Transverse spin azimuthal asymmetries in SIDIS at COMPASS: Multi-D analysis

BAKUR PARSAMYAN

ICTP-Trieste, University of Turin and INFN section of Turin

on behalf of the COMPASS Collaboration

The Abdus Salam International Centre for Theoretical Physics

UNIVERSITÀ DEGLI STUDI DI TORINO

ALMA UNIVERSITAS TAURINENSIS

Twelfth Conference on the Intersections of Particle and Nuclear Physics (CIPANP-2015)

Vail, Colorado

May 19 – 24, 2015

Outline

- Introduction
  - COMPASS experiment
  - SIDIS x-section and TSAs
  - Brief review of recent COMPASS results with TSAs
    - COMPASS: SIDIS – Drell-Yan bridge
- COMPASS multidimensional approach
  - COMPASS multidimensional phase-space
- Results for TSAs from multi-D analysis
  - Mean depolarization factors
  - Sivers asymmetry
  - Collins asymmetry
  - $A_{LT}^{\cos(\phi_h-\phi_S)}$-asymmetry and predictions i.a.w. PRD 73, 114017(2006)
  - $A_{UT}^{\sin\phi_S}$–asymmetry
  - $A_{UT}^{\sin(3\phi_h-\phi_S)}$-asymmetry
- Conclusions

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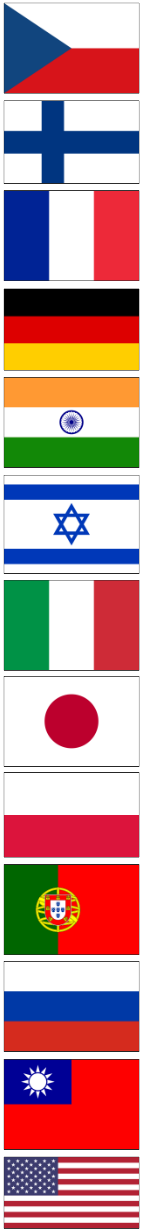
COMPASS collaboration



24 institutions from 13 countries – nearly 250 physicists

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

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

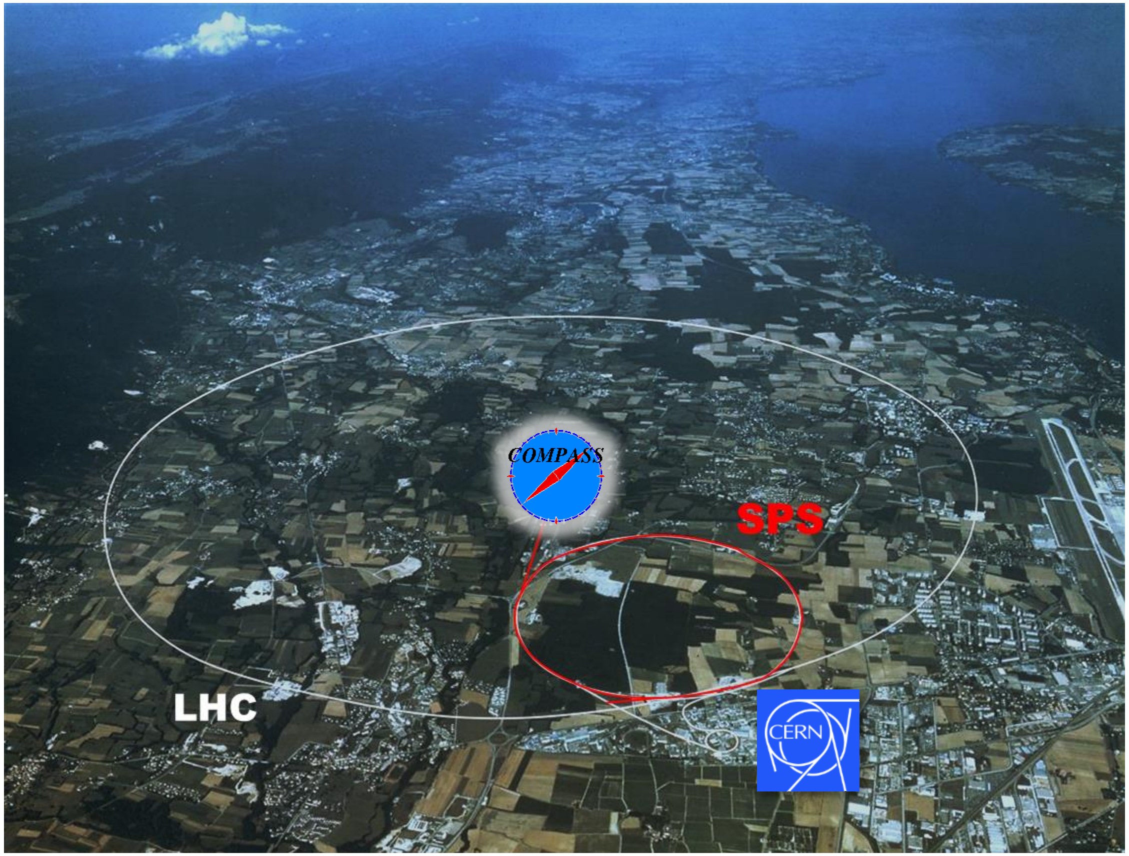
Wide physics program

COMPASS-I

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

COMPASS-II

- **Data taking 2012-2017**
- **Primakoff**
- **Polarized Drell-Yan**
- **DVCS**



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

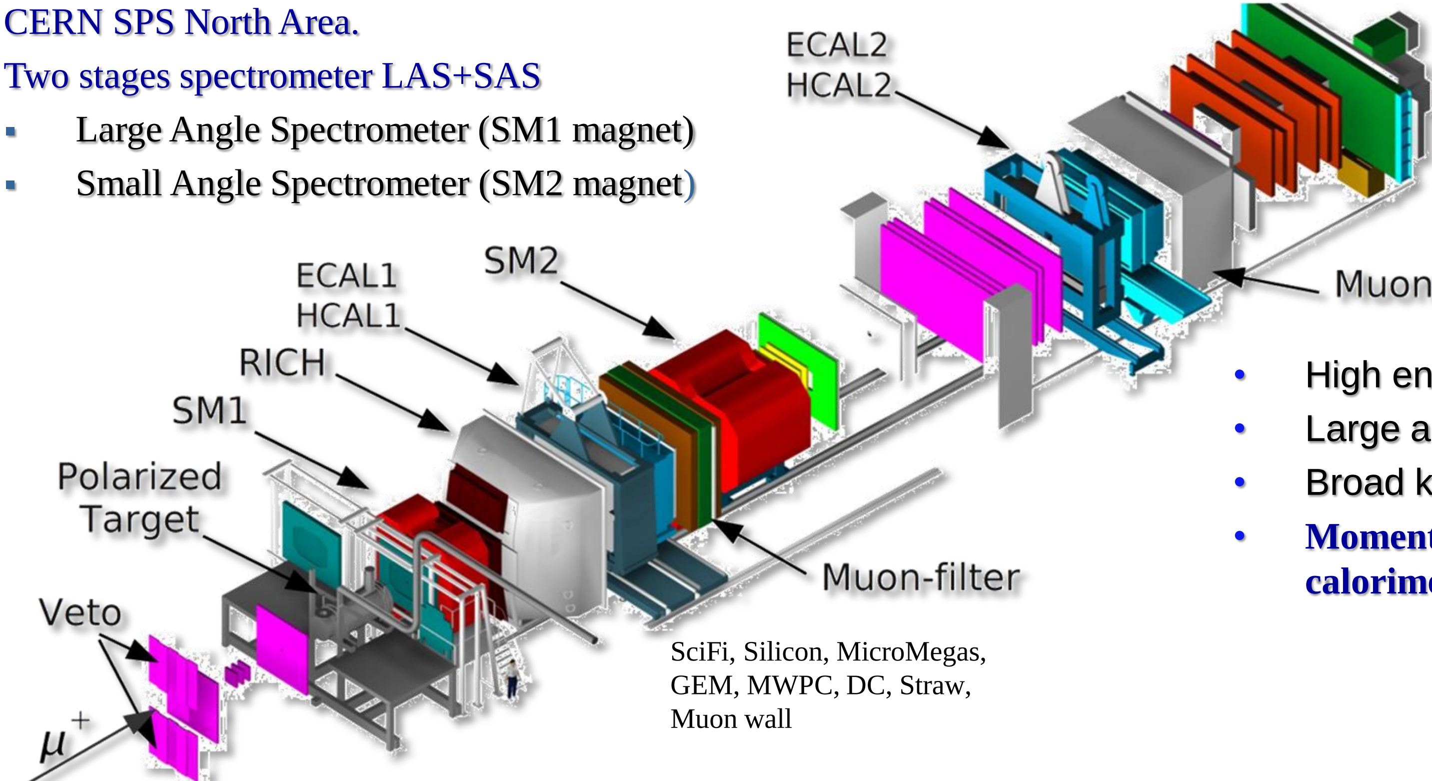
COMPASS experimental setup: Phase I (muon program)

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)



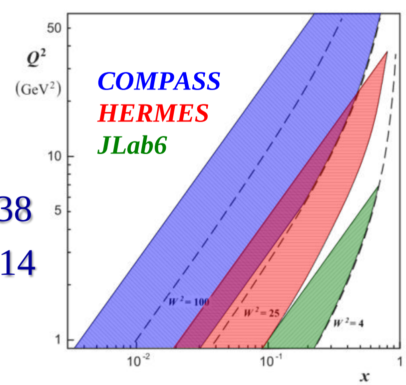
- High energy beam
- Large angular acceptance
- Broad kinematical range
- **Momentum, tracking and calorimetric measurements, PID**

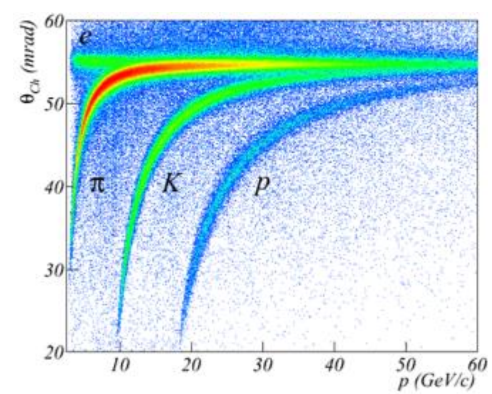
Longitudinally polarized (80%) μ^+ beam:
Energy: 160 GeV/c, Intensity: $2 \cdot 10^8$ μ^+/spill (4.8s).

Target: Solid state (^6LiD or NH_3)

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

Data-taking years: 2002-2011





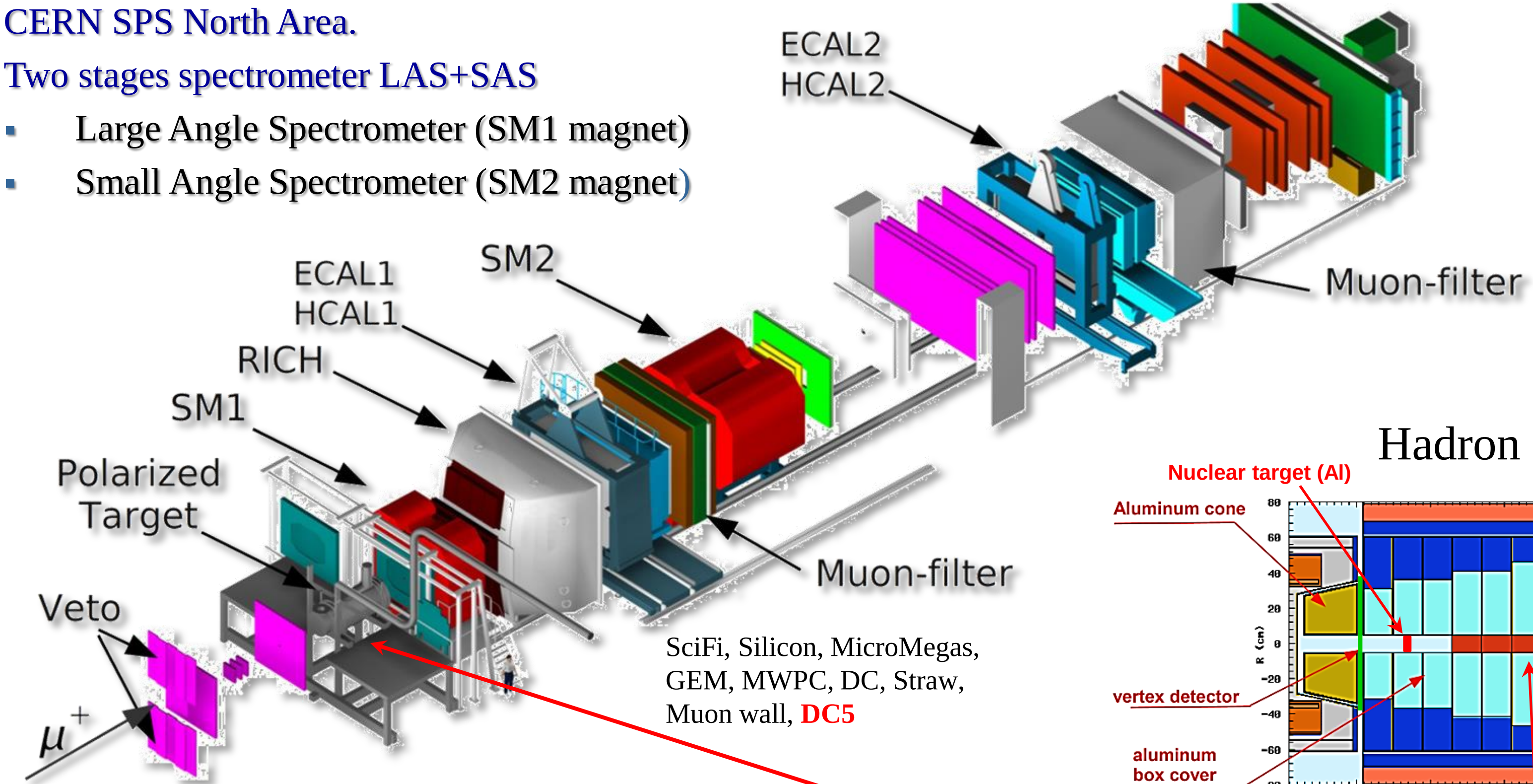
COMPASS experimental setup: Phase II (DY program)

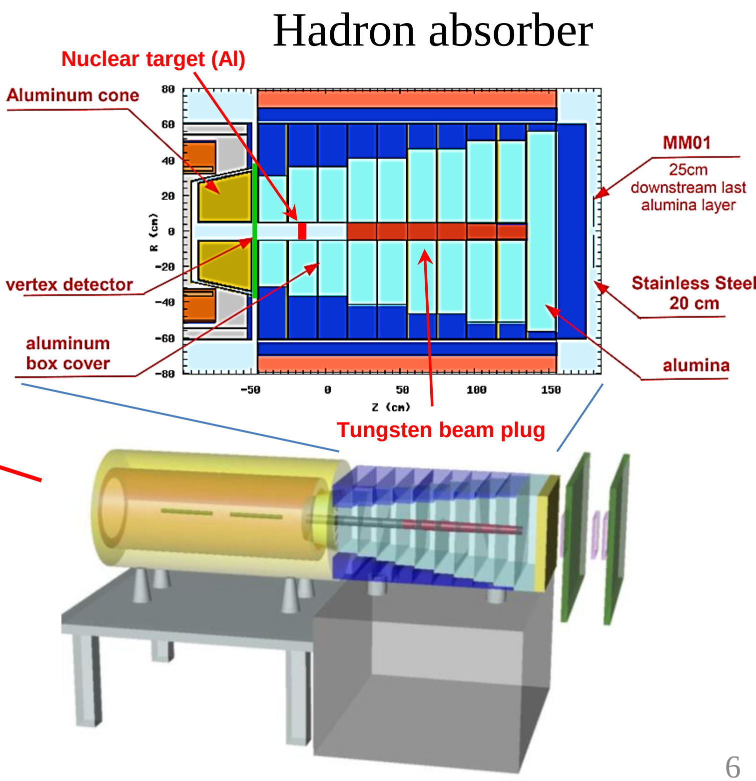
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area.

Two stages spectrometer LAS+SAS

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





High energy π^- beam:

Energy: 190 GeV/c, Intensity: 10^8 π/s

Target: Solid state

- NH_3 2-cell configuration. Polarization T ~ 90%, f ~ 0.22

Data-taking years: 2015 – NOW!

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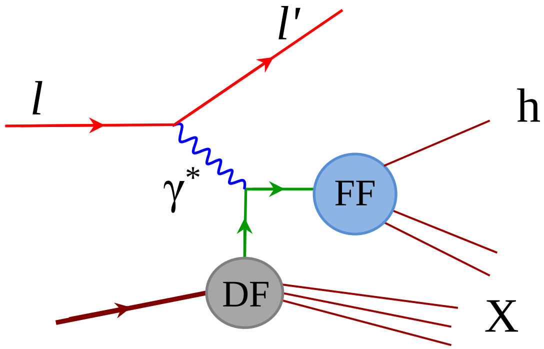
- Conclusions

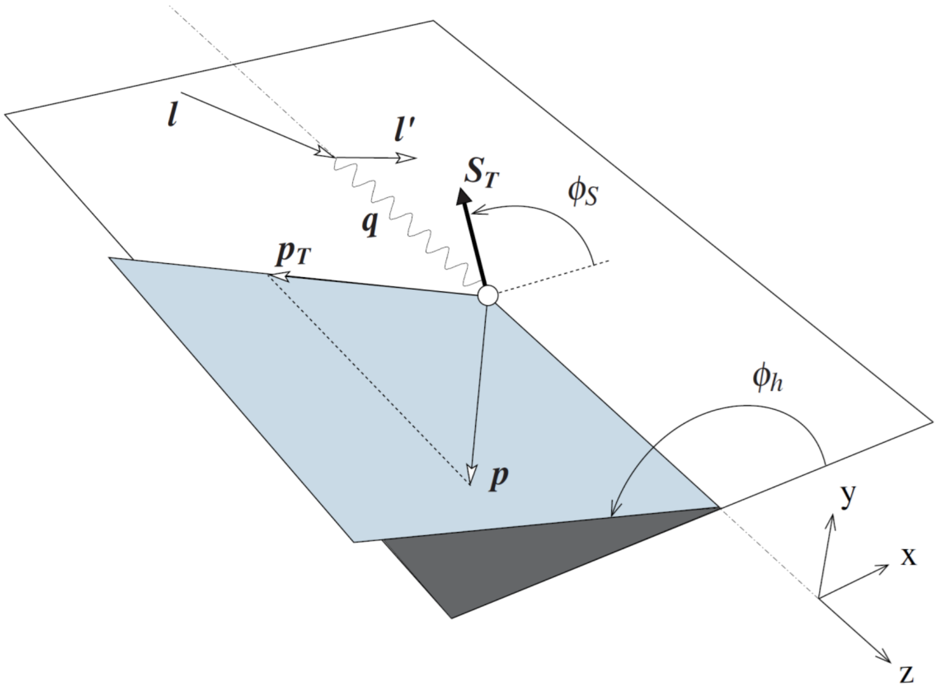
SIDIS x-section

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

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

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





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

SIDIS x-section

A.Kotzinian, Nucl. Phys. B441, 234 (1995).
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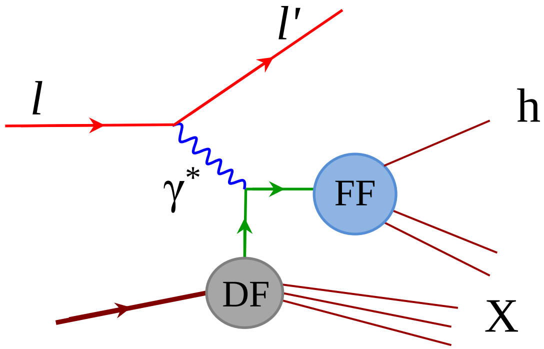
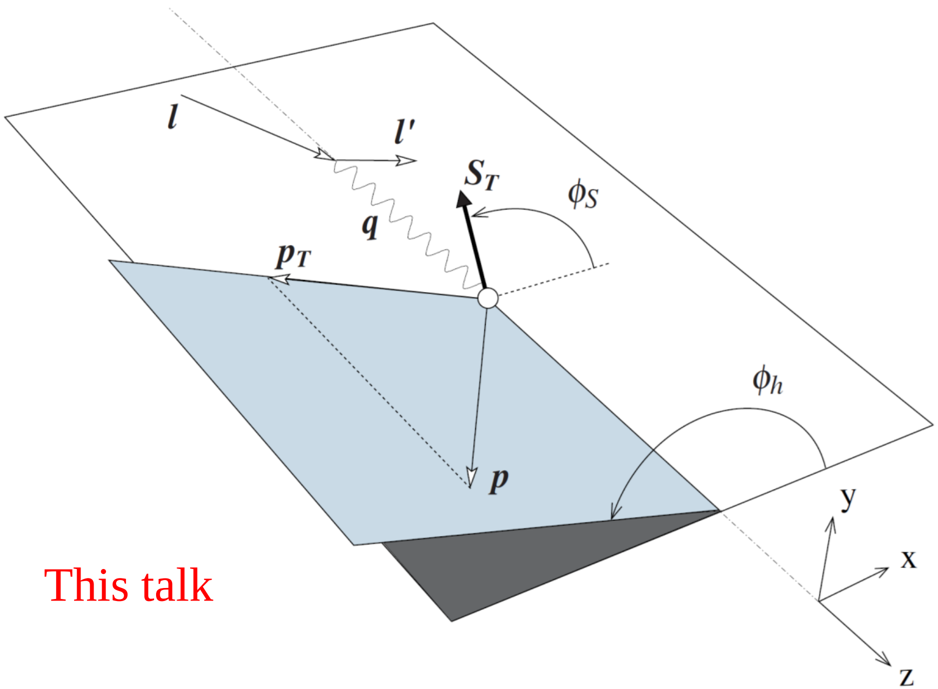
$$\frac{d\sigma}{dxdydzdP_{hT}^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

