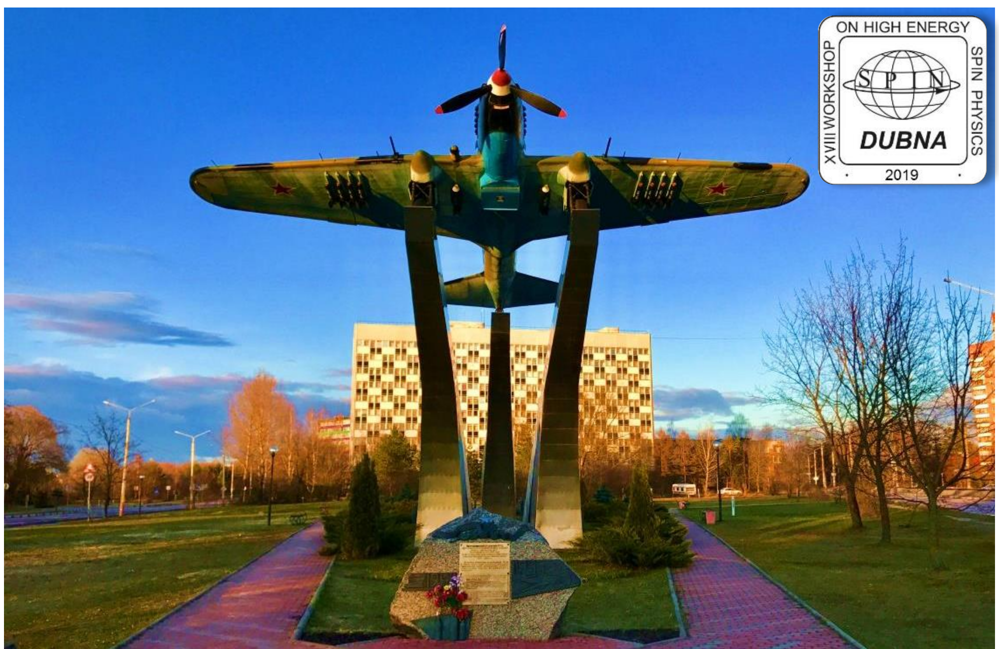
Overview of experimental results on the transverse spin structure of the nucleon obtained from SIDIS and Drell-Yan measurements

BAKUR PARSAMYAN

CERN, JINR,
University of Turin and INFN

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS



XVIII Workshop on High Energy Spin Physics

(DSPIN-2019)

Dubna, Russia

September 2-6, 2019

Introduction: exploring the nucleon spin

- 1964 Quark model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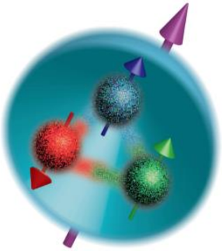
G. Zweig



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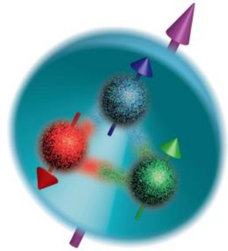

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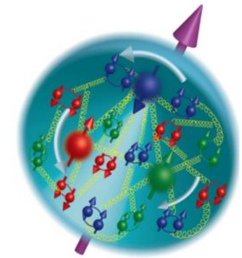

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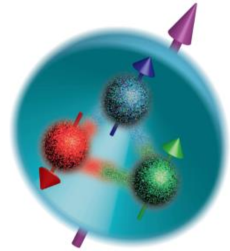

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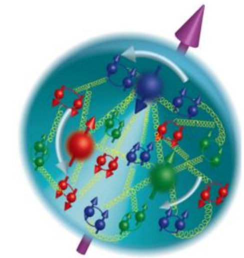

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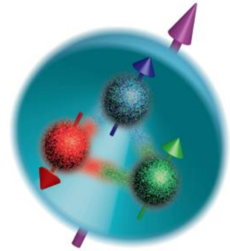

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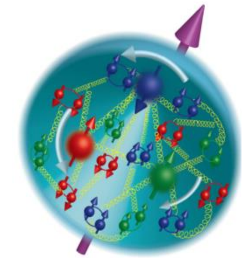

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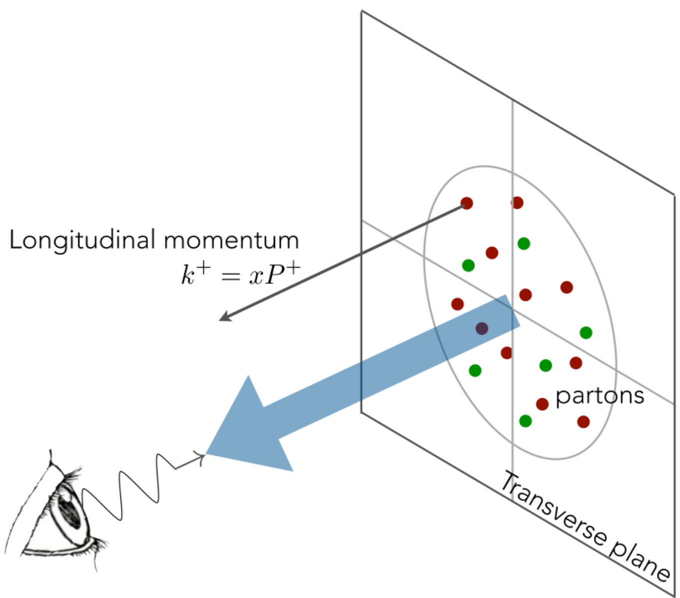

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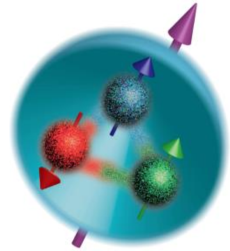

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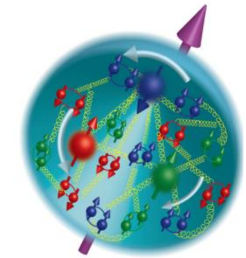

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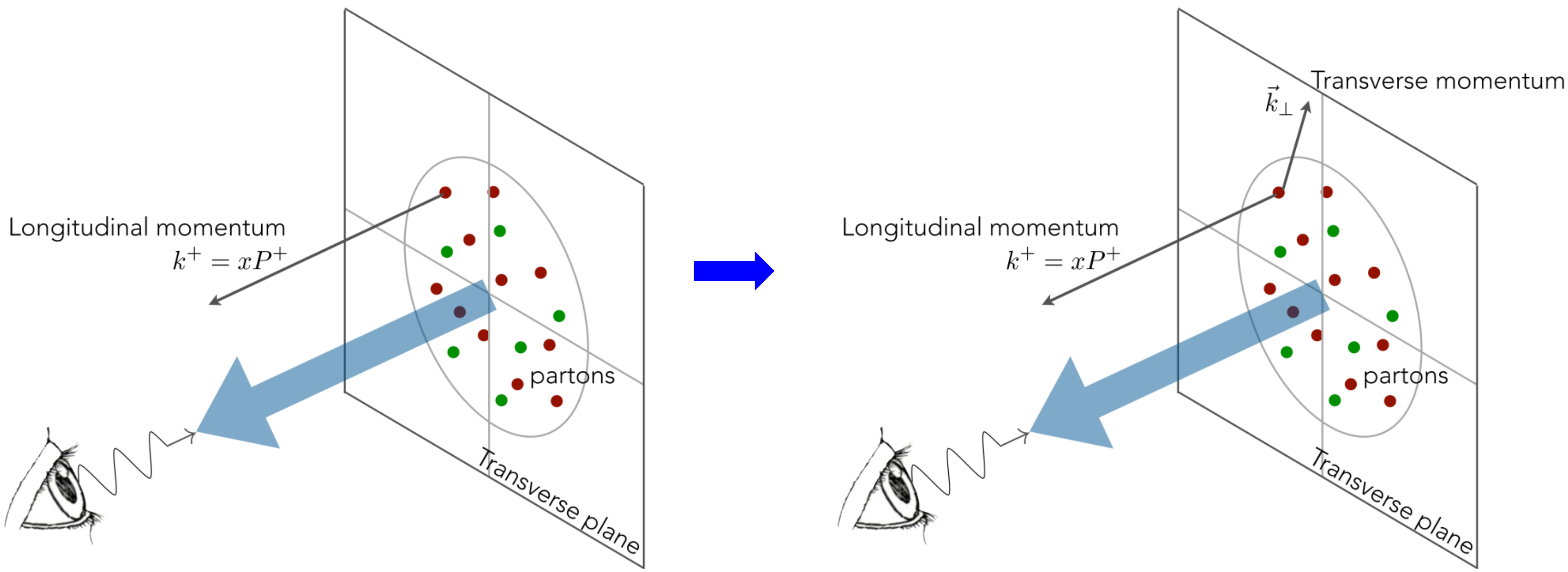

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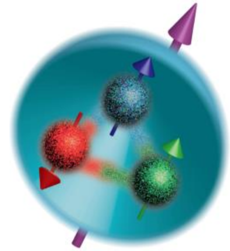

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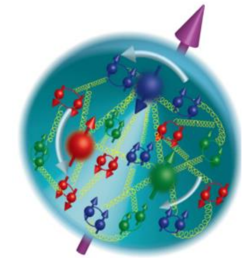

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$$\frac{d\sigma}{dxdydzdP_{hT}^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

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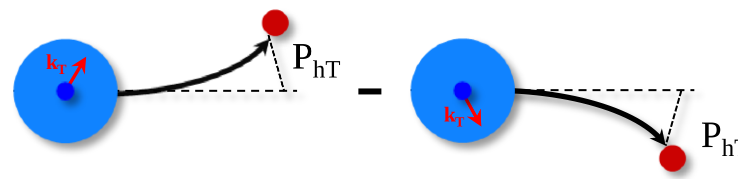
Cahn effect R.N. Cahn, PLB 78 (1978)



Kinematic effect:
non-zero k_T induces an azimuthal modulation

The point that there are azimuthal dependences which arise from the transverse momenta of the partons was clearly stated in this papers:
T.P. Cheng and A. Zee, Phys. Rev. D6 (1972) 885; F. Ravndal, Phys. Lett. 43B (1973) 301.
R.L. Kingsley, Phys. Rev. D10 (1974) 1580; A.M. Kotsinyan, Teor. Mat. Fiz. 24 (1975) 206;
Engl. transl. Theor. Math. Phys. 24 (1976) 776.

A. Kotzinian on behalf of: T.P. Cheng, A. Zee, F. Ravndal, R.L. Kingsley and himself

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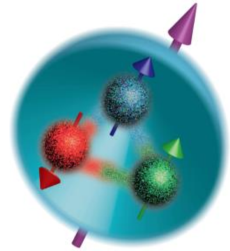

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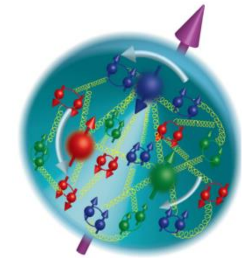

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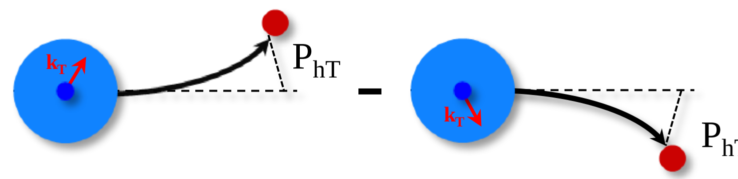
$$\hat{s} \simeq xs\left[1-2\sqrt{1-y}\,\frac{k_T}{Q}\cdot\cos\varphi_q\right]$$

$$\hat{u} \simeq -xs(1-y)\left[1-\frac{2k_T}{Q\sqrt{1-y}}\cdot\cos\varphi_q\right]$$

$$\hat{t} = -Q^2 = -xys, \quad where \quad s=(l+P)^2$$

$$d\sigma^{lp\to l'hX} \propto d\sigma^{lq\to lq} \propto \frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$$



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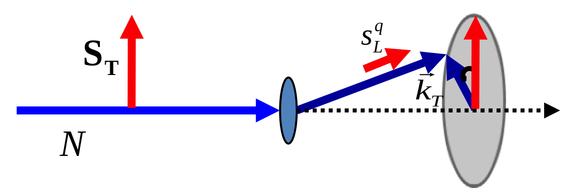

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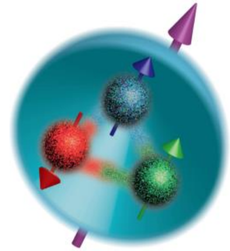

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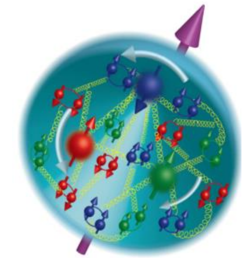

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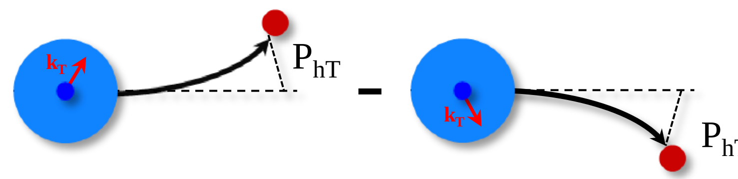

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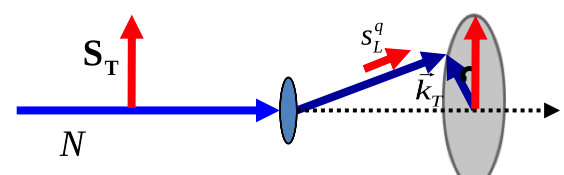

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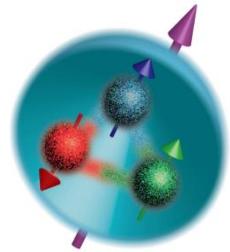

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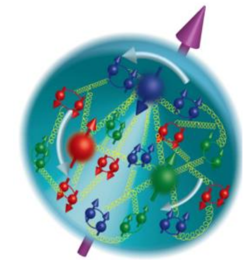

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(EMC) Phys. Lett. B 130 (1983) 118,
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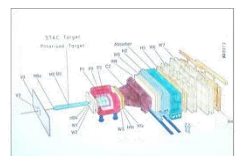

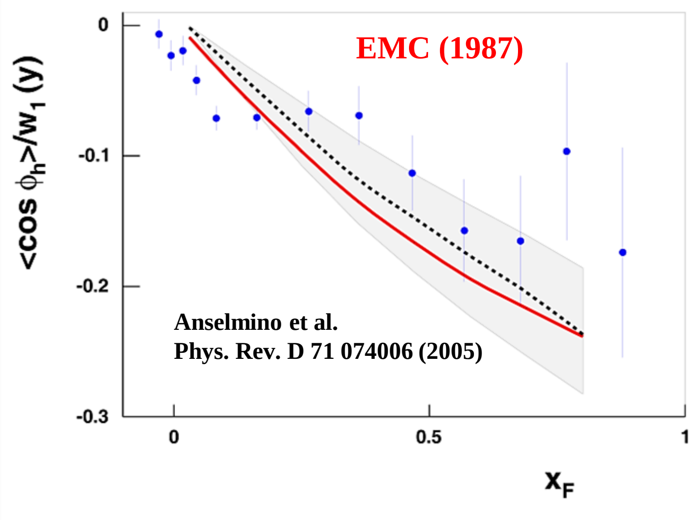

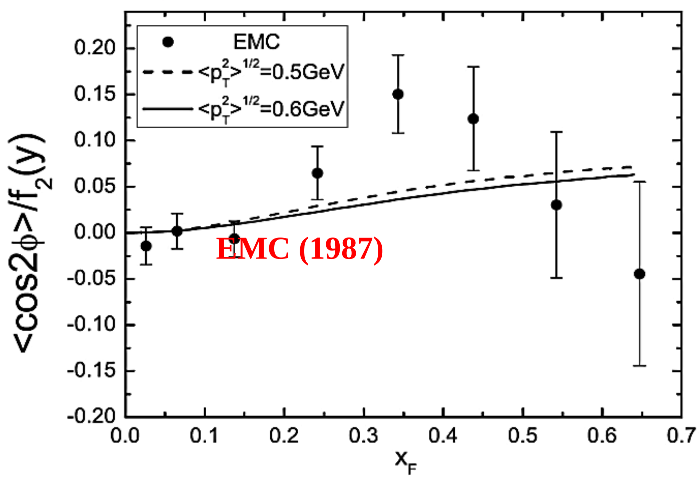

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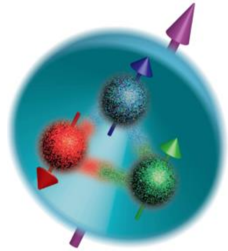

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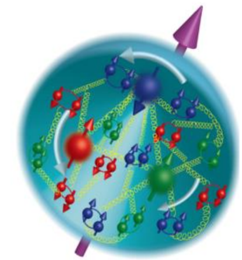

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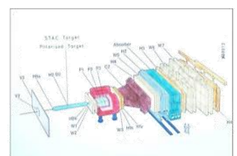

the spin sum rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$$\Delta q = q^+ - q^-$$

Proton: $\Delta u = \frac{4}{3} \quad \Delta d = -\frac{1}{3} \quad \Delta s = 0 \quad (\text{in } \hbar)$

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 1$$

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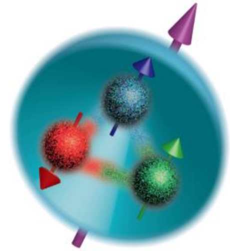

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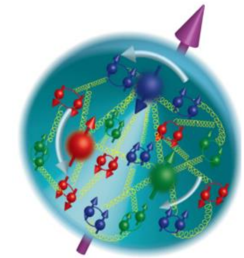

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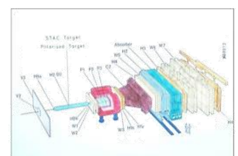
- 1988 EMC measurement spin *puzzle* 

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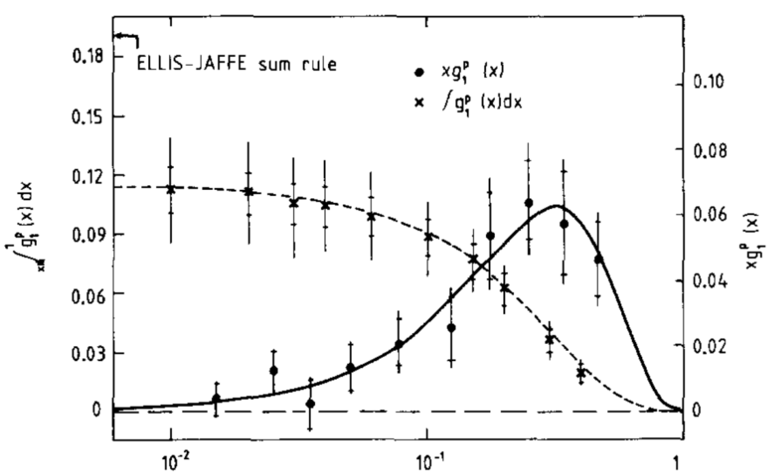

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$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 1$

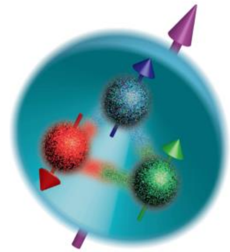
EMC 1988: $\Delta\Sigma \approx 0.12$ – spin crisis

Now: $\Delta\Sigma \approx 0.30$

ΔG – *small* (~0.1) *positive*

Orbital momentum – ?

Introduction: exploring the nucleon spin



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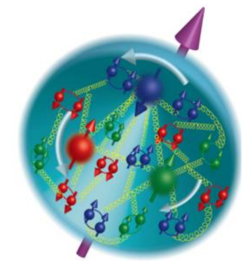

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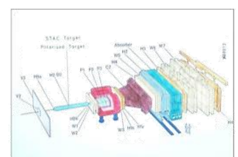

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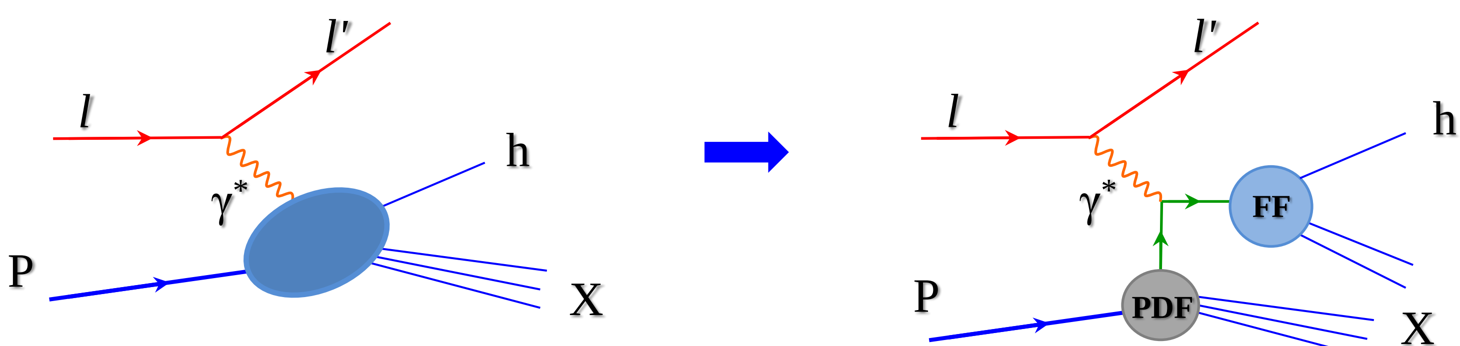

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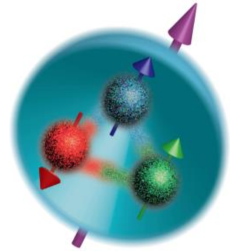

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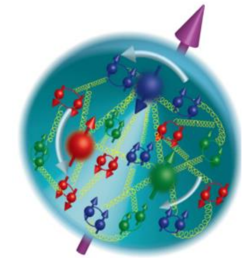

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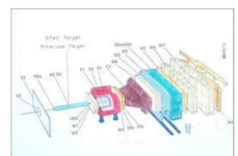

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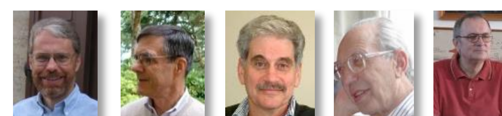

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- 90's spin dependent azimuthal asymmetries and TMDs

A. Kotzinian A. Metz A. Bacchetta D. Boer J. P. Mulders …

quark / nucleon	U	L	T
U	$f_1(x)$		
L		$g_1(x)$	
T			$h_1(x)$

→

quark / nucleon	U	L	T
U	$f_1(x, k_T^2)$		$h_1^{\perp}(x, k_T^2)$
L		$g_1(x, k_T^2)$	$h_{1L}^{\perp}(x, k_T^2)$
T	$f_{1T}^{\perp}(x, k_T^2)$	$g_{1T}(x, k_T^2)$	$h_1(x, k_T^2)$, $h_{1T}^{\perp}(x, k_T^2)$

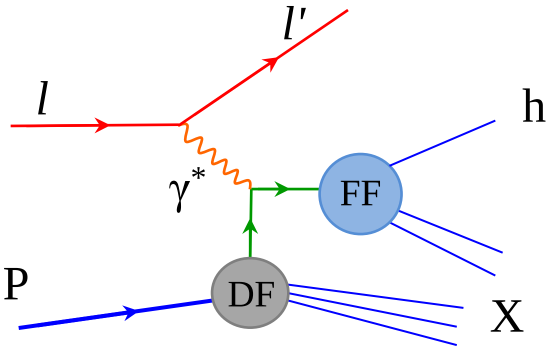
SIDIS x-section

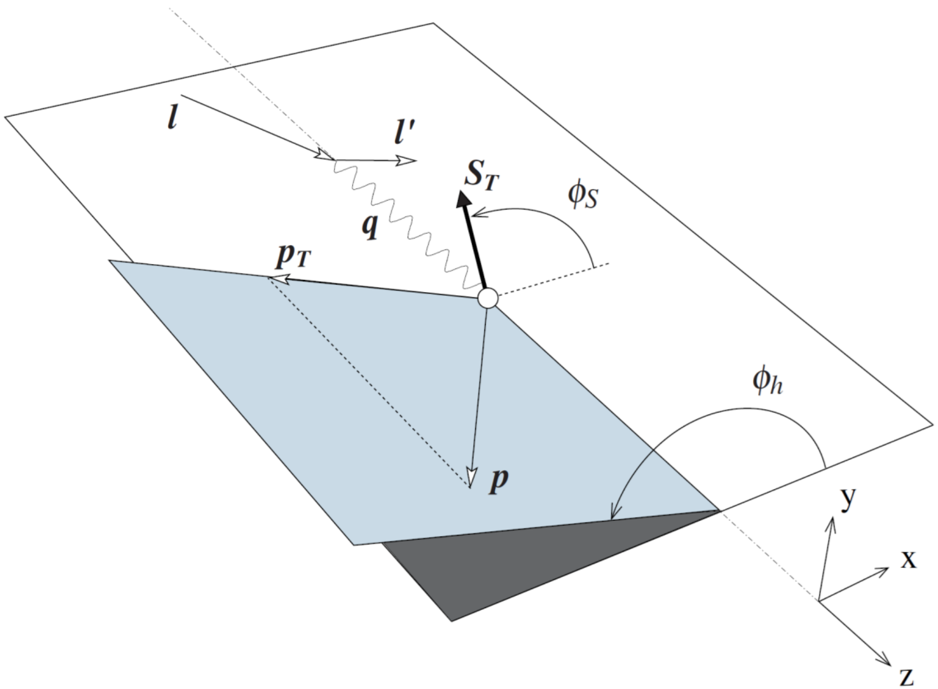
A.Kotzinian, Nucl. Phys. B441, 234 (1995).
Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel JHEP 0702:093 (2007).

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

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

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



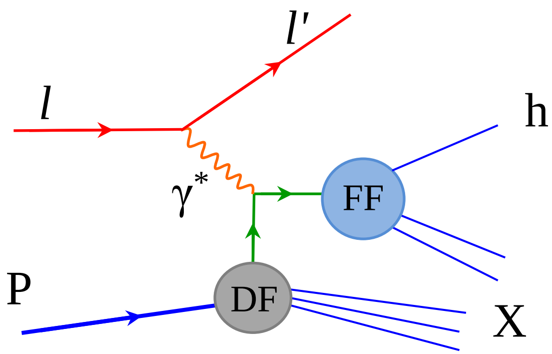


$$A_{U(L),T}^{w(\varphi_h,\varphi_s)}=\frac{F_{U(L),T}^{w(\varphi_h,\varphi_s)}}{F_{UU,T}+\varepsilon F_{UU,L}};\quad \varepsilon=\frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2},\quad \gamma=\frac{2Mx}{Q}$$

SIDIS x-section and TMDs at twist-2

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

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



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**

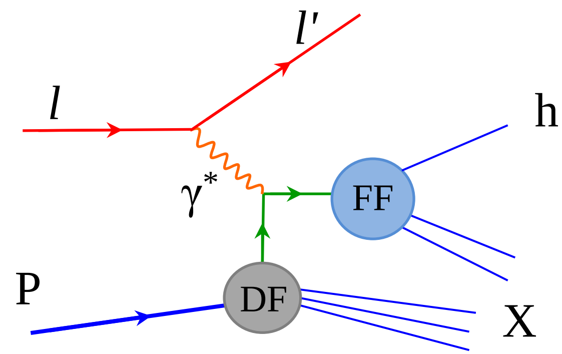
+ two FFs: $D_{1q}^h(z,P_\perp^2)$ and $H_{1q}^{\perp h}(z,P_\perp^2)$

SIDIS x-section and TMDs at twist-2

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

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

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



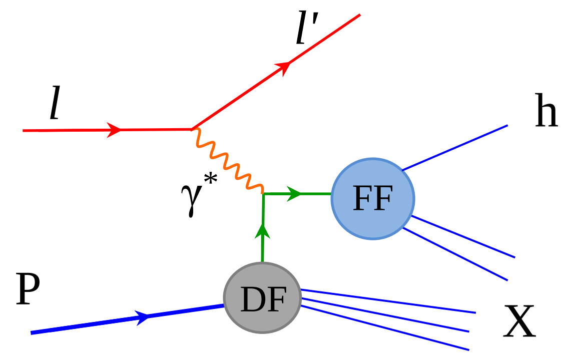
Nucleon \ Quark	U	L	T
U	number density		Boer-Mulders
L		helicity	worm-gear L
T	Sivers	Kotzinian-Mulders worm-gear T	transversity pretzelosity

spin of the nucleon — spin of the quark — k_T

SIDIS x-section and TMDs at twist-2

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

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



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

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

Twist-2

Twist-3

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

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

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

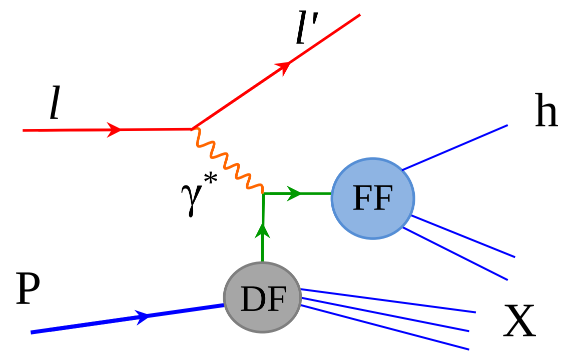
$$A_{LL}^{\cos\phi_h} \overset{WW}{\propto} Q^{-1}\left(g_{1L}^q\otimes D_{1q}^h+\ldots\right)$$

WW = "Wandzura-Wilczek-type approximation"

SIDIS x-section and TMDs at twist-2

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

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



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

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

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

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

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

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

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

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

Twist-2

Twist-3

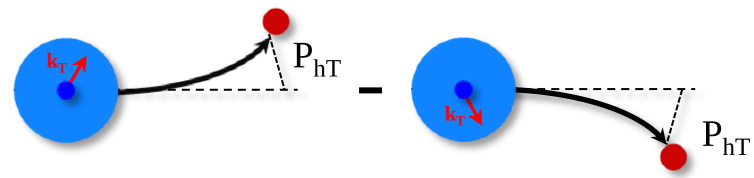
Cahn effect: kinematic interpretation

$$\frac{d\sigma}{dxdydzdP_{hT}^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

$$1+\cos\phi_h\times\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}+\cos(2\phi_h)\times\varepsilon A_{UU}^{\cos(2\phi_h)}+\ldots$$

Cahn effect

***R. N. Cahn,* PLB 78 (1978)**



P. J. Mulders and R. D. Tangerman,
Nucl. Phys. B461 (1996) 197–237
D. Boer, P. J. Mulders, and O. V. Teryaev,
Phys. Rev. D57 (1998) 3057–3064
Bacchetta et al. JHEP *0702:093,2007*

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

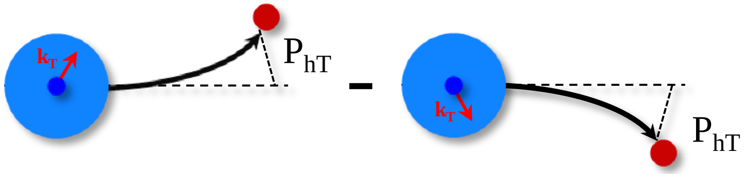
$$C[wfD] = x\sum_q e_q^2\int d^2\boldsymbol{k}_T d^2\boldsymbol{p}_T\delta^{(2)}\left(\boldsymbol{k}_T-\boldsymbol{p}_T-\boldsymbol{P}_{hT}/z\right)w\left(\boldsymbol{k}_T,\boldsymbol{p}_T\right)f^q\left(x,\boldsymbol{k}_T^2\right)D_q^h\left(z,\boldsymbol{k}_T^2\right)$$

