



# Longitudinal spin dependent single-hadron azimuthal asymmetries at COMPASS

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on behalf of the COMPASS Collaboration



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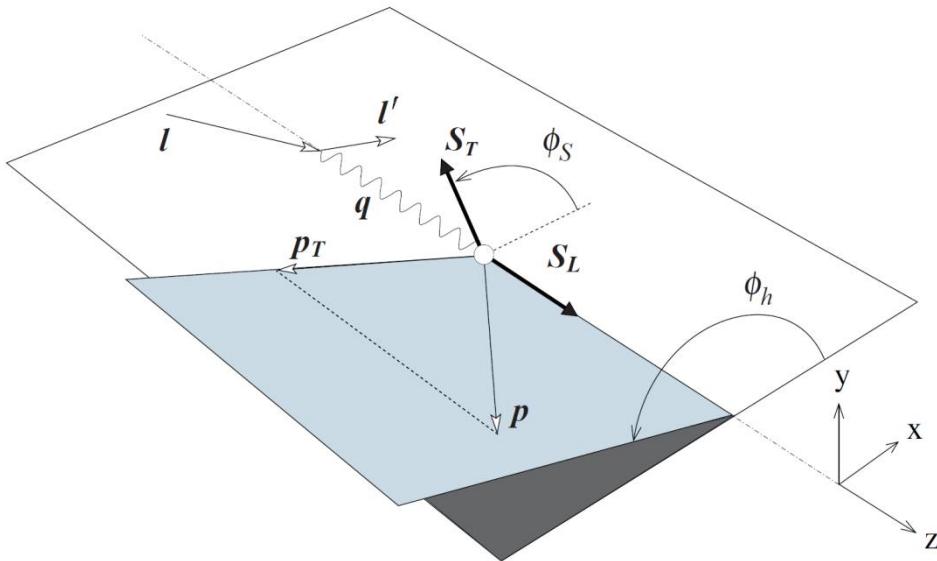
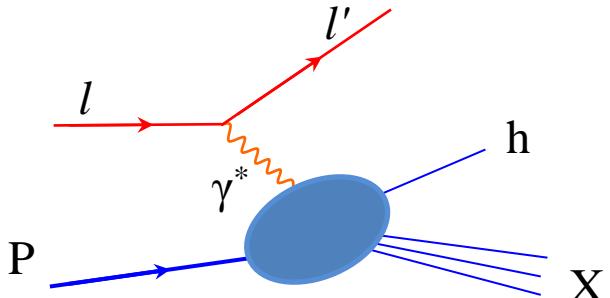
# SIDIS x-section

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



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

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



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

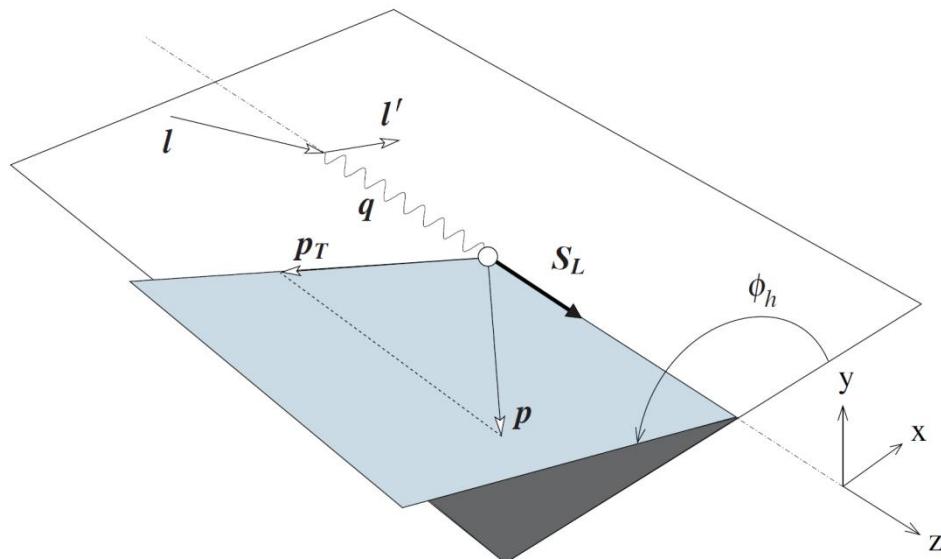
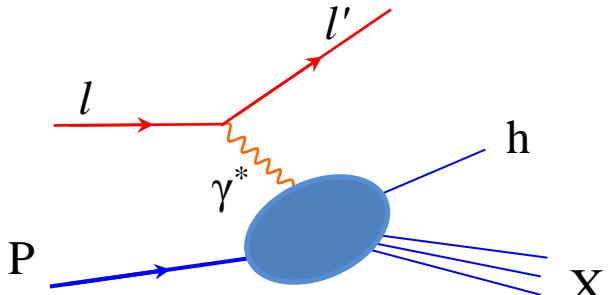
# L-SIDIS x-section

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



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

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

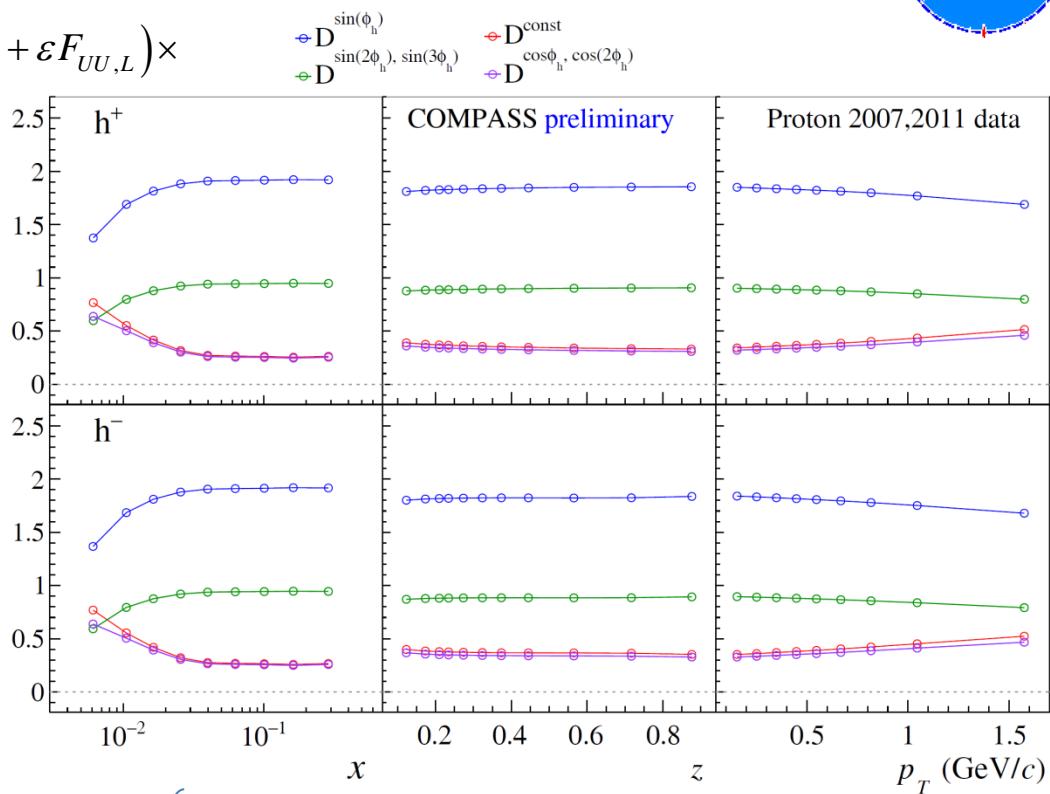


General SIDIS x-section expression contains four target longitudinal spin dependent asymmetries (LSA)

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

# L-SIDIS x-section: depolarization factors

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times \left\{ \begin{array}{l} 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ + S_L \left[ \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right] \\ + S_L \lambda \left[ \sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right] \end{array} \right\} \langle D \rangle$$



Note: Along with effective target polarization and beam polarization COMPASS LSAs are corrected for D(y) depolarization factors.

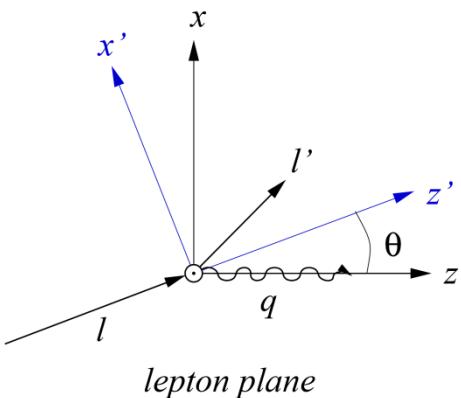
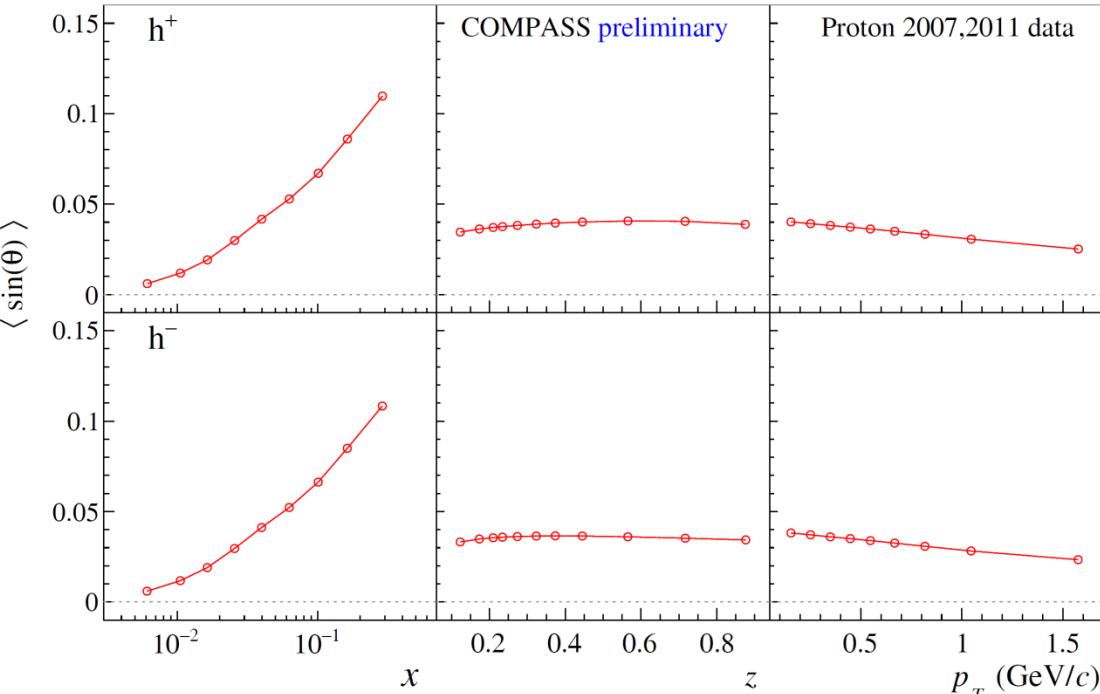
$$A_{UL}^{w(\phi_h)} = \frac{A_{UL,raw}^{w(\phi_h)}}{D^{w(\phi_h)} f |P_L|}, \quad A_{LL}^{w(\phi_h)} = \frac{A_{LL,raw}^{w(\phi_h)}}{D^{w(\phi_h)} \lambda f |P_L|}$$

$$\left\{ \begin{array}{l} D^{\sin(\phi_h)} = \sqrt{2\varepsilon(1+\varepsilon)} \approx \frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2} \\ D^{\sin(2\phi_h)} = \varepsilon \approx \frac{2(1-y)}{1+(1-y)^2} \\ D^1 = \sqrt{(1-\varepsilon^2)} \approx \frac{y(2-y)}{1+(1-y)^2} \\ D^{\cos(\phi_h)} = \sqrt{2\varepsilon(1-\varepsilon)} \approx \frac{2y\sqrt{1-y}}{1+(1-y)^2} \end{array} \right.$$

