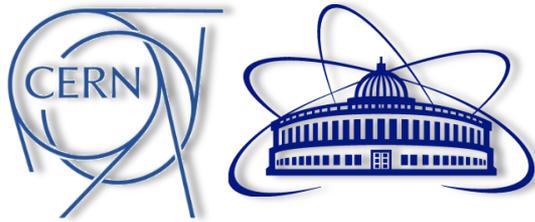




COMPASS experiment: recent results from the spin-programme



Բակուր Պարսամյան

CERN, JINR,
University of Turin and INFN

on behalf of the COMPASS Collaboration

UNIVERSITÀ
DEGLI STUDI
DI TORINO

ALMA UNIVERSITAS
TAURINENSIS



International Workshop on
Correlations in Partonic and
Hadronic Interactions
(CPHI-2018)
Yerevan, Armenia
September 24 – 28, 2018

COMPASS collaboration

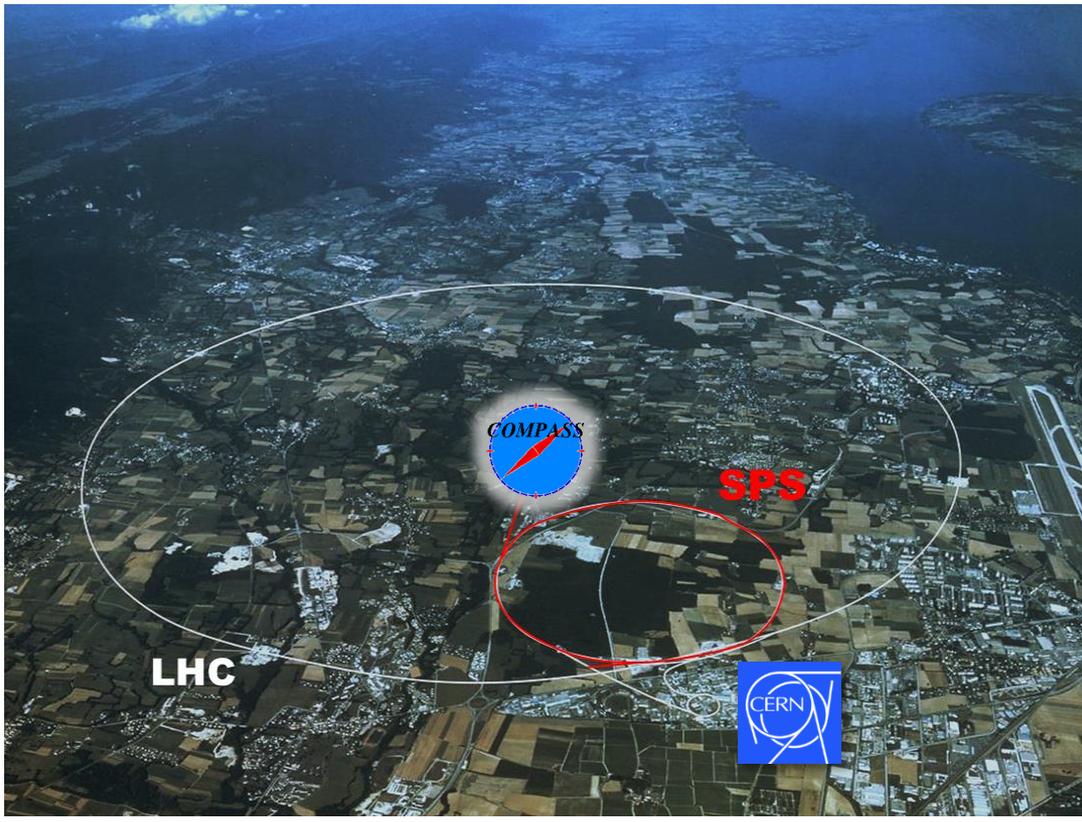


Common Muon and Proton Apparatus for Structure and Spectroscopy



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>



COMPASS collaboration

Common Muon and Proton Apparatus for Structure and Spectroscopy

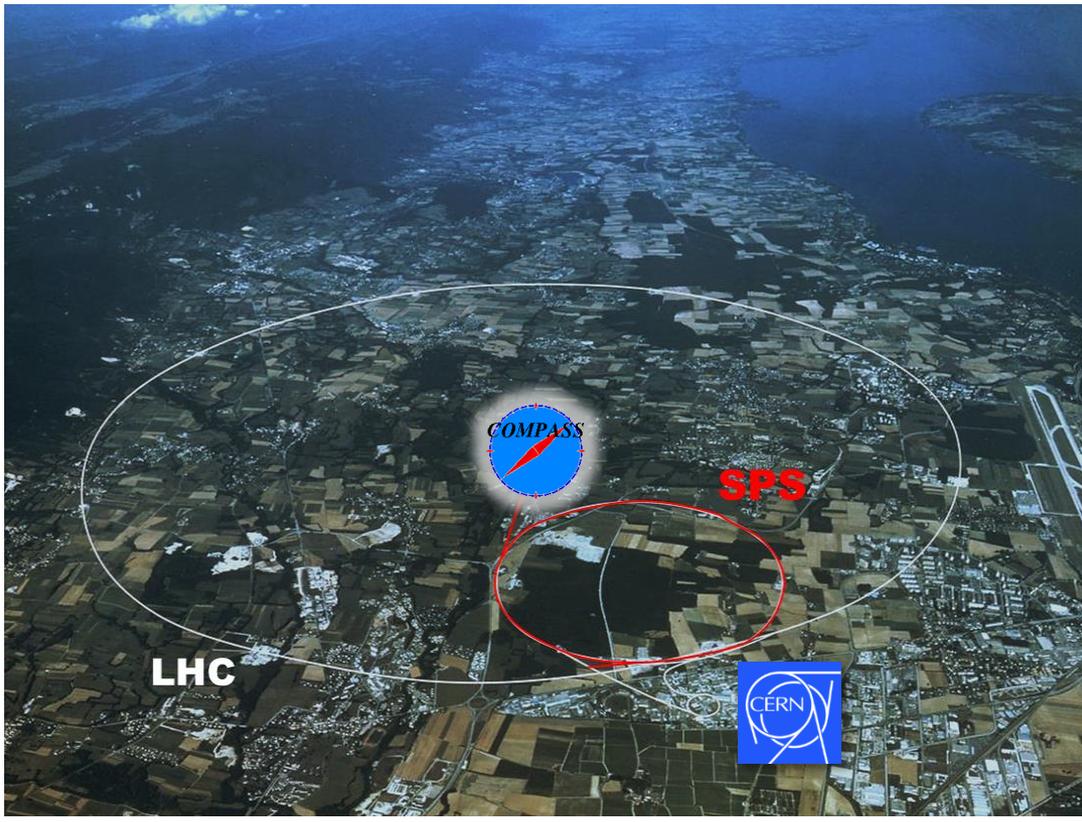


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Wide physics program COMPASS-I

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



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COMPASS-I

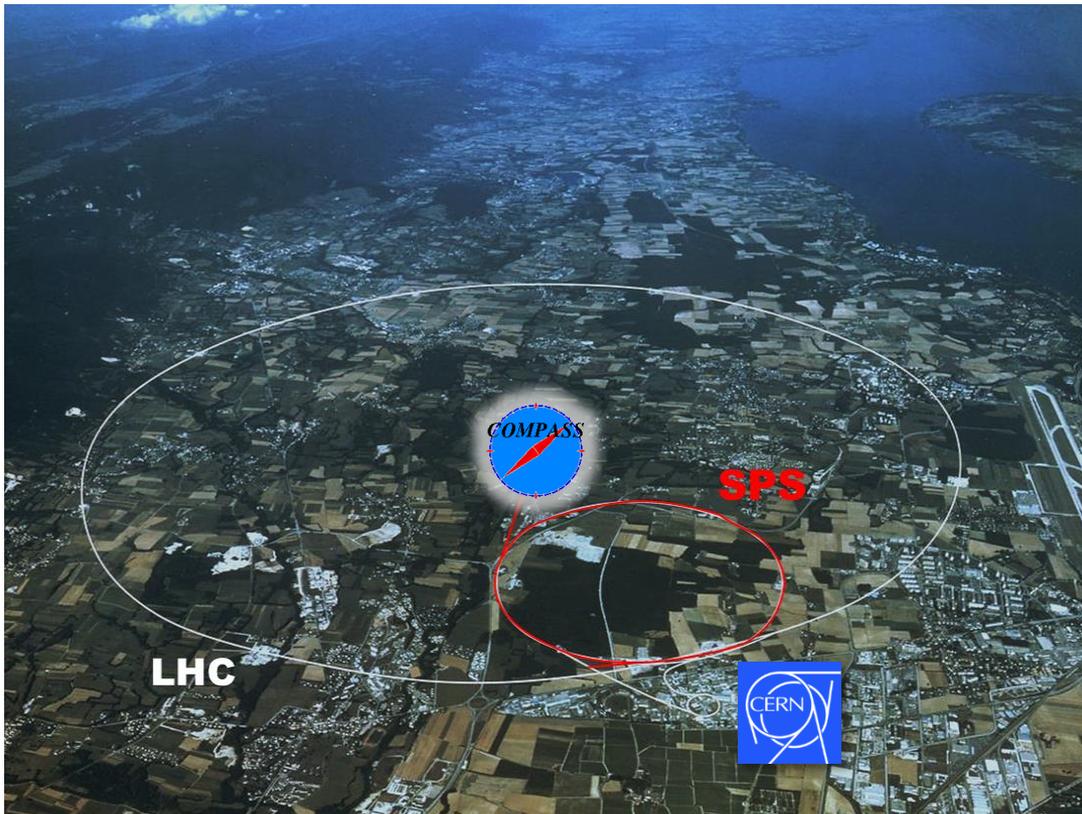
- Data taking 2002-2011
- Muon and hadron beams
- Nucleon spin structure
- Spectroscopy

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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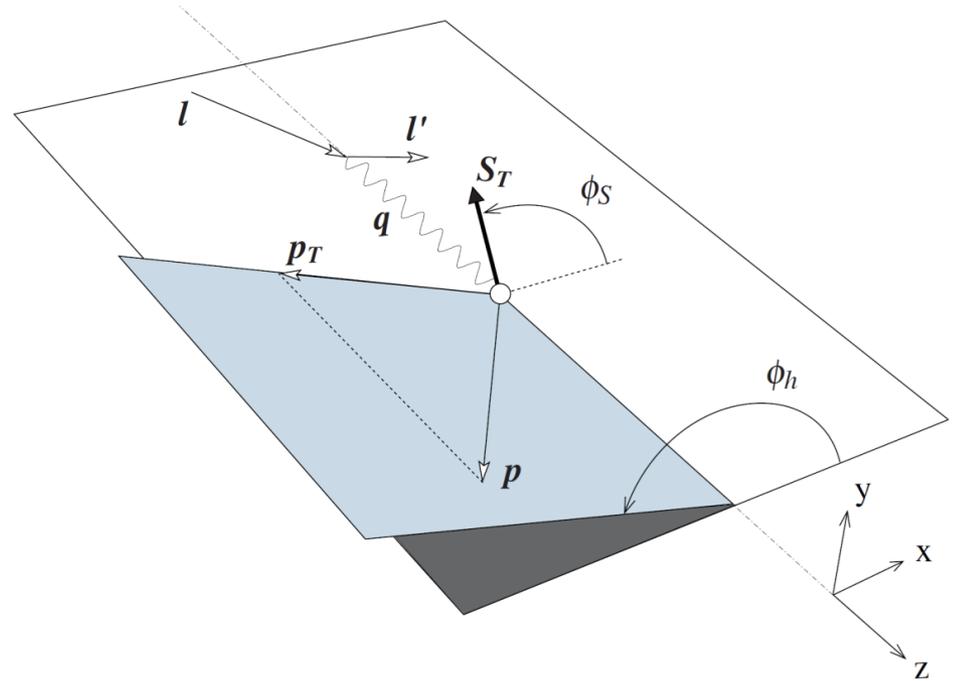
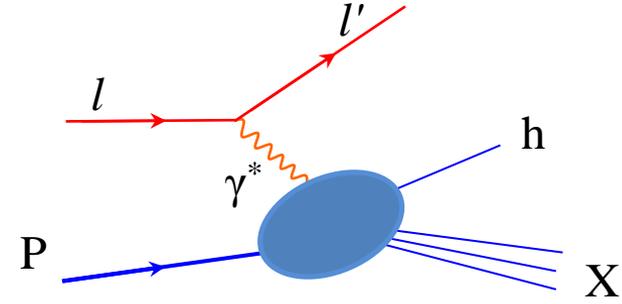


All measured by COMPASS

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

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

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



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

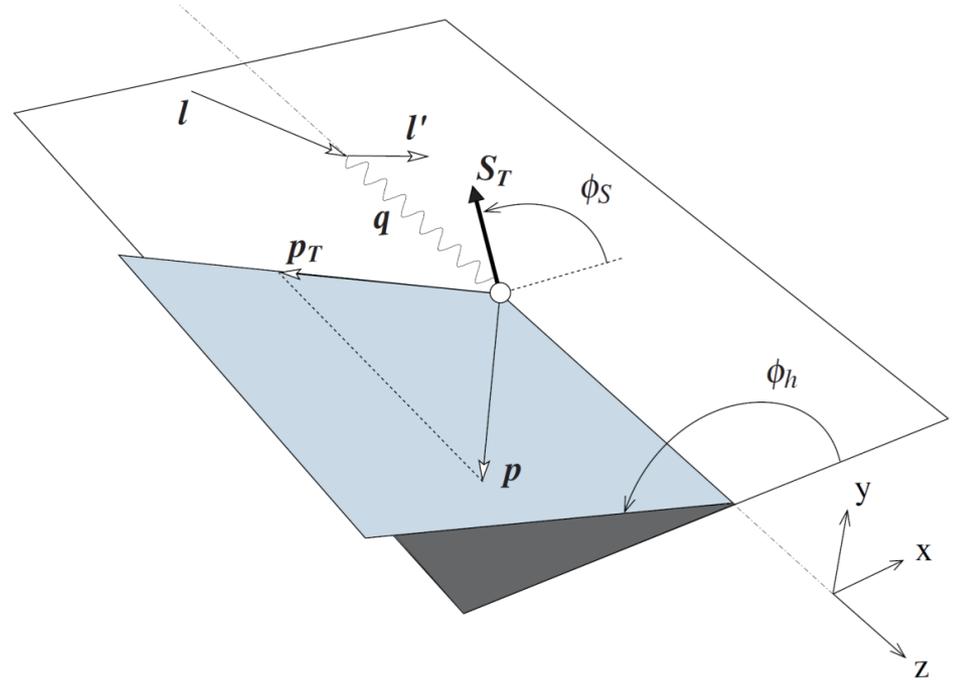
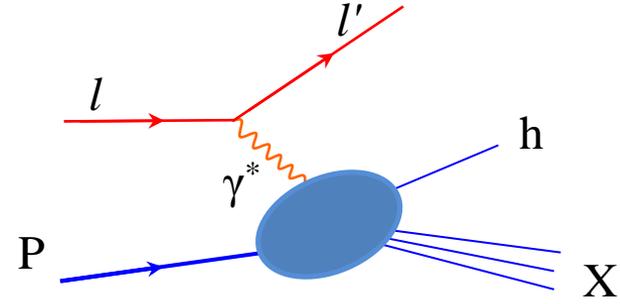


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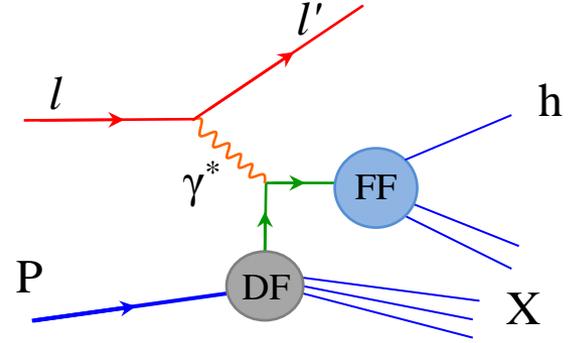


SIDIS x-section and TMDs at twist-2

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

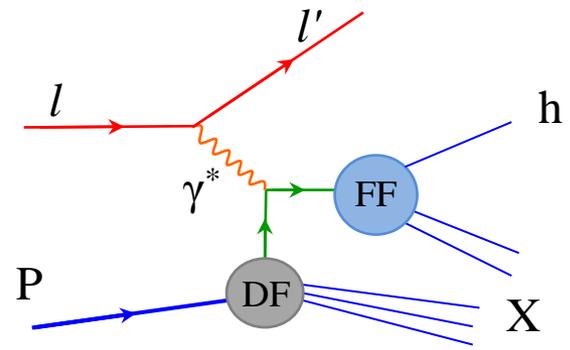
+ two FFs: $D_{1q}^h(z, P_{\perp}^2)$ and $H_{1q}^{\perp h}(z, P_{\perp}^2)$



SIDIS x-section and TMDs at twist-2

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L		helicity	worm-gear L
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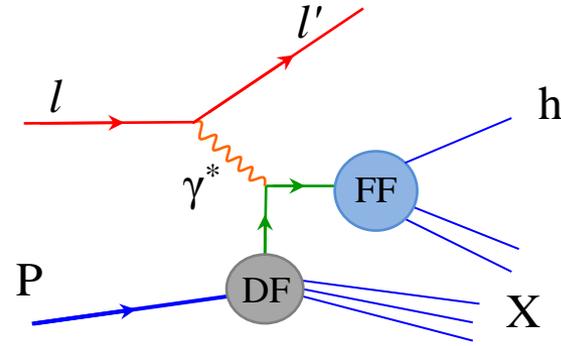
spin of the nucleon
 spin of the quark
 k_T



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

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

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

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

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

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

Twist-2

Twist-3

WW = Wandzura-Wilczek-type approximation

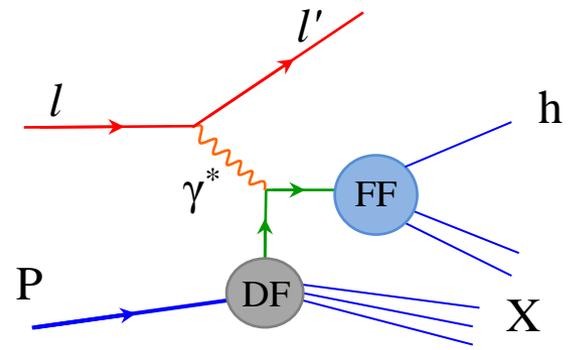


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$$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$

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

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

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

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

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

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

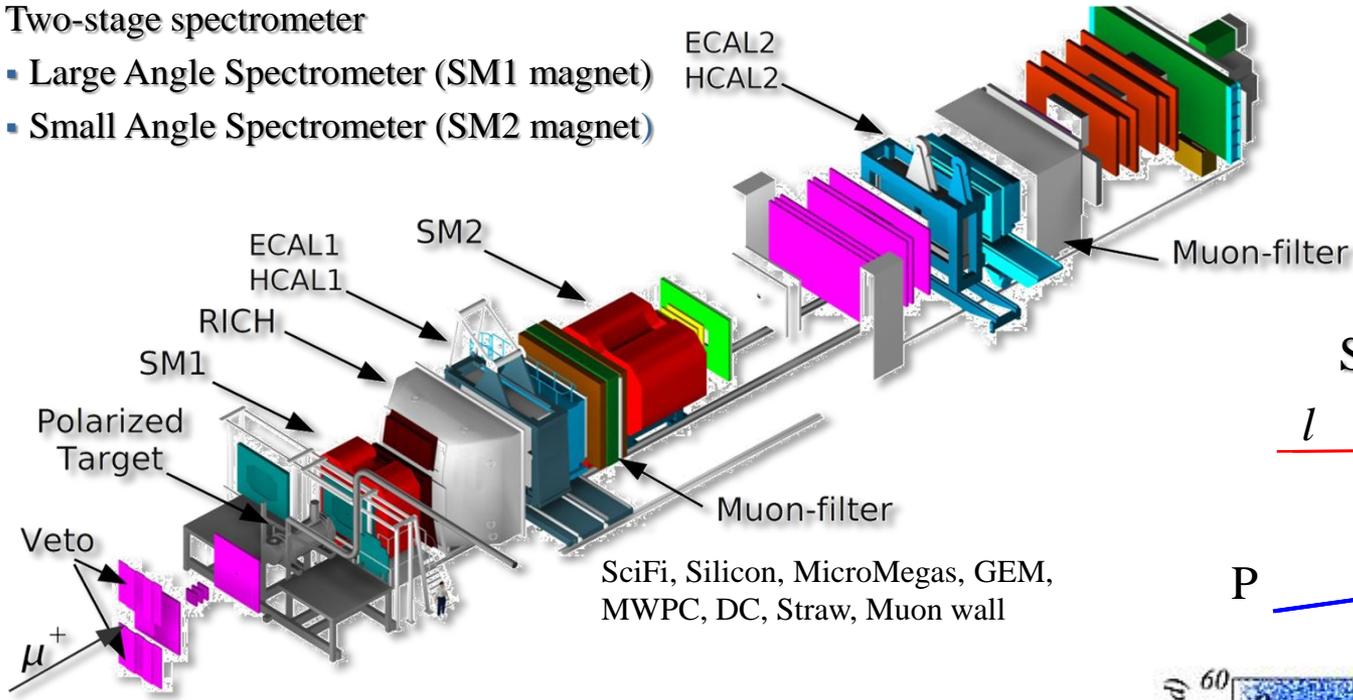
Twist-2
Twist-3



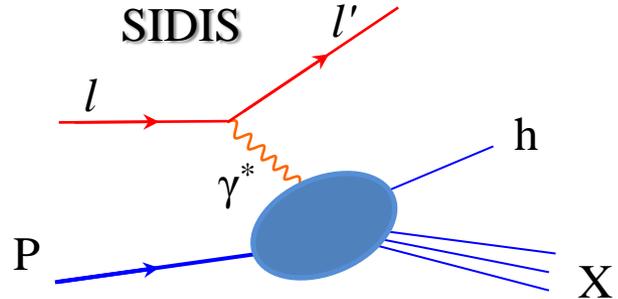
COMPASS experimental setup: Phase I (muon program)

Two-stage spectrometer

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



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

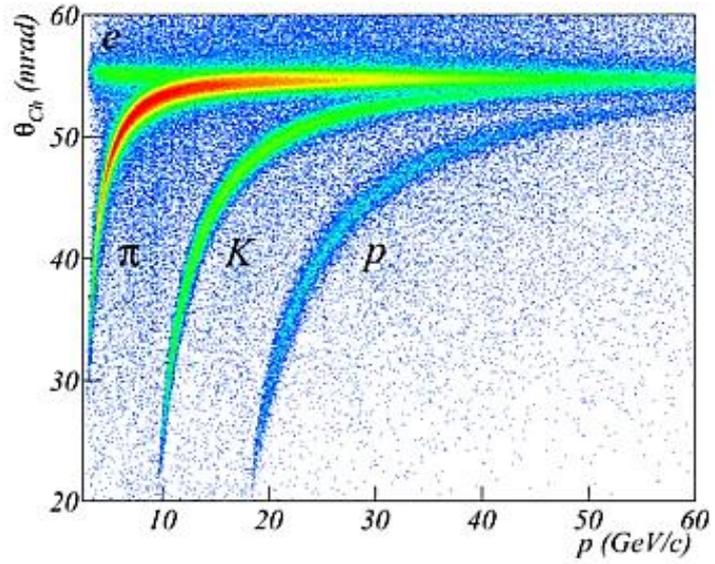


Data-taking years: 2002-2011

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

Target: Solid state (${}^6\text{LiD}$ or NH_3)

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

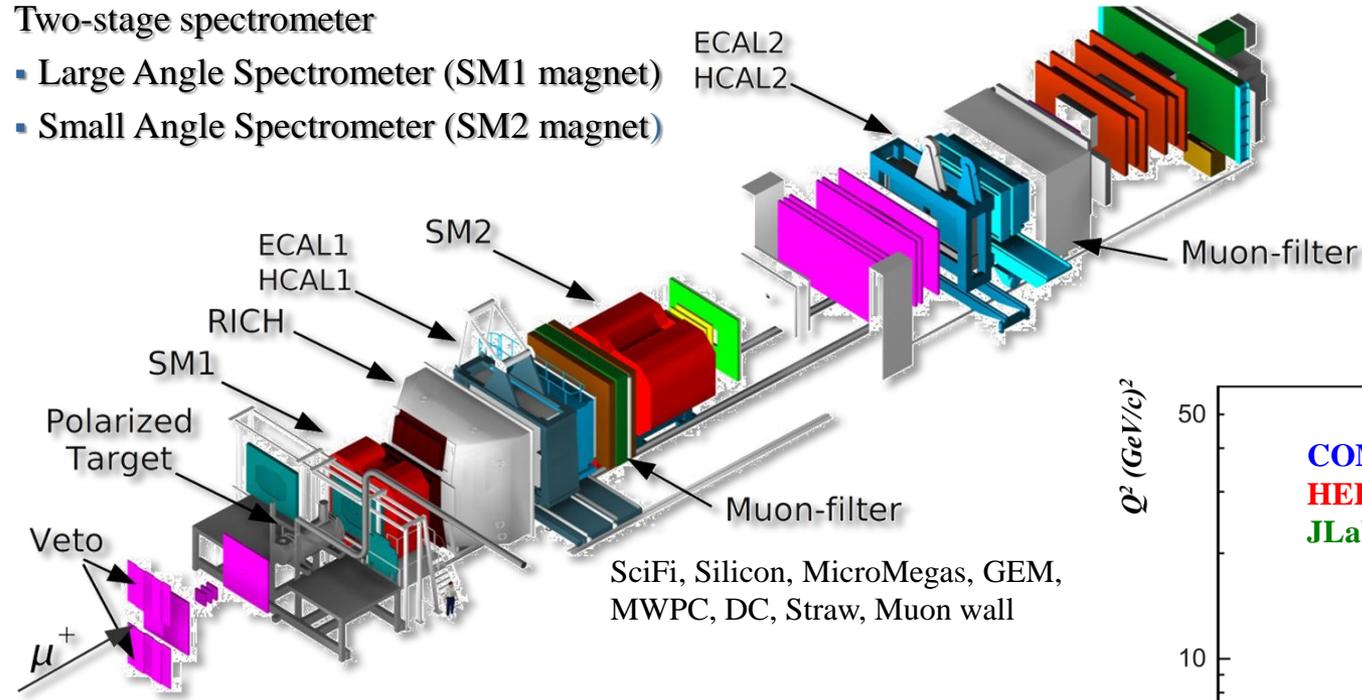




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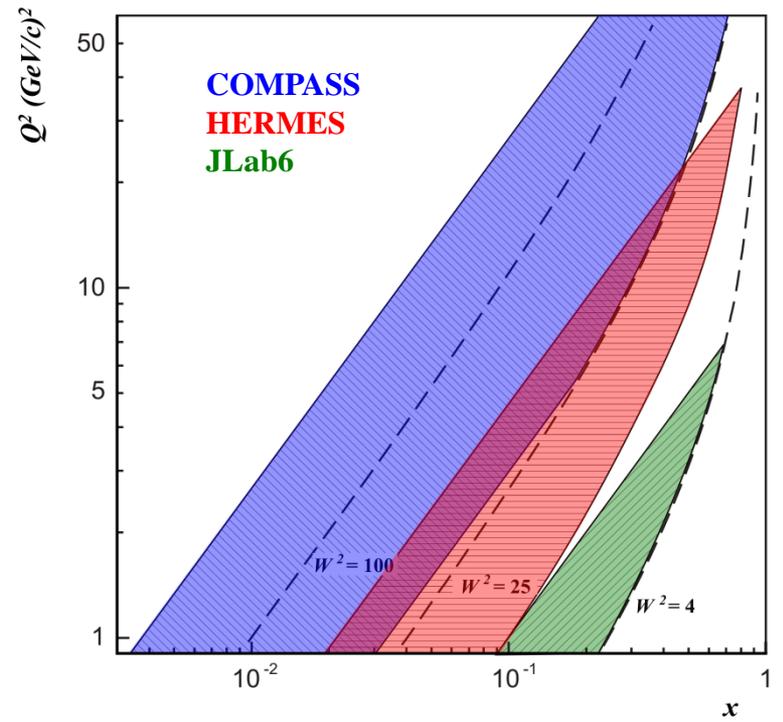


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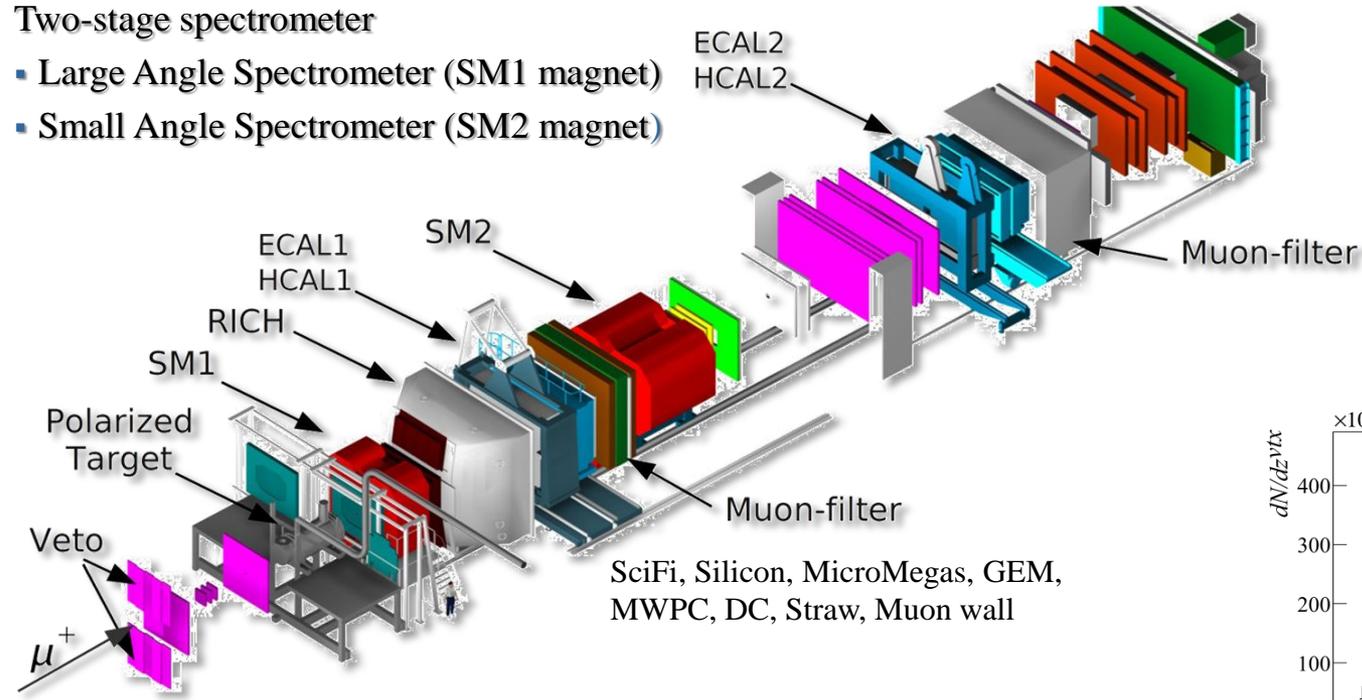




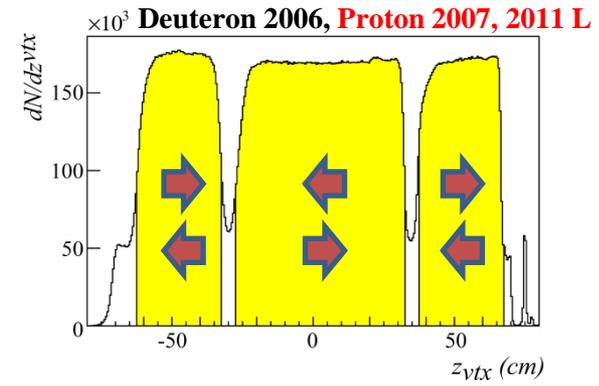
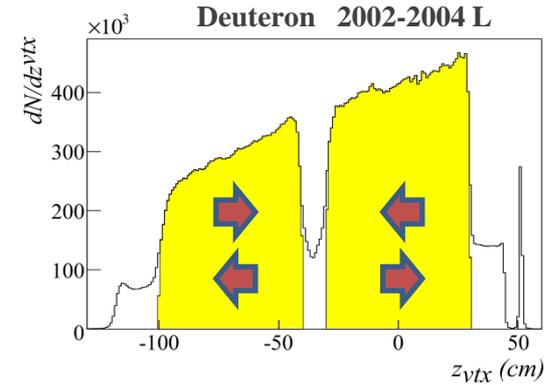
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Data-taking years: 2002-2011

Longitudinally polarized (80%) μ^+ beam:

Energy: 160/200 GeV/c, Intensity: $2 \cdot 10^8 \mu^+$ /spill (4.8s).

Target: Solid state (${}^6\text{LiD}$ or NH_3)

- ${}^6\text{LiD}$ 2-cell configuration. Polarization (L & T) $\sim 50\%$, $f \sim 0.38$
- NH_3 3-cell configuration. Polarization (L & T) $\sim 80\%$, $f \sim 0.14$
- **Data is collected simultaneously with both target spin orientations.**
- **Periodic polarization reversal to minimize systematic effects**



- Unpolarized azimuthal asymmetries (SIDIS)



SIDIS: Unpolarized azimuthal asymmetries

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

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

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

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q} \mathcal{C} \left\{ -\frac{\hat{h} \cdot \mathbf{p}_T}{M_h} \left(x e^q H_{1q}^{\perp h} + \frac{M_h}{M} f_1^q \frac{\tilde{G}_q^{\perp h}}{z} \right) + \frac{\hat{h} \cdot \mathbf{k}_T}{M} \left(x g^{\perp q} D_{1q}^h - \frac{M_h}{M} h_1^{\perp q} \frac{\tilde{E}_q^h}{z} \right) \right\}$$



SIDIS: Unpolarized azimuthal asymmetries

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

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- 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**

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

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

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q} \mathcal{C} \left\{ -\frac{\hat{\mathbf{h}} \cdot \mathbf{p}_T}{M_h} \left(x e^q H_{1q}^{\perp h} + \frac{M_h}{M} f_1^q \frac{\tilde{G}_q^{\perp h}}{z} \right) + \frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} \left(x g^{\perp q} D_{1q}^h - \frac{M_h}{M} h_1^{\perp q} \frac{\tilde{E}_q^h}{z} \right) \right\}$$

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

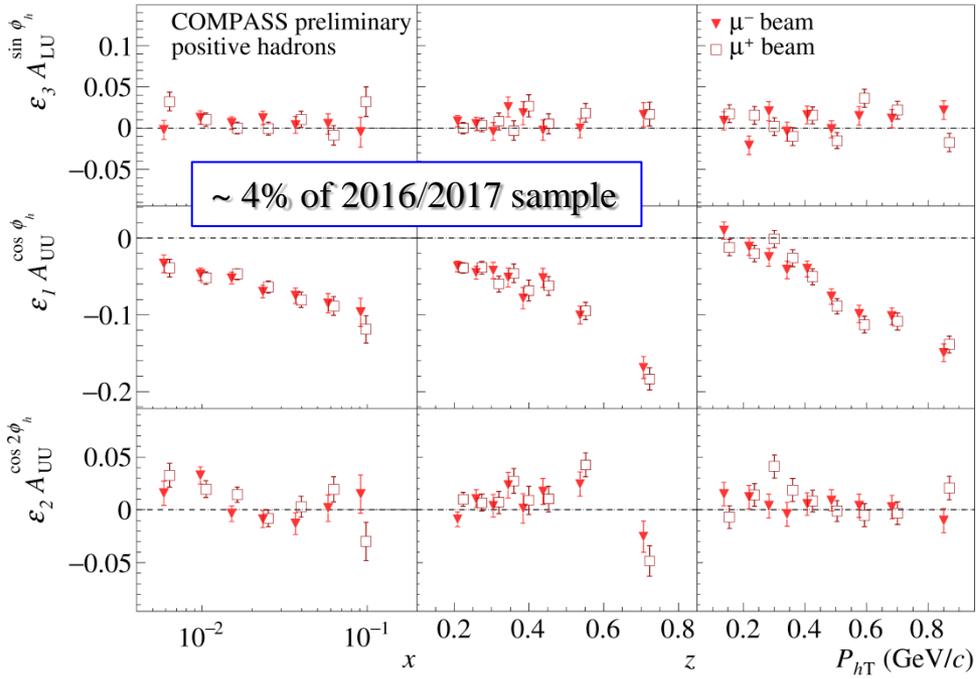


SIDIS: Unpolarized azimuthal asymmetries

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

- 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

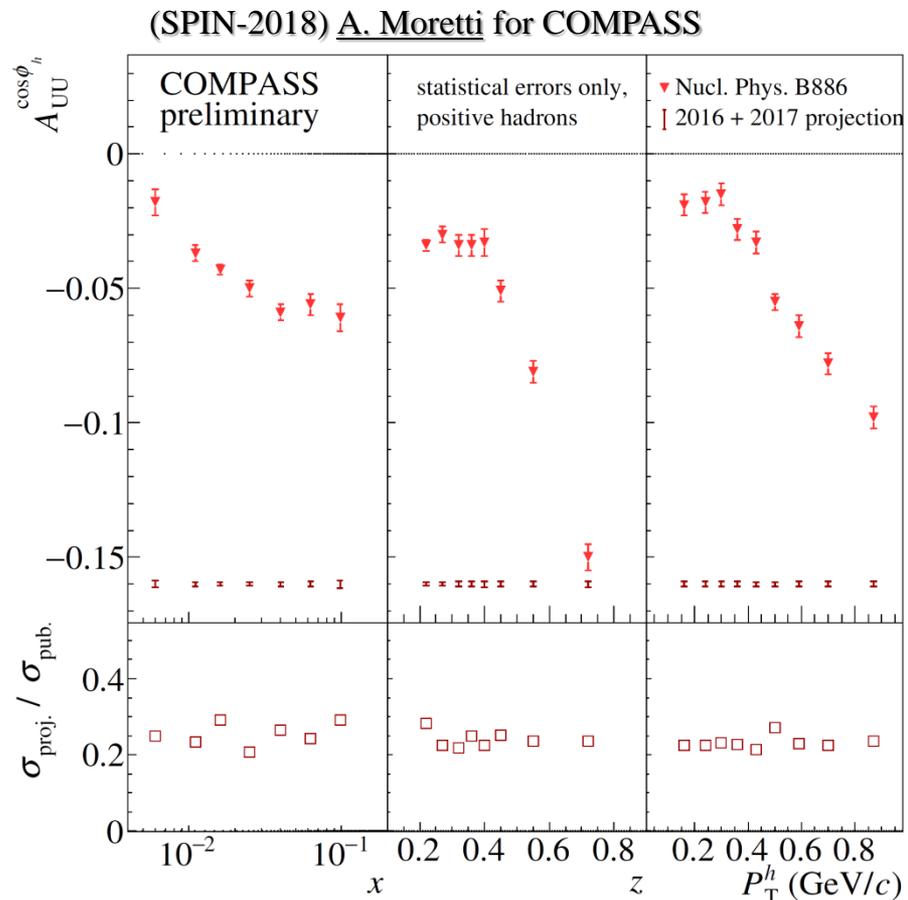
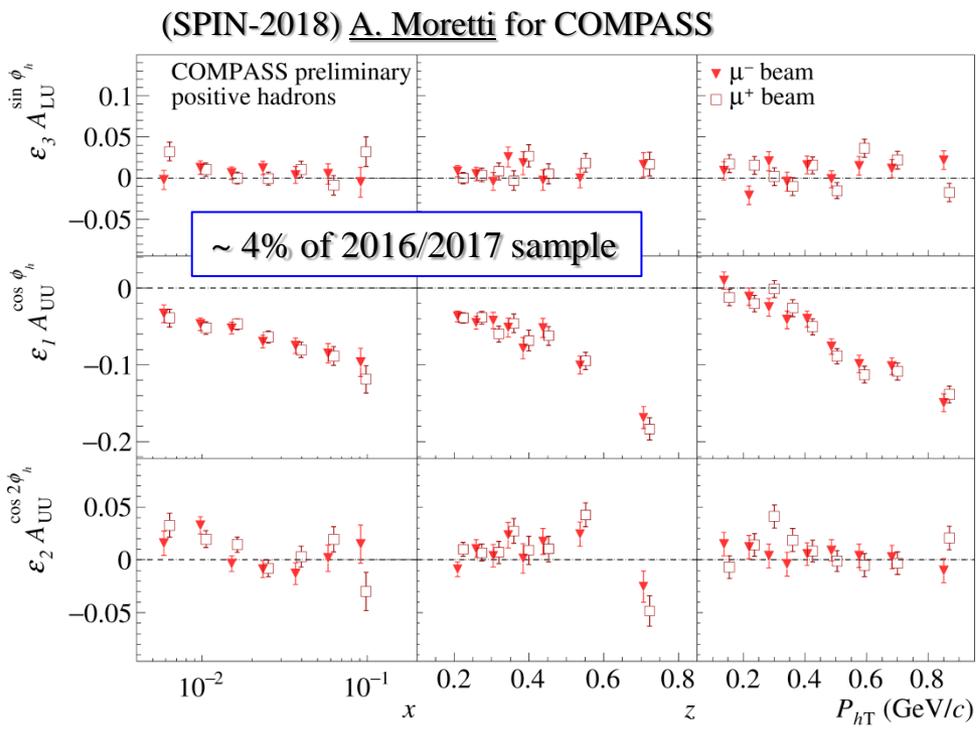