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

SSA ↑

↓ DSA





This talk

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

SIDIS x-section

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COMPASS

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

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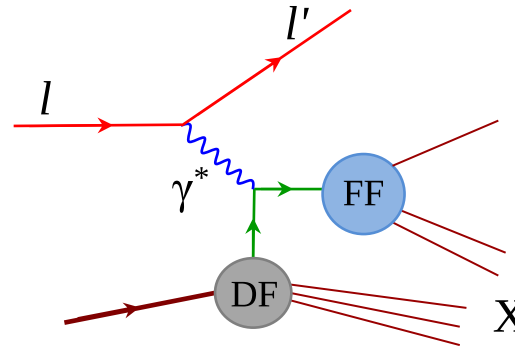
+\ \cos(2\phi_h-\phi_S)\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\right)
\end{array}\right]
\end{array}\right\}$$

SSA ⇧

⇩ DSA



Nucleon \ Quark	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**	$g_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ **worm-gear T**	$h_1^q(x,\mathbf{k}_T^2)$ **transversity** $h_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ **pretzelosity**

SIDIS x-section

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

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

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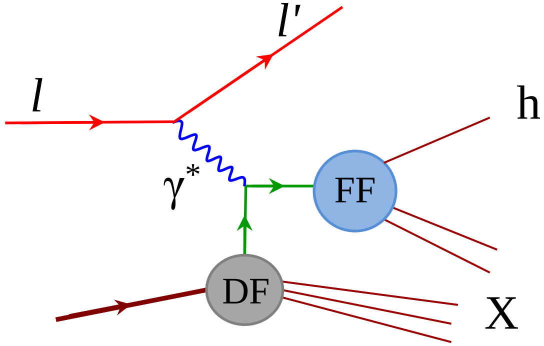
+\ S_L\left[\sin\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\right)+\sin 2\phi_h\left(\varepsilon A_{UL}^{\sin 2\phi_h}\right)\right] \\
+\ S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\cos\phi_h\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\right)\right] \\
+\ S_T\left[\begin{array}{l}\sin(\phi_h-\phi_S)\left(A_{UT}^{\sin(\phi_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

SSA

DSA



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

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

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

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

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

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

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

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

Twist-2

Twist-3

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SIDIS x-section

$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$ SSA [twist-2]

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

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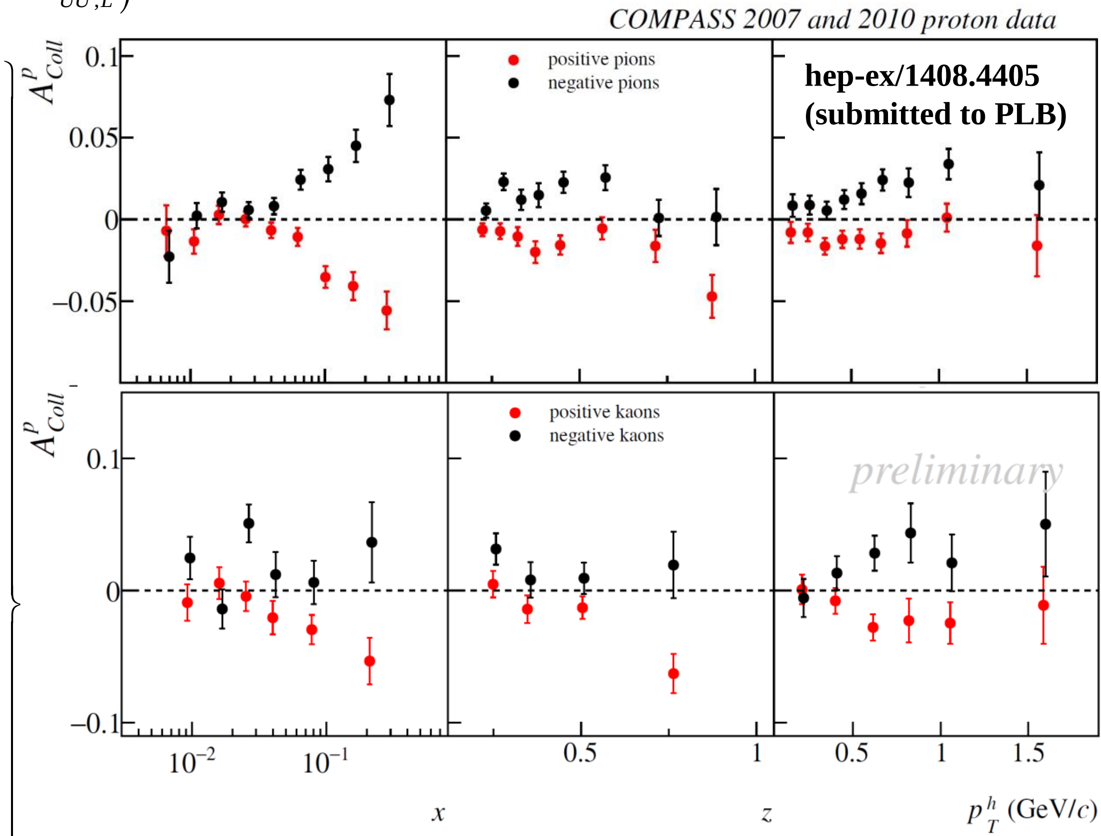
+\ \sin(3\phi_h-\phi_S)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right) \\
+\ \sin\phi_S\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\right) \\
+\ \sin(2\phi_h-\phi_S)\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\right)
\end{array}\right] \\
+\ S_T\lambda\left[\begin{array}{l}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

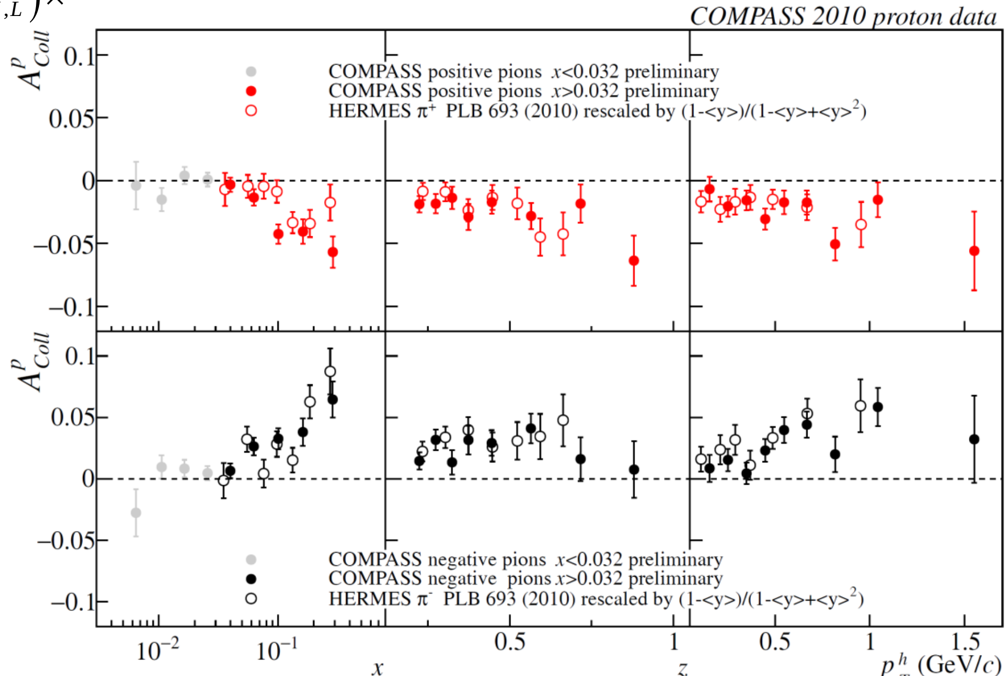


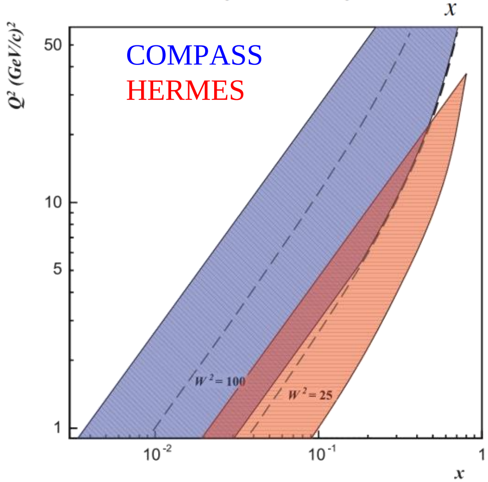
- Asymmetries are compatible with zero at small x
- Strong signal in the valence region of opposite sign for π^+ and π^-
- Opposite sign also for K^+/K^-: Clear negative trend in the valence region for K^+.
- Compatible with zero on deuteron

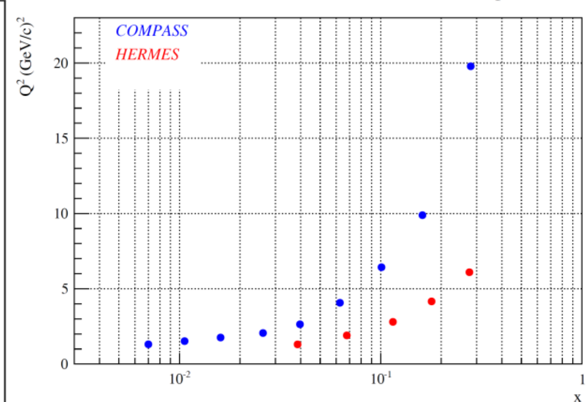
SIDIS x-section

$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$ SSA [twist-2]

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







- COMPASS and HERMES results are compatible - intriguing result! (Q^2 is different by a factor of ~2-3)

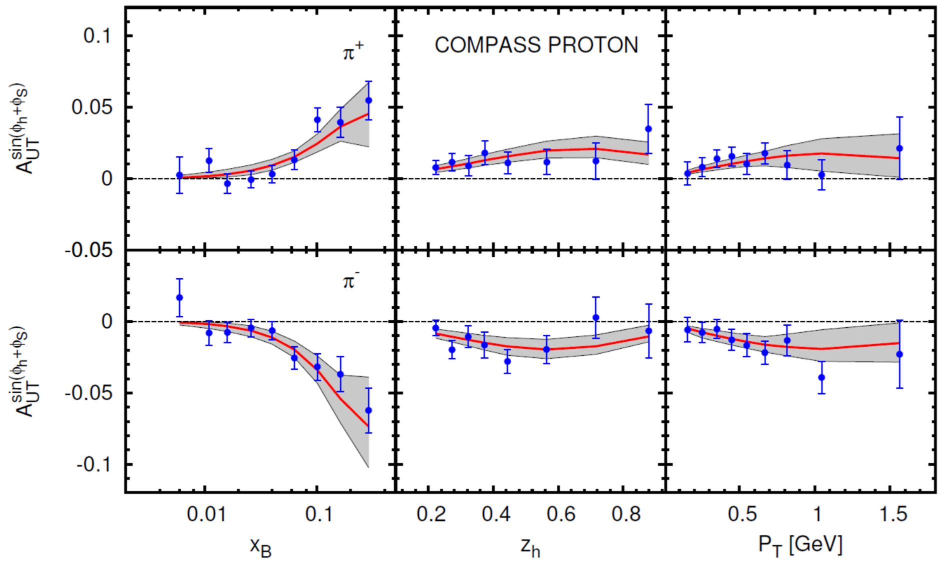
SIDIS x-section

$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$ SSA [twist-2]

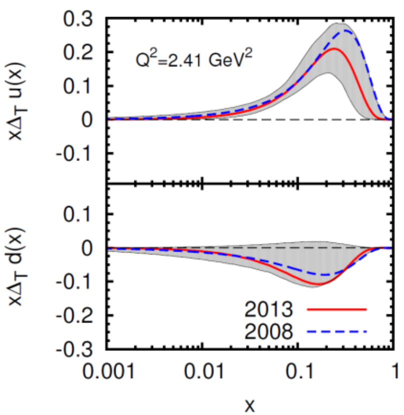
$$\frac{d\sigma}{dxdydzdP_{hT}^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

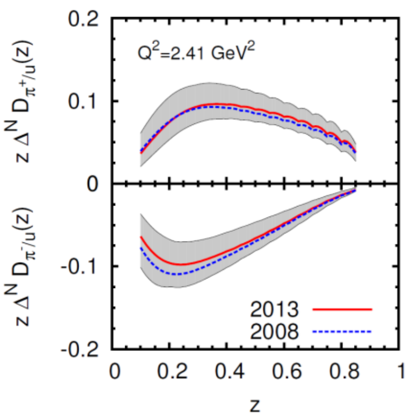
$$\left\{\begin{array}{l}
1+\cos\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\right)+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right) \\
+\ \lambda\sin\phi_h\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\right) \\
+\ S_L\left[\sin\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\right)+\sin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

Anselmino et al. **Phys.Rev. D87 (2013) 094019**



- Global fit of HERMES-COMPASS-BELLE data





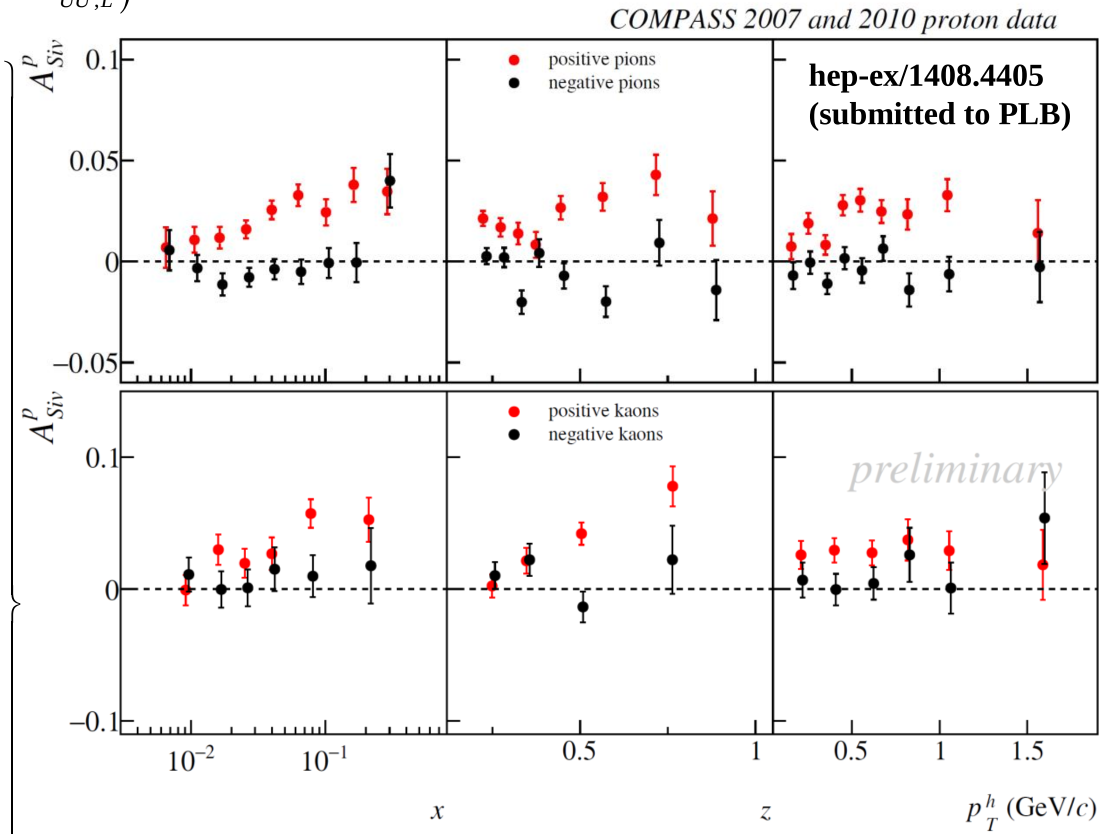
- Transversity PDF + Collins FF

SIDIS x-section

$$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h} \qquad \mathrm{SSA}[\text{twist-2}]$$

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

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



- Significantly large amplitude for π^+ and K^+ in whole range of x
- Some hints of negative signal for π^-
  - Positive signal in the last bin of x?
- Compatible with zero for K^-
- Compatible with zero on deuteron

SIDIS x-section

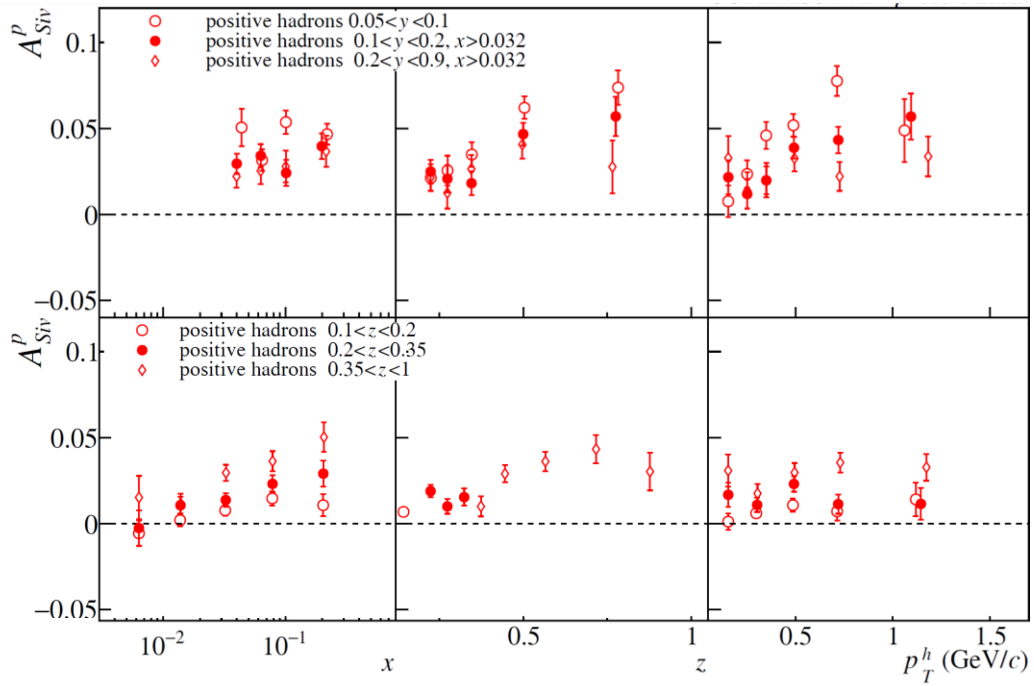
$$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h} \qquad \text{SSA}[\text{twist-2}]$$

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

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

Sivers in “2D” at COMPASS: first attempts

(PLB 717 (2012) 383)



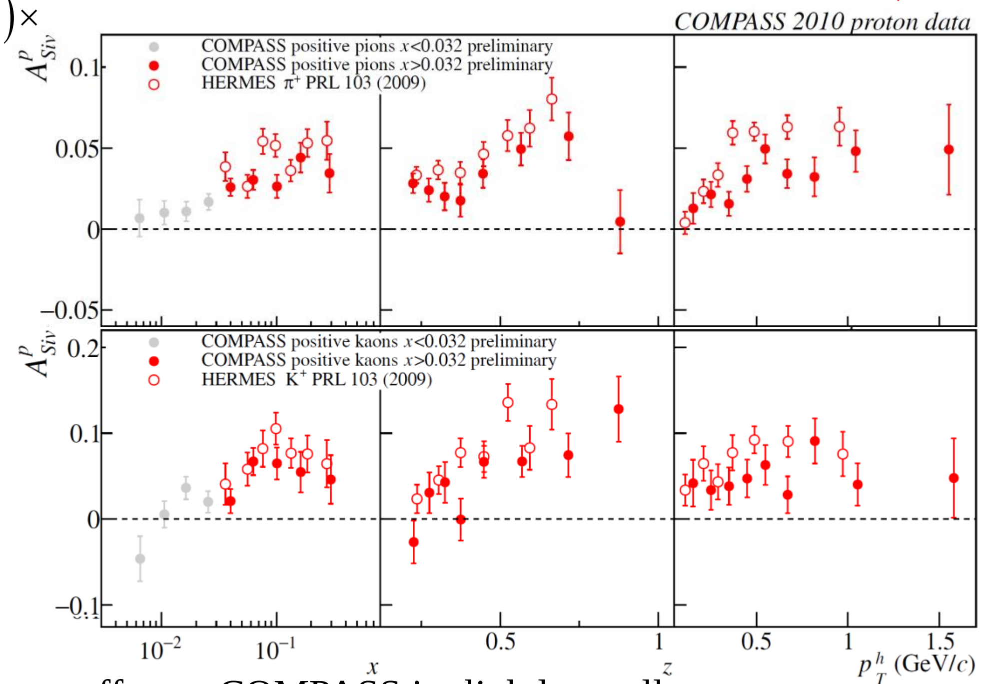
- All TSAs were studied in different x, z, y and W ranges
- Clear x-, y-, z- dependences
- Interesting results already at basic 2D approach
- Highly desirable challenge is to look into asymmetries in the multidimensional phase-space over $x - z - p_T - Q^2$

SIDIS x-section

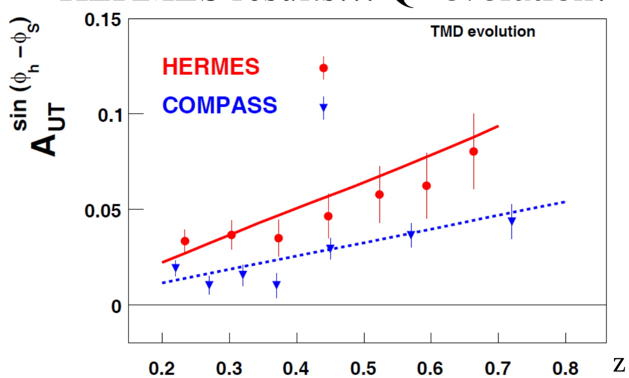
$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$ SSA[twist-2]

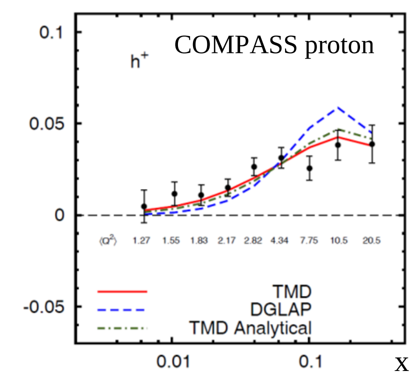
$$\frac{d\sigma}{dx\,dy\,dz\,dP_{hT}^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

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



- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results… Q^2-evolution?