$\hat{\boldsymbol{h}} = \vec{P}_{hT}/|\vec{P}_{hT}|$, $\boldsymbol{p}_T$ – *TM of the quark w.r.t. the direction of the produced hadron*

Cahn effect: kinematic interpretation

$$\frac{d\sigma}{dxdydzdP_{hT}^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

$$1+\cos\phi_h\times\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}+\cos(2\phi_h)\times\varepsilon A_{UU}^{\cos(2\phi_h)}+\ldots$$



Cahn effect

***R. N. Cahn*, PLB 78 (1978)**

***P. J. Mulders and R. D. Tangerman*,**
Nucl. Phys. B461 (1996) 197–237
***D. Boer, P. J. Mulders, and O. V. Teryaev*,**
Phys. Rev. D57 (1998) 3057–3064
***Bacchetta et al. JHEP** 0702:093,2007*

$$x\tilde{h}+\frac{k_T^2}{M^2}h_1^{\perp q} \qquad\qquad x f^{\perp q}+f_1^q$$

$$\downarrow \qquad\qquad \downarrow$$

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

$$\downarrow$$

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

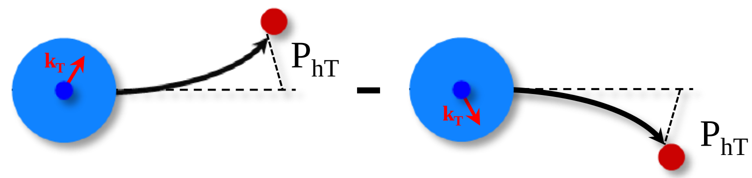
$$C[wfD]=x\sum_q e_q^2\int d^2\boldsymbol{k_T}d^2\boldsymbol{p_T}\delta^{(2)}\left(\boldsymbol{k_T}-\boldsymbol{p_T}-\boldsymbol{P_{hT}}/z\right)w(\boldsymbol{k_T},\boldsymbol{p_T})f^q\left(x,\boldsymbol{k_T^2}\right)D_q^h\left(z,\boldsymbol{k_T^2}\right)$$

$\hat{\boldsymbol{h}}=\vec{P}_{hT}/|\vec{P}_{hT}|$, $\boldsymbol{p_T}$ – *TM of the quark w.r.t. the direction of the produced hadron*

Cahn effect: kinematic interpretation

$$\frac{d\sigma}{dxdydzdP_{hT}^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

$$1+\cos\phi_h\times\sqrt{2\varepsilon(1+\varepsilon)}\,A_{UU}^{\cos\phi_h}+\cos(2\phi_h)\times\varepsilon A_{UU}^{\cos(2\phi_h)}+\dots$$



Cahn effect

***R. N. Cahn*, PLB 78 (1978)**

***P. J. Mulders and R. D. Tangerman*,**
Nucl. Phys. B461 (1996) 197–237
***D. Boer, P. J. Mulders, and O. V. Teryaev*,**
Phys. Rev. D57 (1998) 3057–3064
Bacchetta et al. JHEP *0702:093,2007*

$$x\tilde{h}+\frac{k_T^2}{M^2}h_1^{\perp q} \qquad\qquad x f^{\perp q}+f_1^q$$

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

Wandzura-Wilczek approximation
neglecting quark-gluon-quark correlators
(setting all functions with a tilde to zero)

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

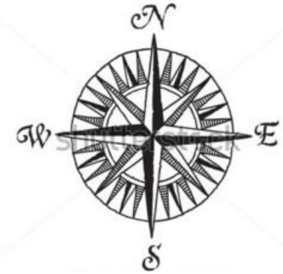
$$F_{UU}^{\cos\phi_h}=\frac{2M}{Q}C\left\{-\frac{\left(\hat{\boldsymbol h}\cdot\boldsymbol p_T\right)k_T^2}{M_hM^2}h_1^{\perp q}H_{1q}^{\perp h}-\frac{\hat{\boldsymbol h}\cdot\boldsymbol k_T}{M}f_1^qD_{1q}^h+\dots\right\}$$

sub-leading Cahn+Boer-Mulders effect

$$C[wfD]=x\sum_q e_q^2\int d^2\boldsymbol k_T\,d^2\boldsymbol p_T\,\delta^{(2)}\left(\boldsymbol k_T-\boldsymbol p_T-\boldsymbol P_{hT}/z\right)w\left(\boldsymbol k_T,\boldsymbol p_T\right)f^q\left(x,\boldsymbol k_T^2\right)D_q^h\left(z,\boldsymbol k_T^2\right)$$

$\hat{\boldsymbol h}=\vec{P}_{hT}/\left|\vec{P}_{hT}\right|$, $\boldsymbol p_T$ – TM of the quark w.r.t. the direction of the produced hadron

COMPASS bridge



SIDIS and single-polarized DY x-sections

SIDIS

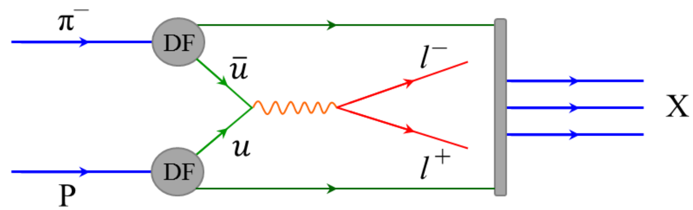
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

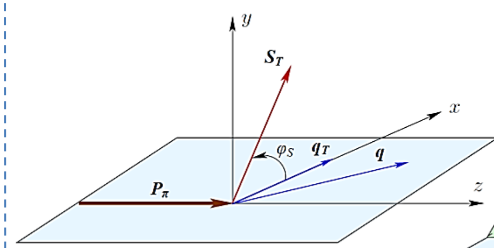
$$\times\left\{\begin{array}{l}
1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\
+\ \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h \\
+\ S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon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

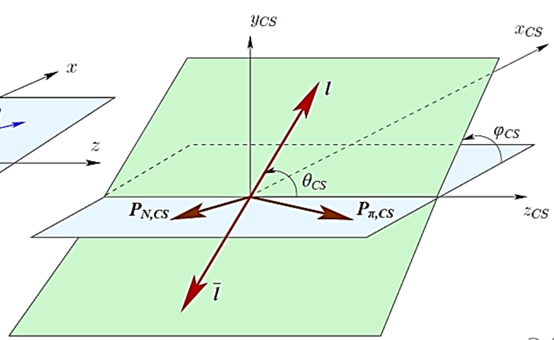
DY

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

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







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

SIDIS

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

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

DY

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

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

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

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

SIDIS

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

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

DY

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

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

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

SIDIS		DY
$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots$	← 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 →	$A_L^{\sin 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1L,p}^{\perp q}$ NICA
$A_{LL} \propto g_{1L}^q \otimes D_{1q}^h$, $A_{LT}^{\cos(\phi_h - \phi_S)} \propto g_{1T}^q \otimes D_{1q}^h$	←→	Double polarized DY

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

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

SIDIS

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

DY

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

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

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

within QCD TMD-framework:

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

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

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

SIDIS

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

DY

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

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

Complementary information from different channels:

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

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

SIDIS

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

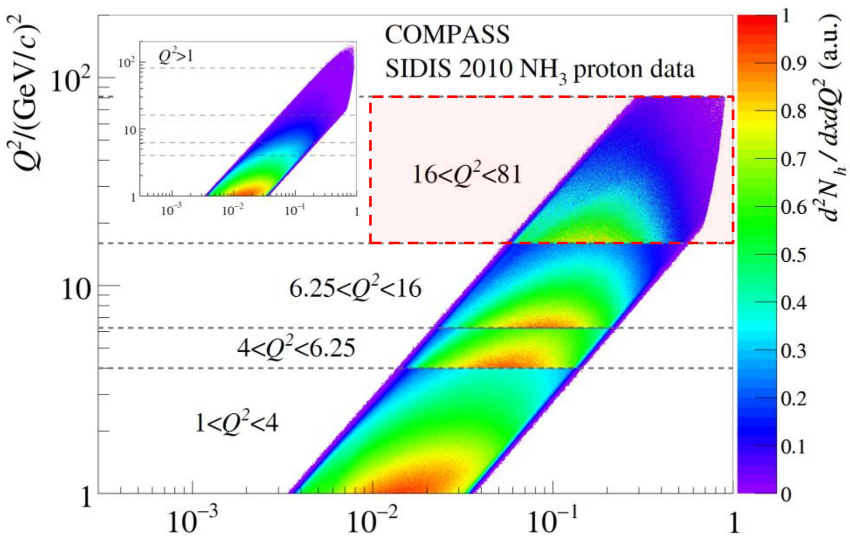
DY

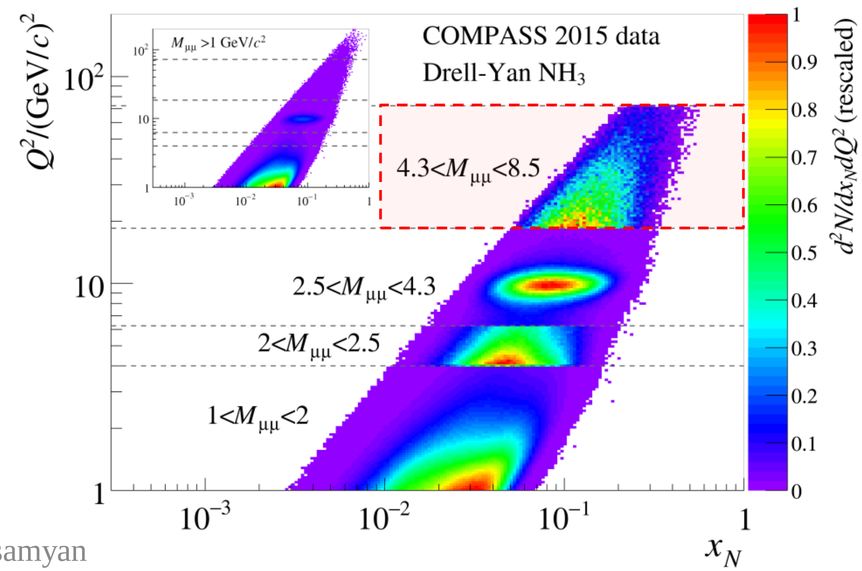
$$\frac{d\sigma^{LO}}{dq^4\,d\Omega} \propto F_U^1\left(1+\cos^2\theta_{CS}\right) \times \left\{ \begin{aligned} & 1+D_{[\sin^2\theta_{CS}]}A_U^{\cos 2\varphi_{CS}}\cos 2\varphi_{CS} \\ & + S_L\sin^2\theta_{CS}\,A_L^{\sin 2\varphi_{CS}}\sin 2\varphi_{CS} \\ & + S_T \left[\begin{aligned} & A_T^{\sin\varphi_S}\sin\varphi_S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

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

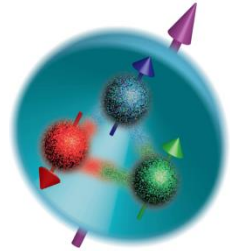
SIDIS-DY bridge

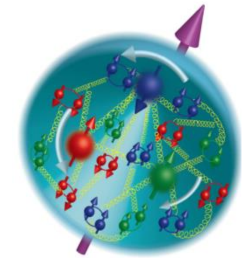
Comparable x:Q² coverage – minimization of possible Q²-evolution effects





Introduction: exploring the nucleon spin





- 1964 Quark model

M. Gell-Mann G. Zweig

- 1969 Parton model

R. Feynman

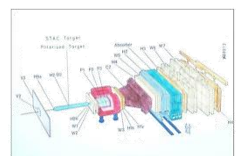
- 1973 asymptotic freedom and QCD

M. Gell-Mann F. A. Wilczek H.D. Politzer D. Gross

- 1978 intrinsic transverse motion of quarks and azimuthal asymmetries

R. N. Cahn …

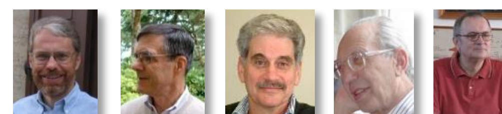
- 1988 EMC measurement spin *puzzle*



the spin sum rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

- 1988 Factorization of Hard Processes in QCD



J. Collins D. Soper G. Sterman A. Efremov O. Teryaev …

- 90's spin dependent azimuthal asymmetries and TMDs

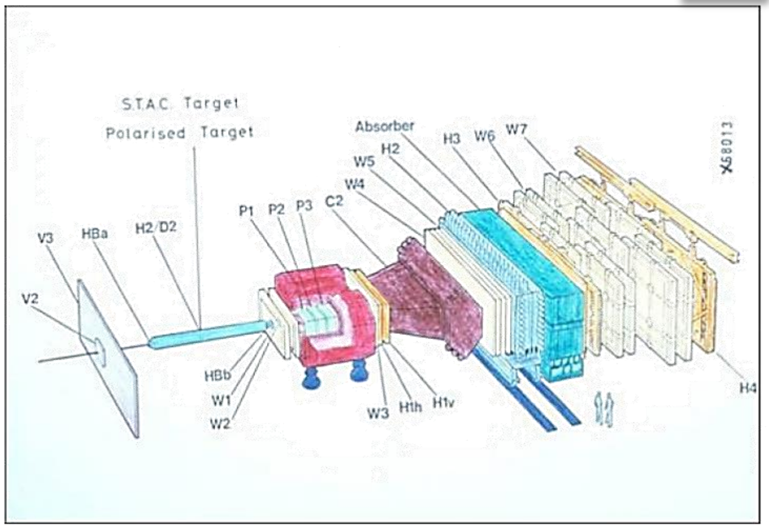
A. Kotzinian A. Metz A. Bacchetta D. Boer J. P. Mulders …

- Late 90's – present – future: spin dependent azimuthal asymmetry measurements

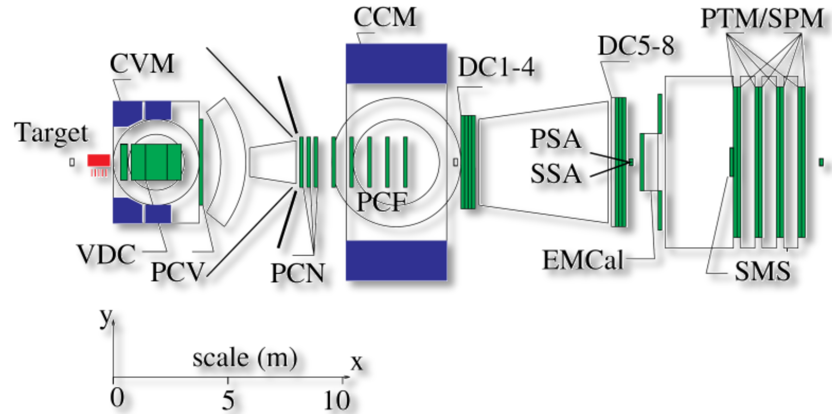
hermes COMPASS Jefferson Lab STAR PHENIX SeaQuest E906 AFTER panda NICA

Experiments in last 35 years: part I

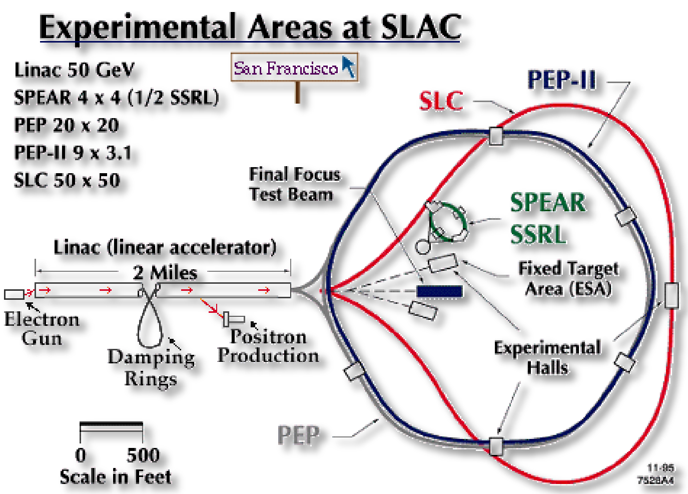
EMC CERN (μ-p, μ-d) @ 280 GeV



Fermilab E665 (μ-p, μ-d) @ 490 GeV

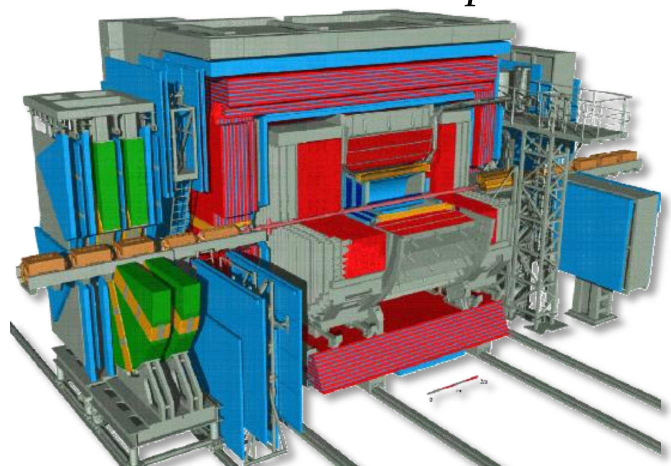


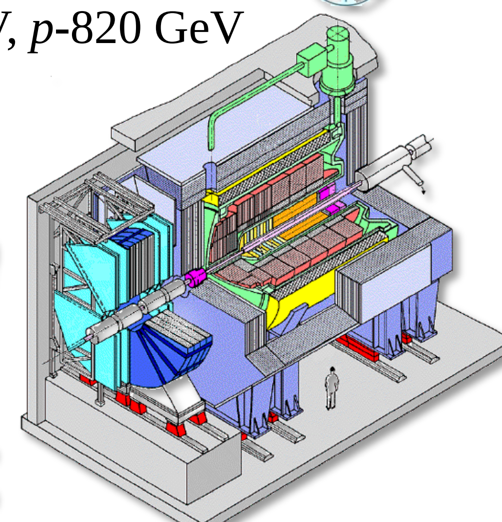
SLAC (e-p, e-d) @ 19.5 GeV



ZEUS *and* H1 e-p collider HERA, DESY

e-27.5 GeV: p-920 GeV, p-820 GeV





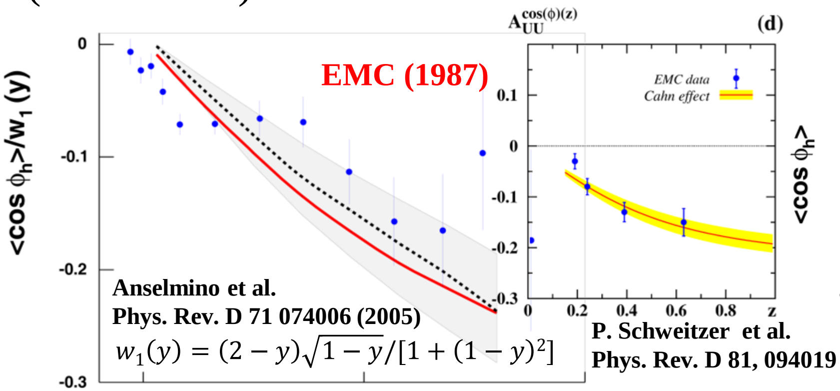
Experiments in last 35 years: first results

(SLAC) **Phys. Rev. Lett. 31,** 786 (1973)
(EMC) **Phys. Lett. B** 130 (1983) 118,
(EMC) **Z. Phys. C34** (1987) 277
(EMC) **Z. Phys. C52**, 361 (1991).
(E665) **Phys. Rev. D48** (1993) 5057
(ZEUS) **Eur. Phys. J. C11**, 251 (1999)
(ZEUS) **Phys. Lett. B 481,** 199 (2000)
(H1) **Phys. Lett. B654,** 148 (2007)

EMC, E665, H1 and ZEUS
- High beam energy, broad kinematic range
- No hadron type and charge distinction (averaged over any possible flavor dependence)
- EMC, ZEUS – only hydrogen target
- E665 – combined hydrogen and deuterium targets
- Not enough statistics to look at differential x-sections in more than two kinematic variables

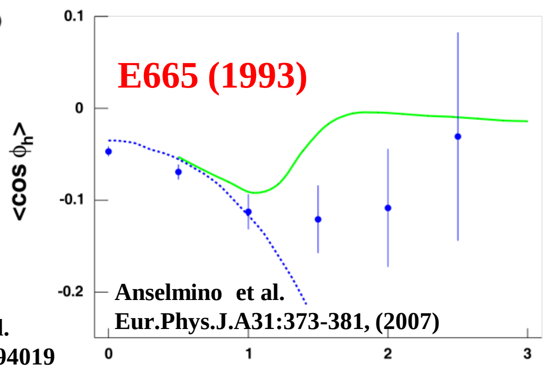
SLAC, JLab hall C
- Relatively low beam energy, restricted kinematic range
- x-sections measured only at a few kinematic points

CLAS Collaboration (JLab hall B)
- Relatively low beam energy
- access to 4D multi-differential x-section

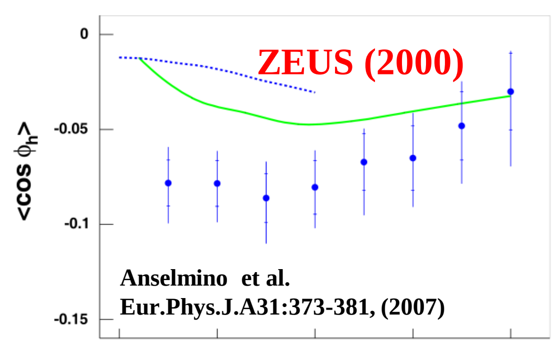


Anselmino et al.
Phys. Rev. D 71 074006 (2005)
$w_1(y) = (2-y)\sqrt{1-y}/[1+(1-y)^2]$

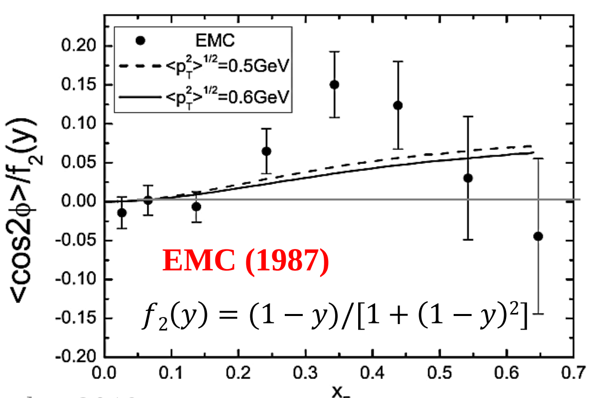
P. Schweitzer et al.
Phys. Rev. D 81, 094019



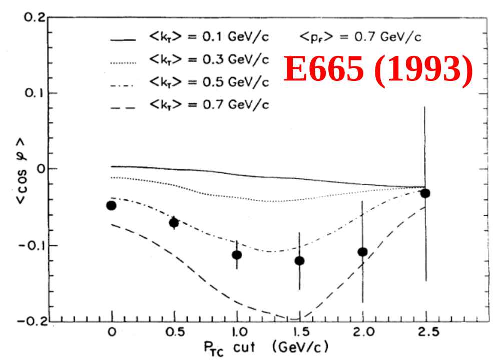
Anselmino et al.
Eur.Phys.J.A31:373-381, (2007)



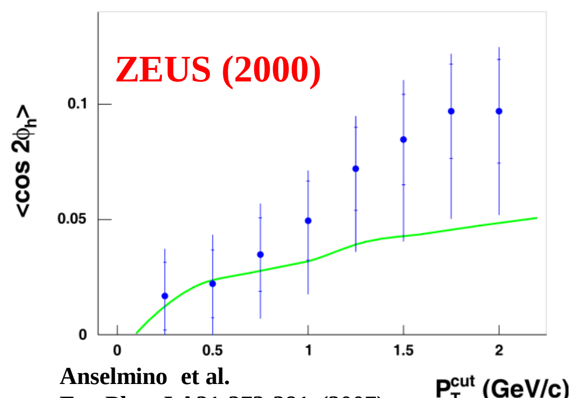
Anselmino et al.
Eur.Phys.J.A31:373-381, (2007)



$f_2(y) = (1-y)/[1+(1-y)^2]$

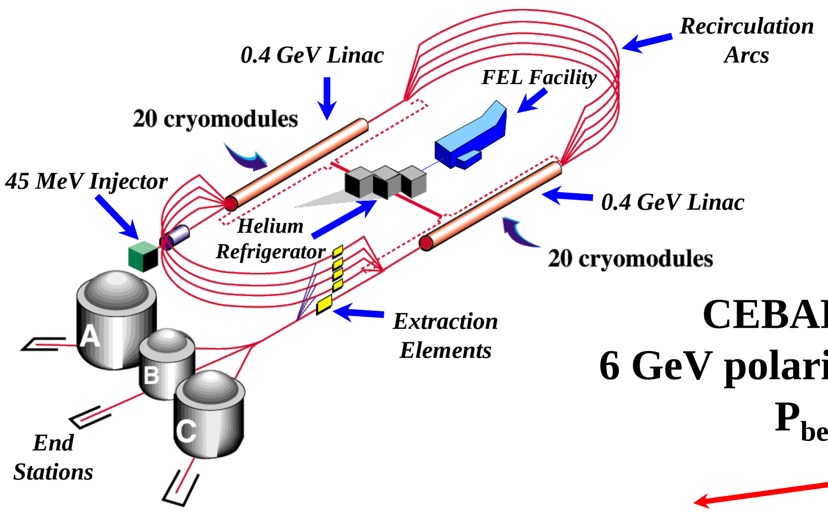


J. Chay, S. D. Ellis, and J. W. Stirling,
Phys. Rev. D 45, 46 (1992), Phys. Lett. B 269, 175 (1991).

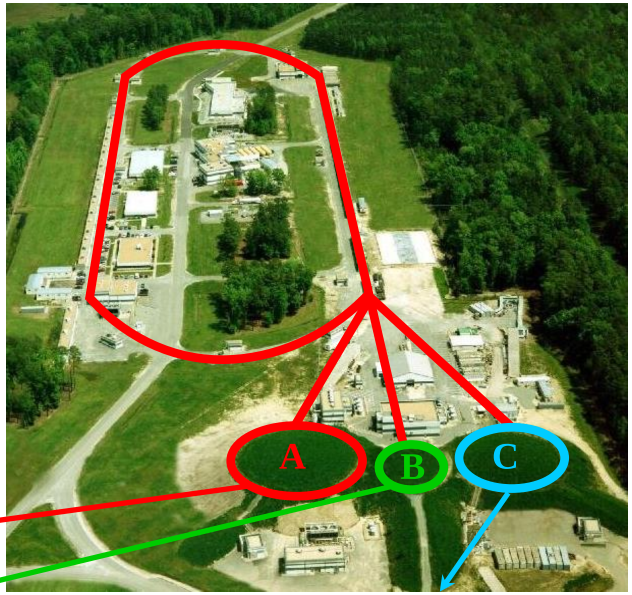


Anselmino et al.
Eur.Phys.J.A31:373-381, (2007)

Jefferson Lab experimental halls

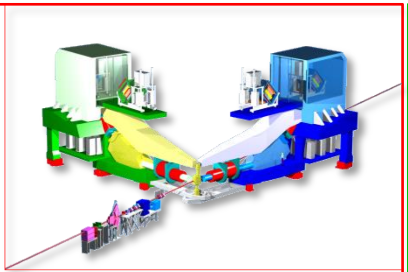


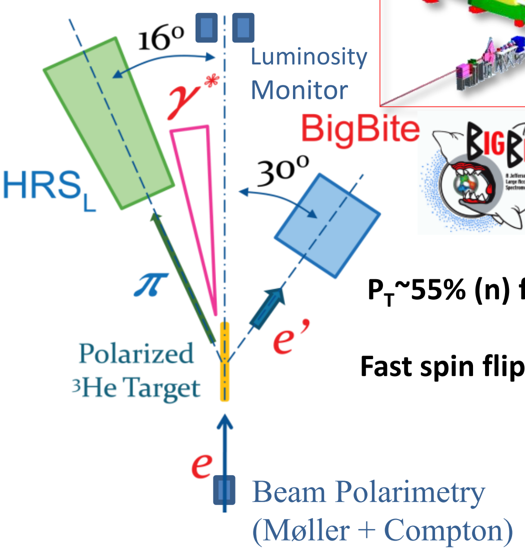
CEBAF accelerator
6 GeV polarized electron beam
$P_{beam} \approx 85\%$



Hall A: two HRS'

$^{3}\overrightarrow{He}$ gas target (40 cm)



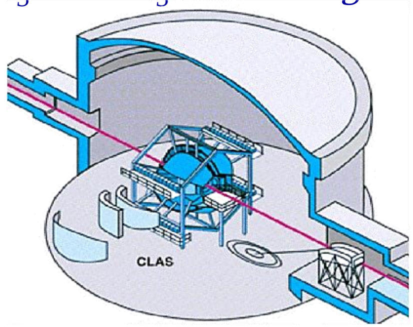


P_T~55% (n) f ~ 0.1-0.3

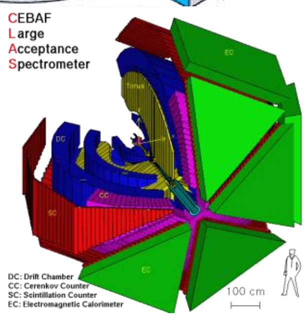
Fast spin flipping (30 Hz)

