Transverse spin asymmetries at COMPASS: beyond Collins and Sivers effects

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on behalf of the COMPASS Collaboration

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Outline

- Introduction
- COMPASS experiment
- Measured asymmetries and theory expectations
  - Re-evaluation of $A_{LT}^{\cos\varphi_S}$:
    from the *lp* to $\gamma{*}p$ cross-section
  - Theory expectations
- Summary

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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).

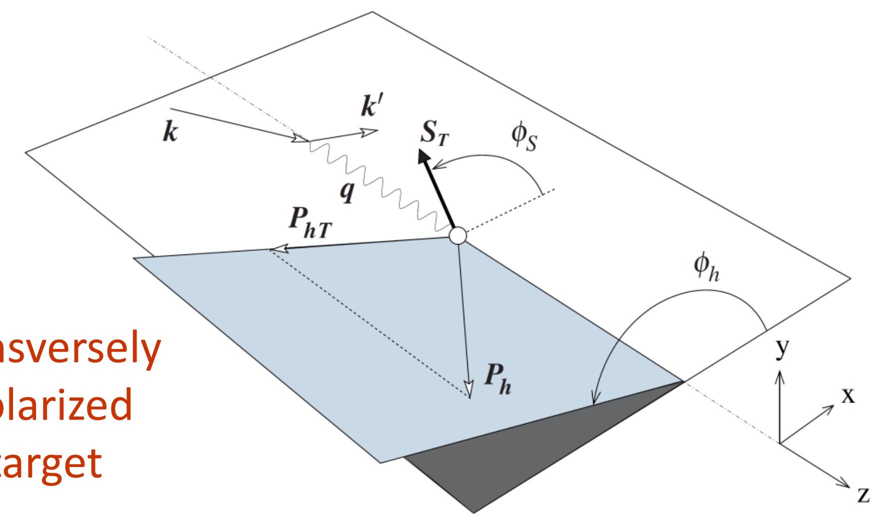
$$\frac{d\sigma}{dx\,dy\,dz\,dP_{hT}^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\,\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

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

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

$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2},\quad \gamma=\frac{2Mx}{Q}$$

transversely polarized target



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$$\left\{ 1+\cos\varphi_h\times\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\varphi_h}+\cos(2\varphi_h)\times\varepsilon A_{UU}^{\cos(2\varphi_h)}+\lambda\sin\varphi_h\times\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\varphi_h}+ \right.$$

← See talk by G. Sbrizzai

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

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

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

Sivers & Collins ← Presented by A. Martin

Twist-2

SSA

DSA

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

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\boxed{\sin(3\varphi_h-\varphi_S)\times\left(\varepsilon A_{UT}^{\sin(3\varphi_h-\varphi_S)}\right)}
\end{array}\right]+ \\
S_T\lambda\left[\begin{array}{l}
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\cos(2\varphi_h-\varphi_S)\times\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\varphi_h-\varphi_S)}\right)
\end{array}\right]
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Sivers & Collins

Pretzelosity

Worm-gear

SSA

DSA

Twist-2

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\boxed{\sin(\varphi_h+\varphi_S)\times\left(\varepsilon A_{UT}^{\sin(\varphi_h+\varphi_S)}\right)}+\\
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\end{array}\right]+\\
S_T\lambda\left[\begin{array}{l}
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\boxed{\cos(2\varphi_h-\varphi_S)\times\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\varphi_h-\varphi_S)}\right)}
\end{array}\right]
\end{array}\right\}$$

Sivers & Collins

Pretzelosity

Worm-gear

Higher twists

SSA

DSA

Twist-2

Twist-3

SIDIS x-section

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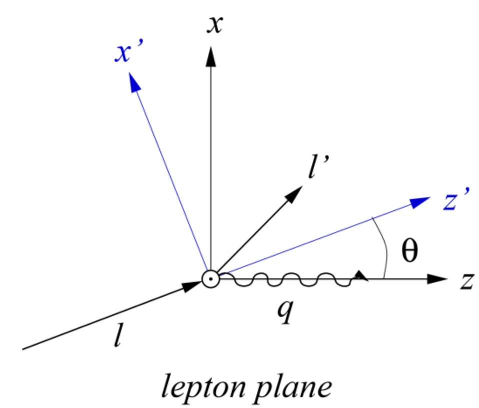

$$\left\{\begin{array}{l}
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\boxed{\sin(\varphi_h-\varphi_S)\times\left(A_{UT}^{\sin(\varphi_h-\varphi_S)}\right)}+\\
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\end{array}\right]
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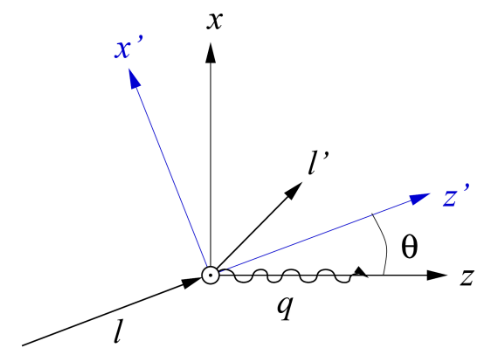

lepton plane

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

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

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

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

$$\frac{d\sigma}{dx\,dy\,dz\,dP_{hT}^2\,d\varphi_h\,d\varphi_S} = \left[\frac{\cos\theta}{1-\sin^2\theta\sin^2\varphi_S}\right]\times\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

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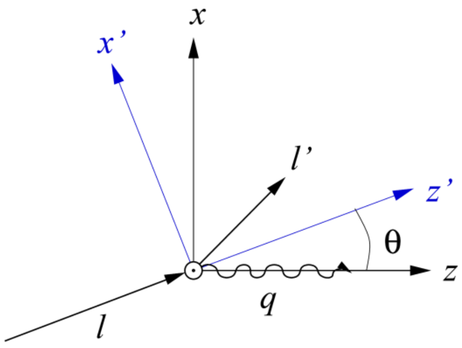
$$\frac{P_T}{\sqrt{1-\sin^2\theta\sin^2\varphi_S}}\left[\begin{aligned}&\sin\varphi_S\times\left(\cos\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\varphi_S}\right)+\\&\sin(\varphi_h-\varphi_S)\times\left(\cos\theta A_{UT}^{\sin(\varphi_h-\varphi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\varphi_h}\right)+\\&\sin(\varphi_h+\varphi_S)\times\left(\cos\theta\varepsilon A_{UT}^{\sin(\varphi_h+\varphi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\varphi_h}\right)+\\&\sin(2\varphi_h-\varphi_S)\times\left(\cos\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\varphi_h-\varphi_S)}+\frac{1}{2}\sin\theta\varepsilon A_{UL}^{\sin 2\varphi_h}\right)+\\&\sin(3\varphi_h-\varphi_S)\times\left(\cos\theta\varepsilon A_{UT}^{\sin(3\varphi_h-\varphi_S)}\right)+\\&\sin(2\varphi_h+\varphi_S)\times\left(\frac{1}{2}\sin\theta\varepsilon A_{UL}^{\sin 2\varphi_h}\right)\end{aligned}\right]+$$

$$\frac{P_T\lambda}{\sqrt{1-\sin^2\theta\sin^2\varphi_S}}\left[\begin{aligned}&\cos\varphi_S\times\left(\cos\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\varphi_S}+\sin\theta\sqrt{(1-\varepsilon^2)}A_{LL}\right)+\\&\cos(\varphi_h-\varphi_S)\times\left(\cos\theta\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\varphi_h-\varphi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\varphi_h}\right)+\\&\cos(2\varphi_h-\varphi_S)\times\left(\cos\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\varphi_h-\varphi_S)}\right)+\\&\cos(\varphi_h+\varphi_S)\times\left(\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\varphi_h}\right)\end{aligned}\right]\Bigg]$$



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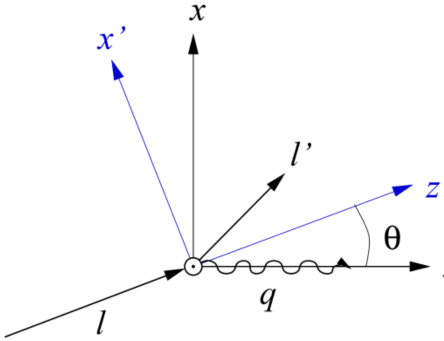
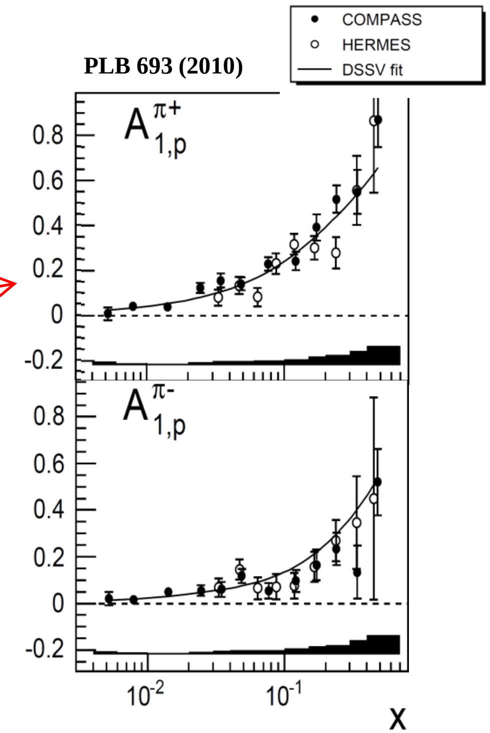
$$\frac{P_T}{\sqrt{1-\sin^2\theta\sin^2\varphi_S}}\Bigg[\sin\varphi_S\times\left(\cos\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\varphi_S}\right)+$$
$$\sin(\varphi_h-\varphi_S)\times\left(\cos\theta A_{UT}^{\sin(\varphi_h-\varphi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\varphi_h}\right)+$$
$$\sin(\varphi_h+\varphi_S)\times\left(\cos\theta\varepsilon A_{UT}^{\sin(\varphi_h+\varphi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\varphi_h}\right)+$$
$$\sin(2\varphi_h-\varphi_S)\times\left(\cos\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\varphi_h-\varphi_S)}+\frac{1}{2}\sin\theta\varepsilon A_{UL}^{\sin2\varphi_h}\right)+$$
$$\sin(3\varphi_h-\varphi_S)\times\left(\cos\theta\varepsilon A_{UT}^{\sin(3\varphi_h-\varphi_S)}\right)+$$
$$\sin(2\varphi_h+\varphi_S)\times\left(\frac{1}{2}\sin\theta\varepsilon A_{UL}^{\sin2\varphi_h}\right)\Bigg]+$$

$$\frac{P_T\lambda}{\sqrt{1-\sin^2\theta\sin^2\varphi_S}}\Bigg[\boxed{\cos\varphi_S\times\left(\cos\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\varphi_S}+\sin\theta\sqrt{(1-\varepsilon^2)}A_{LL}\right)}+$$
$$\cos(\varphi_h-\varphi_S)\times\left(\cos\theta\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\varphi_h-\varphi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\varphi_h}\right)+$$
$$\cos(2\varphi_h-\varphi_S)\times\left(\cos\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\varphi_h-\varphi_S)}\right)+$$
$$\cos(\varphi_h+\varphi_S)\times\left(\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\varphi_h}\right)\Bigg]\Bigg]$$



lepton plane



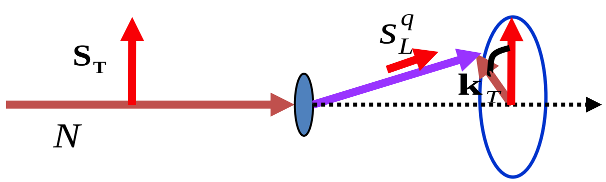
TMD parton distribution functions

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

Nucleon @ twist-2

- transversity: $h_{1T}^{q}(x,\mathbf{k}_T^2)$
- pretzelosity: $h_{1T}^{q\perp}(x,\mathbf{k}_T^2)$
- worm-gear L: $h_{1L}^{q\perp}(x,\mathbf{k}_T^2)$
- Boer-Mulders: $h_{1}^{q\perp}(x,\mathbf{k}_T^2)$
- unpolarised: $f_{1}^{q}(x,\mathbf{k}_T^2)$
- Sivers: $f_{1T}^{q\perp}(x,\mathbf{k}_T^2)$
- helicity: $g_{1L}^{q}(x,\mathbf{k}_T^2)$
- worm-gear T: $g_{1T}^{q\perp}(x,\mathbf{k}_T^2)$



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

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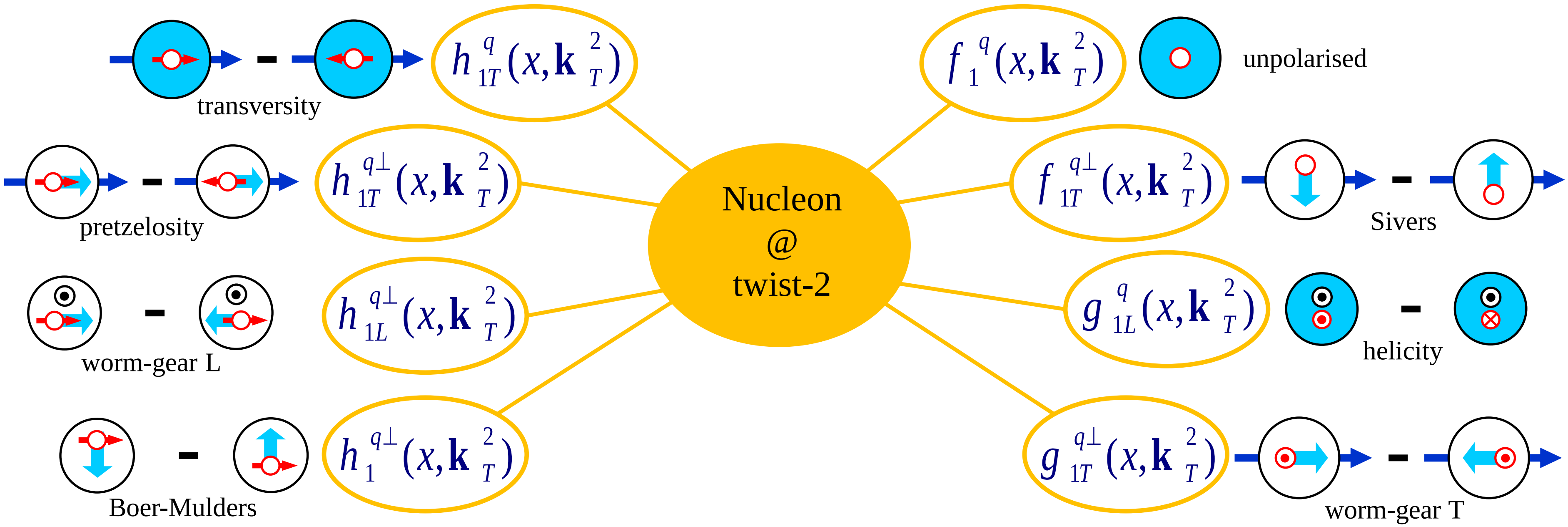
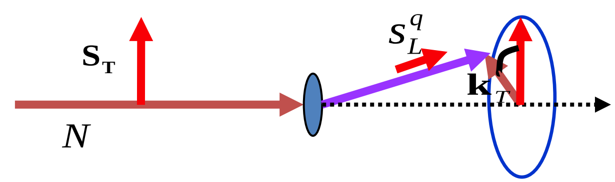


nucleon with transverse or longitudinal spin

parton with transverse or longitudinal spin

parton transverse momentum

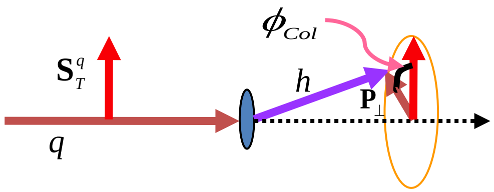
Proton goes out of the screen. Photon goes into the screen



