SIDIS and Drell-Yan transverse spin physics programmes at COMPASS experiment

UNIVERSITÀ DEGLI STUDI DI TORINO

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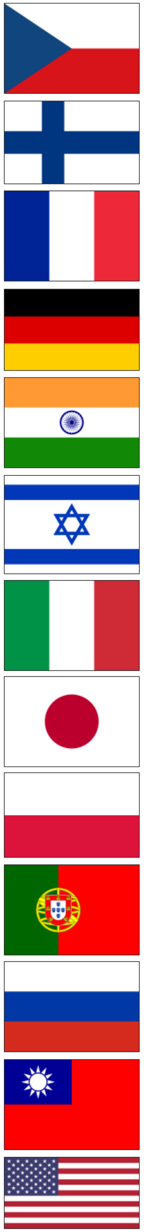
on behalf of the COMPASS Collaboration

7th Workshop of the APS Topical Group on Hadronic Physics

Washington, DC, U.S.

February 1-3, 2017

COMPASS collaboration



24 institutions from 13 countries – nearly 250 physicists

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

Fixed target high-energy experiment at CERN SPS (north area)
Wide physics program

COMPASS-I

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

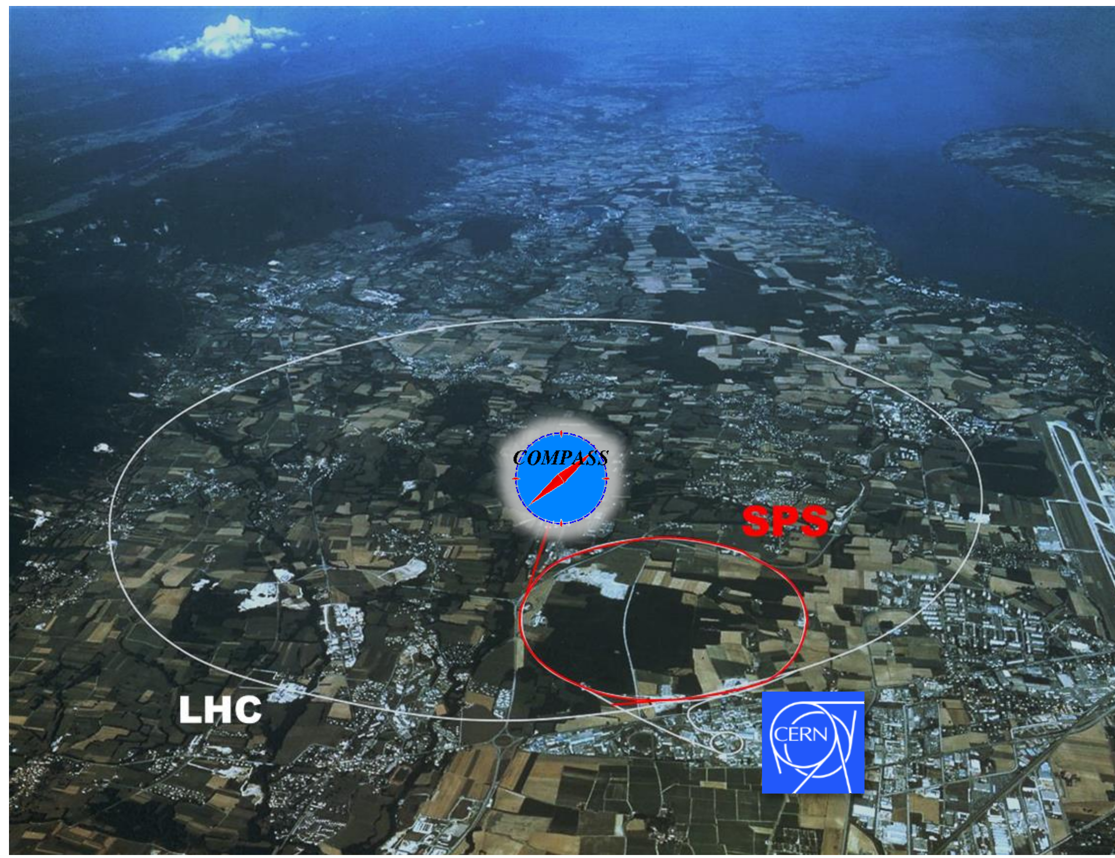
COMPASS-II

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

COMPASS-III under discussion

- **Data taking: beyond 2020**
- **SIDIS, Drell-Yan, DVCS…**

"COMPASS beyond 2020" workshop
CERN, Switzerland, March 2016
"Physics Beyond Colliders" workshop
CERN, Switzerland, September 2016
"IWHSS-2017", COMPASS-workshop
Cortona, Italy, April 2017



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

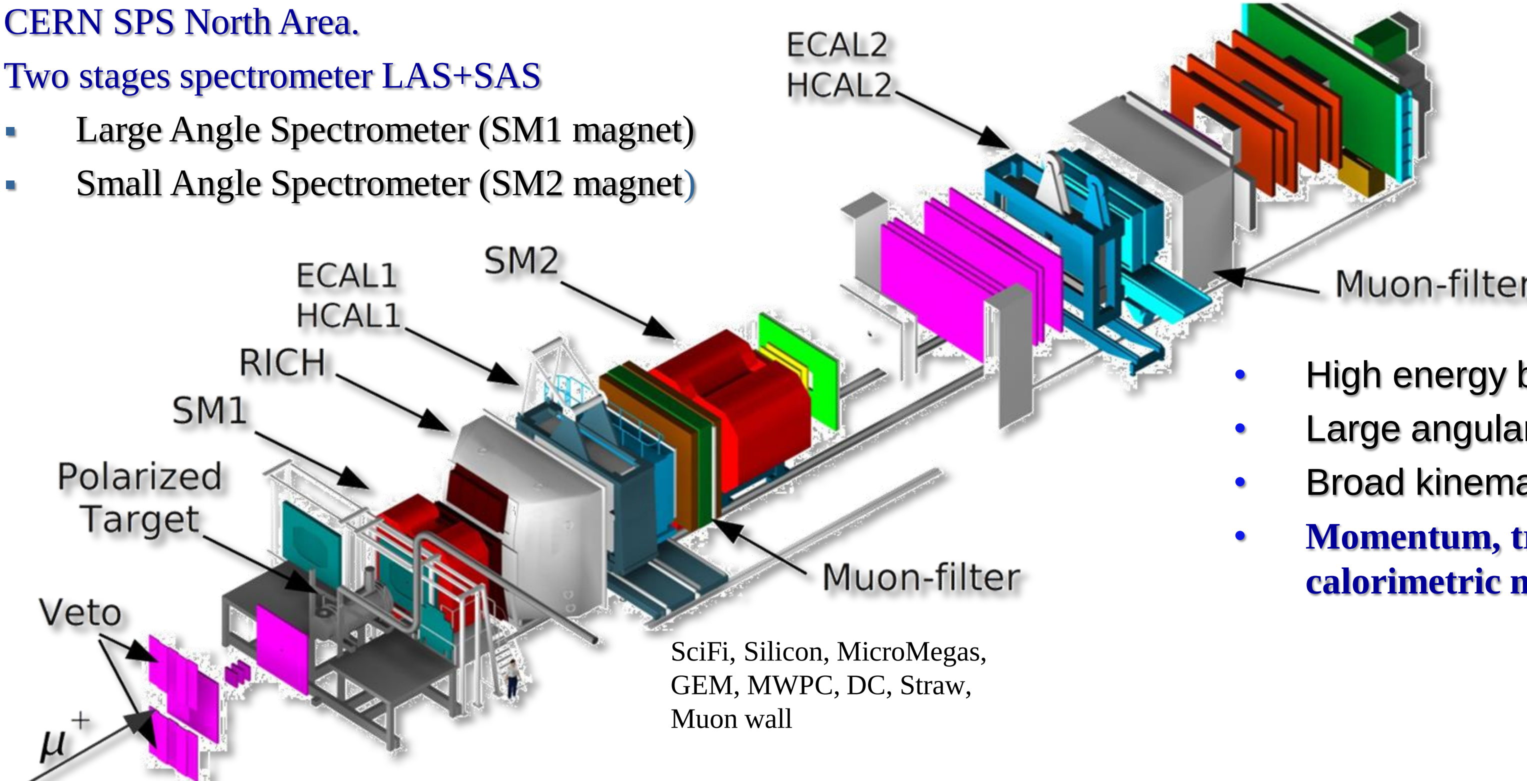
COMPASS experimental setup: Phase I (muon program)

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)



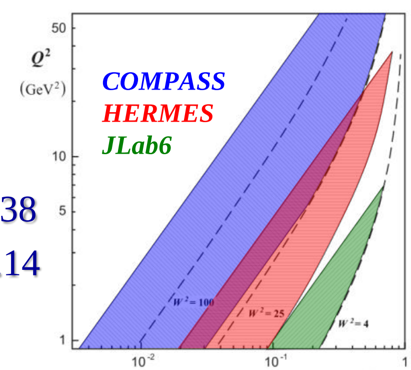
- High energy beam
- Large angular acceptance
- Broad kinematical range
- **Momentum, tracking and calorimetric measurements, PID**

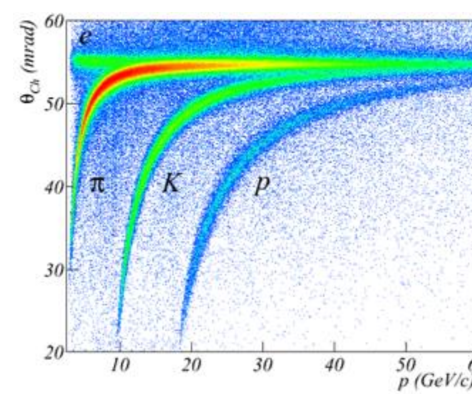
Longitudinally polarized (80%) μ^+ beam:
Energy: 160/200 GeV/c, Intensity: $2 \cdot 10^8$ μ^+/spill (4.8s).

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

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

Data-taking years: 2002-2011





COMPASS experimental setup: Phase II (DY program)

COmmon Muon Proton Apparatus for Structure and Spectroscopy

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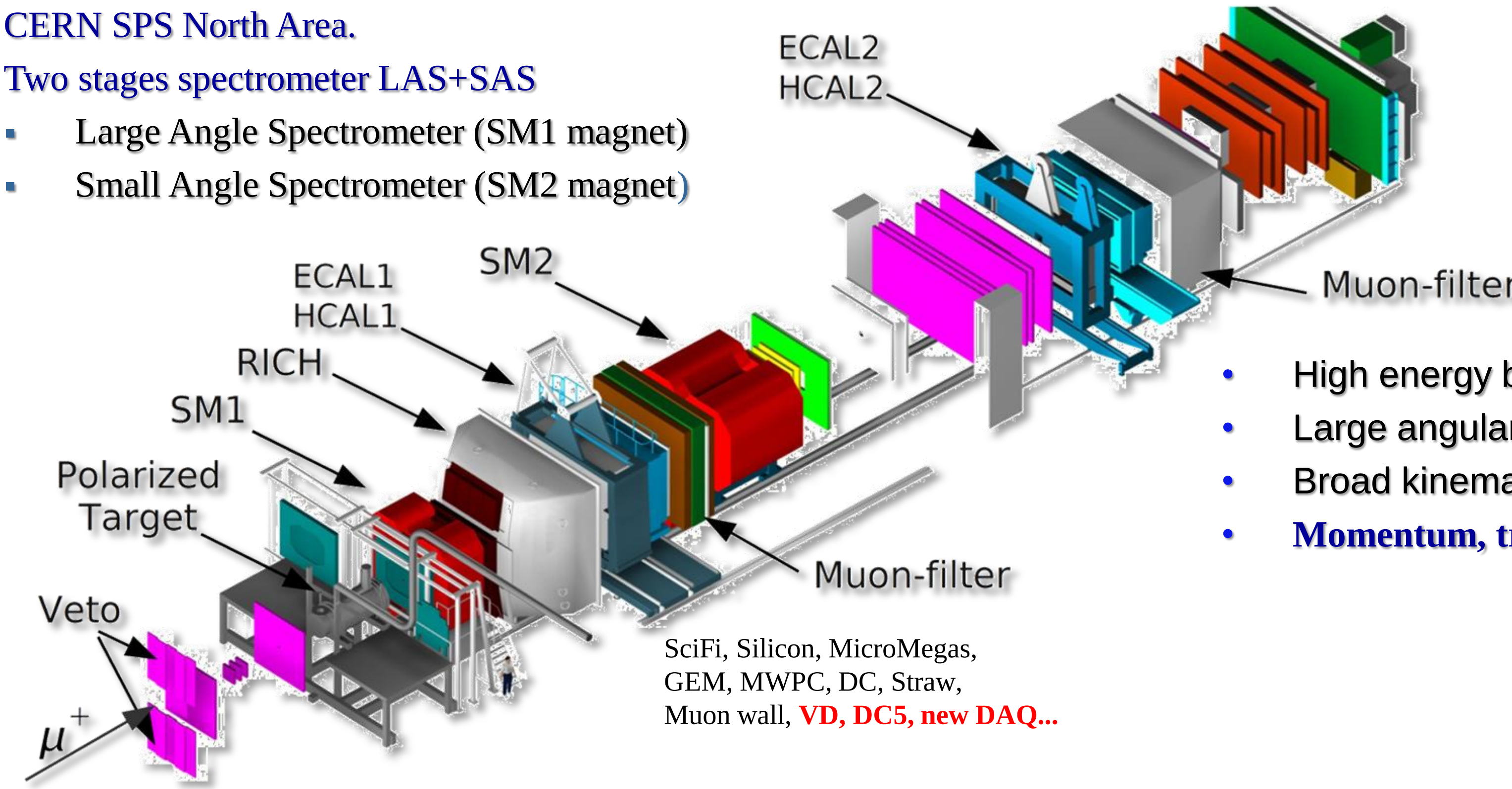
- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)



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

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

Target: Solid state

- NH_3 2-cell configuration. Polarization T ~ 80%, f ~ 0.22
- Data is collected simultaneously for the two target spin orientations. Periodic polarization reversal to minimize systematic effects

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

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)
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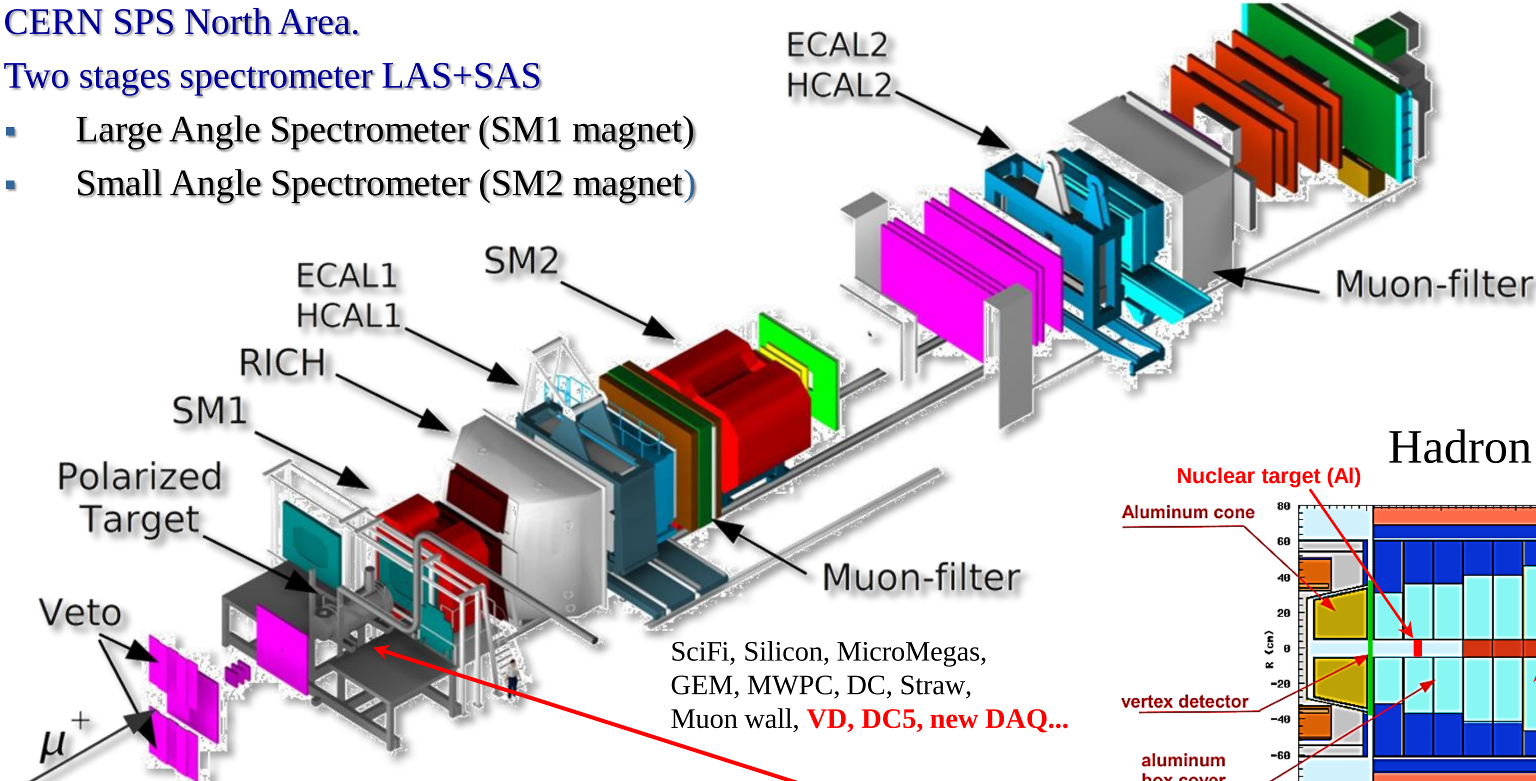
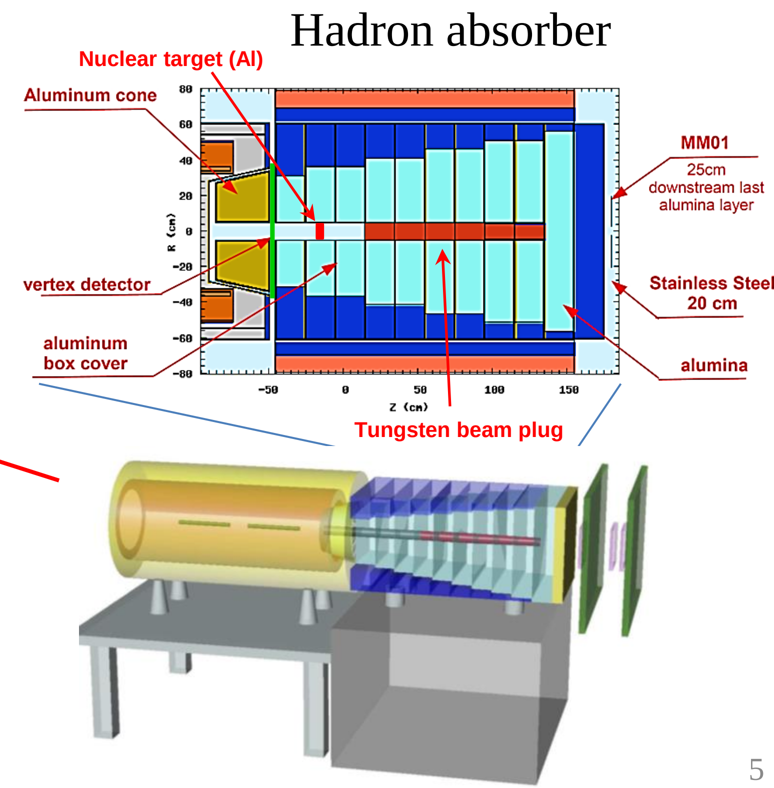


SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon wall, **VD, DC5, new DAQ...**