# L-SIDIS x-section: from $lp$ to $\gamma * p$

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

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



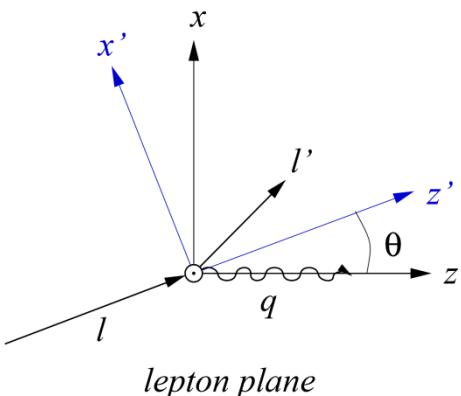
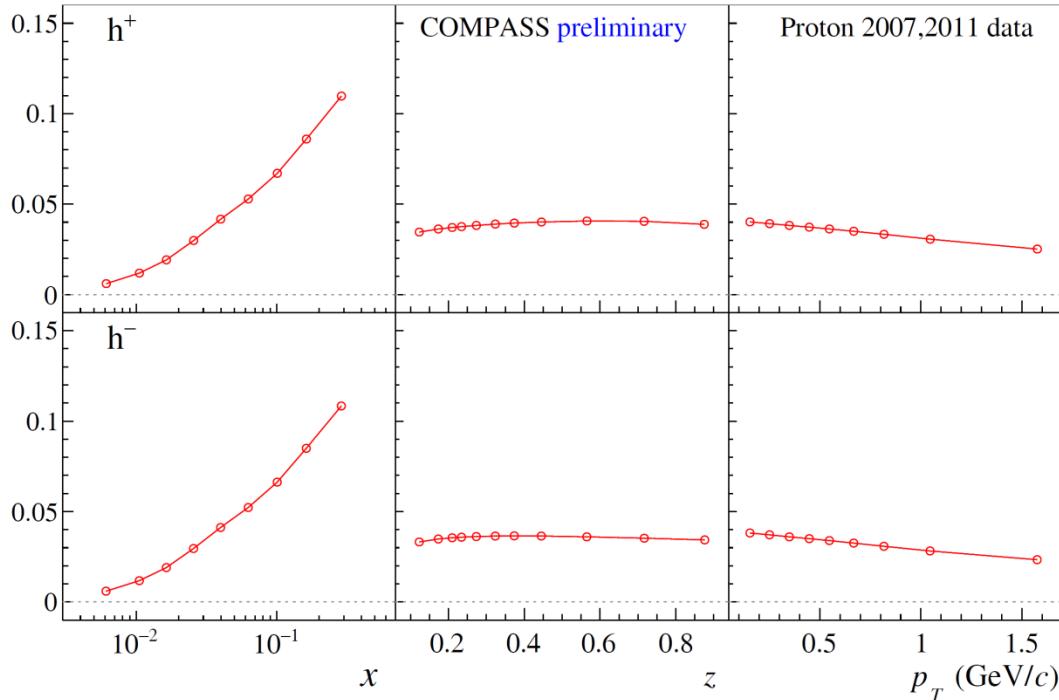
$$\sin \theta = \gamma \sqrt{\frac{1 - y - \frac{1}{4}\gamma^2 y^2}{1 + \gamma^2}}, \quad \gamma = \frac{2Mx}{Q};$$

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

# SIDIS x-section: from $lp$ to $\gamma*p$ ( $P_T=0$ )

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

$$\left\{ \begin{array}{l} 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ + P_L \left[ \begin{array}{l} \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \\ + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \\ - \sin\theta \varepsilon A_{UL}^{\sin 3\phi_h} \sin 3\phi_h \end{array} \right] \\ + P_L \lambda \left[ \begin{array}{l} \sqrt{1-\varepsilon^2} A_{LL} \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \\ - \sin\theta \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos 2\phi_h} \cos 2\phi_h \end{array} \right] \end{array} \right\}$$



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

$\theta \xrightarrow[\text{Bjorken limit}]{} 0 \Rightarrow S_T \approx P_T, \quad S_L \approx P_L$

At COMPASS kinematics  
 $\sin\theta < 0.15$   
 $\cos\theta \approx 1$

# SIDIS x-section: LSA-TSA mixing

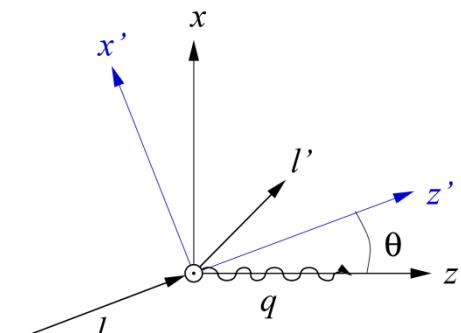
Kotzinian et al.  
 hep-ph/9808368 (1998)  
 hep-ph/9908466 (1999)  
 M. Diehl and S. Sapeta,  
 Eur. Phys. J. C 41 (2005) 515



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

$$\left. \begin{aligned} & 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ & + P_L \left[ \begin{aligned} & \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \\ & + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \\ & - \sin\theta \varepsilon A_{UL}^{\sin 3\phi_h} \sin 3\phi_h \end{aligned} \right] \\ & + P_L \lambda \left[ \begin{aligned} & \sqrt{1-\varepsilon^2} A_{LL} \\ & + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \\ & - \sin\theta \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos 2\phi_h} \cos 2\phi_h \end{aligned} \right] \end{aligned} \right\}$$

LSA	$C(\varepsilon, \theta)$ - factor	Contributing TSA
$A_{UL}^{\sin\phi_h}$	$\sin\theta \frac{1}{\sqrt{2\varepsilon(1+\varepsilon)}}$	$A_{UT}^{\sin(\phi_h - \phi_s)}$
$A_{UL}^{\sin\phi_h}$	$\sin\theta \frac{\varepsilon}{\sqrt{2\varepsilon(1+\varepsilon)}}$	$A_{UT}^{\sin(\phi_h + \phi_s)}$
$A_{UL}^{\sin 2\phi_h}$	$\sin\theta \frac{\sqrt{2\varepsilon(1+\varepsilon)}}{\varepsilon}$	$A_{UT}^{\sin(2\phi_h - \phi_s)}$
$A_{LL}$	$\sin\theta \frac{\sqrt{2\varepsilon(1-\varepsilon)}}{\sqrt{(1-\varepsilon^2)}}$	$A_{LT}^{\cos\phi_s}$
$A_{LL}^{\cos\phi_h}$	$\sin\theta \frac{\sqrt{(1-\varepsilon^2)}}{\sqrt{2\varepsilon(1-\varepsilon)}}$	$A_{LT}^{\cos(\phi_h - \phi_s)}$



lepton plane

26 September 2016

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

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

$$A_L^{true} \approx \left( \frac{A_L^{fit} + C(\varepsilon, \theta) A_T}{\cos\theta} \right)$$

Bakur Parsamyan

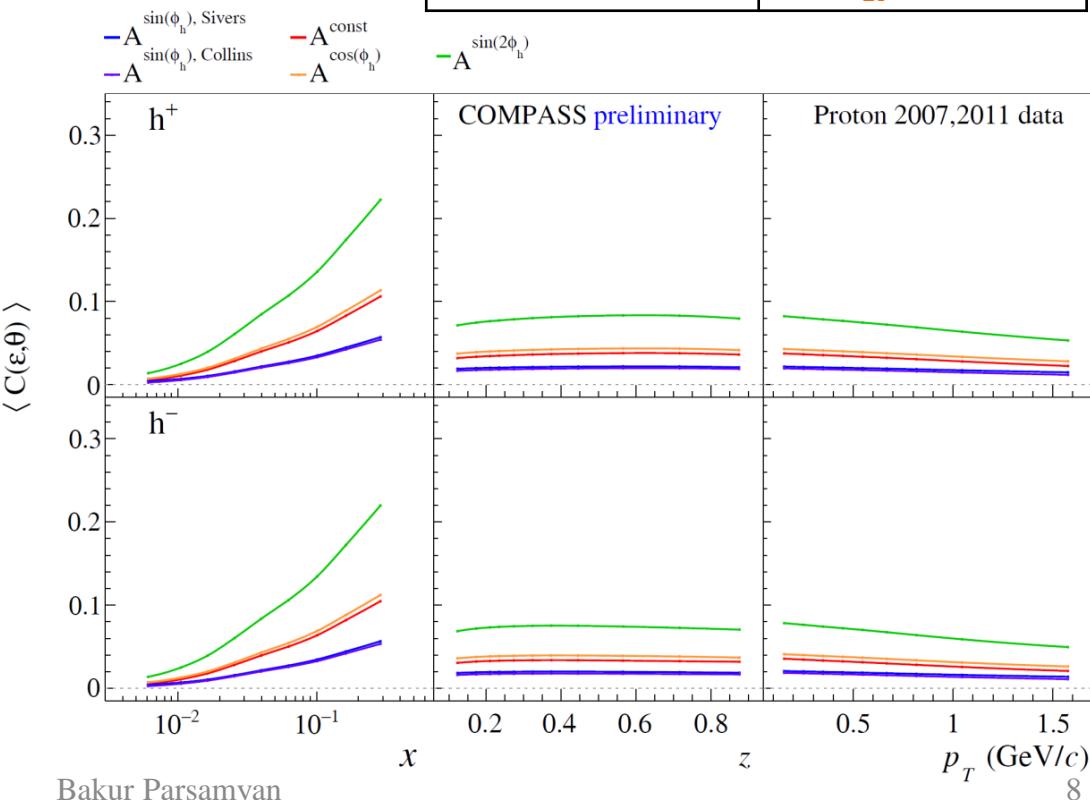
# SIDIS x-section: LSA-TSA mixing

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

$$\left. \begin{aligned} & 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ & + P_L \left[ \begin{aligned} & \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \\ & + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \\ & - \sin\theta\varepsilon A_{UL}^{\sin 3\phi_h} \sin 3\phi_h \end{aligned} \right] \\ & + P_L \lambda \left[ \begin{aligned} & \sqrt{1-\varepsilon^2} A_{LL} \\ & + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \\ & - \sin\theta \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos 2\phi_h} \cos 2\phi_h \end{aligned} \right] \end{aligned} \right\}$$

LSAs can get a contribution of up to 25 % of the size of the corresponding TSAs

LSA	Contributing TSA
$A_{UL}^{\sin\phi_h}$	$A_{UT}^{\sin(\phi_h-\phi_s)}$
$A_{UL}^{\sin\phi_h}$	$A_{UT}^{\sin(\phi_h+\phi_s-\pi)}$
$A_{UL}^{\sin 2\phi_h}$	$A_{UT}^{\sin(2\phi_h-\phi_s)}$
$A_{LL}$	$A_{LT}^{\cos\phi_s}$
$A_{LL}^{\cos\phi_h}$	$A_{LT}^{\cos(\phi_h-\phi_s)}$

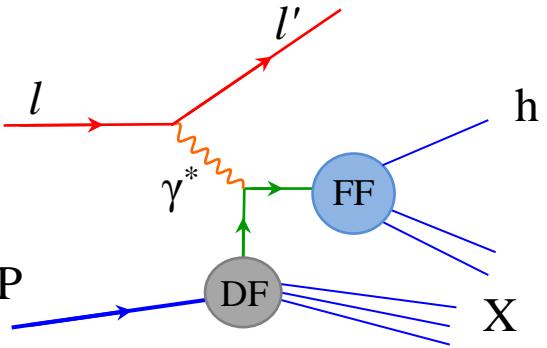


# Interpretation in terms of TMDs

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

$$\left. \begin{aligned} & 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ & + P_L \left[ \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \right. \\ & \quad \left. + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right. \\ & \quad \left. - \sin\theta\varepsilon A_{UL}^{\sin 3\phi_h} \sin 3\phi_h \right] \\ & + P_L \lambda \left[ \sqrt{1-\varepsilon^2} A_{LL} \\ & \quad + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \\ & \quad - \sin\theta \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos 2\phi_h} \cos 2\phi_h \right] \end{aligned} \right\}$$