Hall B: CLAS

$N\vec{H}_3$ and $N\vec{D}_3$ HD-Ice targets

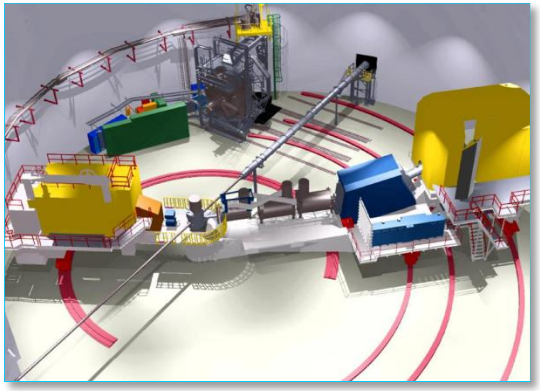


Polarizations
Beam: ~80%
NH_3 proton 80%
ND_3 ~30%
HD-Ice
(H-75%,D-25%)
f ~ 0.15

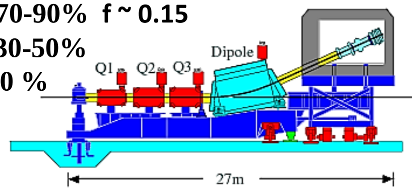


Hall C: HMS+SOS

$N\vec{H}_3$ and $N\vec{D}_3$ LiD targets

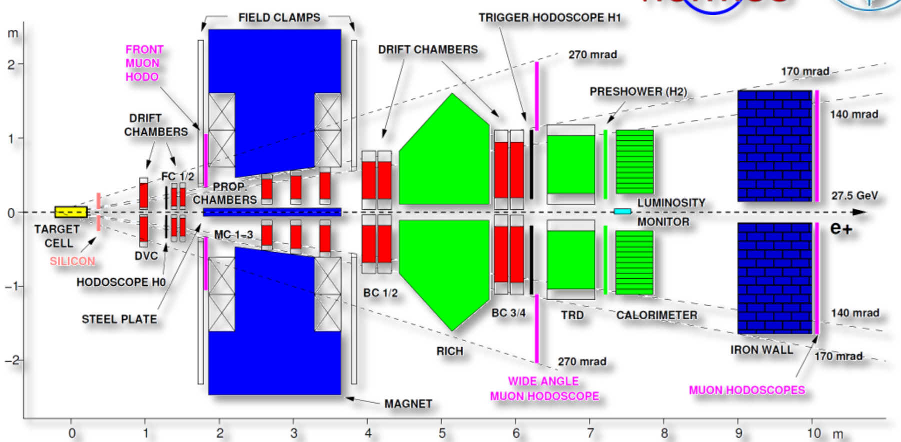


Polarizations
NH3: ~70-90% f ~ 0.15
ND3: ~30-50%
LiD: ~30 %



Experiments in last 35 years: part II

HERA MEasurement of Spin



Location: DESY, HERA

Beam: *e^+/e^-, polarized (both helicity states)(<60%), 27.5 GeV*

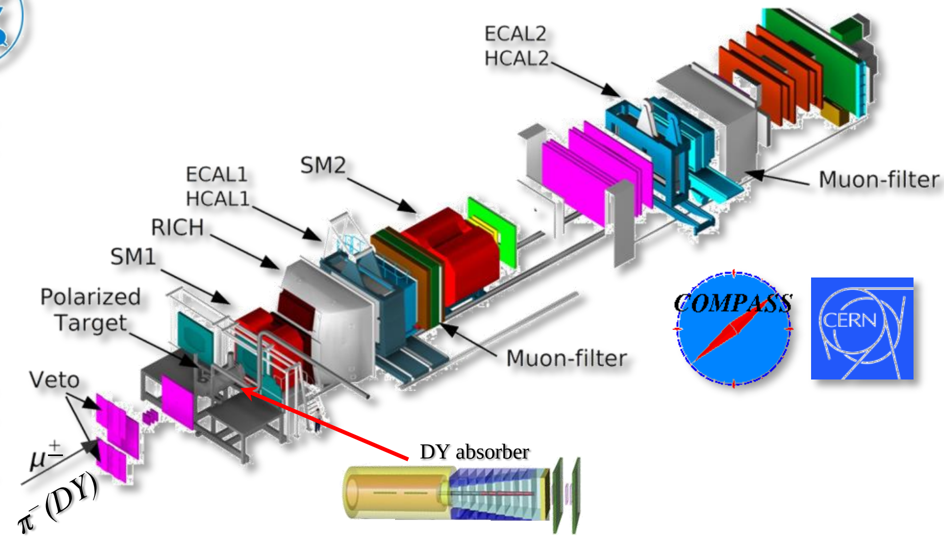
Target: *Gaseous target (H/D)*

- H/D Polarization (L & T) ~ 70-85%, f ~ 1
- Direct access to hydrogen or deuterium

Fast spin reversal (<1s)

- Same acceptance for different polarization states
- single cell configuration
- Hydrogen - measurements only with transverse polarization
- Deuterium - both transverse and longitudinal polarization measurements

COmmon Muon Proton Apparatus for Structure and Spectroscopy



Location: CERN SPS North Area. (2-stage spectrometer LAS-SAS)

Beam: *μ^+/μ^-, longitudinally polarized (~80%), 160/200 GeV*

Beam (DY): *π^-, 190 GeV, Intensity: 10^8 π/s*

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

- *LH single cell unpolarized target (2016/2017)*
- ^{6}LiD Polarization (L & T) ~ 50%, f ~ 0.38 (SIDIS)
- NH_3 Polarization (L & T) ~ 80%, f ~ 0.14 (SIDIS)
- NH_3 Polarization (T) ~ 70%, f ~ 0.18 (Drell-Yan)

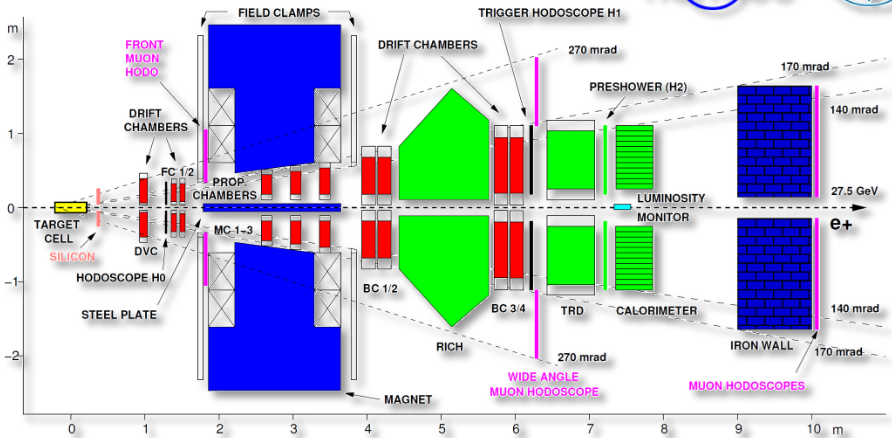
2- or 3-cell polarized target configurations

Neighboring cells are polarized in opposite directions

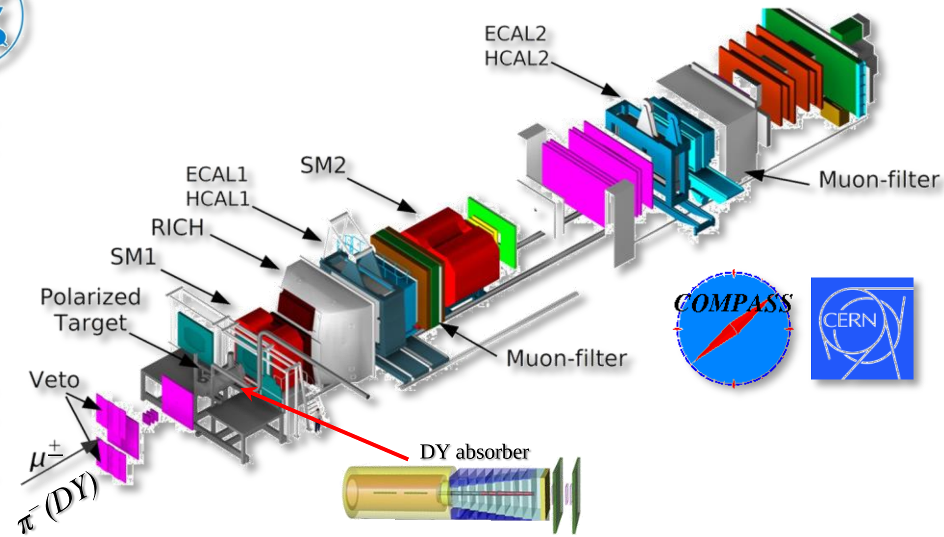
- Data is collected simultaneously for the two target spin orientations. Spin reversal after each ~4-5 days

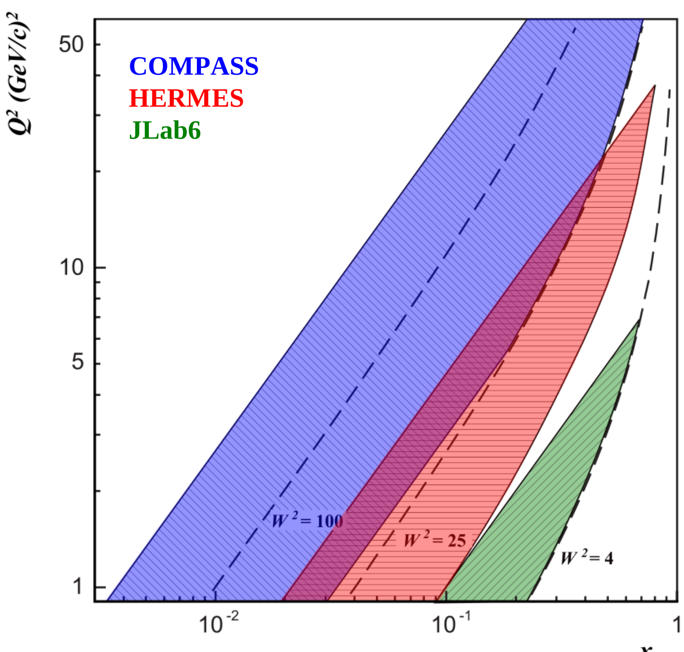
Experiments in last 35 years: part II

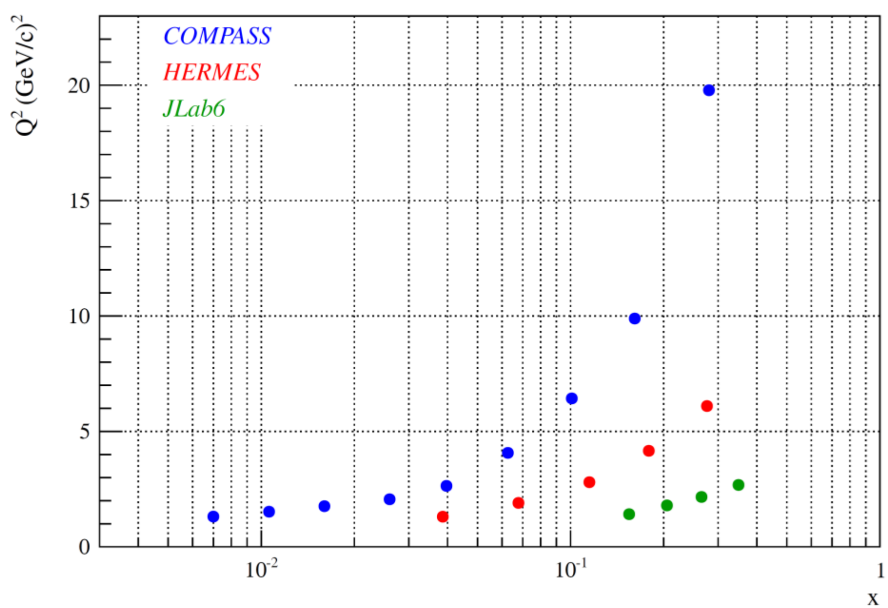
HERA MEasurement of Spin



COmmon Muon Proton Apparatus for Structure and Spectroscopy



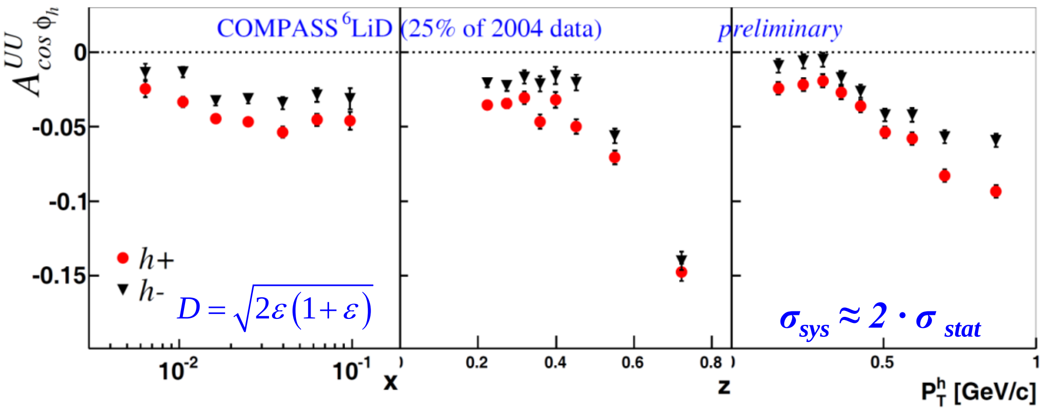


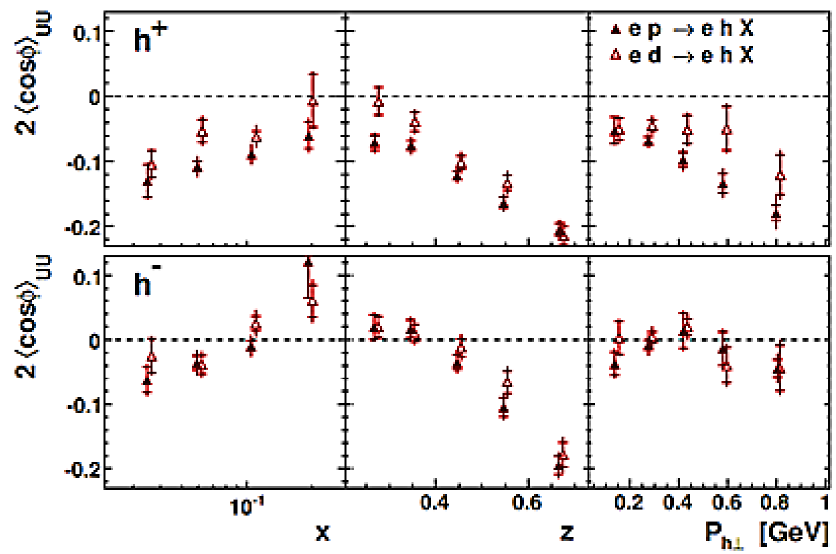


$A_{UU}^{\cos\phi}$ and $A_{UU}^{\cos 2\phi}$ amplitudes h^+/h^-

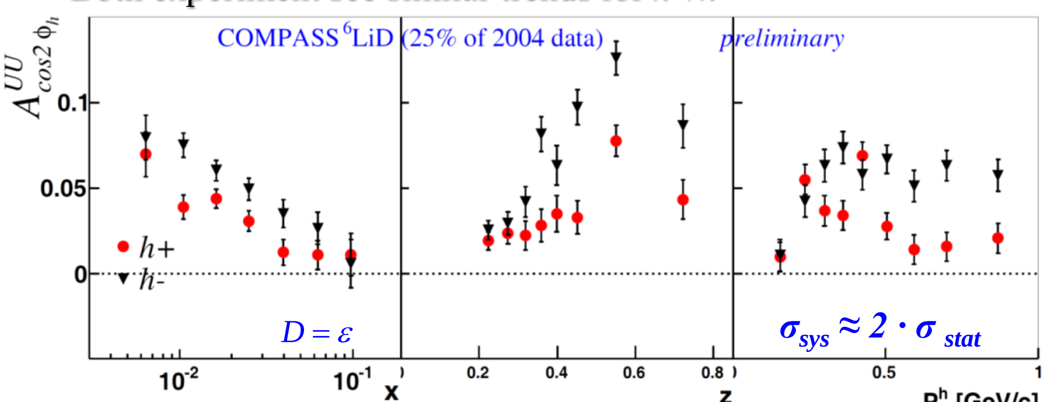
For COMPASS recent results see talk by A. Moretti

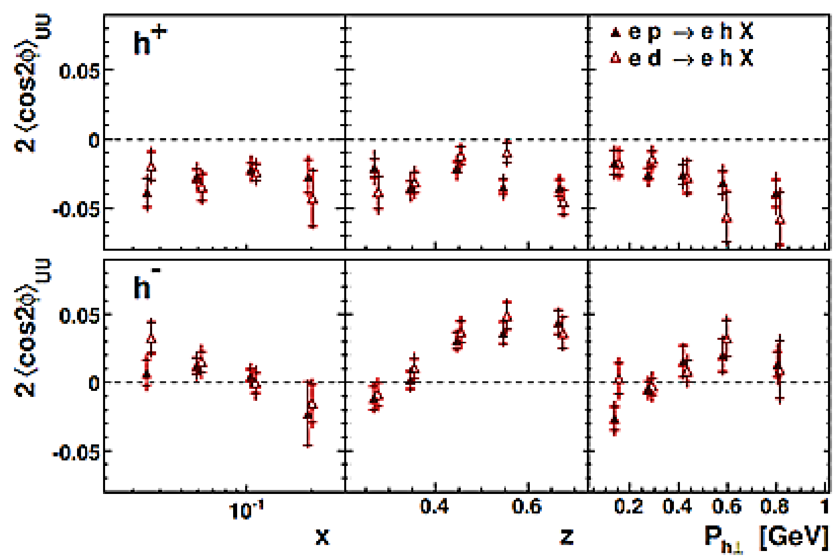
- Both experiments have P and D data
- Together with p_T – multiplicities provides access to intrinsic transverse motion of quarks inside the nucleon





- Comparison is not straightforward (different kinematics, Q^{-1})
- Both experiment see similar trends for h^+/h^-





- Similar trends for h^+/h^-
- No sign change for h^+/h^- at COMPASS

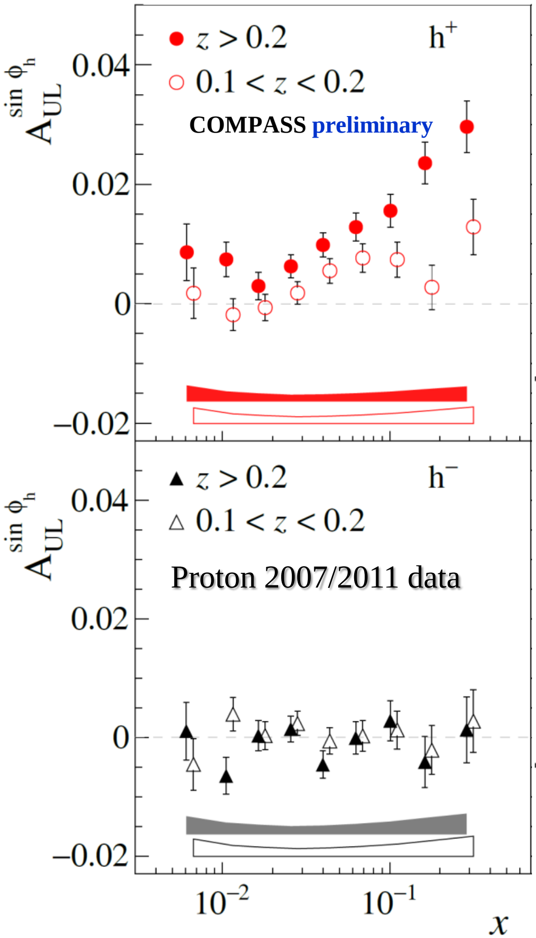
- Longitudinal spin dependent asymmetries in SIDIS: selected results

SIDIS: target longitudinal spin dependent asymmetries

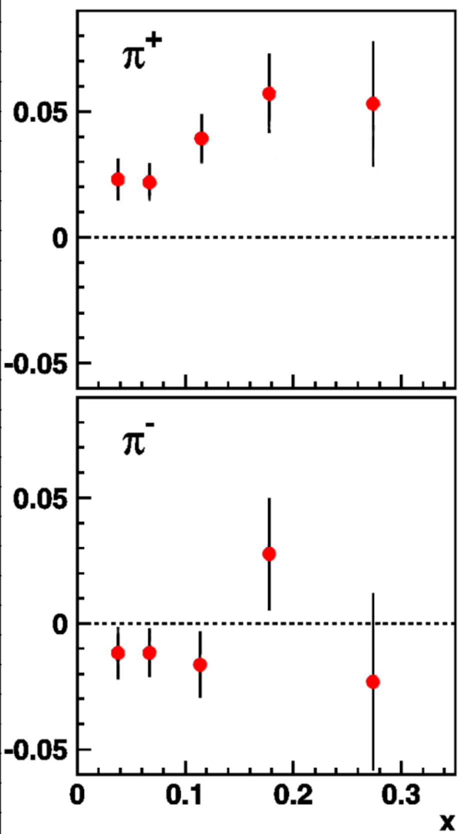
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\; S_L\sqrt{2\varepsilon\left(1+\varepsilon\right)}A_{UL}^{\sin\phi_h}\sin\phi_h+\ldots\right\}$$

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

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



HERMES PLB 622 (2005) 14

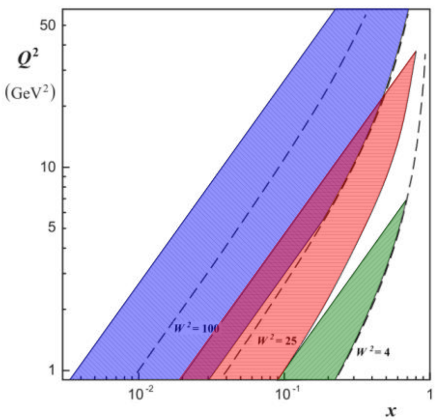


- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- **Non-zero trend for h⁺, h⁻ compatible with zero, clear *z*-dependence**

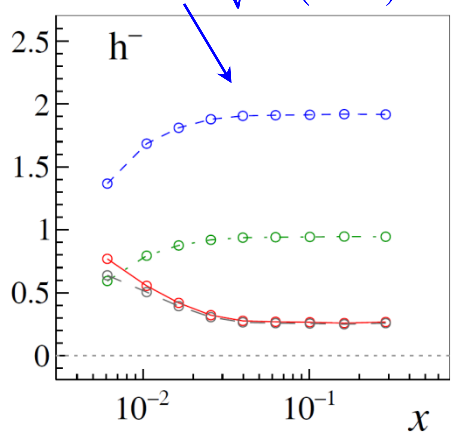
SIDIS: target longitudinal spin dependent asymmetries

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

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



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



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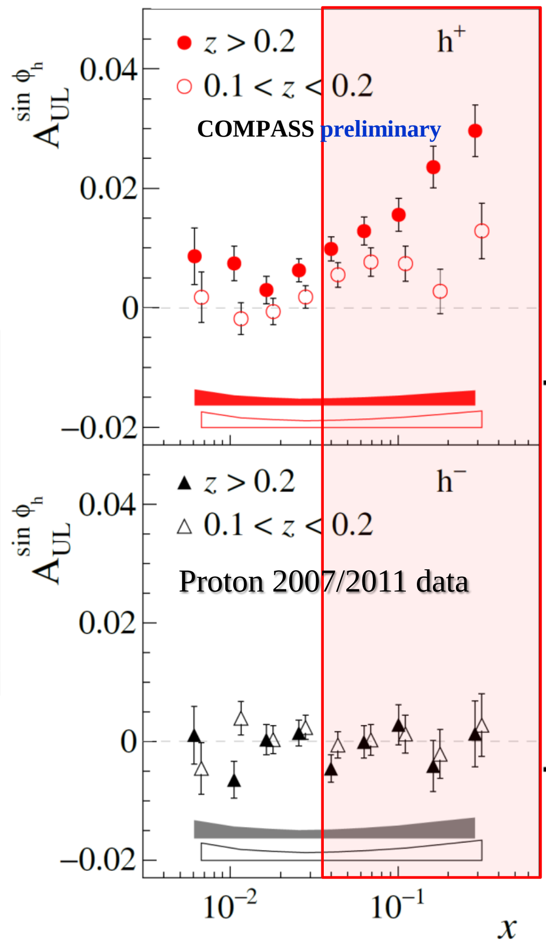
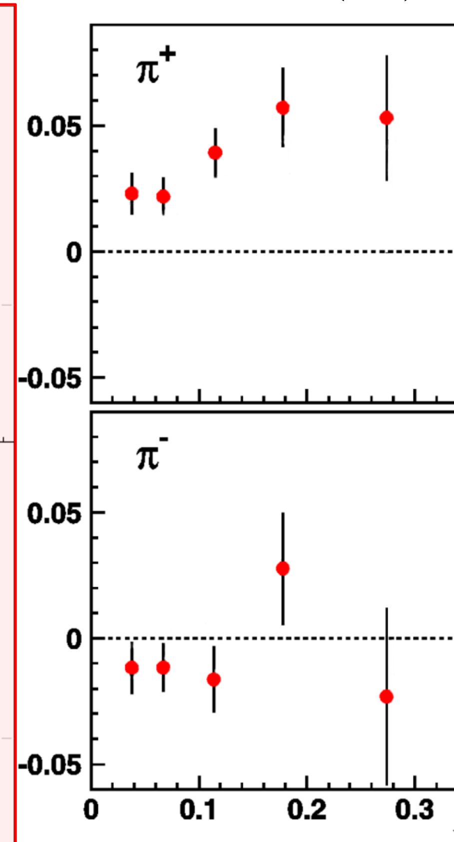


HERMES PLB 622 (2005) 14



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SIDIS: target longitudinal spin dependent asymmetries

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

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

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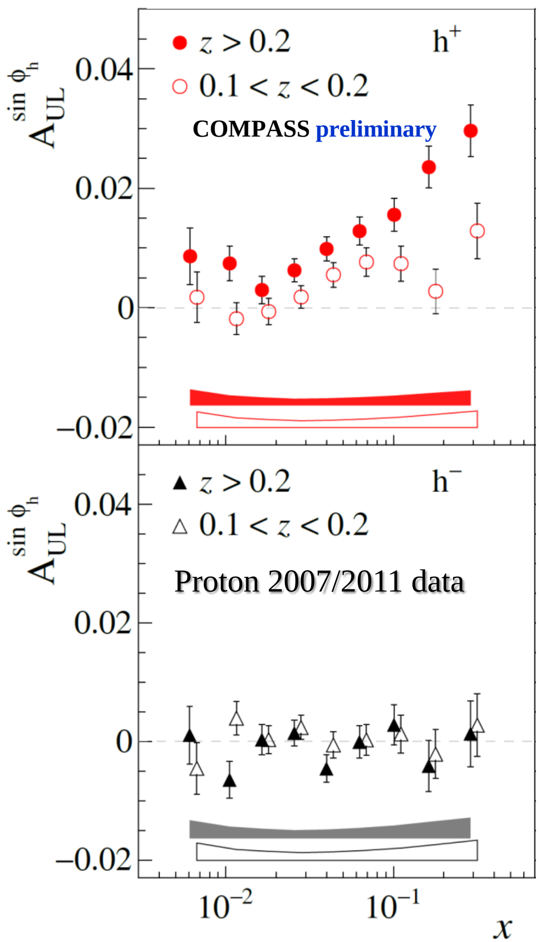
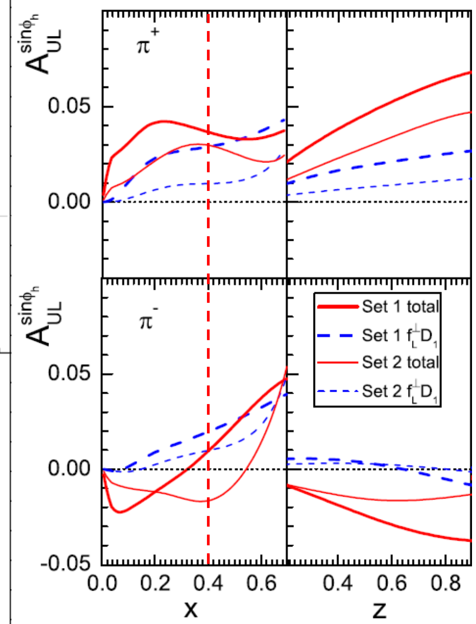
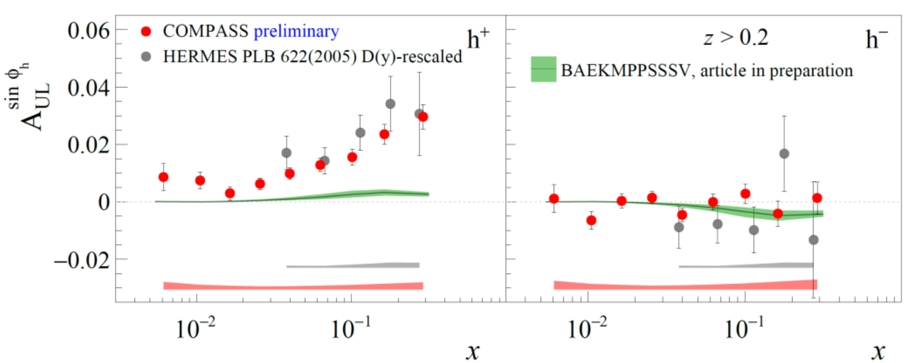


Zhun Lu
Phys. Rev. D 90, 014037(2014)



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

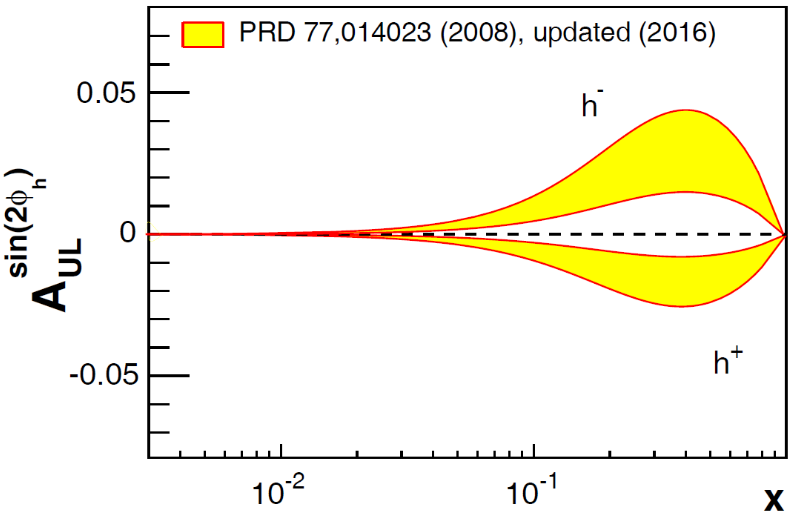


- Q-suppression, TSA-mixing
- Various different "twist" ingredients
- **Non-zero trend for h^+, h^- compatible with zero, clear z-dependence**

SIDIS: target longitudinal spin dependent asymmetries

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

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



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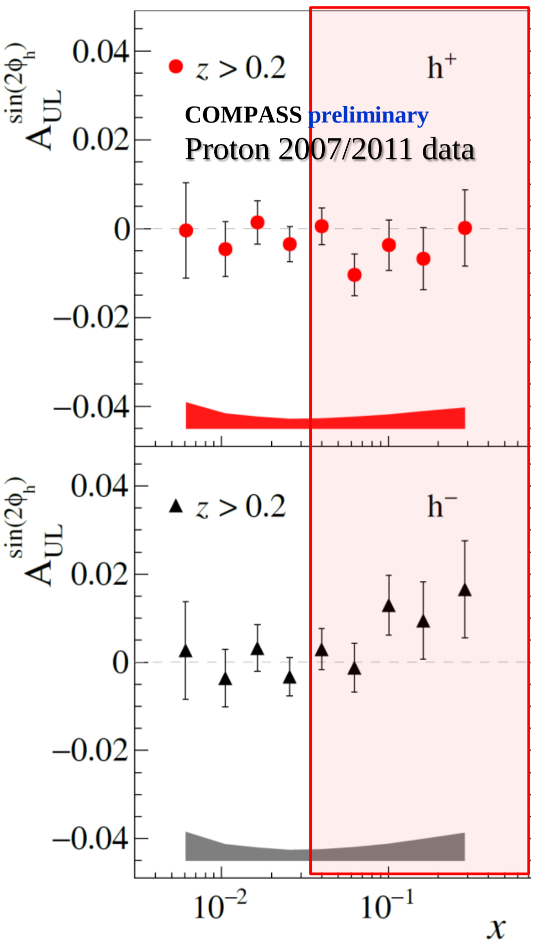
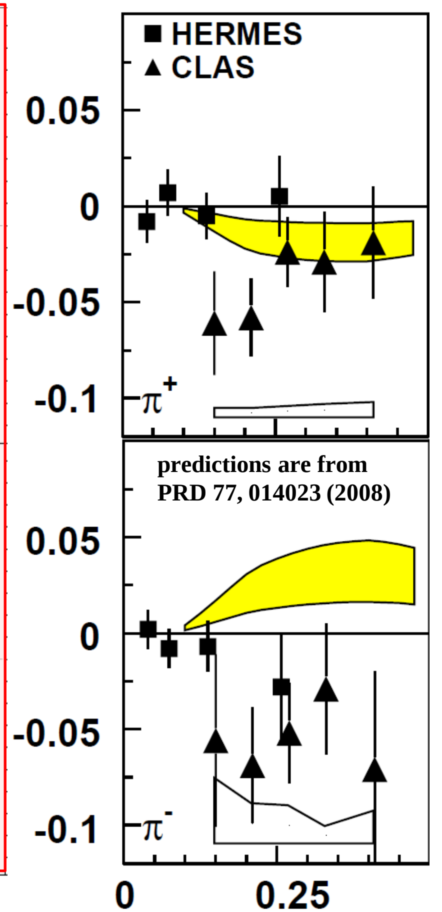


PRL 105,262002(2010)



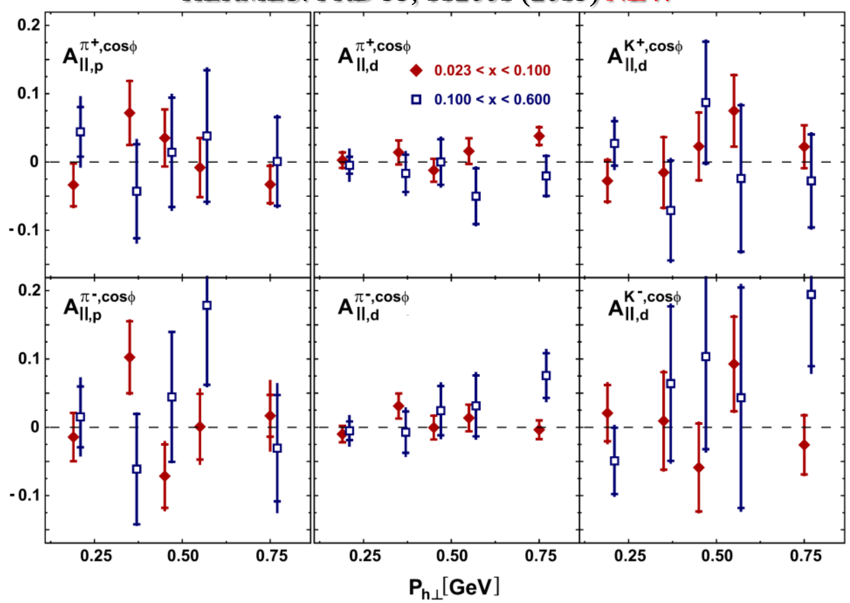
- Only "twist-2" ingredients
- Additional p_T-suppression
- Collins-like behavior?
- In agreement with model predictions
- Discrepancy COMPASS vs. HERMES and JLab?

