Transverse spin azimuthal asymmetries in SIDIS at COMPASS

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on behalf of the COMPASS Collaboration

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Outline

- Introduction
  - SIDIS x-section and TSAs
  - Brief review of recent COMPASS results with TSAs
- COMPASS multidimensional approach NEW
  - COMPASS multidimensional phase-space
- Results for TSAs NEW (Shown for the first time!)
  - 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
  - Mean depolarization factors
- Corrections for *lp* to $\gamma{*}p$ transition
- Conclusions

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SIDIS x-section

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

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

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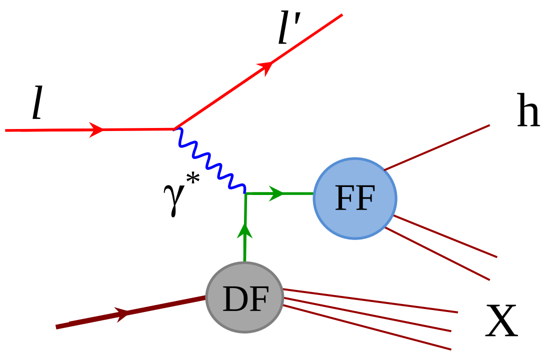
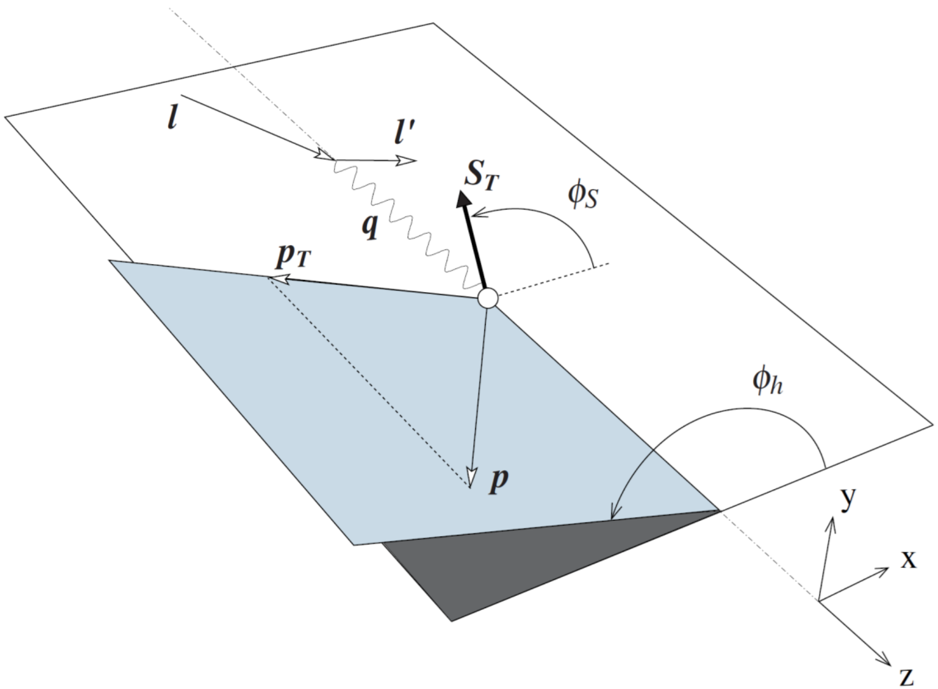
\end{aligned}\right]
\end{aligned}\right\}$$





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

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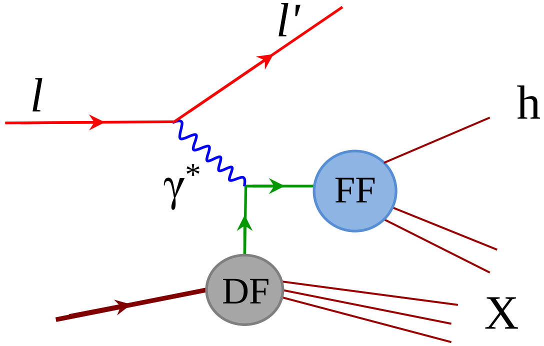
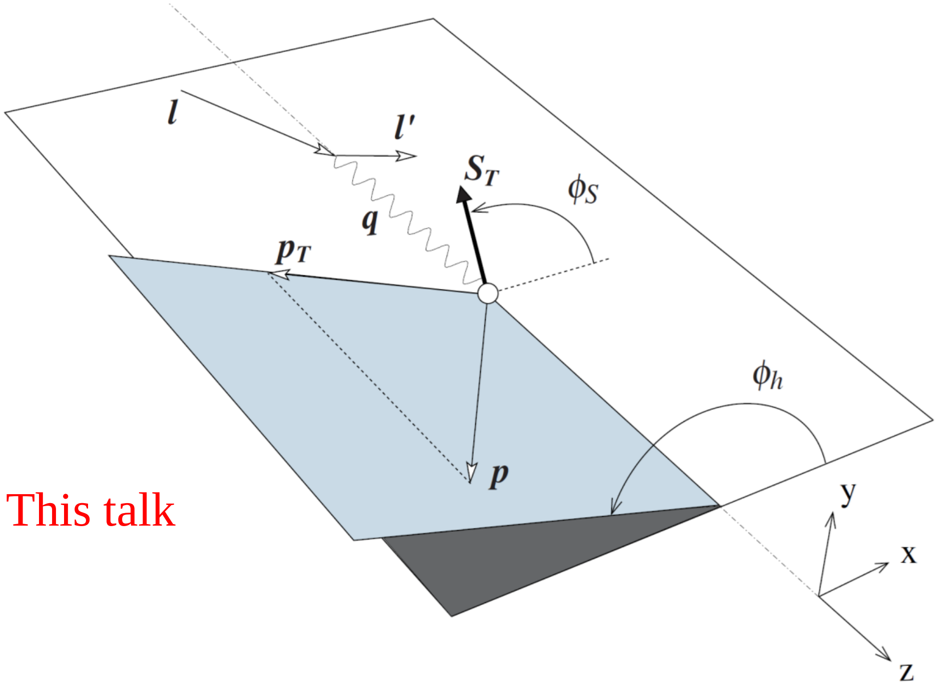
\end{array}\right]
\end{array}\right\}$$

This talk





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

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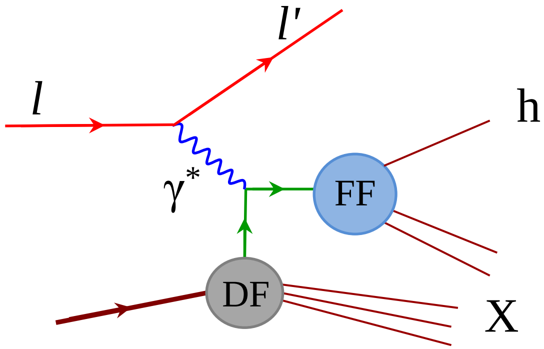
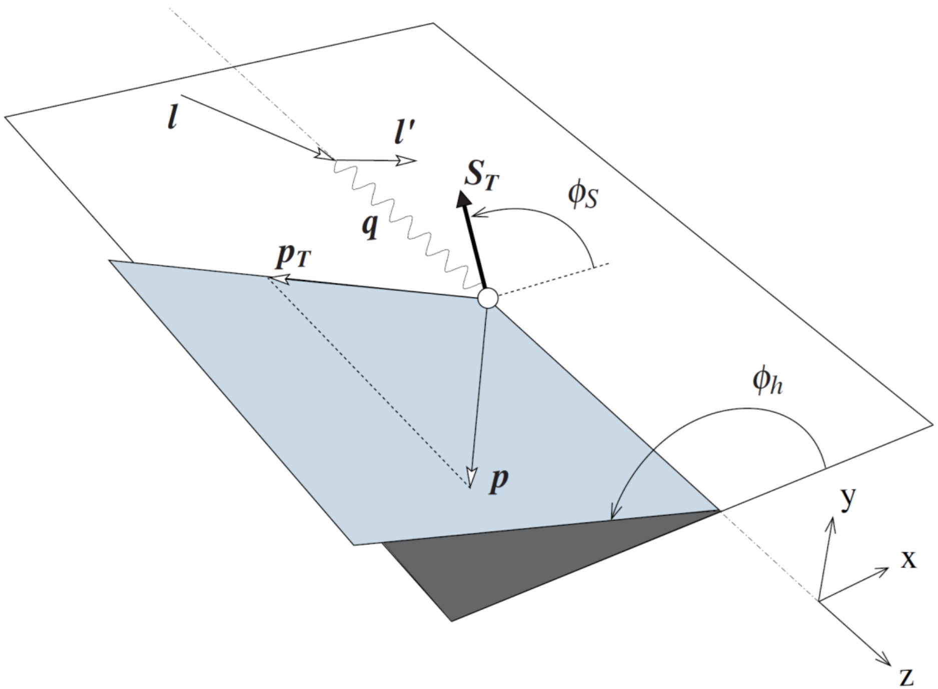
+\ \cos(2\phi_h-\phi_S)\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\right)
\end{array}\right]
\end{array}\right\}$$

SSA (the S_T terms)

DSA (the $S_T\lambda$ terms)





