



Polarized Drell-Yan at COMPASS-II: Transverse Spin Physics Program

UNIVERSITÀ
DEGLI STUDI
DI TORINO

ALMA UNIVERSITAS
TAURINENSIS



BAKUR PARSAMYAN

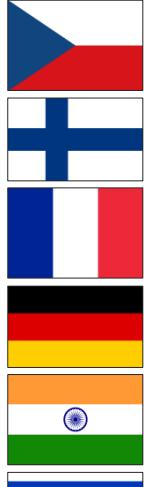
University of Turin and INFN section of Turin

on behalf of the COMPASS Collaboration



The 22nd International Symposium
on Spin Physics (Spin2016)
UIUC, Urbana-Champaign, U.S.
September 25 - 30, 2016

COMPASS collaboration



24 institutions from 13 countries – nearly 250 physicists

Common Muon and Proton Apparatus for Structure and Spectroscopy

- CERN SPS north area
- Fixed target experiment
- Taking data since 2002

Wide physics program

COMPASS-I

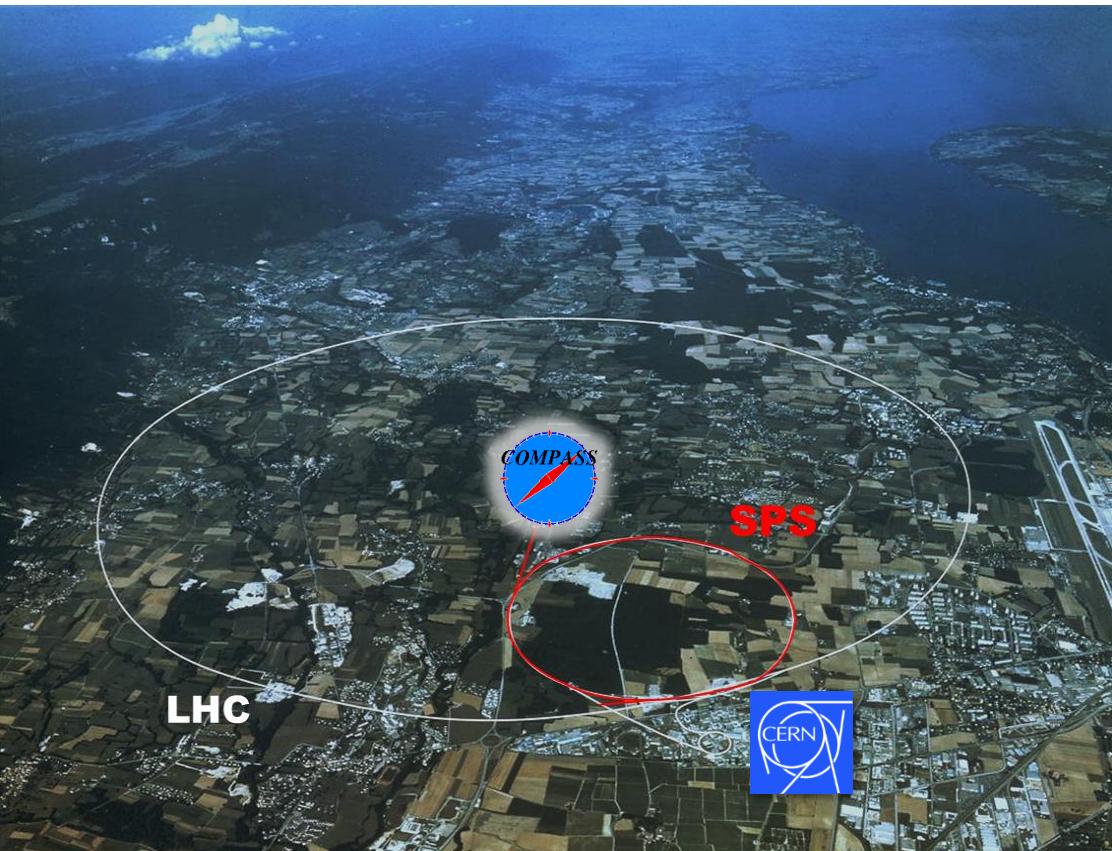
- Muon and hadron beams
- Nucleon spin structure
- Spectroscopy

COMPASS-I talks at SPIN2016:
V. Andrieux, F. Bradamante, N. Makke,
B. Parsamyan, G. Sbrizzai, L. Silva, S. Sirtl,
M. Wilfert

COMPASS-II

- Data taking 2012-2018
- Primakoff
- DVCS (GPD+SIDIS)
- Polarized Drell-Yan

COMPASS-II talks at SPIN2016:
V. Andrieux, A. Ferrero, R. Heitz, M. Gorzellik,
M. Meyer, G. Nukazuka, B. Parsamyan,
C. Quintans, L. Silva



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

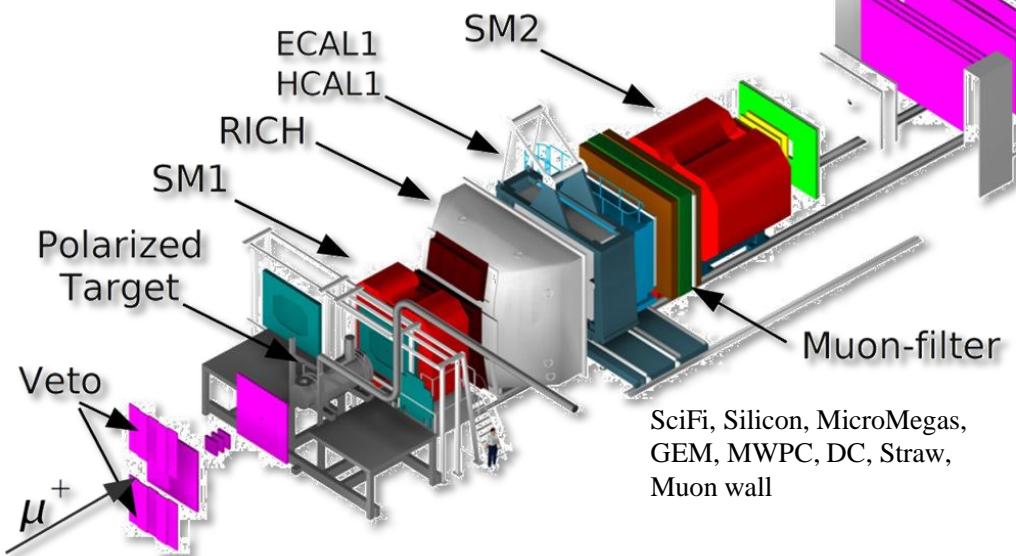
COMPASS experimental setup: Phase I (muon program)

COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area.

Two stages spectrometer LAS+SAS

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



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

- See talks by:
 V. Andrieux,
 F. Bradamante,
 N. Makke,
 B. Parsamyan,
 G. Sbrizzai,
 S. Sirtl,
 M. Wilfert
- High energy beam
 - Large angular acceptance
 - Broad kinematical range
 - Momentum, tracking and calorimetric measurements, PID

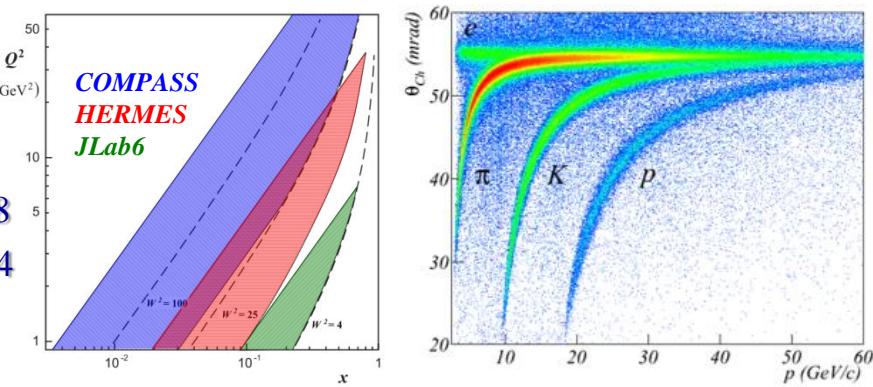
Longitudinally polarized (80%) μ^+ beam:

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 ~ 0.38
- NH_3 3-cell configuration. Polarization (L & T) $\sim 80\%$, f ~ 0.14

Data-taking years: 2002-2011



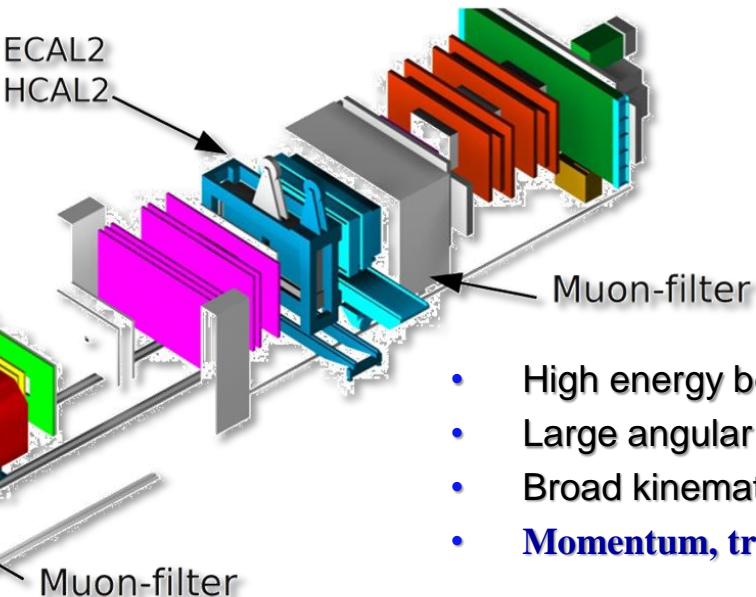
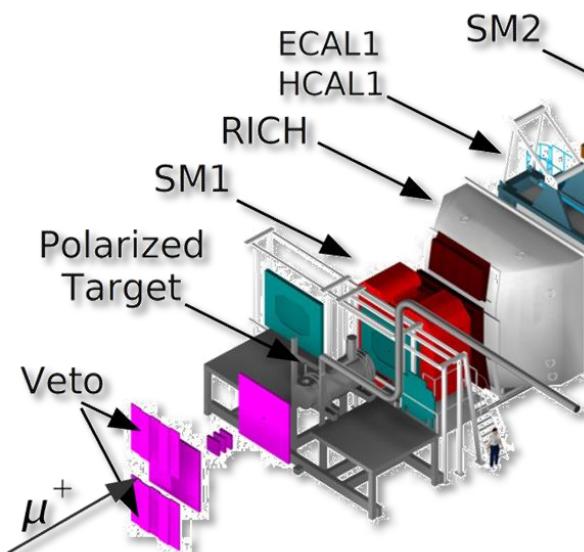
COMPASS experimental setup: Phase II (DY program)

COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area.

Two stages spectrometer LAS+SAS

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



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

- High energy beam
- Large angular acceptance
- Broad kinematical range
- **Momentum, tracking**

See talks by:
J. Matousek,
G. Nukazuka,
B. Parsamyan,
L. Silva

High energy π^- beam:

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

Target: Solid state

- NH₃ 2-cell configuration. Polarization T ~ 80%, f ~ 0.22
- Data is collected simultaneously for the two target spin orientations.
Polarization reversal after each ~5-7 days

Data-taking years: 2014-2015

COMPASS experimental setup: Phase II (DY program)

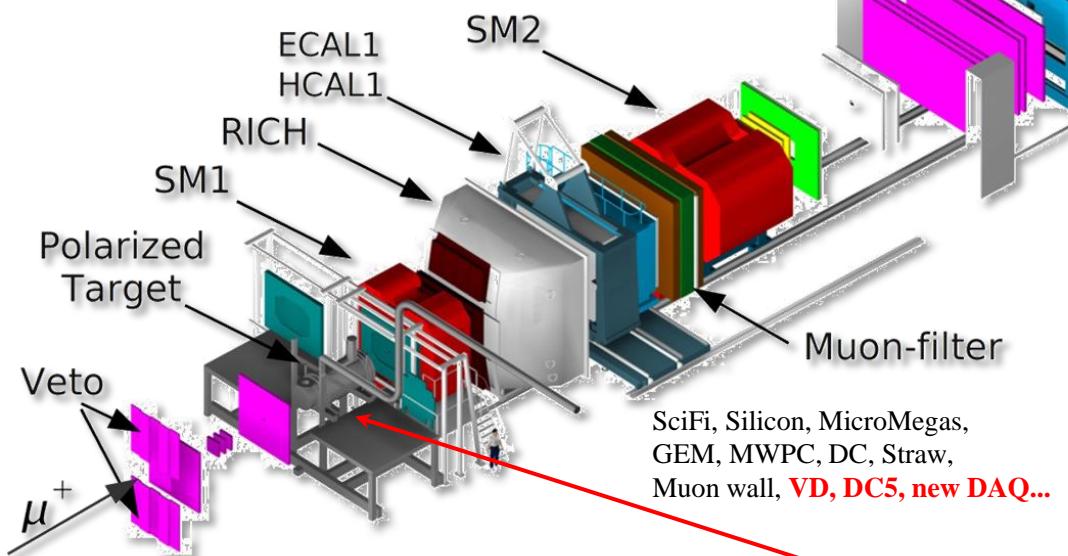


COmmon Muon Proton Apparatus for Structure and Spectroscopy

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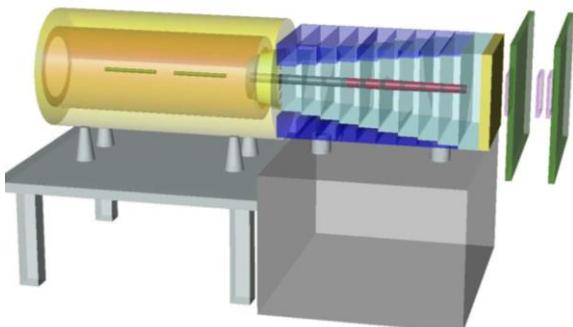
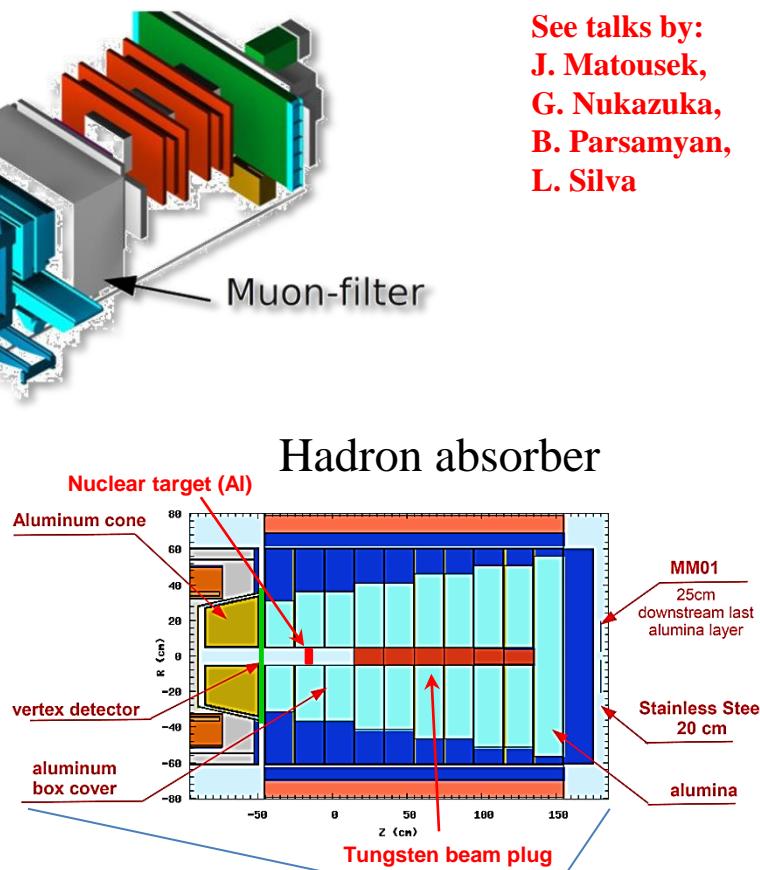
Target: Solid state