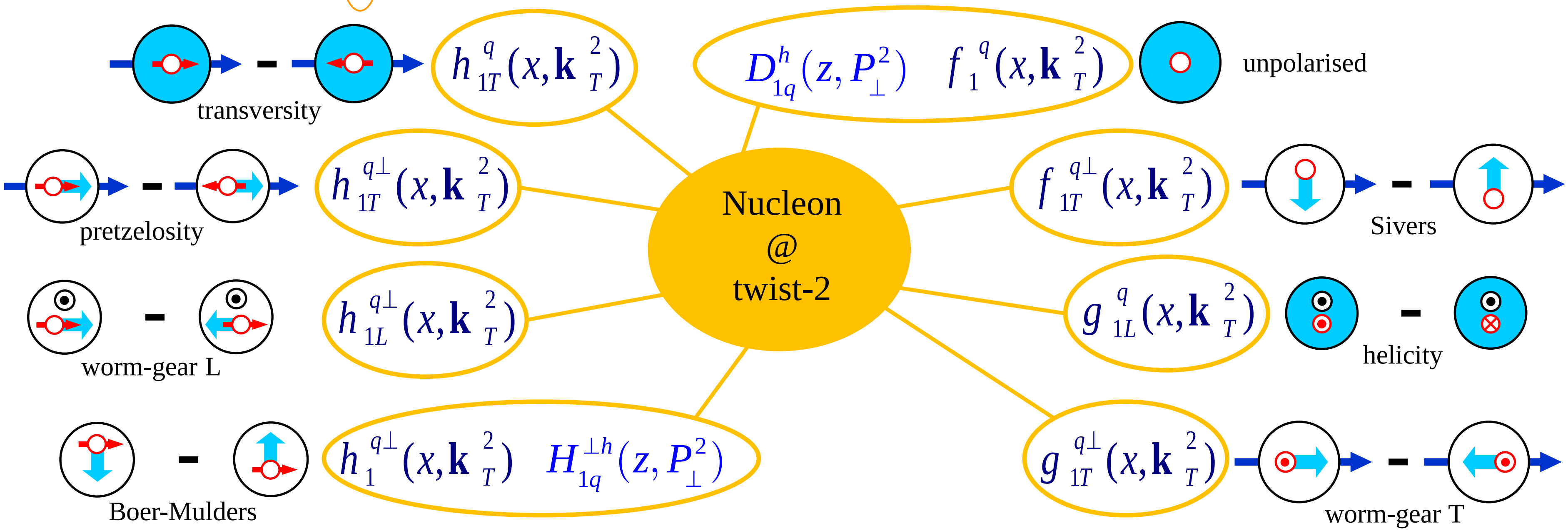
$\mathbf{k}_T$ – intrinsic transverse momentum of the quark

TMD parton distribution functions and FFs

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



$\mathbf{P}_\perp$ – transverse momentum of the fragmenting quark w.r.t. the direction of the produced hadron

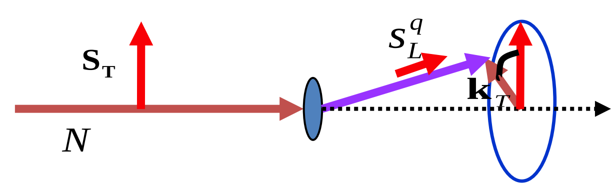


nucleon with transverse or longitudinal spin

parton with transverse or longitudinal spin

parton transverse momentum

Proton goes out of the screen. Photon goes into the screen



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

Interpretation of the transverse asymmetries

Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel JHEP 0702:093 (2007).

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

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:

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

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

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

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

From “raw” to physics asymmetries

$$A_{UT}^{w(\phi_h,\phi_s)} = \frac{A_{UT,raw}^{w(\phi_h,\phi_s)}}{D^{w(\phi_h,\phi_s)}(y)\, f\, |P_T|},\quad A_{LT}^{w(\phi_h,\phi_s)} = \frac{A_{LT,raw}^{w(\phi_h,\phi_s)}}{D^{w(\phi_h,\phi_s)}(y)\, f P_{beam}\, |P_T|}$$

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

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

$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2 y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2 y^2},\quad \gamma = \frac{2Mx}{Q}$$

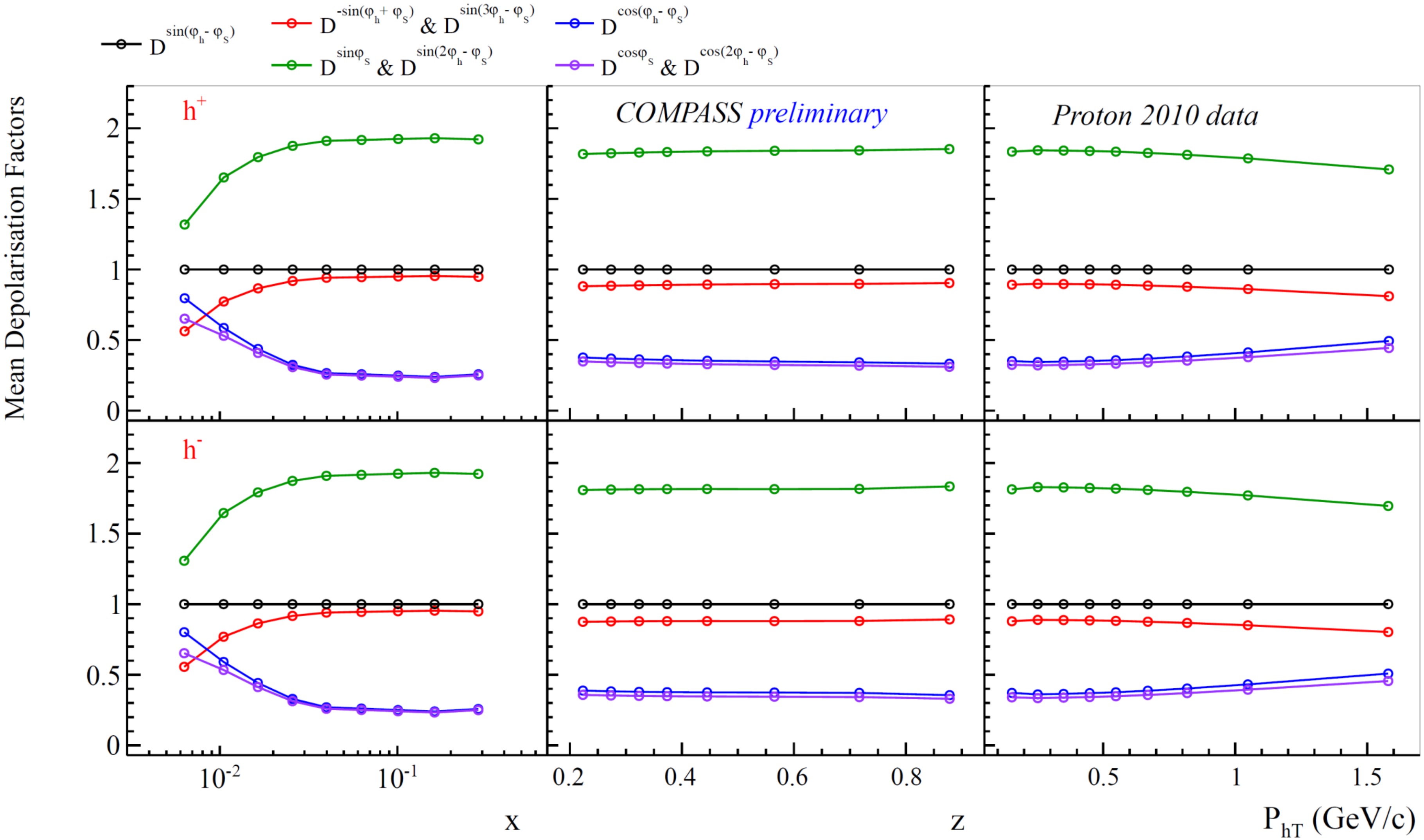
$$D^{\sin(2\phi_h-\phi_S)}(y) = D^{\sin(\phi_S)}(y) = \sqrt{2\varepsilon(1+\varepsilon)} \approx \frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2}$$

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

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

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

Mean Depolarization Factors



Outline

- Introduction
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  - Re-evaluation of $A_{LT}^{\cos\varphi_S}$:
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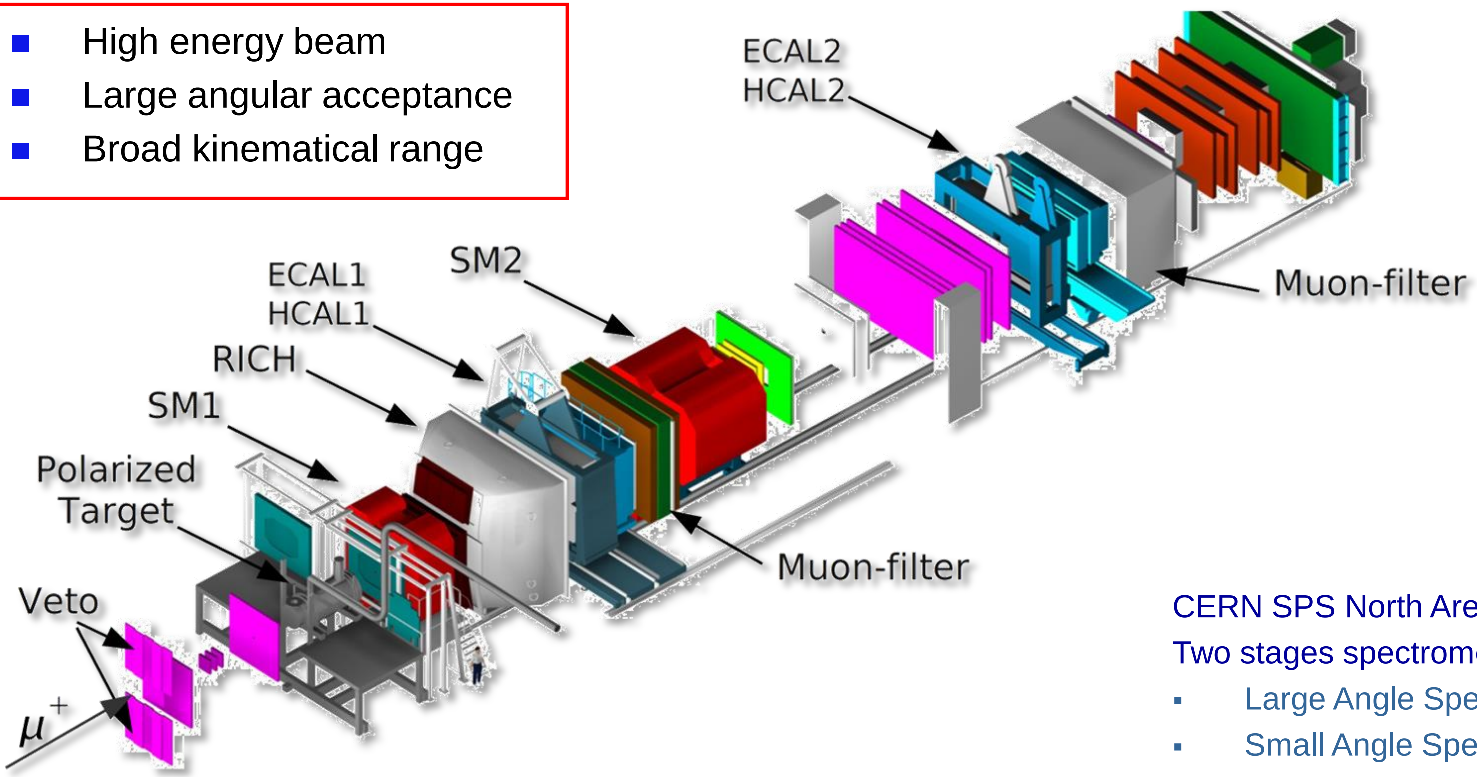
COMPASS experimental setup

COmmon Muon Proton Apparatus for Structure and Spectroscopy

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



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.

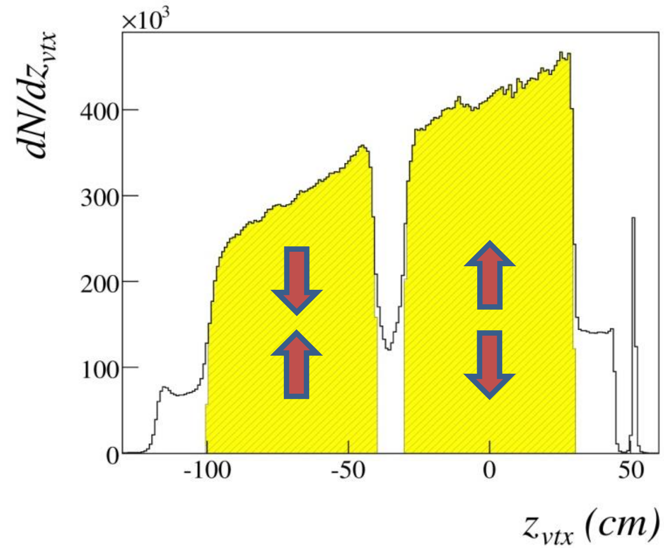
Longitudinally polarized μ^+ beam (160 Gev/c).
Longitudinally or Transversely polarized ^{6}LiD or NH_3 target
Momentum, tracking and calorimetric measurements, PID

COMPASS Polarized target system

solid state target operated in frozen spin mode

Years 2002-2004

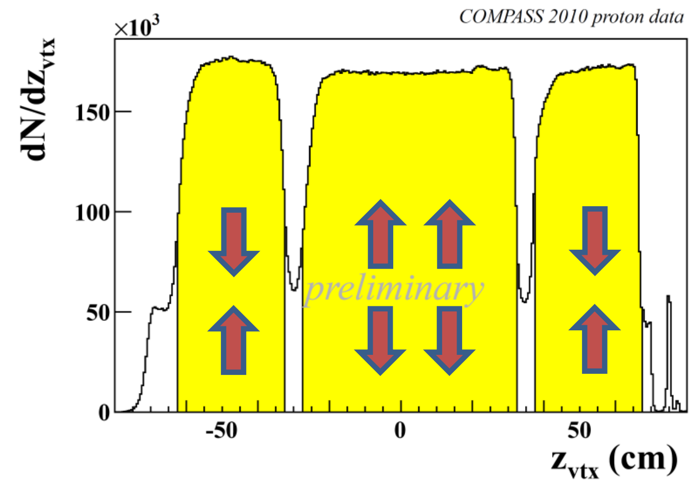
Deuteron - ^{6}LiD:
- Two 60 cm long ^{6}LiD cells with opposite polarization
- Polar angle acceptance – 70 mrad
- Target Polarization ±50%
- dilution factor f = 0.38