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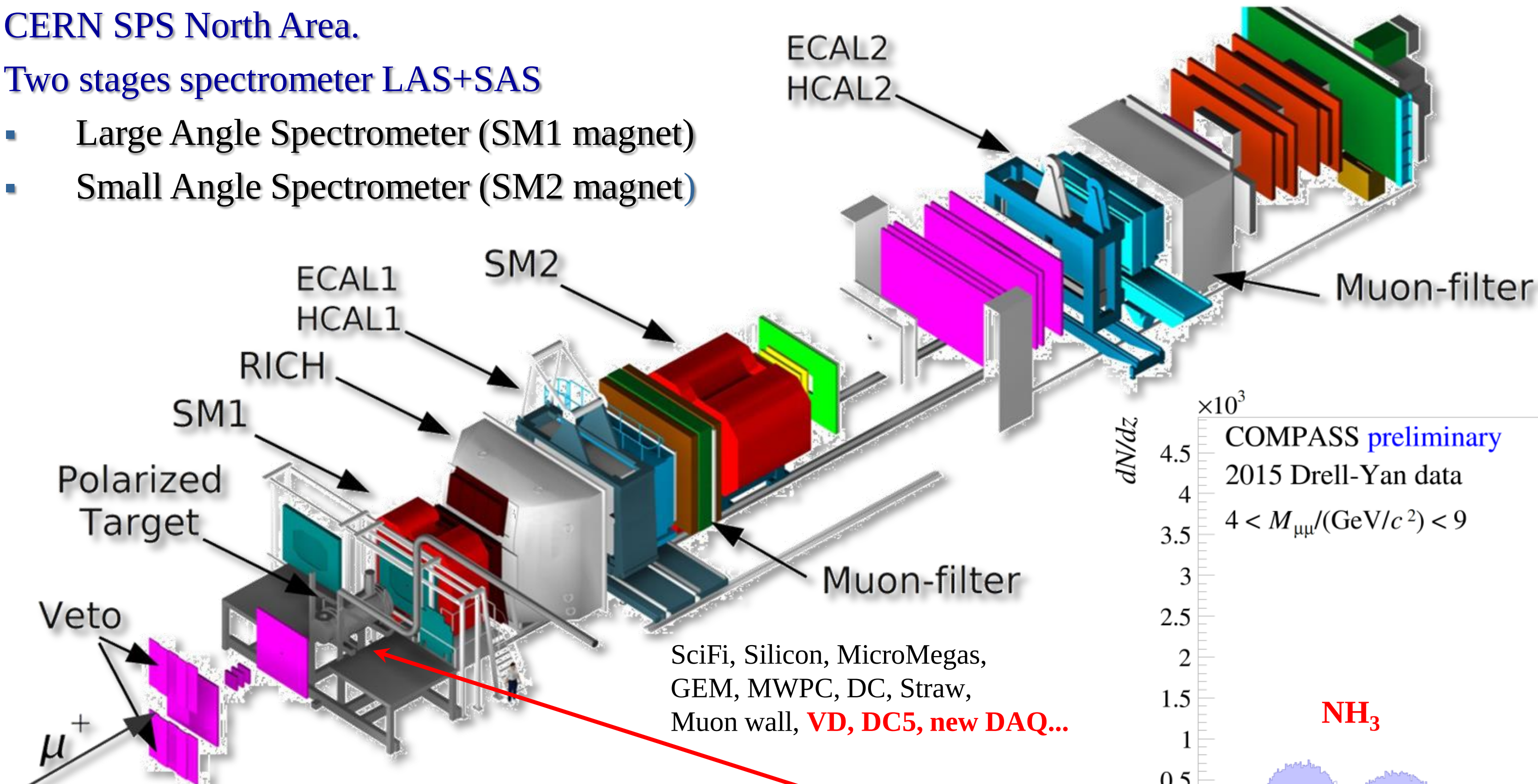

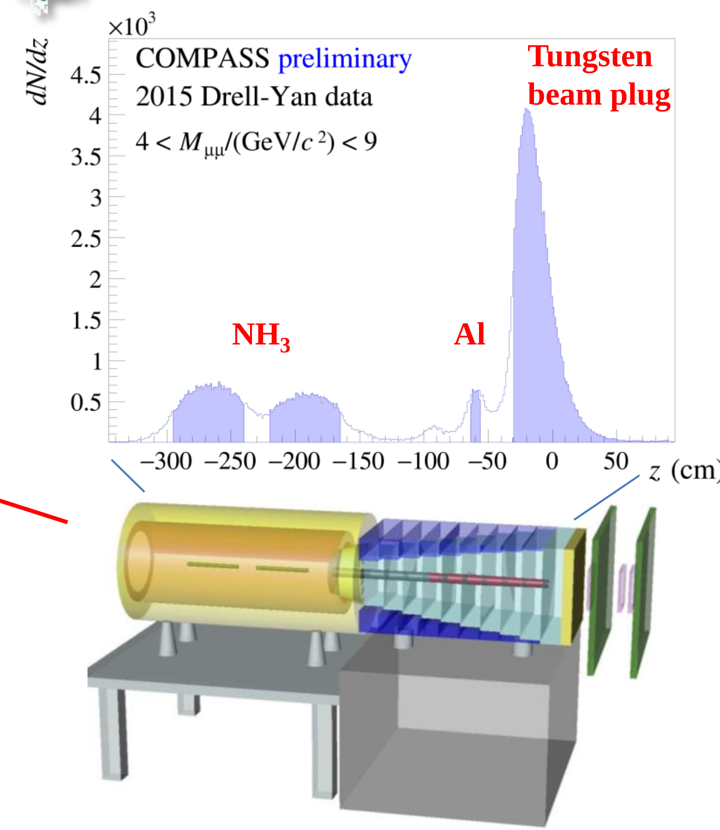

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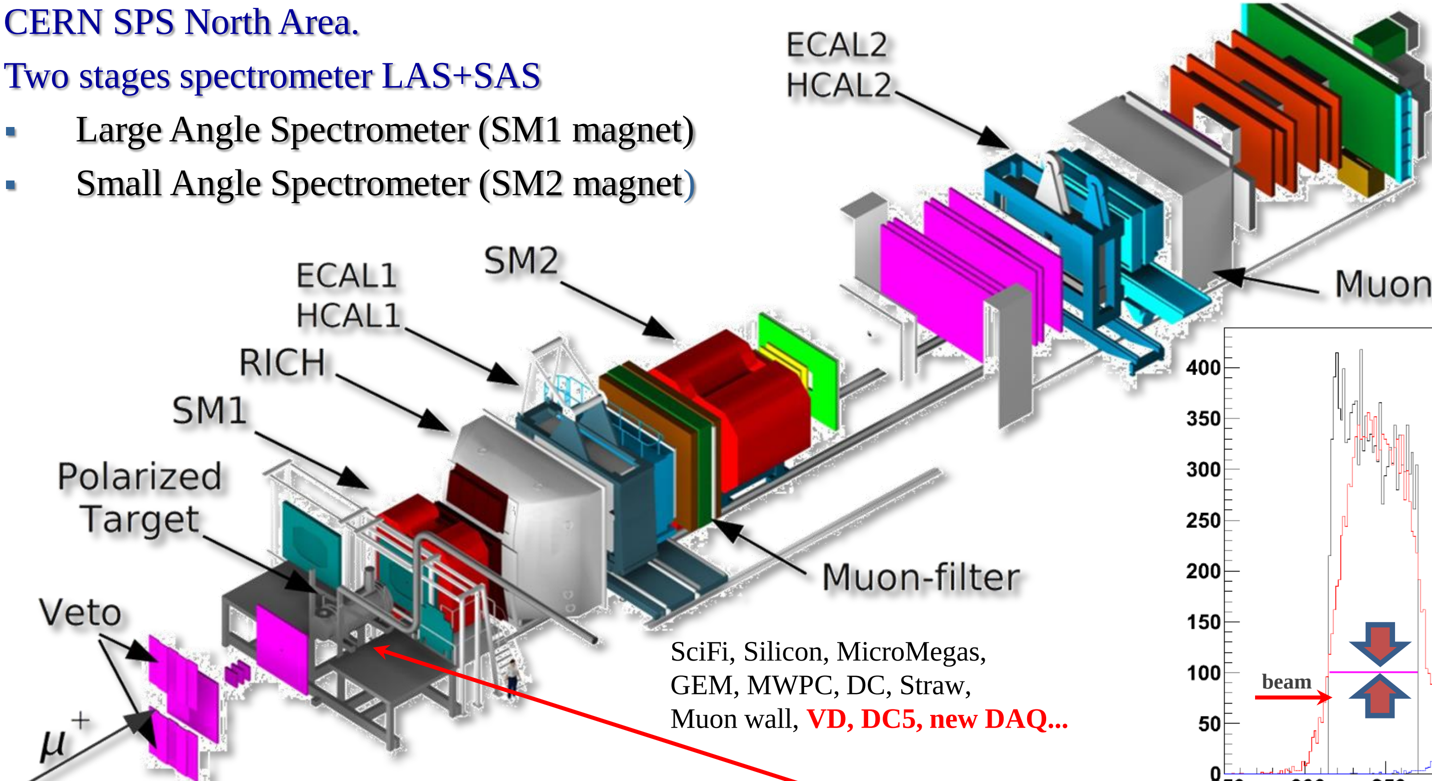

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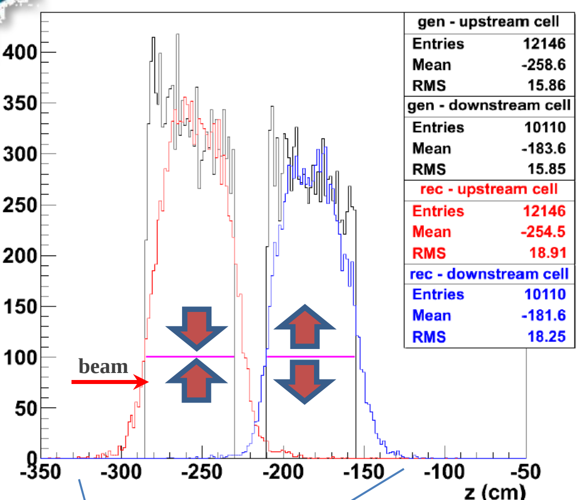

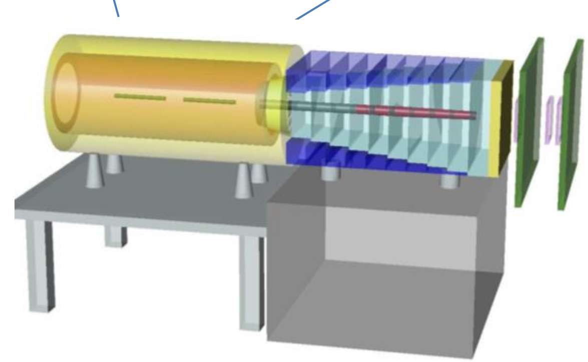

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Data-taking years: 2014(test), 2015, 2018

- SIDIS x-section

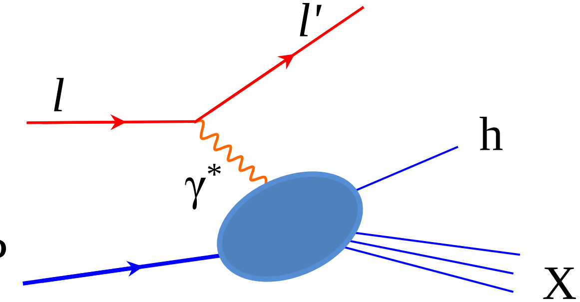
SIDIS x-section

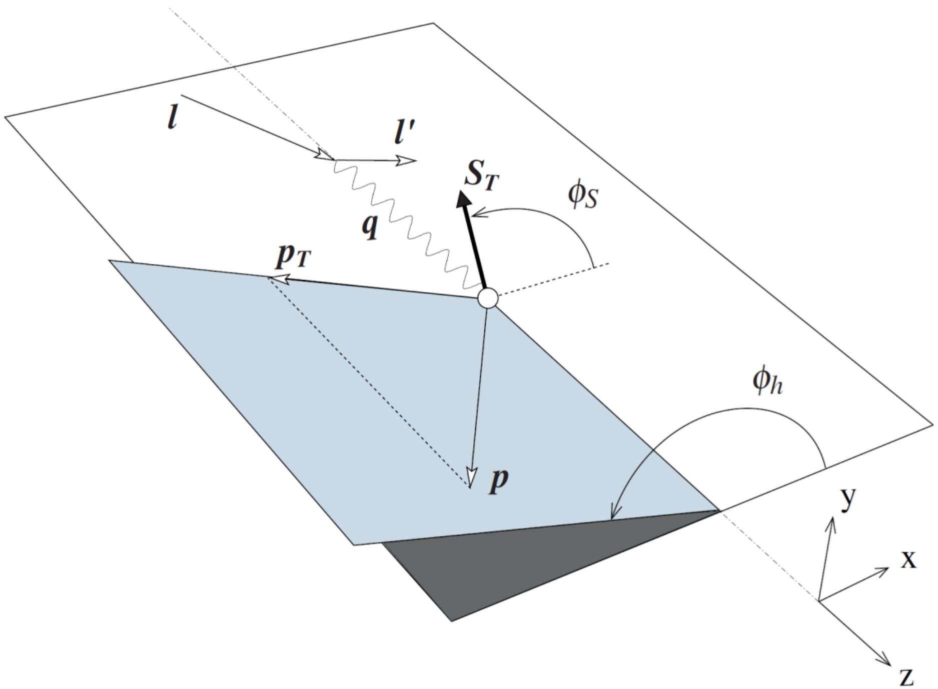
A.Kotzinian, Nucl. Phys. B441, 234 (1995).
Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel JHEP 0702:093 (2007).

All measured by COMPASS

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

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





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

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

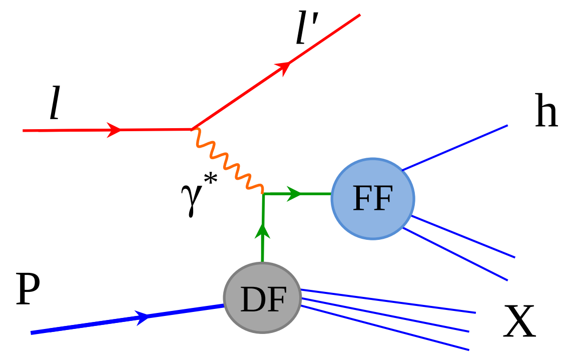
$$\times \Bigg\{ 1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h + \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h$$

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

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

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

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



Nucleon \ Quark	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	$h_1^q(x,\mathbf{k}_T^2)$ transversity $h_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ pretzelosity

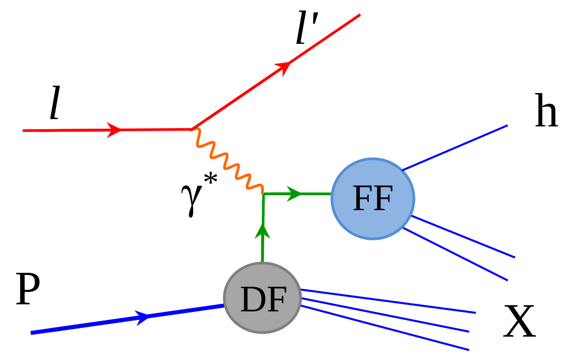
+ two FFs: $D_{1q}^h(z,P_\perp^2)$ and $H_{1q}^{\perp h}(z,P_\perp^2)$

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

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



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

spin of the nucleon   spin of the quark k_T

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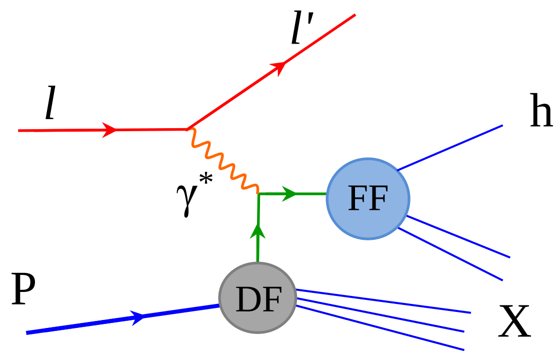
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

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



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

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

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

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

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

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

Twist-2

Twist-3

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

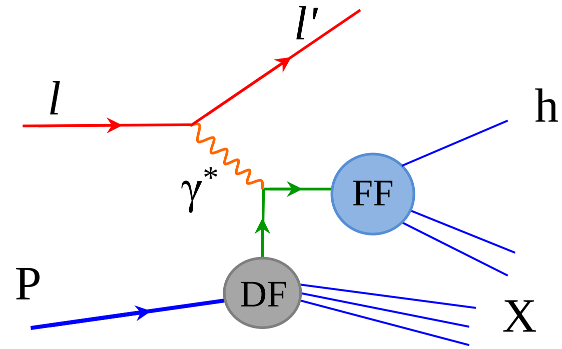
$$\times \Bigg\{ 1 + \sqrt{2\varepsilon(1+\varepsilon)}\,A_{UU}^{\cos\phi_h}\cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h + \lambda\sqrt{2\varepsilon(1-\varepsilon)}\,A_{LU}^{\sin\phi_h}\sin\phi_h$$

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

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

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

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



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

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

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

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

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

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

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

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

Twist-2

Twist-3

- Selected former measurements

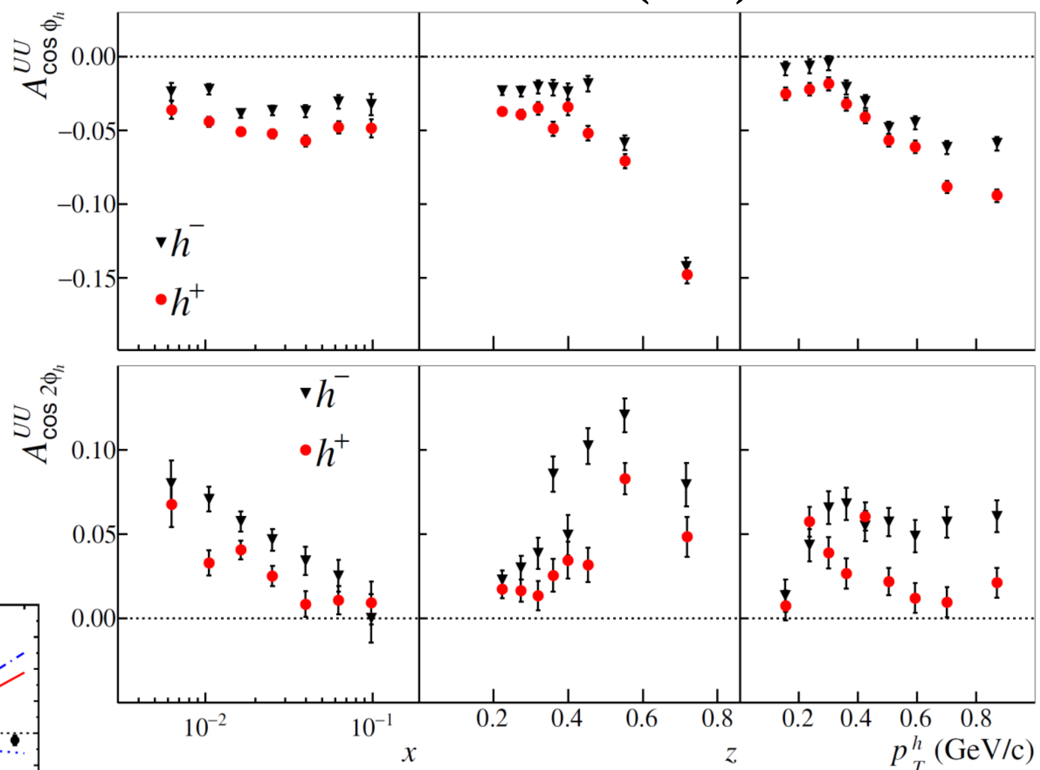
The $A_{UU}^{\cos\phi_h}$ and $A_{UU}^{\cos 2\phi_h}$ asymmetries (Cahn+BM)

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

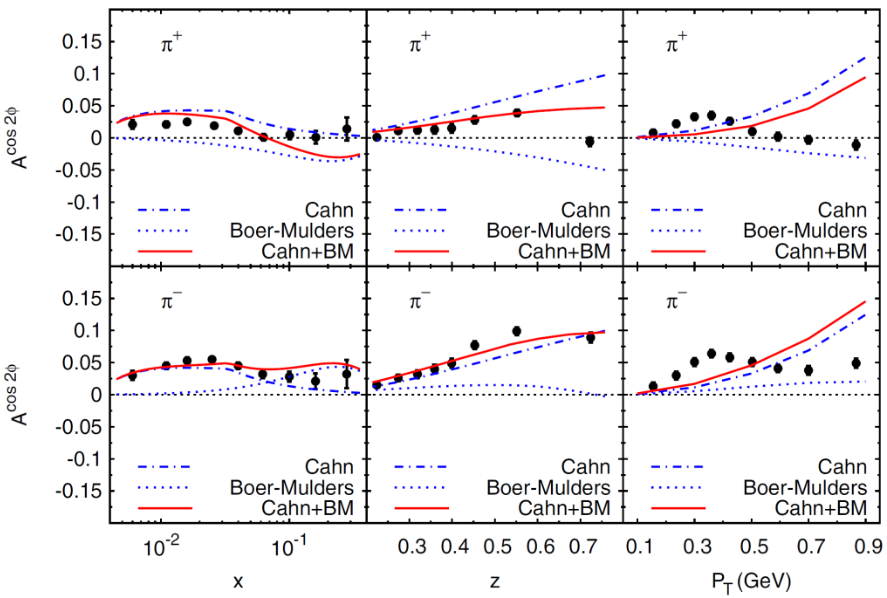
$$\times \begin{Bmatrix} 1 + \sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\ + \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h \end{Bmatrix}$$

