Transverse spin dependent azimuthal asymmetries at COMPASS

SIDIS asymmetries beyond Collins and Sivers

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On behalf of the COMPASS collaboration

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Outlook

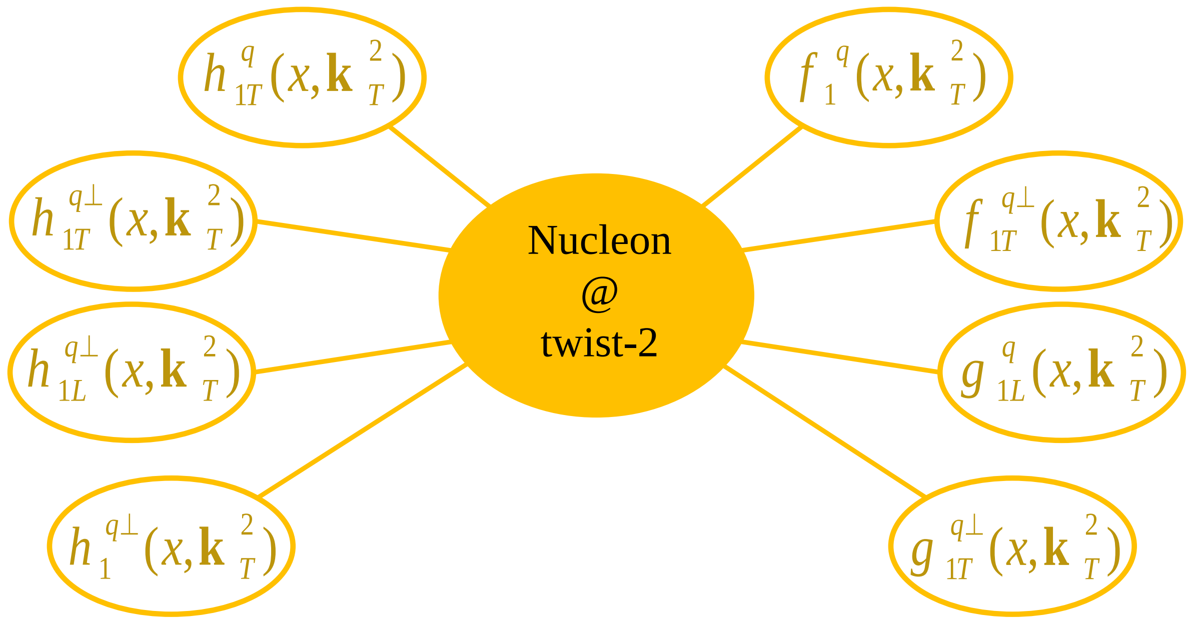
- Introduction
- COMPASS experiment
- Experimental results and theoretical predictions
- Summary

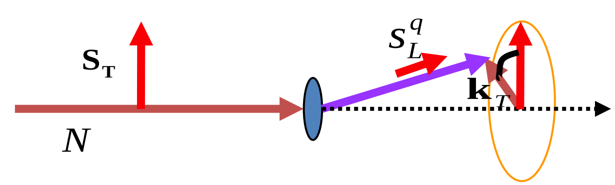
Introduction

TMD parton distributon functions

Collins, Soper (81,82); Ji, Ma, Yuan (03, 04); Collins, Metz (04) – Definition of TMD DF's and FF's & QCD factorization of SIDIS.

LO QCD = Simple parton model + Factorized twist-2 PDF & FF





$\mathbf{k}_T$ – intrinsic transverse momentum of the quark

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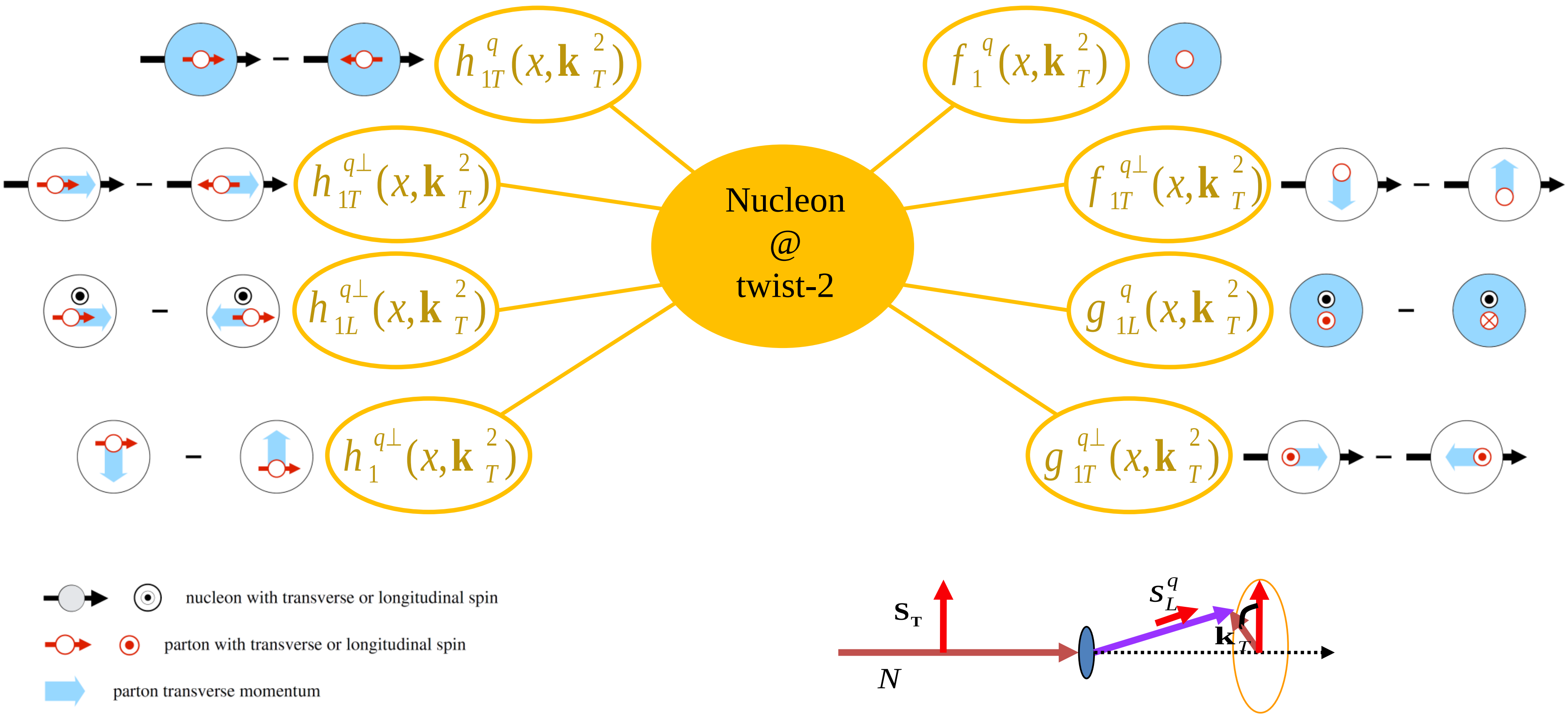

Proton goes out of the screen/ photon goes into the screen

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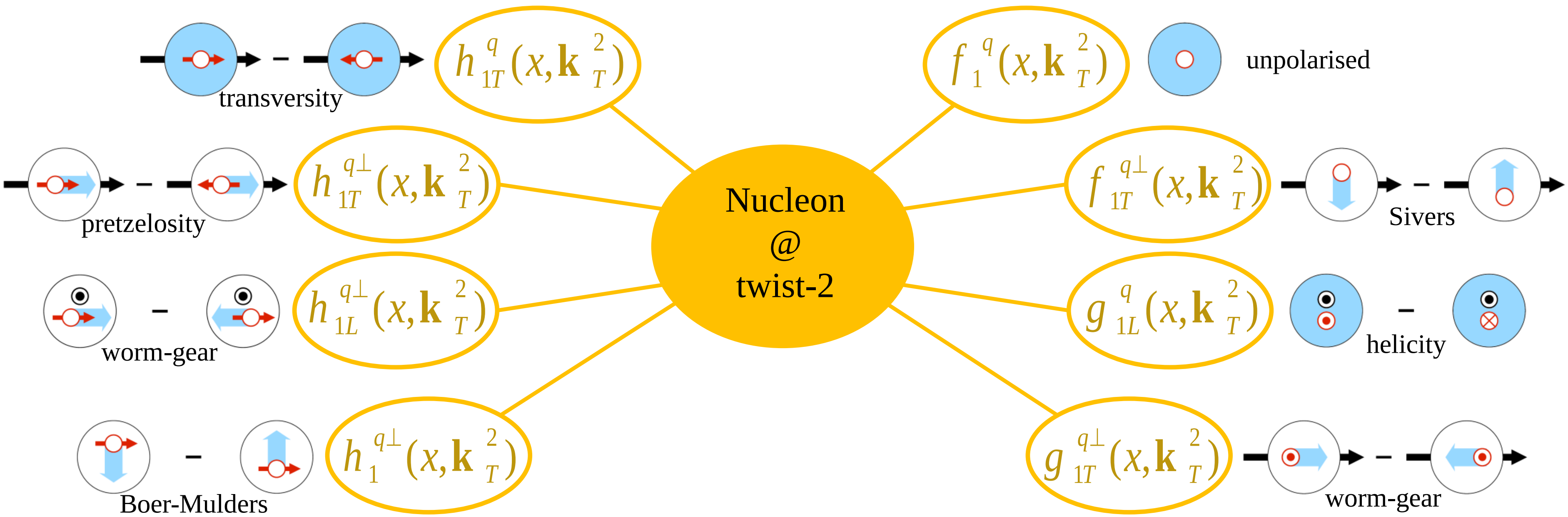

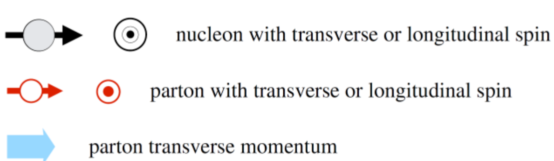

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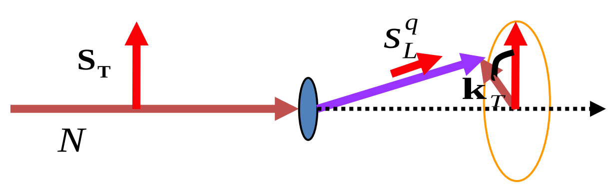


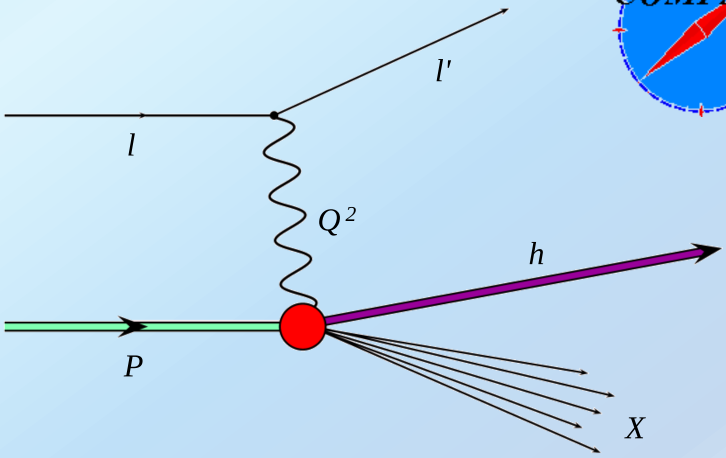
$\mathbf{k}_T$ – intrinsic transverse momentum of the quark

TMD parton distributon functions

Ganesha is widely revered as the Remover of Obstacles and more generally as Lord of Beginnings patron of arts and sciences, and the deva of intellect and wisdom. Courtesy of Wikipedia

Kinematical conventions

Semi Inclusive Deep Inelastic Scattering $\ell N \to \ell' h X$



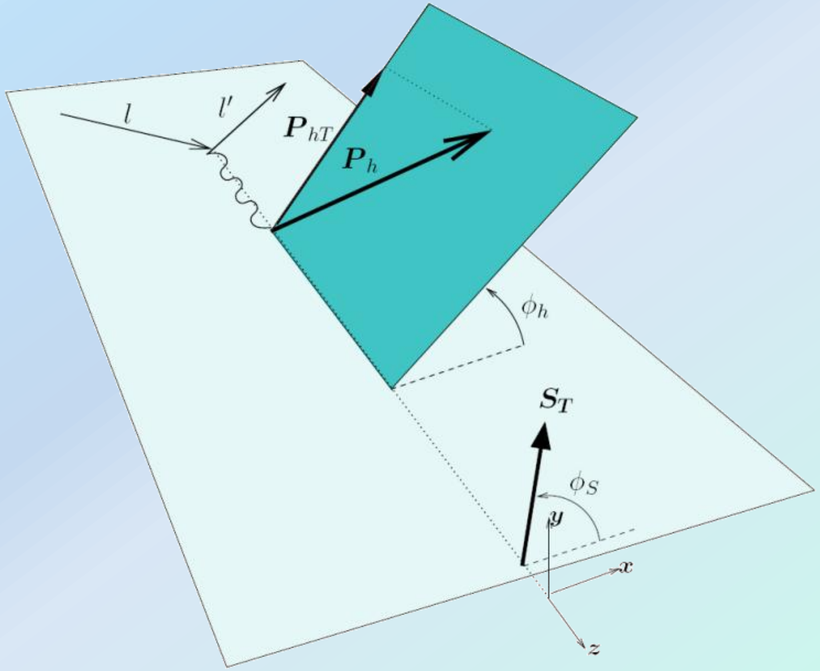
l and l' - momentum of the initial and the final state lepton;

P is the target nucleon momentum (mass), S -its spin;

P_h is the final hadron momentum;

ϕ_h -hadron azimuthal angle,

ϕ_S -Spin azimuthal angle.



$$Q^2 = -q^2 = -(l - l')^2 = 2MExy;$$

$$\nu = E - E';$$

$$x = Q^2 / 2Pq = Q^2 / 2M\nu;$$

$$y = Pq / Pl = \nu / E;$$

$$W^2 = (P + q)^2 = M^2 + 2M\nu - Q^2;$$

Large Q^2 and $W^2 \to$ DIS regime;

$$z = PP_h / Pq = E_h / \nu.$$

Polarized SIDIS cross-section

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

model independent expression, also valid for exclusive reactions and for entire phase space of SIDIS (TFR, CFR)

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\times$$
$$\times\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h}$$
$$+\varepsilon\cos(2\phi_h)F_{UU}^{\cos(2\phi_h)} + P_L^l\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}$$
$$+S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)F_{UL}^{\sin(2\phi_h)}\right]$$
$$+S_L^N P_L^l\left[\sqrt{1-\varepsilon^2}F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h F_{LL}^{\cos\phi_h}\right]$$
$$+\left|S_T^N\right|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$
$$+\varepsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}$$
$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$
$$+\left|S_T^N\right|P_L^l\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}$$
$$+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

