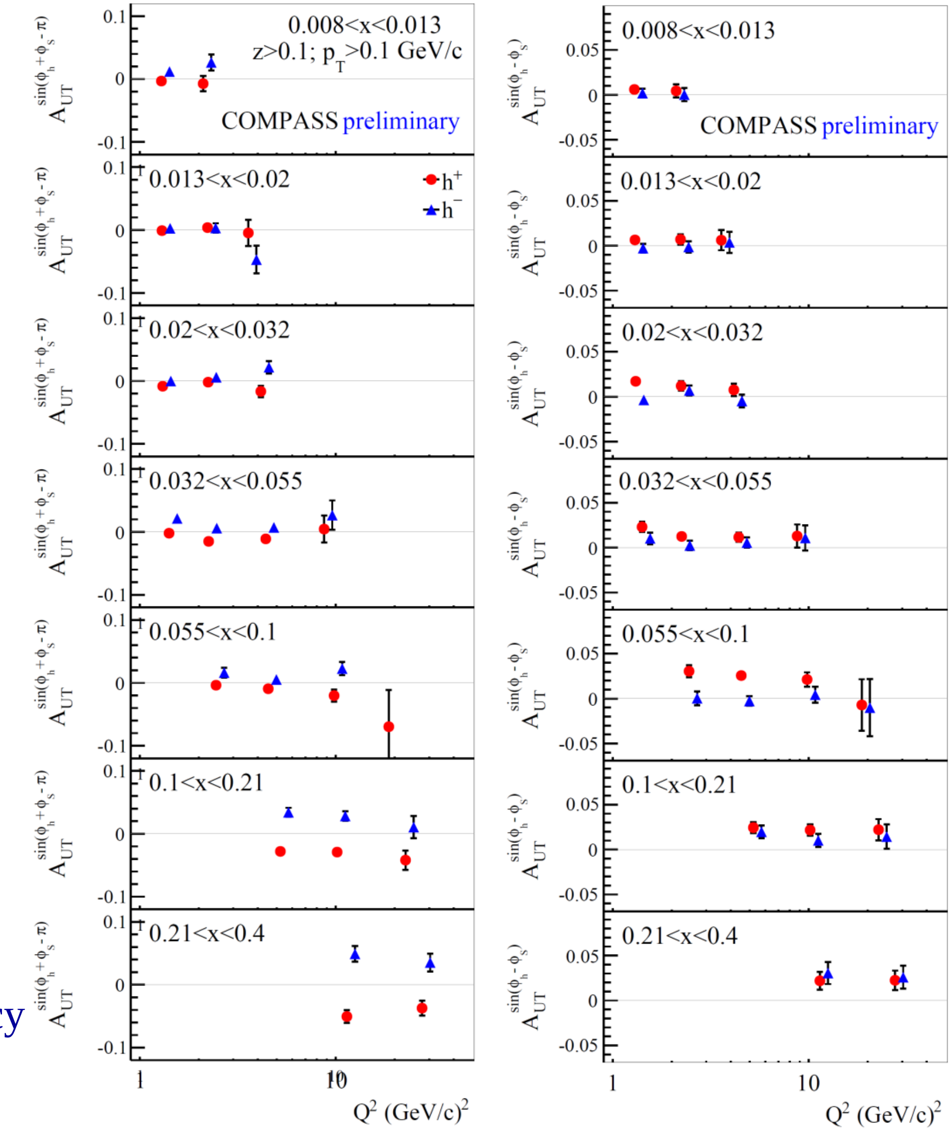
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \ldots \right\}$$

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

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

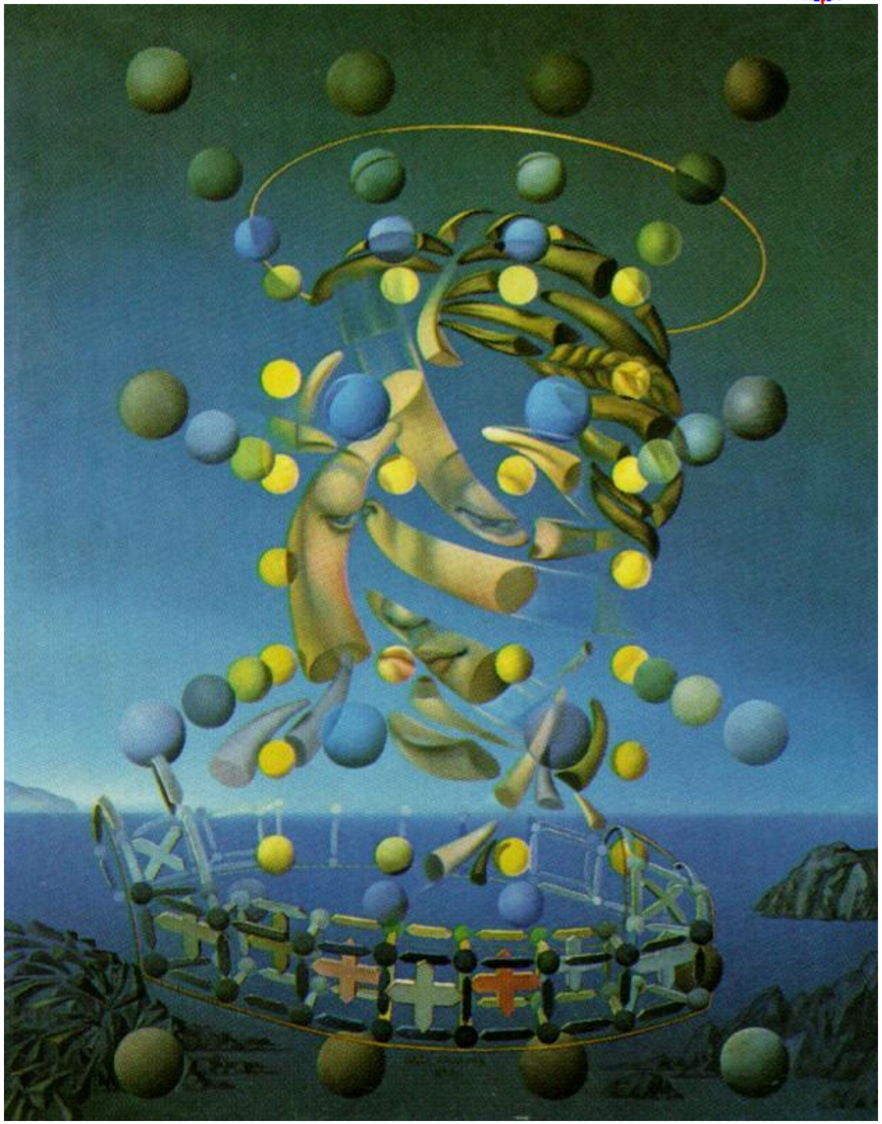
B.Parsamyan (for COMPASS) arXiv:1504.01599 [hep-ex] (SPIN-2014)





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

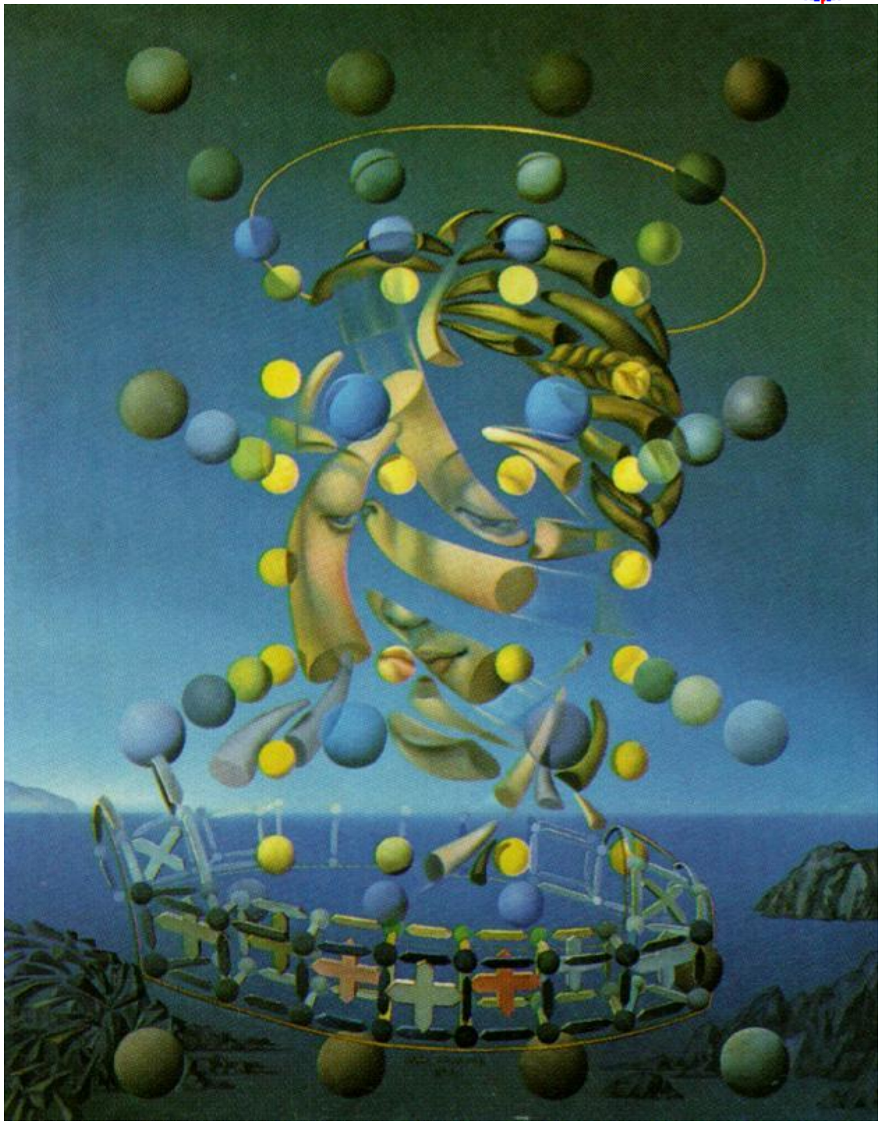
"1D"



Salvador Dali *"Maximum Speed of Raphael's Madonna"*

“Nature” *“1D”*

Raphael *“Madonna del Prato”*



Salvador Dali *“Maximum Speed of Raphael's Madonna”*

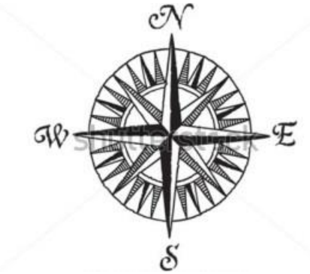
“Nature”

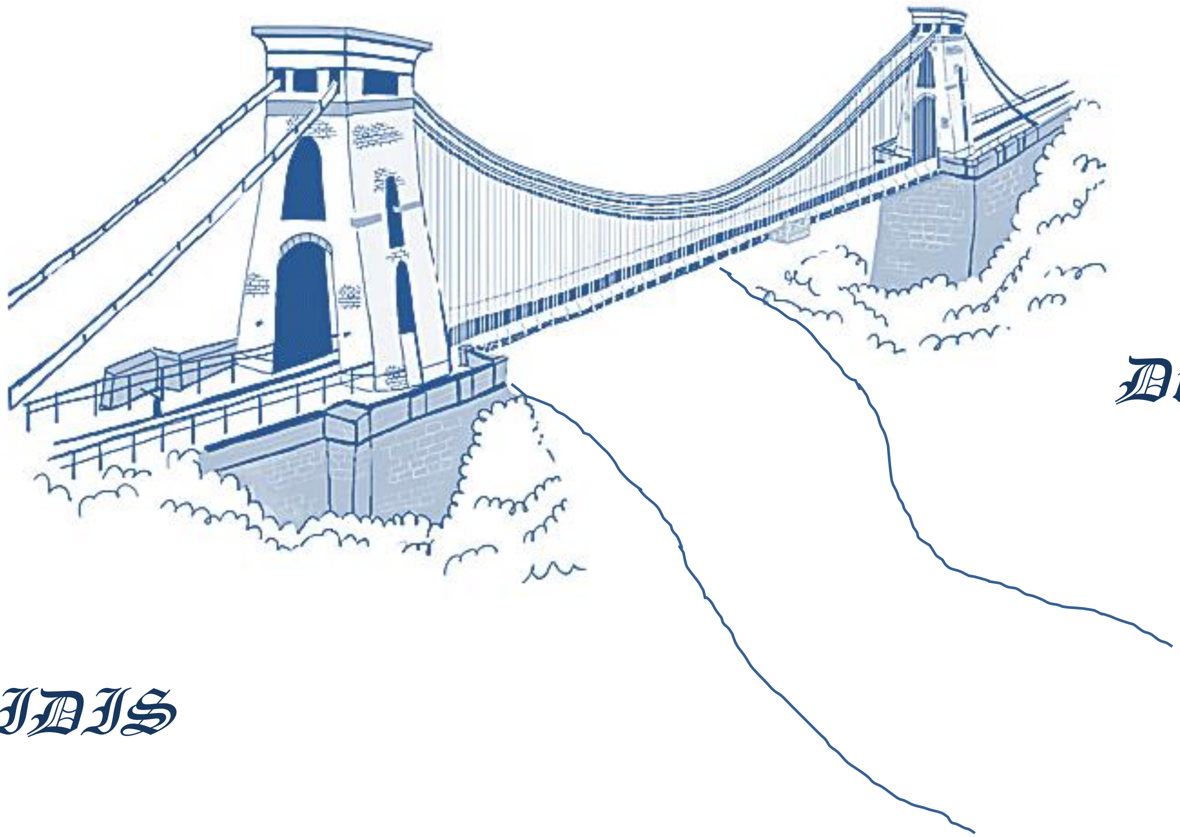
“multi-D” with available statistics

Raphael *“Madonna del Prato”*

Raphael *“Madonna del Prato” (poor resolution)*

COMPASS bridge





Drell-Yan

SIDIS

SIDIS and single-polarized DY x-sections

SIDIS

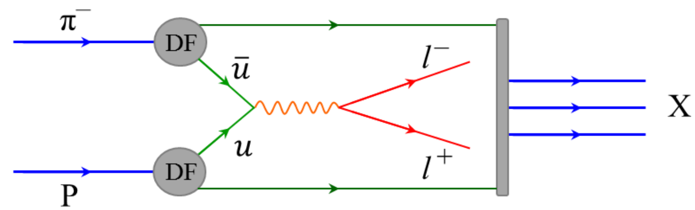
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

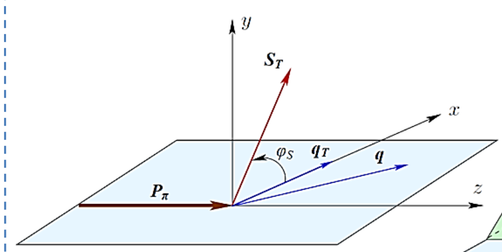
$$\times \left\{ \begin{array}{l}
1 + \sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\
+ \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h \\
+ S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h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

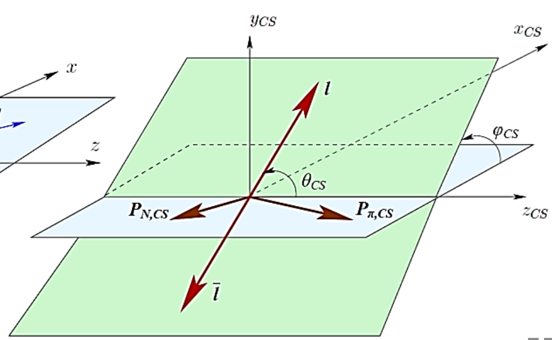
DY

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

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







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

SIDIS

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

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

SIDIS-DY bridge

DY

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

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

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

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

SIDIS

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

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

DY

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

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

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

SIDIS-DY bridge

SIDIS		DY
$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots$	Boer-Mulders	$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h - \phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$	Sivers	$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h + \phi_S)} \propto h_1^q \otimes H_{1q}^{\perp h}$	Transversity	$A_T^{\sin(2\varphi_{CS} - \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^q$
$A_{UT}^{\sin(3\phi_h - \phi_S)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$	Pretzelosity	$A_T^{\sin(2\varphi_{CS} + \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$
$A_{UL}^{\sin 2\phi_h} \propto h_{1L}^{\perp q} \otimes H_{1q}^{\perp h}$	Worm-gear L	$A_L^{\sin 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1L,p}^{\perp q}$
$A_{LL} \propto g_{1L}^q \otimes D_{1q}^h$, $A_{LT}^{\cos(\phi_h - \phi_S)} \propto g_{1T}^q \otimes D_{1q}^h$	⟷	Double polarized DY

COMPASS accesses all 8 twist-2 nucleon TMD PDFs in SIDIS and 5 nucleon+2 pion TMD PDFs in DY

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

SIDIS

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

DY

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

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

COMPASS

SIDIS-DY bridge

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

within QCD TMD-framework:

$h_1^{\perp q}$ & $f_{1T}^{\perp q}$ TMD PDFs are expected to be "conditionally" universal (SIDIS ↔ DY: sign change)

h_1^q & $h_{1T}^{\perp q}$ TMD PDFs are expected to be "genuinely" universal (SIDIS ↔ DY: no sign change)

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

SIDIS

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

DY

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

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

SIDIS-DY bridge

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

Complementary information from different channels:

- SIDIS-DY bridging of nucleon TMD PDFs
- Multiple access to Collins FF $H_{1q}^{\perp h}$ and pion Boer-Mulders PDF $h_{1,\pi}^{\perp q}$

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

SIDIS

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

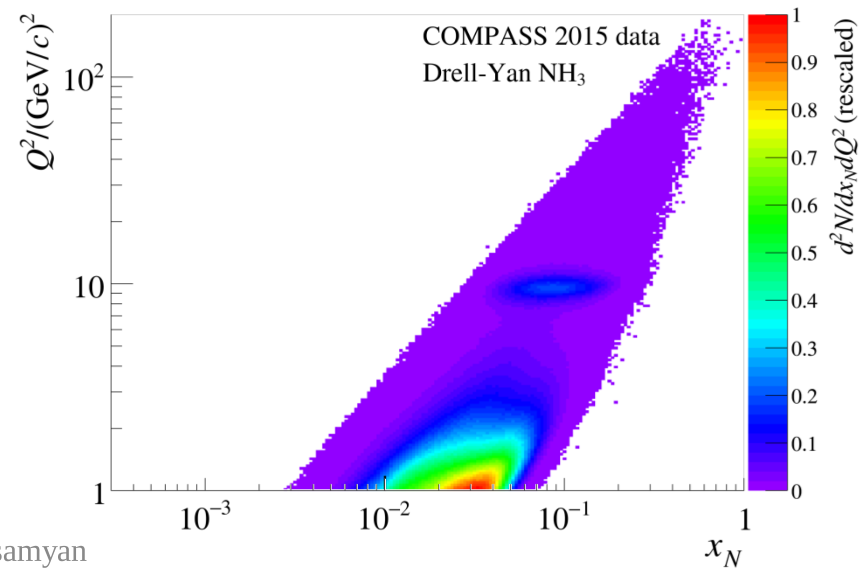
DY

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

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

SIDIS-DY bridge

COMPASS x:Q² phase space (DY 2015 data)



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

SIDIS

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

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

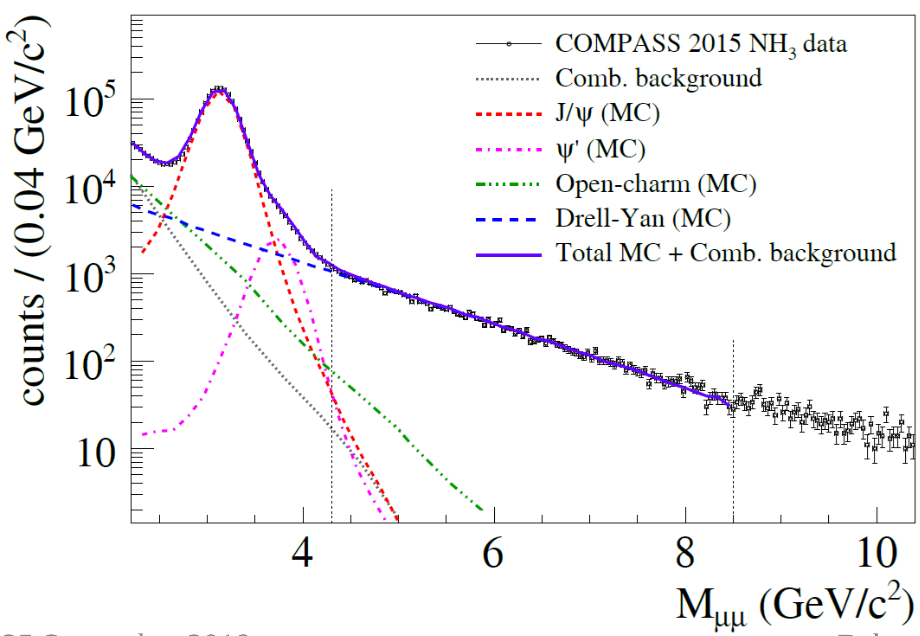
SIDIS-DY bridge

DY

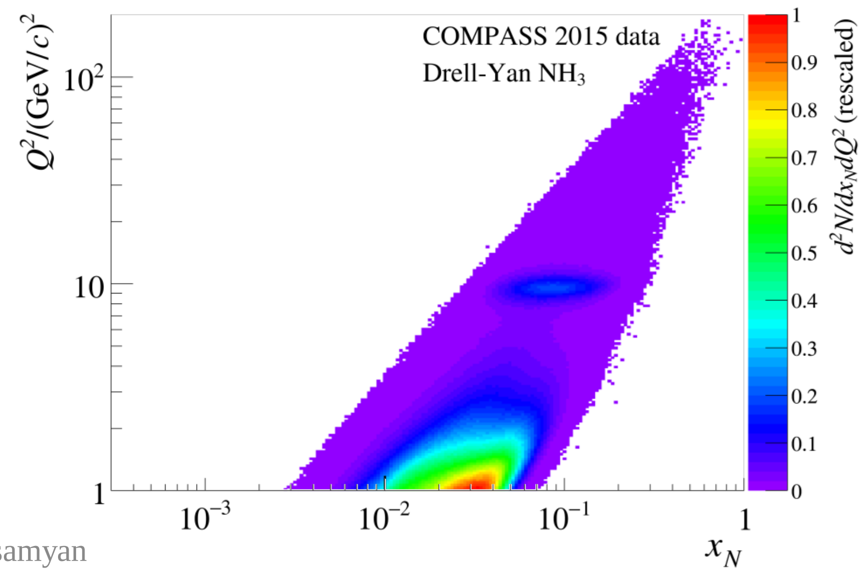
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right)$$

