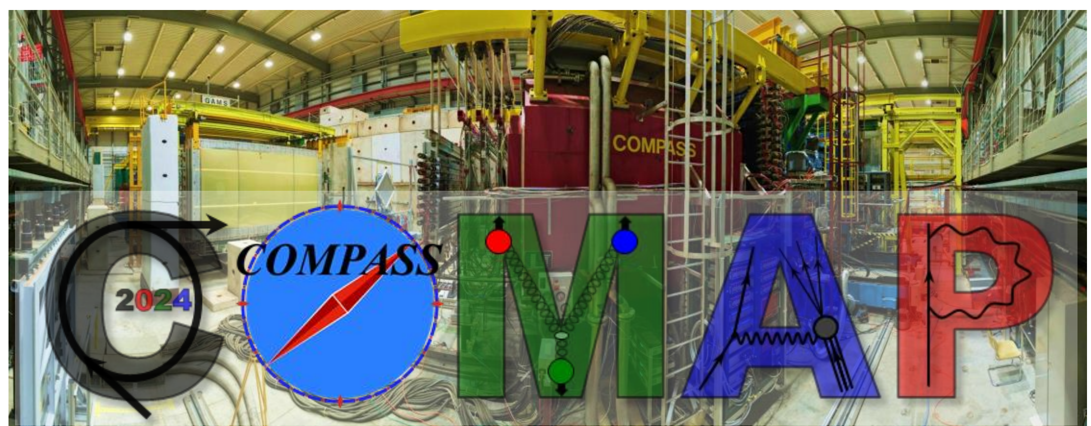
SIDIS longitudinal-spin-dependent asymmetries at COMPASS

Bakur Parsamyan

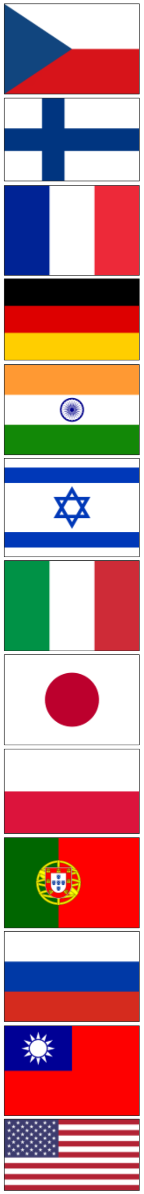
AANL(Yerevan), CERN
and
INFN (Torino)

6th COMPASS Analysis Phase mini-workshop (COMAP-VI)
January 24th, 2024, CERN



COMPASS collaboration

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



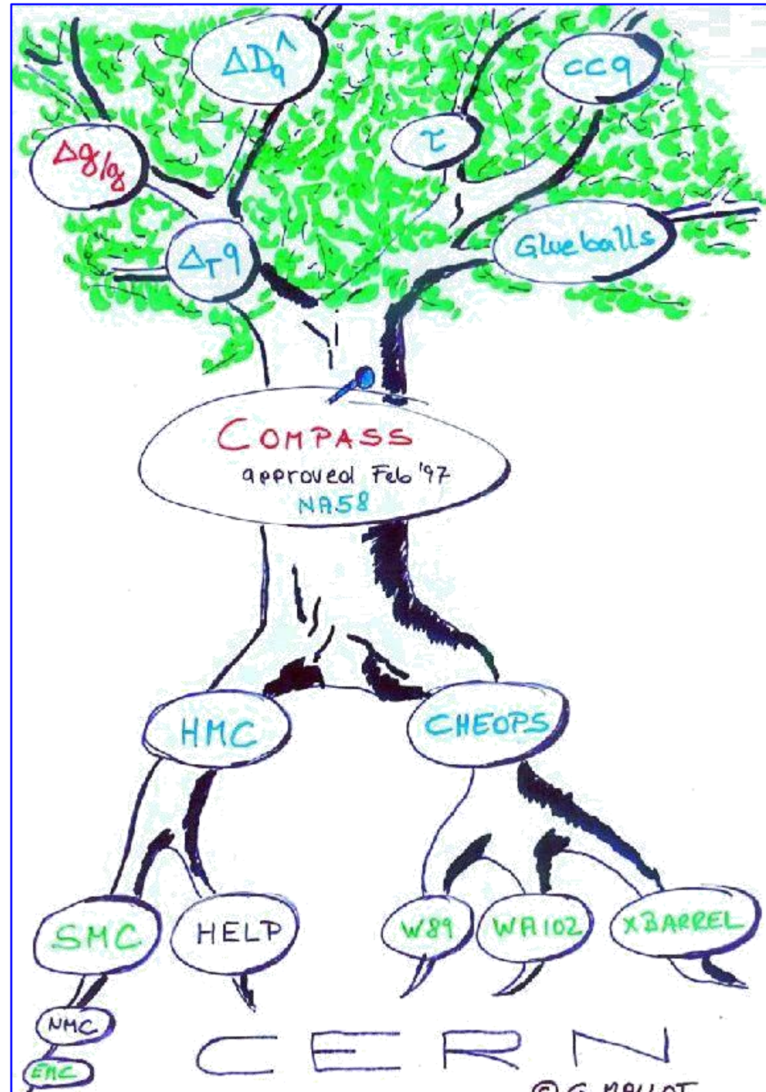
25 institutions from 13 countries
– nearly 200 physicists (in 2022)

- **CERN SPS north area**
- **Fixed target experiment**
- **Approved in 1997 (25 years)**
- **Taking data since 2002 (20 years)**

International Workshop on Hadron Structure and Spectroscopy

IWHSS-2022 workshop (anniversary edition)

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



COMPASS collaboration

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

28 institutions from 14 countries
– nearly 210 physicists (in 2023: start of the Analysis Phase)

3 new groups joined the COMPASS collaboration in 2023
UCon (US), AANL (Armenia), NCU (Taiwan)

- **CERN SPS north area**
- **Fixed target experiment**
- **Approved in 1997 (25 years)**
- **Taking data since 2002 (20 years)**

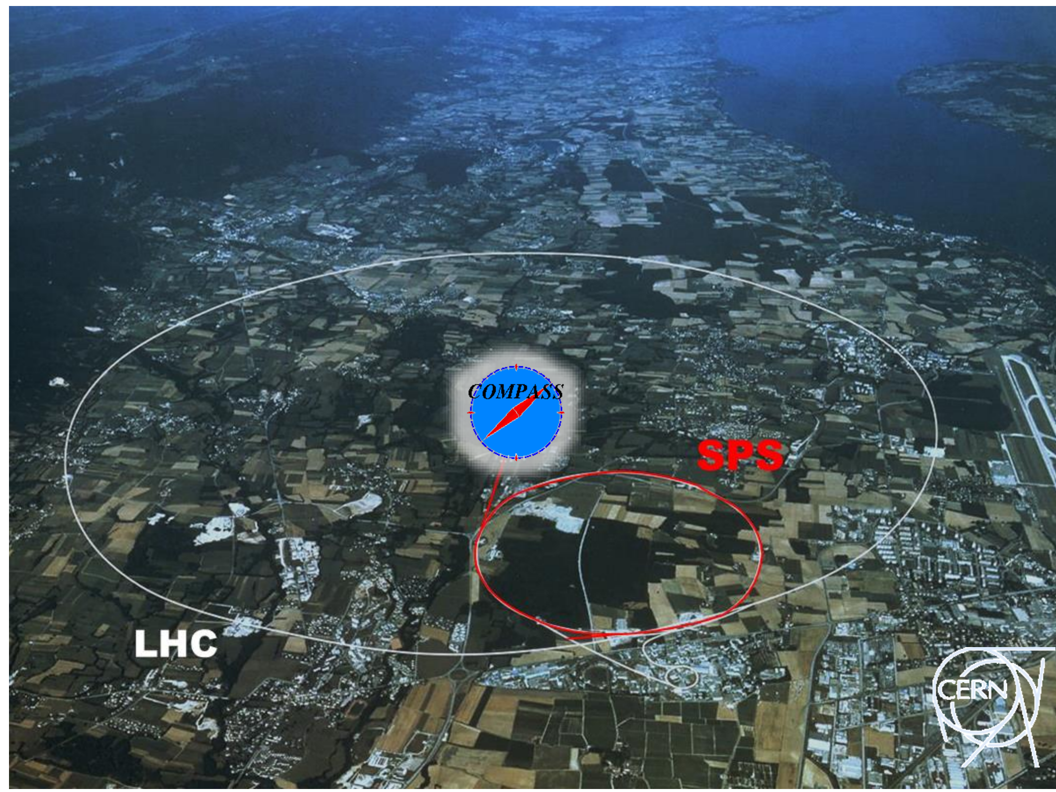
Wide physics program

COMPASS-I

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

COMPASS-II

- **Data taking 2012-2022**
- **Primakoff**
- **DVCS (GPD+SIDIS)**
- **Polarized Drell-Yan**
- **Transverse deuteron SIDIS 2022**



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

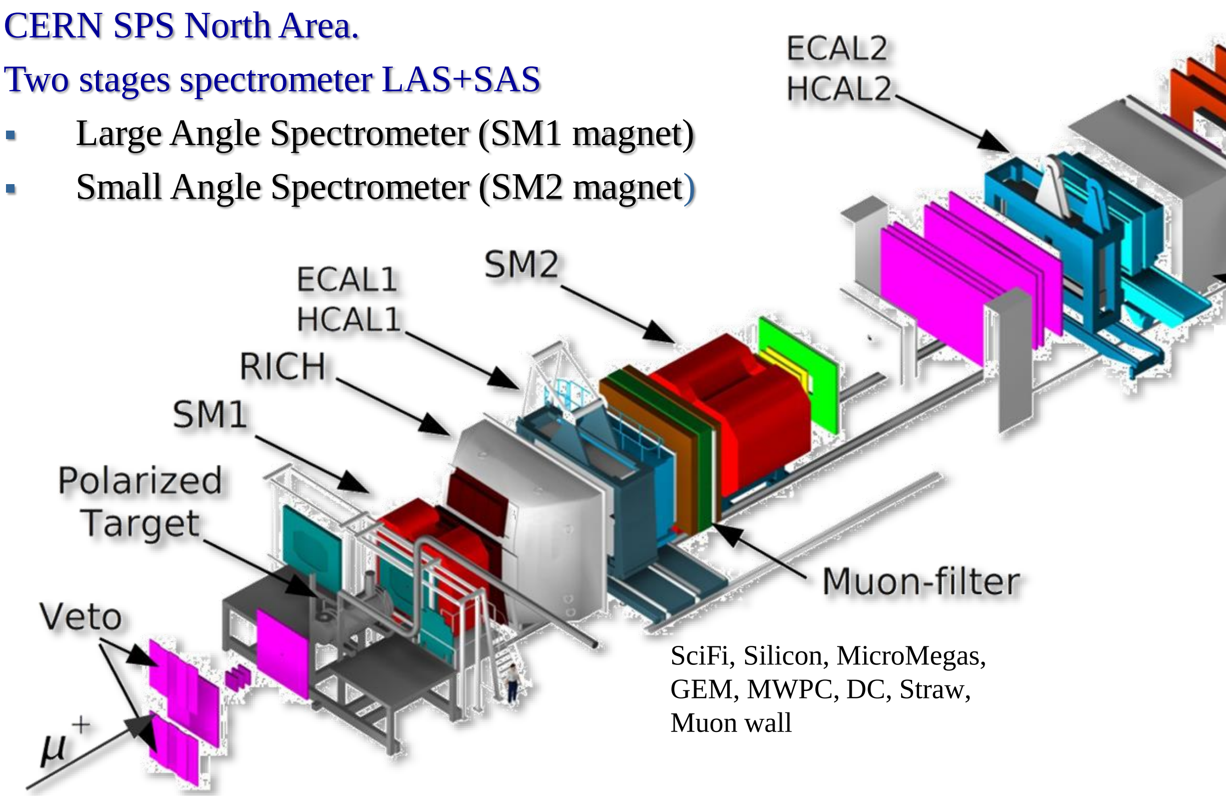
COMPASS experimental setup: Phase I (muon program)

COmmon Muon Proton Apparatus for Structure and Spectroscopy

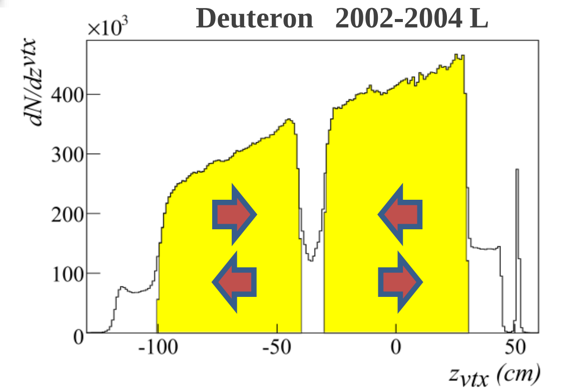
CERN SPS North Area.

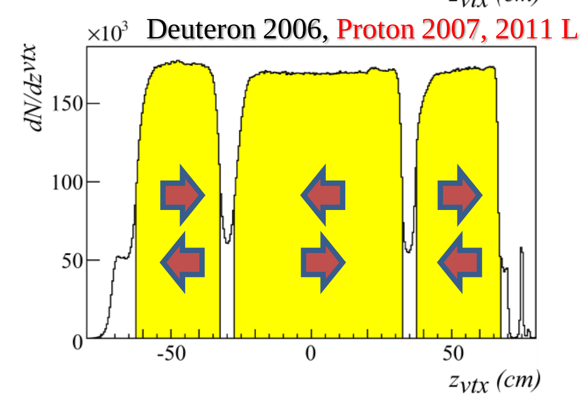
Two stages spectrometer LAS+SAS

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



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





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

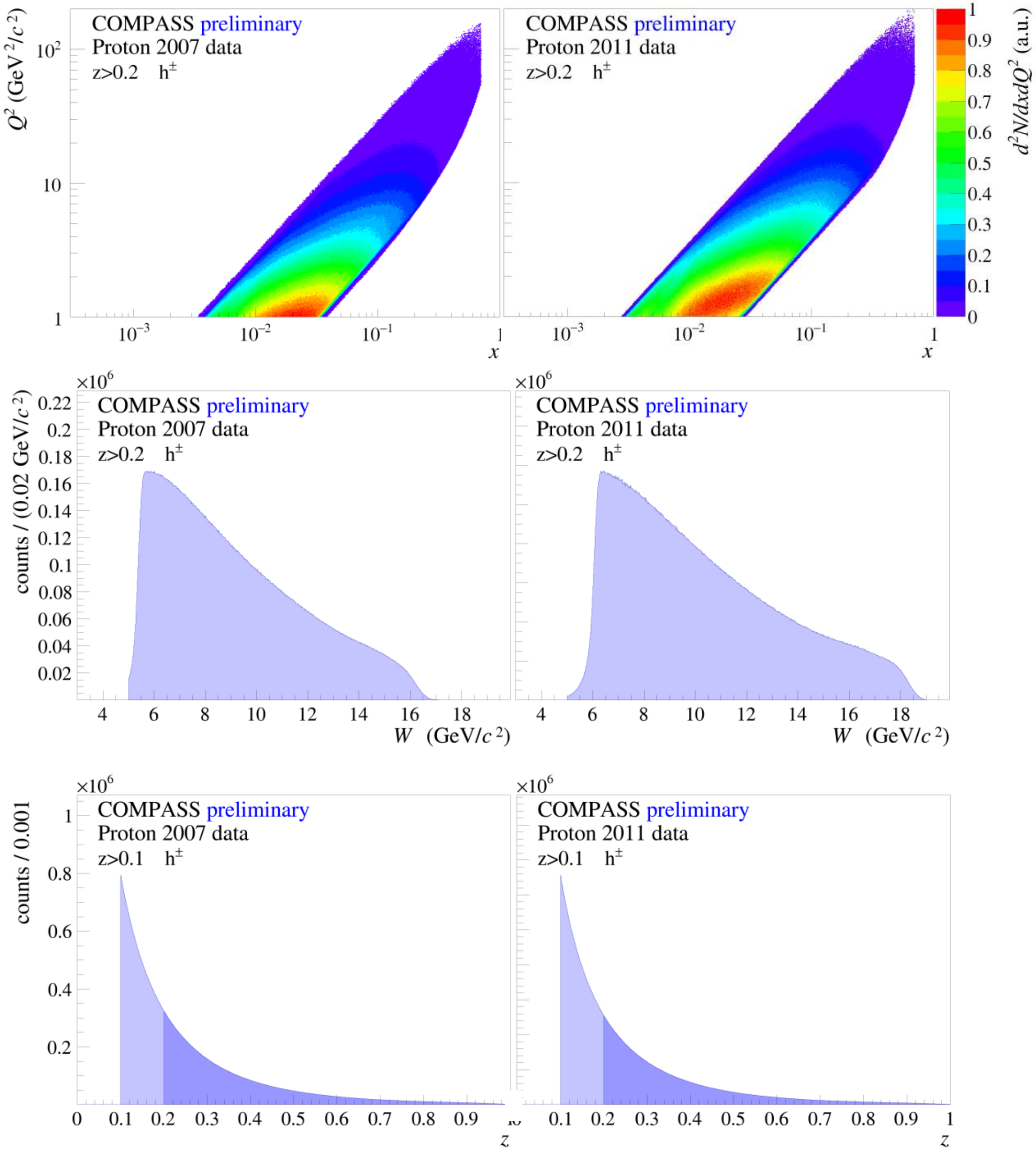
Target: Solid state (^6LiD or NH_3)