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$$\boxed{\begin{aligned}&\times\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h}\\&+\varepsilon\cos(2\phi_h)F_{UU}^{\cos(2\phi_h)}+P_L^l\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}\end{aligned}}$$

unpolarized target

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

$$+S_L^N P_L^l\left[\sqrt{1-\varepsilon^2}F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h F_{LL}^{\cos\phi_h}\right]$$

$$+\left|S_T^N\right|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\varepsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+\left|S_T^N\right|P_L^l\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}$$

$$+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

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unpolarized target

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

$$+\left|S_T^N\right|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$
$$+\varepsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}$$
$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$
$$+\left|S_T^N\right|P_L^l\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}$$
$$+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

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unpolarized target

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

$$+\left|S_T^N\right|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$
$$+\varepsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}$$
$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

transversely polarized target

$$+\left|S_T^N\right|P_L^l\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}$$
$$+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

transversely polarized target & longitudinally polarized beam

Polarized SIDIS cross-section (transverse part)

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

Twist-2

Twist-3

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{\ldots$$

$$+\left|S_T^N\right|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\varepsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

SSA

DSA

$$+\left|S_T^N\right|P_L^l\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}$$

$$+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

Polarized SIDIS cross-section (transverse part)

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$$\frac{d\sigma}{dxdyd\psi dzd\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{\ldots$$

$$+\left|S_T^N\right|\Big[\sin(\phi_h-\phi_S)\left(\boxed{F_{UT,T}^{\sin(\phi_h-\phi_S)}}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\varepsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+\left|S_T^N\right|P_L^l\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}$$

$$+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

Sivers

Twist-2

Twist-3

SSA

DSA

Polarized SIDIS cross-section (transverse part)

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

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} &= \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{\ldots \\
&+\left|S_T^N\right|\Big[\sin(\phi_h-\phi_S)\left(\boxed{F_{UT,T}^{\sin(\phi_h-\phi_S)}}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
&+\varepsilon\sin(\phi_h+\phi_S)\boxed{F_{UT}^{\sin(\phi_h+\phi_S)}}+\varepsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
&+\left|S_T^N\right|P_L^l\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S} \\
&+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},
\end{aligned}
$$

Twist-2

Twist-3

Sivers

Collins

See talks by G. Pesaro and A. Richter

SSA

DSA

Polarized SIDIS cross-section (transverse part)

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$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{\ldots$$

$$+\left|S_T^N\right|\Big[\sin(\phi_h-\phi_S)\left(\boxed{F_{UT,T}^{\sin(\phi_h-\phi_S)}}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\varepsilon\sin(\phi_h+\phi_S)\boxed{F_{UT}^{\sin(\phi_h+\phi_S)}}+\varepsilon\sin(3\phi_h-\phi_S)\boxed{F_{UT}^{\sin(3\phi_h-\phi_S)}}$$

$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+\left|S_T^N\right|P_L^l\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\boxed{F_{LT}^{\cos(\phi_h-\phi_S)}}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}$$

$$+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

Twist-2

Twist-3

Sivers

Collins

See talks by G. Pesaro and A. Richter

Pretzelosity

Worm Gear

SSA

DSA

Polarized SIDIS cross-section (transverse part)

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

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{\ldots$$

$$+\left|S_T^N\right|\Big[\sin(\phi_h-\phi_S)\Big(\boxed{F_{UT,T}^{\sin(\phi_h-\phi_S)}}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big)$$

$$+\varepsilon\sin(\phi_h+\phi_S)\boxed{F_{UT}^{\sin(\phi_h+\phi_S)}}+\varepsilon\sin(3\phi_h-\phi_S)\boxed{F_{UT}^{\sin(3\phi_h-\phi_S)}}$$

$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S\boxed{F_{UT}^{\sin\phi_S}}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)\boxed{F_{UT}^{\sin(2\phi_h-\phi_S)}}\Big]$$

$$+\left|S_T^N\right|P_L^l\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\boxed{F_{LT}^{\cos(\phi_h-\phi_S)}}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S\boxed{F_{LT}^{\cos\phi_S}}$$

$$+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)\boxed{F_{LT}^{\cos(2\phi_h-\phi_S)}}\Big]\Big\},$$

Twist-2

Twist-3

Sivers

Collins

See talks by G. Pesaro and A. Richter

Pretzelosity

Worm Gear

SSA

DSA

Higher twists

Interpretation of the transverse asymmetries

$$A_{U(L),T}^{w_i(\varphi_h,\varphi_s)} = \frac{F_{U(L),T}^{w_i(\varphi_h,\varphi_s)}}{F_{UU,T}}$$

Within QCD parton model $A_i \propto DF \otimes FF \quad (i=1,..8)$

Twist-2:

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

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

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

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

single spin

double spin

Twist-2 + k_T/Q kinematical corrections:

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

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

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

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

UT and LT asymmetries

$$\frac{1}{w_i(\phi_h,\phi_s)}\frac{d\sigma^{\uparrow}-d\sigma^{\downarrow}}{d\sigma^{\uparrow}+d\sigma^{\downarrow}} = A_{U(L)T,raw}^{w_i(\phi_h,\phi_s)} \quad i=1,..,5\,(i=6,..,8)$$

$$A_{UT}^{\sin(\phi_h+\phi_s)} = \frac{A_{UT,raw}^{\sin(\phi_h+\phi_s)}}{D^{\sin(\phi_h+\phi_s)}(y)\, f\, |S_T|}$$

$$A_{UT}^{\sin(3\phi_h-\phi_s)} = \frac{A_{UT,raw}^{\sin(3\phi_h-\phi_s)}}{D^{\sin(3\phi_h-\phi_s)}(y)\, f\, |S_T|}$$

$$D^{\sin(\phi_h+\phi_S)}(y) = D^{\sin(3\phi_h-\phi_S)}(y) = \frac{2(1-y)}{1+(1-y)^2}$$

UT

$$A_{UT}^{\sin(2\phi_h-\phi_s)} = \frac{A_{UT,raw}^{\sin(2\phi_h-\phi_s)}}{D^{\sin(2\phi_h-\phi_s)}(y)\, f\, |S_T|}$$

$$A_{UT}^{\sin(\phi_s)} = \frac{A_{UT,raw}^{\sin(\phi_s)}}{D^{\sin(\phi_s)}(y)\, f\, |S_T|}$$

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

$$A_{UT}^{\sin(\phi_h-\phi_s)} = \frac{A_{UT,raw}^{\sin(\phi_h-\phi_s)}}{D^{\sin(\phi_h-\phi_s)}(y)\, f\, |S_T|}$$

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

$$A_{LT}^{\cos(2\phi_h-\phi_s)} = \frac{A_{LT,raw}^{\cos(2\phi_h-\phi_s)}}{D^{\cos(2\phi_h-\phi_s)}(y)\, fP_{beam}\, |S_T|}$$

$$A_{LT}^{\cos(\phi_s)} = \frac{A_{LT,raw}^{\cos(\phi_s)}}{D^{\cos(\phi_s)}(y)\, fP_{beam}\, |S_T|}$$

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

LT

$$A_{LT}^{\cos(\phi_h-\phi_s)} = \frac{A_{LT,raw}^{\cos(\phi_h-\phi_s)}}{D^{\cos(\phi_h-\phi_s)}(y)\, fP_{beam}\, |S_T|}$$

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

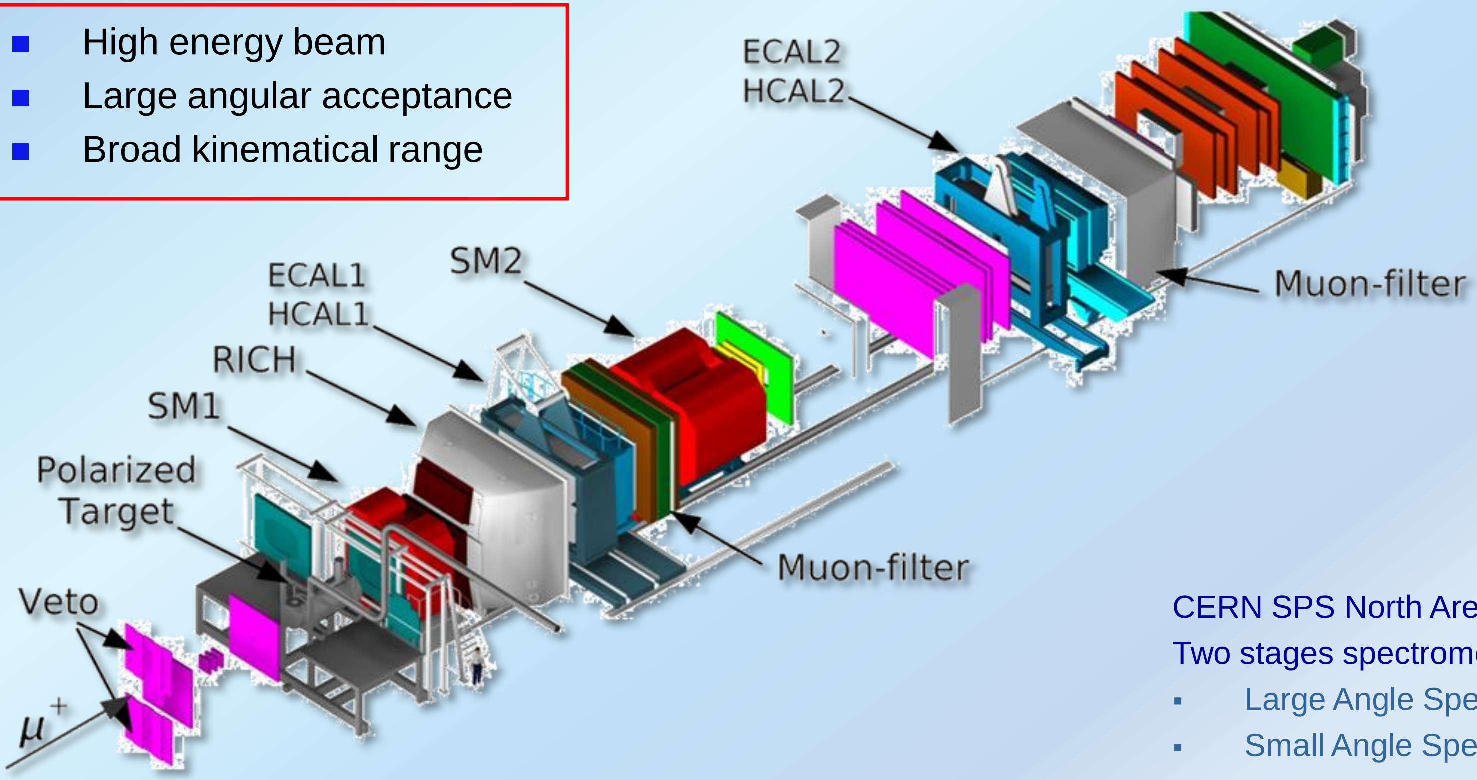
$D^{w_i(\phi_h,\phi_s)}$ – Depolarization factor, f - target dilution factor, S_T - target polarization

COMPASS experiment

COMPASS experimental setup

COmmon Muon Proton Apparatus for Structure and Spectroscopy

- High energy beam
- Large angular acceptance
- Broad kinematical range



Longitudinally polarized μ^+ beam (160 Gev/c).
Longitudinally or Transversely polarized ^{6}LiD or NH_3 target
Momentum, tracking and calorimetric measurements, PID

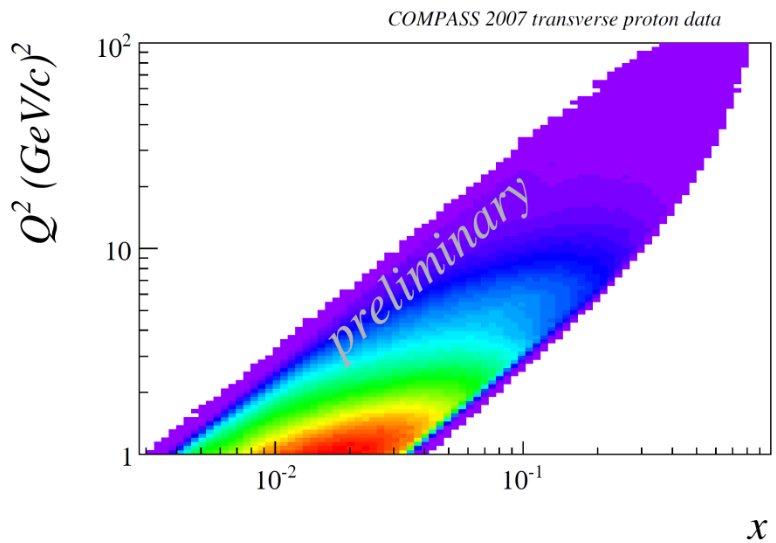
CERN SPS North Area.
Two stages spectrometer
- Large Angle Spectrometer (SM1)
- Small Angle Spectrometer (SM2)

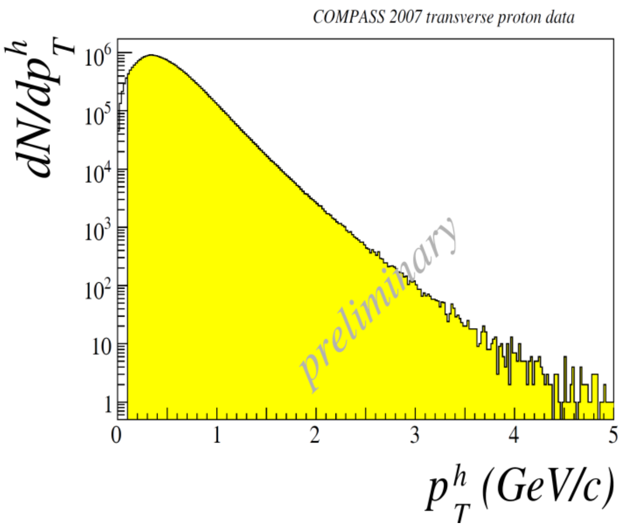
Hadron & Muon high energy beams.
Beam rates: 10^8 muons/s, $5 \cdot 10^7$ hadrons/s.