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

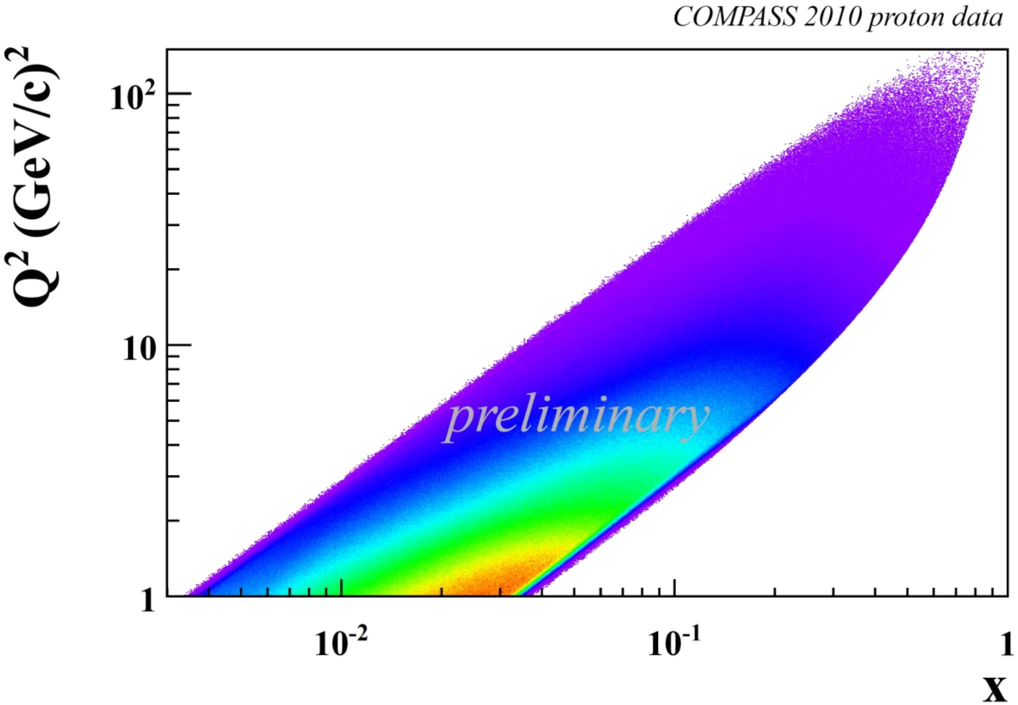
Years 2007 and 2010

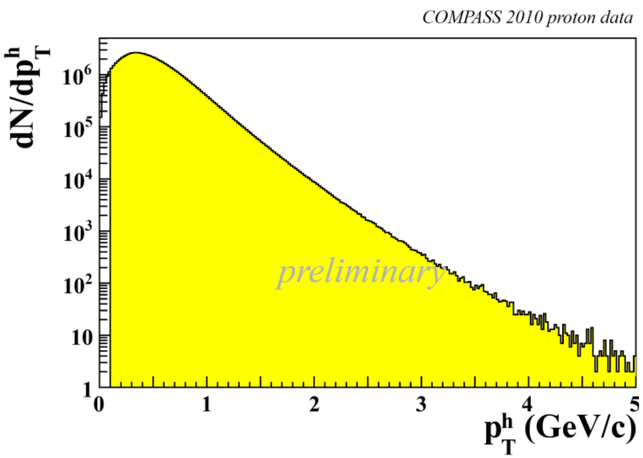
Proton - NH_3:
- Three cells system (30 cm,60cm, 30cm)
- Polar angle acceptance – 180 mrad (new magnet in 2006)
- Target Polarization ±90%
- dilution factor f = 0.14

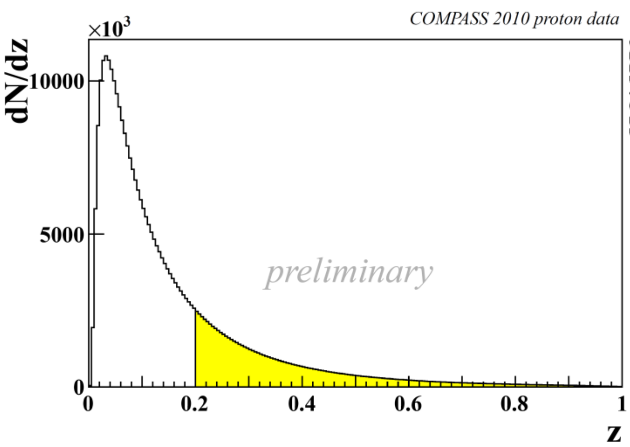


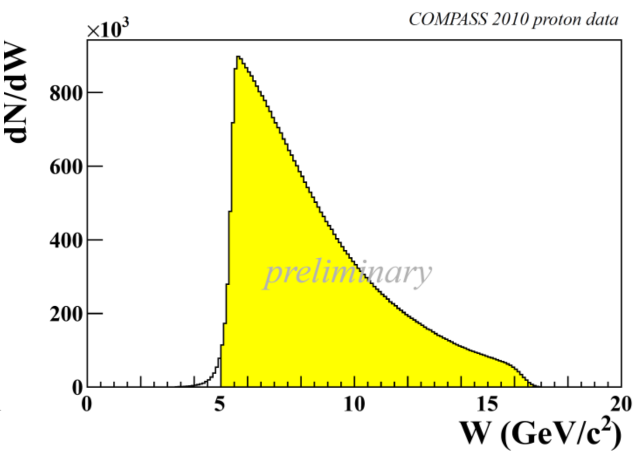
Data selection

- DIS cuts :
  - $Q^2 > 1\ GeV^2$
  - $0.1 < y < 0.9$
  - $W > 5$ GeV
- Hadron cuts :
  - $z > 0.2$
  - $P_{hT} > 0.1$ GeV/c









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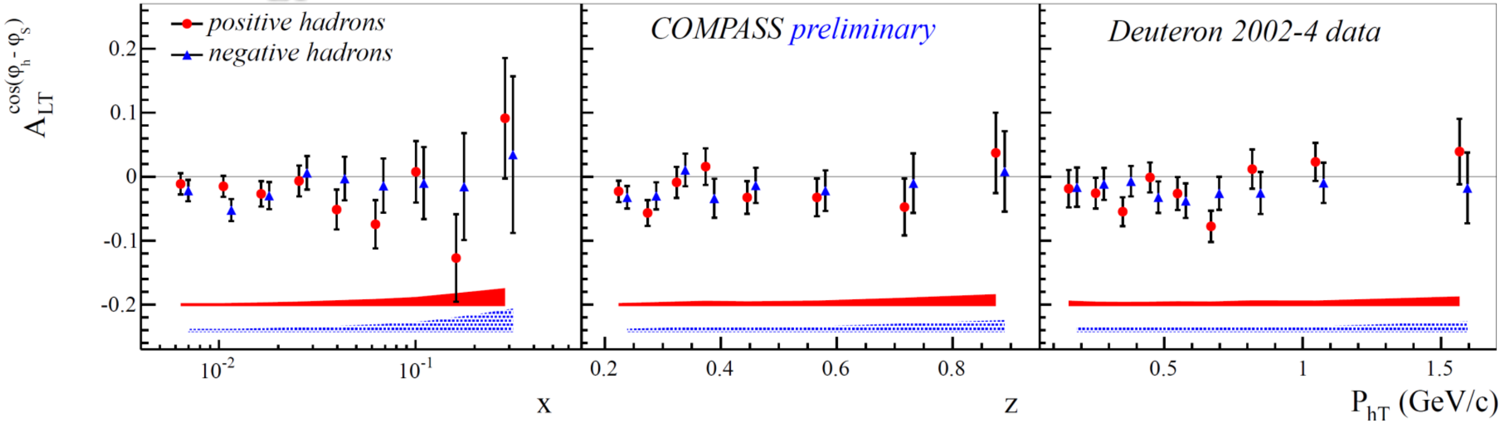
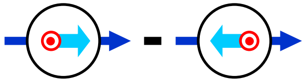
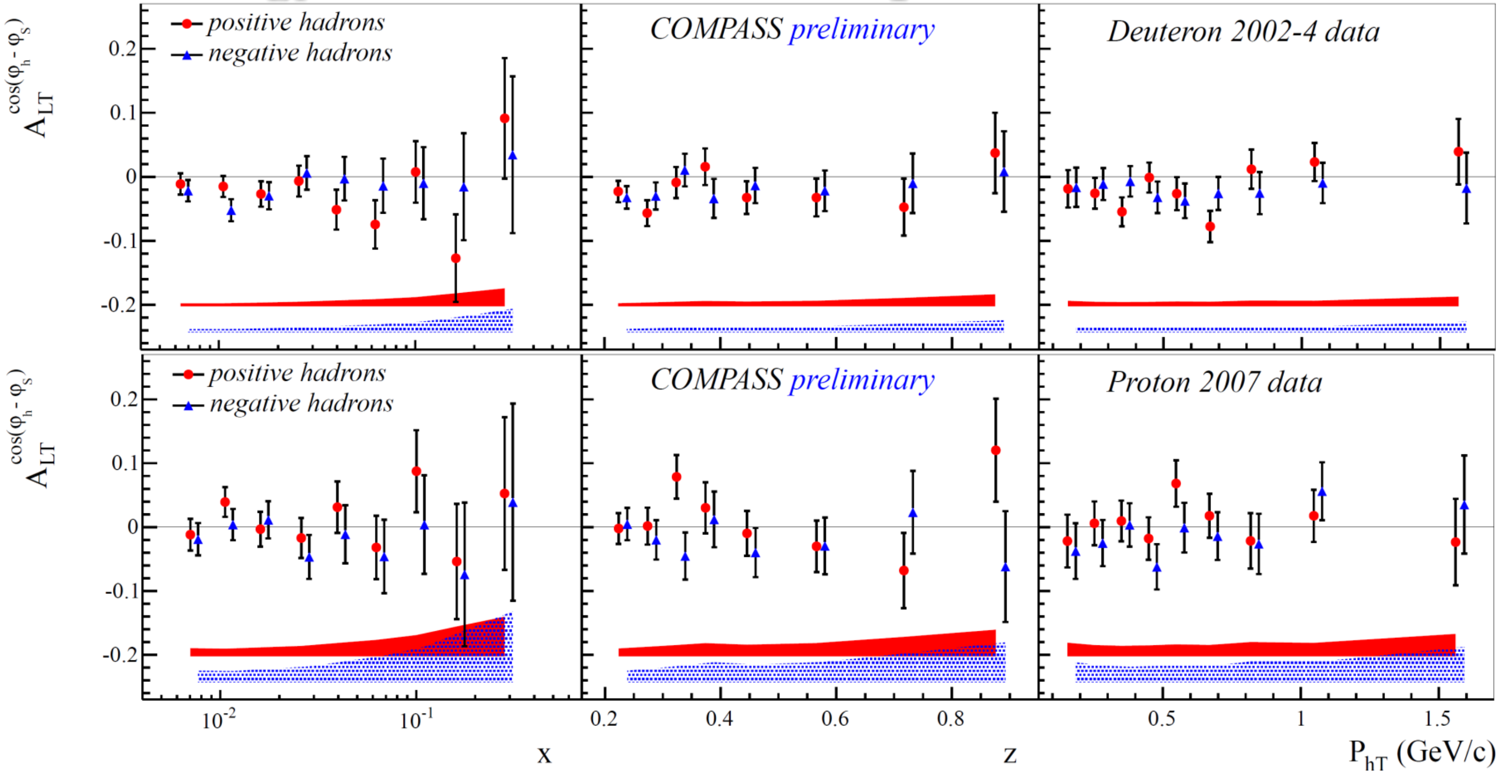
Results for $A_{LT}^{cos(\varphi_h-\varphi_S)}$ deuteron



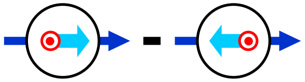
$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$, "Worm Gear" PDF g_{1T}^{q} :



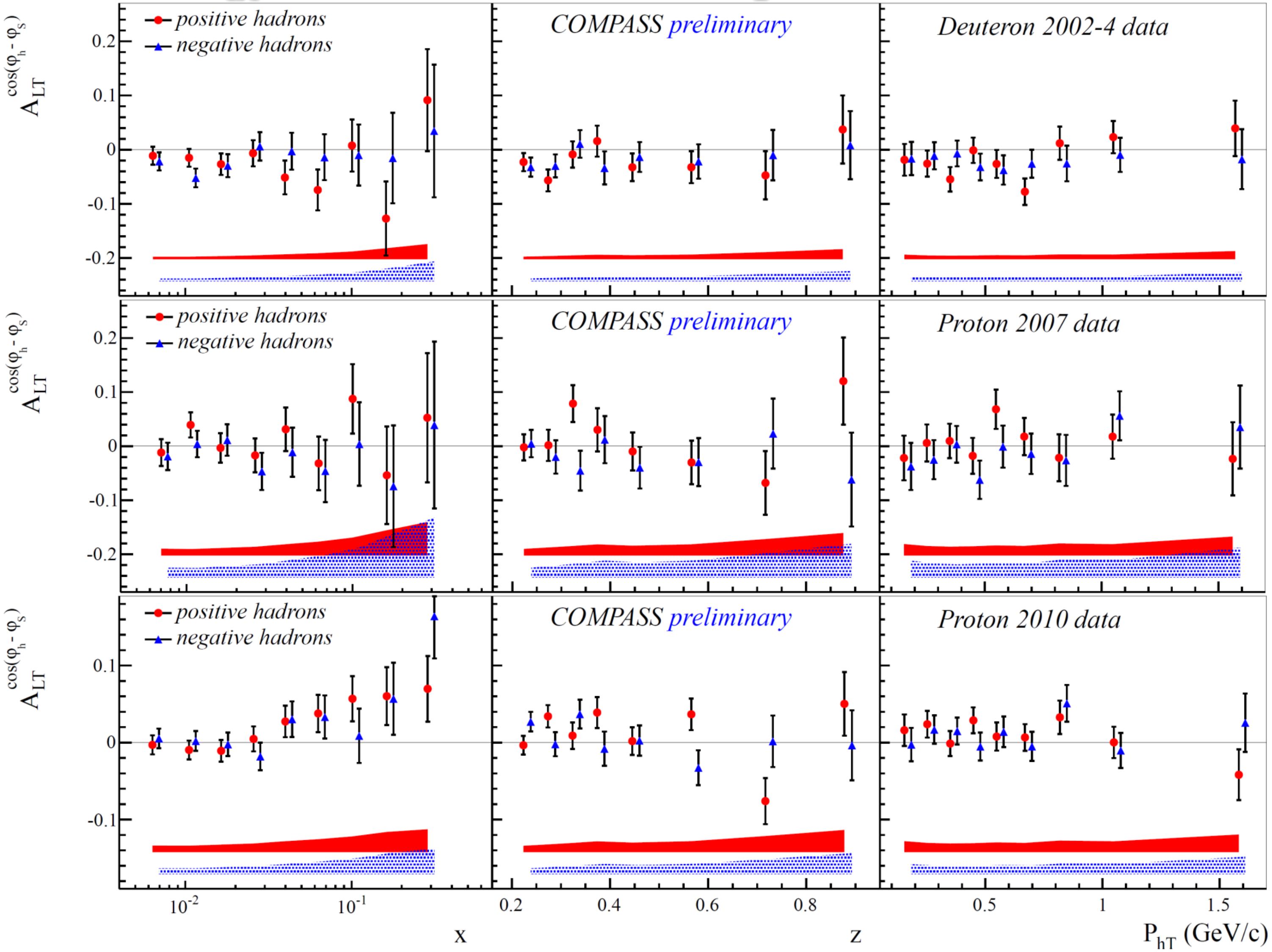
Results for $A_{LT}^{\cos(\varphi_h-\varphi_S)}$ deuteron & proton 2007



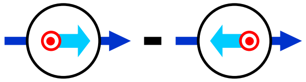
$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$, "Worm Gear" PDF g_{1T}^q :