Access to various “twist-2,-3” functions  
Different kinematic suppressions



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

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

# Interpretation in terms of TMDs

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

Twist-2

Twist-3

$$\left\{
 \begin{aligned}
 & 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\
 & + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \\
 & + P_L \left[ \begin{aligned}
 & \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \\
 & + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \\
 & - \sin\theta \varepsilon A_{UL}^{\sin 3\phi_h} \sin 3\phi_h
 \end{aligned} \right] \\
 & + P_L \lambda \left[ \begin{aligned}
 & \sqrt{1-\varepsilon^2} A_{LL} \\
 & + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \\
 & - \sin\theta \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos 2\phi_h} \cos 2\phi_h
 \end{aligned} \right]
 \end{aligned}
 \right\}$$

$A_{UL}^{\sin\phi_h} \stackrel{WW}{\propto} Q^{-1} (h_{1L}^{\perp q} \otimes H_{1q}^{\perp h} + \dots)$   
 $A_{UL}^{\sin 2\phi_h} \propto h_{1L}^{\perp q} \otimes H_{1q}^{\perp h}$   
 $\underline{A_{UL}^{\sin 3\phi_h} \leftrightarrow A_{UT}^{\sin(3\phi_h - \phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}}$   
 $A_{LL} \propto g_{1L}^q \otimes D_{1q}^h$   
 $A_{LL}^{\cos\phi_h} \stackrel{WW}{\propto} Q^{-1} (g_{1L}^q \otimes D_{1q}^h + \dots)$   
 $\underline{A_{LL}^{\cos 2\phi_h} \leftrightarrow A_{LT}^{\cos(2\phi_h - \phi_s)} \stackrel{WW}{\propto} Q^{-1} (g_{1T}^q \otimes D_{1q}^h + \dots)}$

Access to various “twist-2,-3” functions  
 Different kinematic suppressions

# Interpretation in terms of TMD PDFs and FFs

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

Twist-2

Twist-3

$$\left\{ \begin{array}{l} 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ + P_L \left[ \begin{array}{l} \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \\ + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \\ - \sin\theta \varepsilon A_{UL}^{\sin 3\phi_h} \sin 3\phi_h \end{array} \right] \\ + P_L \lambda \left[ \begin{array}{l} \sqrt{1-\varepsilon^2} A_{LL} \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \\ - \sin\theta \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos 2\phi_h} \cos 2\phi_h \end{array} \right] \end{array} \right\}$$

$$\begin{aligned} & A_{UL}^{\sin\phi_h} \stackrel{WW}{\propto} Q^{-1} (h_{1L}^{\perp q} \otimes H_{1q}^{\perp h} + \dots) \leftarrow \begin{cases} A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h \\ A_{UT}^{\sin(\phi_h + \phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h} \end{cases} \\ & A_{UL}^{\sin 2\phi_h} \propto h_{1L}^{\perp q} \otimes H_{1q}^{\perp h} \leftarrow \begin{cases} A_{UT}^{\sin(2\phi_h - \phi_s)} \stackrel{WW}{\propto} Q^{-1} (h_1^q \otimes H_{1q}^{\perp h} + \dots) \end{cases} \\ & A_{UL}^{\sin 3\phi_h} \leftrightarrow A_{UT}^{\sin(3\phi_h - \phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} \\ & A_{LL} \propto g_{1L}^q \otimes D_{1q}^h \leftarrow \begin{cases} A_{LT}^{\cos(\phi_s)} \stackrel{WW}{\propto} Q^{-1} (g_{1T}^q \otimes D_{1q}^h + \dots) \end{cases} \\ & A_{LL}^{\cos\phi_h} \stackrel{WW}{\propto} Q^{-1} (g_{1L}^q \otimes D_{1q}^h + \dots) \leftarrow \begin{cases} A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h \end{cases} \\ & A_{LL}^{\cos 2\phi_h} \leftrightarrow A_{LT}^{\cos(2\phi_h - \phi_s)} \stackrel{WW}{\propto} Q^{-1} (g_{1T}^q \otimes D_{1q}^h + \dots) \end{aligned}$$

Access to various “twist-2,-3” functions  
 Different kinematic suppressions  
 Mixing with TSAs



- Former HERMES, JLab and COMPASS experimental results on LSAs

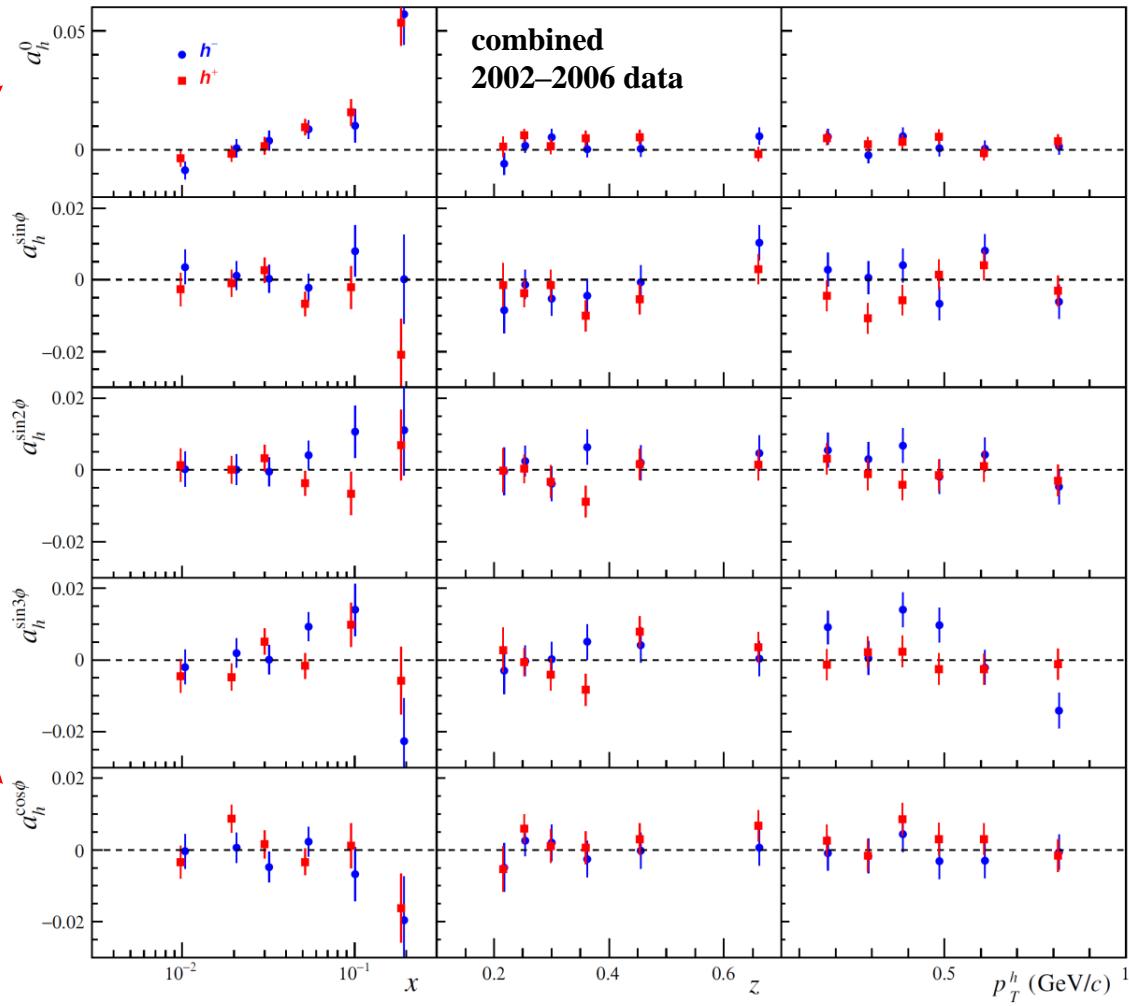
# Existing measurements: COMPASS

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

Combined D-sample, NEW! 21/09/2016  
CERN-EP-2016-245, arXiv:1609.06062 [hep-ex]

$$\left. \begin{aligned} & 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ & + P_L \left[ \begin{aligned} & \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \\ & + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \\ & - \sin\theta \varepsilon A_{UL}^{\sin 3\phi_h} \sin 3\phi_h \end{aligned} \right] \\ & + P_L \lambda \left[ \begin{aligned} & \sqrt{1-\varepsilon^2} A_{LL} \\ & + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \\ & - \sin\theta \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos 2\phi_h} \cos 2\phi_h \end{aligned} \right] \end{aligned} \right\}$$

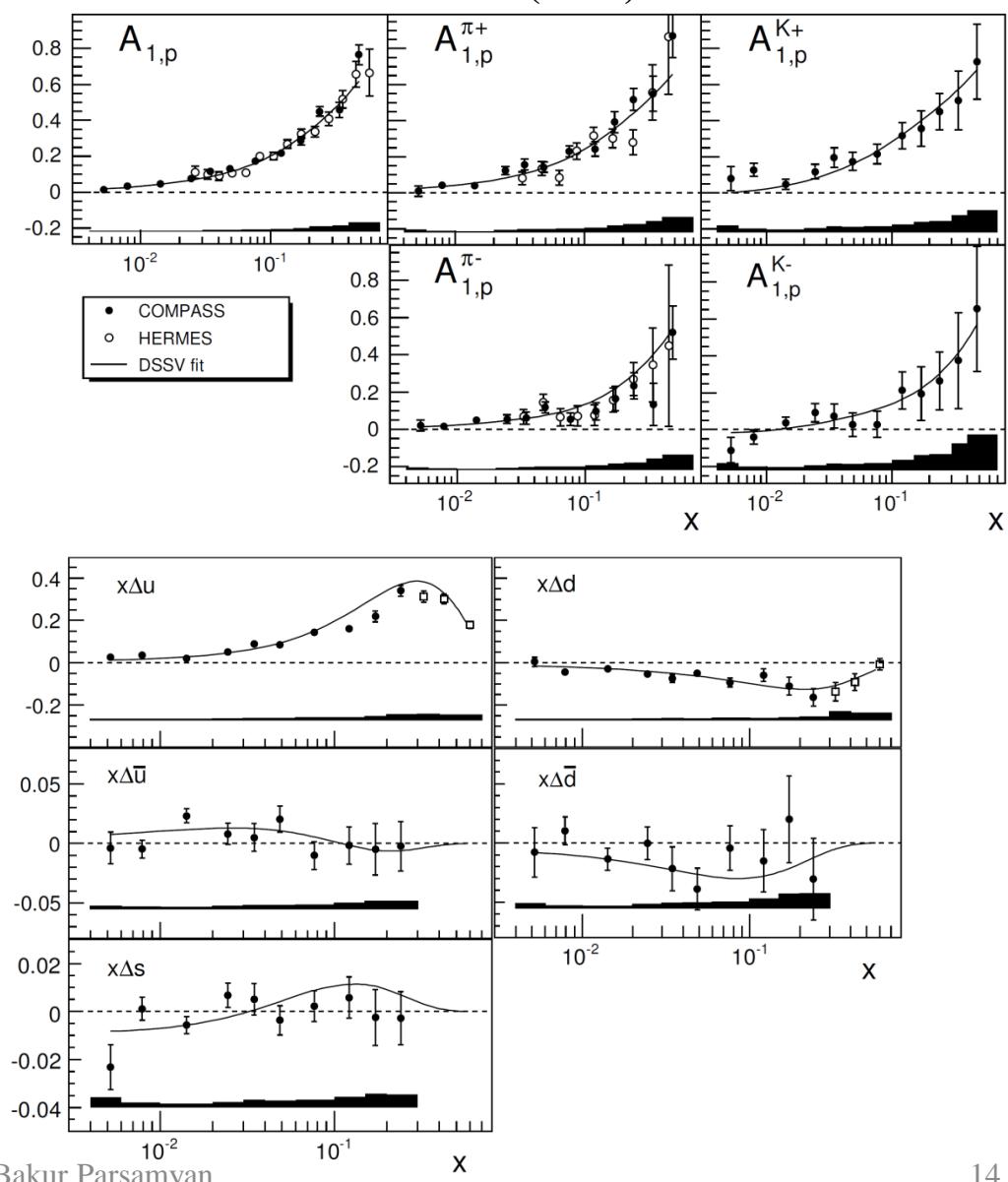
- COMPASS collected large amount of SIDIS data with longitudinally polarized D/P targets (2002-2011)