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- Projected uncertainties for 2016+2017 sample are ~5 times smaller compared to published asymmetries
- Systematic errors are also expected to be considerably smaller





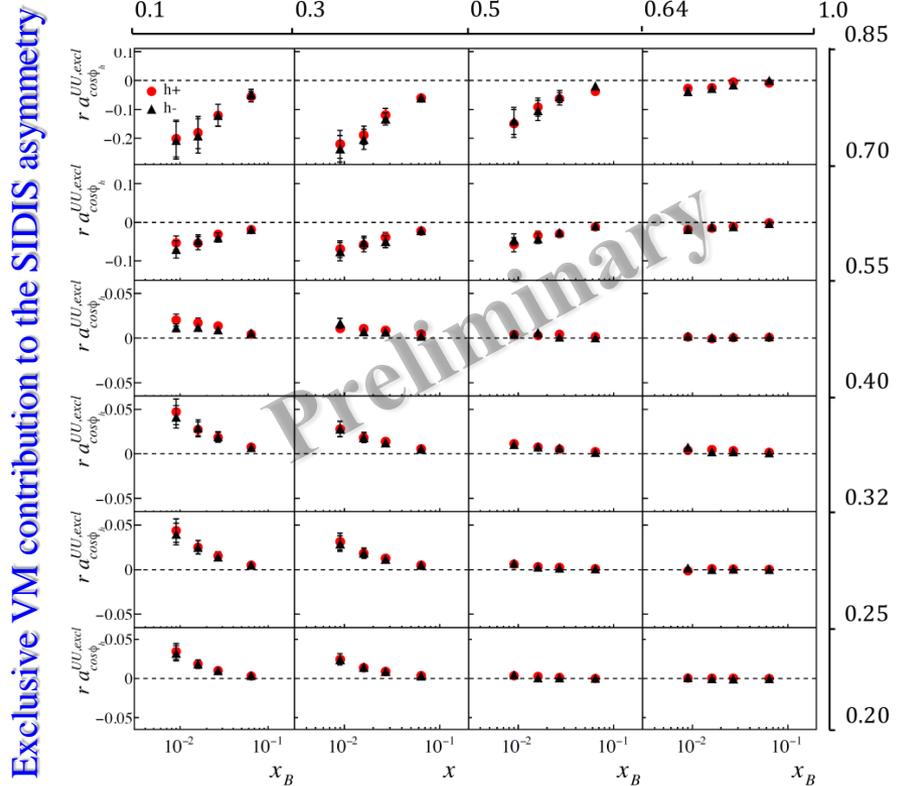
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- First preliminary proton results from COMPASS (2016-2017 DVCS-run) were presented at SPIN-2018
- **Similarly strong kinematic dependences compared to published COMPASS-deuteron results**
- Projected uncertainties for 2016+2017 sample are ~5 times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

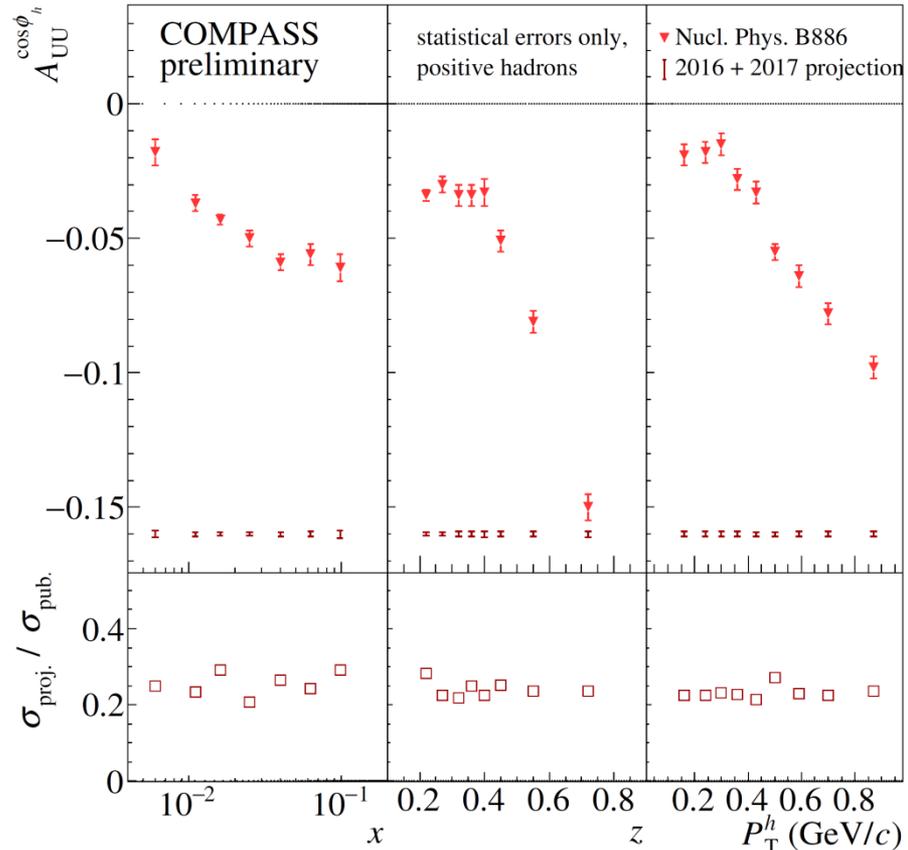
(SPIN-2018)

A. Kerbizi for COMPASS $P_T(\text{GeV}/c)$



Exclusive VM contribution to the SIDIS asymmetry

(SPIN-2018) A. Moretti for COMPASS





- Longitudinal target spin dependent azimuthal asymmetries (SIDIS)



SIDIS: target longitudinal spin dependent asymmetries

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

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

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

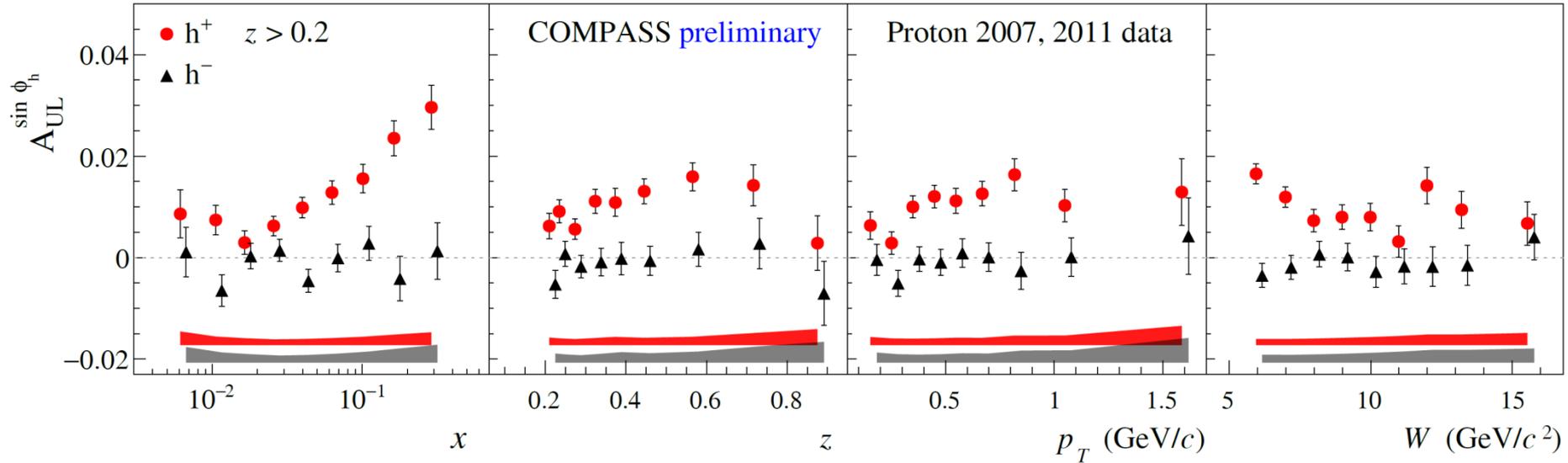


SIDIS: target longitudinal spin dependent asymmetries

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

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B.Parsamyan (for COMPASS) [arXiv:1801.01488](https://arxiv.org/abs/1801.01488) [hep-ex] (DIS-2017)



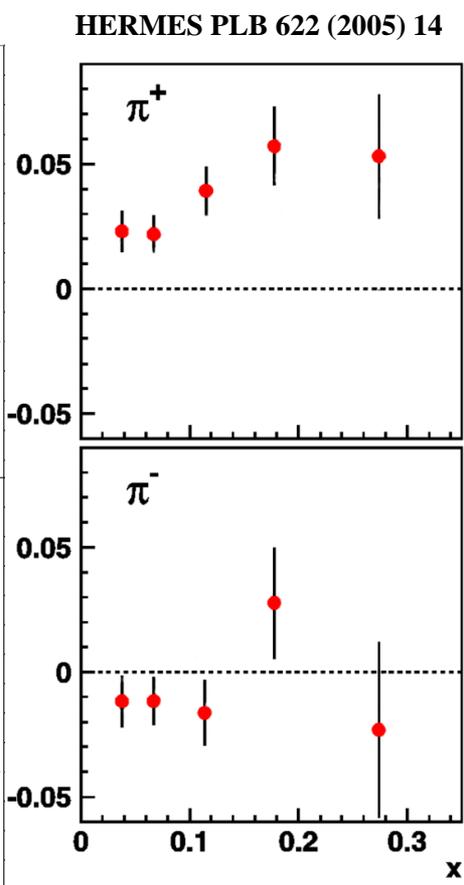
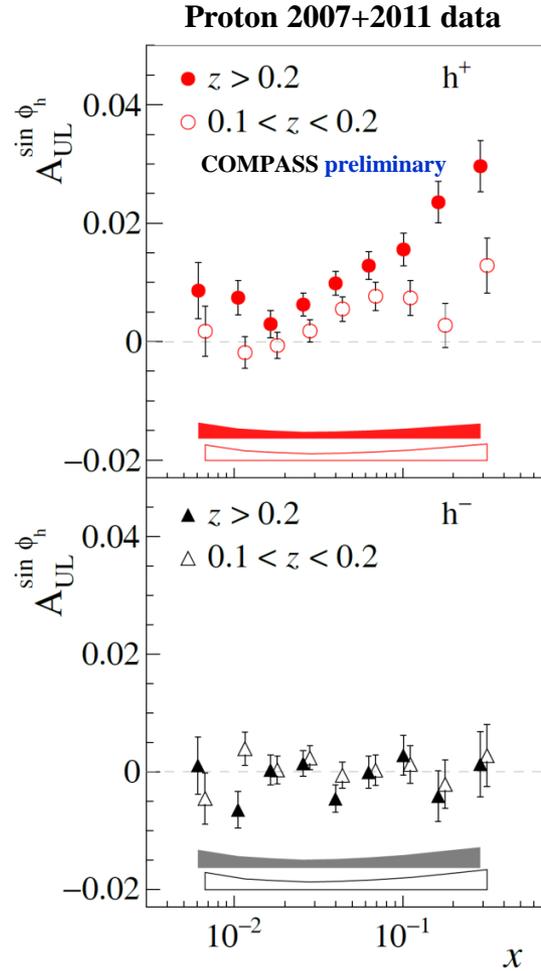
- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- **Non-zero trend for h^+ , h^- compatible with zero**



SIDIS: target longitudinal spin dependent asymmetries

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

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



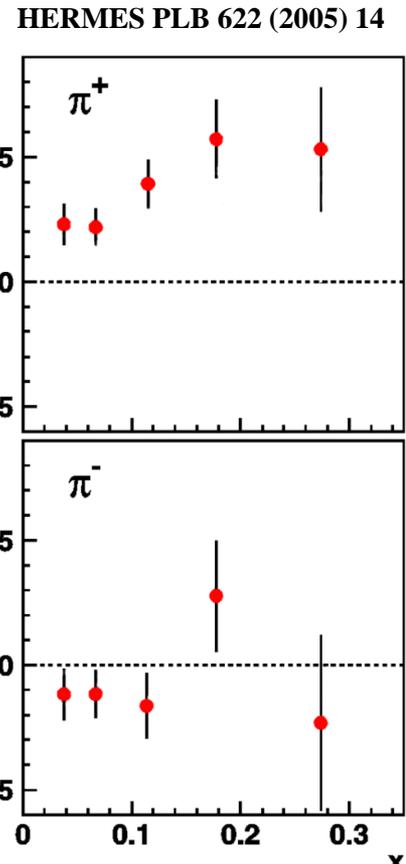
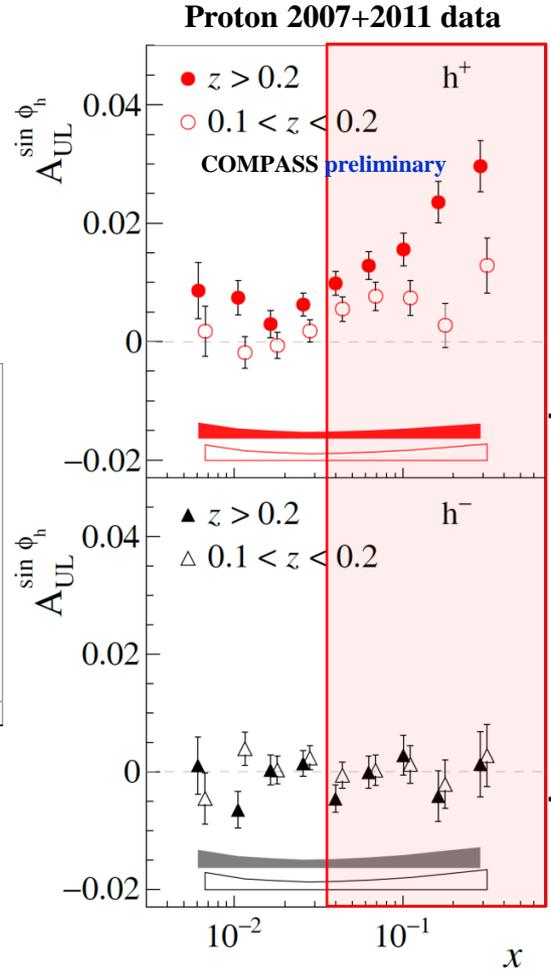
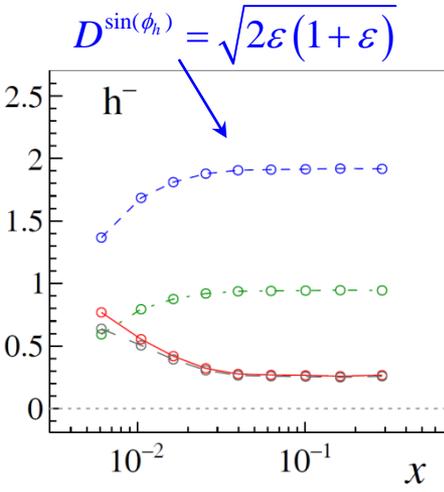
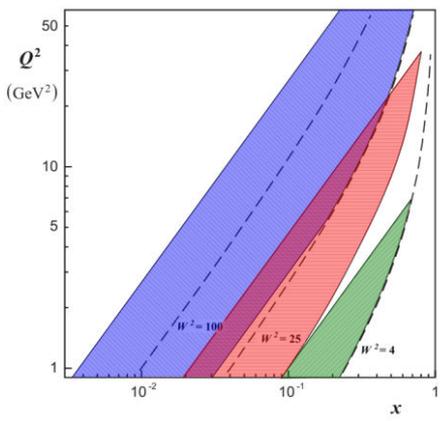
- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- **Non-zero trend for h^+ , h^- compatible with zero, clear z -dependence**



SIDIS: target longitudinal spin dependent asymmetries

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

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



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



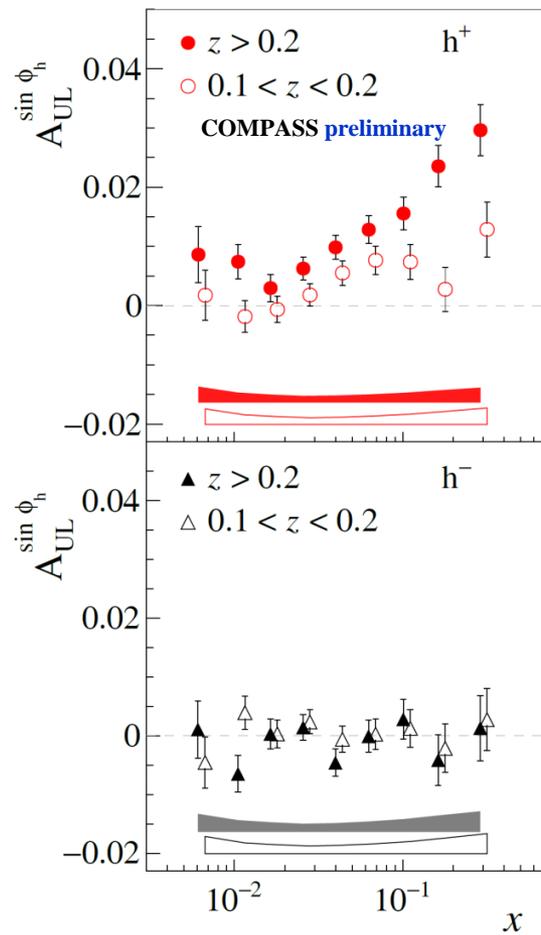
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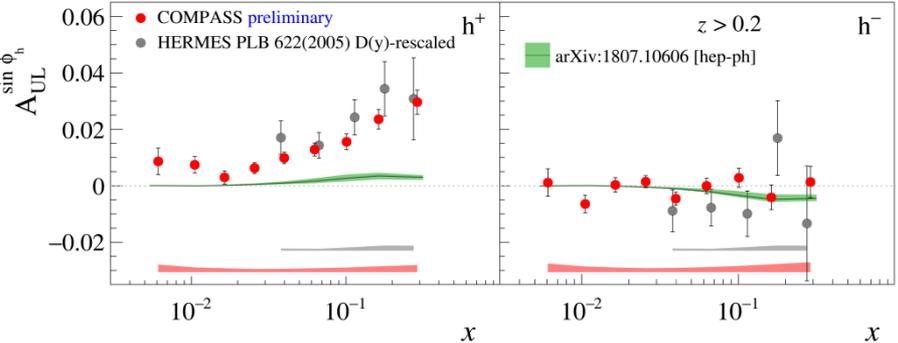
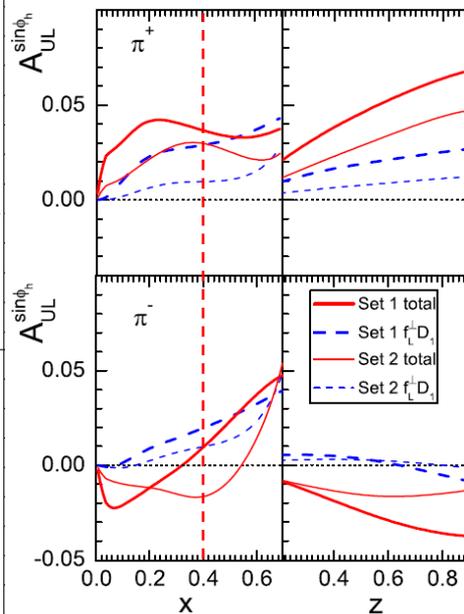
$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q} \mathcal{C} \left\{ -\frac{\hat{h} \cdot \mathbf{p}_T}{M_h} \left(x h_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) + \frac{\hat{h} \cdot \mathbf{k}_T}{M} \left(x f_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{H}_q^h}{z}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

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 \[hep-ph\]](https://arxiv.org/abs/1807.10606)

Proton 2007+2011 data



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



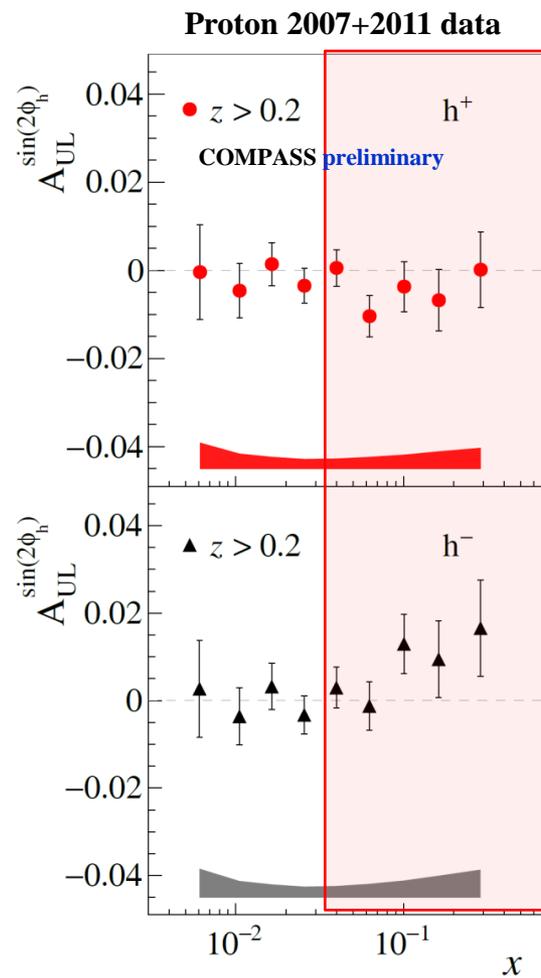
- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- **Non-zero trend for h⁺, h⁻ compatible with zero, clear z-dependence**

SIDIS: target longitudinal spin dependent asymmetries

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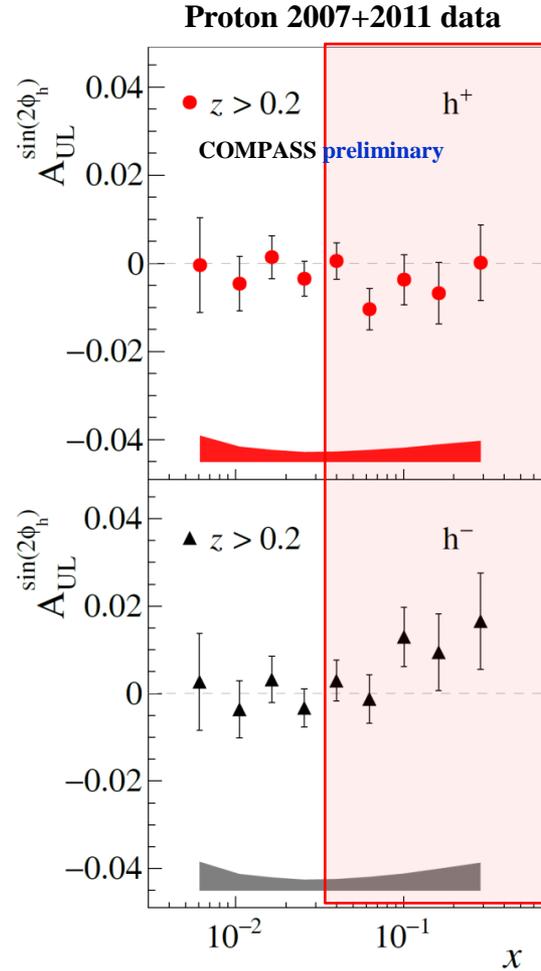
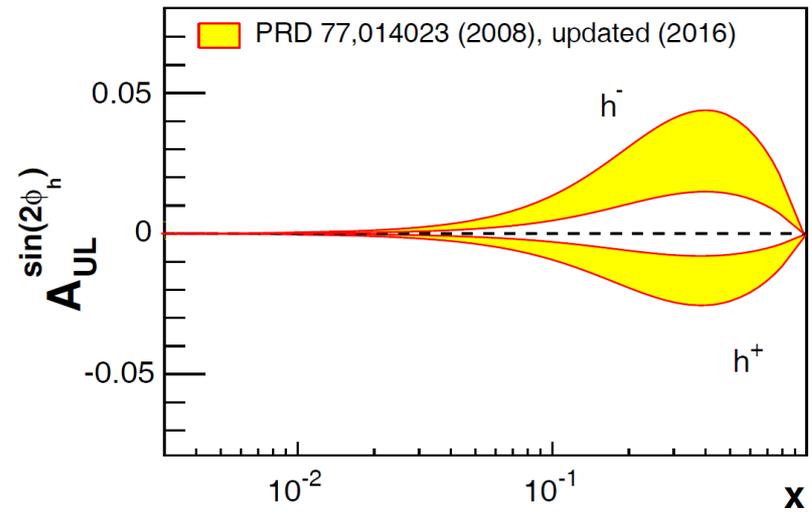
- Only “twist-2” ingredients
- Additional p_T -suppression
- **Collins-like behavior?**
- **In agreement with model predictions**



SIDIS: target longitudinal spin dependent asymmetries

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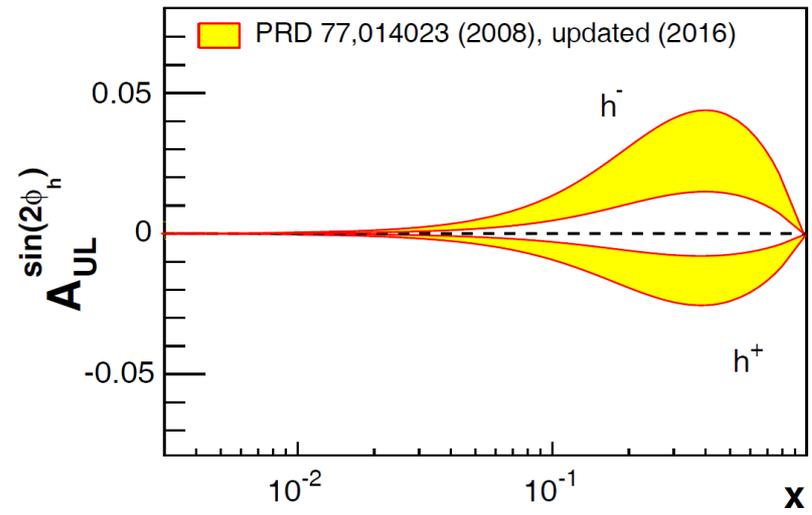
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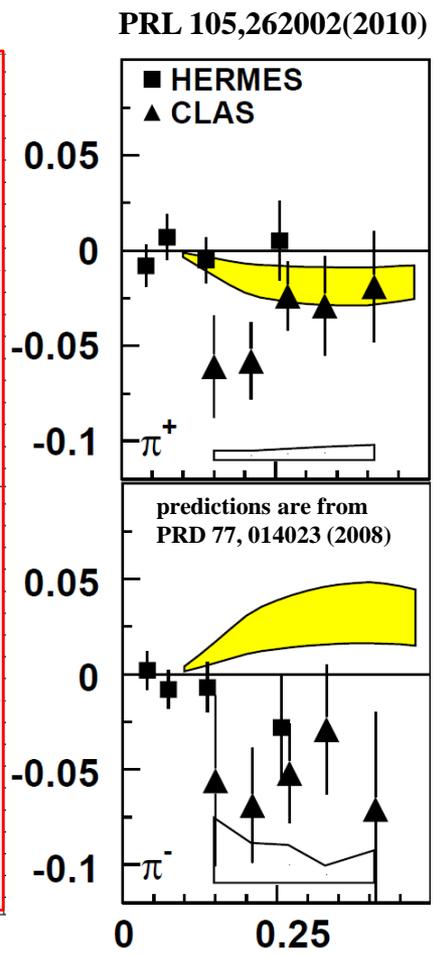
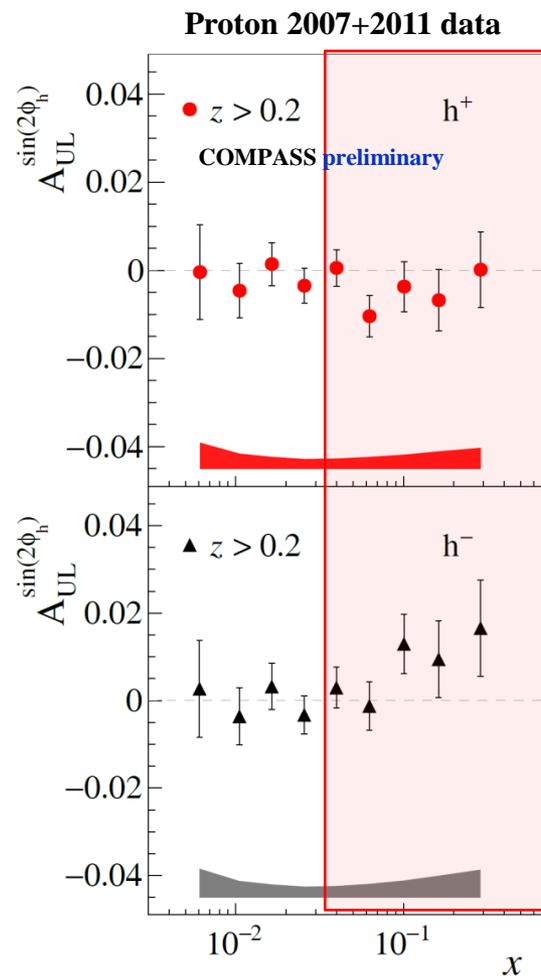
SIDIS: target longitudinal spin dependent asymmetries

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

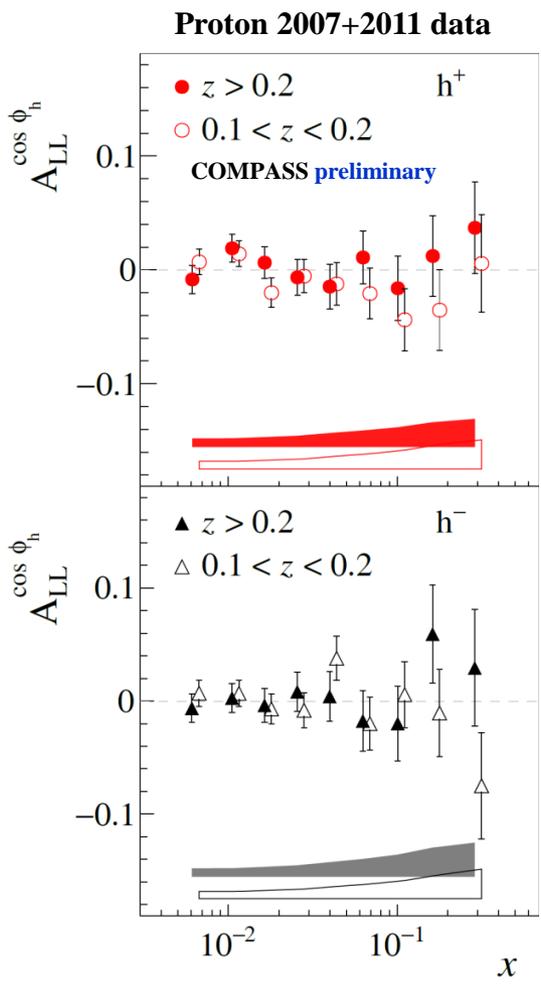


SIDIS: target longitudinal spin dependent asymmetries

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

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

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

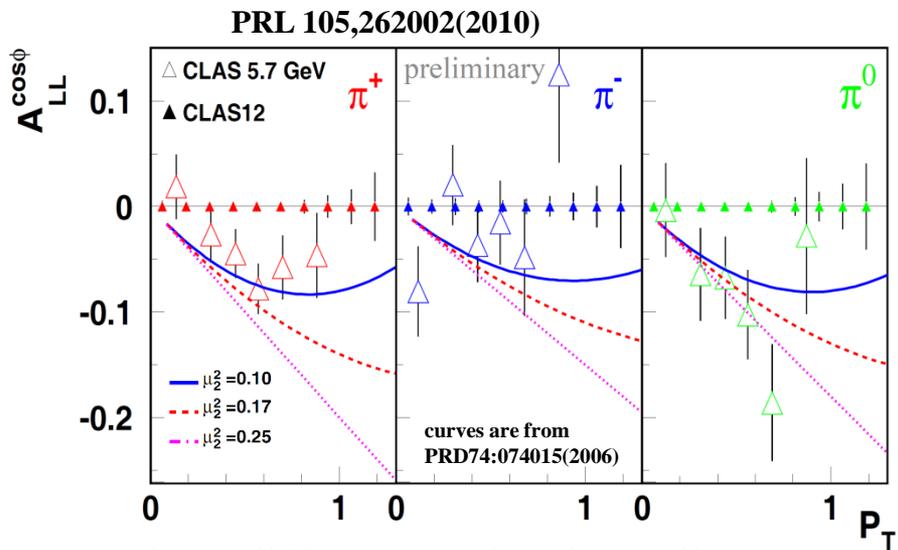




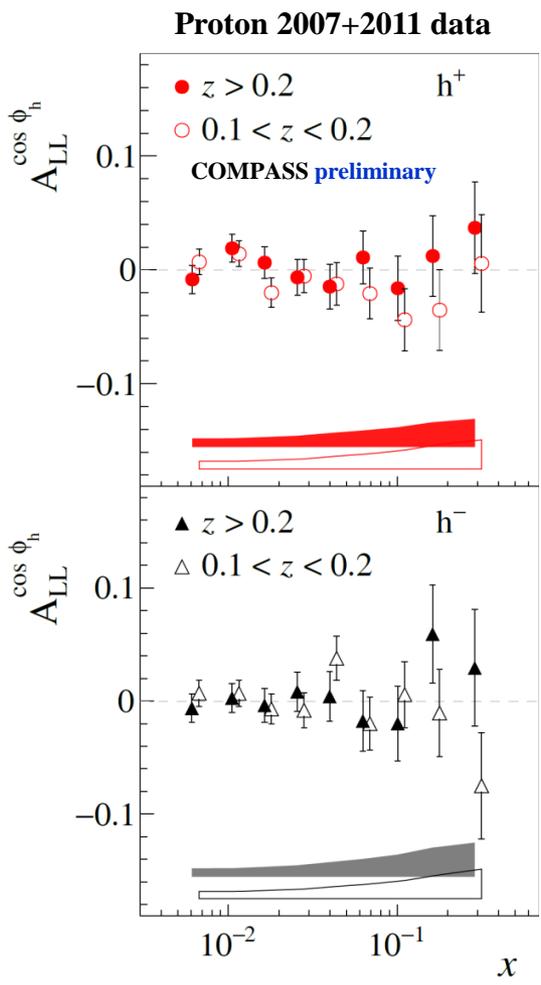
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- Various different “twist” ingredients,
- Q-suppression
- Non zero at JLab

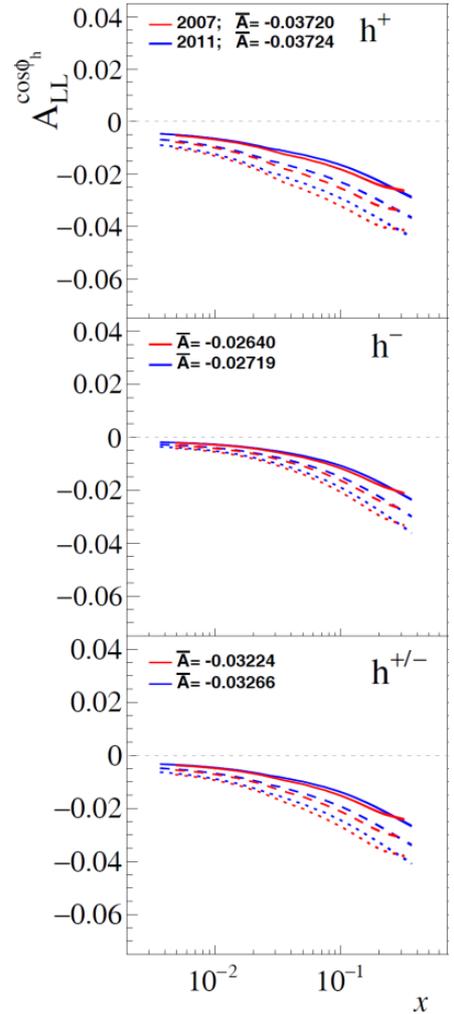
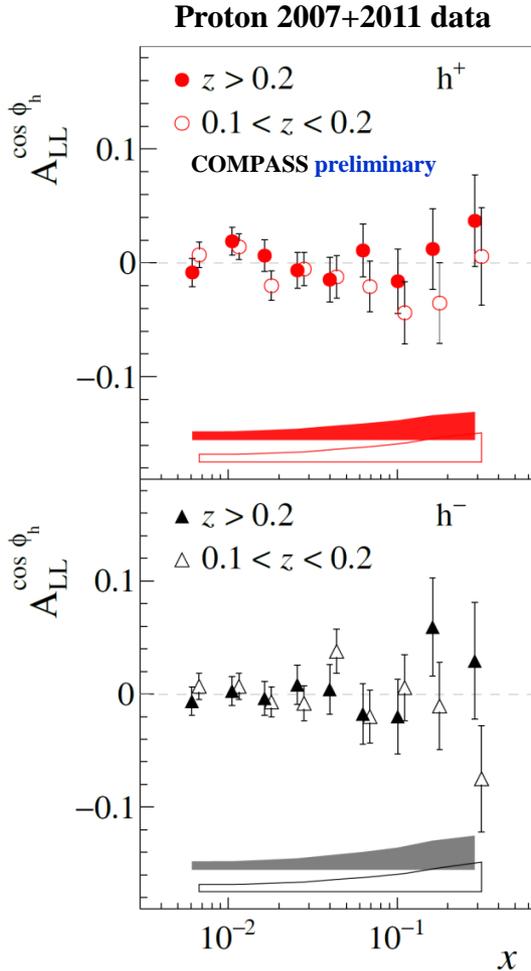
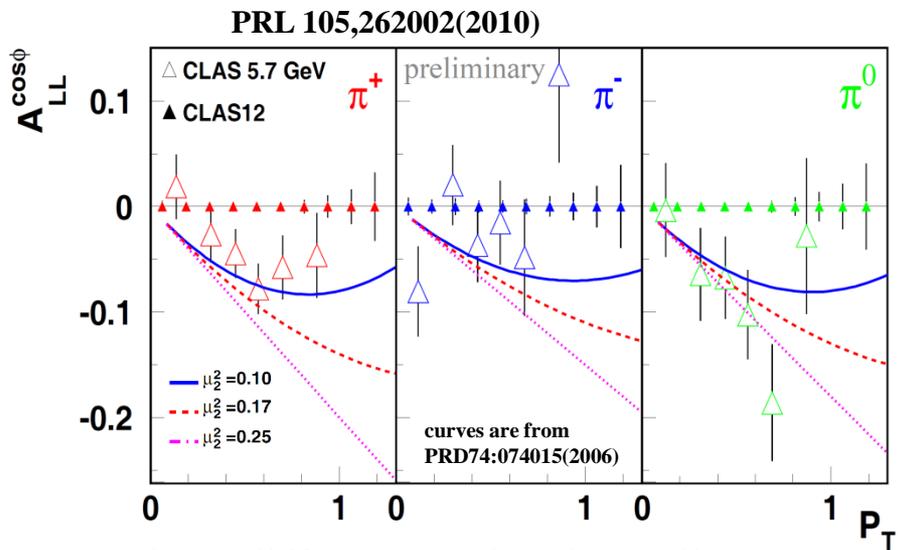