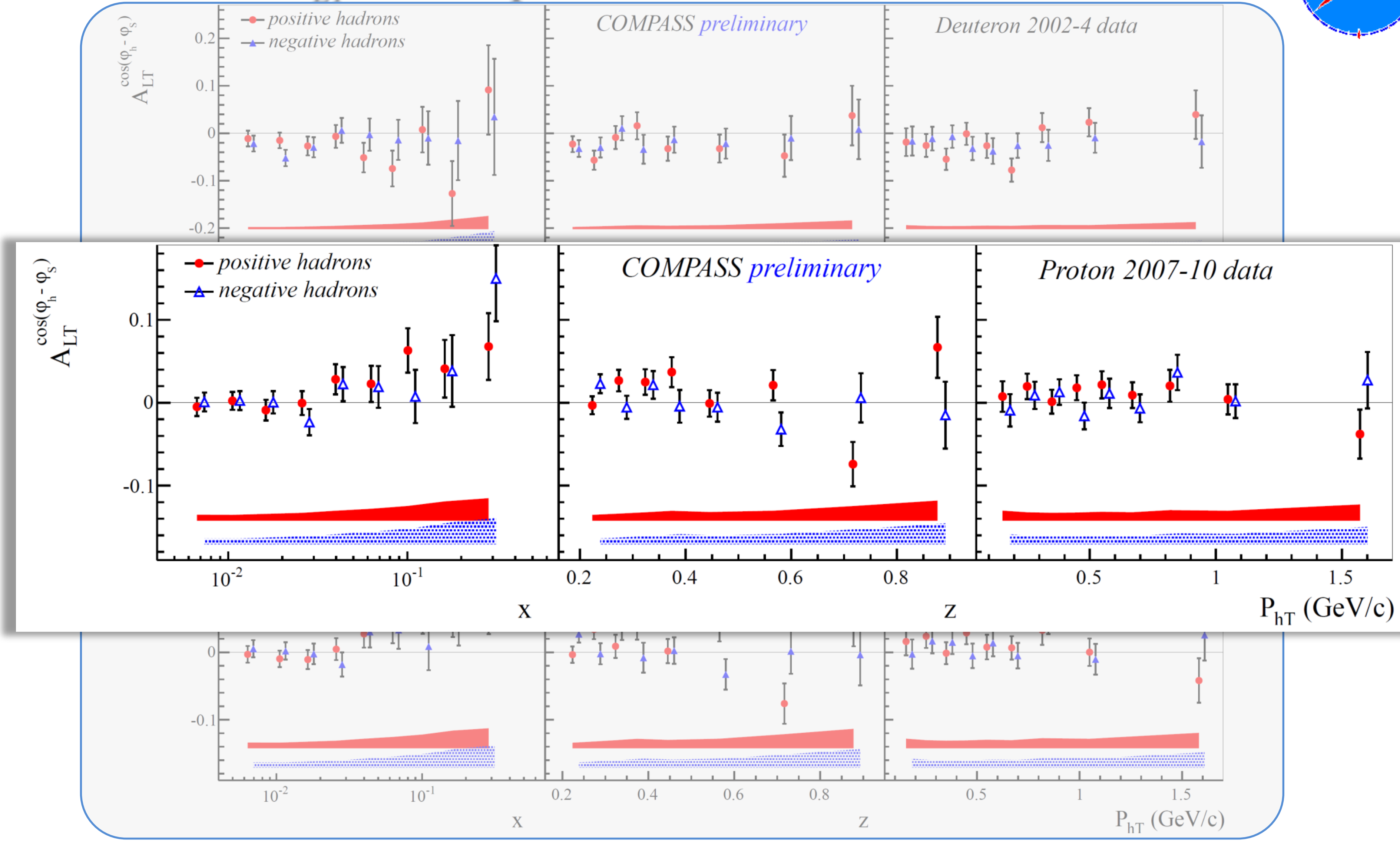
Results for $A_{LT}^{\cos(\varphi_h-\varphi_S)}$ deuteron & proton

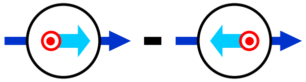


$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$, "Worm Gear" PDF g_{1T}^q :

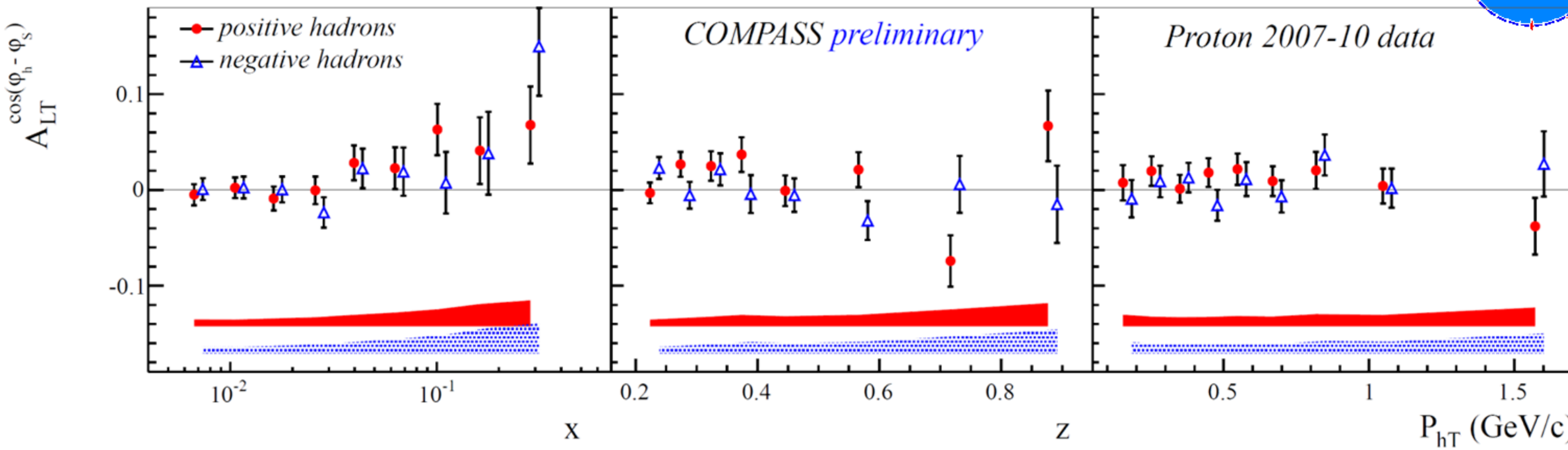


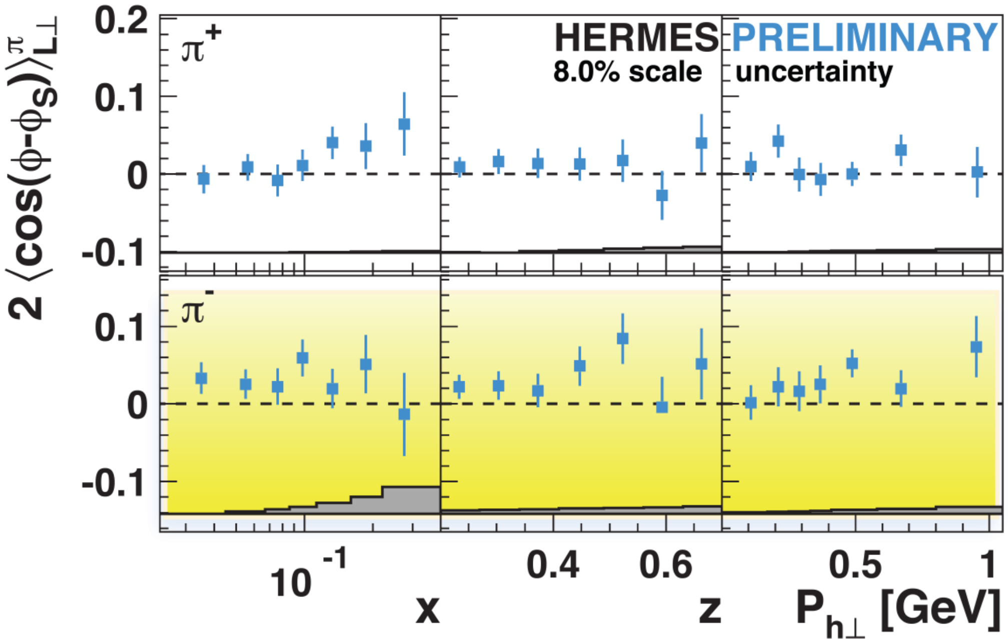
Results for $A_{LT}^{\cos(\varphi_h-\varphi_S)}$ proton 2007-2010



$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$, "Worm Gear" PDF g_{1T}^q : 

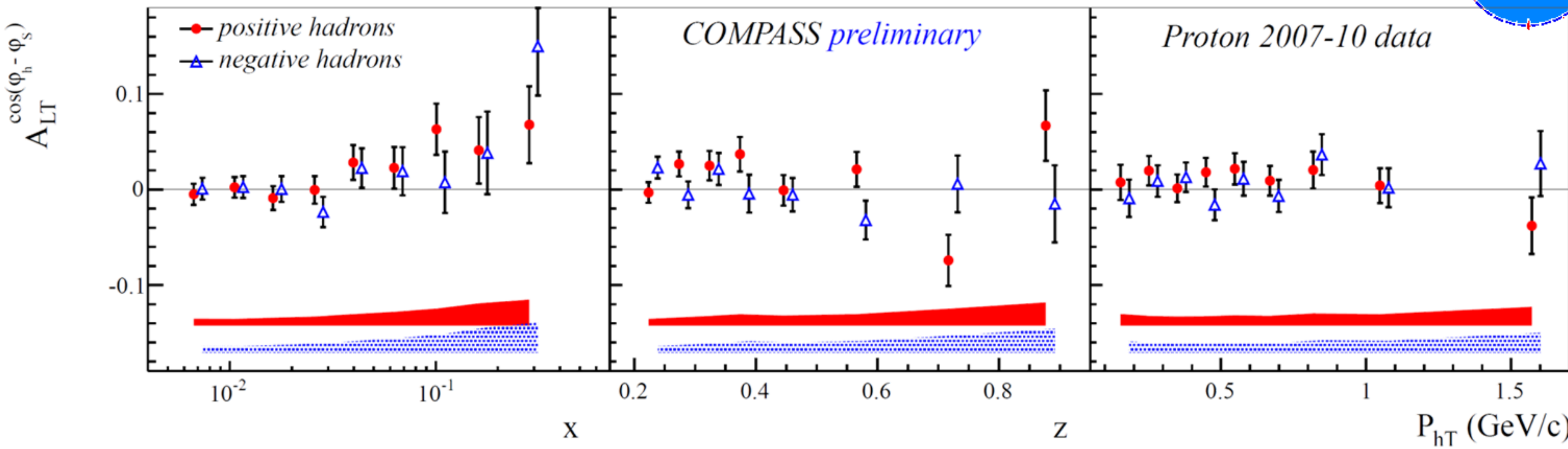
Results for $A_{LT}^{\cos(\varphi_h-\varphi_S)}$ COMPASS - HERMES



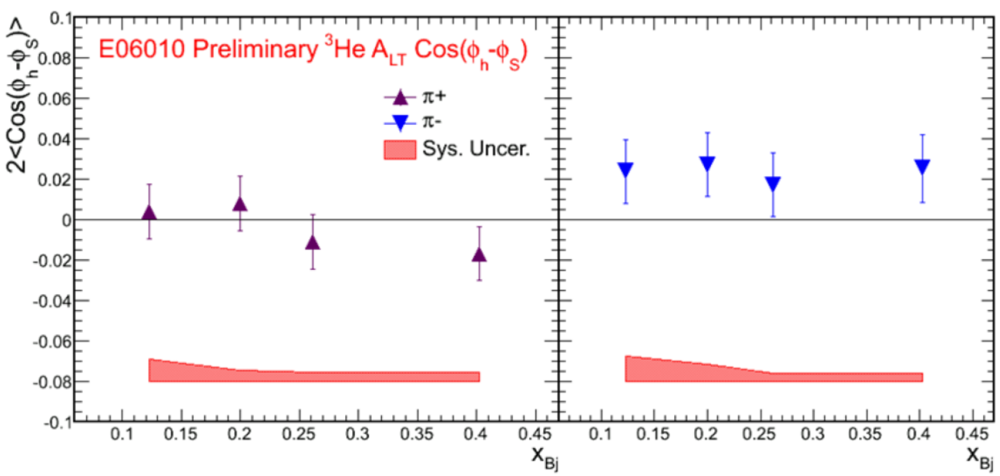


Similar trend for $A_{LT}^{\cos(\varphi_h-\varphi_S)}$ asymmetry is present in HERMES preliminary results.

Results for $A_{LT}^{\cos(\varphi_h-\varphi_S)}$ COMPASS - JLab



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

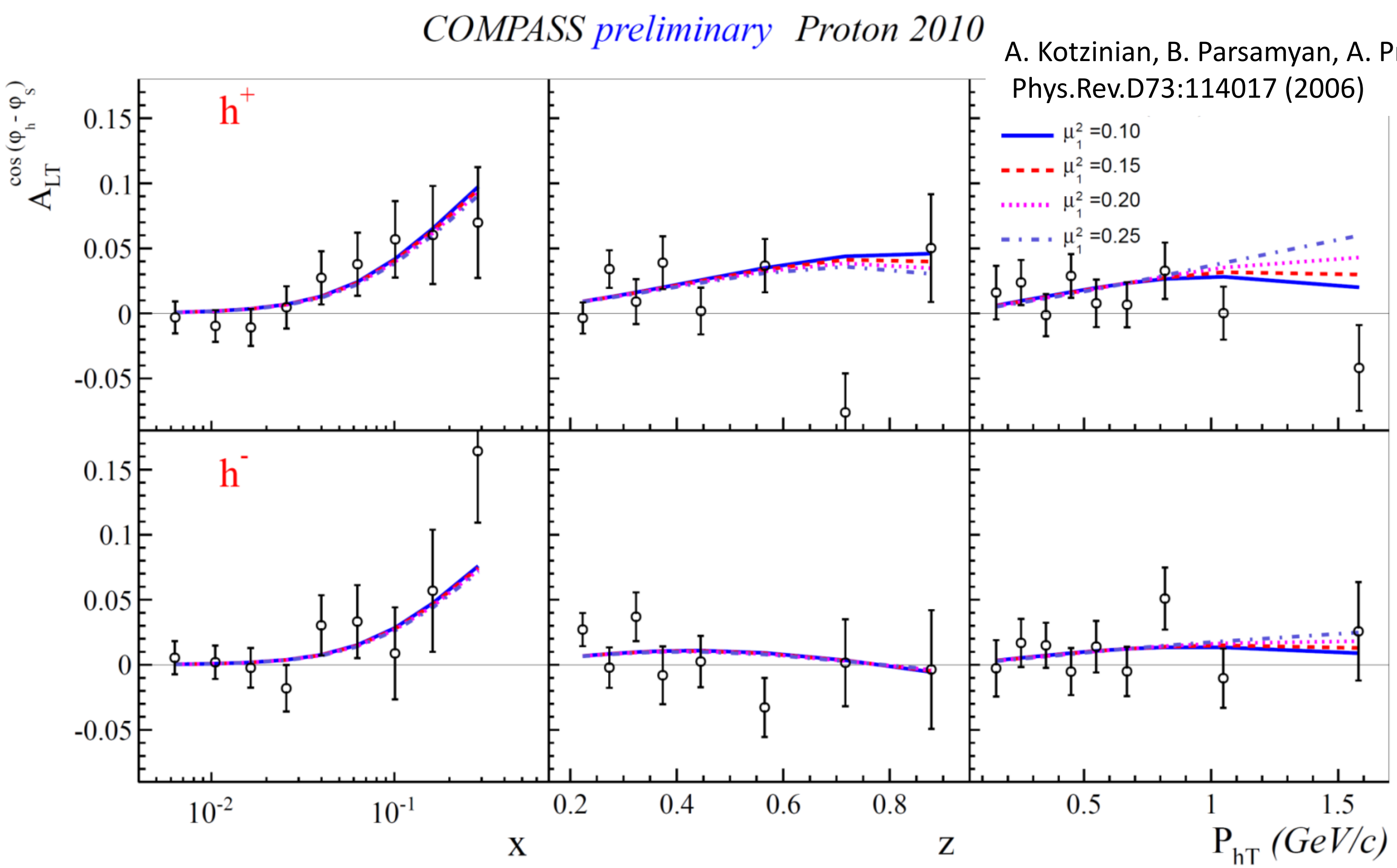


$$\propto \frac{g_{1T}^{\perp q}(x) \otimes D_{1q}^h(z)}{f_1^q(x) \otimes D_{1q}^h(z)}$$

- 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.

Ph.D. thesis of J. Huang (MIT 2011).