- Complicated mixture Cahn+BM
- Large effects both for h^+ and h^-
- Multi-D results available HERMES P/D COMPASS D and currently also P (DVCS)
- Global Cahn+BM fit attempts see f.i. PRD91,074019 (2015)

COMPASS **NPB 886 (2014) 1046**



V. Barone, S. Melis, A. Prokudin, **PRD 81,** 114026 (2010)



$$A_{UU}^{\cos\phi_h} \propto \frac{2M}{Q}\left\{-f_1^q \otimes D_{1q}^h - h_1^{\perp q} \otimes H_{1q}^{\perp h}\right\}$$

$$A_{UU}^{\cos 2\phi_h} \propto -h_1^{\perp q} \otimes H_{1q}^{\perp h} + \left(\frac{M}{Q}\right)^2 f_1^q \otimes D_{1q}^h + \ldots.$$

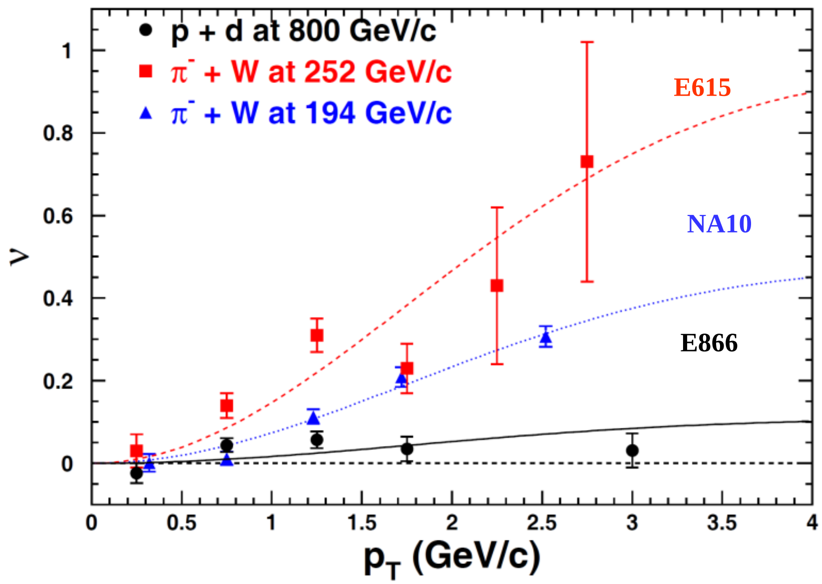
Unpolarized Drell-Yan

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

$$\lambda = A_U^1, \mu = A_U^{\cos\phi_{CS}}, \nu = 2A_U^{\cos 2\phi_{CS}}$$

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

Experimentally observed large ν and violation of the LT-relation →
non-perturbative QCD effects, BM TMD PDF
or



- Clear effect also in Drell-Yan
- Energy and quark flavour dependence
  - Smaller effect for sea quarks

Unpolarized Drell-Yan

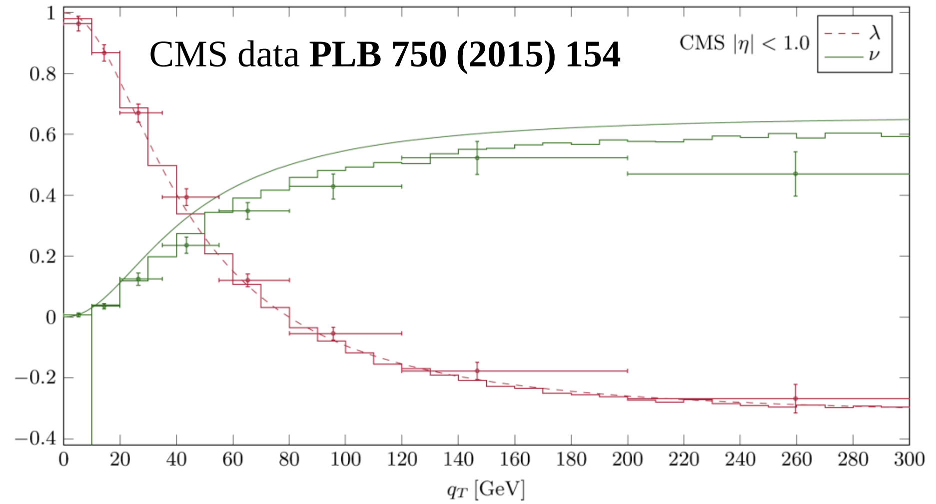
$$\frac{d\sigma}{d\Omega} \propto \left(F_U^1 + F_U^2\right)\left\{1 + A_U^1 \cos^2\theta_{CS} + \sin 2\theta_{CS} A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + \sin^2\theta_{CS} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}\right\}$$

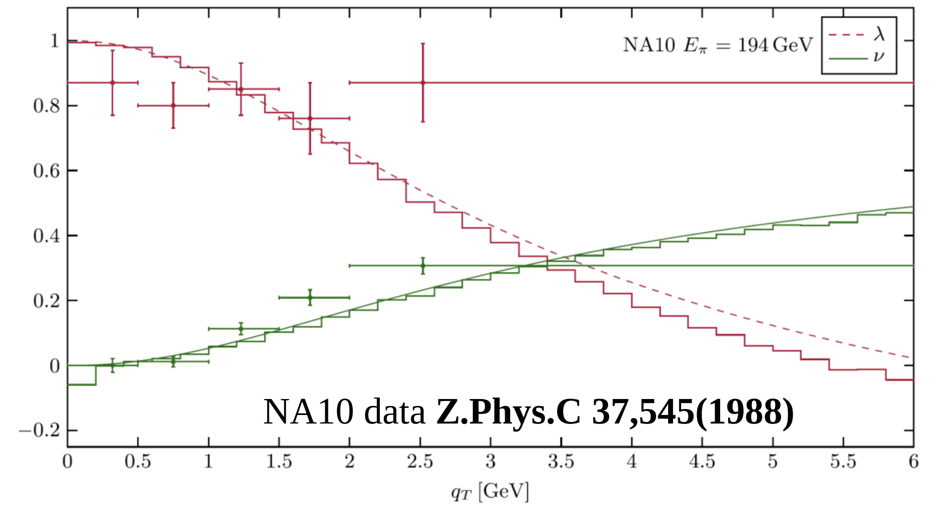
$$\lambda = A_U^1, \mu = A_U^{\cos\phi_{CS}}, \nu = 2A_U^{\cos 2\phi_{CS}}$$

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

Experimentally observed large ν and violation of the LT-relation →
non-perturbative QCD effects, BM TMD PDF
or
QCD radiative effects? NLO QCD description?
M. Lambertsen and W. Vogelsang **PRD93, 114013 (2016)**
J.-C. Peng. et al. **PLB 758 (2016) 384**

Long waited input!
In 2015 COMPASS collected -NH_3, -W, -Al data
First and only experiment to measure meson-induced Drell-Yan in past 25 years.





Unpolarized Drell-Yan

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

$$\lambda = A_U^1, \mu = A_U^{\cos\phi_{CS}}, \nu = 2A_U^{\cos 2\phi_{CS}}$$

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

Experimentally observed large ν and violation of the LT-relation →
non-perturbative QCD effects, BM TMD PDF
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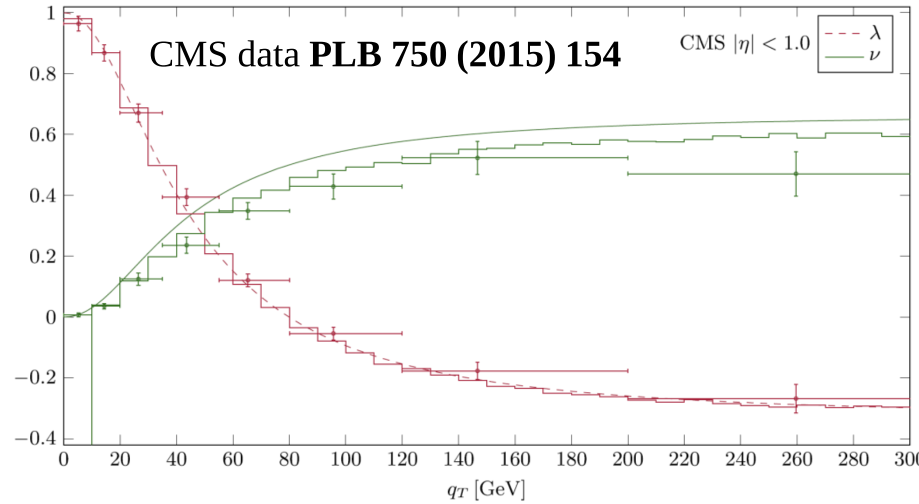
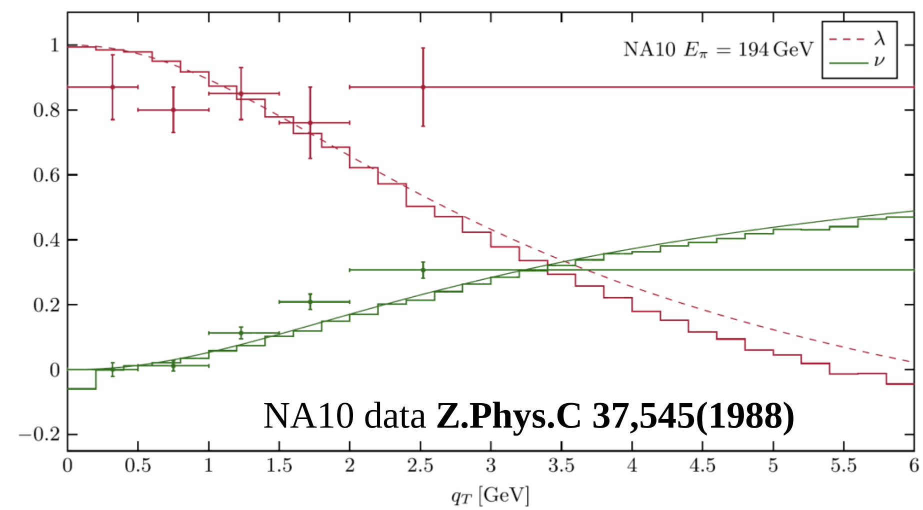
QCD radiative effects? NLO QCD description?
M. Lambertsen and W. Vogelsang **PRD93, 114013 (2016)**
J.-C. Peng. et al. **PLB 758 (2016) 384**



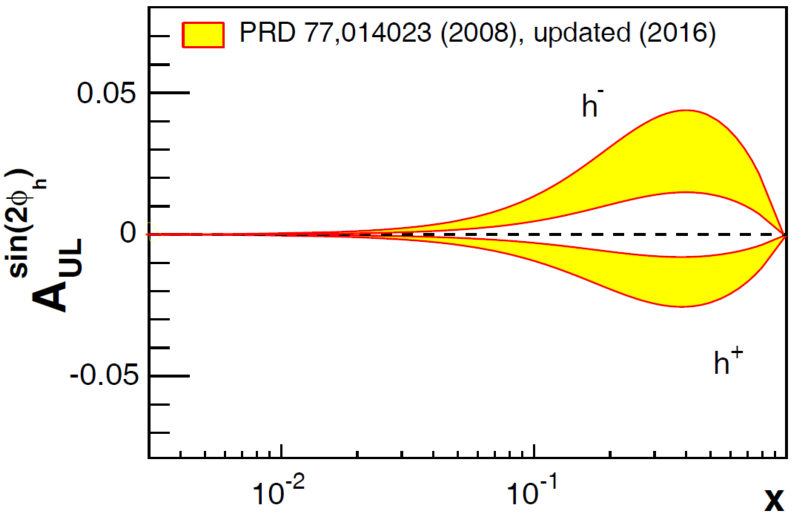


Ideas for COMPASS-III (>2020)
Unpolarized/polarized Drell-Yan measurements with RF-separated kaon and antiproton beams and proton/deuteron targets.

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

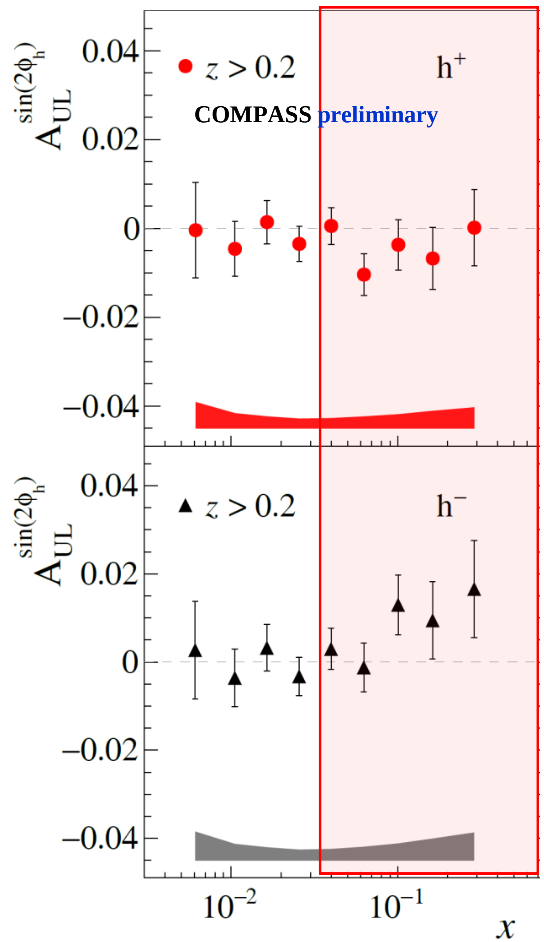
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L\,\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h + \ldots\right\}$$

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

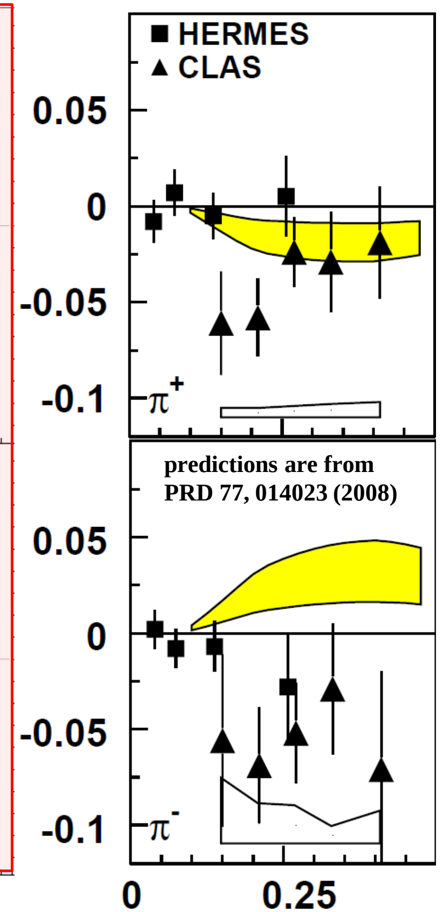


First shown at SPIN-2016 NEW!

Proton 2007+2011 data



PRL 105,262002(2010)



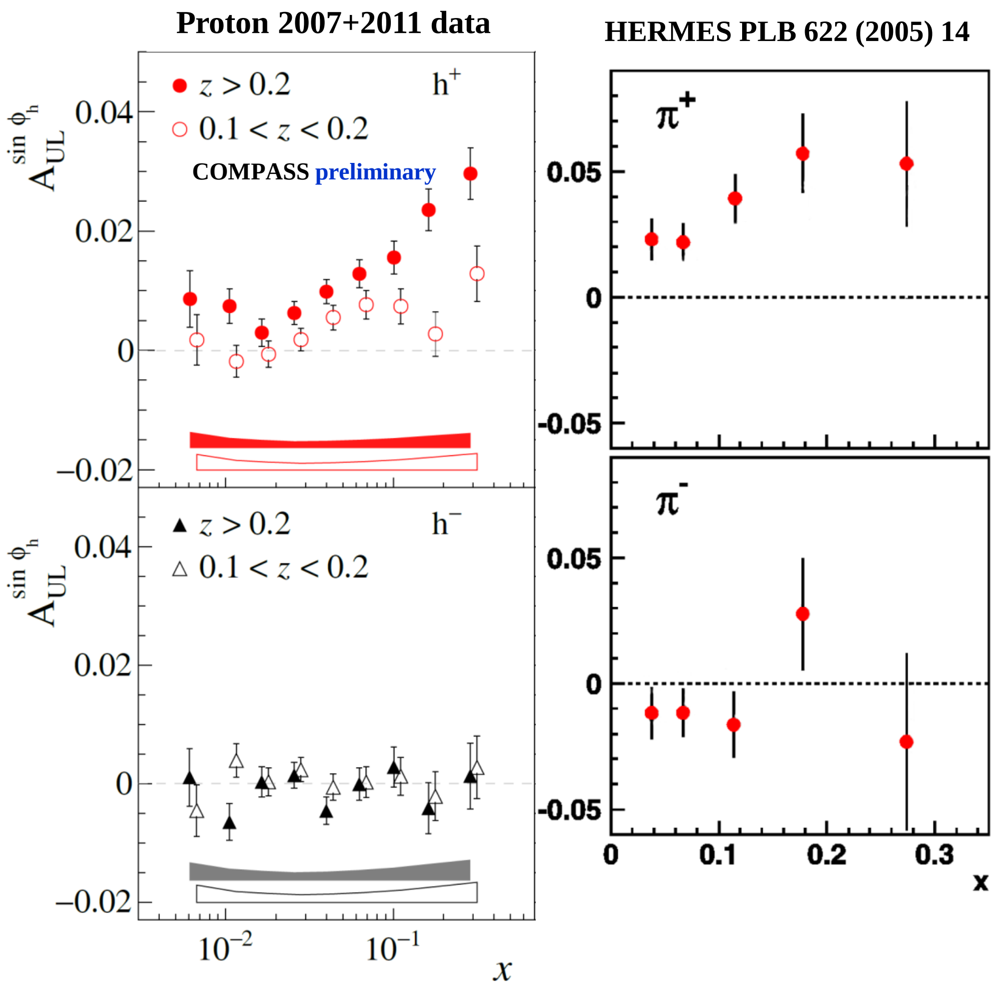
- Only "twist-2" ingredients
- Additional p_T-suppression
- **Collins-like behavior?**
- **In agreement with model predictions**
- **Discrepancy with HERMES and JLab?**

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

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

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

First shown at SPIN-2016 **NEW!**



- Q-suppression, TSA-mixing
- Various different "twist" ingredients
- **Similar to HERMES non-zero trend for h$^+$, clear *z*-dependence, h$^-$ compatible with zero**

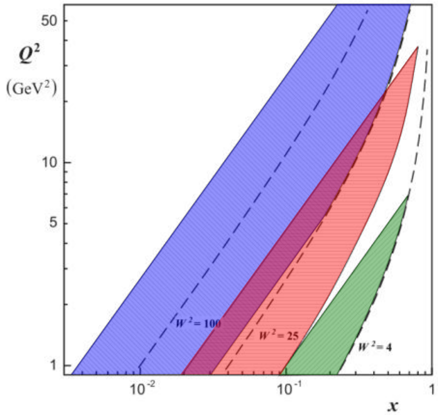
The $A_{UL}^{\sin\phi_h}$ asymmetry

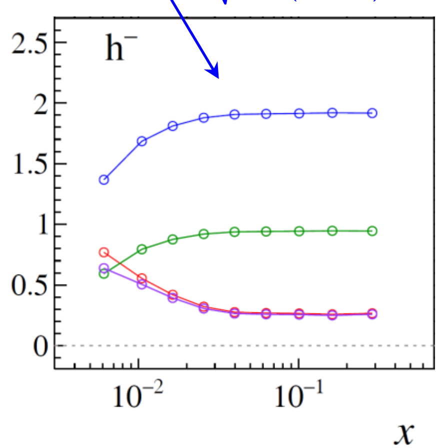
$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+S_L\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\ldots\right\}$$

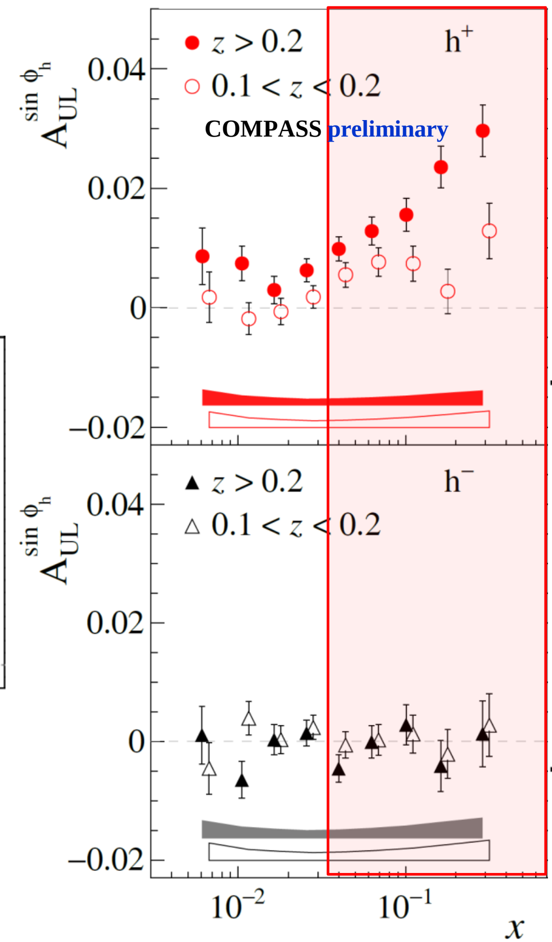
$$F_{UL}^{\sin\phi_h}=\frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xh_L^q H_{1q}^{\perp h}+\frac{M_h}{M}g_{1L}^q\frac{\tilde{G}_q^{\perp h}}{z}\right)+\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xf_L^{\perp q}D_{1q}^h-\frac{M_h}{M}h_{1L}^{\perp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

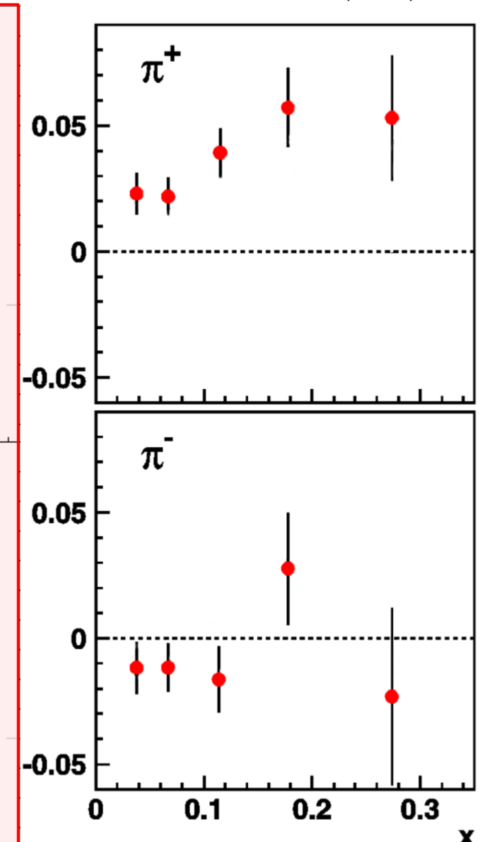
First shown at SPIN-2016 NEW!