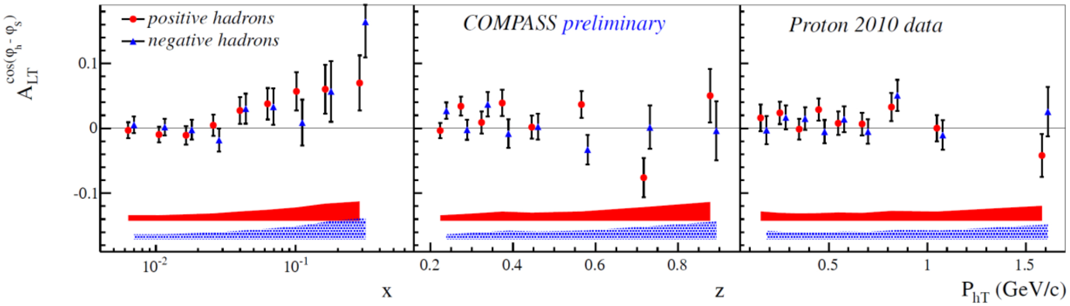
S. M. Aybat, A. Prokudin, T. C. Rogers **PRL 108 (2012) 242003**
M. Anselmino, M. Boglione, S. Melis **PRD 86 (2012) 014028**

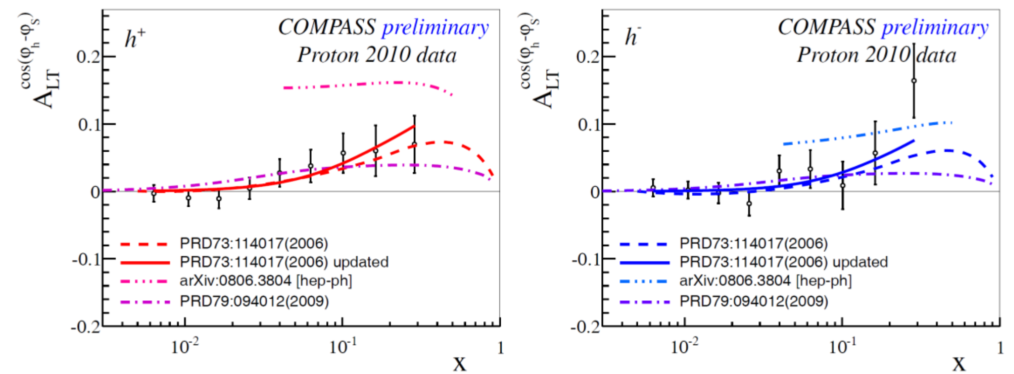
SIDIS x-section

$A_{LT}^{\cos(\phi_h-\phi_S)} \propto g_{1T}^q \otimes D_{1q}^h$ DSA[twist-2]

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

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





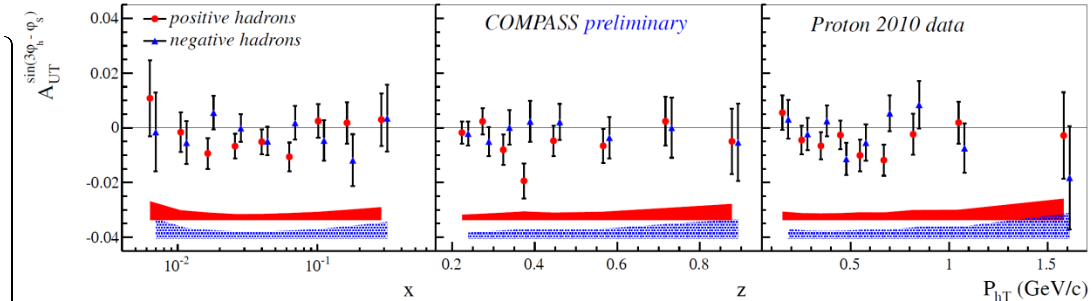
- Gives access to g_{1T} "twist-2" PDF (worm-gear-T)
- Visible signal for h+ (*preliminary* confirmation also by HERMES)
- In agreement with several model predictions
- Compatible with zero on deuteron

SIDIS x-section

$$A_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} \quad \text{SSA[twist-2]}$$

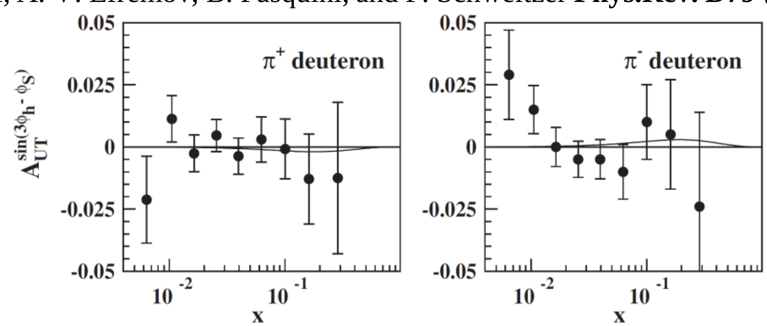
$$\frac{d\sigma}{dxdydzdP_{hT}^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

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

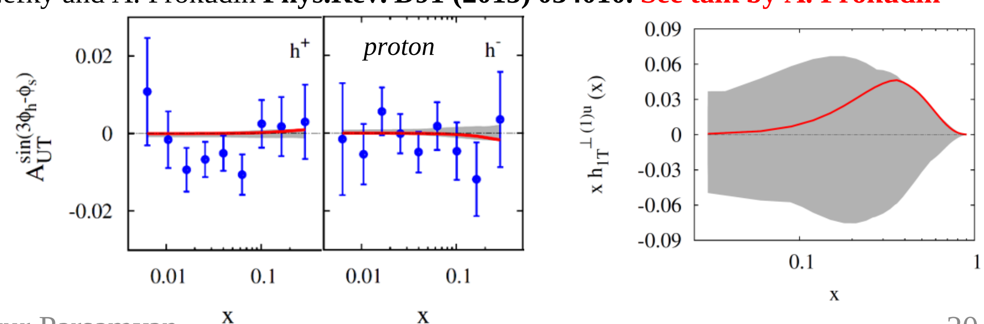


- All compatible with zero within uncertainties (P/D)
- Suppressed by a factor of $\sim|p_T|^2$ w.r.t the Collins and Sivers amplitudes

S. Boffi, A. V. Efremov, B. Pasquini, and P. Schweitzer **Phys.Rev. D79 (2009) 094012**



C. Lefky and A. Prokudin **Phys.Rev. D91 (2015) 034010. See talk by A. Prokudin**



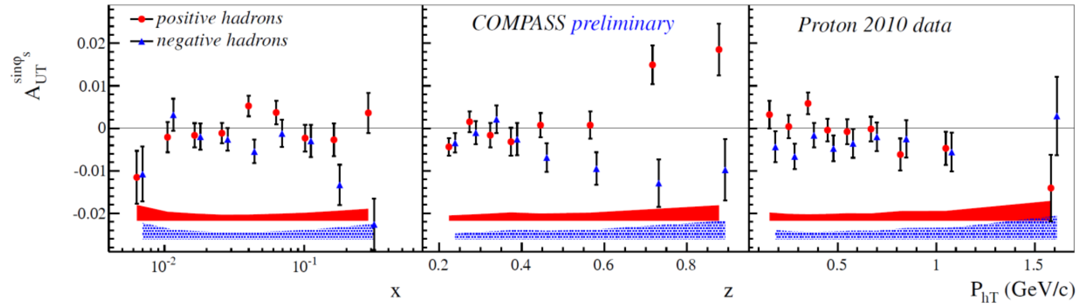
SIDIS x-section

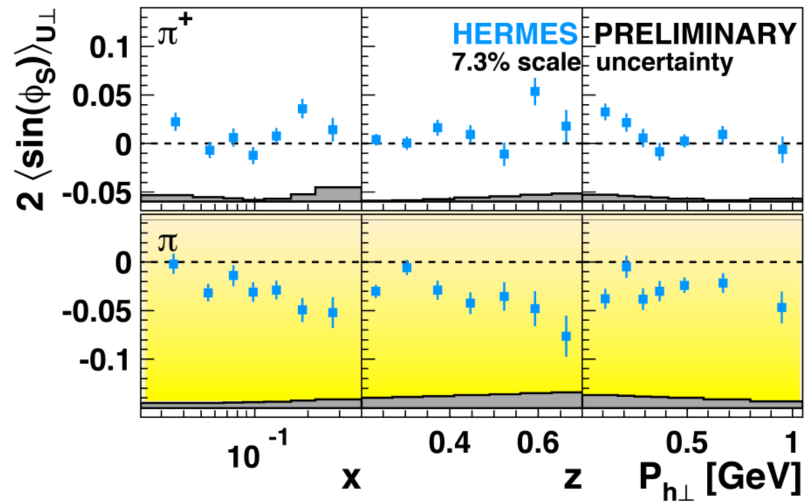
$$A_{UT}^{\sin(\phi_S)} \overset{WW}{\propto} Q^{-1}\left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right)$$

SSA [higher-twist]

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

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





- Higher twist effect..
- In WW-approximation is related to Sivers and Collins
- Non-zero trend for negative hadrons both in COMPASS and HERMES
- Compatible with zero on deuteron

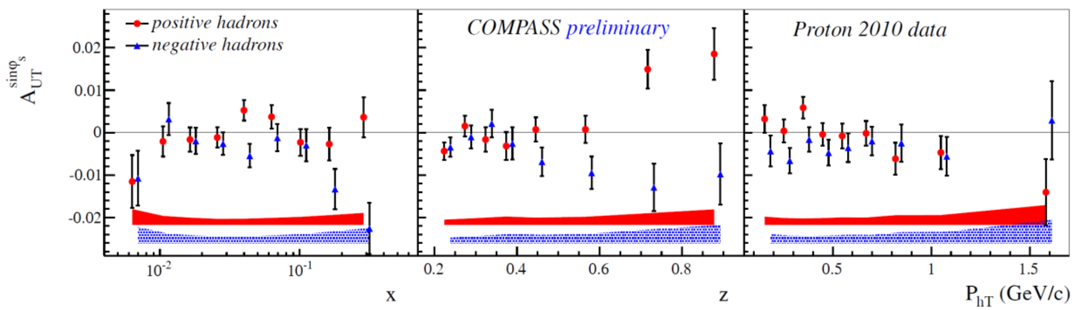
SIDIS x-section

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

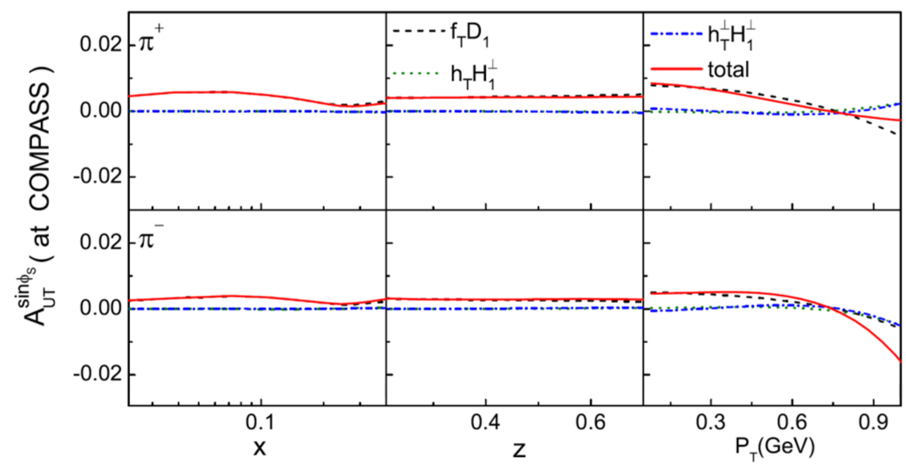
SSA [higher-twist]

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

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



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



- Higher twist effect..
- In WW-approximation is related to Sivers and Collins
- Non-zero trend for negative hadrons both in COMPASS and HERMES
- Compatible with zero on deuteron

SIDIS x-section

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

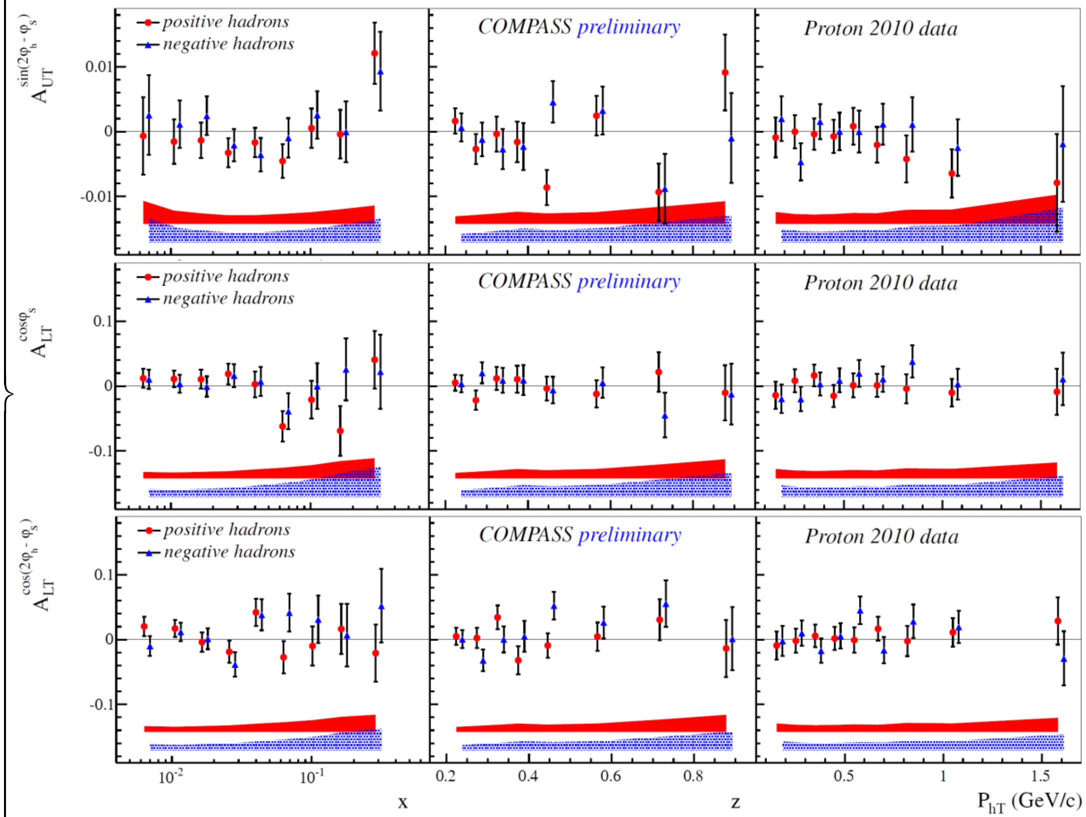
$$\left\{\begin{array}{l}
1+\cos\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\right)+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right)\\
+\ \lambda\sin\phi_h\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\right)\\
+\ S_L\left[\sin\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\right)+\sin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

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

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

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

SSA / DSA [higher-twist]



- All compatible with zero within uncertainties (P/D)

SIDIS x-section

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

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

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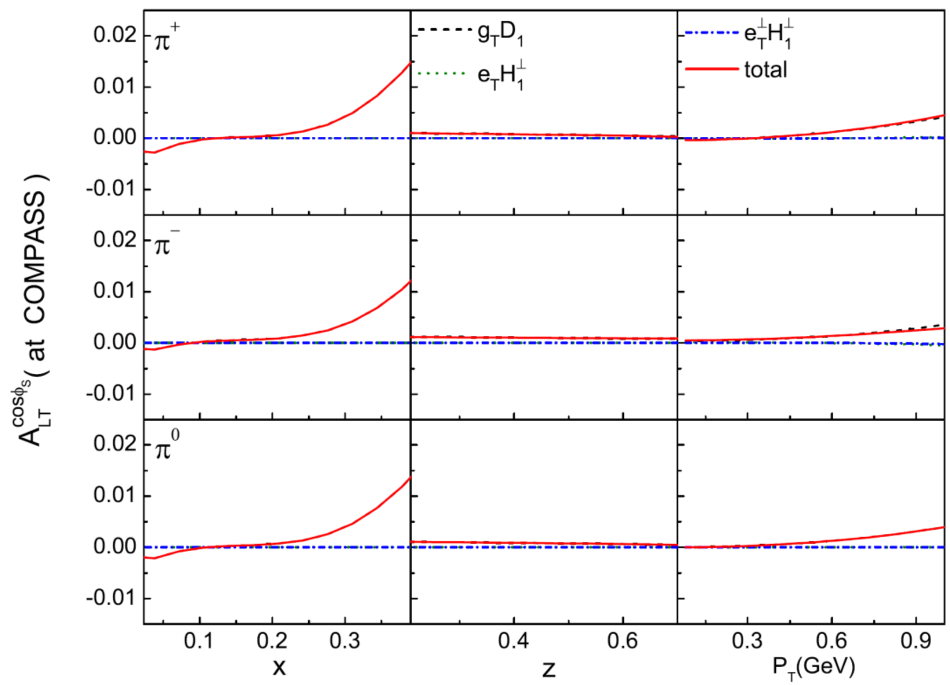
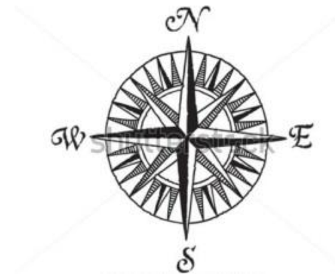
$$\left\{\begin{aligned}
&1+\cos\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\right)+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right)\\
&+\lambda\sin\phi_h\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\right)\\
&+S_L\left[\sin\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\right)+\sin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

W. Mao, Z. Lu, B.Q. Ma and I. Schmidt, **Phys.Rev. D91 (2015) 034029**



- All compatible with zero within uncertainties (P/D)