- NH_3 2-cell configuration. Polarization $T \sim 80\%$, $f \sim 0.22$
- Data is collected simultaneously for the two target spin orientations. Polarization reversal after each $\sim 5\text{-}7$ days

Data-taking years: 2014-2015

Bakur Parsamyan

See talks by:
J. Matousek,
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L. Silva



COMPASS experimental setup: Phase II (DY program)

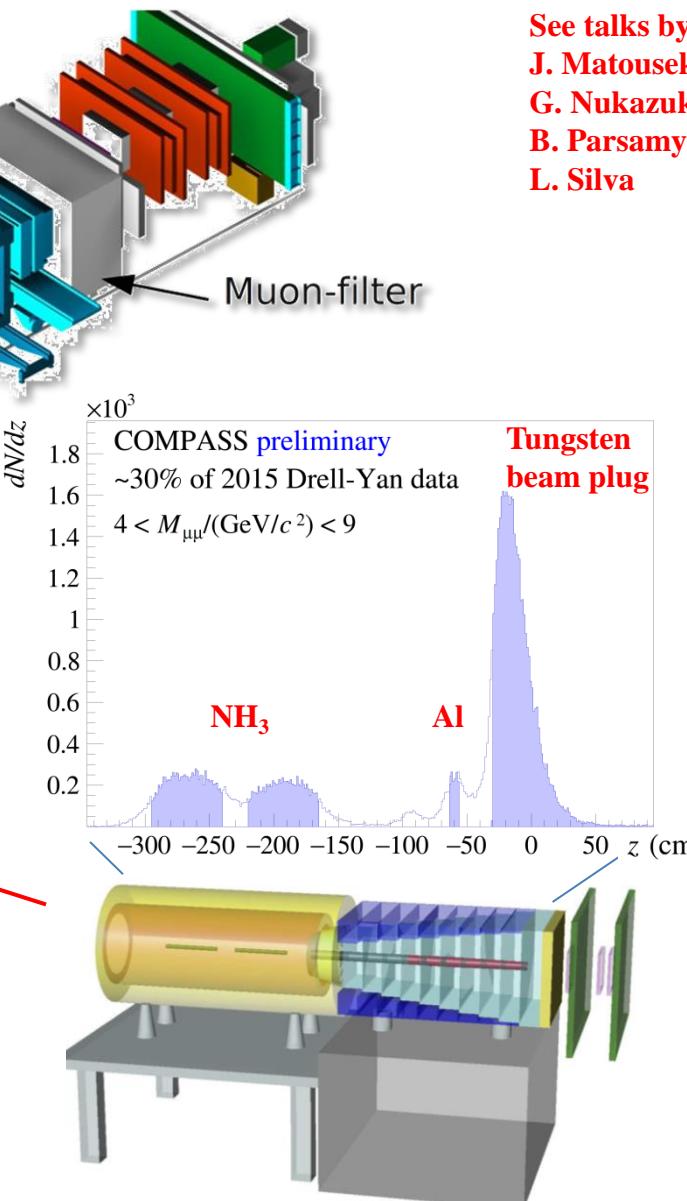
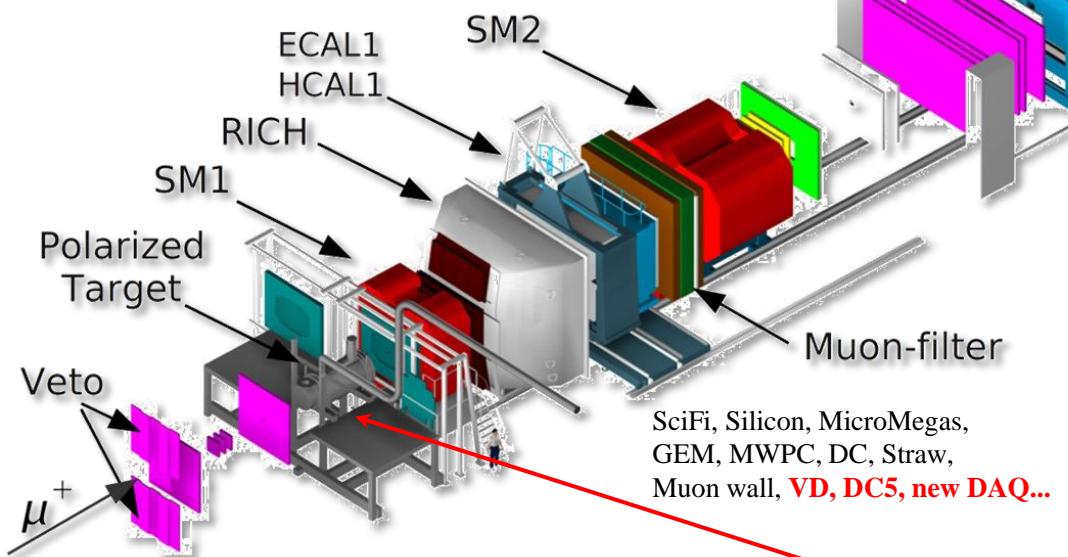


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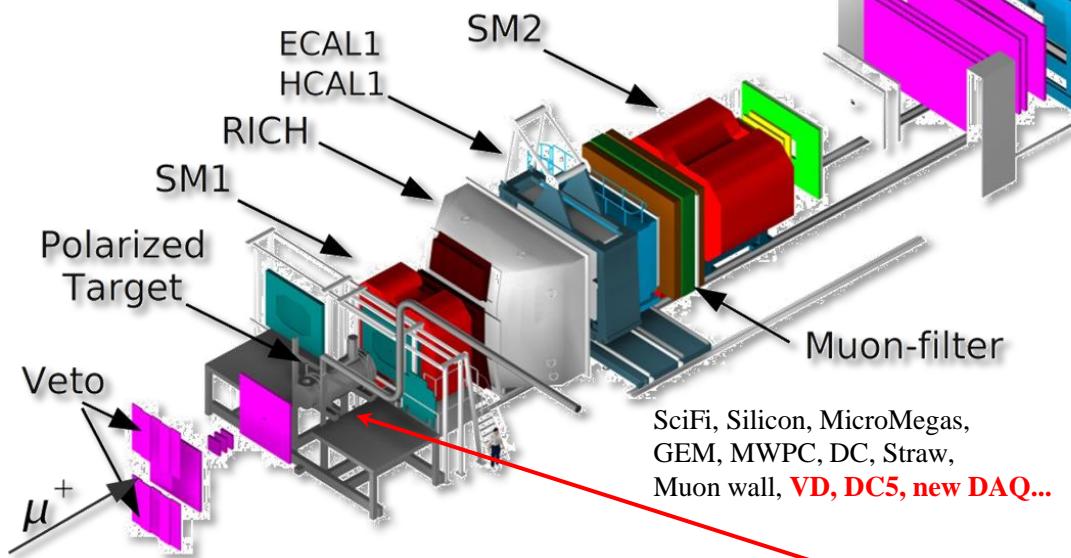
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High energy π^- beam:

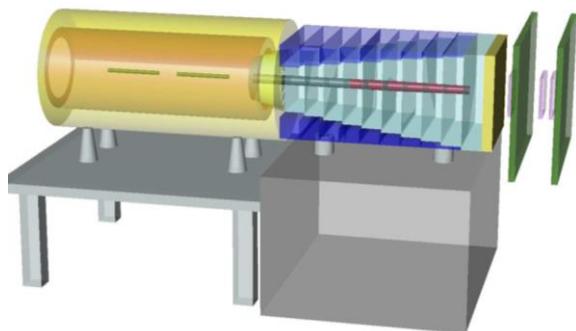
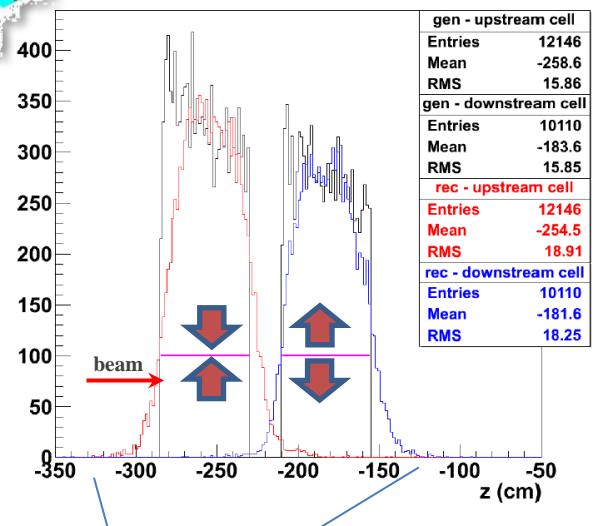
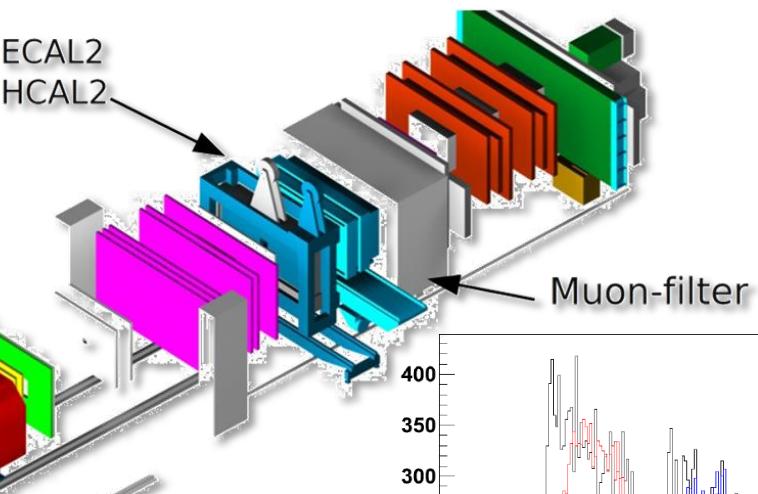
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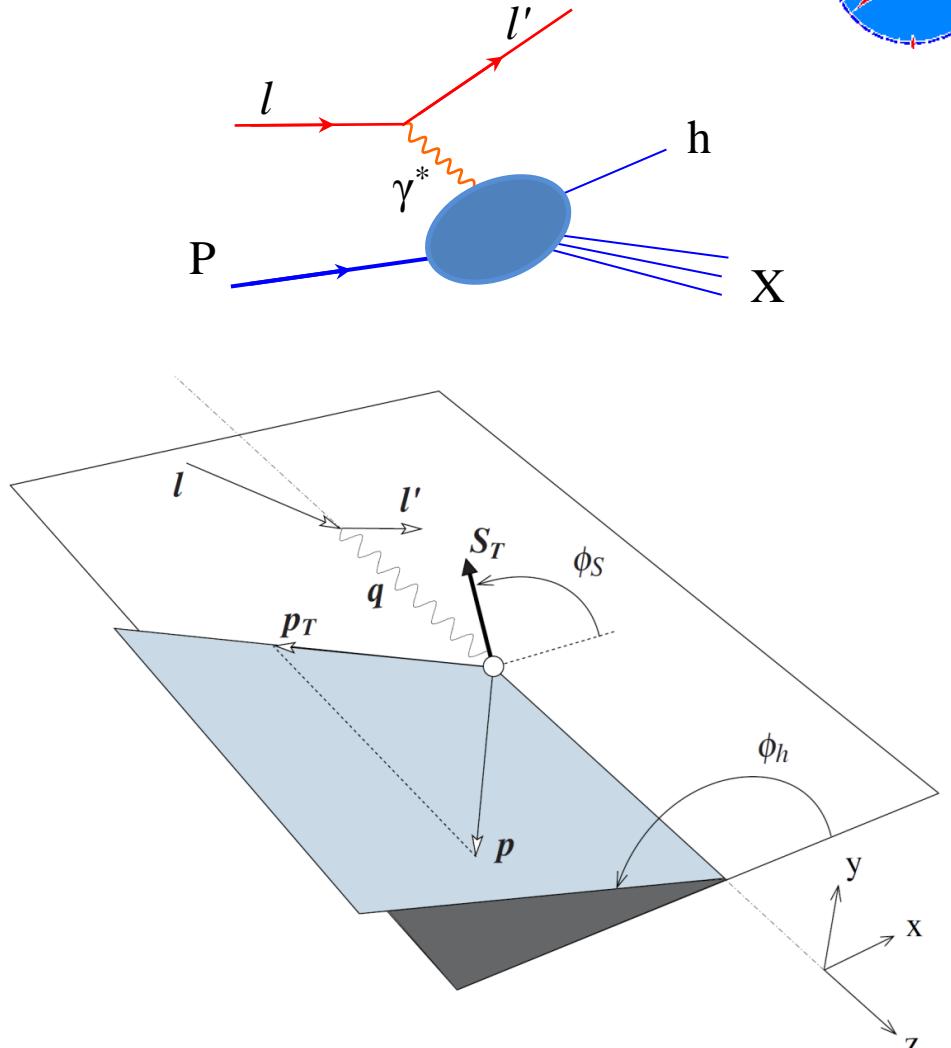
- SIDIS x-section

SIDIS x-section

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



$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_s} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times \left\{ \begin{array}{l} 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ + S_L \left[\sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right] \\ + S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right] \\ \times \left[\begin{array}{l} A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_s} \sin\phi_s \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h - \phi_s)} \sin(2\phi_h - \phi_s) \end{array} \right] \\ + S_T \left[\begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_s} \cos\phi_s \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h - \phi_s)} \cos(2\phi_h - \phi_s) \end{array} \right] \end{array} \right\}$$



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

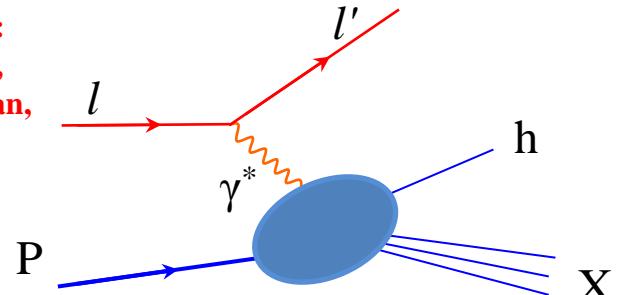
SIDIS x-section

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



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

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

$$\times \left[A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) + \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_s} \sin\phi_s + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h - \phi_s)} \sin(2\phi_h - \phi_s) \right]$$