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









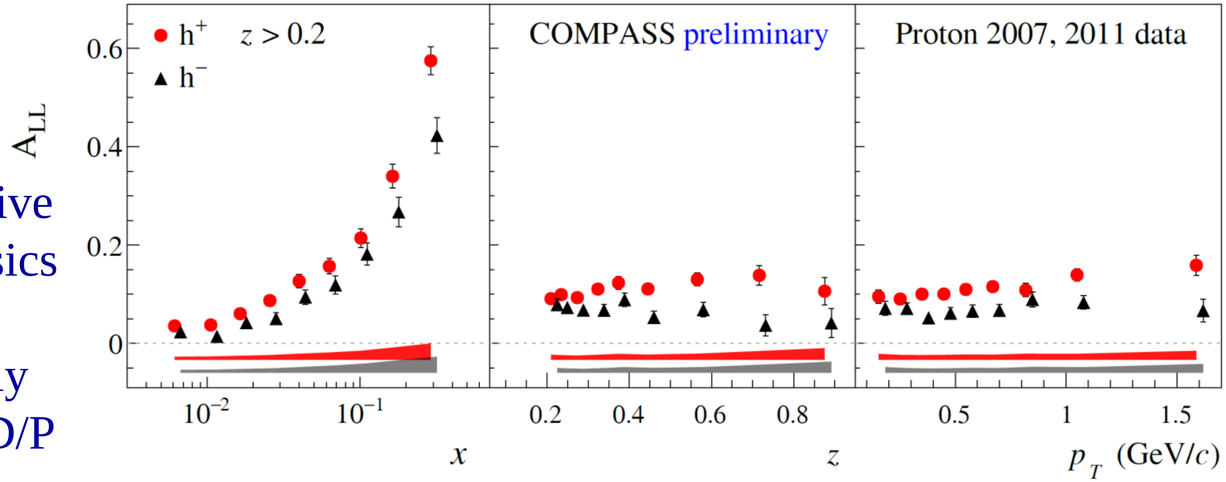
- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- **Similar to HERMES non-zero trend for h⁺, clear *z*-dependence, h⁻ compatible with zero**

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

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

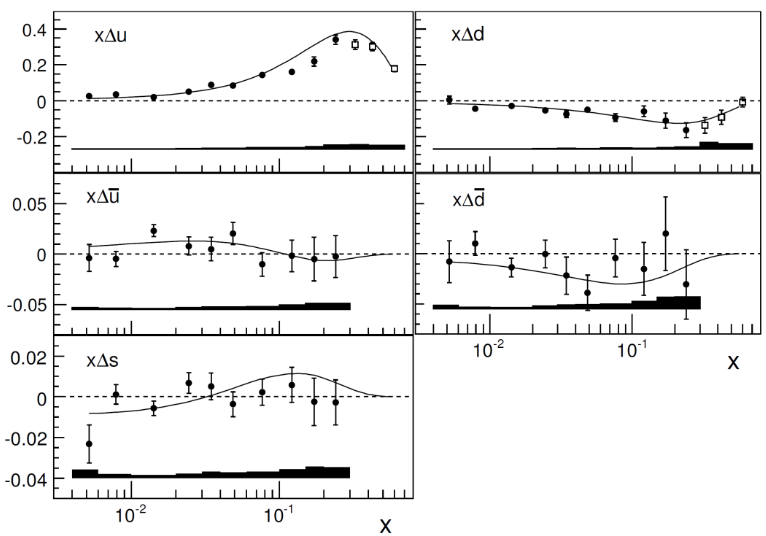
First shown at SPIN-2016 NEW!

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

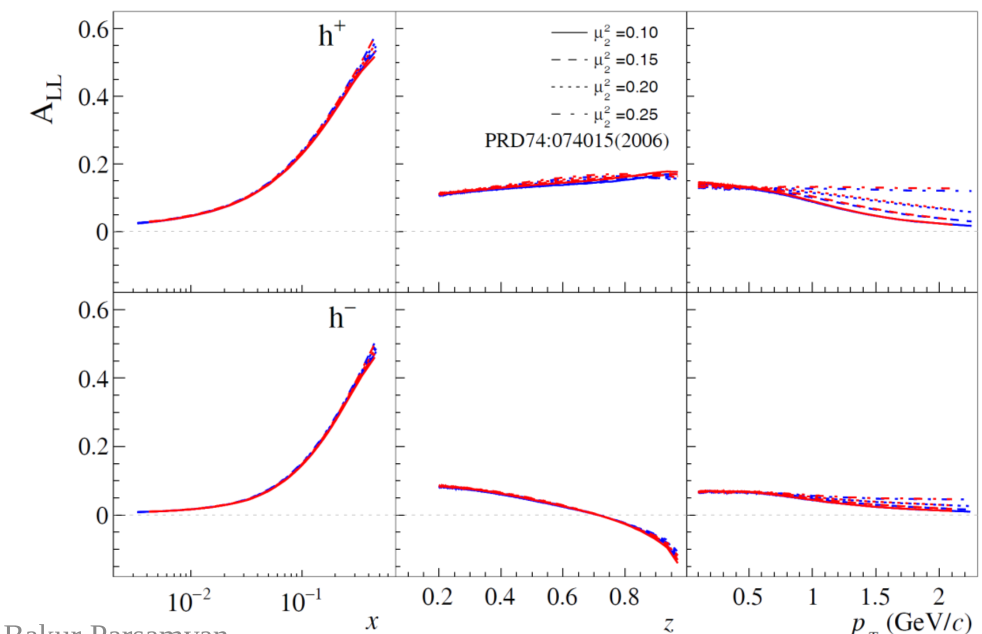


- Measurement of (semi-)inclusive $A_1(A_{LL})$ is one of the key physics topics of COMPASS
- Large amount of longitudinally polarized data collected with D/P targets (2002-2011)

PLB 693 (2010) 227–235



COMPASS Proton-2007, -2011 kinematics



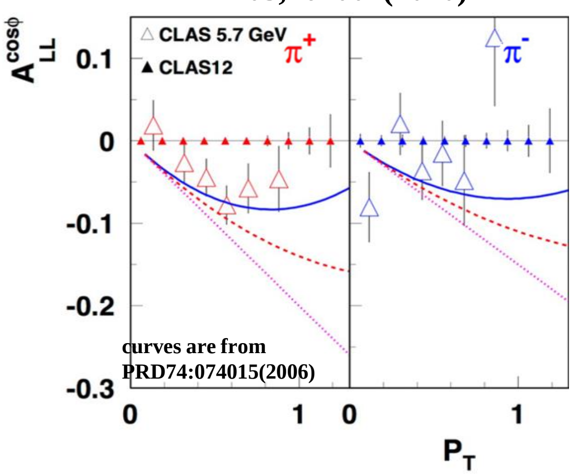
The $A_{LL}^{\cos\phi_h}$ asymmetry

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

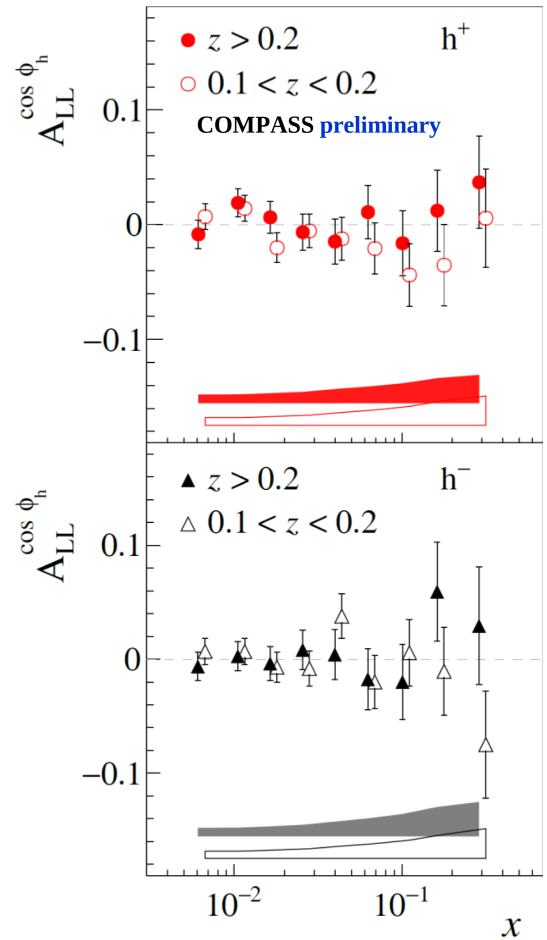
$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h}\left(xe_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{D}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\left(xg_L^{\perp q} D_{1q}^h - \frac{M_h}{M}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

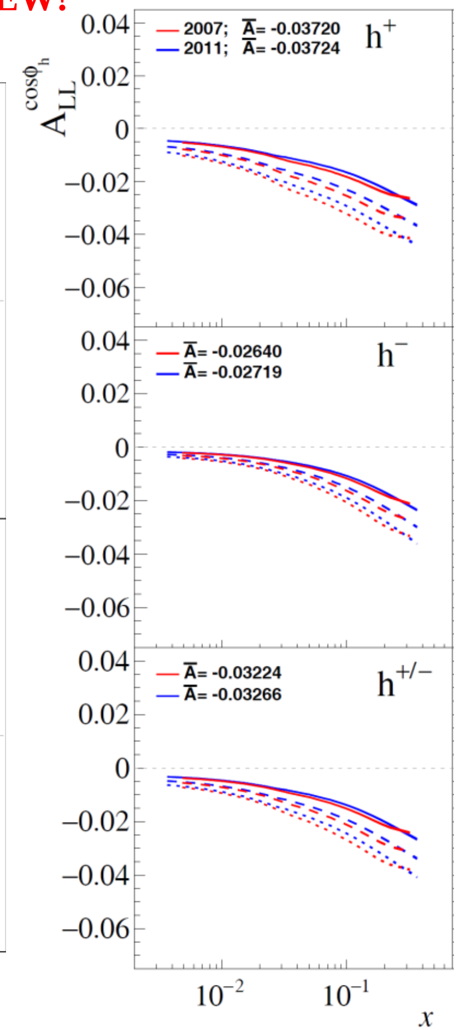
First shown at SPIN-2016 NEW!

PRL 105,262002(2010)



Proton 2007+2011 data





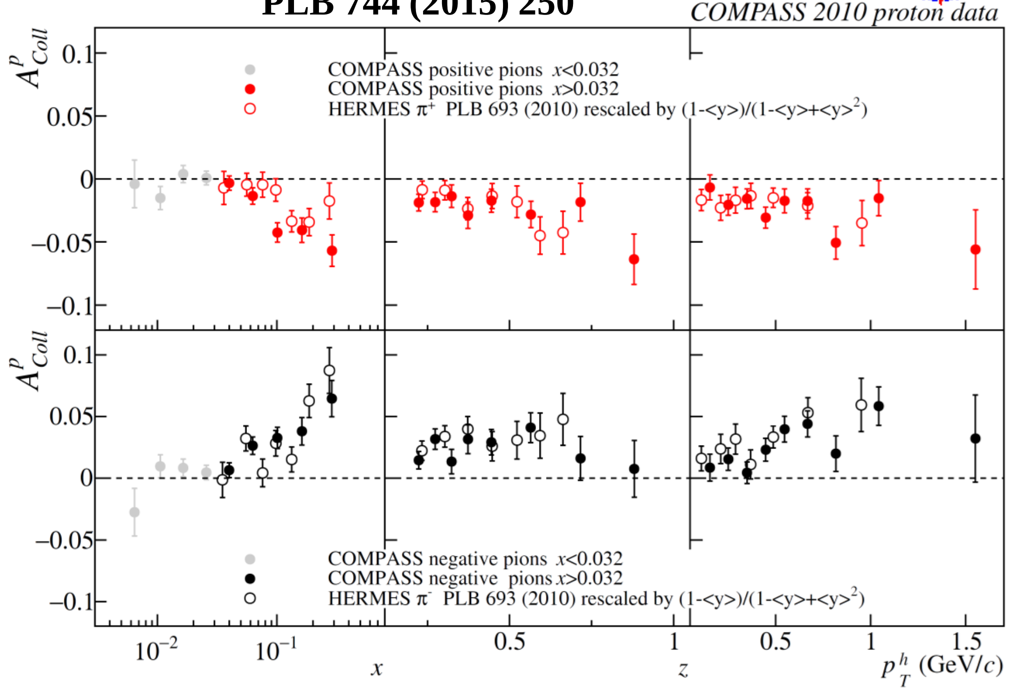
- Various different "twist" ingredients,
- Q-suppression
- Non zero at JLab
- **Small and compatible with zero, in agreement with model predictions**

SIDIS TSAs (Collins)

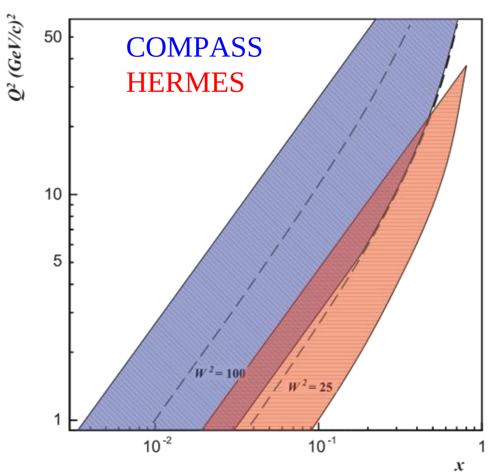
$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h} \quad \text{SSA [twist-2]}$$

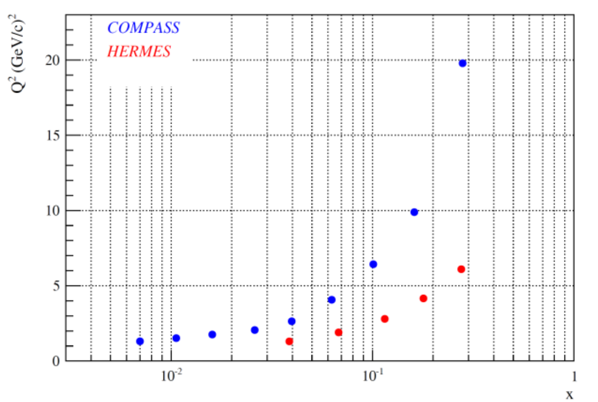
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{ 1 + \ldots \right.$$
$$+ S_T \left[A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S)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

PLB 744 (2015) 250



- Measured on P/D in SIDIS and in dihadron SIDIS
  COMPASS and HERMES obtained compatible results on Collins TSA (Q^2 is different by a factor of ~2-3)
- **No Q^2-evolution? Intriguing result!**





SIDIS TSAs (Collins)

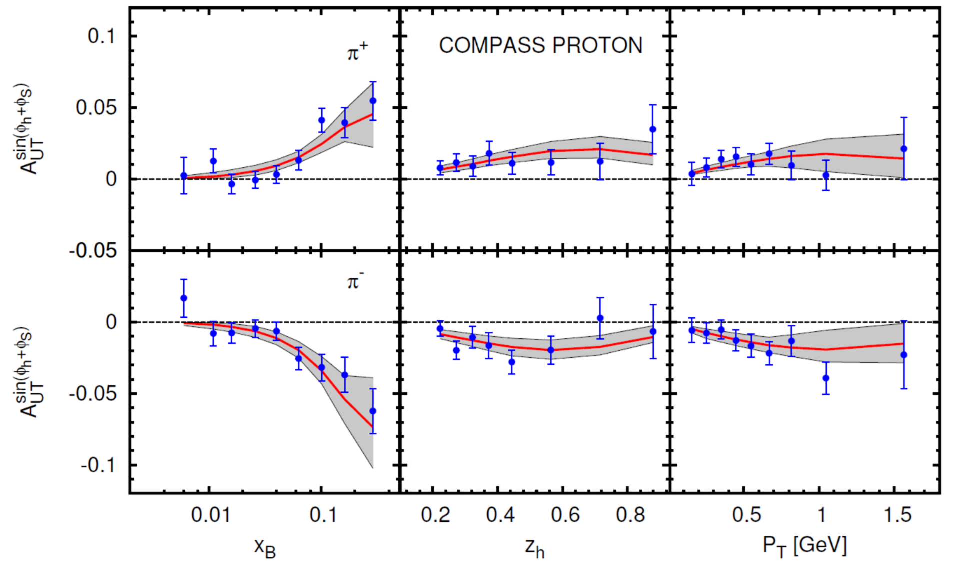
$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h} \quad \text{SSA [twist-2]}$$

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

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

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

Anselmino et al. **Phys.Rev. D87 (2013) 094019**

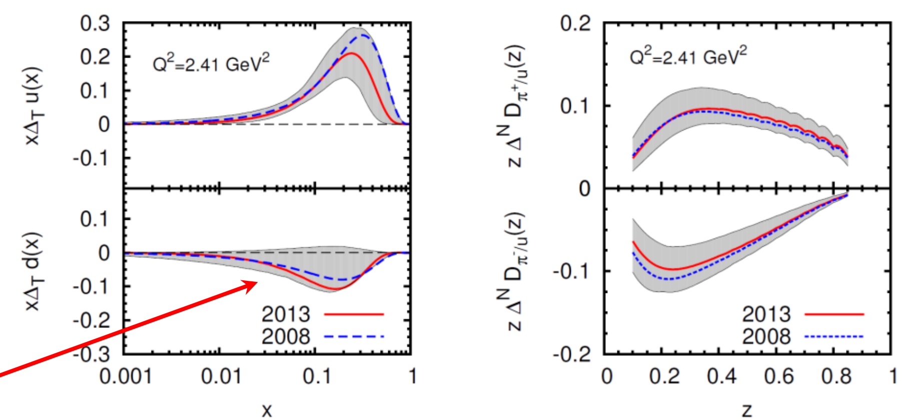


- Global fit of HERMES-COMPASS-BELLE data

Extensive phenomenological studies and various global fits by different groups

Ideas for COMPASS-III (>2020)