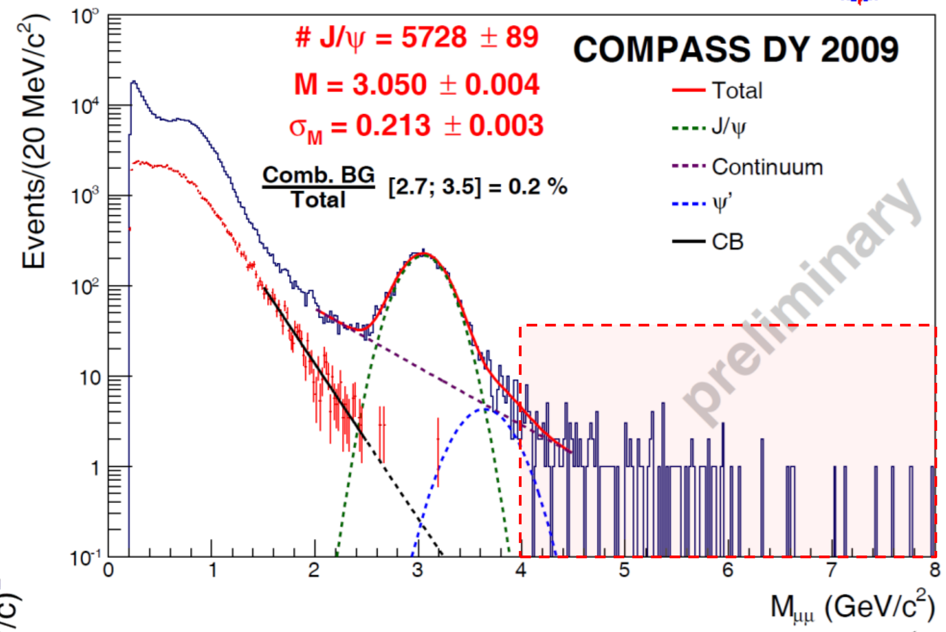
COMPASS bridge

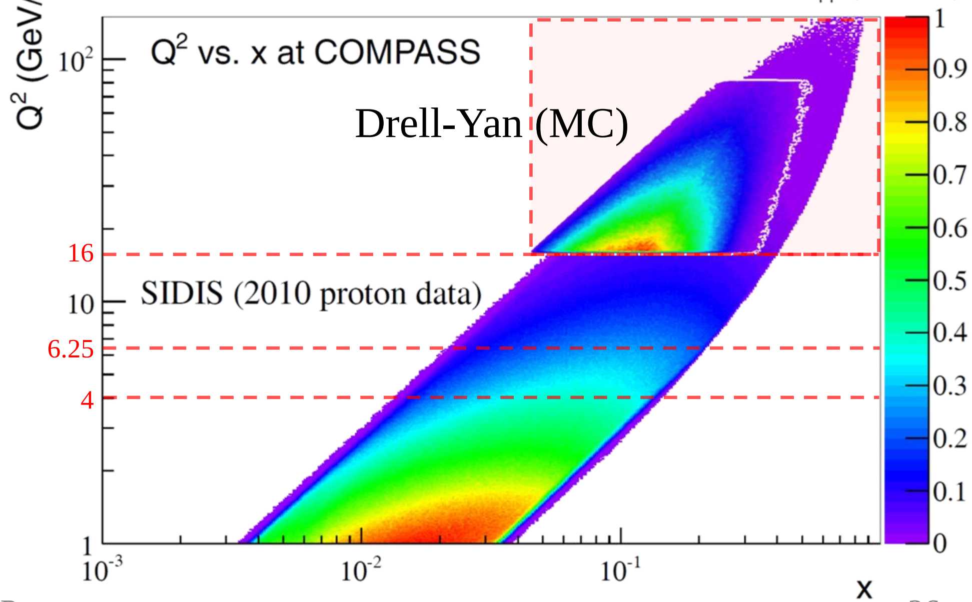


COMPASS x:Q^2 phase-space: SIDIS – Drell-Yan

Four Q^2(or mass)-ranges:

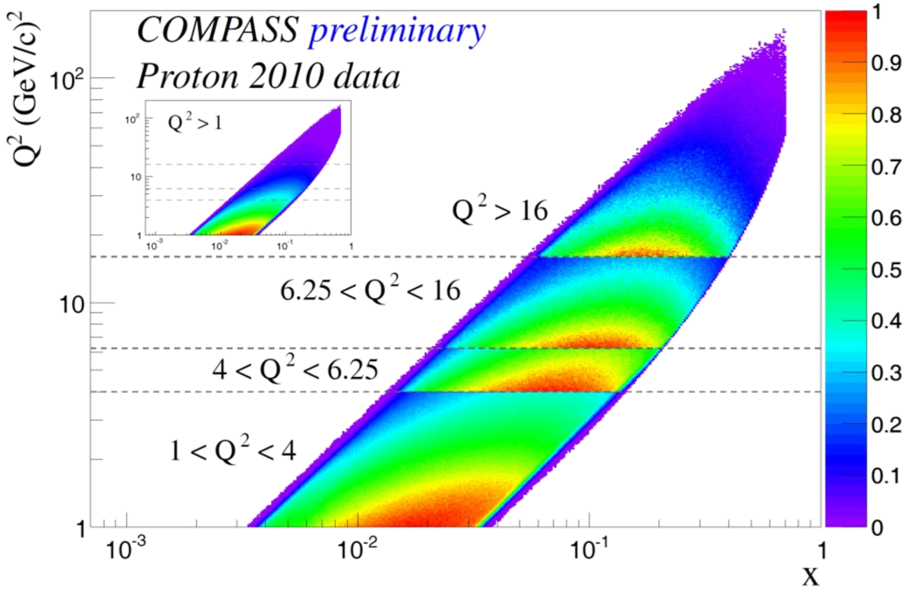
- $1 < Q^2/(GeV/c)^2 < 4$ “Low mass”
  - Large combinatorial background
    - Pion and kaon decays
    - Open-charm (bottom) semi-leptonic decays $D\bar{D}$, $B\bar{B}$
  - smaller asymmetries
- $4 < Q^2/(GeV/c)^2 < 6.25$ “Intermediate”
  - High DY-cross section
  - Still low signal/background
- $6.25 < Q^2/(GeV/c)^2 < 16$ “J/ψ”
  - Strong J/ψ-signal → study of J/ψ physics
  - Difficult to disentangle DY
  - Lower background
- $Q^2/(GeV/c)^2 > 16$ “High mass”
  - Beyond J/ψ peak
  - Negligible background
  - Low cross-section
  - Valence region → largest asymmetries

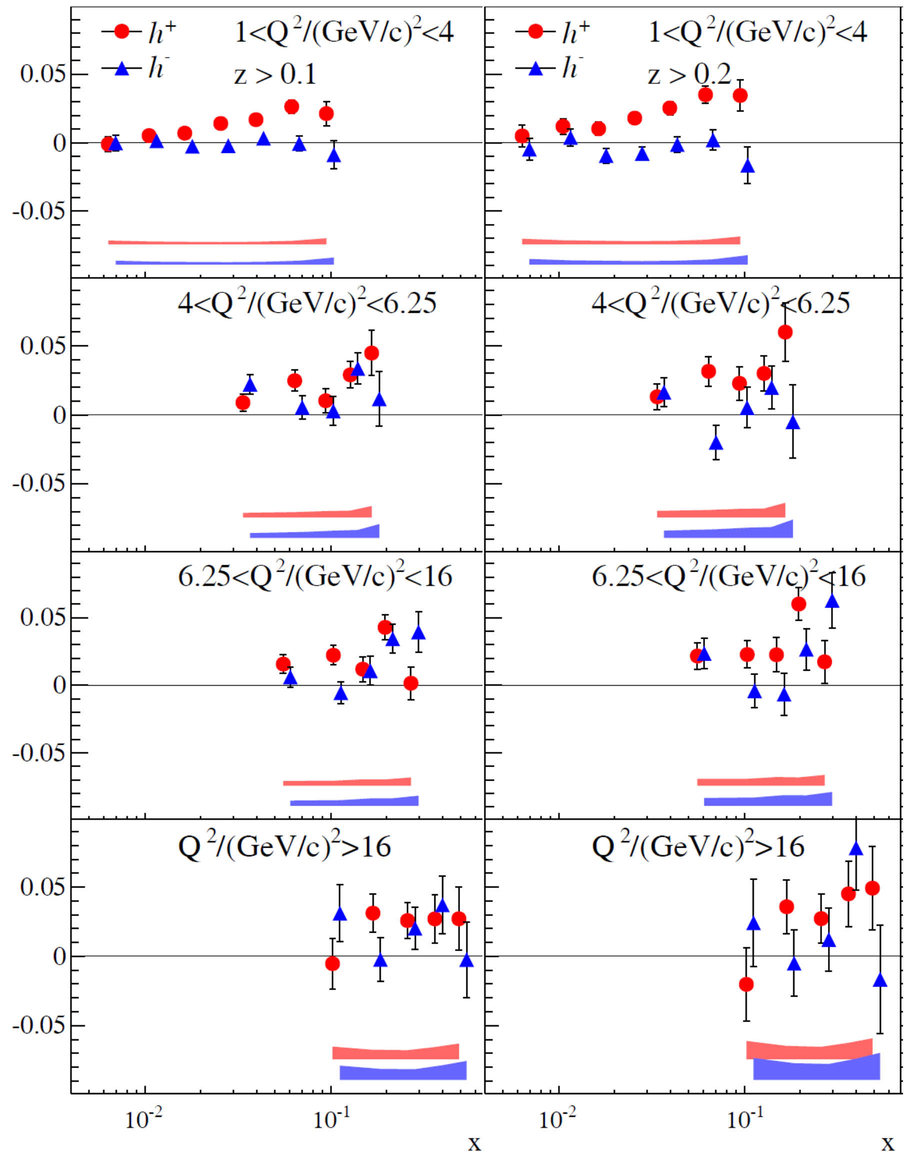




SIDIS asymmetries in Drell-Yan Q^2 ranges

First shown at the Transversity-2014 conference **arXiv:1411.1568 [hep-ex]**





Towards 3D…

Four Q^2-ranges:

- $1 < Q^2/(GeV/c)^2 < 4$ "Low mass"
- $4 < Q^2/(GeV/c)^2 < 6.25$ "Intermediate"
- $6.25 < Q^2/(GeV/c)^2 < 16$ "J/ψ range"
- $Q^2/(GeV/c)^2 > 16$ "High mass range"

For each Q^2-range → two different z-ranges:

- $z \in [0.2; 1.0]$ – standard selection (cuts)
- $z \in [0.1; 1.0]$ – Extended region: Low z ($z \in [0.1; 0.2]$) + std. selection (cuts)

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

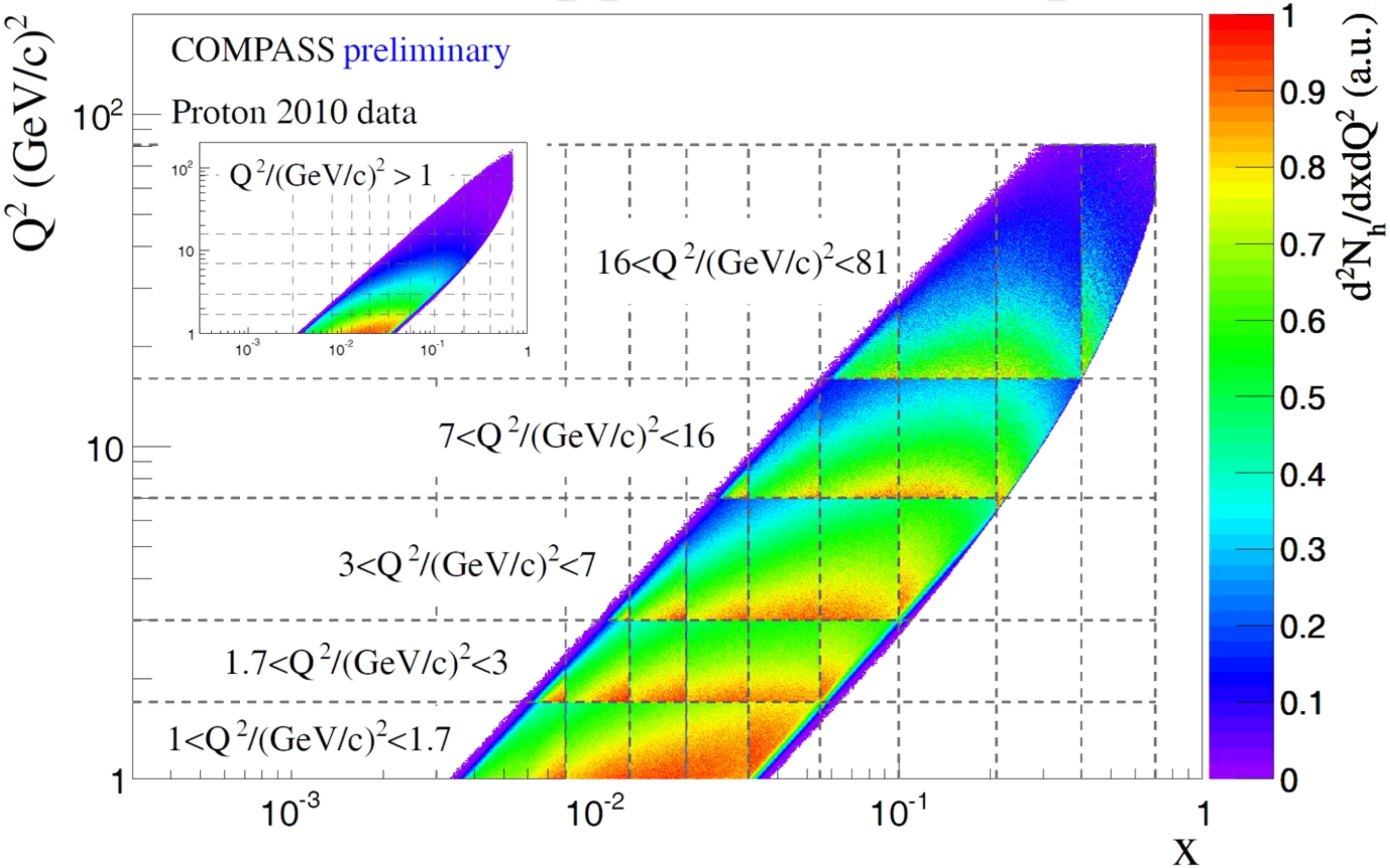
Multidimensional approach concept I ($x:Q^2$)

- 1st option (2D asymmetries):
  - x-, z-, p_T-, and W- dependences in 5 Q^2-bins
- 2nd option (3D asymmetries):
  - x-dependence in $Q^2:z$ grid (5×5)
  - Q^2-dependence in $x:z$ grid (9×5)
  - x-dependence in $Q^2:p_T$ grid (5×5)
  - Q^2-dependence in $x:p_T$ grid (9×5)
- 3rd option (4D asymmetries)
  - x-dependence in $z:Q^2:p_T$ grid (2×5×5)
  - Q^2-dependence in $z:x:p_T$ grid (2×9×5)

Q^2 ranges:	z ranges:	p_T ranges:
$1 < Q^2 < 1.7$	$z > 0.1$	$p_T > 0.1$
$1.7 < Q^2 < 3$	$z > 0.2$	$0.1 < p_T < 0.75$
$3 < Q^2 < 7$	$0.1 < z < 0.2$	$0.1 < p_T < 0.3$
$7 < Q^2 < 16$	$0.2 < z < 0.4$	$0.3 < p_T < 0.75$
$16 < Q^2 < 81$	$0.4 < z < 1.0$	$p_T > 0.75$

x bins: 0.003, 0.008, 0.013, 0.02, 0.032, 0.055, 0.10, 0.21, 0.40, 0.7

Multidimensional approach concept I (x:Q²)



Q^2 ranges:

- $1 < Q^2 < 1.7$
- $1.7 < Q^2 < 3$
- $3 < Q^2 < 7$
- $7 < Q^2 < 16$
- $16 < Q^2 < 81$

z ranges:

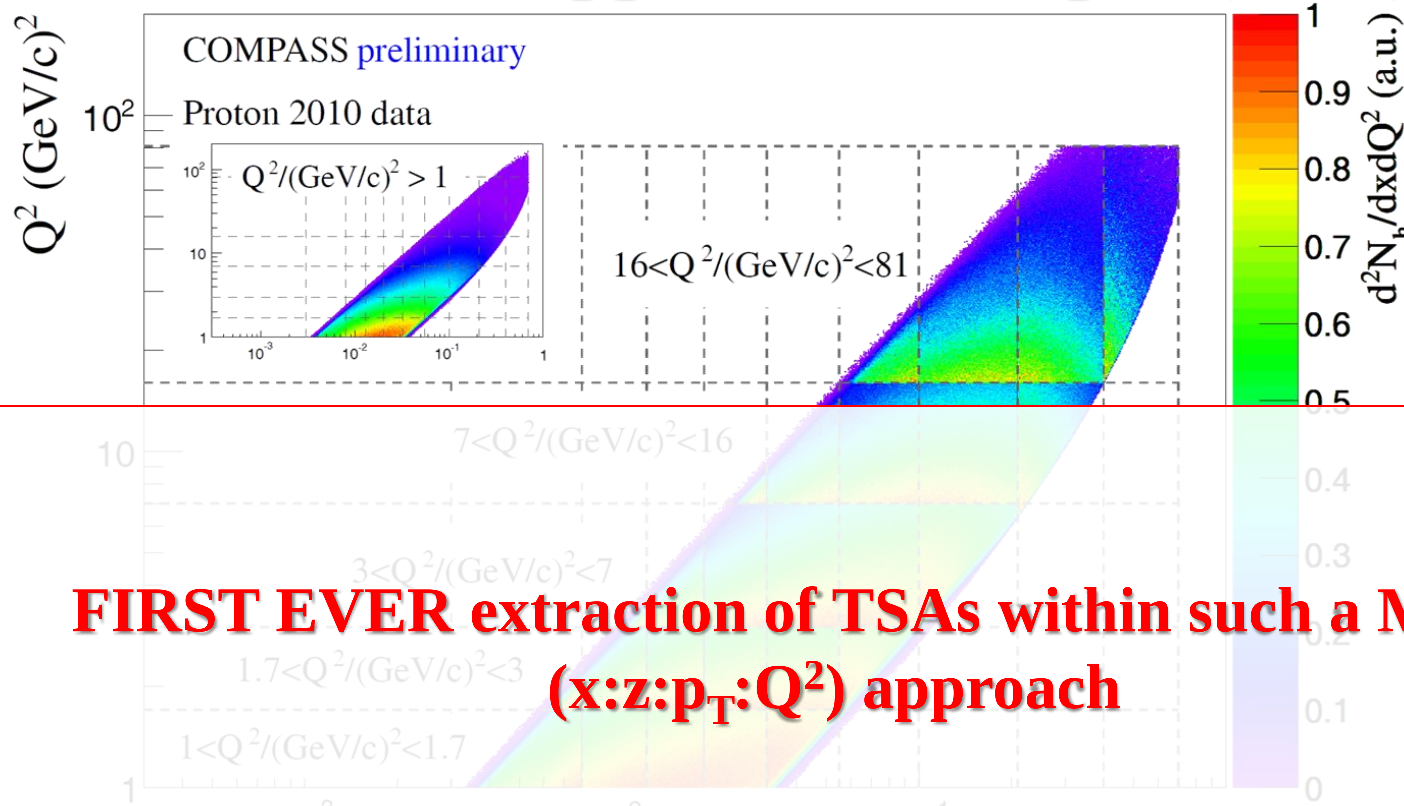
- $z > 0.1$
- $z > 0.2$
- $0.1 < z < 0.2$
- $0.2 < z < 0.4$
- $0.4 < z < 1.0$

p_T ranges:

- $p_T > 0.1$
- $0.1 < p_T < 0.75$
- $0.1 < p_T < 0.3$
- $0.3 < p_T < 0.75$
- $p_T > 0.75$

x bins: 0.003, 0.008, 0.013, 0.02, 0.032, 0.055, 0.10, 0.21, 0.40, 0.7

Multidimensional approach concept I ($x:Q^2$)



FIRST EVER extraction of TSAs within such a Multi-D ($x:z:p_T:Q^2$) approach

Results first shown at the SPIN-2014 conference arXiv:1504.01599 **[hep-ex]**

Q^2 ranges:
- $1 < Q^2 < 1.7$
- $1.7 < Q^2 < 3$
- $3 < Q^2 < 7$
- $7 < Q^2 < 16$
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z ranges:
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- $0.1 < z < 0.2$
- $0.2 < z < 0.4$
- $0.4 < z < 1.0$

p_T ranges:
- $p_T > 0.1$
- $0.1 < p_T < 0.75$
- $0.1 < p_T < 0.3$
- $0.3 < p_T < 0.75$
- $p_T > 0.75$

x bins: 0.003, 0.008, 0.013, 0.02, 0.032, 0.055, 0.10, 0.21, 0.40, 0.7

Multidimensional approach concept II ($z{:}p_T$)

3D asymmetries:

- Asymmetries from 3 x-ranges in $z{:}p_T$ bins (7×6)
- Asymmetries from 3 x-ranges in $p_T{:}z$ bins ($z{:}p_T$ - transposed)

x ranges:

- **all x**
- **$x<0.032$**
- **$x>0.032$**

z bins:

- **$0.1 < z < 0.15$**
- **$0.15 < z < 0.2$**
- **$0.2 < z < 0.25$**
- **$0.25 < z < 0.3$**
- **$0.3 < z < 0.4$**
- **$0.4 < z < 0.65$**
- **$0.65 < z < 1$**

p_T bins:

- **$0.1 < p_T < 0.2$**
- **$0.2 < p_T < 0.3$**
- **$0.3 < p_T < 0.5$**
- **$0.5 < p_T < 0.75$**
- **$0.75 < p_T < 1.0$**
- **$p_T > 1.0$**

Multidimensional approach concept II ($z:p_T$)

3D asymmetries:

- Asymmetries from 3 x-ranges in $z:p_T$ bins (7×6)
- Asymmetries from 3 x-ranges in $p_T:z$ bins ($z:p_T$ - transposed)

x ranges:

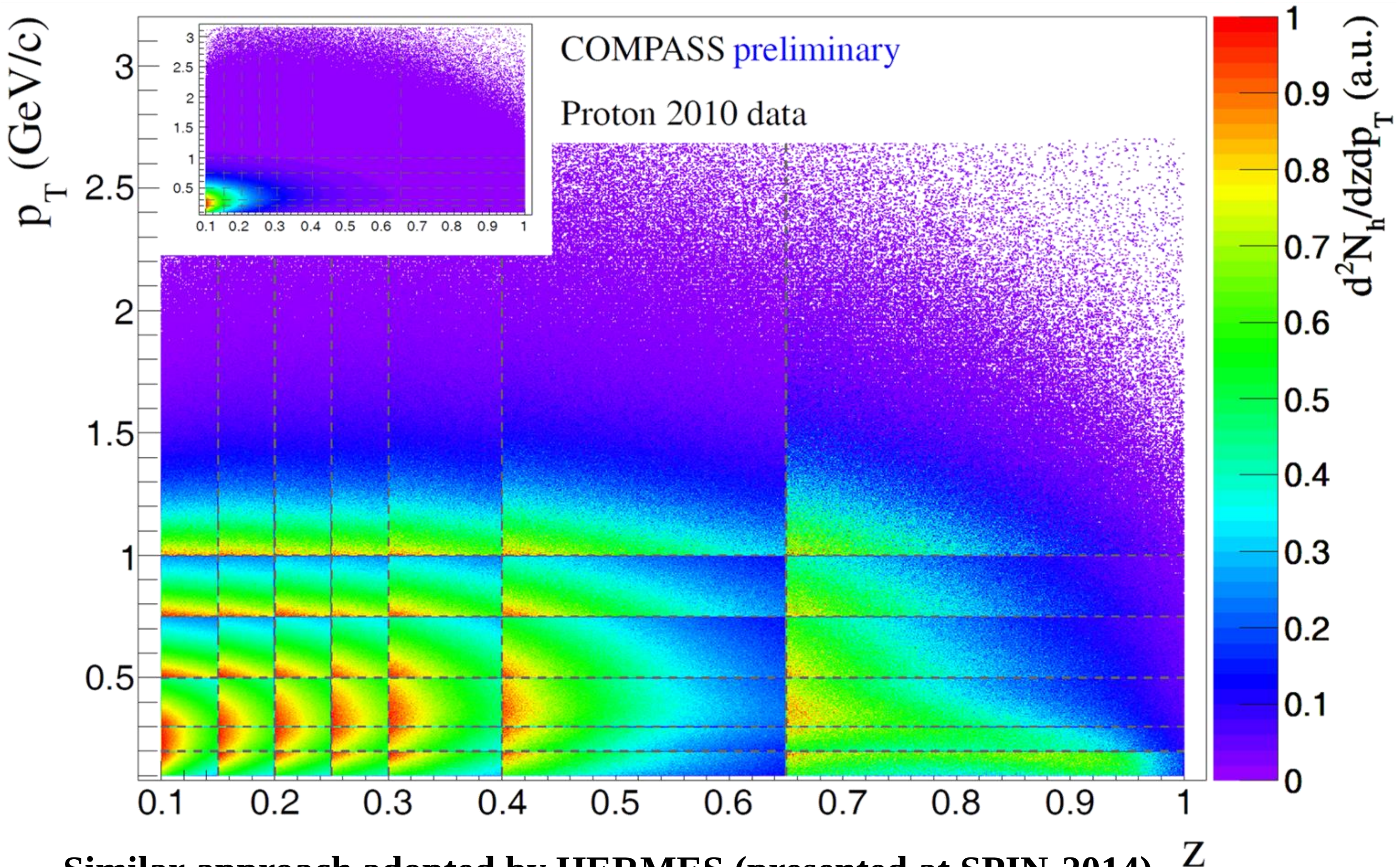
- **all x**
- **x<0.032**
- **x>0.032**

z bins:

- **$0.1 < z < 0.15$**
- **$0.15 < z < 0.2$**
- **$0.2 < z < 0.25$**
- **$0.25 < z < 0.3$**
- **$0.3 < z < 0.4$**
- **$0.4 < z < 0.65$**
- **$0.65 < z < 1$**

p_T bins:

- **$0.1 < p_T < 0.2$**
- **$0.2 < p_T < 0.3$**
- **$0.3 < p_T < 0.5$**
- **$0.5 < p_T < 0.75$**
- **$0.75 < p_T < 1.0$**
- **$p_T > 1.0$**



Similar approach adopted by HERMES (presented at SPIN-2014)

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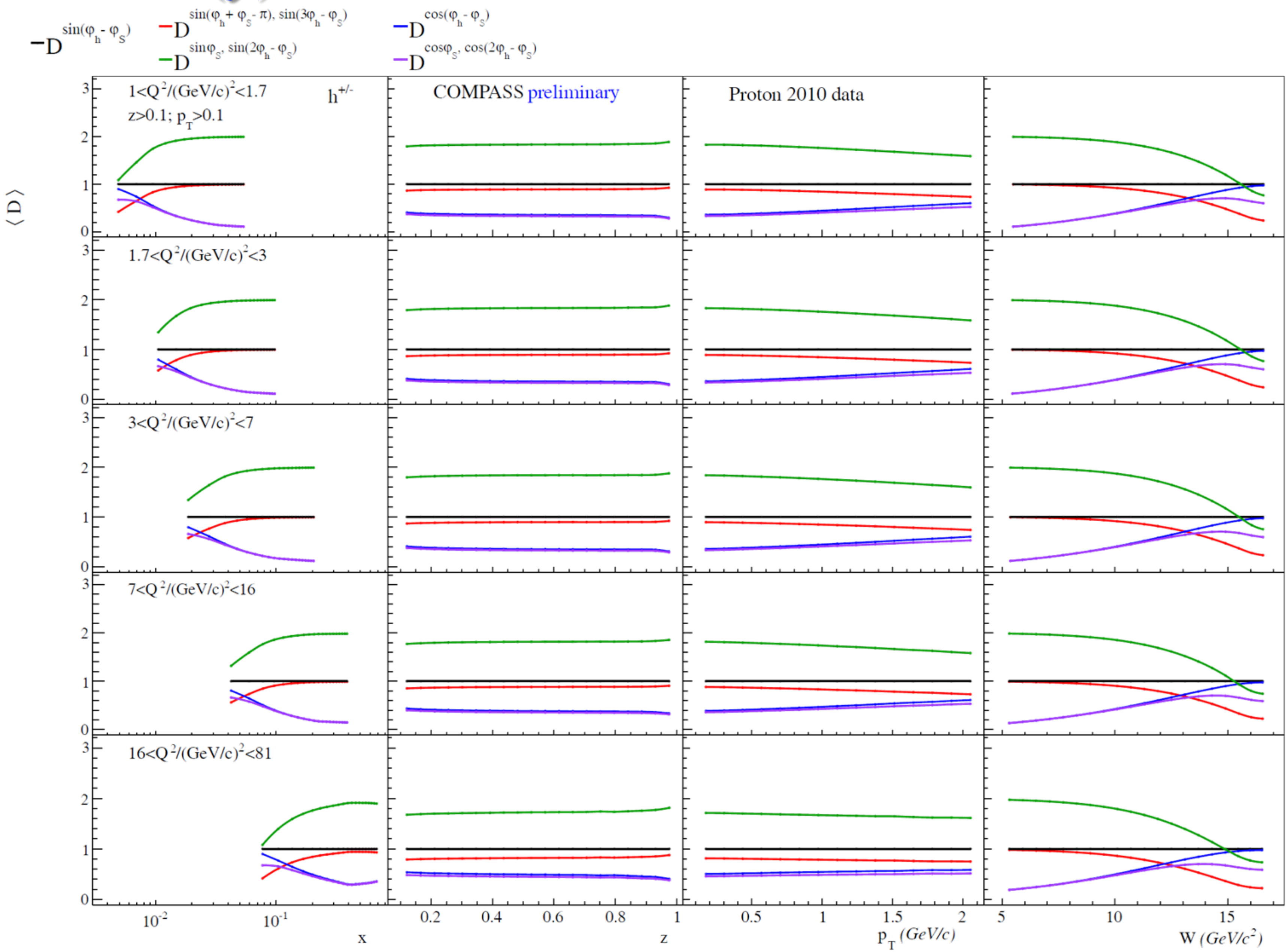
Mean D(y)-factors



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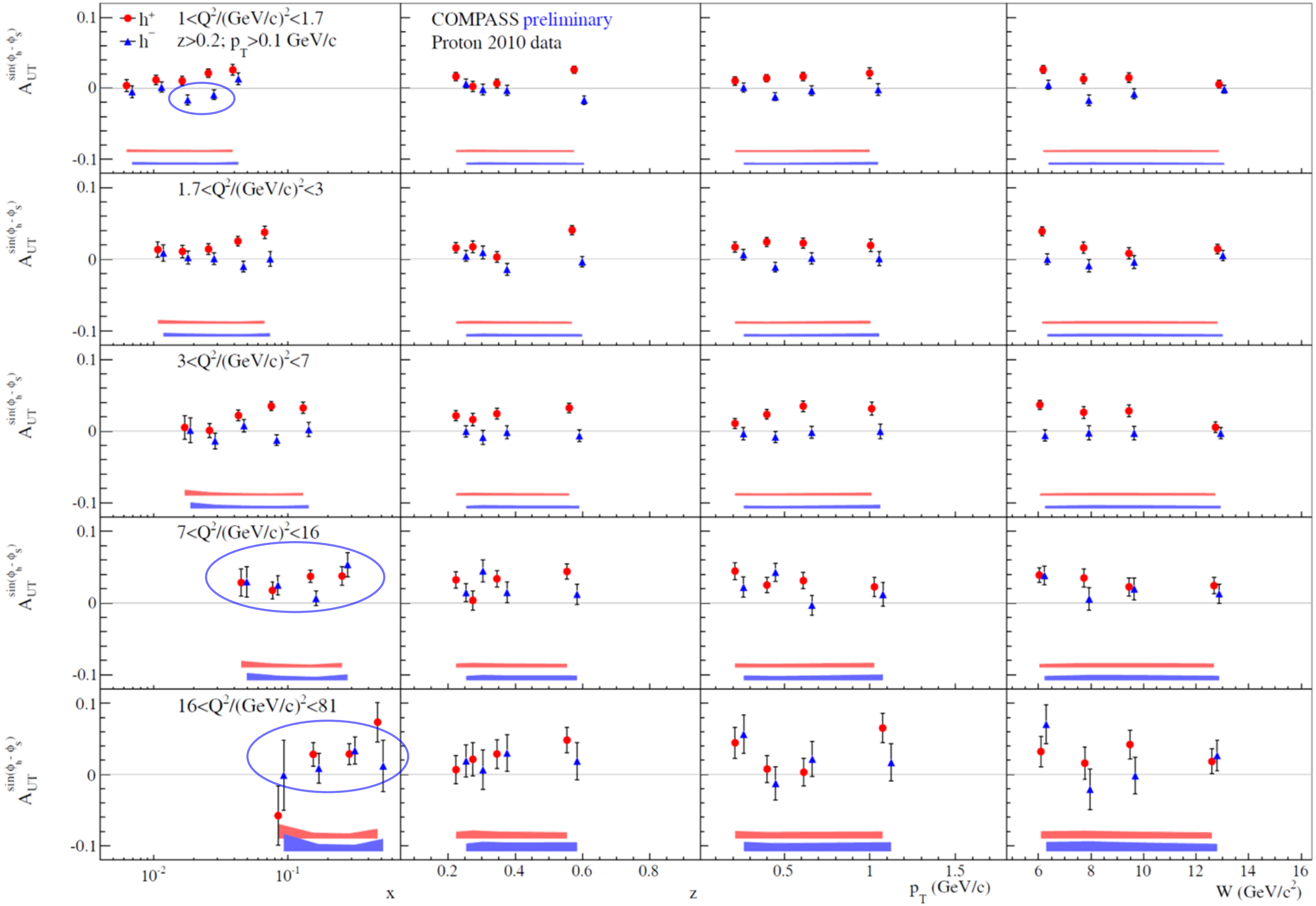
- Conclusions

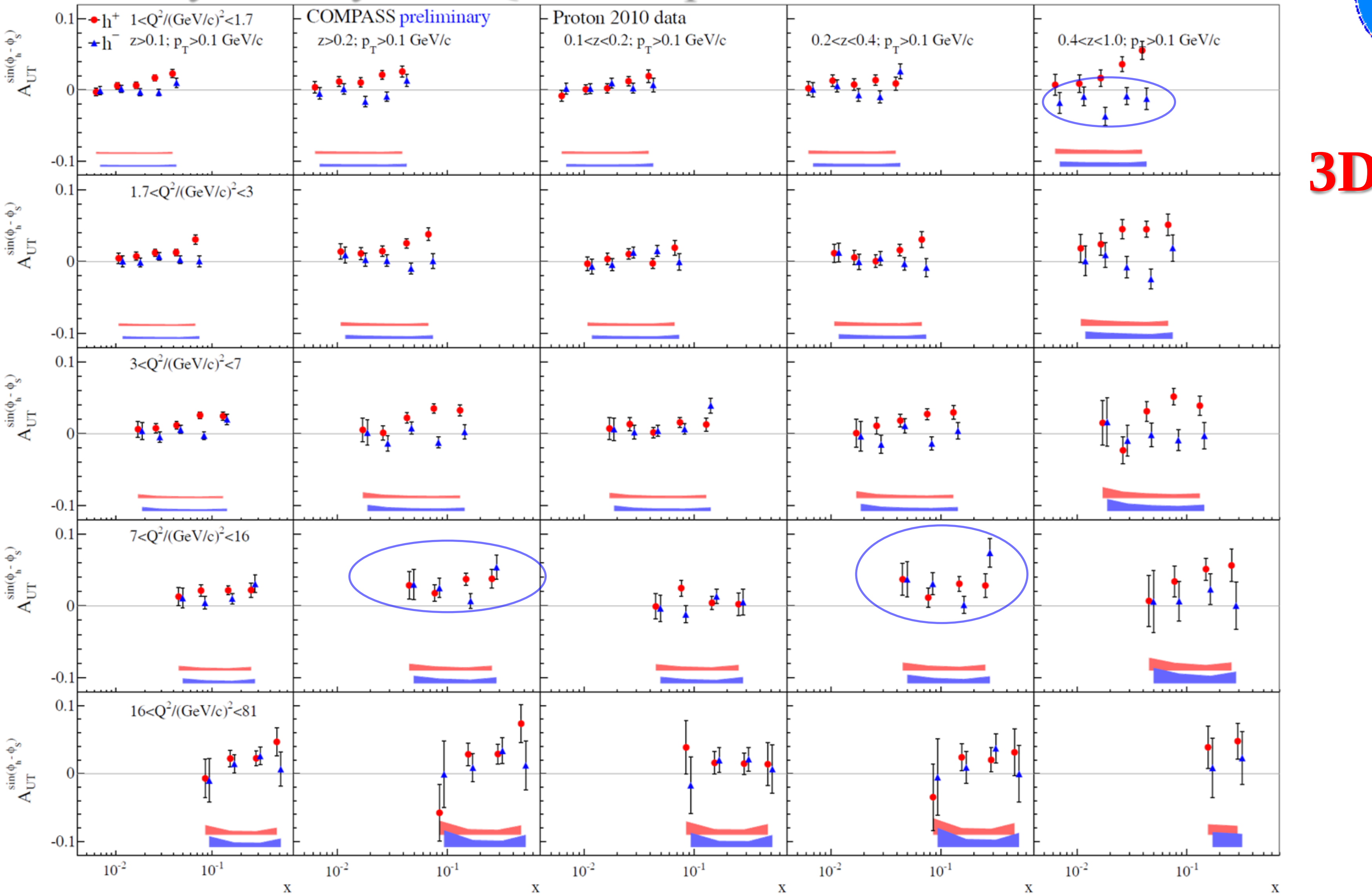
Sivers asymmetry: x, z, p_T and W dependences in 5 Q^2-ranges



2D

- **Positive amplitude for h^+ (increasing with x)**
- **Positive h^- amplitude at relatively large x (>0.032) and Q^2 (>7)**
- **Some hint for a possible negative h^- amplitude at low x (<0.032) and Q^2 (<7)**

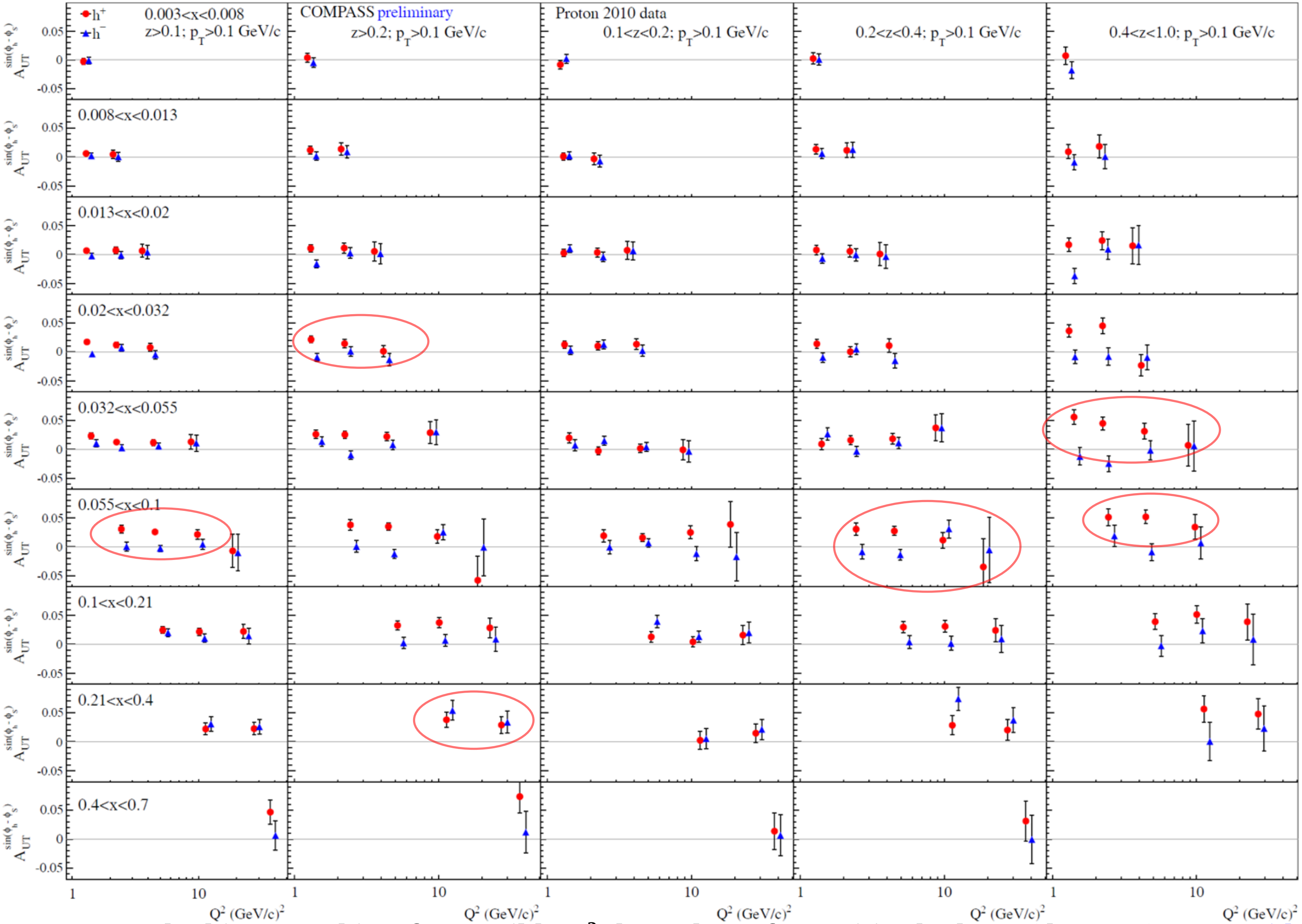
Sivers asymmetry: 3D Q^2-z-x dependence



- **Positive amplitude for h^+ (increasing with x and z)**
- **Positive h^- amplitude at relatively large x (>0.032) and Q^2 (>7) at intermediate and large z**
- **Some hint for a possible negative h^- amplitude at low x (<0.032) and Q^2 (<7)) at intermediate and large z**