SIDIS: target longitudinal spin dependent asymmetries

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

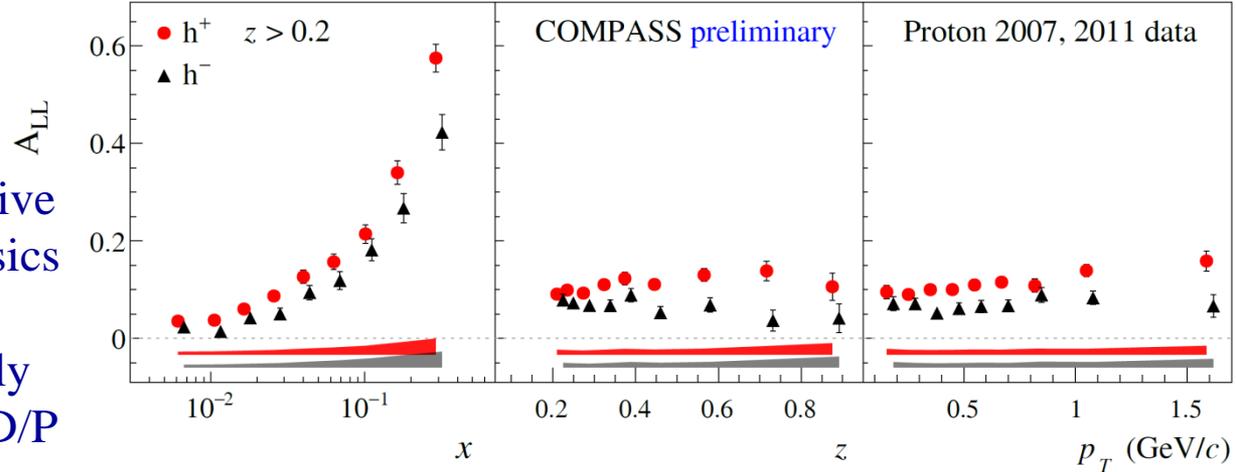


SIDIS: target longitudinal spin dependent asymmetries

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

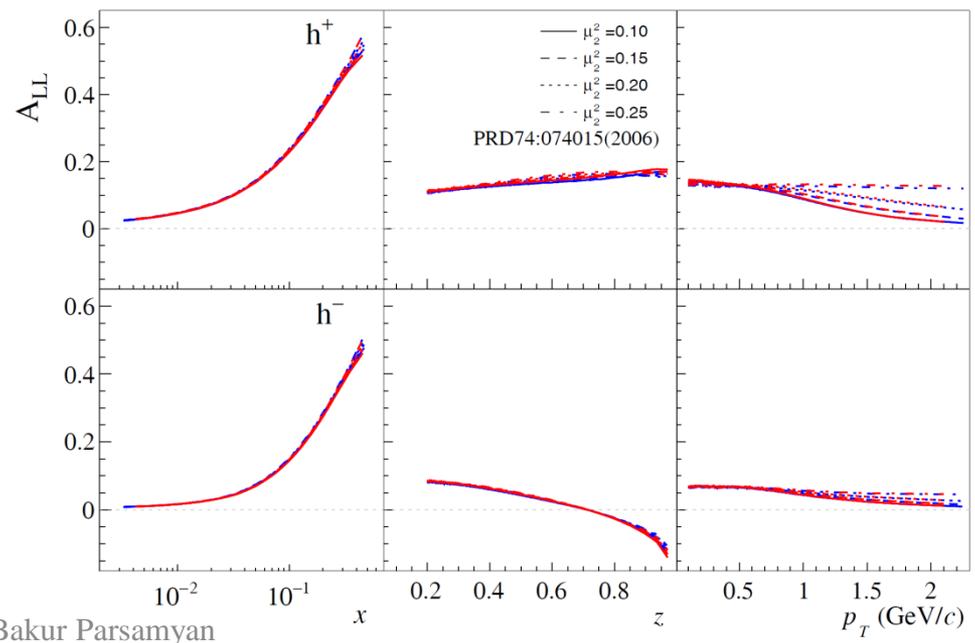
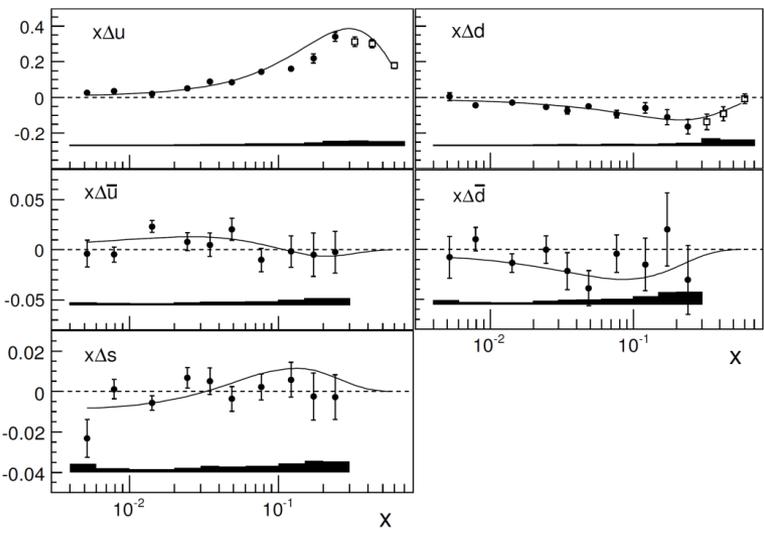
$$F_{LL}^1 = \mathcal{C} \left\{ g_{1L}^q D_{1q}^h \right\}$$

- 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)



COMPASS Proton-2007, -2011 kinematics

PLB 693 (2010) 227-235





SIDIS: target longitudinal spin dependent asymmetries

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

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

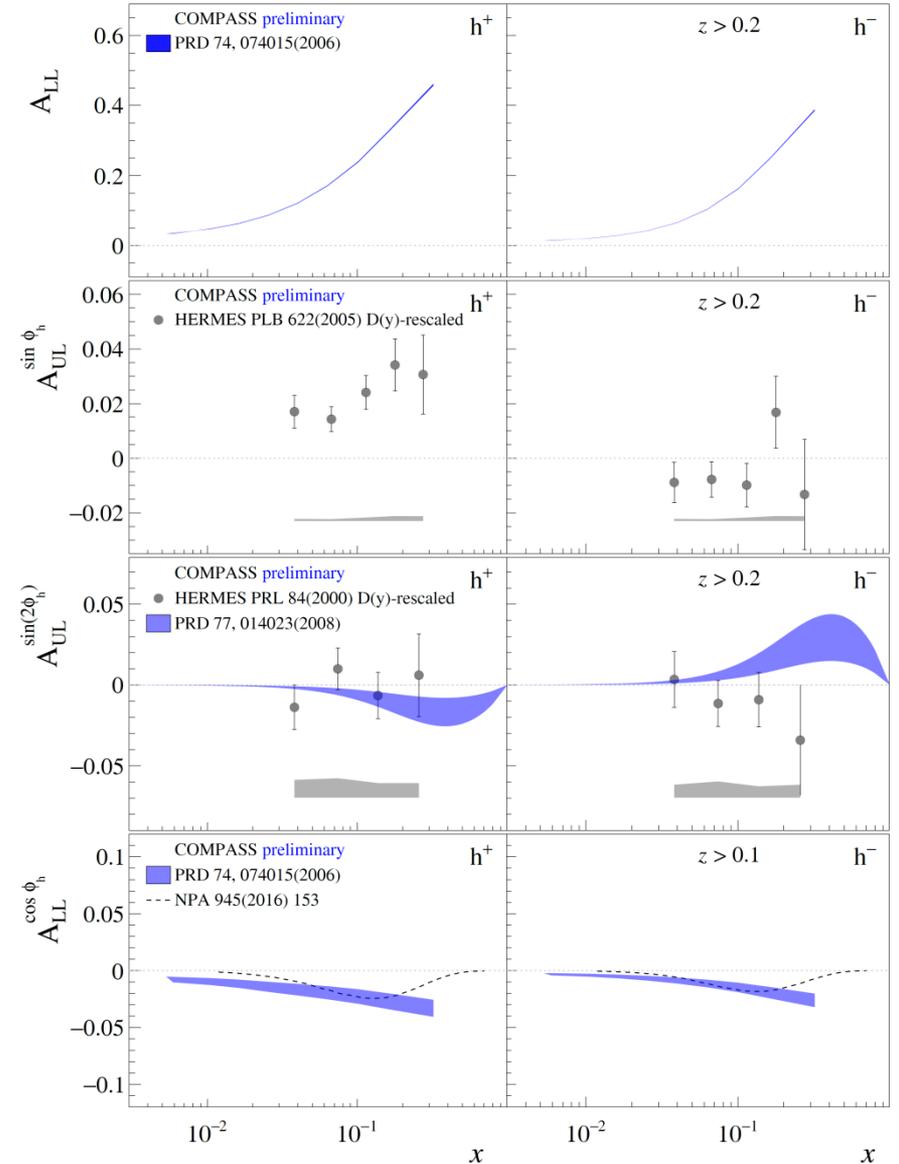
$$+ S_L \lambda \left[\begin{array}{l} \sqrt{1-\varepsilon^2} A_{LL} \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \end{array} \right] \left. \right\}$$

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

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

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

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





SIDIS: target longitudinal spin dependent asymmetries

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

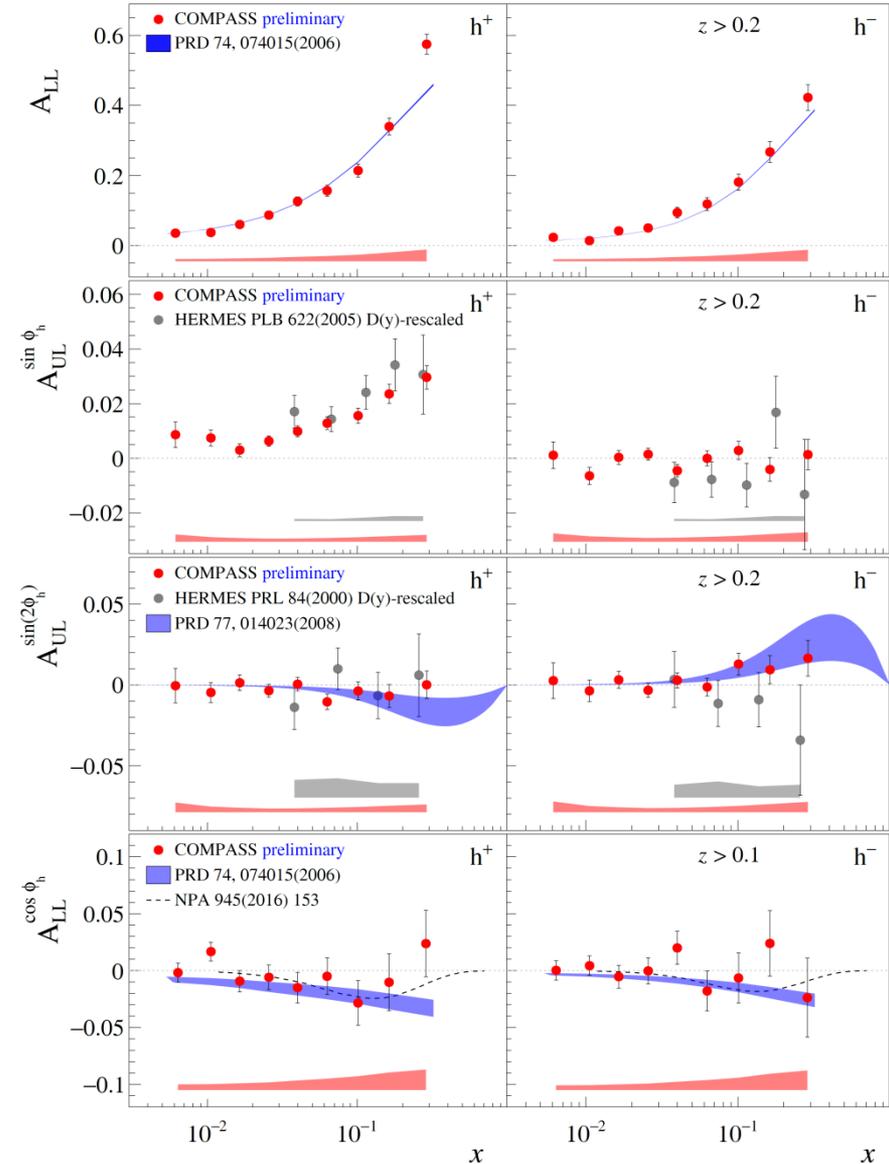
$$+ S_L \left[\begin{array}{l} \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \\ + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \end{array} \right]$$

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

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**

B. Parsamyan (for COMPASS) [arXiv:1801.01488](https://arxiv.org/abs/1801.01488) [hep-ex]





- Transverse target spin dependent azimuthal asymmetries (SIDIS)



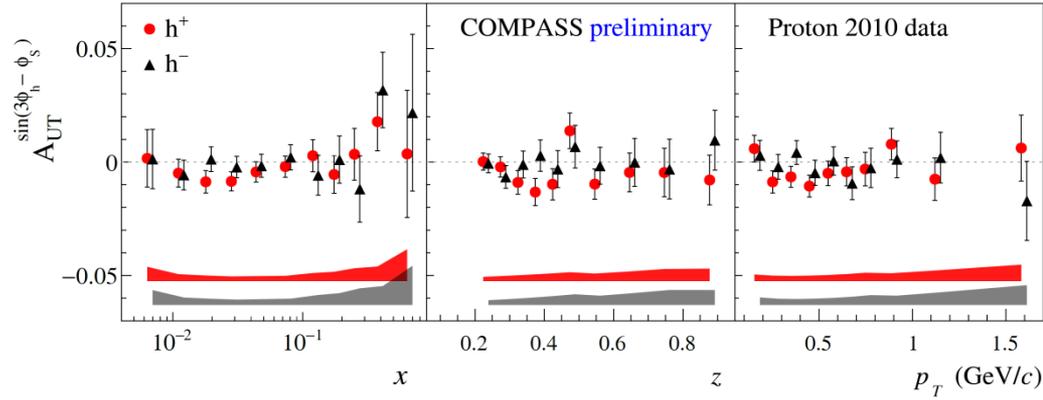
SIDIS: target transverse spin dependent asymmetries

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

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

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

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



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**

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



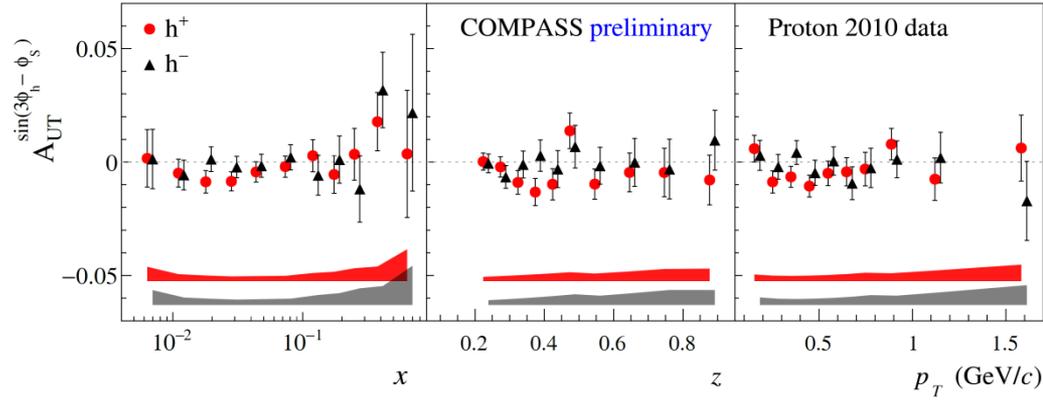
SIDIS: target transverse spin dependent asymmetries

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

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



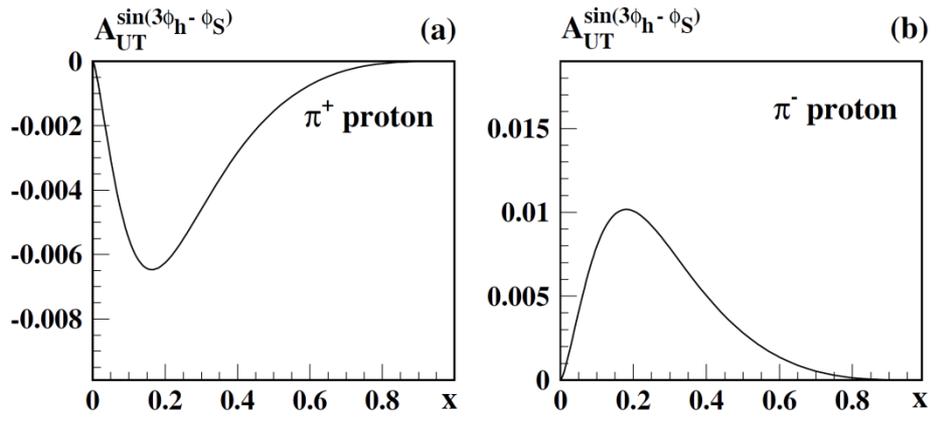
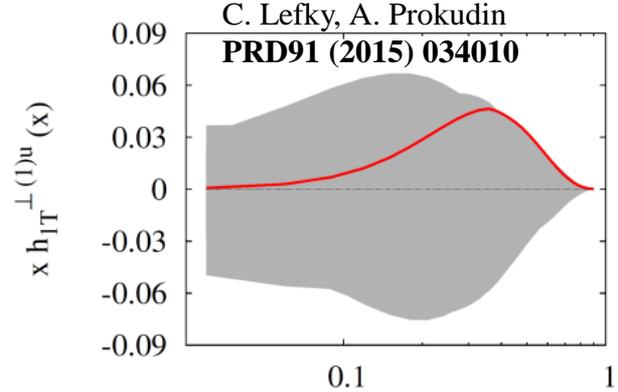
COMPASS results

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- $h_{1T}^{\perp q}$ is also small (see e.g. PLB769 (2017) 84-89)
- **Small, compatible with zero asymmetry**
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$$F_{UT}^{\sin(3\phi_h - \phi_S)} = C \left[\frac{2(\hat{h} \cdot k_T)(k_T \cdot p_T) + k_T^2(\hat{h} \cdot p_T) - 4(\hat{h} \cdot k_T)^2(\hat{h} \cdot p_T)}{2M^2 M_h} h_{1T}^{\perp q} H_{1q}^{\perp h} \right]$$

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





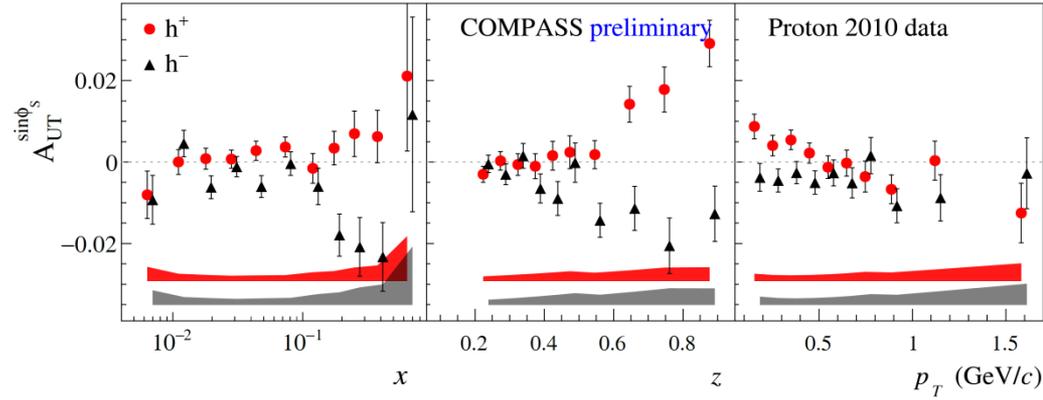
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$$+ S_T \lambda \left[\begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) \\ + \dots \end{array} \right]$$

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



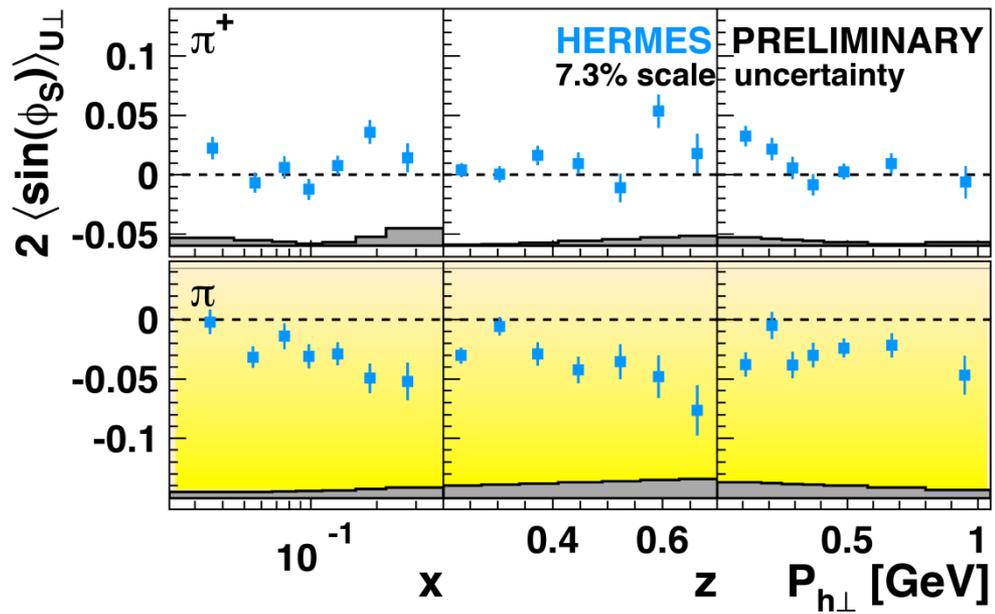
COMPASS results

- $A_{UT}^{\sin\phi_S}$
- Q-suppression
- Various different “twist” ingredients
- Within WW is related to Sivers and Collins
- **Small asymmetry, non-zero signal for h^- ?**

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

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

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





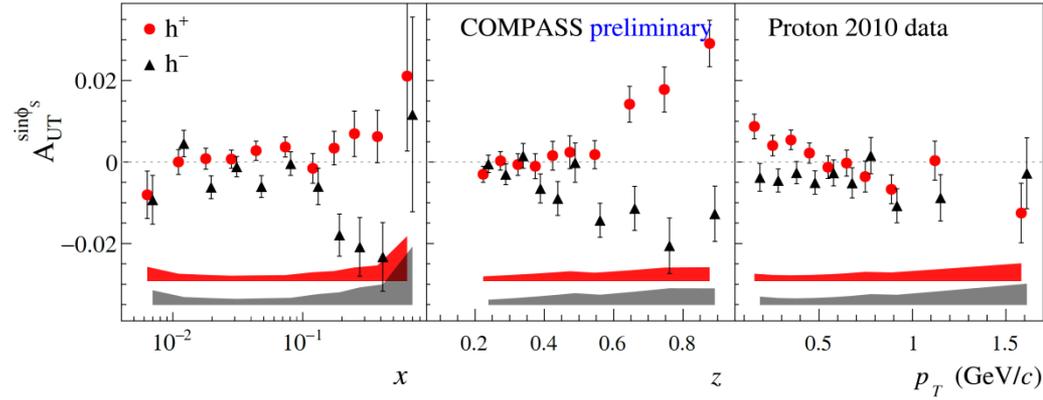
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$$+ S_T \lambda \left[\begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) \\ + \dots \end{array} \right]$$

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



COMPASS results

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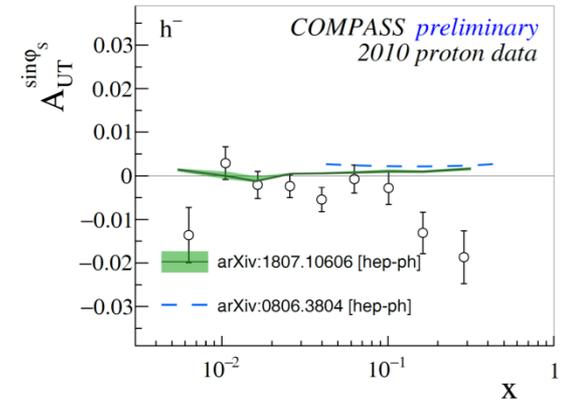
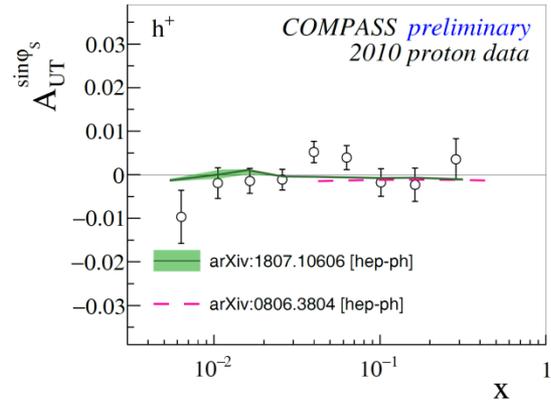
$$A_{UT}^{\sin(\phi_S)} \stackrel{WW}{\propto} Q^{-1} \left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \dots \right)$$

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 \[hep-ph\]](https://arxiv.org/abs/1807.10606)

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

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

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





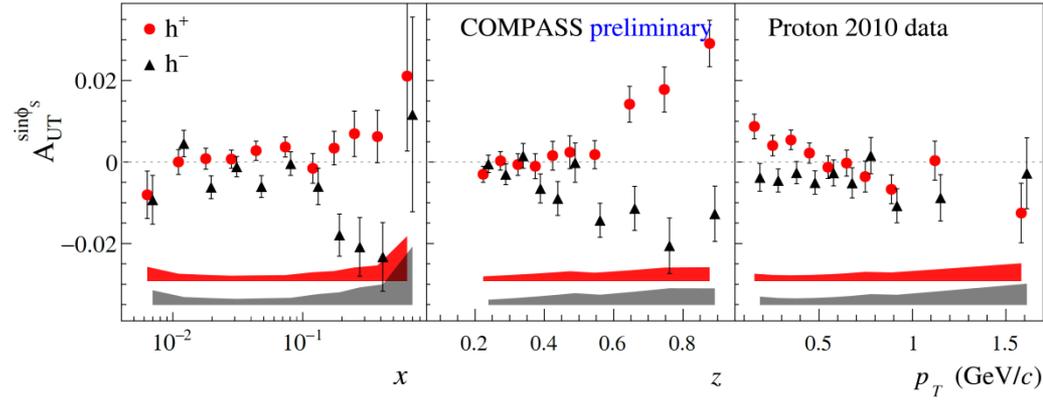
SIDIS: target transverse spin dependent asymmetries

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

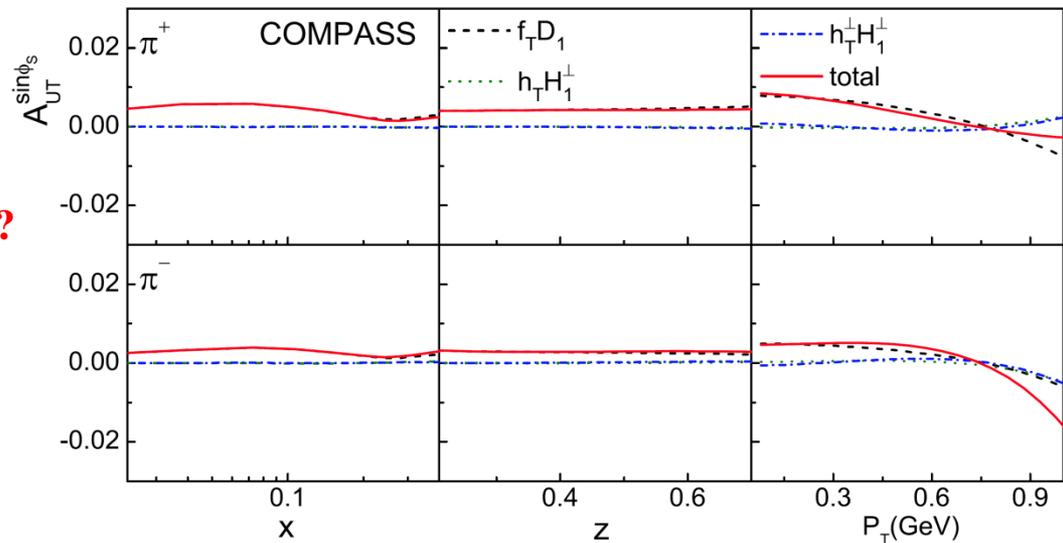
B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



COMPASS results

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- 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



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

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



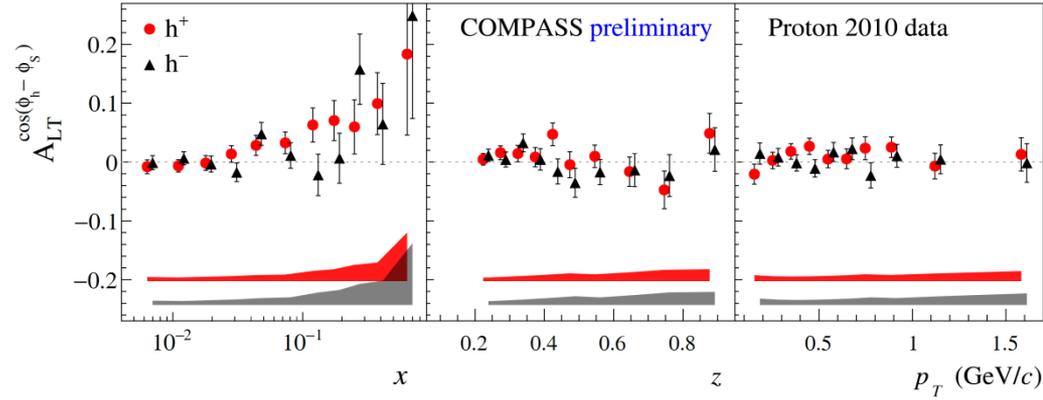
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B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042

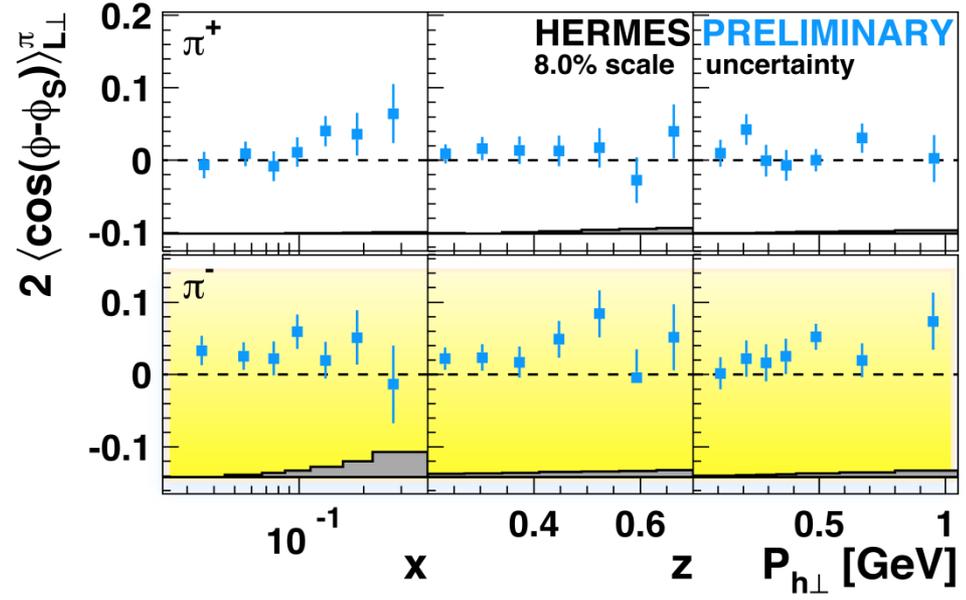


COMPASS results

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

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

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





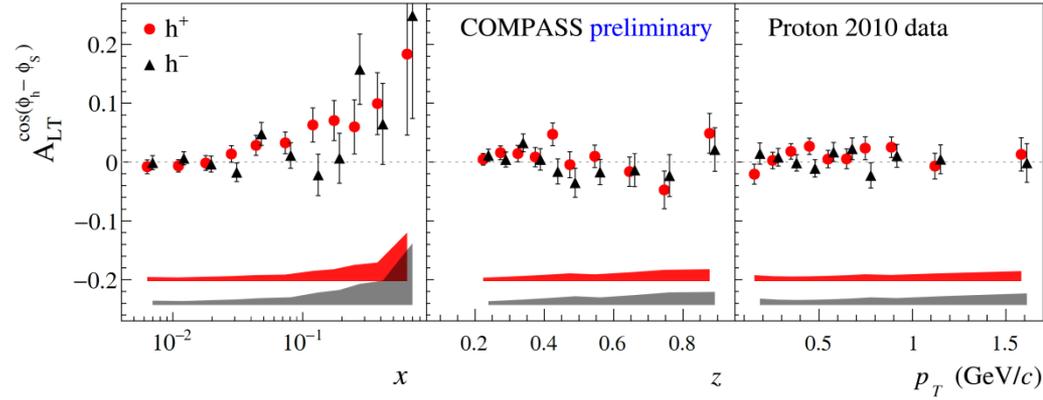
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B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



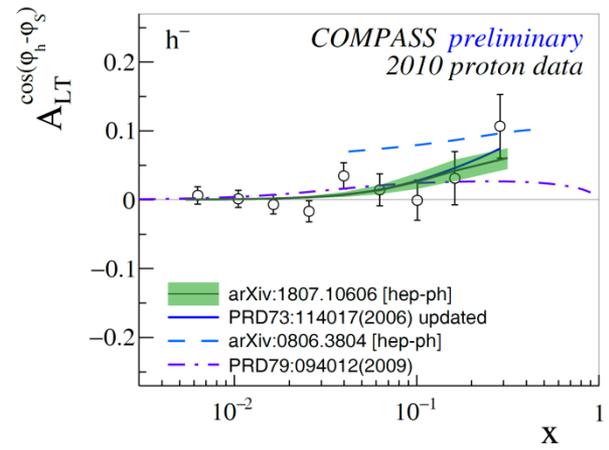
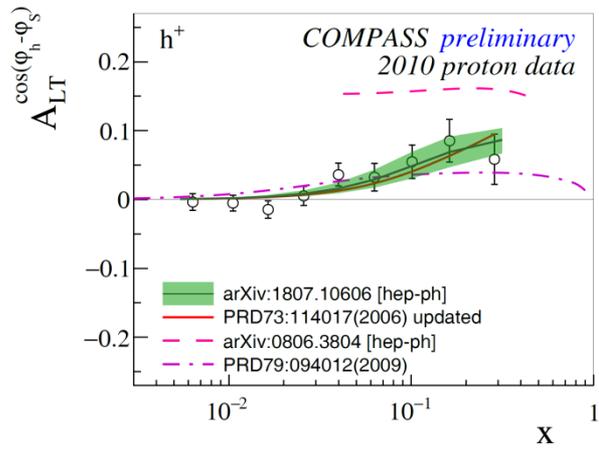
COMPASS results

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S. Bastami, H. Avakian, A. V. Efremov, A. Kotzinian, B. U. Musch, B. Parsamyan, A. Prokudin, M. Schlegel, G. Schnell, P. Schweitzer, W. Vogelsang
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$$F_{LT}^{\cos(\phi_h - \phi_S)} = C \left[\frac{\hat{h} \cdot \mathbf{k}_T}{M} g_{1T}^q D_{1q}^h \right]$$





SIDIS TSAs (Collins)

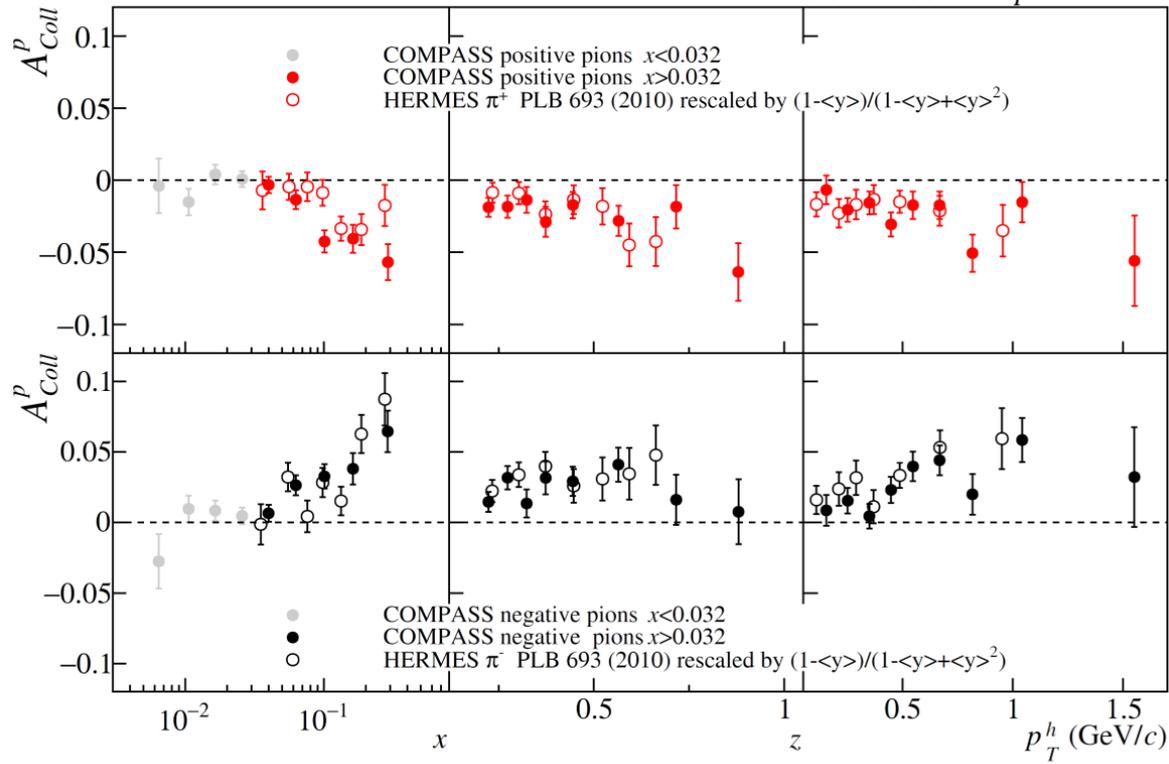
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \dots \right\}$$

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

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

COMPASS PLB 744 (2015) 250

COMPASS 2010 proton data





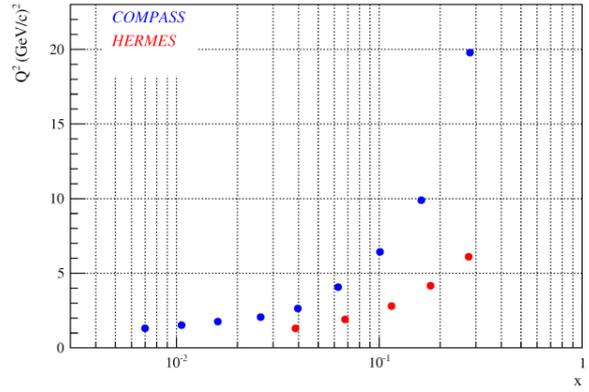
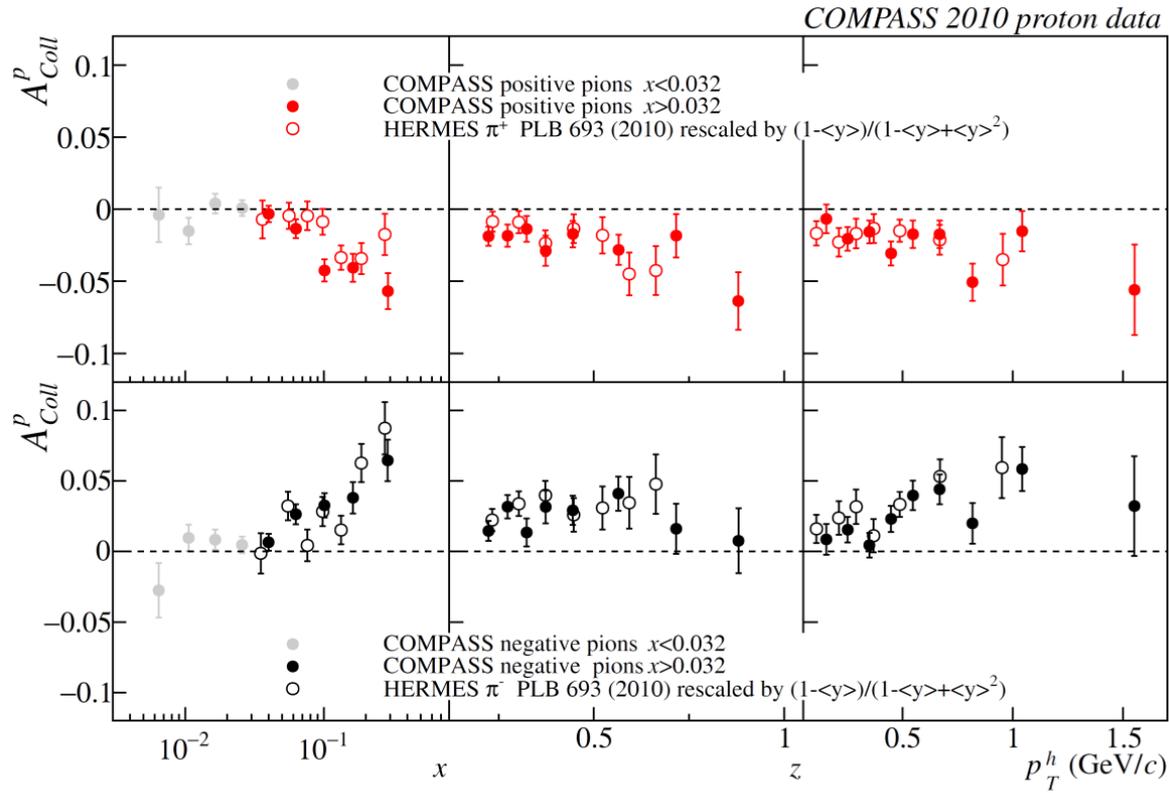
SIDIS TSAs (Collins)