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

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



COMPASS x:Q² phase space (DY 2015 data)



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

SIDIS

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

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

SIDIS-DY bridge

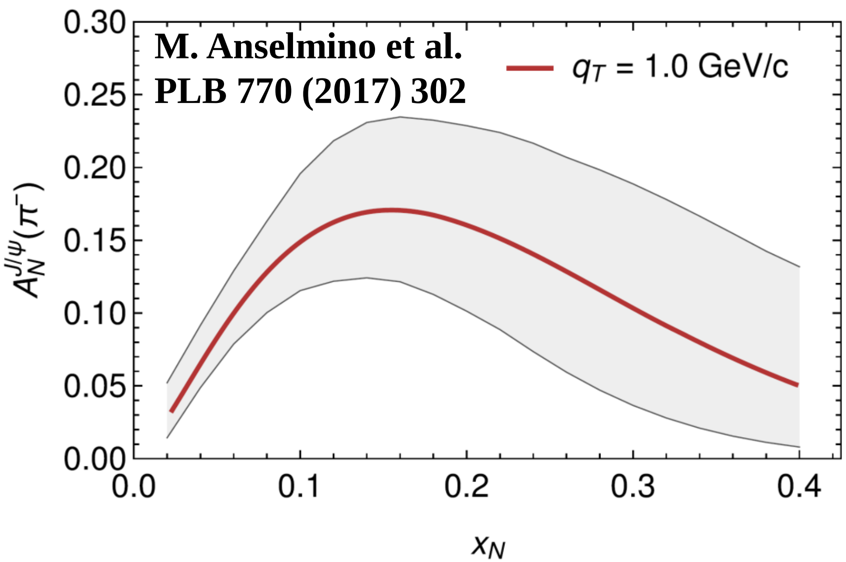
DY

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

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

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

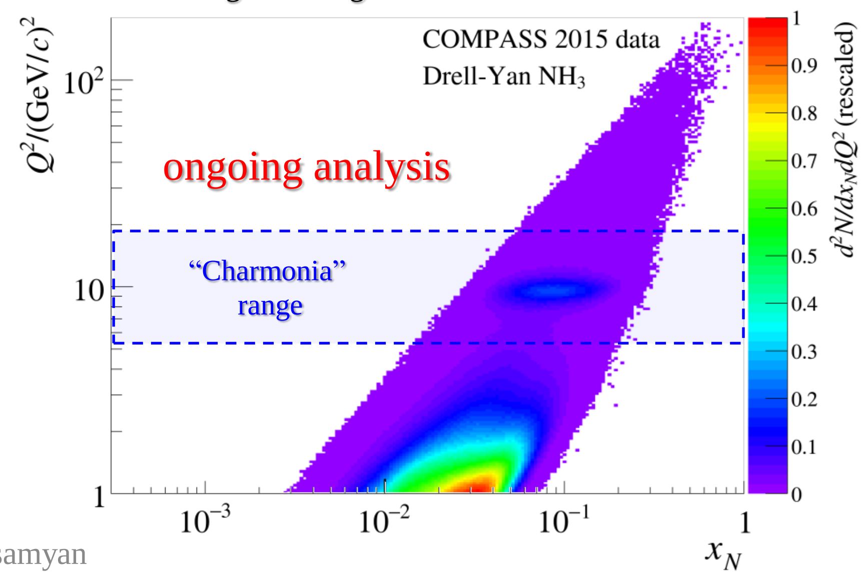
$\langle x_\pi \rangle = 0.31, \langle x_N \rangle = 0.09, \langle x_F \rangle = 0.22, \langle q_T \rangle = 1.1$ GeV/c



2.5 < M /(GeV/c2) < 4.3 "Charmonia mass"

Strong J/ψ-signal → study of J/ψ physics

Good signal/background



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

SIDIS

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

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

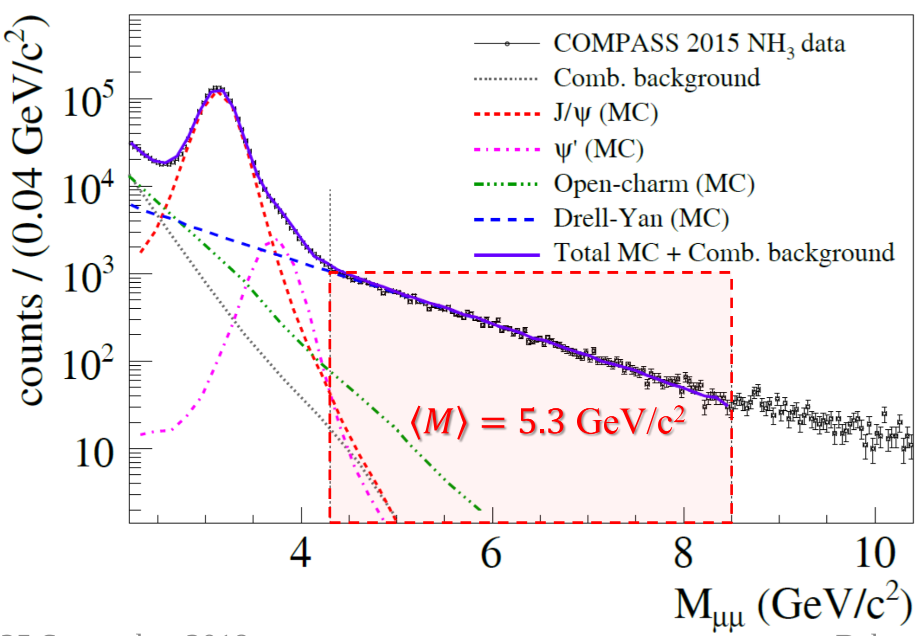
SIDIS-DY bridge

DY

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

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

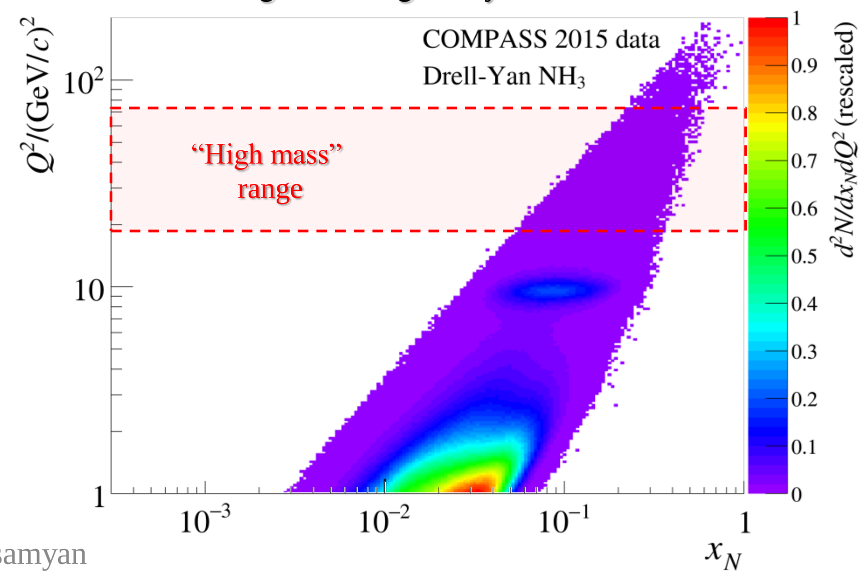
where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1 + \cos^2\theta_{CS}\right)$



4.3 < M /(GeV/c²) < 8.5 "High mass" range

Beyond charmonium region, background < 3%

Valence region → largest asymmetries



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

SIDIS

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

SIDIS-DY bridge

DY

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

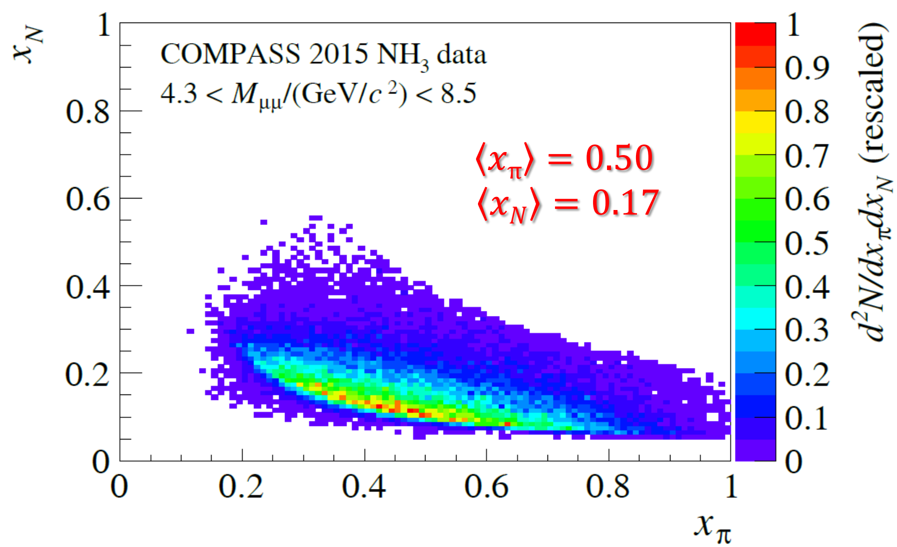
where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1+\cos^2\theta_{CS}\right)$

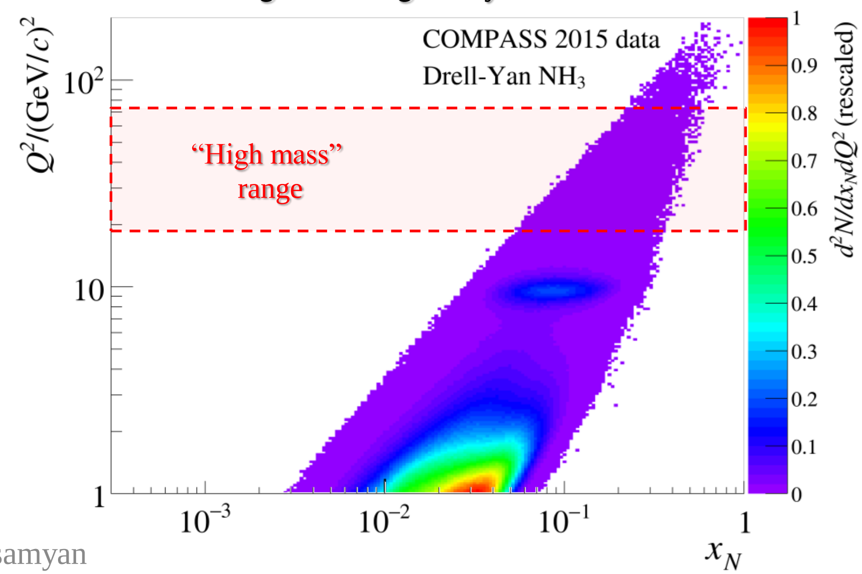
$4.3 < M/(\mathrm{GeV}/c^2) < 8.5$ "High mass" range

Beyond charmonium region, background < 3%

Valence region → largest asymmetries

HM events are in the valence quark range





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

SIDIS

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

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

DY

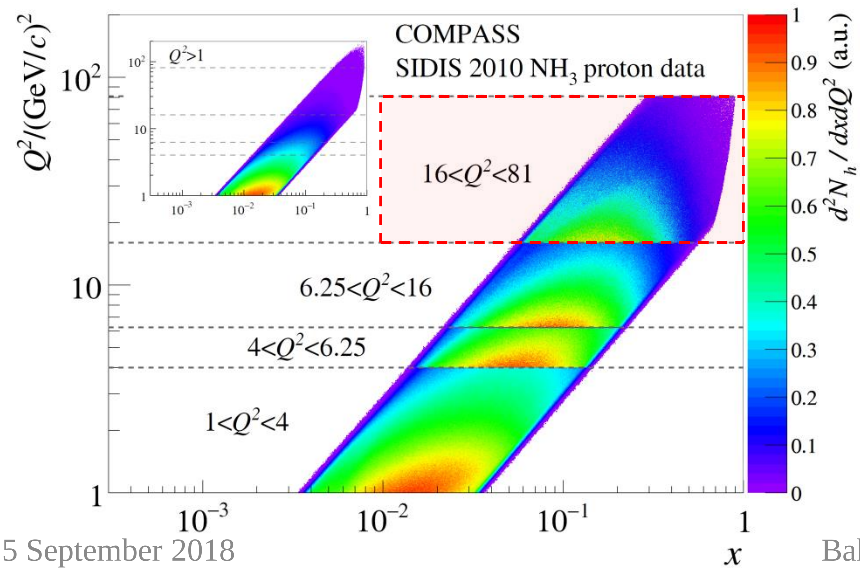
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1 + \cos^2\theta_{CS}\right)$$

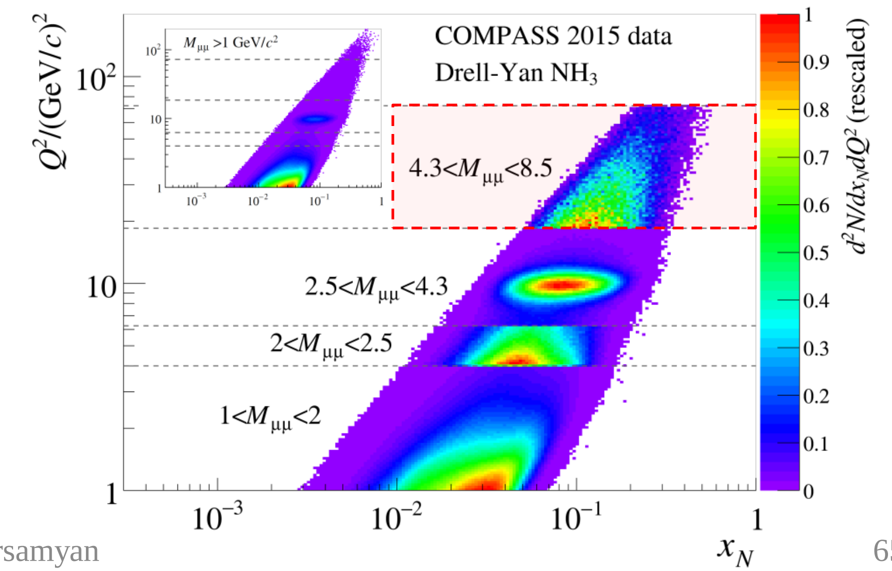
$$\times \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S} \sin\varphi_S \\ + D_{[\sin^2\theta_{CS}]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)}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

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

SIDIS-DY bridge

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

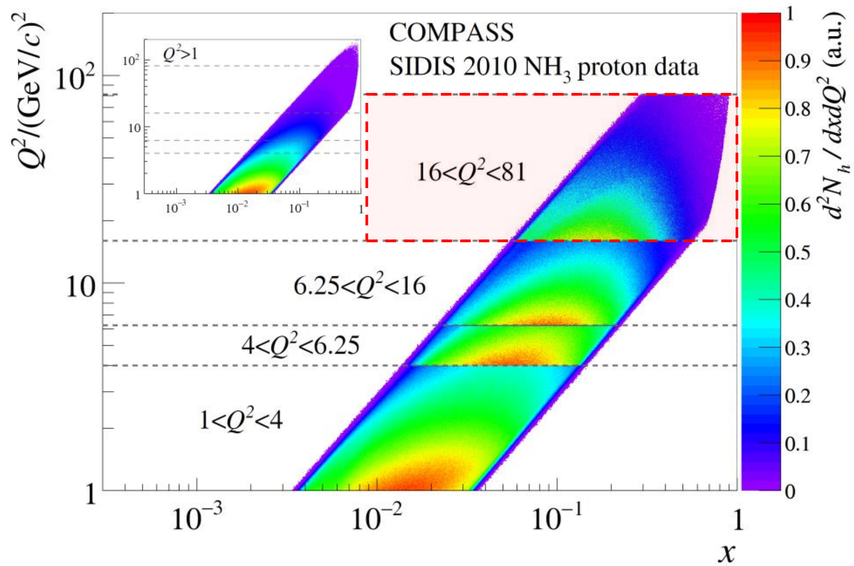


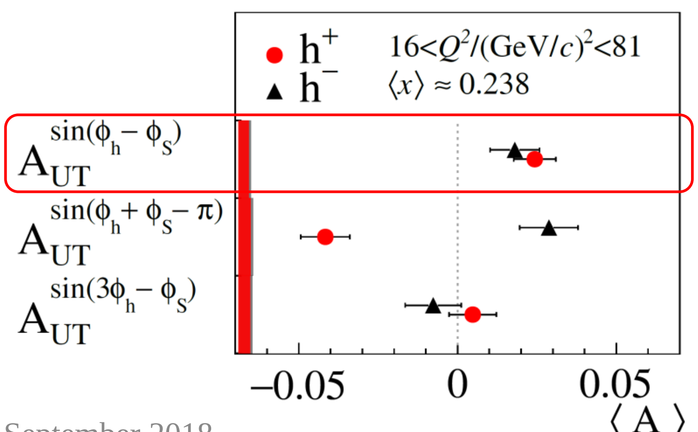


SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

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

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





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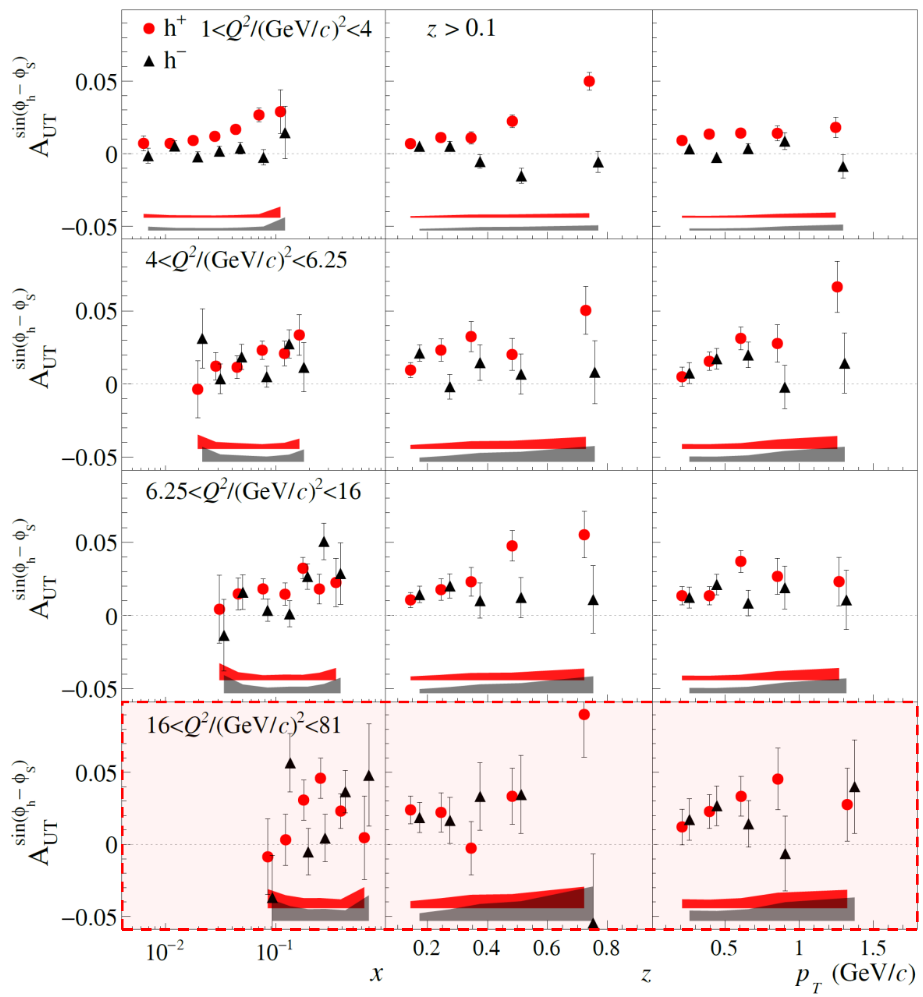
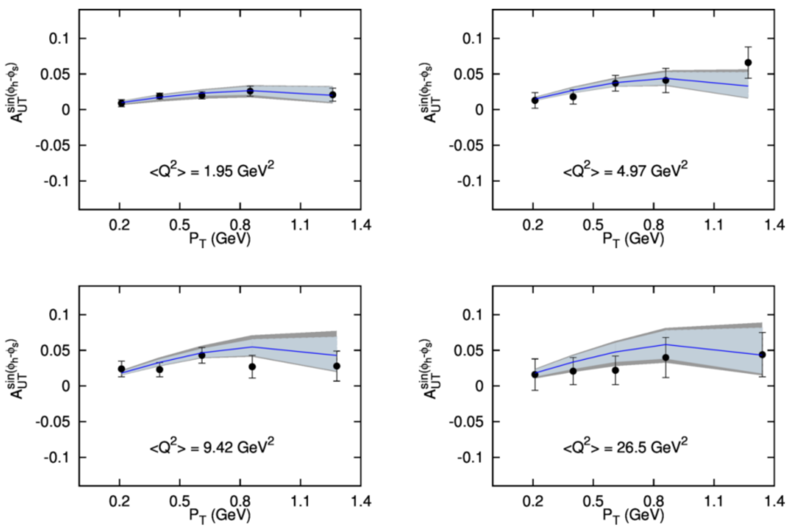


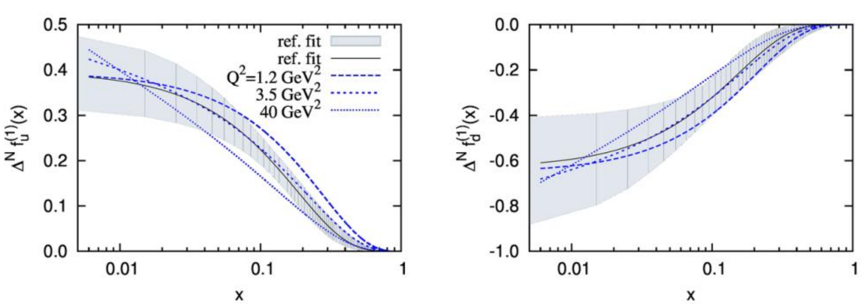
SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