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



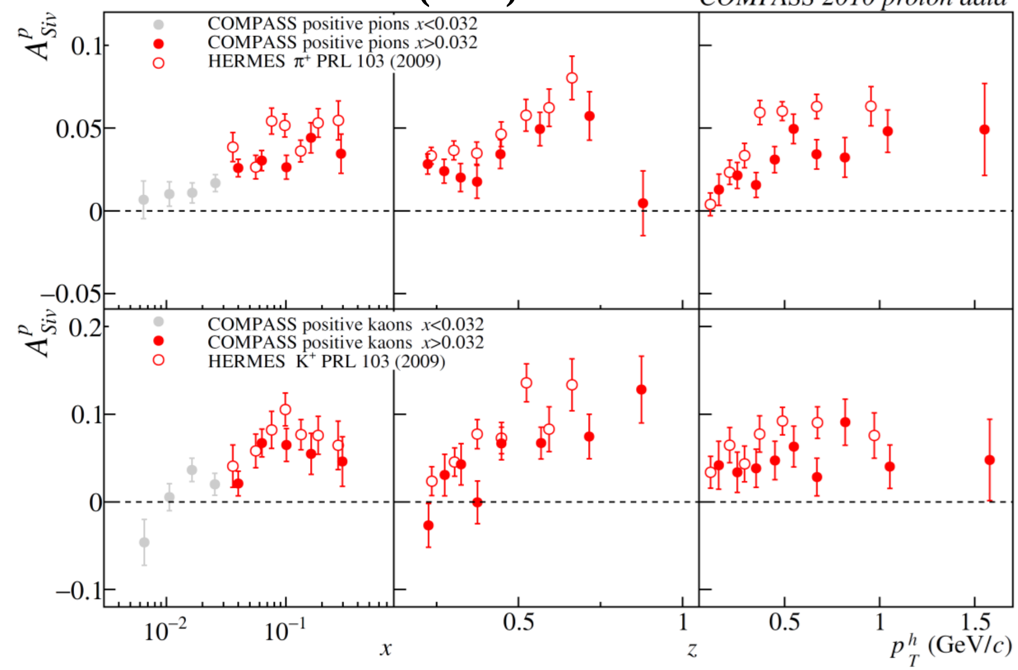
- Transversity PDF + Collins FF

SIDIS TSAs (Sivers)

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

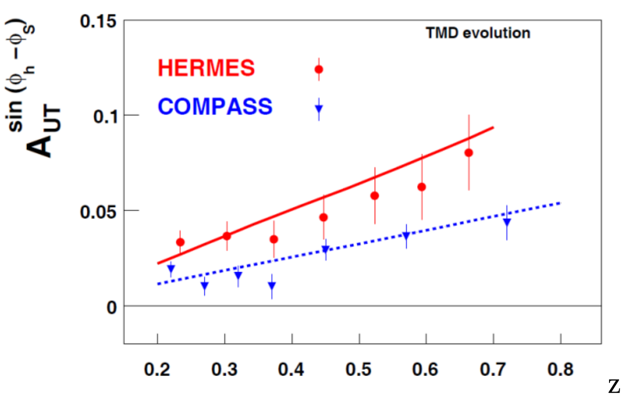
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\Bigg\{ 1+\ldots$$
$$+ S_T \left[A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S)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

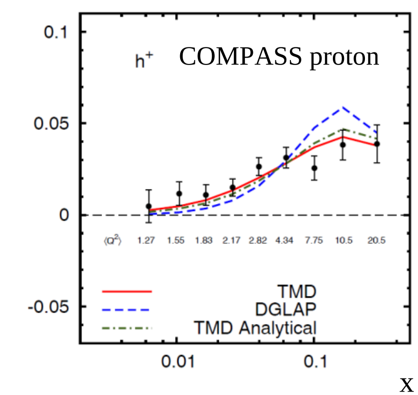
PLB 744 (2015) 250



- Measured on proton and deuteron
- Gluon Sivers paper: submitted to PLB CERN-EP/2017-003, hep-ex/1701.02453

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





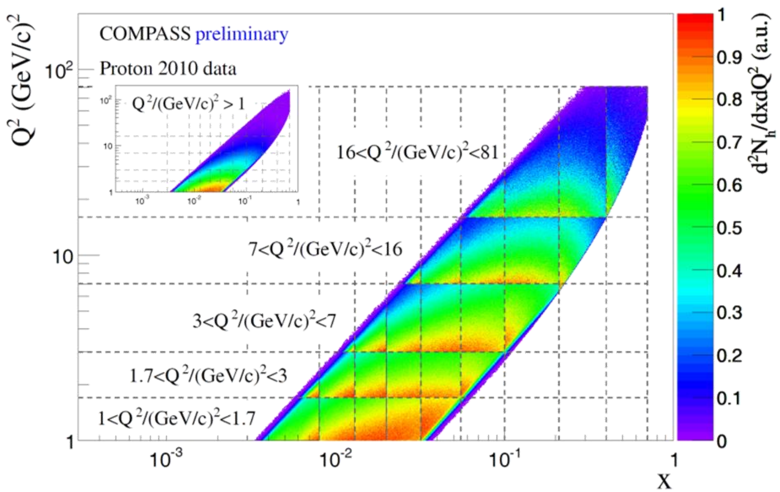
S. M. Aybat, A. Prokudin, T. C. Rogers **PRL 108 (2012) 242003**
M. Anselmino, M. Boglione, S. Melis **PRD 86 (2012) 014028**

Multi-D TSA analysis

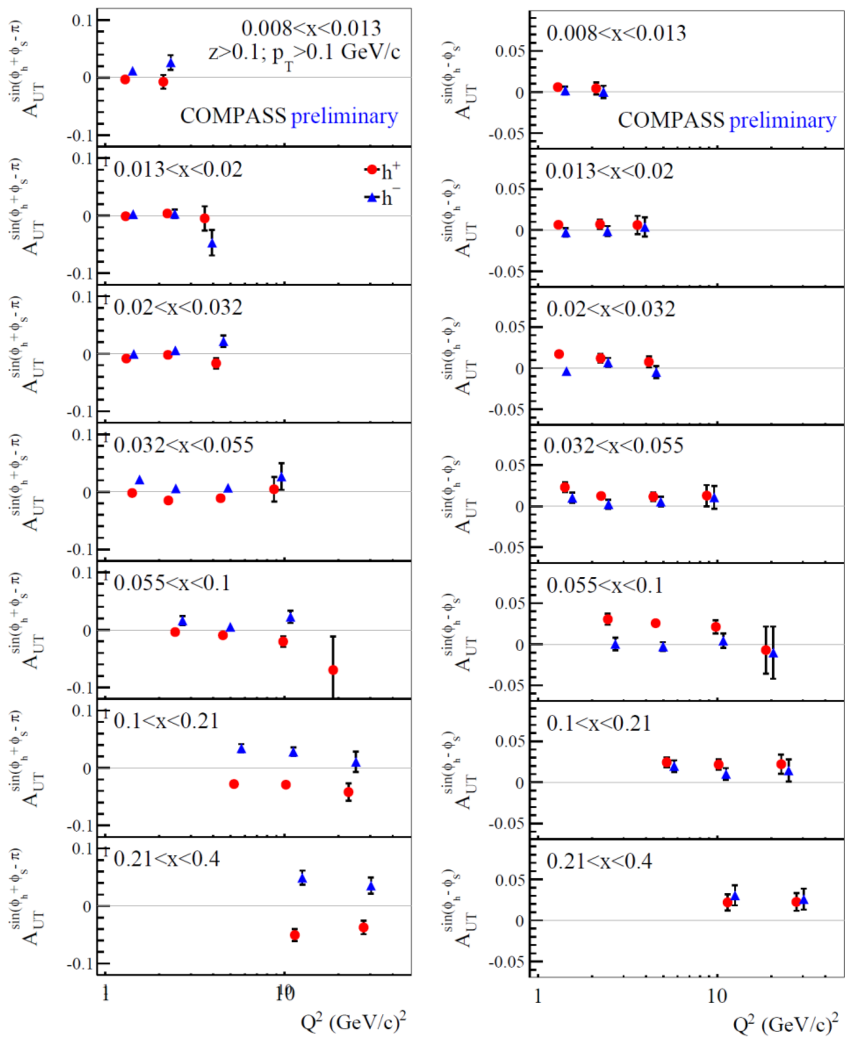
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\Bigg\{ 1 + \ldots$$

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

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



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



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

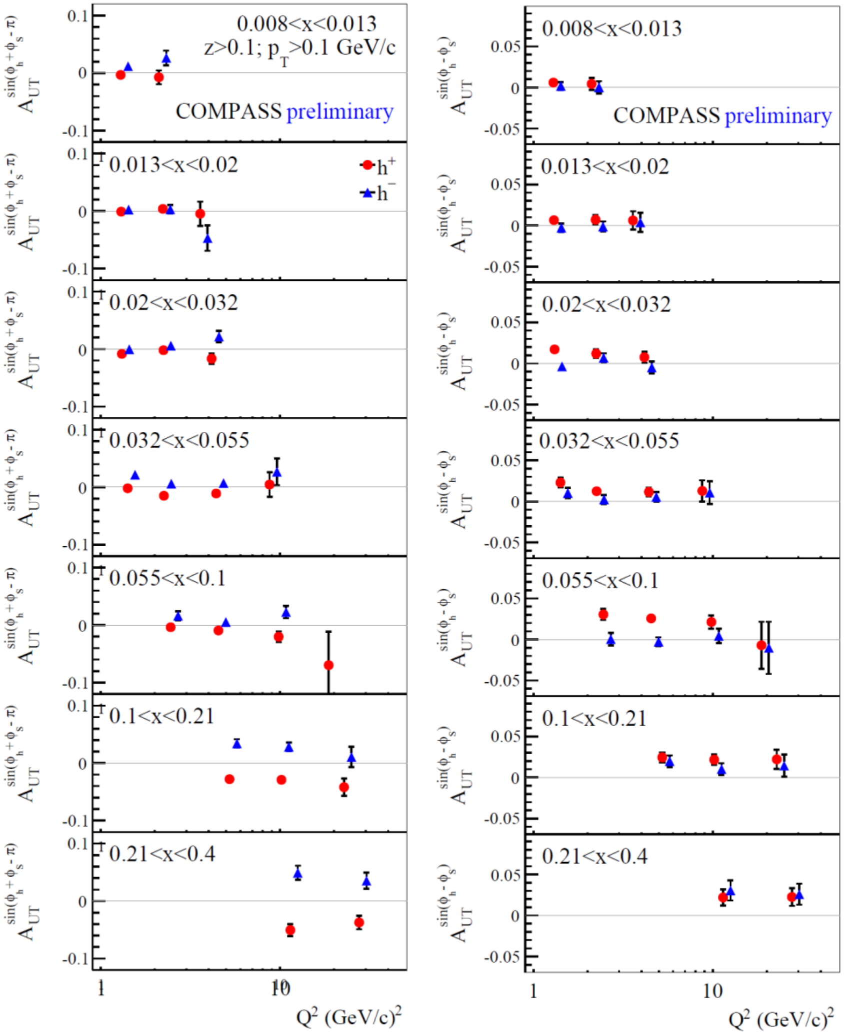
Multi-D TSA analysis

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

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

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

Results first shown at the SPIN-2014 conference
arXiv:1504.01599 [hep-ex]



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

Ideas for COMPASS-III (>2020)

- SIDIS proton measurements with different beam energies using M2 beamline possibilities (60-280 GeV/c)
- Direct input for evolution studies!

Sivers TSA SIDIS→DY

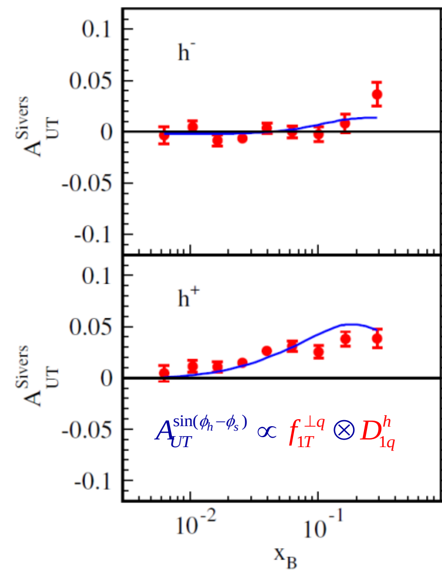
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\Bigg\{ 1 + \ldots$$

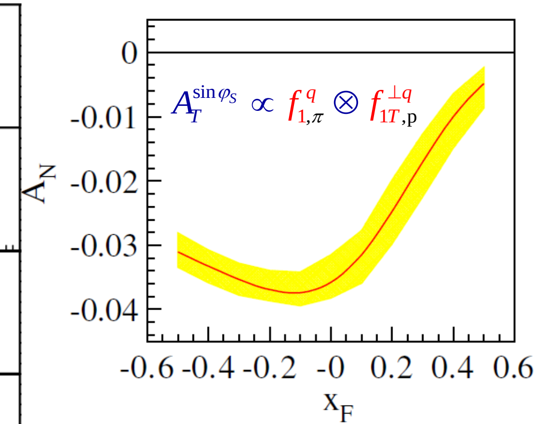
$$+ S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S \\ + \sqrt{2\varepsilon(1+\varepsilon)}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

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

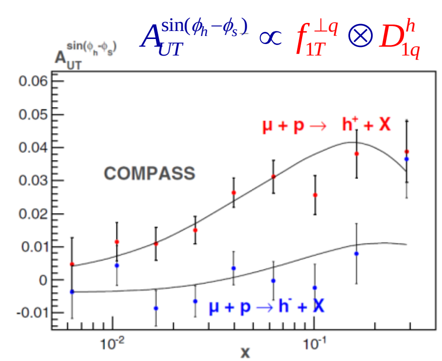
- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan

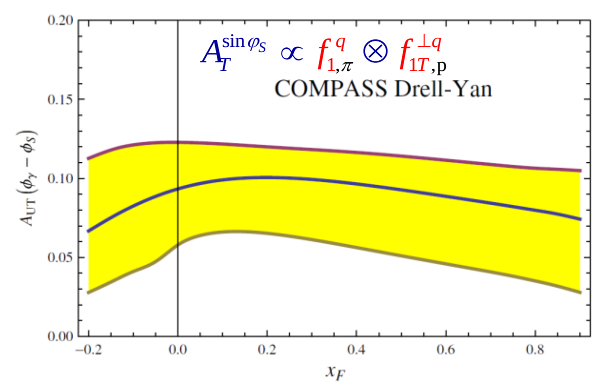
M.G. Echevarria, A.Idilbi, Z.B. Kang and I. Vitev,
"QCD Evolution of the Sivers Asymmetry"
PRD 89 074013 (2014)





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)

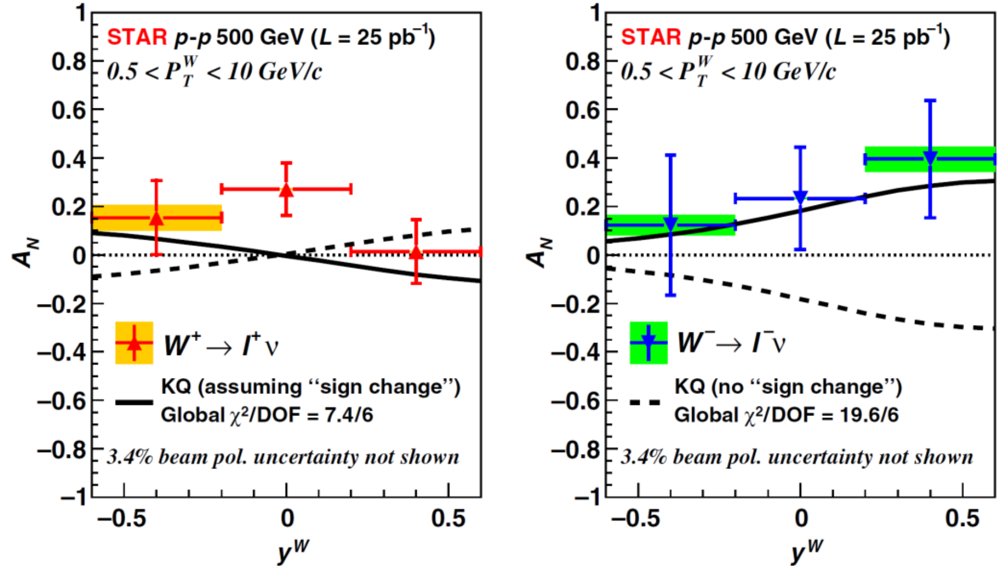




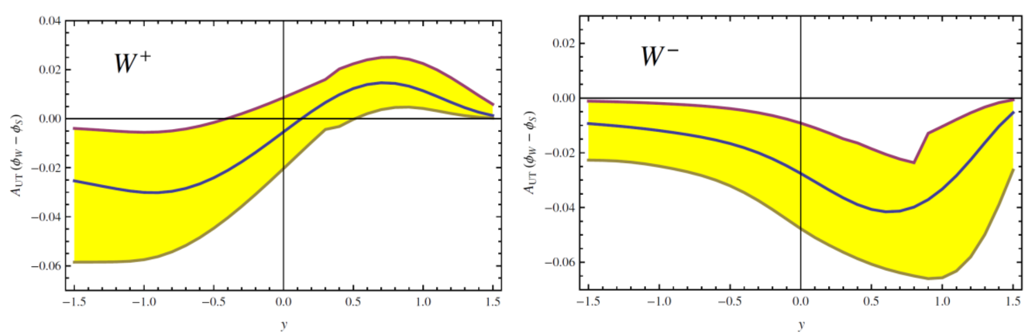
Sivers TSA SIDIS→DY

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

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



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)



- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan
- First experimental investigation of Sivers-nonuniversality by STAR
- Different hard scale compared to FT
- Evolution effects may play a substantial role

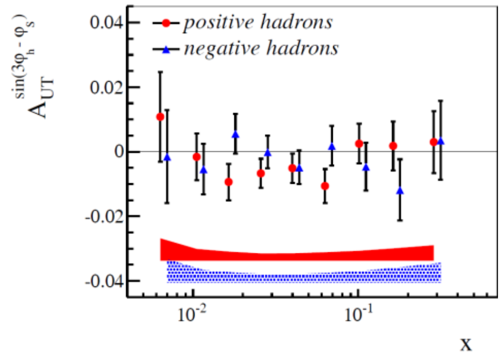
SIDIS TSAs (Pretzelosity and Kotzinian-Mulders)

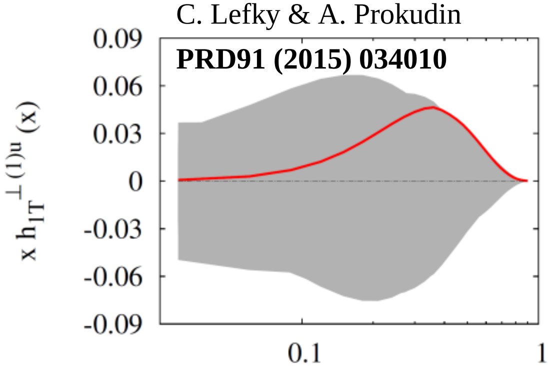
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\Bigg\{ 1 + \ldots$$

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

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

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

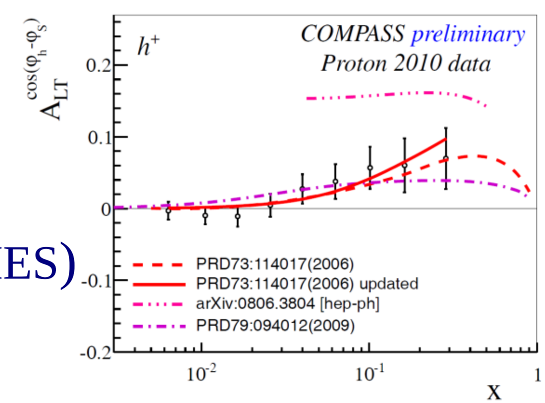


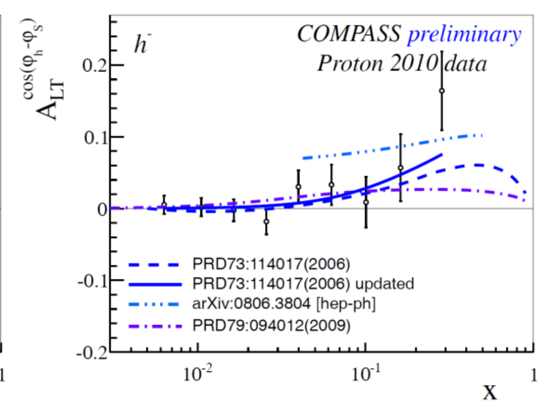


- All compatible with zero within uncertainties (P/D)
- Suppressed by a factor of $\sim|p_T|^2$ w.r.t the Collins and Sivers TSAs