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- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q² is different by a factor of ~2-3)
- **No Q²-evolution? Intriguing result!**

COMPASS PLB 744 (2015) 250





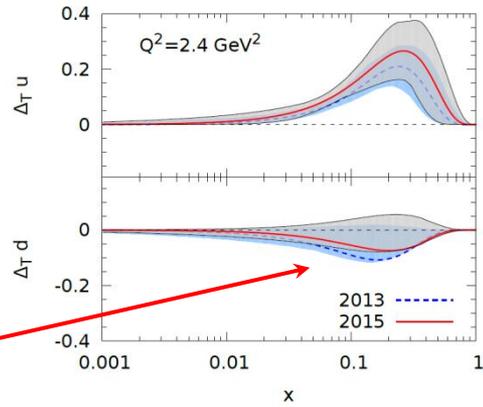
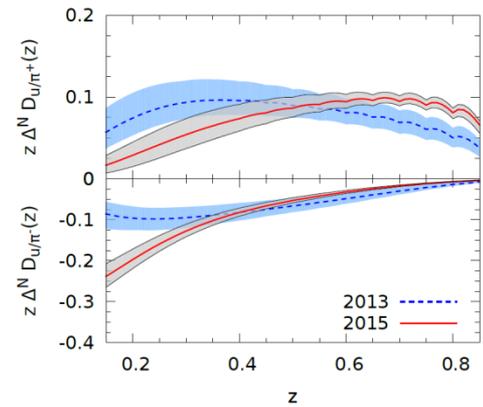
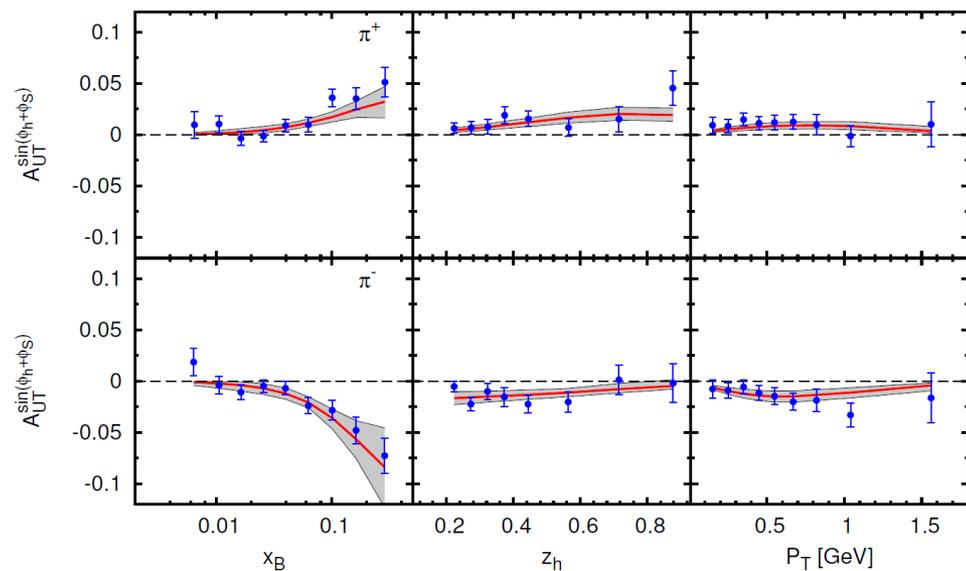
SIDIS TSAs (Collins)

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

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q² is different by a factor of ~2-3)
- **No Q²-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



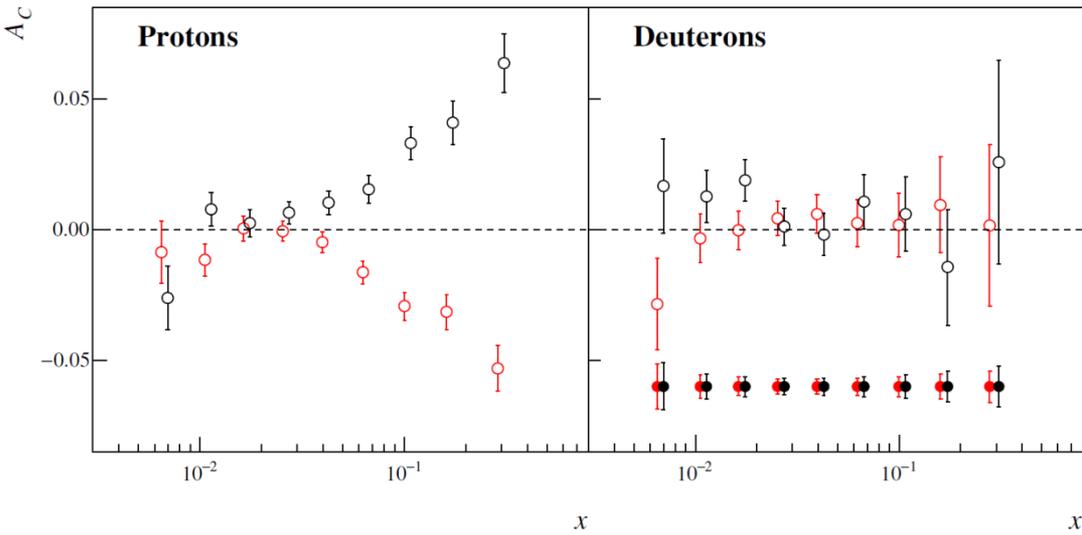
SIDIS TSAs (Collins)

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

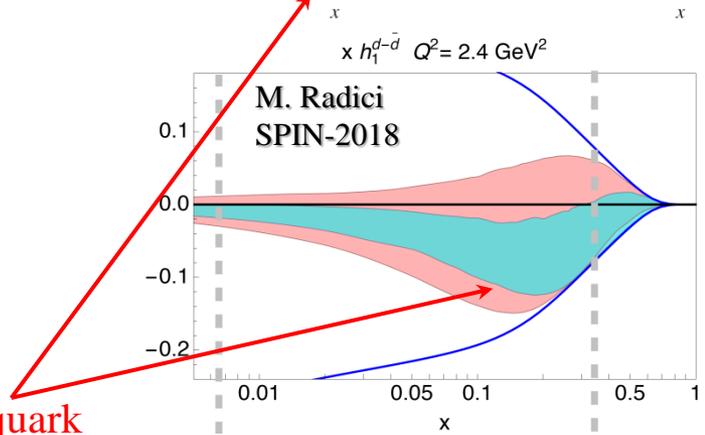
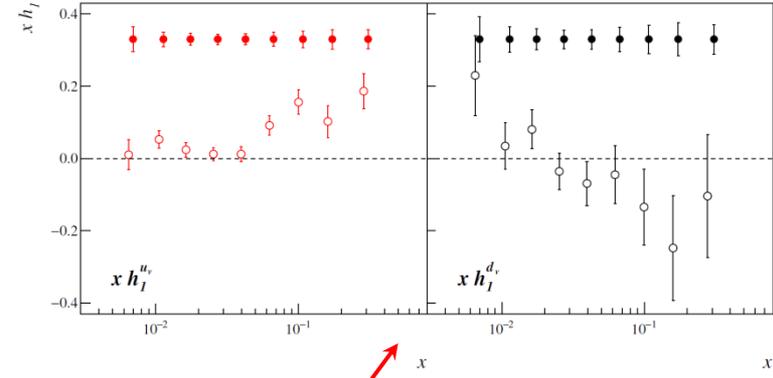
$$F_{UT}^{\sin(\phi_h + \phi_S)} = C \left[-\frac{\hat{h} \cdot p_T}{M_h} h_1^q H_{1q}^{\perp h} \right]$$

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q² is different by a factor of ~2-3)
- **No Q²-evolution? Intriguing result!**
- Extensive phenomenological studies and various global fits by different groups

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



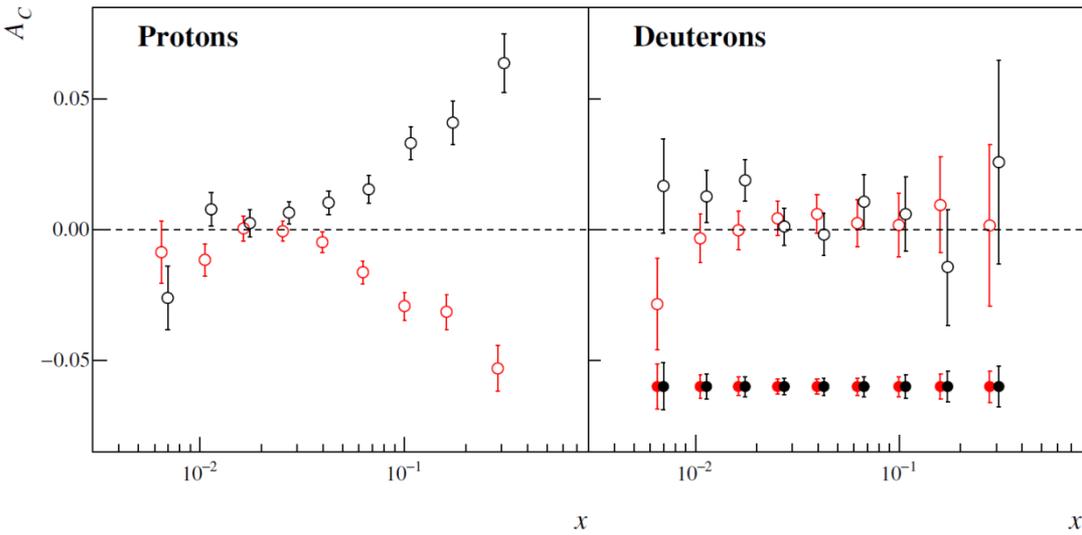
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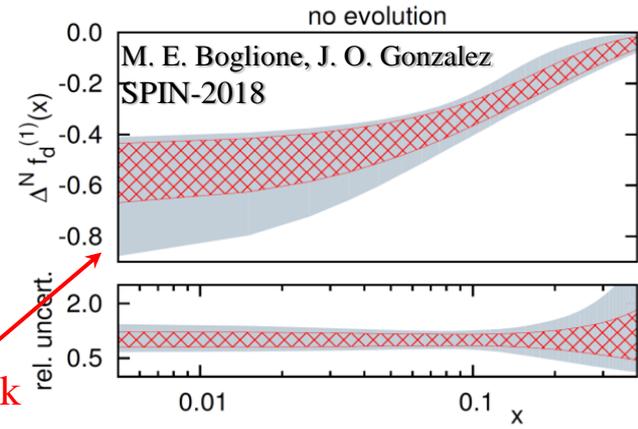
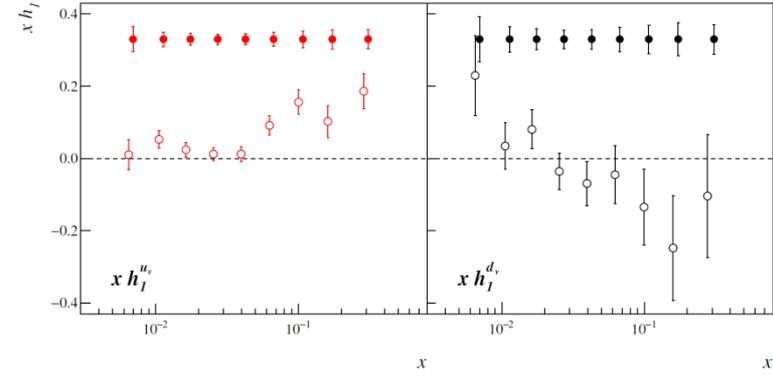
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COMPASS-II (2021 run – approved!)

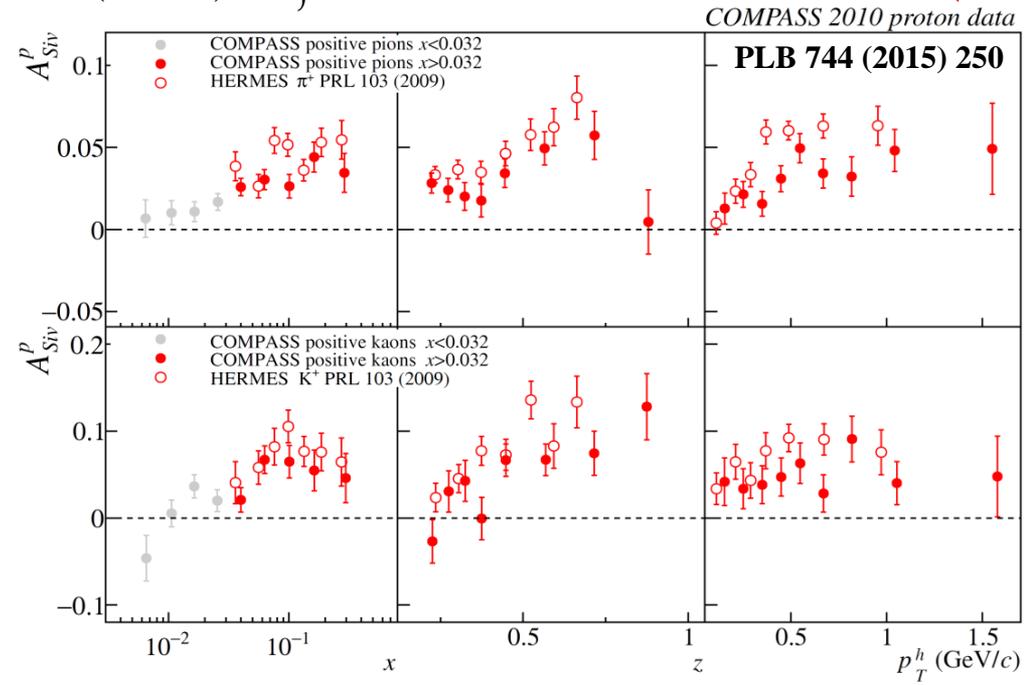
- Deuteron measurement to be repeated
- Will be crucial to constrain also the Sivers TMD PDF for the d-quark

SIDIS TSAs (Sivers)

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

- 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 $\sim 2-3$)
- **Q^2 -evolution? Intriguing result!**



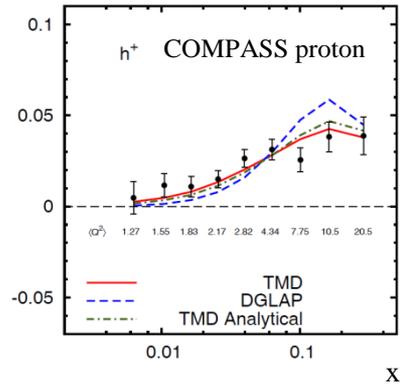
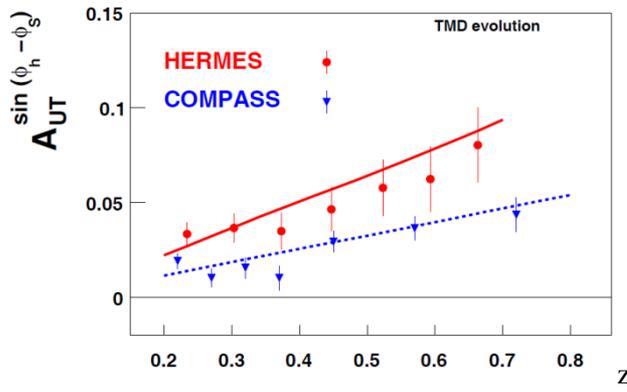
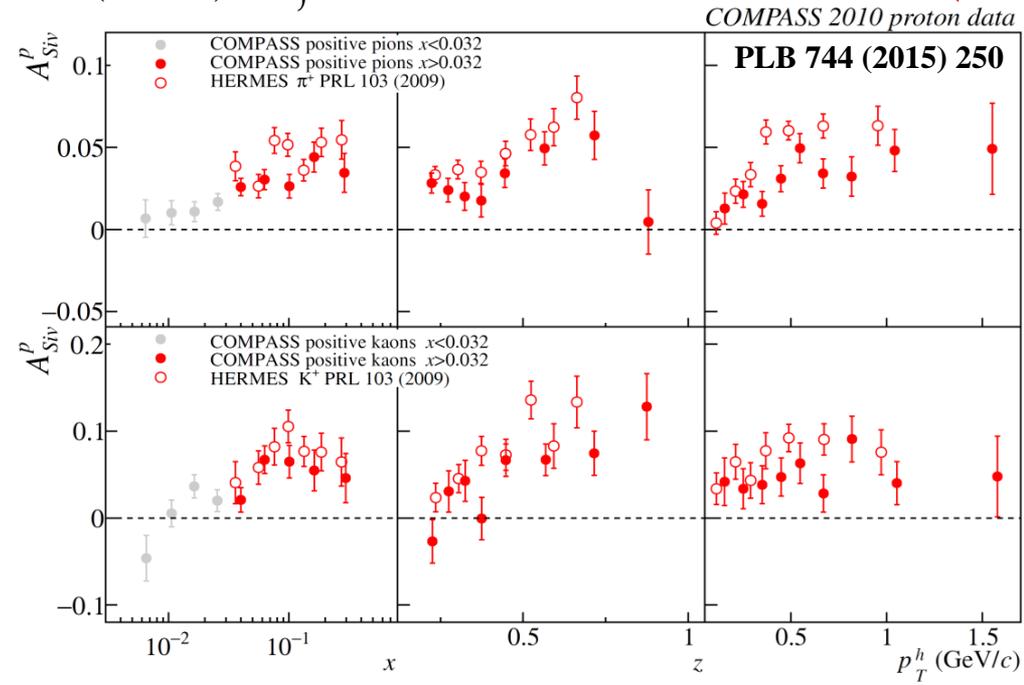


SIDIS TSAs (Sivers)

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- Recently - gluon Sivers paper
PLB 772 (2017) 854
- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results (Q² is different by a factor of ~2-3)
- **Q²-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**

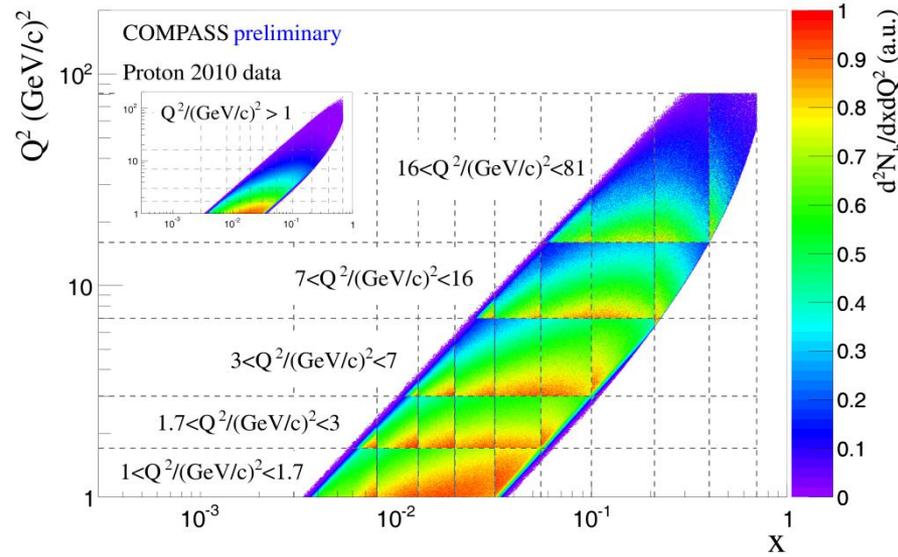


Multi-D TSA analysis

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

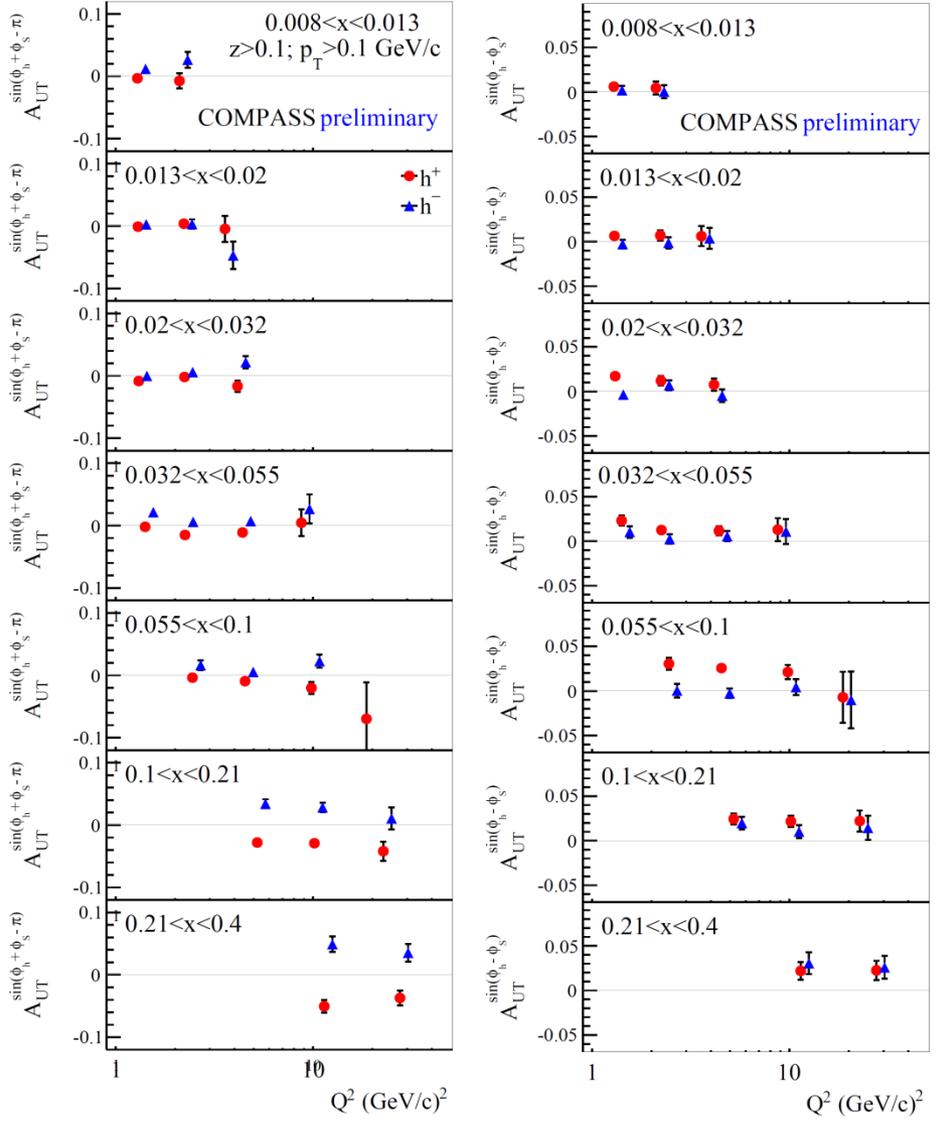
$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C \left[-\frac{\hat{h} \cdot \mathbf{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h \right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$

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

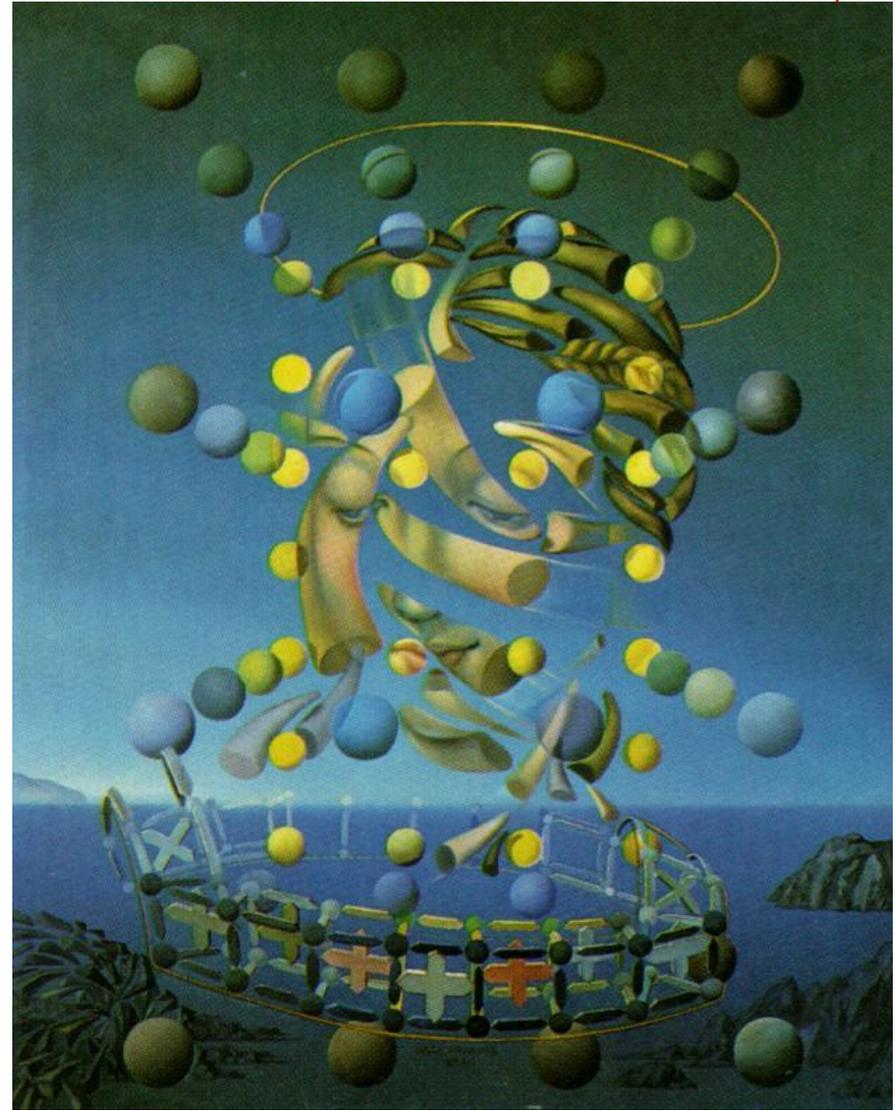


- No clear Q^2 -dependence within statistical accuracy
- Possible decreasing trend for Sivers TSA?

B. Parsamyan (for COMPASS) [arXiv:1504.01599](https://arxiv.org/abs/1504.01599) [hep-ex] (SPIN-2014)



“1D”



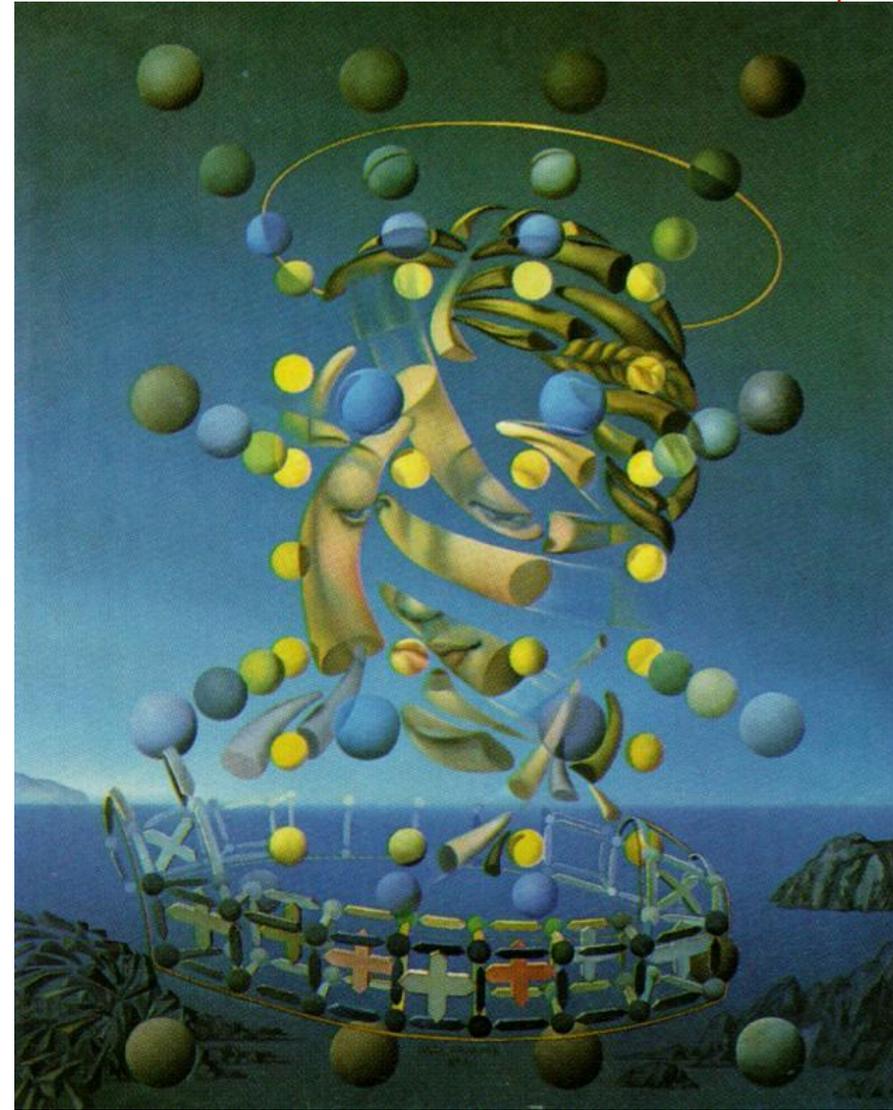
Salvador Dali "Maximum Speed of Raphael's Madonna"

“Nature”



Raphael *“Madonna del Prato”*

“ID”



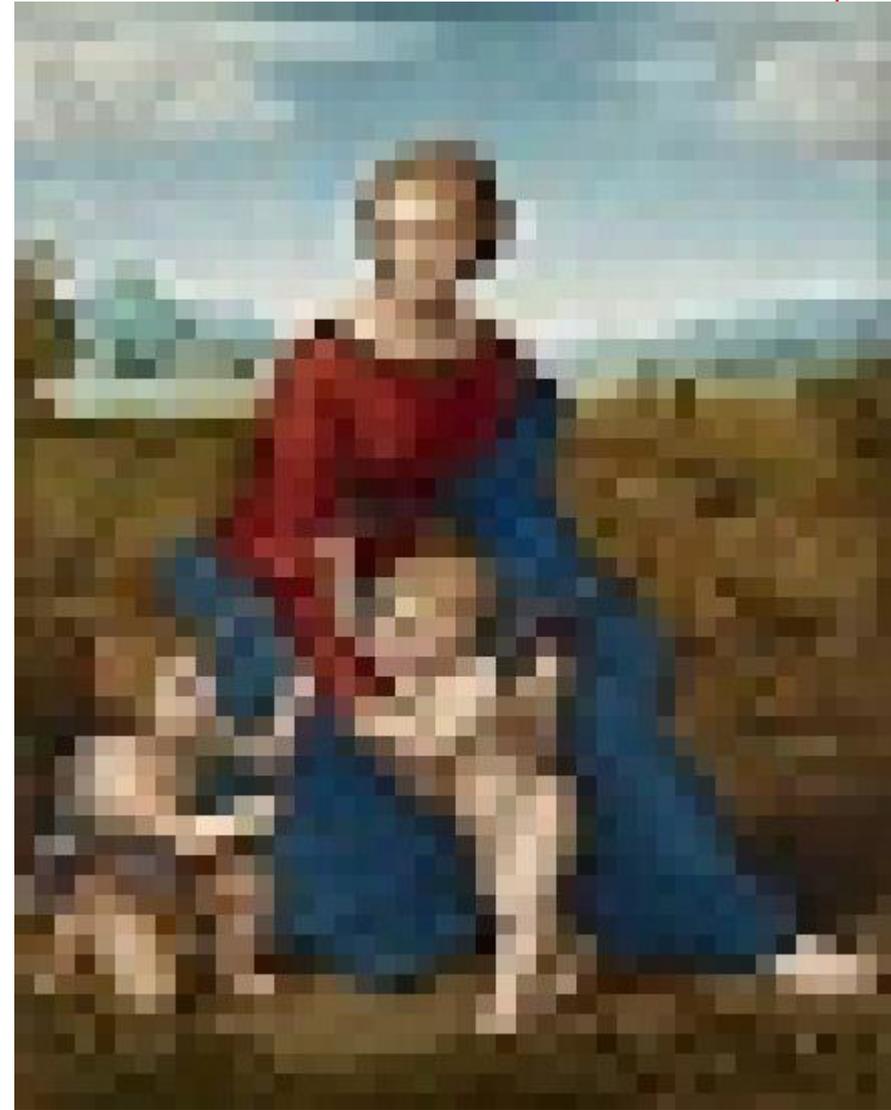
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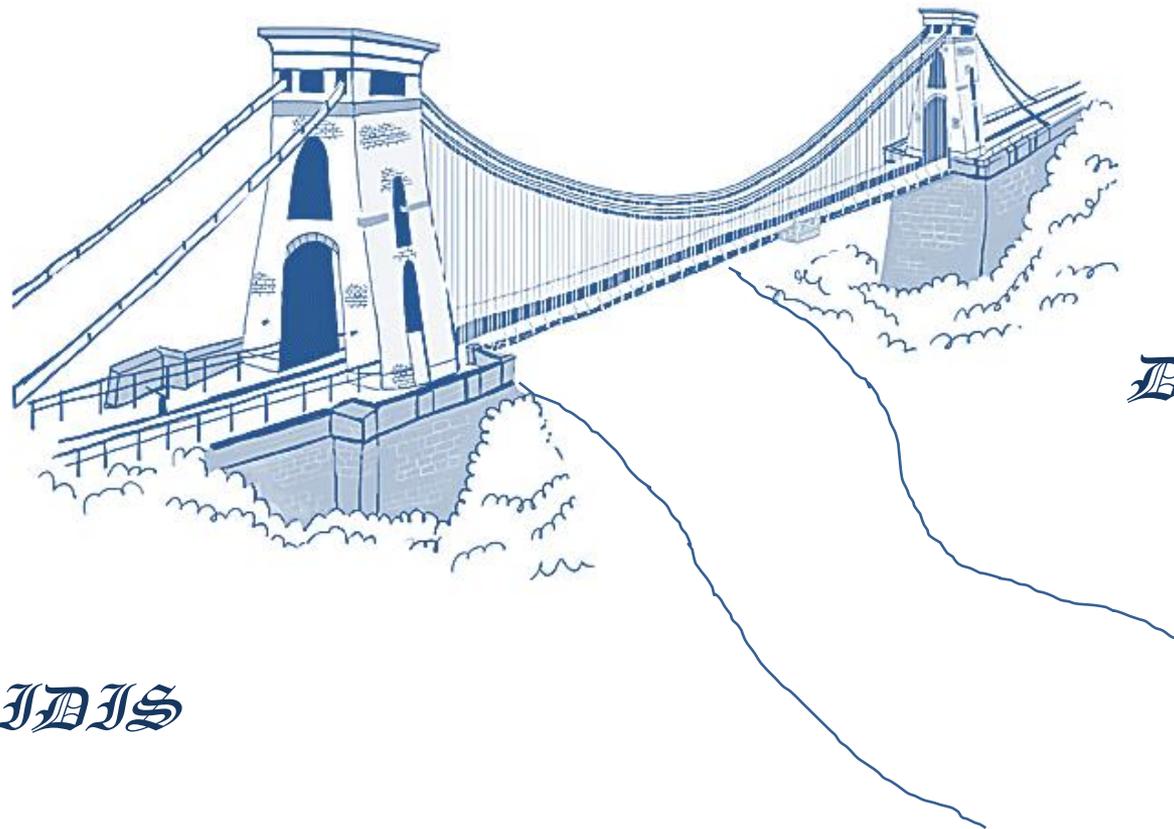
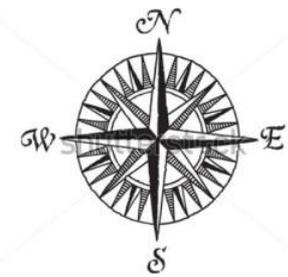
Raphael *“Madonna del Prato”*

“multi-D” with available statistics



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

COMPASS bridge



Drell-Van

SIDS

SIDIS and single-polarized DY x-sections

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

SIDIS

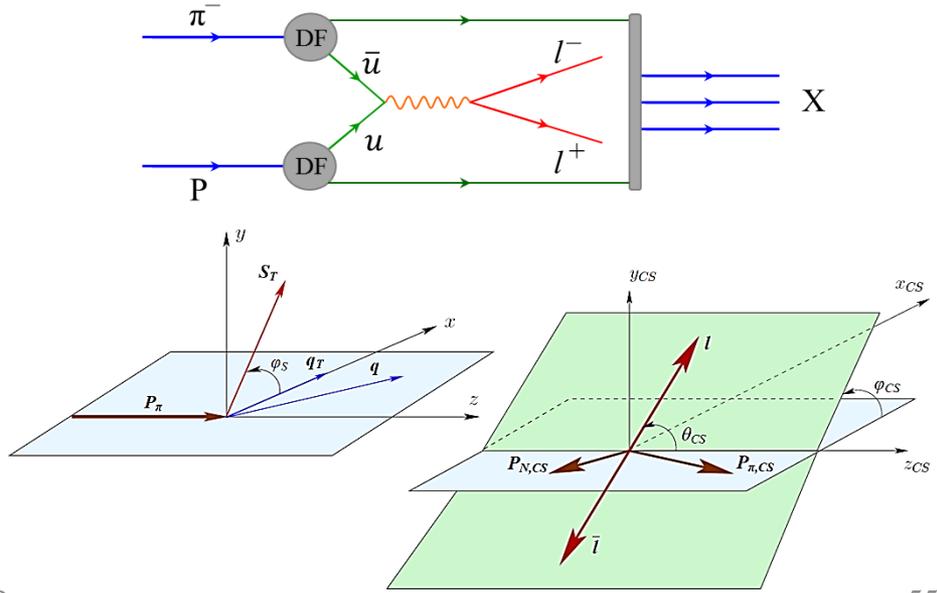
$$\left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L})$$

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

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

DY

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





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

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

SIDIS

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

DY

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



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

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



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

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

SIDIS

SIDIS-DY bridge

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

DY

$$1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h$$

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

$$+ S_T \begin{bmatrix} A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \end{bmatrix}$$

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

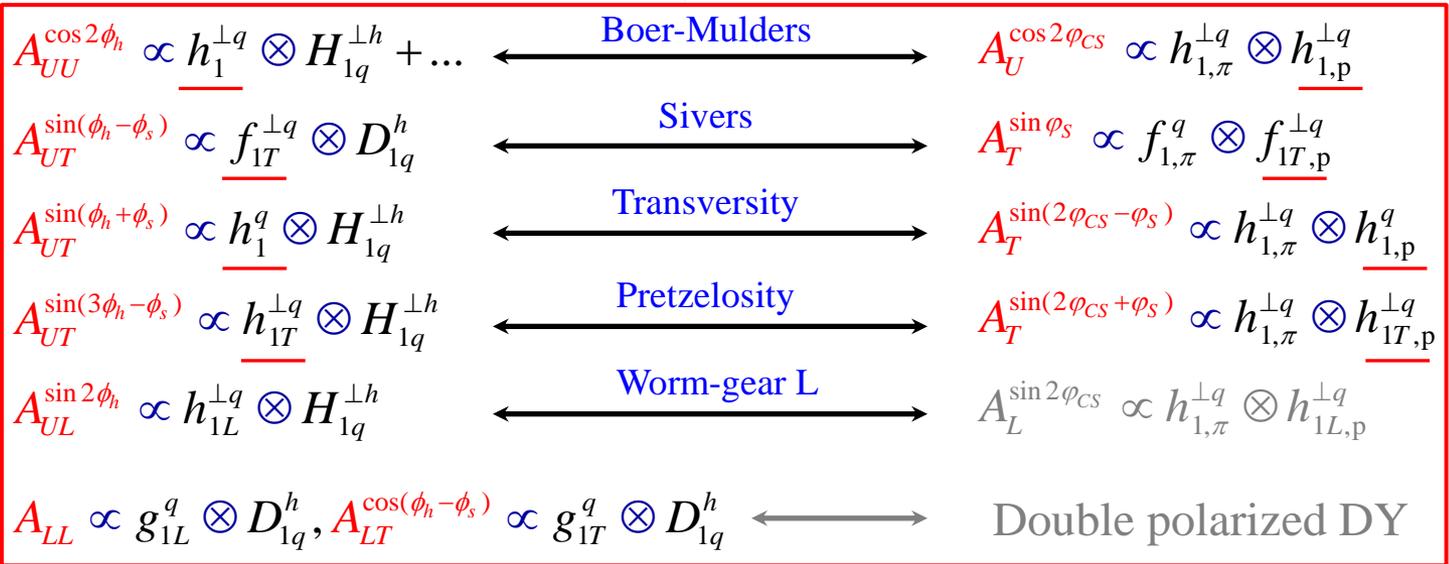
×

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

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

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

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



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)