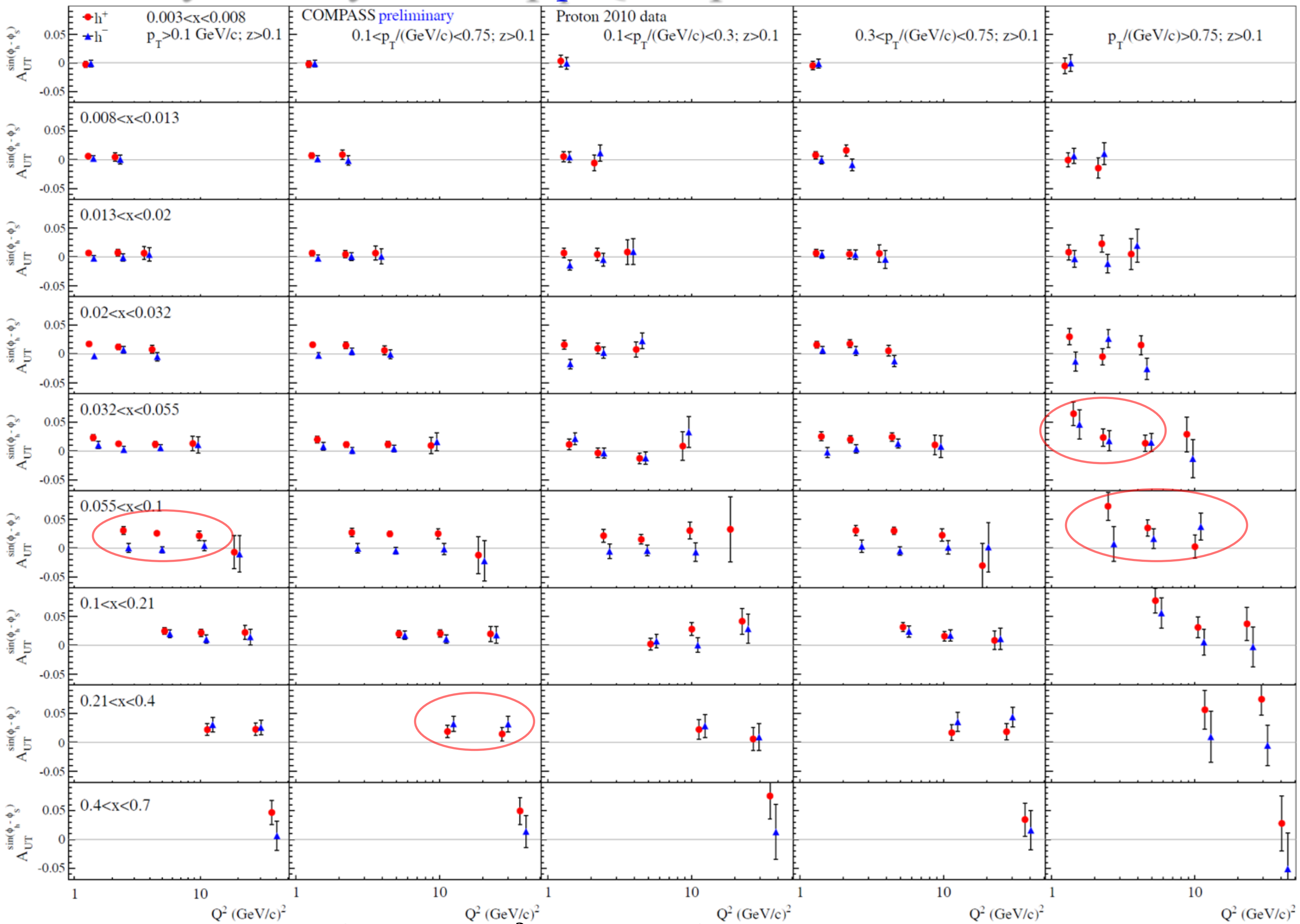
Sivers asymmetry: 3D x-z-Q^2 dependence

3D



- **In several x-bins some hints for possible Q^2-dependence for positive hadrons (decrease) more evident at large z**
- **At low z effect for h^+ is smaller in general**
- **No clear picture for negative hadrons**

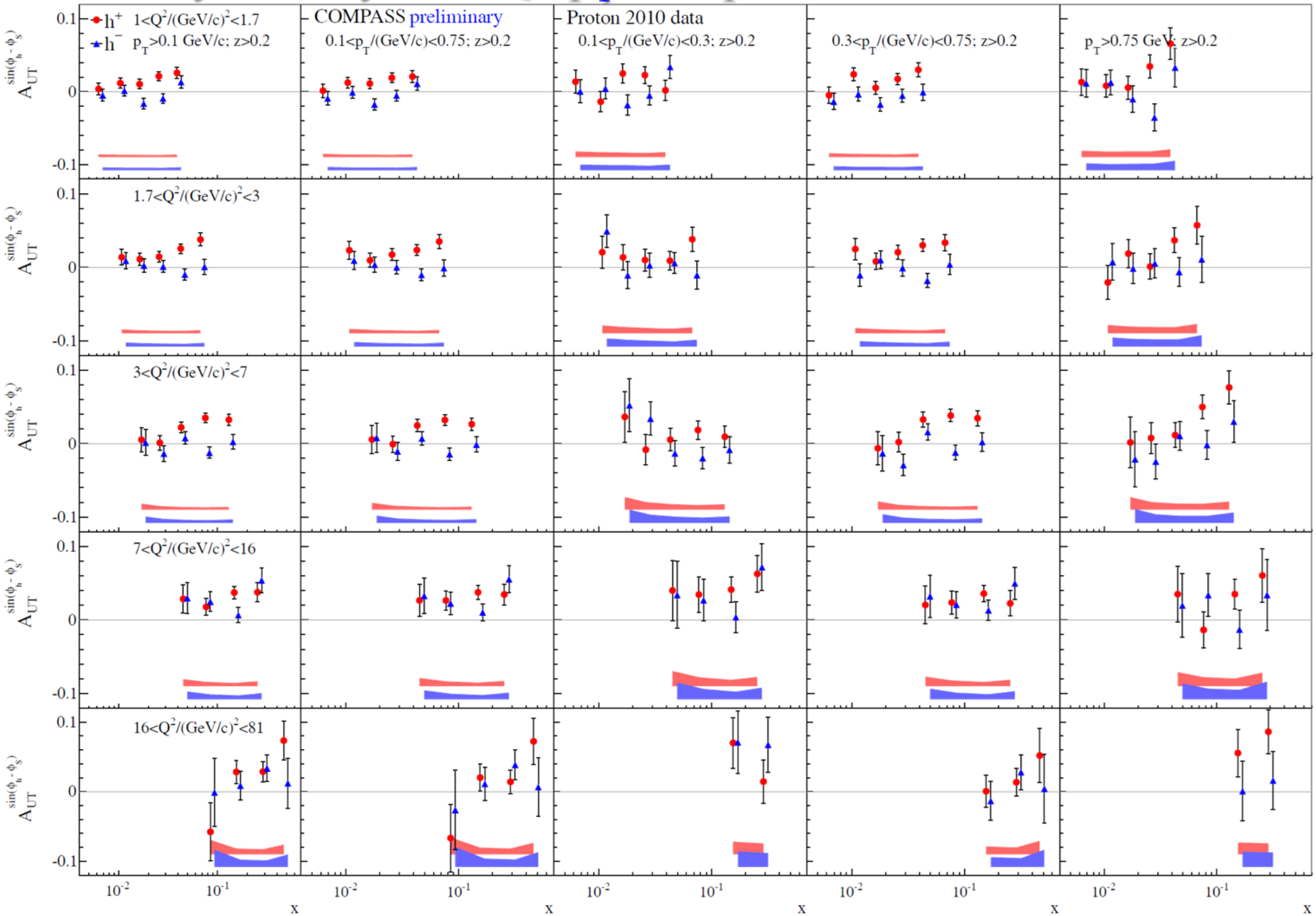
Sivers asymmetry: 3D x-p_T-Q^2 dependence



3D

- **In several x-bins hints for possible Q^2-dependence for positive hadrons (decrease) more evident at large z and p_T**
- **At low z and p_T effect for h^+ is smaller in general**
- **No clear picture for negative hadrons**

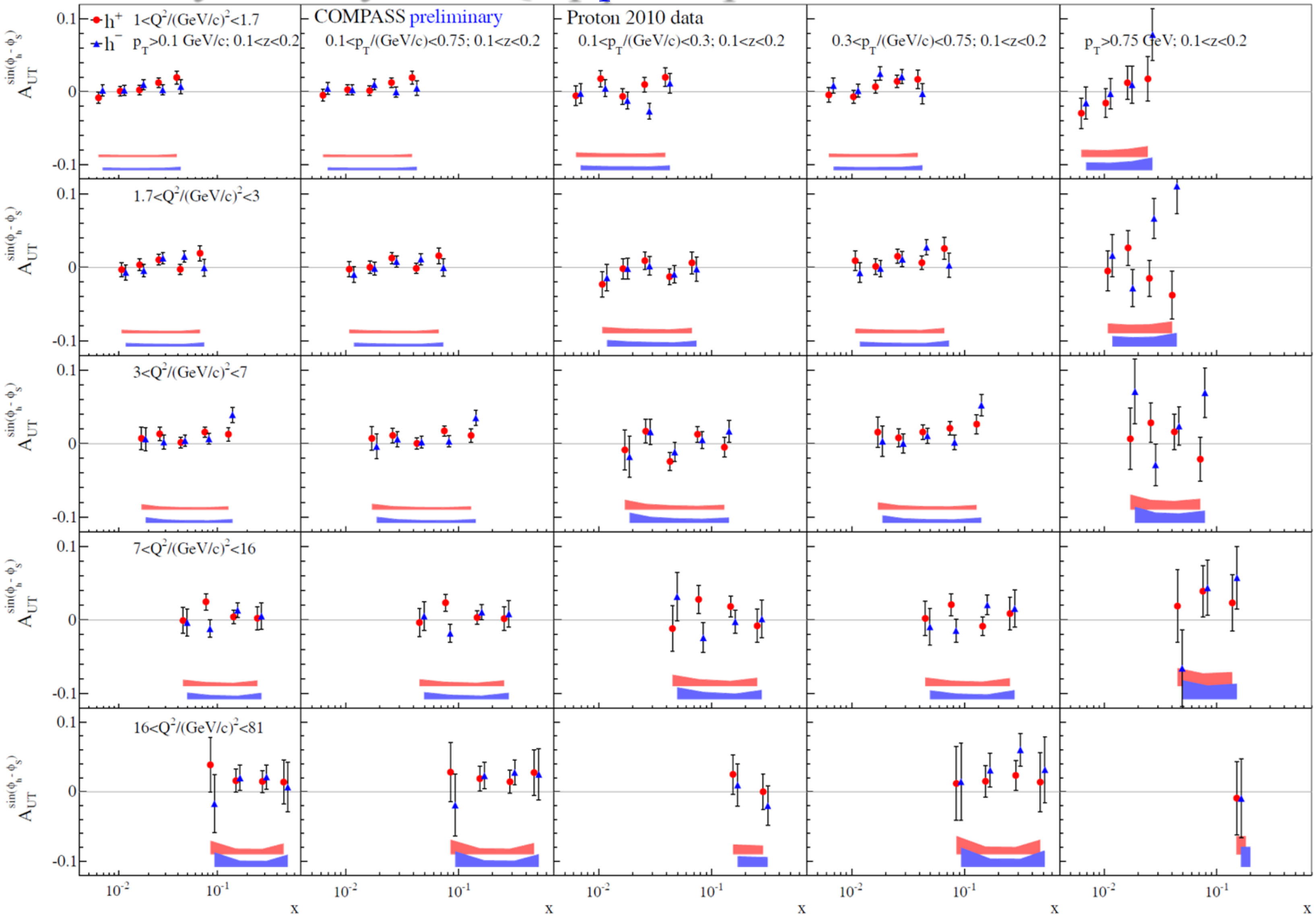
Sivers asymmetry: 4D Q^2-p_T-x dependence at z>0.2



4D

- **Positive amplitude for h^+ (increasing with x and z and p_T)**
- **Positive h^- amplitude at relatively large x (>0.032) and Q^2 (>7) at intermediate and large z (all p_T)**
- **Some hint for a possible negative h^- amplitude at low x (<0.032) and Q^2 (<7)) at intermediate and large z (all p_T)**

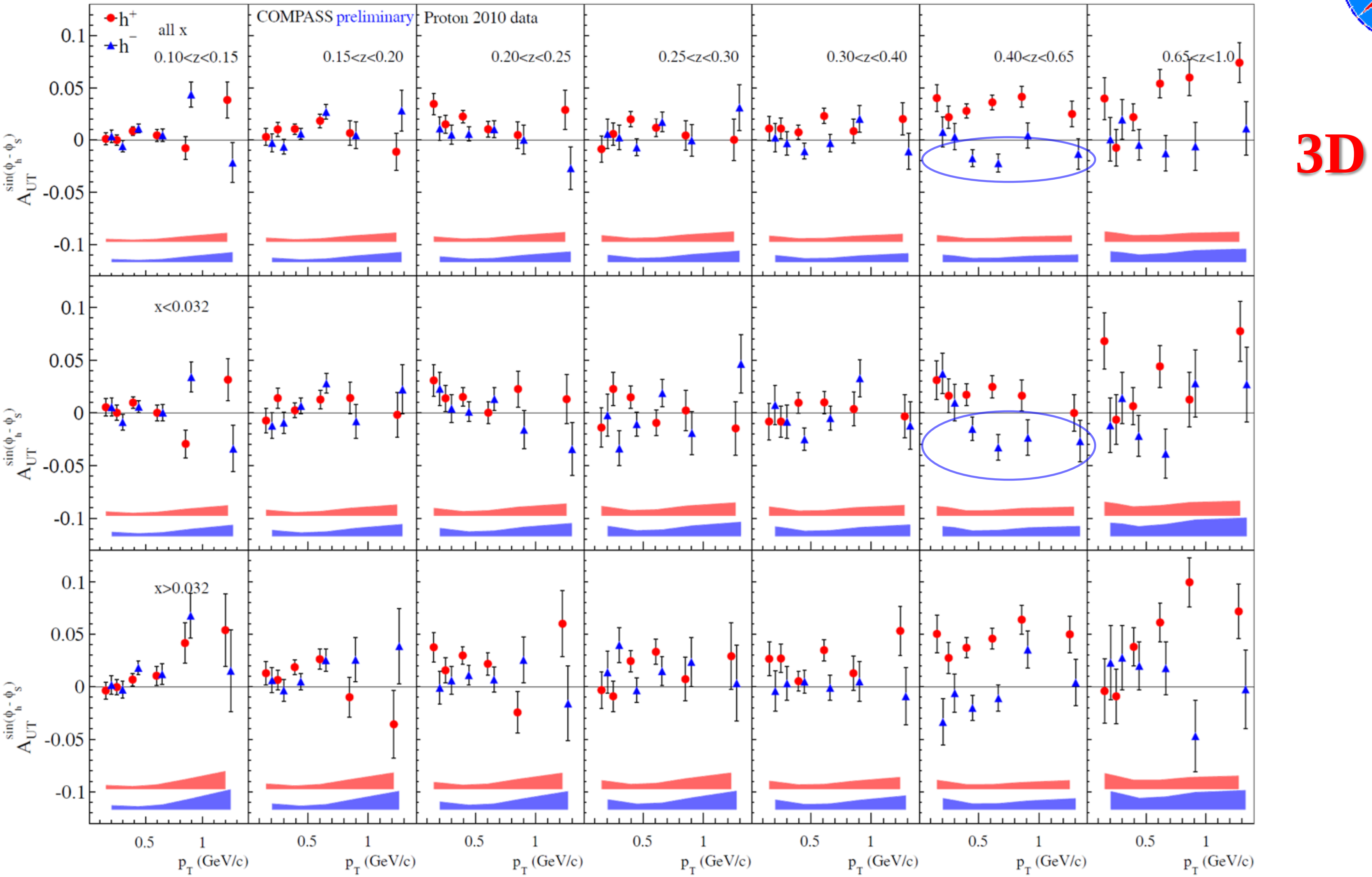
Sivers asymmetry: 4D Q^2-p_T-x dependence at 0.1<z<0.2



4D

- **Positive amplitude for h⁺ (increasing with x and z and p_T)**
- **Positive h⁻ amplitude at relatively large x (>0.032) and Q^2 (>7) at intermediate and large z (all p_T)**
- **Some hint for a possible negative h⁻ amplitude at low x (<0.032) and Q^2 (<7)) at intermediate and large z (all p_T)**

Sivers asymmetry: 3D x-z-p_T dependence



- **Positive amplitude for h^+ (increasing with x and z and p_T)**
- **Positive h^- amplitude at relatively large x (>0.032) and Q^2 (>7) at intermediate and large z (all p_T)**
- **Some hint for a possible negative h^- amplitude at low x (<0.032) and Q^2 (<7)) at intermediate and large z (all p_T)**