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

- 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





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

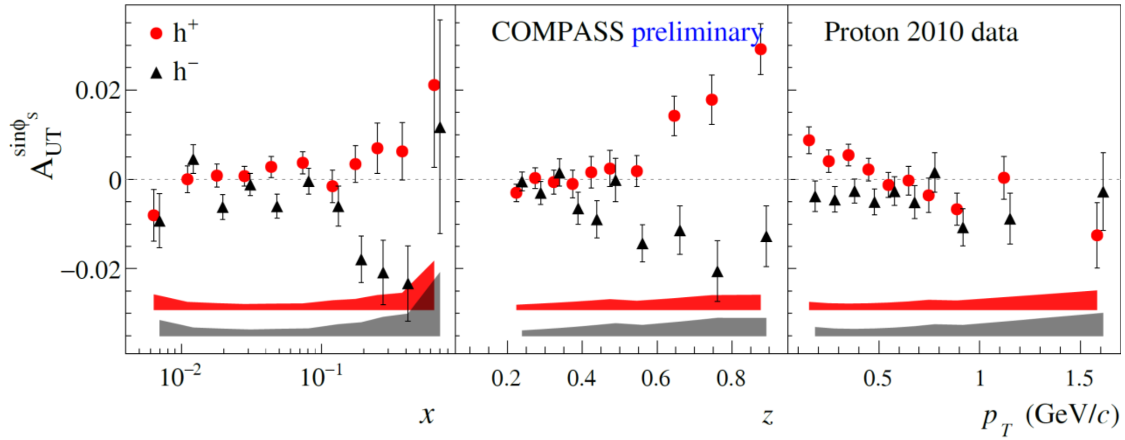
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{ 1+\ldots \right.$$

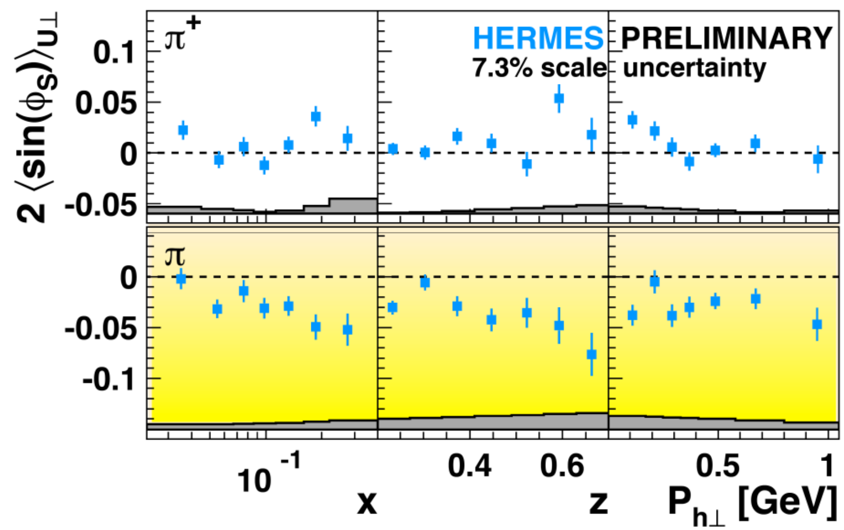
$$+\ S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) \\ +\ \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) \\ +\ \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) \\ +\ \boxed{\sqrt{2\varepsilon(1+\varepsilon)}\,A_{UT}^{\sin\phi_S} \sin\phi_S} \\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

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

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

SSA[higher-twist]





- Higher twist effect..
- Within WW-approximation can be related to Sivers and Collins TSAs
- Non-zero trend for negative hadrons both at COMPASS and HERMES
- Compatible with zero on deuteron

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

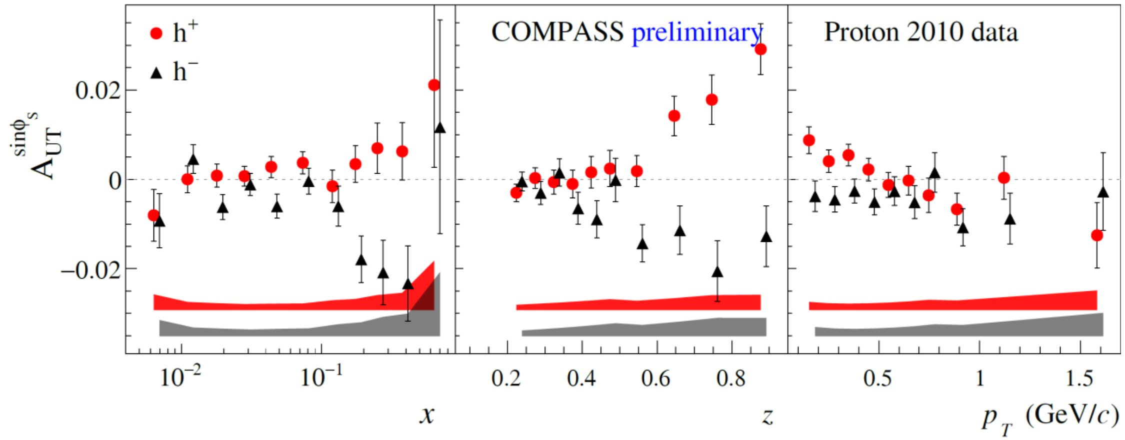
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{ 1 + \ldots \right.$$

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

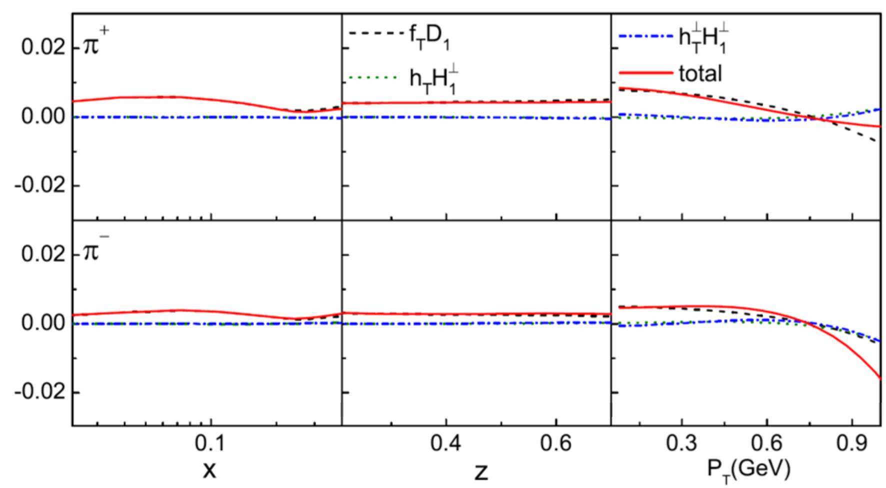
$$\left. + S_T\lambda \left[\begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h - \phi_S) \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_S} \cos\phi_S \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h-\phi_S)} \cos(2\phi_h - \phi_S) \end{array} \right]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

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

SSA[higher-twist]

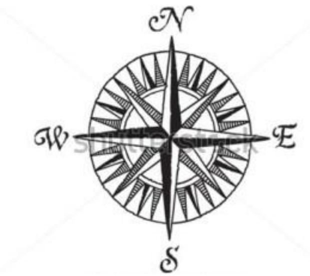


W. Mao, Z. Lu and B.Q. Ma **Phys.Rev. D 90 (2014) 014048**



- Higher twist effect..
- Within WW-approximation can be related to Sivers and Collins TSAs
- Non-zero trend for negative hadrons both at COMPASS and HERMES
- Compatible with zero on deuteron

COMPASS bridge



SIDIS and single-polarized DY x-sections

SIDIS

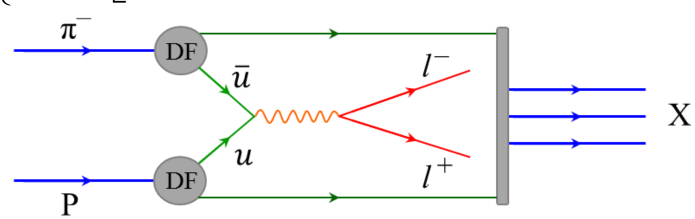
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)$$

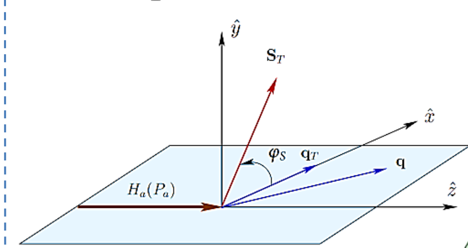
$$\times \left\{ \begin{aligned} & 1 + \sqrt{2\varepsilon(1+\varepsilon)}\,A_{UU}^{\cos\phi_h}\cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\ & + \lambda\sqrt{2\varepsilon(1-\varepsilon)}\,A_{LU}^{\sin\phi_h}\sin\phi_h \\ & + S_L \left[\sqrt{2\varepsilon(1+\varepsilon)}\,A_{UL}^{\sin\phi_h}\sin\phi_h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

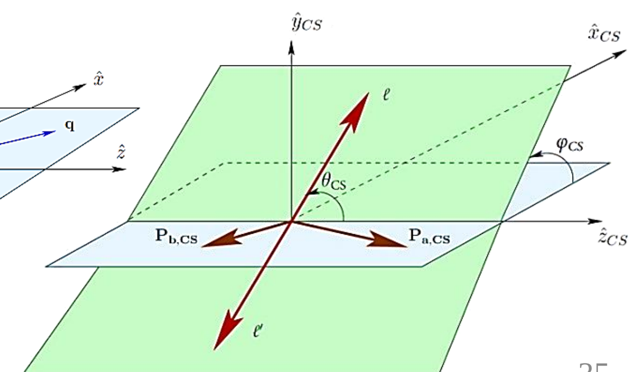
DY

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

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







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

SIDIS

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

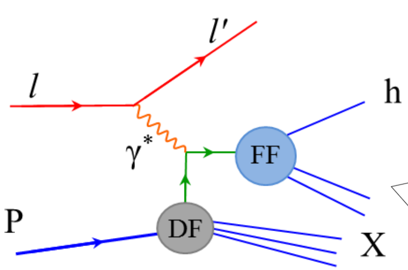
$$\times \begin{Bmatrix} 1+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\ + S_L\,\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h + S_L\lambda\sqrt{1-\varepsilon^2}\,A_{LL} \\ + S_T \begin{bmatrix} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ +\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S)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

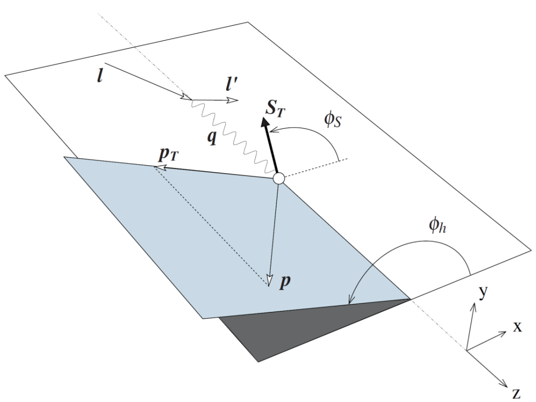
DY

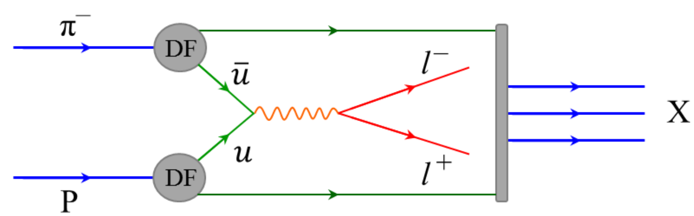
$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1\left(1+\cos^2\theta_{CS}\right)$$

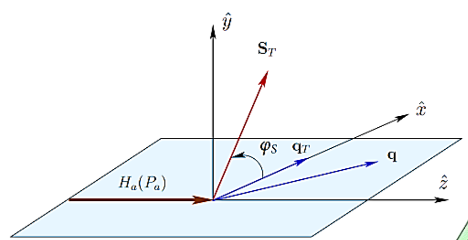
$$\times \begin{Bmatrix} 1+D_{[\sin^2\theta_{CS}]}A_U^{\cos 2\varphi_{CS}}\cos 2\varphi_{CS} \\ + S_L\sin^2\theta_{CS}A_L^{\sin 2\varphi_{CS}}\sin 2\varphi_{CS} \\ + S_T \begin{bmatrix} A_T^{\sin\varphi_S}\sin\varphi_S \\ +D_{[\sin^2\theta_{CS}]}\begin{pmatrix} A_T^{\sin(2\varphi_{CS}+\varphi_S)}\sin(2\varphi_{CS}+\varphi_S)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

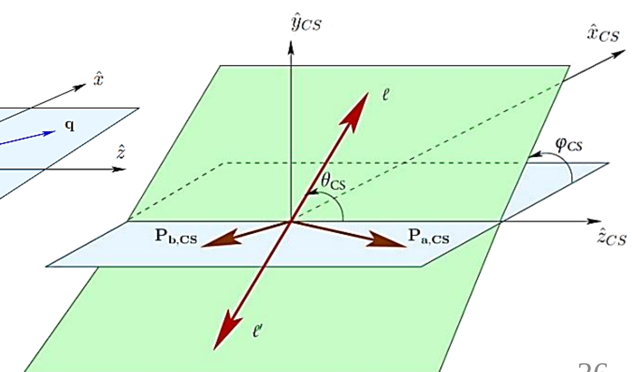
where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS}/\left(1+\cos^2\theta_{CS}\right)$











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

SIDIS

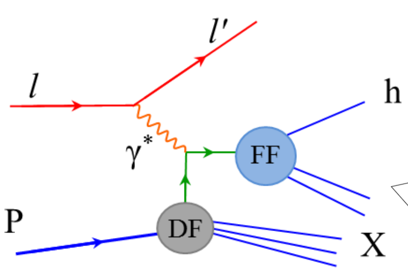
$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right) \times \left\{ \begin{array}{l} 1+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\ + S_L\, \varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2}\, A_{LL} \\ + S_T \left[\begin{array}{l}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

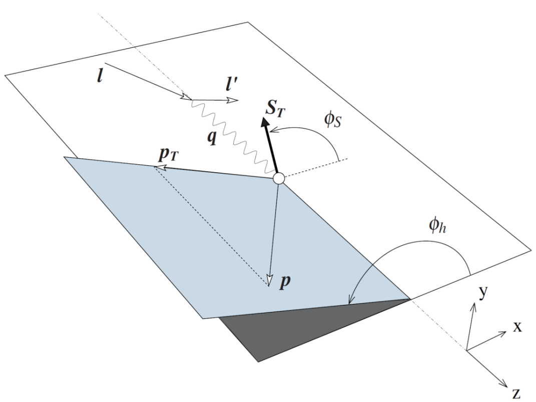
DY

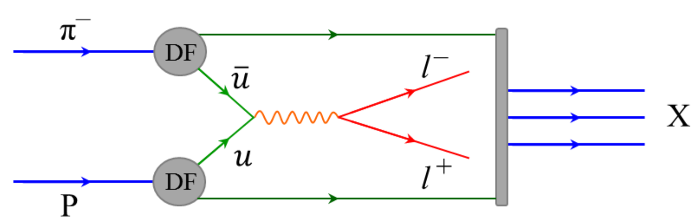
$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1\left(1+\cos^2\theta_{CS}\right) \times \left\{ \begin{array}{l} 1+D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}}\cos 2\varphi_{CS} \\ + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}}\sin 2\varphi_{CS} \\ + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S}\sin\varphi_S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

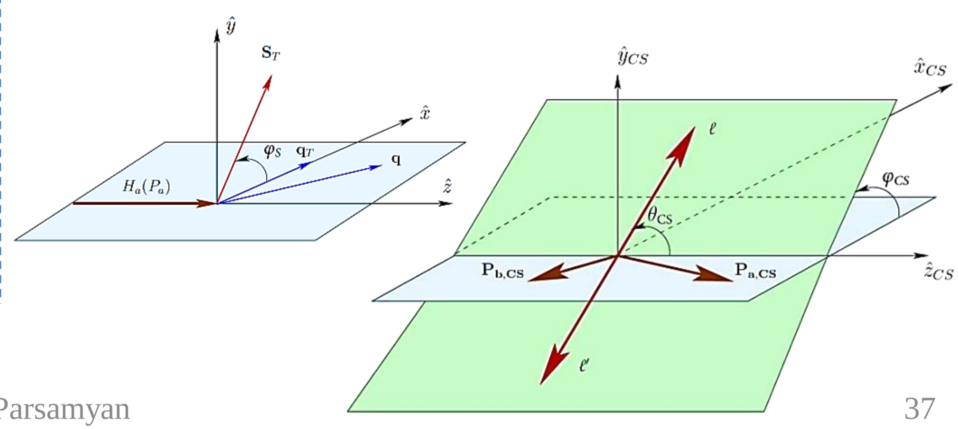
where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1+\cos^2\theta_{CS}\right)$

SIDIS-DY bridge









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

SIDIS

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

DY

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

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

COMPASS

SIDIS-DY bridge

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

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

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

SIDIS

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

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

SIDIS-DY bridge

DY

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

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

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

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

within QCD TMD-framework:

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

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

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

SIDIS

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

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

SIDIS-DY bridge

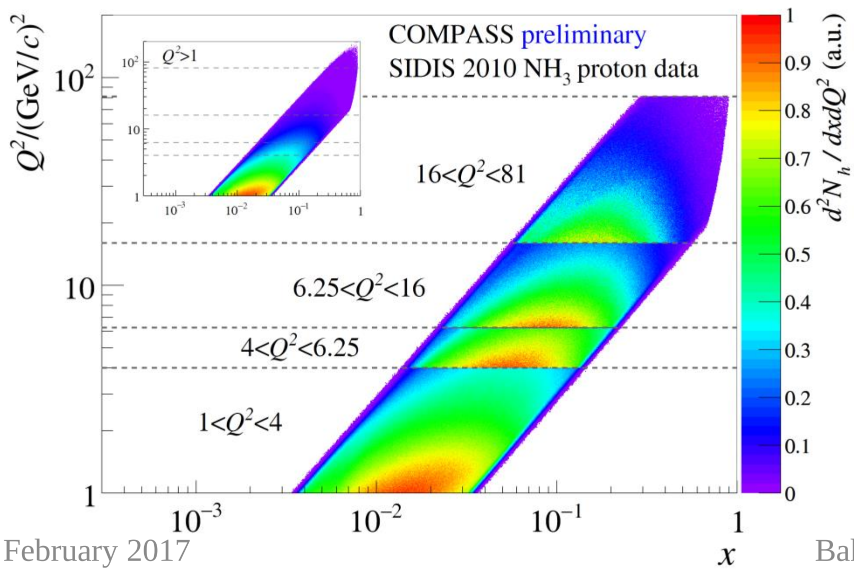
DY

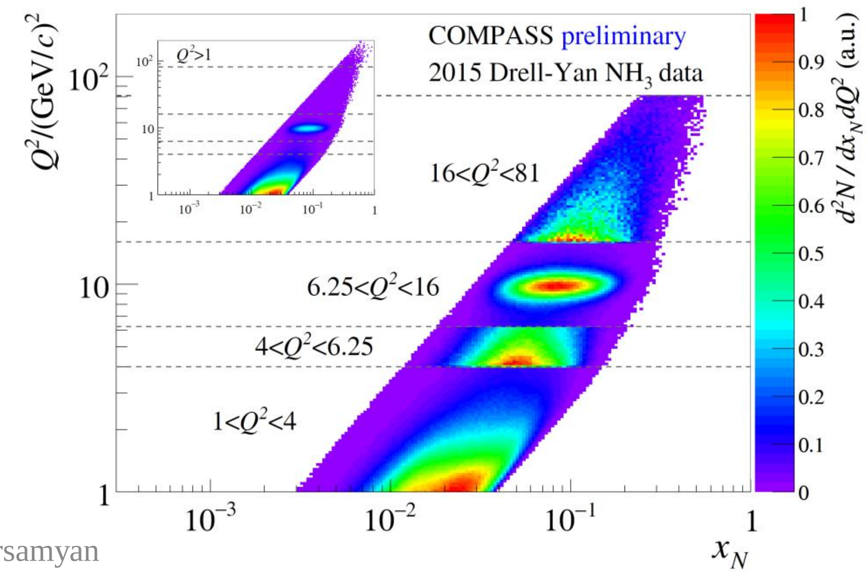
$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1\left(1+\cos^2\theta_{CS}\right)$$