$A_{LT}^{\cos(\varphi_h-\varphi_S)}$ and predictions from PRD 73, 114017(2006)



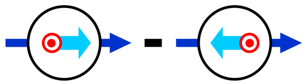
A. Kotzinian, B. Parsamyan, A. Prokudin
Phys.Rev.D73:114017 (2006)

Calculations are done using:
for g_{1T} the model:

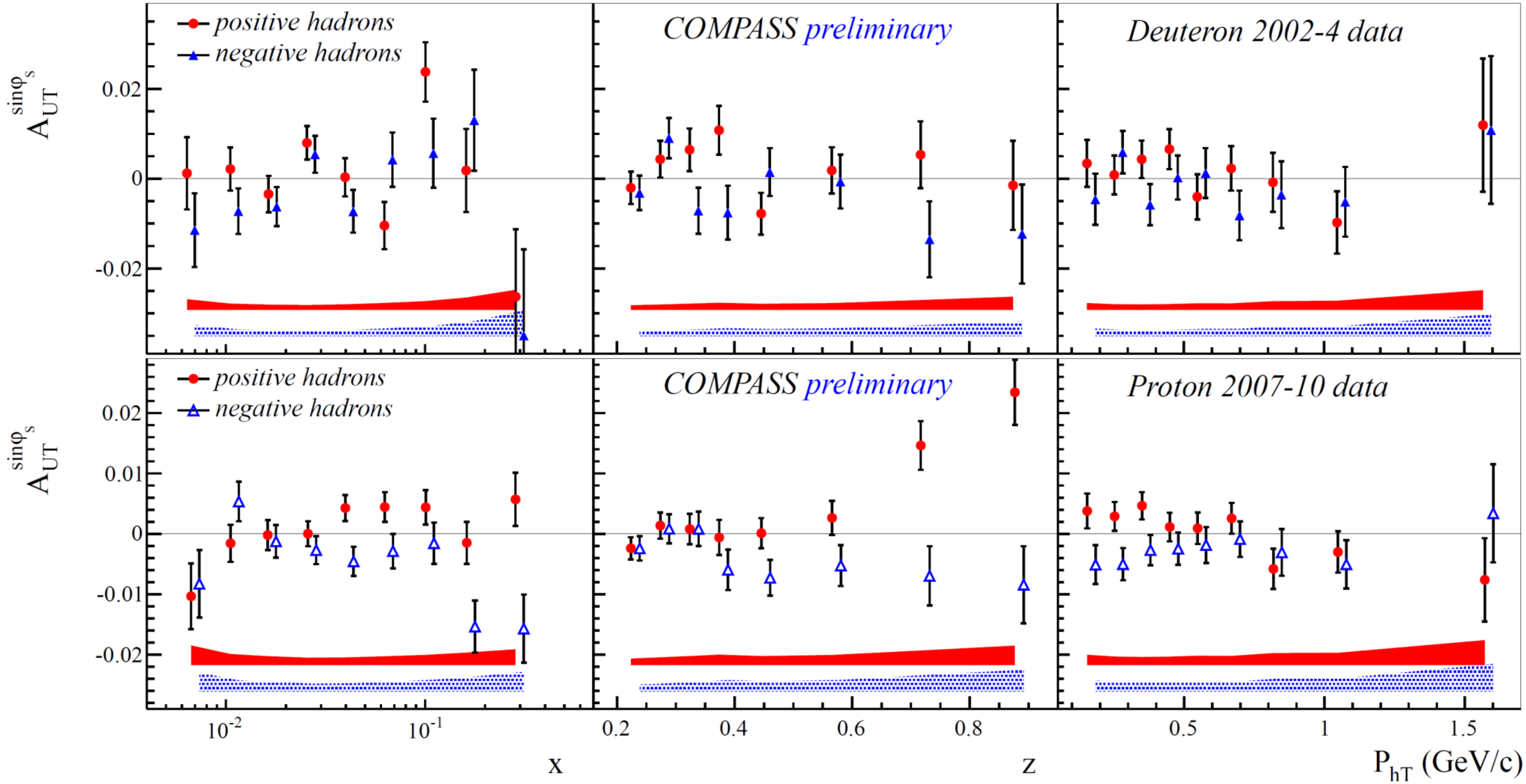
$$g_{1T}^{q(1)}(x,k_T^2) \approx x\int_x^1 dy \frac{g_1^q(y)}{y}$$

based on the Wandzura and Wilczek approximation;
Gaussian parameterization for k_T dependence;
LO GRV, GRSV2000 DFs and Kretzer FFs

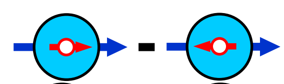
Asymmetry is evaluated in COMPASS specific mean kinematic points extracted from the data.
The predictions shows a good level of agreement with the experimentally extracted asymmetry

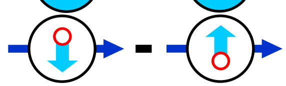
$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$, "Worm Gear" PDF g_{1T}^q : 

Results for $A_{UT}^{\sin\varphi_S}$ on deuteron and proton

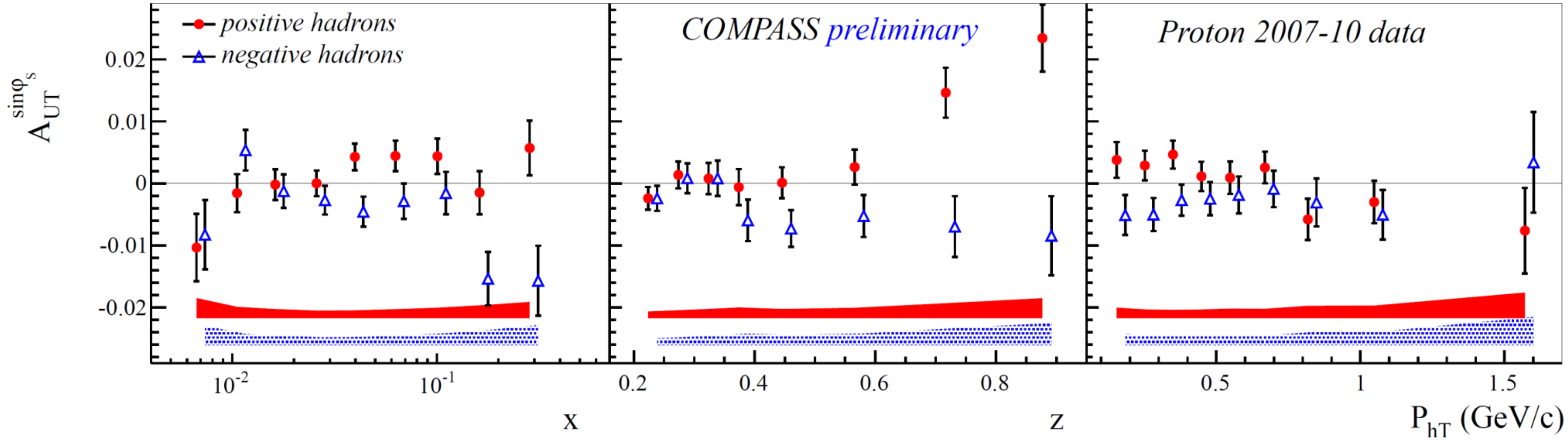


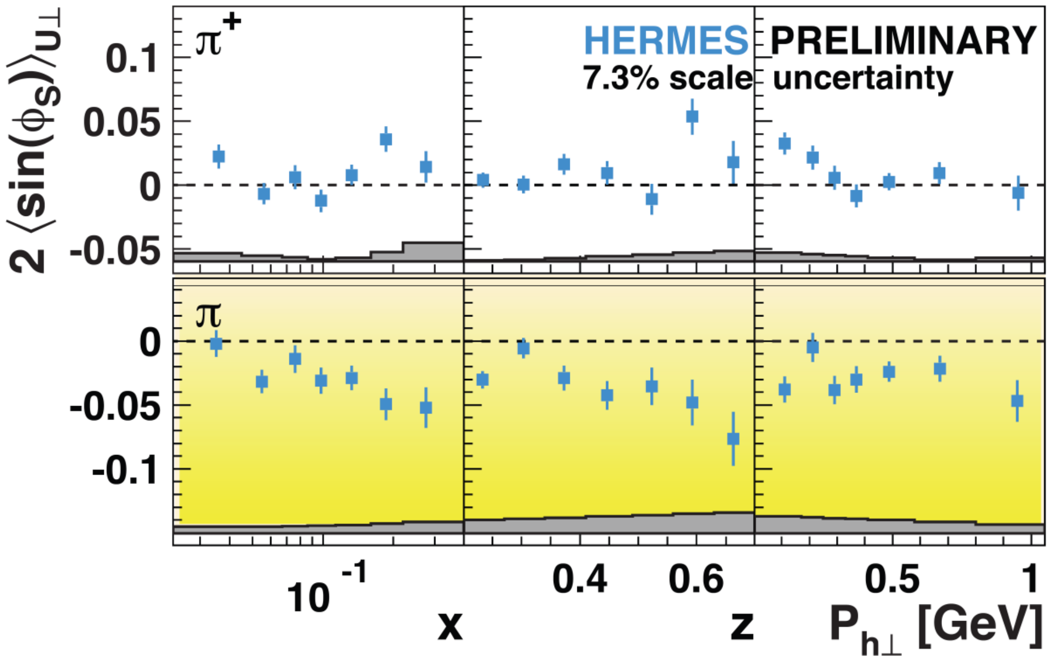
$$A_{UT}^{\sin\phi_s} \propto \frac{M}{Q}\left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right),$$

"Transversity" PDF h_1^q : 

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

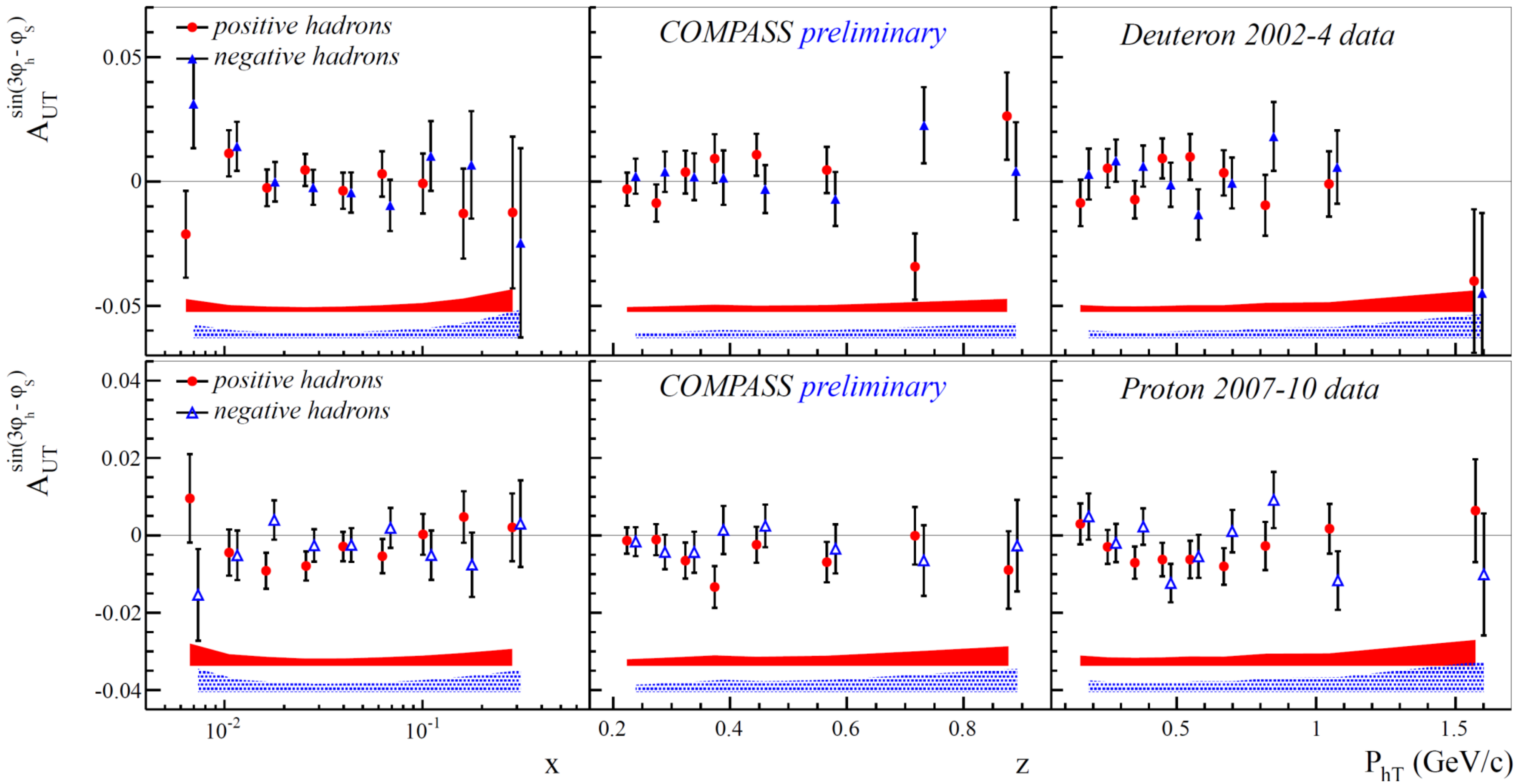
Results for $A_{UT}^{\sin\varphi_S}$ COMPASS - HERMES



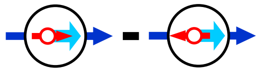


Signs of a non-zero $A_{UT}^{\sin\varphi_S}$ asymmetry have been observed both by HERMES and COMPASS.