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

SIDIS

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

DY

**SIDIS-DY
bridge**

×

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

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

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

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

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

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

within QCD TMD-framework:

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

$\underline{h_1^q}$ & $\underline{h_{1T}^q}$ 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

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

SIDIS

DY

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

←

$$1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h$$

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

SIDIS-DY bridge

←

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

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

×

$$+ S_T \begin{bmatrix} A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \end{bmatrix}$$

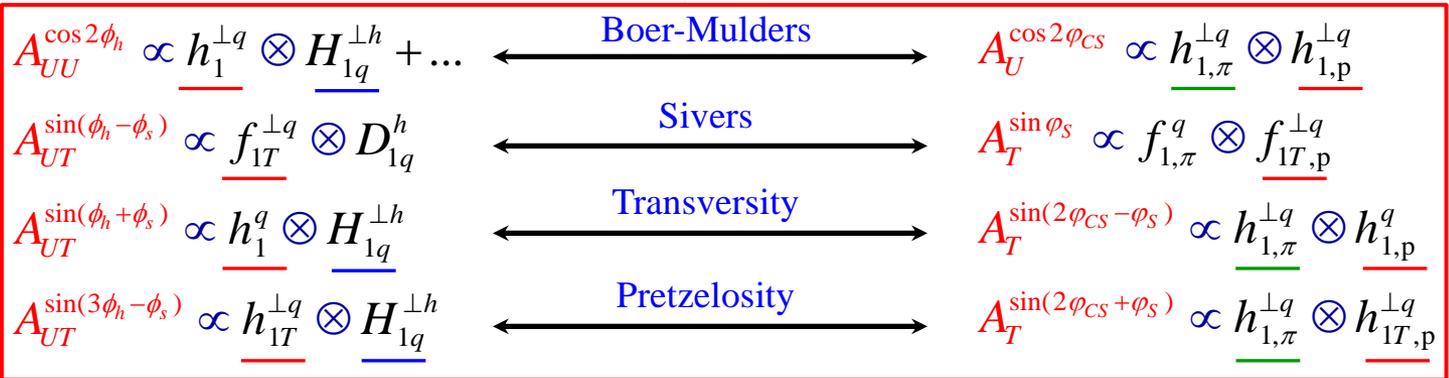
$$+ S_T \lambda \left[\sqrt{(1 - \varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \right]$$

×

×

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

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



Complementary information from different channels :

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



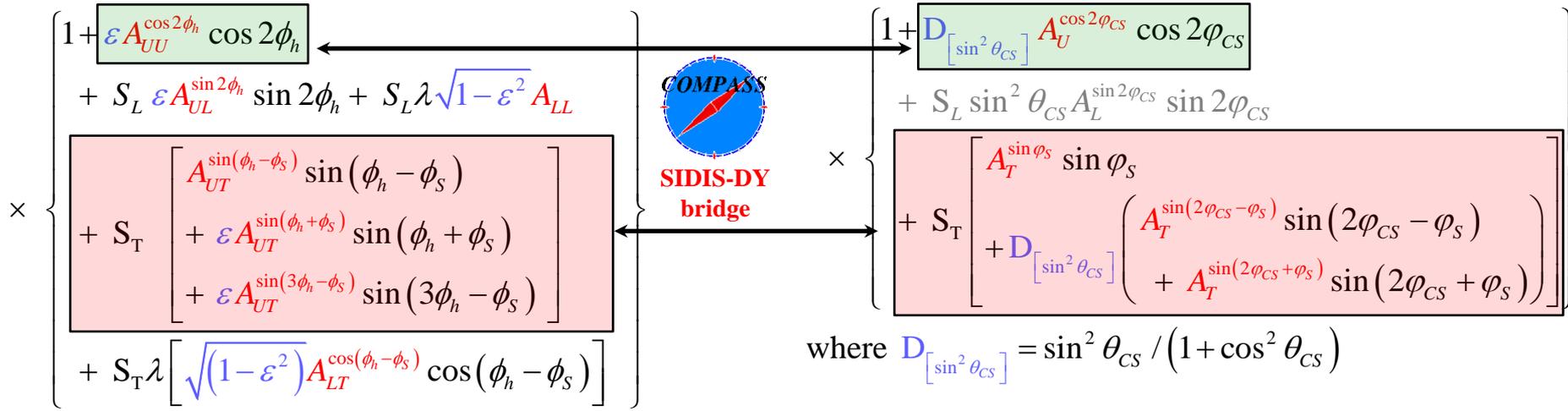
SIDIS and single-polarized DY x-sections at twist-2 (LO)

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

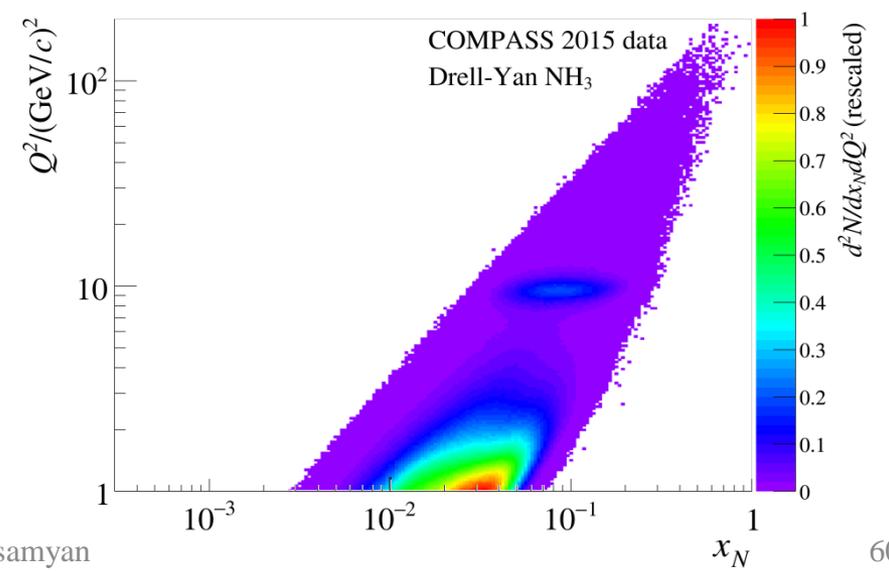
SIDIS

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

DY



COMPASS x:Q² phase space (DY 2015 data)





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

SIDIS

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

SIDIS

DY

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

←

$$1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h$$

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

←

←

SIDIS-DY bridge

←

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

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

×

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

×

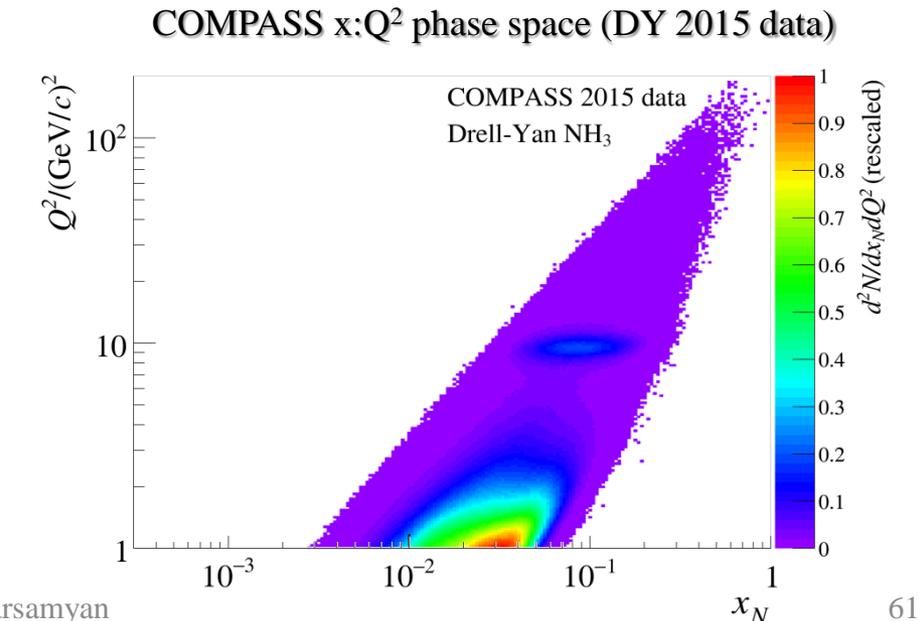
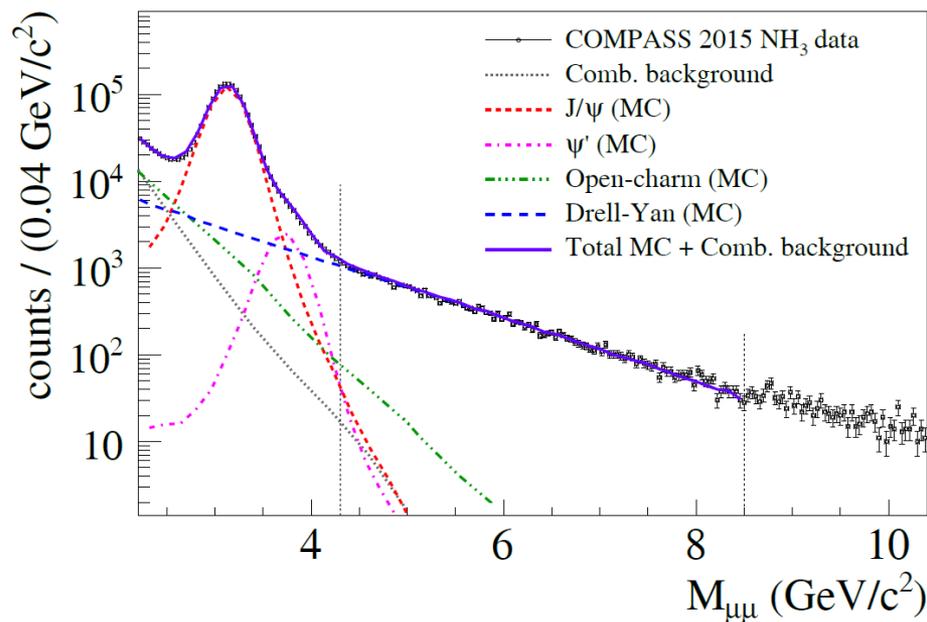
×

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

+

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

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





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

SIDIS

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

SIDIS-DY bridge

DY

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

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

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

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

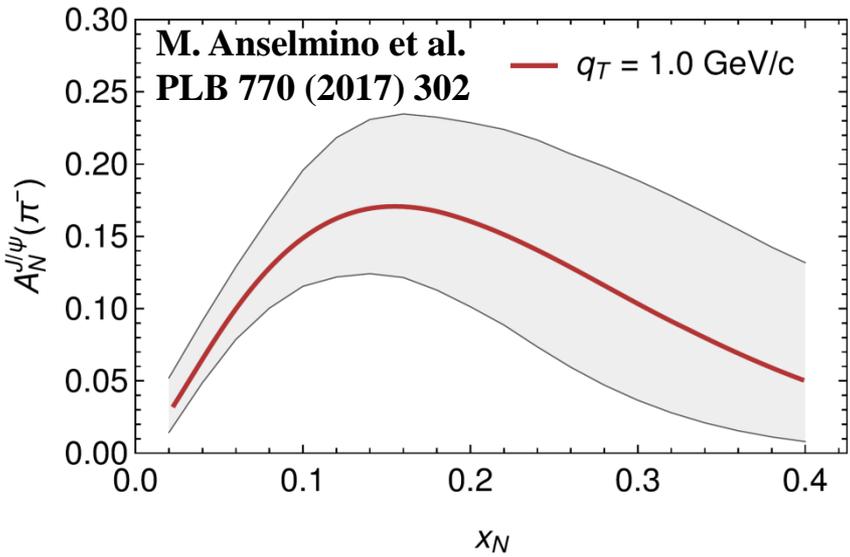
\times

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

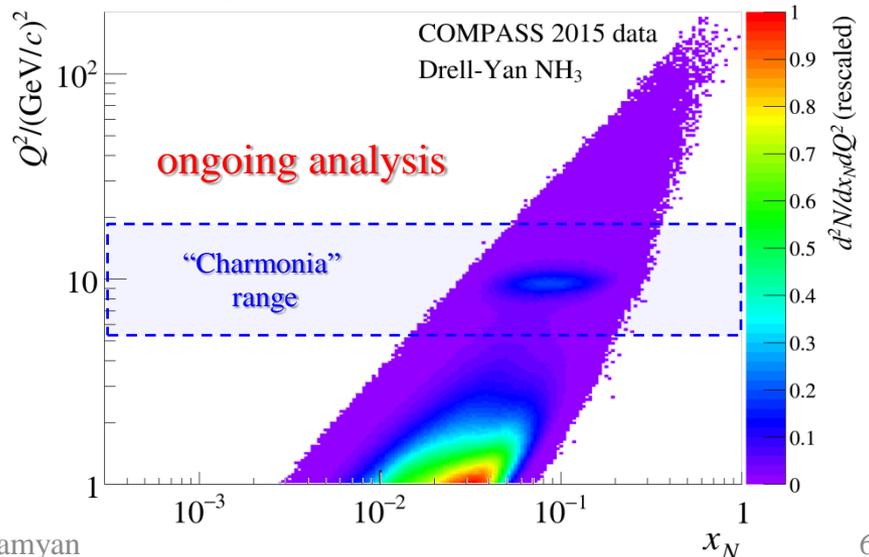
$\times \left[\begin{array}{l} A_T^{\sin \varphi_S} \sin \varphi_S \\ + D_{[\sin^2 \theta_{CS}]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \\ + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \end{array} \right) \end{array} \right]$

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

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



$2.5 < M / (\text{GeV}/c^2) < 4.3$ “Charmonia mass”
 Strong J/ψ -signal \rightarrow study of J/ψ physics
 Good signal/background





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

SIDIS

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

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

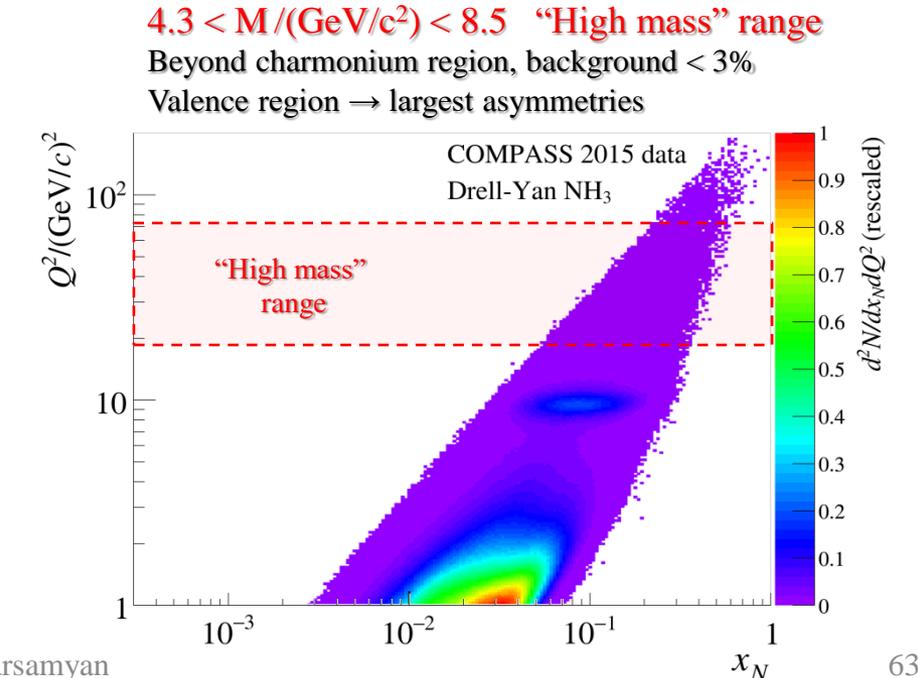
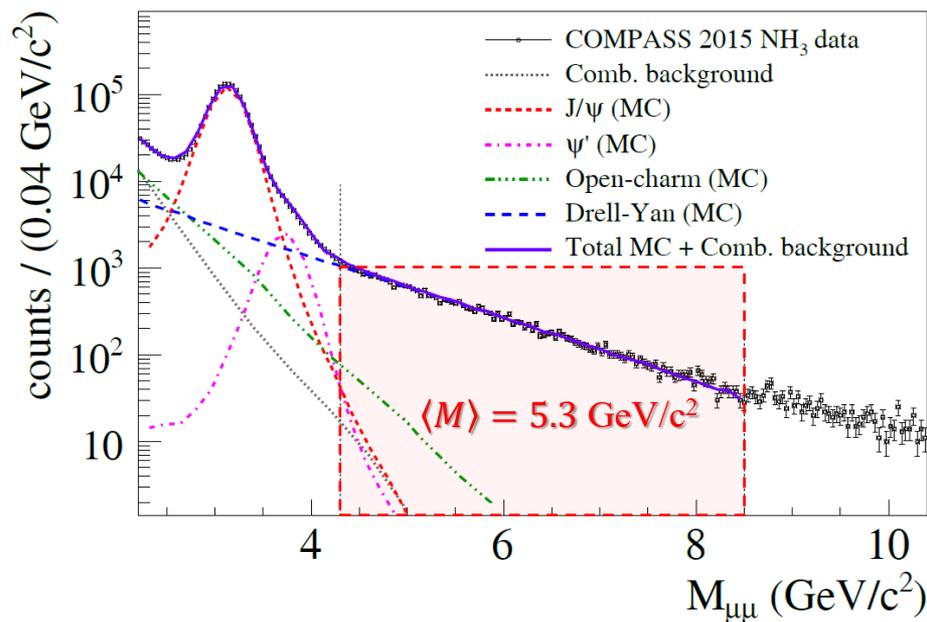
**SIDIS-DY
bridge**

DY

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

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

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





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

SIDIS

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

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

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

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

**SIDIS-DY
bridge**

DY

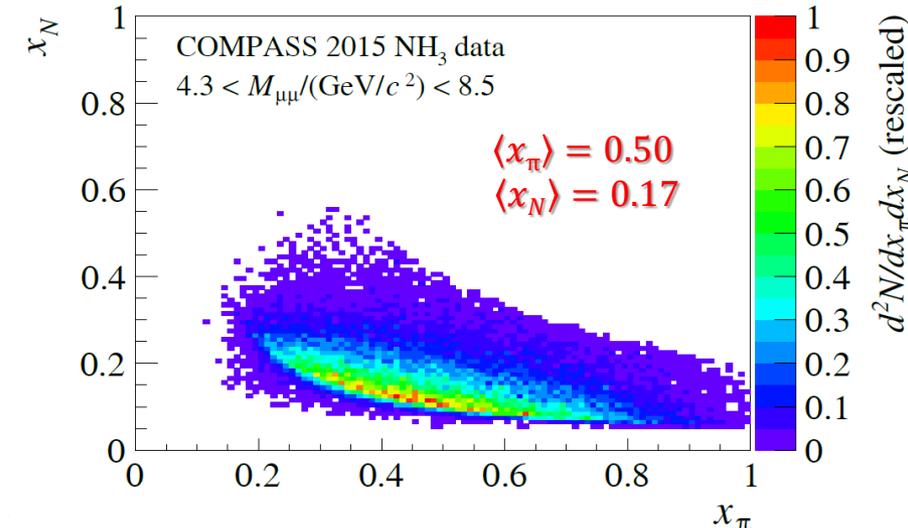
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS})$$

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

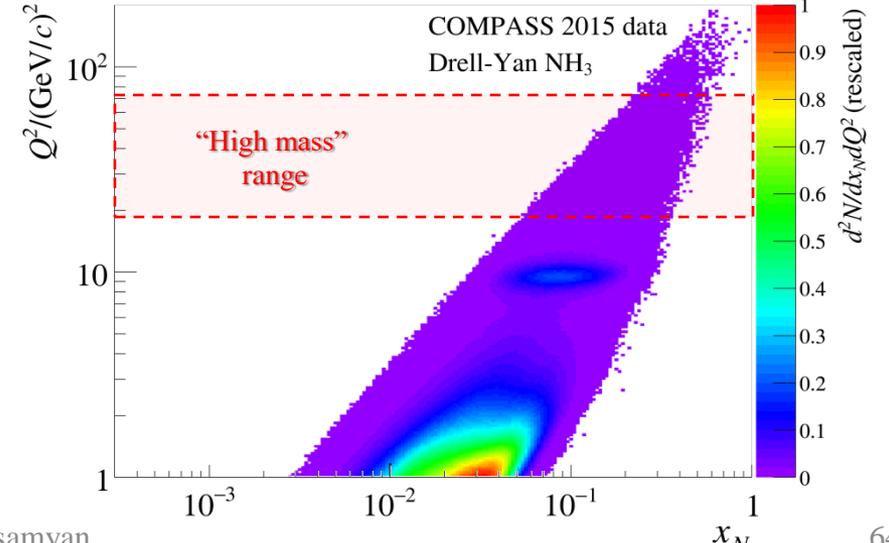
$$\times \left[\begin{array}{l} A_T^{\sin \varphi_S} \sin \varphi_S \\ + D_{[\sin^2 \theta_{CS}]} \left(A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \right. \right. \\ \left. \left. + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \right) \right]$$

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

HM events are in the valence quark range



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

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

SIDIS-DY bridge

DY

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

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

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

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

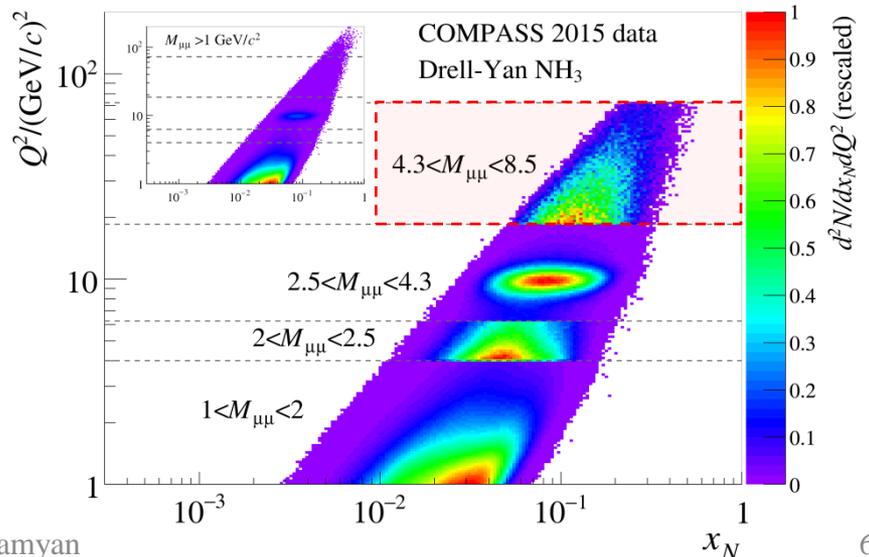
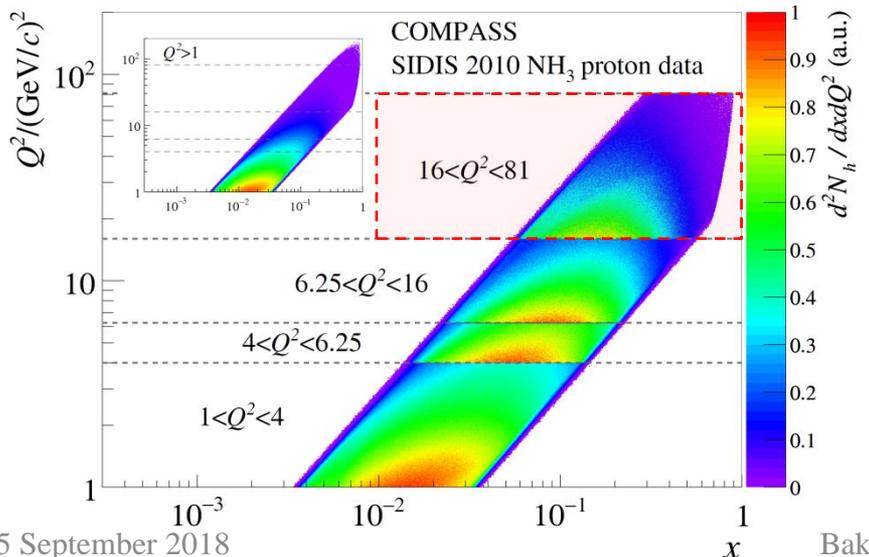
\times

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

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

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

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



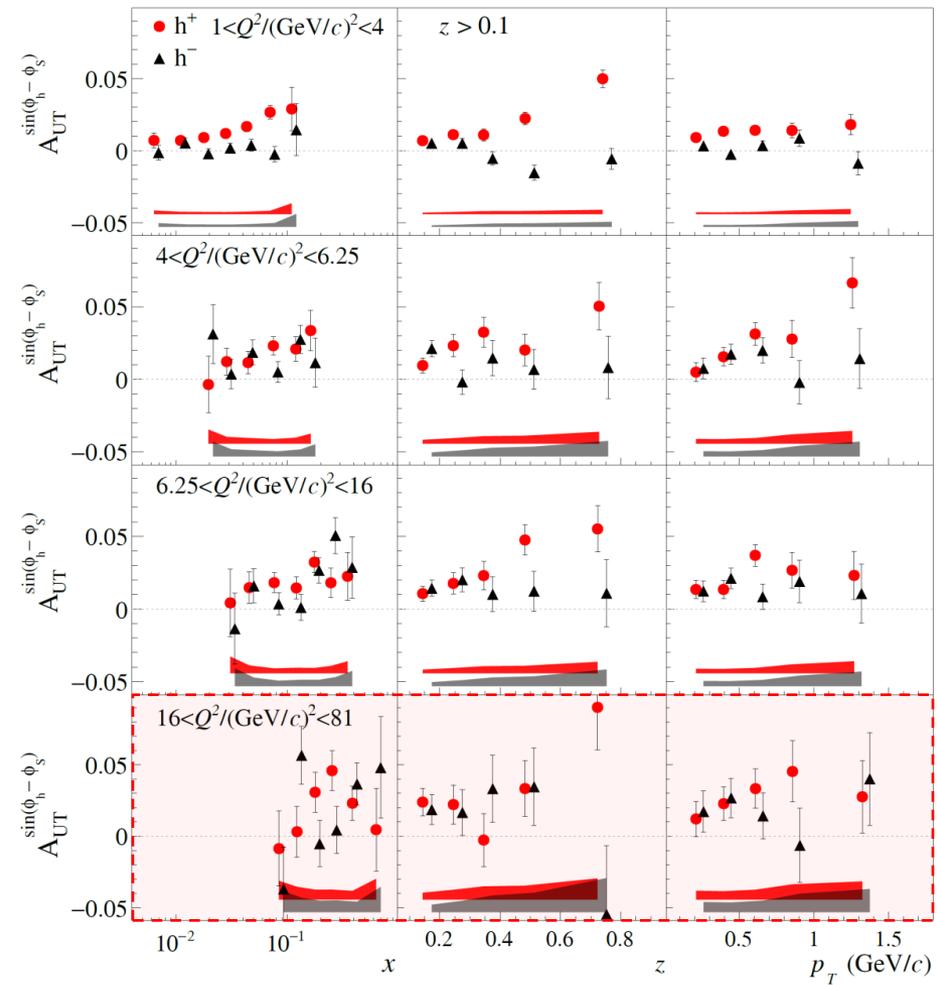
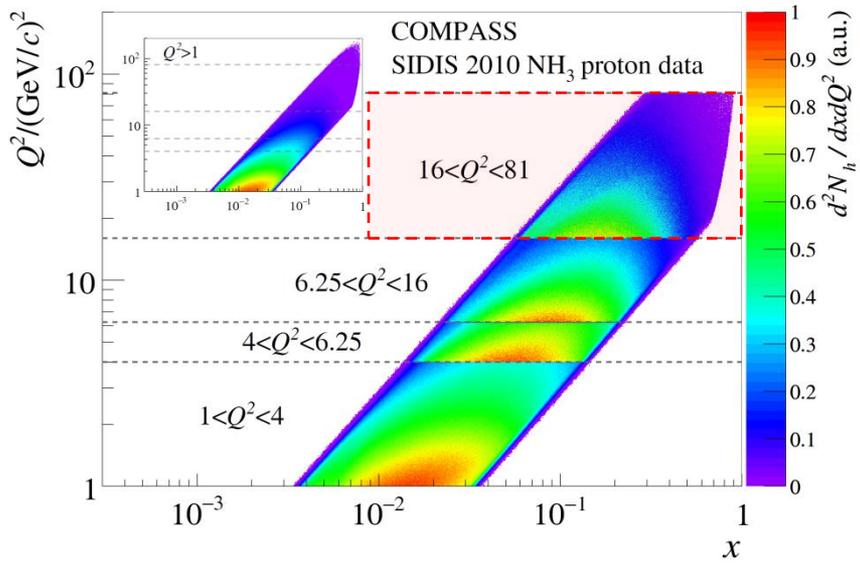


SIDIS Sivers TSA in COMPASS Drell-Yan Q^2 -ranges

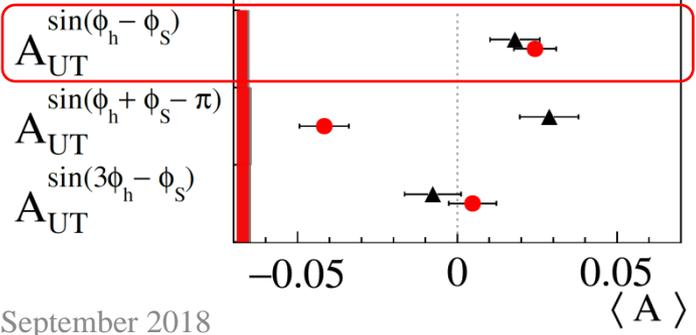
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \dots \right\}$$

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

COMPASS PLB 770 (2017) 138



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



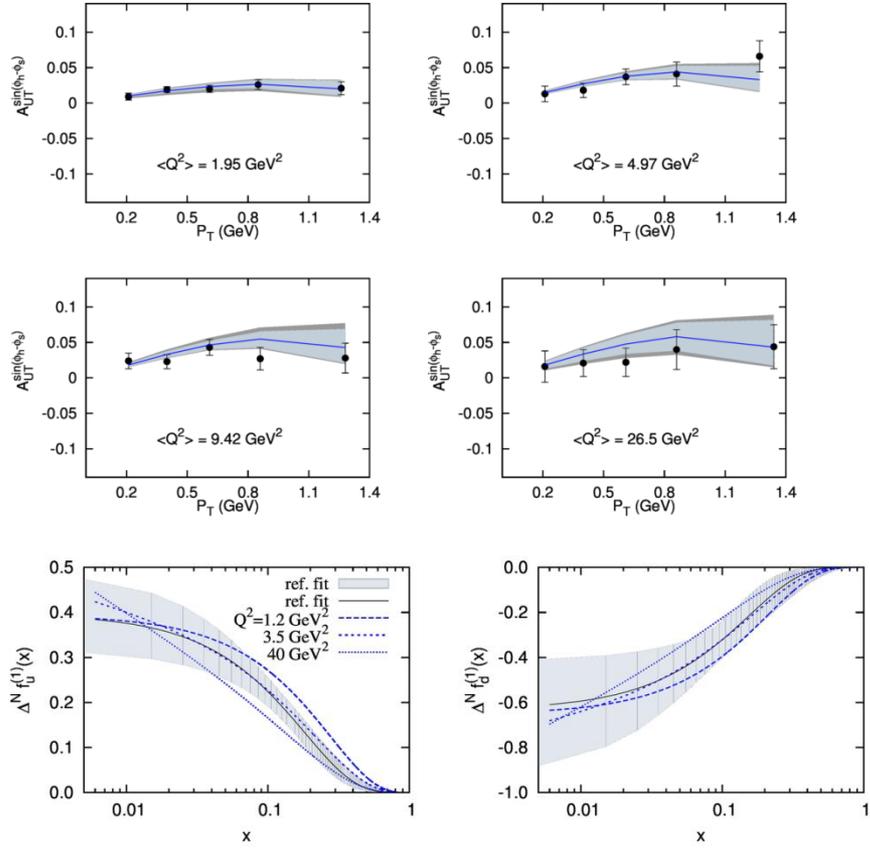


SIDIS Sivers TSA in COMPASS Drell-Yan Q^2 -ranges

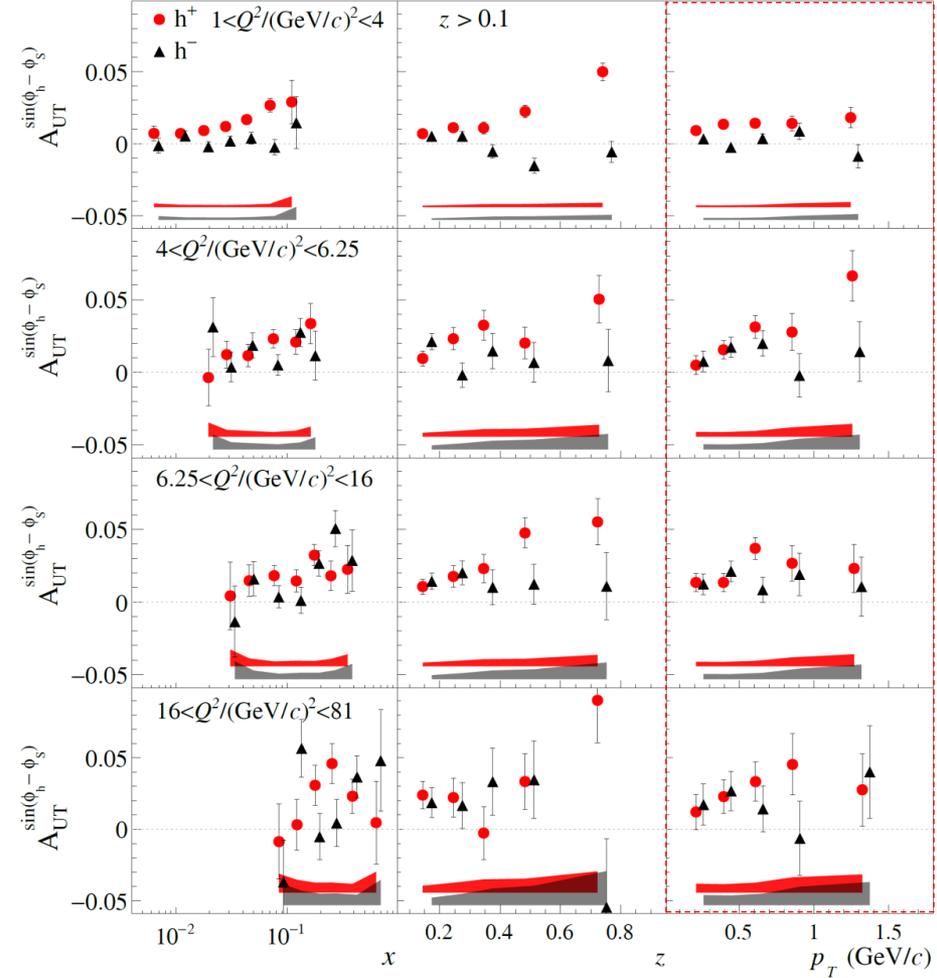
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \dots \right\}$$

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

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



COMPASS PLB 770 (2017) 138





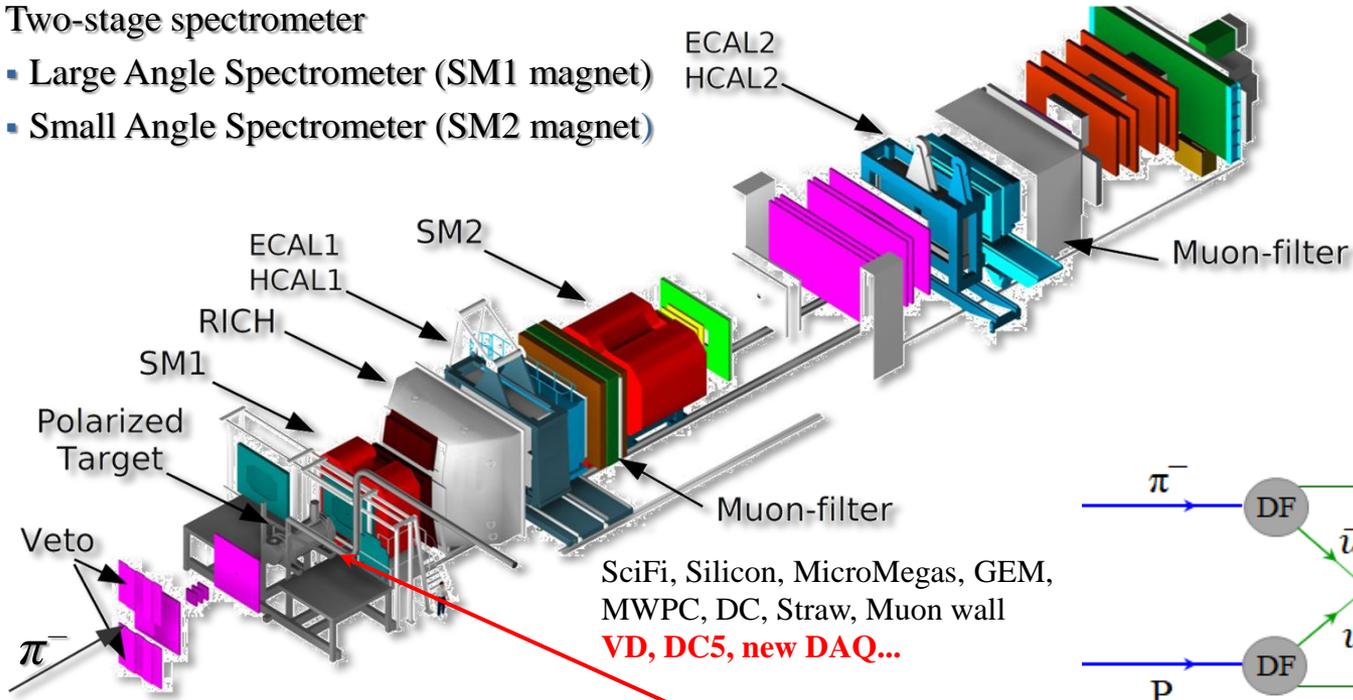
- Results from first ever measurement of Drell-Yan TSAs



COMPASS experimental setup: Phase II (DY program)

Two-stage spectrometer

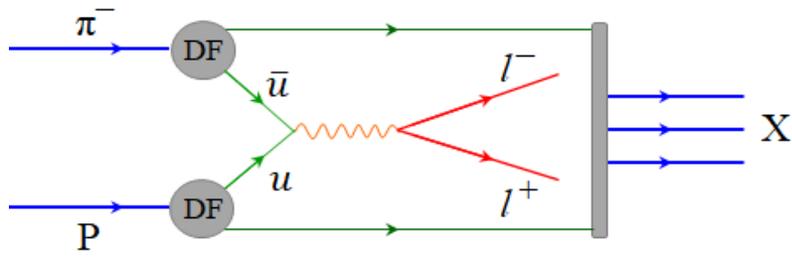
- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)



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

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

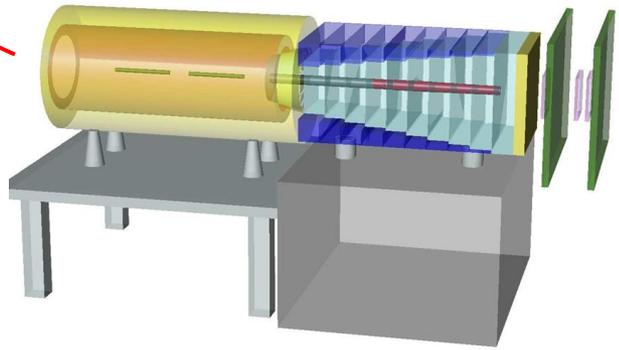
Drell-Yan



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

High energy π^- beam:
 Energy: 190 GeV/c, Intensity: $10^8 \pi/s$
 Target: Solid state

- NH_3 2-cell configuration. Polarization $T \sim 73\%$, $f \sim 0.18$

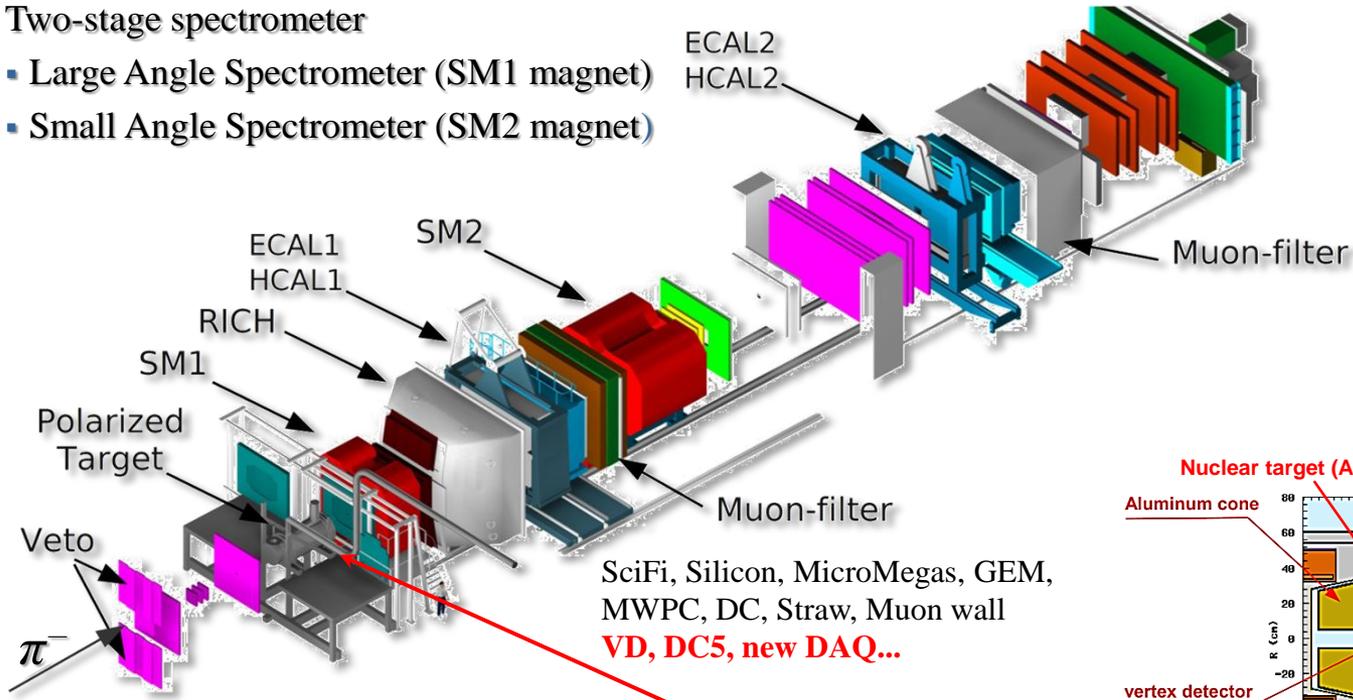




COMPASS experimental setup: Phase II (DY program)

Two-stage spectrometer

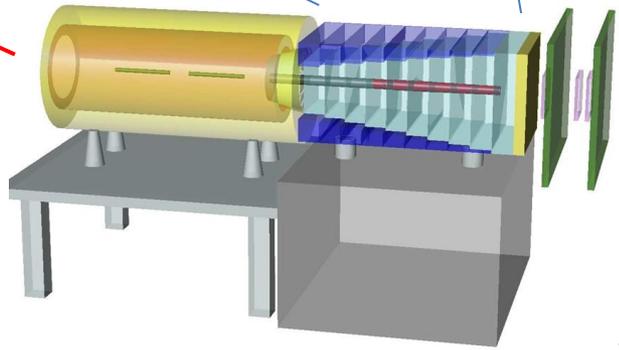
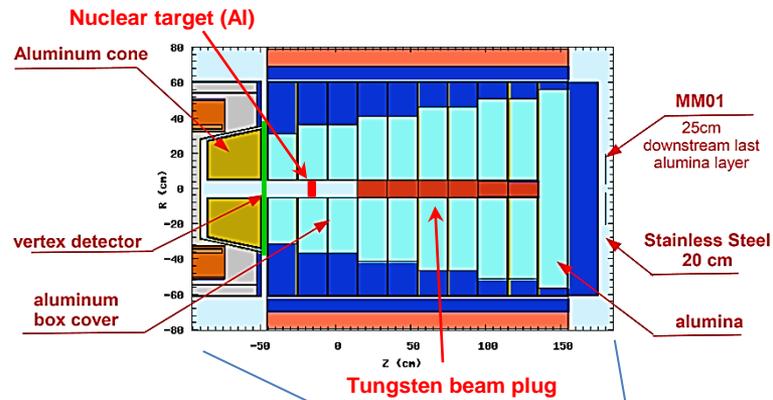
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SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon wall
VD, DC5, new DAQ...