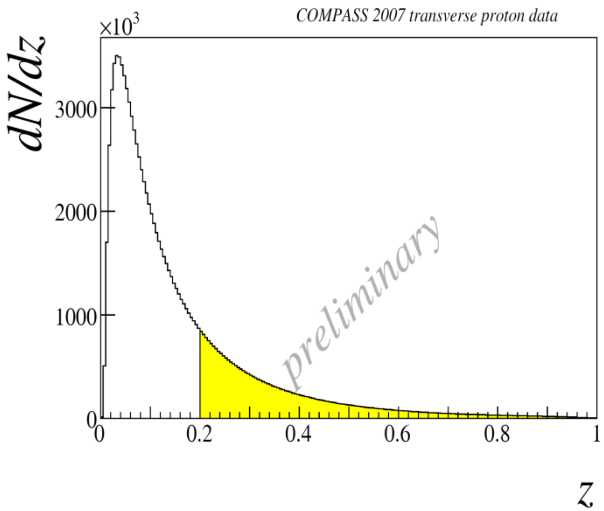
Kinematical distributions

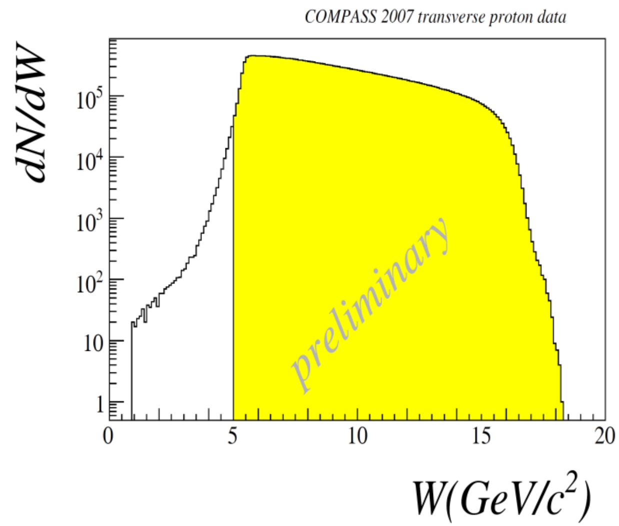
- DIS cuts :
  - $Q^2 > 1\ GeV^2$
  - $0.1 < y < 0.9$
  - $W > 5\ GeV$

- Hadron cuts :
  - $z > 0.2$
  - $p_t > 0.1\ GeV/c$









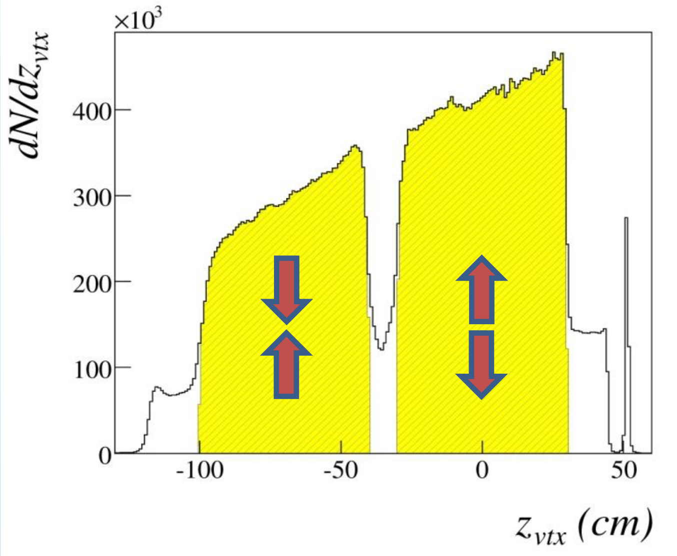
Polarized target system

solid state target operated in frozen spin mode

Years 2002-2004

Deuteron - ^{6}LiD:

- Two 60 cm long ^{6}LiD cells with opposite polarization
- Polar angle acceptance – 70 mrad
- Target Polarization ±50%
- dilution factor f = 0.38
- time dedicated to transverse polarization ~20%
- Acquired statistics ~ $15.5 \cdot 10^6$ hadrons
- $1/\langle f \cdot P_T \rangle^2$ (scales σ^2_{stat}) = $1/(0.38 \cdot 0.5)^2 \approx 28$



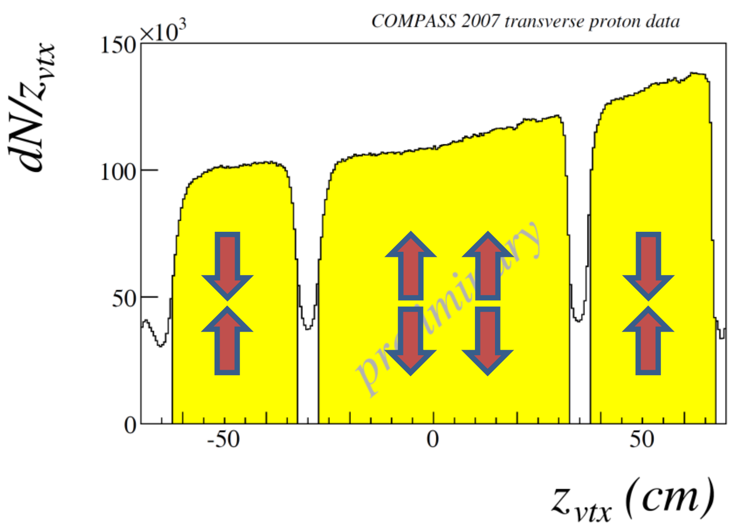
Data is collected simultaneously for the two target spin orientations

Polarization reversal after each ~4-5 days

Years 2007 and 2010 (running now)

Proton - NH_3:

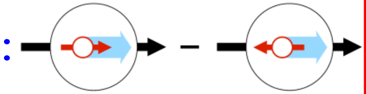
- Three cells system (30 cm,60cm, 30cm)
- Polar angle acceptance – 180 mrad (new magnet in 2006)
- Target Polarization ±90%
- dilution factor f = 0.14
- time dedicated to transverse polarization ~50%
- Acquired statistics ~ $27 \cdot 10^6$ hadrons
- $1/\langle f \cdot P_T \rangle^2$ (scales σ^2_{stat}) = $1/(0.14 \cdot 0.9)^2 \approx 63$



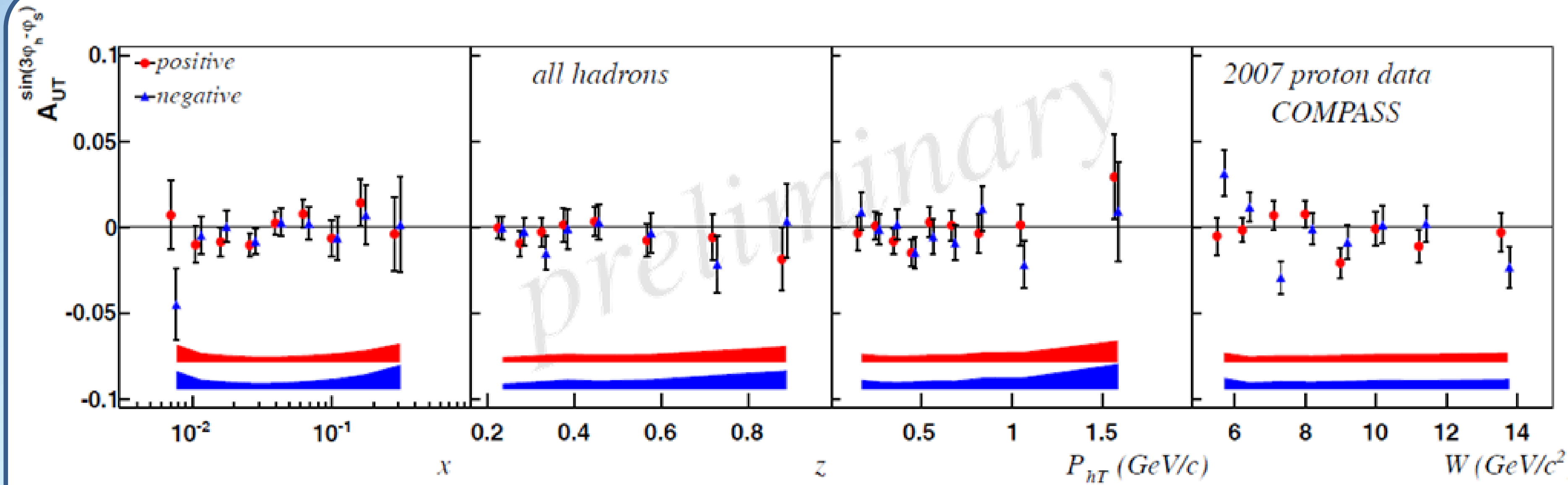
Similar statistical precision for both data sets

Experimental data
and
theoretical predictions

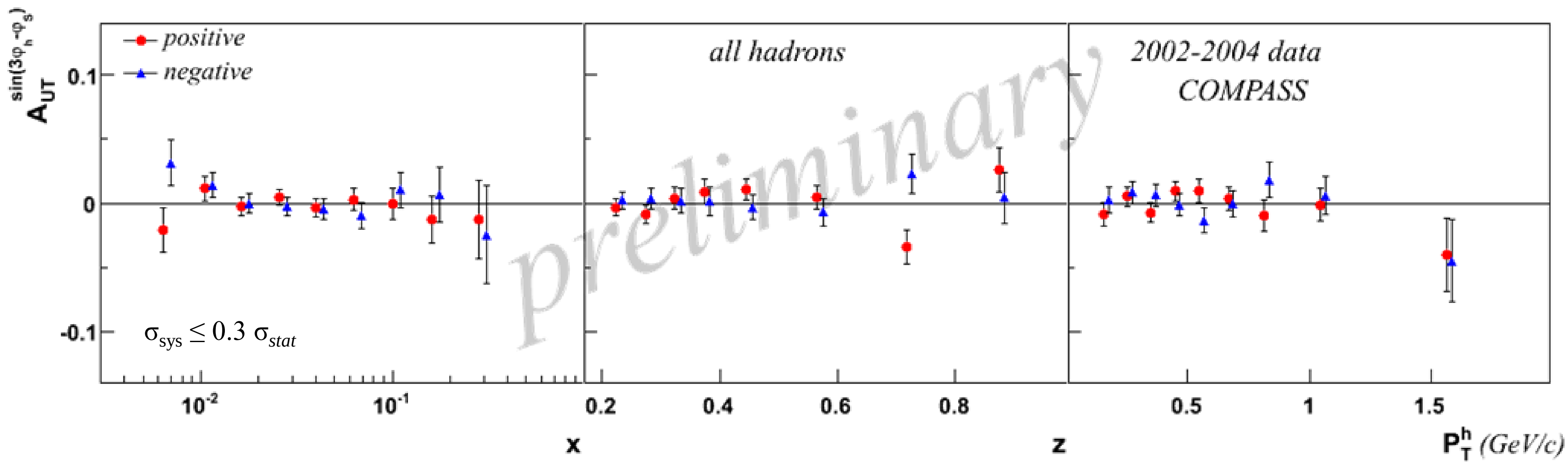
Results for $A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$,

"Pretzelosity" PDF $h_{1T}^{\perp q}$: 

COMPASS proton and deuteron



Asymmetries for both proton and deuteron are small, compatible with zero within uncertainties



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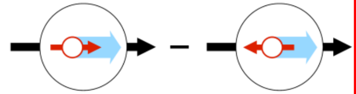
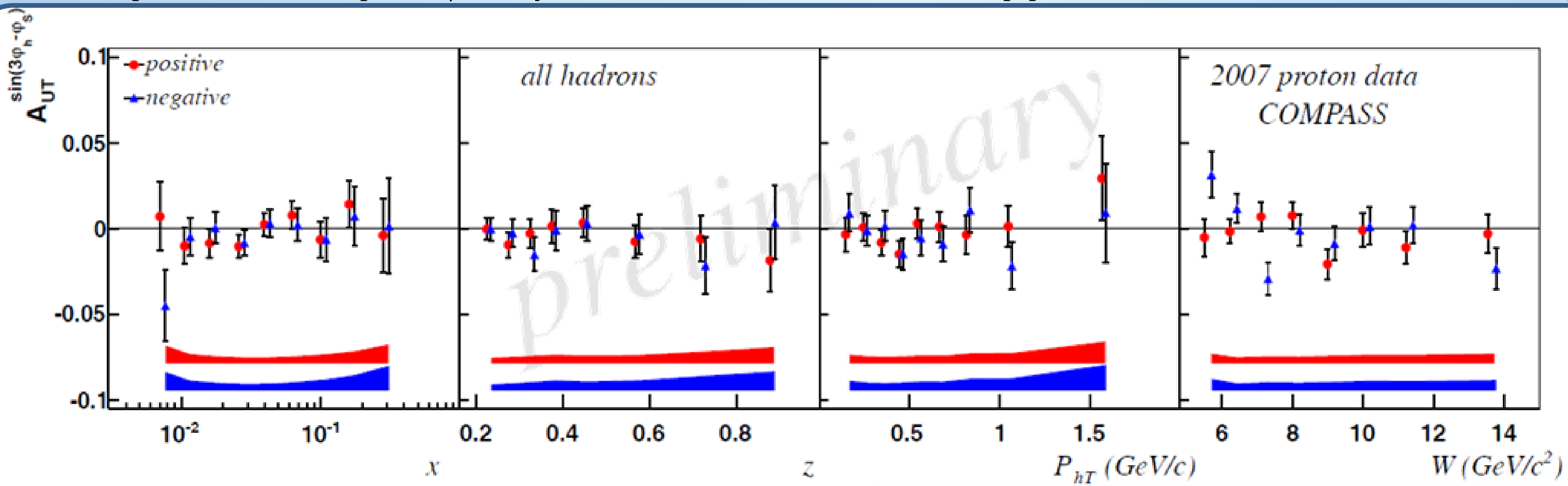
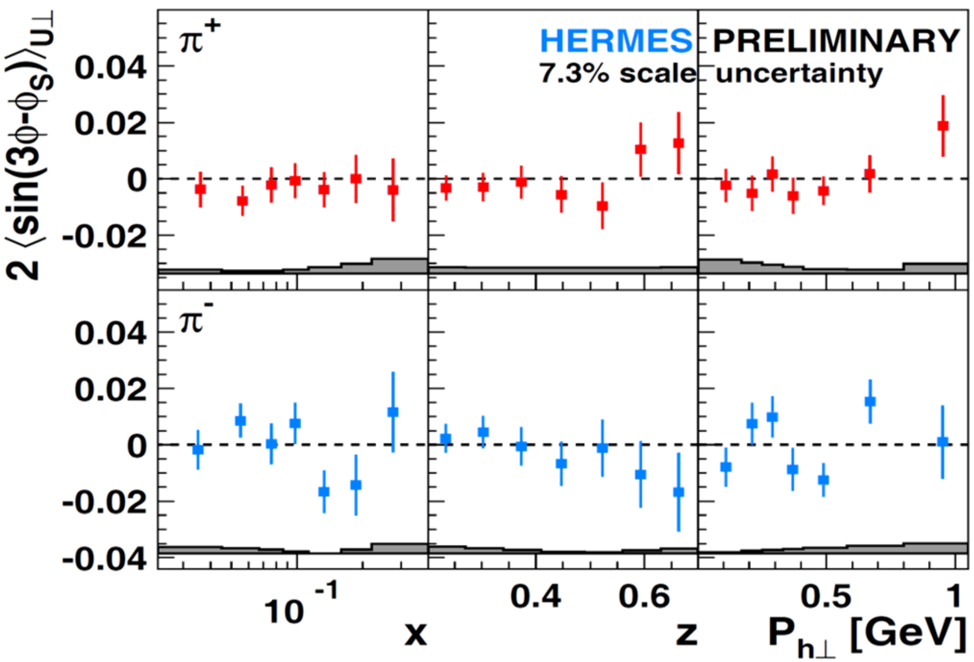
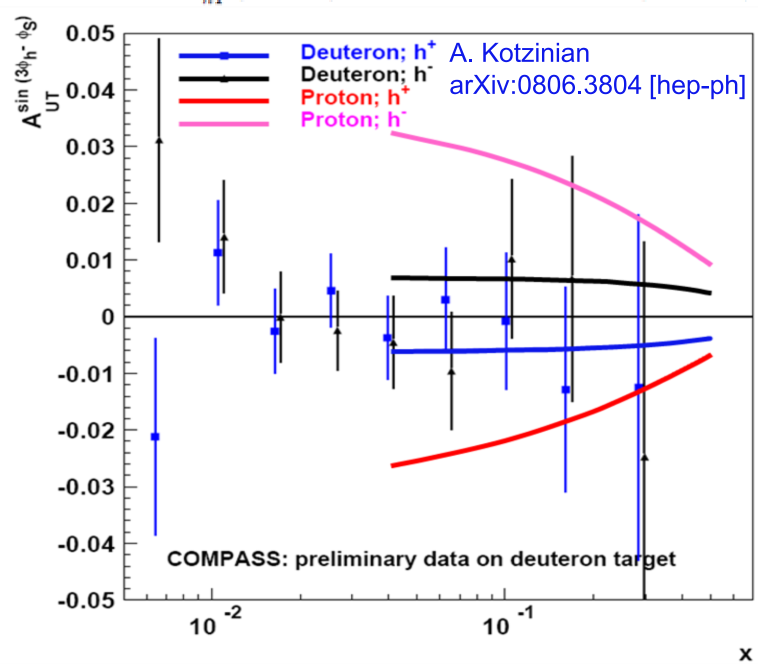