SIDIS: target longitudinal spin dependent asymmetries

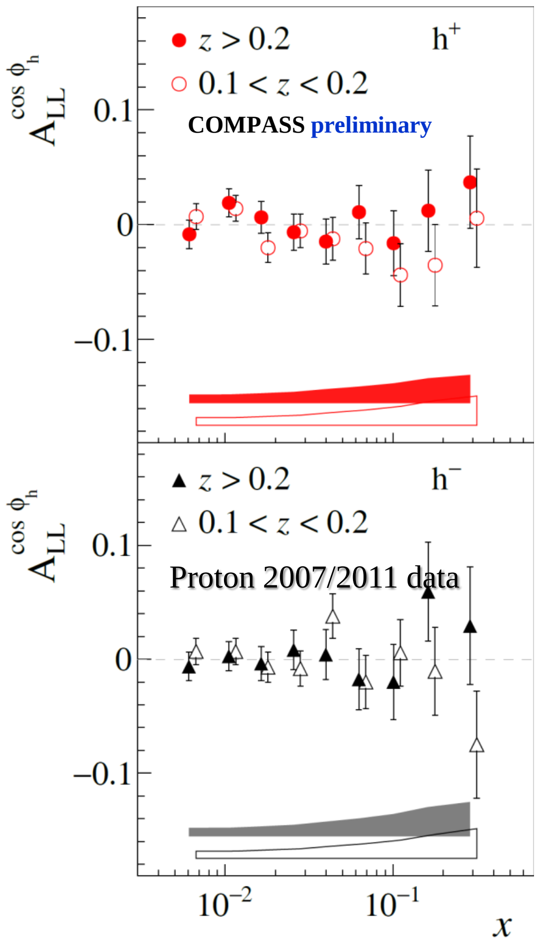
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h + \ldots\right\}$$

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

HERMES: PRD 99, 112001 (2019) **NEW**



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



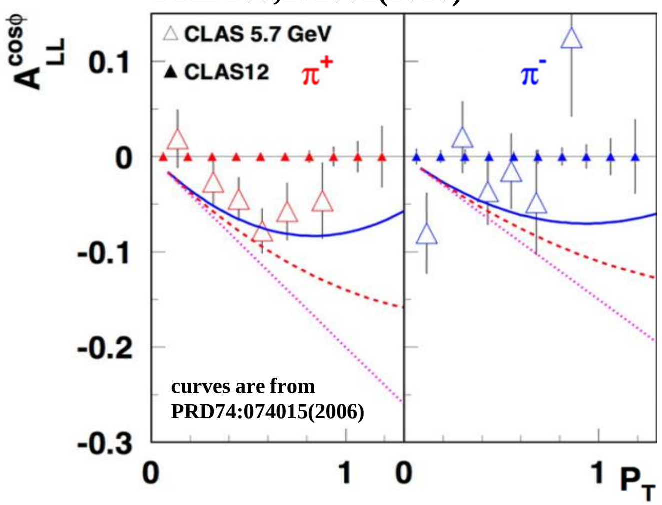
- Various different “twist” ingredients, factor Q^{-1}
- Non zero at JLab
- HERMES/COMPASS - small and compatible with zero, in agreement with model predictions

SIDIS: target longitudinal spin dependent asymmetries

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

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

PRL 105,262002(2010)



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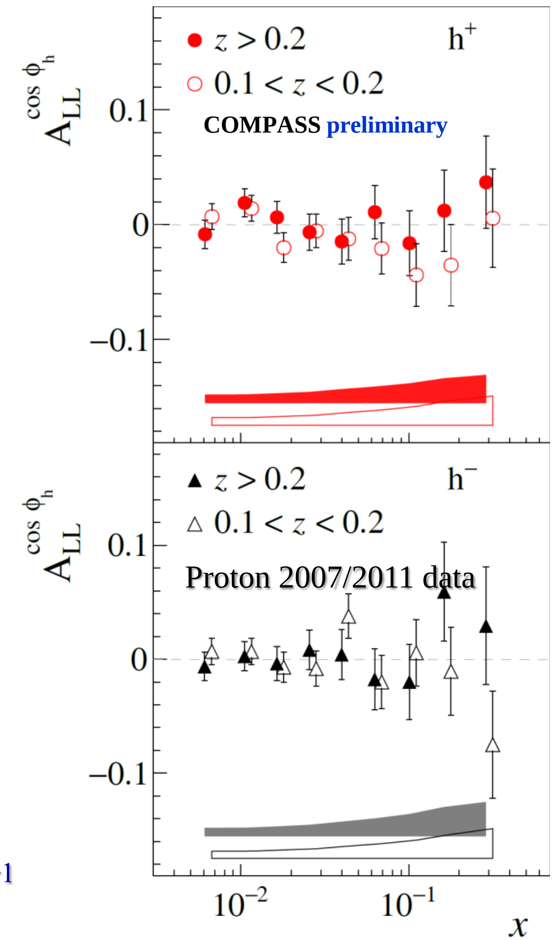
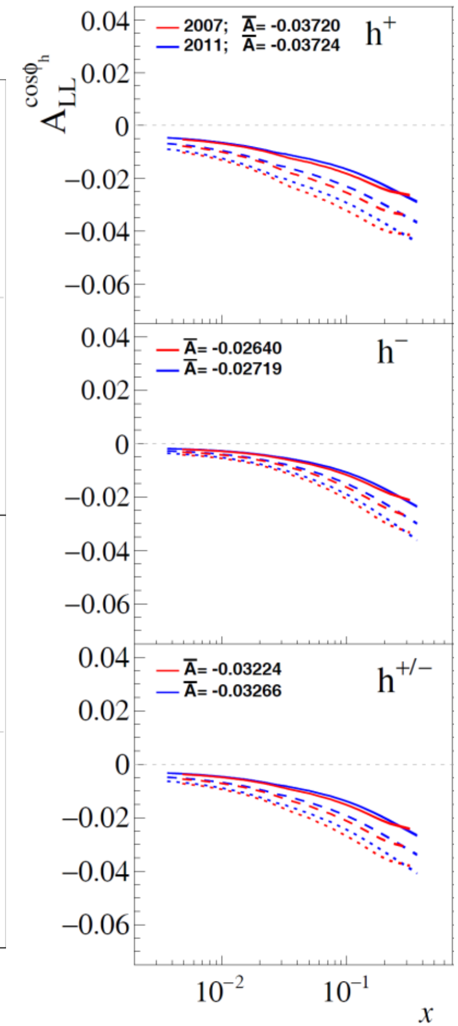




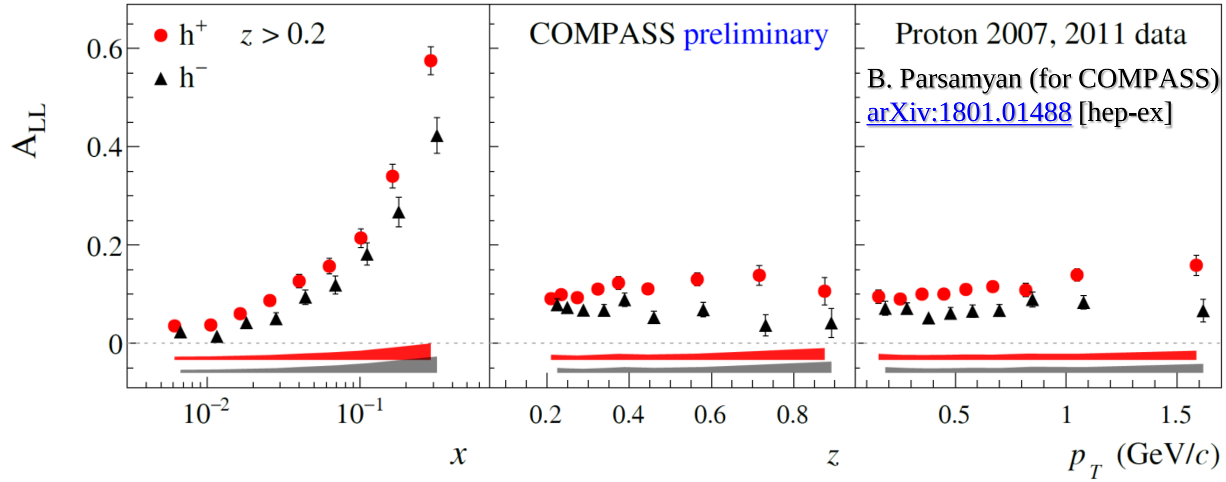
- Various different “twist” ingredients, factor Q^{-1}
- Non zero at JLab
- HERMES/COMPASS - small and compatible with zero, in agreement with model predictions

SIDIS: target longitudinal spin dependent asymmetries

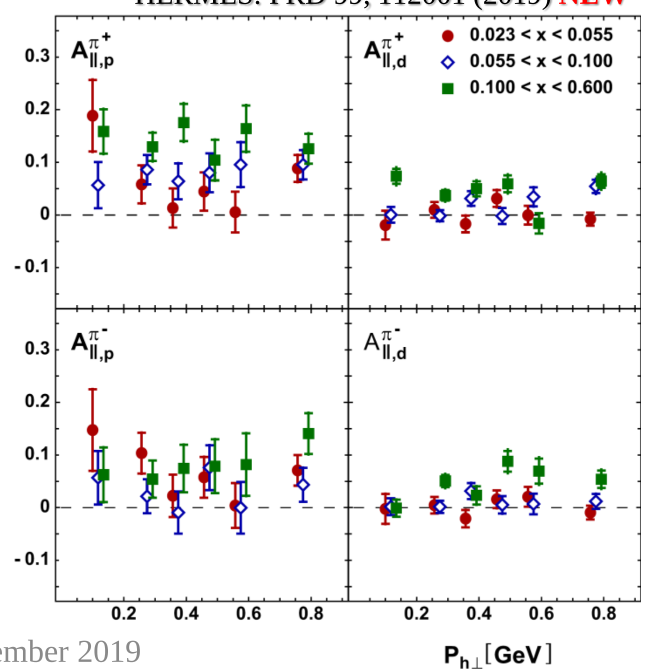
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL} + \ldots\right\}$$

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

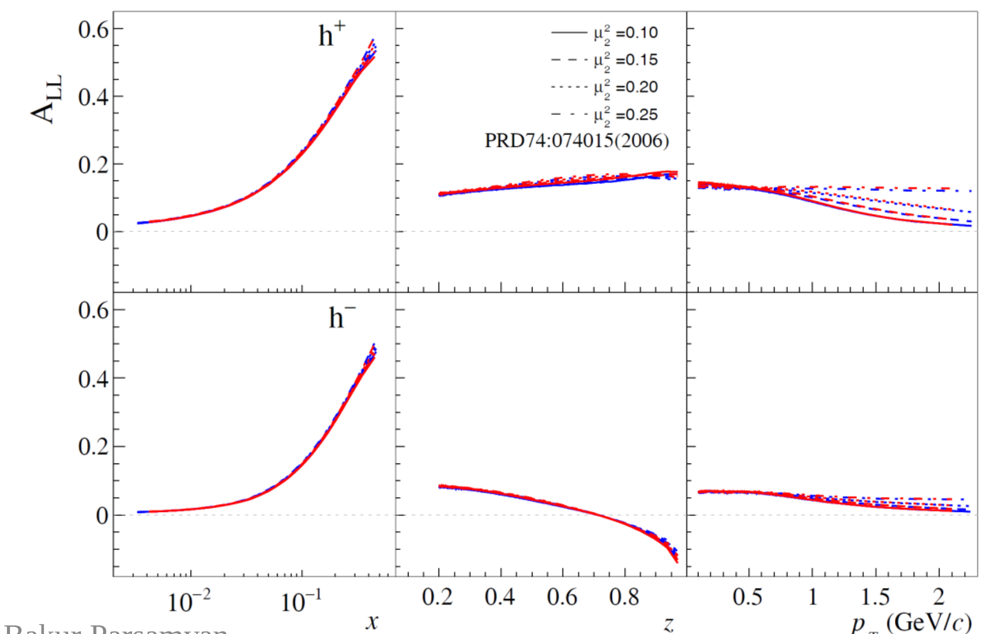
- Measurement of (semi-)inclusive A_1(A_{LL}) is one of the key physics topics of HERMES/COMPASS
- Large amount of P/D data
- No P_T-dependence observed



HERMES: PRD 99, 112001 (2019) **NEW**



COMPASS Proton-2007, -2011 kinematics



- Transverse spin dependent asymmetries in SIDIS and Drell-Yan: selected results

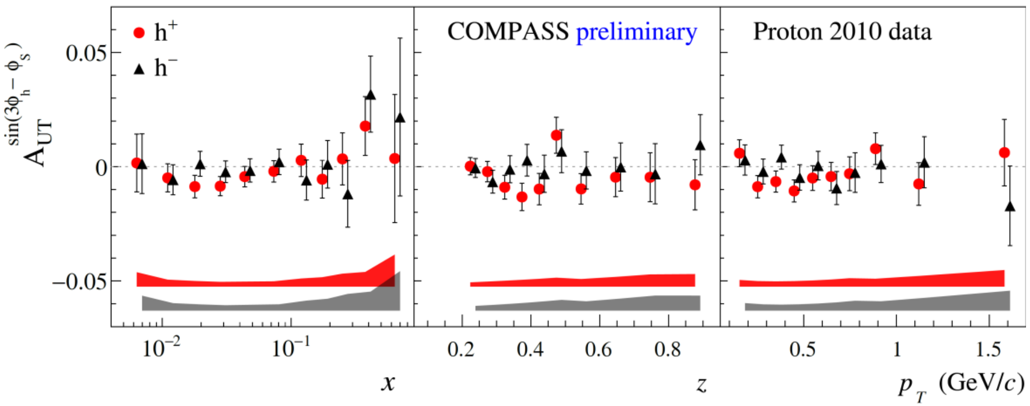
SIDIS: target transverse spin dependent asymmetries

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

SIDIS: target transverse spin dependent asymmetries

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

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



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

COMPASS/HERMES results

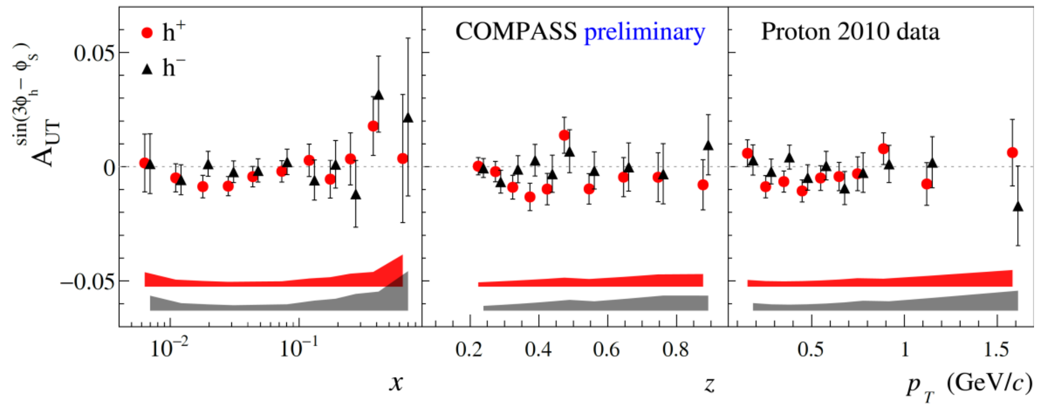
$A_{UT}^{\sin(3\phi_h-\phi_S)}$

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

SIDIS: target transverse spin dependent asymmetries

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

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

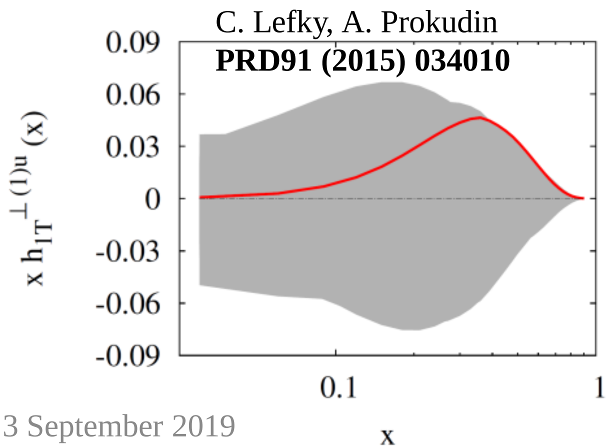


$$F_{UT}^{\sin(3\phi_h - \phi_S)} = C\left[\frac{2(\hat{h}\cdot k_T)(k_T\cdot p_T) + k_T^2(\hat{h}\cdot p_T) - 4(\hat{h}\cdot k_T)^2(\hat{h}\cdot p_T)}{2M^2 M_h} h_{1T}^{\perp q} H_{1q}^{\perp h} \right]$$

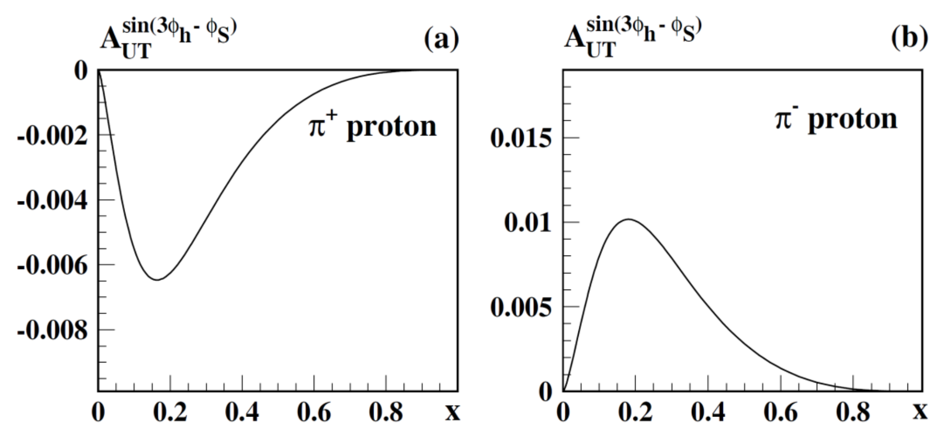
COMPASS/HERMES results

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

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



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



SIDIS - Drell-Yan TSAs: Pretzelosity

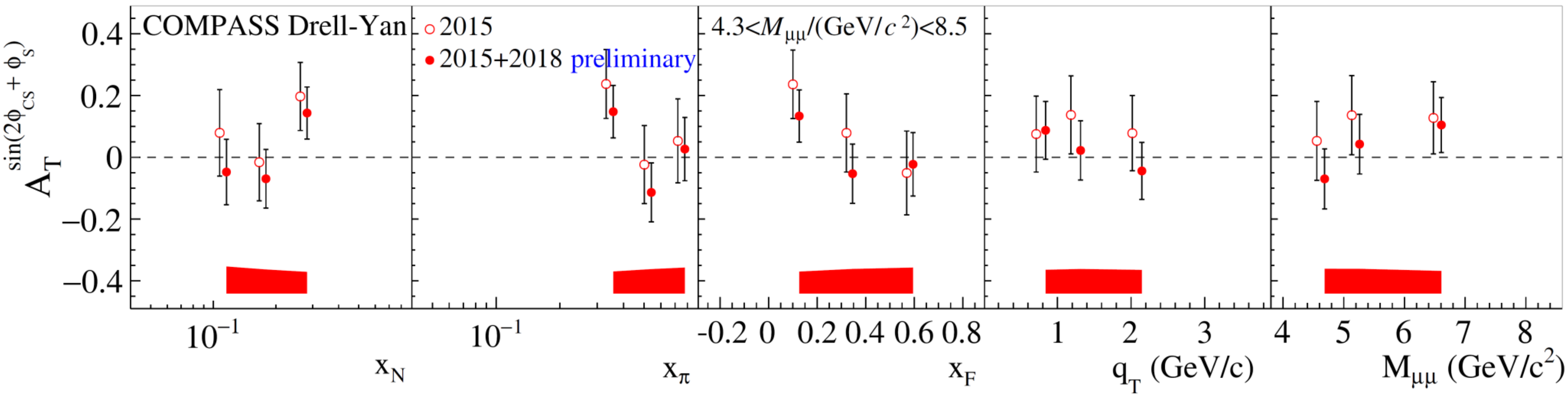
B. Parsamyan (COMPASS at DIS-2019)
arXiv:1908.01727 [hep-ex]

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

Pretzelosity DY TSA

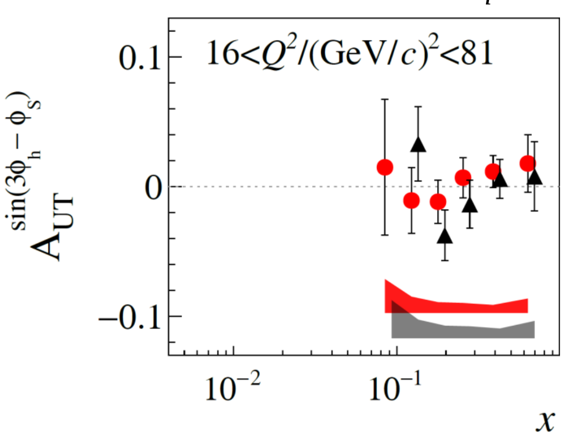
$$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$$

COMPASS 2015 (*PRL 119, 112002 (2017)*) + 2018 (~50%)

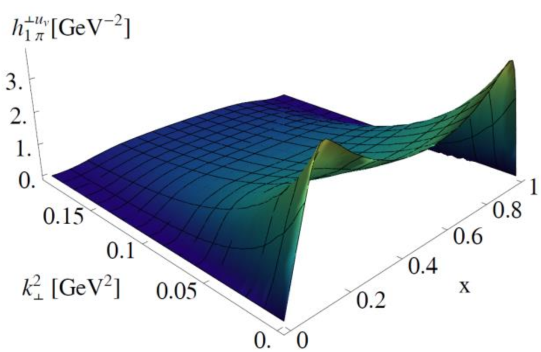


Pretzelosity SIDIS TSA

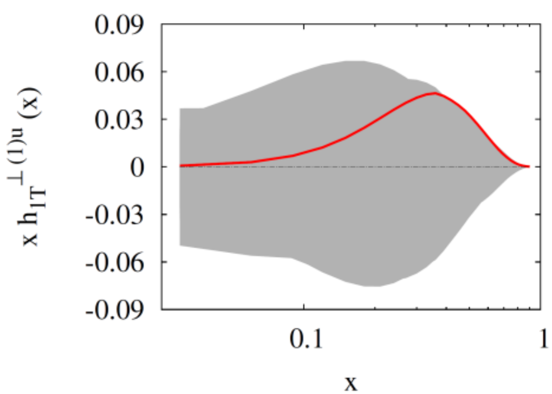
$$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$



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



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



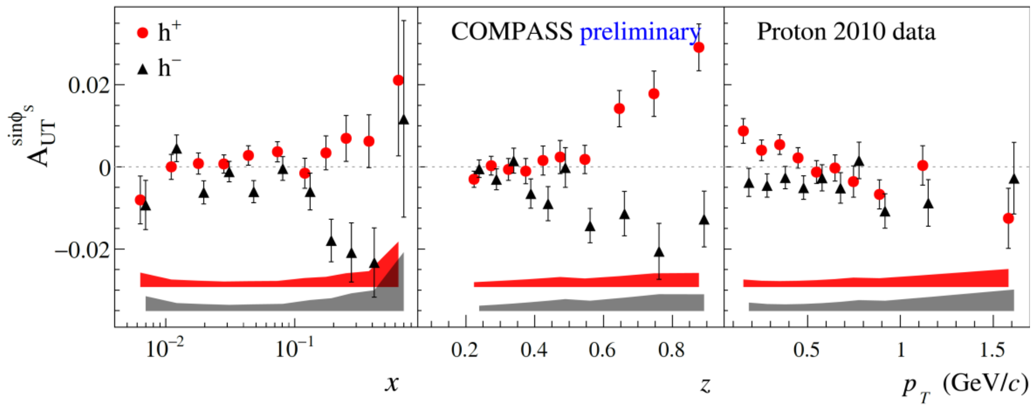
SIDIS: target transverse spin dependent asymmetries

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

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

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

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

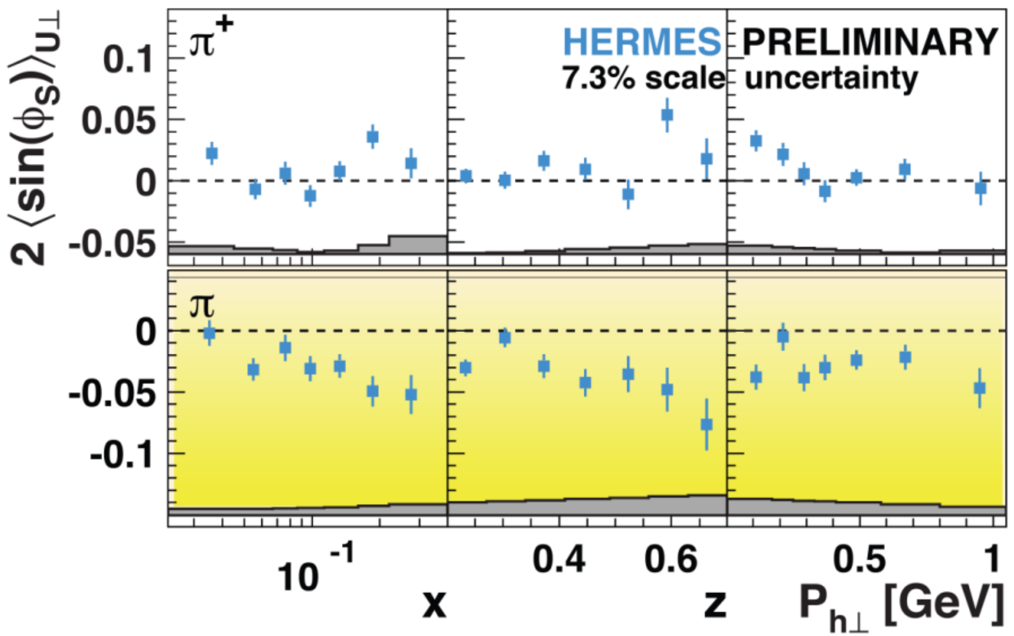


COMPASS/HERMES results

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

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

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



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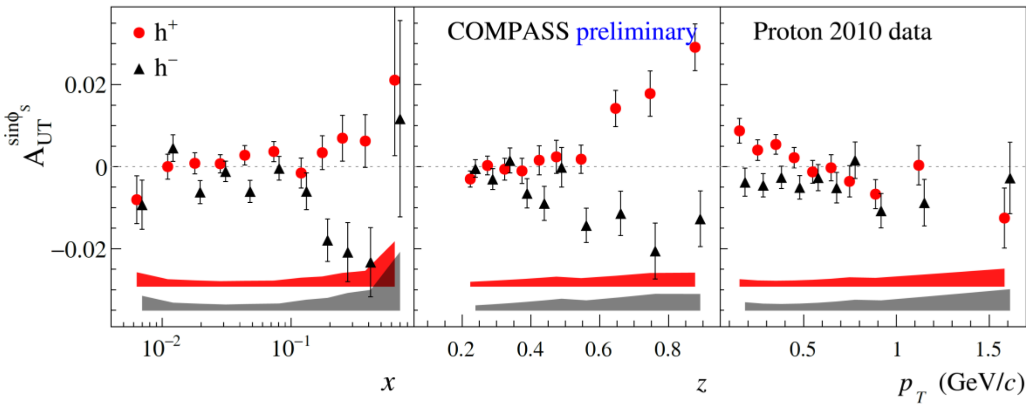
$$+\ S_T\left[\begin{array}{l} +\ \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\ +\ \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\ +\ \ldots \end{array}\right]$$
$$\left. +\ S_T\lambda\left[\begin{array}{l} \sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)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

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



COMPASS/HERMES results

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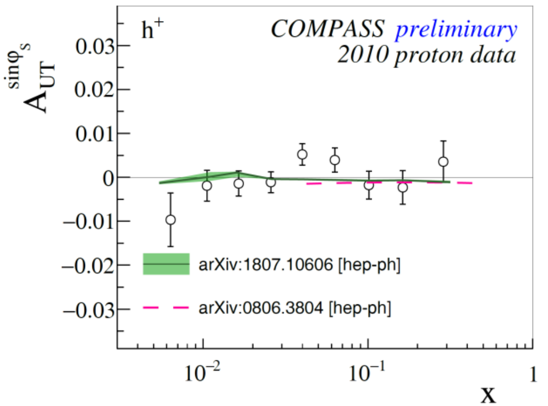
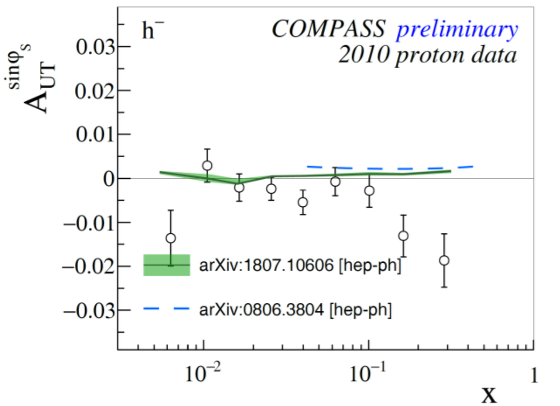
- Q-suppression
- Various different "twist" ingredients
- Within WW is related to Sivers and Collins
- **Small asymmetry, non-zero signal for h⁻?**