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

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

M. Boglione, U. D'Alesio, C. Flore and J.O. Gonzalez-Hernandez
JHEP 1807 (2018) 148





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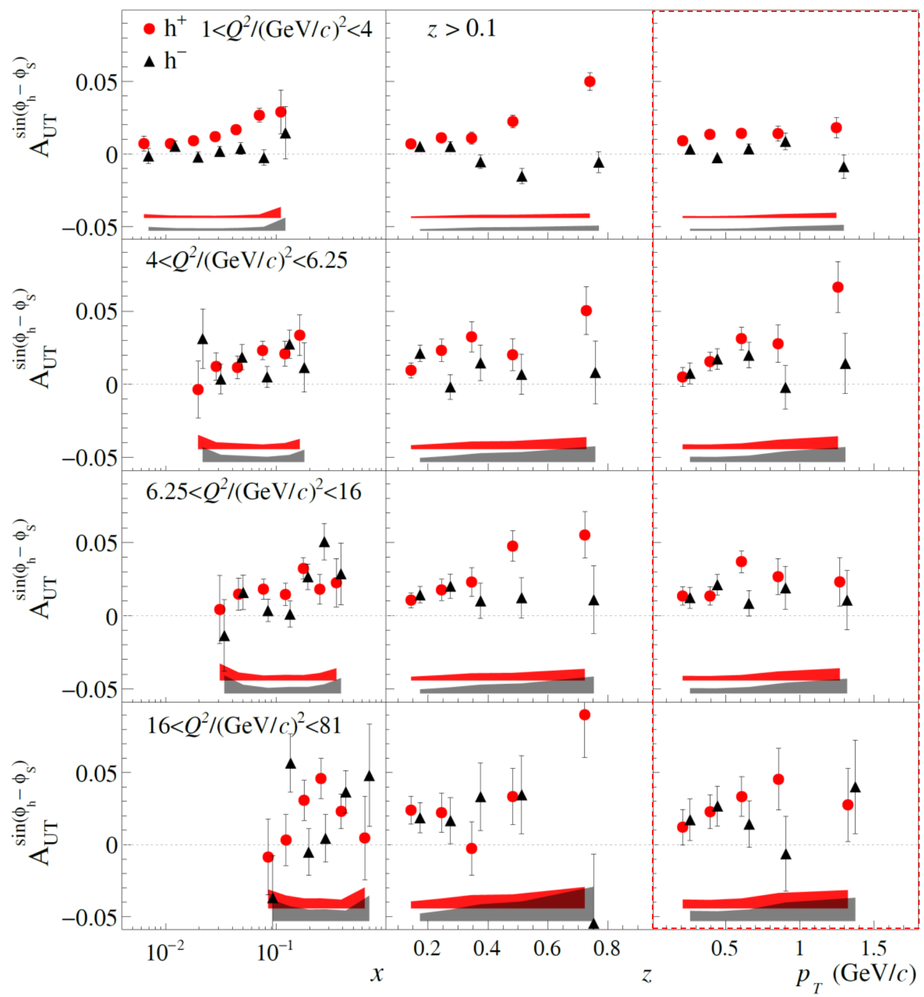
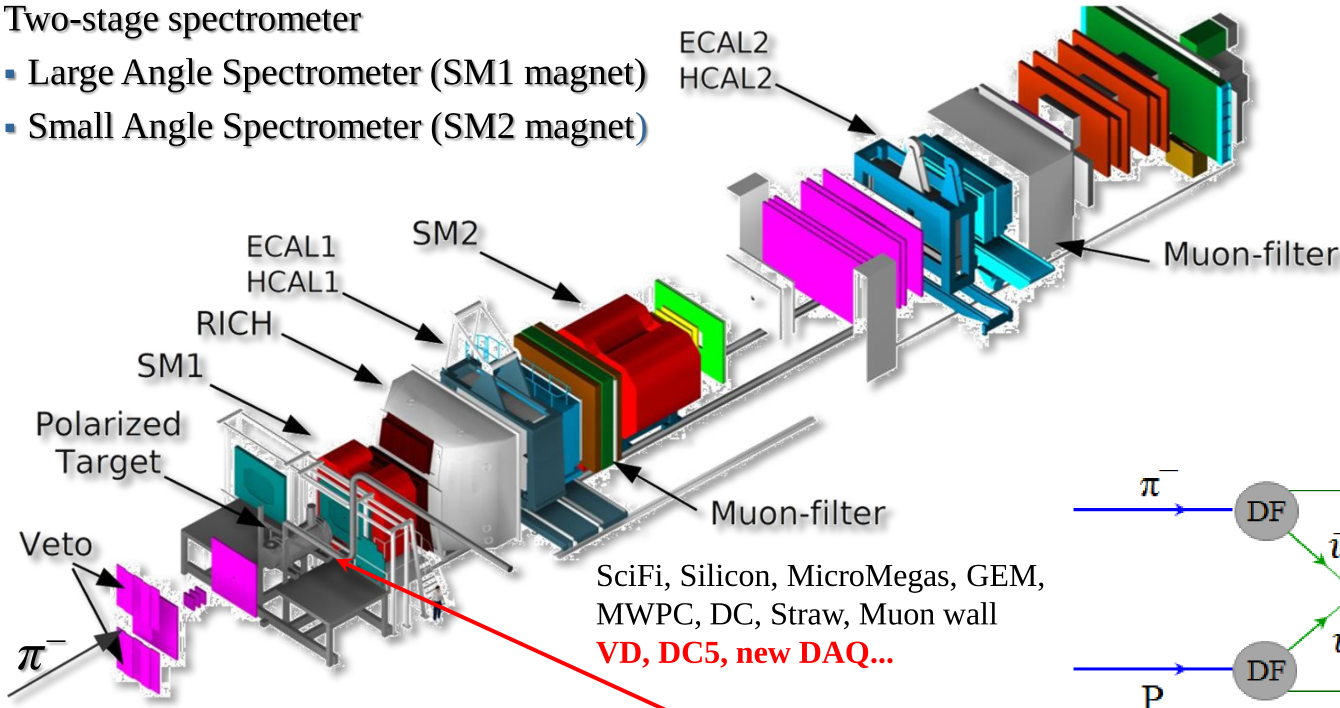


- Results from first ever measurement of Drell-Yan TSAs

COMPASS experimental setup: Phase II (DY program)

Two-stage spectrometer

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

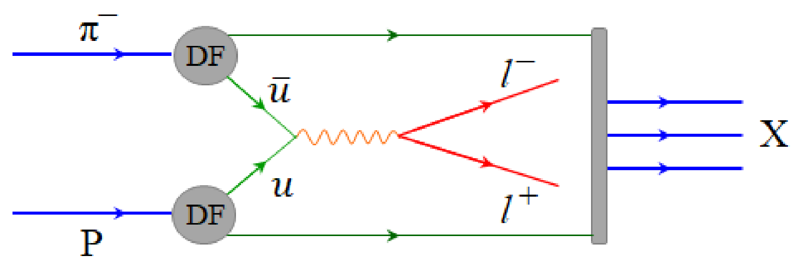


SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon wall

VD, DC5, new DAQ...

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

Drell-Yan



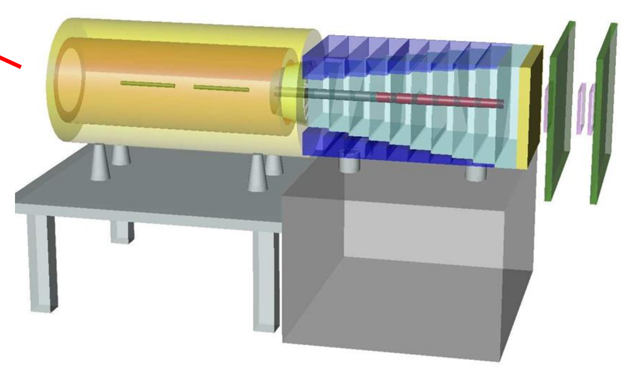
Data-taking years: 2014 (test) 2015 and 2018

High energy π^- beam:

Energy: 190 GeV/c, Intensity: 10^8 π/s

Target: Solid state

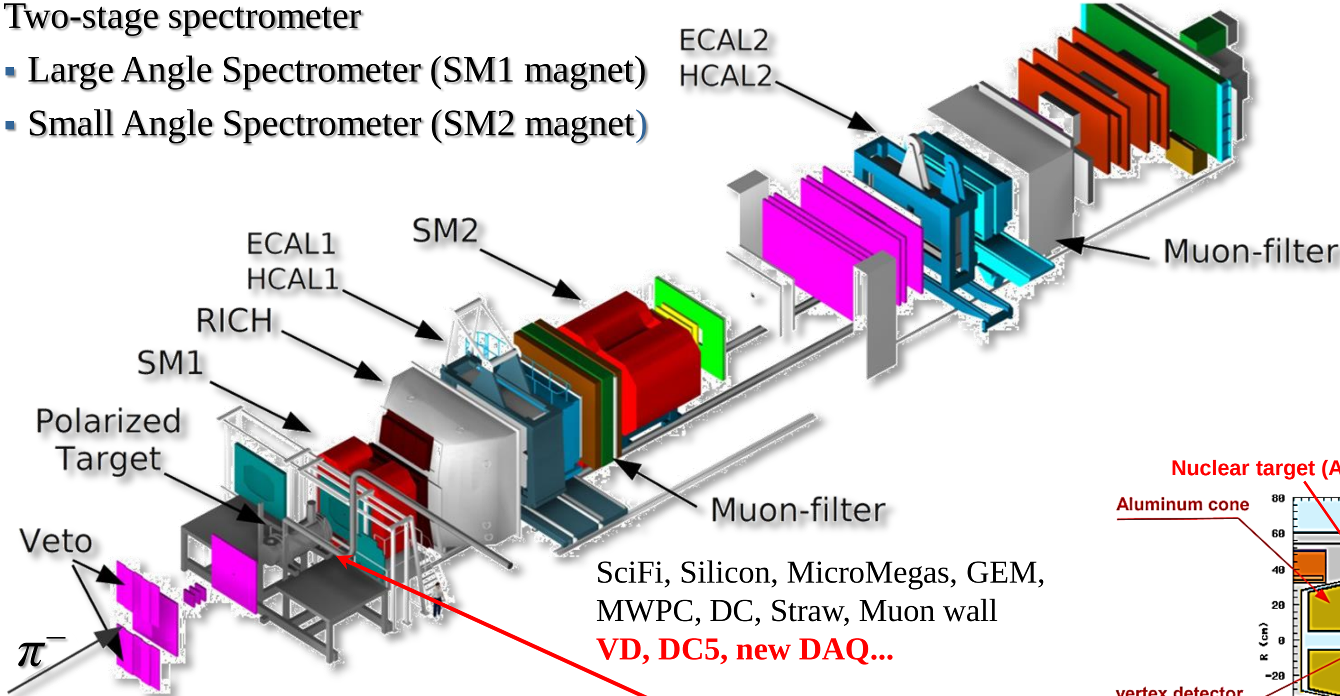
- NH_3 2-cell configuration. Polarization T ~ 73%, f ~ 0.18



COMPASS experimental setup: Phase II (DY program)

Two-stage spectrometer

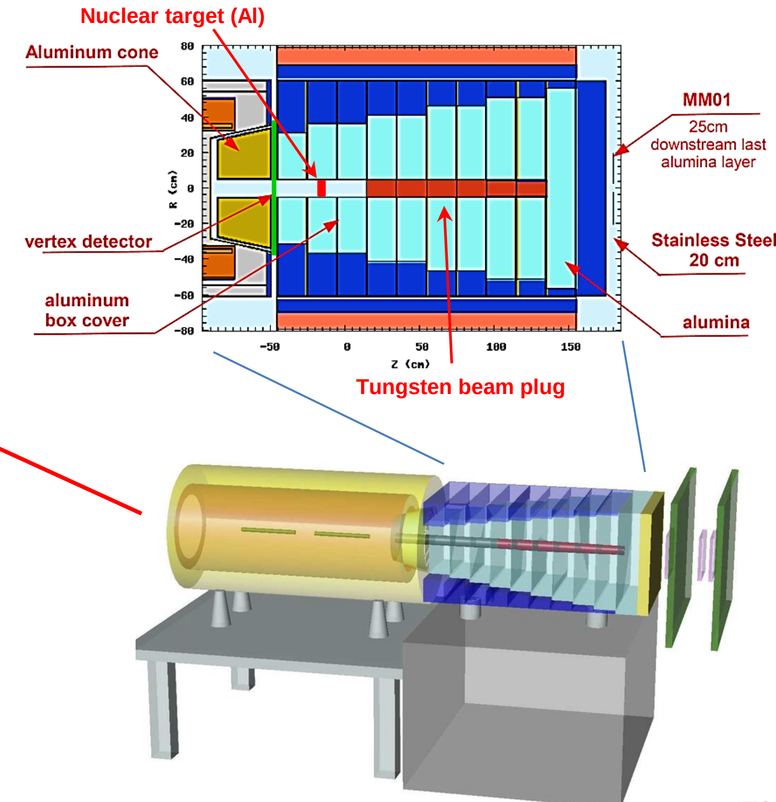
- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)



SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon wall
VD, DC5, new DAQ...

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

Hadron absorber



Data-taking years: 2014 (test) 2015 and 2018

High energy π^- beam:

Energy: 190 GeV/c, Intensity: 10^8 π/s

Target: Solid state

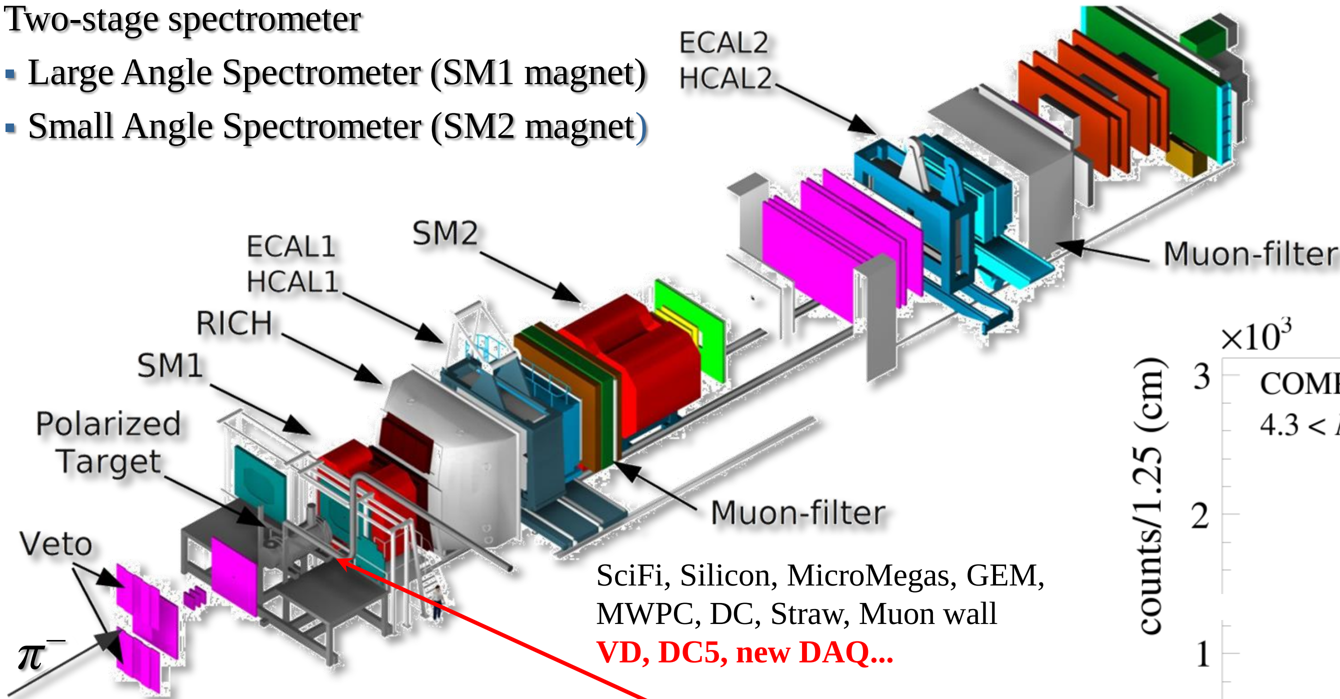
- NH_3 2-cell configuration. Polarization T ~ 73%, f ~ 0.18

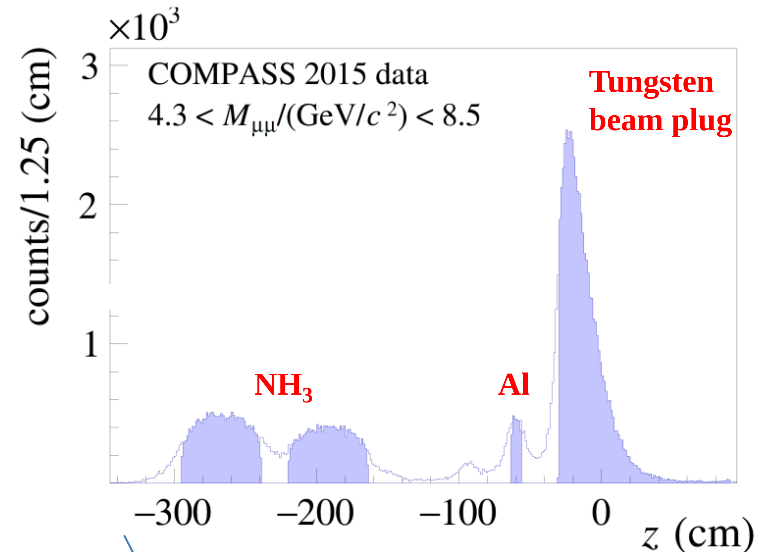
COMPASS experimental setup: Phase II (DY program)

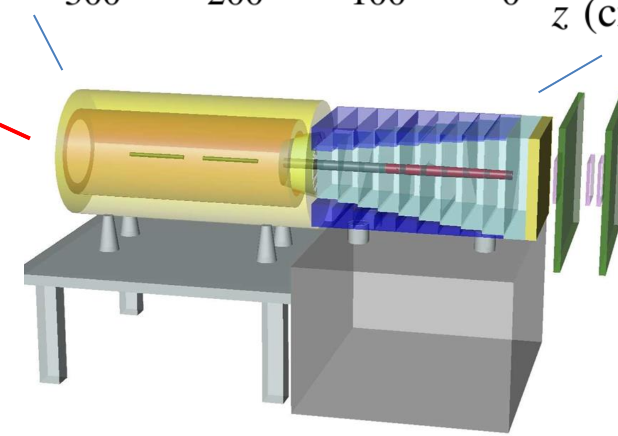
Two-stage spectrometer

- 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







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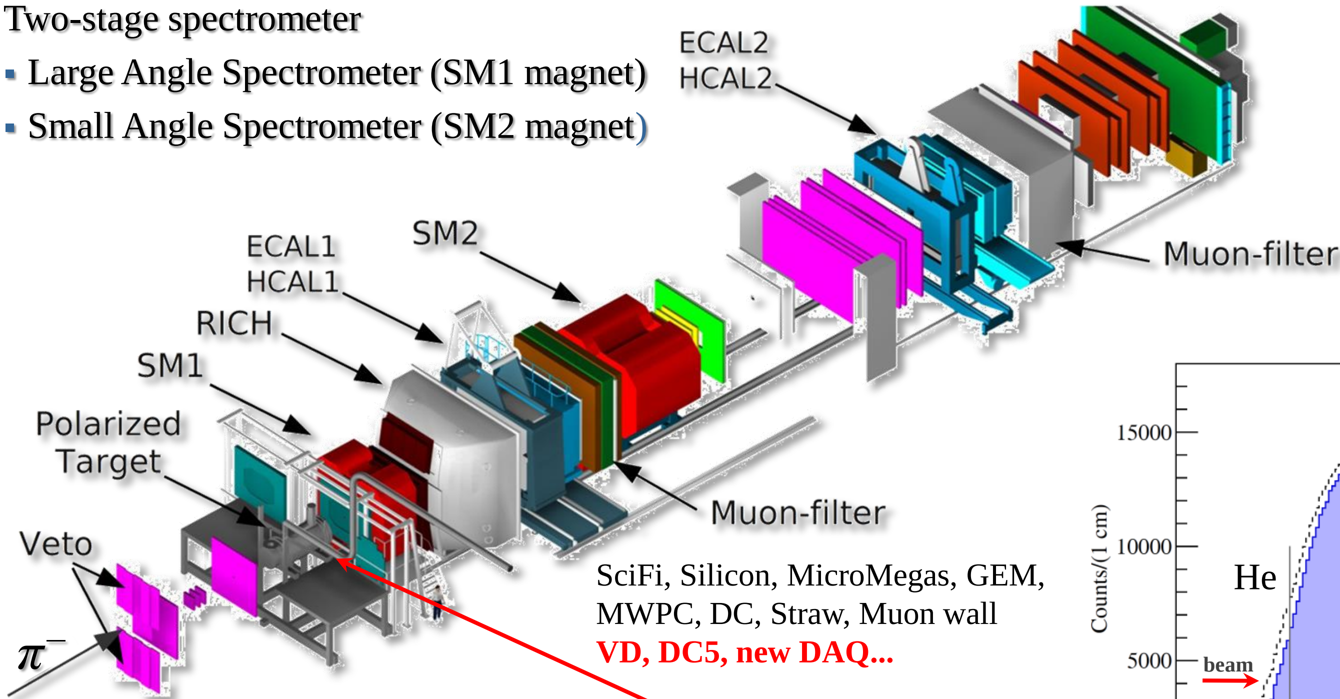

- High energy beam
- Large angular acceptance
- Broad kinematical range
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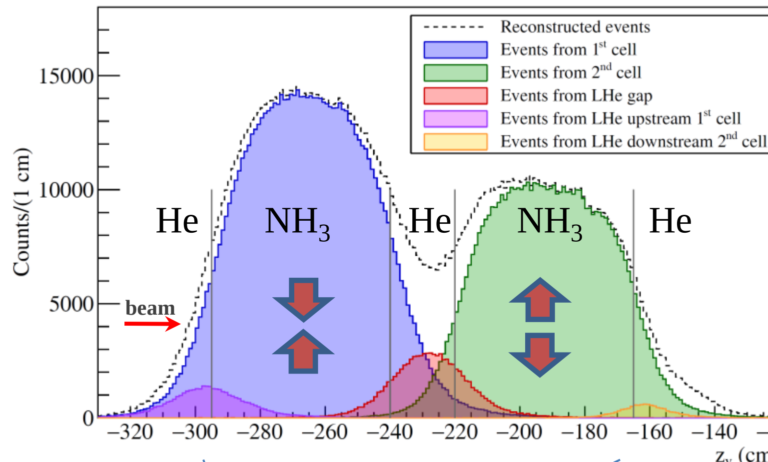
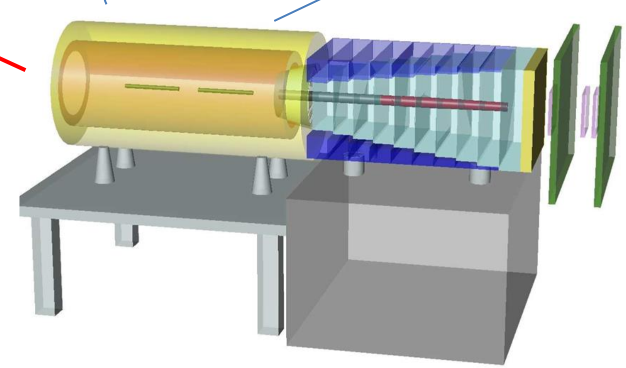
SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon wall
VD, DC5, new DAQ...