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

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

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





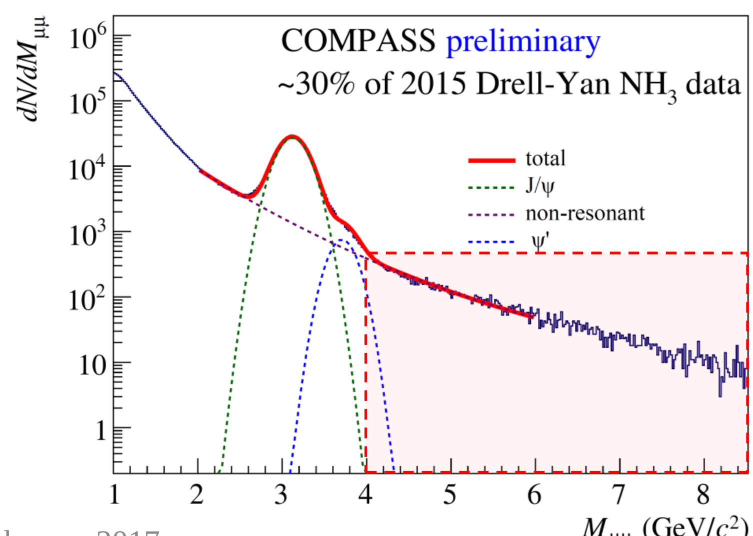
- COMPASS Drell-Yan mass ranges

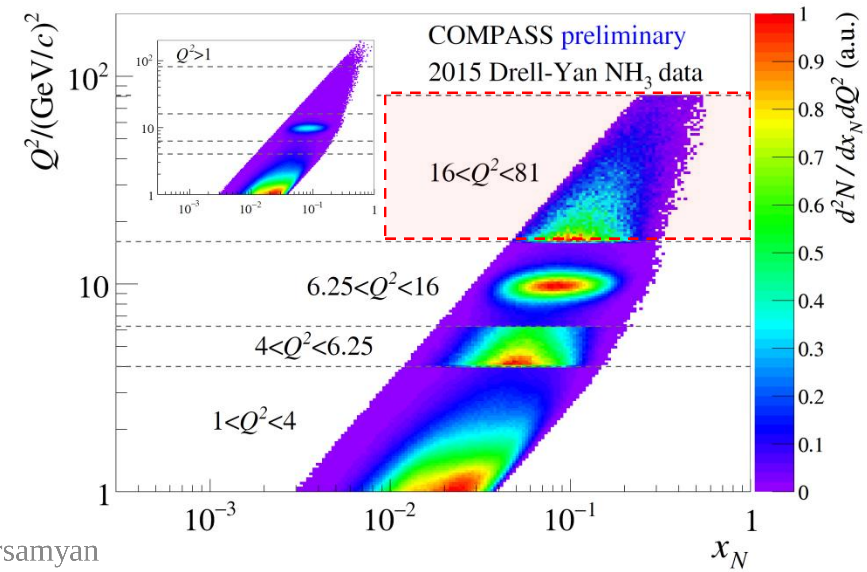
COMPASS DY mass ranges

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

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

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





COMPASS DY high-mass range

- $1 < Q^2/(\mathrm{GeV}/c)^2 < 4$ "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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- $Q^2/(\mathrm{GeV}/c)^2 > 16$ "High mass"
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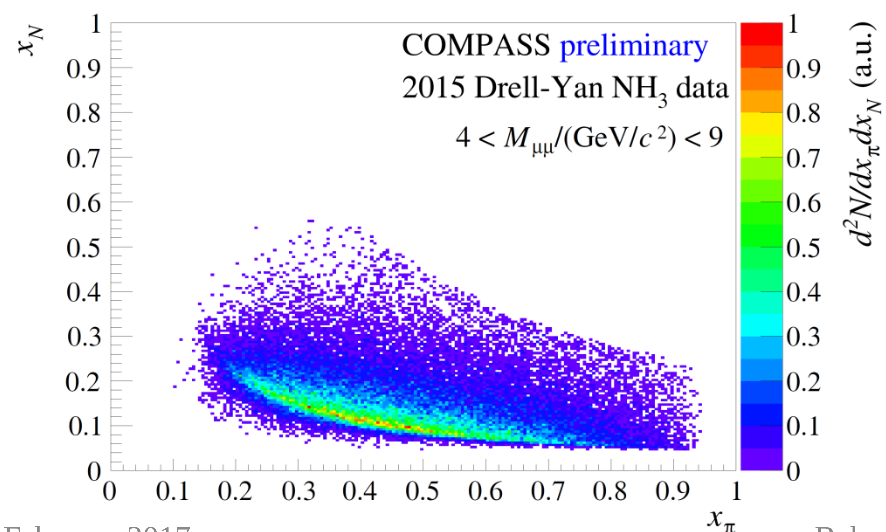
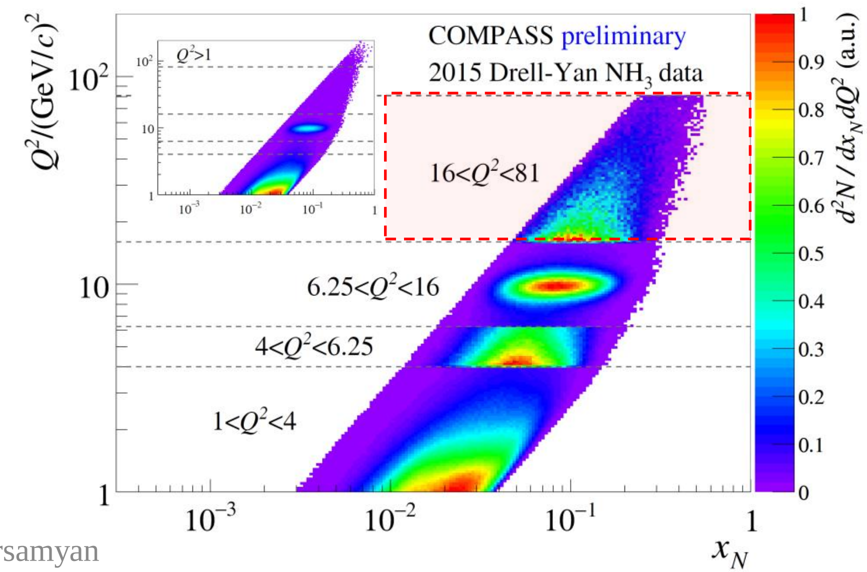
  - Beyond charmonium region, negligible CB
  - Valence region → largest asymmetries

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

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

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

- $1 < Q^2/(\mathrm{GeV}/c)^2 < 4$ "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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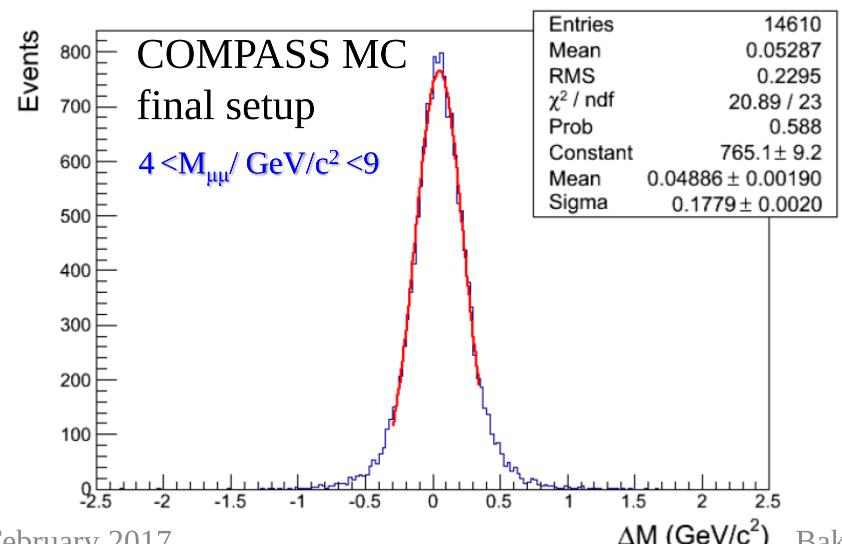
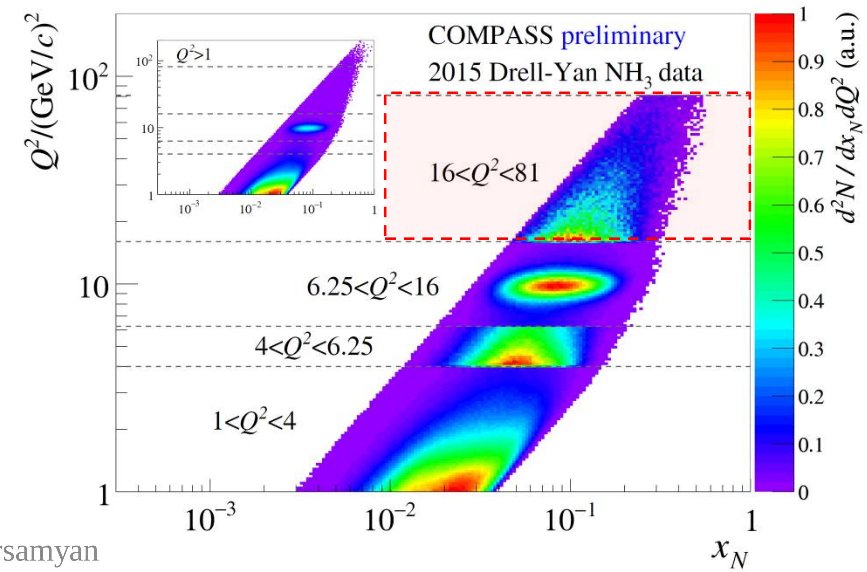
  - Valence region → largest asymmetries

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

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

Good mass resolution $\Delta M \approx 180$ MeV/c²





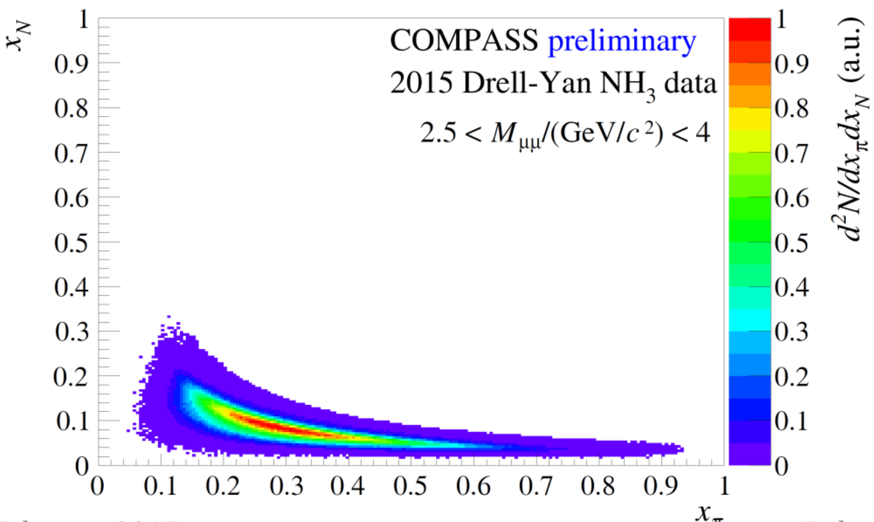
COMPASS DY J/ψ-mass range

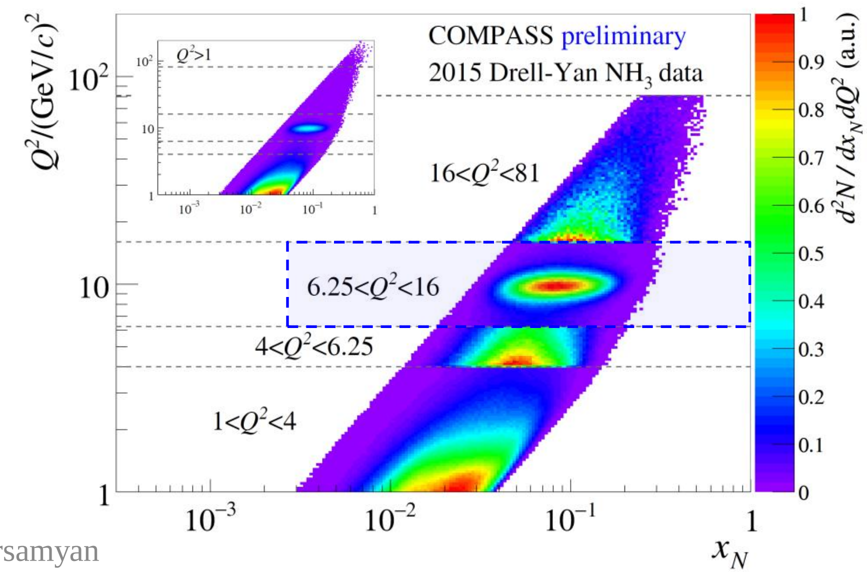
- $1 < Q^2/(\mathrm{GeV}/c)^2 < 4$ "Low mass"
  - Large combinatorial background: Open-charm (bottom) semi-leptonic decays $D\bar{D}$, $B\bar{B}$, pion and kaon decays
  - small asymmetries
- $4 < Q^2/(\mathrm{GeV}/c)^2 < 6.25$ "Intermediate"
  - High DY-cross section
  - Still low DY-signal/background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

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

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

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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  - Large combinatorial background: Open-charm (bottom) semi-leptonic decays $D\bar{D}$, $B\bar{B}$, pion and kaon decays
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where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1+\cos^2\theta_{CS}\right)$

J/ψ-region sample is much larger comparing to HM
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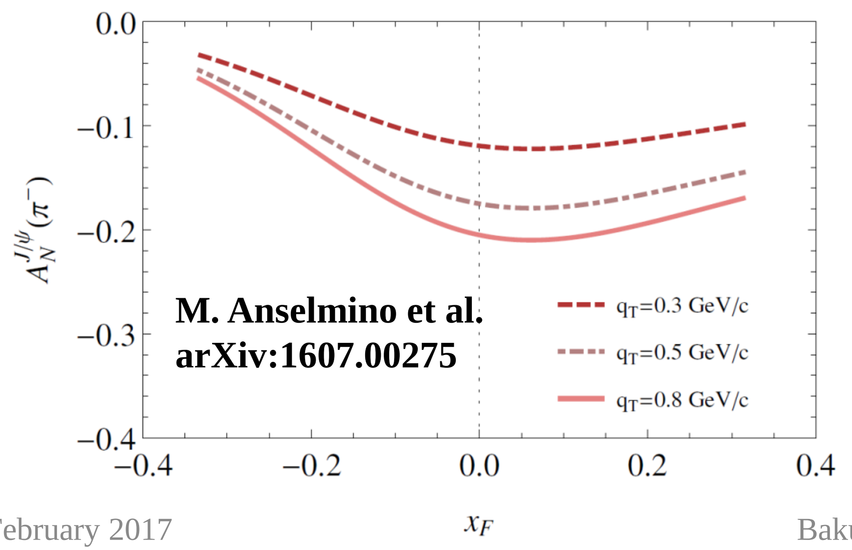
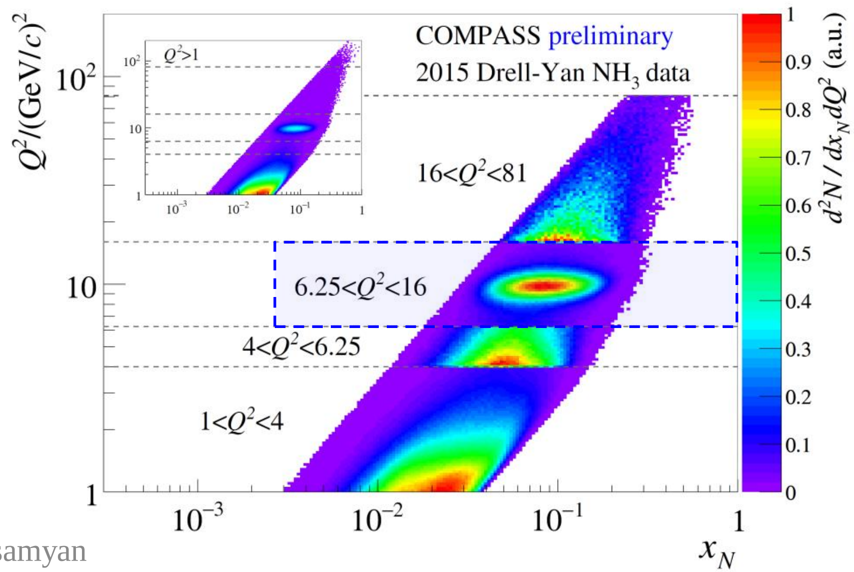
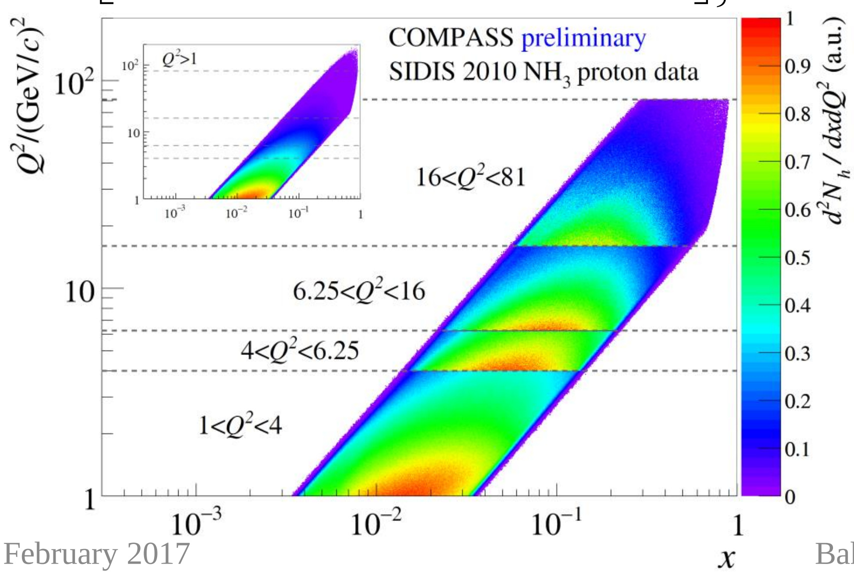




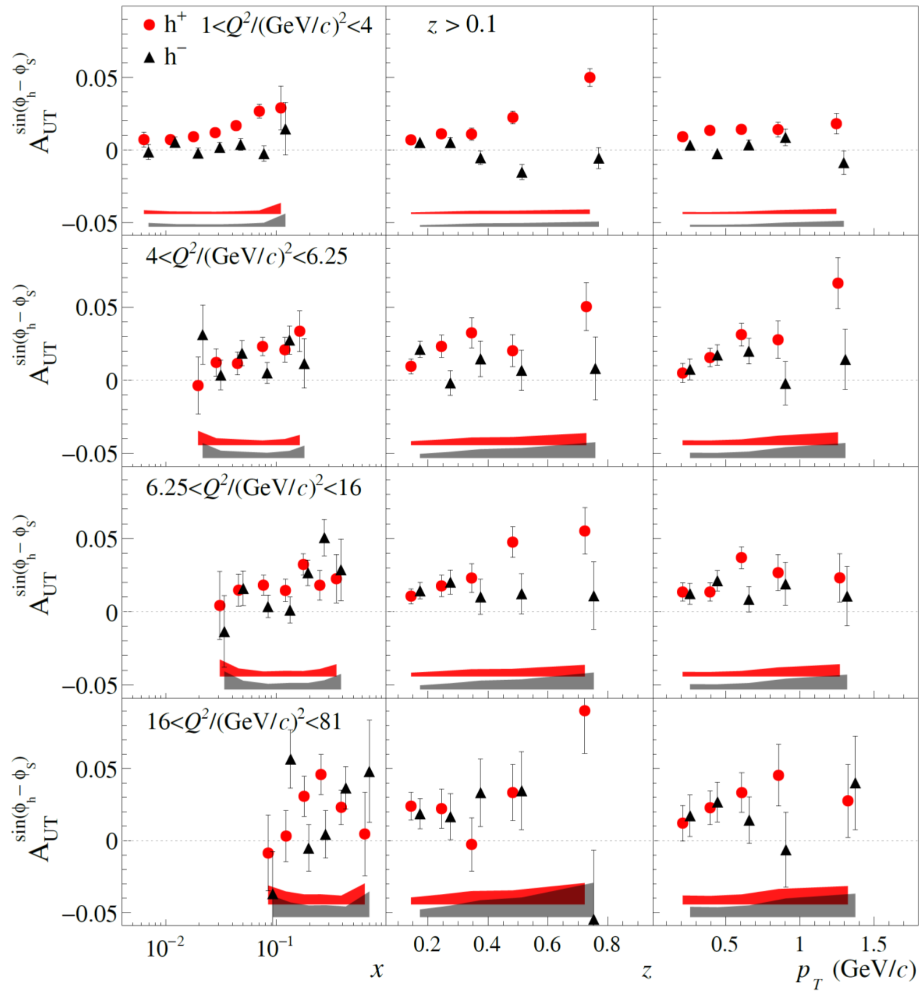
- SIDIS TSAs in COMPASS Drell-Yan mass ranges