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

SSA

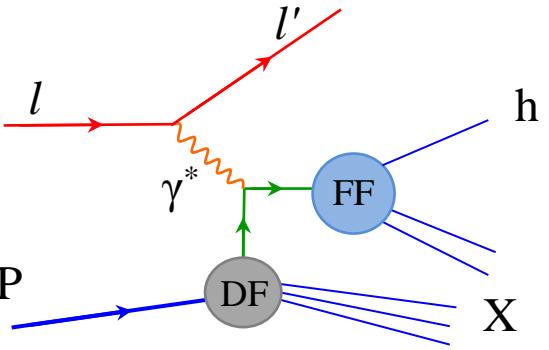
DSA

This talk

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

SIDIS x-section and TMDs at twist-2

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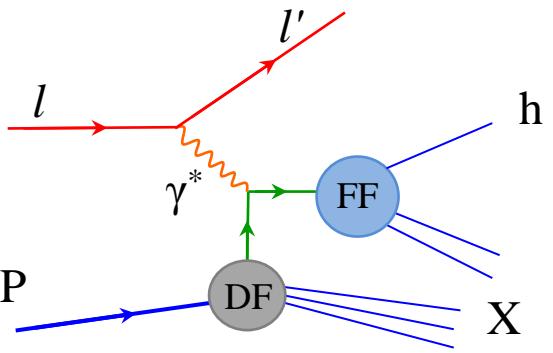


Quark Nucleon	U	L	T
U	$f_1^q(x, \mathbf{k}_T^2)$ number density		$h_1^{q\perp}(x, \mathbf{k}_T^2)$ Boer-Mulders
L		$g_1^q(x, \mathbf{k}_T^2)$ helicity	$h_{1L}^{q\perp}(x, \mathbf{k}_T^2)$ worm-gear L
T	$f_{1T}^{q\perp}(x, \mathbf{k}_T^2)$ Sivers	$g_{1T}^{q\perp}(x, \mathbf{k}_T^2)$ Kotzinian-Mulders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

$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_s} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ \begin{array}{l} 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ + S_L \left[\sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right] \\ + S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right] \\ \\ \times \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_s)} \sin(\phi_h - \phi_s) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_s)} \sin(\phi_h + \phi_s) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_s)} \sin(3\phi_h - \phi_s) \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_s} \sin\phi_s \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h-\phi_s)} \sin(2\phi_h - \phi_s) \end{array} \right] \\ \\ + S_T \lambda \left[\begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_s)} \cos(\phi_h - \phi_s) \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_s} \cos\phi_s \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h-\phi_s)} \cos(2\phi_h - \phi_s) \end{array} \right] \end{array} \right\}$$



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

↑ spin of the nucleon ↑ spin of the quark ↗ k_T

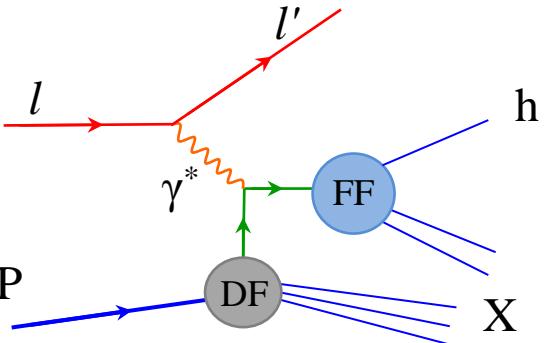
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$$\left. \begin{aligned} & 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ & + S_L \left[\sqrt{2\varepsilon(1+\varepsilon)}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

$$\times \left. \begin{aligned} & A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) \\ & + \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) \\ & + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \\ & + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_s} \sin\phi_s \\ & + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h - \phi_s)} \sin(2\phi_h - \phi_s) \end{aligned} \right\}$$

$$+ S_T \left. \begin{aligned} & \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \\ & + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_s} \cos\phi_s \\ & + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h - \phi_s)} \cos(2\phi_h - \phi_s) \end{aligned} \right\}$$



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

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

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

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

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

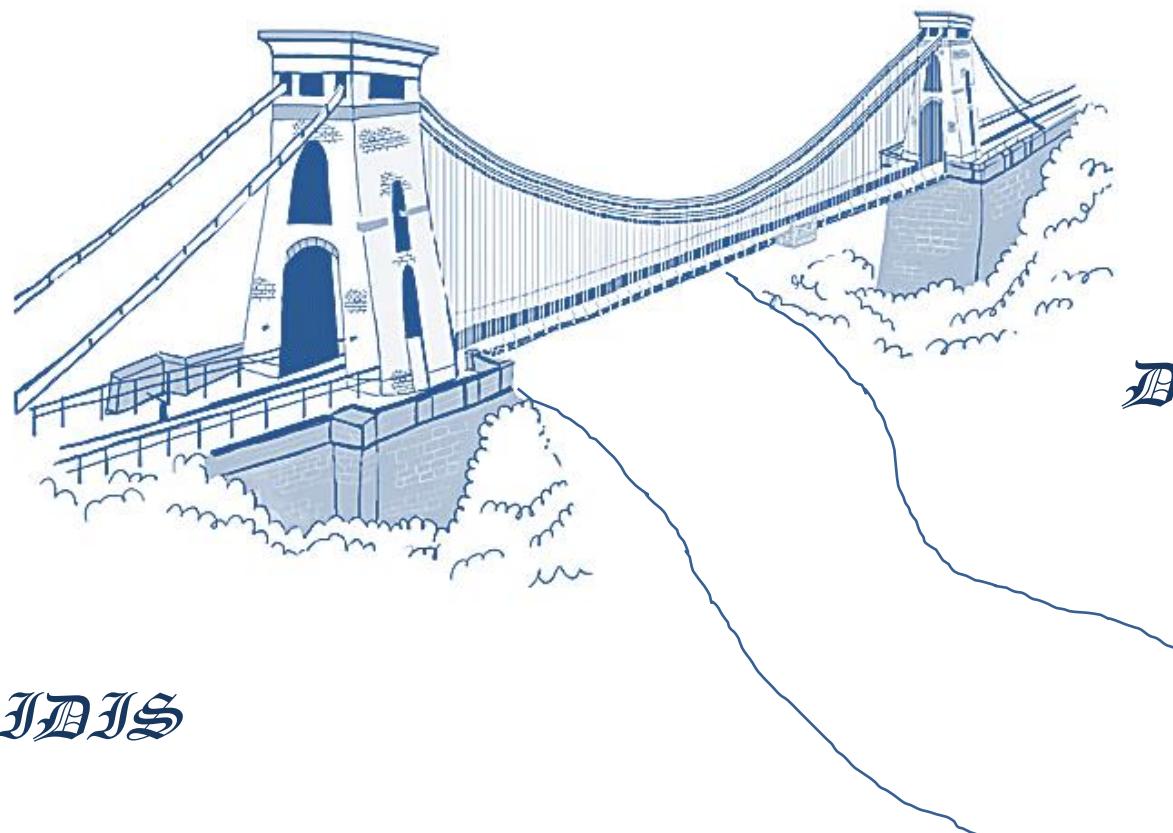
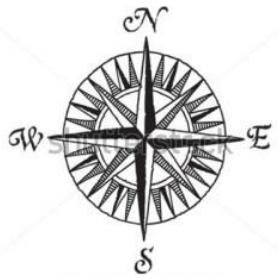
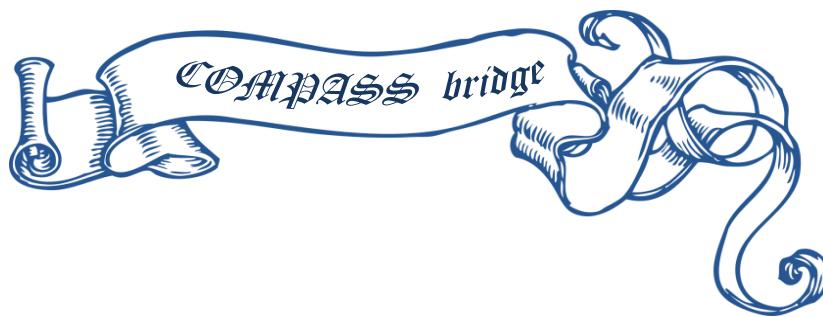
$$A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$

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

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

Twist-2

Twist-3



Drell-Pan

SIDS

SIDIS and single-polarized DY x-sections

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

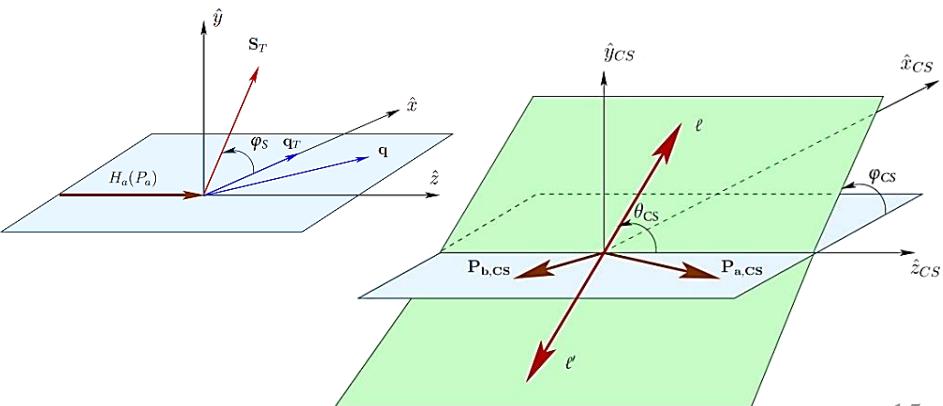
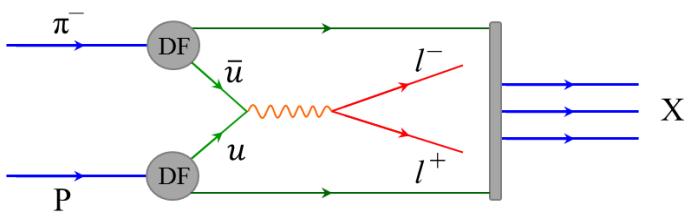
$$\left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L})$$

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

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

$$\frac{d\sigma}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1$$

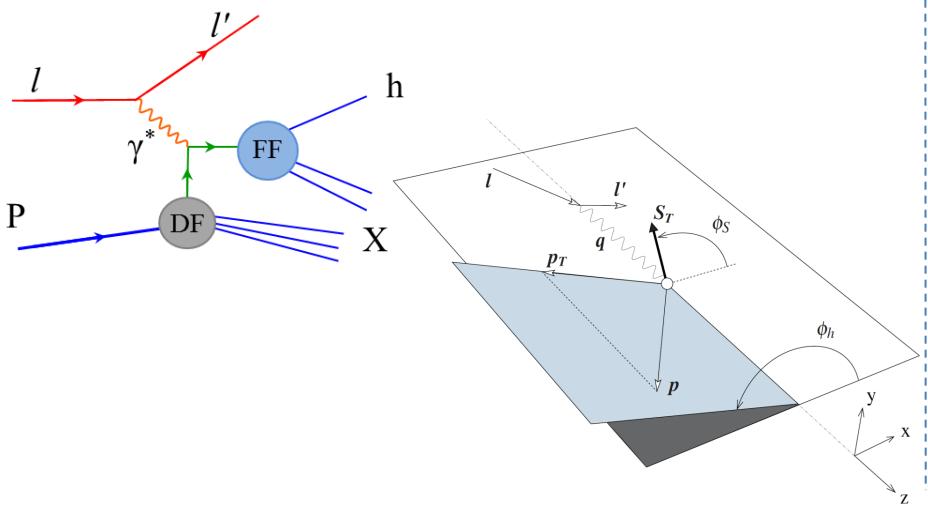
$$\times \left. \begin{aligned} & \left[1 + A_U^1 \cos^2 \theta_{CS} \right. \\ & + \sin 2\theta_{CS} A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + \sin^2 \theta_{CS} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ & \left. \times \left[\left(A_T^{\sin\varphi_s} + \cos^2 \theta_{CS} \tilde{A}_T^{\sin\varphi_s} \right) \sin\varphi_s \right. \right. \\ & + \sin 2\theta_{CS} \left(A_T^{\sin(\varphi_{CS} + \varphi_s)} \sin(\varphi_{CS} + \varphi_s) \right. \\ & \left. + A_T^{\sin(\varphi_{CS} - \varphi_s)} \sin(\varphi_{CS} - \varphi_s) \right) \\ & \left. \left. + \sin^2 \theta_{CS} \left(A_T^{\sin(2\varphi_{CS} + \varphi_s)} \sin(2\varphi_{CS} + \varphi_s) \right. \right. \right. \\ & \left. \left. \left. + A_T^{\sin(2\varphi_{CS} - \varphi_s)} \sin(2\varphi_{CS} - \varphi_s) \right) \right] \right] \end{aligned} \right\}$$



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

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

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

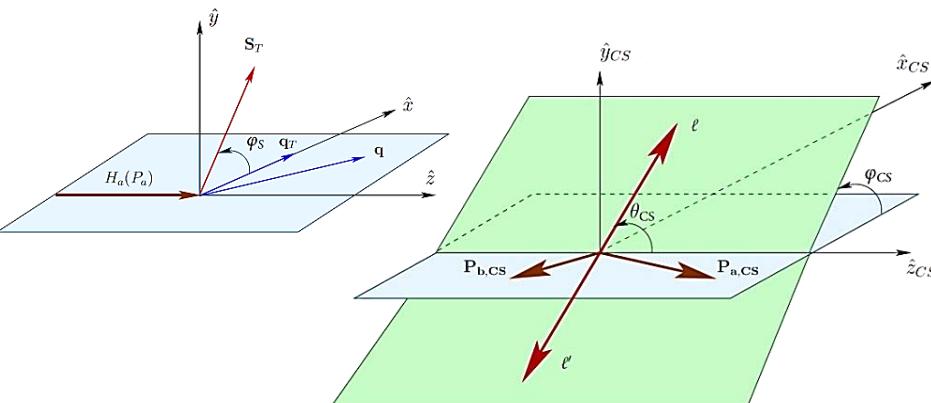
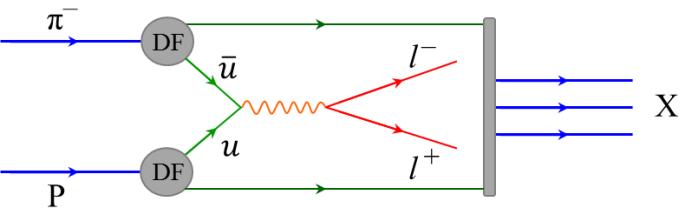


$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 (1 + \cos^2 \theta_{CS})$$

See talk by
L. Silva

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

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)

$$\frac{d\sigma^{LO}}{dx dy dz dp_T^2 d\phi_h d\phi_s} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times \left\{ \begin{array}{l} 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \end{array} \right] \\ + S_T \lambda \left[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \right] \end{array} \right\}$$

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left(1 + \cos^2 \theta_{CS} \right) \times \left\{ \begin{array}{l} 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS} \\ + S_T \left[\begin{array}{l} A_T^{\sin \phi_s} \sin \phi_s \\ + D_{[\sin^2 \theta_{CS}]} \left(A_T^{\sin(2\phi_{CS} + \phi_s)} \sin(2\phi_{CS} + \phi_s) \right. \\ \left. + A_T^{\sin(2\phi_{CS} - \phi_s)} \sin(2\phi_{CS} - \phi_s) \right) \end{array} \right] \end{array} \right\}$$