Data-taking years: 2014 (test) 2015 and 2018

High energy π^- beam:
Energy: 190 GeV/c, Intensity: 10^8 π/s

Target: Solid state

- NH_3 2-cell configuration. Polarization T ~ 73%, f ~ 0.18
- Data is collected simultaneously with both target spin orientations
  Periodic polarization reversal to minimize systematic effects

Single-polarized DY x-section: unpolarized part

$$\lambda = A_U^1 = \frac{F_U^1 - F_U^2}{F_U^1 + F_U^2}, \mu = A_U^{\cos\varphi_{CS}}, \nu = 2A_U^{\cos 2\varphi_{CS}}$$

- **“naive” Drell–Yan model**
  collinear (k_T=0) LO pQCD no rad. processes
  λ=1, (F_U^2=0), μ=ν=0
- **Intrinsic transverse motion + QCD effects**
  λ≠1, μ ≠ 0, ν ≠ 0 but 1–λ=2ν (Lam-Tung)
- **Experiment,**
  λ≠1, μ ≠ 0, ν ≠ 0

$$\frac{d\sigma}{dq^4 d\Omega} \propto \left(F_U^1 + F_U^2\right) \times \left\{ \begin{array}{l} 1 + A_U^1 \cos^2\theta_{CS} + \\ \sin^2\theta_{CS} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + \sin 2\theta_{CS} A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} \end{array} \right\}$$

COMPASS ongoing analysis

Single-polarized DY x-section: unpolarized part

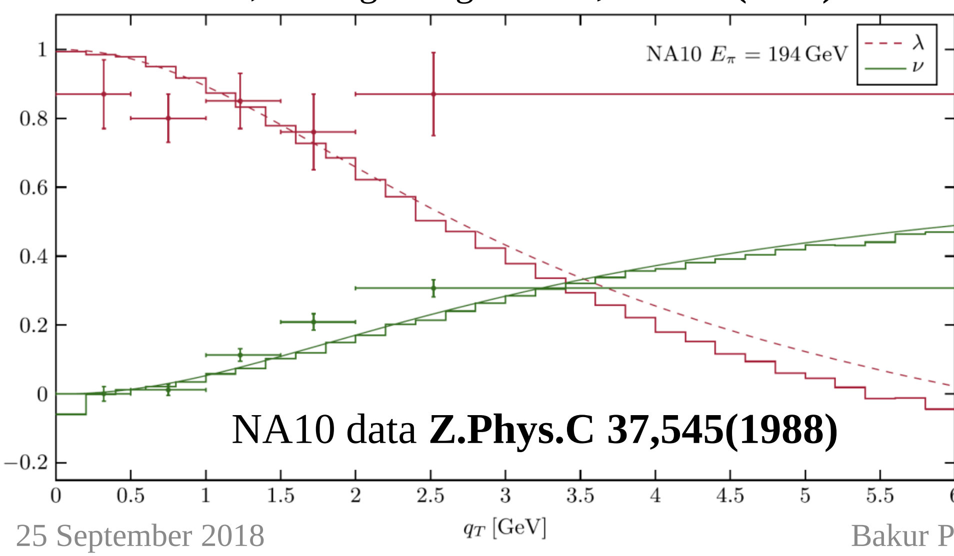
$$\lambda = A_U^1 = \frac{F_U^1 - F_U^2}{F_U^1 + F_U^2}, \mu = A_U^{\cos\varphi_{CS}}, \nu = 2A_U^{\cos 2\varphi_{CS}}$$

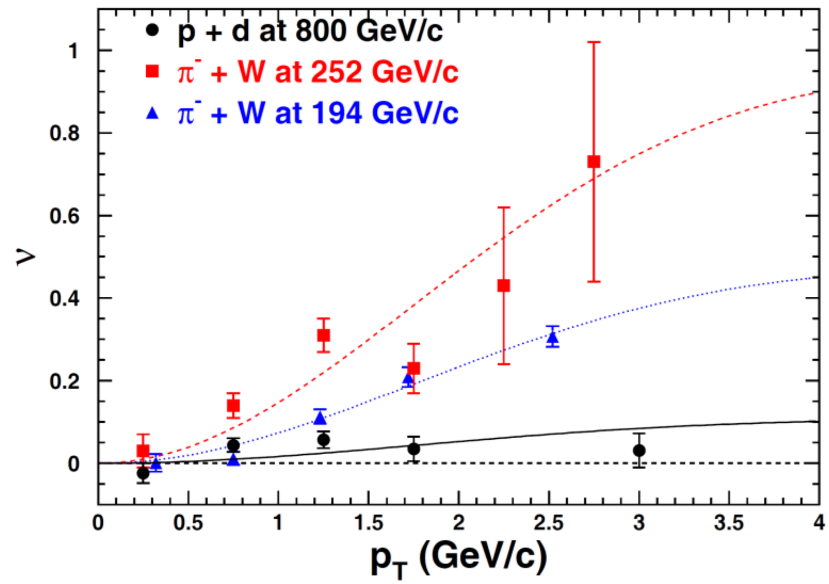
- **"naive" Drell–Yan model**
  collinear (k_T=0) LO pQCD no rad. processes
  $\lambda=1$, ($F_U^2=0$), $\mu=\nu=0$
- **Intrinsic transverse motion + QCD effects**
  $\lambda\neq1$, $\mu \neq 0$, $\nu \neq 0$ but $1-\lambda=2\nu$ (Lam-Tung)
- **Experiment,**
  $\lambda\neq1$, $\mu \neq 0$, $\nu \neq 0$
- $\nu \neq 0$ - Energy and quark flavour dependence, QCD radiative effects, non-coplanarity
  (PRD93, 114013 (2016), PLB 758 (2016) 384)

$$\frac{d\sigma}{dq^4 d\Omega} \propto \left(F_U^1 + F_U^2\right) \times \left\{ \begin{array}{l} 1 + A_U^1 \cos^2\theta_{CS} + \\ \sin^2\theta_{CS} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + \sin 2\theta_{CS} A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} \end{array} \right\}$$

COMPASS ongoing analysis

M. Lambertsen, W. Vogelsang **PRD93, 114013 (2016)**





Single-polarized DY x-section: transverse part

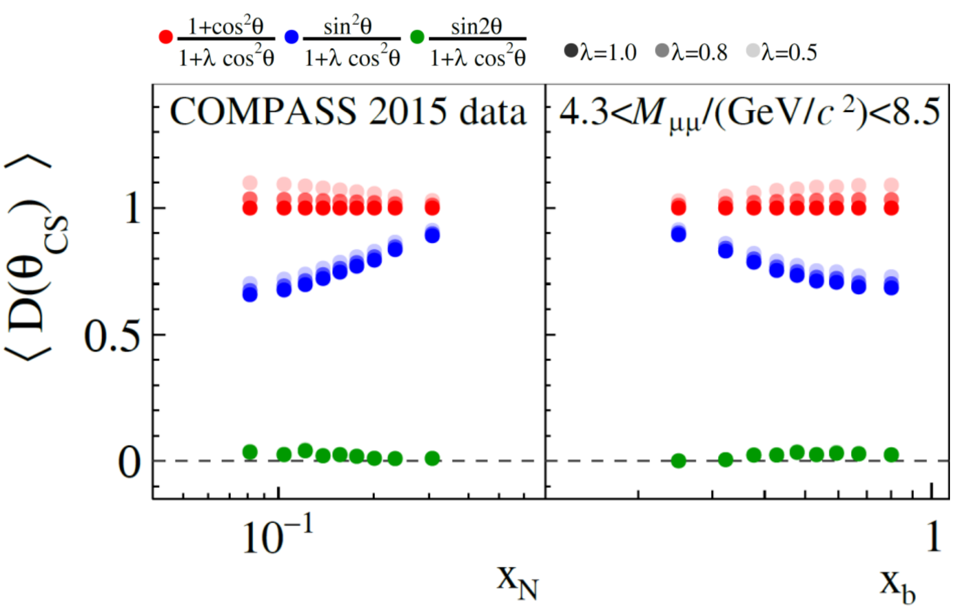
$$\lambda = A_U^1 = \frac{F_U^1 - F_U^2}{F_U^1 + F_U^2}, \mu = A_U^{\cos\varphi_{CS}}, \nu = 2A_U^{\cos 2\varphi_{CS}}$$

- **"naive" Drell–Yan model**
  collinear (k_T=0) LO pQCD no rad. processes
  $\lambda=1$, ($F_U^2=0$), $\mu=\nu=0$
- **Intrinsic transverse motion + QCD effects**
  $\lambda\neq1$, $\mu \neq 0$, $\nu \neq 0$ but $1-\lambda=2\nu$ (Lam-Tung)
- **Experiment,**
  $\lambda\neq1$, $\mu \neq 0$, $\nu \neq 0$

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

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

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



- All five Drell-Yan TSAs are extracted simultaneously using extended unbinned Maximum likelihood estimator.
- Depolarization factors are evaluated under assumption $A_U^1=1$
- Possible impact of $A_U^1\neq1$ scenarios lead to a normalization uncertainty of at most −5%.

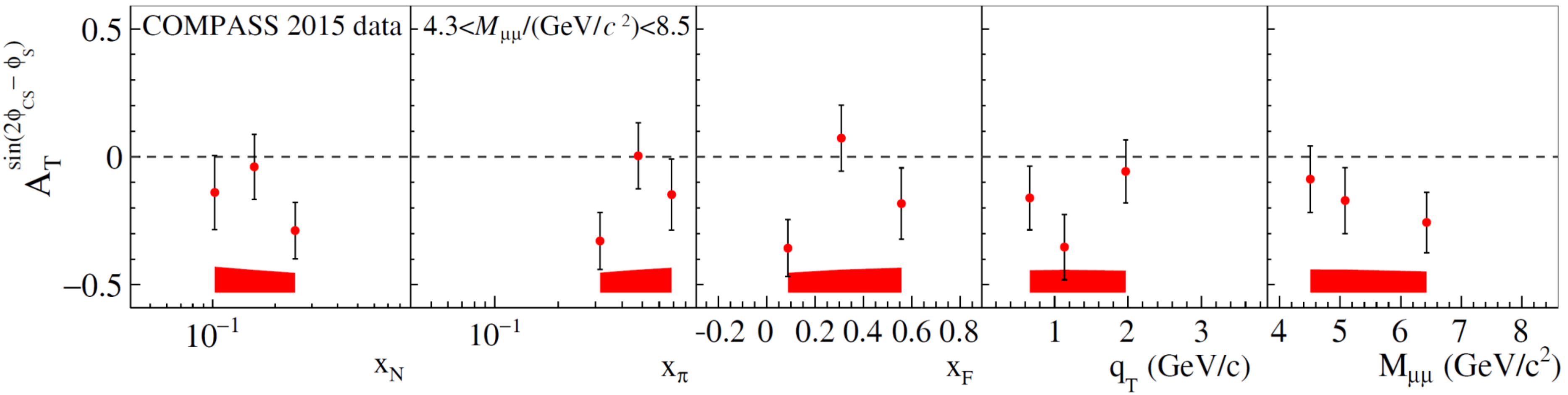
Drell-Yan TSAs – Transversity

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

Transversity DY TSA

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

COMPASS **PRL 119, 112002 (2017)**



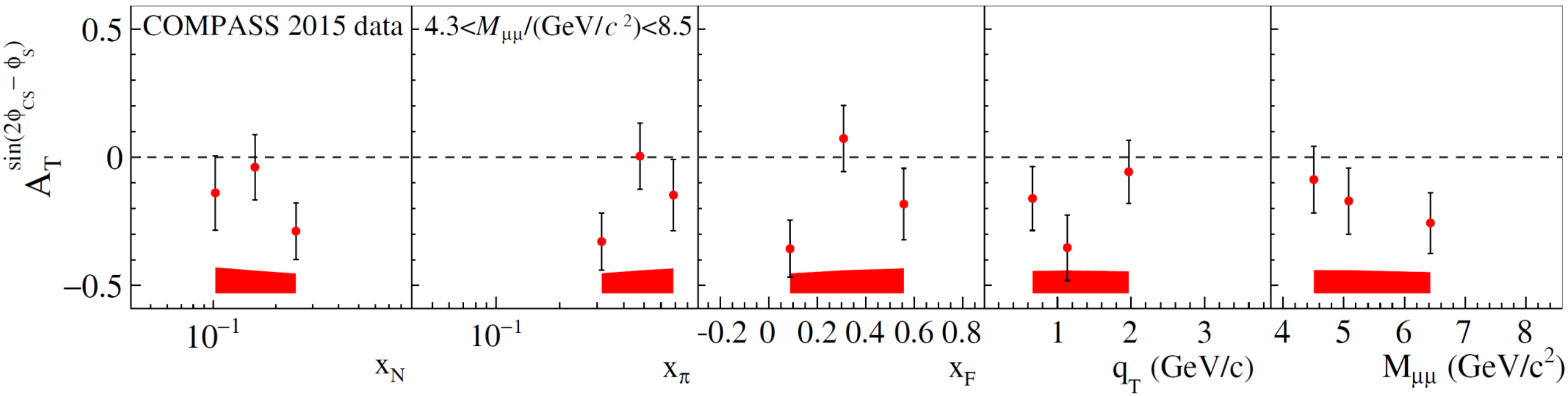
Drell-Yan TSAs – Transversity

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

Transversity DY TSA

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

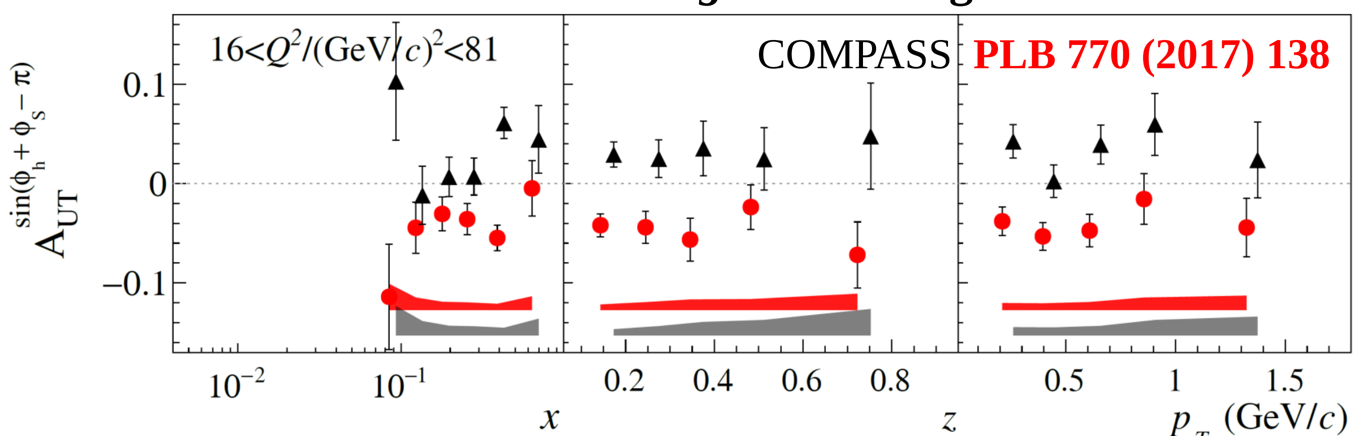
COMPASS PRL 119, 112002 (2017)



SIDIS in Drell-Yan *high-mass* range

Collins SIDIS TSA

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



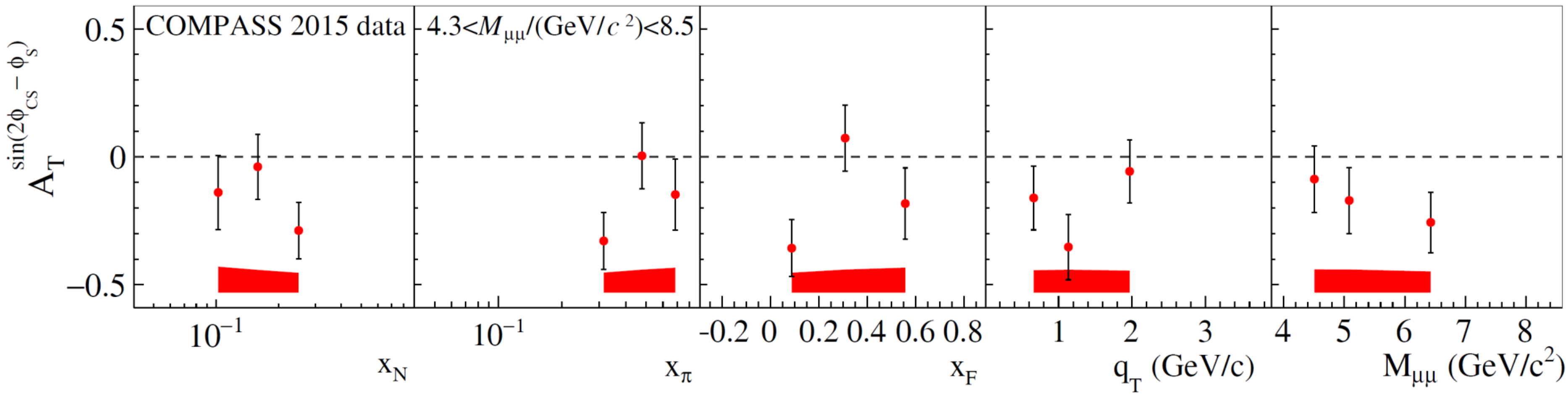
Drell-Yan TSAs – Transversity

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

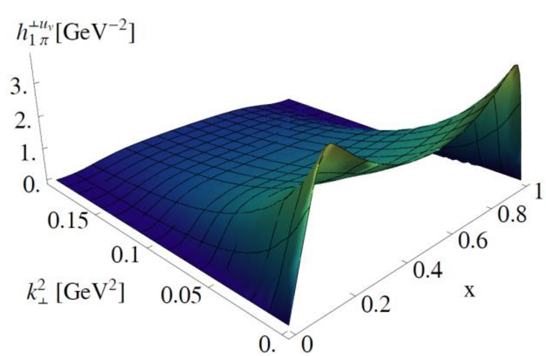
Transversity DY TSA

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

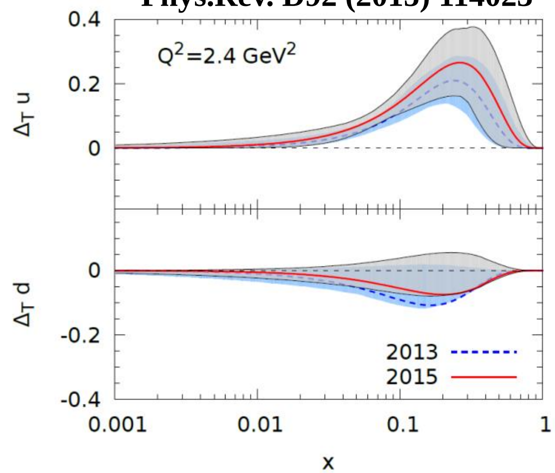
COMPASS PRL 119, 112002 (2017)



B. Pasquini, P. Schweitzer
Phys.Rev. D90 (2014) 014050



M. Anselmino et al.
Phys.Rev. D92 (2015) 114023



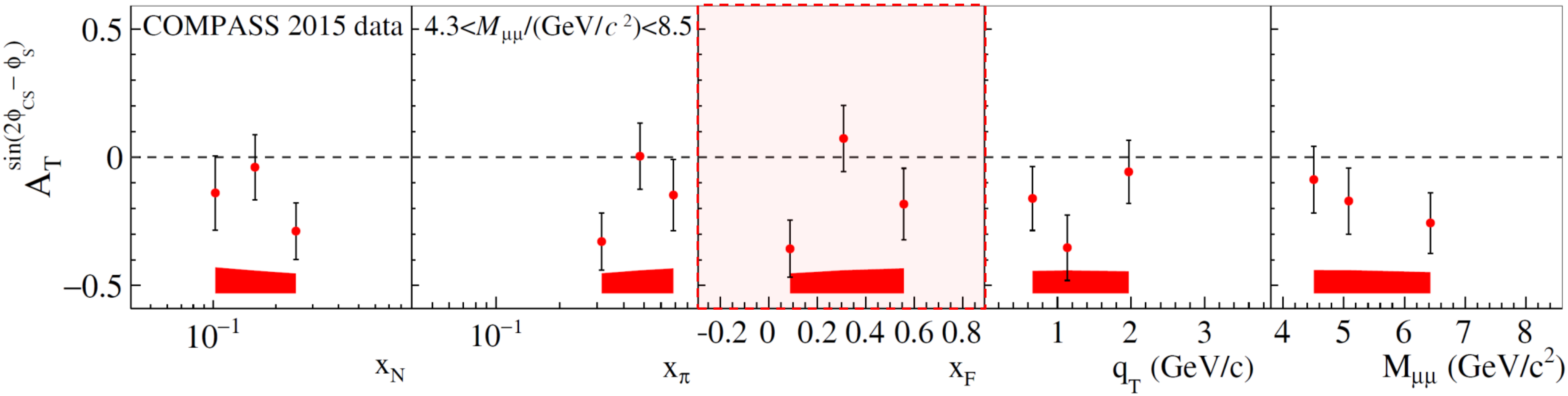
Drell-Yan TSAs – Transversity

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

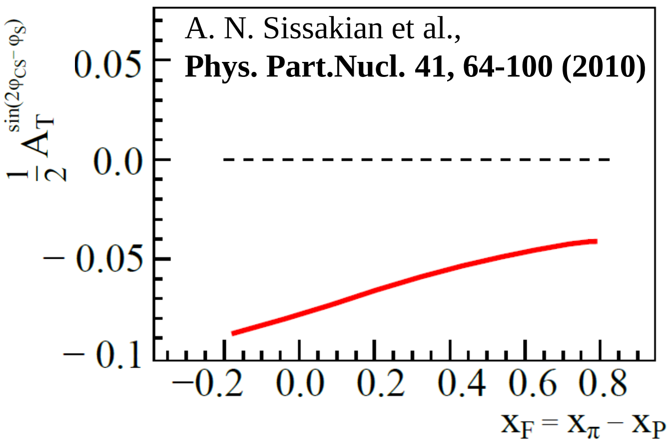
Transversity DY TSA

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

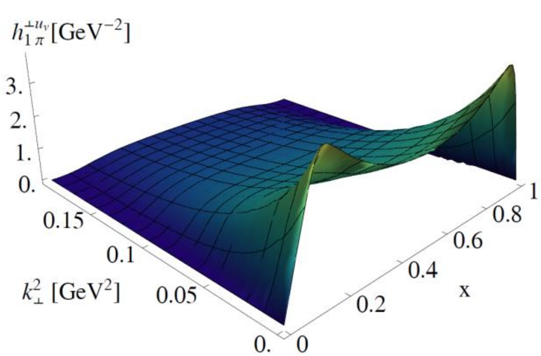
COMPASS PRL 119, 112002 (2017)