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

Data-taking years: 2002-2011

Data is collected simultaneously for the two target spin orientations
Polarization reversal after each ~1-2 days

Kinematics 2007(160 GeV/c), 2011 (200 GeV/c)



Two years of longitudinal data with NH_3 target:
2007: 160 GeV μ^+ – beam
2011: 200 GeV μ^+ – beam

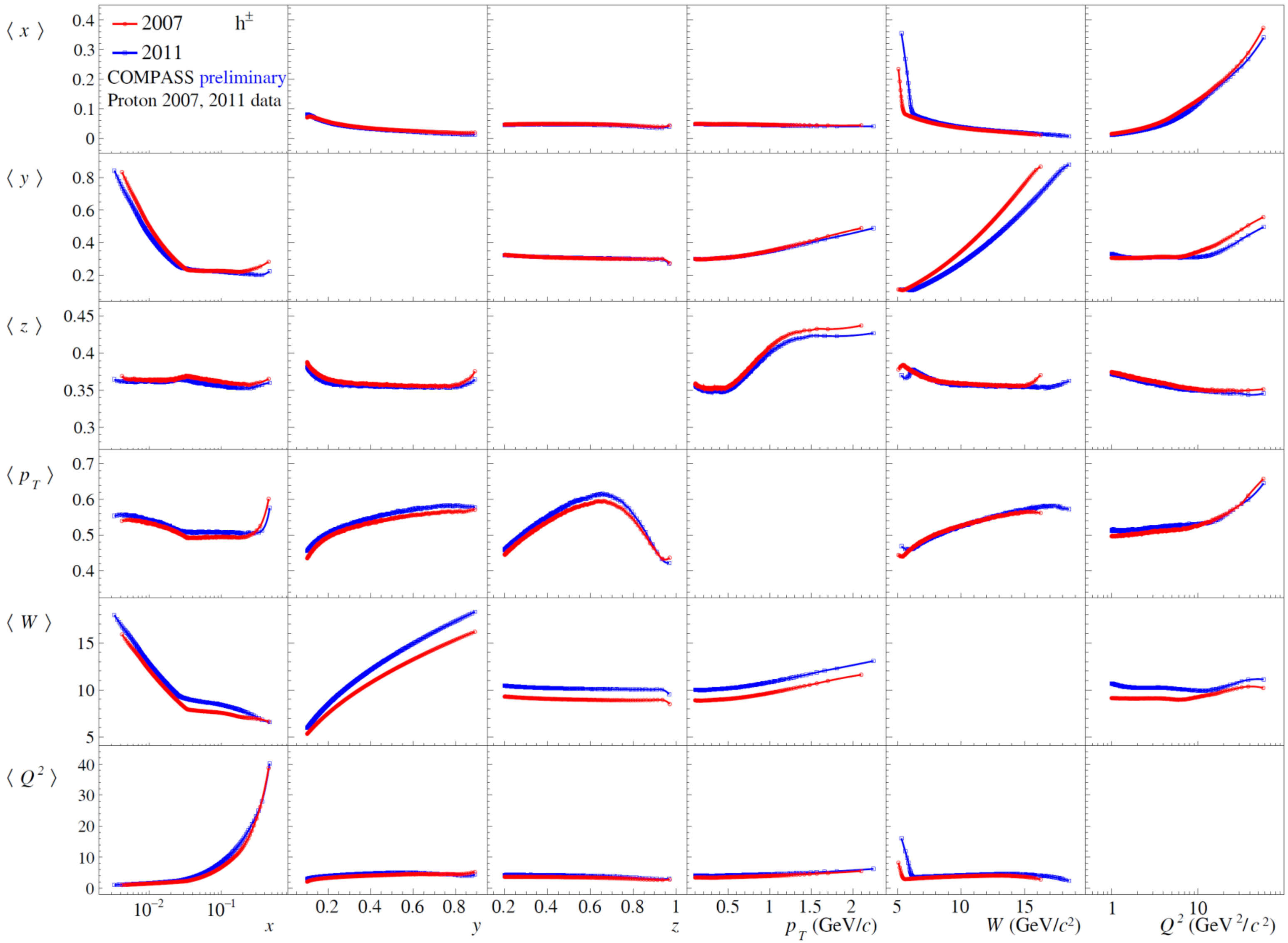
Kinematic cuts

DIS variables:
$Q^2 > 1$ (GeV/c)^2
$0.0025 < x < 0.7$
$0.1 < y < 0.9$
$W > 5$ GeV/c^2

Hadronic cuts:
z>0.2, 0.1<z<0.2
p_T>0.1 GeV/c

Comparable kinematic distributions

Kinematics 2007(160 GeV/c), 2011 (200 GeV/c)



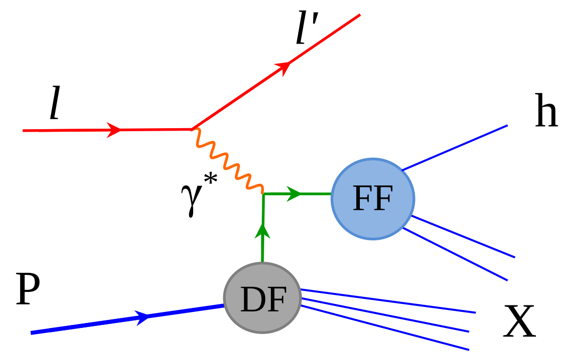
Comparable kinematic distributions

Only results from merged 2007+2011 sample are shown

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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



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

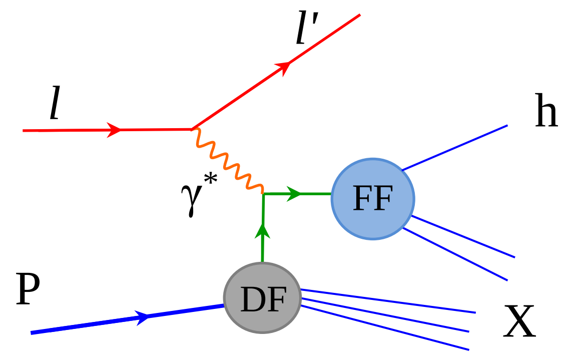
spin of the nucleon **spin of the quark** $\mathbf{k_T}$

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

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



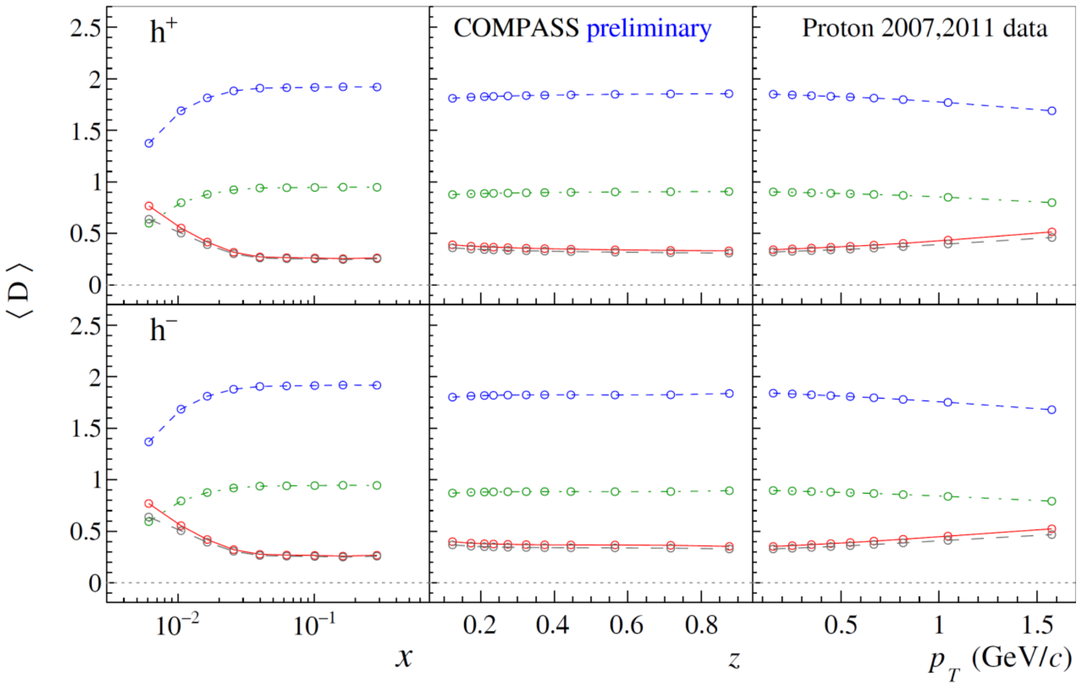
Nucleon \ Quark	U	L	T
U	$f_1^q(x,\boldsymbol{k}_T^2)$ **number density**		$h_1^{\perp q}(x,\boldsymbol{k}_T^2)$ **Boer-Mulders**
L		$g_1^q(x,\boldsymbol{k}_T^2)$ **helicity**	$h_{1L}^{\perp q}(x,\boldsymbol{k}_T^2)$ **worm-gear L**
T	$f_{1T}^{\perp q}(x,\boldsymbol{k}_T^2)$ **Sivers**	$g_{1T}^q(x,\boldsymbol{k}_T^2)$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

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

SIDIS: target longitudinal spin dependent asymmetries

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

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



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

$$D^{\sin(2\phi_h)} = \varepsilon \approx \frac{2(1-y)}{1+(1-y)^2}$$

$$D^{1} = \sqrt{(1-\varepsilon^2)} \approx \frac{y(2-y)}{1+(1-y)^2}$$

$$D^{\cos(\phi_h)} = \sqrt{2\varepsilon(1-\varepsilon)} \approx \frac{2y\sqrt{1-y}}{1+(1-y)^2}$$

SIDIS: target longitudinal spin dependent asymmetries

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

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

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

$$A_{UL}^{\sin\phi_h} \overset{WW}{\propto} Q^{-1}\left(h_{1L}^{\perp q} \otimes H_{1q}^{\perp h} + \ldots\right) \leftarrow \begin{cases} A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h \\ A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h} \end{cases}$$

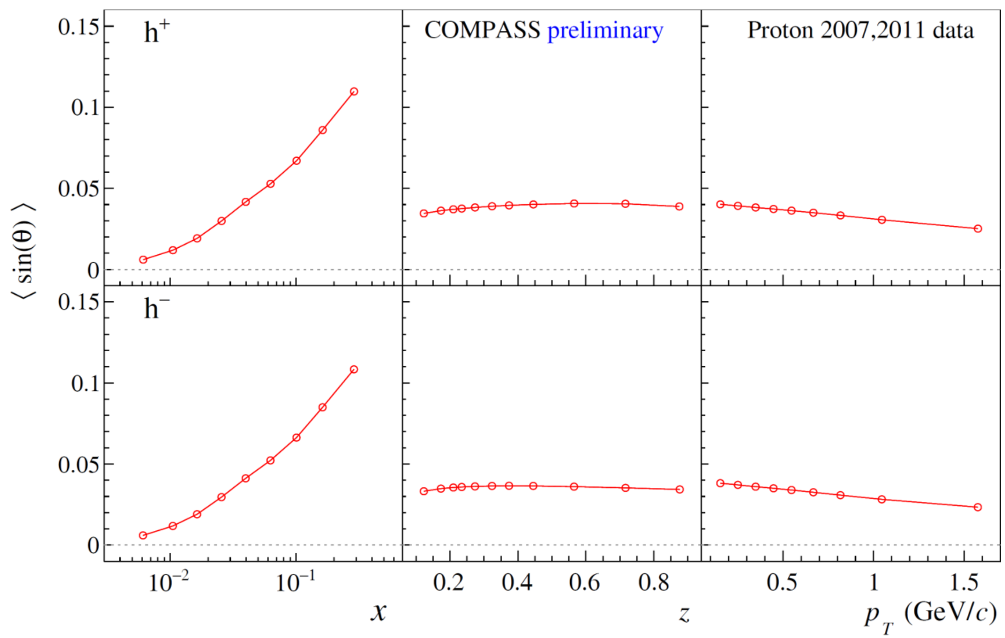
$$A_{UL}^{\sin 2\phi_h} \propto h_{1L}^{\perp q} \otimes H_{1q}^{\perp h} \leftarrow \left\{ A_{UT}^{\sin(2\phi_h-\phi_s)} \overset{WW}{\propto} Q^{-1}\left(h_1^q \otimes H_{1q}^{\perp h} + \ldots\right)\right.$$

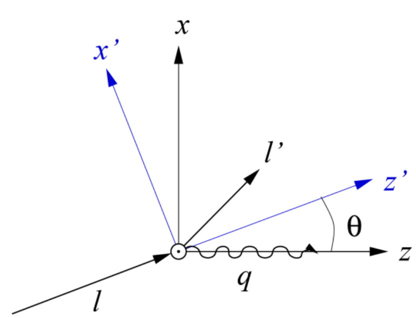
$$A_{UL}^{\sin 3\phi_h} \leftrightarrow A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

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

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

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





lepton plane

$$\sin\theta = \gamma\sqrt{\frac{1-y-\frac{1}{4}\gamma^2 y^2}{1+\gamma^2}}, \quad \gamma = \frac{2Mx}{Q};$$

$$\theta \xrightarrow{\text{Bjorken limit}} 0 \Rightarrow S_T \simeq P_T,\ S_L \simeq P_L$$