COMPASS proton, HERMES proton | Theory: A. Kotzinian, arXiv:0806.3804 [hep-ph]







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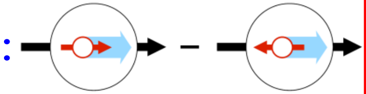
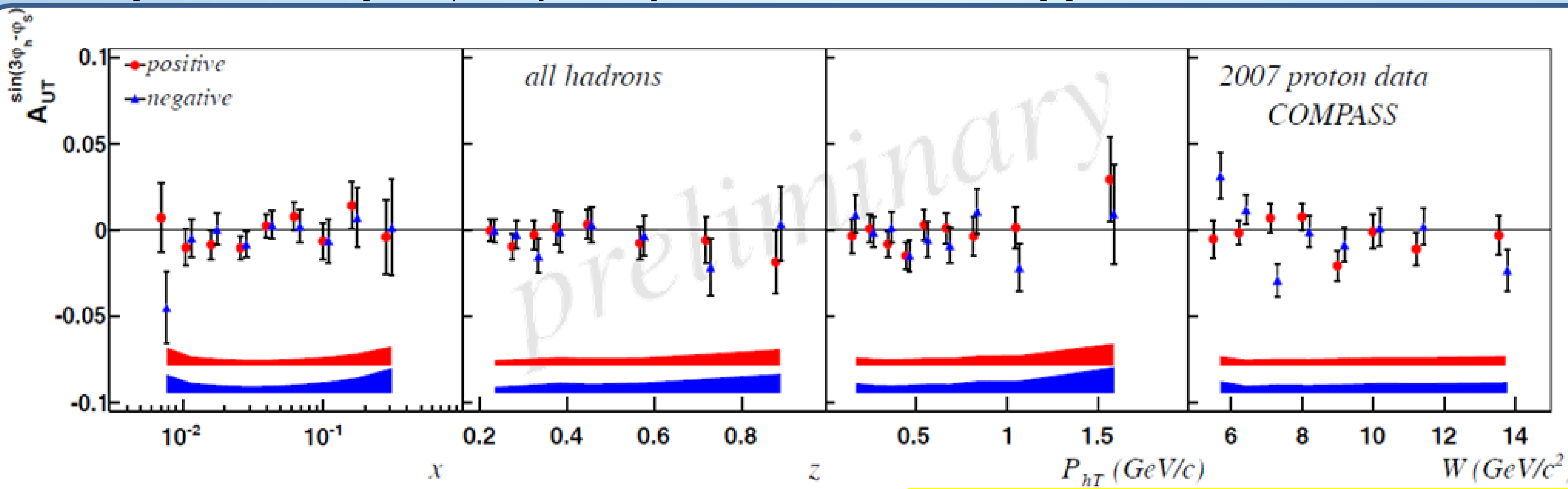
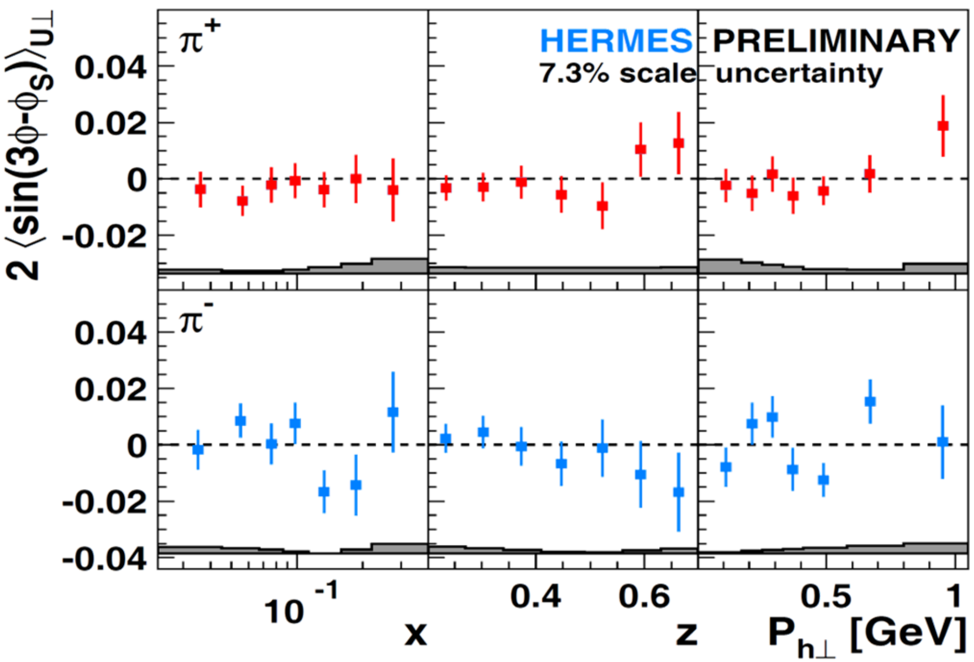
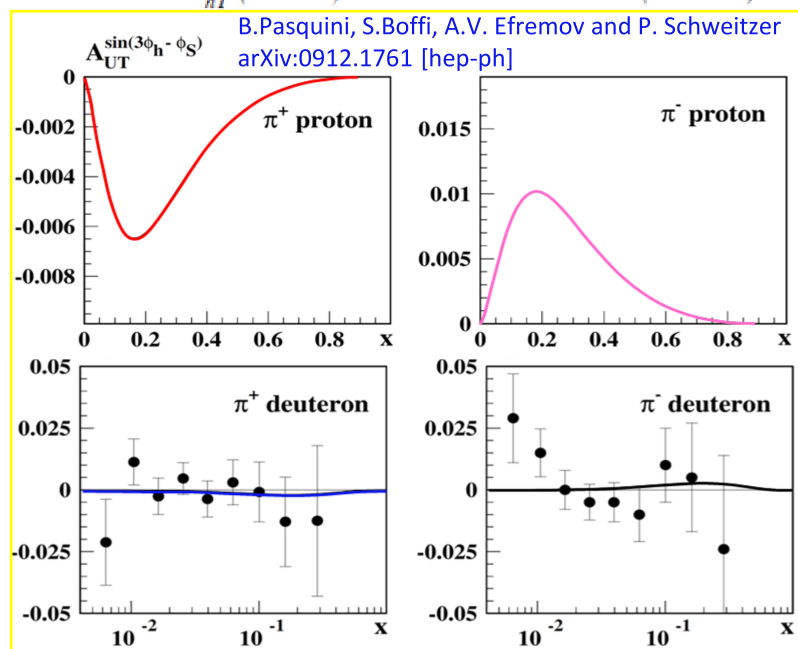
"Pretzelosity" PDF $h_{1T}^{\perp q}$:



COMPASS proton, HERMES proton | Theory: B.Pasquini et al. arXiv:0912.1761 [hep-ph]



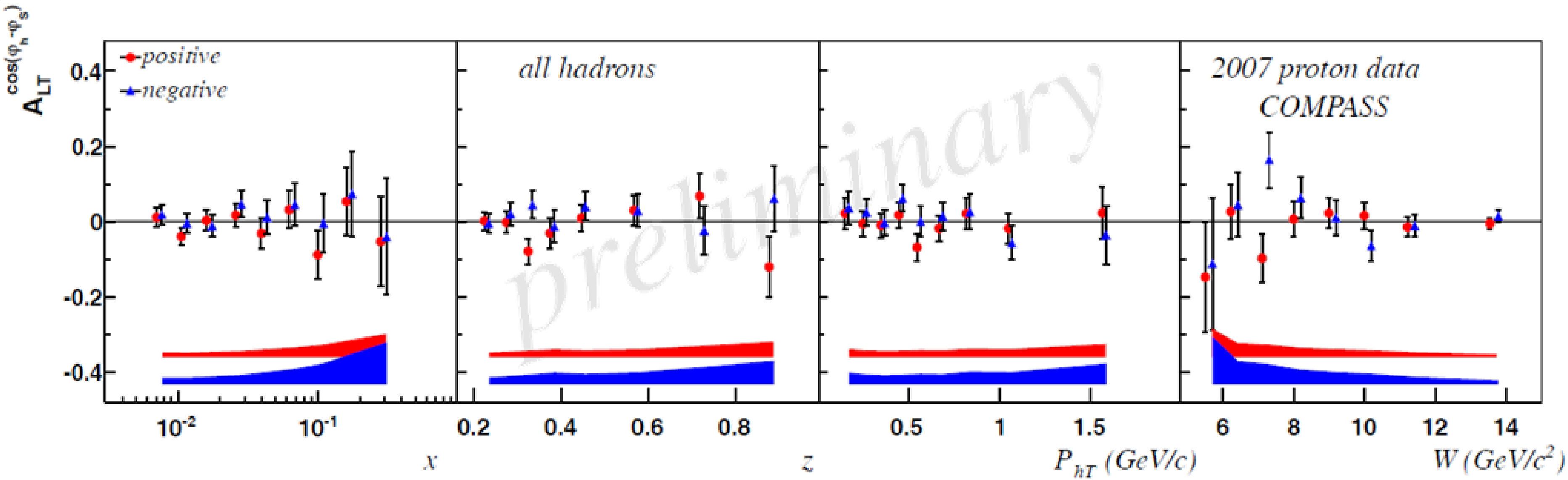




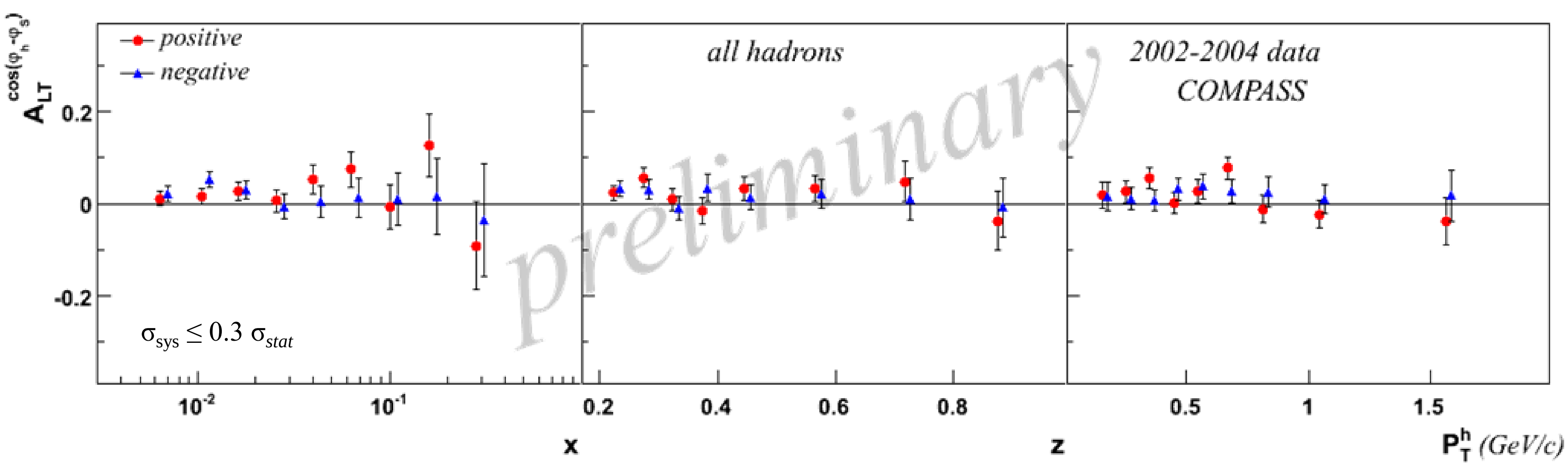
Results for $A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$,

"Worm Gear" PDF g_{1T}^q :

COMPASS proton and deuteron



Asymmetries for both proton and deuteron are small, compatible with zero within uncertainties



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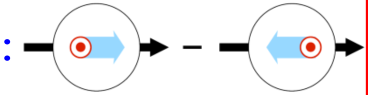
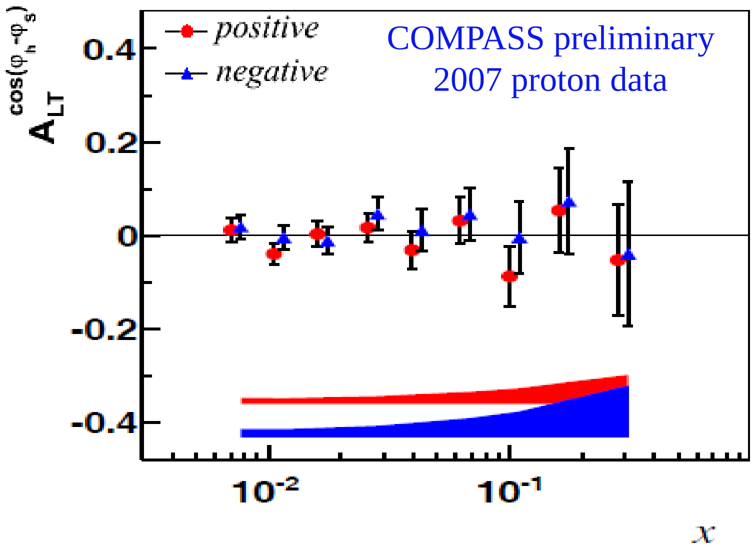
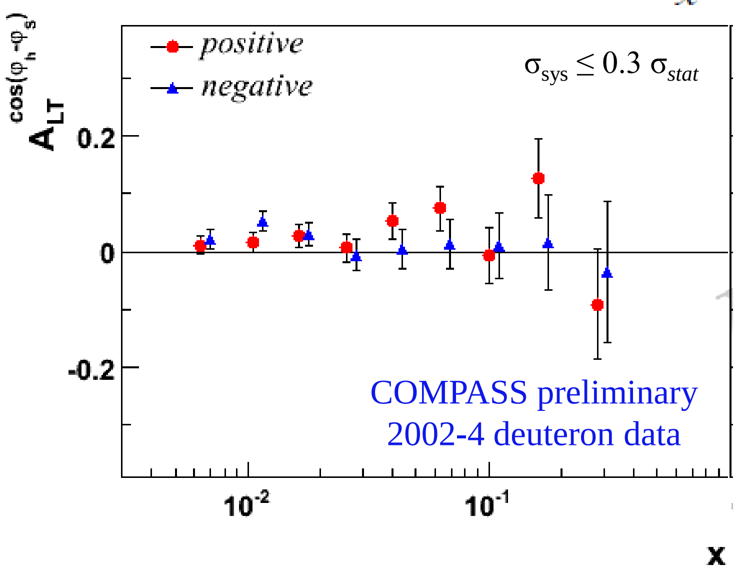
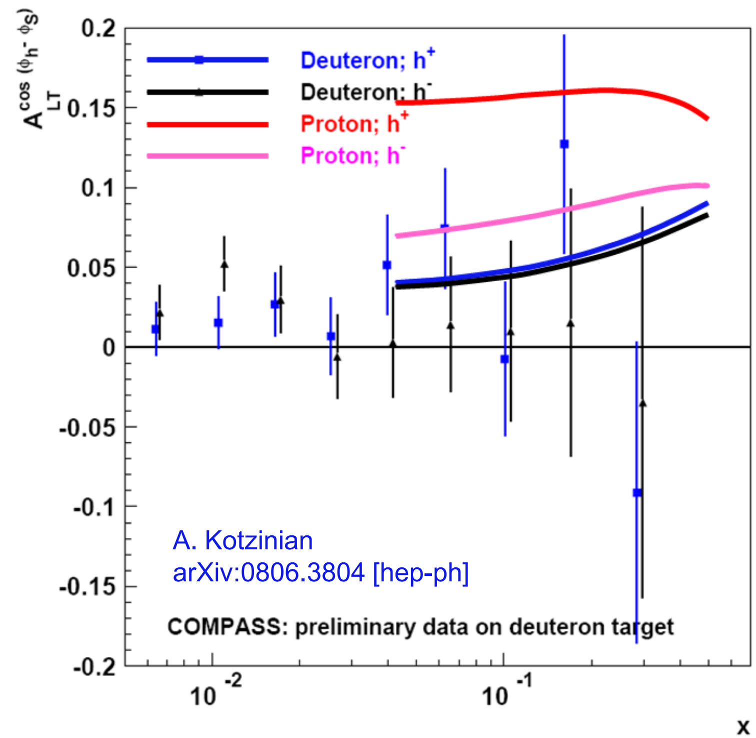