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

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COMPASS

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\end{array}\right]
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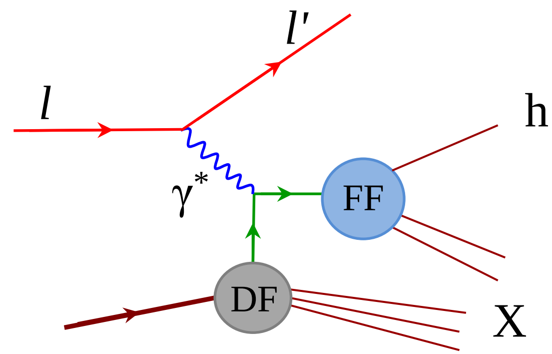
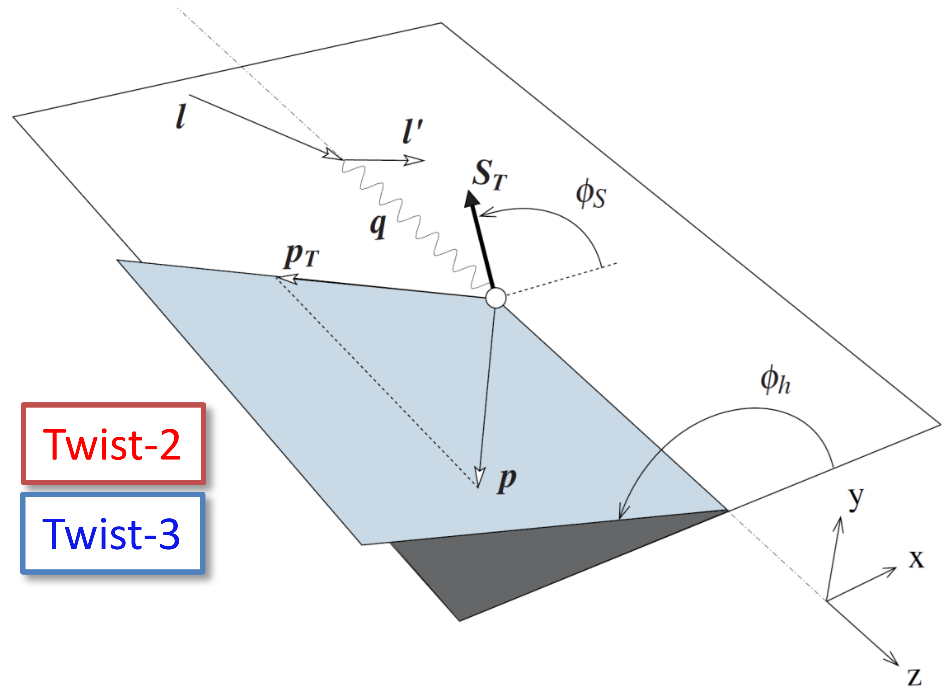
SSA ↑

↓ DSA

Twist-2

Twist-3





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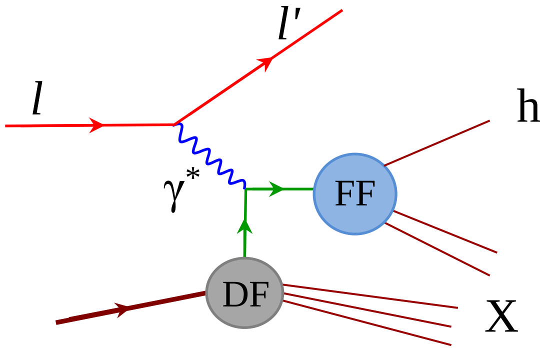
$$\begin{Bmatrix} 1+\cos\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\right)+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right) \\ +\lambda\sin\phi_h\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\right) \\ +S_L\left[\sin\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\right)+\sin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

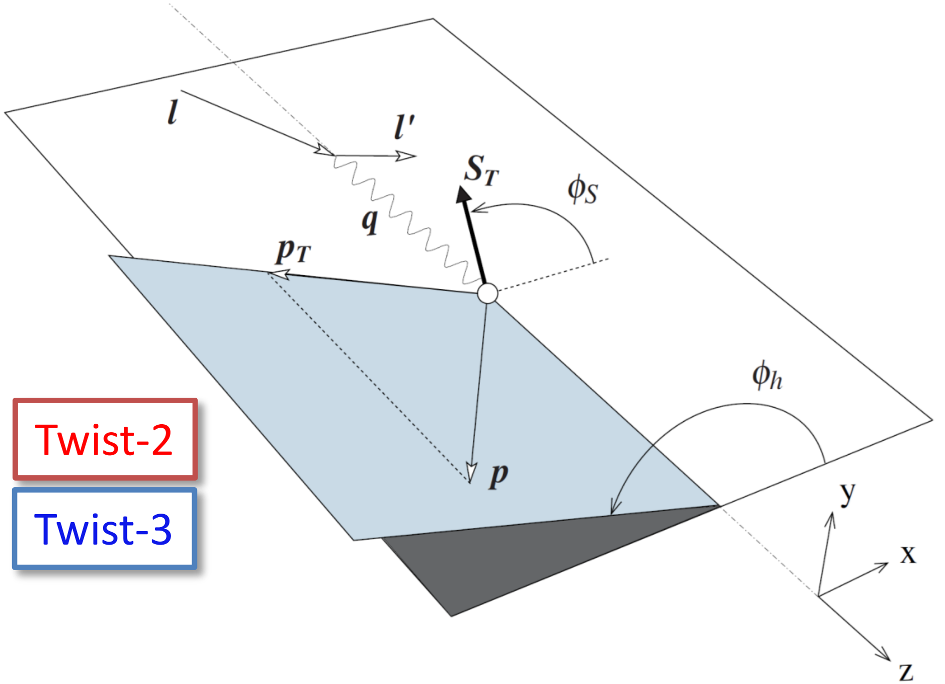
SSA

DSA

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]

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

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&+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]\\
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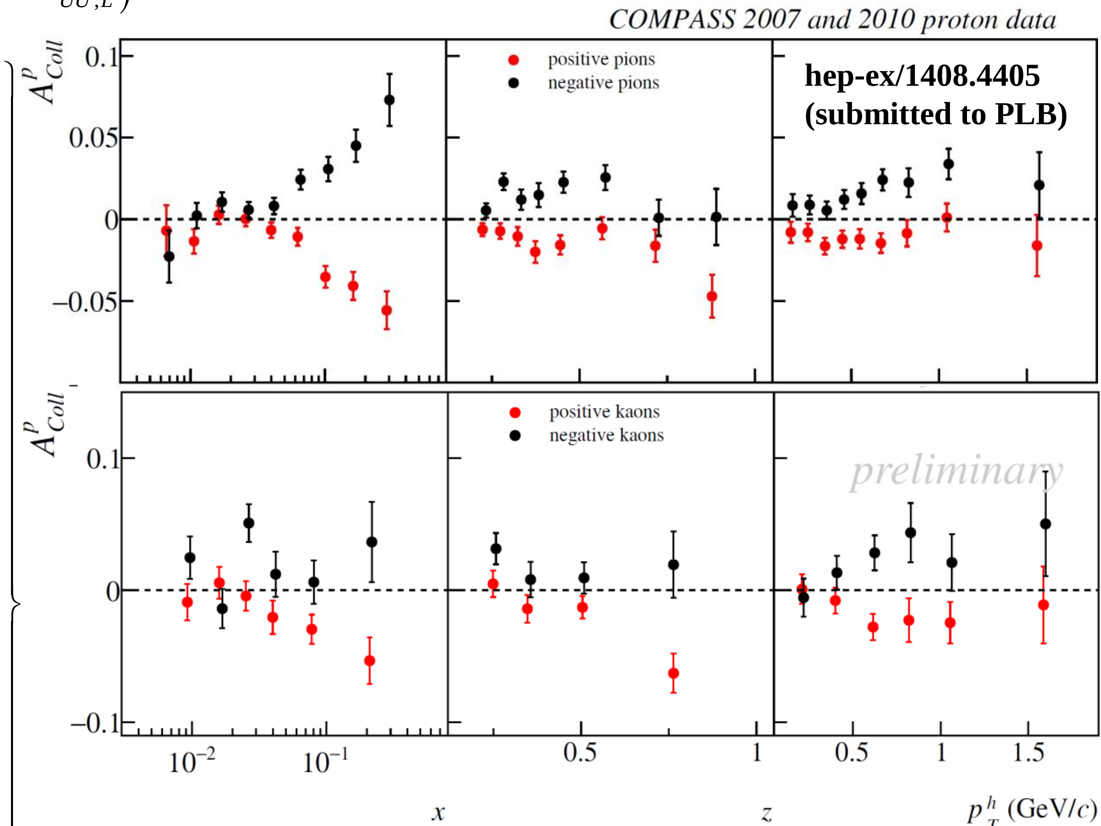
\end{aligned}\right\}$$



- 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]