SIDIS: target longitudinal spin dependent asymmetries

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

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

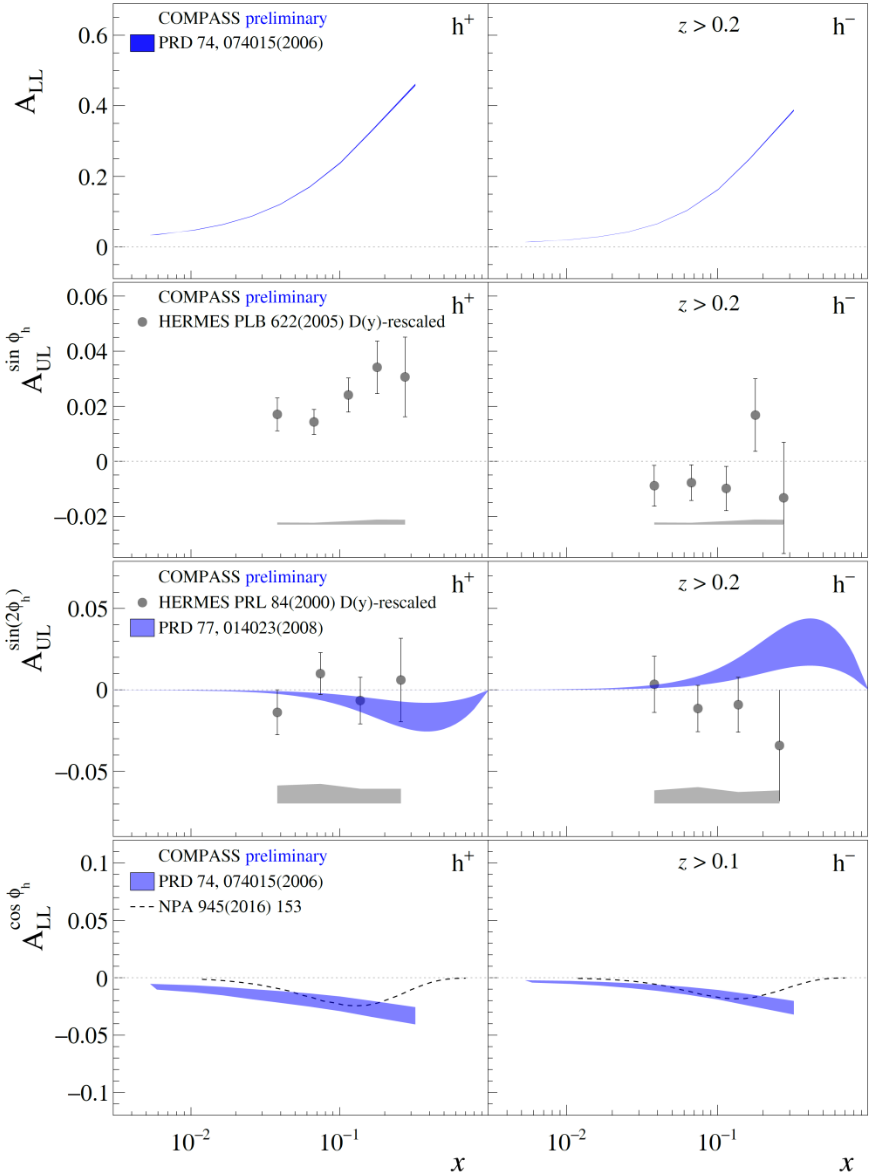
$$+ S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right] \Big\}$$

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

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

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

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



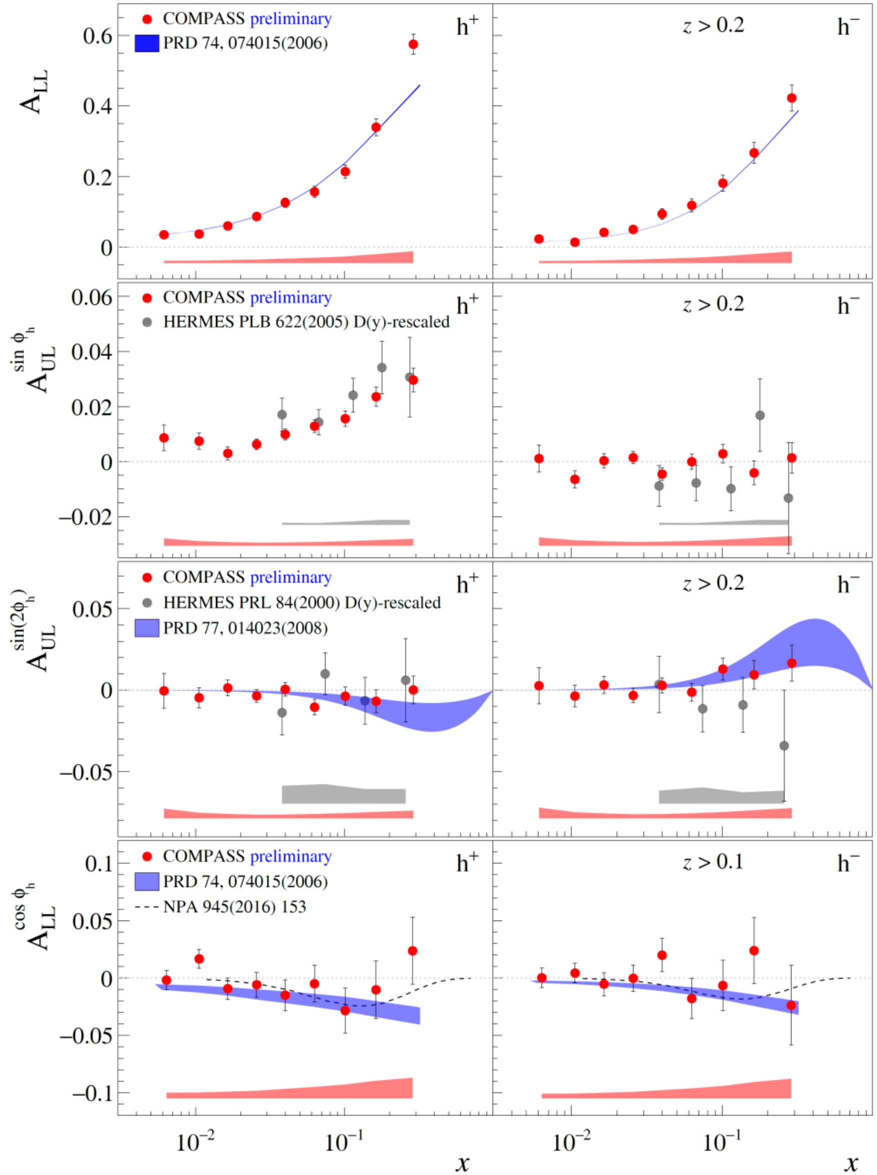
SIDIS: target longitudinal spin dependent asymmetries

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

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

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

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



COMPASS collected large amount of L-SIDIS data

Unprecedented precision for some amplitudes!

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

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

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

- Only "twist-2" ingredients
- Additional p_T-suppression
- Compatible with zero, in agreement with models
- Collins-like behavior?

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

- Q-suppression, Various different "twist" ingredients
- Compatible with zero, in agreement with models

SIDIS: target longitudinal spin dependent asymmetries

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

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

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

COMPASS collected large amount of L-SIDIS data

Unprecedented precision for some amplitudes!

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

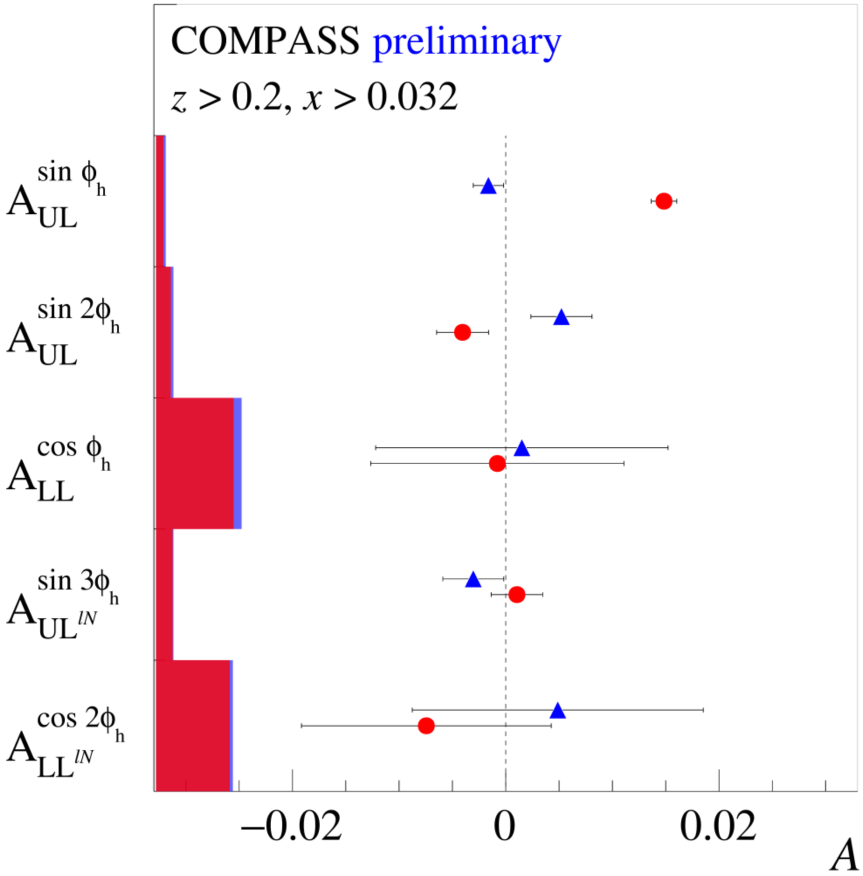
- Q-suppression, Various different "twist" ingredients
- Sizable TSA-mixing
- Significant h^+ asymmetry, clear z-dependence
- h^- compatible with zero

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

- Only "twist-2" ingredients
- Additional p_T-suppression
- Compatible with zero, in agreement with models
- Collins-like behavior?

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

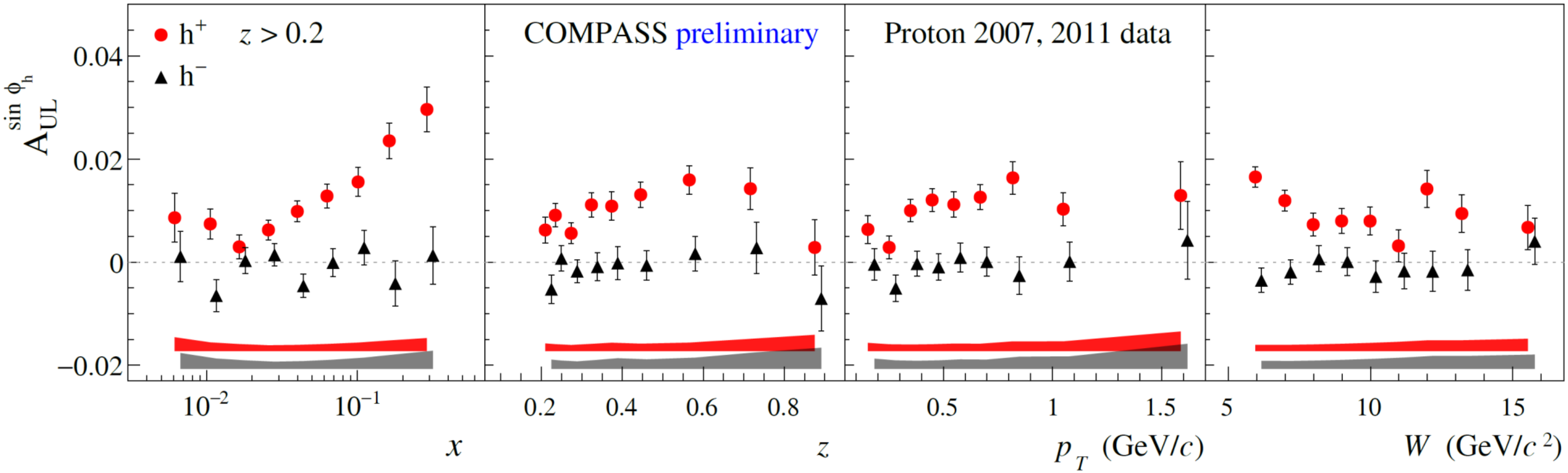
- Q-suppression, Various different "twist" ingredients
- Compatible with zero, in agreement with models



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

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

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

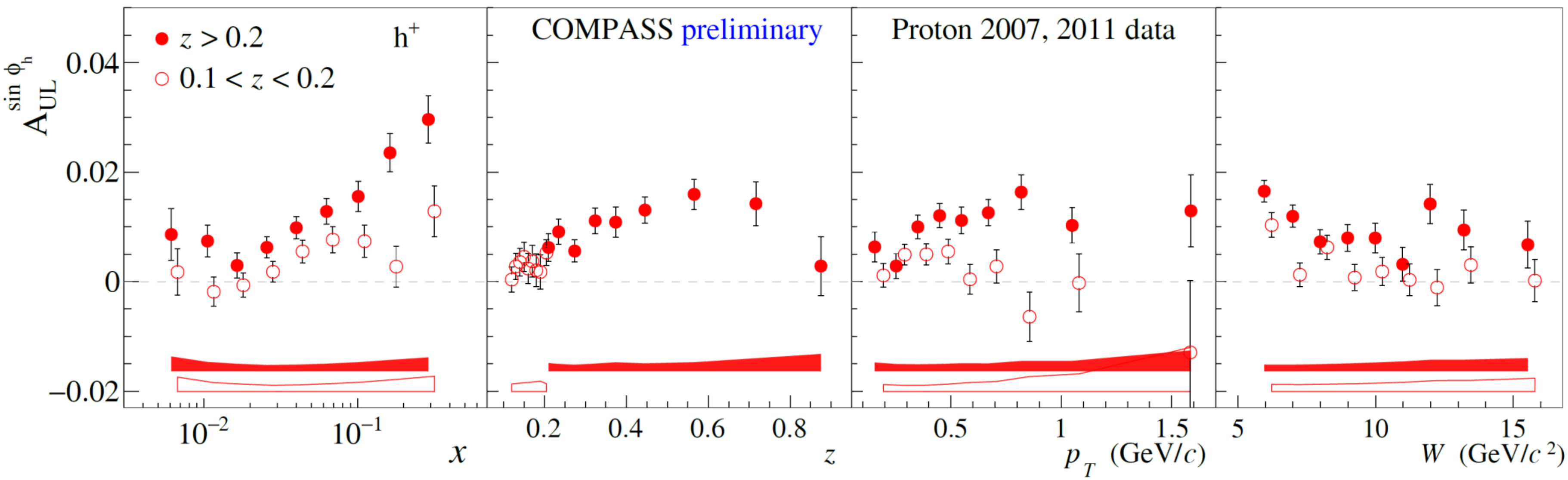


- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- Non-zero trend for h$^+$, h$^-$ compatible with zero