COMPASS proton and deuteron | Theory: A. Kotzinian, arXiv:0806.3804 [hep-ph]







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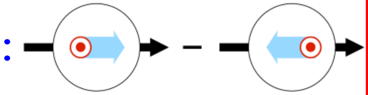
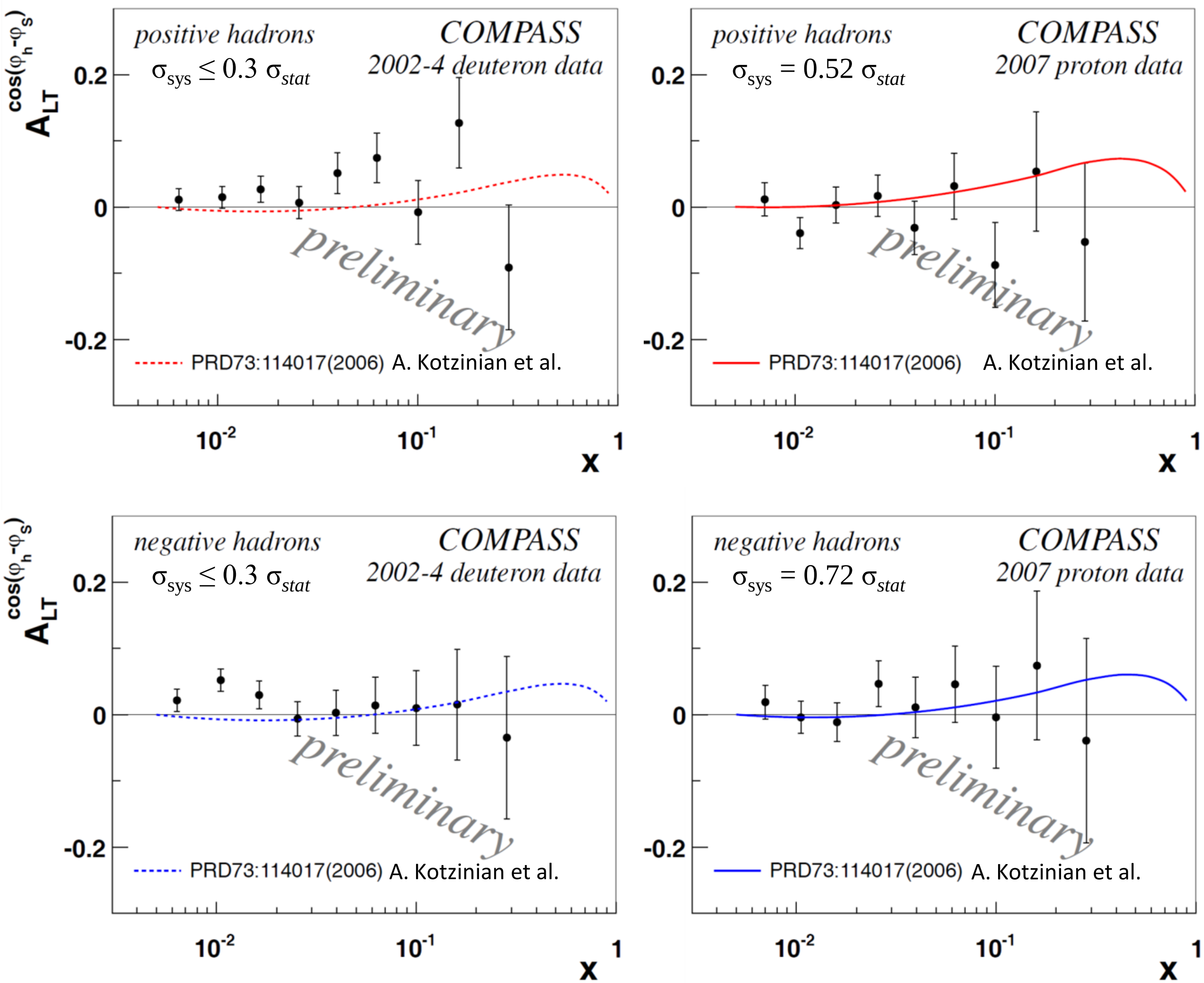
"Worm Gear" PDF g_{1T}^q : 

COMPASS proton and deuteron | Theory: A. Kotzinian et al. Phys.Rev.D73:114017 (2006)



A. Kotzinian, B. Parsamyan, A. Prokudin Phys.Rev.D73:114017 (2006)

Predictions done using for g_{1T} model

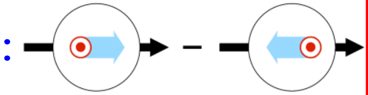
$$g_{1T}^{q(1)}(x,k_T^2) \approx x\int_x^1 dy \frac{g_1^q(y)}{y}$$

Gaussian parametrization for k_T dependence and LO GRV, GRSV2000 DFs and Kretzer FFs

Statistical precision is not enough to check the theory

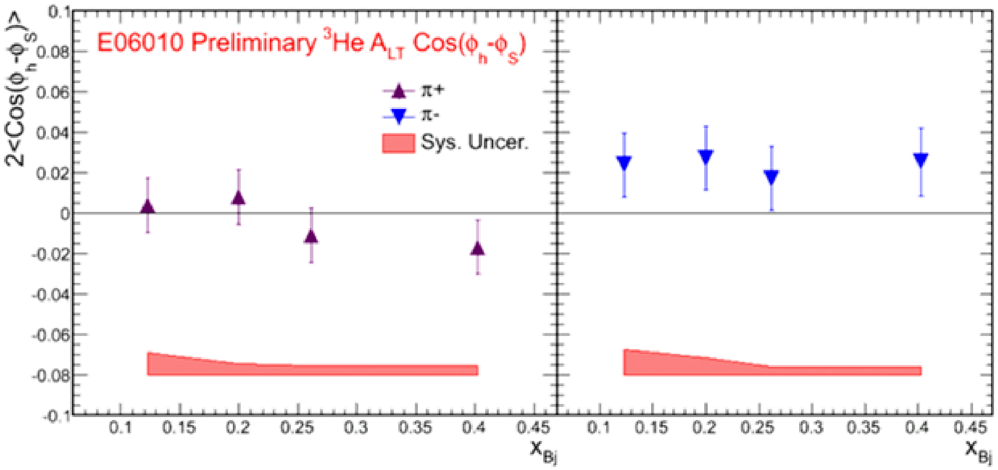
Results for $A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$,

"Worm Gear" PDF g_{1T}^q :



JLab neutron | Theory: A. Kotzinian et al. Phys.Rev.D73:114017 (2006)

^{3}He double-spin asymmetry A_{LT}

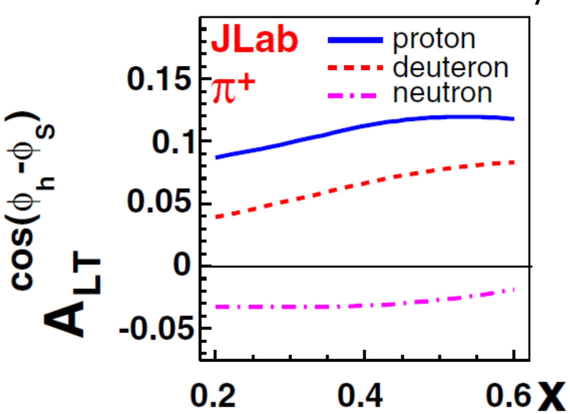


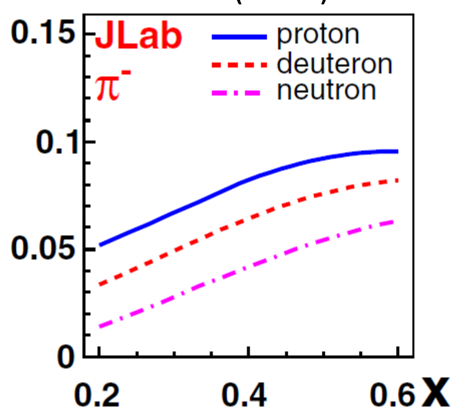
$$\propto \frac{g_{1T}^{\perp q}(x) \otimes D_{1q}^h(z)}{f_1^q(x) \otimes D_{1q}^h(z)}$$

- First observation of a none-zero A_{LT}.
- First measurement on neutron(^{3}He).
- Relate to quark TMD $g_{1T}(x, k_T)$.
- The real part of quark L=0 ✖ L=1 interference, "twin-brother" of Sivers.

Xiaodong Jiang, June 21-25, Trento TMD2010

A. Kotzinian et al. Phys.Rev.D73:114017 (2006)





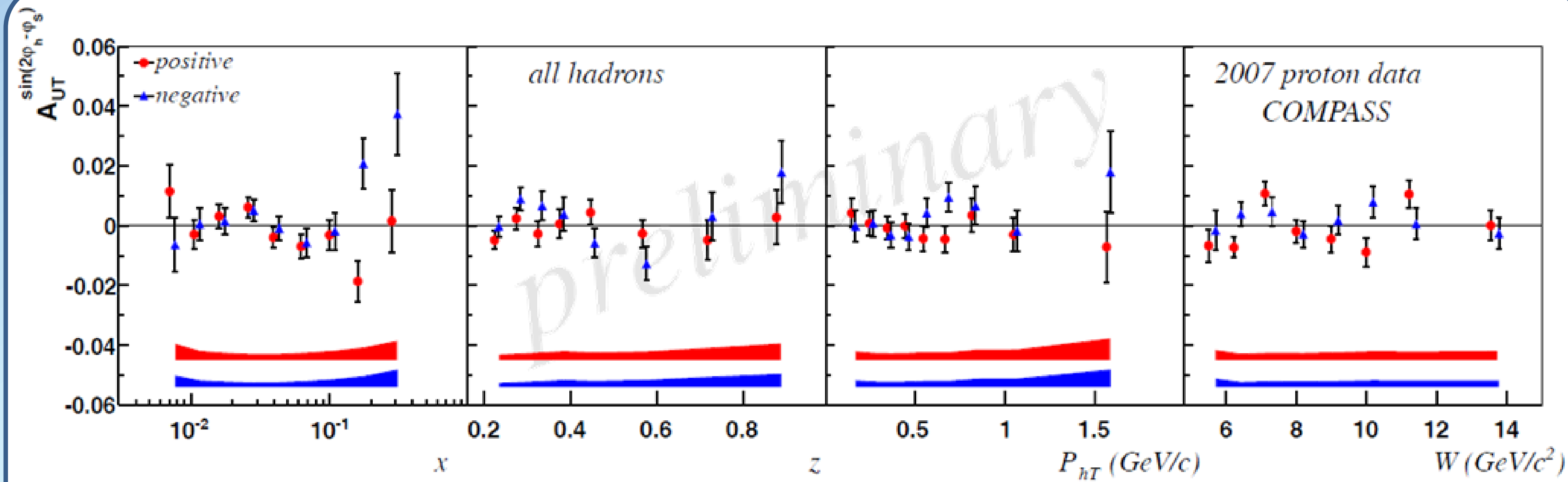
Note: calculations were done for relatively large x,y,z kinematical regions in order to maximize asymmetry.