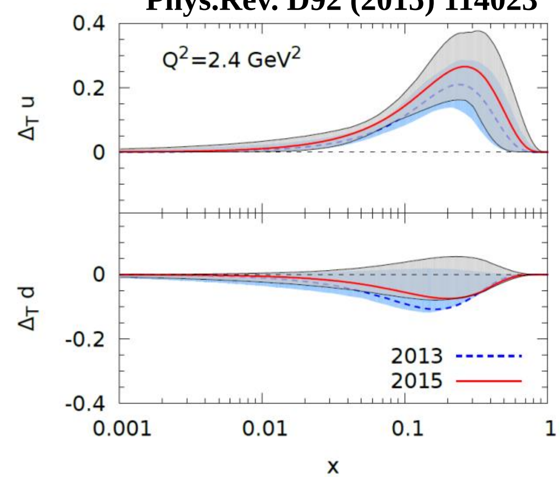
A. N. Sissakian et al.,
Phys. Part.Nucl. 41, 64-100 (2010)



B. Pasquini, P. Schweitzer
Phys.Rev. D90 (2014) 014050



M. Anselmino et al.
Phys.Rev. D92 (2015) 114023



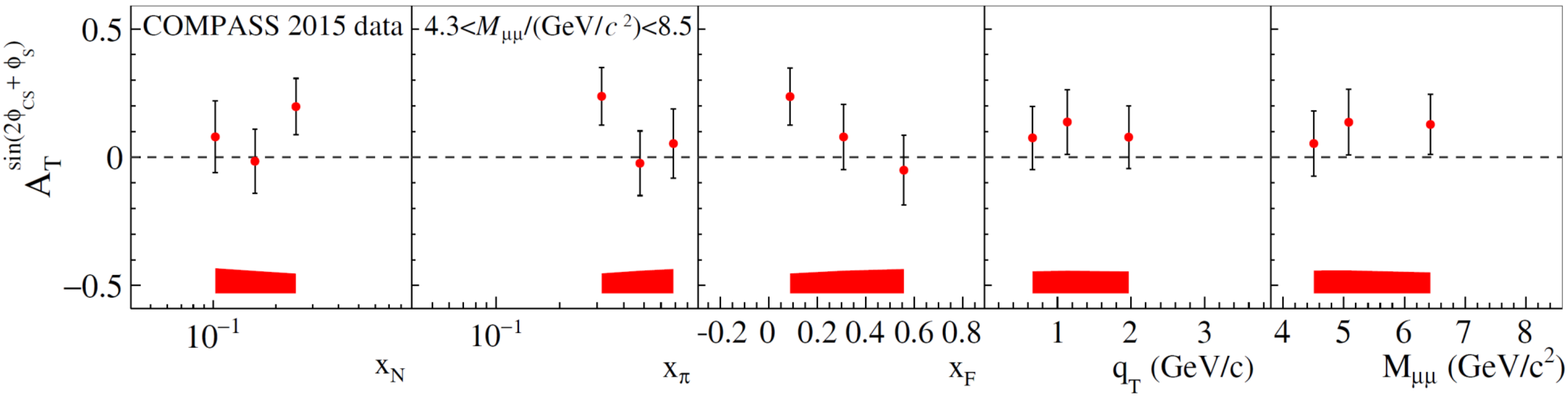
Drell-Yan TSAs – Pretzelosity

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

Pretzelosity DY TSA

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

COMPASS PRL 119, 112002 (2017)



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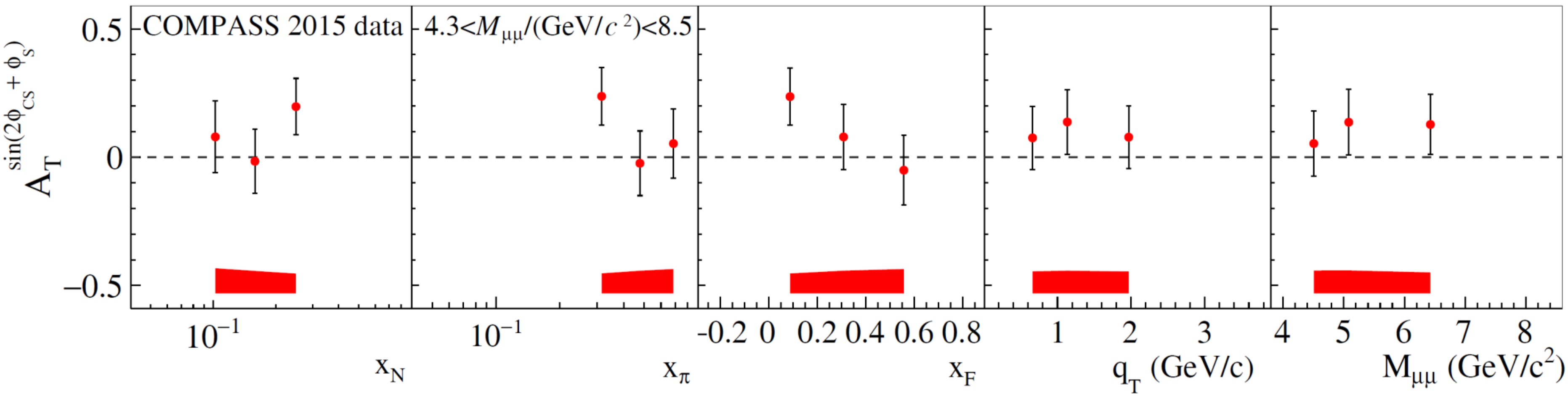
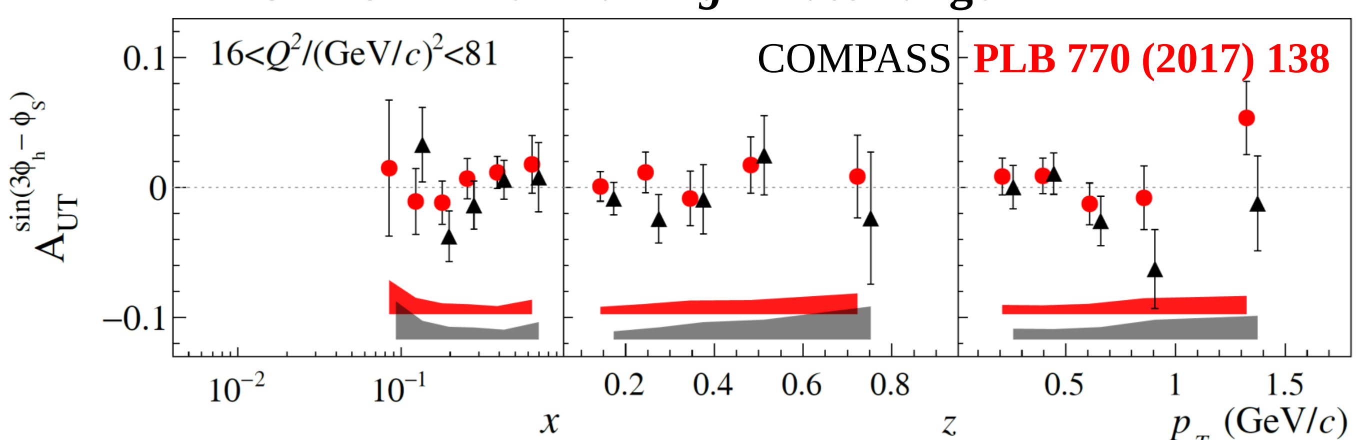
COMPASS PRL 119, 112002 (2017)



Pretzelosity SIDIS TSA

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

SIDIS in Drell-Yan *high-mass* range



Drell-Yan TSAs – Pretzelosity

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

Pretzelosity DY TSA

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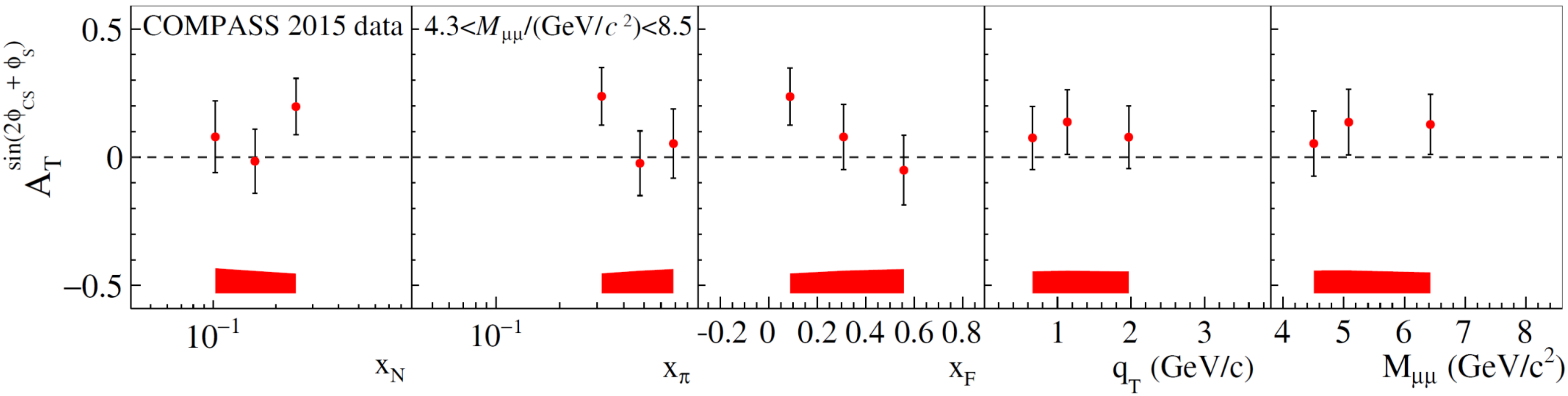
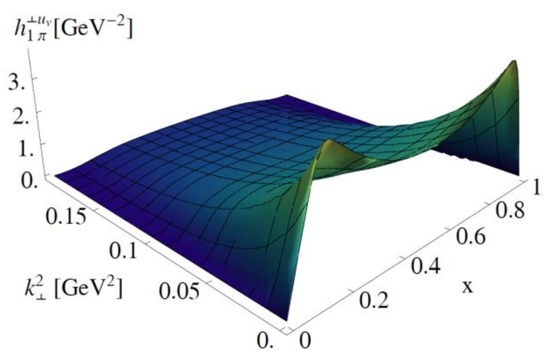
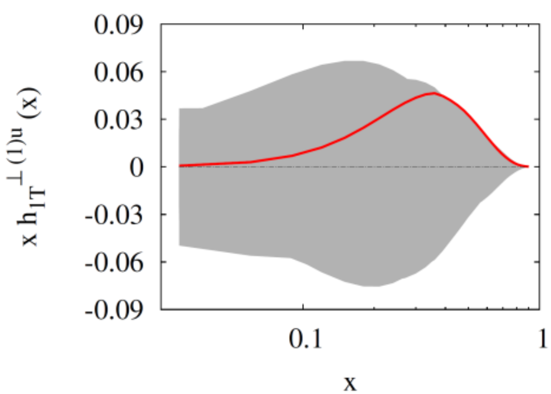
COMPASS PRL 119, 112002 (2017)



B. Pasquini, P. Schweitzer
Phys.Rev. D90 (2014) 014050



C. Lefky, A. Prokudin
PRD91 (2015) 034010



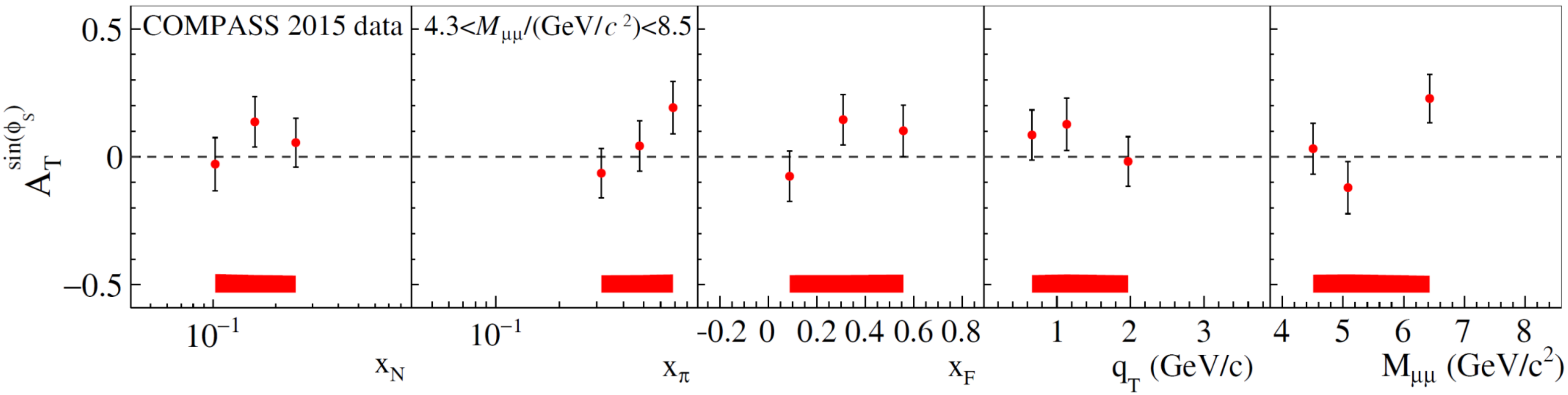
Drell-Yan TSAs – Sivers

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

Sivers DY TSA

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

COMPASS **PRL 119, 112002 (2017)**



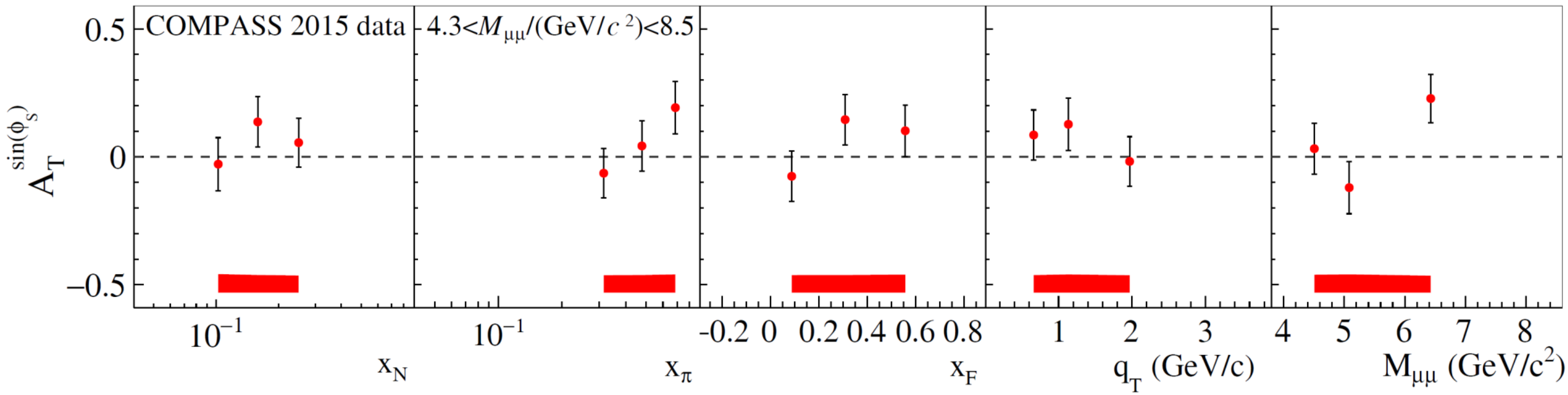
Drell-Yan TSAs – Sivers

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

Sivers DY TSA

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

COMPASS PRL 119, 112002 (2017)

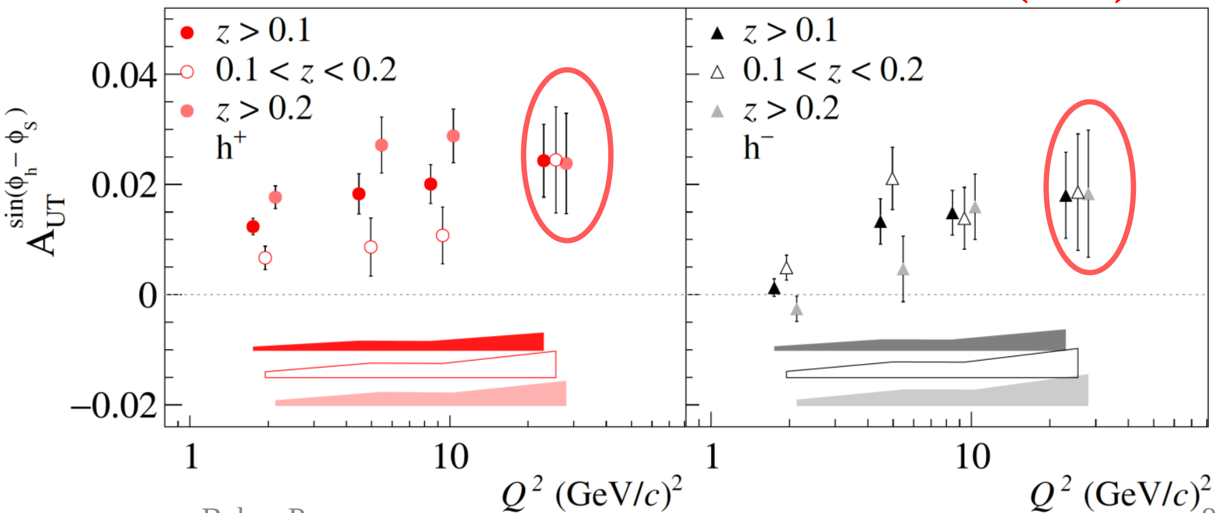


SIDIS in Drell-Yan *high-mass* range

COMPASS **PLB 770 (2017) 138**

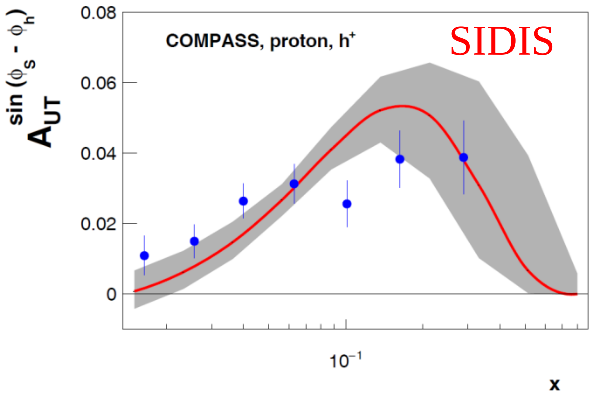
Sivers SIDIS TSA

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

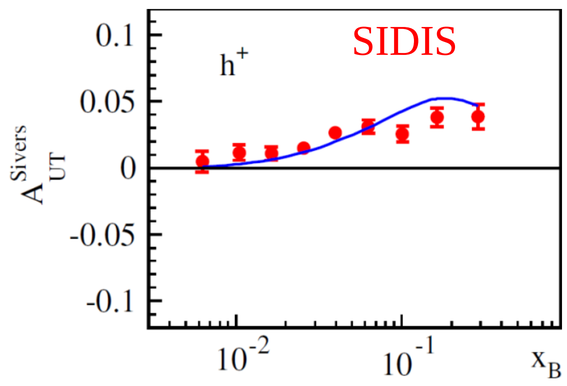


Sivers asymmetry in Drell-Yan: sign change

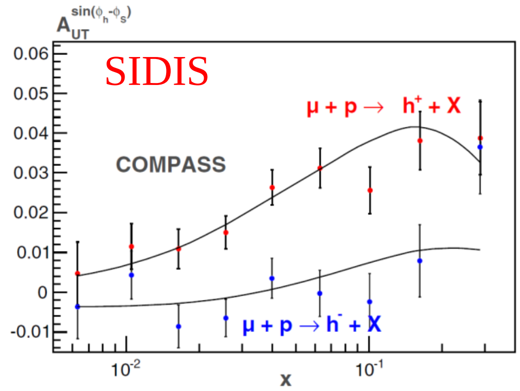
DGLAP (2016)
M. Anselmino et al., **JHEP 1704 (2017) 046**



TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**

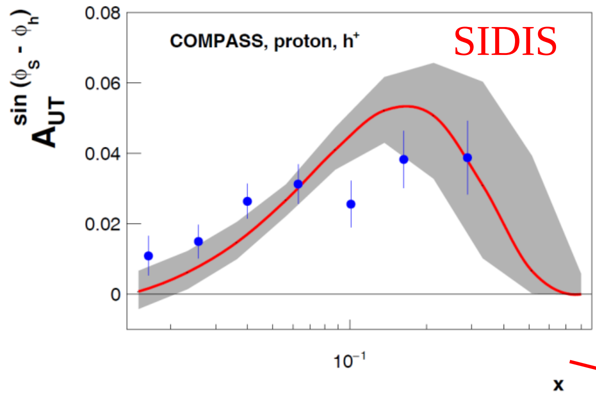


TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**

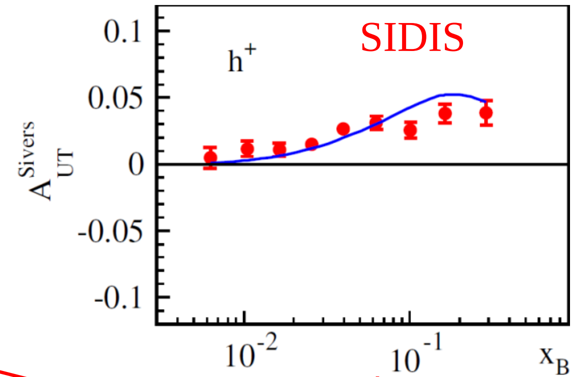


Sivers asymmetry in Drell-Yan: sign change

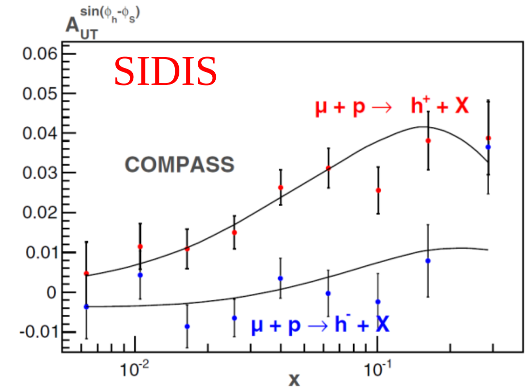
DGLAP (2016)
M. Anselmino et al., **JHEP 1704 (2017) 046**