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

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

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

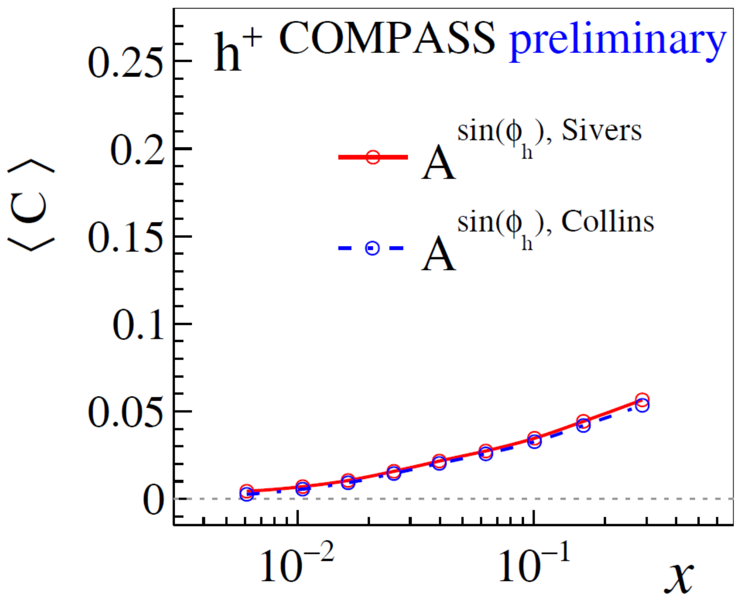


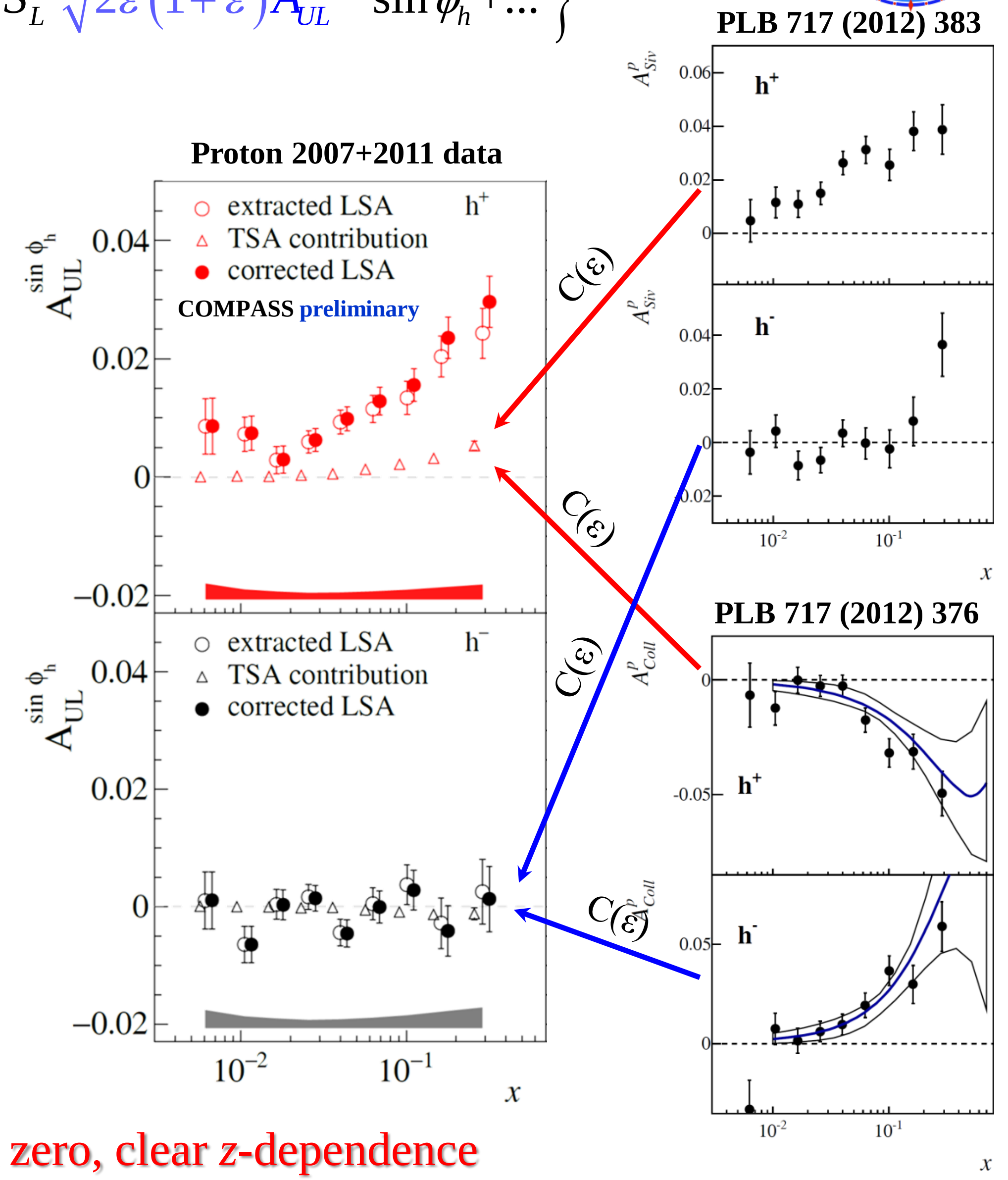
- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- Non-zero trend for h^+, h^- compatible with zero, clear *z*-dependence

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

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

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



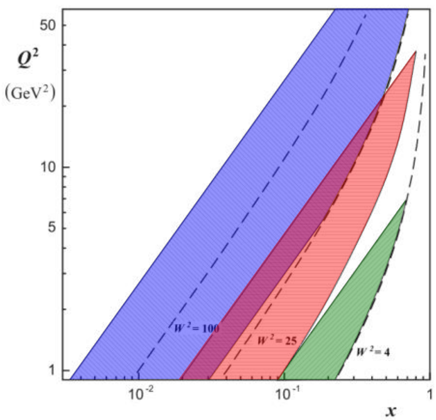


- Q-suppression, TSA-mixing
- Various different "twist" ingredients
- Non-zero trend for h⁺, h⁻ compatible with zero, clear z-dependence

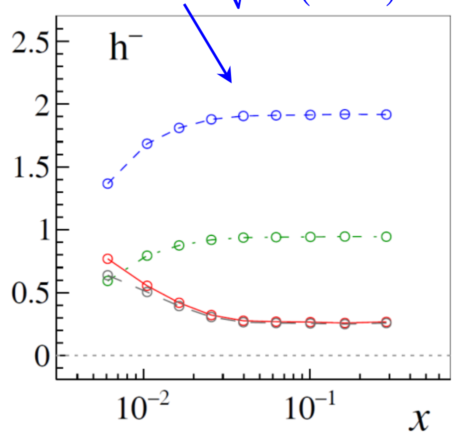
The $A_{UL}^{\sin\phi_h}$ asymmetry

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

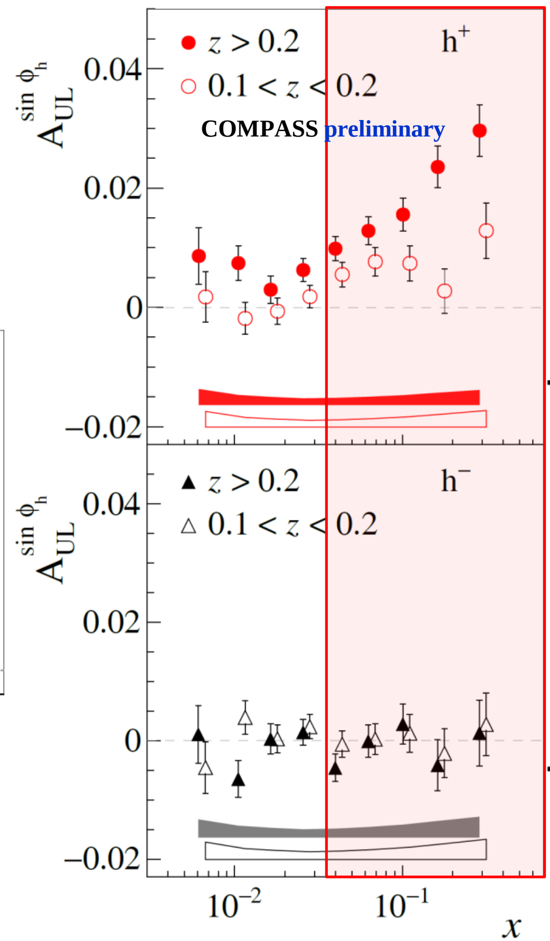
$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(x h_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(x f_L^{\perp q} D_{1q}^h - \frac{M_h}{M}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



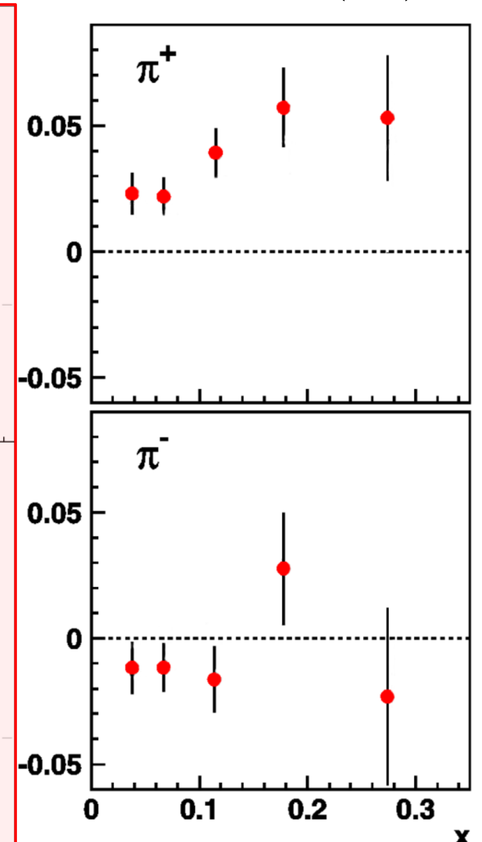
$$D^{\sin(\phi_h)} = \sqrt{2\varepsilon(1+\varepsilon)}$$



Proton 2007+2011 data



HERMES PLB 622 (2005) 14



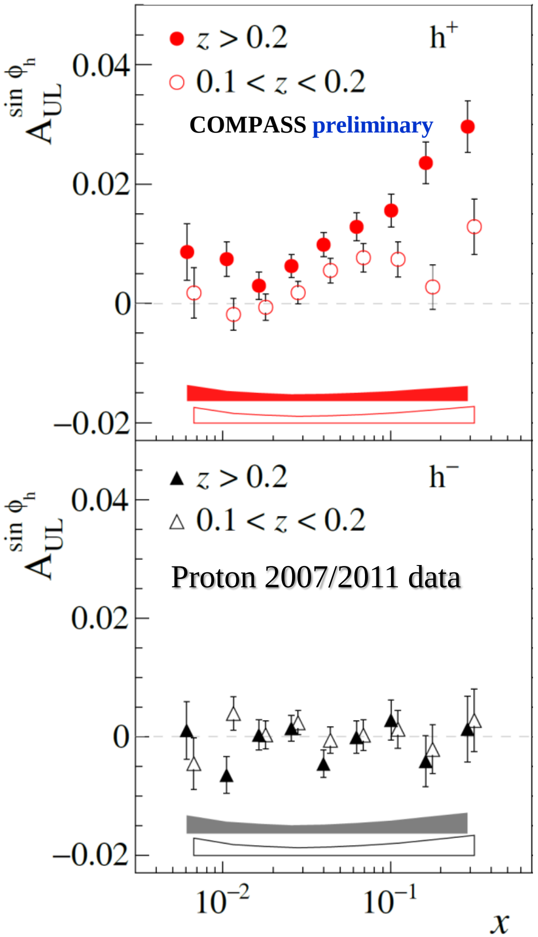
- Q-suppression, TSA-mixing
- Various different "twist" ingredients
- Non-zero trend for h$^+$, h$^-$ compatible with zero, clear z-dependence

SIDIS: target longitudinal spin dependent asymmetries

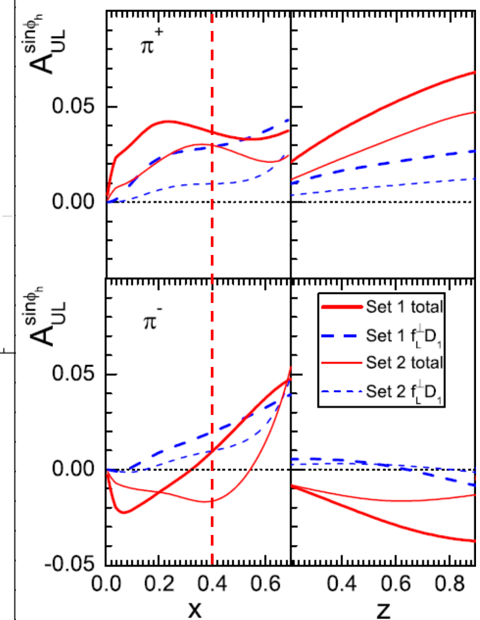
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \ldots\right\}$$

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

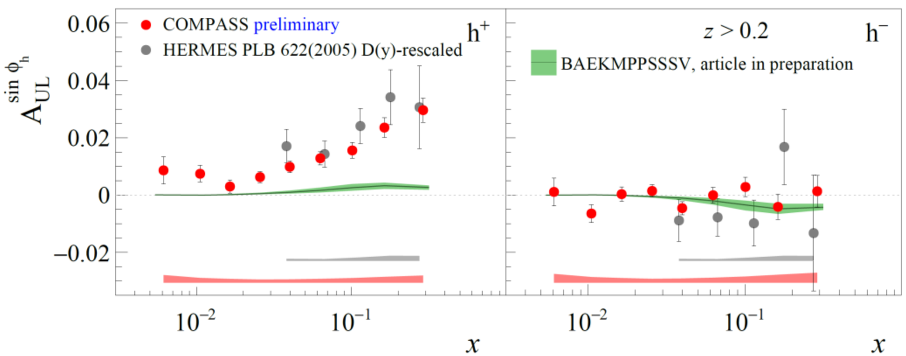
B. Parsamyan (for COMPASS)
arXiv:1801.01488 [hep-ex]



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



S. Bastami et al. JHEP 1906 (2019) 007:
"SIDIS in Wandzura-Wilczek-type approximation"



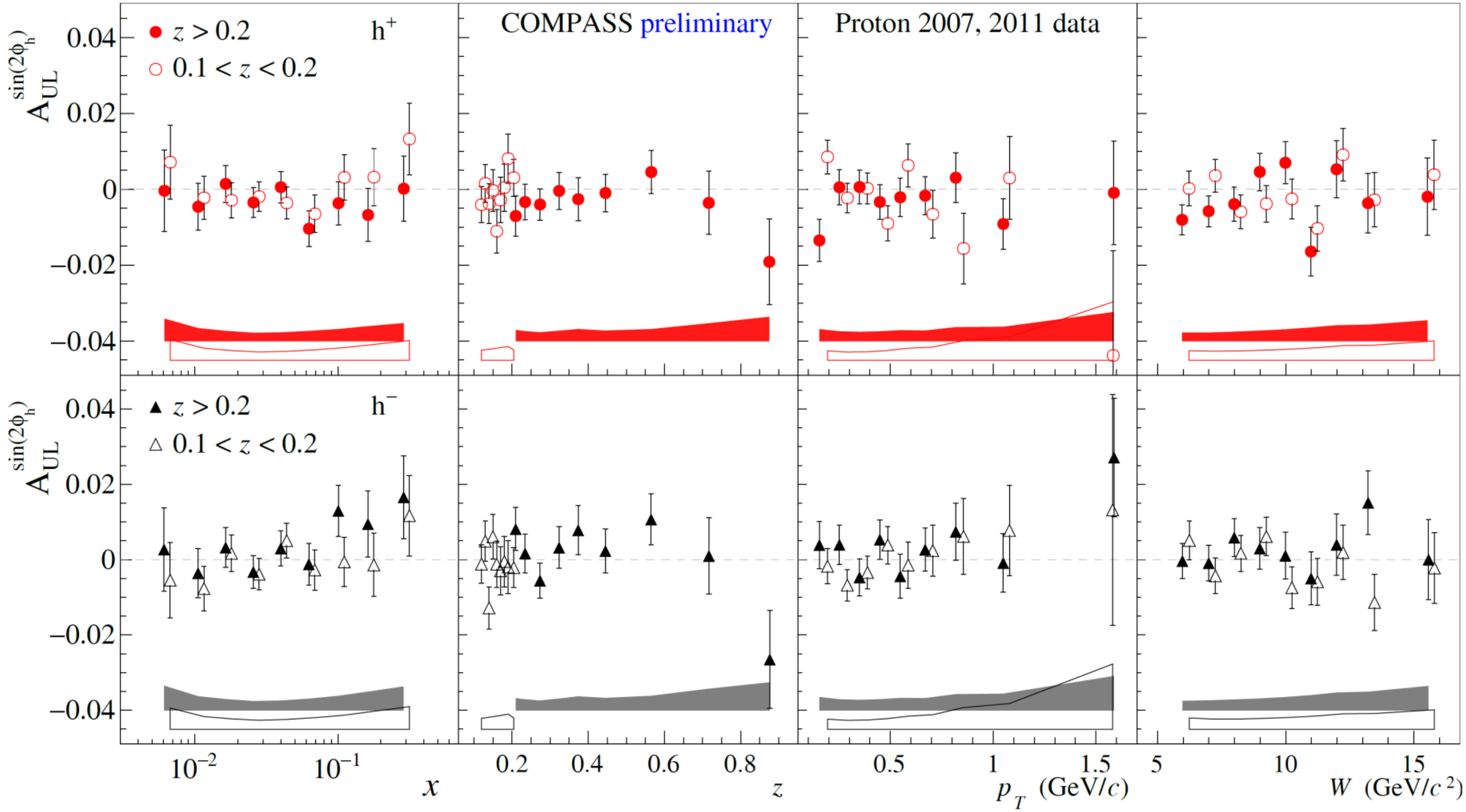
- Q-suppression, TSA-mixing
- Various different "twist" ingredients
- Non-zero trend for h^+, h^- compatible with zero, clear z-dependence