Hadron absorber



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

High energy π^- beam:
 Energy: 190 GeV/c, Intensity: $10^8 \pi/s$
 Target: Solid state

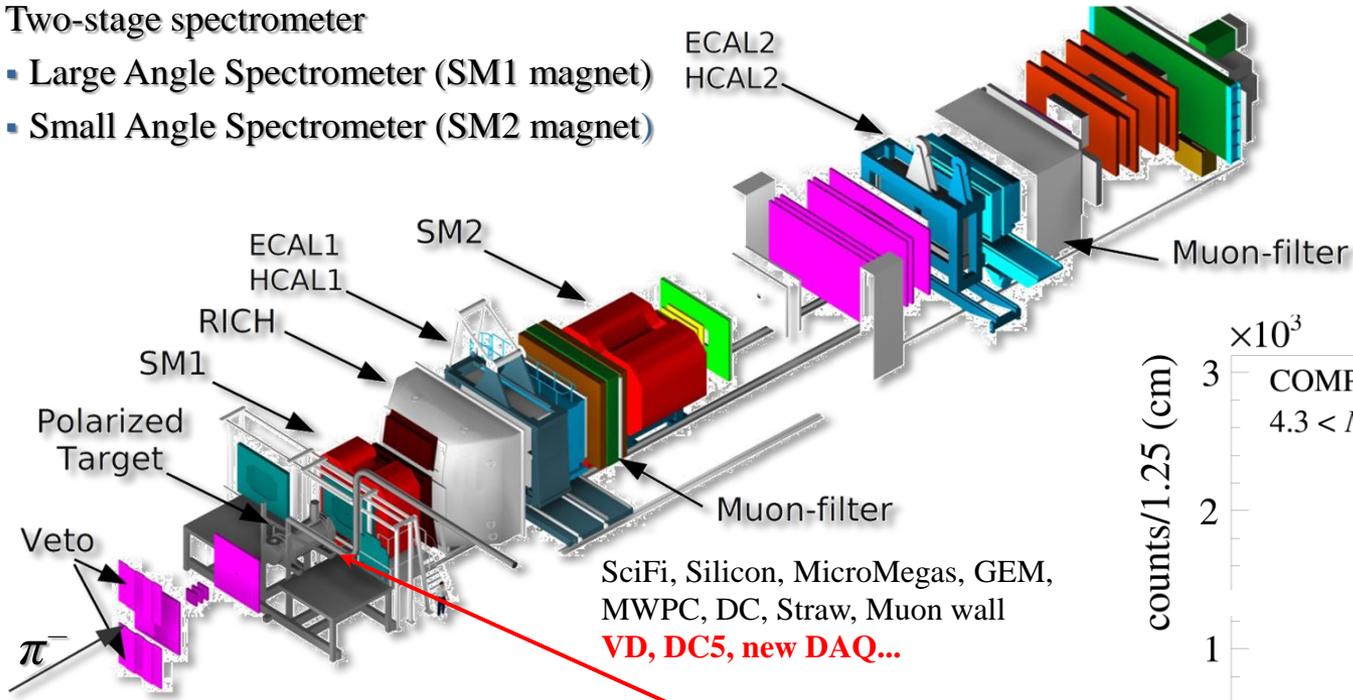
- NH_3 2-cell configuration. Polarization $T \sim 73\%$, $f \sim 0.18$



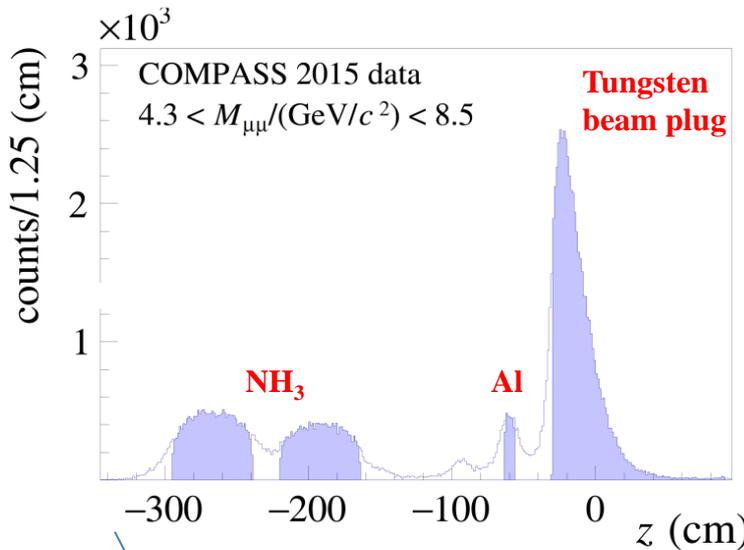
COMPASS experimental setup: Phase II (DY program)

Two-stage spectrometer

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- High energy beam
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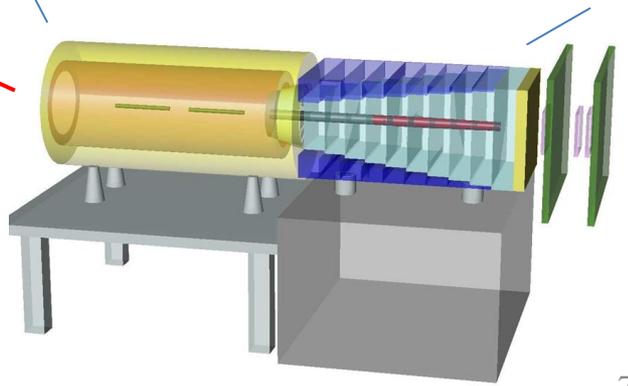
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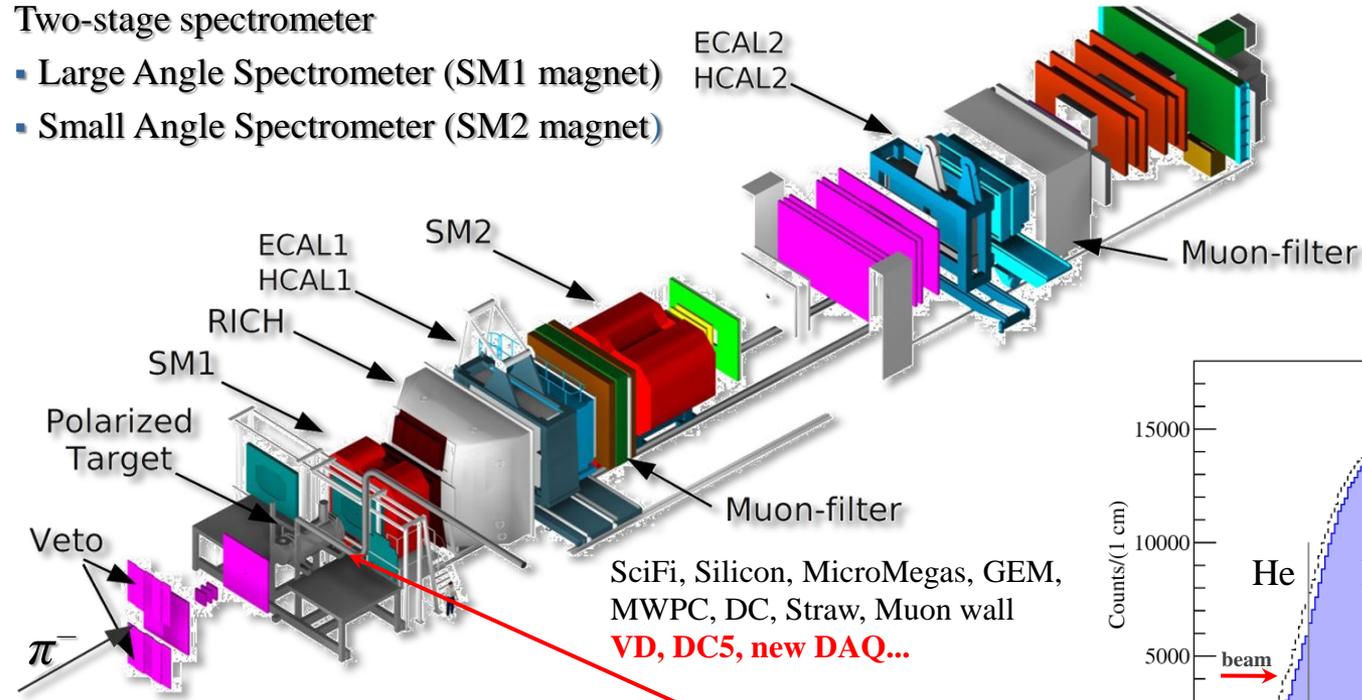




COMPASS experimental setup: Phase II (DY program)

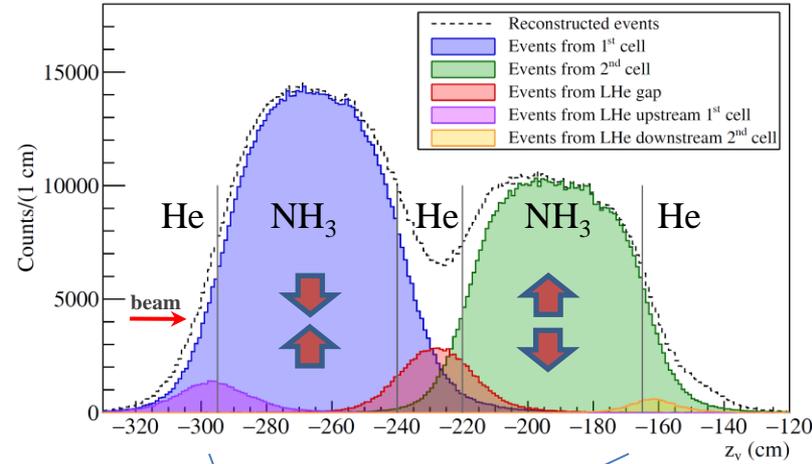
Two-stage spectrometer

- Large Angle Spectrometer (SM1 magnet)
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- High energy beam
- Large angular acceptance
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SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon wall
VD, DC5, new DAQ...



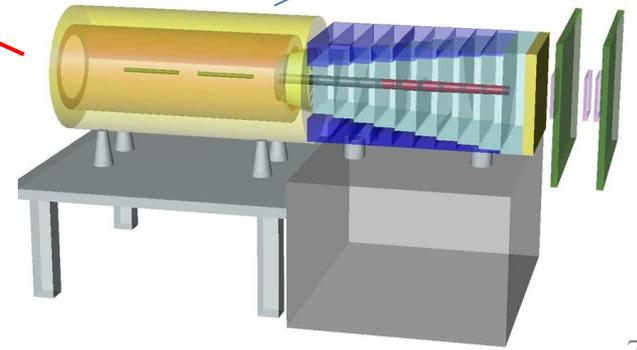
Data-taking years: 2014 (test) 2015 and 2018

High energy π^- beam:

Energy: 190 GeV/c, Intensity: $10^8 \pi/s$

Target: Solid state

- NH_3 2-cell configuration. Polarization $T \sim 73\%$, $f \sim 0.18$
- **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
 $\lambda=1, (F_U^2=0), \mu=\nu=0$
- **Intrinsic transverse motion + QCD effects**
 $\lambda \neq 1, \mu \neq 0, \nu \neq 0$ but $1-\lambda=2\nu$ (Lam-Tung)
- **Experiment,**
 $\lambda \neq 1, \mu \neq 0, \nu \neq 0$

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

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

COMPASS ongoing analysis



Single-polarized DY x-section: unpolarized part

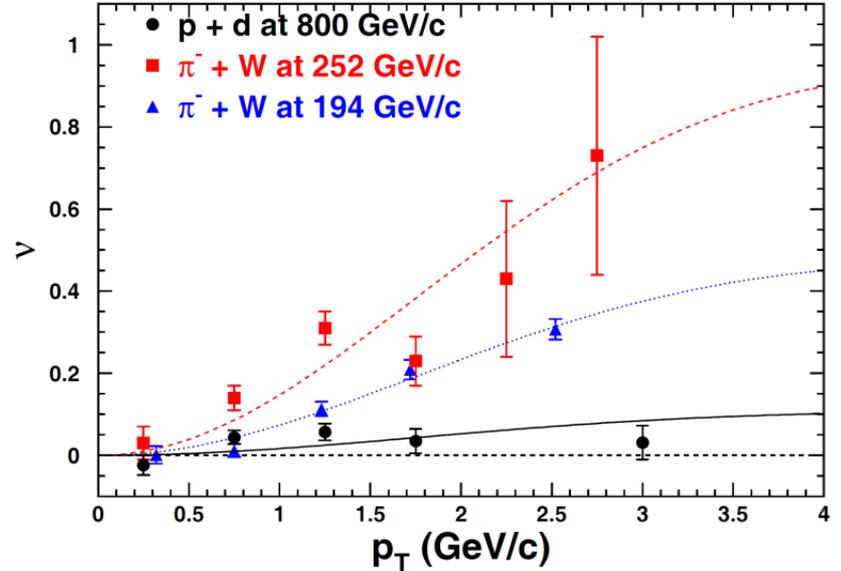
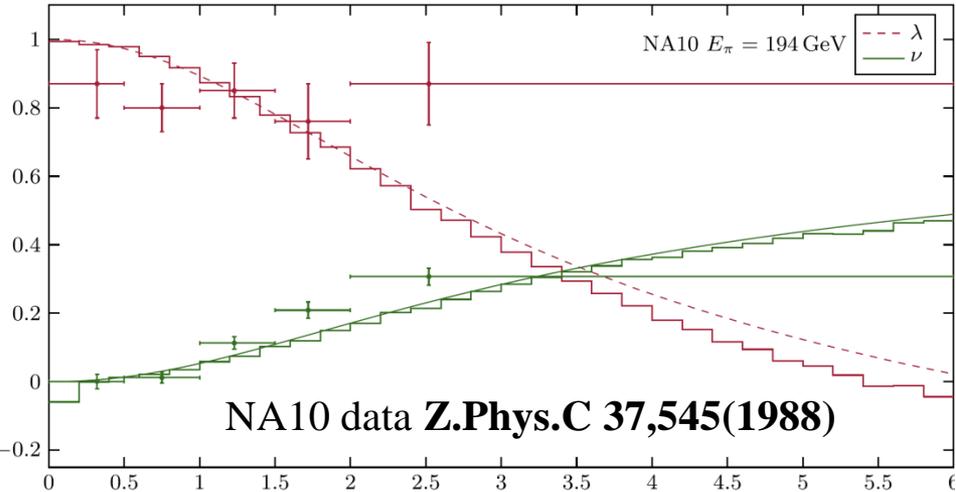
$$\lambda = A_U^1 = \frac{F_U^1 - F_U^2}{F_U^1 + F_U^2}, \mu = A_U^{\cos\varphi_{CS}}, \nu = 2A_U^{\cos 2\varphi_{CS}}$$

- **“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**
 $\lambda \neq 1, \mu \neq 0, \nu \neq 0$ but $1-\lambda=2\nu$ (Lam-Tung)
- **Experiment,**
 $\lambda \neq 1, \mu \neq 0, \nu \neq 0$
- $\nu \neq 0$ - Energy and quark flavour dependence,
QCD radiative effects, non-coplanarity
(PRD93, 114013 (2016), PLB 758 (2016) 384)

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

COMPASS ongoing analysis

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





Single-polarized DY x-section: transverse part

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

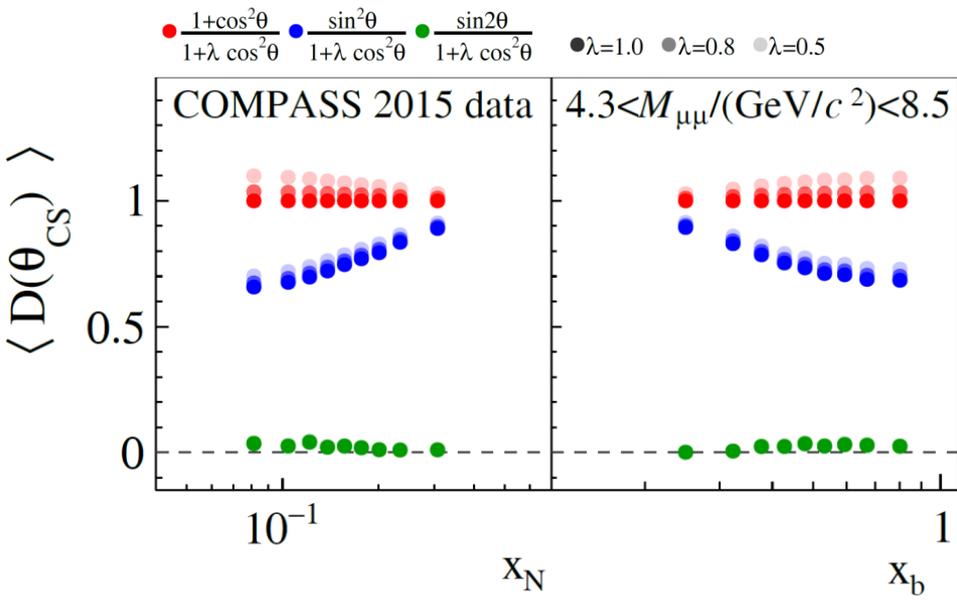
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- **Experiment,**
 $\lambda \neq 1, \mu \neq 0, \nu \neq 0$

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

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

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

- 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 $A_U^1 \neq 1$ scenarios lead to a normalization uncertainty of at most -5% .





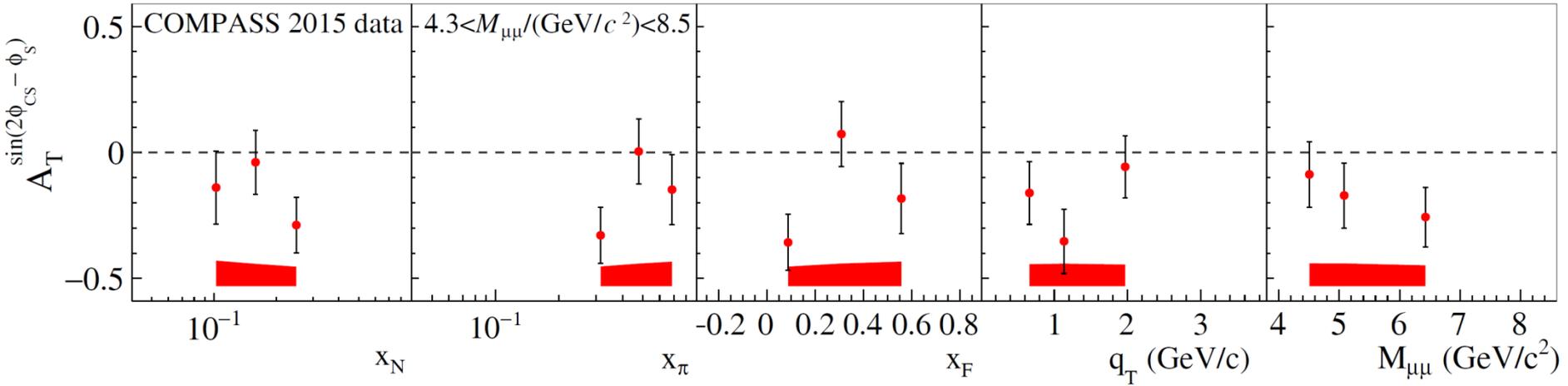
Drell-Yan TSAs – Transversity

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

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)





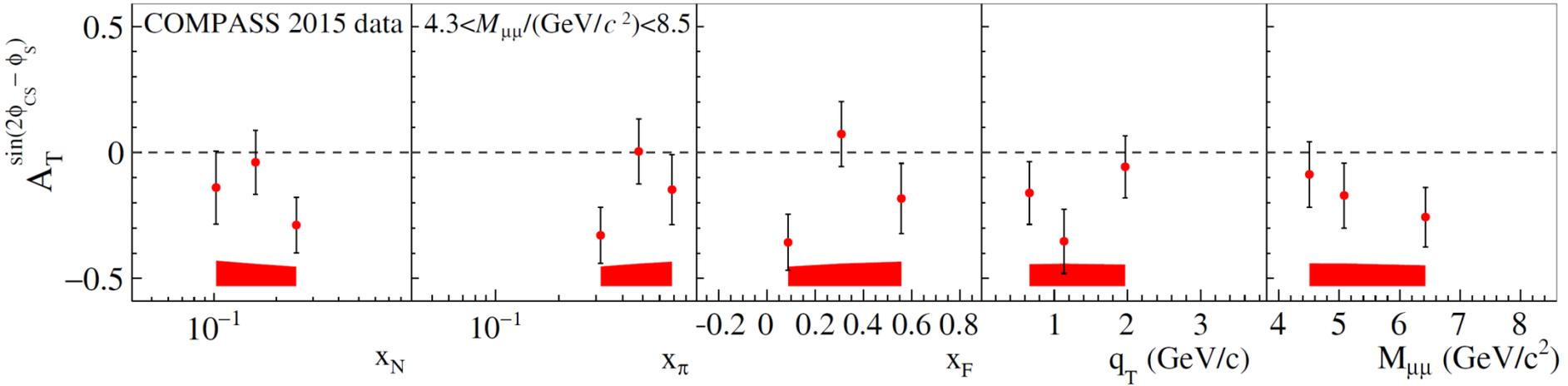
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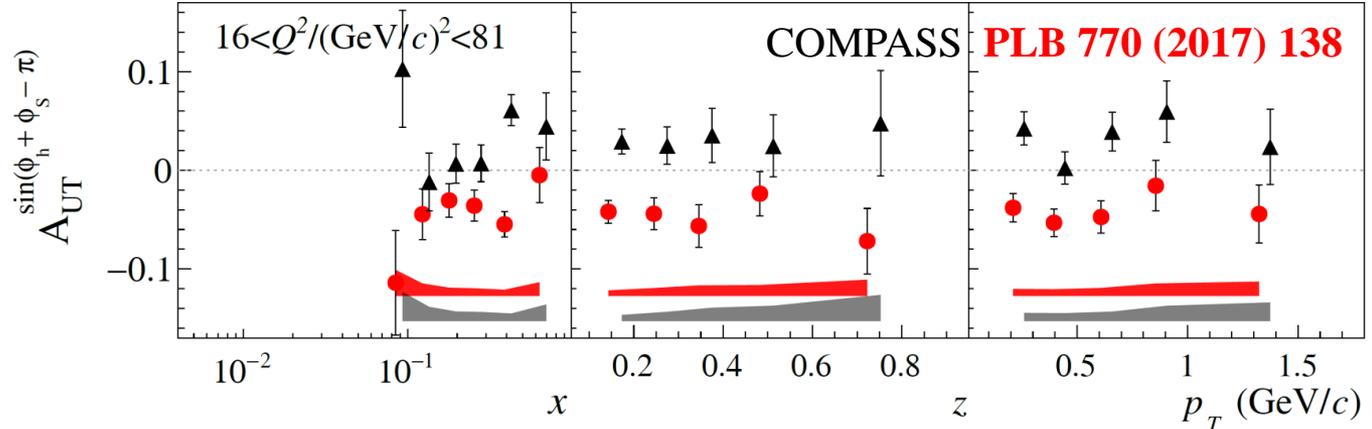
COMPASS PRL 119, 112002 (2017)



SIDIS in Drell-Yan high-mass range

Collins SIDIS TSA

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





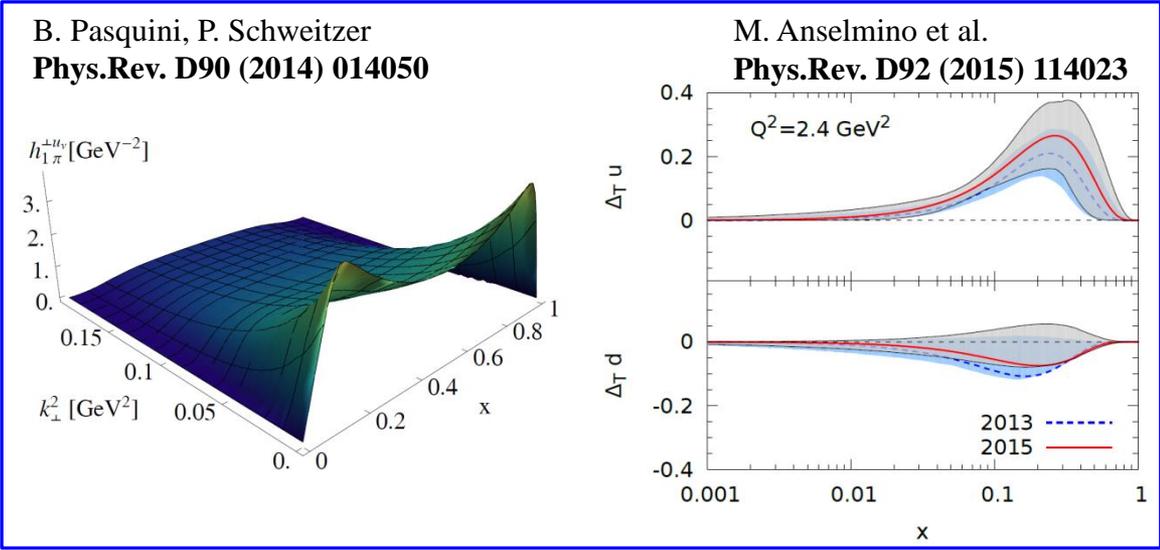
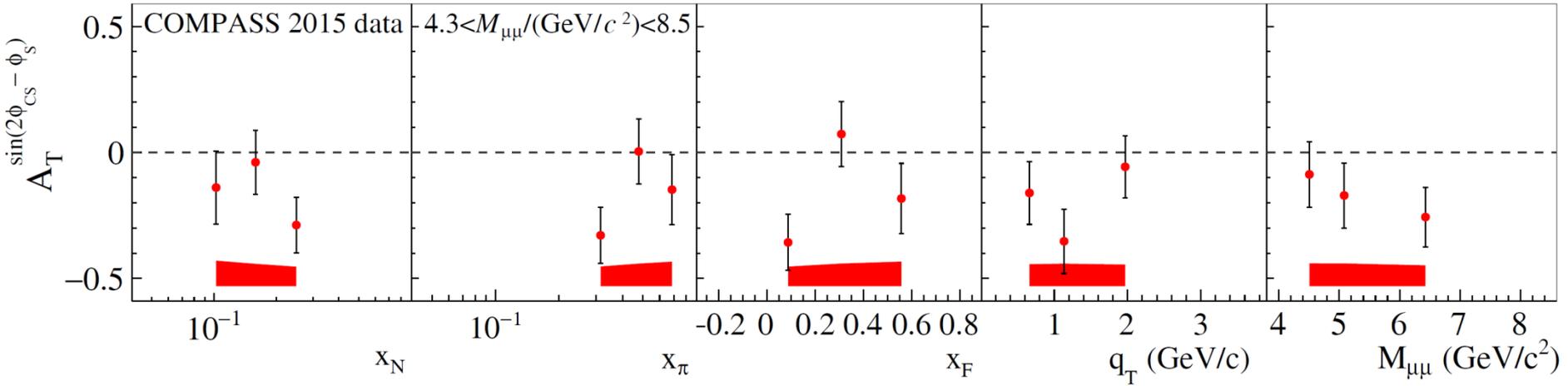
Drell-Yan TSAs – Transversity

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

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)





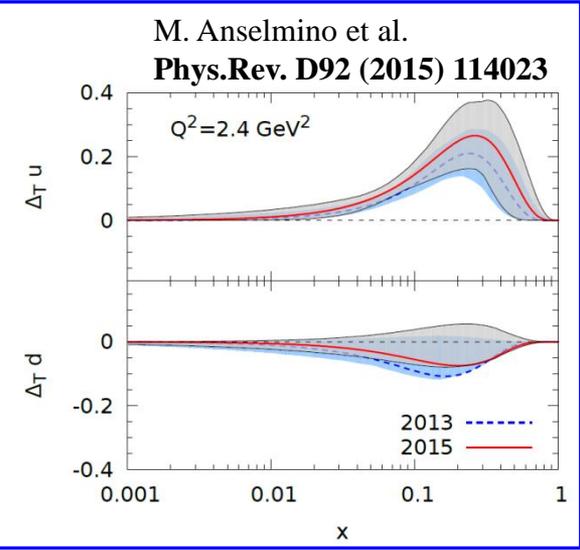
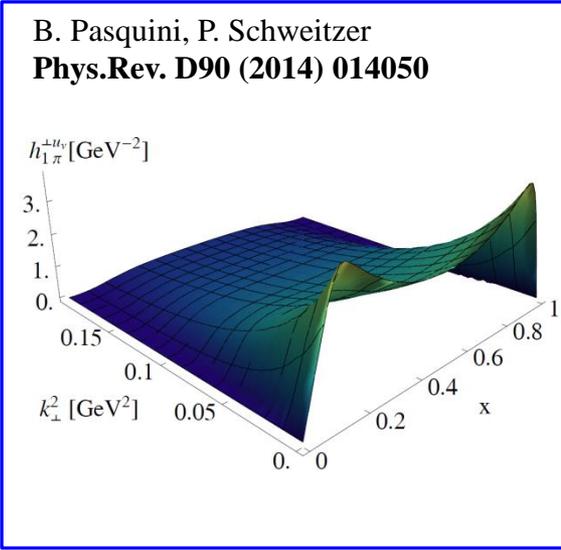
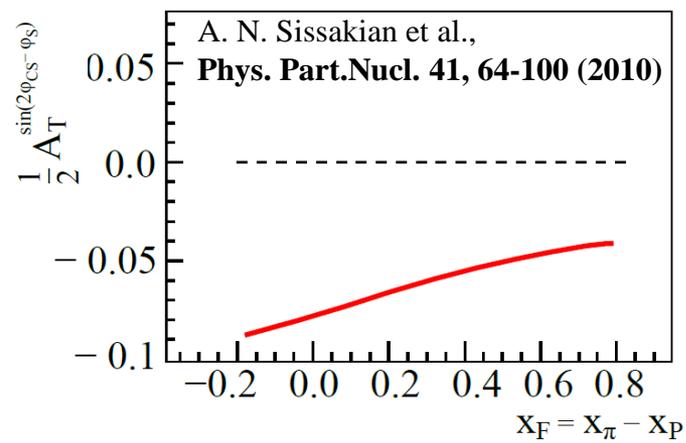
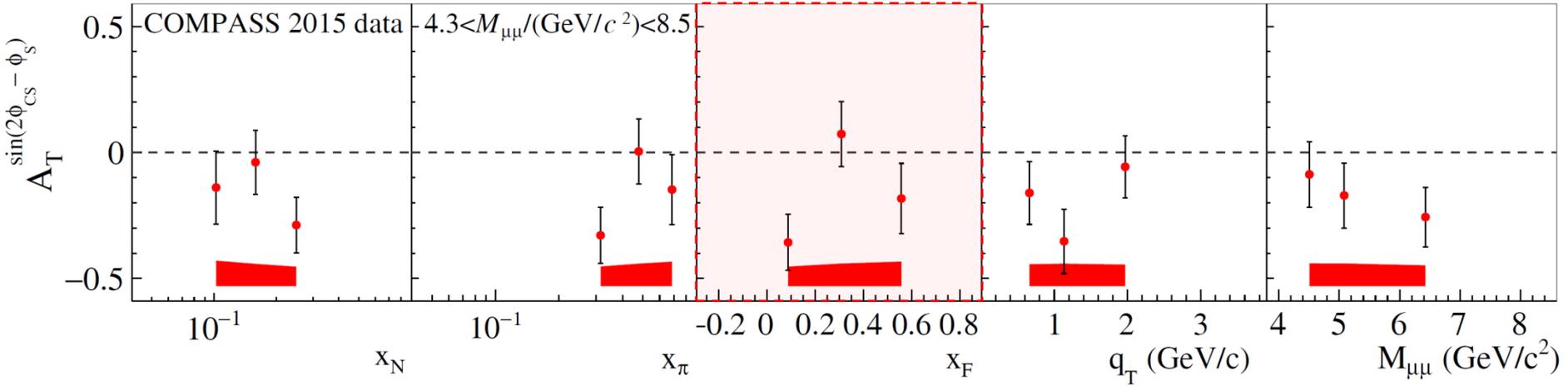
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Transversity DY TSA

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

COMPASS PRL 119, 112002 (2017)





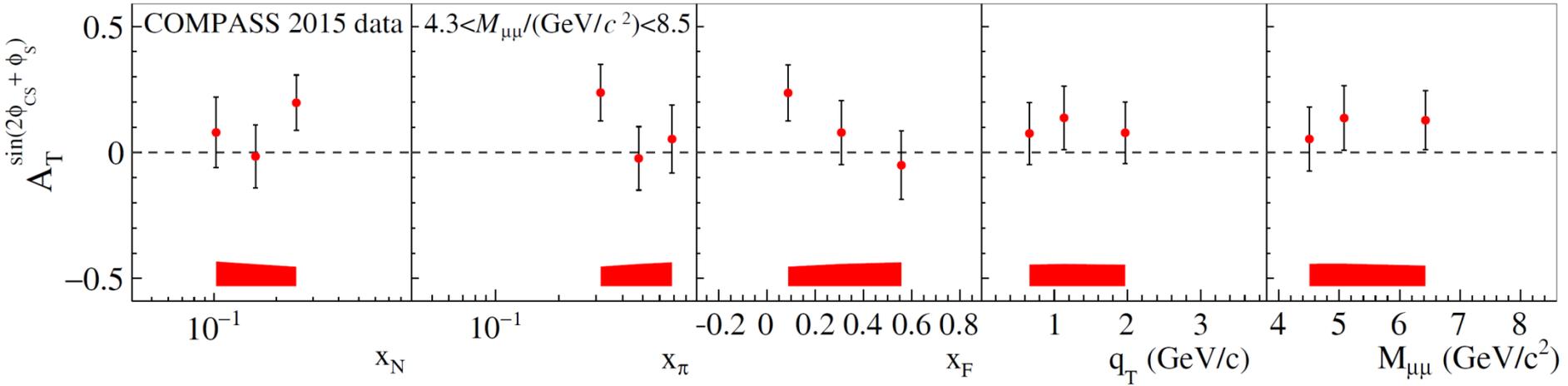
Drell-Yan TSAs – Pretzelosity

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

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)





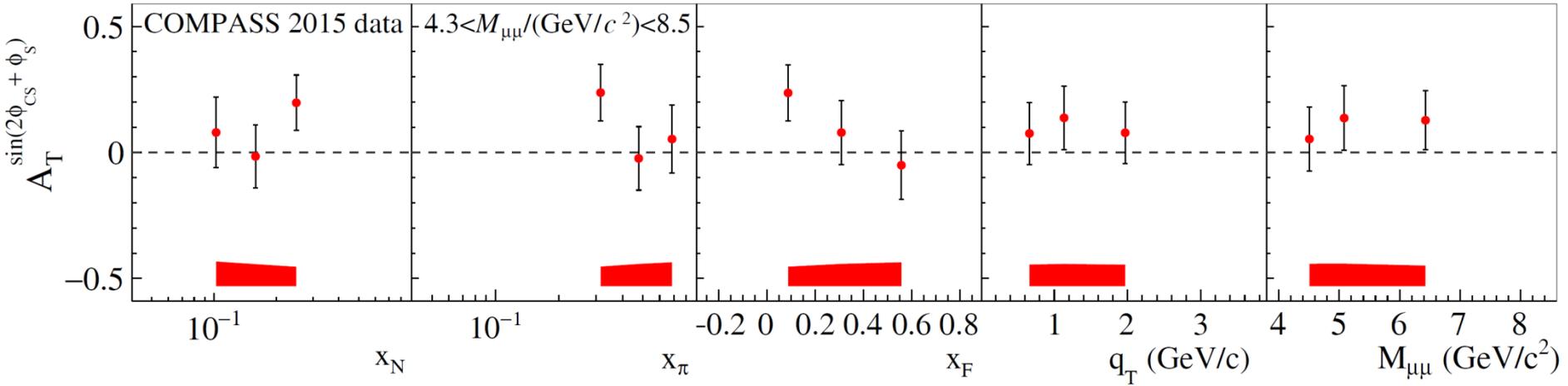
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Pretzelosity DY TSA