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

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

within QCD TMD-framework:

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

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

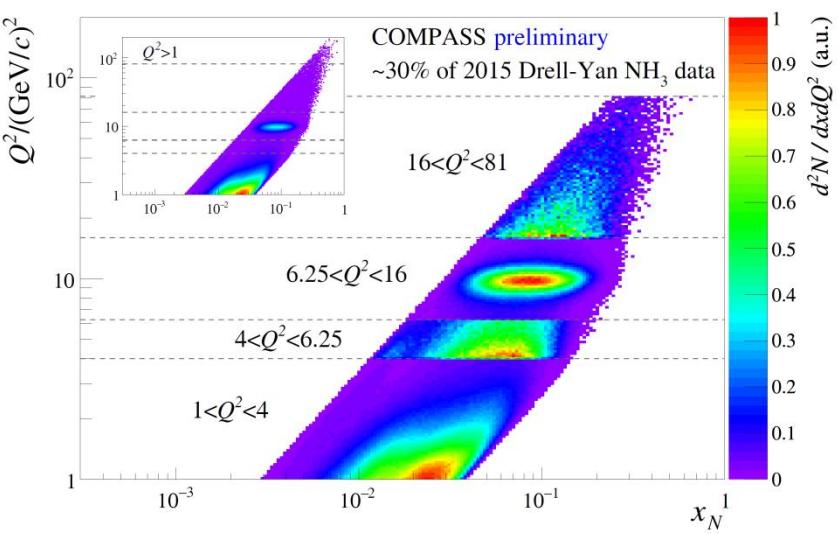
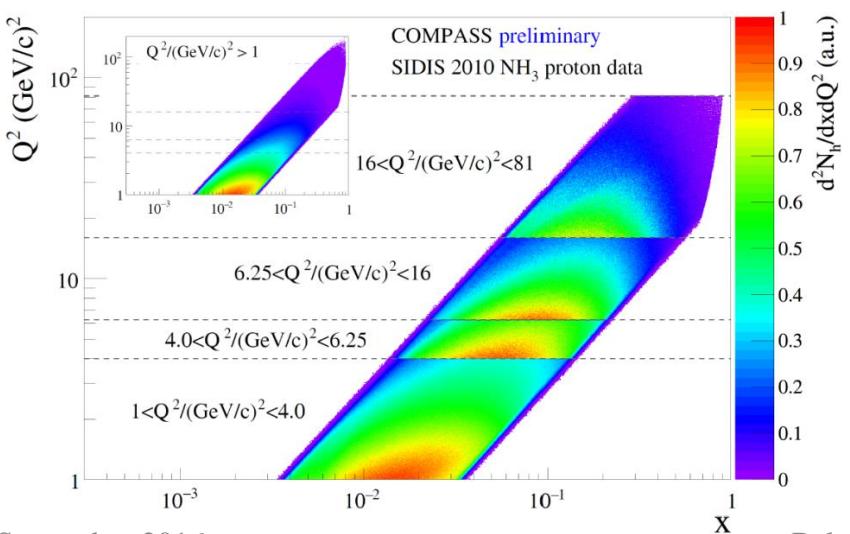
SIDIS and single-polarized DY x-sections at twist-2 (LO)

$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_s} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times \left\{ \begin{array}{l} 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \end{array} \right] \\ + S_T \lambda \left[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \right] \end{array} \right\}$$

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left(1 + \cos^2 \theta_{CS} \right) \times \left\{ \begin{array}{l} 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS} \\ + S_T \left[\begin{array}{l} A_T^{\sin \phi_s} \sin \phi_s \\ + D_{[\sin^2 \theta_{CS}]} \left(A_T^{\sin(2\phi_{CS} + \phi_s)} \sin(2\phi_{CS} + \phi_s) \right. \\ \left. + A_T^{\sin(2\phi_{CS} - \phi_s)} \sin(2\phi_{CS} - \phi_s) \right) \end{array} \right] \end{array} \right\}$$

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





- Selected COMPASS SIDIS one dimensional results

SIDIS TSAs (Collins)

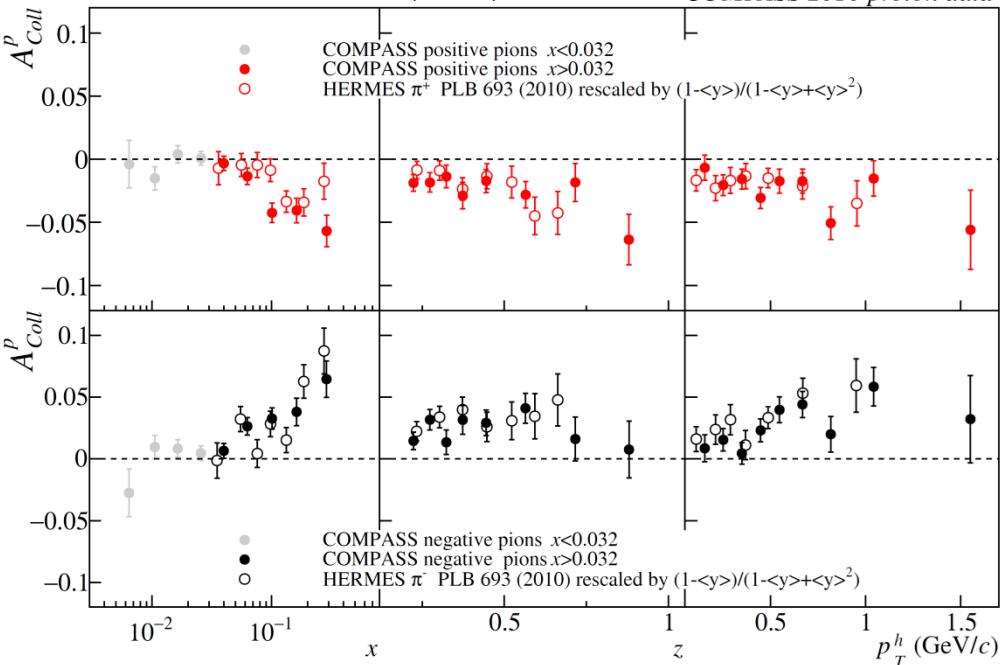
$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_s} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times \left\{ \begin{array}{l} 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \end{array} \right] \\ + S_T \lambda \left[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \right] \end{array} \right\}$$

$$A_{UT}^{\sin(\phi_h + \phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h} \quad \text{SSA [twist-2]}$$



PLB 744 (2015) 250

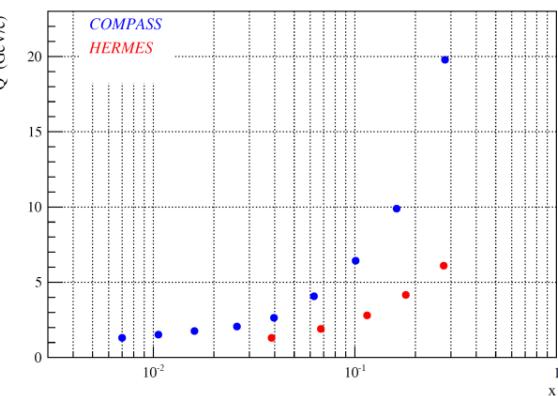
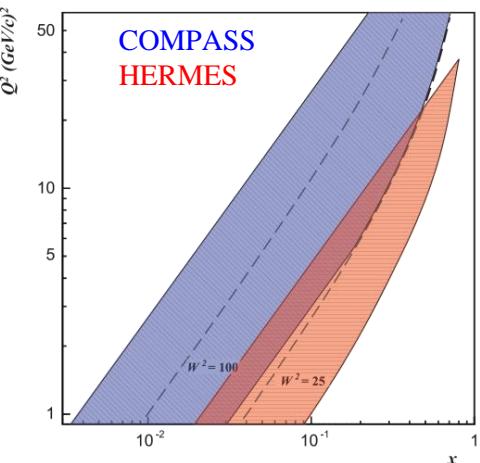
COMPASS 2010 proton data



COMPASS and HERMES results for Collins effect are compatible
(Q^2 is different by a factor of $\sim 2\text{-}3$)

No Q^2 -evolution? Intriguing result!

See also talks by:
F. Bradamante, G. Sbrizzai



SIDIS TSAs (Sivers)

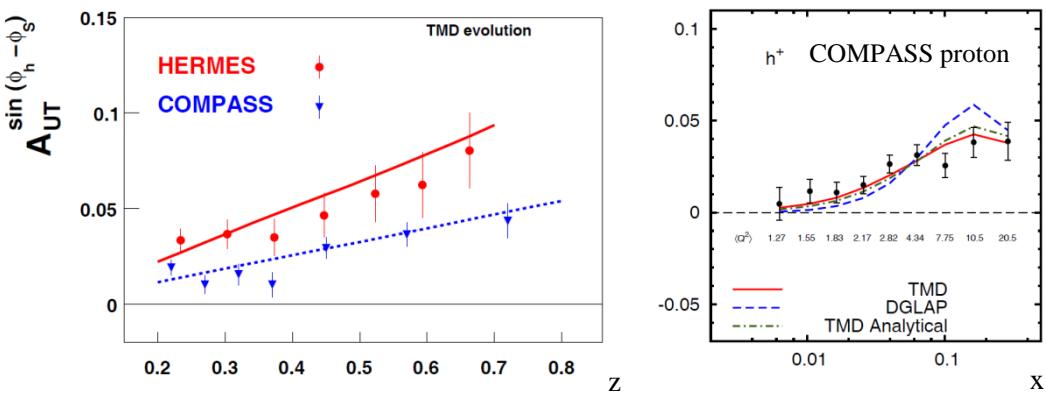
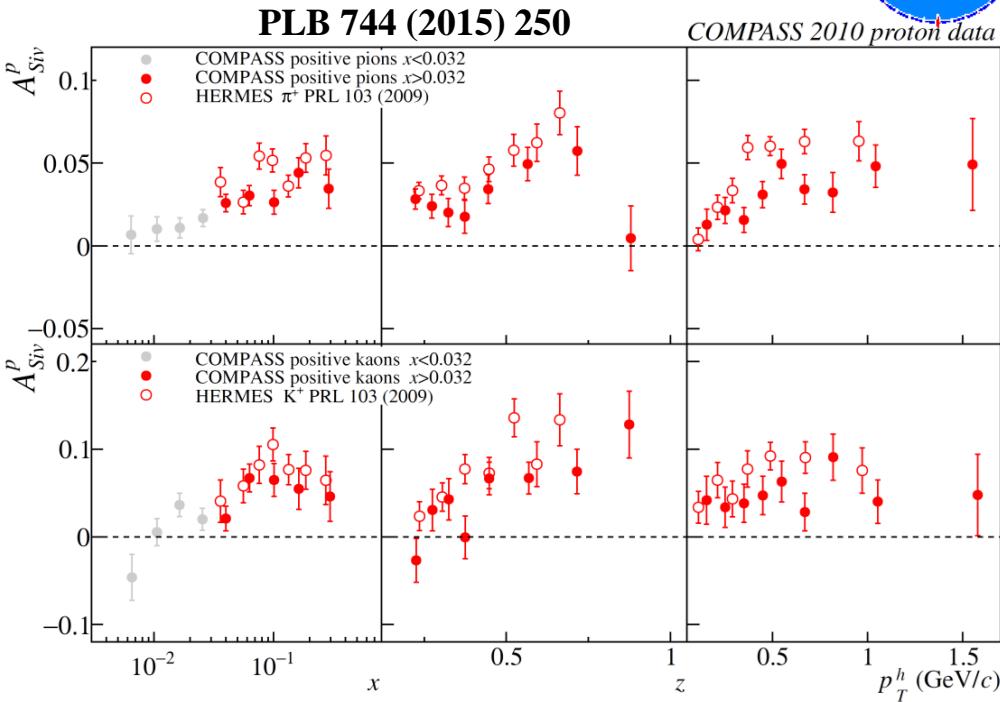
$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times \left\{ 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h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

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!

See also talks by:
F. Bradamante, G. Sbrizzai

$$A_{UT}^{\sin(\phi_h - \phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h \quad \text{SSA [twist-2]}$$

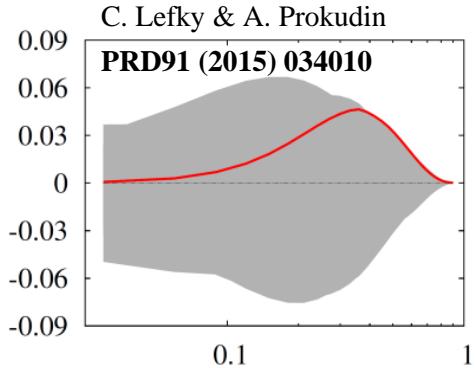
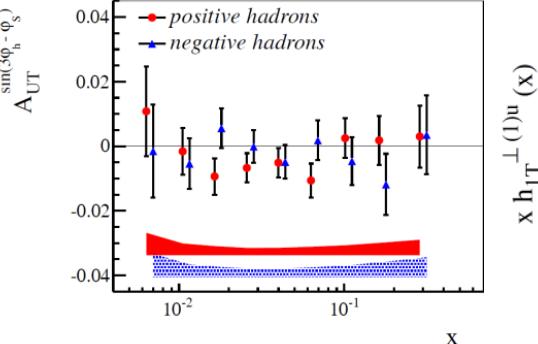


- S. M. Aybat, A. Prokudin, T. C. Rogers **PRL 108 (2012) 242003**
M. Anselmino, M. Boglione, S. Melis **PRD 86 (2012) 014028**

SIDIS TSAs (Pretzelosity and Kotzinian-Mulders)

$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_s} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times \left\{ \begin{array}{l} 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) \\ + \boxed{\varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s)} \end{array} \right] \\ + S_T \lambda \left[\boxed{\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s)} \right] \end{array} \right\}$$

$$A_{UT}^{\sin(3\phi_h - \phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} \text{ SSA [twist-2]}$$



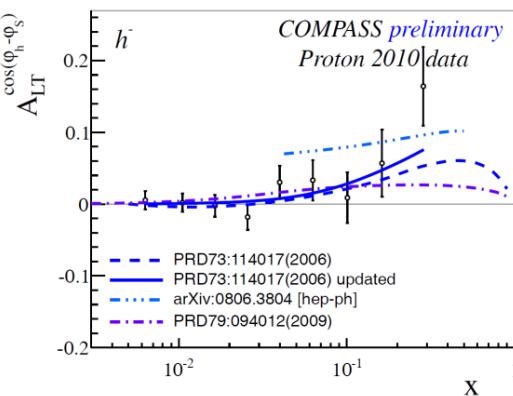
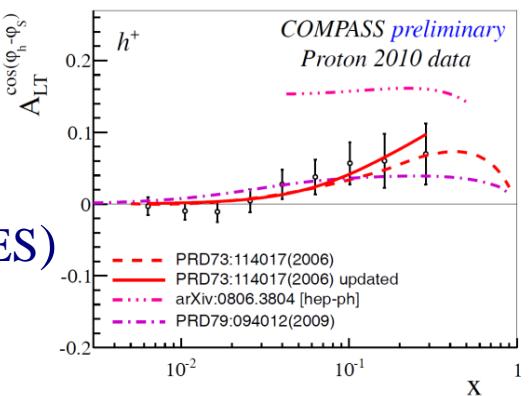
- All compatible with zero within uncertainties (P/D)
- Suppressed by a factor of $\sim |p_T|^2$ w.r.t the Collins and Sivers amplitudes

$$A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h \text{ DSA [twist-2]}$$