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

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

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

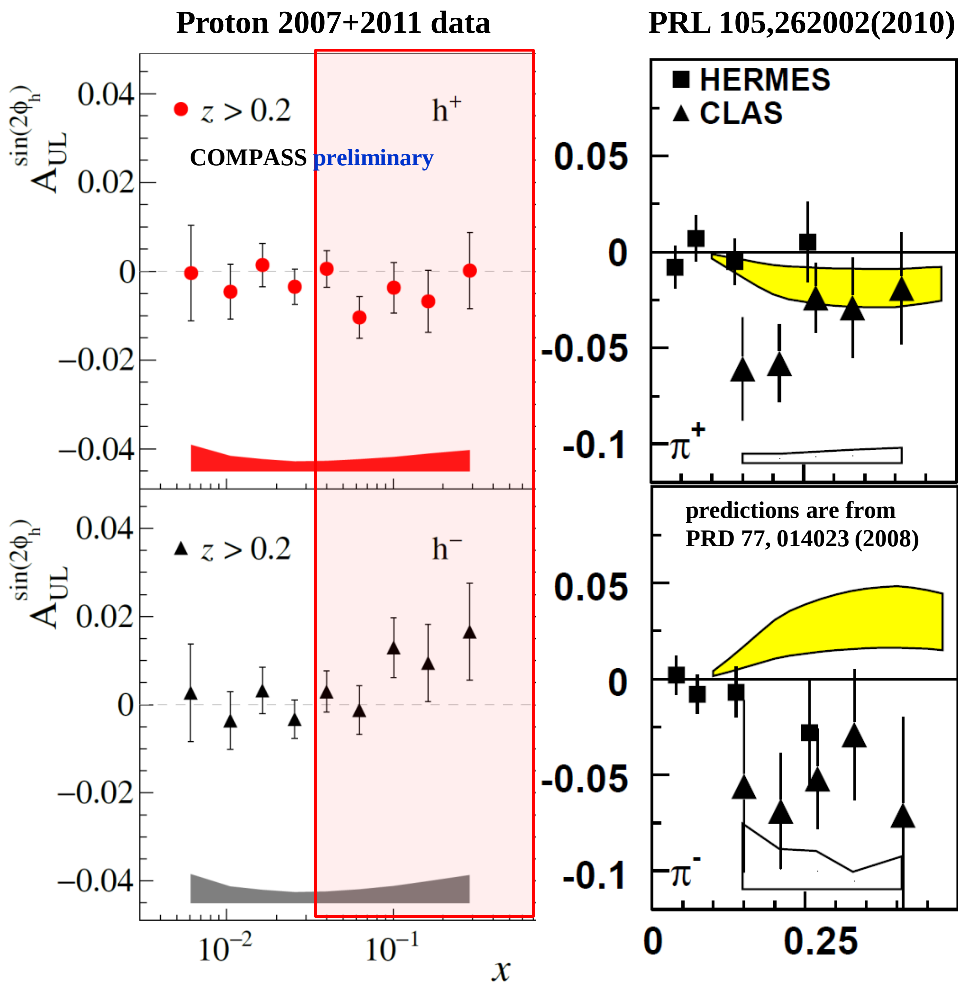
- Only "twist-2" ingredients
- Additional p_T-suppression



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

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

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

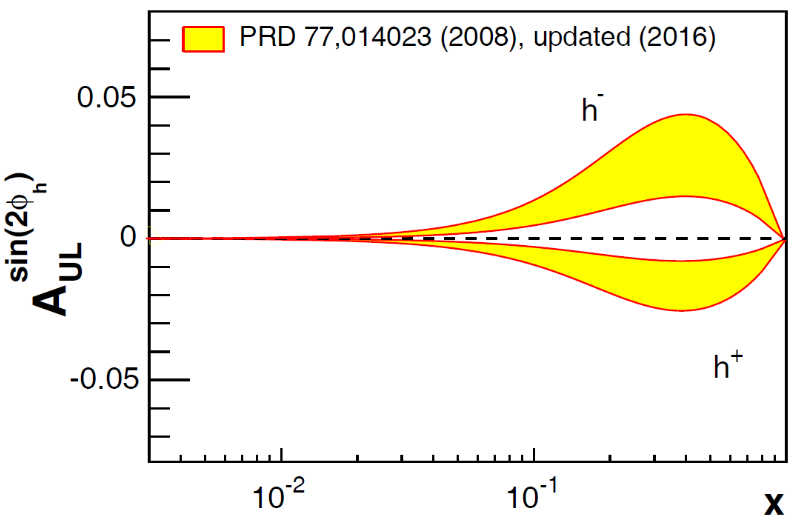


- Only "twist-2" ingredients
- Additional p_T-suppression
- Collins-like behavior?
- In agreement with model predictions
- Discrepancy with HERMES and JLab?

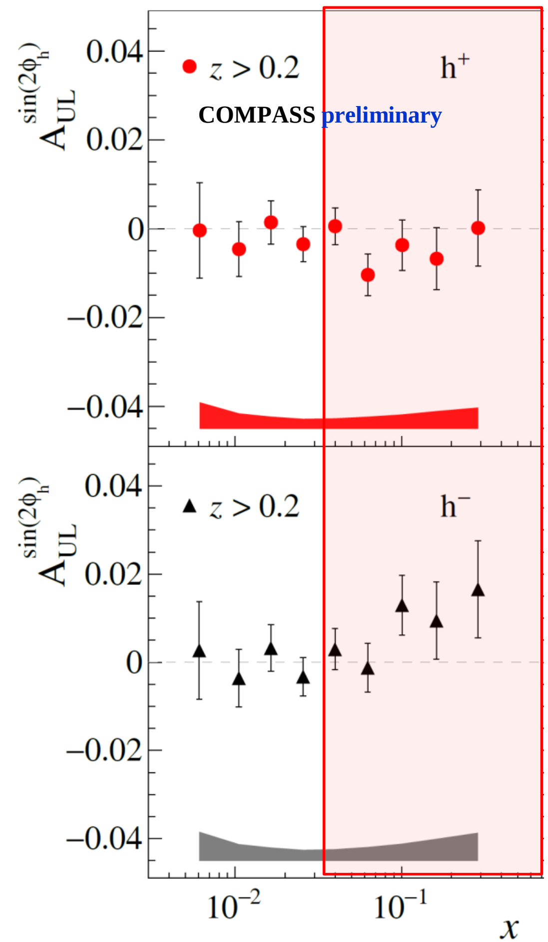
The $A_{UL}^{\sin 2\phi_h}$ asymmetry

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

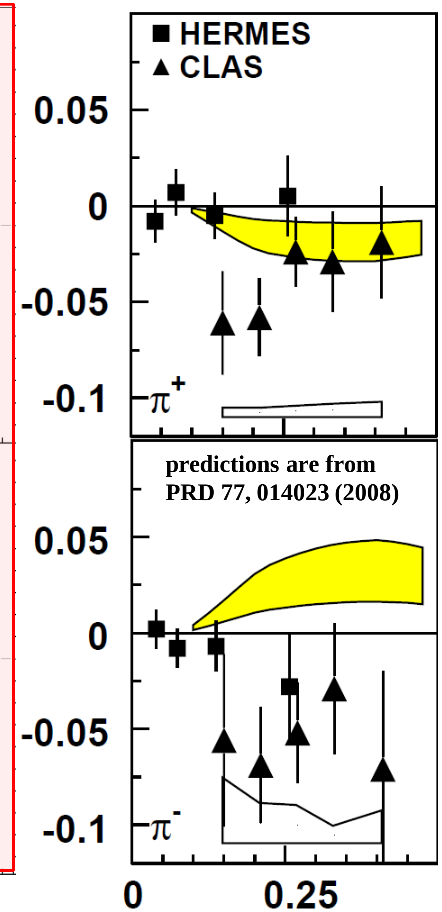
$$F_{UL}^{\sin 2\phi_h} = \mathcal{C}\left\{-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right) - \boldsymbol{p}_T\cdot\boldsymbol{k}_T}{MM_h} h_{1L}^{\perp q} H_{1q}^{\perp h}\right\}$$



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?

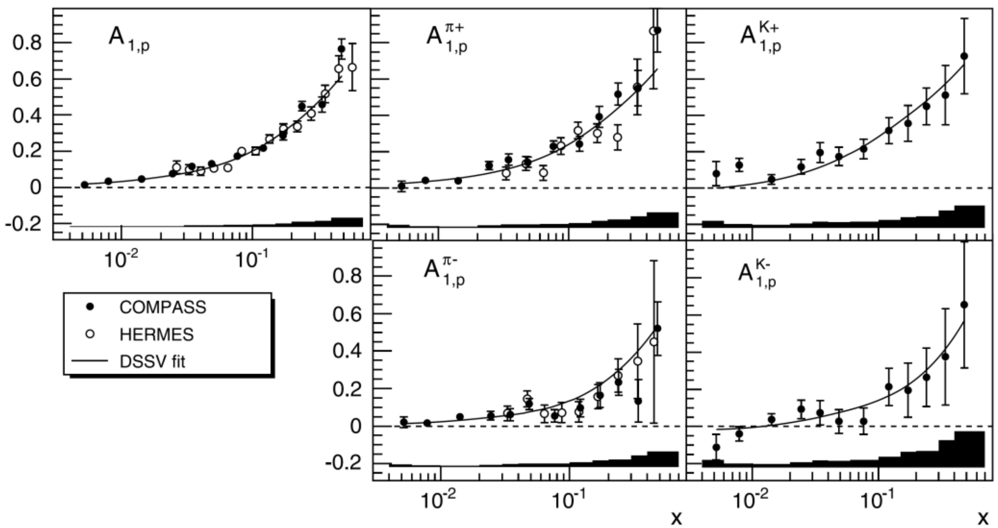
The A_{LL} asymmetry

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

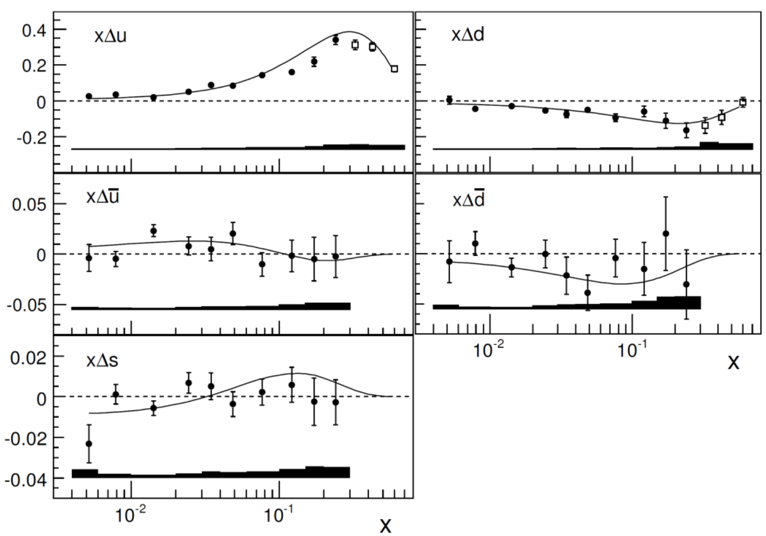
$$F_{LL}^1 = \mathcal{C}\left\{g_{1L}^q D_{1q}^h\right\}$$

- Measurement of (semi-)inclusive $A_1(A_{LL})$ is one of the key physics topics of HERMES/COMPASS
- Large amount of P/D data
- No P_T-dependence observed

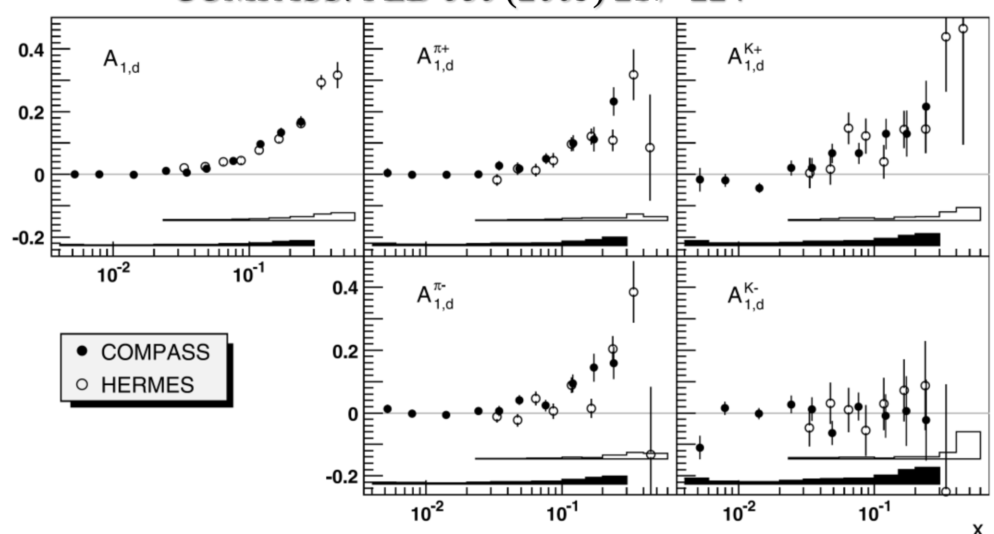
COMPASS: PLB 693 (2010) 227–235



COMPASS: PLB 693 (2010) 227–235



COMPASS: PLB 680 (2009) 217–224

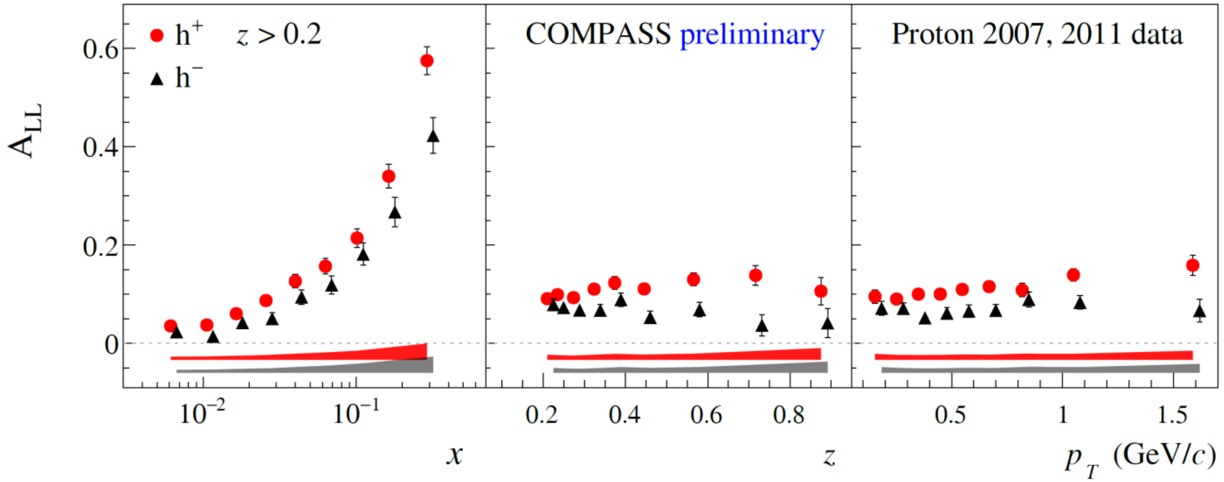


The A_{LL} asymmetry

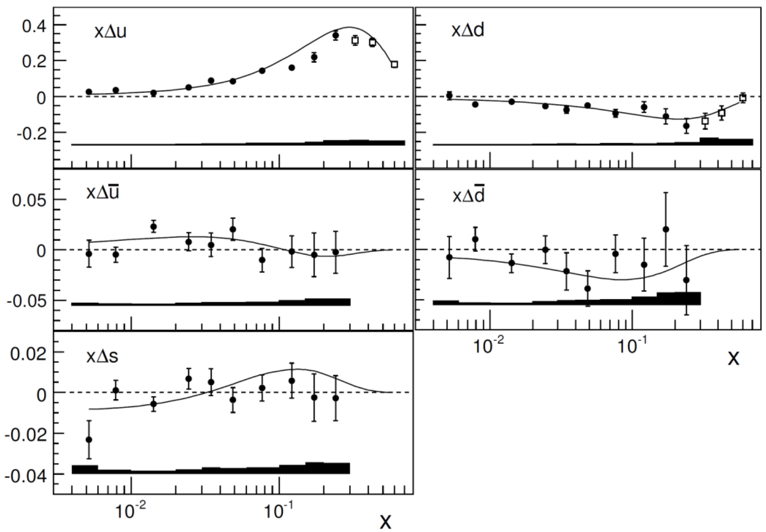
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL} + \ldots\right\}$$