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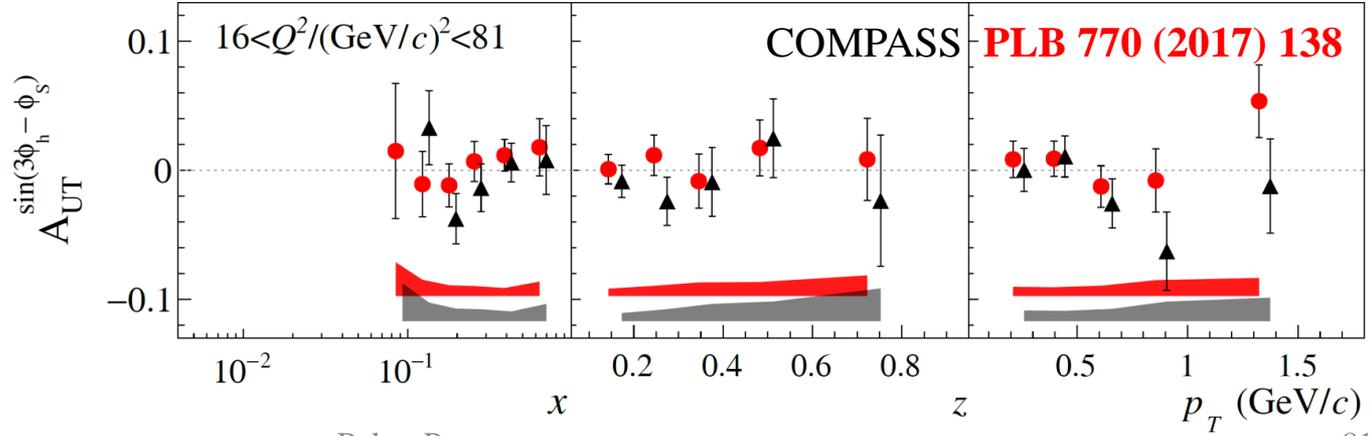
COMPASS PRL 119, 112002 (2017)



SIDIS in Drell-Yan high-mass range

Pretzelosity SIDIS TSA

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





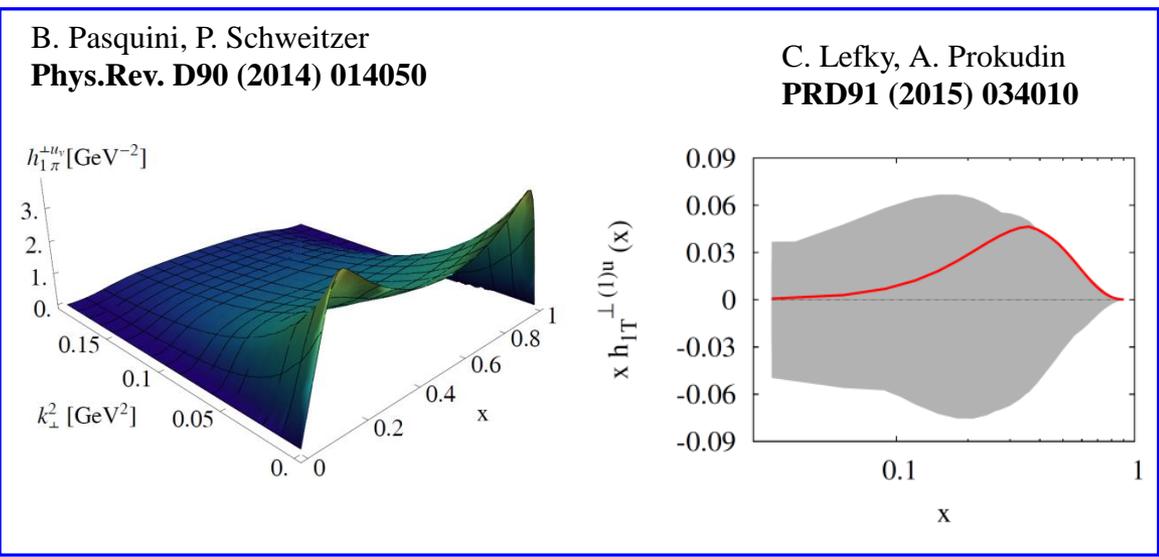
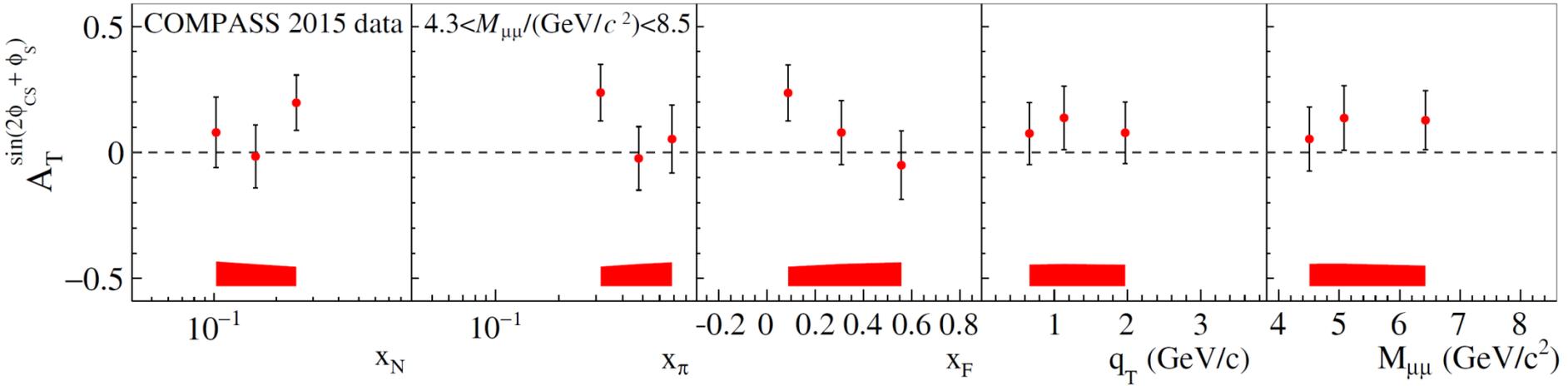
Drell-Yan TSAs – Pretzelosity

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

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)





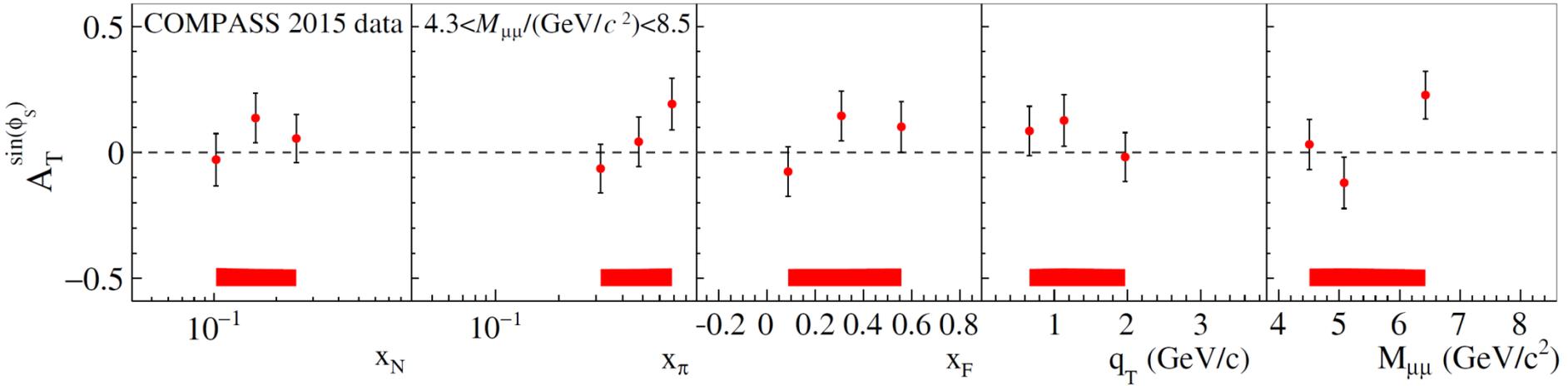
Drell-Yan TSAs – Sivers

$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \dots + S_T [A_T^{\sin\phi_S} \sin\phi_S + \dots]$$

Sivers DY TSA

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

COMPASS PRL 119, 112002 (2017)





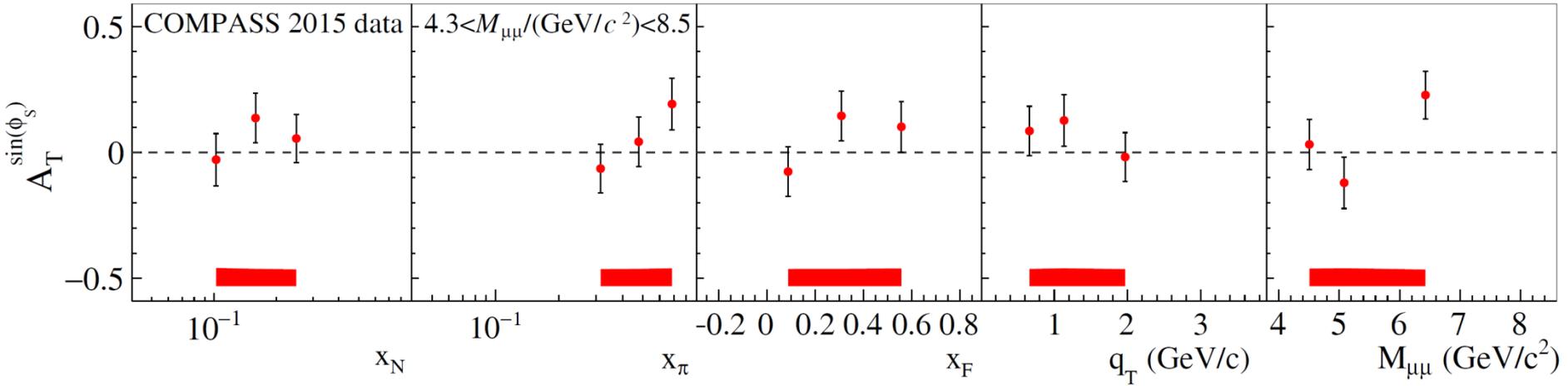
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Sivers DY TSA

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

COMPASS PRL 119, 112002 (2017)

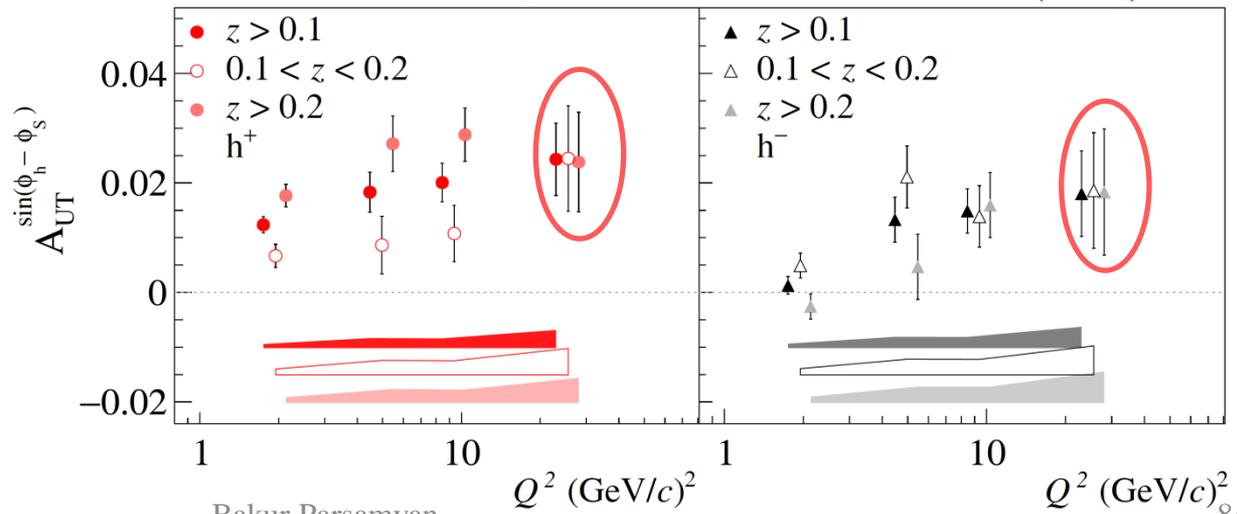


SIDIS in Drell-Yan high-mass range

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)

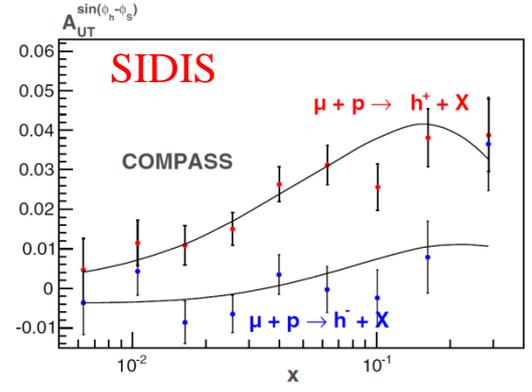
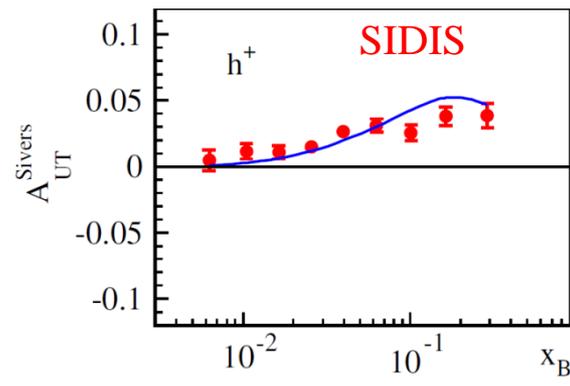
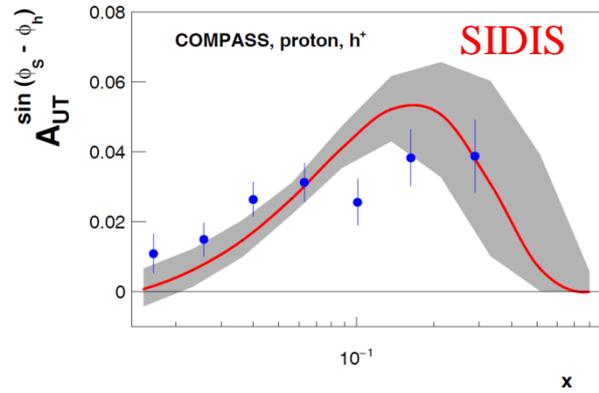
M. Anselmino et al., **JHEP 1704 (2017) 046**

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)

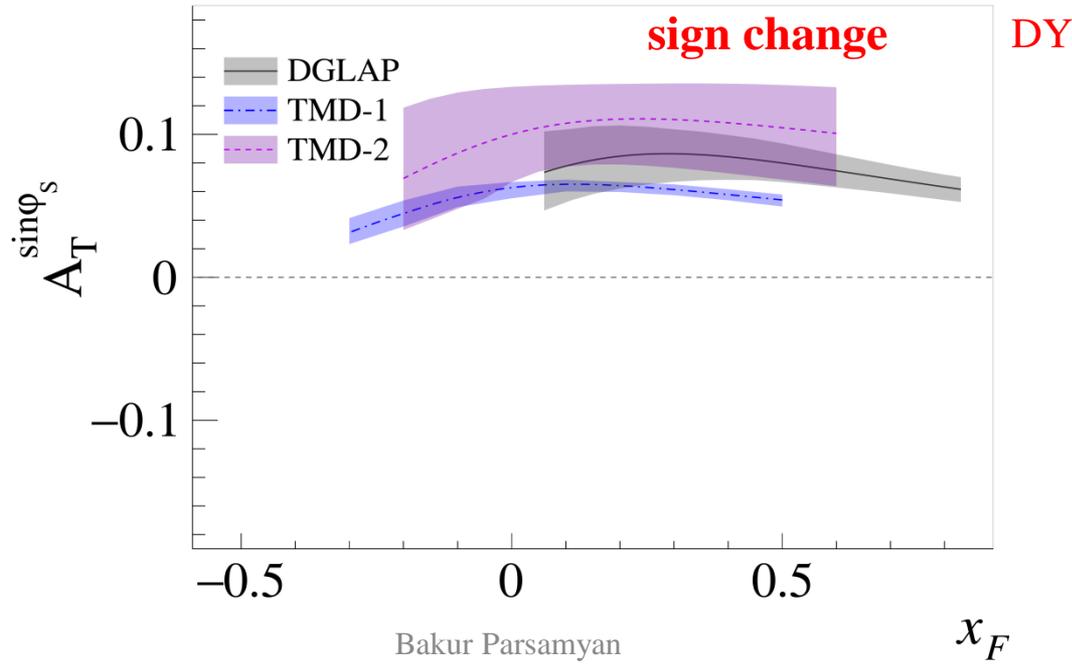
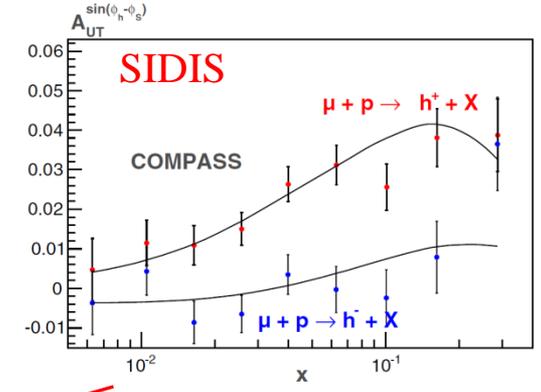
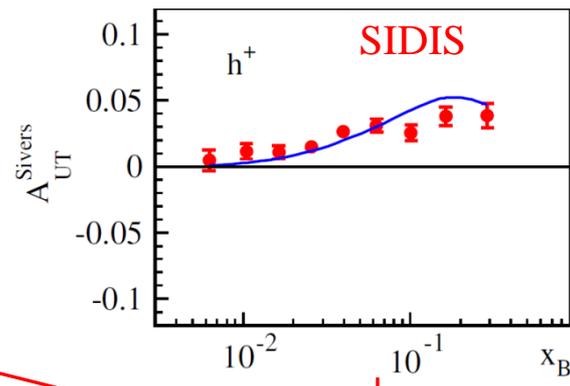
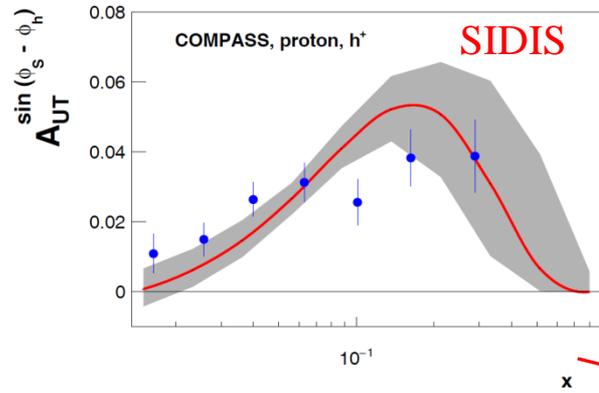
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Sivers asymmetry in Drell-Yan: sign change

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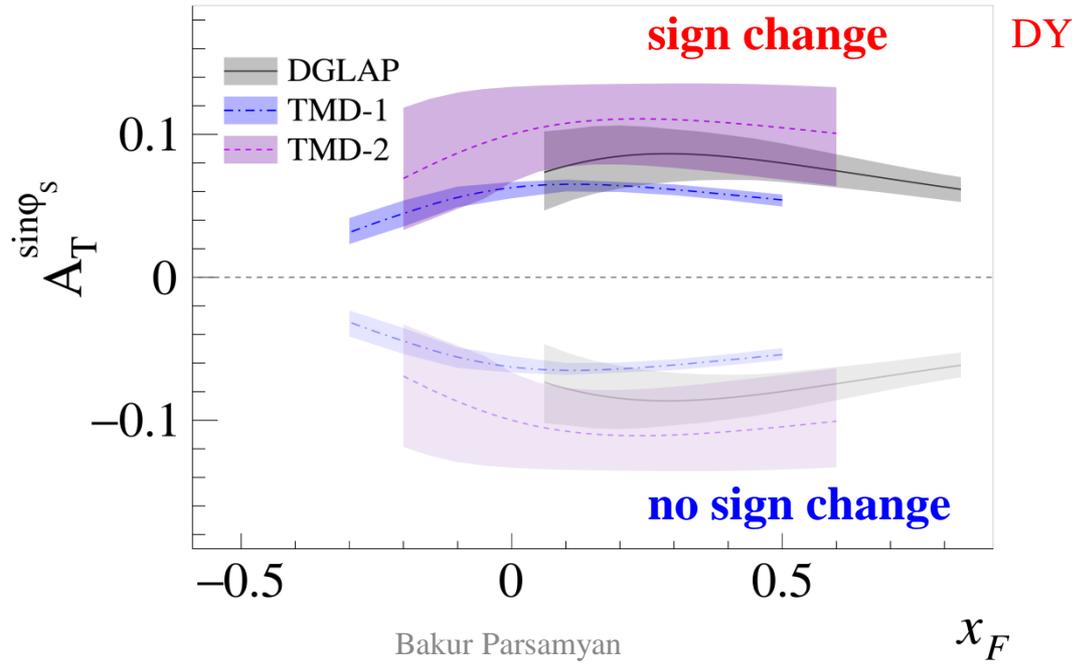
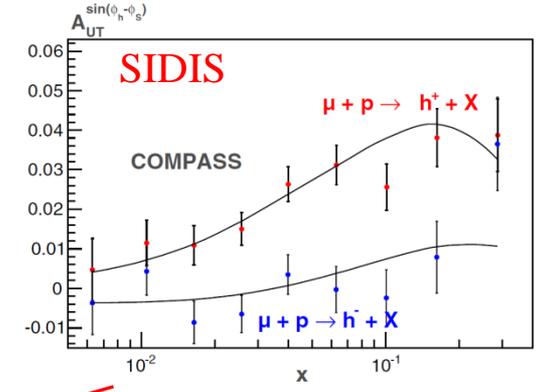
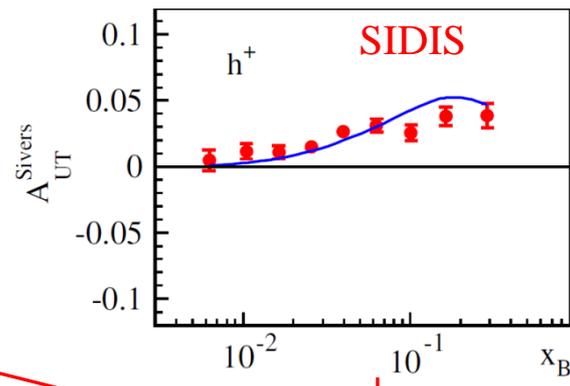
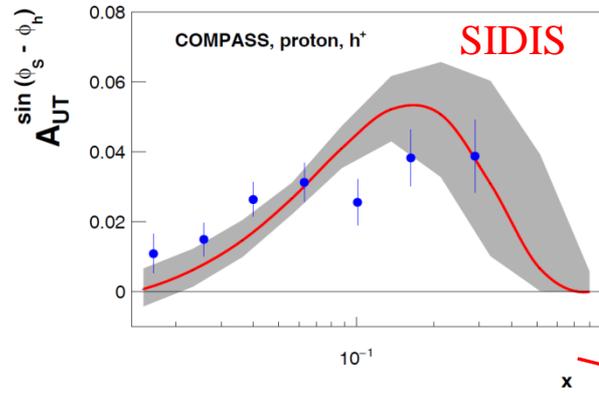
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P. Sun, F. Yuan, PRD88, 114012





Sivers asymmetry in Drell-Yan: sign change

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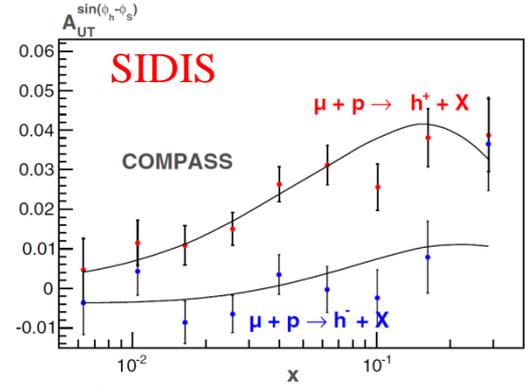
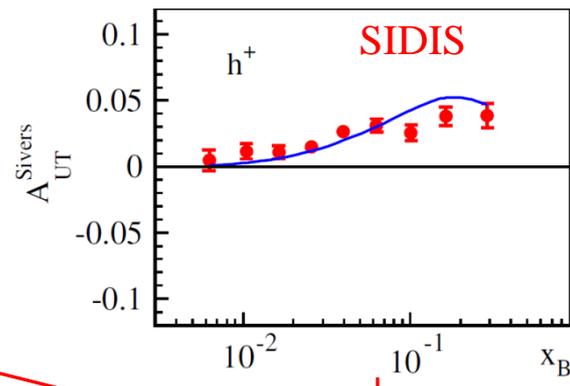
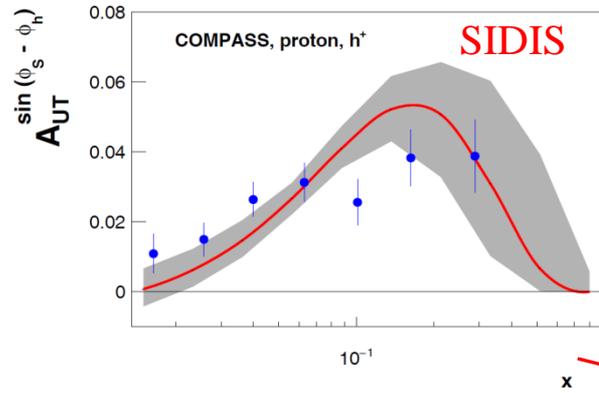
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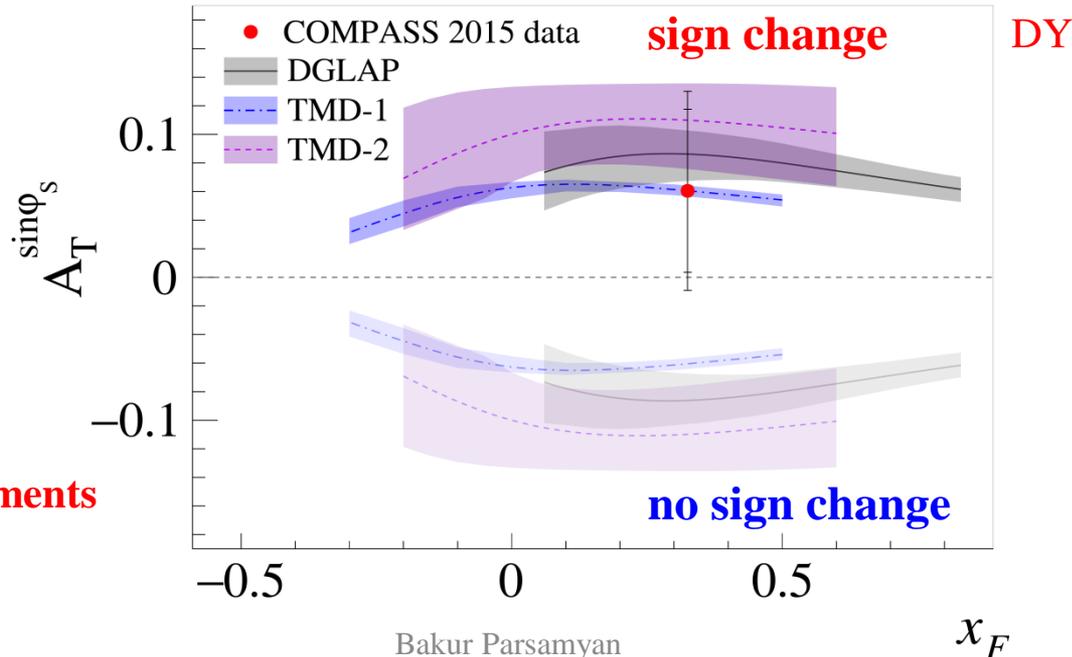
TMD-2 (2013)

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)



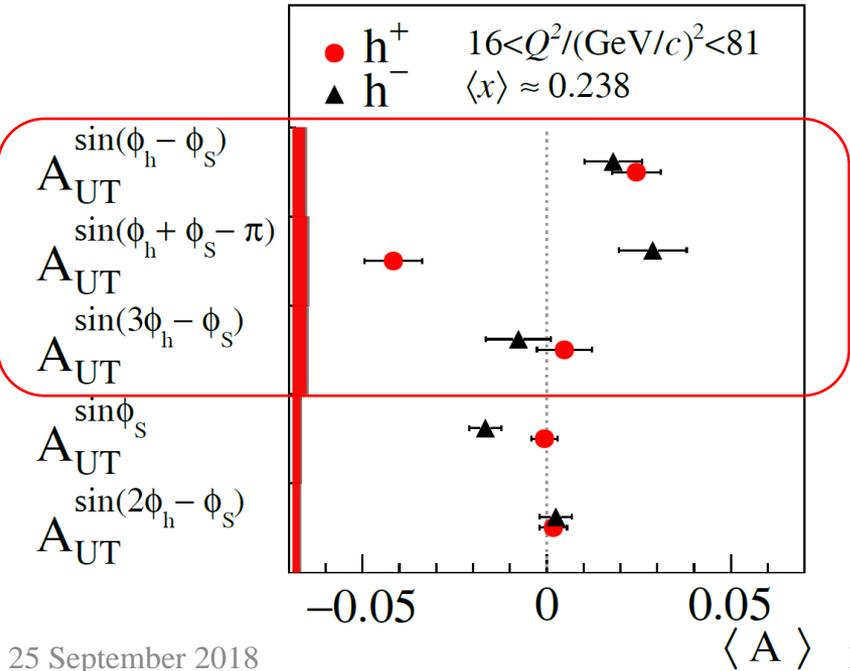
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots \right.$$

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

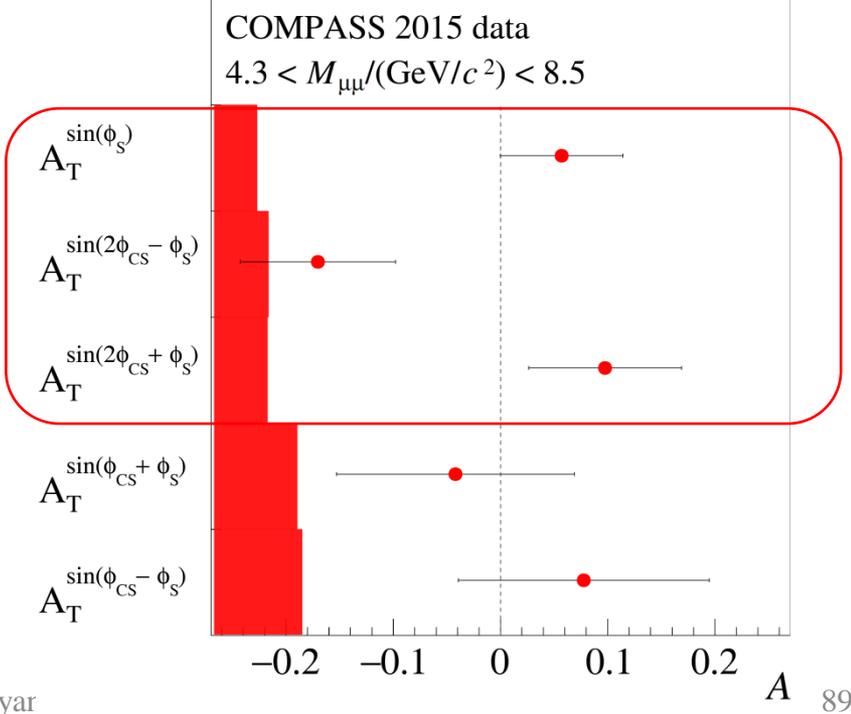
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS}) \left\{ 1 + \dots \right.$$

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

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](https://arxiv.org/abs/1808.00848) [hep-ex]

XIV International Workshop on Hadron Structure and Spectroscopy

Longitudinal and Transverse Spin Structure of the Nucleon
 Fragmentation Functions
 Search for Glueballs, Hybrid Mesons and Multiquark States
 Meson Spectroscopy
 TMDs, GPDs and GTMDs
 New opportunities for physics beyond colliders
 Cosmic rays and accelerator physics

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iwhss17@to.infn.it
iwhss17.to.infn.it
 @iwhss17

IWHSS17 April 2-5 Cortona

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CAEN UPO

ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED

TRENTO, ITALY
 Institutional Member of the European Expert Committee N

Castello di Trento ("Trent"), watercolor 19.8 x 27.7, painted by A. Direr on his way back from Venice (1495), British Museum.

Dilepton Production with Meson and Antiproton Beams

Trento, November 6-16, 2017

Main Topics
 Theoretical and experimental aspects of high-mass dilepton production with meson and antiproton beams.
 Physics of partonic structures of pion and kaon.
 Exclusive Drell-Yan process.
 Opportunities to carry out new measurements on high-mass lepton pairs productions using meson and antiproton beams.

Invited speakers
 Vincent Andrianne (U. Illinois), Mauro Anselmino (U. Turin), Franco Arleo (Ecole Polytechnique), Johannes Bernhard (CERN), Dan Li (GSI), Stan Brodsky (SLAC), Jian-Ping Chen (LAL, ALA Obeyesee (Helmholtz, Mainz), Oleg Denisov (INFN, Torino), Mike Grosse-Perdekamp (U. Illinois), Boris Gruber (Tech U. Munich), Aleksey Guskov (LJMU, Dublin), Cynthia Hadjidakis (UPN, Orsay), Paul Hebebrand (U. Washington), Li. Maryland/Shanghai/Jiaotong U., Peter Krol (U. Wuppertal), Shunzo Kumano (KEK), Wally Melnitchuk (LAL), Hiroyuki Nisami (Chiba U.), Bakur Parsamyan (U. Torino), Bogdan Povh (U. Heidelberg), Caterina Marqueti Quintana (LJMU), Paul Reimer (LAL), Craig Roberts (ANU), Takahiro Sawada (U. Michigan), Ingo Schienbein (LJMU, Giessen), Rikutarō Yoshida (Univ. Tokyo)

Organizers
 Jen-Chieh Peng (Department of Physics, University of Illinois at Urbana-Champaign) jcpeng@illinois.edu
 Wen-Chen Chang (Institute of Physics, Academia Sinica) changwc@phys.sinica.edu.tw
 Stephane Florschütz (Nuclear Physics Division, INFN, GSA, Saclay) Stephane.Florschutz@cern.ch
 Oleg Tereshchenko (Bogoliubov Laboratory of Theoretical Physics, JINR) teresh@theor.jinr.ru

Director of the ECT*, Professor Jochen Wambach (ECT*)

The ECT* is sponsored by the "Fondazione Bruno Kessler" in collaboration with the "Associazione alla Cultura" (Fondazione Antononi di Trento) leading agencies of the Member and Associated States and has the support of the Department of Physics of the University of Trento. For local organization please contact: Enzo Cometti - ECT* Secretariat - Villa Tambosi - Strada della Torretta, 296 - 38123 Villazano (Trento) Italy - (39-0461) 314723 Fax: (39-0461) 314750. E-mail: enzo.cometti@ect-trento.it <http://www.ect-trento.it>

Physics Beyond Colliders

The annual workshop of the Physics Beyond Colliders study group is to be held at CERN, Geneva, on 21-22 November, 2017.

Members of the study group, the workshop will be offered by the CERN complex for future projects that explore open questions in fundamental physics. The workshop will present the progress and development of the study group, the workshop will stimulate and discuss new ideas. Registration and abstract submission, as well as the mandate and on the workshop web site: <https://indico.cern.ch/event/604728/>

jamme, registration and abstract submission, as well as the mandate and on the workshop web site: <https://indico.cern.ch/event/604728/>
 Jackel, Mike Lamont, Connie Potter, Claude Vallée.