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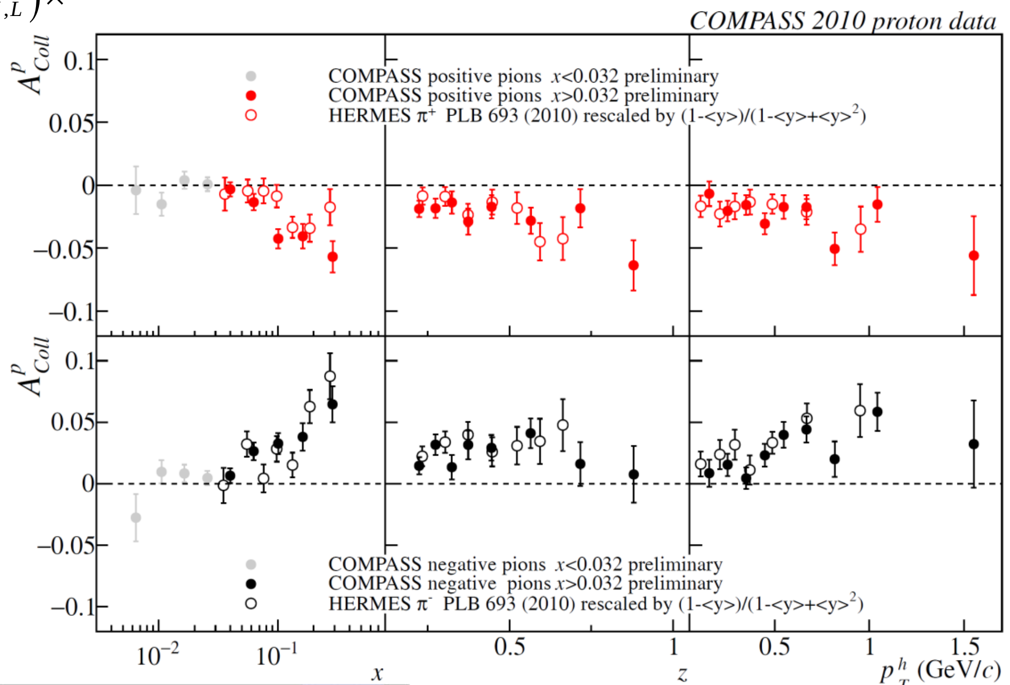
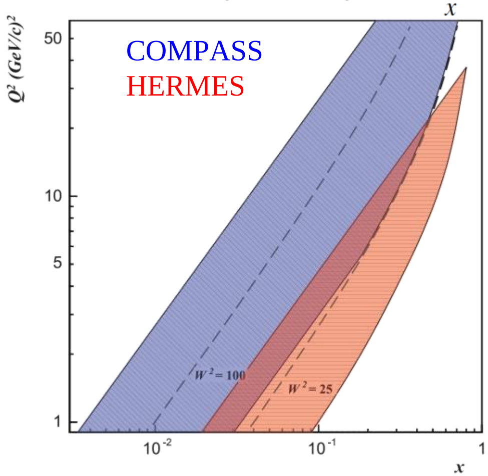
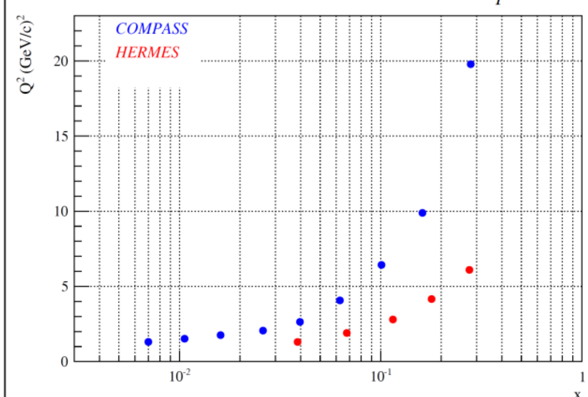
\end{array}\right]\Bigg\}
\end{aligned}
$$







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

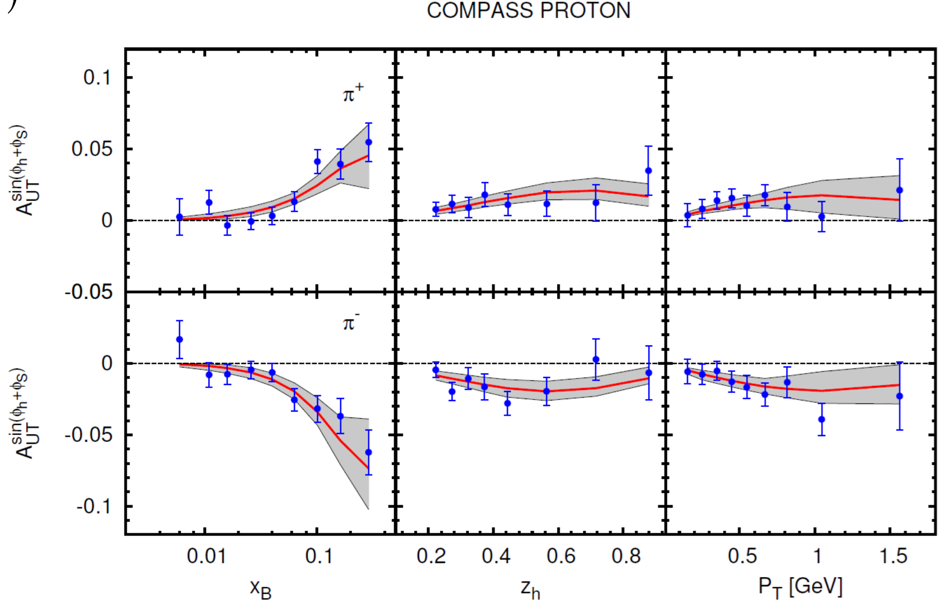
SIDIS x-section

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

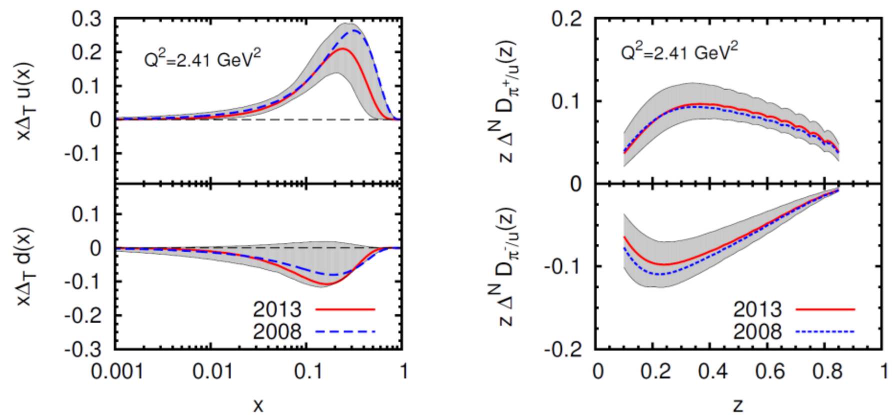
$$\frac{d\sigma}{dxdydzdP_{hT}^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