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

- Measurement of (semi-)inclusive A_1(A_{LL}) is one of the key physics topics of HERMES/COMPASS
- Large amount of P/D data
- No P_T-dependence observed



PLB 693 (2010) 227–235

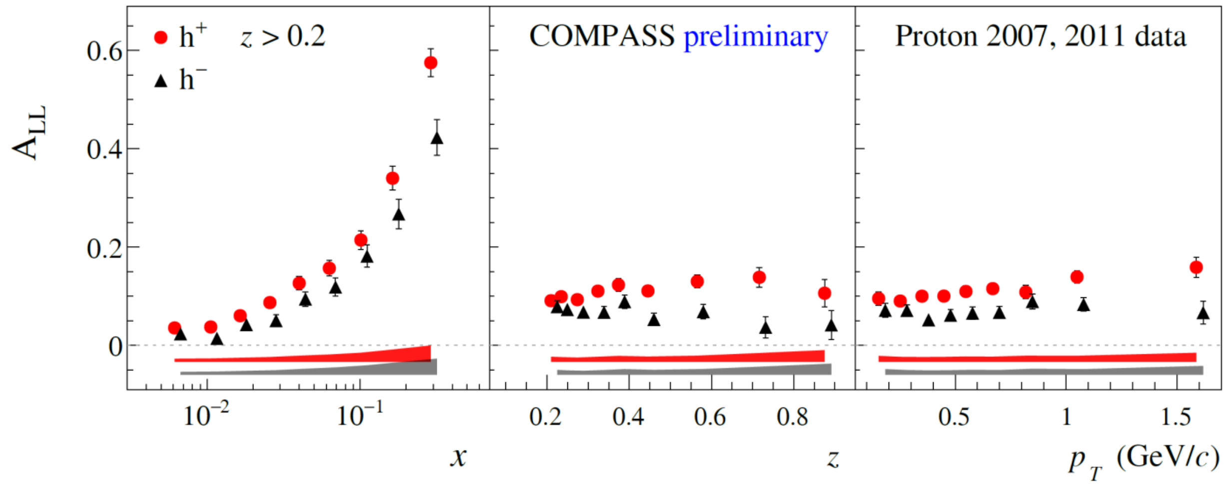


The A_{LL} asymmetry

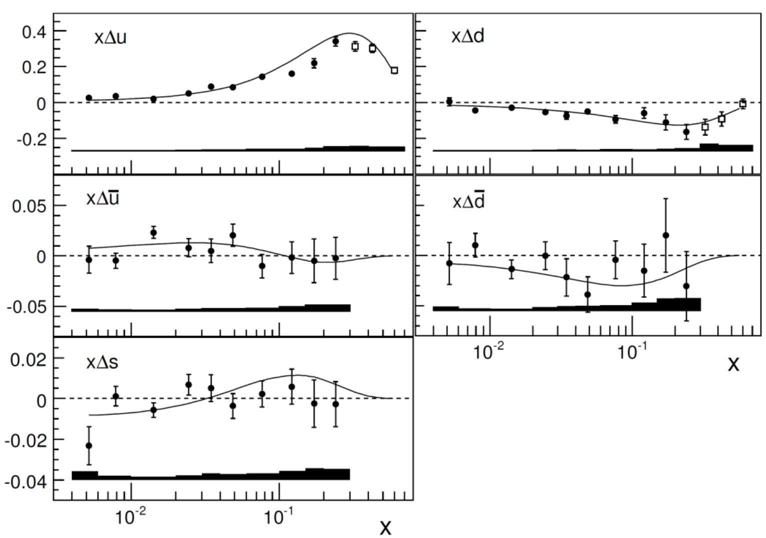
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL} + \ldots\right\}$$

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

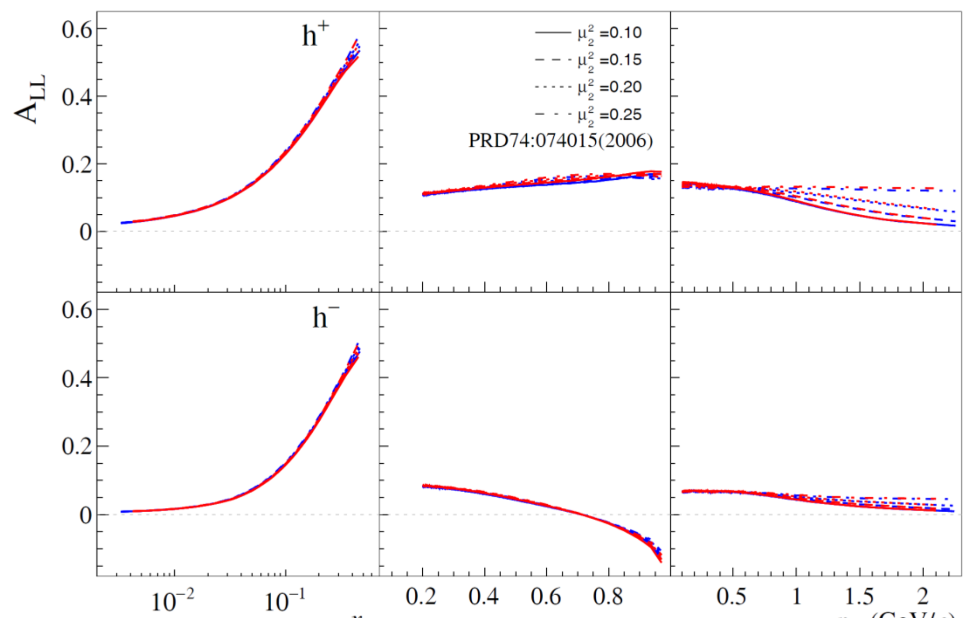
- Measurement of (semi-)inclusive $A_1(A_{LL})$ is one of the key physics topics of HERMES/COMPASS
- Large amount of P/D data
- No P_T-dependence observed



PLB 693 (2010) 227–235



COMPASS Proton-2007, -2011 kinematics

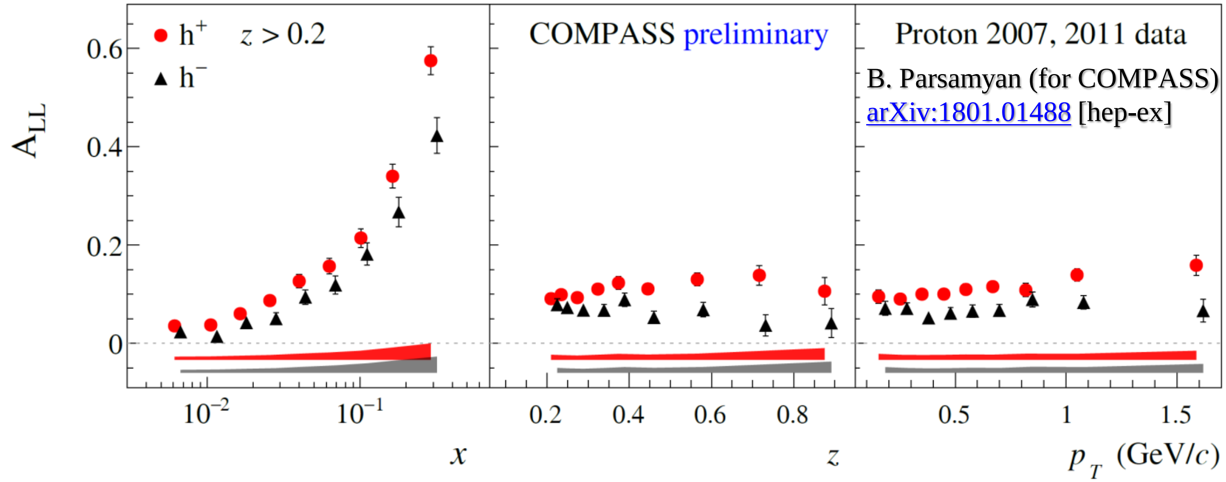


SIDIS: target longitudinal spin dependent asymmetries

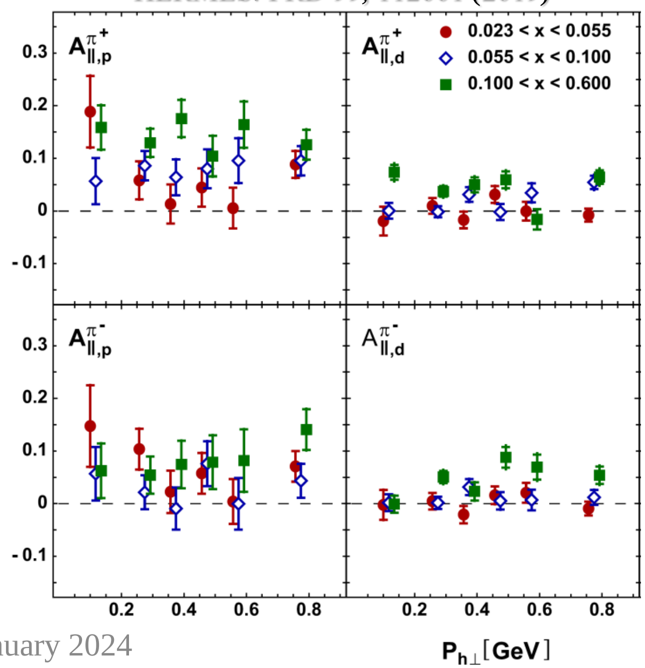
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL} + \ldots\right\}$$

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

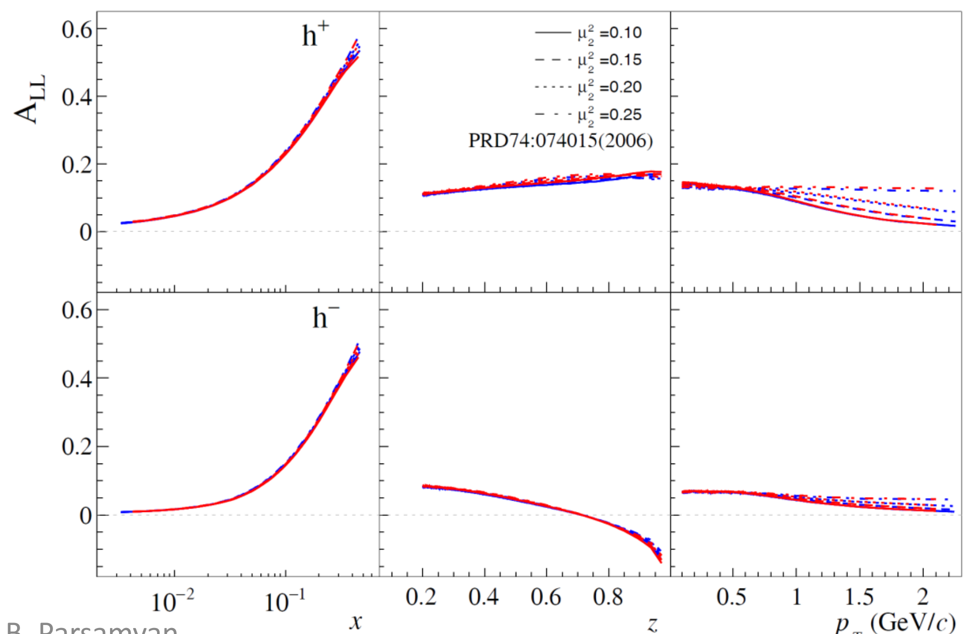
- Measurement of (semi-)inclusive $A_1(A_{LL})$ is one of the key physics topics of HERMES/COMPASS
- Large amount of P/D data
- No P_T-dependence observed



HERMES: PRD 99, 112001 (2019)



COMPASS Proton-2007, -2011 kinematics

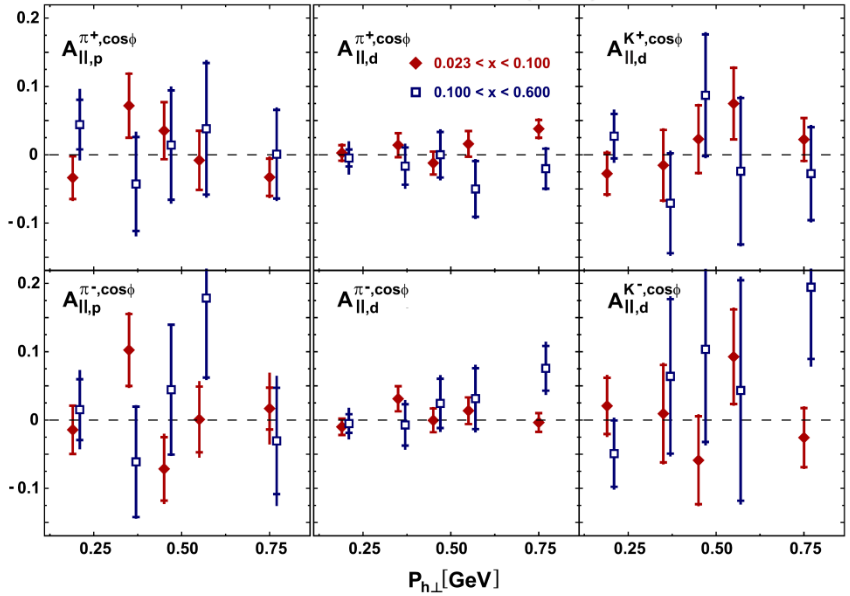


SIDIS: target longitudinal spin dependent asymmetries

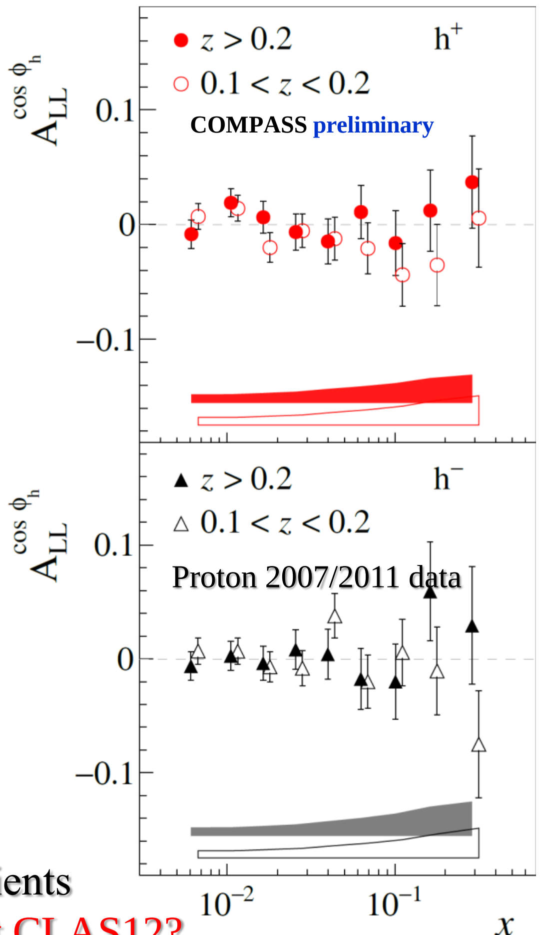
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h + \ldots\right\}$$

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

HERMES: PRD 99, 112001 (2019)