# Existing measurements: COMPASS

$$\frac{d\sigma}{dxdydzdp_T^2d\phi_hd\phi_S} = \left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times \\ \left\{ 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \right. \\ + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ + P_L \left[ \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \right. \\ \left. + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right. \\ \left. - \sin\theta\varepsilon A_{UL}^{\sin 3\phi_h} \sin 3\phi_h \right] \\ + P_L \lambda \left[ \sqrt{1-\varepsilon^2} A_{LL} \right. \\ \left. + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right. \\ \left. - \sin\theta\sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos 2\phi_h} \cos 2\phi_h \right]$$

PLB 693 (2010) 227–235



- COMPASS collected large amount of SIDIS data with longitudinally polarized D/P targets (2002-2011)

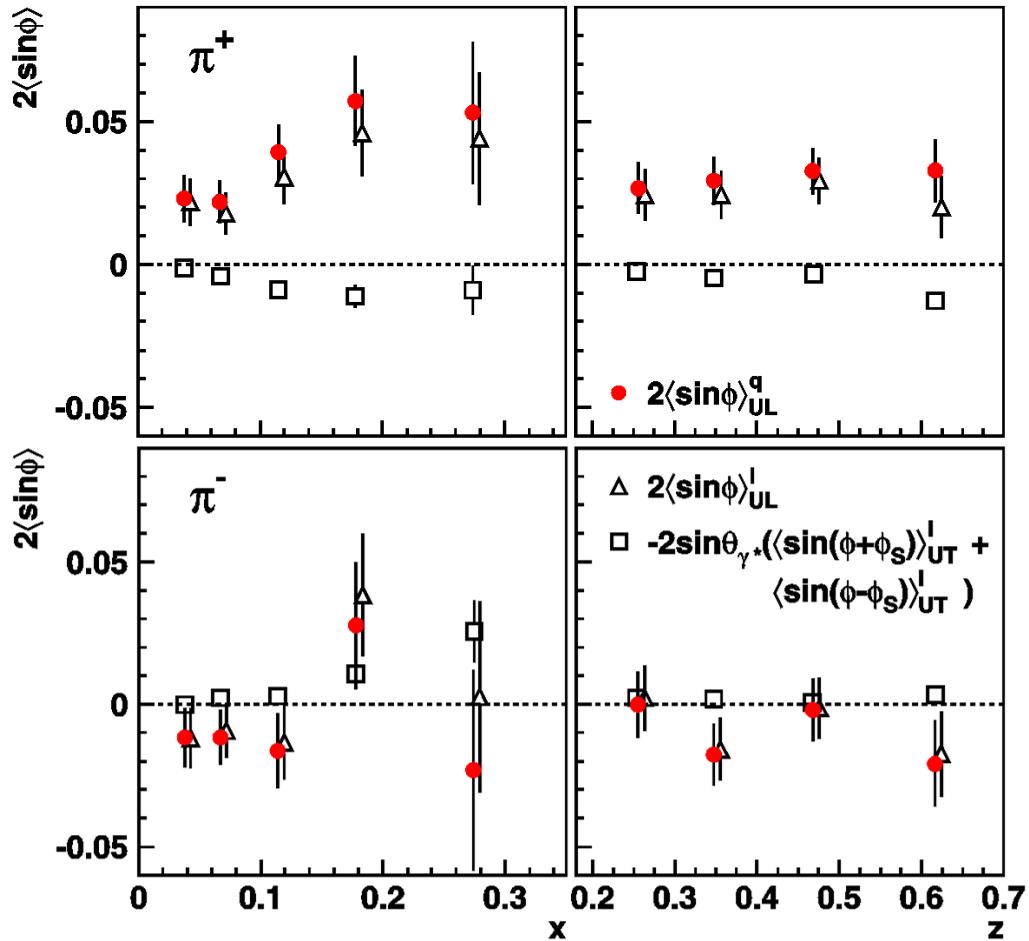
For COMPASS results on  $A_1(A_{LL})$  and helicity distributions see talks by M. Wilfert and V. Andrieux

# Existing measurements: HERMES, CLAS

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

$$\left. \begin{aligned} & 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \\ & + P_L \left[ \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \right. \\ & \quad \left. + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right. \\ & \quad \left. - \sin\theta \varepsilon A_{UL}^{\sin 3\phi_h} \sin 3\phi_h \right] \\ & + P_L \lambda \left[ \sqrt{1-\varepsilon^2} A_{LL} \right. \\ & \quad \left. + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right. \\ & \quad \left. - \sin\theta \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos 2\phi_h} \cos 2\phi_h \right] \end{aligned} \right\}$$

HERMES PLB 622 (2005) 14



- COMPASS collected large amount of SIDIS data with longitudinally polarized D/P targets (2002-2011)
- Similar measurements have been performed by HERMES (P/D)

# Existing measurements: HERMES, CLAS

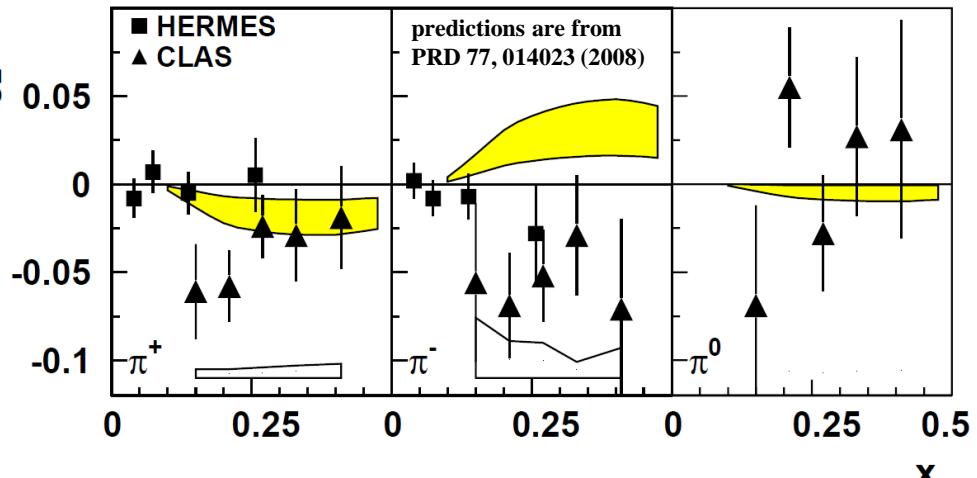
$$\frac{d\sigma}{dxdydzdp_T^2d\phi_hd\phi_s} = \left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times$$

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

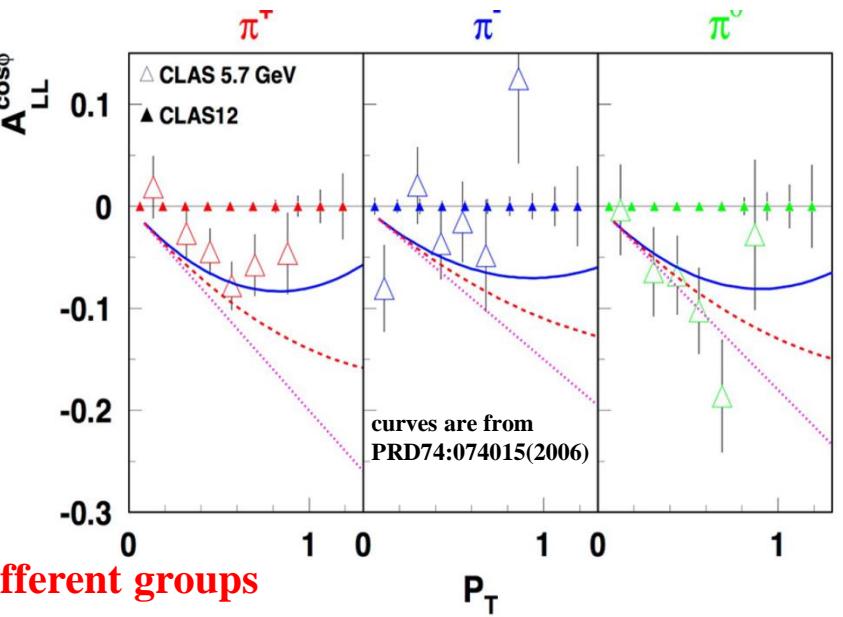
$$\left. \begin{aligned} & + P_L \left[ \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \right. \\ & \left. + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right. \\ & \left. - \sin\theta \varepsilon A_{UL}^{\sin 3\phi_h} \sin 3\phi_h \right] \end{aligned} \right\}$$

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

$A^{\sin 2\phi}$

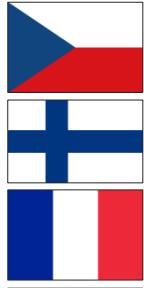


$A^{\cos\phi}$



- COMPASS collected large amount of SIDIS data with longitudinally polarized D/P targets (2002-2011)
- Similar measurements have been performed by HERMES (P/D) and Jlab (P)
- Non zero effects, interesting measurement
- Several theoretical predictions are available from different groups
- Prospects for future measurements

# COMPASS collaboration



24 institutions from 13 countries – nearly 250 physicists

## Common Muon and Proton Apparatus for Structure and Spectroscopy

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

### Wide physics program

#### COMPASS-I

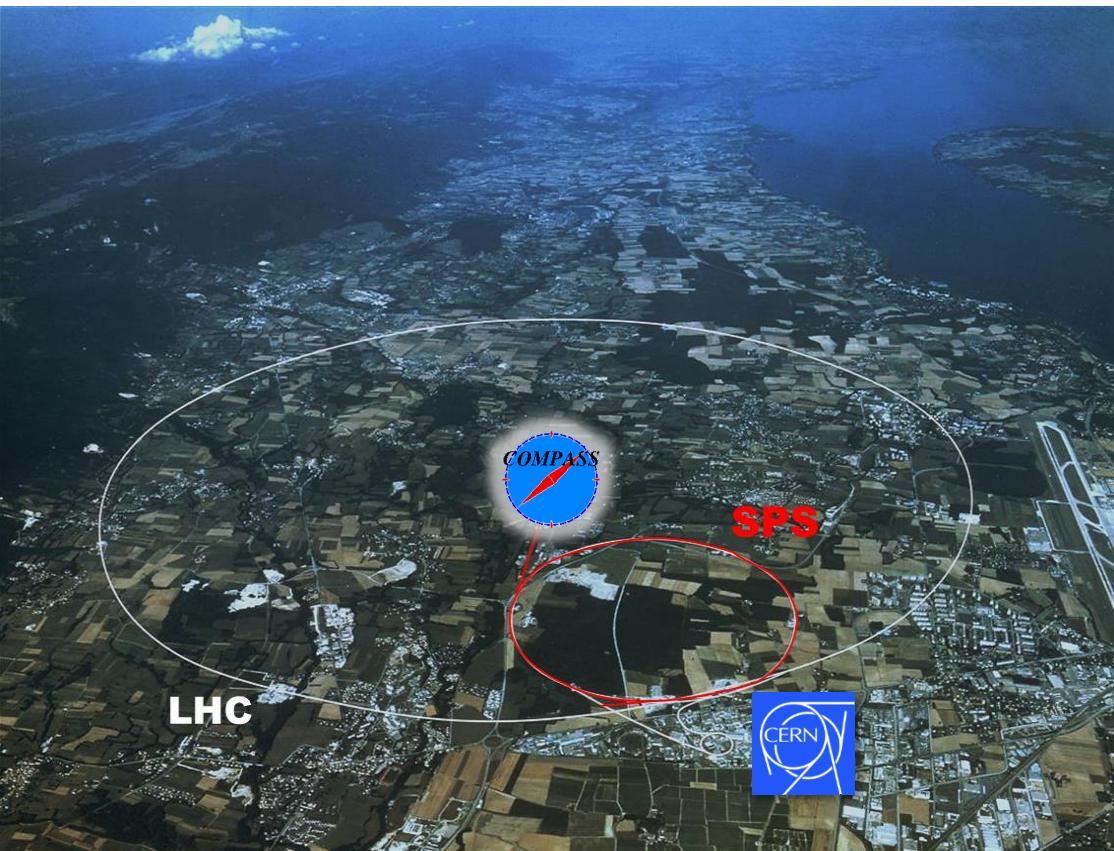
- Muon and hadron beams
- Nucleon spin structure
- Spectroscopy