- Not accessible in single-polarized DY
- Gives access to g_{1T} “twist-2” PDF (Kotzinian-Mulders or worm-gear-T)
- Clear signal for h^+
(preliminary confirmation also by HERMES)
- In agreement with several models

See also talks by:

F. Bradamante, G. Sbrizzai

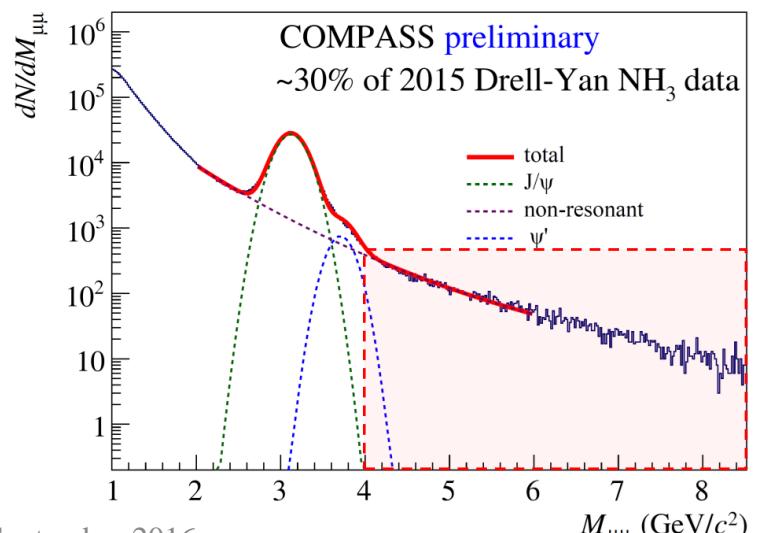




- COMPASS Drell-Yan mass ranges

COMPASS DY mass ranges

- $1 < Q^2 / (\text{GeV}/c)^2 < 4$ “Low mass”
 - Large combinatorial background:
Open-charm (bottom) semi-leptonic decays $D\bar{D}$, $B\bar{B}$, pion and kaon decays
 - small asymmetries
- $4 < Q^2 / (\text{GeV}/c)^2 < 6.25$ “Intermediate”
 - High DY-cross section
 - Still low DY-signal/background ratio
- $6.25 < Q^2 / (\text{GeV}/c)^2 < 16$ “ J/ψ ”
 - Strong J/ψ -signal → study of J/ψ physics
 - Lower background
- $Q^2 / (\text{GeV}/c)^2 > 16$ “High mass”
 - Low DY cross-section
 - Beyond charmonium region, negligible CB
 - Valence region → largest asymmetries

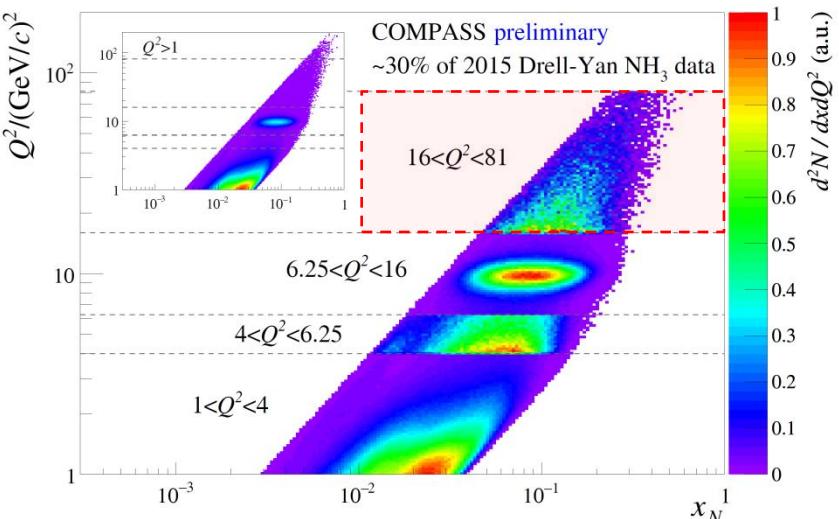


$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left(1 + \cos^2 \theta_{CS} \right)$$

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

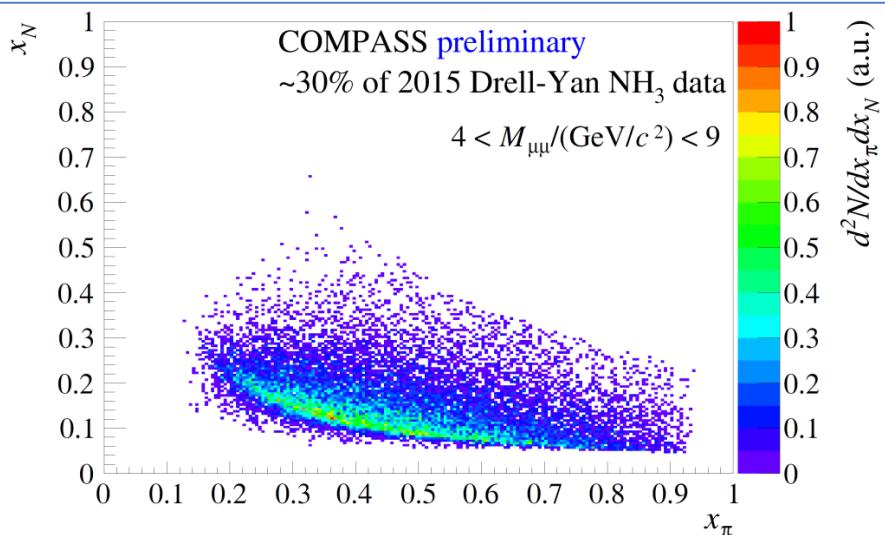
$$\left. + S_T \left[A_T^{\sin \varphi_S} \sin \varphi_S + D_{[\sin^2 \theta_{CS}]} \left(A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) + A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \right) \right] \right\}$$

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



COMPASS DY high-mass range

- $1 < Q^2 / (\text{GeV}/c)^2 < 4$ “Low mass”
 - Large combinatorial background:
Open-charm (bottom) semi-leptonic decays $D\bar{D}$, $B\bar{B}$, pion and kaon decays
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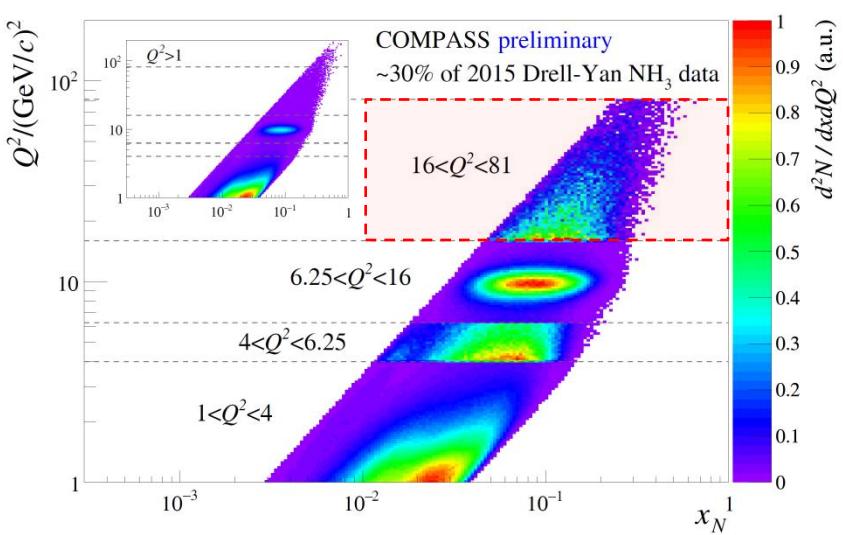
$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left(1 + \cos^2 \theta_{CS} \right)$$

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

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

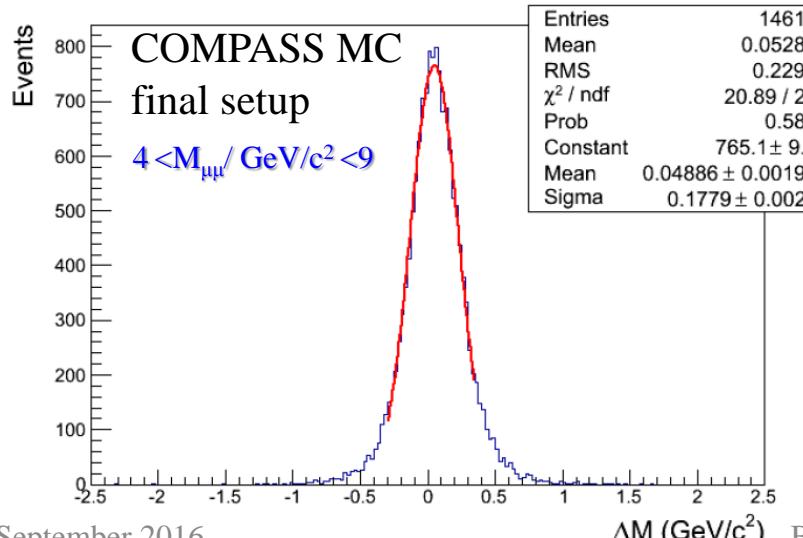
where $D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / (1 + \cos^2 \theta_{CS})$

Accepted events are in the valence quark range
 $(\langle x_\pi \rangle \sim 0.47, \langle x_N \rangle \sim 0.16, \langle x_F \rangle \sim 0.3, \langle q_T \rangle \sim 1.1)$



COMPASS DY high-mass range

- $1 < Q^2 / (\text{GeV}/c)^2 < 4$ “Low mass”
 - Large combinatorial background:
Open-charm (bottom) semi-leptonic decays $D\bar{D}$, $B\bar{B}$, pion and kaon decays
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$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left(1 + \cos^2 \theta_{CS} \right)$$

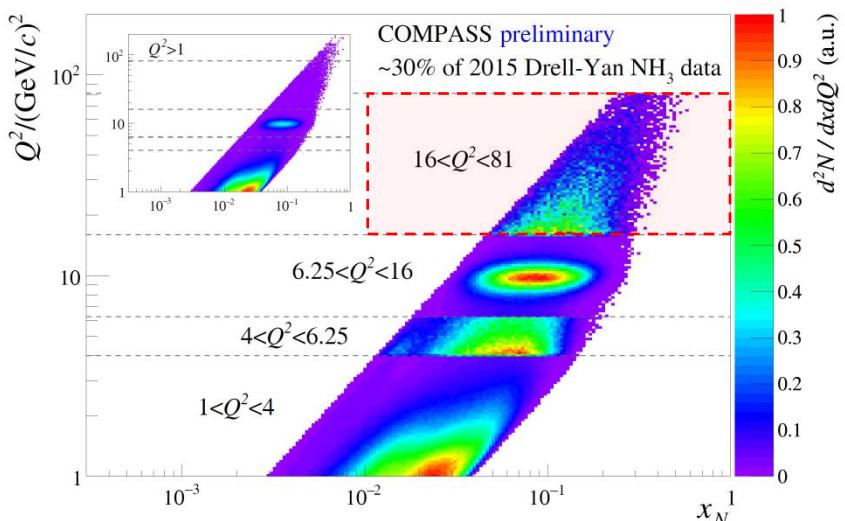
$$\times \left\{ 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \right.$$

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

$$\left. \left. \left. + A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \right) \right] \right\}$$

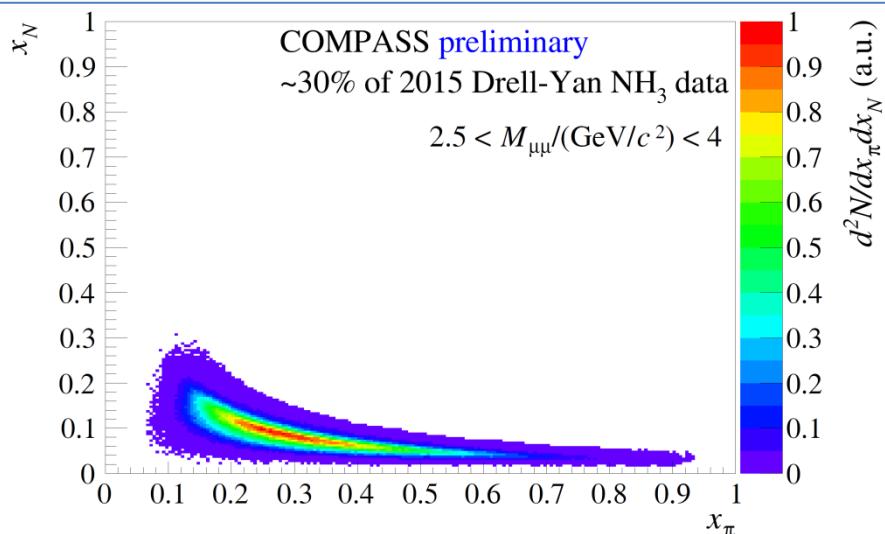
where $D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / (1 + \cos^2 \theta_{CS})$

Good mass resolution $\Delta M \approx 180 \text{ MeV}/c^2$



COMPASS DY J/ ψ -mass range

- $1 < Q^2 / (\text{GeV}/c)^2 < 4$ “Low mass”
 - Large combinatorial background:
Open-charm (bottom) semi-leptonic decays $D\bar{D}$, $B\bar{B}$, pion and kaon decays
 - small asymmetries
- $4 < Q^2 / (\text{GeV}/c)^2 < 6.25$ “Intermediate”
 - High DY-cross section
 - Still low DY-signal/background ratio
- $6.25 < Q^2 / (\text{GeV}/c)^2 < 16$ “J/ ψ ”
 - Strong J/ ψ -signal → study of J/ ψ physics
 - Lower background
- $Q^2 / (\text{GeV}/c)^2 > 16$ “High mass”
 - Low DY cross-section
 - Beyond charmonium region, negligible CB
 - Valence region → largest asymmetries



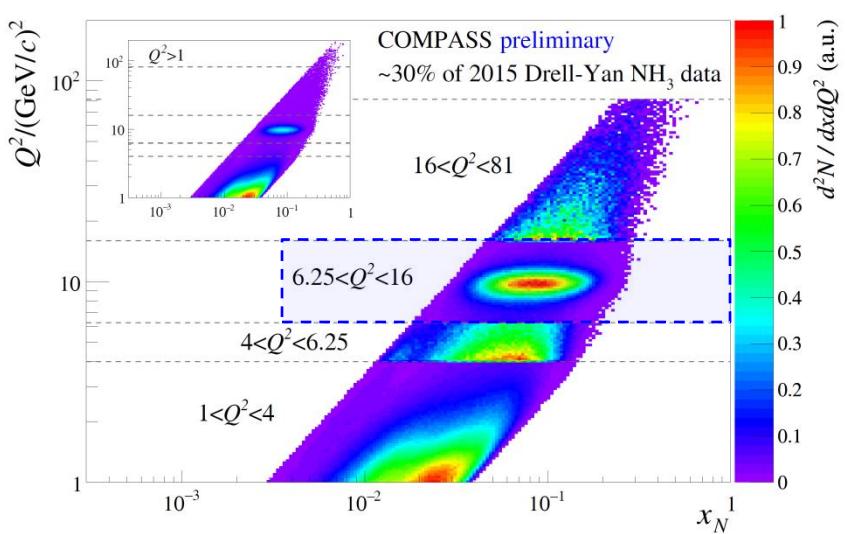
$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left(1 + \cos^2 \theta_{CS} \right)$$