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

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

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

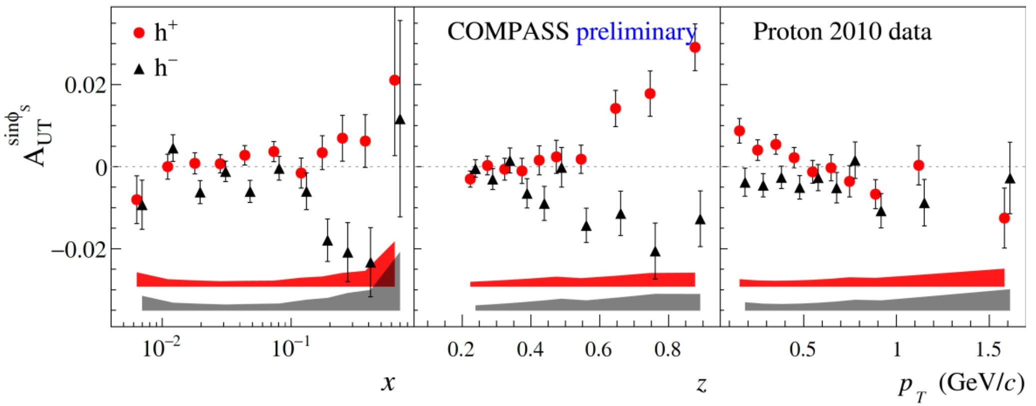




SIDIS: target transverse spin dependent asymmetries

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

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



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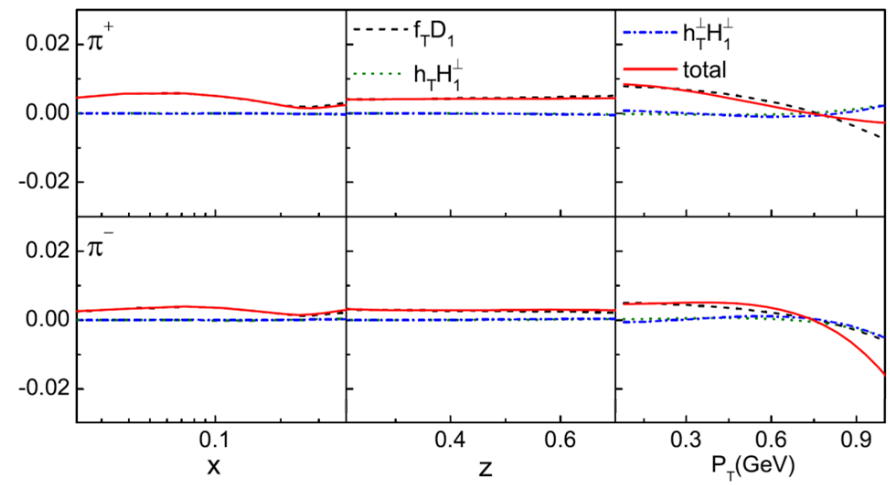
W. Mao, Z. Lu and B.Q. Ma Phys.Rev. D 90 (2014) 014048



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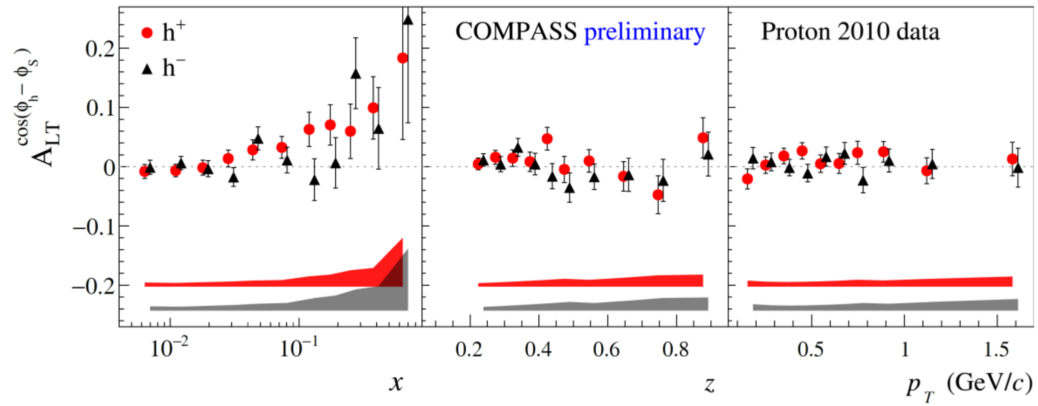
$$+ S_T \lambda \left[\begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) \\ + \ldots \end{array} \right] \Bigg\}$$

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

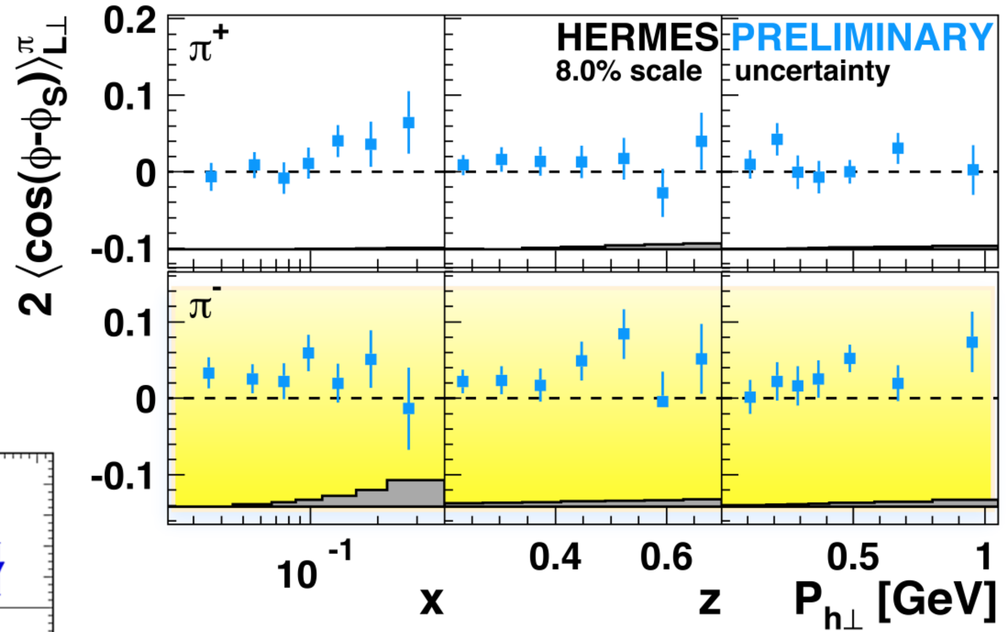


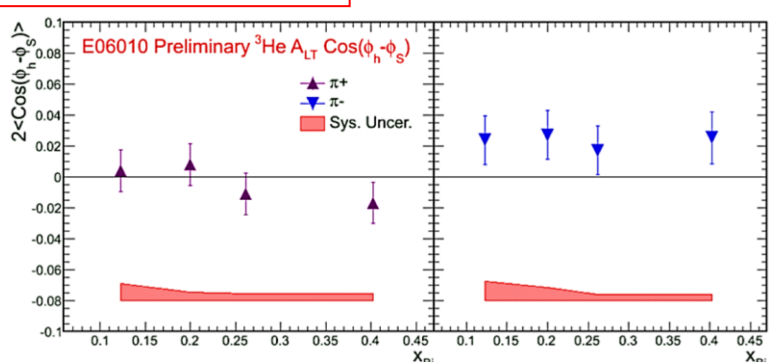
COMPASS/HERMES/JLab results

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

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

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





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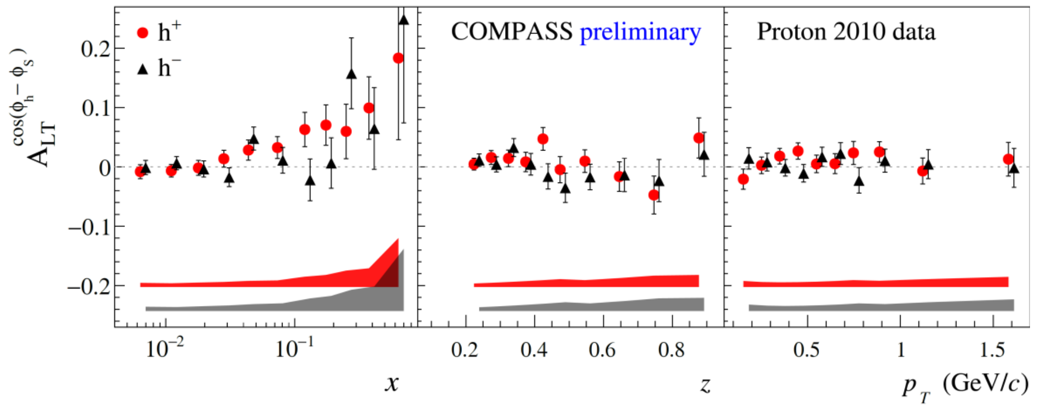
B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



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S. Bastami et al. JHEP 1906 (2019) 007:
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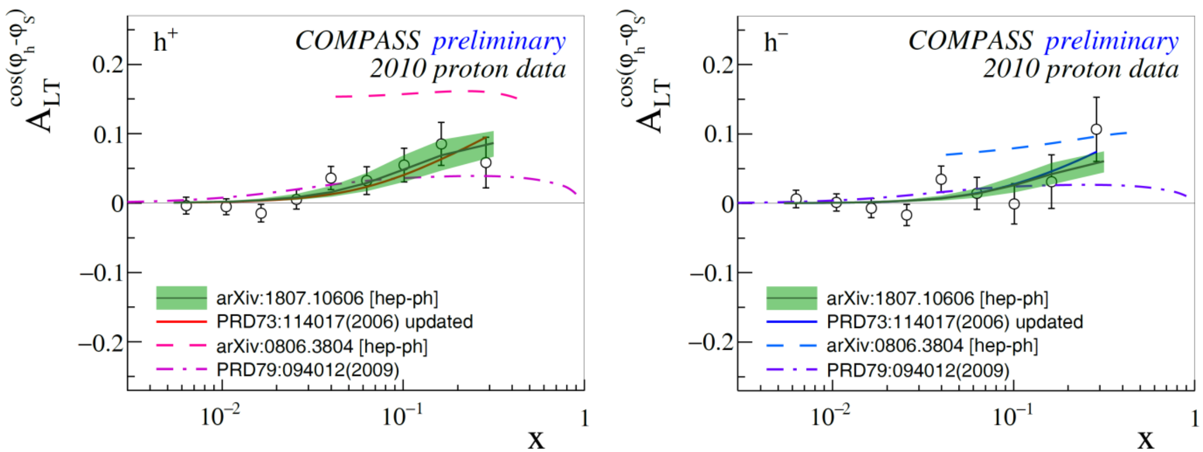


- Transverse spin dependent asymmetries in SIDIS and Drell-Yan: Transversity PDF

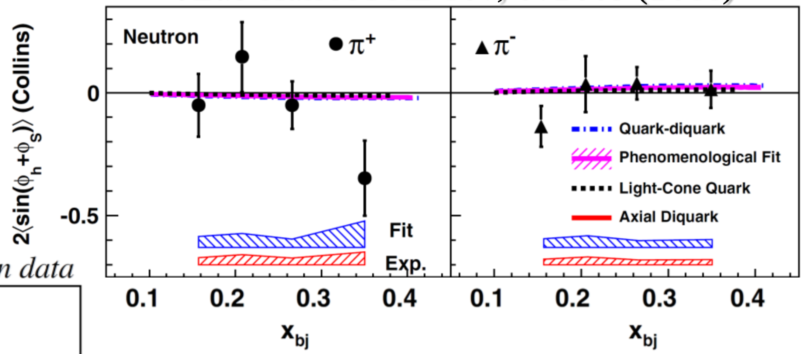
SIDIS TSAs: Collins effect and Transversity

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

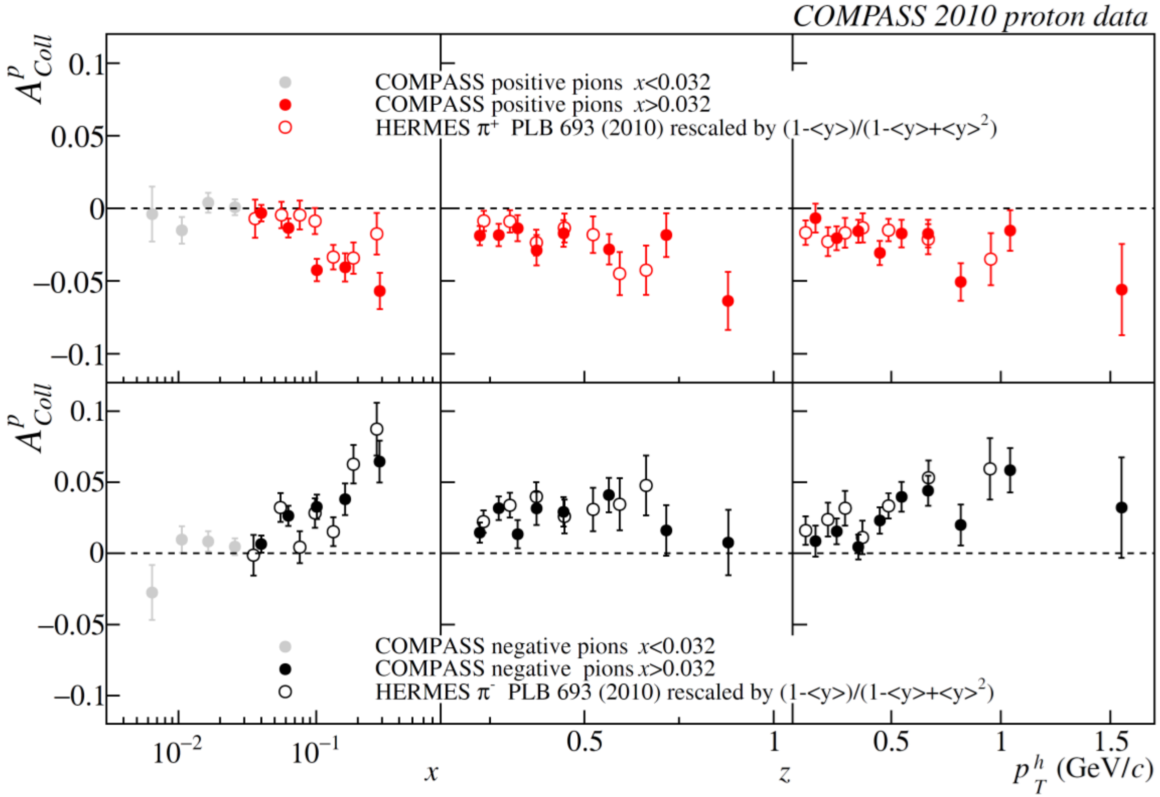
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}} \cdot \boldsymbol{p}_T}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

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

JLab Hall A PRL 107, 072003 (2011)



COMPASS PLB 744 (2015) 250



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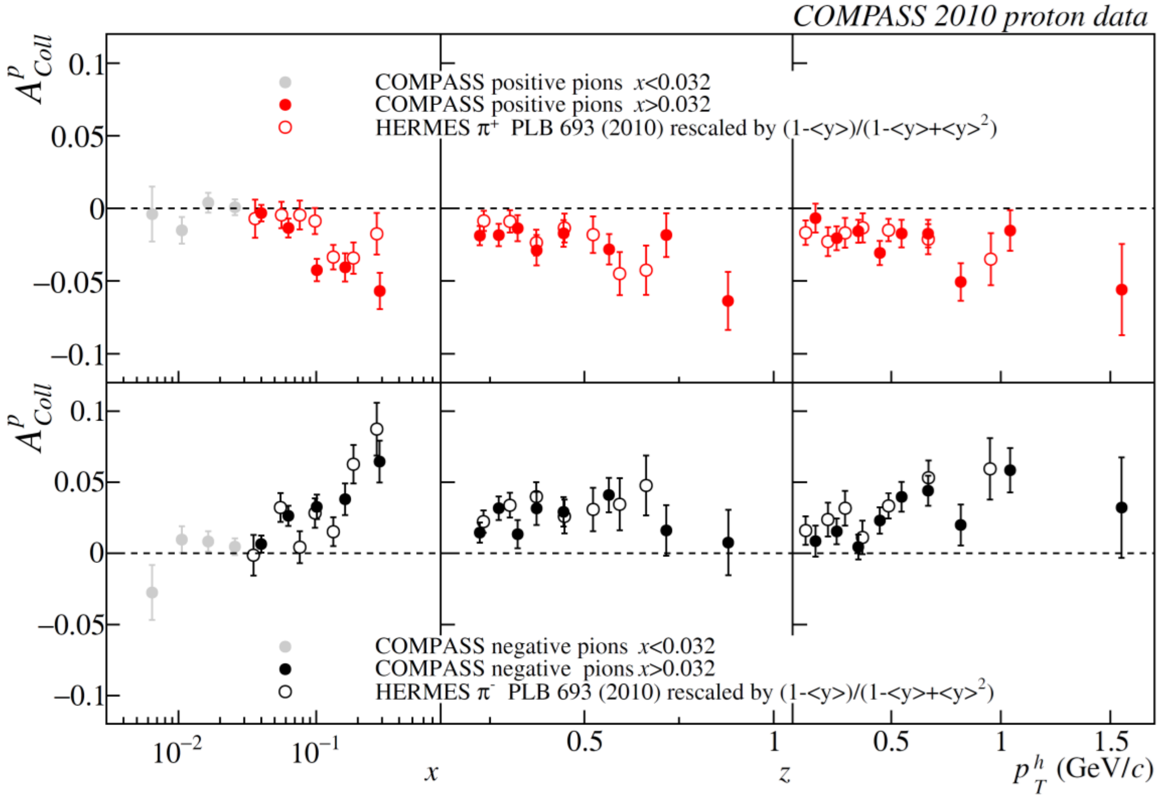
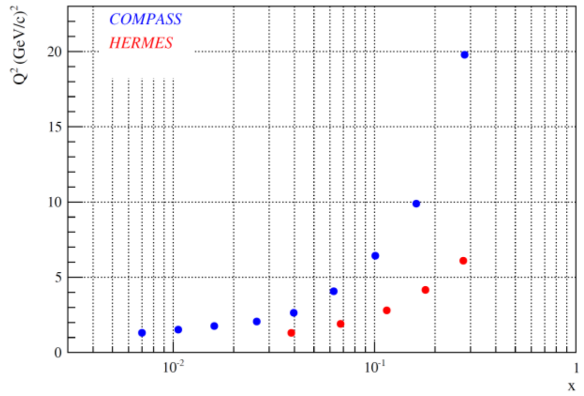
COMPASS PLB 744 (2015) 250





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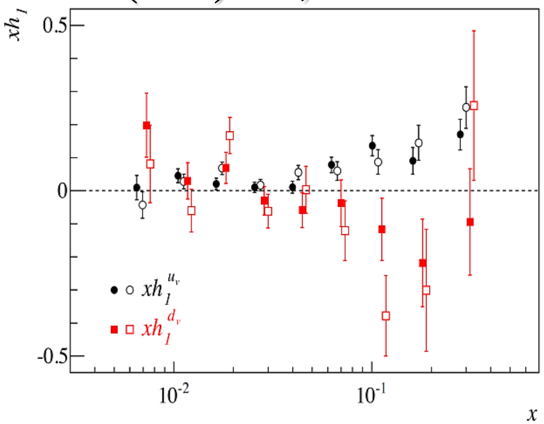
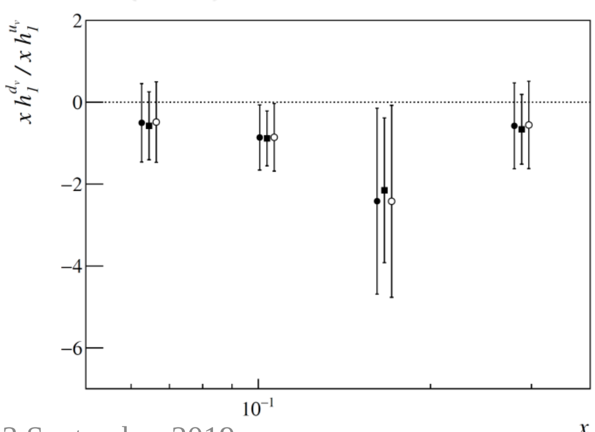
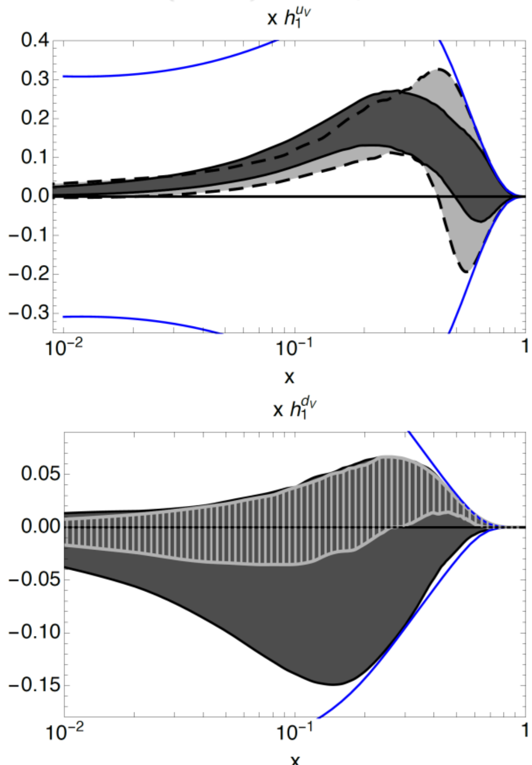
A. Martin, F. Bradamante, V. Barone
PRD91 (2015) no.1, 014034



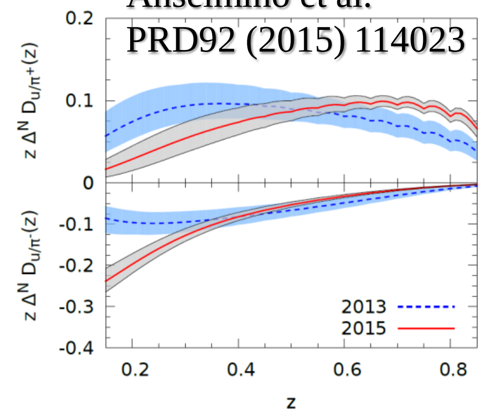
A. Martin, F. Bradamante, V. Barone et al.
PRD99 (2019) no.11, 114004

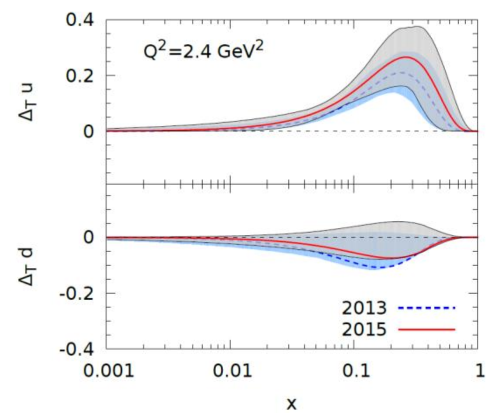


M. Radici and A. Bacchetta
PRL 120 (2018) no.19, 192001



Anselmino et al.
PRD92 (2015) 114023





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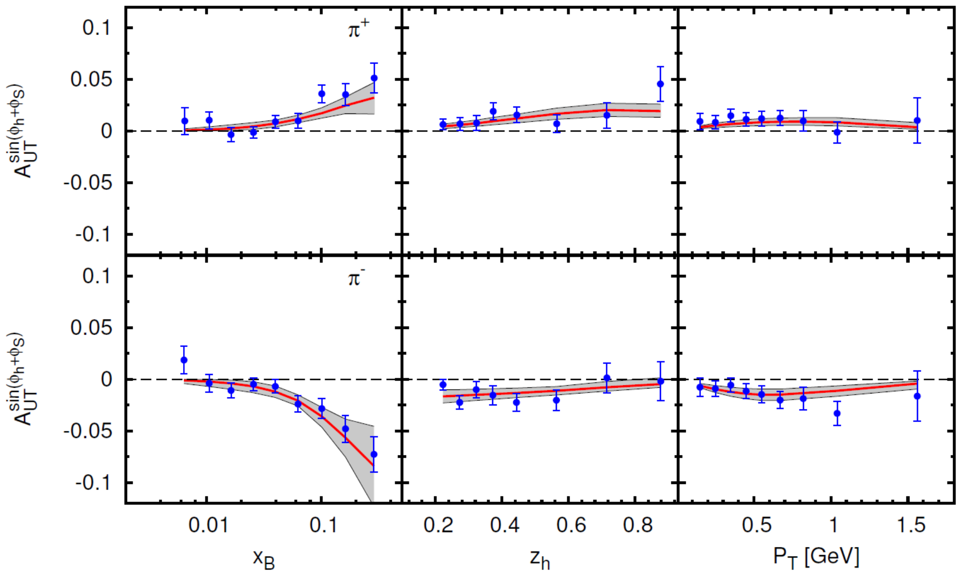
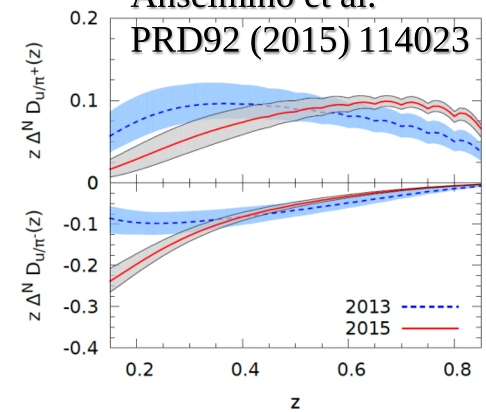
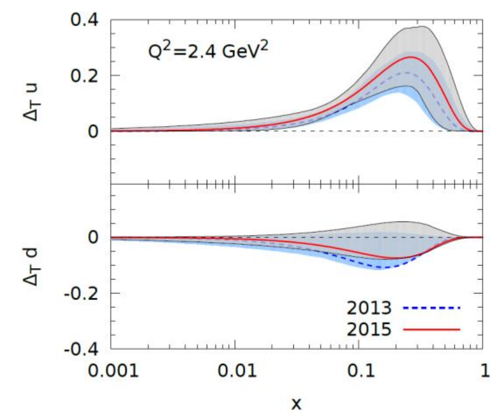
Global fit HERMES-COMPASS-BELLE data
Anselmino et al. **Phys.Rev. D92 (2015) 114023**



Anselmino et al.
PRD92 (2015) 114023





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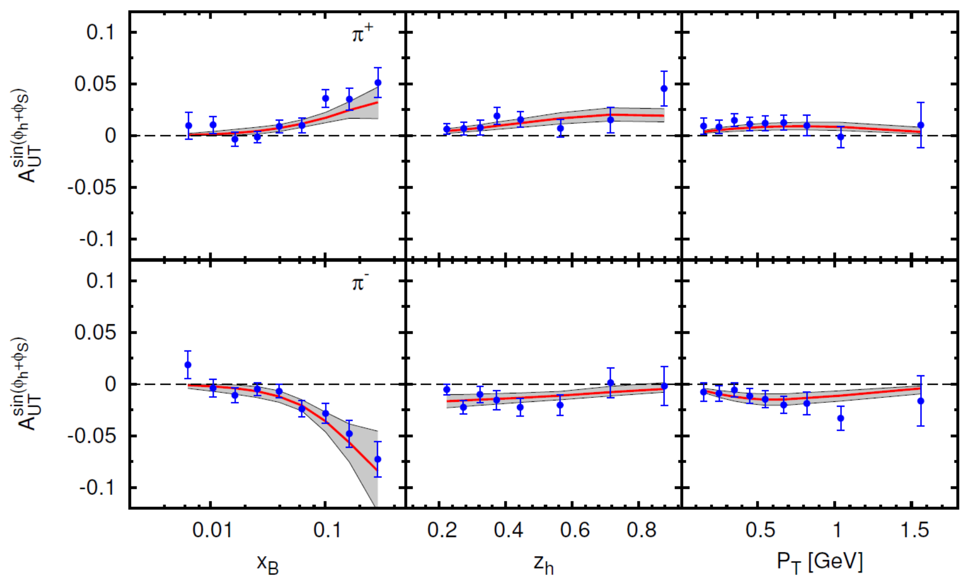

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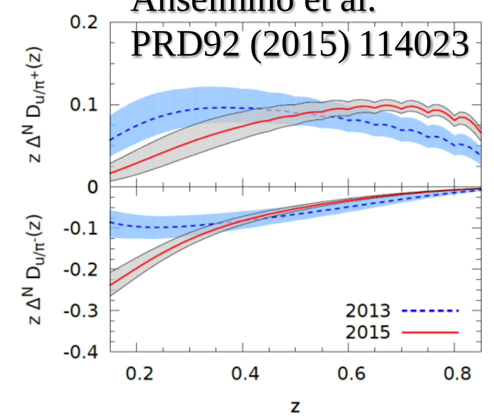
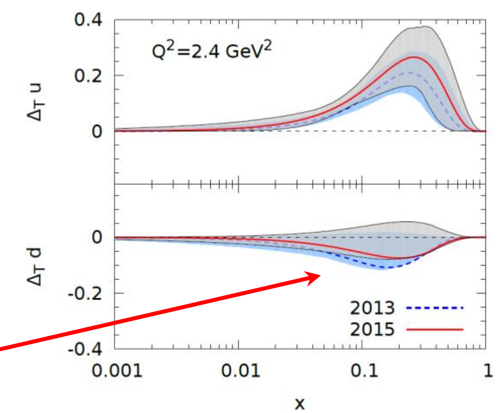
PRD92 (2015) 114023





COMPASS-II (2021)

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

SIDIS TSAs: Collins effect and Transversity

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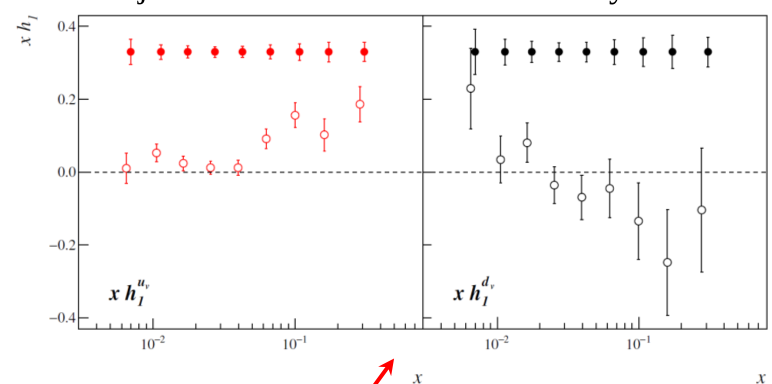
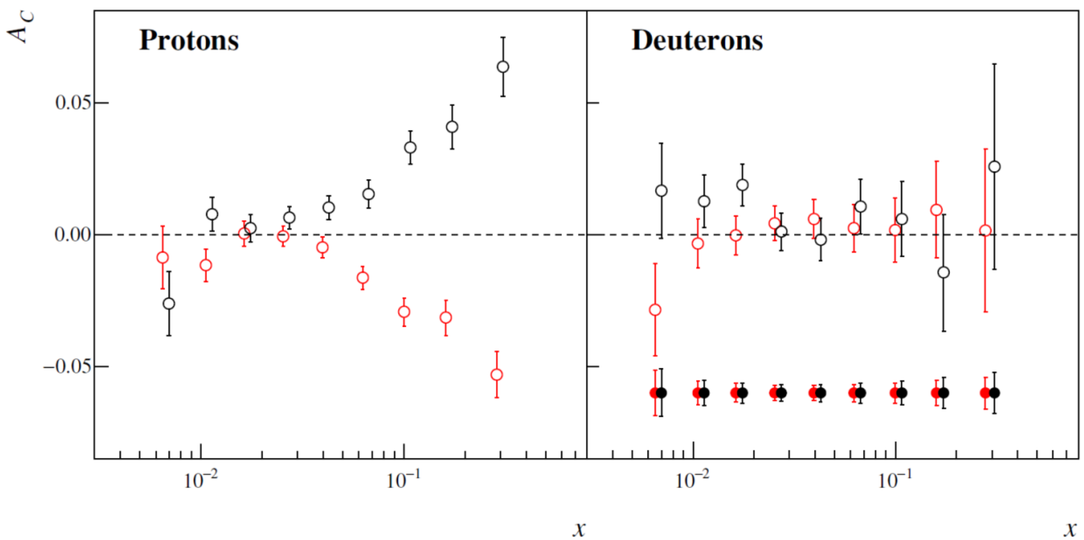
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p}_T}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

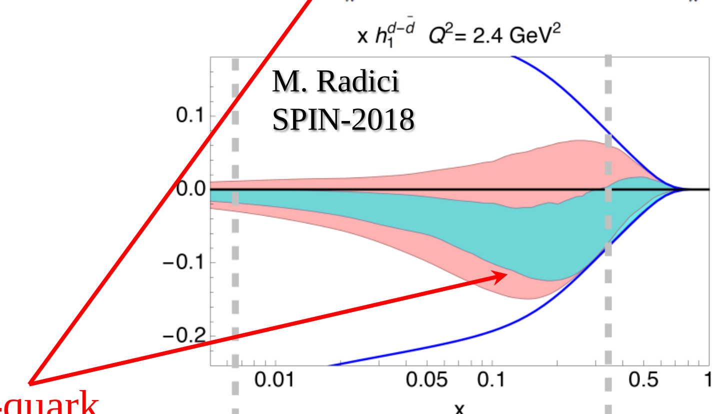
- Measured on P/D/N in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
- **No Q^2-evolution? Intriguing result!**
- Extensive phenomenological studies and various global fits by different groups

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



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





COMPASS-II (2021 run – approved!)