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

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

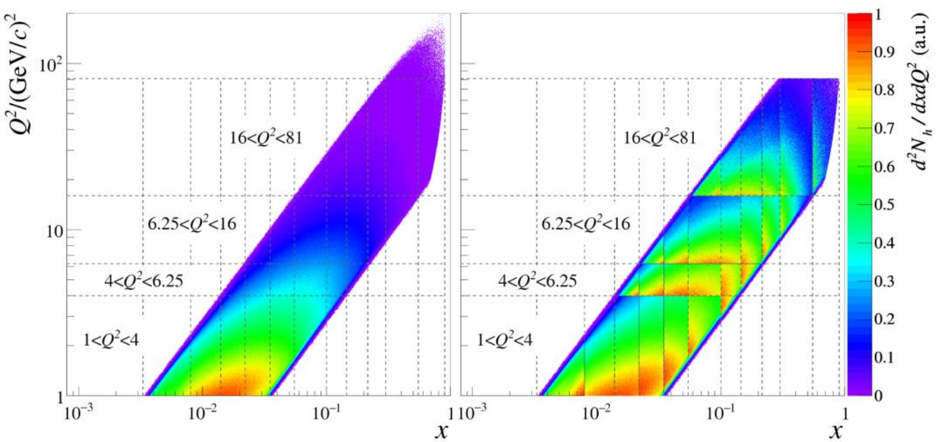


NEW! 23 September 2016
CERN-EP-2016-250, arXiv:1609.07374 [hep-ex]

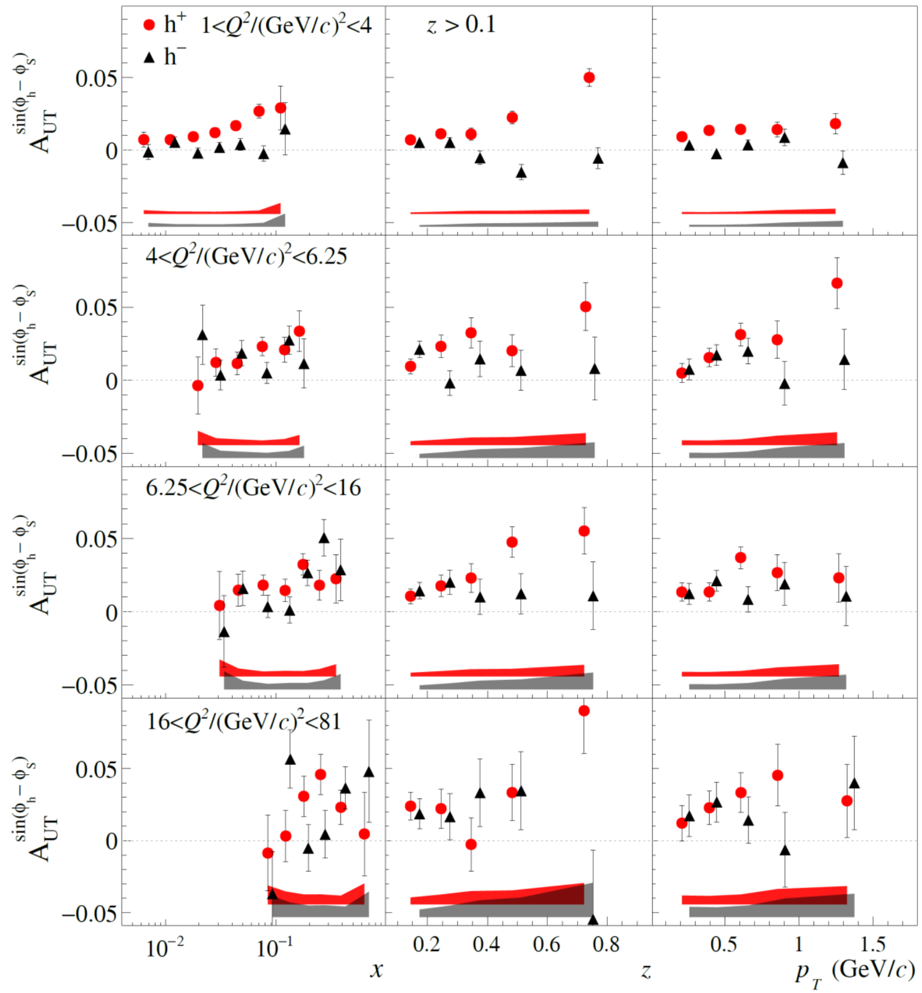


SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

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



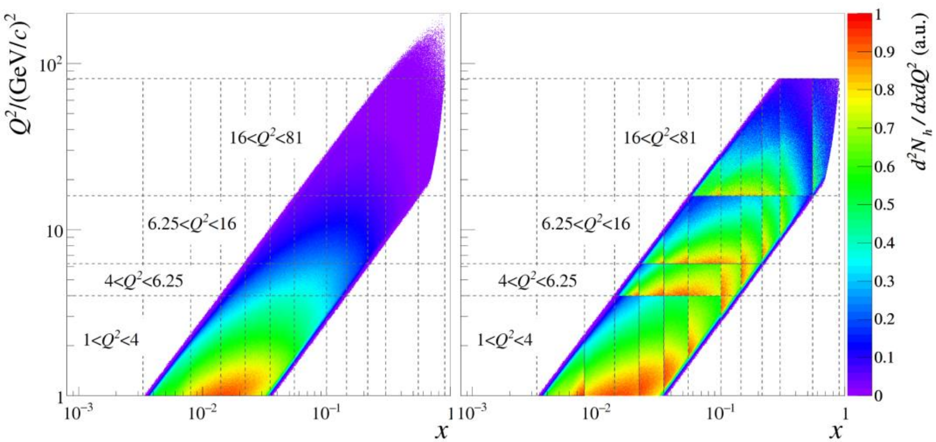
NEW! 23 September 2016
[CERN-EP-2016-250](), [arXiv:1609.07374 [hep-ex]]()



A multi-dimensional input for TMD evolution studies

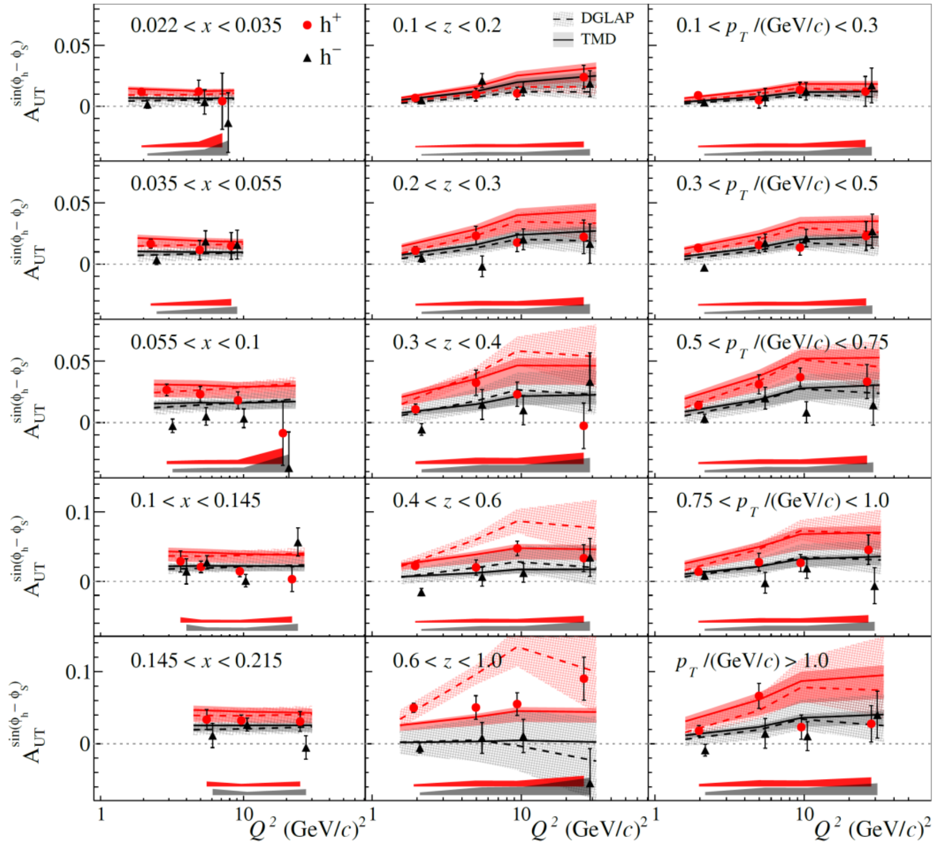
SIDIS Sivers TSA in COMPASS Drell-Yan Q²-ranges

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



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)

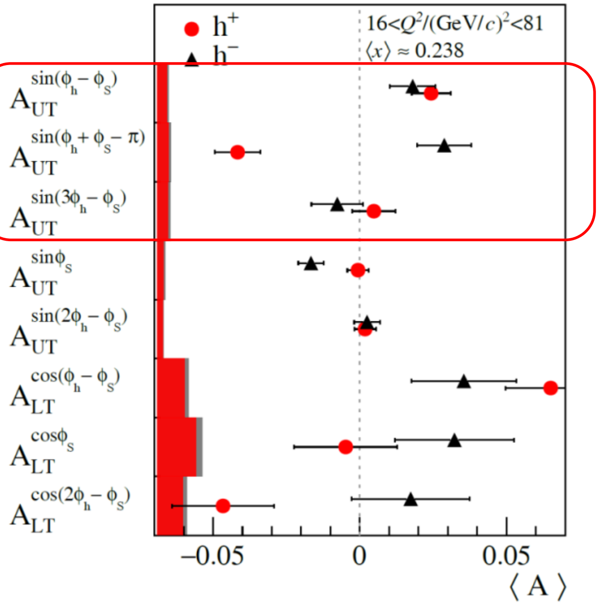
SIDIS and DY TSAs at COMPASS (high-mass range)

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

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

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

arXiv:1609.07374 [hep-ex]



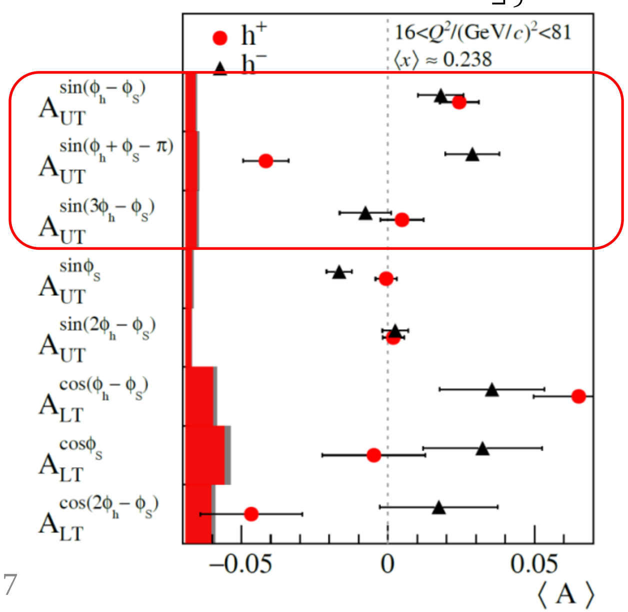
SIDIS and DY TSAs at COMPASS (high-mass range)

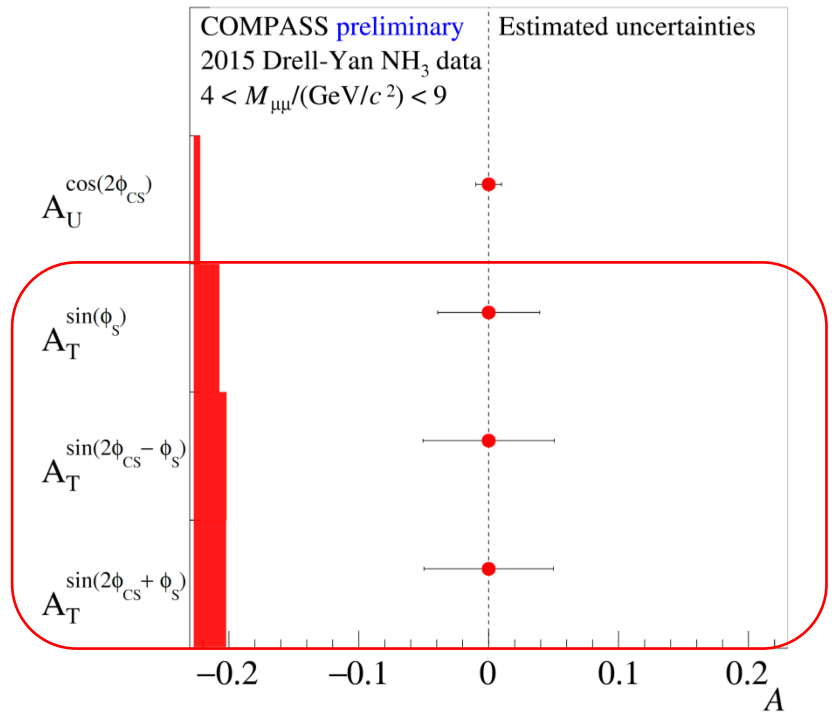
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{ 1+\ldots \right.$$
$$+\,S_T\left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ +\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ +\,\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)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

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

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

arXiv:1609.07374 [hep-ex]

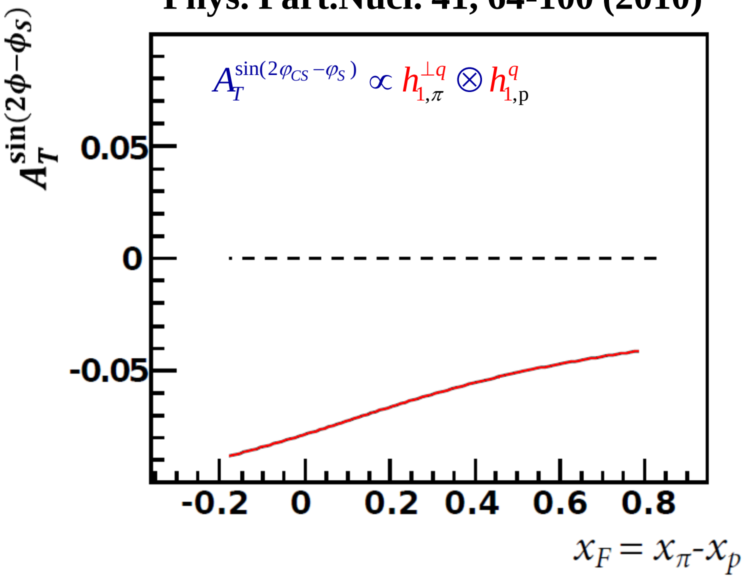


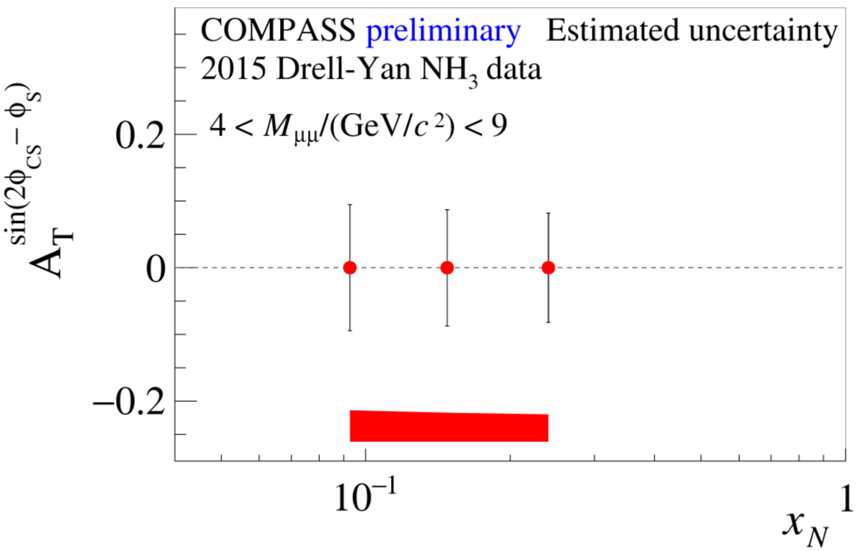


More news at DIS-2017 and at IWHSS-2017

Drell-Yan TSAs at COMPASS: predictions

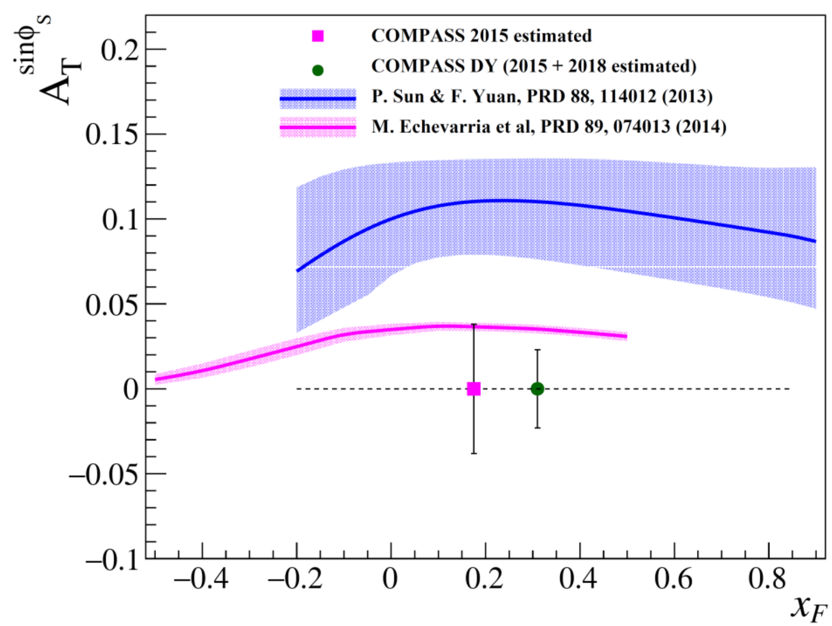
A. N. Sissakian et al.,
Phys. Part.Nucl. 41, 64-100 (2010)





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

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



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

COMPASS "beyond 2020" - selected SIDIS/DY ideas

- SIDIS
  - High precision measurements with transversely polarized deuterium target
    → crucial for flavour separation of TMD PDFs
  - Repeating measurement of SIDIS azimuthal asymmetries with transversely polarized proton target, but using different beam energies
    (M2 beamline 60-280 GeV/*c*)
    → direct test of TMD-evolution
- Drell-Yan
  - Unique polarized and unpolarized measurements with RF-separated kaon and antiproton beams and proton/deuterium/nuclear targets
    → flavour separation, kaon structure, BM TMD PDF for kaons, Lam-Tung for kaons, J/Ψ production mechanism, EMC effect, exclusive Drell-Yan

In parallel, various ideas for spectroscopy and DVCS measurments

New groups, collaborators, ideas are welcome!

http://iwhss17.to.infn.it

Announcement

The workshop occurs when a community of physicists is exploring high-energy particle physics opportunities for fixed-target experiments at CERN beyond 2020 (CERN Long Shutdown 2 2019-2020). These discussions already started with the "COMPASS beyond 2020" workshop in March 2016 and the "Physics Beyond Colliders" kick-off workshop organized by CERN in September 2016.

The physics discussed at the Workshop will mainly be related to the most recent results, open issues and short and long future programmes on Spectroscopy, Drell-Yan, DVCS and SIDIS, remaining open-minded to new possible programmes.

Physics topics:

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

Date/place:

- April 2-5, 2017, Cortona, Italy

Conclusions

- During phase one COMPASS has measured all possible SIDIS azimuthal LSAs and TSAs.
- In 2015 COMPASS has successfully collected first ever polarized DY data becoming the first experiment to measure both SIDIS and DY TSAs
  - Unique opportunity to compare the Sivers TMD PDFs obtained from two processes and to test QCD sign-change prediction at practically the same hard scale, thereby minimizing TMD evolution effects.
  - Preliminary results are expected to be in time for DIS-2017.
- 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
- A second year of polarized DY data-taking will take place in 2018

- COMPASS phase-III is being discussed to take place after 2020
  - Particular attention is given to possible SIDIS and Drell-Yan measurements

Thank you!