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

Phys.Rev. D87 (2013) 094019



- Global fit of HERMES-COMPASS-BELLE data



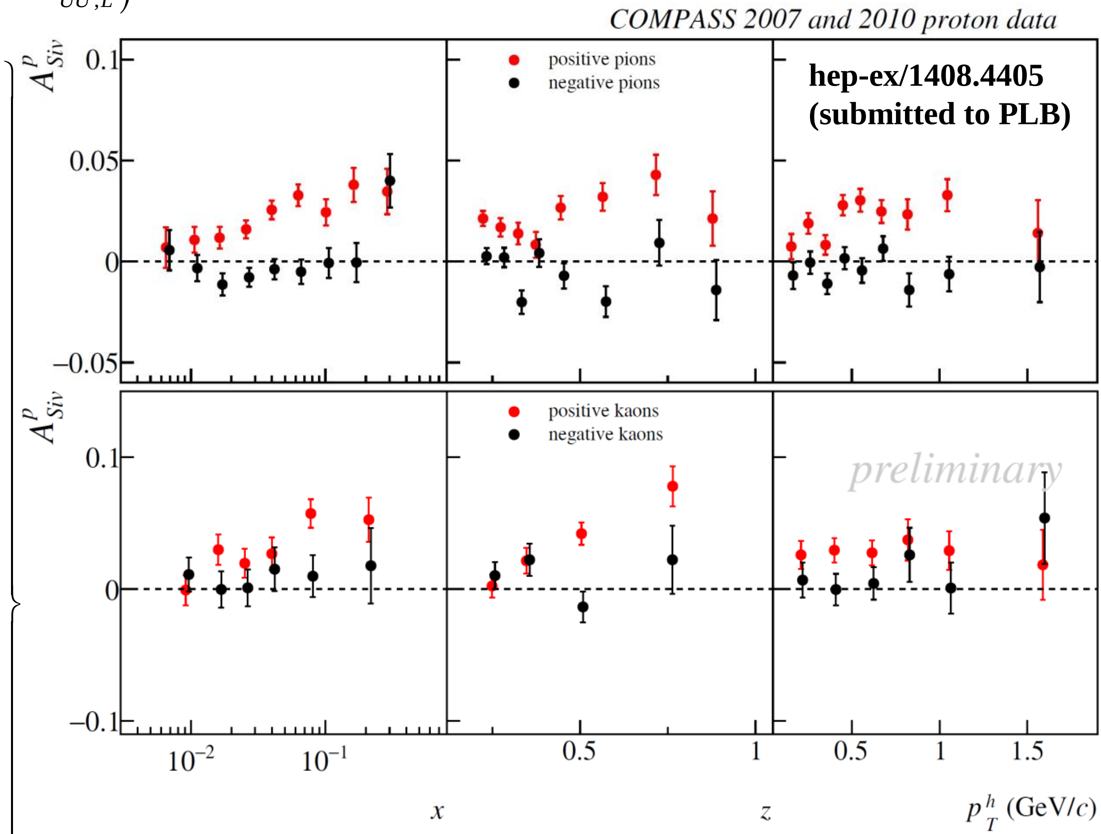
- Transversity PDF + Collins FF

SIDIS x-section

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

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

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

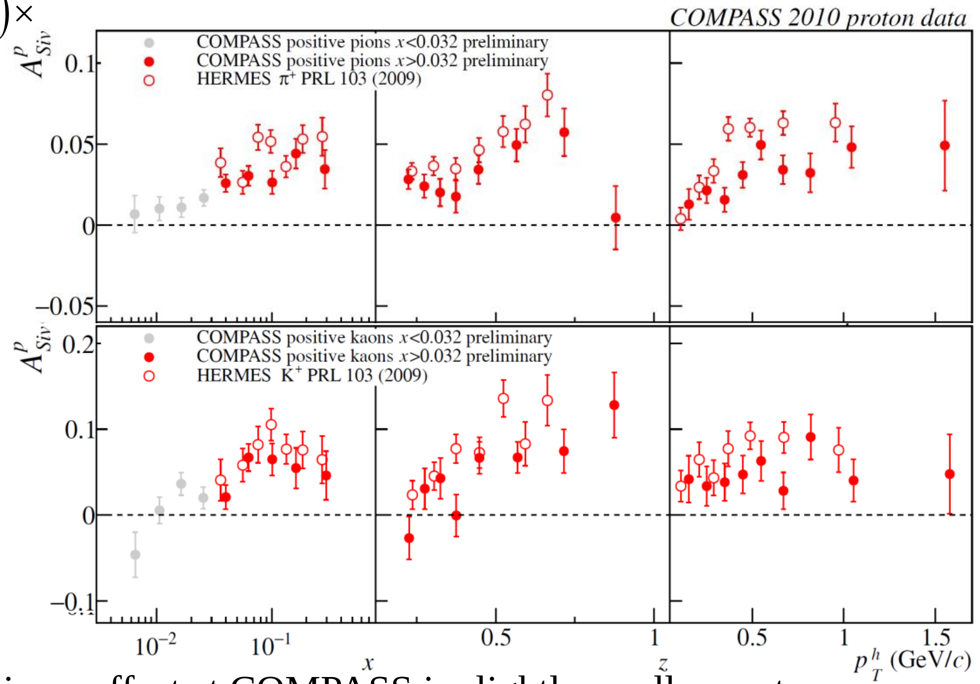


- Significantly large amplitude for π^+ and K^+ in whole range of x
- Some hints of negative signal for π^-
  - Positive signal in the last bin of x?
- Compatible with zero for K^-
- Compatible with zero on deuteron

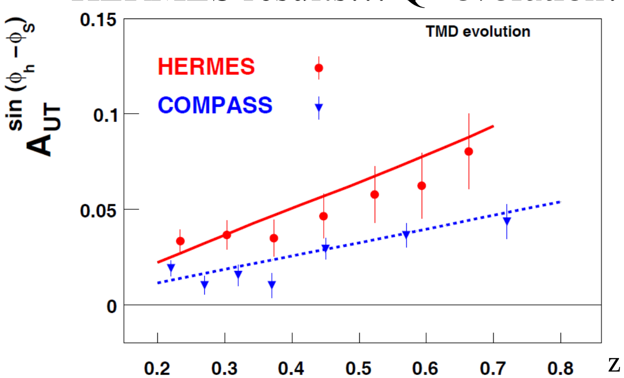
SIDIS x-section

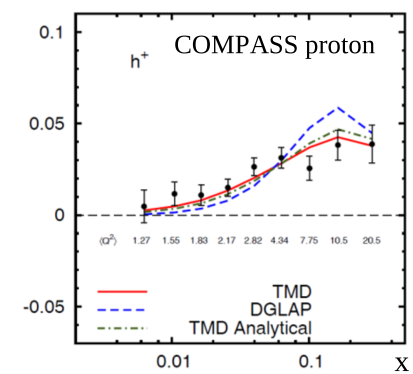
$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h} \qquad \mathrm{SSA}\left[\text{twist-2}\right]$$

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



- 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

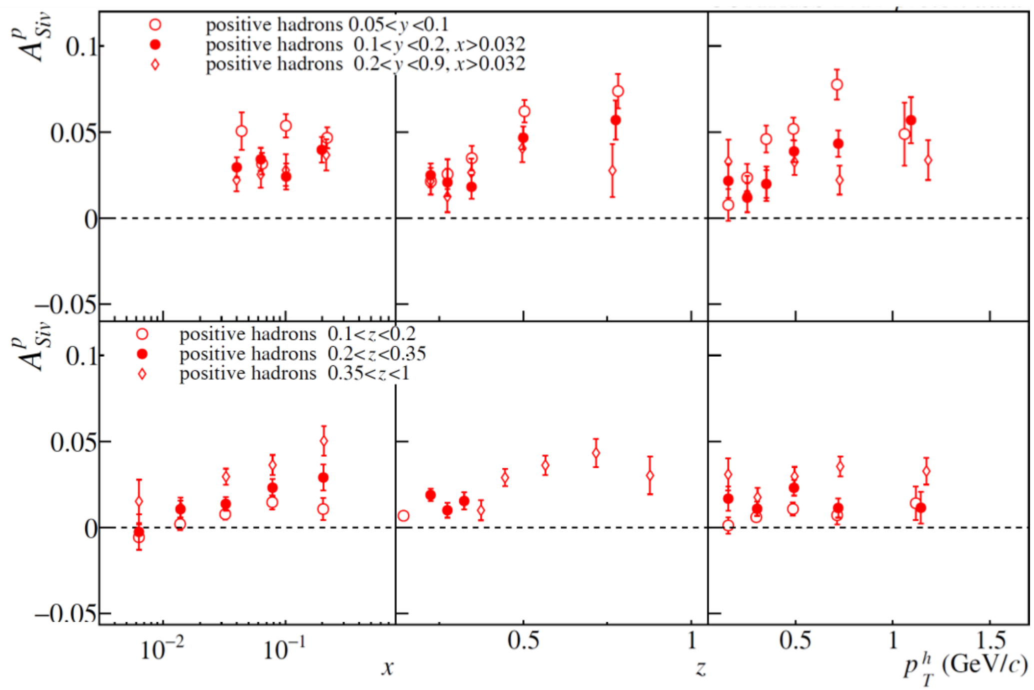
$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$ SSA[twist-2]

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

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

Sivers in "2D" at COMPASS: first attempts

(PLB 717 (2012) 383)



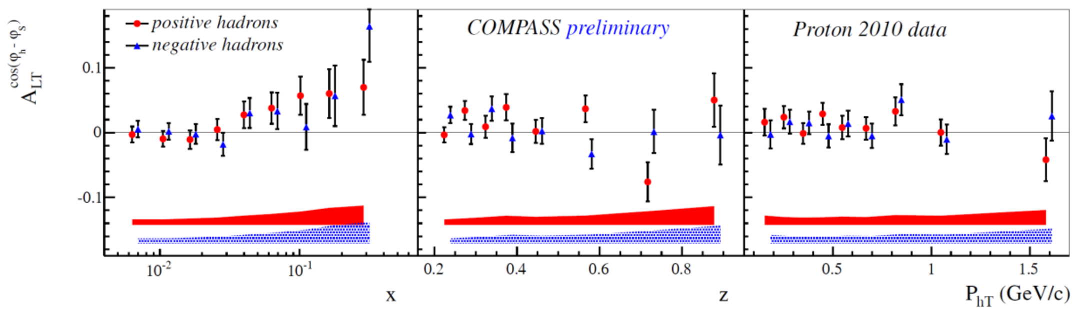
- All TSAs were studied in different x, z, y and W ranges
- Clear z-, x-, y- dependencies
- Interesting results already at basic 2D approach
- Highly desirable challenge is to look into asymmetries in the multidimensional phase-space over $x - z - p_T - Q^2$