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

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

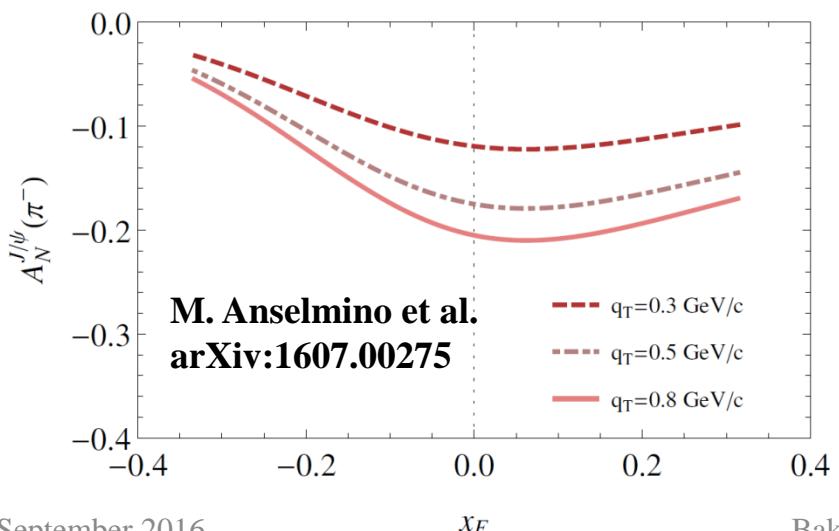
where $D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / (1 + \cos^2 \theta_{CS})$

J/ ψ -region sample is much larger comparing to HM
($\langle x_\pi \rangle \sim 0.3$, $\langle x_N \rangle \sim 0.09$, $\langle x_F \rangle \sim 0.2$, $\langle q_T \rangle \sim 1.0$)



COMPASS DY J/ ψ -mass range

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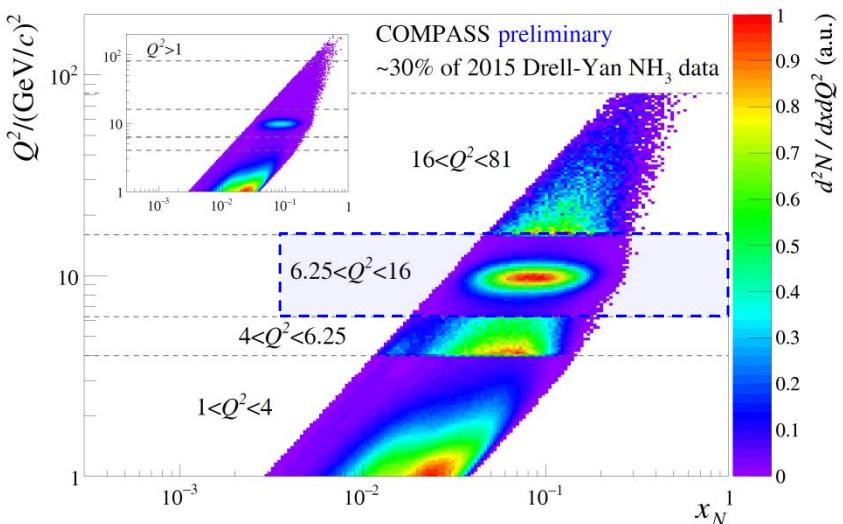
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$$\times \left\{ 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \right.$$

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

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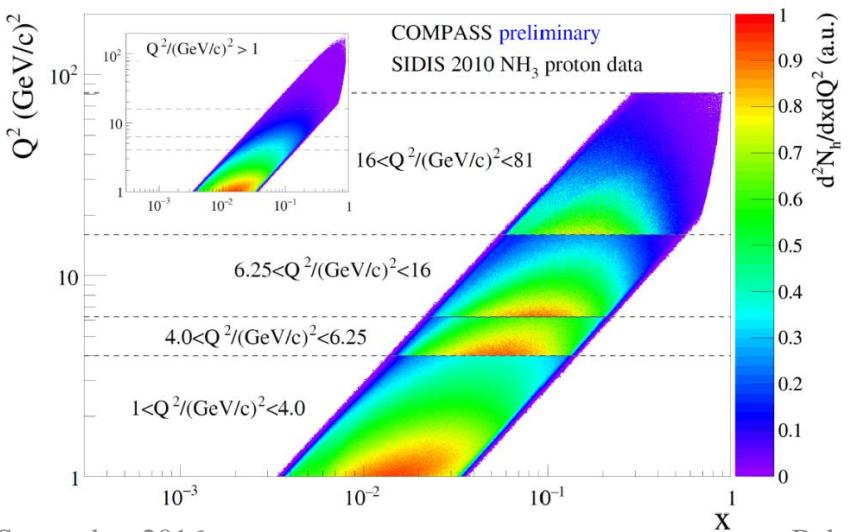




- SIDIS TSAs in COMPASS Drell-Yan mass ranges → towards multi-D

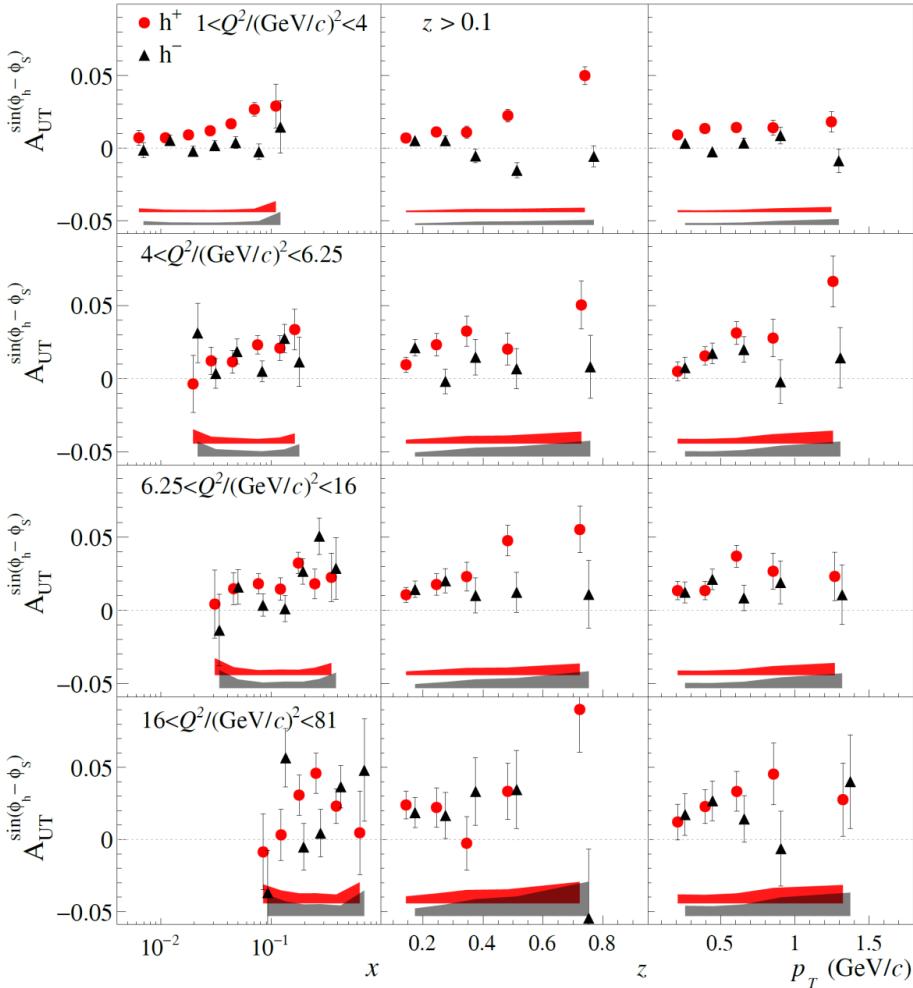
SIDIS Sivers TSA in COMPASS Drell-Yan Q²-ranges

$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_s} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times \left\{ 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \end{array} \right] + S_T \lambda \left[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \right] \right\}$$



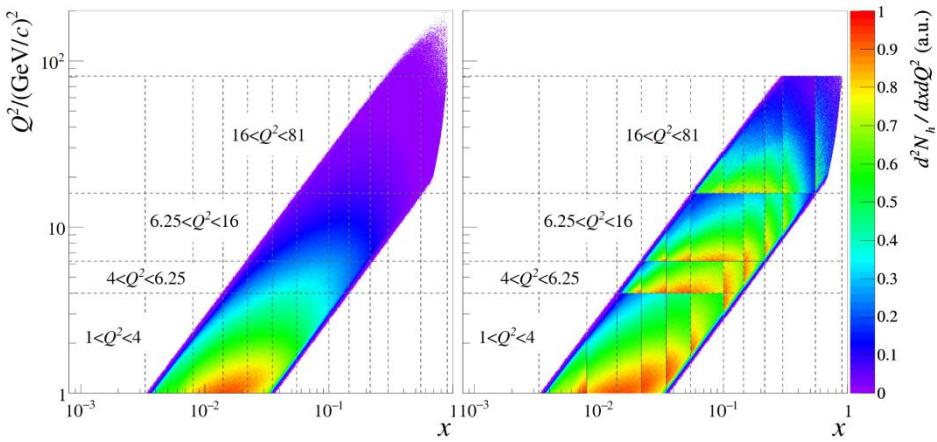
NEW! 23 September 2016

CERN-EP-2016-250, arXiv:1609.07374 [hep-ex]



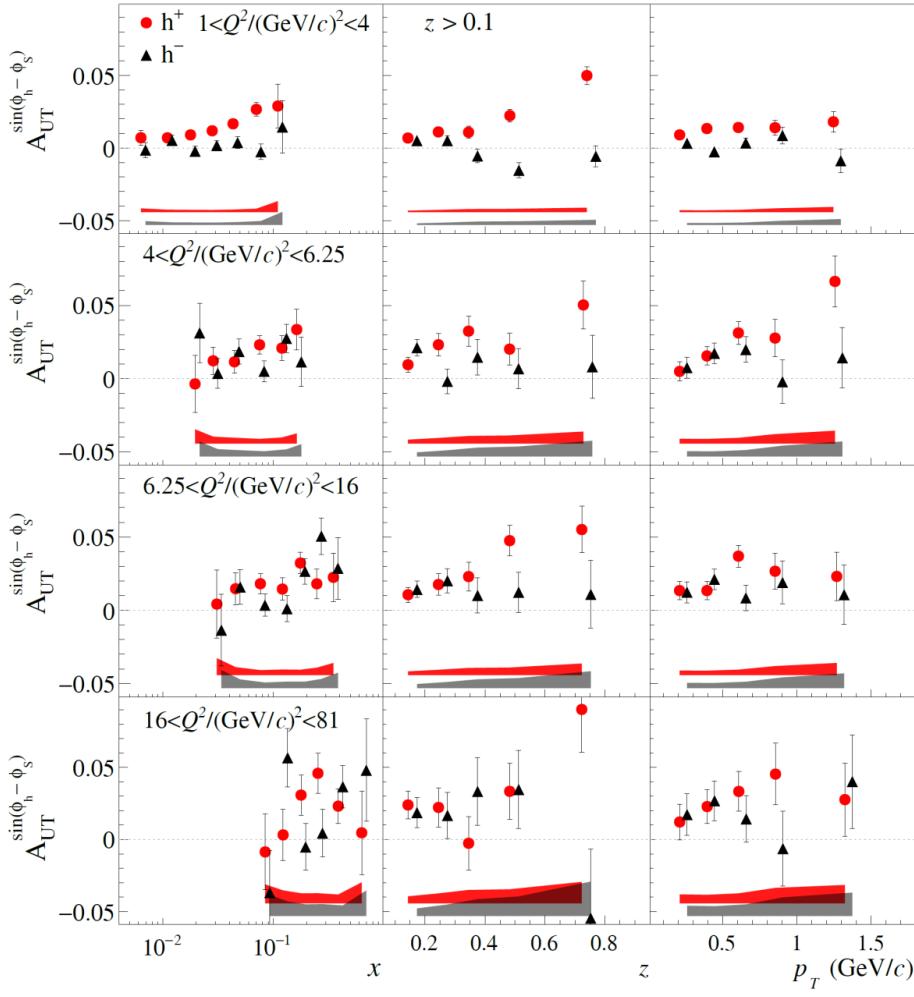
SIDIS Sivers TSA in COMPASS Drell-Yan Q²-ranges

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NEW! 23 September 2016

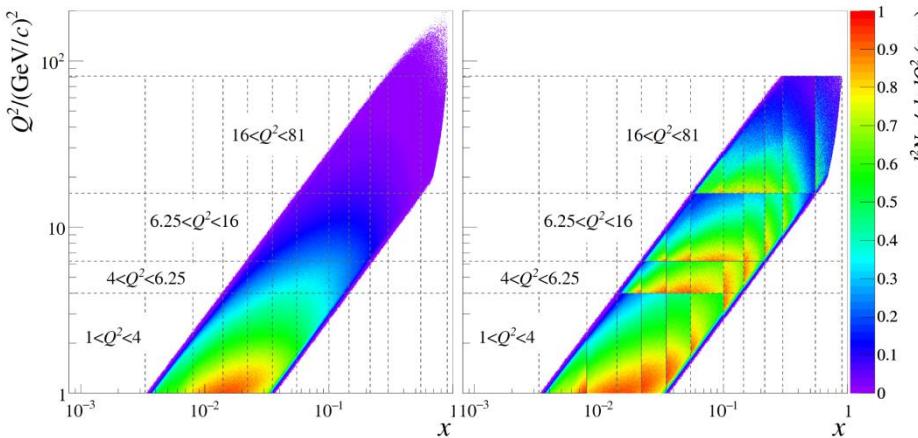
CERN-EP-2016-250, arXiv:1609.07374 [hep-ex]



A multi-dimensional input for TMD evolution studies

SIDIS Sivers TSA in COMPASS Drell-Yan Q²-ranges

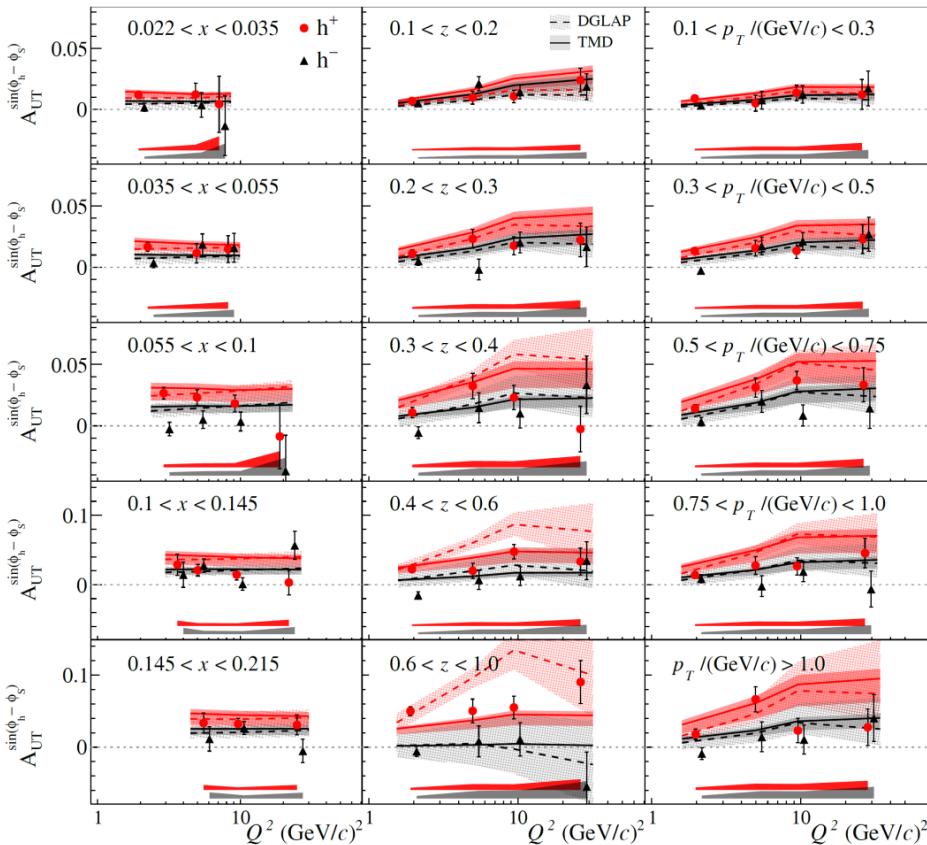
$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_s} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times \left\{ 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + S_T \left[A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) + \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \right] + S_T \lambda \left[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \right] \right\}$$



A multi-dimensional input for TMD evolution studies

NEW! 23 September 2016

[CERN-EP-2016-250](#), arXiv:1609.07374 [hep-ex]



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.