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

SIDIS TSAs: Collins effect and Transversity

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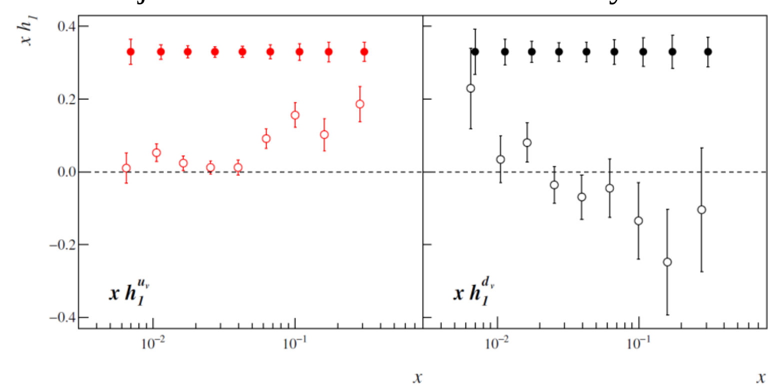

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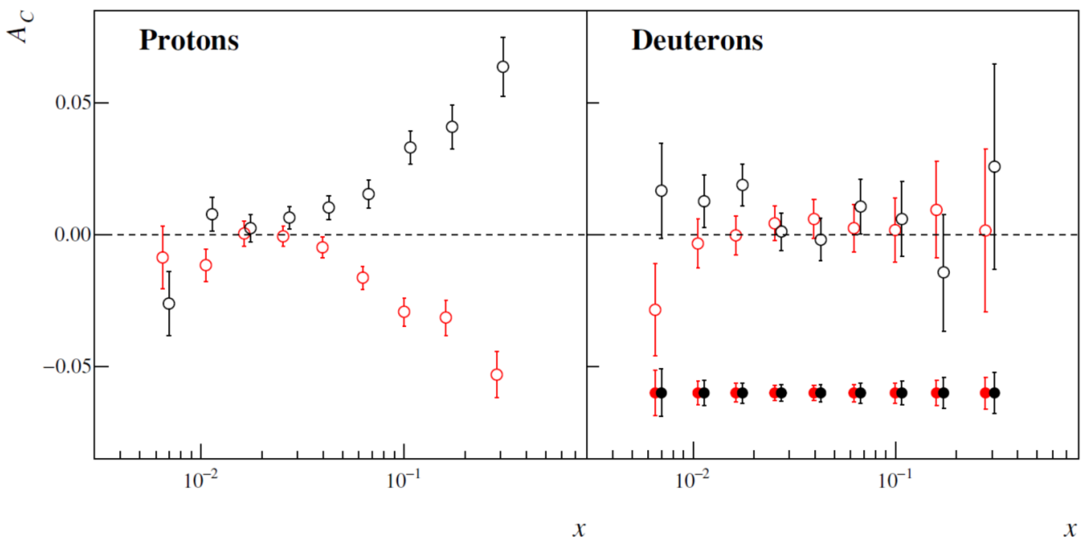

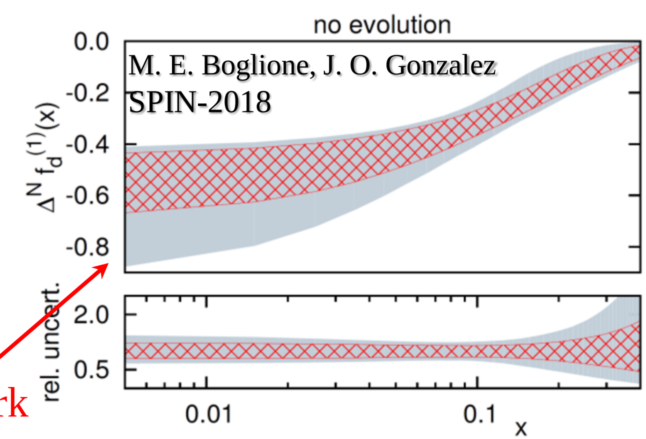

COMPASS-II (2021 run – approved!)

- Deuteron measurement to be repeated
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SIDIS – Drell-Yan TSAs: Transversity

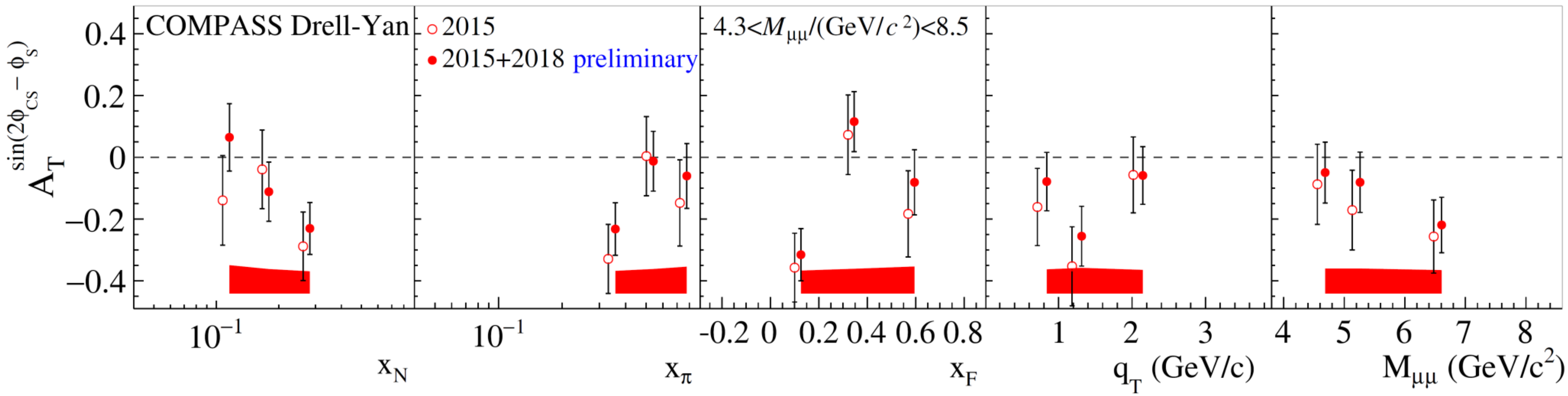
B. Parsamyan (COMPASS at DIS-2019)
arXiv:1908.01727 [hep-ex]

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

Transversity DY TSA

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

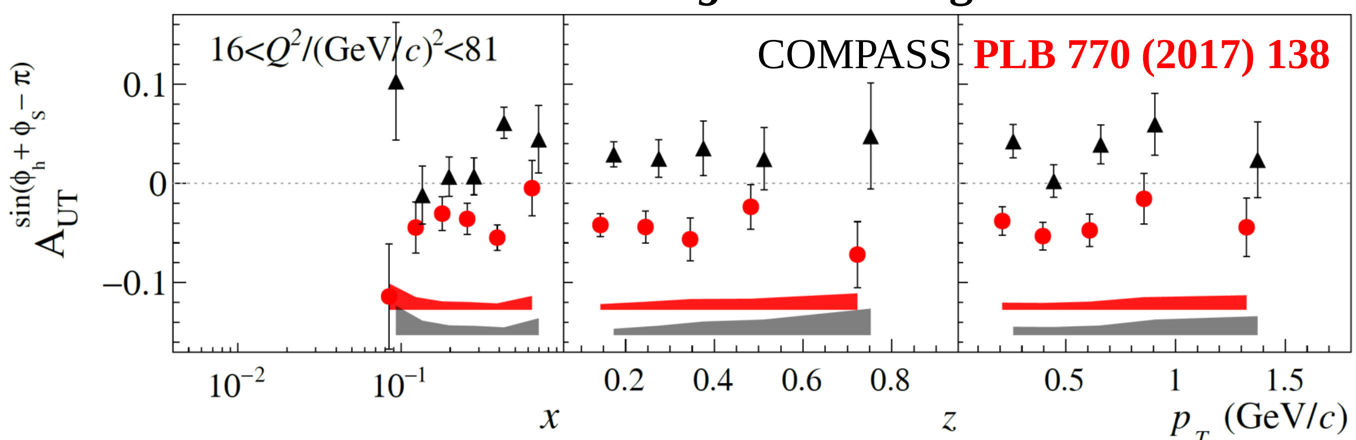
COMPASS 2015 (*PRL 119, 112002 (2017)*) + 2018 (~50%)



SIDIS in Drell-Yan *high-mass* range

Collins SIDIS TSA

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



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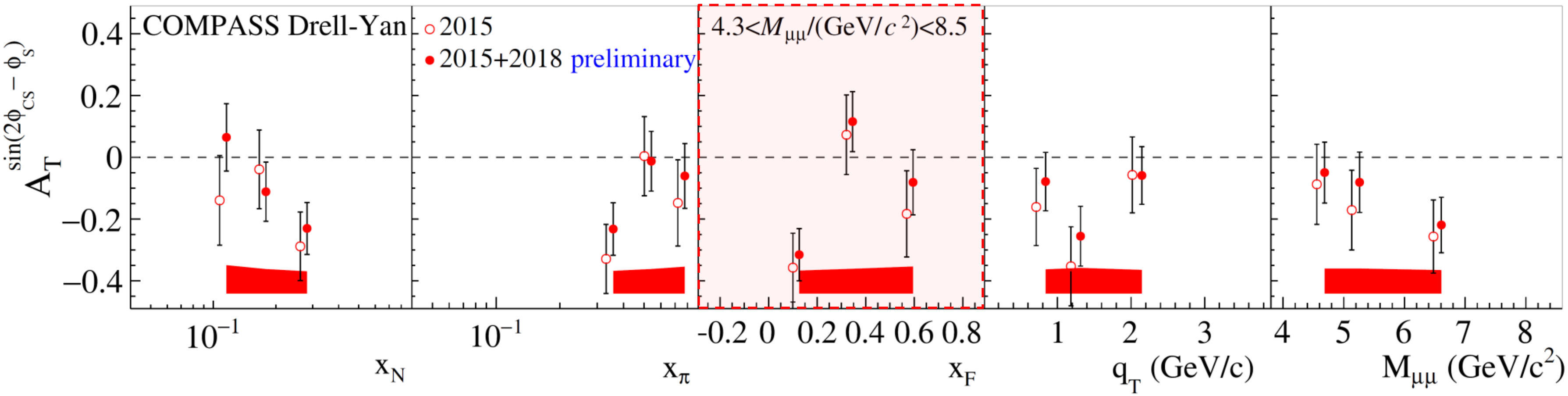
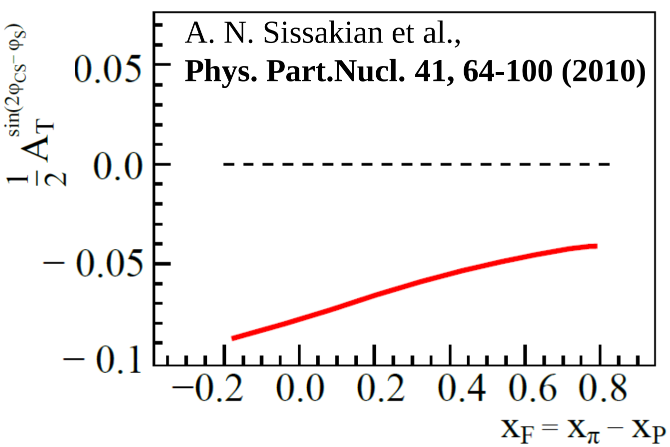
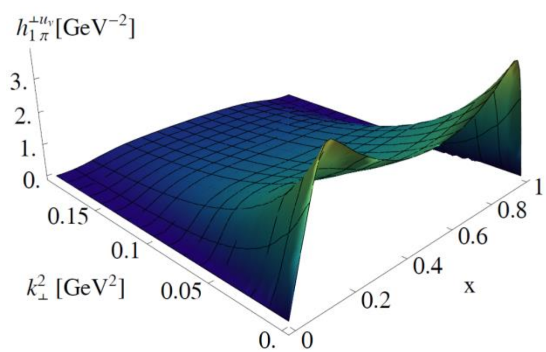
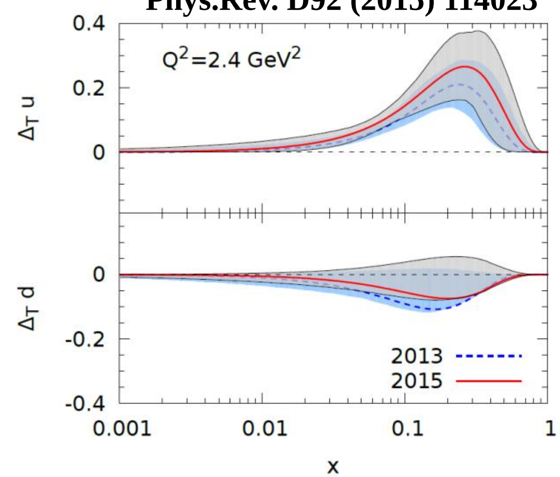




B. Pasquini, P. Schweitzer
Phys.Rev. D90 (2014) 014050



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



- Transverse spin dependent asymmetries in SIDIS and Drell-Yan: Sivers PDF

SIDIS TSAs: Sivers effect

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

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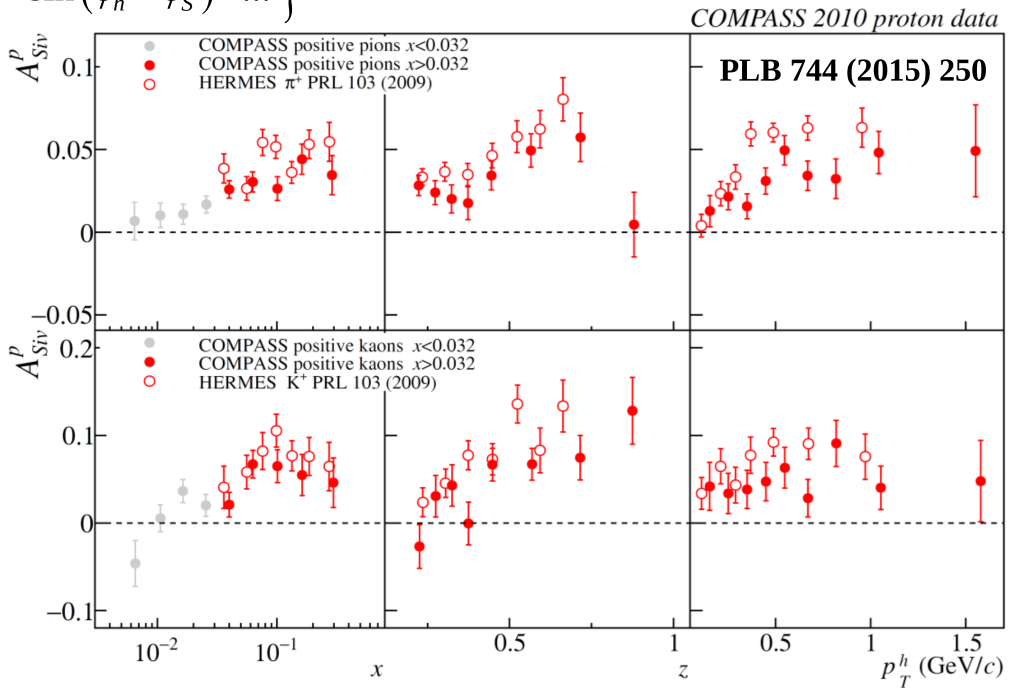
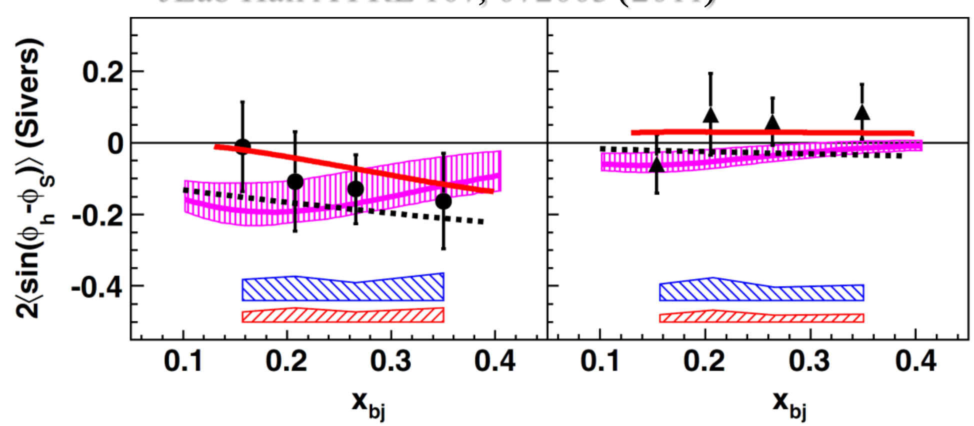
- Measured on proton and deuteron
- Recently - gluon Sivers paper PLB 772 (2017) 854



JLab Hall A PRL 107, 072003 (2011)



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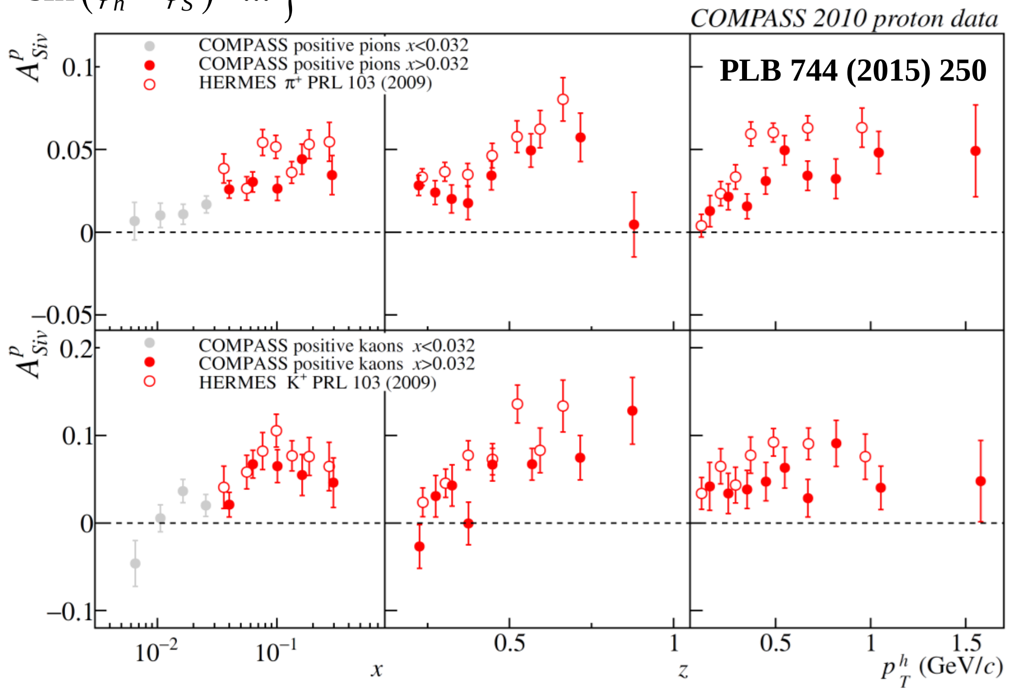

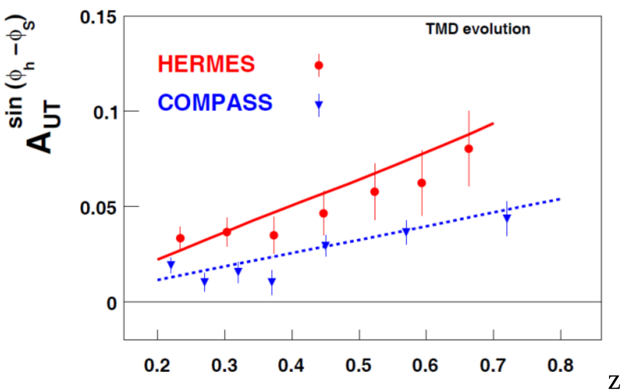

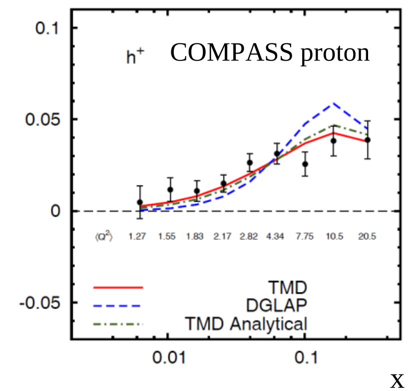

S. M. Aybat, A. Prokudin, T. C. Rogers **PRL 108 (2012) 242003**
M. Anselmino, M. Boglione, S. Melis **PRD 86 (2012) 014028**

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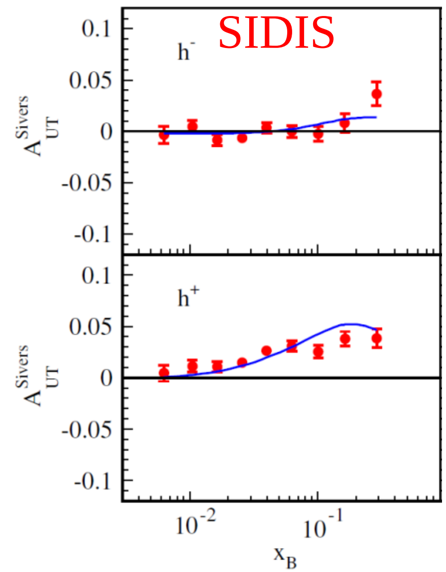
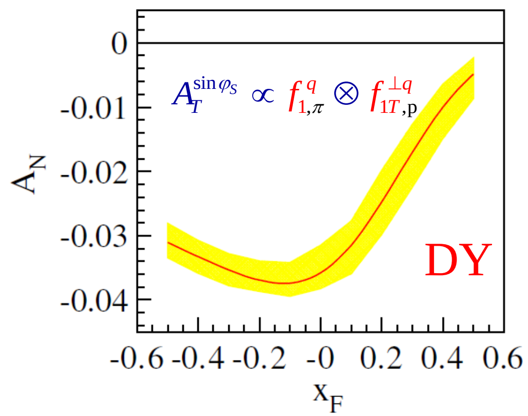
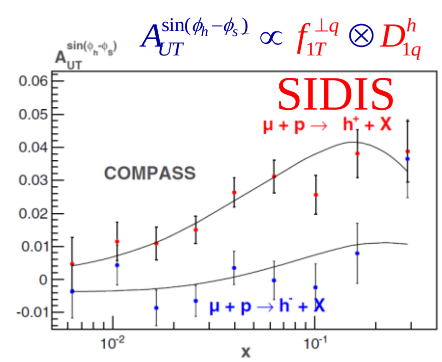
- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan

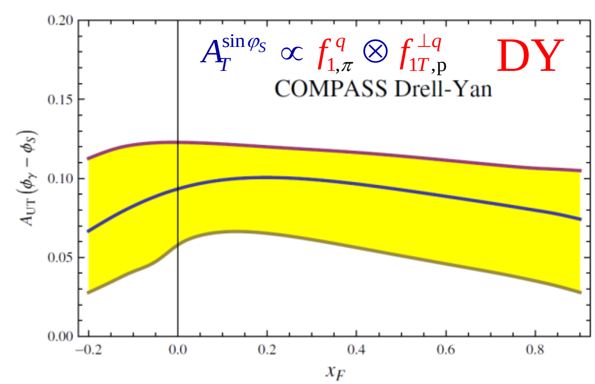
M.G. Echevarria, A.Idilbi, Z.B. Kang and I. Vitev, **PRD 89 074013 (2014)**





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





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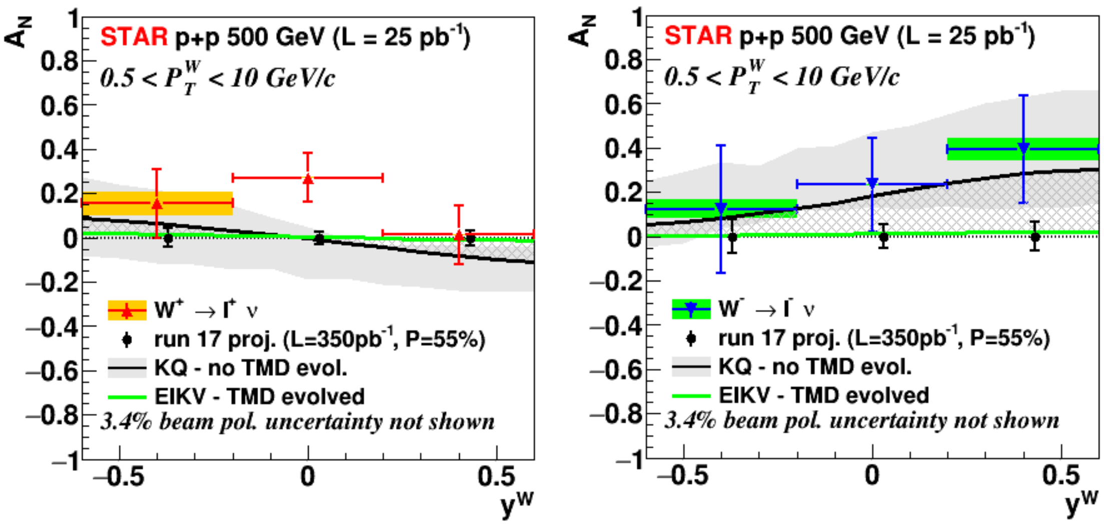
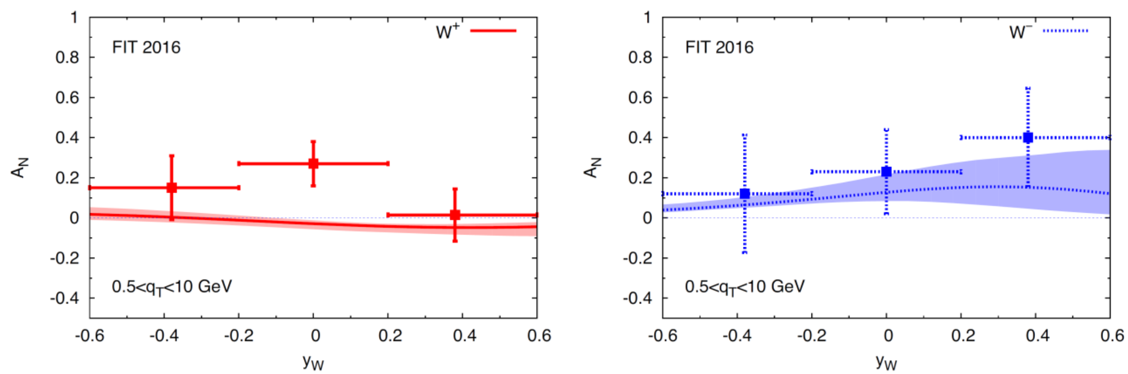
- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan