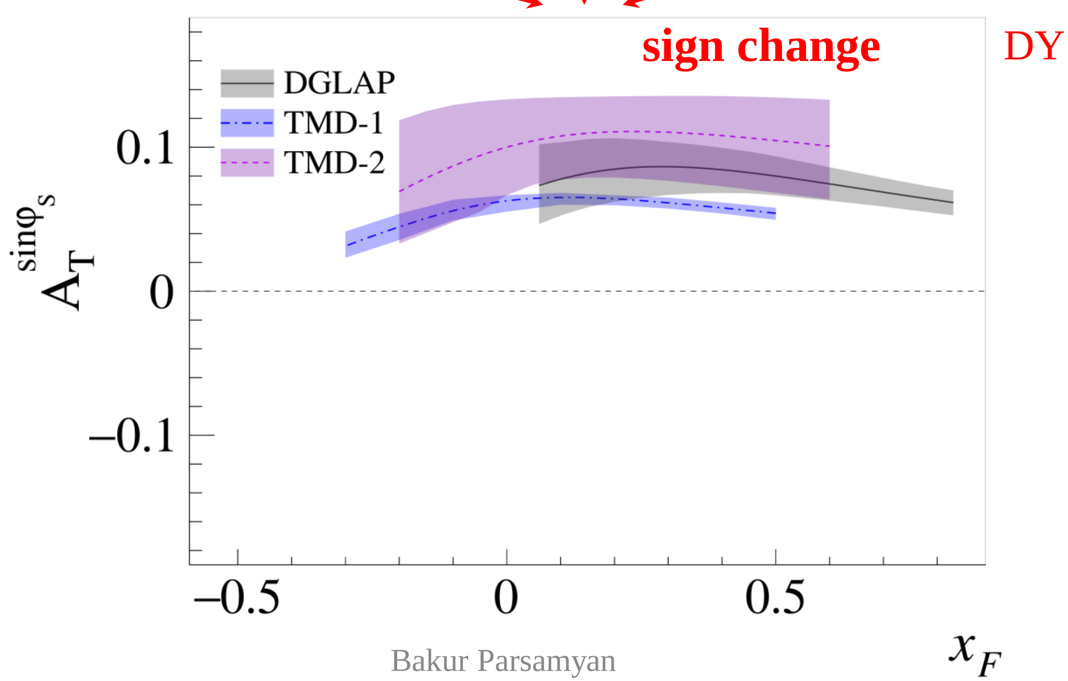


TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



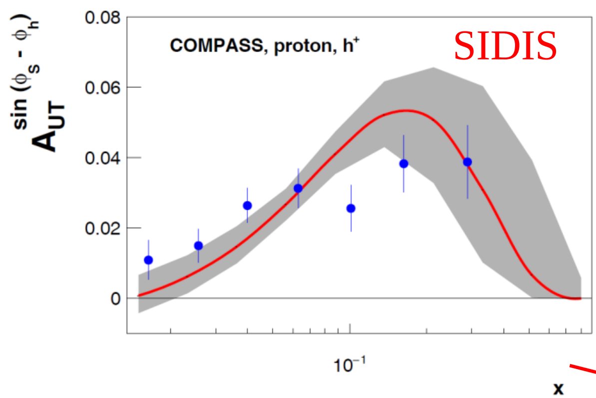
TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**



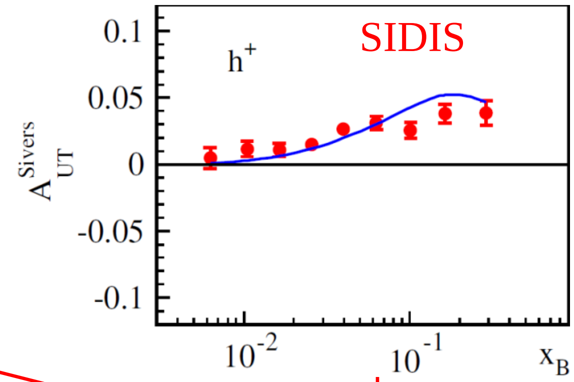


Sivers asymmetry in Drell-Yan: sign change

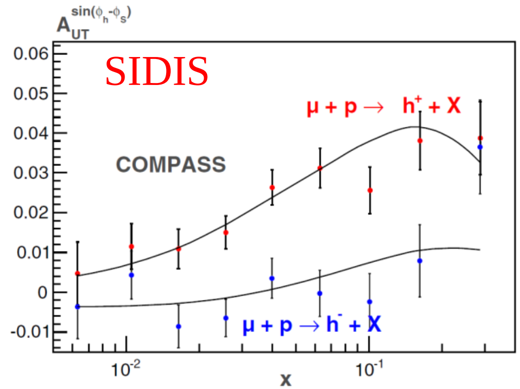
DGLAP (2016)
M. Anselmino et al., **JHEP 1704 (2017) 046**

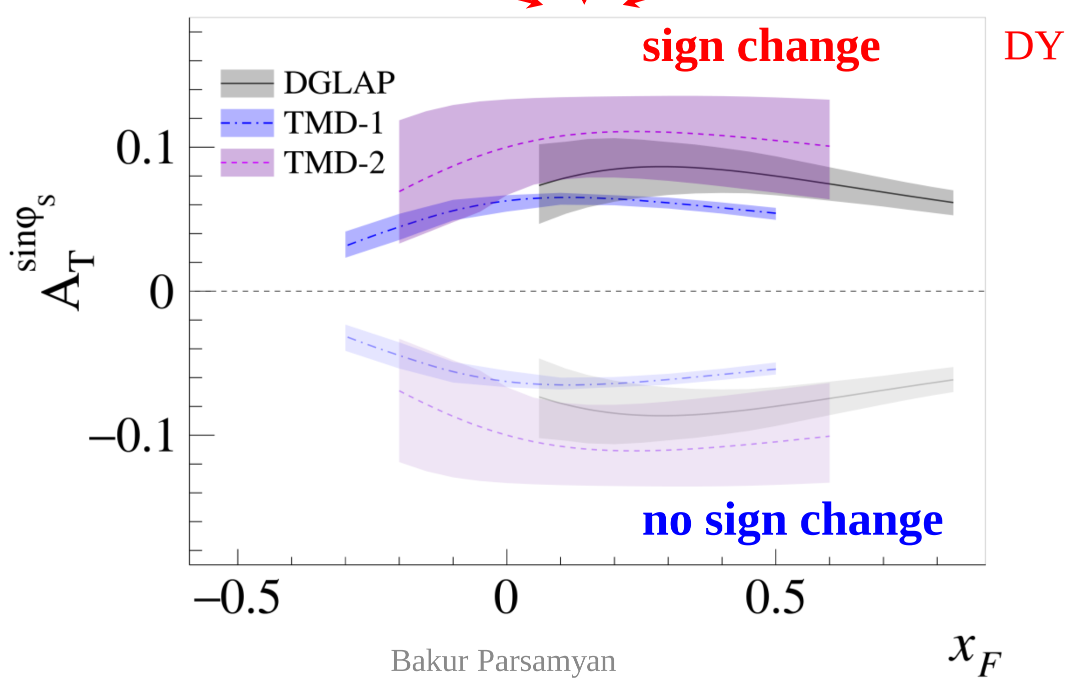


TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



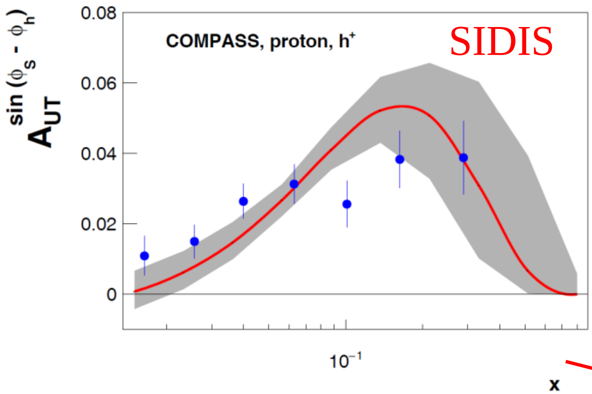
TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**



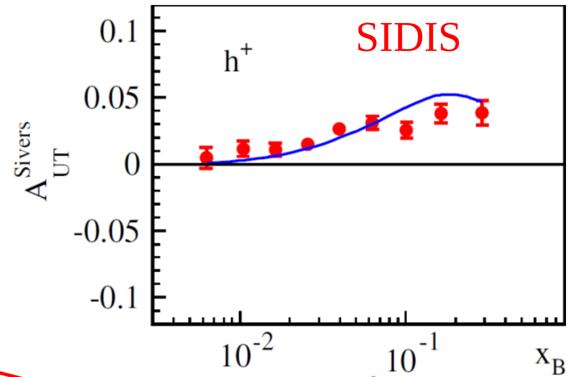


Sivers asymmetry in Drell-Yan: sign change

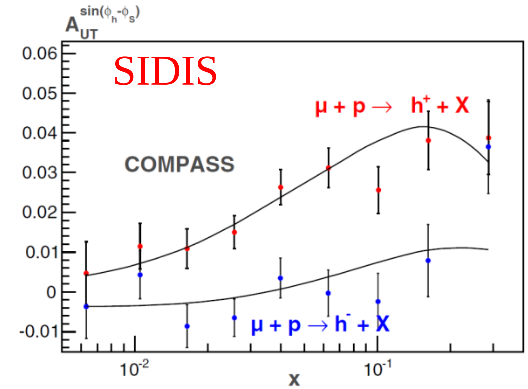
DGLAP (2016)
M. Anselmino et al., **JHEP 1704 (2017) 046**



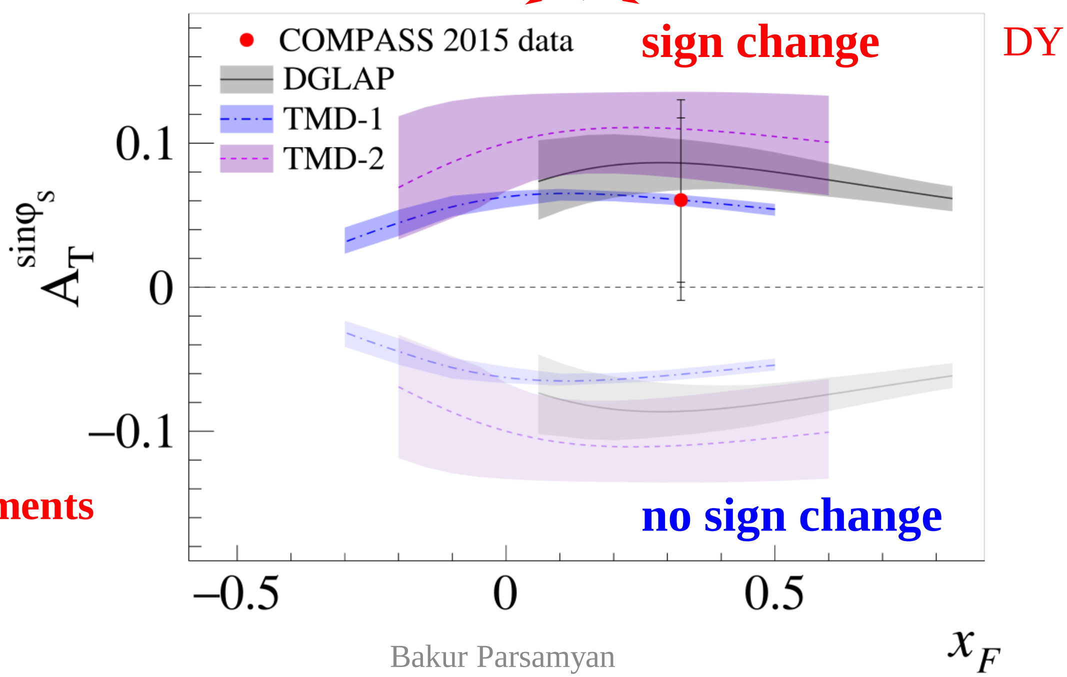
TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**



COMPASS
PRL 119, 112002 (2017)



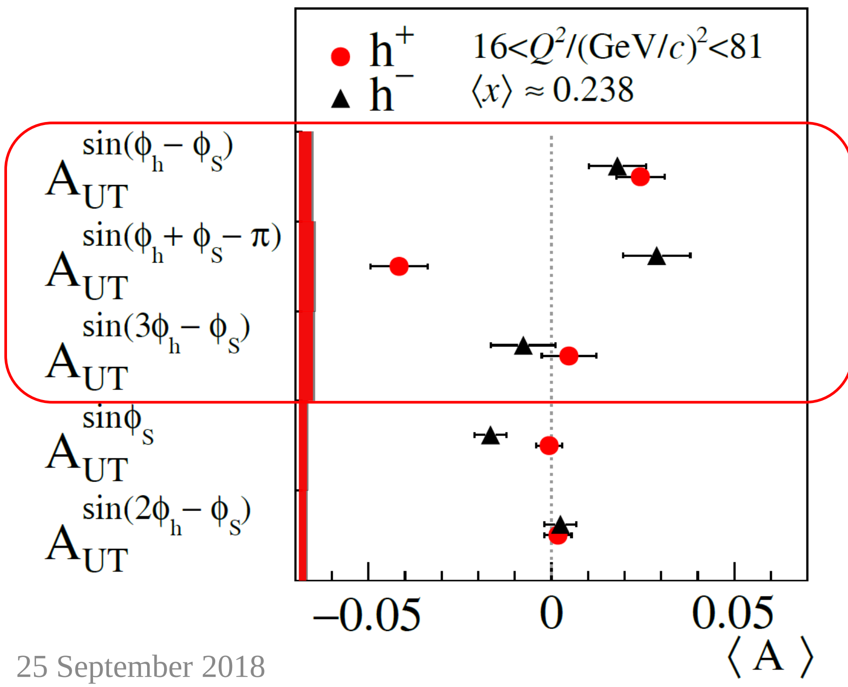
In 2018 – 2nd round of polarized DY measurements at COMPASS

SIDIS and DY TSAs at COMPASS (high-mass range)

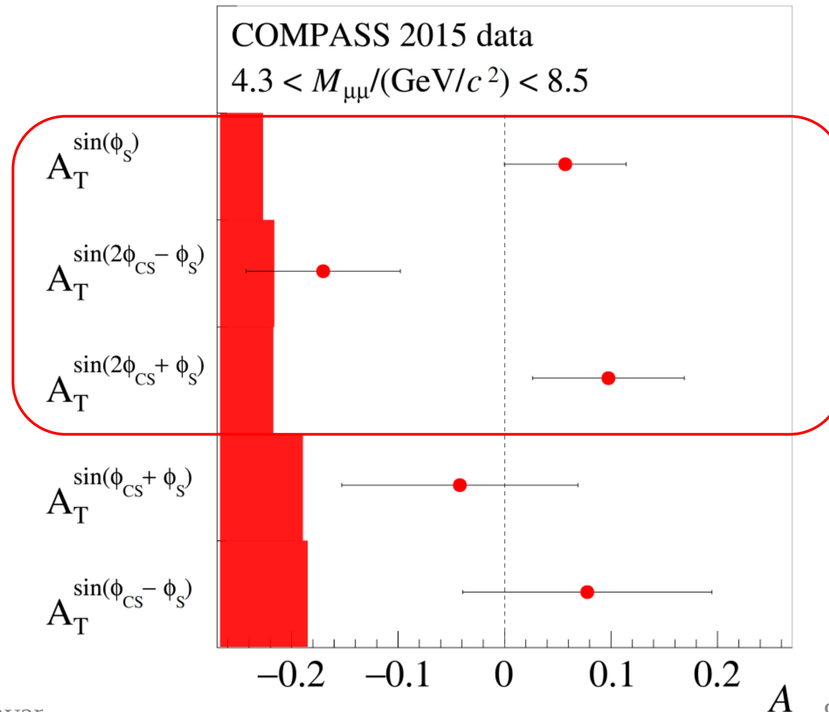
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{ 1 + \ldots + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h - \phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h + \phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}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

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

COMPASS PLB 770 (2017) 138



COMPASS PRL 119, 112002 (2017)



A new QCD facility at the M2 beam line of the CERN SPS

COMPASS beyond 2020 workshop, CERN, March 21-22, 2016
Physics Beyond Colliders kick-off workshop CERN, September 6-7, 2016
IWHSS17 COMPASS workshop, Cortona, Italy, April 2-5, 2017
Dilepton Productions with Meson and Antiproton Beams workshop, ECT*, Trento, Italy, November 2017
Physics Beyond Colliders annual workshop, CERN, November 21-22, 2017
IWHSS18 – COMPASS workshop, Bonn, Germany, March 19-21, 2018
Mini Workshop for a QCD Facility at the SPS after 2021 – CERN, 20 June 2018
IWHSS19 – COMPASS workshop, Aveiro, Portugal, June 23-28, 2019

Letter of Intent (Draft 1.0)
arXiv:1808.00848 [hep-ex]

A new QCD facility at the M2 beam line of the CERN SPS

COMPASS

Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware Additions
μp elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^{\pm}$	high-pr. H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	$\mu^{\pm}$	$NH_3^{\uparrow}$	2022 2 years	recoil silicon, modified PT magnet
Input for DMS	$\overline{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	LHe target
$\overline{p}$-induced Spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	2022 2 years	target spectr.: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^{\pm}$	C/W	2022 1-2 years	
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	~100	10^8	25-50	$K^{\pm}, \overline{p}$	$NH_3^{\uparrow}$, C/W	2026 2-3 years	"active absorber", vertex det.
Primakoff (RF)	Kaon polarisi-bility & pion life time	~100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^{\pm}$ $\pi^{\pm}$	LH2, Ni	non-exclusive 2026 1-2 years	hodoscope
K-induced Spectroscopy (RF)	High-precision strange-meson spectrum	50-100	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^{\pm}, \pi^{\pm}$	from H to Pb	2026 1 year	

Standard muon beams Standard hadron beams RF-separated hadron beams

A new QCD facility
at the M2 beam line of the CERN SPS

HOME DOCUMENTS WORKSHOPS TIMELINES I AM INTERESTED

Welcome

Over the past four decades, measurements at the external beam lines of the CERN SPS have been at the center of worldwide attention. These experimental results have challenged QCD as our theory describing visible matter, thus serving as important input to develop improvements of the theory.

As of today, these beam lines remain unique and bear great potential for a significant future advancement of our understanding of hadronic matter. Hence we propose to establish a world-unique QCD facility that will use the external SPS M2 beam line in conjunction with a universal spectrometer in the experimental hall EHN2. After a major upgrade in a second phase, it will be possible to produce unique beams with considerably enhanced fractions of kaons or anti-protons, thereby opening access to a wide range of new physics opportunities.

The Letter of Intent available on this site is summarizing most of the present ideas for possible future measurements to be performed at the CERN M2 beam line. It was prepared with the objective to serve as a basis for building a broad community dedicated to these new studies. During the forthcoming year the document is expected to evolve towards a full proposal for a new experimental facility.
It is planned to be ready in time for the 2019/2020 Update of the European Strategy for Particle Physics.

I am interested to join e-mail list of NQF to stay updated

Your name *

Your email address *

Message for us

Send message Preview

- Home
- Documents
- Workshops
- Timelines
- I am interested

Contact

CERN
CH-1211 Geneva 23
Switzerland

NQF-M2@cern.ch

https://nqf-m2.web.cern.ch

Conclusions

- During phase I COMPASS has measured all possible SIDIS azimuthal LSAs and TSAs
  - Recently COMPASS has performed first multidimensional analysis of SIDIS proton TSAs: PLB 770 (2017) 138
    - No hints for significant Q^2-dependences of Sivers and Collins TSAs
    - 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
  - COMPASS has measured SIDIS proton LSAs with unprecedented precision
    - *twist-2* $A_{UL}^{\sin 2\phi_h}$ asymmetry seem to exhibit a Collins-like behavior
    - Significant effect was observed for *subleading-twist* $A_{UL}^{\sin\phi_h}$ LSA
- In 2015 COMPASS has successfully collected first ever polarized DY data PRL 119, 112002 (2017)
  - A second year of polarized DY data-taking will take place in 2018
- COMPASS-II proposal addendum: SIDIS run in 2021 with transversely polarized deuteron target was recently approved!