- From COMPASS SIDIS to COMPASS Drell-Yan
(DY high-mass range)

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

$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_s} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times \left\{ \begin{array}{l} 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \end{array} \right] \\ + S_T \lambda \left[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \right] \end{array} \right\}$$

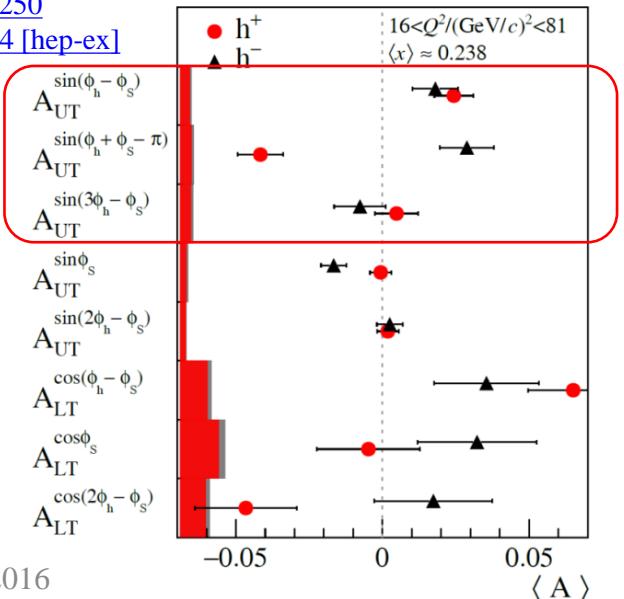
$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left(1 + \cos^2 \theta_{CS} \right) \times \left\{ \begin{array}{l} 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS} \\ + S_T \left[\begin{array}{l} A_T^{\sin \phi_s} \sin \phi_s \\ + D_{[\sin^2 \theta_{CS}]} \left(A_T^{\sin(2\phi_{CS} + \phi_s)} \sin(2\phi_{CS} + \phi_s) \right. \\ \left. + A_T^{\sin(2\phi_{CS} - \phi_s)} \sin(2\phi_{CS} - \phi_s) \right) \end{array} \right] \end{array} \right\}$$

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

NEW! 23 September 2016

CERN-EP-2016-250

arXiv:1609.07374 [hep-ex]



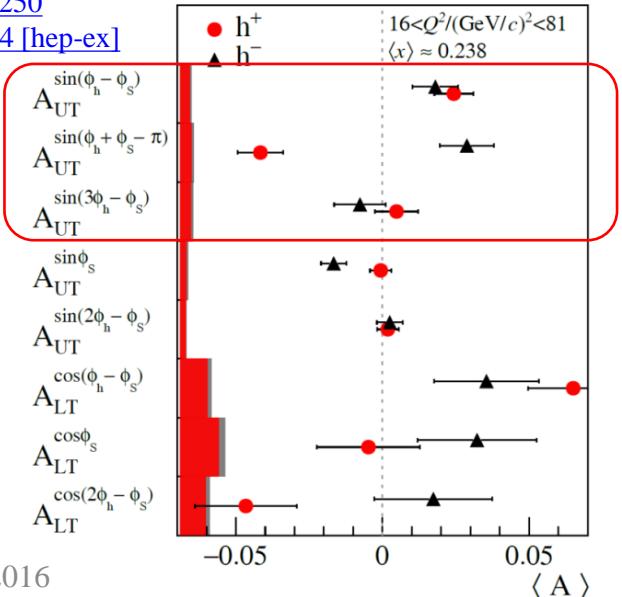
SIDIS and DY TSAs at COMPASS (high-mass range)

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

NEW! 23 September 2016

CERN-EP-2016-250

arXiv:1609.07374 [hep-ex]

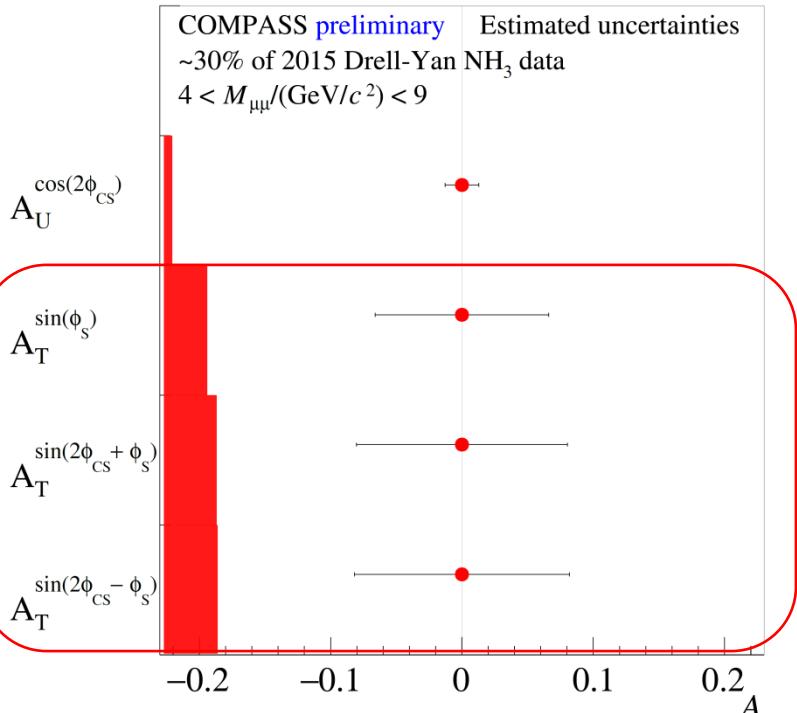


26 September 2016

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left(1 + \cos^2 \theta_{CS} \right) \times \left\{ \begin{array}{l} 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS} \\ + S_T \left[A_T^{\sin \phi_S} \sin \phi_S \right. \\ \left. + D_{[\sin^2 \theta_{CS}]} \left(A_T^{\sin(2\phi_{CS} + \phi_S)} \sin(2\phi_{CS} + \phi_S) \right. \right. \\ \left. \left. + A_T^{\sin(2\phi_{CS} - \phi_S)} \sin(2\phi_{CS} - \phi_S) \right) \right] \end{array} \right\}$$

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

COMPASS preliminary Estimated uncertainties
~30% of 2015 Drell-Yan NH₃ data
 $4 < M_{\mu\mu}/(\text{GeV}/c^2) < 9$

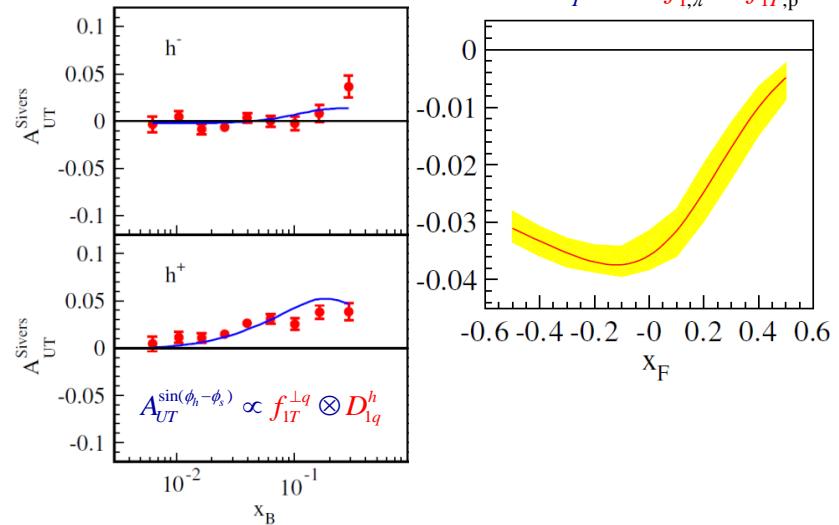


Bakur Parsamyan

Drell-Yan Sivers effect at COMPASS: predictions

M.G. Echevarria, A.Idilbi, Z.B. Kang and I. Vitev,
 "QCD Evolution of the Sivers Asymmetry"

PRD 89 074013 (2014)



$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left(1 + \cos^2 \theta_{CS} \right)$$

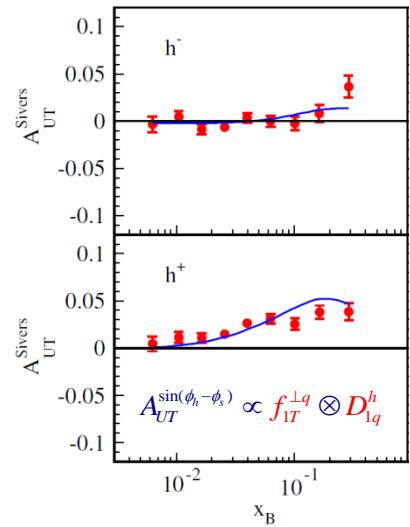
$$\times \left\{ 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS} \right. \\ \left. + S_T \left[A_T^{\sin \phi_S} \sin \phi_S \right. \right. \\ \left. \left. + D_{[\sin^2 \theta_{CS}]} \left(A_T^{\sin(2\phi_{CS} + \phi_S)} \sin(2\phi_{CS} + \phi_S) \right. \right. \right. \\ \left. \left. \left. + A_T^{\sin(2\phi_{CS} - \phi_S)} \sin(2\phi_{CS} - \phi_S) \right) \right] \right\}$$

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

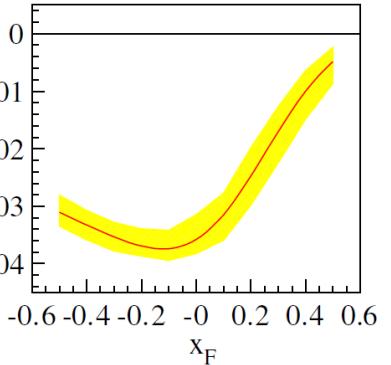
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$$A_T^{\sin\phi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$$



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

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left(1 + \cos^2 \theta_{CS} \right)$$

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

$$\left. + S_T \left[A_T^{\sin \phi_S} \sin \phi_S \right. \right.$$

$$\left. \left. + D_{[\sin^2 \theta_{CS}]} \left(A_T^{\sin(2\phi_{CS} + \phi_S)} \sin(2\phi_{CS} + \phi_S) \right. \right. \right.$$

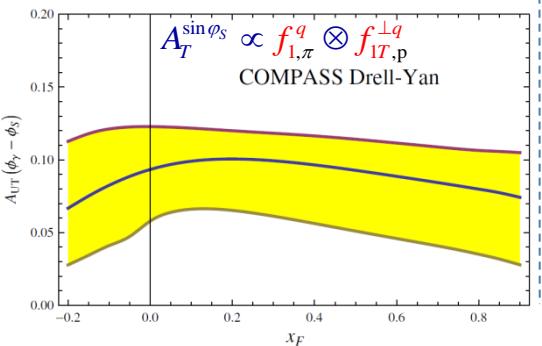
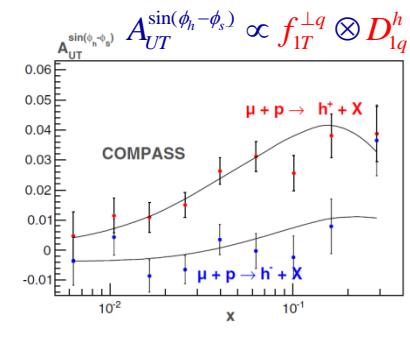
$$\left. \left. \left. + A_T^{\sin(2\phi_{CS} - \phi_S)} \sin(2\phi_{CS} - \phi_S) \right) \right] \right\}$$

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

P. Sun and F. Yuan,

"Transverse momentum dependent evolution: Matching SIDIS processes to Drell-Yan and W/Z boson production".