Results for $A_{UT}^{\sin(3\varphi_h-\varphi_S)}$ deuteron & proton



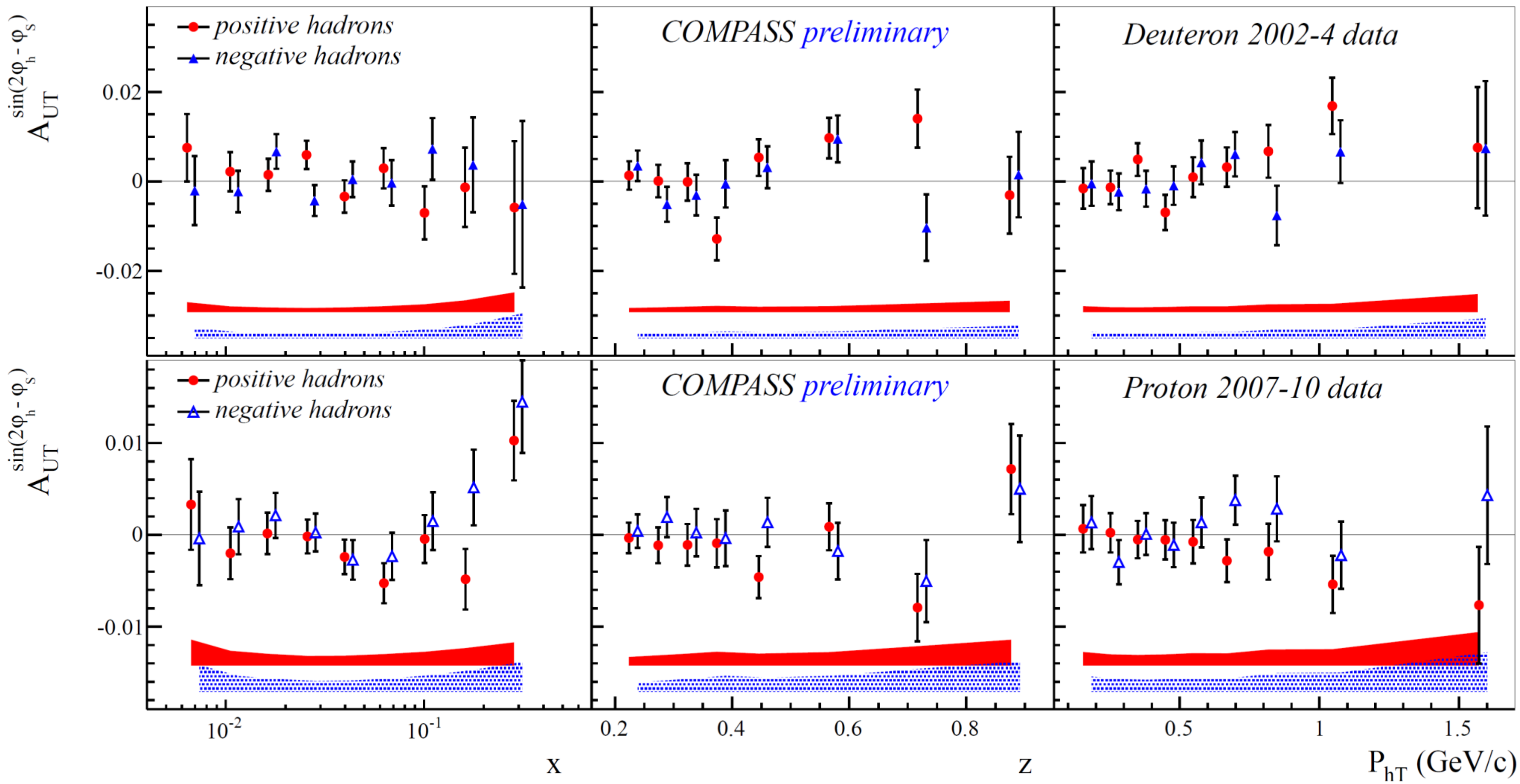
$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$, "Pretzelosity" PDF $h_{1T}^{\perp q}$:



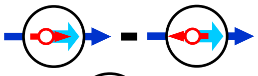
Expected to be suppressed by a factor of ~$|\mathbf{P}_{\mathbf{hT}}|^2$ with respect to the Collins and Sivers amplitudes

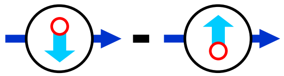
Asymmetries for both proton and deuteron are compatible with zero within uncertainties

Results for $A_{UT}^{\sin(2\varphi_h-\varphi_S)}$ deuteron & proton



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

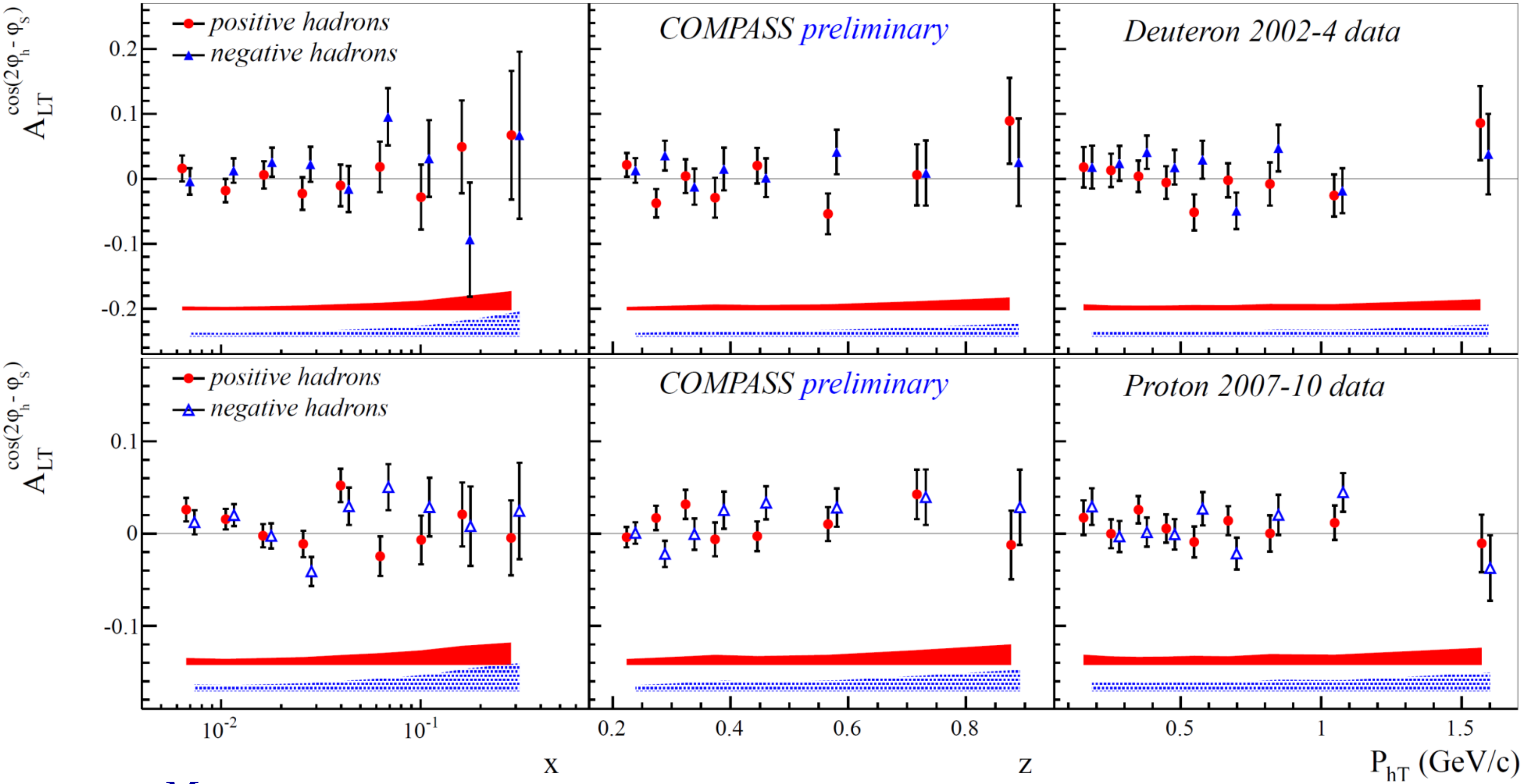
"Pretzelosity" PDF $h_{1T}^{\perp q}$: 

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

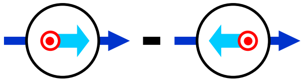
At low $|\mathbf{P_{hT}}|$ expected to be suppressed by a factor of $\sim|\mathbf{P_{hT}}|$ with respect to the Collins and Sivers

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

Results for $A_{LT}^{\cos(2\varphi_h-\varphi_S)}$ deuteron & proton



$$A_{LT}^{\cos(2\phi_h-\phi_s)} \propto \frac{M}{Q}\left(g_{1T}^q \otimes D_{1q}^h + \ldots\right),$$ "Worm Gear" PDF g_{1T}^q :



At low $|\mathbf{P_{hT}}|$ expected to be suppressed by a factor of ~$|\mathbf{P_{hT}}|$ with respect to the Collins and Sivers

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

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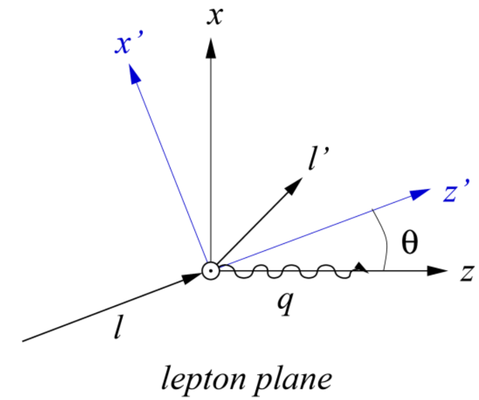
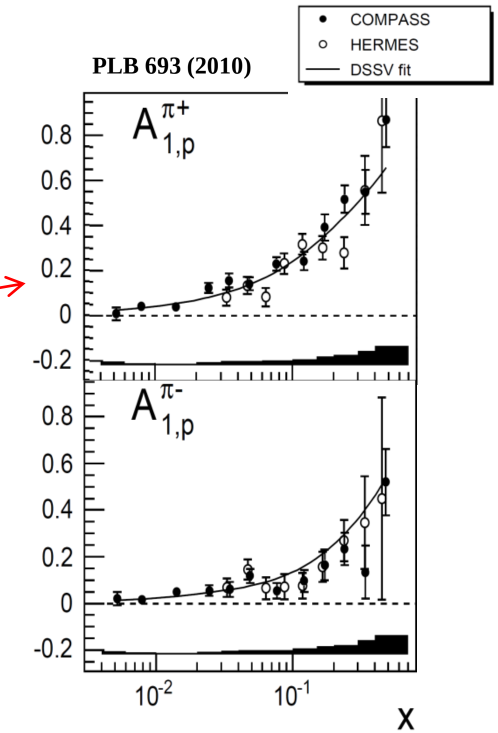
SIDIS x-section: from *lp* to *γ*p* ($P_L=0$)

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

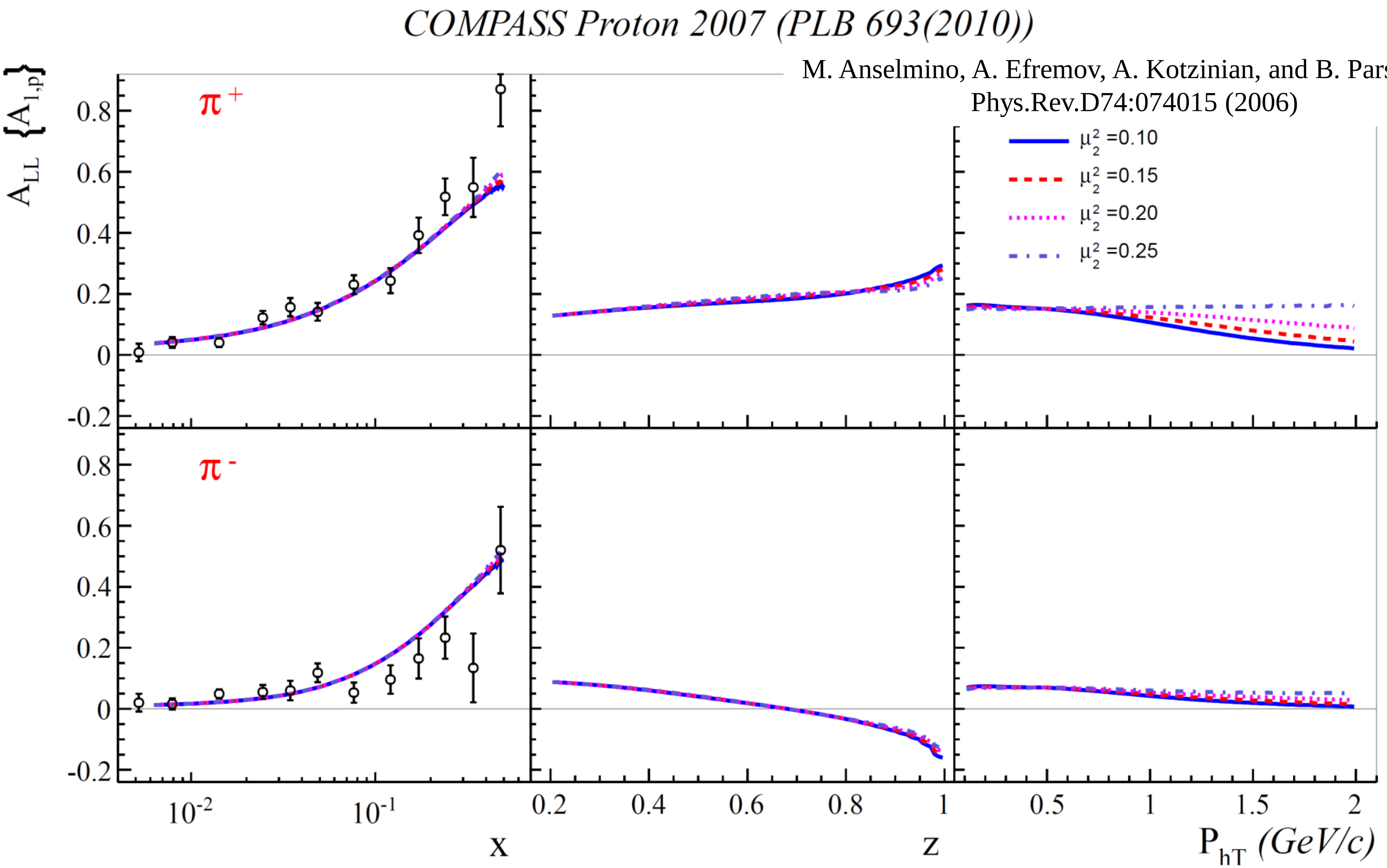
$$\frac{d\sigma}{dxdydzdP_{hT}^2\,d\varphi_h\,d\varphi_S}=\left[\frac{\cos\theta}{1-\sin^2\theta\sin^2\varphi_S}\right]\times\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

$$\begin{aligned}\Bigg[\,&1+\cos\varphi_h\times\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\varphi_h}+\cos(2\varphi_h)\times\varepsilon A_{UU}^{\cos(2\varphi_h)}+\lambda\sin\varphi_h\times\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\varphi_h}+\\
&\frac{P_T}{\sqrt{1-\sin^2\theta\sin^2\varphi_S}}\left[\begin{aligned}&\sin\varphi_S\times\left(\cos\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\varphi_S}\right)+\\
&\sin(\varphi_h-\varphi_S)\times\left(\cos\theta A_{UT}^{\sin(\varphi_h-\varphi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\varphi_h}\right)+\\
&\sin(\varphi_h+\varphi_S)\times\left(\cos\theta\varepsilon A_{UT}^{\sin(\varphi_h+\varphi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\varphi_h}\right)+\\
&\sin(2\varphi_h-\varphi_S)\times\left(\cos\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\varphi_h-\varphi_S)}+\frac{1}{2}\sin\theta\varepsilon A_{UL}^{\sin 2\varphi_h}\right)+\\
&\sin(3\varphi_h-\varphi_S)\times\left(\cos\theta\varepsilon A_{UT}^{\sin(3\varphi_h-\varphi_S)}\right)+\\
&\sin(2\varphi_h+\varphi_S)\times\left(\frac{1}{2}\sin\theta\varepsilon A_{UL}^{\sin 2\varphi_h}\right)\end{aligned}\right]+\\
&\frac{P_T\lambda}{\sqrt{1-\sin^2\theta\sin^2\varphi_S}}\left[\begin{aligned}&\boxed{\cos\varphi_S\times\left(\cos\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\varphi_S}+\sin\theta\sqrt{(1-\varepsilon^2)}A_{LL}\right)}+\\
&\cos(\varphi_h-\varphi_S)\times\left(\cos\theta\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\varphi_h-\varphi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\varphi_h}\right)+\\
&\cos(2\varphi_h-\varphi_S)\times\left(\cos\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\varphi_h-\varphi_S)}\right)+\\
&\cos(\varphi_h+\varphi_S)\times\left(\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\varphi_h}\right)\end{aligned}\right]\Bigg]\end{aligned}$$