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

#### COMPASS-II

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

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



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

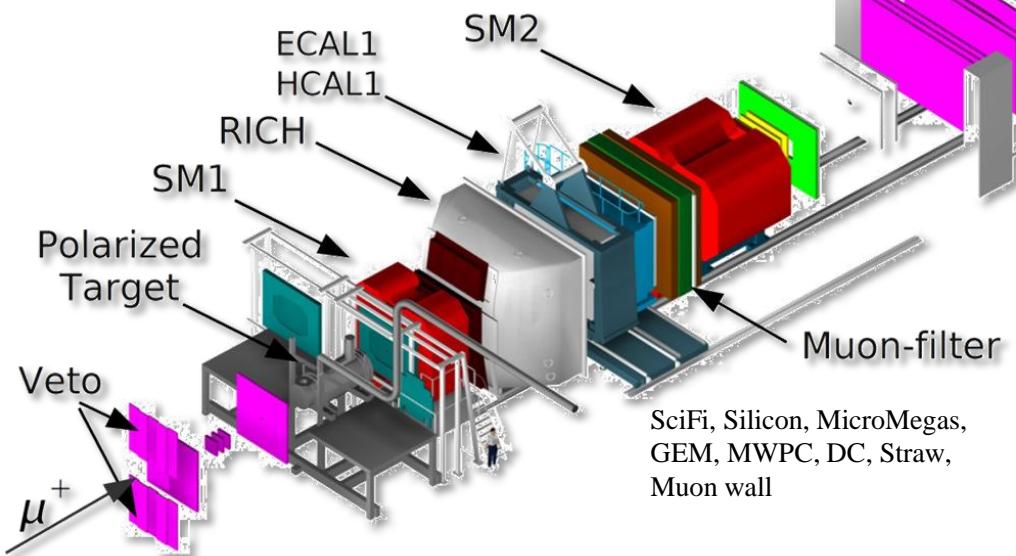
# COMPASS experimental setup: Phase I (muon program)

## COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area.

Two stages spectrometer LAS+SAS

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



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

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

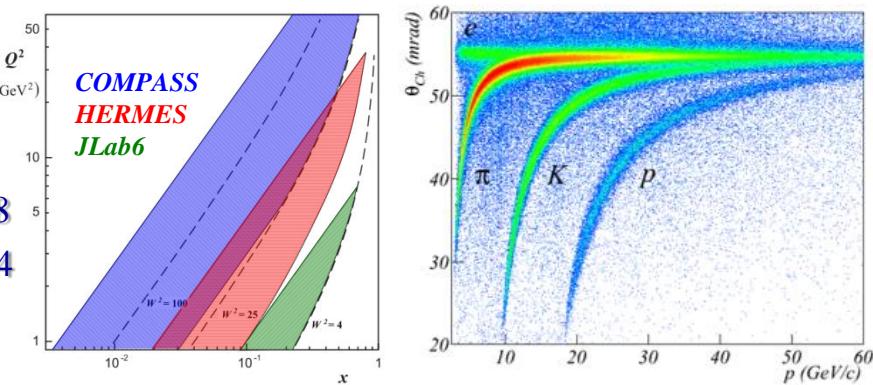
Longitudinally polarized (80%)  $\mu^+$  beam:

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

Target: Solid state ( ${}^6\text{LiD}$  or  $\text{NH}_3$ )

- ${}^6\text{LiD}$  2-cell configuration. Polarization (L & T)  $\sim 50\%$ , f  $\sim 0.38$
- $\text{NH}_3$  3-cell configuration. Polarization (L & T)  $\sim 80\%$ , f  $\sim 0.14$

**Data-taking years: 2002-2011**



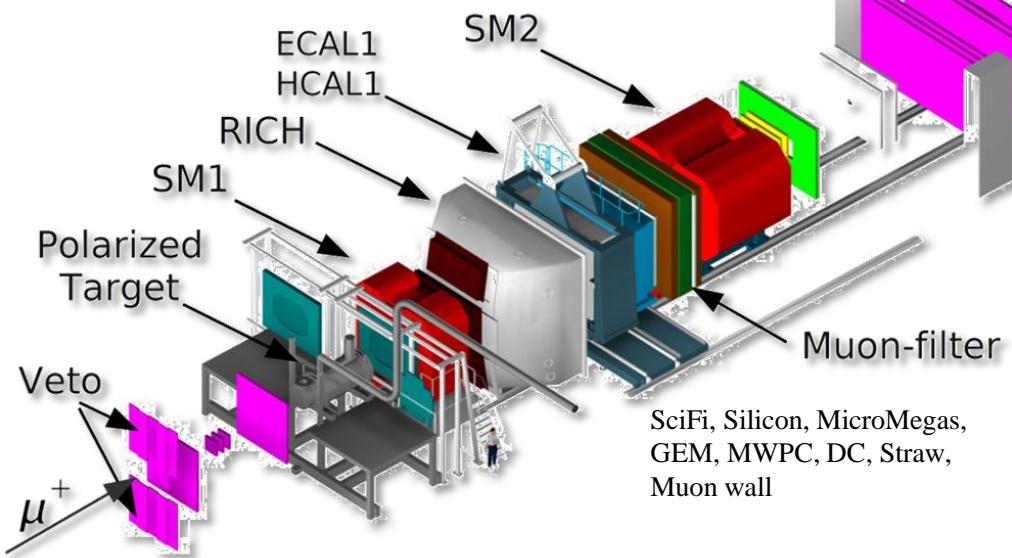
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Muon wall

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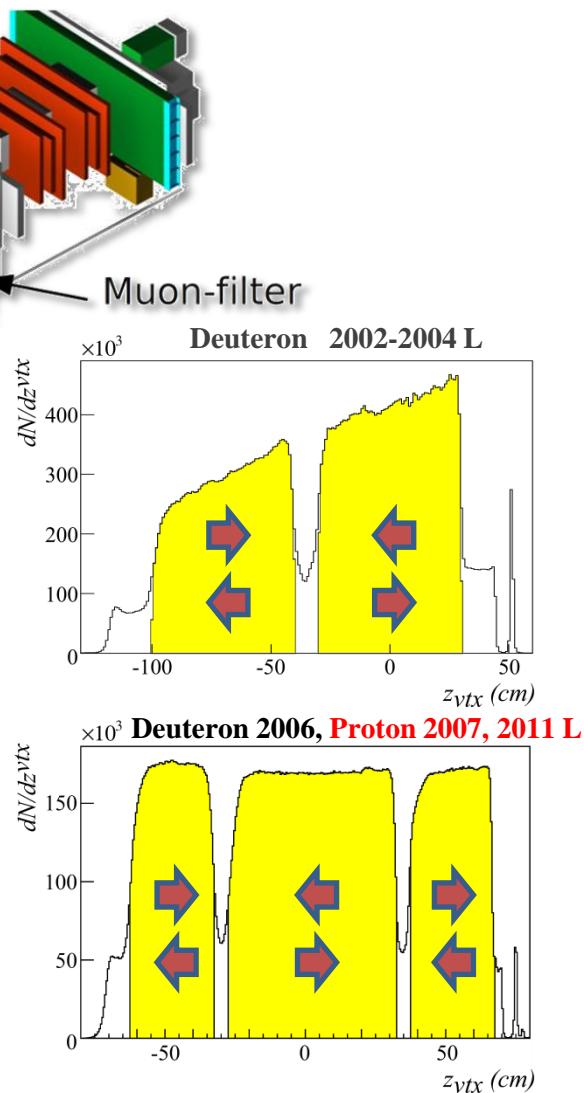
Energy: 160/200 GeV/c, Intensity:  $2 \cdot 10^8 \mu^+$ /spill (4.8s).

Target: Solid state ( ${}^6\text{LiD}$  or  $\text{NH}_3$ )

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- $\text{NH}_3$  3-cell configuration. Polarization (L & T)  $\sim 80\%$ , f  $\sim 0.14$

**Data-taking years: 2002-2011**

Data is collected simultaneously for the two target spin orientations  
Polarization reversal after each  $\sim 1\text{-}2$  days