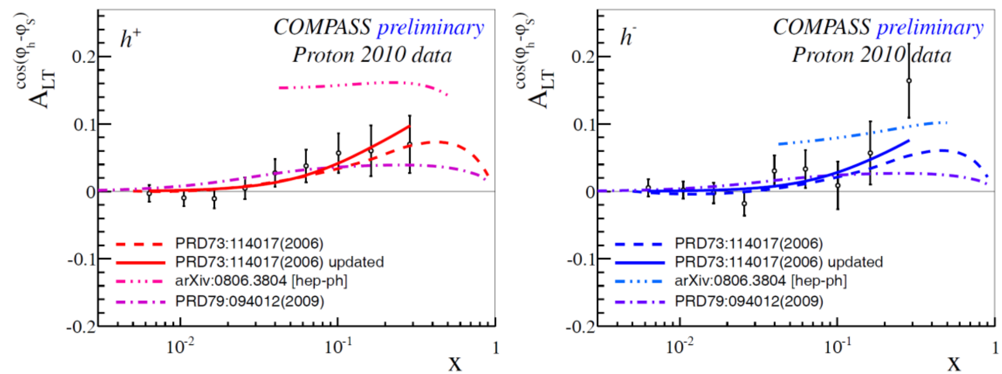
SIDIS x-section

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

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

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



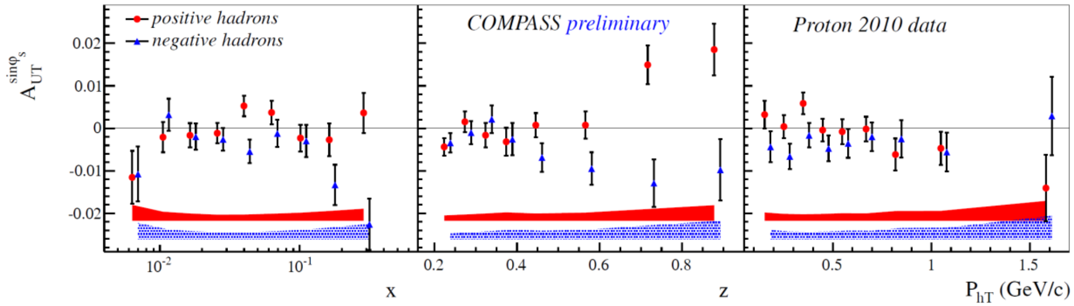


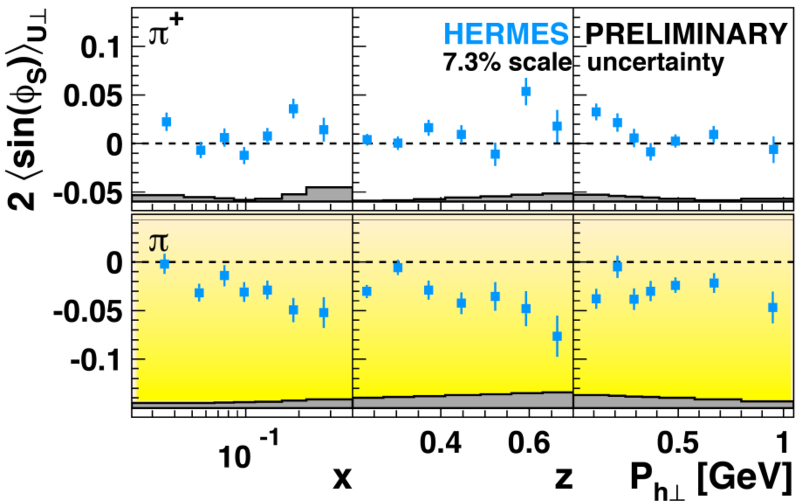
- Gives access to g_{1T} "twist-2" PDF (worm-gear-T)
- Visible signal for h^+ (*preliminary* confirmation also by HERMES)
- In agreement with several model predictions
- Compatible with zero on deuteron

$$A_{UT}^{\sin(\phi_s)} \overset{WW}{\propto} Q^{-1}\left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right) \quad \text{SSA}\left[\text{higher-twist}\right]$$

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

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





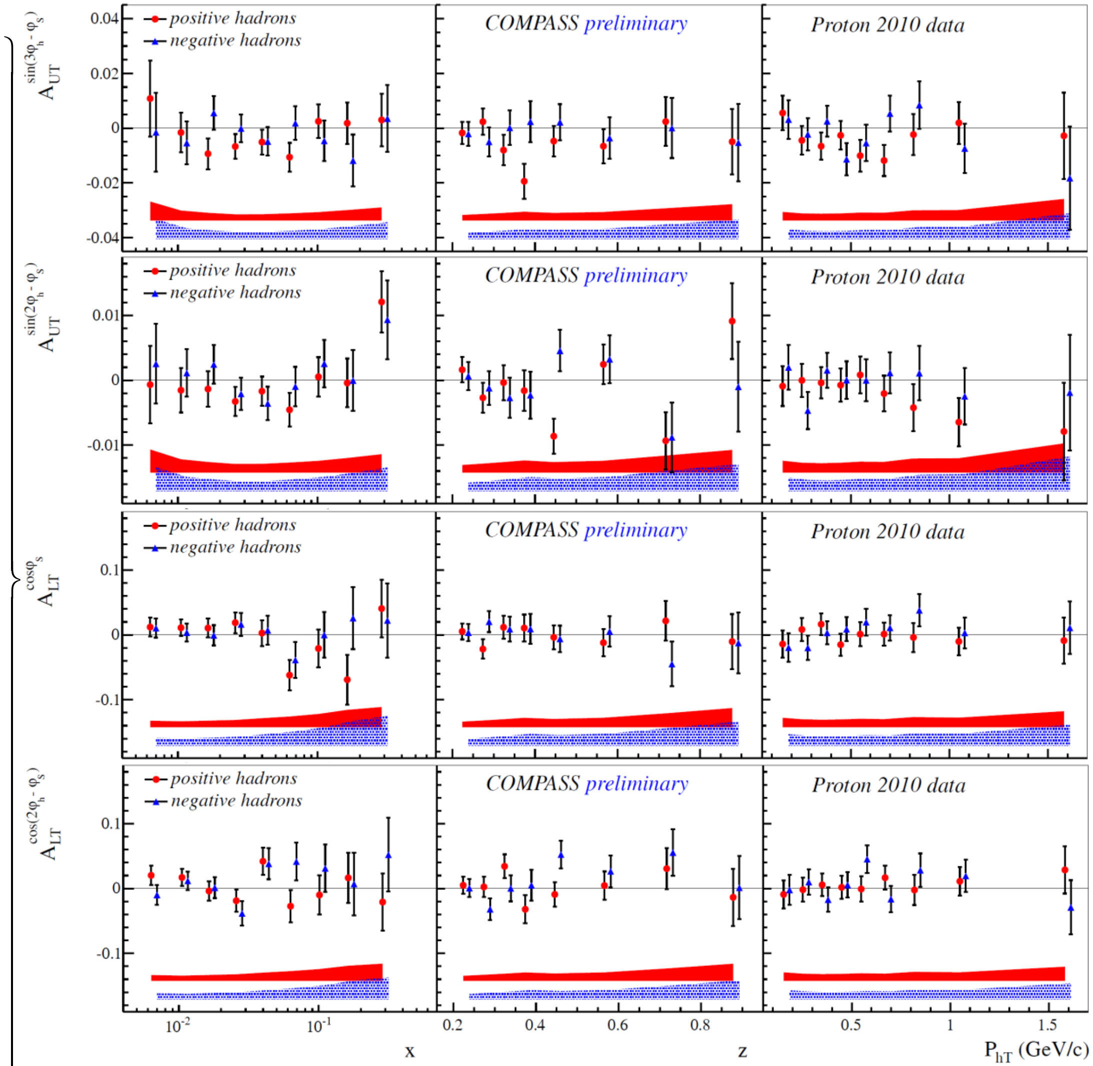
- Higher twist effect..
- In WW-approximation is related to Sivers and Collins
- Non-zero trend for negative hadrons both in COMPASS and HERMES
- Compatible with zero on deuteron

$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q}\otimes H_{1q}^{\perp h}$ SSA[twist-2]; $A_{UT}^{\sin(2\phi_h-\phi_s)} \overset{WW}{\propto} Q^{-1}\left(h_{1T}^{\perp q}\otimes H_{1q}^{\perp h} + f_{1T}^{\perp q}\otimes D_{1q}^{h}+\ldots\right)$ SSA[higher-twist]

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

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

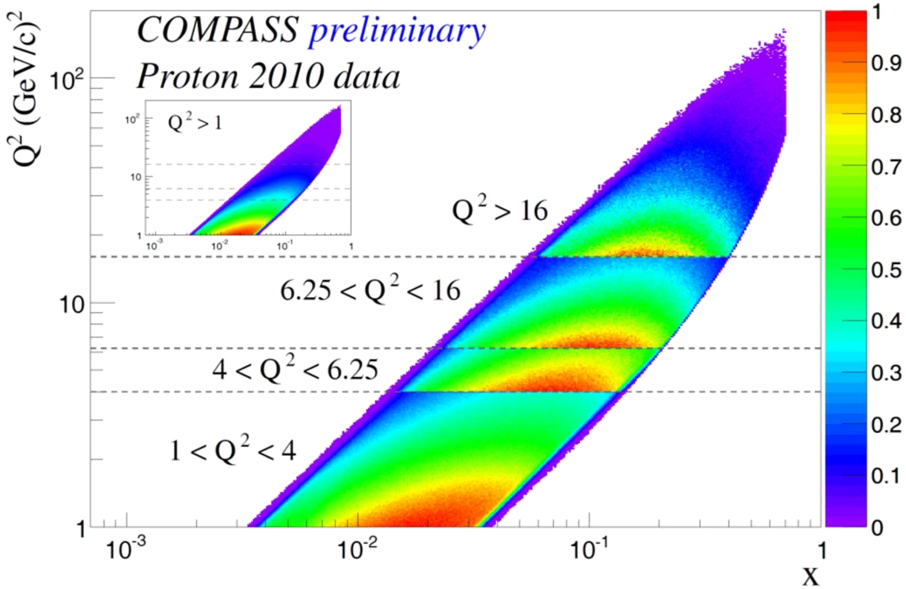
$$\left\{\begin{array}{l}
1+\cos\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\right)+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right)\\
+\ \lambda\sin\phi_h\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\right)\\
+\ S_L\left[\sin\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\right)+\sin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