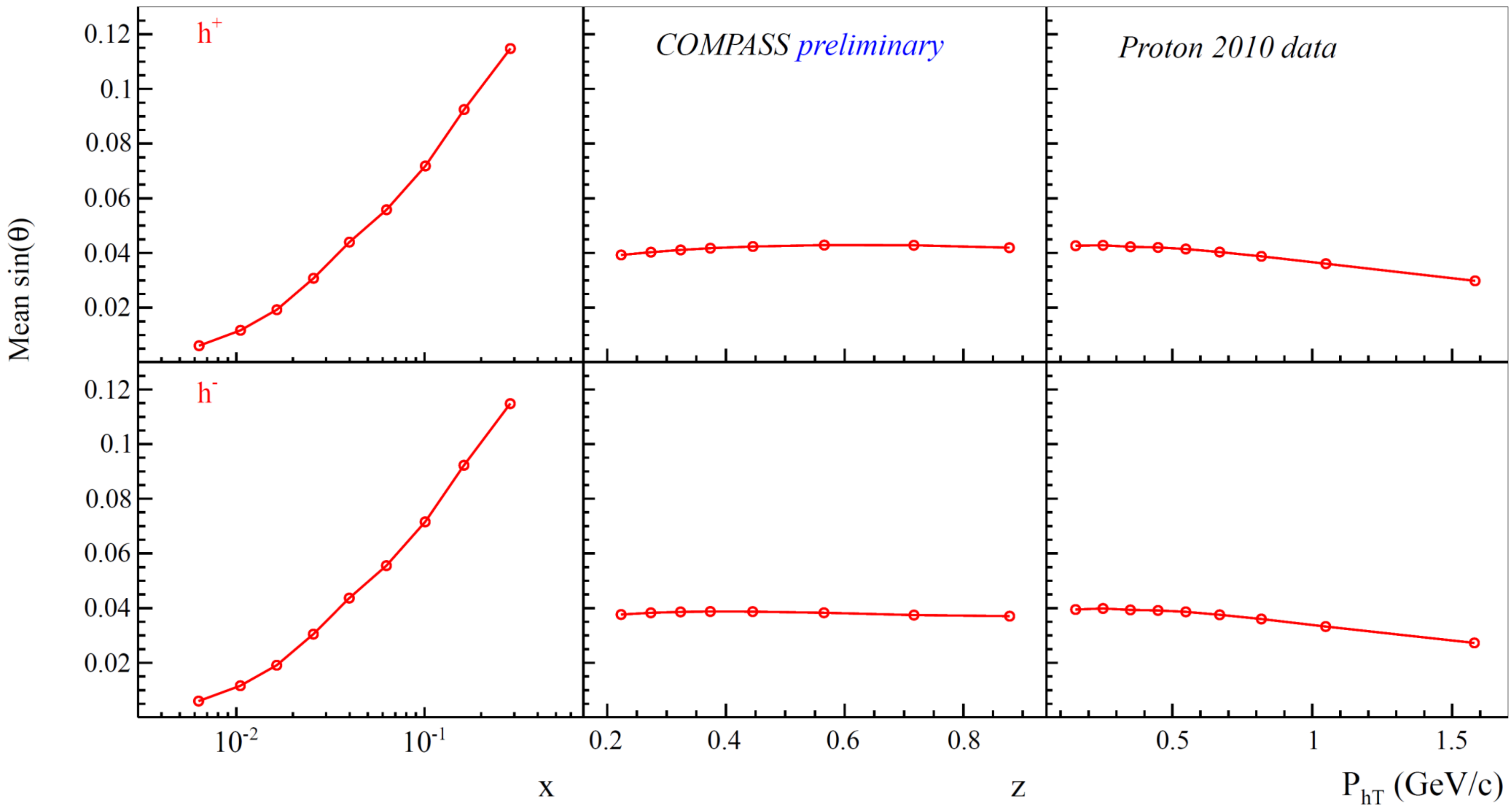
A_{LL} evaluated according to the PRD **74,** 074015 (2006)



Asymmetry is evaluated in COMPASS specific mean kinematic points extracted from the data.
Good level of agreement up to x≈0.3, which allows us to use the predicted z and P_{hT} – dependencies in $A_{LT}^{\cos(\varphi_S)}$-*correction.*

Mean sinθ-values

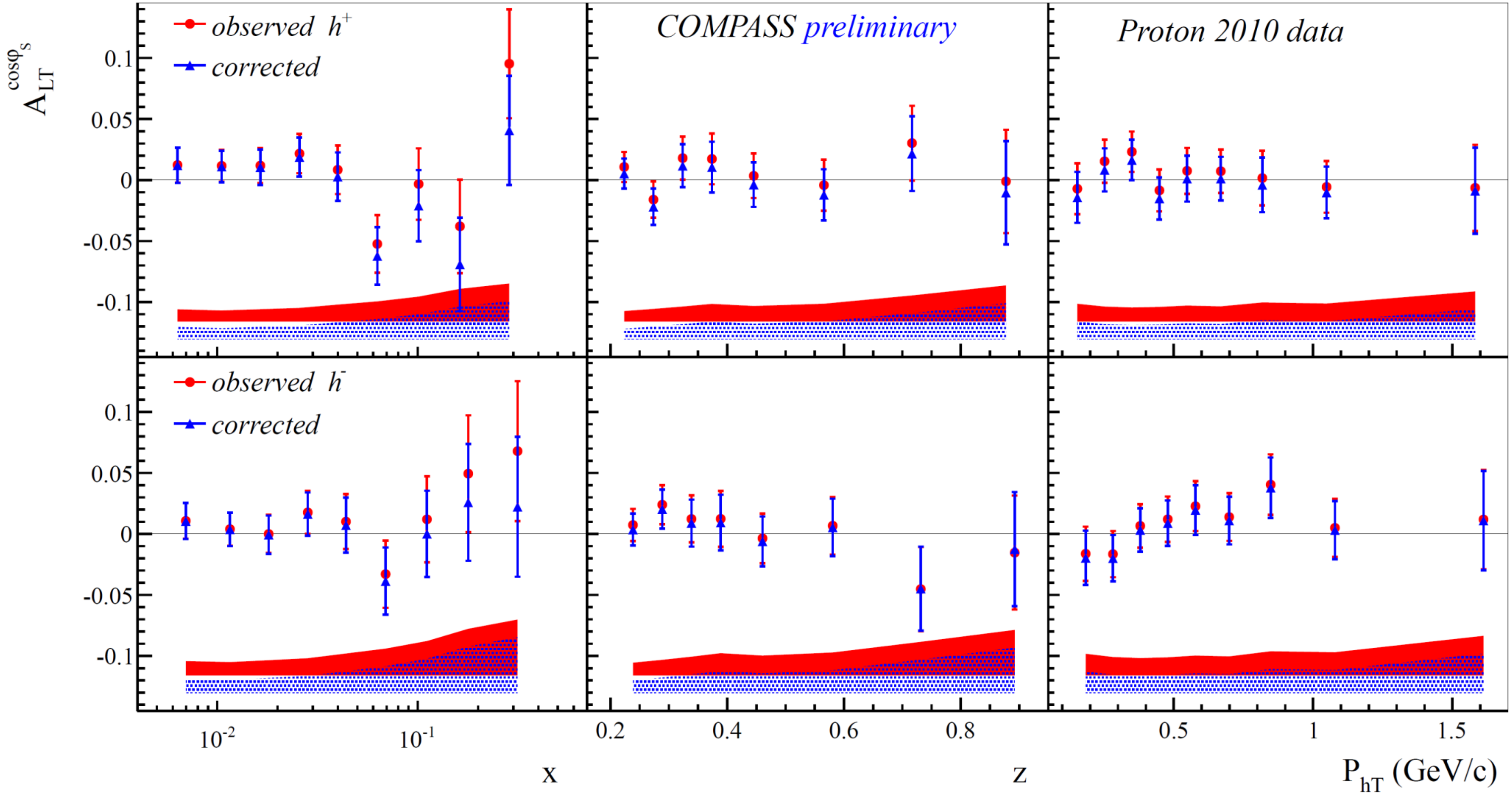
$$\sin\theta = \gamma\sqrt{\frac{1-y-\frac{1}{4}\gamma^2 y^2}{1+\gamma^2}}, \ \gamma = \frac{2Mx}{Q};$$



The sinθ is small at COMPASS kinematics. The maximum reached value is ~ 0.12 and the mean is around 0.04 (cosθ ≈ 1).

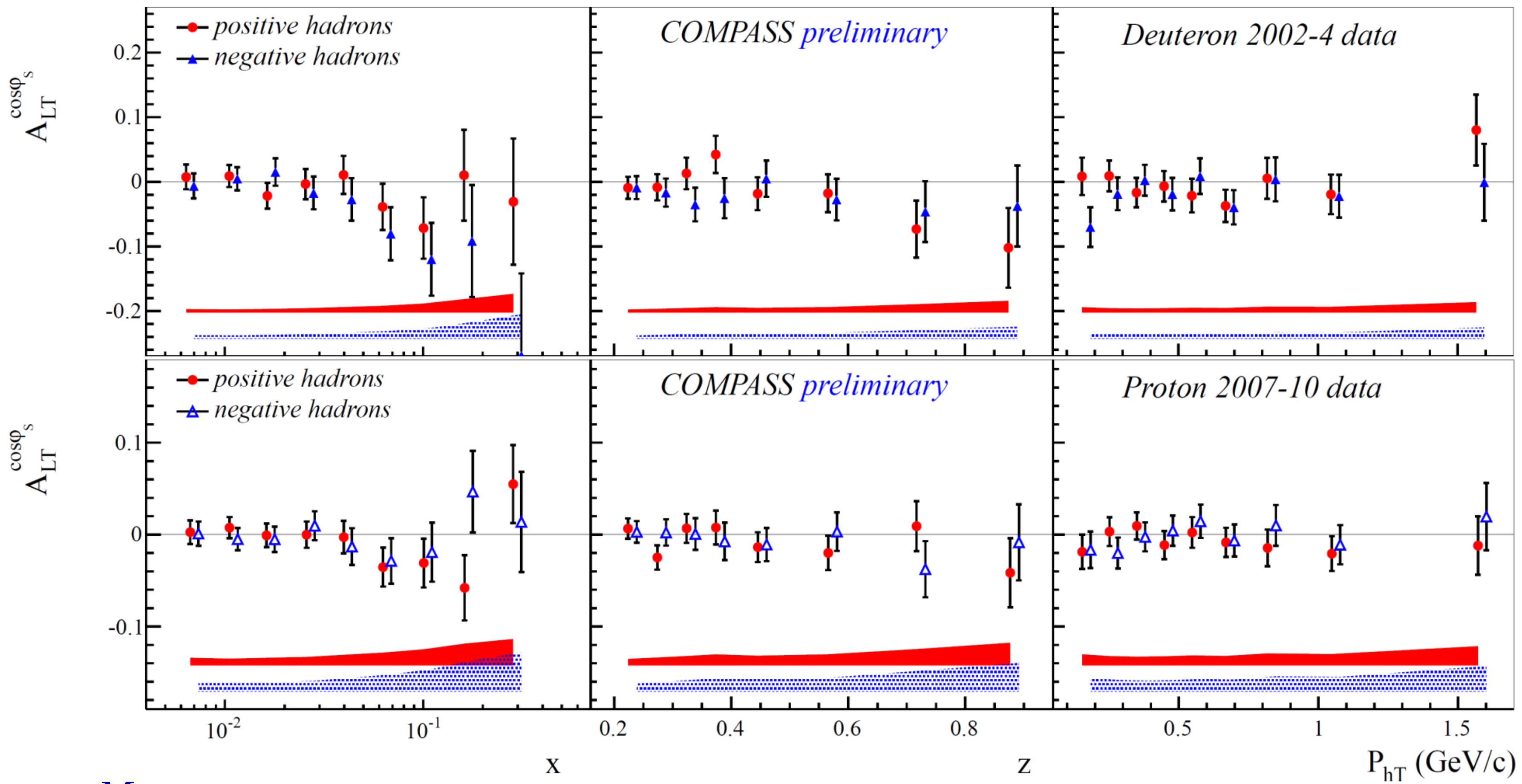
Corrected $A_{LT}^{\cos\varphi_S}$

$$A_{LT}^{\cos\varphi_S}{}' \approx \left(\cos\theta A_{LT}^{\cos\varphi_S} - \sin\theta \frac{\sqrt{(1-\varepsilon^2)}}{\sqrt{2\varepsilon(1-\varepsilon)}} A_{LL} \right)$$

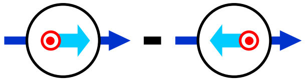


As expected, at large x the corrections become sizable.

Results for $A_{LT}^{\cos\varphi_S}$ deuteron & proton



$$A_{LT}^{\cos\phi_s} \propto \frac{M}{Q}\left(g_{1T}^{q} \otimes D_{1q}^{h} + \ldots\right),$$ "Worm Gear" PDF g_{1T}^{q} :



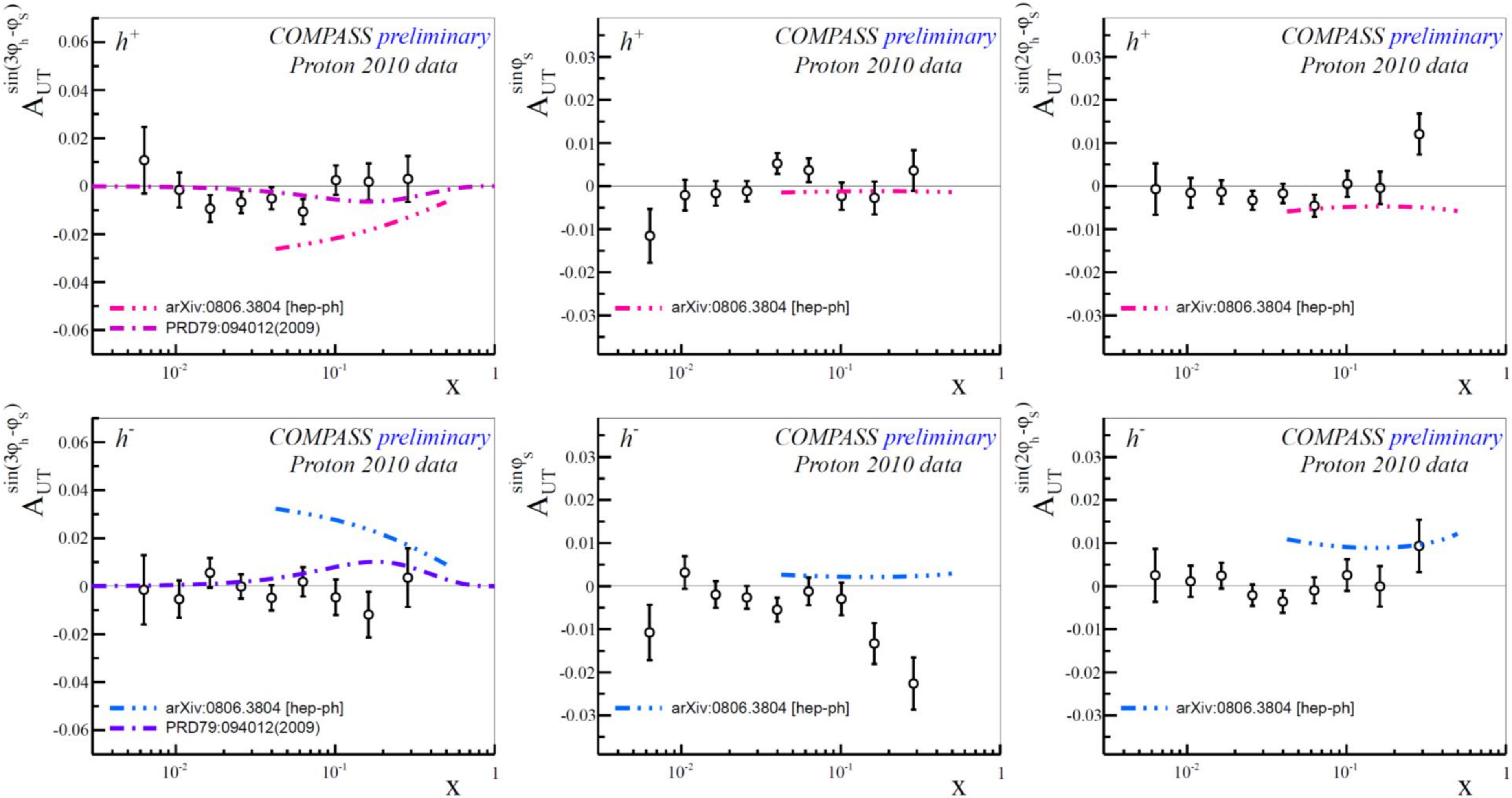
Asymmetries for both proton and deuteron are compatible with zero within uncertainties