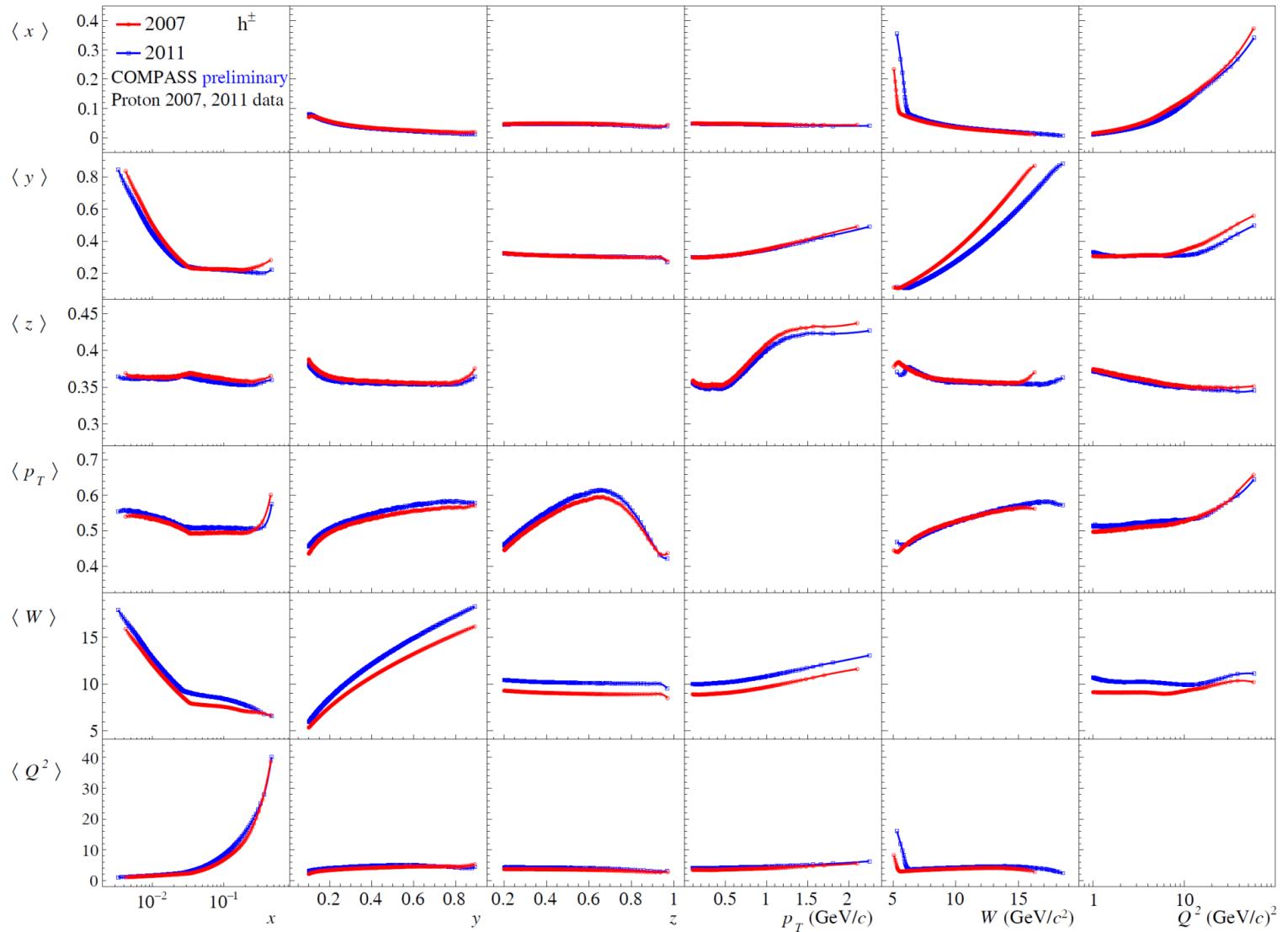




- Proton SIDIS single-hadron azimuthal LSAs at COMPASS

**NEW! Shown for the 1<sup>st</sup> time!**

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



Comparable kinematic distributions

Only results from merged 2007+2011 sample are shown

# COMPASS results for the $A_{UL}^{\sin\phi_h}$ asymmetry

**NEW! Shown for the 1<sup>st</sup> time!**

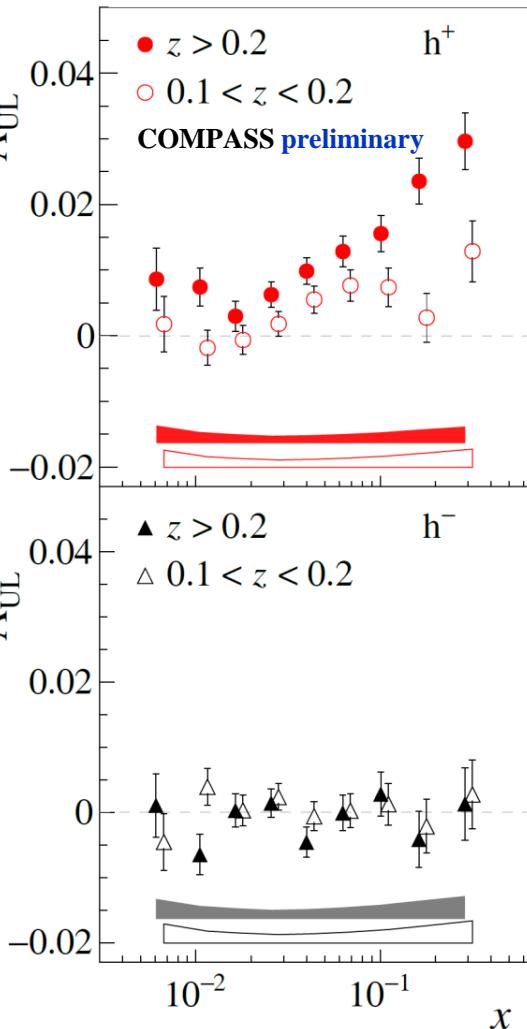
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_s} = \left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times$$

$$\left\{ \begin{array}{l} 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ + P_L \left[ \begin{array}{l} \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \\ + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \\ - \sin\theta \varepsilon A_{UL}^{\sin 3\phi_h} \sin 3\phi_h \end{array} \right] \\ + P_L \lambda \left[ \begin{array}{l} \sqrt{1-\varepsilon^2} A_{LL} \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \\ - \sin\theta \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos 2\phi_h} \cos 2\phi_h \end{array} \right] \end{array} \right\}$$

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

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

Proton 2007+2011 data



# COMPASS results for the $A_{UL}^{\sin\phi_h}$ asymmetry

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

$$\left\{ 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \right.$$

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

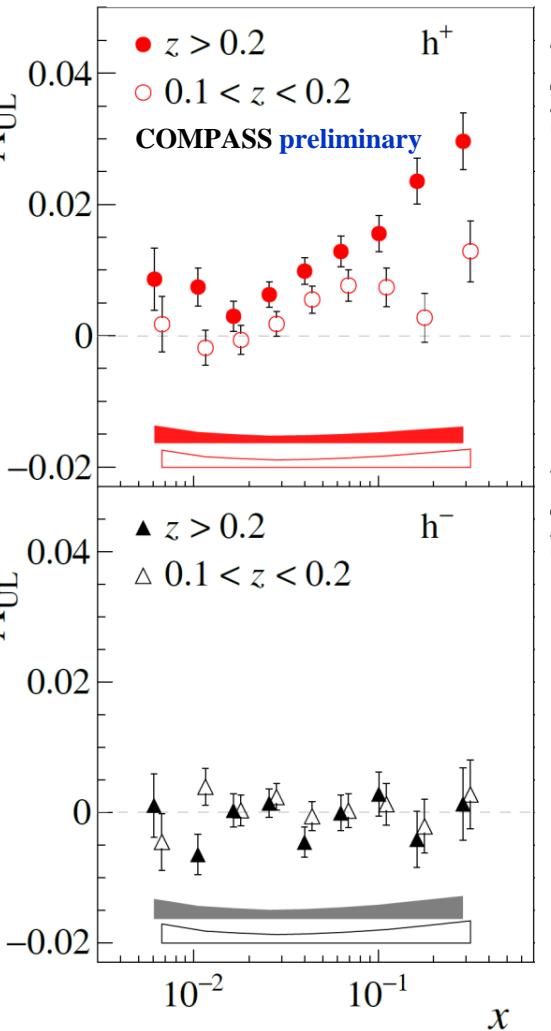
$$+ P_L \left[ \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \right. \\ \left. + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right. \\ \left. - \sin\theta\varepsilon A_{UL}^{\sin 3\phi_h} \sin 3\phi_h \right]$$

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

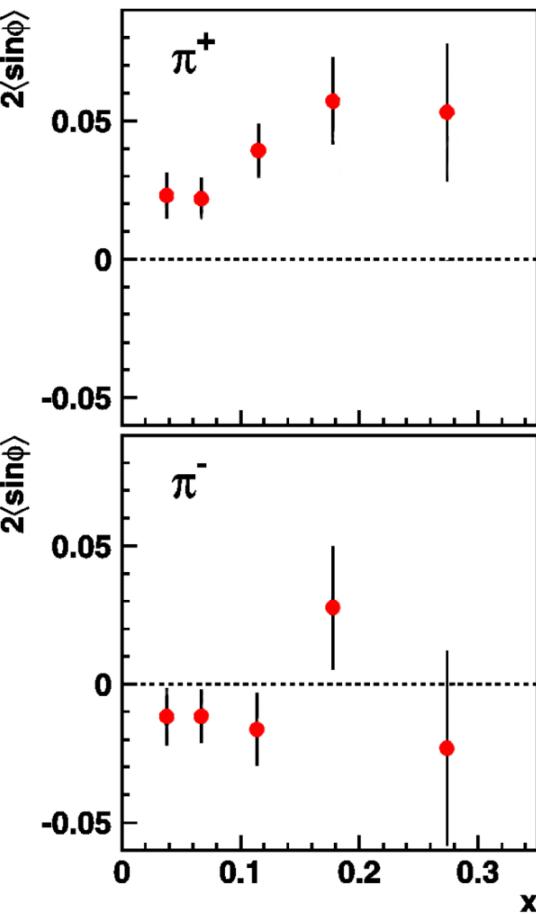
$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q} C \left\{ -\frac{\hat{\mathbf{h}} \cdot \mathbf{p}_T}{M_h} \left( x h_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) \right. \\ \left. + \frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} \left( x f_L^{\perp q} D_{1q}^h - \frac{M_h}{M}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

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Proton 2007+2011 data



HERMES  
PLB 622 (2005) 14



# COMPASS results for the $A_{UL}^{\sin\phi_h}$ asymmetry

**NEW! Shown for the 1<sup>st</sup> time!**

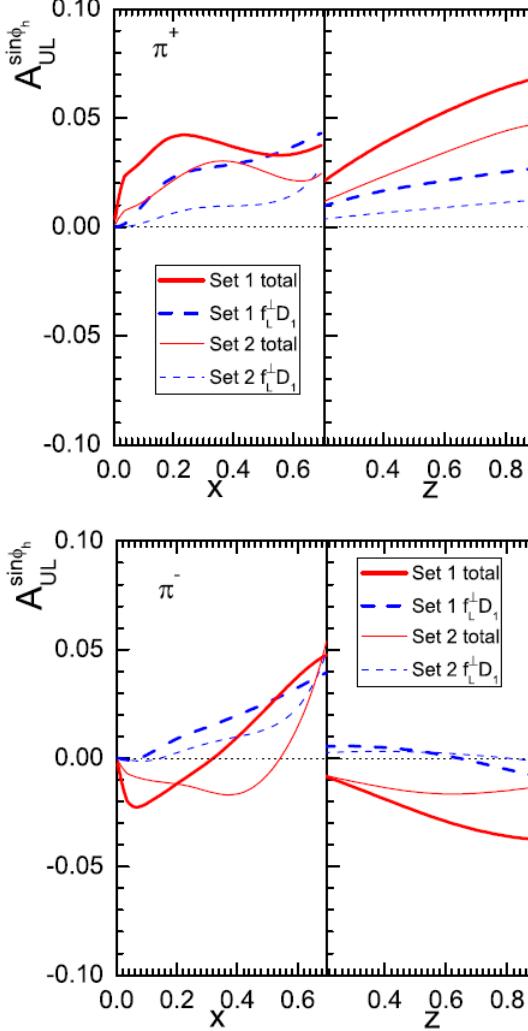
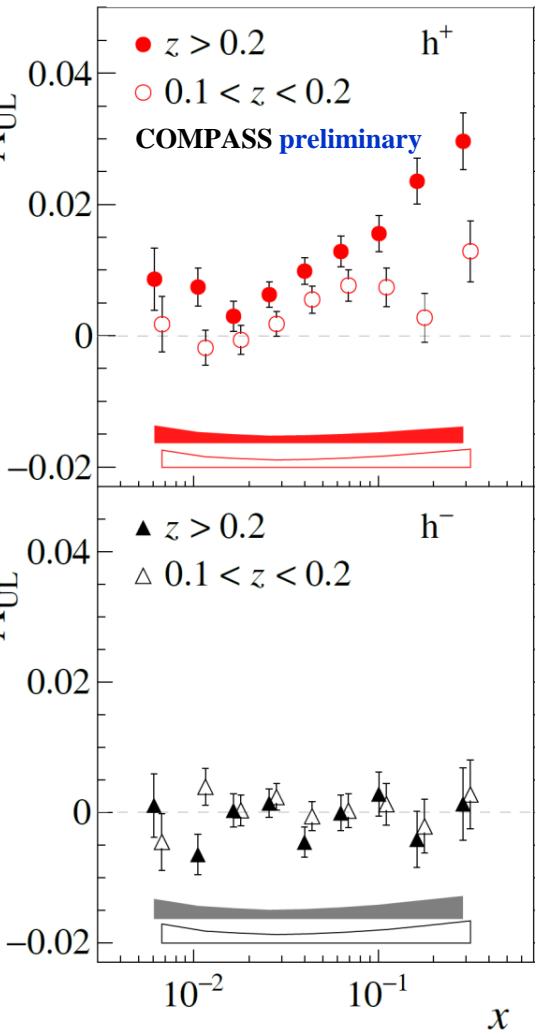
Zhun Lu  
Phys. Rev. D 90, 014037(2014)

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

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

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Proton 2007+2011 data



# $A_{UL}^{\sin\phi_h}$ mixing with $A_{UT}^{\sin(\phi_h - \phi_s)}$ and $A_{UT}^{\sin(\phi_h + \phi_s)}$

NEW! Shown for the 1<sup>st</sup> time!