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

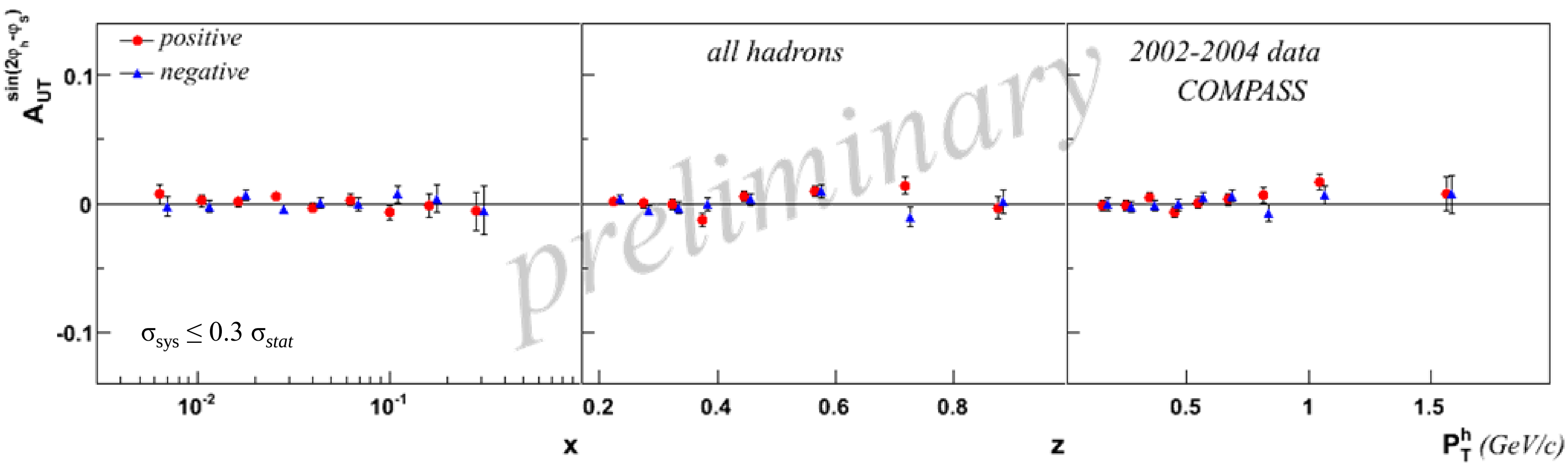
"Pretzelosity" PDF $h_{1T}^{\perp q}$:

"Sivers" PDF $f_{1T}^{\perp q}$:

COMPASS proton and deuteron



Asymmetries for both proton and deuteron are small, compatible with zero within uncertainties



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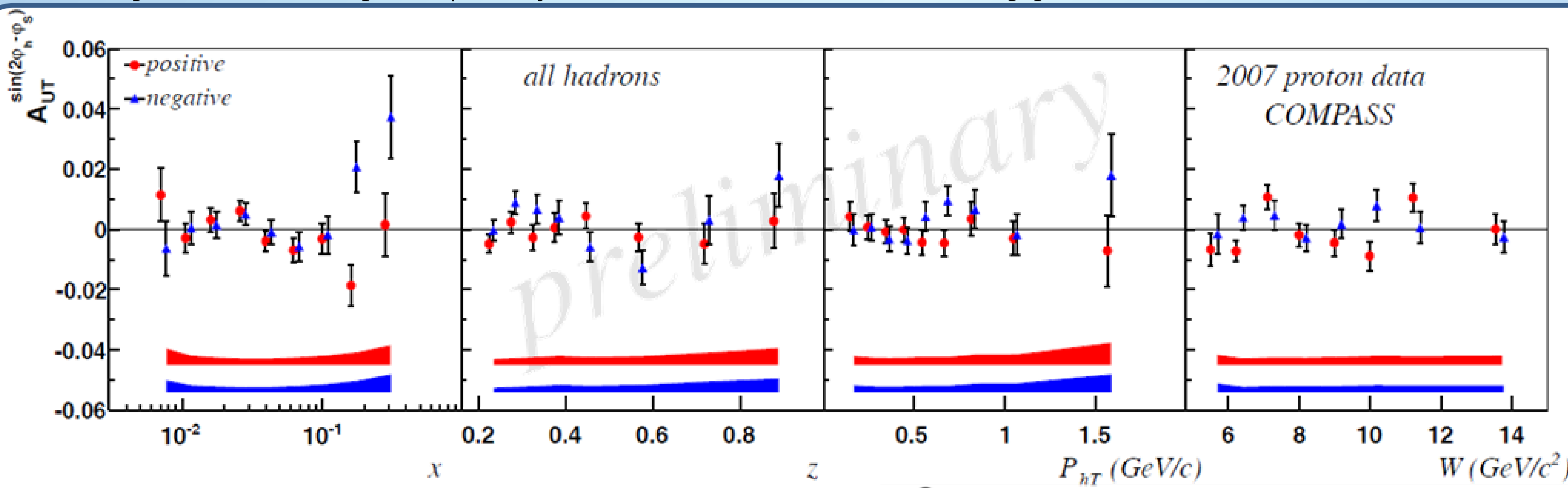
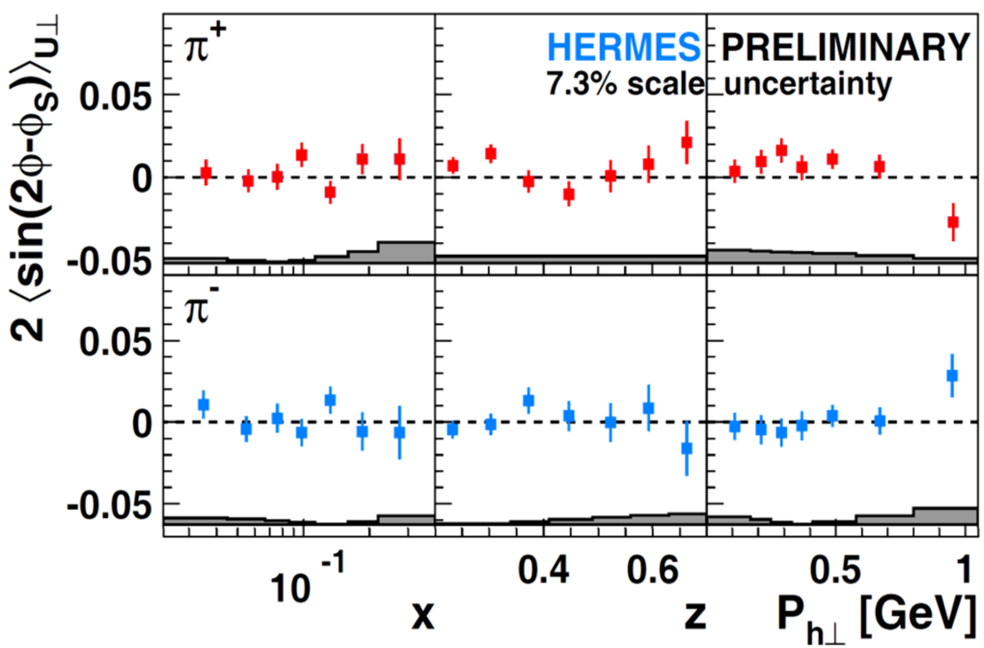
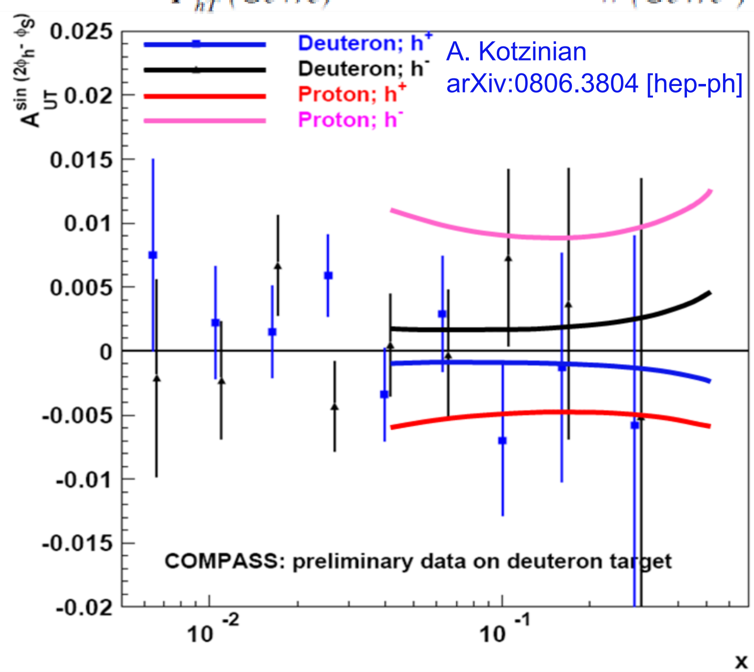
COMPASS proton, HERMES proton | Theory: A. Kotzinian, arXiv:0806.3804 [hep-ph]





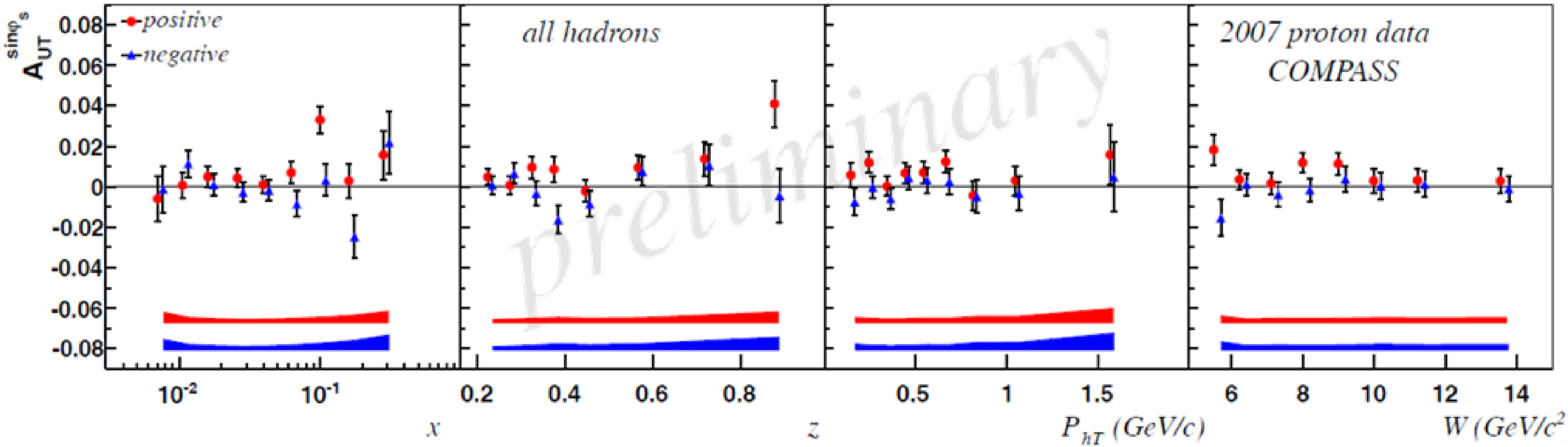


Results for $A_{UT}^{\sin(\phi_s)} \propto \frac{M}{Q}\left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^{h}\right)+..,$

"Transversity" PDF h_1^q :

"Sivers" PDF $f_{1T}^{\perp q}$:

COMPASS proton and deuteron



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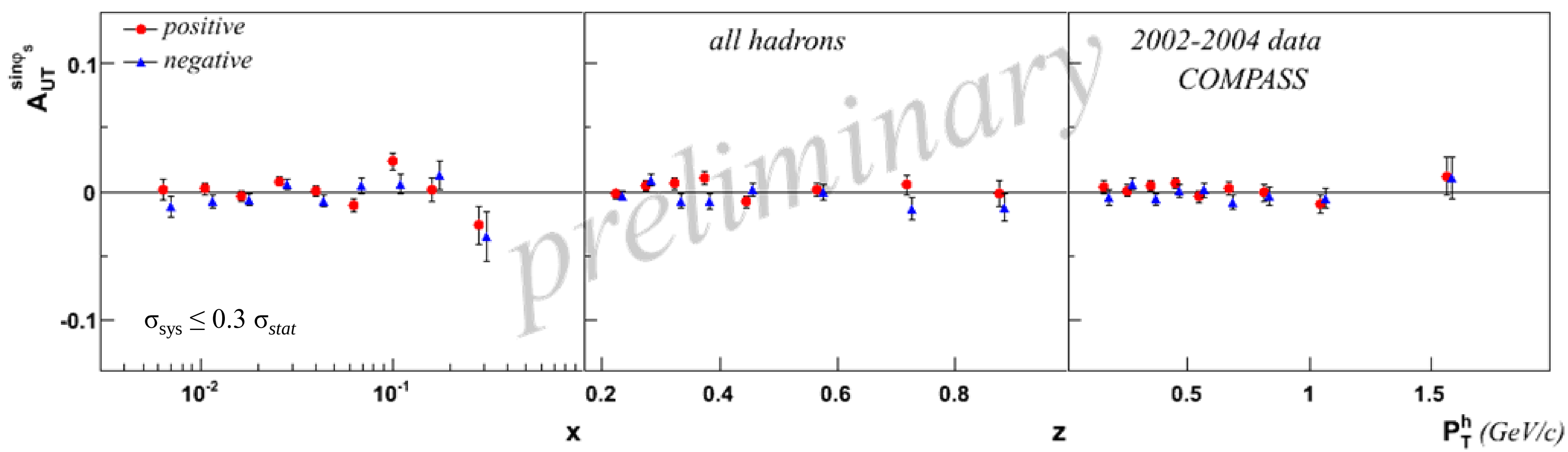

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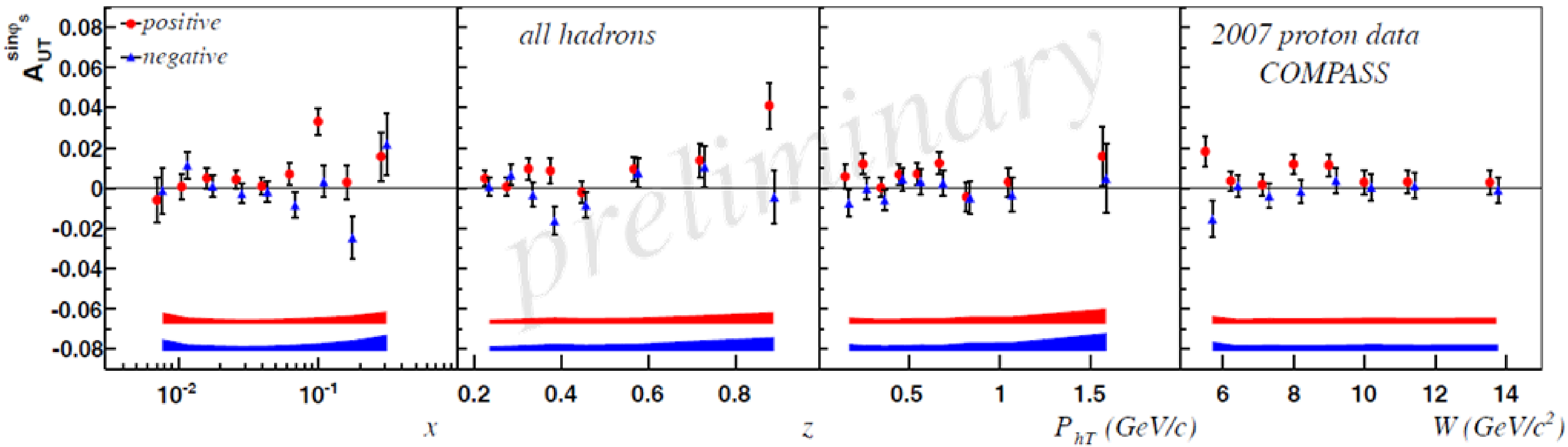
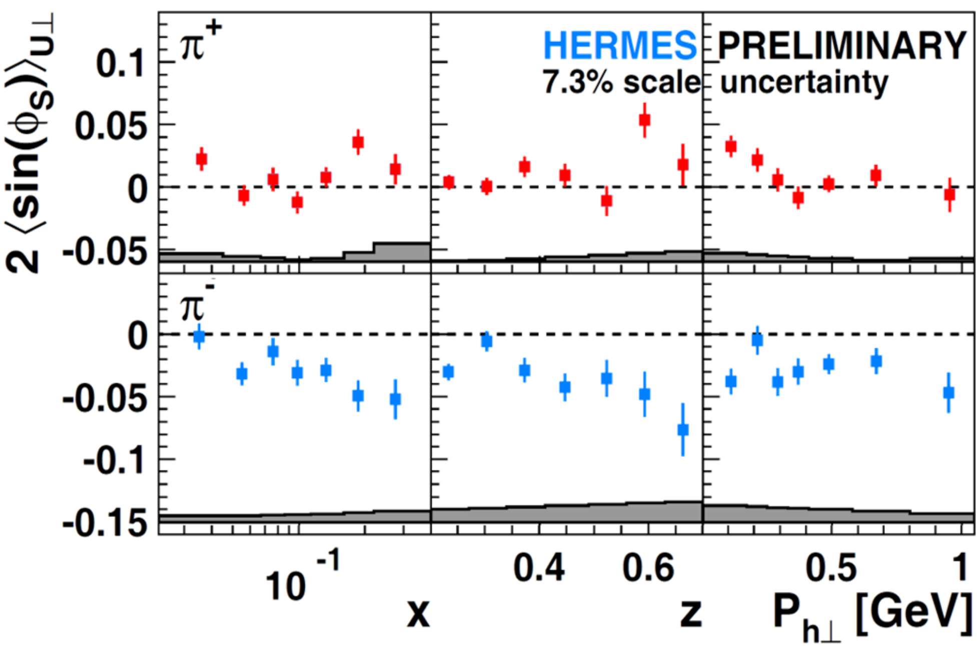
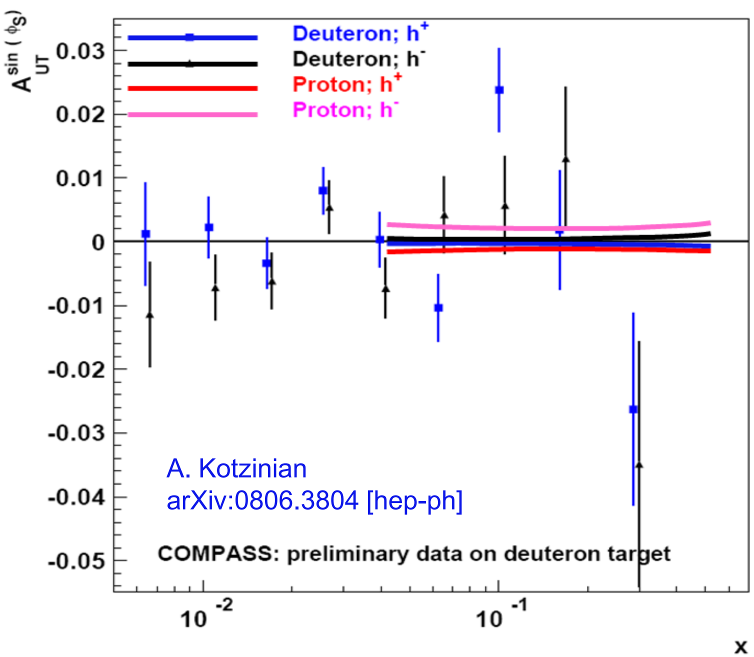
COMPASS proton, HERMES proton | Theory: A. Kotzinian, arXiv:0806.3804 [hep-ph]