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

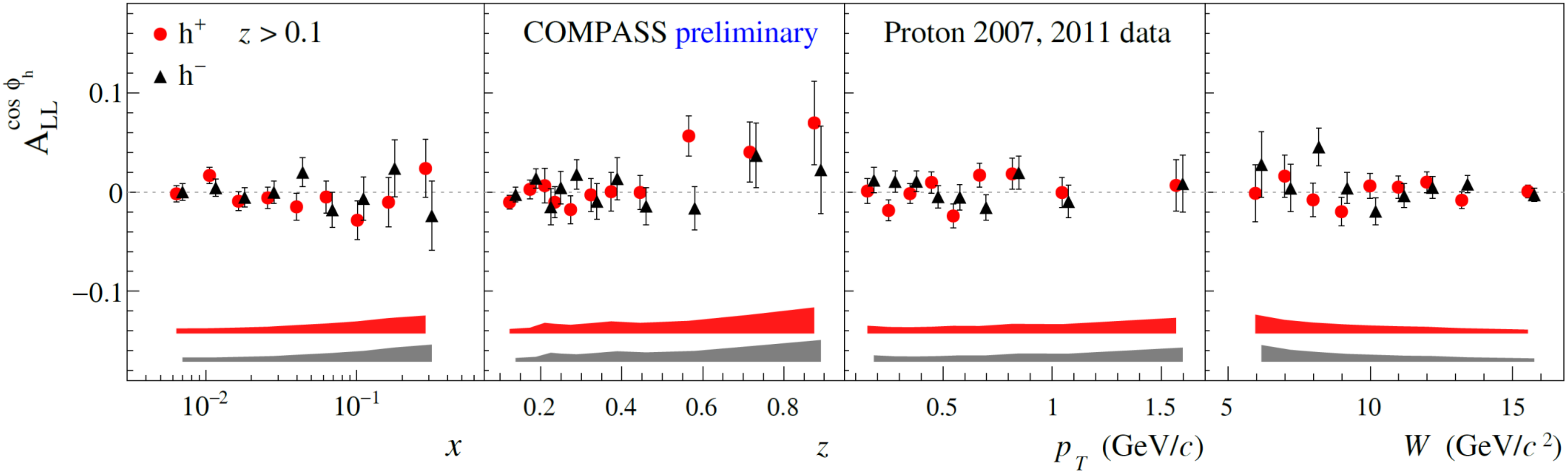


- Q-suppression, various different "twist" ingredients
- Measured to be non zero at CLAS6, what about CLAS12?
- HERMES/COMPASS - small and compatible with zero, in agreement with model predictions

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

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

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



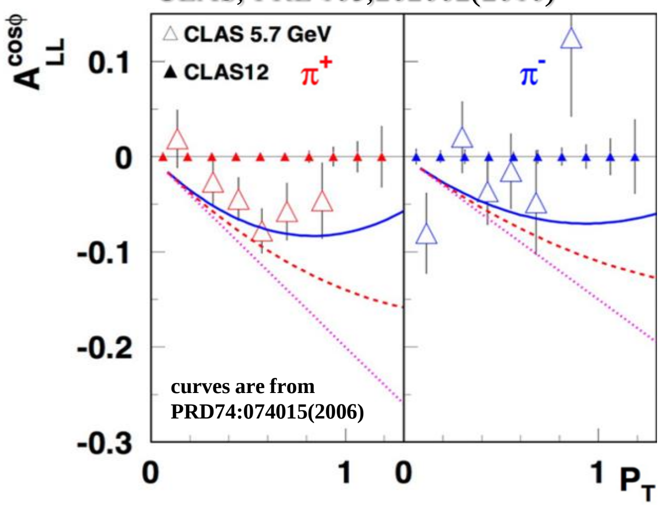
- Q-suppression, various different "twist" ingredients
- Measured to be non zero at CLAS6, what about CLAS12?
- HERMES/COMPASS - small and compatible with zero, in agreement with model predictions

SIDIS: target longitudinal spin dependent asymmetries

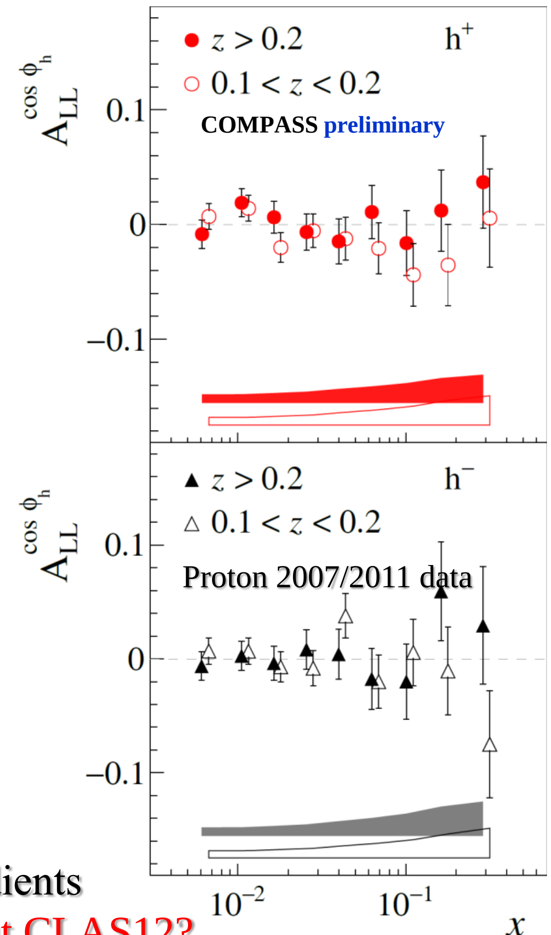
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1+\ldots+ S_L\lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h + \ldots\right\}$$

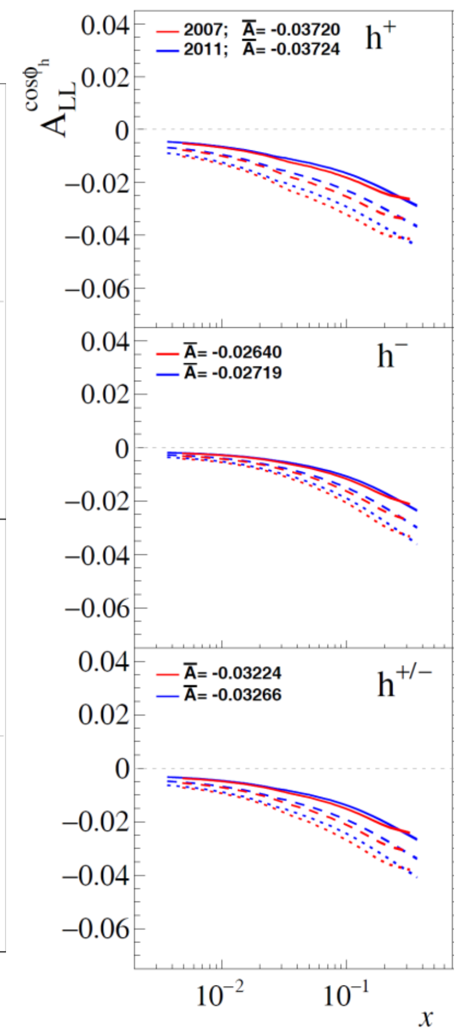
$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h}\left(xe_L^q H_{1q}^{\perp h} + \frac{M_h}{M}g_{1L}^q\frac{\tilde{D}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\left(xg_L^{\perp q}D_{1q}^h - \frac{M_h}{M}h_{1L}^{\perp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

CLAS, PRL 105,262002(2010)



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

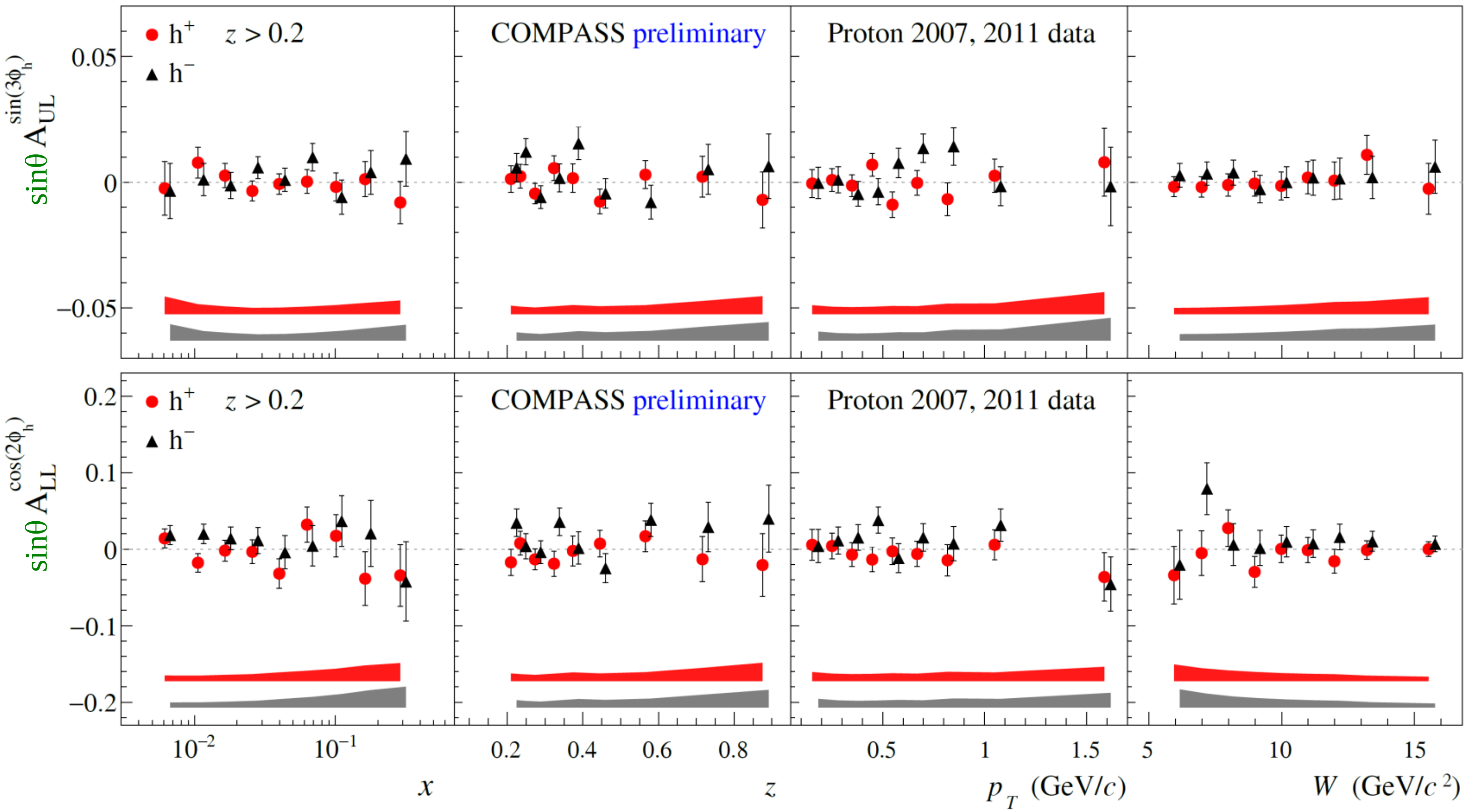




- Q-suppression, various different "twist" ingredients
- Measured to be non zero at CLAS6, what about CLAS12?
- HERMES/COMPASS - small and compatible with zero, in agreement with model predictions

COMPASS results for $A_{UL}^{\sin 3\phi_h}$ and $A_{LL}^{\cos 2\phi_h}$ asymmmetries

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left\{1 + \ldots - \sin\theta\varepsilon A_{UL}^{\sin 3\phi_h} \sin 3\phi_h + P_L \lambda \left[-\sin\theta\sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos 2\phi_h} \cos 2\phi_h + \ldots \right] \right\}$$



- Alternative way to access corresponding TSAs
- $\sin(\theta)$ suppression
- Other suppressions at the "TSA"-level ($|p_T|^3$, Q^{-1})
- Compatible with zero

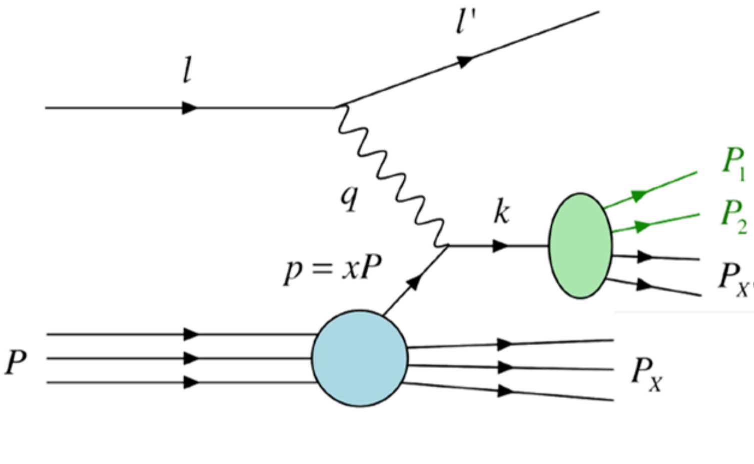
$$A_{UL}^{\sin 3\phi_h} \leftrightarrow A_{UT}^{\sin(3\phi_h - \phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

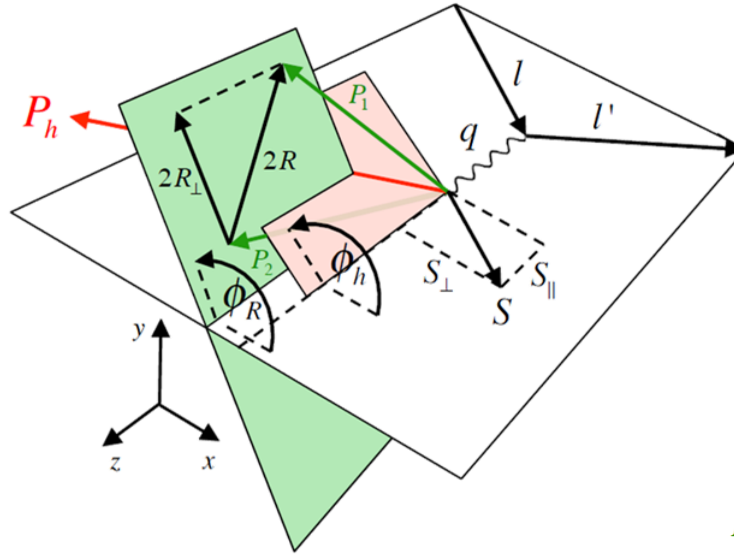
$$A_{LL}^{\cos 2\phi_h} \leftrightarrow A_{LT}^{\cos(2\phi_h - \phi_s)} \propto Q^{-1}\left(g_{1T}^q \otimes D_{1q}^h + \ldots\right)$$

Theoretical Framework: Di-hadron SIDIS

Bacchetta & Radici: Phys. Rev. D69 094002
Bacchetta & Radici & Gliske: Phys. Rev. D90 114027

$$\mu(l) + p(P) \to \mu(l') + h_1^+(P_1) + h_2^-(P_2) + X$$

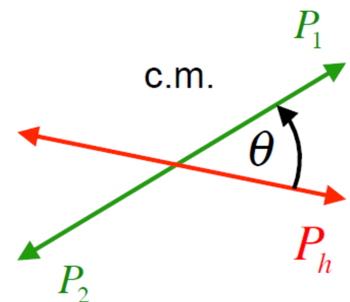




- X-section modulated in azimuthal angles ϕ_h and ϕ_R

$$\boldsymbol{R}_\perp \leftrightarrow \boldsymbol{R}_T = \frac{z_2 \boldsymbol{P}_{1\perp} - z_1 \boldsymbol{P}_{2\perp}}{z_1 + z_2} \qquad \text{with} \qquad z_i = \frac{E_i}{E - E'}$$

- Negligible transverse polarization mixing $S_\perp \approx 0$
- Partial wave expansion in θ, restricted to s- & p-waves



$$\langle\theta\rangle = \pi/2$$

θ is the emission angle between h+ in the c.m. frame and the momentum of the di-hadron in the target rest frame