Outline

- Introduction
- COMPASS experiment
- **Measured asymmetries and theory expectations**
  - Re-evaluation of $A_{LT}^{\cos\varphi_S}$:
    from the *lp* to $\gamma{*}p$ cross-section
  - Theory expectations
- Summary

"UT" asymmetries and theoretical predictions x-dependence only

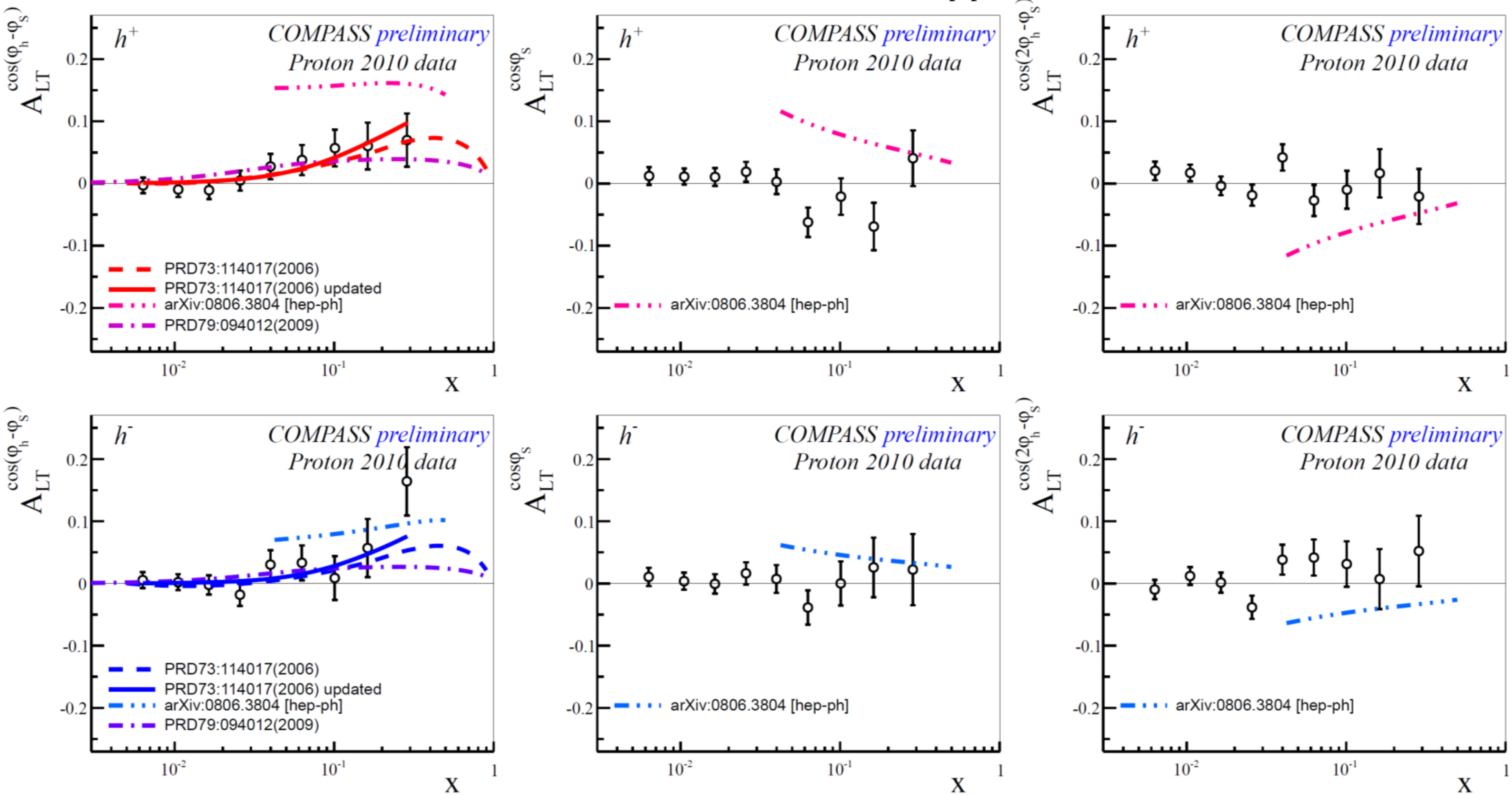
S. Boffi, A.V. Efremov, B. Pasquini and P. Schweitzer PRD79:094012(2009)
A. Kotzinian arXiv:0806.3804[hep-ph]



“LT” asymmetries and theoretical predictions

x-dependence only

A. Kotzinian, B. Parsamyan, A. Prokudin Phys.Rev.D73:114017 (2006)
S. Boffi, A.V. Efremov, B. Pasquini and P. Schweitzer PRD79:094012(2009)
A. Kotzinian arXiv:0806.3804[hep-ph]



The predictions for $A_{LT}^{\cos(\varphi_h-\varphi_S)}$ shows a good level of agreement with the experimentally extracted asymmetry.

Outline

- Introduction
- COMPASS experiment
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Summary

- Six “beyond Collins and Sivers” transverse spin asymmetries

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

have been extracted from COMPASS deuteron 2002-2004, proton 2007 and now also proton 2010 data.

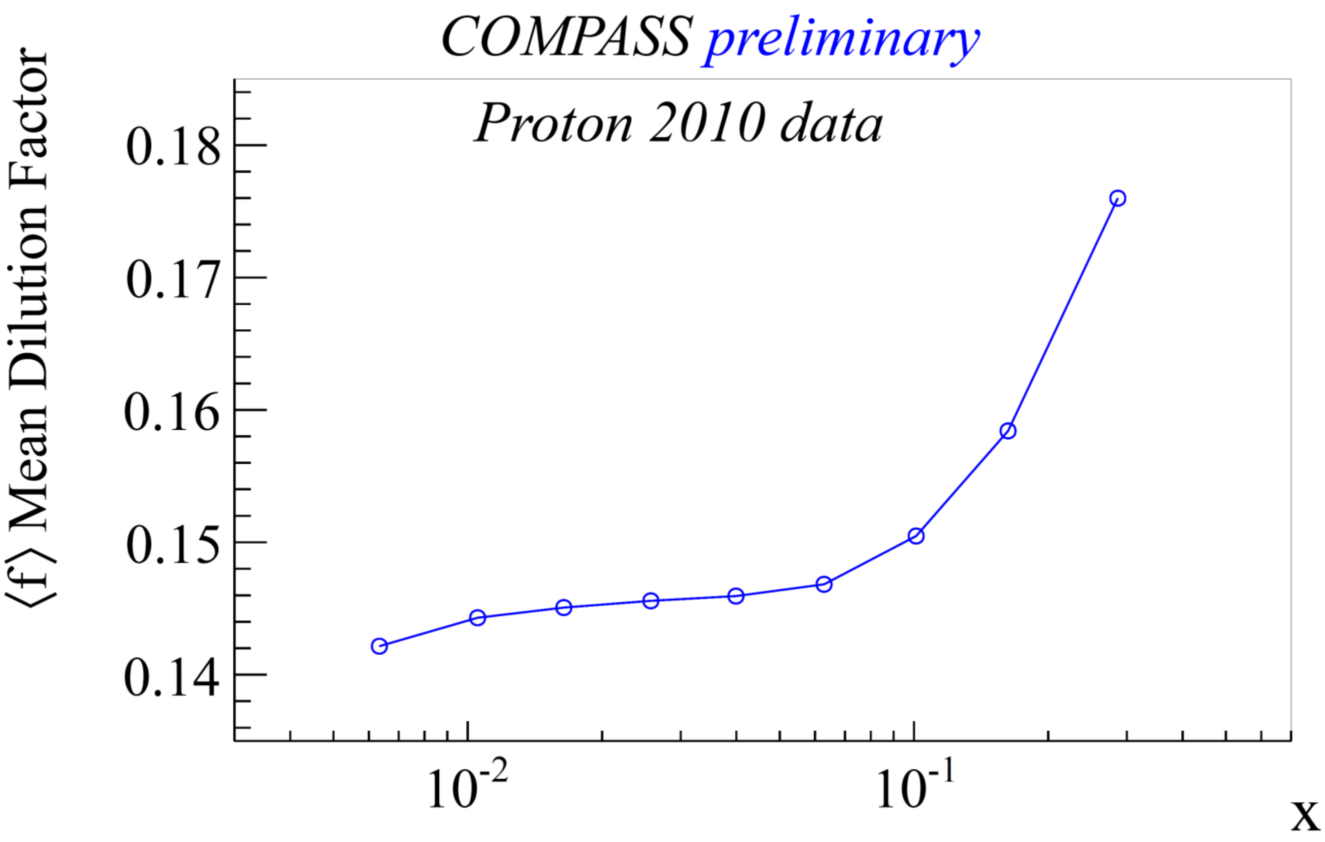
- “Deuteron” and “proton 2007” asymmetries found to be consistent with zero within the statistical accuracy of the measurement.
- Higher statistics and improved quality of the 2010 proton data allowed to reveal a non-zero trend for the $A_{LT}^{cos(\varphi_h-\varphi_S)}$ and $A_{UT}^{sin\varphi_S}$ amplitudes.
- Observed effects confirm HERMES preliminary results.
- COMPASS results for the $A_{LT}^{cos(\varphi_h-\varphi_S)}$ showed a good level of agreement with the theoretical predictions.

- Next → Six asymmetries for pions and kaons.

Thank you!

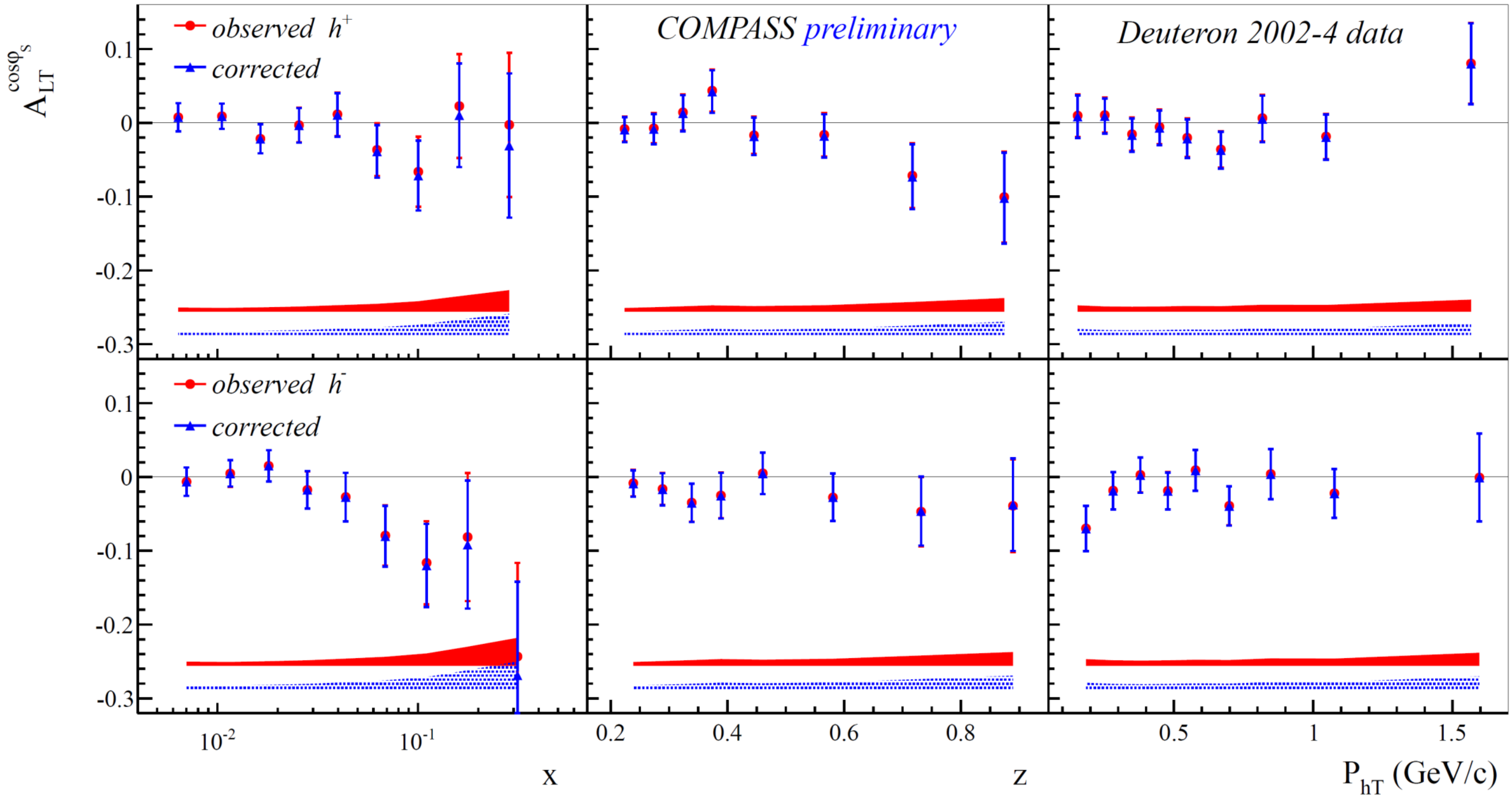
Spare slides

Dilution factor



Corrected $A_{LT}^{\cos\varphi_S}$ deuteron

$$A_{LT}^{\cos\varphi_S\prime} \approx \left(\cos\theta A_{LT}^{\cos\varphi_S} - \sin\theta \frac{\sqrt{\left(1-\varepsilon^2\right)}}{\sqrt{2\varepsilon\left(1-\varepsilon\right)}} A_{LL} \right)$$



$A_{LT}^{\cos(\varphi_h-\varphi_S)}$ asymmetry *PRD73:114017,(2006)*

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

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

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

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

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

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

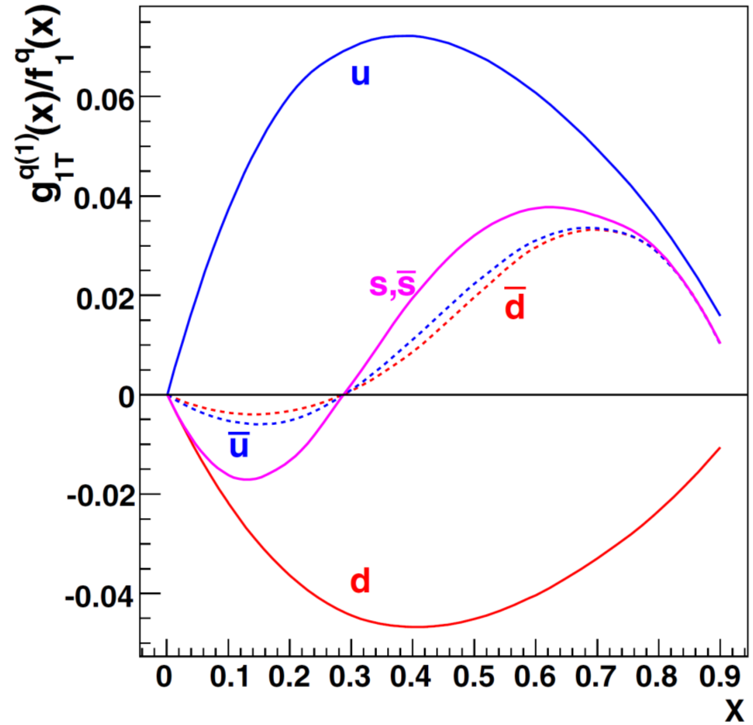
holds if $\mu_1^2 \leq 0.246\ (\mathrm{GeV/c})^2$

Predictions done for: $\mu_1^2 = 0.1, 0.15\ and\ 0.25(GeV/c)^2$

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

$A_{LT}^{\cos(\varphi_h-\varphi_S)}$ asymmetry *PRD73:114017,(2006)*

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



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