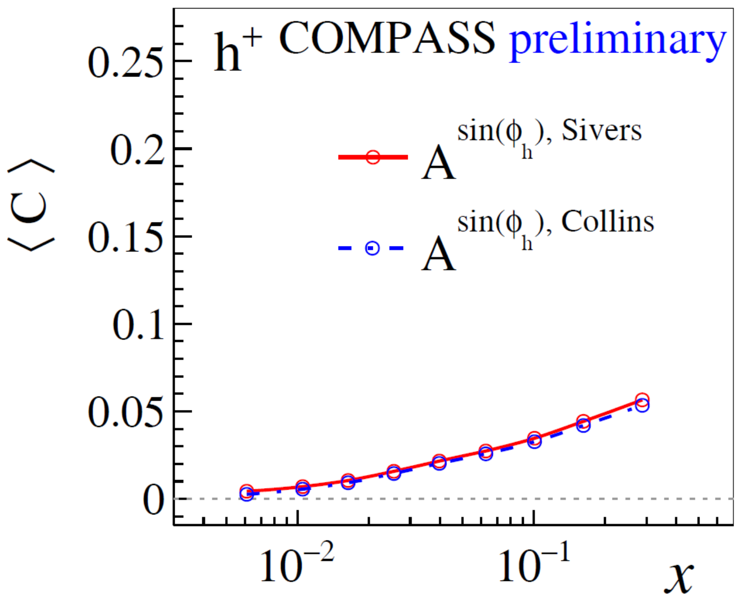
- Prospects for a future experiment at CERN (SPS M2) are being actively discussed
  - Letter of Intent (Draft 1.0) is now public - arXiv:1808.00848 [hep-ex]
  - Particular attention is given to possible Drell-Yan measurements

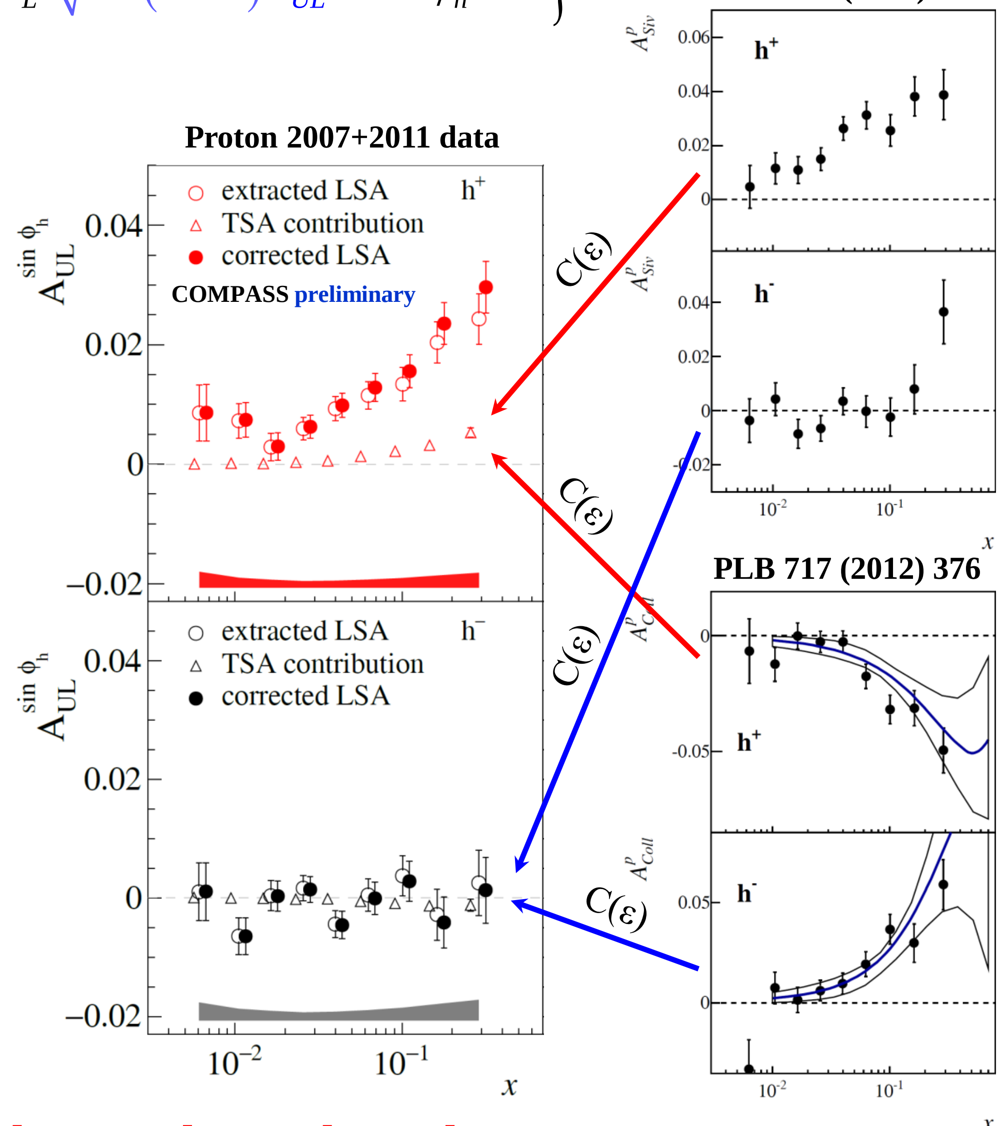
Spare slides

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

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

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





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

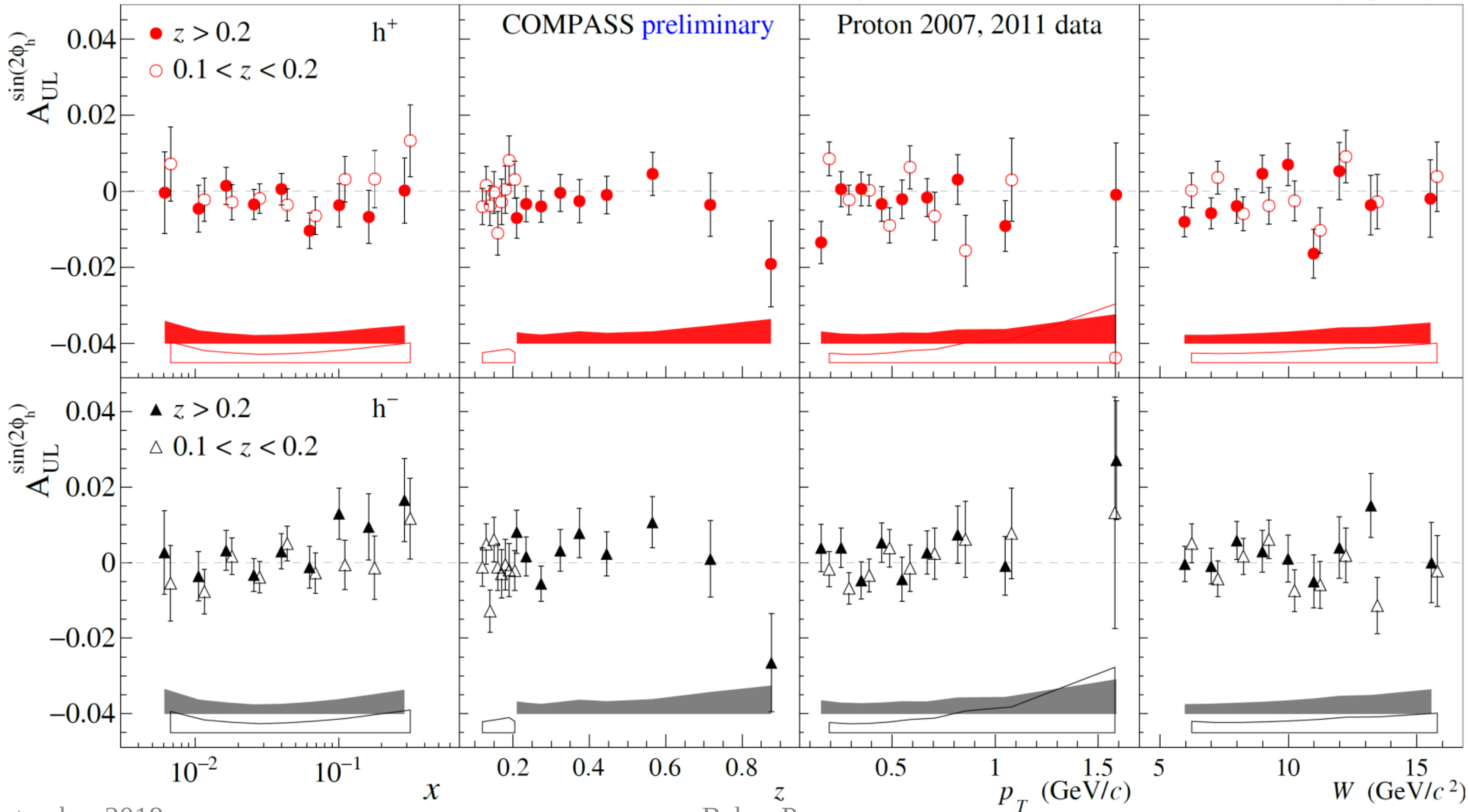
SIDIS: target longitudinal spin dependent asymmetries

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

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

- Only "twist-2" ingredients
- Additional p_T-suppression

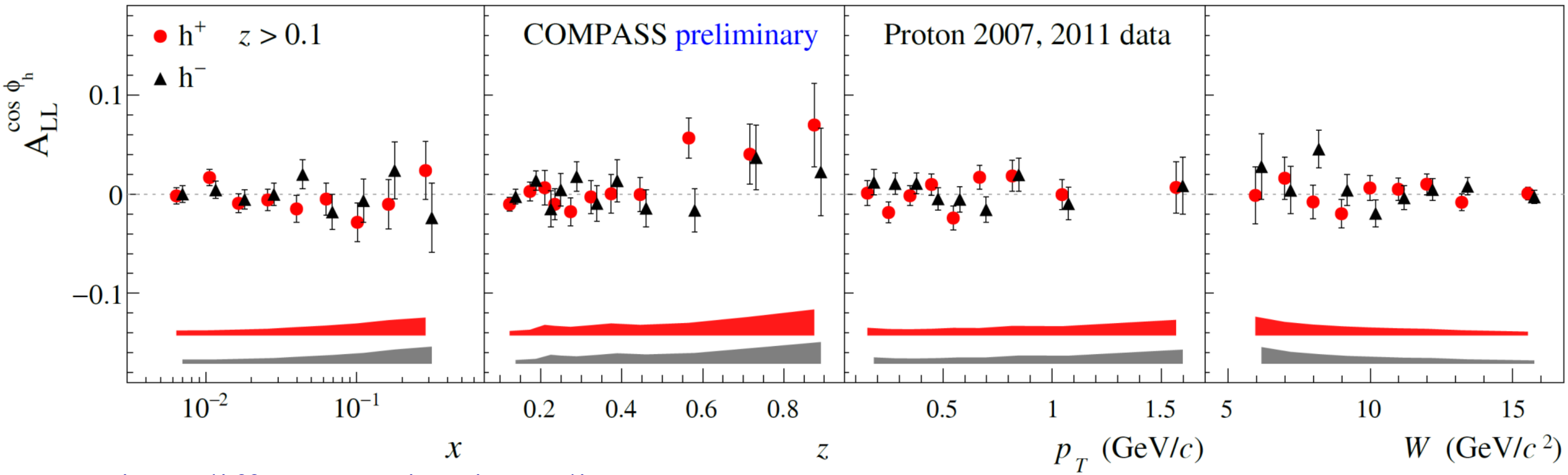
B. Parsamyan (for COMPASS) arXiv:1801.01488 [hep-ex] (DIS-2017)



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

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

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



- Various different “twist” ingredients,
- Q-suppression

SIDIS: target longitudinal spin dependent asymmetries

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

COMPASS collected large amount of L-SIDIS data

Unprecedented precision!

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

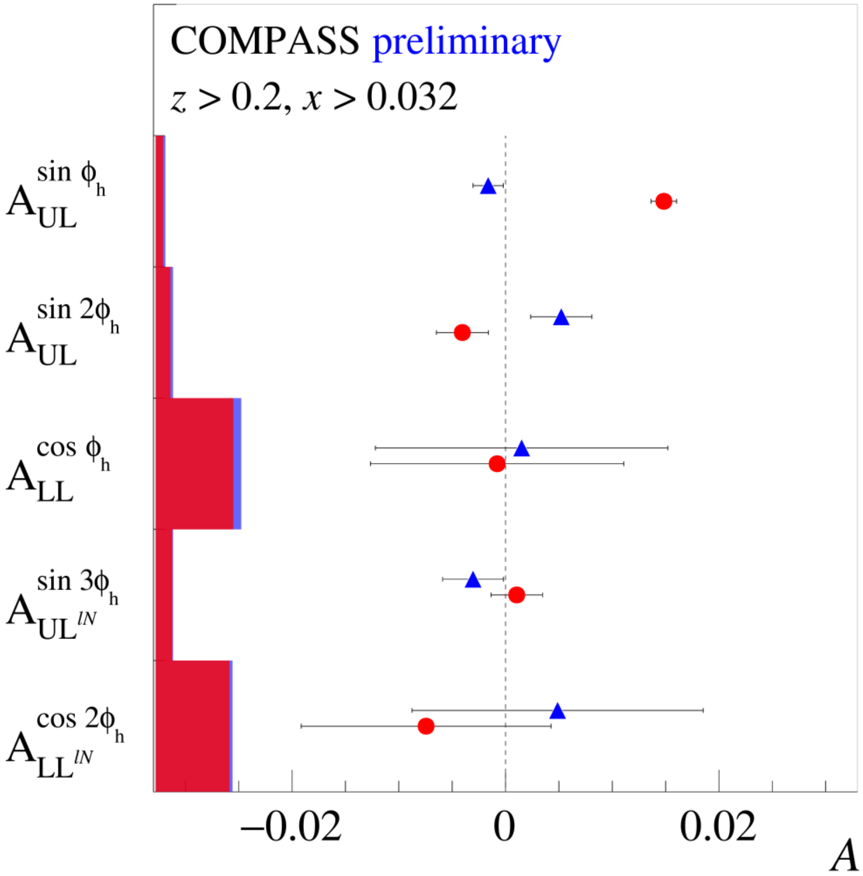
- Q-suppression, Various different "twist" ingredients
- Sizable TSA-mixing
- **Significant h^+ asymmetry, clear *z*-dependence,**
- **h^- compatible with zero**

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

- 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**

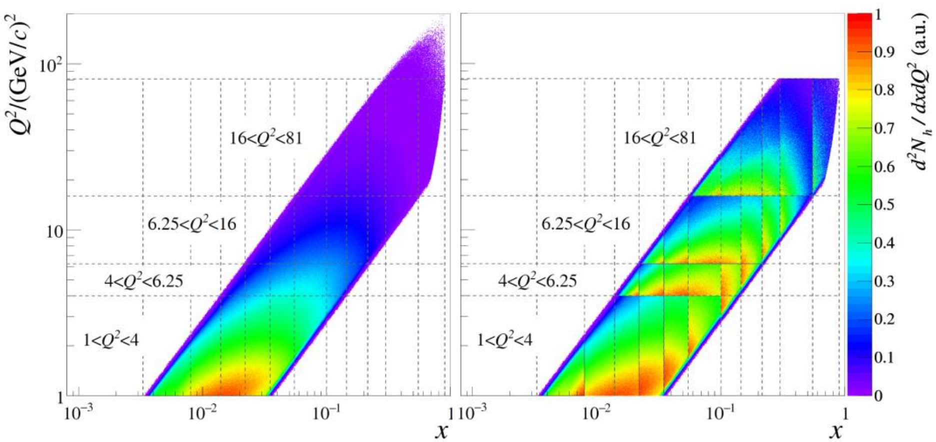


SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

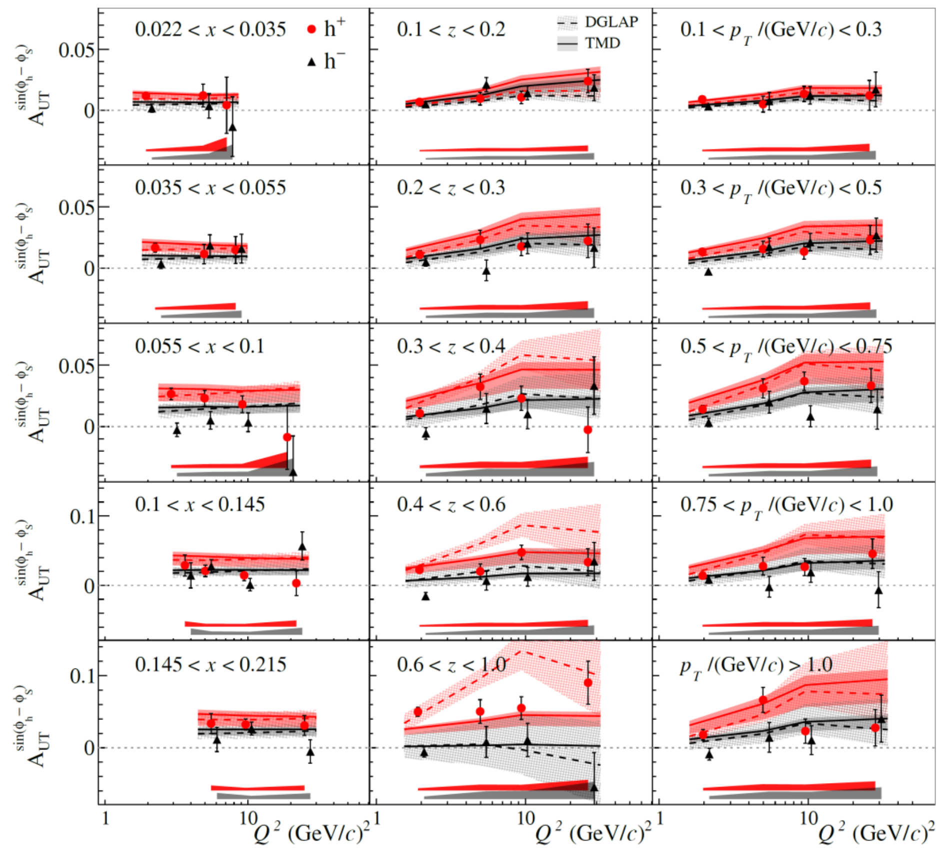
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \ldots\right\}$$

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

COMPASS PLB 770 (2017) 138



Multi-dimensional input for TMD evolution studies



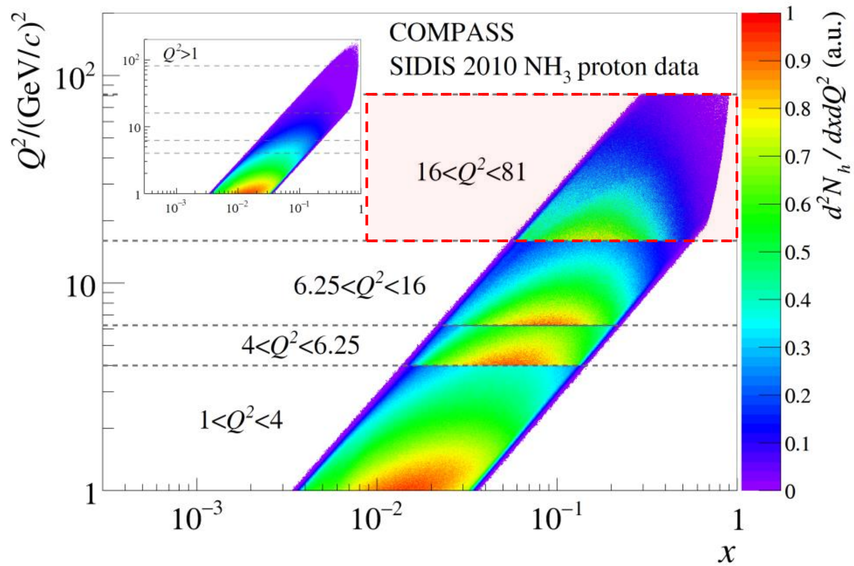
The solid (dashed) curves represent the calculations for TMD (DGLAP) evolution for the Sivers TSAs based on the best fit of 1D COMPASS and HERMES data from **Phys. Rev. D86 (2012) 014028** by M. Anselmino et al.

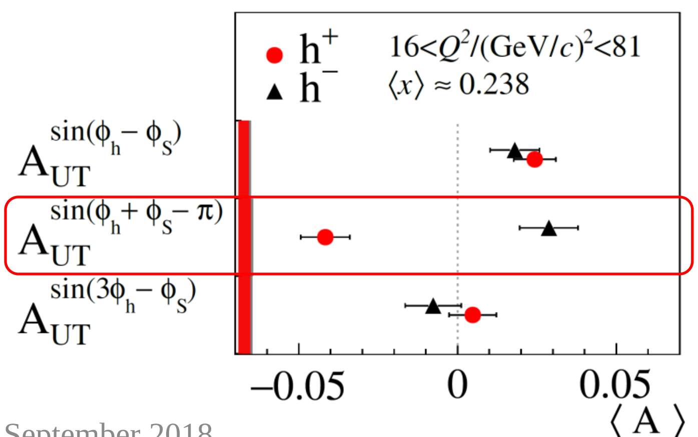
- No clear Q^2-dependence within statistical accuracy
- Possible decreasing trend for Sivers TSA?