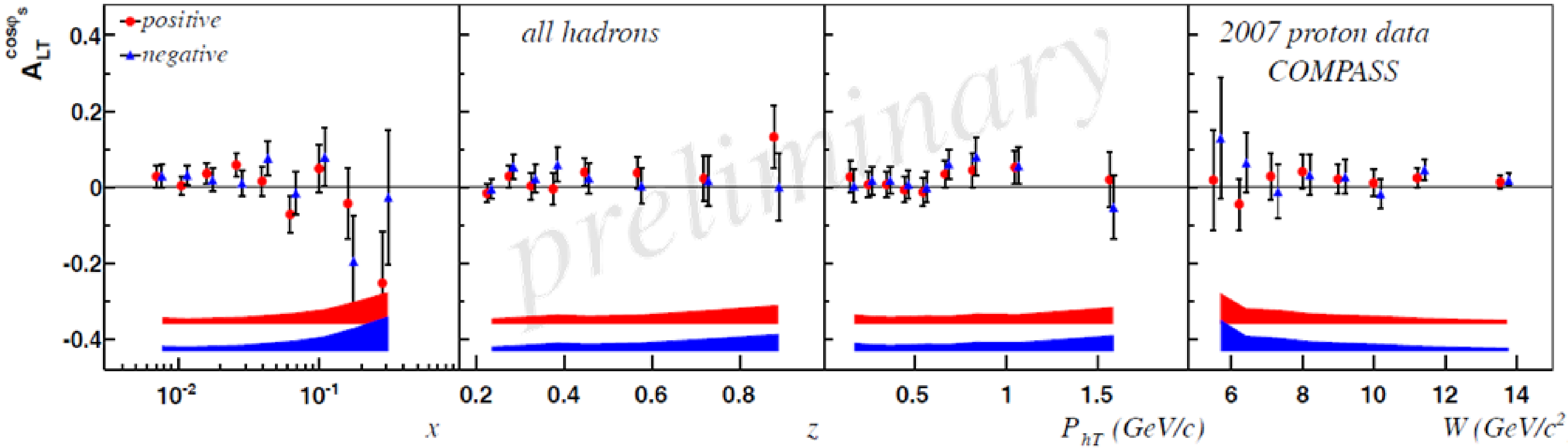




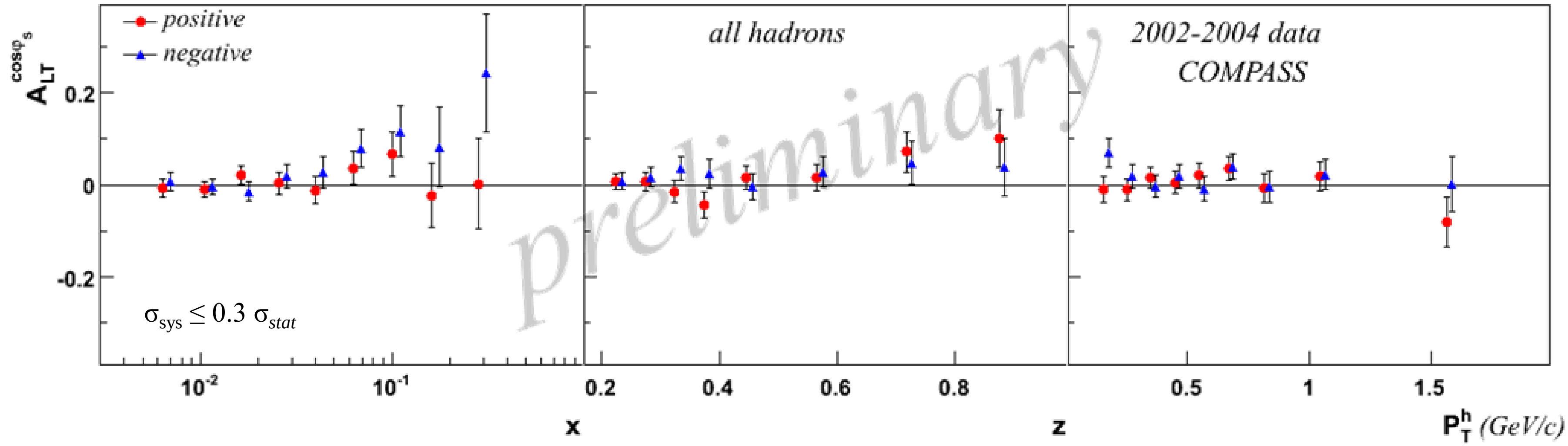
Results for $A_{LT}^{\cos(\phi_s)} \propto \frac{M}{Q} g_{1T}^{q} \otimes D_{1q}^{h} + ..,$

"Worm Gear" PDF g_{1T}^{q} :

COMPASS proton and deuteron



Asymmetries for both proton and deuteron are small, compatible with zero within uncertainties



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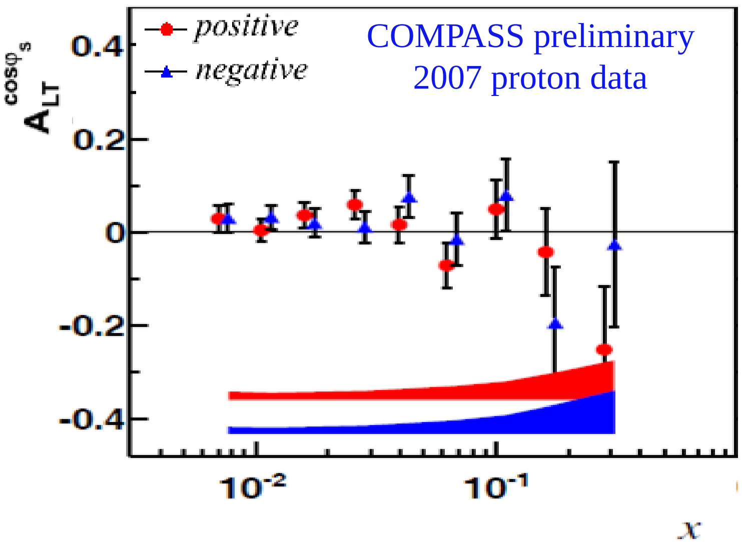

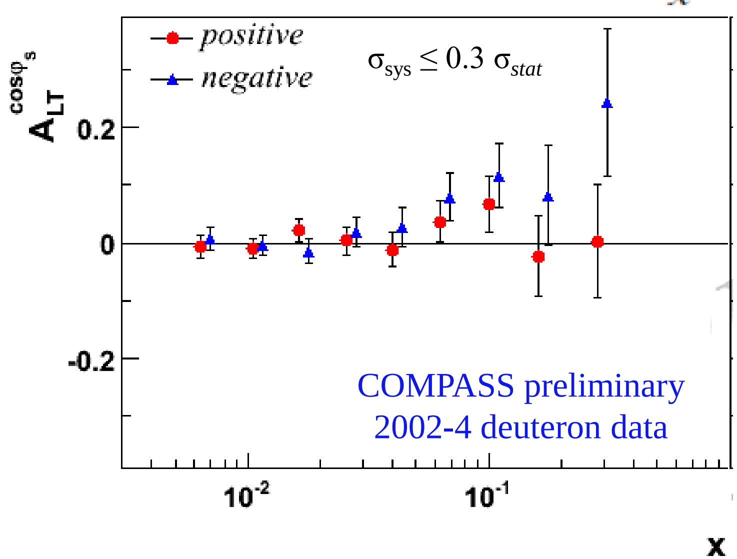

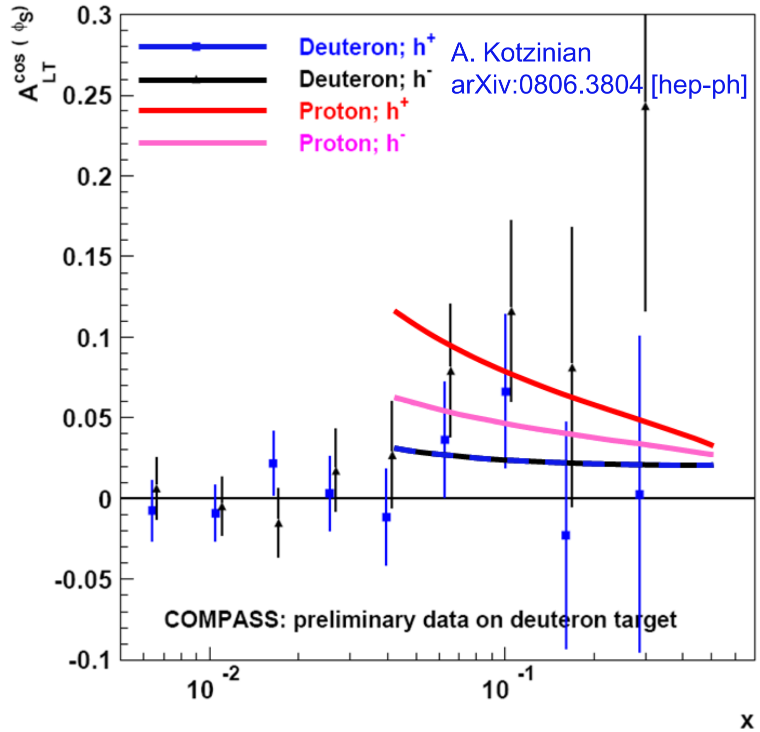

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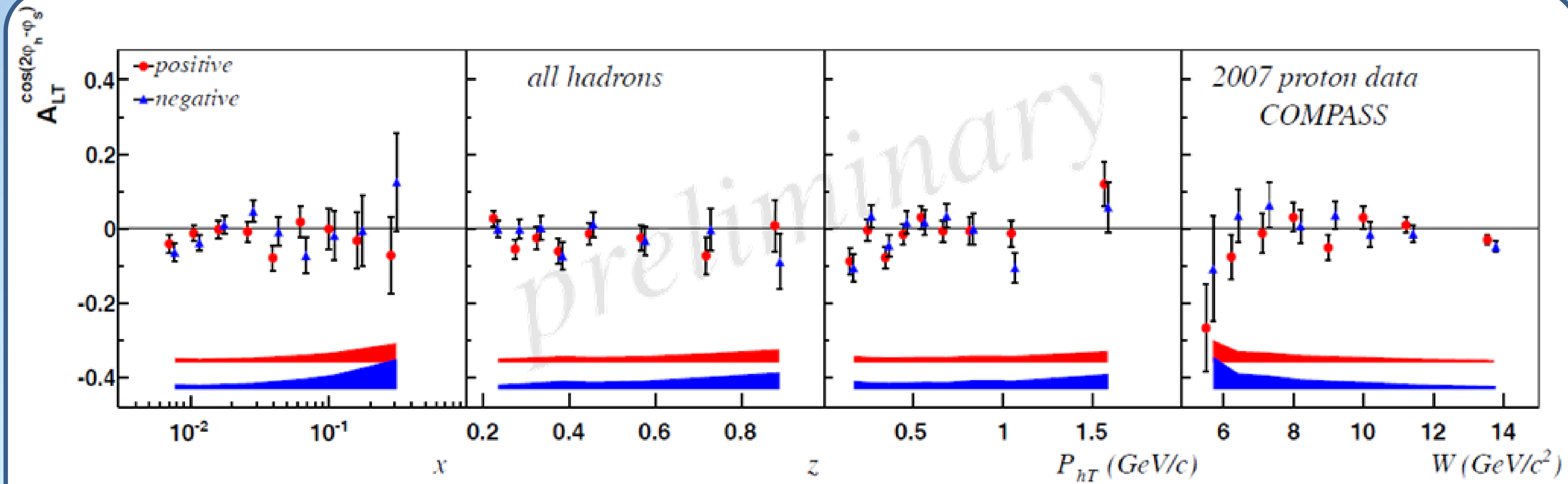
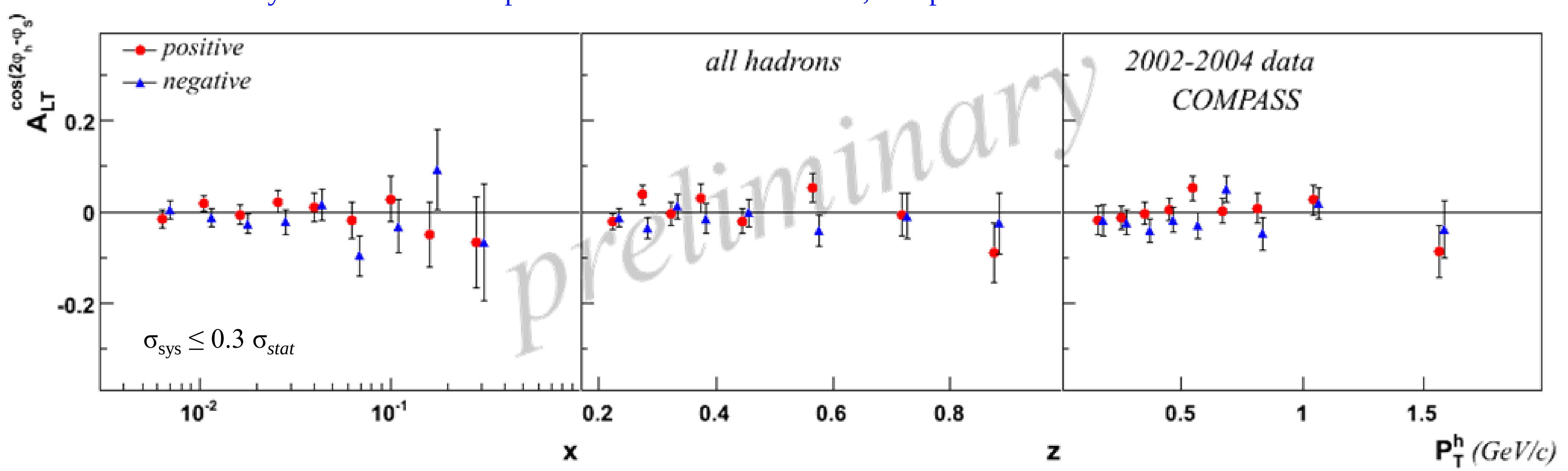
"Worm Gear" PDF g_{1T}^q :