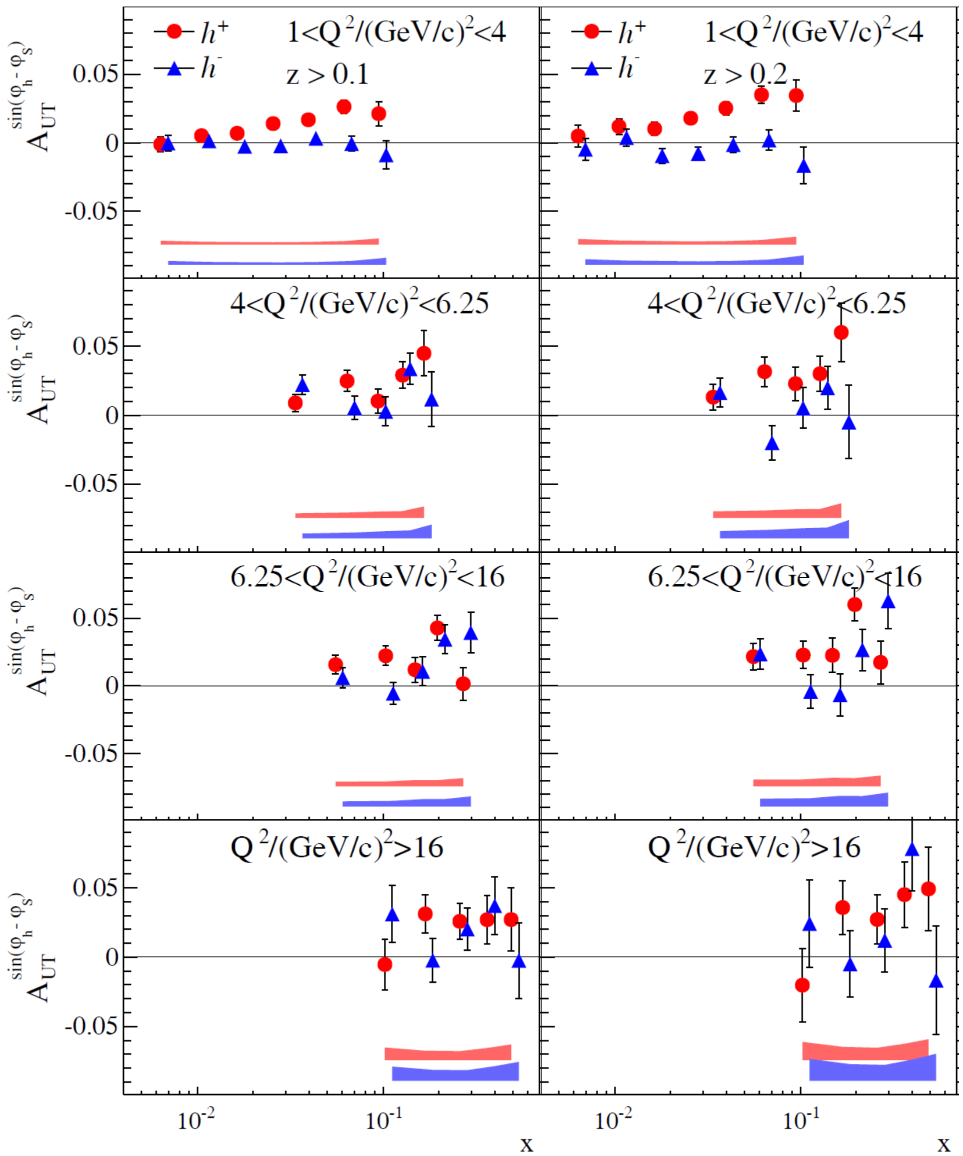


- All compatible with zero within uncertainties (P/D)

SIDIS asymmetries in Drell-Yan Q^2 ranges

First shown at the Transversity-2014 **(for details see talk by B. Parsamyan on Friday)**





Towards 3D…

Four Q^2-ranges:

- $1 < Q^2/(\mathrm{GeV}/c)^2 < 4$ “Low mass”
- $4 < Q^2/(\mathrm{GeV}/c)^2 < 6.25$ “Intermediate”
- $6.25 < Q^2/(\mathrm{GeV}/c)^2 < 16$ “J/ψ range”
- $Q^2/(\mathrm{GeV}/c)^2 > 16$ “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)

Outline

- Introduction
  - SIDIS x-section and TSAs
  - Brief review of recent COMPASS results with TSAs
- COMPASS multidimensional approach NEW
  - COMPASS multidimensional phase-space
- Results for TSAs NEW (Shown for the first time!)
  - 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
  - Mean depolarization factors
- Corrections for *lp* to *γ*p* transition
- Conclusions

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

- 1^{st} option (2D asymmetries):
  - x-, z-, p_T-, and W- dependencies in 5 Q^2-bins

NEW!

Shown for the first time!

- 2^{nd} option (3D asymmetries):
  - x-dependency in $Q^2{:}z$ grid (5×5)
  - Q^2-dependency in $x{:}z$ grid (9×5)
  - x-dependency in $Q^2{:}p_T$ grid (5×5)
  - Q^2-dependency in $x{:}p_T$ grid (9×5)
- 3^{rd} option (4D asymmetries)
  - x-dependency in $z{:}Q^2{:}p_T$ grid (2×5×5)
  - Q^2-dependency in $z{:}x{:}p_T$ grid (2×9×5)

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:

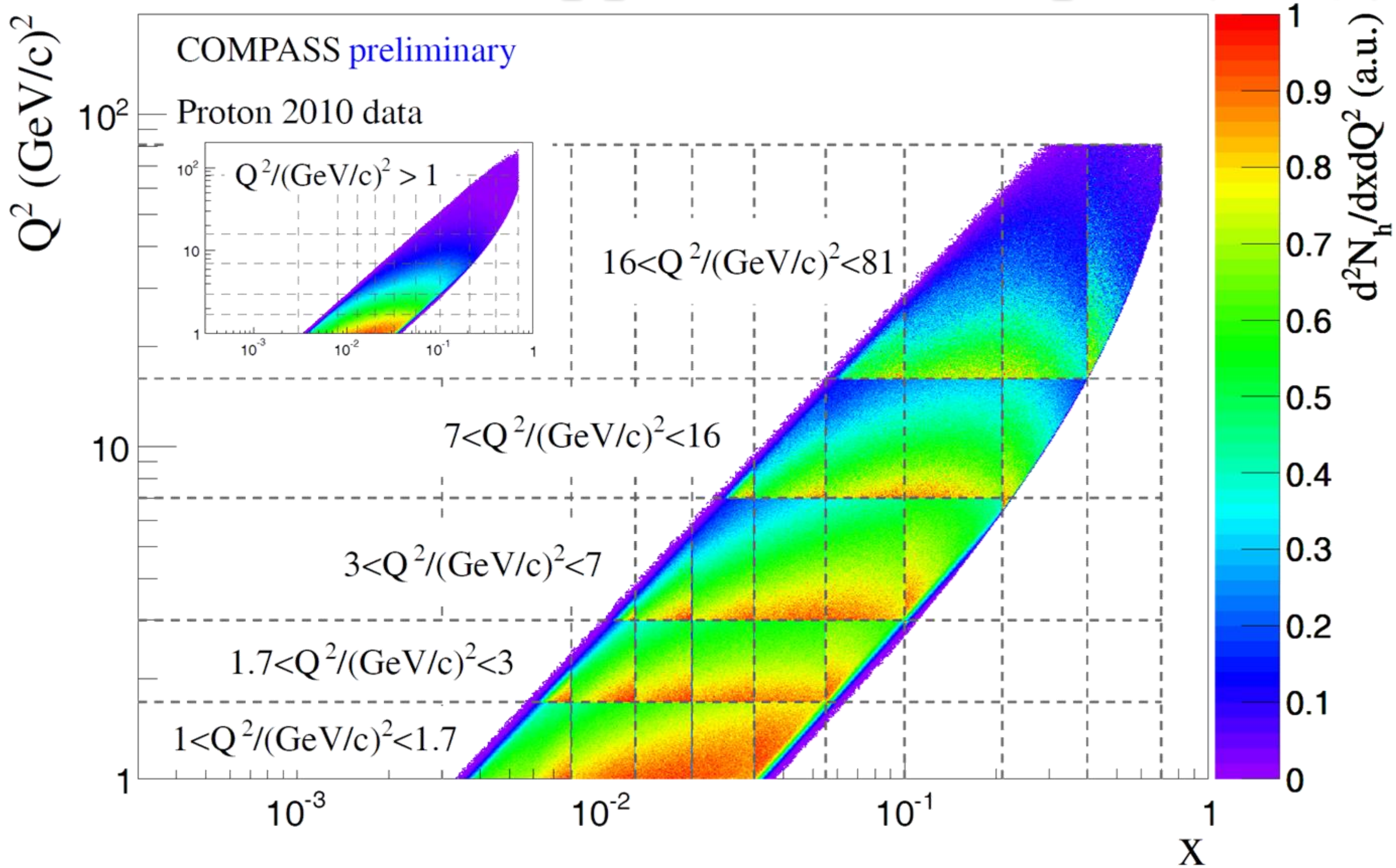
- $z > 0.1$
- $z > 0.2$
- $0.1 < z < 0.2$
- $0.2 < z < 0.4$
- $0.4 < z < 1.0$

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 ($x:Q^2$)



NEW!

Shown for the first time!