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

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



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



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

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

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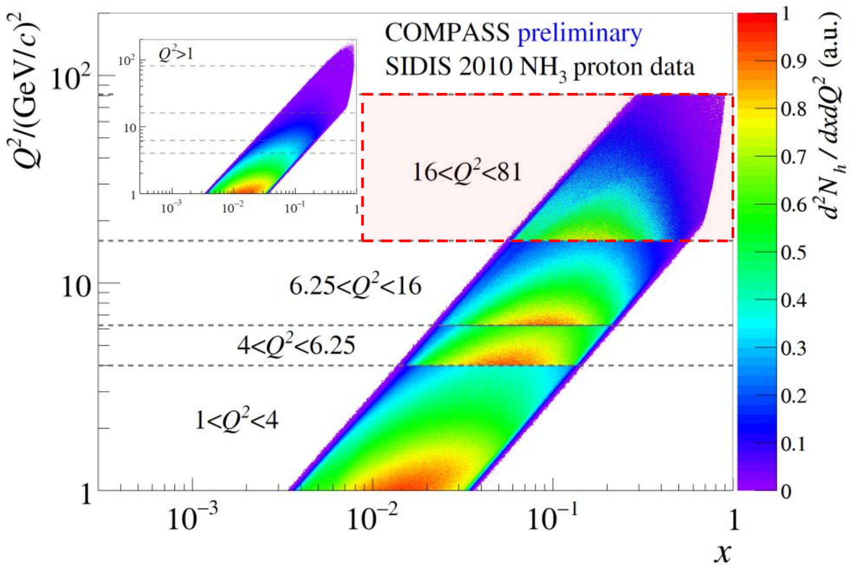
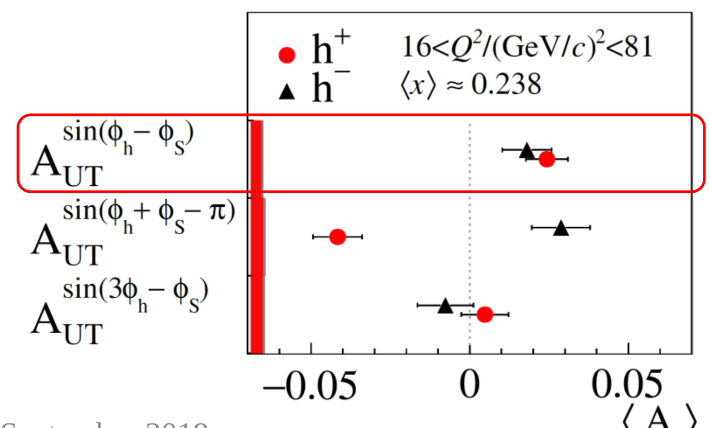
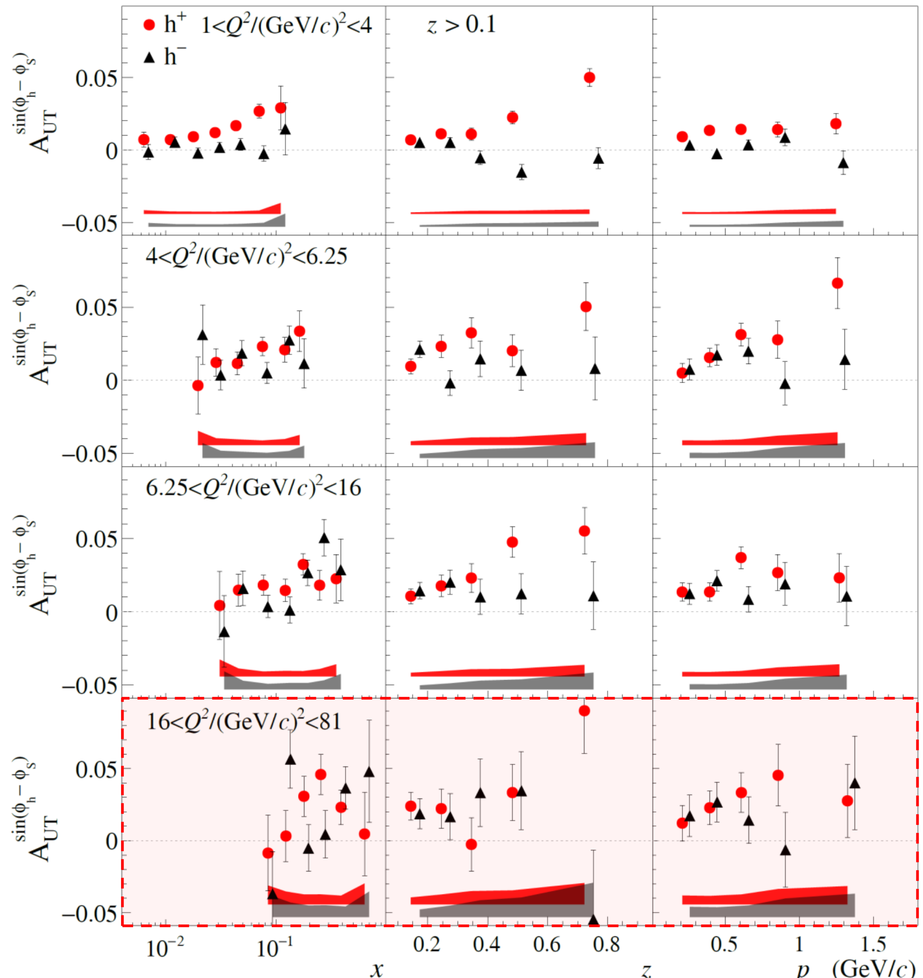
COMPASS PLB 770 (2017) 138







1st COMPASS multi-D fit done for all eight TSAs

SIDIS – Drell-Yan TSAs: Sivers

B. Parsamyan (COMPASS at DIS-2019)
arXiv:1908.01727 [hep-ex]

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

Sivers DY TSA

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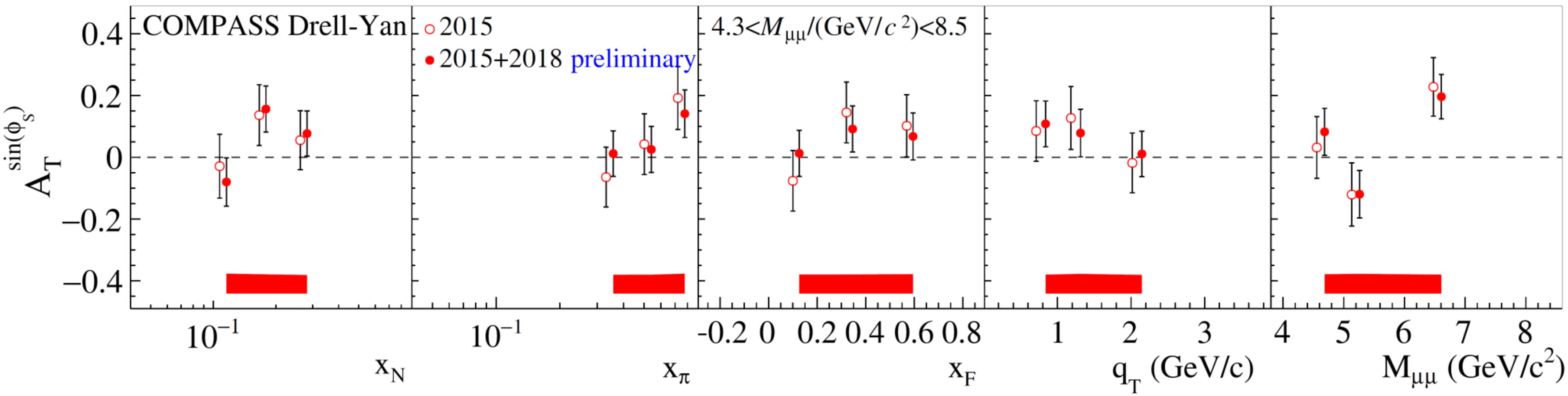
COMPASS 2015 (*PRL 119, 112002 (2017)*) + 2018 (~50%)



SIDIS in Drell-Yan *high-mass* range

COMPASS **PLB 770 (2017) 138**

Sivers SIDIS TSA

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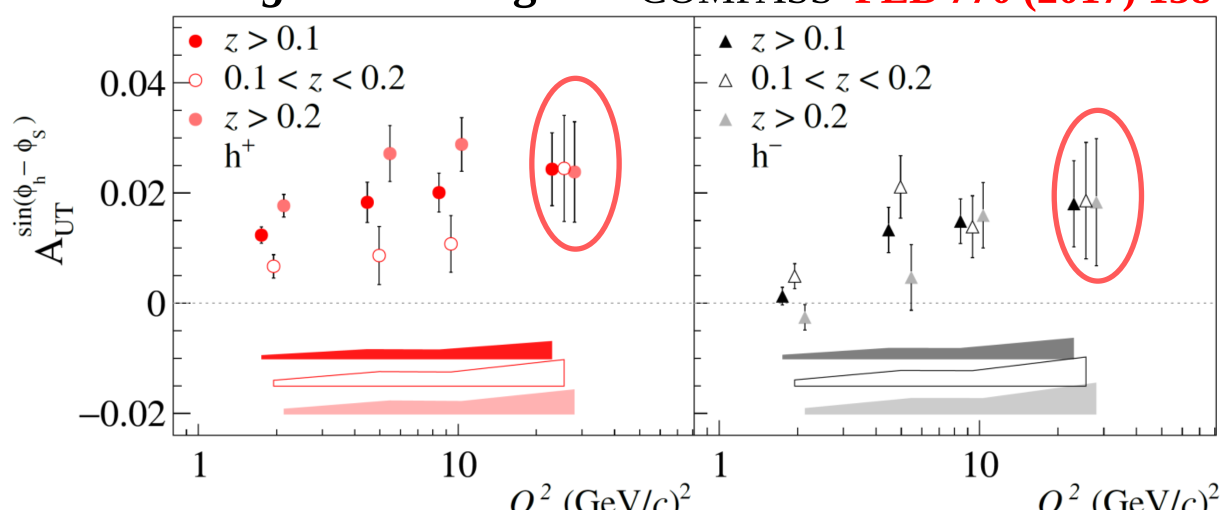
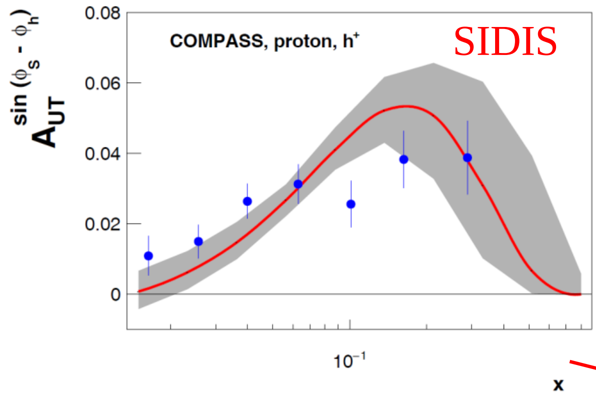
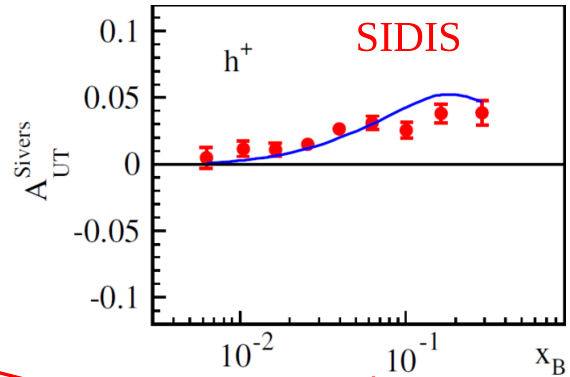


Sivers asymmetry in Drell-Yan: sign change

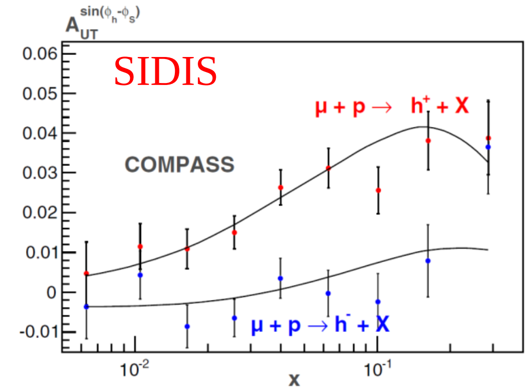
DGLAP (2016)
M. Anselmino et al., **JHEP 1704 (2017) 046**



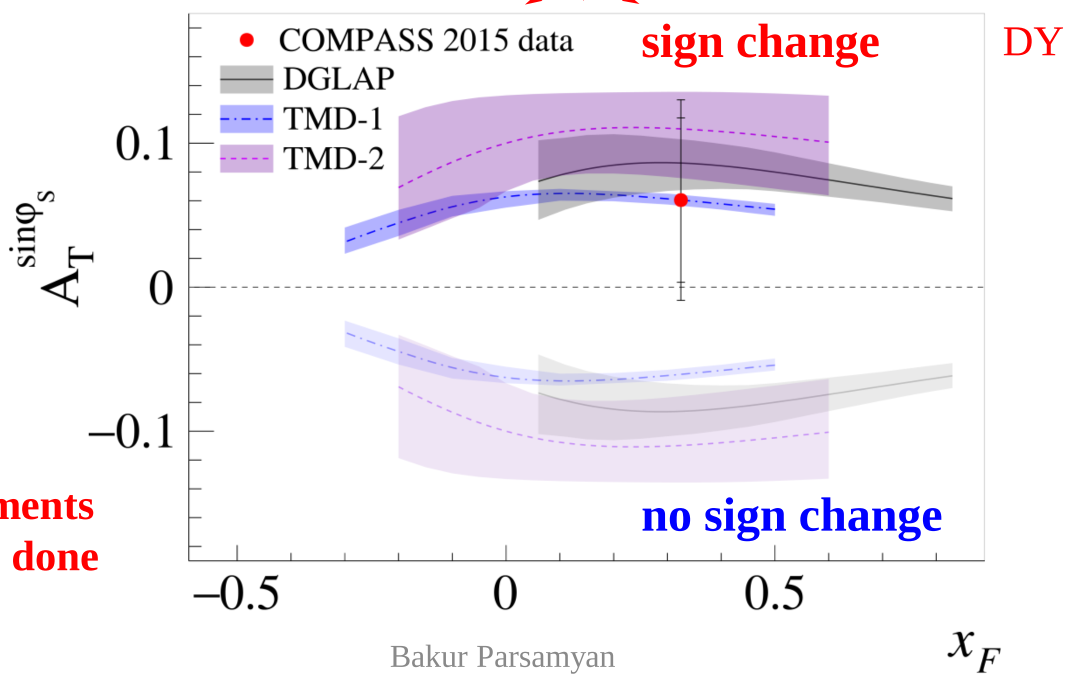
TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



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



COMPASS
PRL 119, 112002 (2017)

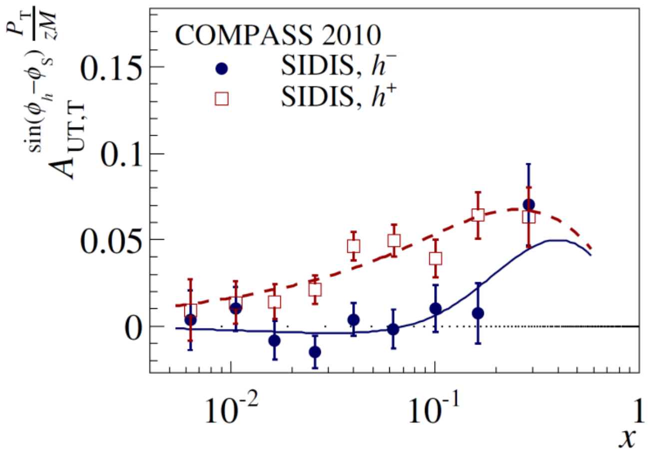


In 2018 – 2nd round of polarized DY measurements at COMPASS has been done

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

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

COMPASS **NPB 940 (2019) 34** NEW



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

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

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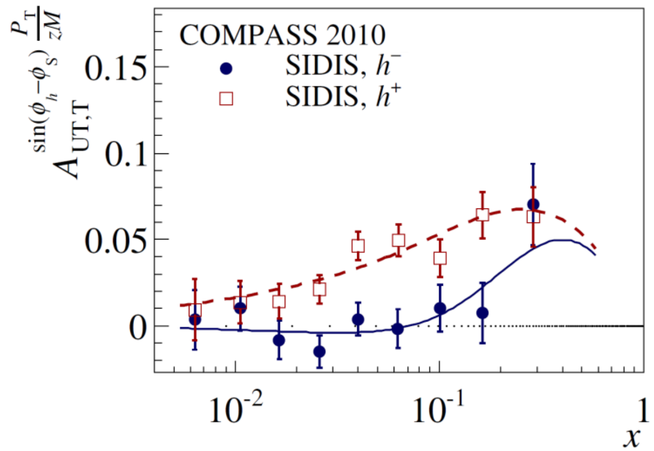
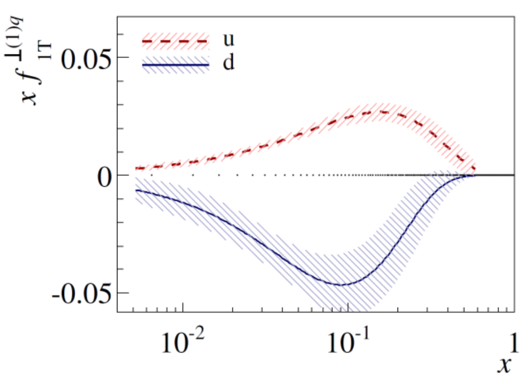
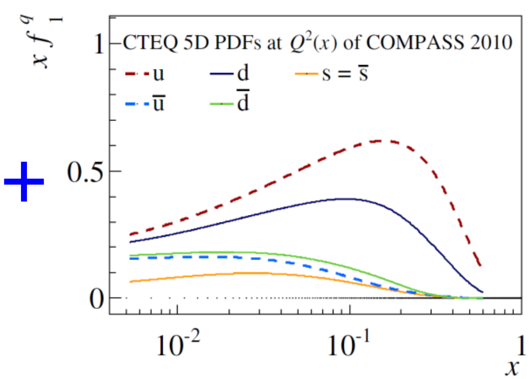
Sivers *w*TSA in DY: $A_{T}^{\sin\varphi_S} \propto f_{1,\pi}^{q} \times f_{1T,p}^{\perp q\,(1)}$

COMPASS **NPB 940 (2019) 34** **NEW**







Valence quark dominance

No Q^2-evolution for Sivers PDF

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

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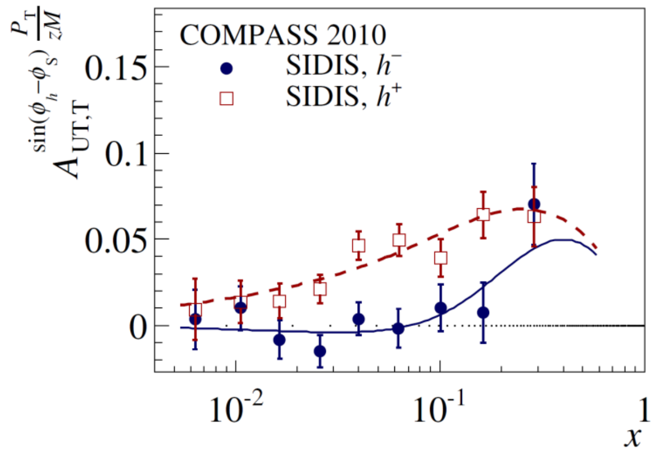
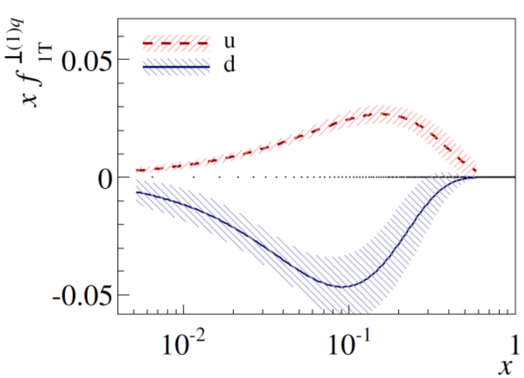
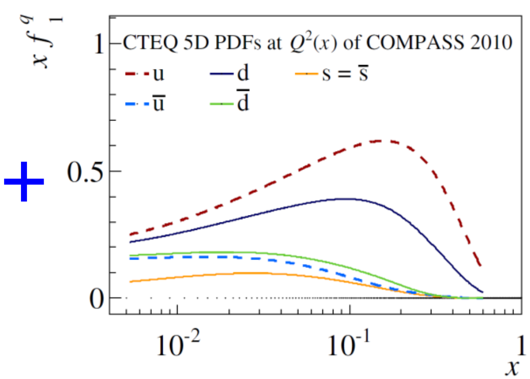
Sivers *w*TSA in DY: $A_{T}^{\sin\varphi_S} \propto f_{1,\pi}^{q} \times f_{1T,p}^{\perp q\,(1)}$

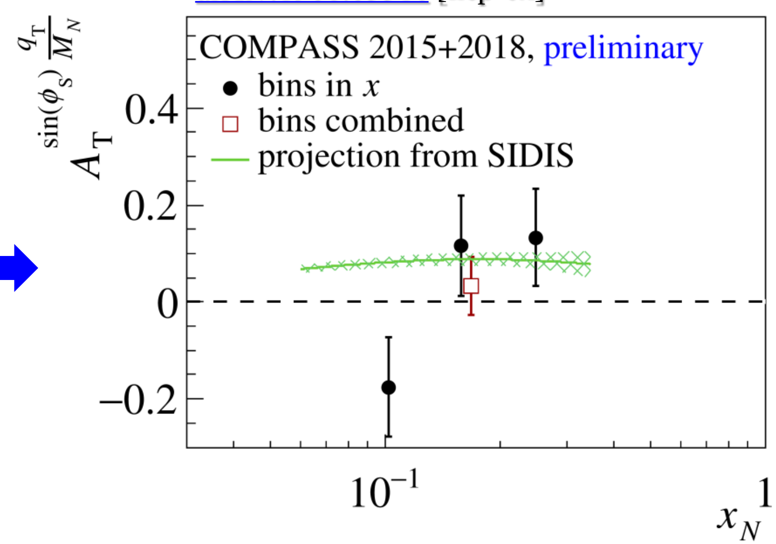
COMPASS **NPB 940 (2019) 34** NEW







J. Matoušek (COMPASS at DSPIN-2017)
arXiv:1710.06497 [hep-ex]
R. Longo (COMPASS at DIS-2019)
arXiv:1908.03310 [hep-ex]



- Towards high precision multi-D analysis

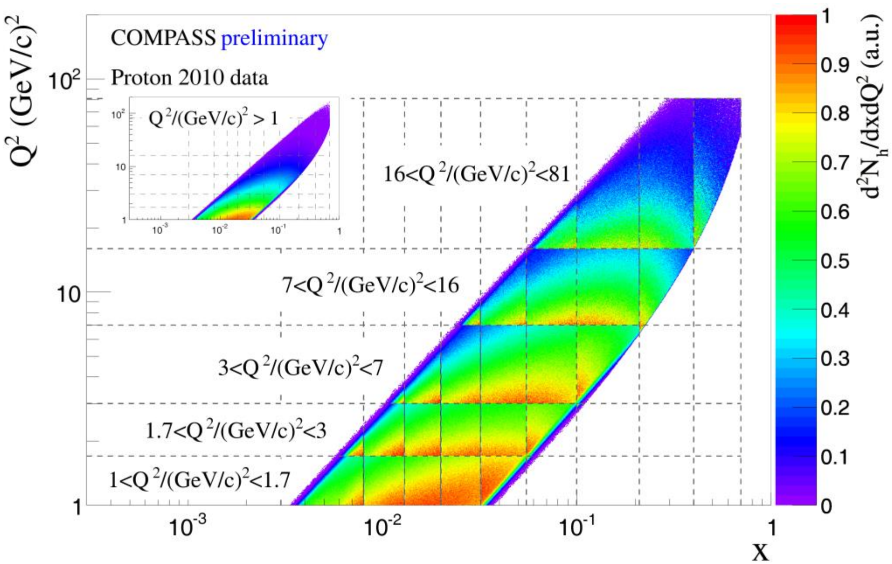
COMPASS/HEMRES Multi-D TSA analyses

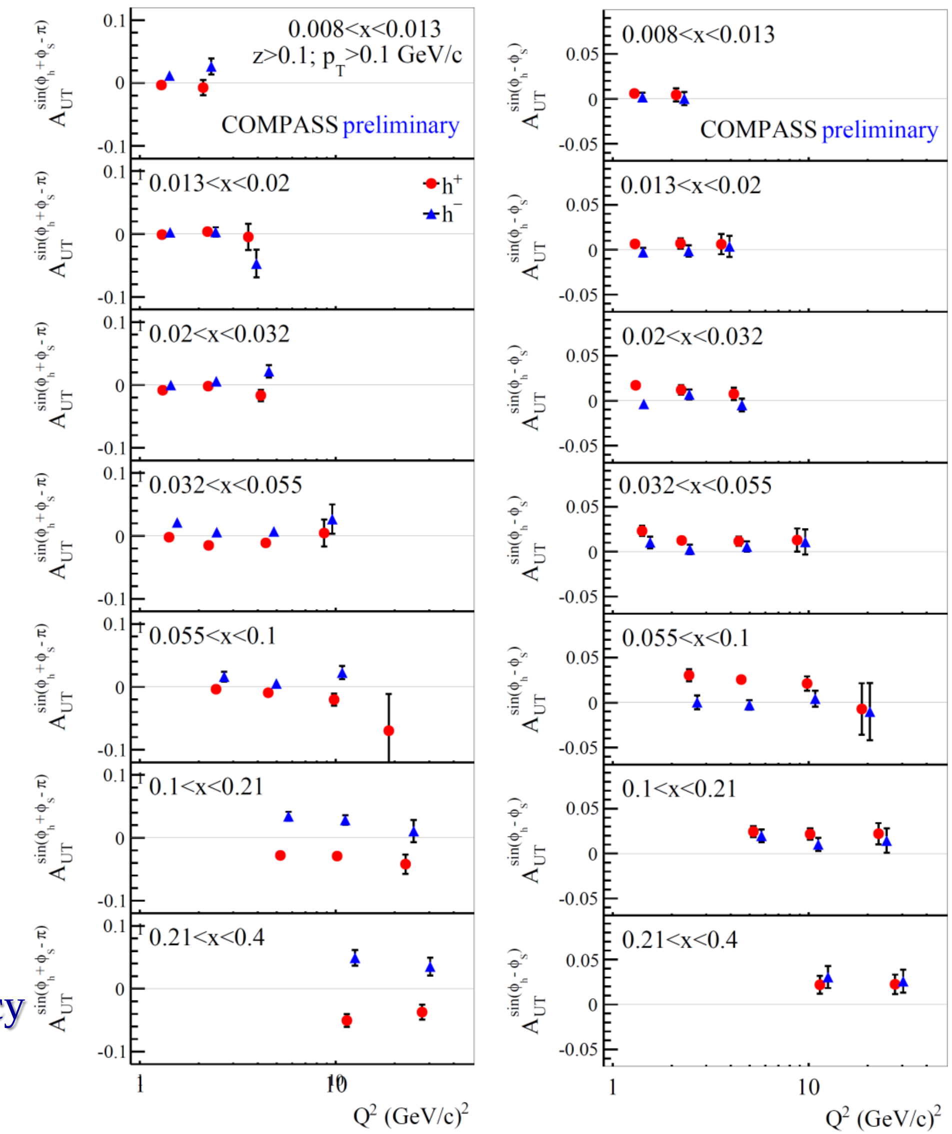
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+S_T\, A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S)+S_T\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S)\ldots\right\}$$

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

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

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





3D x:Q^2:z or x:Q^2:p_T x:z:p_T

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

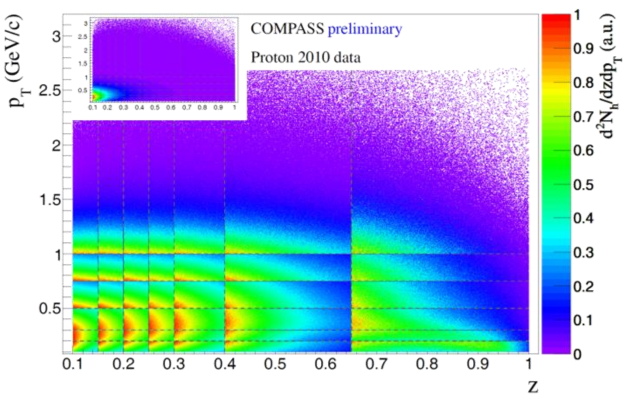
COMPASS/HEMRES Multi-D TSA analyses

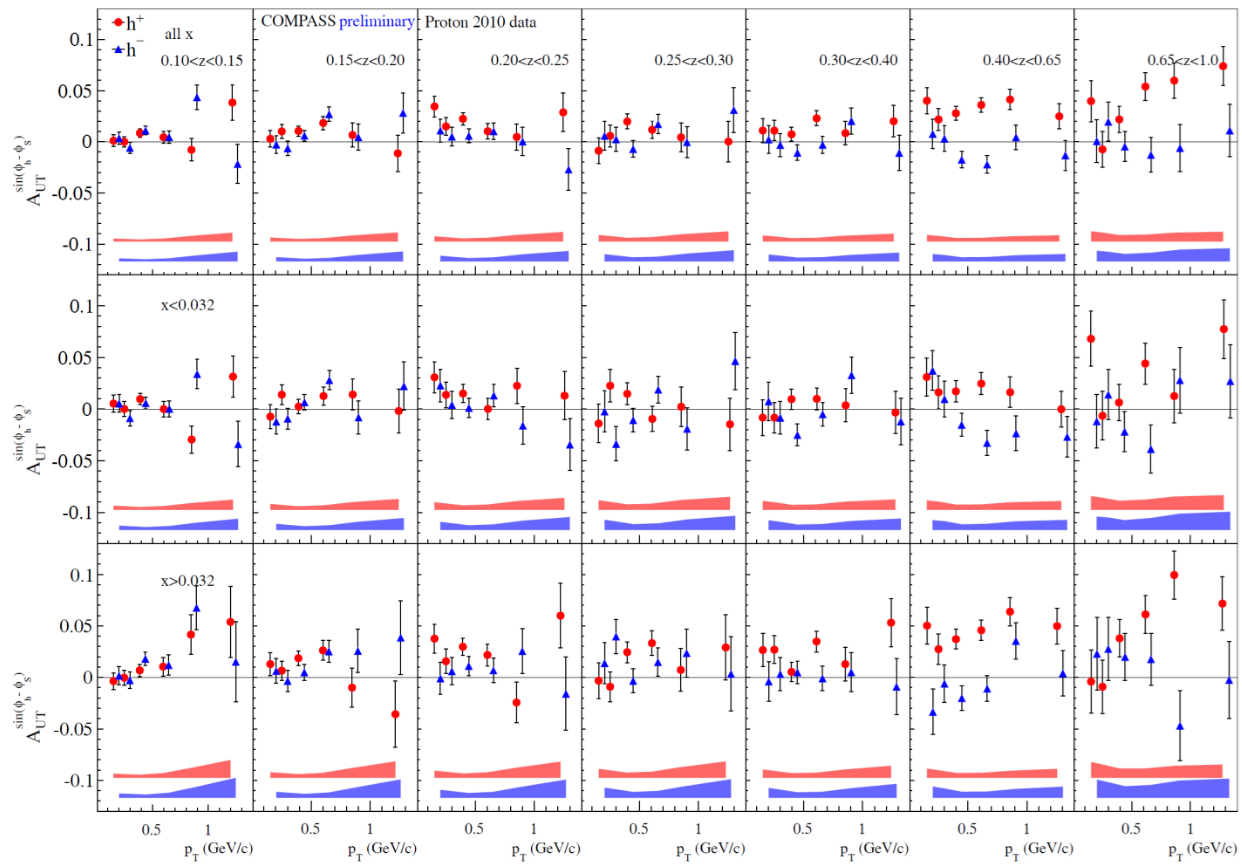
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) + S_T \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) \ldots\right\}$$

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

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

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





3D $x{:}Q^2{:}z$ or $x{:}Q^2{:}p_T$ $x{:}z{:}p_T$

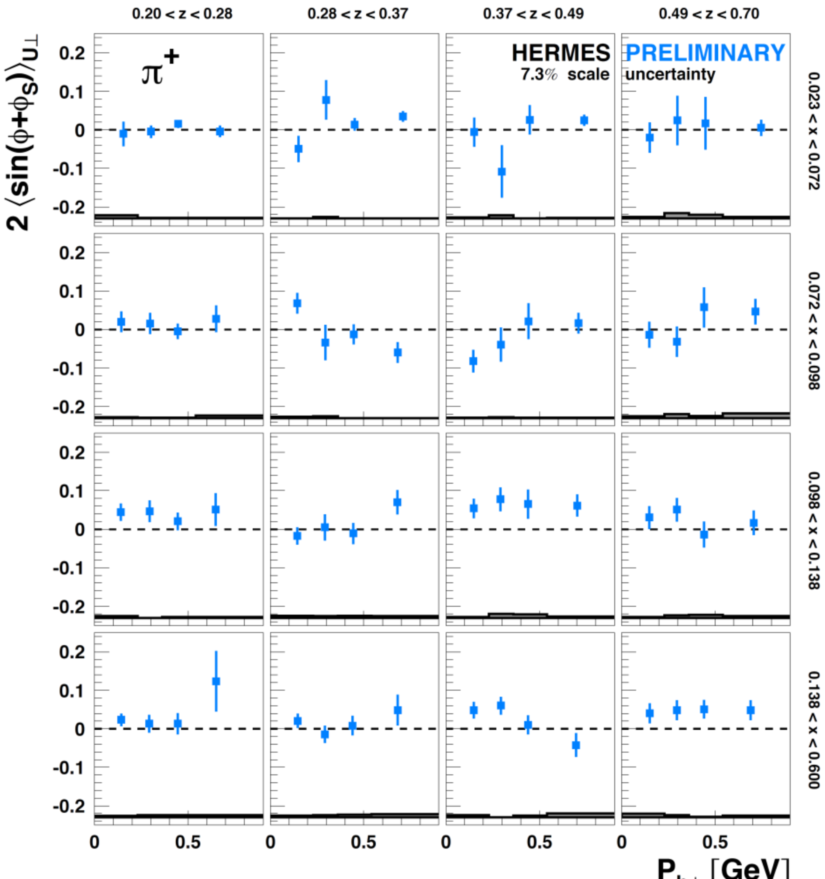
- No clear Q^2-dependence within statistical accuracy
- Possible decreasing trend for Sivers TSA?
- Negative amplitude for h^- at large z?