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

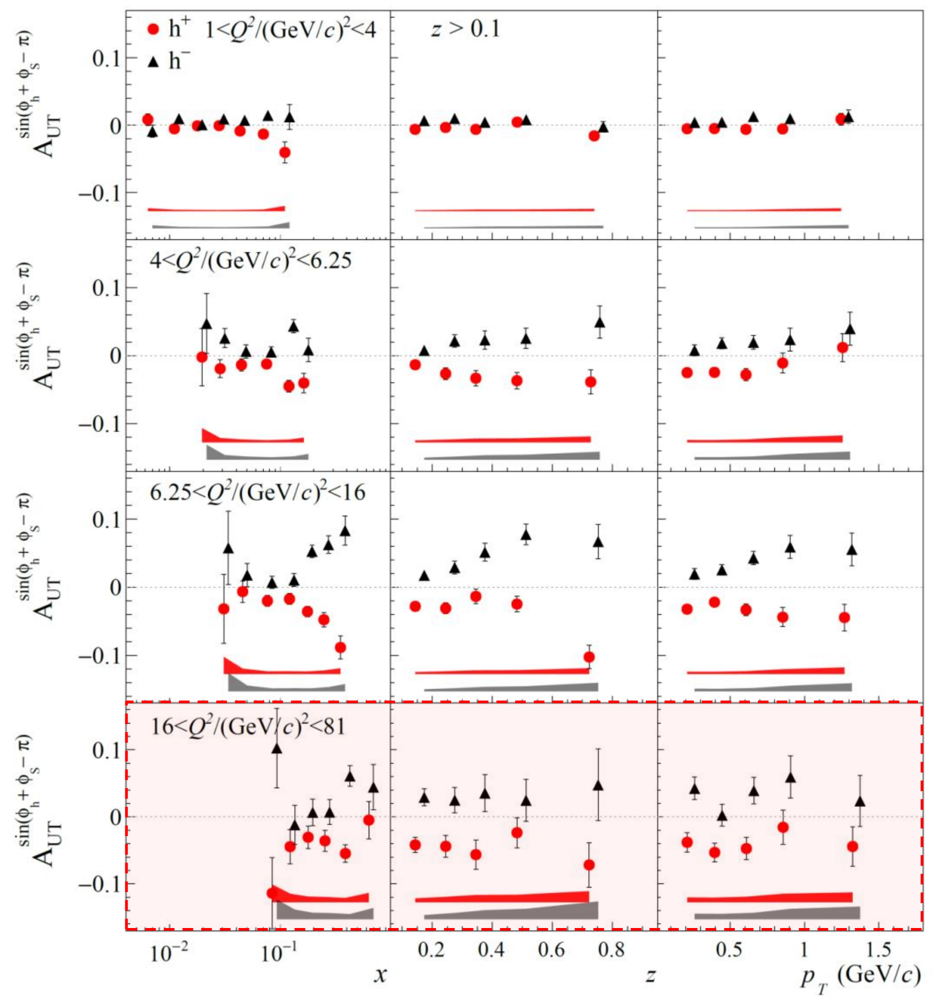
$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\right\}$$

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





COMPASS PLB 770 (2017) 138



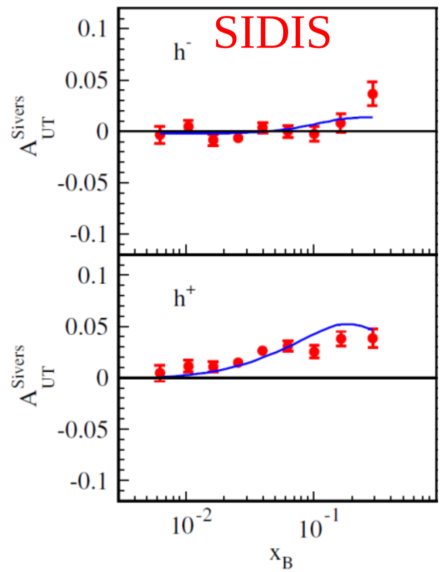
SIDIS TSAs (Sivers)

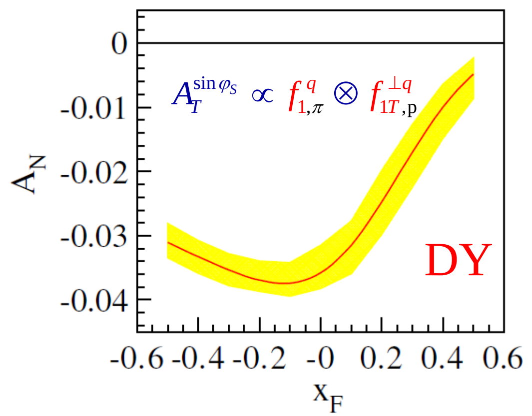
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \ldots\right\}$$

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

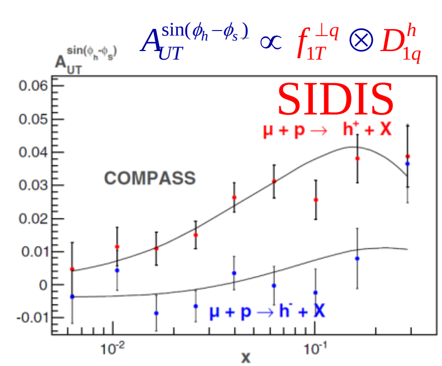
- Measured on proton and deuteron
- Recently - gluon Sivers paper PLB 772 (2017) 854
- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results (Q^2 is different by a factor of ~2-3)
- **Q^2-evolution? Intriguing result!**
- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan
- Sivers TMD PDF is predicted to change the sign between SIDIS and DY

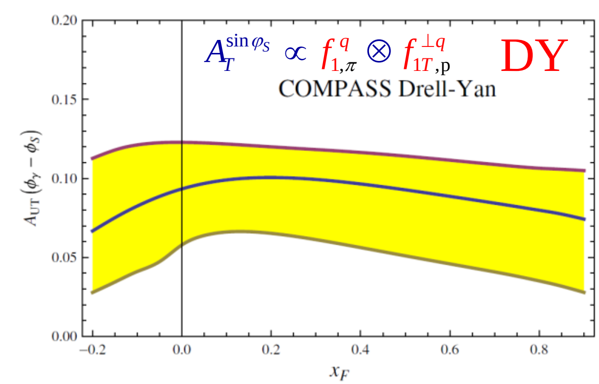
M.G. Echevarria, A.Idilbi, Z.B. Kang and I. Vitev, **PRD 89 074013 (2014)**





P. Sun and F. Yuan, **PRD 88 11, 114012 (2013)**

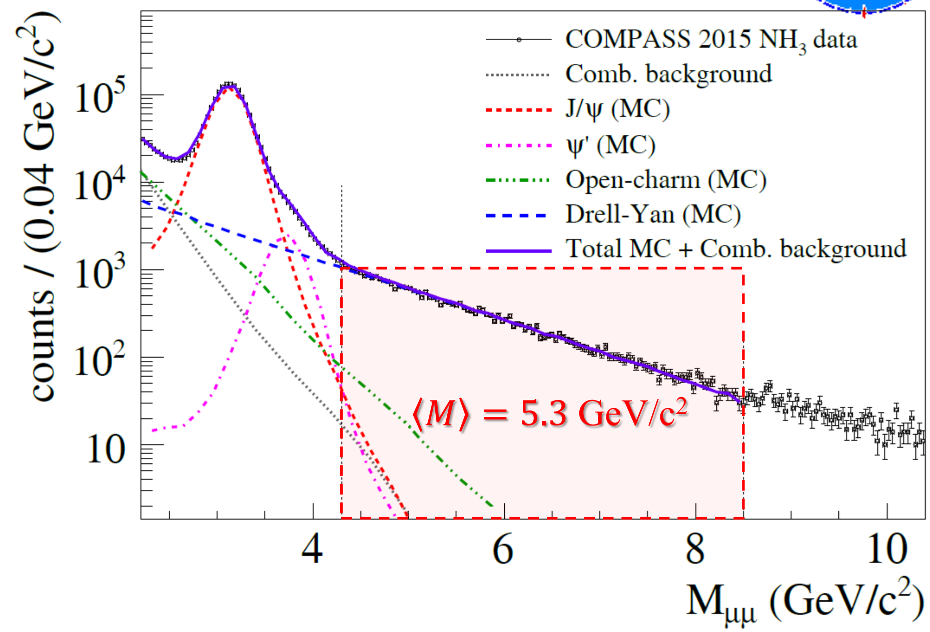




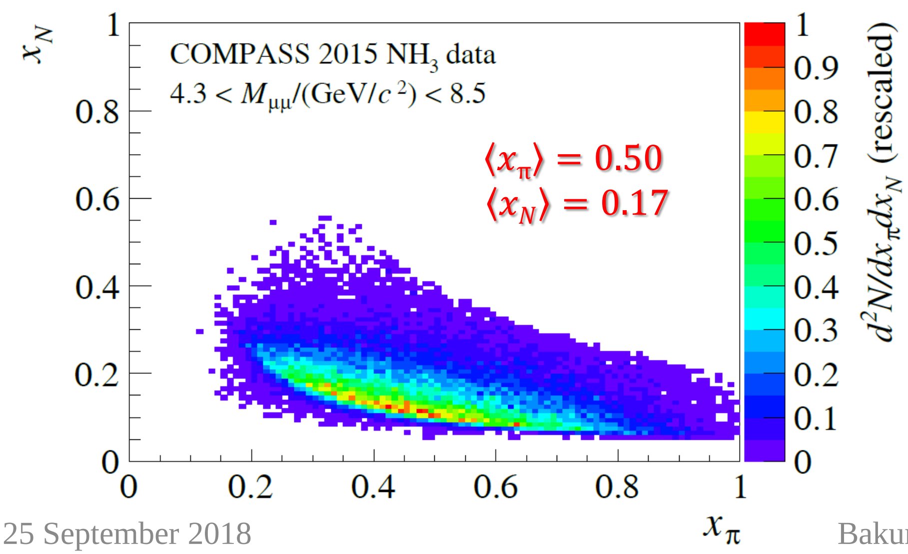
COMPASS DY: high mass range

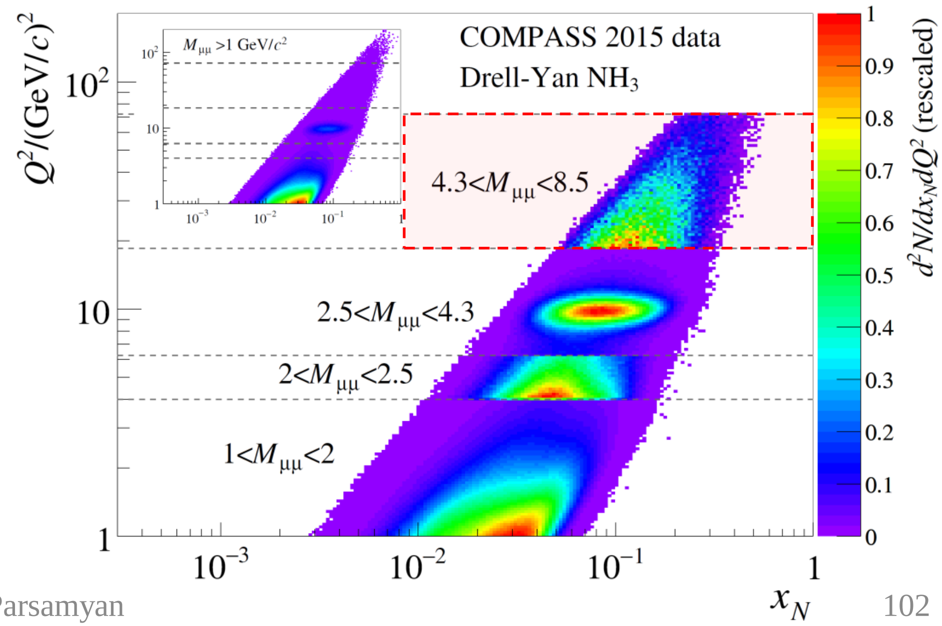
- $1.0 < M/(GeV/c^2) < 2.0$ "Low mass"
  - Large background contamination, combinatorial, Open-charm (B) $D\bar{D}$, $B\bar{B}$, π, K decays
- $2.0 < M/(GeV/c^2) < 2.5$ "Intermediate mass"
  - High DY-cross section
  - Still low DY-signal/background ratio
- $2.5 < M/(GeV/c^2) < 4.3$ "Charmonia mass"
  - 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

Final sample: 35 000 dimuons in HM



HM events are in the valence quark range





SIDIS TSAs (Sivers)

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

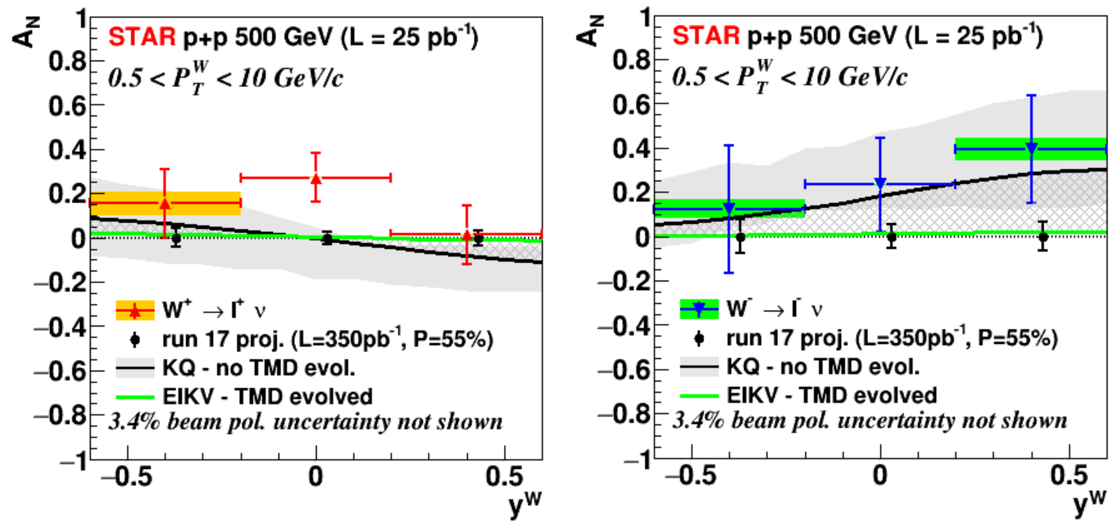
- Measured on proton and deuteron
- Recently - gluon Sivers paper PLB 772 (2017) 854

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

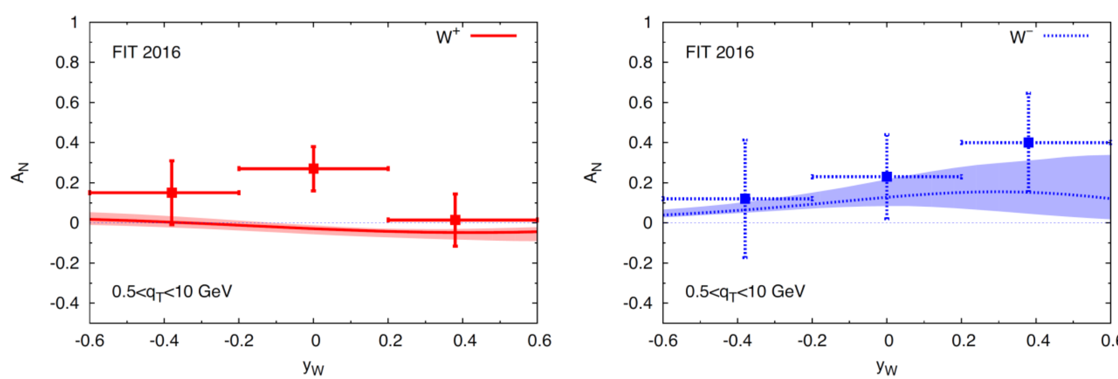
- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan
- Sivers TMD PDF is predicted to change the sign between SIDIS and DY

- First experimental investigation of Sivers-non-universality by STAR
- Different hard scale compared to FT
- Evolution effects may play a substantial role

STAR collaboration: **PRL 116, 132301 (2016)**



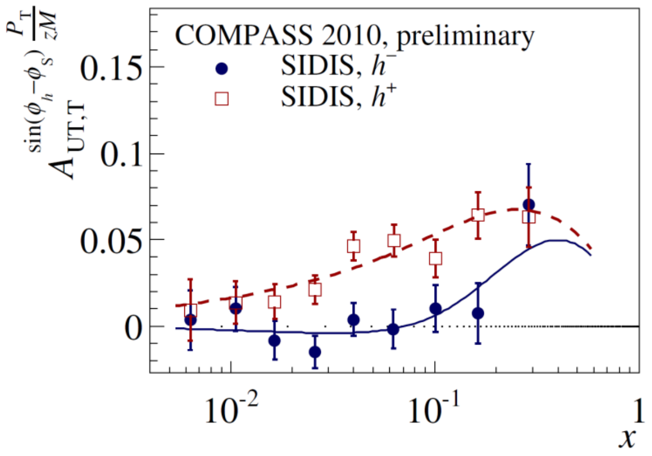
M. Anselmino et al., **JHEP 1704 (2017) 046** (no TMD evolution)



The p_T (q_T) – weighted SIDIS(DY) Sivers asymmetry

General formalism was first introduced in 1997 (A. Kotzinian and P. Mulders, **PLB 406 (1997) 373**)

F. Bradamante (COMPASS at SPIN-2016)
arXiv:1702.00621 [hep-ex]



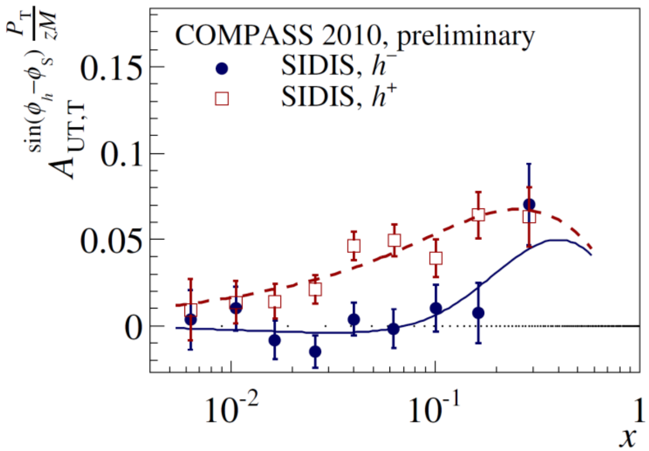
Sivers TSA in SIDIS: $A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$

Sivers *w*TSA in SIDIS: $A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q\,(1)} \times D_{1q}^h$

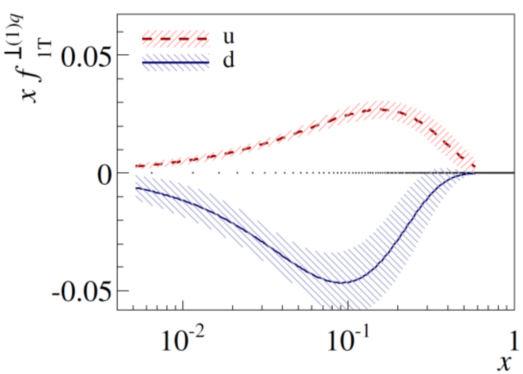
The p_T (q_T) – weighted SIDIS(DY) Sivers asymmetry

General formalism was first introduced in 1997 (A. Kotzinian and P. Mulders, **PLB 406 (1997) 373**)

F. Bradamante (COMPASS at SPIN-2016)
arXiv:1702.00621 [hep-ex]



Sivers TSA in SIDIS:	$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$
Sivers *w*TSA in SIDIS:	$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q\,(1)} \times D_{1q}^{h}$
Sivers TSA in DY:	$A_{T}^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$
Sivers *w*TSA in DY:	$A_{T}^{\sin\varphi_S} \propto f_{1,\pi}^{q} \times f_{1T,p}^{\perp q\,(1)}$



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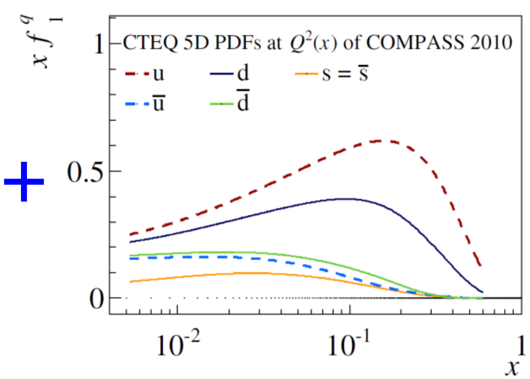

Valence quark dominance
No Q^2-evolution for Sivers PDF

$$A_T^{\sin\varphi_S \frac{q_T}{M_P}} \approx \frac{f_{1T,p}^{\perp u\,(1)}}{f_{1,p}^{u}}$$

The p_T (q_T) – weighted SIDIS(DY) Sivers asymmetry

General formalism was first introduced in 1997 (A. Kotzinian and P. Mulders, **PLB 406 (1997) 373**)

F. Bradamante (COMPASS at SPIN-2016)
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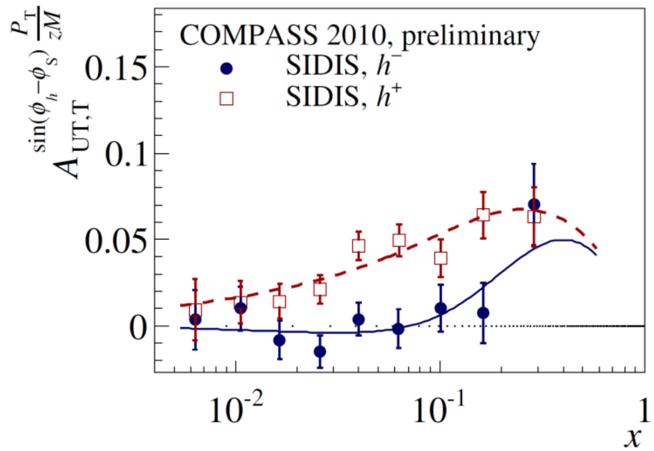

Sivers TSA in SIDIS: $A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$

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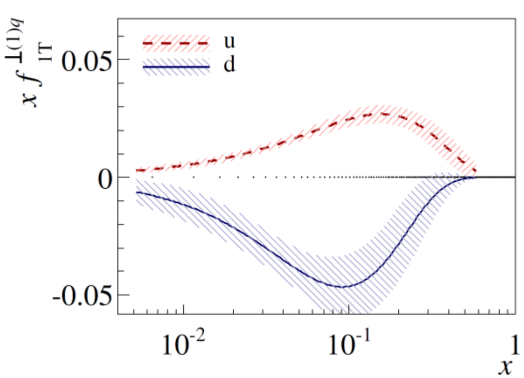
Sivers *w*TSA in DY: $A_{T}^{\sin\varphi_S} \propto f_{1,\pi}^{q} \times f_{1T,p}^{\perp q\,(1)}$



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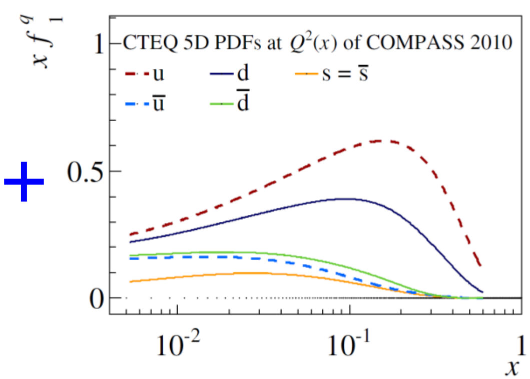
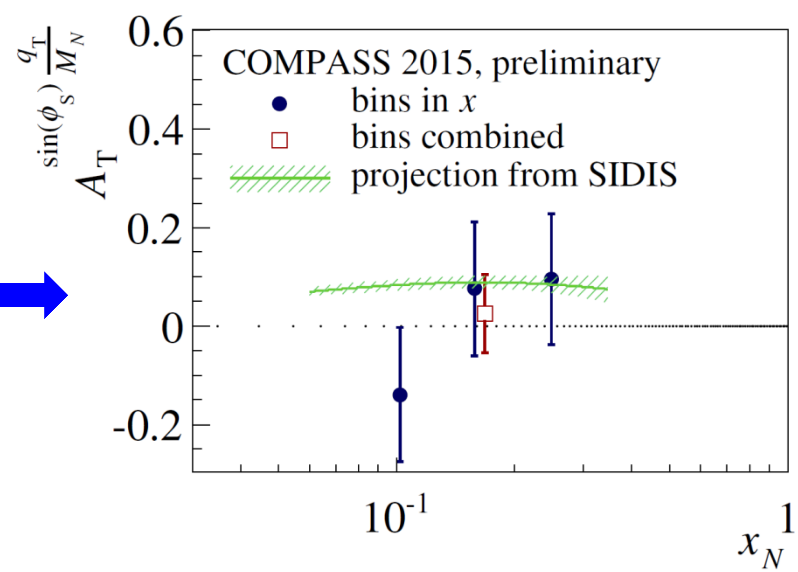


J. Matoušek (COMPASS at DSPIN-2017)
arXiv:1710.06497 [hep-ex]



Lorentz-invariance relations

The "bag" model, "spectator" model, "light-cone constituent quark" model, "chiral quark soliton" model, "covariant parton" model with intrinsic 3D-symmetric parton orbital motion, "quark-traget" model