IWHSS18 XV International Workshop on Hadron Structure and Spectroscopy

March 19-21, 2018
 Bonn, Germany

iwhs2018@physik.uni-bonn.de
<https://cern.ch/iwhs-2018>

COMPASS

Transverse Spin Structure of the Nucleon
 TMD's, GPD's and GTMD's
 Meson Structure
 Meson Spectroscopy
 Search for Exotics
 New Opportunities for fixed Target Physics

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 Matthias Finger (Charles Univ., Prague, Czech Repub.)
 Matthias Grosse Perdekamp (Uppsala, Illinois, USA)

Takahiro Inami (Tohoku Univ., Japan)
 Bernhard Knieff (HHSK, Bonn, Germany)
 Fabienne Kume (CEA-IRFU Saclay, France)
 Gerhard Kramer (CEA-IRFU Saclay, France)
 Wolf Dieter Nowak (Munich Univ., Germany)
 Gianluigi Pastore (INFN, Univ.Pisa, Italy)
 Stephan Paul (TU Muenchen, Germany)
 Jen-chieh Peng (Univ. Illinois, USA)
 Adam Szczepaniak (Univ. Indiana, USA)
 Andrzej Szczepaniak (INFN, Warsaw, Poland)
 Oleg Tereshchenko (INFN, Bologna, Italy)
 Oleg Tereshchenko (INFN, Bologna, Italy)

Jan Friedrich (TU Muenchen, Germany)
 Takahiro Inami (Tohoku Univ., Japan)
 Oleg Tereshchenko (INFN, Bologna, Italy)
 Oleg Tereshchenko (INFN, Bologna, Italy)
 Alexander Nagevsky (JINR, Dubna, Russia)
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 Adam Szczepaniak (Univ. Indiana, USA)
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UNIVERSITÄT BONN



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

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	μ^\pm	high-pr. H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	μ^\pm	NH_3^\uparrow	2022 2 years	recoil silicon, modified PT magnet
Input for DMS	\bar{p} production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	LHe target
\bar{p} -induced Spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	\bar{p}	LH2	2022 2 years	target spectr.: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	π^\pm	C/W	2022 1-2 years	
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	~ 100	10^8	25-50	K^\pm, \bar{p}	NH_3^\uparrow , C/W	2026 2-3 years	"active absorber", vertex det.
Primakoff (RF)	Kaon polarisability & 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 π^\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, π^\pm	from H to Pb	2026 1 year	

Standard muon beams Standard hadron beams RF-separated hadron beams



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

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Contact

CERN
CH-1211 Geneva 23
Switzerland
NQF-M2@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](https://arxiv.org/abs/1808.00848) [hep-ex]
 - Particular attention is given to possible Drell-Yan measurements

Spare slides

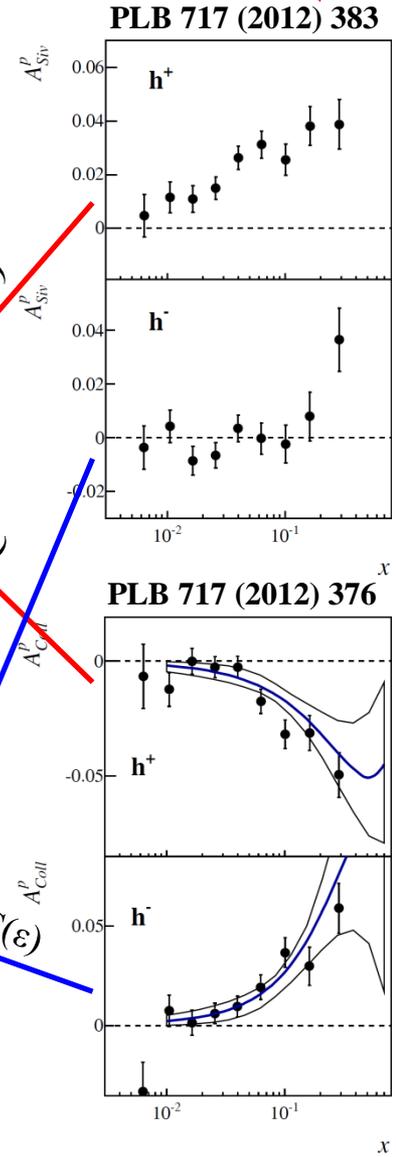
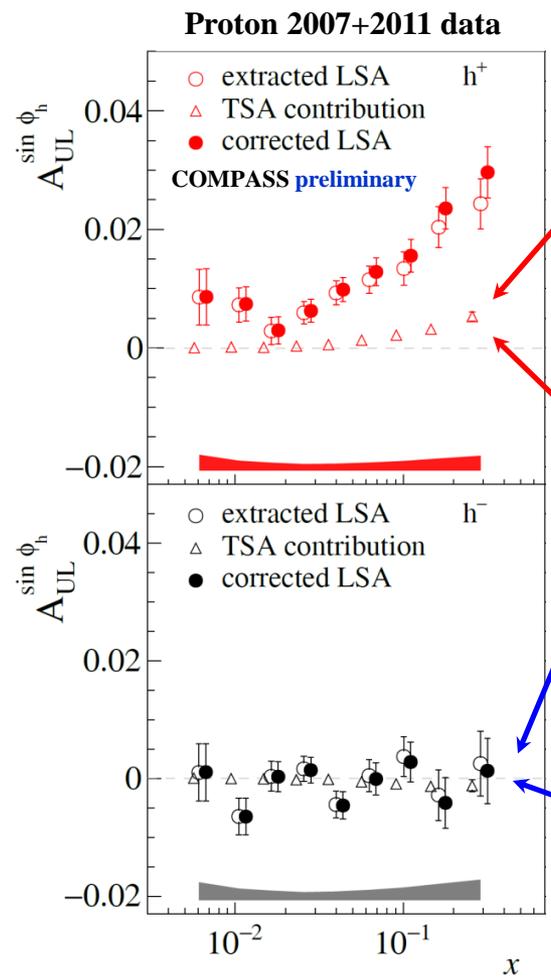
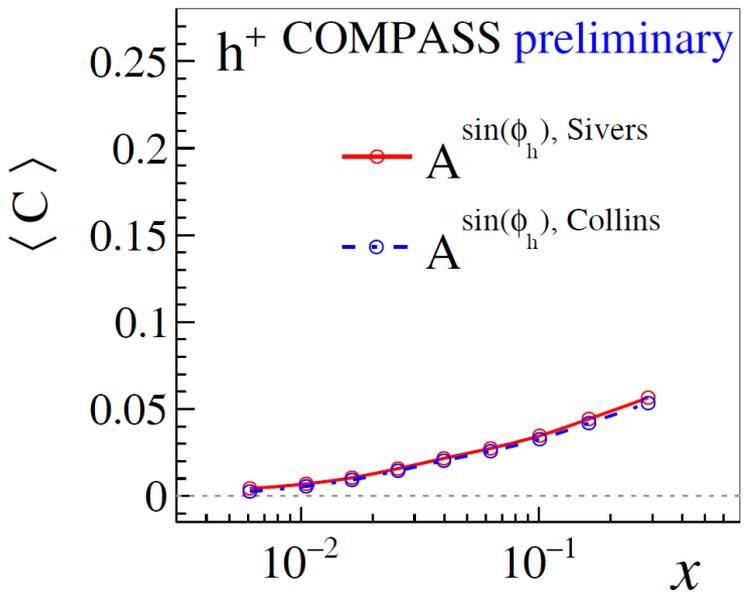




The $A_{UL}^{\sin\phi_h}$ asymmetry

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

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



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



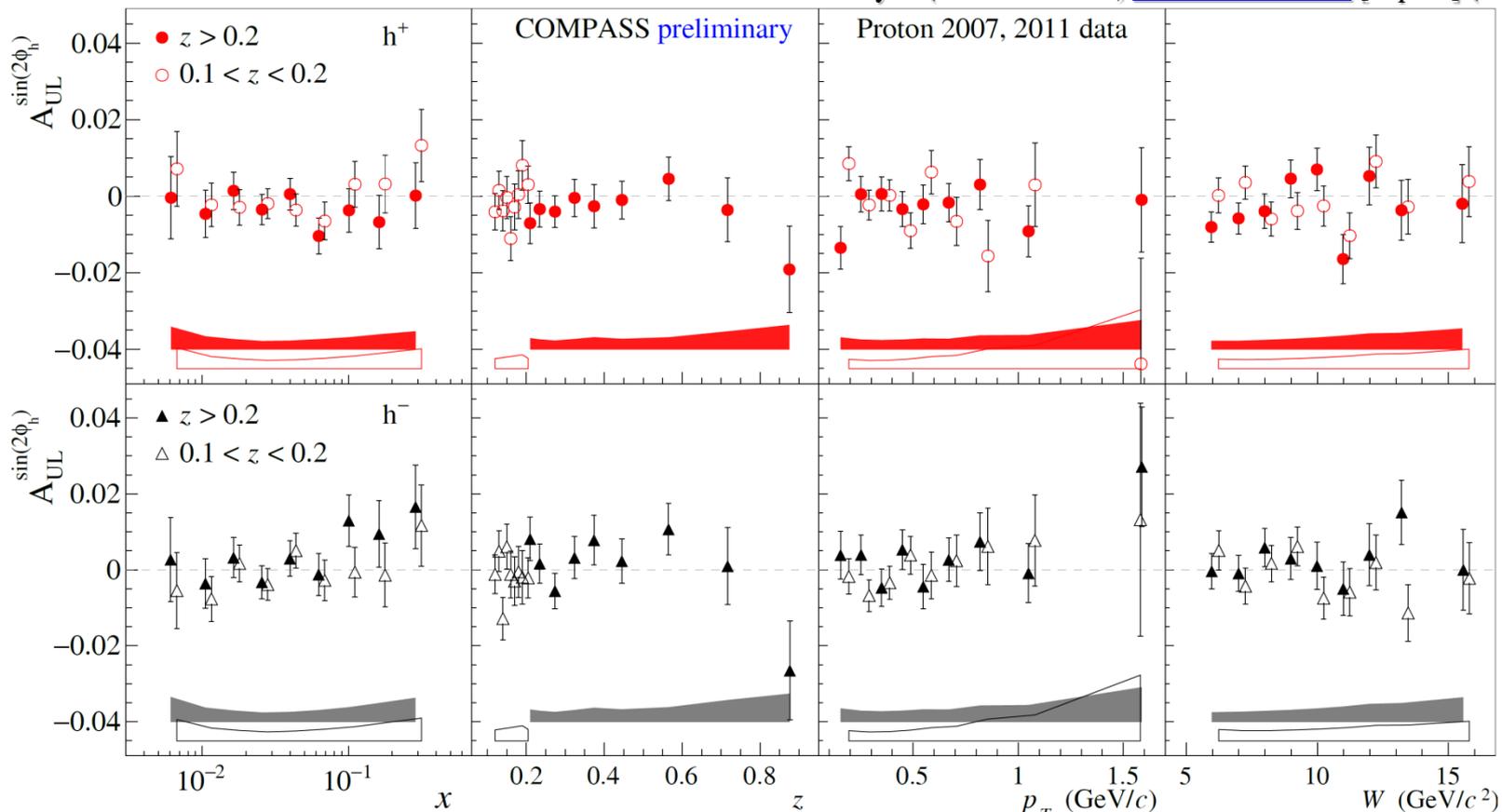
SIDIS: target longitudinal spin dependent asymmetries

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

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

- Only “twist-2” ingredients
- Additional p_T -suppression

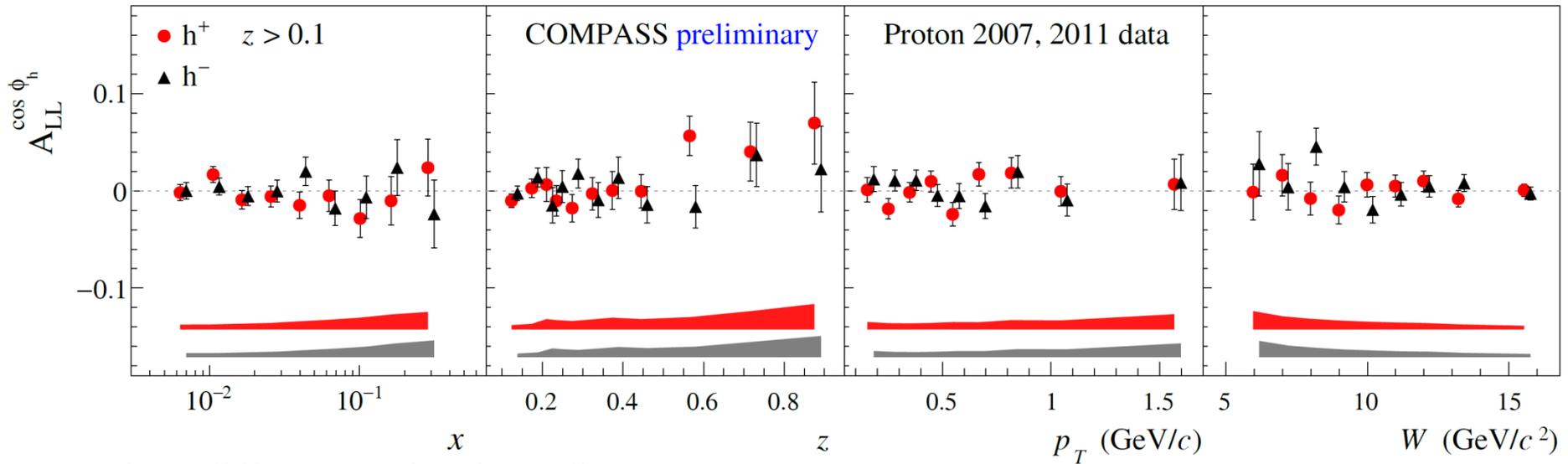
B. Parsamyan (for COMPASS) [arXiv:1801.01488](https://arxiv.org/abs/1801.01488) [hep-ex] (DIS-2017)



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

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

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



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



SIDIS: target longitudinal spin dependent asymmetries

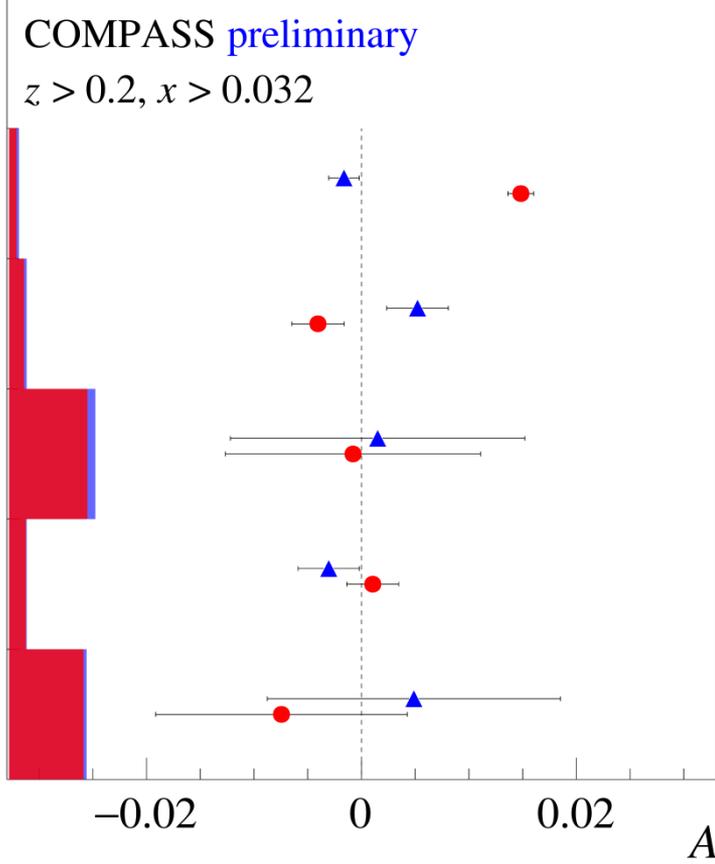
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots \right.$$

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

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

COMPASS collected large amount of L-SIDIS data
Unprecedented precision!

- Q-suppression, Various different “twist” ingredients
- Sizable TSA-mixing
- **Significant h⁺ asymmetry, clear z-dependence,**
- **h⁻ compatible with zero**
- Only “twist-2” ingredients
- Additional p_T-suppression
- **Compatible with zero, in agreement with models**
- **Collins-like behavior?**
- Q-suppression, Various different “twist” ingredients
- **Compatible with zero, in agreement with models**



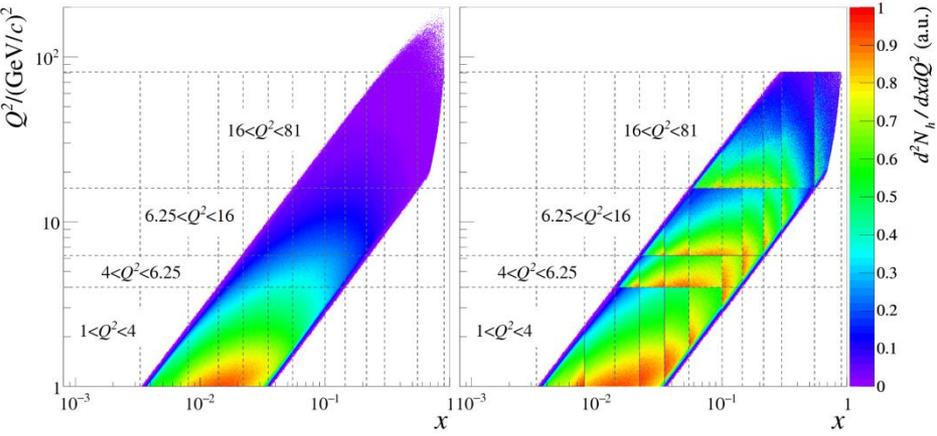


SIDIS Sivers TSA in COMPASS Drell-Yan Q^2 -ranges

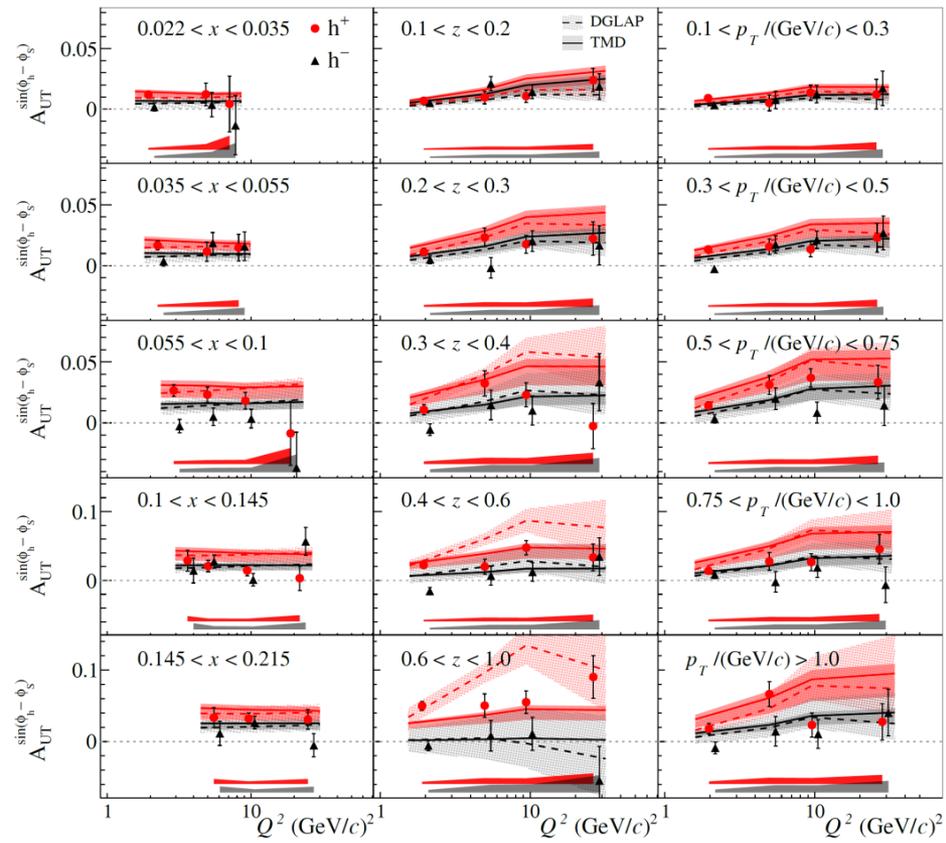
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \dots \right\}$$

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

COMPASS **PLB 770 (2017) 138**



Multi-dimensional input for TMD evolution studies



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

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.

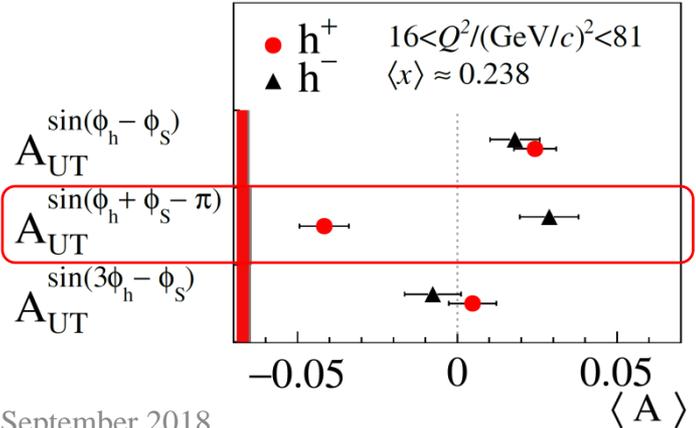
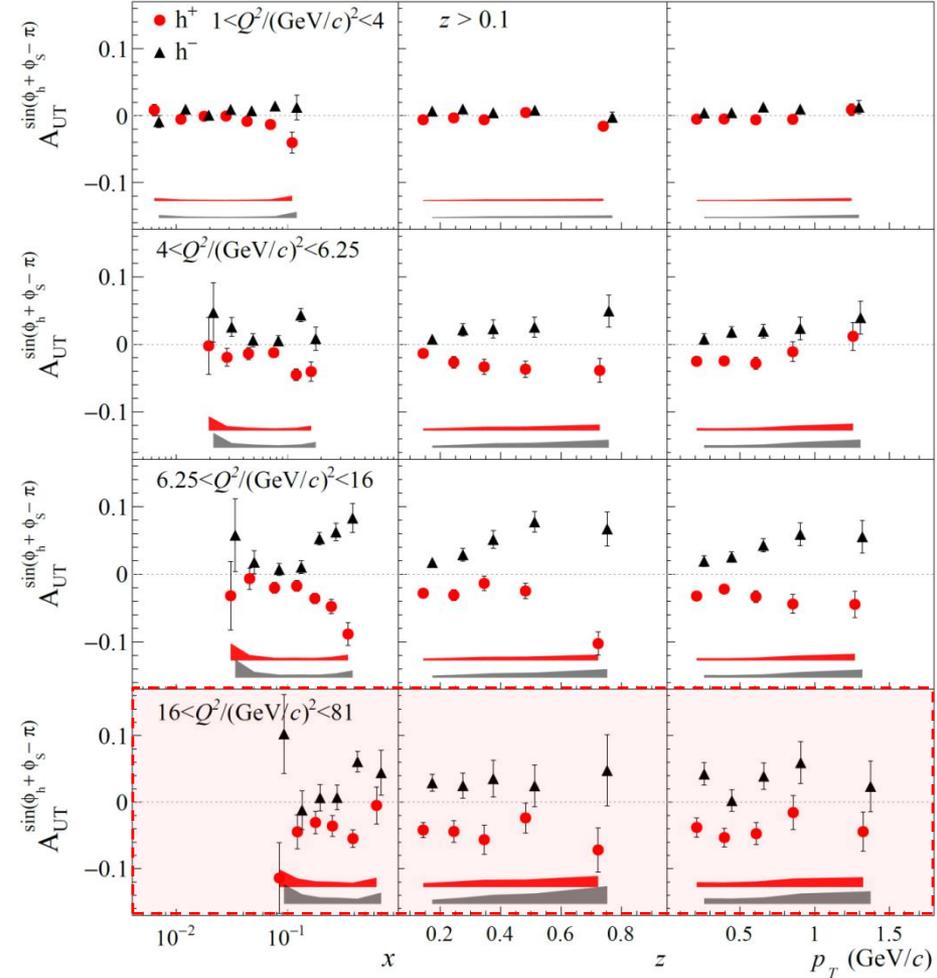
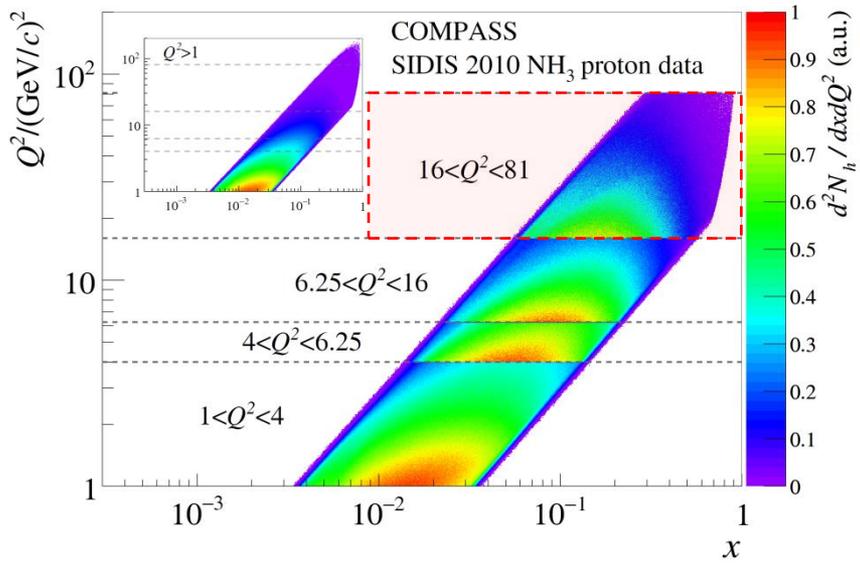


SIDIS Collins TSA in COMPASS Drell-Yan Q^2 -ranges

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

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

COMPASS **PLB 770 (2017) 138**





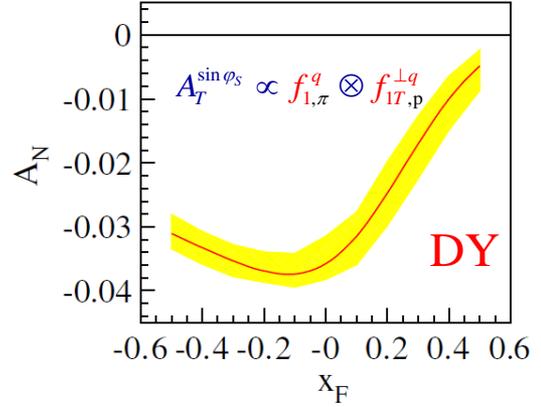
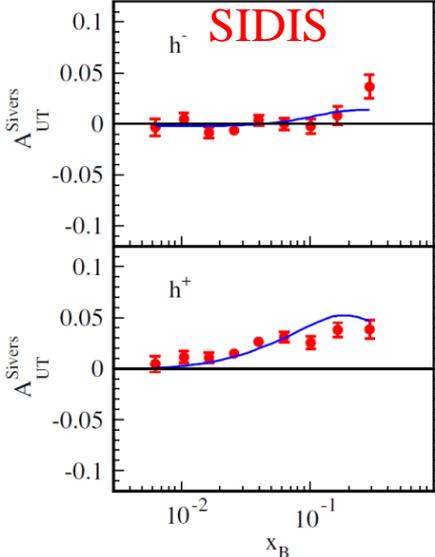
SIDIS TSAs (Sivers)

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

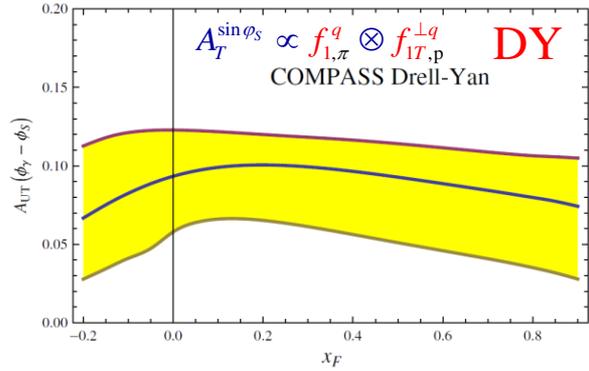
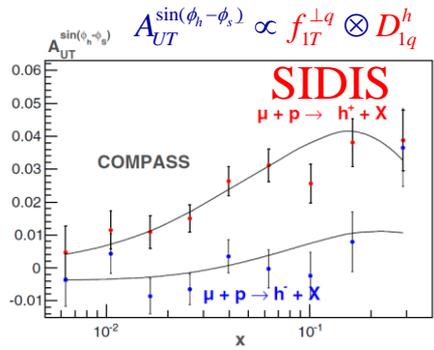
$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C \left[-\frac{\hat{h} \cdot \mathbf{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h \right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$

- 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 $\sim 2-3$)
- **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)**



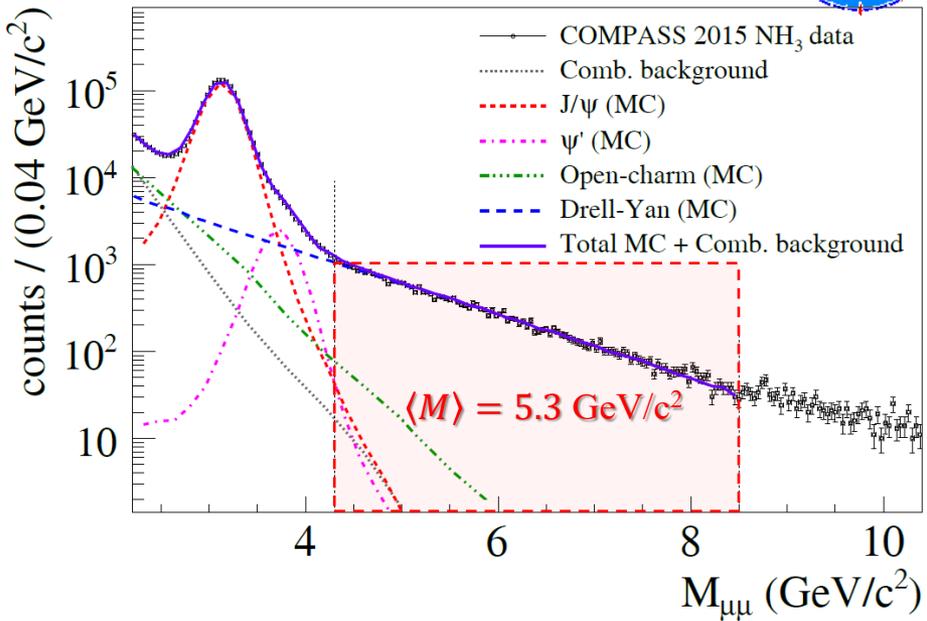
P. Sun and F. Yuan, **PRD 88 11, 114012 (2013)**



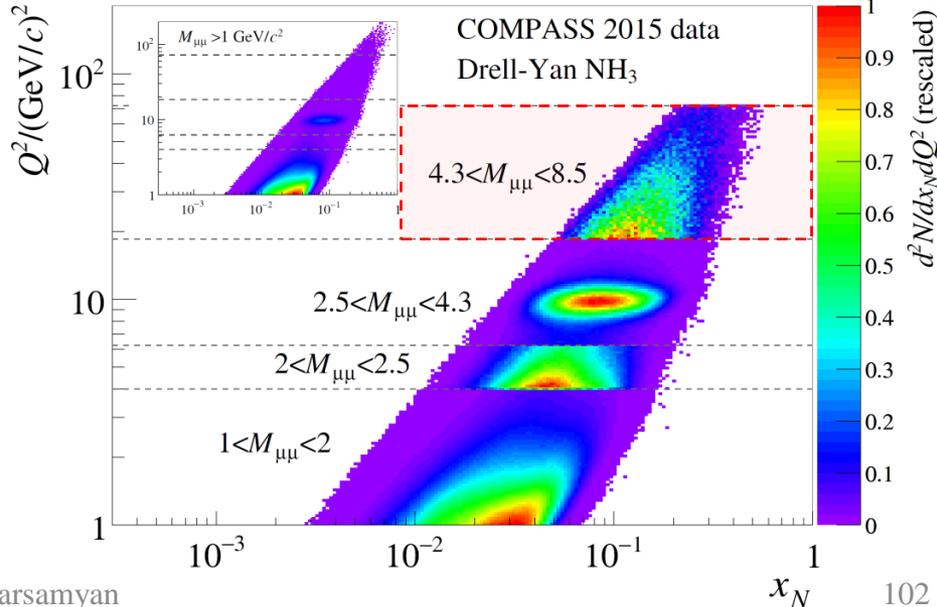
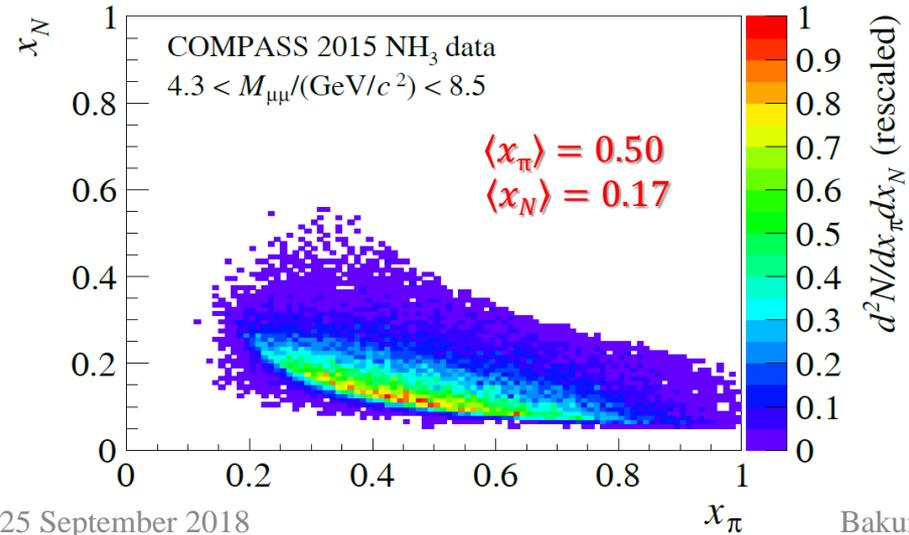
COMPASS DY: high mass range

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

Final sample: 35 000 dimuons in HM



HM events are in the valence quark range





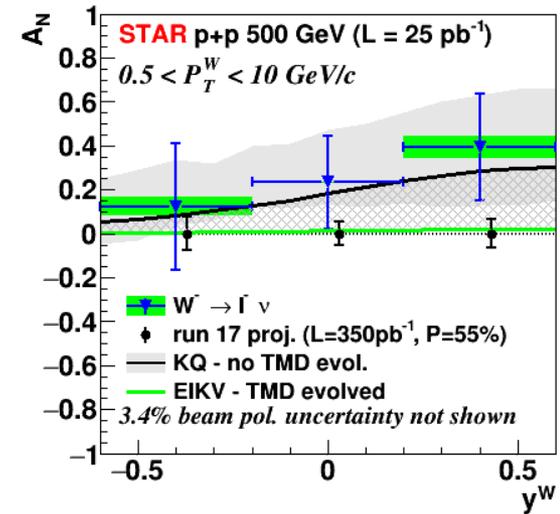
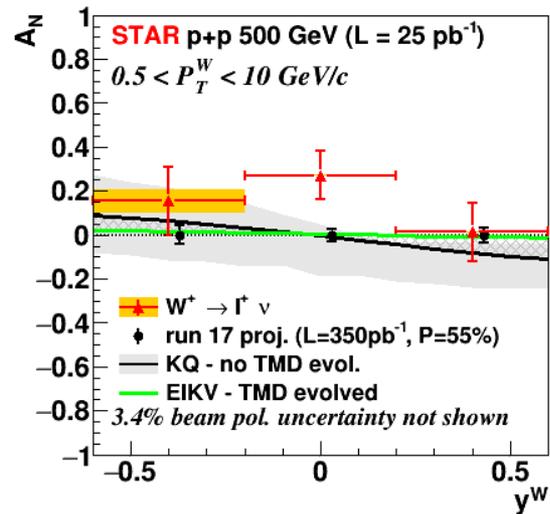
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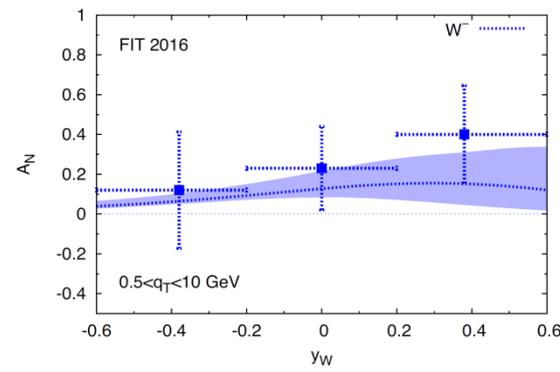
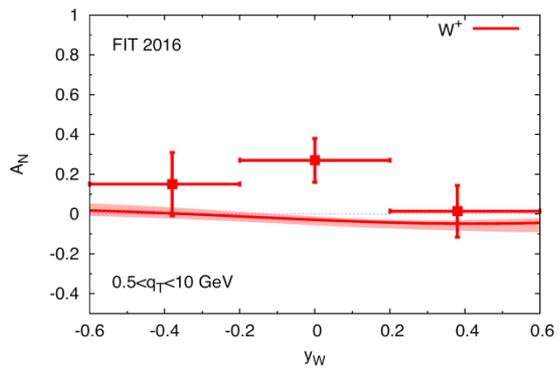
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- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan
- **Sivers TMD PDF is predicted to change the sign between SIDIS and DY**
- First experimental investigation of Sivers-non-universality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

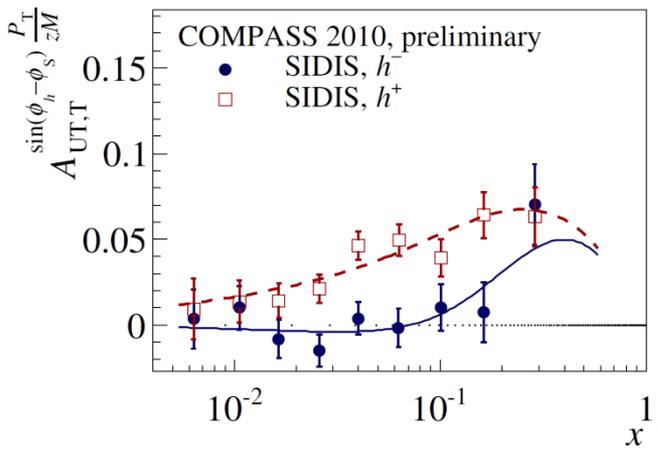




The p_T (q_T) – weighted SIDIS(DY) Siverts asymmetry

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](https://arxiv.org/abs/1702.00621) [hep-ex]



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

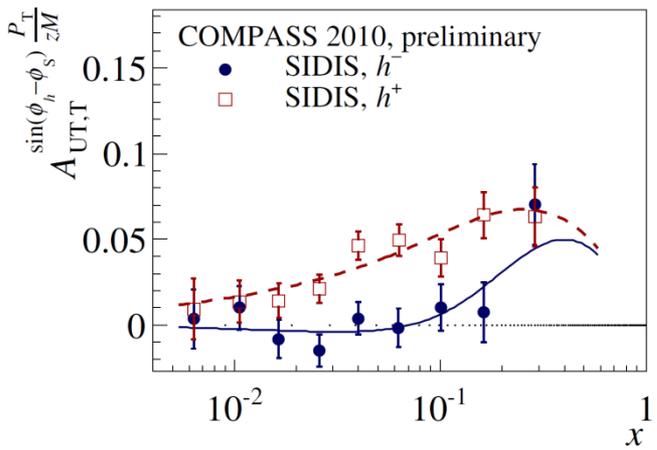
Siverts wTSA in SIDIS: $A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q (1)} \times D_{1q}^h$



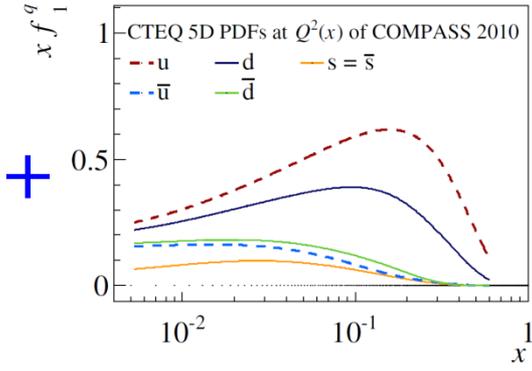
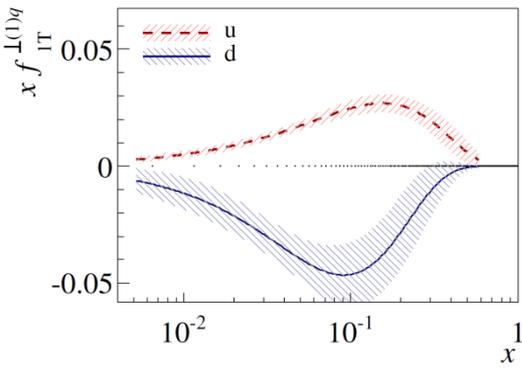
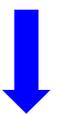
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Sivers wTSA in SIDIS:	$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q (1)} \times D_{1q}^h$
Sivers TSA in DY:	$A_T^{\sin \phi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$
Sivers wTSA in DY:	$A_T^{\sin \phi_S} \propto f_{1,\pi}^q \times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



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

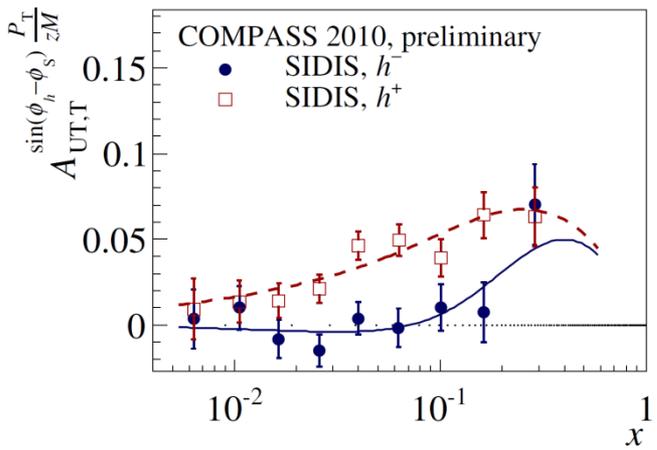
$$A_T^{\sin \phi_S} \frac{q_T}{M_P} \approx \frac{f_{1T,p}^{\perp u (1)}}{f_{1,p}^u}$$



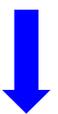
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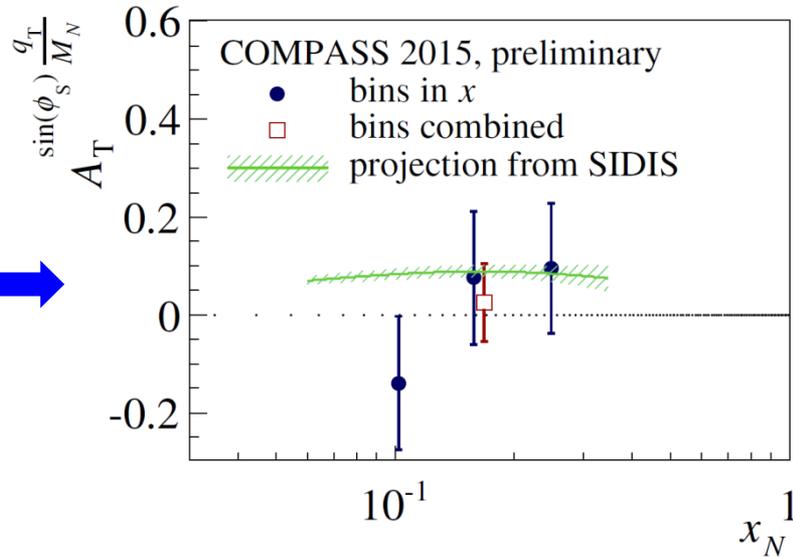
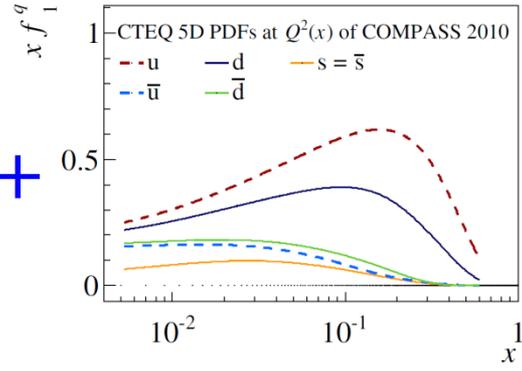
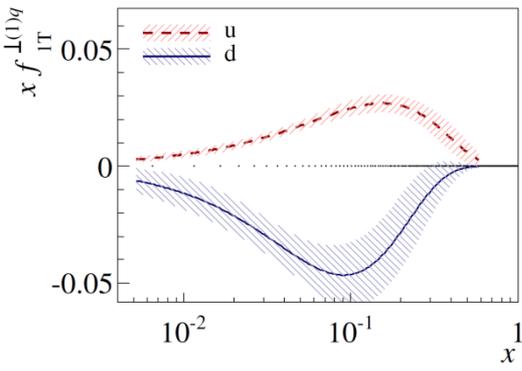
F. Bradamante (COMPASS at SPIN-2016)
[arXiv:1702.00621](https://arxiv.org/abs/1702.00621) [hep-ex]



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



J. Matoušek (COMPASS at DSPIN-2017)
[arXiv:1710.06497](https://arxiv.org/abs/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