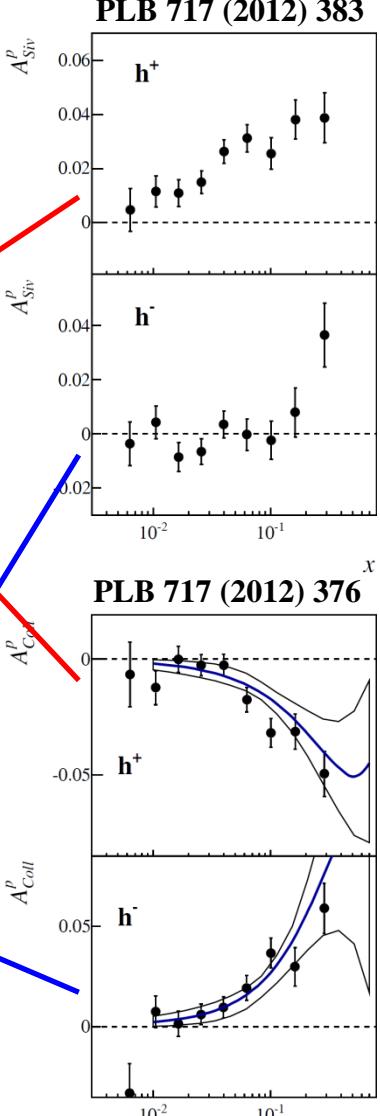
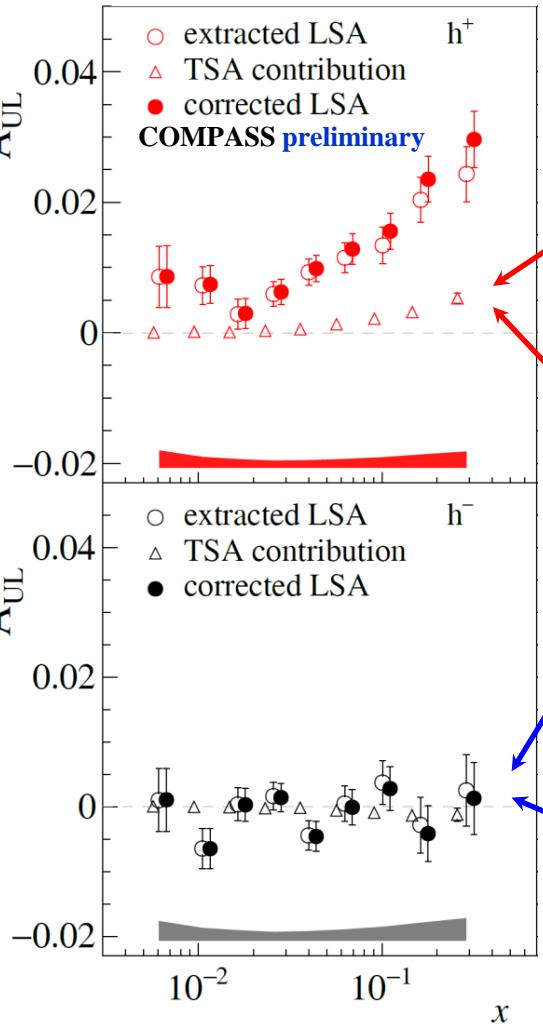
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_s} = \left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times$$

$$\left. \begin{aligned} & 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ & + P_L \left[ \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \right. \\ & \quad \left. + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right. \\ & \quad \left. - \sin\theta\varepsilon A_{UL}^{\sin 3\phi_h} \sin 3\phi_h \right] \\ & + P_L \lambda \left[ \sqrt{1-\varepsilon^2} A_{LL} \right. \\ & \quad \left. + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right. \\ & \quad \left. - \sin\theta \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos 2\phi_h} \cos 2\phi_h \right] \end{aligned} \right\}$$

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

- Q-suppression, TSA-mixing
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Proton 2007+2011 data



# COMPASS results for the $A_{UL}^{\sin 2\phi_h}$ asymmetry

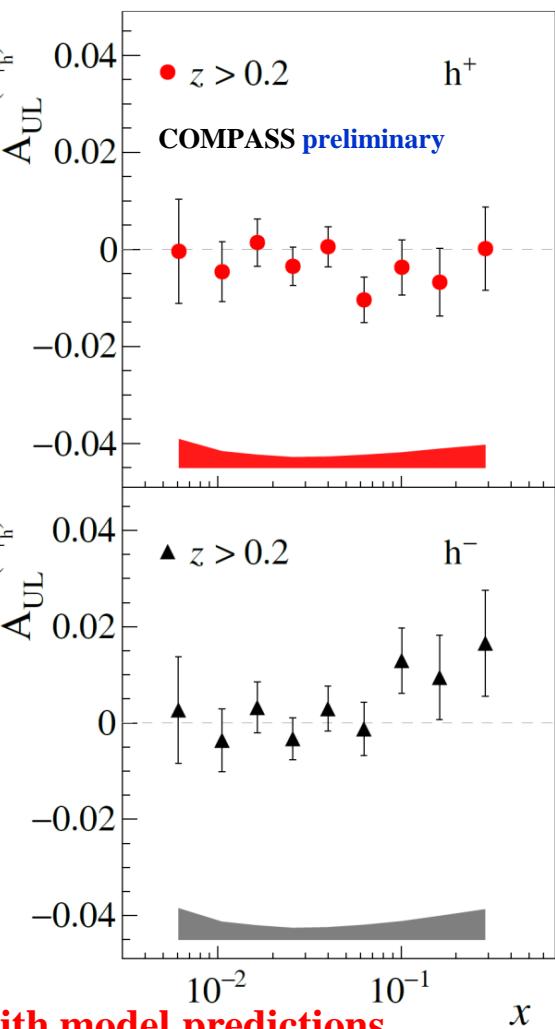
**NEW! Shown for the 1<sup>st</sup> time!**

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

$$\left. \begin{aligned} & 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ & + P_L \left[ \begin{aligned} & \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \\ & + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \\ & - \sin\theta \varepsilon A_{UL}^{\sin 3\phi_h} \sin 3\phi_h \end{aligned} \right] \\ & + P_L \lambda \left[ \begin{aligned} & \sqrt{1-\varepsilon^2} A_{LL} \\ & + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \\ & - \sin\theta \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos 2\phi_h} \cos 2\phi_h \end{aligned} \right] \end{aligned} \right\}$$

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

Proton 2007+2011 data



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

# COMPASS results for the $A_{UL}^{\sin 2\phi_h}$ asymmetry

NEW! Shown for the 1<sup>st</sup> time!

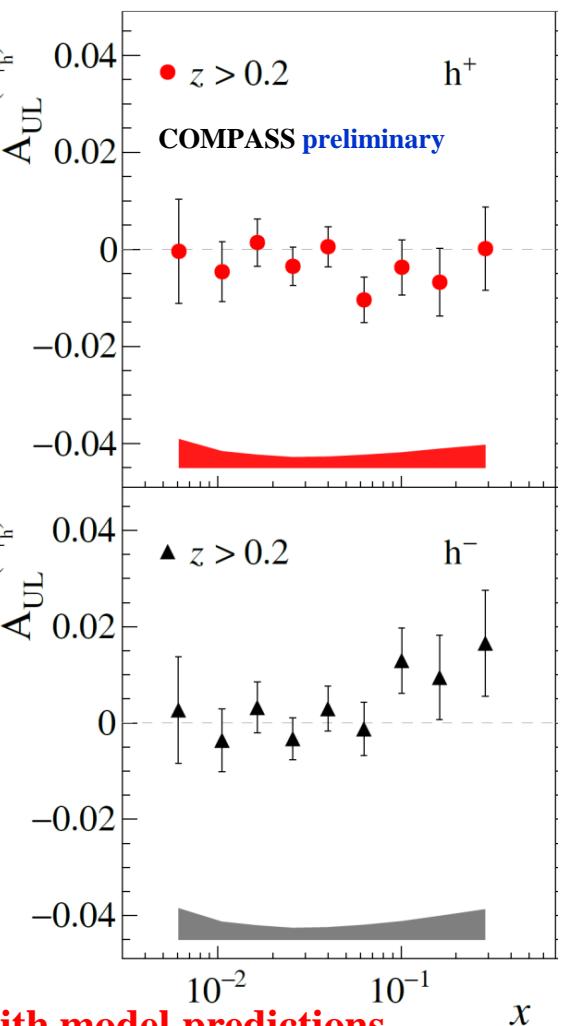
$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_s} = \left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times$$

$$\left. \begin{aligned} & 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ & + P_L \left[ \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \right. \\ & \quad \left. + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h - \sin\theta\varepsilon A_{UL}^{\sin 3\phi_h} \sin 3\phi_h \right] \\ & + P_L \lambda \left[ \sqrt{1-\varepsilon^2} A_{LL} \\ & \quad + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \\ & \quad - \sin\theta \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos 2\phi_h} \cos 2\phi_h \right] \end{aligned} \right\}$$

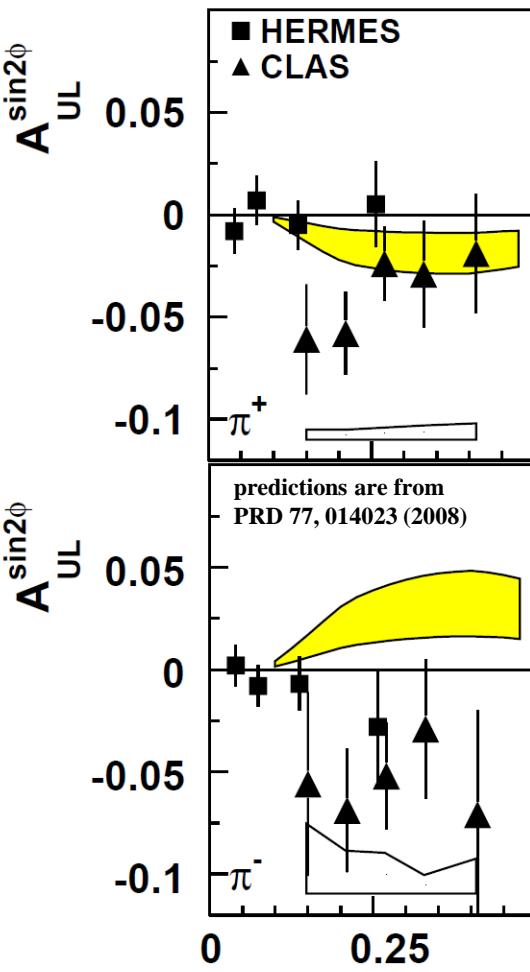
$$F_{UL}^{\sin 2\phi_h} = \mathcal{C} \left\{ -\frac{2(\hat{h} \cdot p_T)(\hat{h} \cdot k_T) - p_T \cdot k_T}{MM_h} h_{1L}^{\perp q} H_{1q}^{\perp h} \right\}$$

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

Proton 2007+2011 data



PRL 105, 262002 (2010)