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:

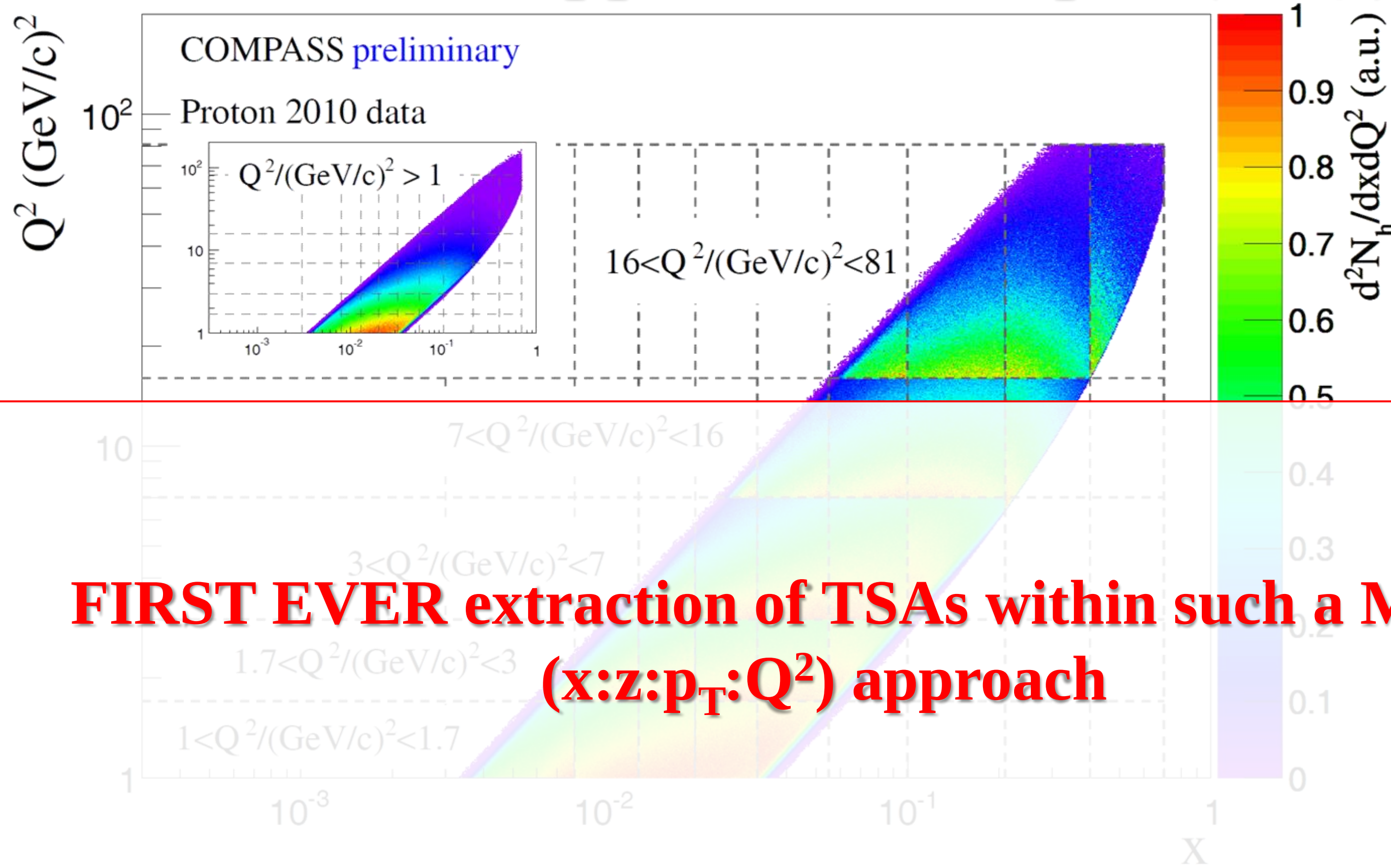
- $z > 0.1$
- $z > 0.2$
- $0.1 < z < 0.2$
- $0.2 < z < 0.4$
- $0.4 < z < 1.0$

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 ($x:Q^2$)



NEW!

Shown for the first time!

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

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

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

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)

NEW!

Shown for the first time!

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)

NEW!

Shown for the first time!

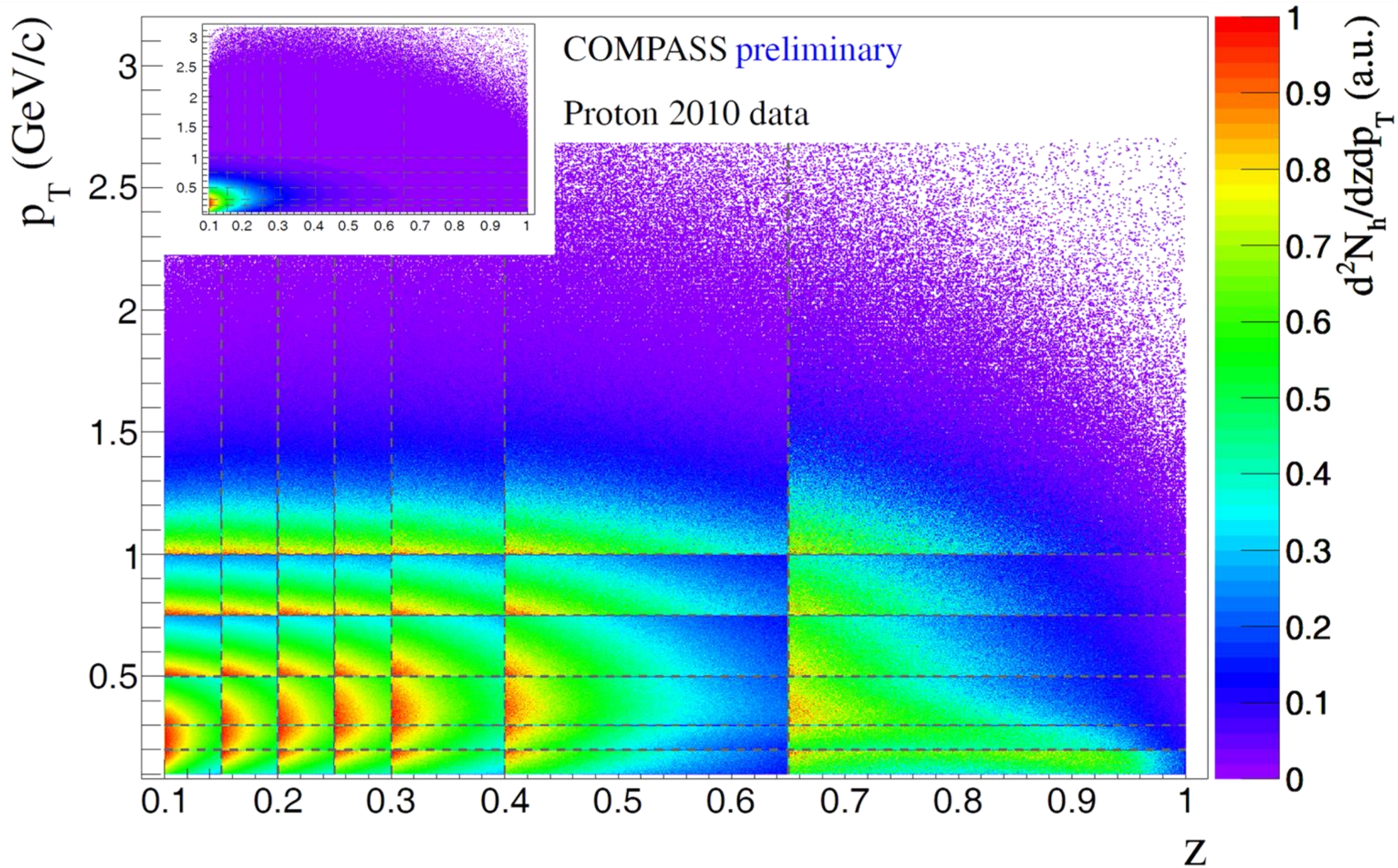
3D asymmetries:

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



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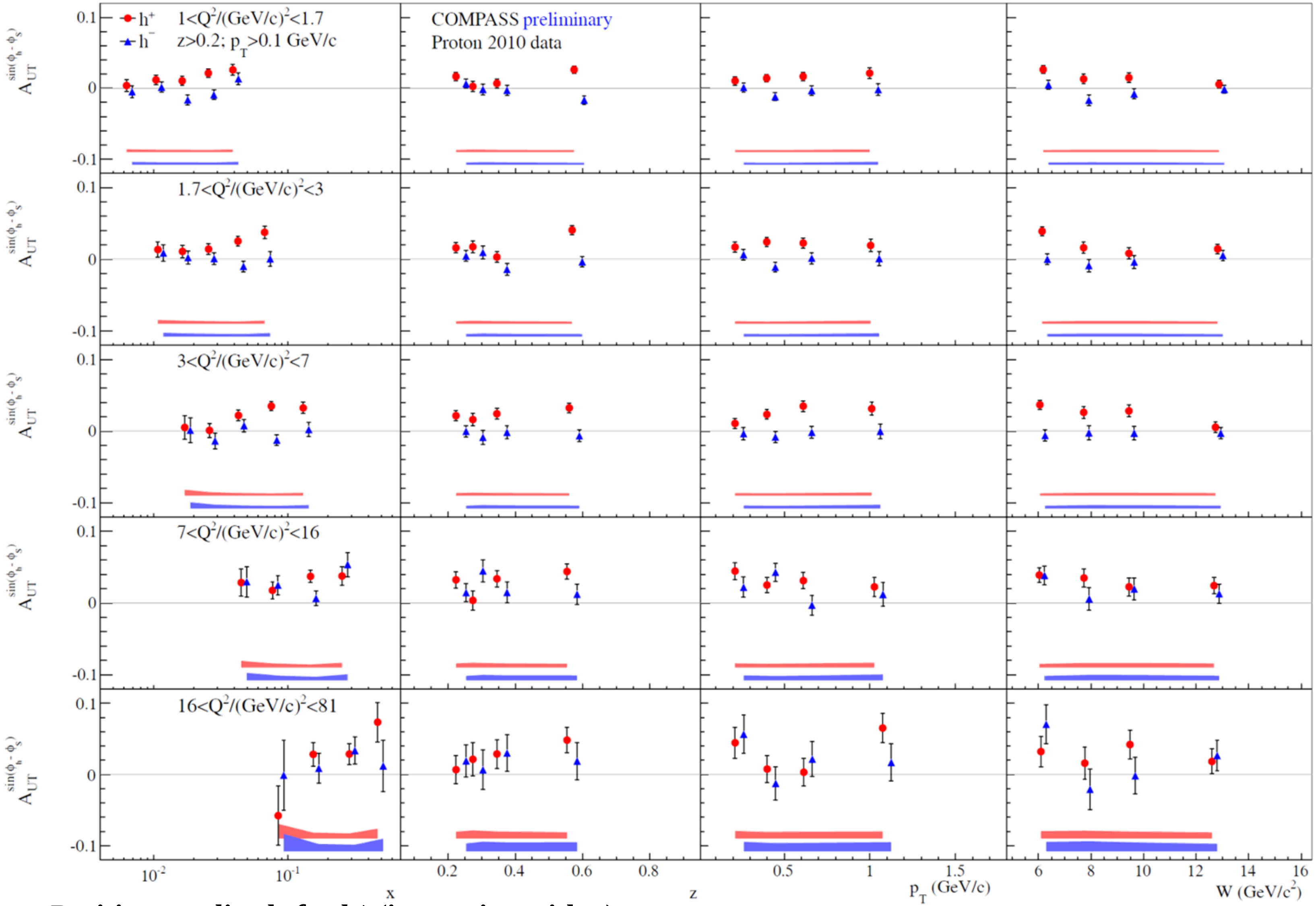
Sivers asymmetry: x, z, p_T and W dependencies in 5 Q^2-ranges