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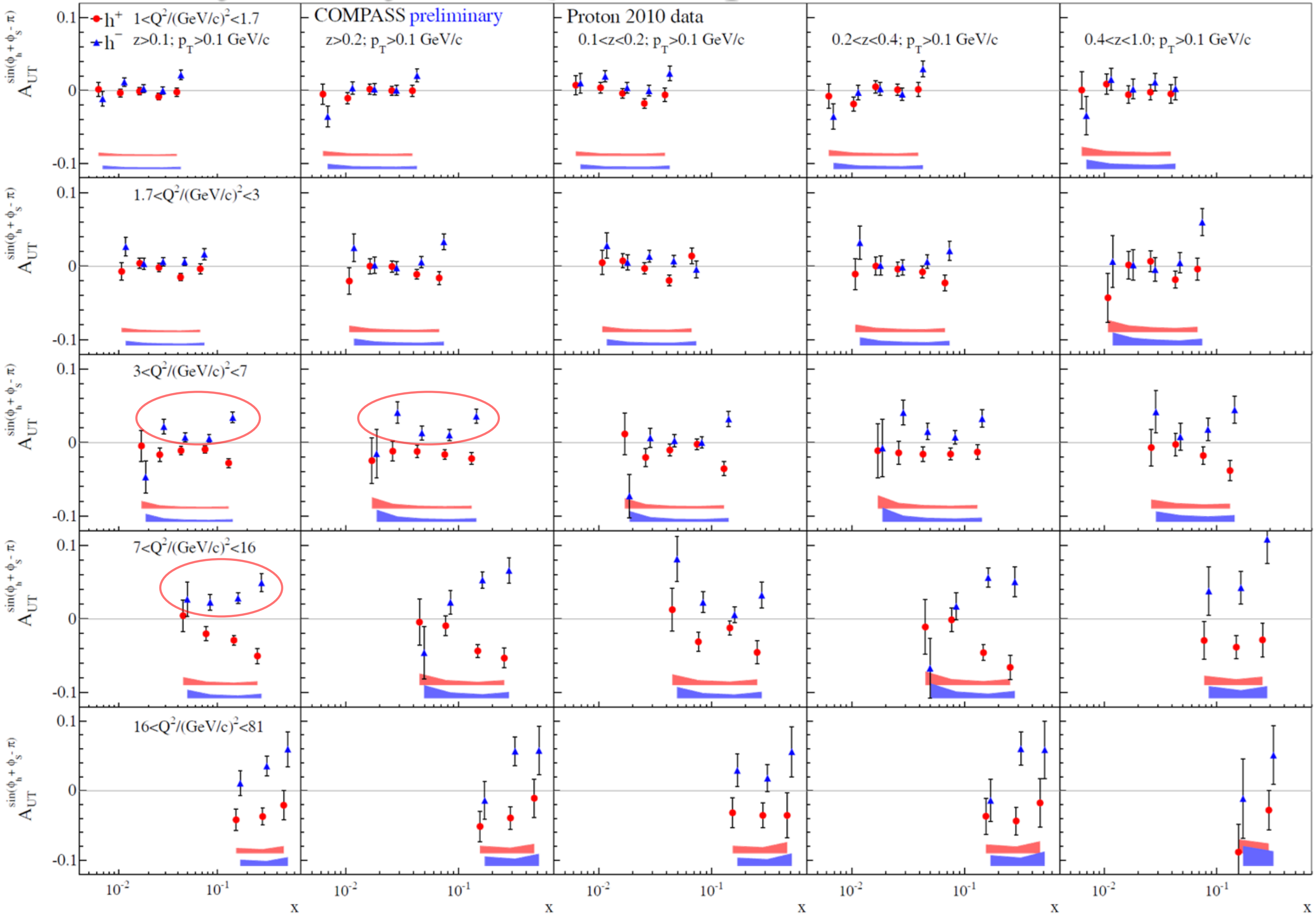
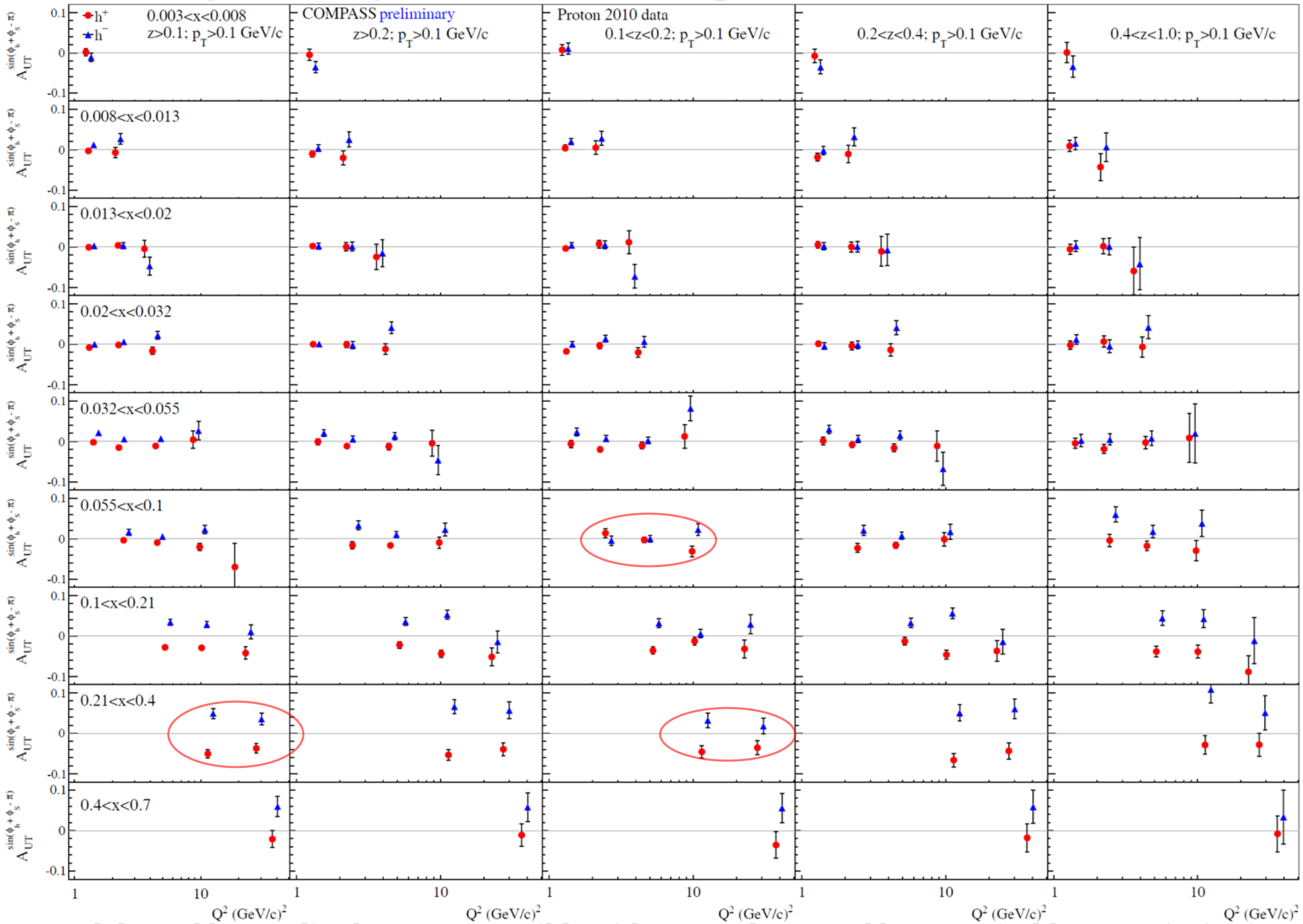
Collins asymmetry: 3D Q^2-z-x dependence

3D



- **Both h^+ and h^- amplitudes are compatible with zero at low x and become sizable (opposite in sign) from x>0.032**
- **Both h^+ and h^- amplitudes tend to increase with x, but with some "irregularities"**
- **Both h^+ and h^- amplitudes tend to increase with z.**

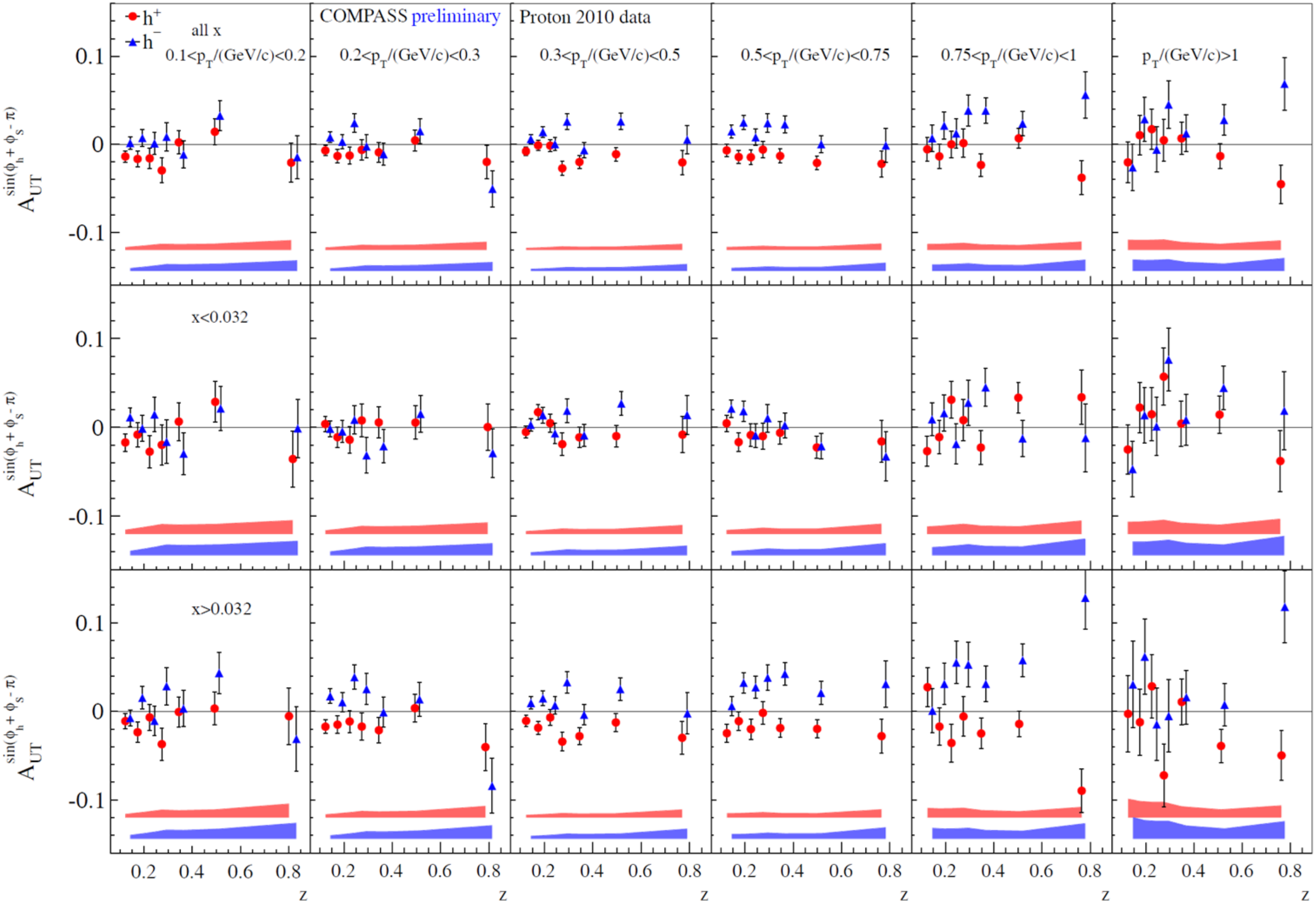
Collins asymmetry: 3D x-z-Q^2 dependence



3D

- **Both h^+ and h^- amplitudes are compatible with zero at low x and become sizable (opposite in sign) from x>0.032**
- **Both h^+ and h^- amplitudes tend to increase with x, but with some "irregularities"**
- **Both h^+ and h^- amplitudes tend to increase with z. Some weak Q^2-dependences. Not clear.**

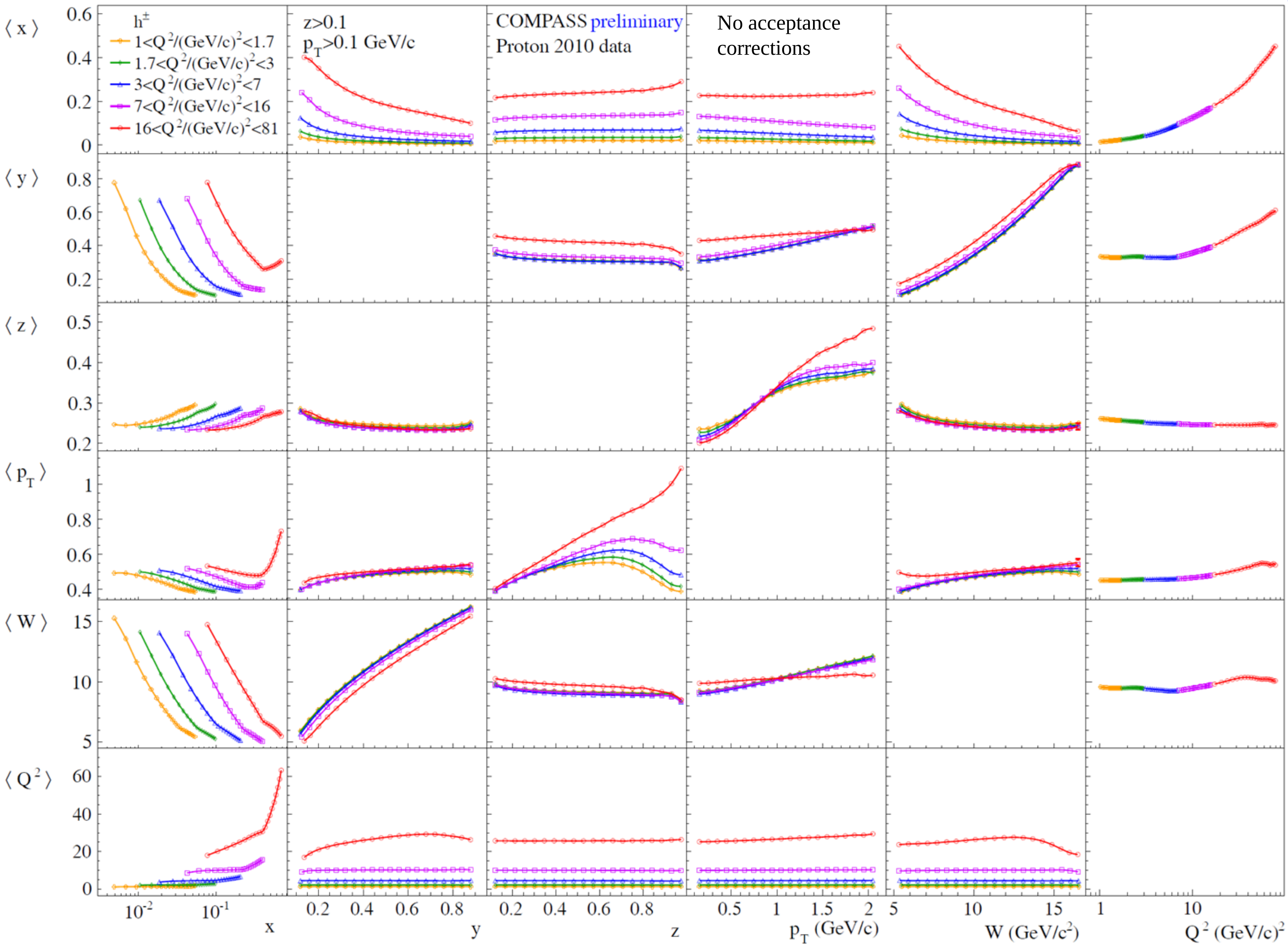
Collins asymmetry: 3D x-p_T-z dependence



3D

- **Both h^+ and h^- amplitudes are compatible with zero at low x and become sizable (opposite in sign) from x>0.032**
- **Both h^+ and h^- amplitudes tend to increase with x, but with some “irregularities”**
- **Both h^+ and h^- amplitudes tend to increase with z and $p_{T.}$**

Kinematical map: z>0.1, p_T>0.1



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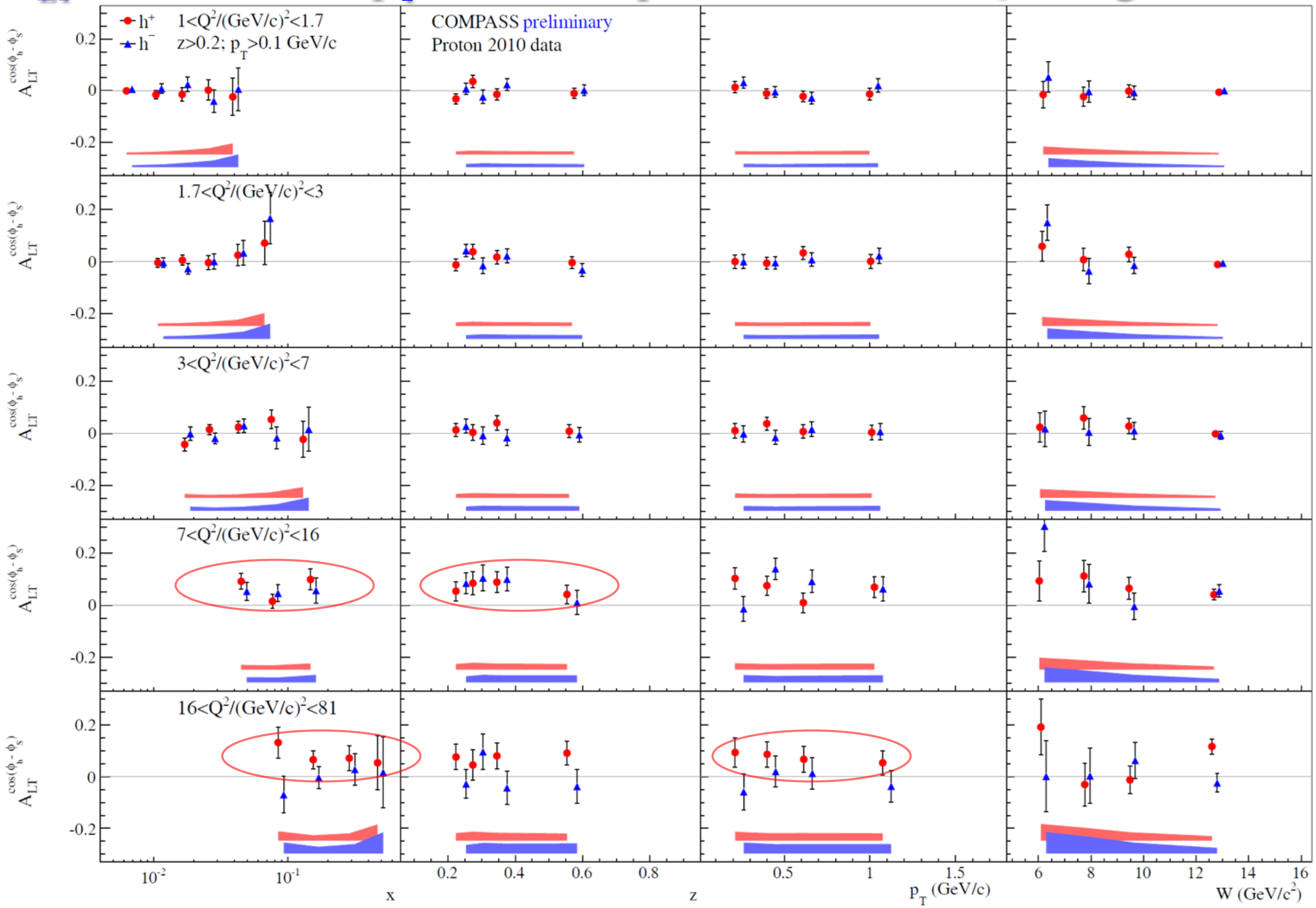
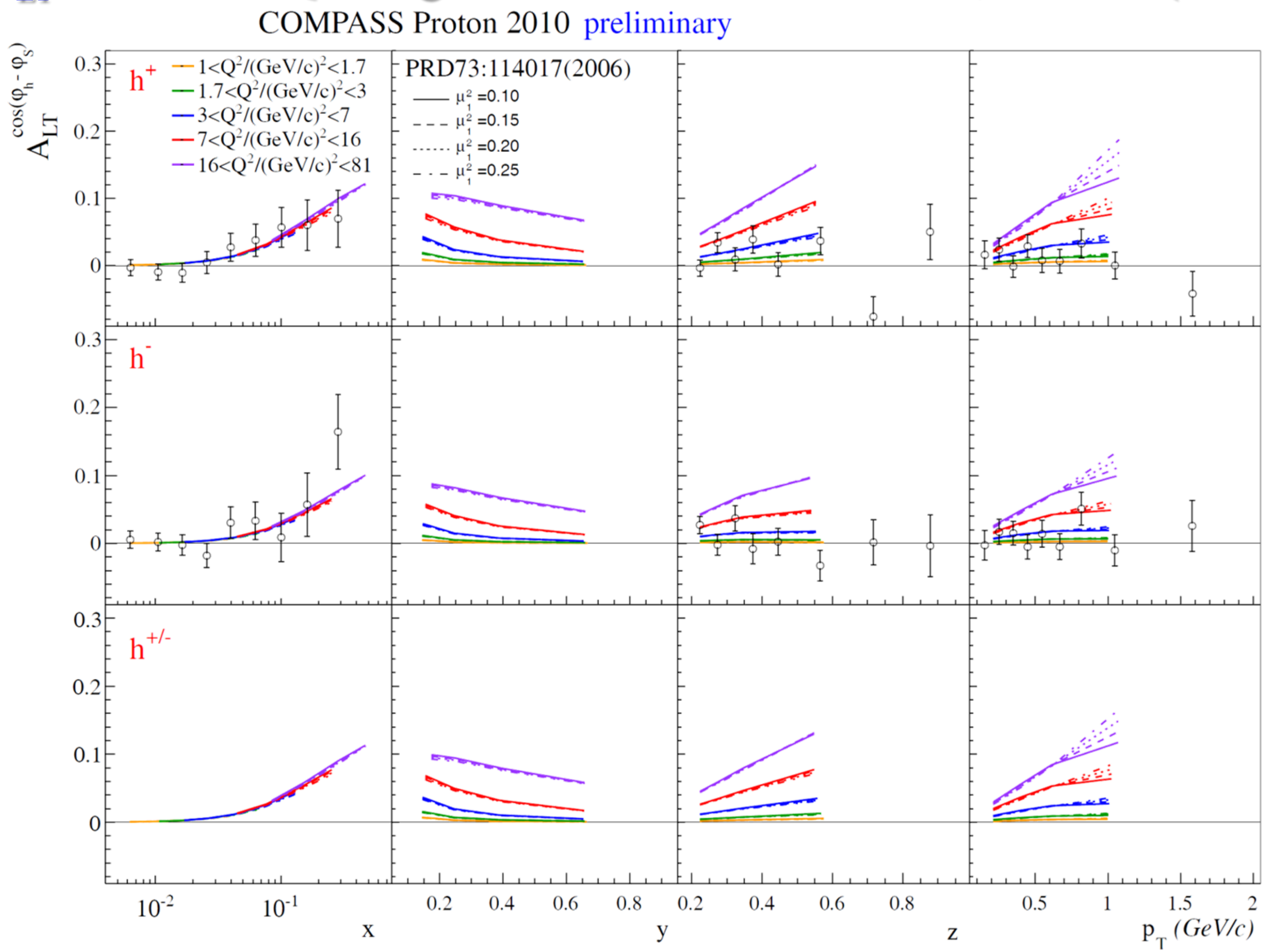
$A_{LT}^{cos(\phi_h-\phi_S)}$: x, z, p_T and W dependences in 5 Q^2-ranges