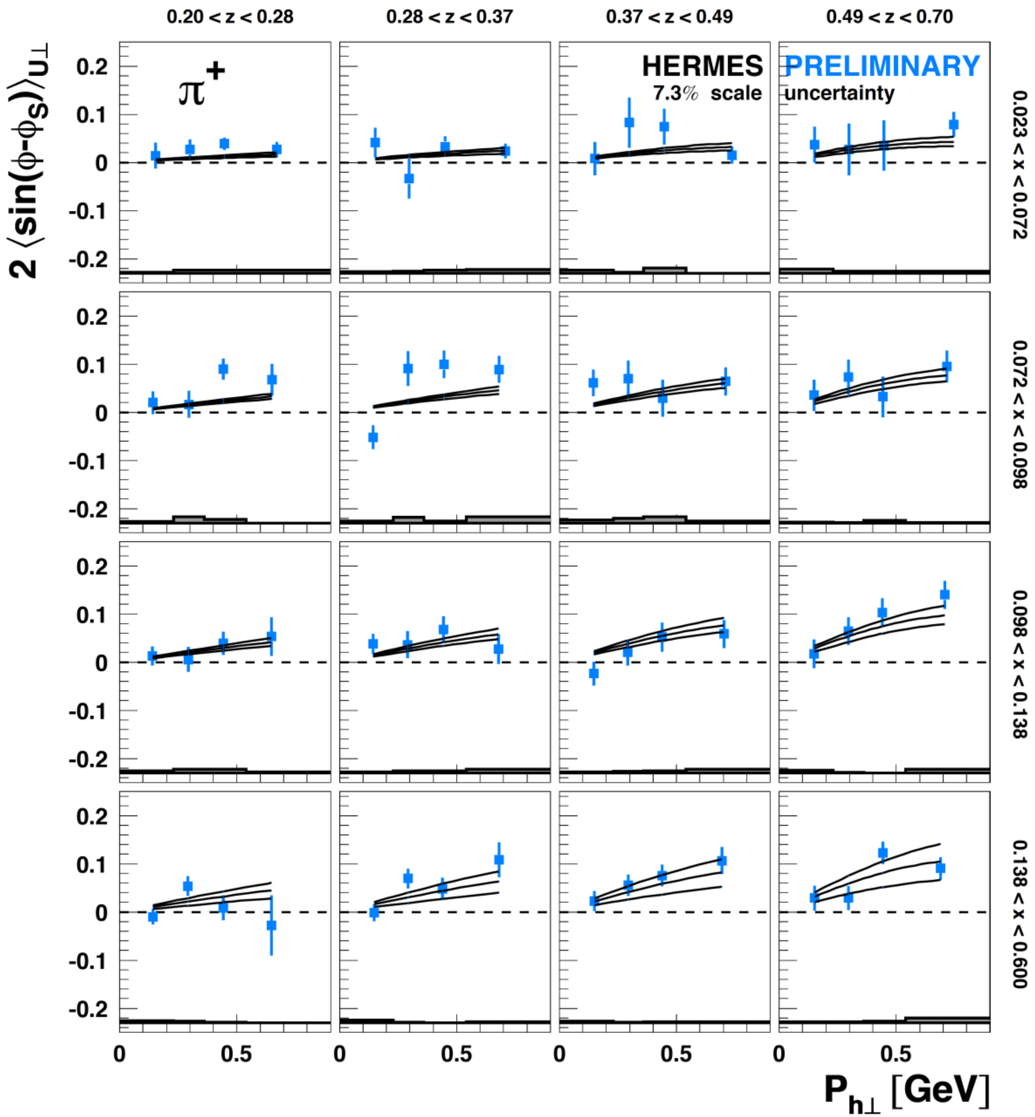
COMPASS/HEMRES Multi-D TSA analyses

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

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

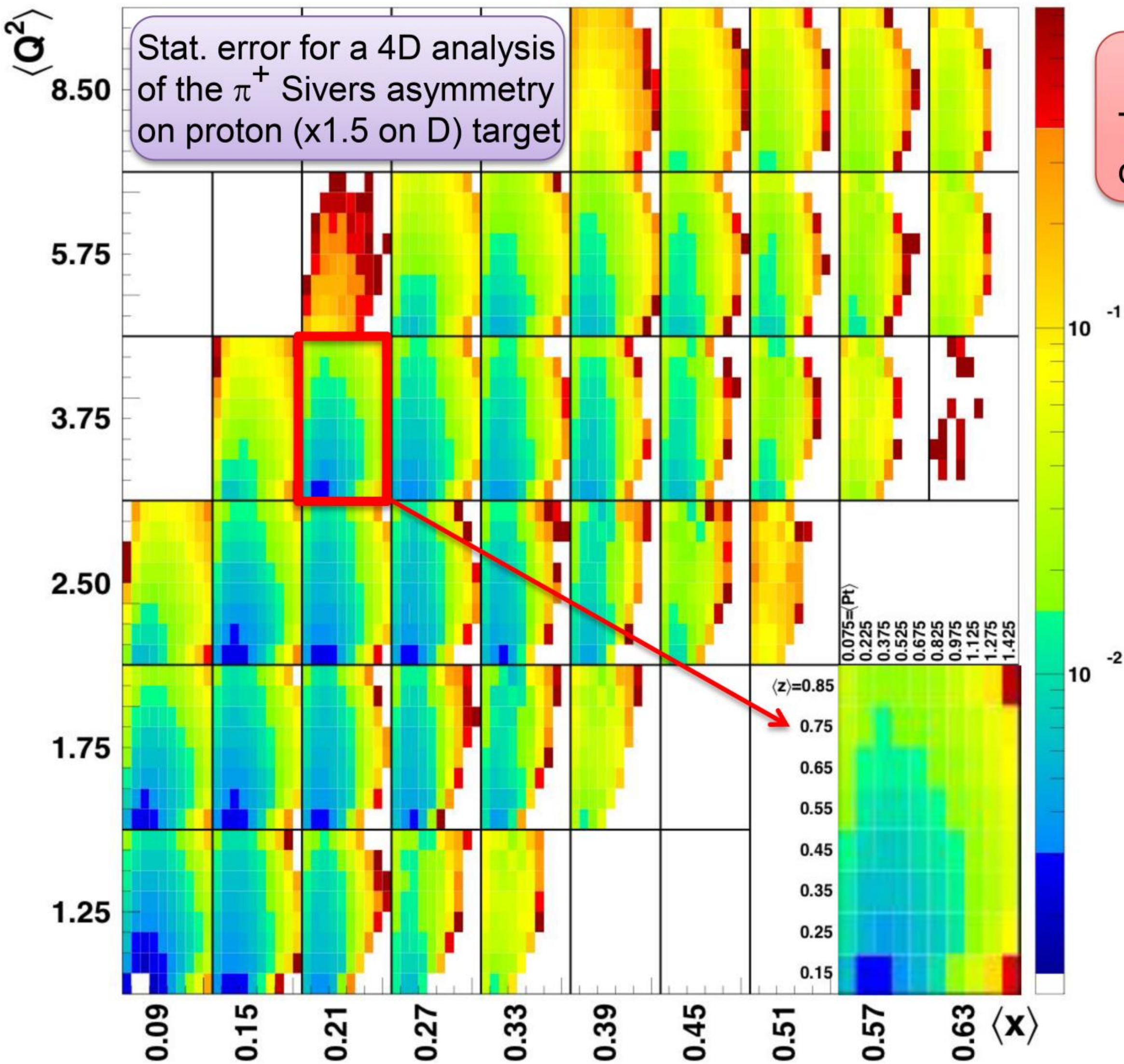
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p}_T}{M_h} h_1^q H_{1q}^{\perp h}\right]$$





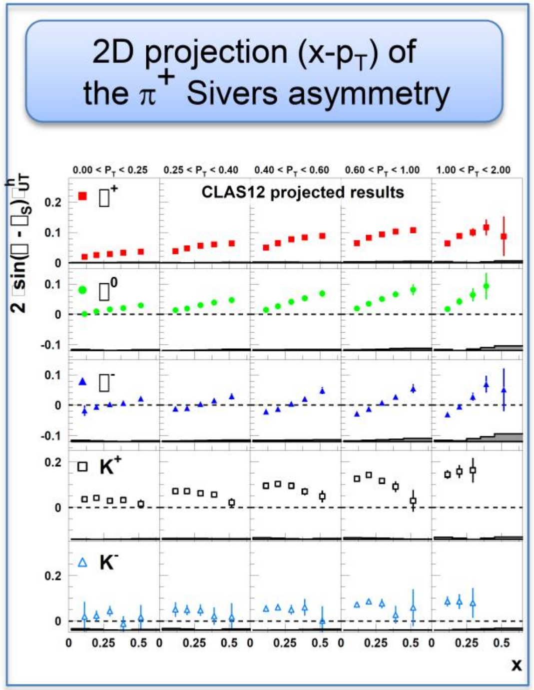
Future Multi-D TSA analysis at JLab 12

Statistical precision

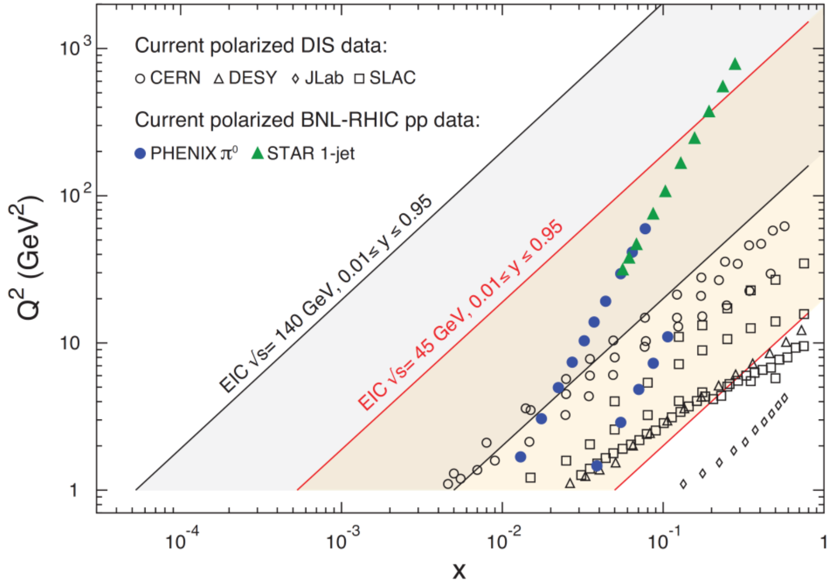


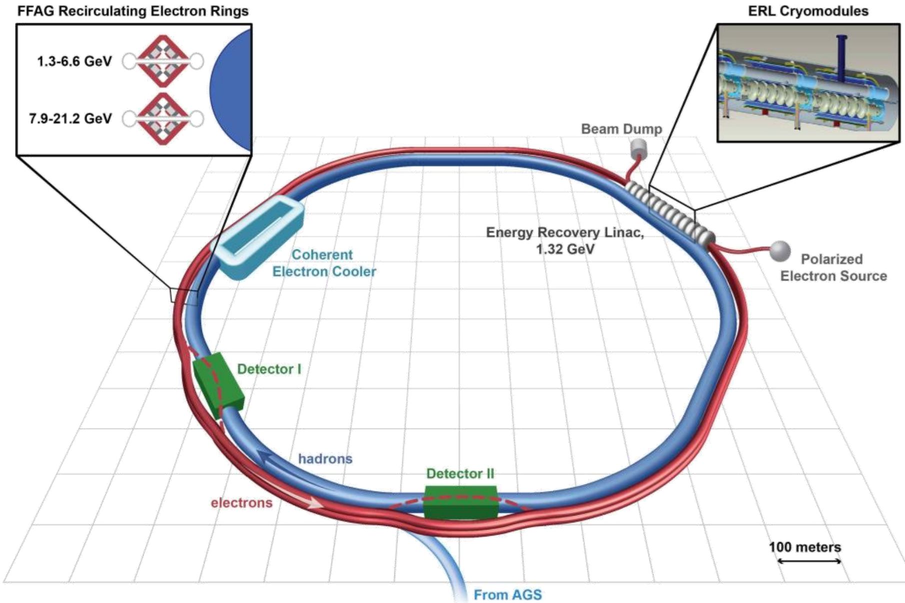
4D analysis is possible

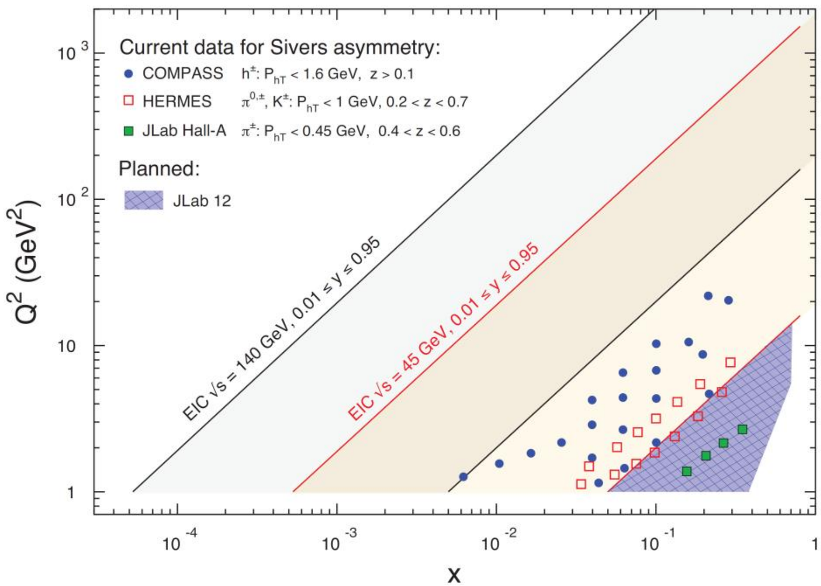
The wanted high-Q^2 high-p_T defines the beam-time request



Electron Ion Collider: The Next QCD Frontier







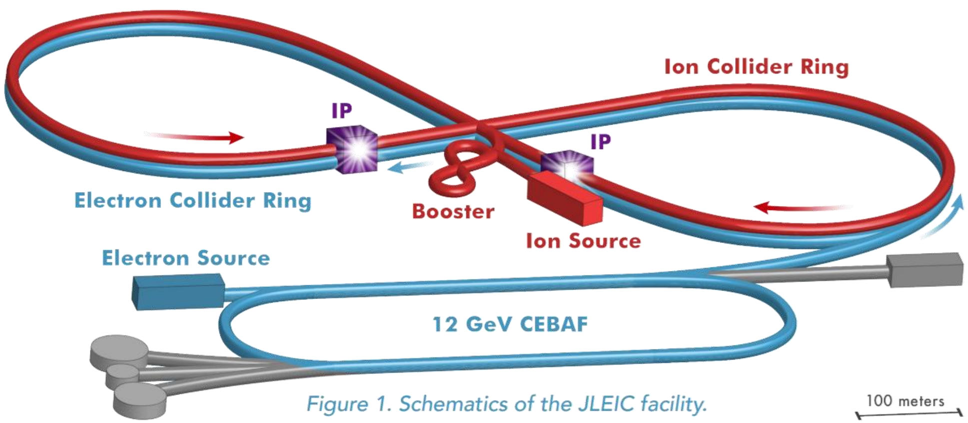
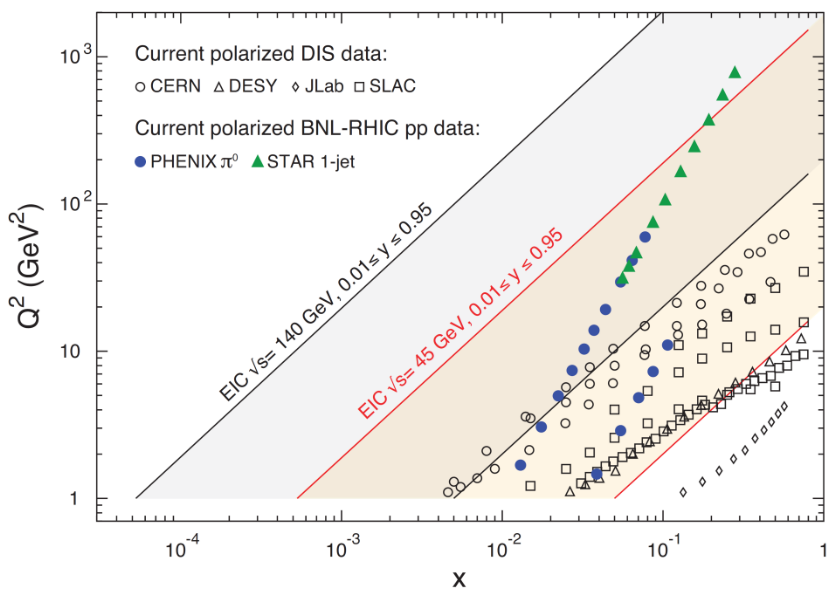
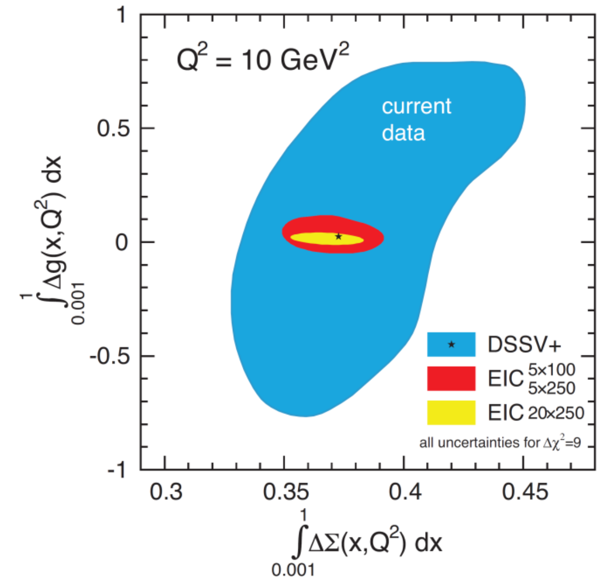
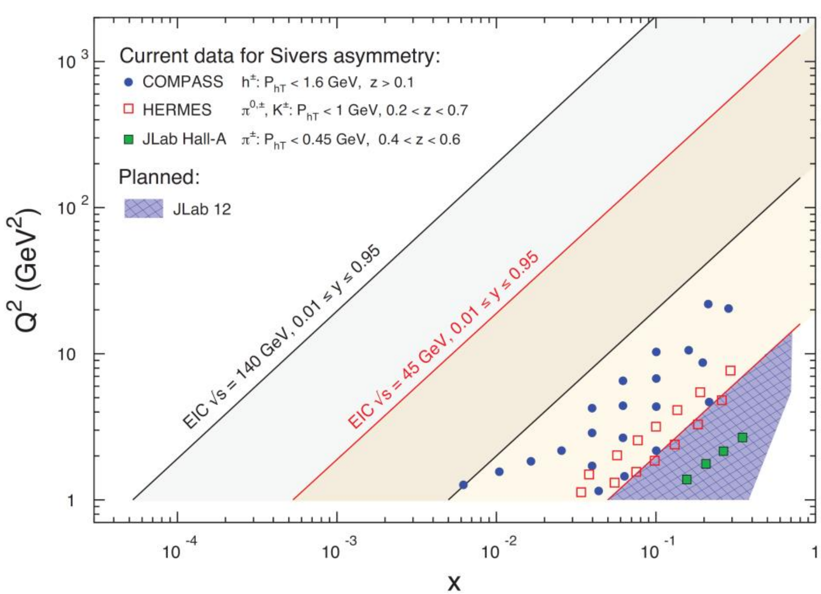


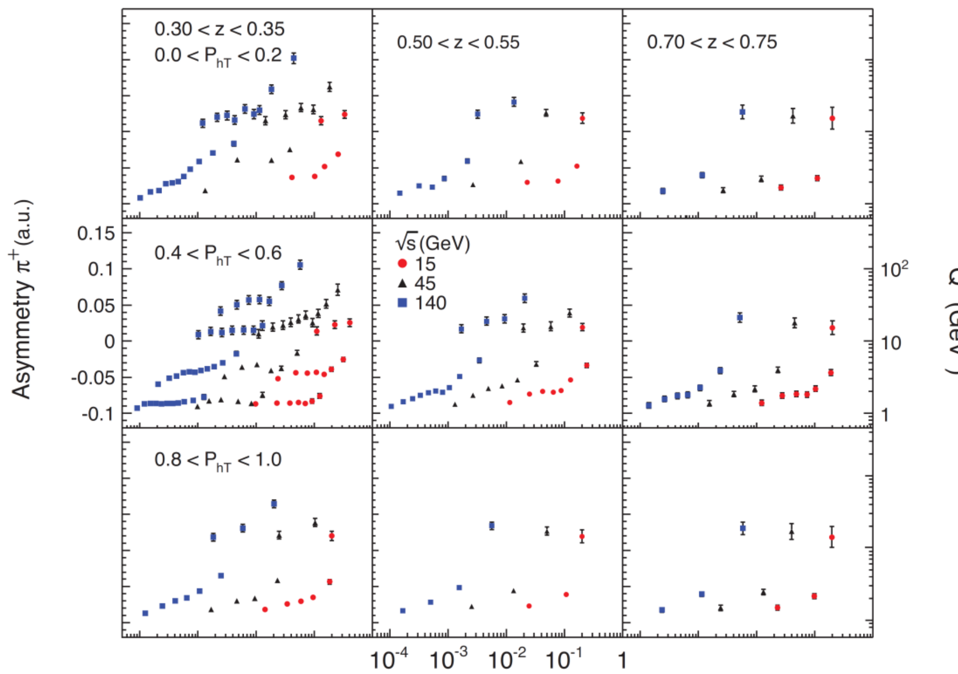
Figure 1. Schematics of the JLEIC facility.

Electron Ion Collider: The Next QCD Frontier









1. Exploration phase

First measurements

Parton model interpretation

Last decade

2. Consolidation phase

Measurements from several experiments

First global fits, validation of TMD factorisation and evolution

Next decade

3. Precision phase

Electron Ion Collider

Global fits, to a level comparable to standard PDFs

Courtesy of A. Bacchetta

Spare slides

Nucleon TMD PDFs accessed in SIDIS and DY

SIDIS

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

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

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

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

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

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

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

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

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

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

Single polarized DY (LO)

$$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$$

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

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

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

- Boer-Mulders: $A_{UU}^{\cos\phi_h}$ ↔ $A_U^{\cos 2\varphi_{CS}}$
- Boer-Mulders: $A_{UU}^{\cos 2\phi_h}$ ↔ $A_U^{\cos 2\varphi_{CS}}$
- Sivers: $A_{UT}^{\sin(\phi_h-\phi_s)}$ ↔ $A_T^{\sin\varphi_S}$
- Transversity: $A_{UT}^{\sin(\phi_h+\phi_s)}$ ↔ $A_T^{\sin(2\varphi_{CS}-\varphi_S)}$
- Pretzelosity: $A_{UT}^{\sin(3\phi_h-\phi_s)}$ ↔ $A_T^{\sin(2\varphi_{CS}+\varphi_S)}$

Quark / Nucleon	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**

Nucleon TMD PDFs accessed in SIDIS and DY

SIDIS

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

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

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

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

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

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

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

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

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

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

Single polarized DY (LO)

$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$

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

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

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

Boer-Mulders

Boer-Mulders

Sivers

Transversity

Pretzelosity

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

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

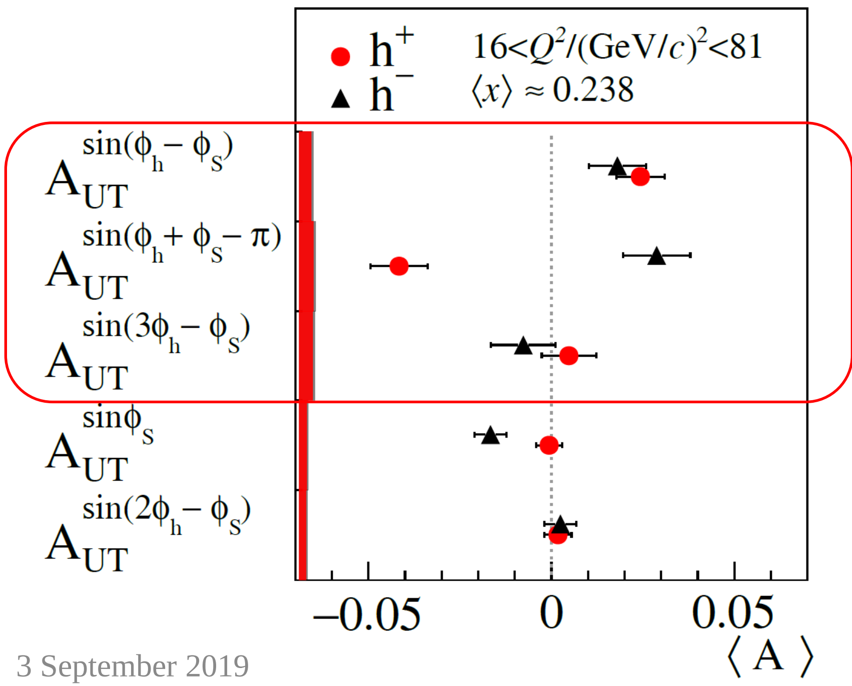
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\Bigg\{ 1 + \ldots$$

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

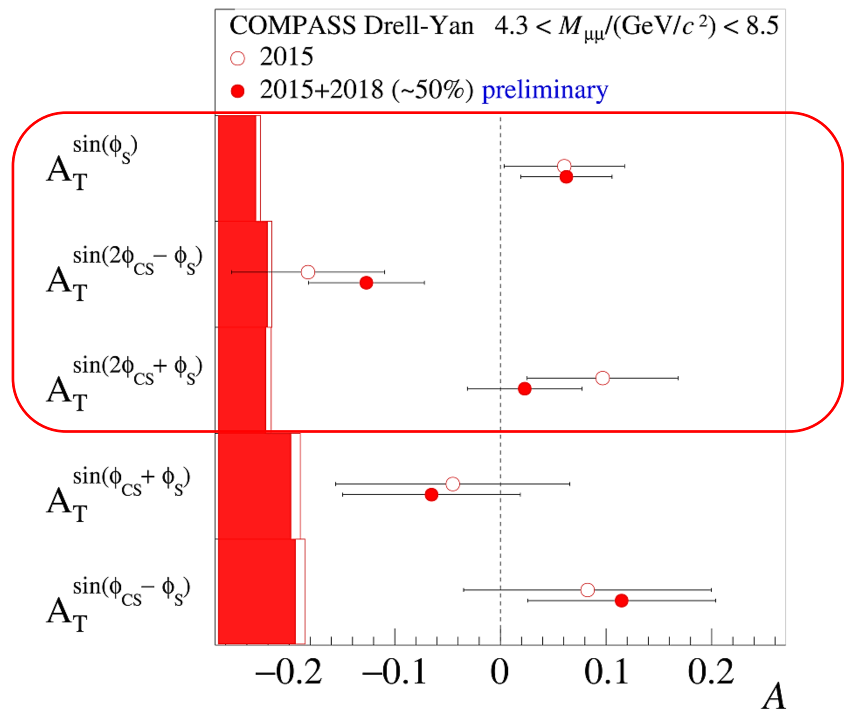
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1 + \cos^2\theta_{CS}\right)\Bigg\{ 1 + \ldots$$

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

COMPASS PLB 770 (2017) 138



COMPASS 2015 + 2018 (~50%)



D. Kikoła et al. arXiv:1702.01546 [hep-ex]

Experiment	particles	beam energy (GeV)	$\sqrt{s}$ (GeV)	$x^{\uparrow}$	$\mathcal{L}$ (cm^{-2}s^{-1})	$\mathcal{P}_{\text{eff}}$	$\mathcal{F}$ (cm^{-2}s^{-1})
AFTER@LHCb	$p + p^{\uparrow}$	7000	115	$0.05 \div 0.95$	$1 \cdot 10^{33}$	80%	$6.4 \cdot 10^{32}$
AFTER@LHCb	$p+{}^{3}\text{He}^{\uparrow}$	7000	115	$0.05 \div 0.95$	$2.5 \cdot 10^{32}$	23%	$1.4 \cdot 10^{31}$
AFTER@ALICE$_{\mu}$	$p + p^{\uparrow}$	7000	115	$0.1 \div 0.3$	$2.5 \cdot 10^{31}$	80%	$1.6 \cdot 10^{31}$
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	190	19	$0.1 \div 0.3$	$2 \cdot 10^{33}$	18%	$6.5 \cdot 10^{31}$
PHENIX/STAR (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider	510	$0.05 \div 0.1$	$2 \cdot 10^{32}$	50%	$5.0 \cdot 10^{31}$
E1039 (FNAL)	$p + p^{\uparrow}$	120	15	$0.1 \div 0.45$	$4 \cdot 10^{35}$	15%	$9.0 \cdot 10^{33}$
E1027 (FNAL)	$p^{\uparrow} + p$	120	15	$0.35 \div 0.9$	$2 \cdot 10^{35}$	60%	$7.2 \cdot 10^{34}$
NICA (JINR)	$p^{\uparrow} + p$	collider	26	$0.1 \div 0.8$	$1 \cdot 10^{32}$	70%	$4.9 \cdot 10^{31}$
fsPHENIX (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider	200	$0.1 \div 0.5$	$8 \cdot 10^{31}$	60%	$2.9 \cdot 10^{31}$
fsPHENIX (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider	510	$0.05 \div 0.6$	$6 \cdot 10^{32}$	50%	$1.5 \cdot 10^{32}$
PANDA (GSI)	$\bar{p} + p^{\uparrow}$	15	5.5	$0.2 \div 0.4$	$2 \cdot 10^{32}$	20%	$8.0 \cdot 10^{30}$