PRD 88 11, 114012 (2013)

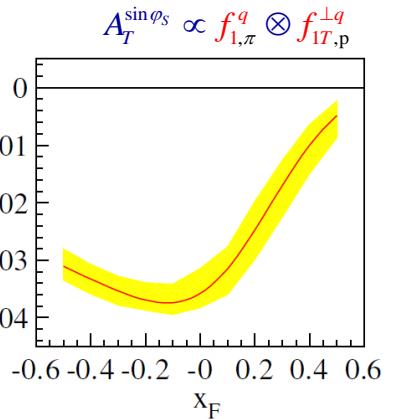
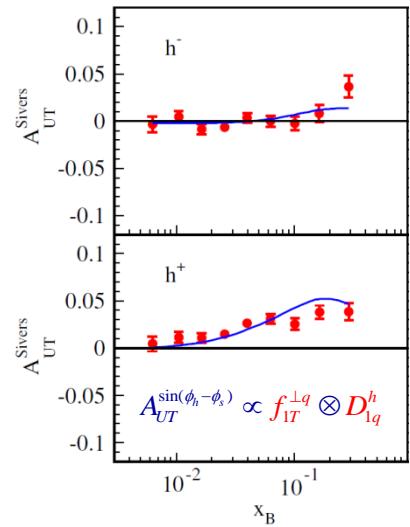


$$A_T^{\sin\phi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$$

Drell-Yan Sivers effect at COMPASS: predictions

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



$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left(1 + \cos^2 \theta_{CS} \right)$$

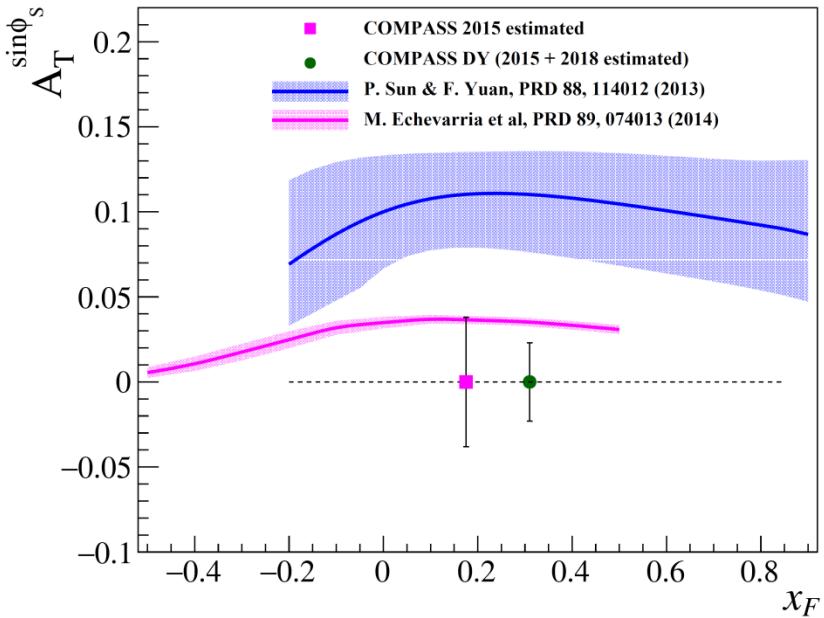
$$\times \left\{ 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS} \right.$$

$$\left. + S_T \left[A_T^{\sin \phi_S} \sin \phi_S \right. \right.$$

$$\left. \left. + D_{[\sin^2 \theta_{CS}]} \left(A_T^{\sin(2\phi_{CS} + \phi_S)} \sin(2\phi_{CS} + \phi_S) \right. \right. \right.$$

$$\left. \left. \left. + A_T^{\sin(2\phi_{CS} - \phi_S)} \sin(2\phi_{CS} - \phi_S) \right) \right] \right\}$$

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

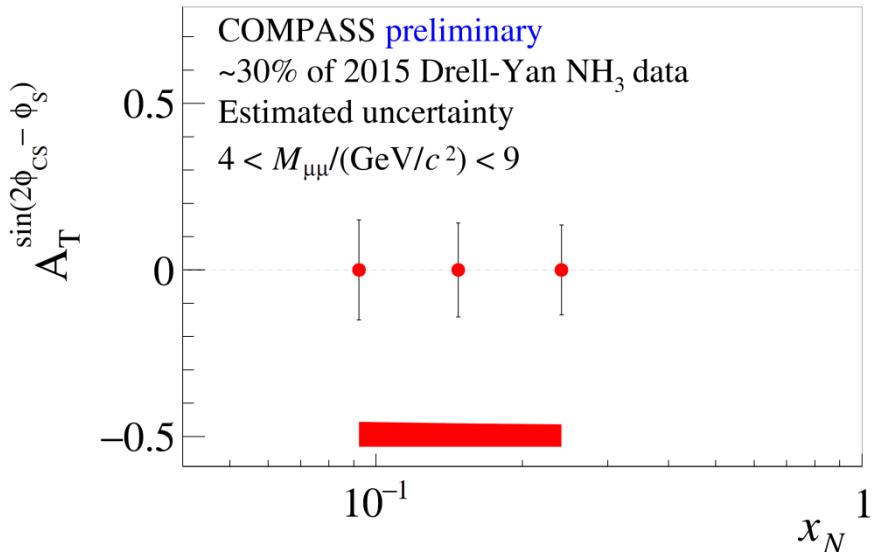
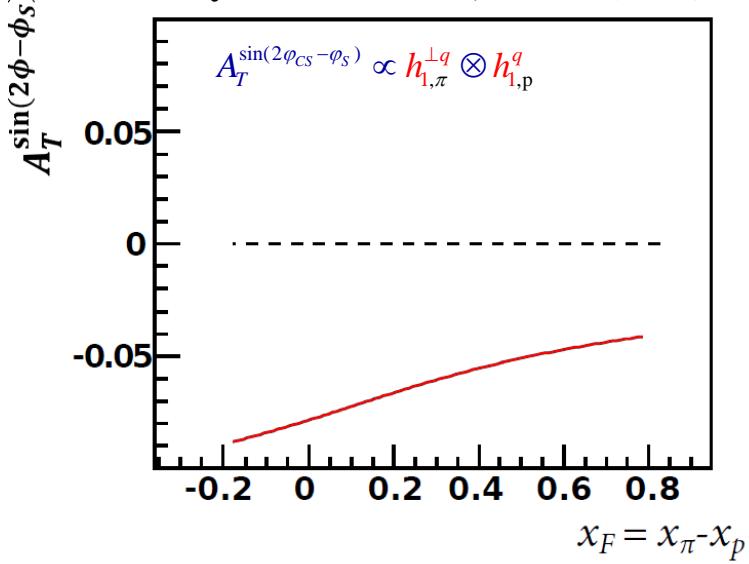


Enough precision to verify the sign-change and to distinguish between different predictions

Drell-Yan Transversity and Petzeloosity at COMPASS



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

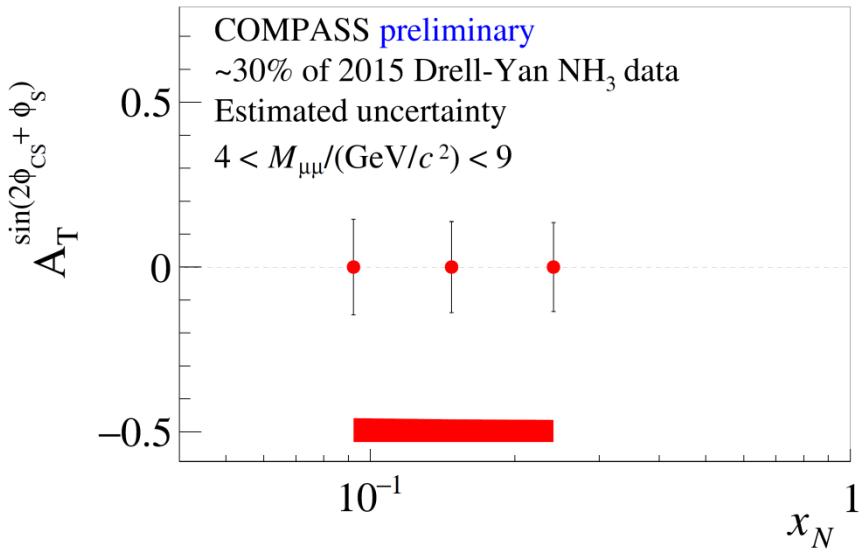


$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left(1 + \cos^2 \theta_{CS} \right)$$

$$A_T^{\sin(2\phi_{CS} - \phi_S)} \propto \left[1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS} \right. \\ \left. + S_T \left[A_T^{\sin \phi_S} \sin \phi_S + D_{[\sin^2 \theta_{CS}]} \left(A_T^{\sin(2\phi_{CS} + \phi_S)} \sin(2\phi_{CS} + \phi_S) \right. \right. \right. \\ \left. \left. \left. + A_T^{\sin(2\phi_{CS} - \phi_S)} \sin(2\phi_{CS} - \phi_S) \right) \right] \right]$$

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

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



Conclusions

- The COMPASS experiment is the only place to explore the transverse spin structure of the nucleon by either SIDIS or DY measurements, using a similar setup.
 - This opens the unique opportunity, when comparing the Sivers TMD PDFs obtained from the two alternative experimental approaches, to test the opposite-sign prediction by QCD at practically the same hard scale, thereby minimizing possible bias introduced by TMD evolution.
- COMPASS has measured SIDIS proton TSAs at Drell-Yan mass-ranges
 - The Sivers and Collins SIDIS-TSAs are measured to be non-zero at high-mass range [CERN-EP-2016-250](#), [arXiv:1609.07374 \[hep-ex\]](#)
 - The pretzelosity SIDIS-TSA is found be compatible with zero
- In 2015 COMPASS has successfully collected first polarized Drell-Yan data
 - COMPASS became the first experiment to measure both SIDIS and Drell-Yan TSAs
 - Also the first and only experiment to measure meson-induced Drell-Yan in past 25 years
 - By now ~30% of collected raw data has been processed/analyzed. Work is ongoing.
 - Preliminary results are expected by the end of the 2016.
 - Expected statistical accuracy of Sivers asymmetry should allow to test sign-change and possibly to study the effect in several kinematical bins.
 - Several important studies are ongoing also for the polarization-independent part of the DY cross-section (see talk by Luis Silva)
- A second year of data-taking is planned for 2018. To be approved.
- COMPASS Drell-Yan program is being discussed to continue in phase-III (see talk by V. Andrieux)

Thank you!



Spare slides

Nucleon TMD PDFs accessed in SIDIS and DY

SIDIS

$$\begin{aligned}
 A_{UU}^{\cos\phi_h} &\propto Q^{-1} \left(f_1^q \otimes D_{1q}^h \rightarrow h_1^{\perp q} \otimes H_{1q}^{\perp h} + \dots \right) \\
 A_{UU}^{\cos 2\phi_h} &\propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + Q^{-1} \left(f_1^q \otimes D_{1q}^h + \dots \right) \\
 A_{UT}^{\sin(\phi_h - \phi_s)} &\propto f_{1T}^{\perp q} \otimes D_{1q}^h \\
 A_{UT}^{\sin(\phi_h + \phi_s)} &\propto h_1^q \otimes H_{1q}^{\perp h} \\
 A_{UT}^{\sin(3\phi_h - \phi_s)} &\propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} \\
 A_{LT}^{\cos(\phi_h - \phi_s)} &\propto g_{1T}^q \otimes D_{1q}^h \\
 A_{UT}^{\sin(\phi_s)} &\propto Q^{-1} \left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \dots \right) \\
 A_{UT}^{\sin(2\phi_h - \phi_s)} &\propto Q^{-1} \left(h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \dots \right) \\
 A_{LT}^{\cos(\phi_s)} &\propto Q^{-1} \left(g_{1T}^q \otimes D_{1q}^h + \dots \right) \\
 A_{LT}^{\cos(2\phi_h - \phi_s)} &\propto Q^{-1} \left(g_{1T}^q \otimes D_{1q}^h + \dots \right)
 \end{aligned}$$

Single polarized DY (LO)

$$\begin{aligned}
 A_U^{\cos 2\phi_{CS}} &\propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q} \\
 A_T^{\sin \varphi_S} &\propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q} \\
 A_T^{\sin(2\phi_{CS} - \varphi_S)} &\propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^q \\
 A_T^{\sin(2\phi_{CS} + \varphi_S)} &\propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}
 \end{aligned}$$

Sivers

Transversity

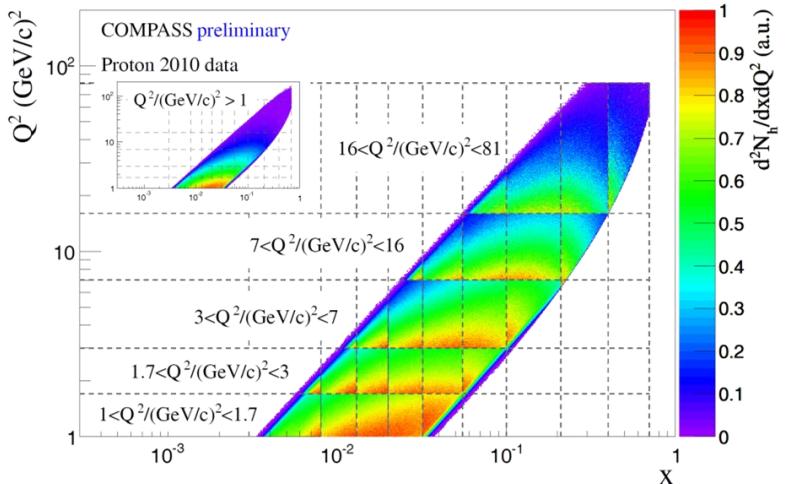
Pretzelosity

All the answers are encoded in the data...
 In few years many new asymmetries
 measured by different experiments in
 different reactions, at different energies
 and kinematical ranges will wait for a
 “global analysis”...

SIDIS x-section

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

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

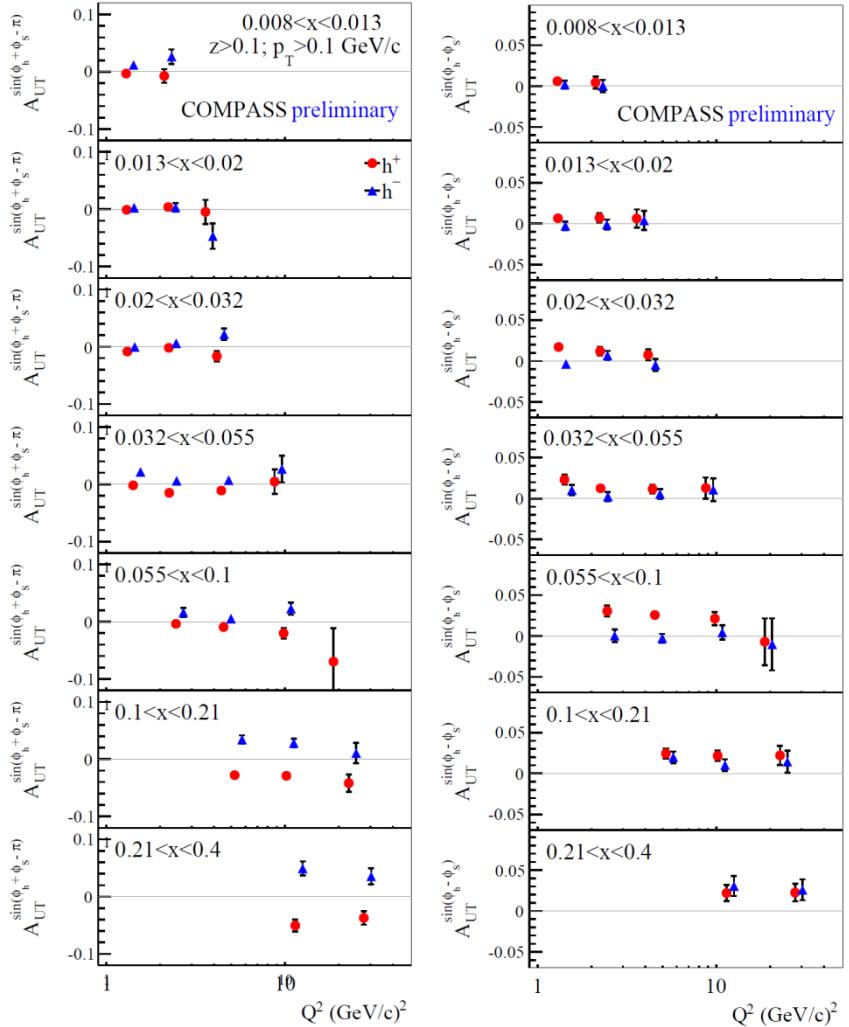


$$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$

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

SSA [twist-2] 
SSA [twist-2]

Results first shown at the SPIN-2014 conference [arXiv:1504.01599 \[hep-ex\]](https://arxiv.org/abs/1504.01599)



No clear Q^2 -dependence of the Sivers and Collins TSAs within statistical accuracy.
Some hints for a possible decreasing trend of Sivers TSA