# COMPASS results for the $A_{LL}^{\cos\phi_h}$ asymmetry

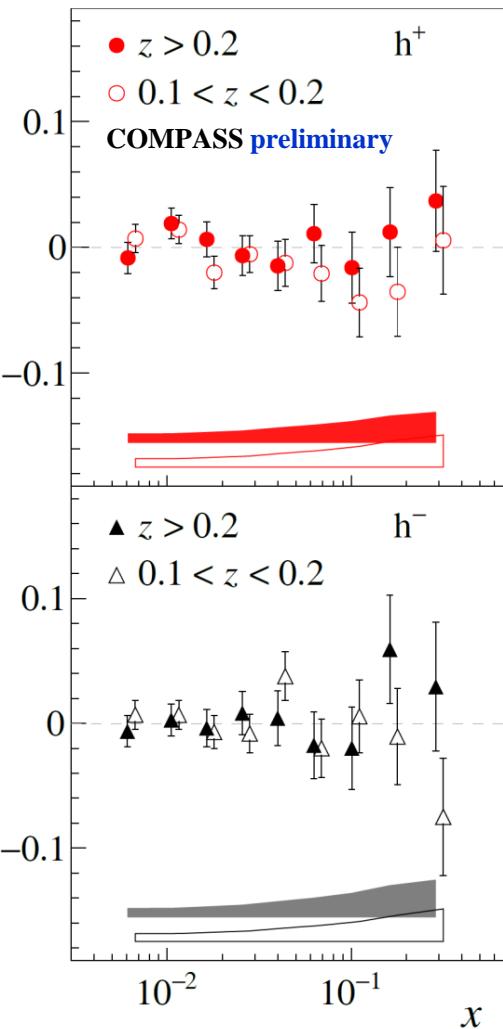
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$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_s} = \left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times$$

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

Proton 2007+2011 data



- Various different “twist” ingredients,
- Q-suppression
- **Compatible with zero, in agreement with model predictions**

# COMPASS results for the $A_{LL}^{\cos\phi_h}$ asymmetry

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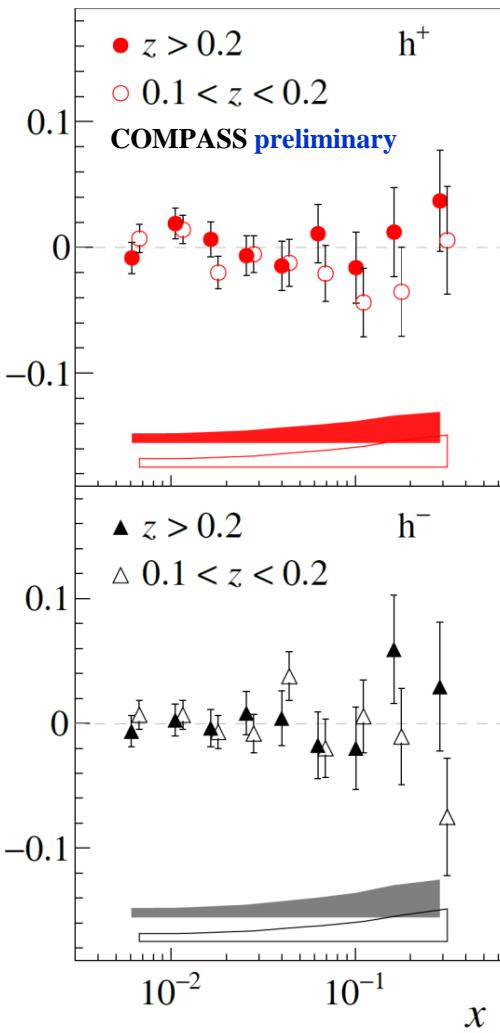
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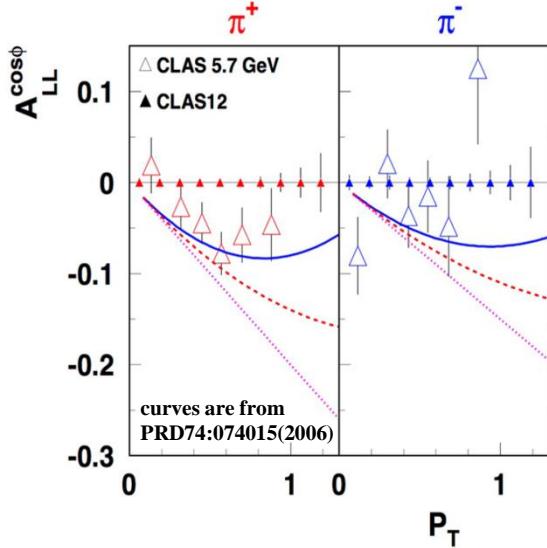
$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q} \mathcal{C} \left\{ -\frac{\hat{\mathbf{h}} \cdot \mathbf{p}_T}{M_h} \left( xe_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{D}_q^{\perp h}}{z} \right) \right. \\ \left. + \frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} \left( xg_L^{\perp q} D_{1q}^h -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

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Proton 2007+2011 data



PRL 105,262002(2010)



# COMPASS results for the $A_{LL}^{\cos\phi_h}$ asymmetry

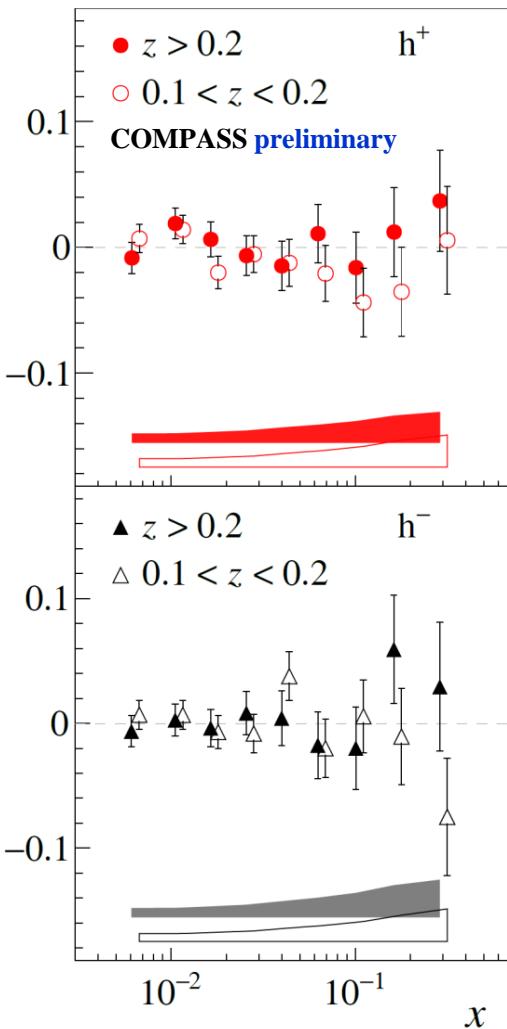
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$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_s} = \left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times$$

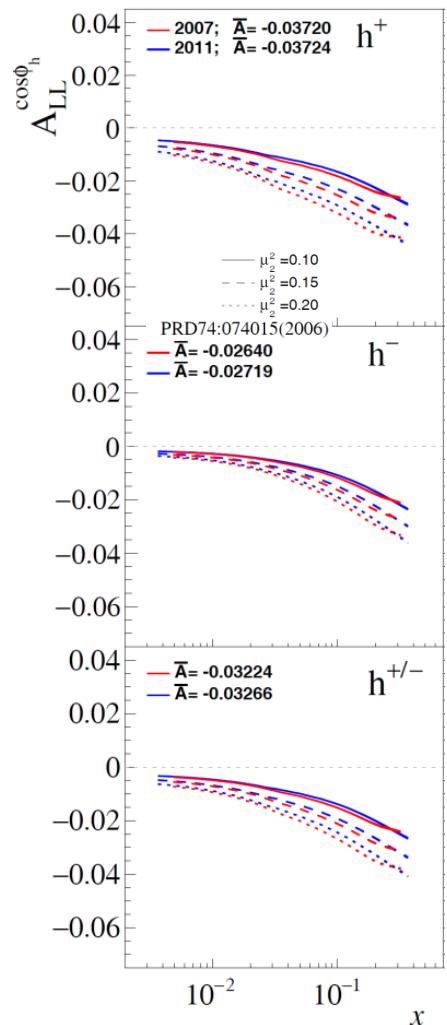
$$\left. \begin{aligned} & 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ & + P_L \left[ \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \right. \\ & \quad \left. + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right. \\ & \quad \left. - \sin\theta \varepsilon A_{UL}^{\sin 3\phi_h} \sin 3\phi_h \right] \\ & + P_L \lambda \left[ \sqrt{1-\varepsilon^2} A_{LL} \right. \\ & \quad \left. + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right. \\ & \quad \left. - \sin\theta \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos 2\phi_h} \cos 2\phi_h \right] \end{aligned} \right\} \cos\phi_h$$

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

Proton 2007+2011 data



PRD74:074015(2006)



- Various different “twist” ingredients,
- Q-suppression
- **Compatible with zero, in agreement with model predictions**



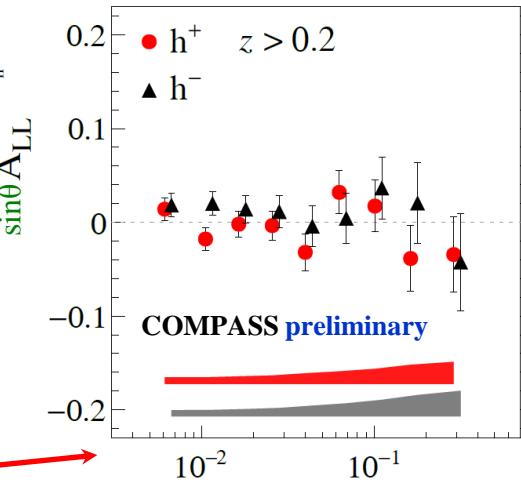
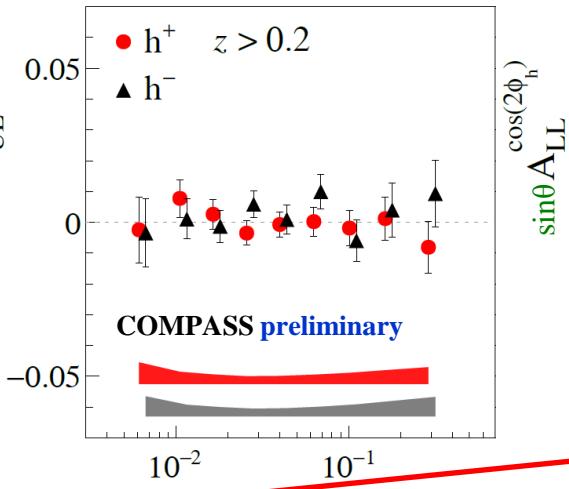
# COMPASS results for $A_{UL}^{sin3\phi_h}$ and $A_{LL}^{cos2\phi_h}$ asymmetries

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

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Proton 2007+2011 data



$$A_{UL}^{sin3\phi_h} \leftrightarrow A_{UT}^{sin(3\phi_h - \phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

$$A_{LL}^{cos2\phi_h} \leftrightarrow A_{LT}^{cos(2\phi_h - \phi_s)} \propto Q^{-1} (g_{1T}^q \otimes D_{1q}^h + \dots)$$

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



# Conclusions

- COMPASS has measured all possible single-hadron SIDIS LSAs from combined deuteron 2002-2006 and proton 2007/2011 data sample
- Together with existing measurements of proton TSAs these results complete the whole set of all possible proton SIDIS spin dependent azimuthal asymmetries
- This allowed us to evaluate the mixing between SIDIS LSAs and TSAs arising from the difference of target polarization components in  $lp$  and  $\gamma*p$  systems
- Whereas azimuthal LSAs on deuteron appear to be compatible with zero, for some of the proton LSAs non-zero signals are observed
- A clear effect was observed for  $A_{UL}^{sin\phi_h}$  with positive hadrons, while for negative hadrons the asymmetry is found to be compatible with zero
  - in agreement with HERMES observations
- The  $A_{UL}^{sin^2\phi_h}$  appear to exhibit opposite sign “Collins-like” behavior for  $h^+$  and  $h^-$ 
  - in agreement with model predictions
  - possible positive signal for negative hadrons appears to contradict HERMES and Jlab observations
- The  $A_{LL}^{cos\phi_h}$  asymmetry is found to be small and compatible with zero within statistical accuracy which does not contradict available model predictions

Thank you!