2D

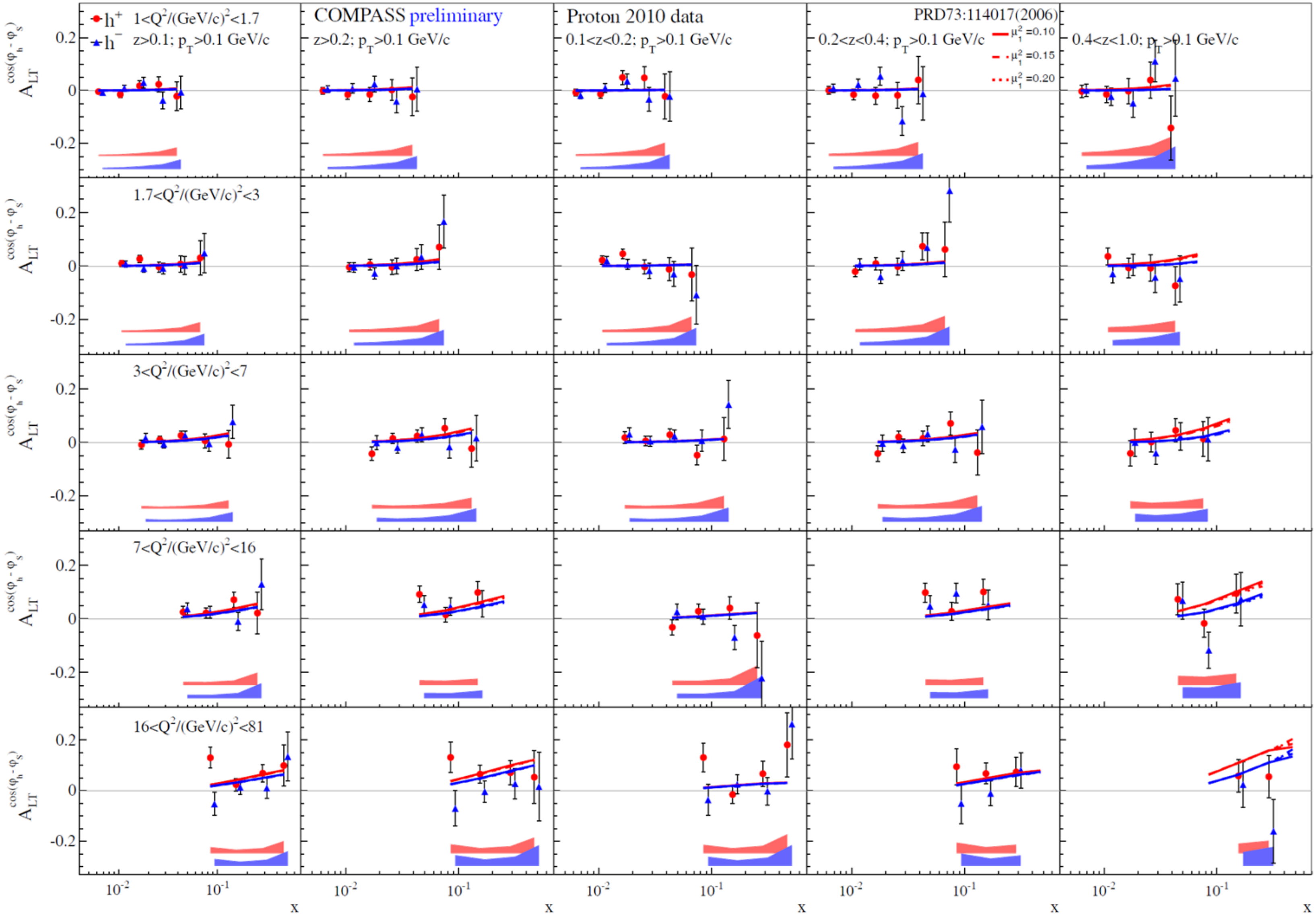
- **Positive amplitude for h^+ at large x (>0.032) and Q^2 (>3)**
- **Signal for negative hadrons is not evident.**

$A_{LT}^{\cos(\phi_h-\phi_S)}$: 5 Q^2 ranges. Predictions - PRD 73, 114017(2006)



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

$A_{LT}^{\cos(\phi_h-\phi_S)}$: 3D Q²-z-x dependence: Predictions - PRD 73, 114017(2006)



3D

Asymmetry is evaluated in COMPASS specific mean kinematic points extracted from the data.
The predictions show a good level of agreement with the experimentally extracted asymmetry.
Statistical accuracy is not enough for further studies.

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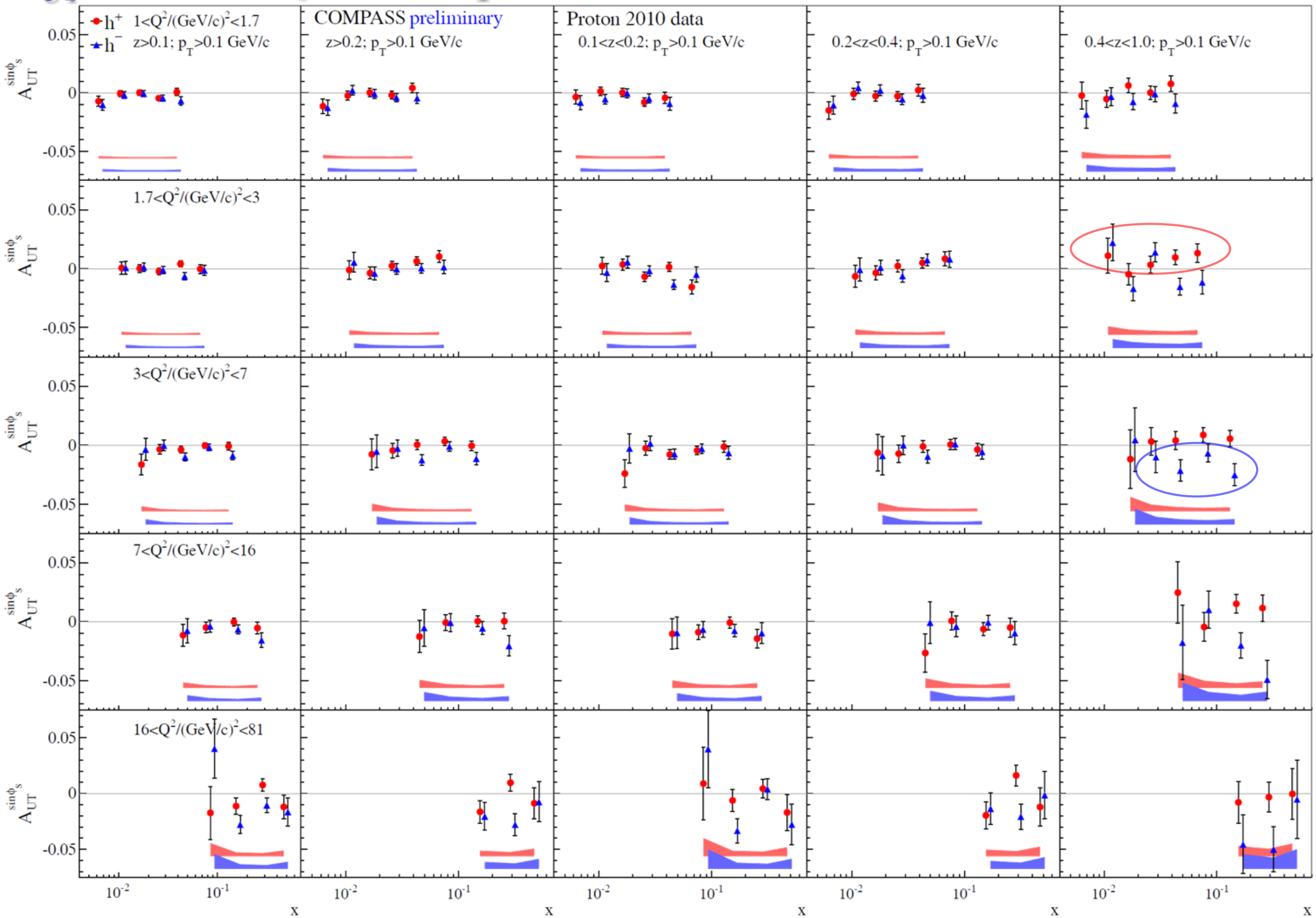
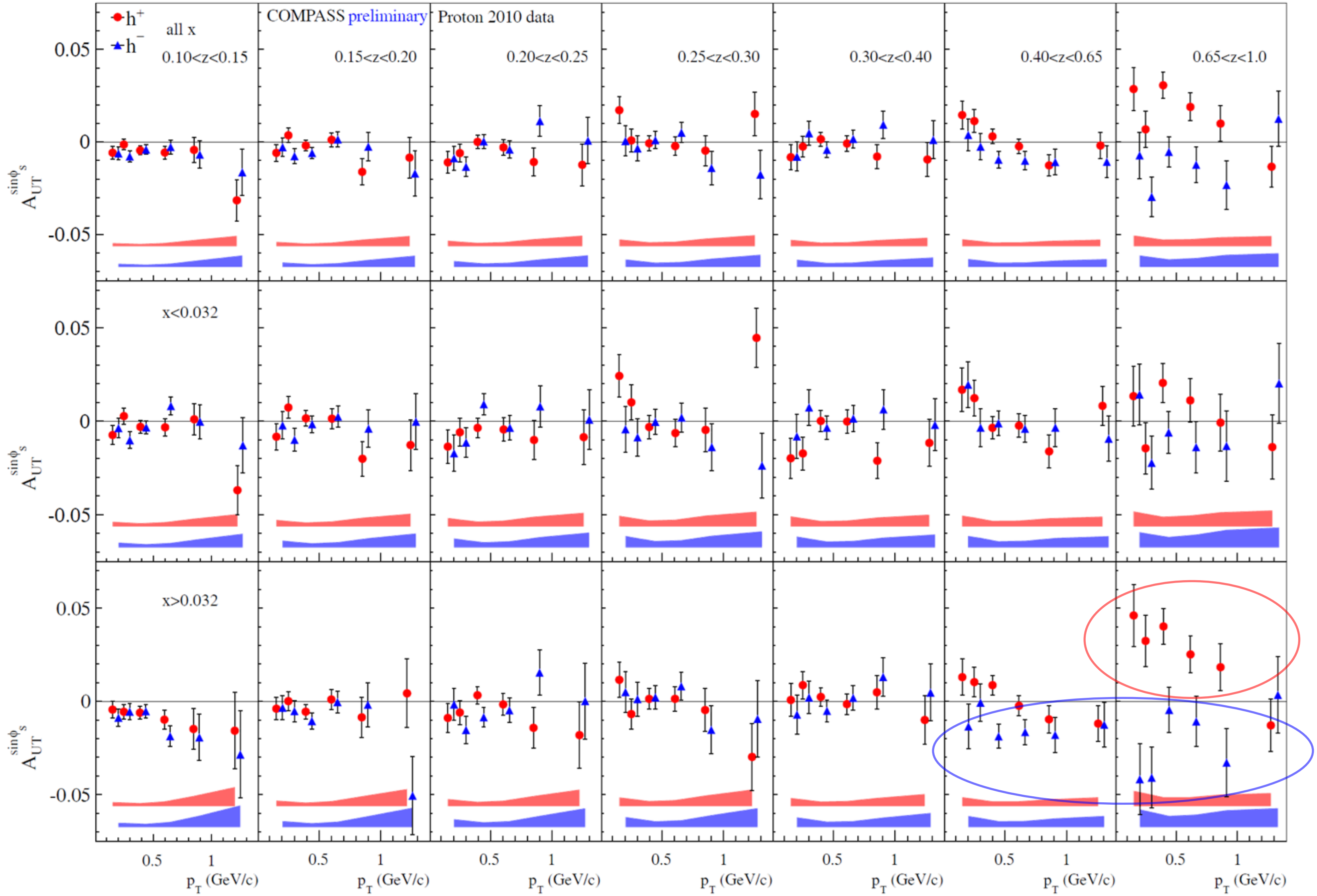
$A_{UT}^{\sin\phi_S}$: 3D Q^2-z-x dependence



3D

- **Negative amplitude for h⁻ (at large x) increasing with z**
- **Some hint for positive h⁺ signal at large z**
- **The only "twist-3" asymmetry showing non-zero signal**

$A_{UT}^{\sin\phi_S}$: 3D x-z-p_T dependence



3D

- **Negative amplitude for h⁻ (at large x) increasing with z**
- **Clear positive h⁺ signal at large z (decreasing with p_T)**
- **The only "twist-3" asymmetry showing non-zero signal**

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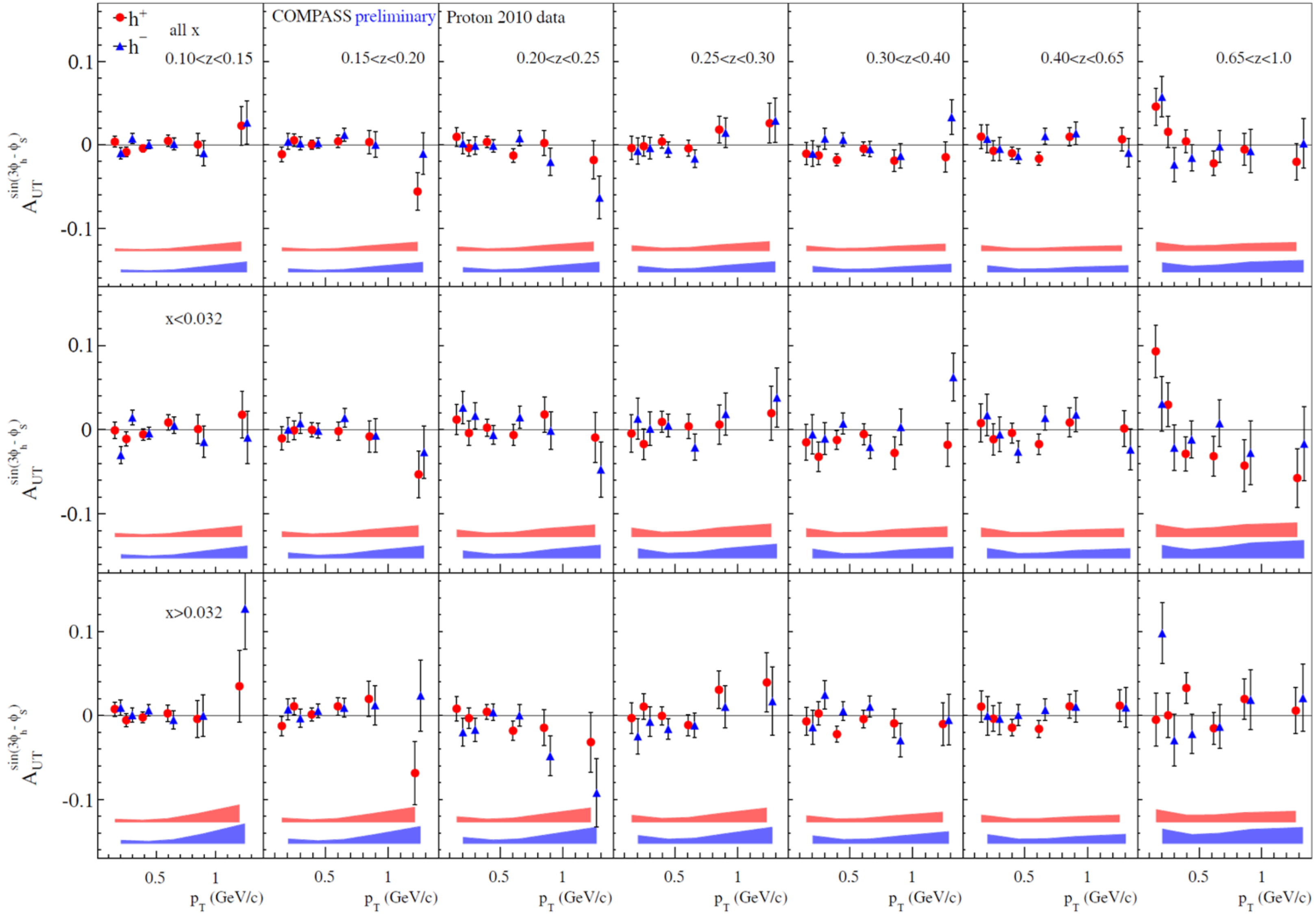
$A_{UT}^{\sin(3\phi_h-\phi_S)}$: 3D x-z-$p_T$ dependence



3D

- **Expected to be suppressed by a factor of ~$|p_T|^2$ with respect to the Collins and Sivers amplitudes**
- **Asymmetries are compatible with zero within uncertainties.**

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- **Conclusions**

Conclusions

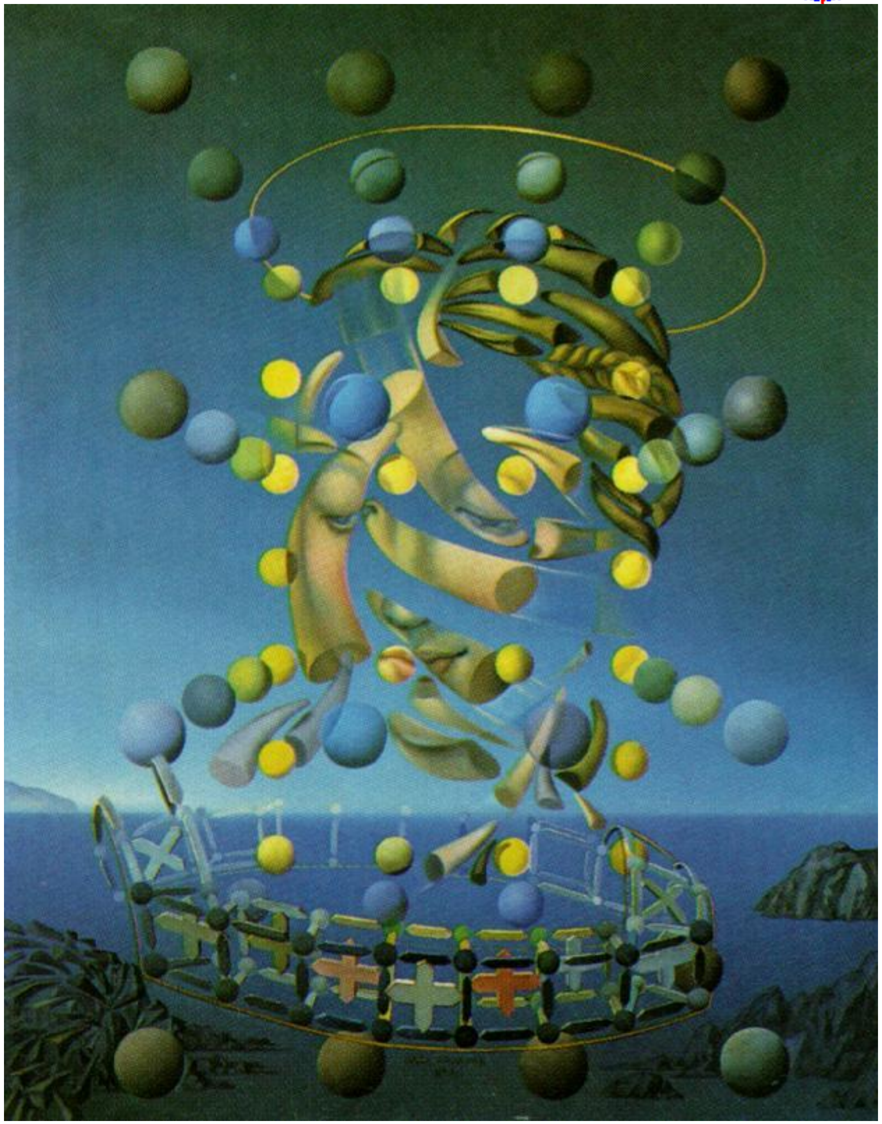
- First ever extraction of transverse spin asymmetries in multidimensional grids:
  - 2D – Q^2:x; Q^2:z; Q^2:p_T; Q^2:W
  - 3D – Q^2:z:x (x:z:Q^2); Q^2:p_T:x (x:p_T:Q^2)
  - 4D – z:Q^2:p_T:x; p_T:Q^2:z:x
  - 3D – x:z:p_T (x:p_T:z);
- TSAs for *unidentified* charged hadrons have been extracted from COMPASS proton data of 2010.
- Several asymmetries show a non-zero trend in different regions
  - Collins, Sivers, $A_{LT}^{\cos(\phi_h-\phi_S)}$, $A_{UT}^{\sin\phi_S}$
  - Predictions for the $A_{LT}^{\cos(\phi_h-\phi_S)}$ are in good agreement with the experimental results within the statistical accuracy
- Many interesting observations!
- Important input for TMD-evolution studies, various phenomenological analyses and global analyses!

Thank you!

“Nature”

“1D”

Raphael *“Madonna del Prato”*



Salvador Dali *“Maximum Speed of Raphael's Madonna”*

"Nature" *"multi-D" with available statistics*

Raphael *"Madonna del Prato"*

Raphael *"Madonna del Prato" (poor resolution)*