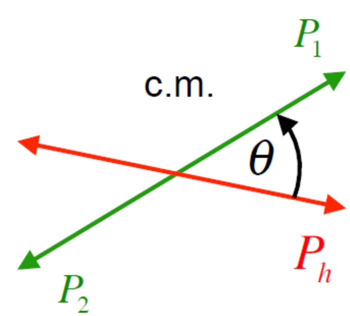
Theoretical Framework: Di-hadron SIDIS at twist-2

$$d\sigma = d\sigma_{UU} + \lambda d\sigma_{LU} + \boldsymbol{S}_L\left(d\sigma_{UL} + \lambda d\sigma_{LL}\right) + \boldsymbol{S}_L\left(d\sigma_{UT} + \lambda d\sigma_{LT}\right)$$

Bacchetta & Radici: Phys. Rev. D69 094002
Bacchetta & Radici & Gliske: Phys. Rev. D90 114027

$$\begin{aligned}
d\sigma_{UL} \propto\; & \sin(\phi_h - \phi_R)\left(A_{UL}^{\sin(\phi_h-\phi_R)\sin\theta}\sin\theta + A_{UL}^{\sin(\phi_h-\phi_R)\sin 2\theta}\sin 2\theta\right) \\
& + \sin(2\phi_h - 2\phi_R)\, A_{UL}^{\sin(2\phi_h-2\phi_R)\sin^2\theta}\sin^2\theta \\
& + \varepsilon\left\{\sin(2\phi_h)\left(A_{UL}^{\sin(2\phi_h)} + A_{UL}^{\sin(2\phi_h)\cos\theta}\cos\theta + A_{UL}^{\sin(2\phi_h)\frac{1}{3}(3\cos^2\theta-1)}\frac{1}{3}\left(3\cos^2\theta-1\right)\right)\right. \\
& + \sin(\phi_h + \phi_R)\left(A_{UL}^{\sin(\phi_h+\phi_R)\sin\theta}\sin\theta + A_{UL}^{\sin(\phi_h+\phi_R)\sin 2\theta}\sin 2\theta\right) \\
& + \sin(2\phi_R)\, A_{UL}^{\sin(2\phi_R)\sin^2\theta}\sin^2\theta \\
& + \sin(3\phi_h - \phi_R)\left(A_{UL}^{\sin(3\phi_h-\phi_R)\sin\theta}\sin\theta + A_{UL}^{\sin(3\phi_h-\phi_R)\sin 2\theta}\sin 2\theta\right) \\
& \left. + \sin(4\phi_h - 2\phi_R)\, A_{UL}^{\sin(4\phi_h-2\phi_R)\sin^2\theta}\sin^2\theta\right\}
\end{aligned}$$

$$\begin{aligned}
d\sigma_{LL} \propto\; & \sqrt{1-\varepsilon^2}\left\{A_{LL}^{1} + A_{LL}^{\cos\theta}\cos\theta + A_{LL}^{\frac{1}{3}(3\cos^2\theta-1)}\frac{1}{3}\left(3\cos^2\theta-1\right)\right. \\
& + \cos(\phi_h - \phi_R)\left(A_{LL}^{\cos(\phi_h-\phi_R)\sin\theta}\sin\theta + A_{LL}^{\cos(\phi_h-\phi_R)\sin 2\theta}\sin 2\theta\right) \\
& \left. + \cos(2\phi_h - 2\phi_R)\, A_{LL}^{\cos(2\phi_h-2\phi_R)}\right\}
\end{aligned}$$

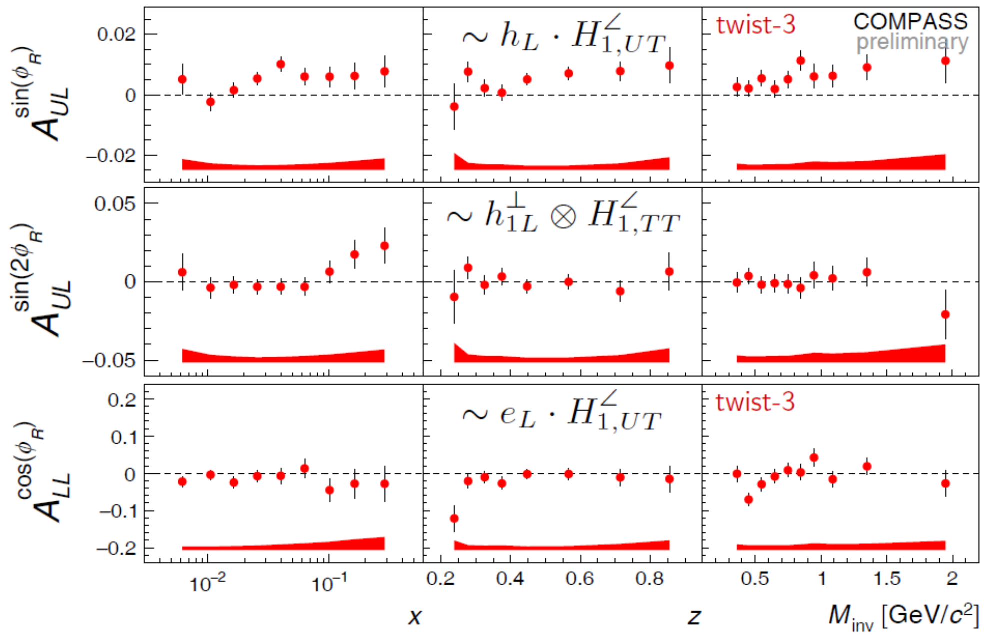


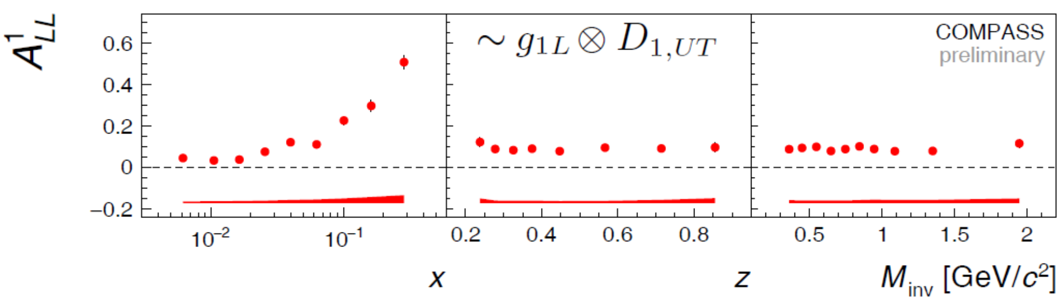
$$\langle\theta\rangle = \pi/2$$

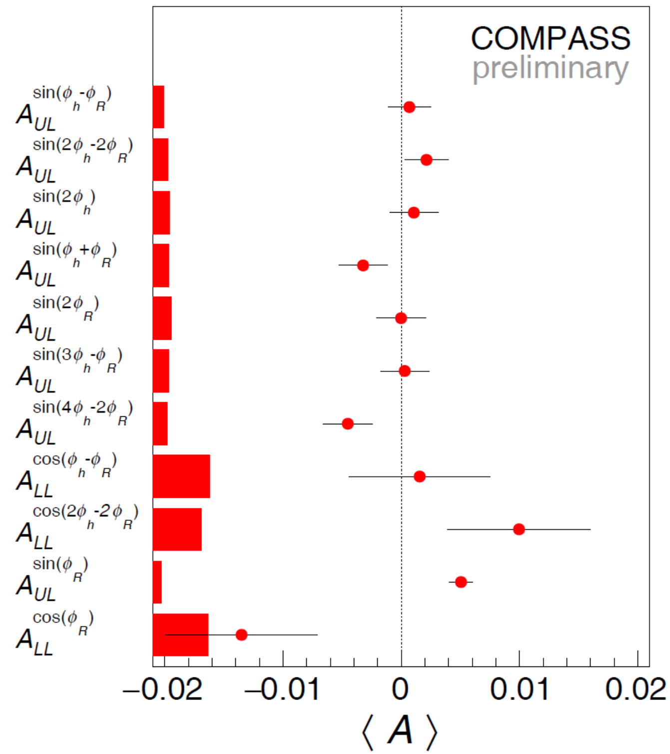
θ is the emission angle between h^+ in the c.m. frame and the momentum of the di-hadron in the target rest frame

Selected results for di-hadron asymmetries

COMPASS (NH_3) 2007+2011 data: preliminary



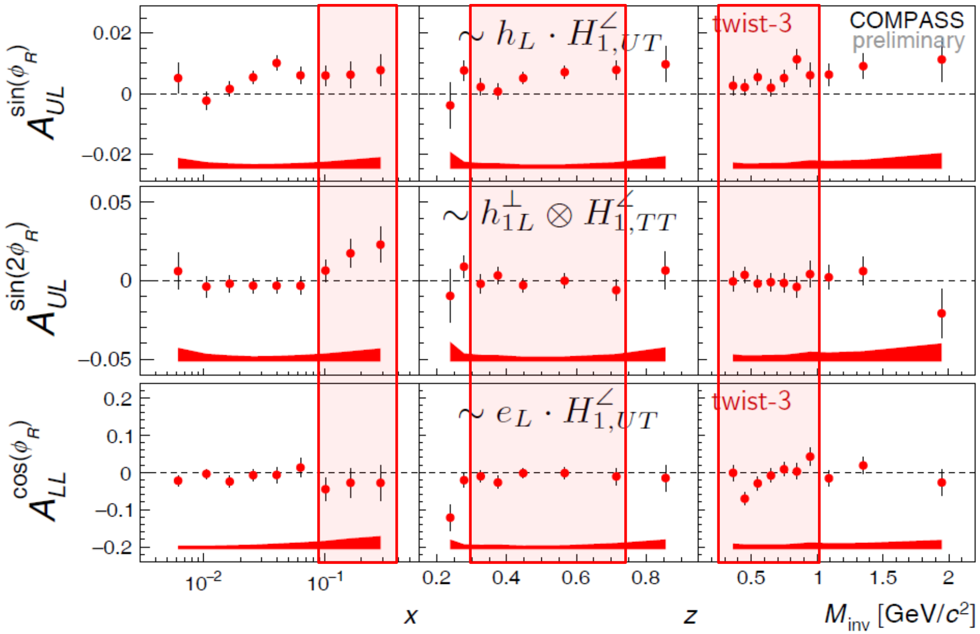


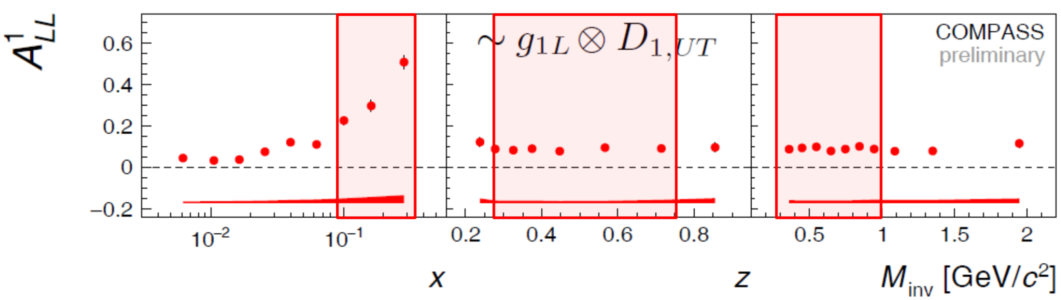


- Alternative way to access various twist-2/-3 distributions
- Non zero signal for $A_{UL}^{\sin\phi_R}$ and A_{LL}^{1}

Selected results for di-hadron LSAs

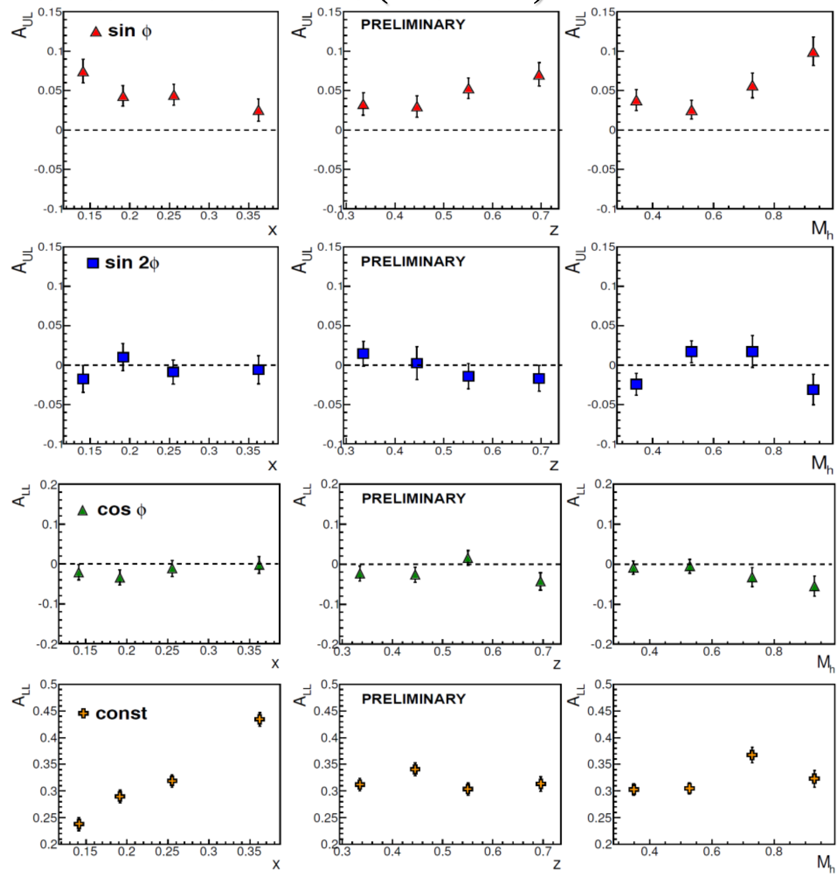
COMPASS (NH_3) 2007+2011 data: preliminary





CLAS 6 GeV (NH_3)

S. A. Pereira: PoS (DIS 2014) 231

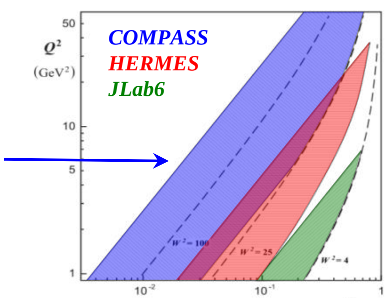


$Q^2 > 1$ (GeV/c)^2

$0.0025 < x < 0.7$

$0.1 < y < 0.9$

$W > 5$ GeV/c^2



- Alternative way to access various twist-2/-3 distributions
- Non zero signal for $A_{UL}^{\sin\phi_R}$ and A^1_{LL}
- CLAS-COMPASS: different behavior for $A_{UL}^{\sin 2\phi_R}$ at large x?

Conclusions

- COMPASS has measured all possible single-/di-hadron SIDIS LSAs from combined deuteron 2002-2006 and proton 2007/2011 data sample
- Together with existing measurements of proton TSAs these results complete the whole set of all possible proton SIDIS spin dependent azimuthal asymmetries
- This allowed us to evaluate the mixing between SIDIS LSAs and TSAs arising from the difference of target polarization components in *lp* and $\gamma{*}p$ systems
- Whereas azimuthal LSAs on deuteron appear to be compatible with zero, for some of the proton LSAs non-zero signals are observed
- A clear effect was observed for $A_{UL}^{sin\phi_h}$ with positive hadrons, while for negative hadrons the asymmetry is found to be compatible with zero
    - in agreement with HERMES observations
- The $A_{UL}^{sin2\phi_h}$ appear to exhibit opposite sign "Collins-like" behavior for h^+ and h^-
    - in agreement with model predictions
    - possible positive signal for negative hadrons appears to contradict HERMES and Jlab observations
- The $A_{LL}^{cos\phi_h}$ asymmetry is found to be small and compatible with zero within statistical accuracy which does not contradict available model predictions
- Non-zero signal was observed for $A_{UL}^{sin\phi_R}$ and A_{LL}^{1} di-hadron asymmetries related to h_L and g_{1L} PDFs, correspondingly.

Thank you!

Joint XX-th International Workshop on Hadron Structure and Spectroscopy

and 5-th Workshop on Correlations in Partonic and Hadronic Interactions

https://indico.cern.ch/e/IWHSS-CPHI-2024

Yerevan, Armenia
30 September – 4 October, 2024