COMPASS proton and deuteron



Asymmetries for both proton and deuteron are small, compatible with zero within uncertainties



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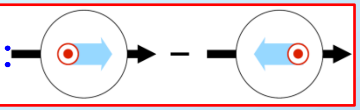

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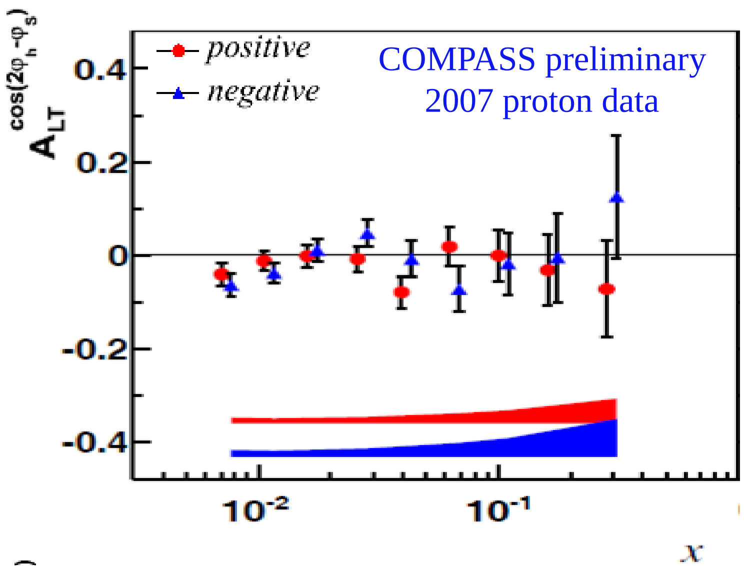
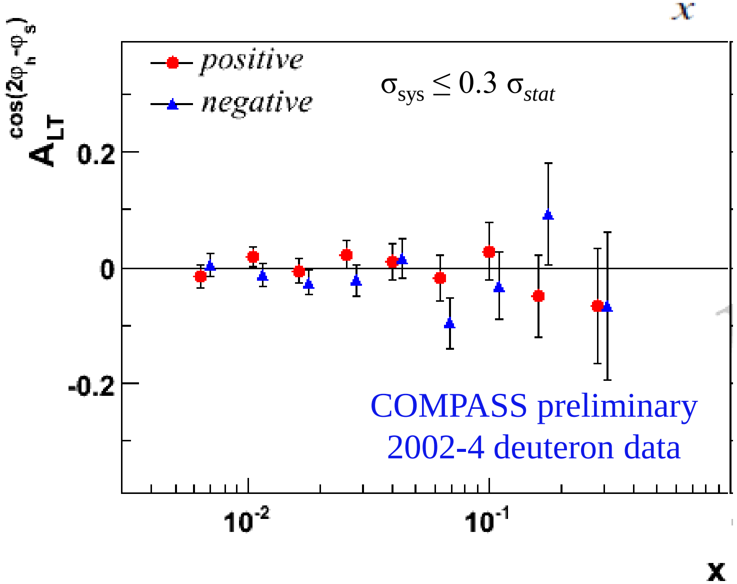
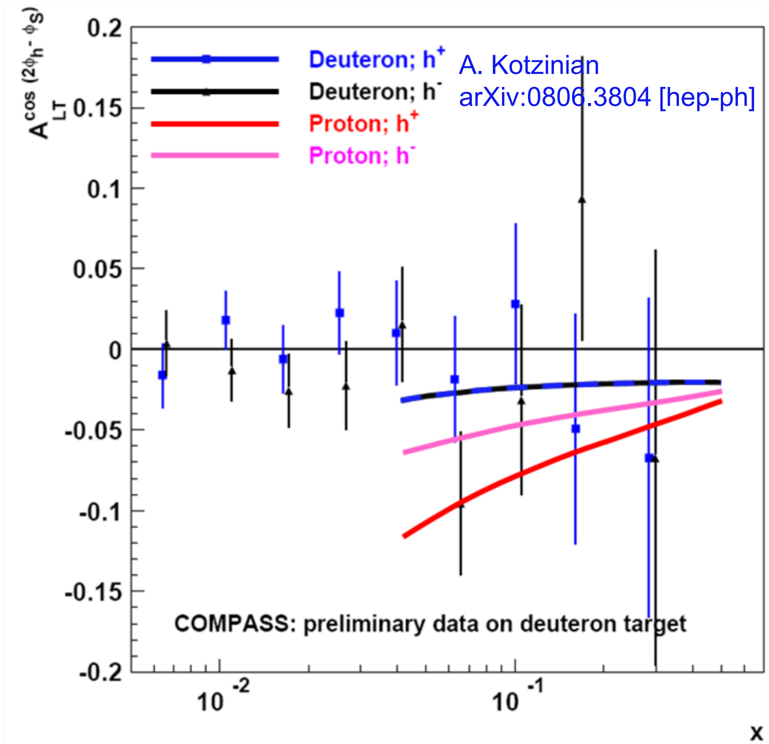






Summary

COMPASS, in addition to Collins and Sivers asymmetries (see talks by G. Pesaro and A. Richter) has also measured the other six asymmetries, which are allowed in SIDIS:

$$A_{UT}^{\sin(3\varphi_h-\varphi_s)},\ A_{UT}^{\sin\varphi_s},\ A_{UT}^{\sin(2\varphi_h-\varphi_s)},\ A_{LT}^{\cos(\varphi_h-\varphi_s)},\ A_{LT}^{\cos\varphi_s}\ \&\ A_{LT}^{\cos(2\varphi_h-\varphi_s)}$$

COMPASS deuteron data 2002-2004

- All six asymmetries are small, compatible with zero
- This is in agreement with the theory predictions

COMPASS proton data 2007

- All six asymmetries are mostly small and compatible with zero within statistical uncertainties
- More precise data is needed in order to compare/validate the theoretical predictions

COMPASS proton data 2010

- Hopefully to be presented at SPIN2011…

Thank you!!!

A_{LT} asymmetry *PRD 54, 1229 (1996)*

$$A^h_{LT}(x,y,z,P_{hT},\varphi^h_s) \equiv \frac{1}{\lambda_l \left|\mathbf{S}^N_T\right|} \cdot \frac{d\sigma^{\to\Uparrow} - d\sigma^{\to\Downarrow}}{d\sigma^{\to\Uparrow} + d\sigma^{\to\Downarrow}} = D(y)\cos(\varphi^h_s)\frac{\mathcal{H}_{g_{1T}}}{\mathcal{H}_{f_1}} + \ldots$$

First estimations by *A.Kotzinian & P.Mulders, PRD 54, 1229 (1996)*

$$\left\langle \frac{|\mathbf{P}_{hT}|}{M}\cos(\varphi^h_s)A^h_{LT} \right\rangle(x,y,z) \equiv 2\frac{\int d^2P_{T\perp}\frac{\left|\mathbf{P}_{hT}\right|}{M}\cos(\varphi^h_s)(d\sigma^{\to\Uparrow} - d\sigma^{\to\Downarrow})}{\int d^2P_{T\perp}(d\sigma^{\to\Uparrow} + d\sigma^{\to\Downarrow})} = 2zD(y)\frac{\sum_q e_q^2 g_{1T}^{q(1)}(x)D_q^h(z)}{\sum_q e_q^2 f_1^q(x)D_q^h(z)}$$

Weighted asymmetry is related to the first k_T-momentum of g_{1T}:

$$g_{1T}^{q(1)}(x) \equiv \int d^2k_T \frac{\mathbf{k}_T^2}{2M^2} g_{1T}^q(x,k_T^2)$$

There exists a relation between first momentum of g_{1T} and g_2
(follows from Lorentz invariance, Tangerman & Mulders) :

$$g_{1T}^{q(1)}(x) \equiv \int_0^x g_2^q(y)dy = -\int_x^1 g_2^q(y)dy = (WW - appr) = x\int_x^1 \frac{g_1^q(y)}{y}dy$$

All ingredients (DFs & FFs) are known!

A_{LT} asymmetry *PRD73:114017,(2006)*

COMPASS

A.Kotzinian, B.Parsamyan & A. Prokudin, Phys.Rev. D73 (2006)

$$f_1^q(x,k_T^2) = f_1^q(x)\frac{1}{\pi\mu_0^2}\exp(-\frac{k_T^2}{\mu_0^2}),$$

$$D_q^h(z,P_{hT}^2) = D_q^h(z)\frac{1}{\pi\mu_D^2}\exp(-\frac{P_{hT}^2}{\mu_D^2}),$$

$$g_{1T}^q(x,k_T^2) = g_{1T}^q(x)N\exp(-\frac{k_T^2}{\mu_1^2})$$

N is fixed by

$$g_{1T}^{q(1)}(x) = \int d^2k_T\,\frac{k_T^2}{2M^2}\,g_{1T}^q(x,k_T^2)$$

$$g_{1T}^q(x,k_T^2) = g_{1T}^{q(1)}(x)\frac{2M^2}{\pi\mu_1^4}\exp(-\frac{k_T^2}{\mu_1^2})$$

From analysis of unpolarized P_{hT} dependence and Cahn effect

$$\mu_0^2 = 0.25(GeV/c)^2,\quad \mu_D^2 = 0.2(GeV/c)^2$$

Naïve positivity constraint: $\frac{|k_T|}{M}\left|g_{1T}^q(x,k_T^2)\right| < f_1^q(x,k_T^2)$

holds if $\mu_1^2 \leq 0.246\ (\mathrm{GeV/c})^2$

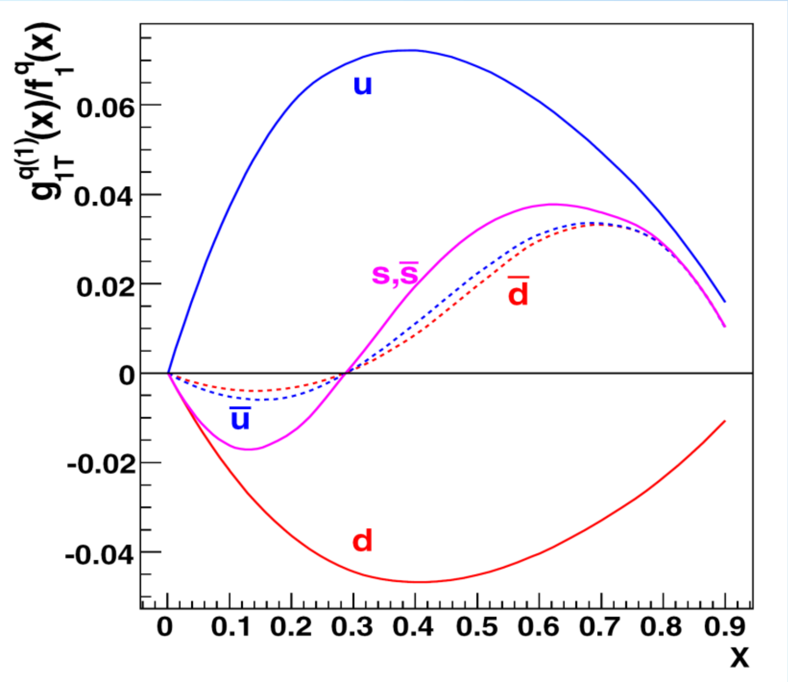
Predictions done for:

$$\boxed{\mu_1^2 = 0.1, 0.15\ and\ 0.25(GeV/c)^2}$$

$$\boxed{A_{LT}^{\cos\phi_h^S}(x,y,z,P_{hT}) = 2\frac{\int_0^{2\pi} d\phi_h^S(d\sigma^{\rightarrow\Uparrow} - d\sigma^{\rightarrow\Downarrow})\cos\phi_h^S}{\int_0^{2\pi} d\phi_h^S(d\sigma^{\rightarrow\Uparrow} + d\sigma^{\rightarrow\Downarrow})}} = 2\frac{\frac{2-y}{xy}\frac{Mz|P_{hT}|}{(\mu_D^2+\mu_1^2z^2)^2}\exp(-\frac{P_{hT}^2}{\mu_D^2+\mu_1^2z^2})\sum_q e_q^2 g_{1T}^{q(1)}(x)D_q^h(z)}{\frac{1+(1-y)^2}{xy^2}\frac{1}{\mu_D^2+\mu_0^2z^2}\exp(-\frac{P_{hT}^2}{\mu_D^2+\mu_0^2z^2})\sum_q e_q^2 f_1^q(x)D_q^h(z)}$$

A_{LT} asymmetry, kinematical cuts *PRD73:114017,(2006)*

$$A_{TMD} = \frac{\boxed{\begin{array}{c}\text{Low}\\ x,\ y,\ z\ \&\ p_T\end{array}} + \boxed{\begin{array}{c}\text{High}\\ x,\ y,\ z\ \&\ p_T\end{array}}}{\boxed{\begin{array}{c}\text{Low}\\ x,\ y,\ z\ \&\ p_T\end{array}} + \boxed{\begin{array}{c}\text{High}\\ x,\ y,\ z\ \&\ p_T\end{array}}}$$



GRV98+GRSV2000 LO, std DFs Kretzer FFs

COMPASS - $Q^2>1.0$ $(GeV/c)^2$, $W^2>25$ GeV^2, $0.05<x_{Bj}<0.6$, $0.5 < y < 0.9$, $0.4 < z < 0.9$, $|P_{h,T}| > 0.5$GeV/c

HERMES - $Q^2>1.0$ $(GeV/c)^2$, $W^2>10$ GeV^2, $0.1<x_{Bj}<0.6$, $0.45 < y < 0.85$, $0.4 < z < 0.9$, $|P_{h,T}| > 0.5$GeV/c

JLab - $Q^2>1.0$ $(GeV/c)^2$, $W^2>4$ GeV^2, $0.2<x_{Bj}<0.6$, $0.4 < y < 0.7$, $0.4 < z < 0.7$, $|P_{h,T}| > 0.5$GeV/c