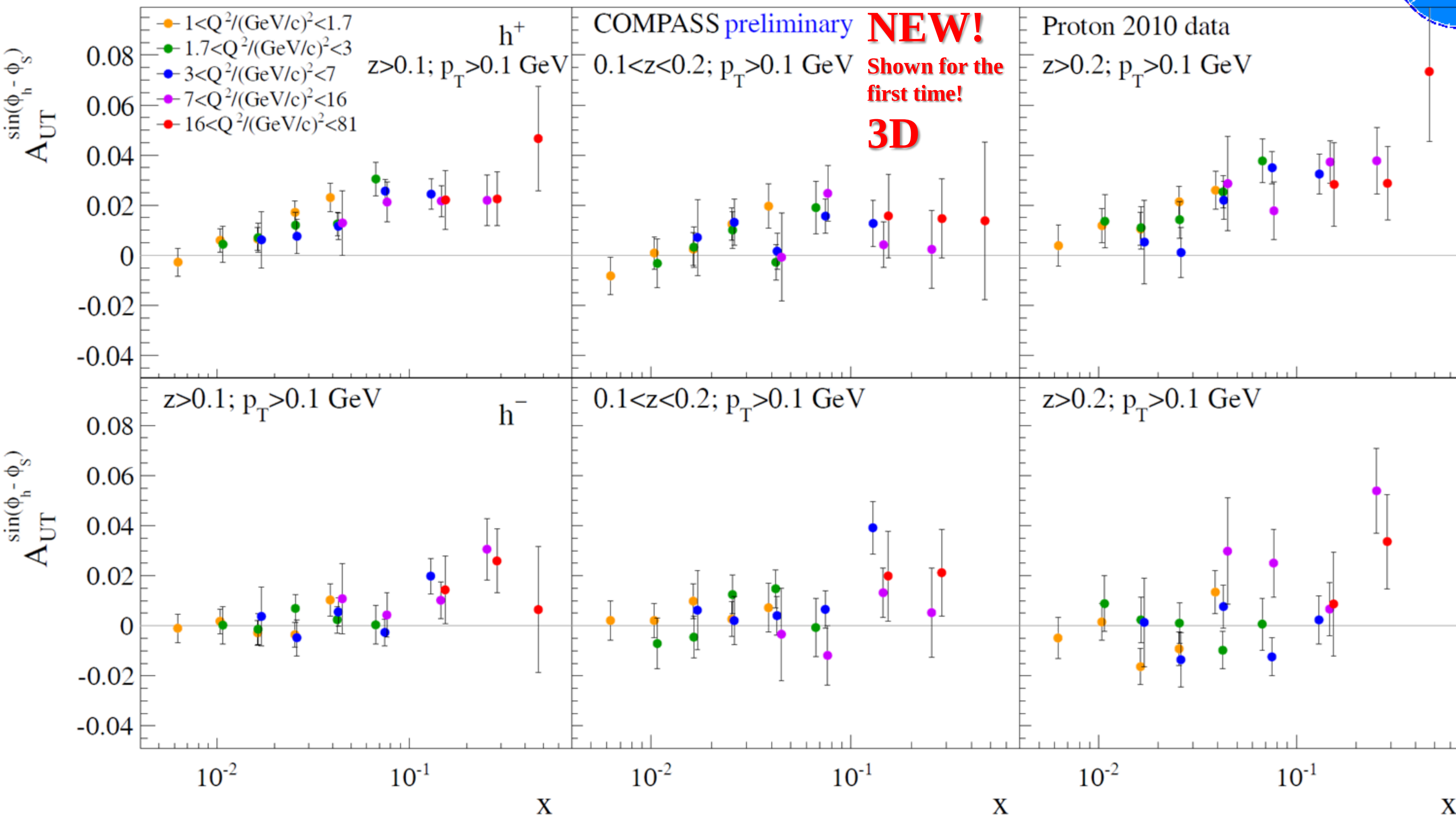
NEW!

Shown for the first time!

2D

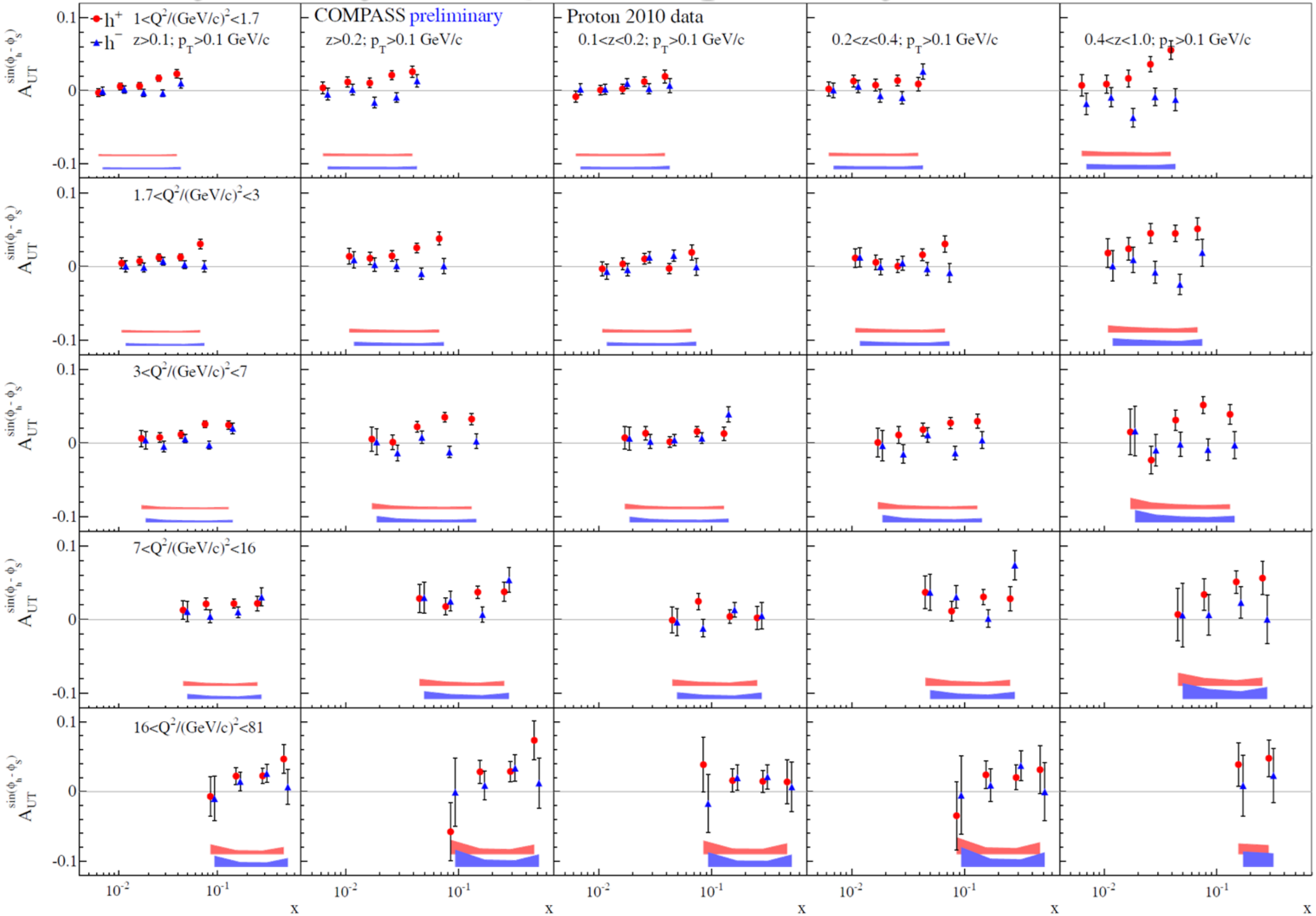
- **Positive amplitude for h^+ (increasing with x)**
- **Positive h^- amplitude at relatively large x (>0.032) and Q^2 (>7)**
- **Some hint for a possible negative h^- amplitude at low x (<0.032) and Q^2 (<7)**

Sivers asymmetry: x-dependency in 5 Q^2-ranges and different z



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

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



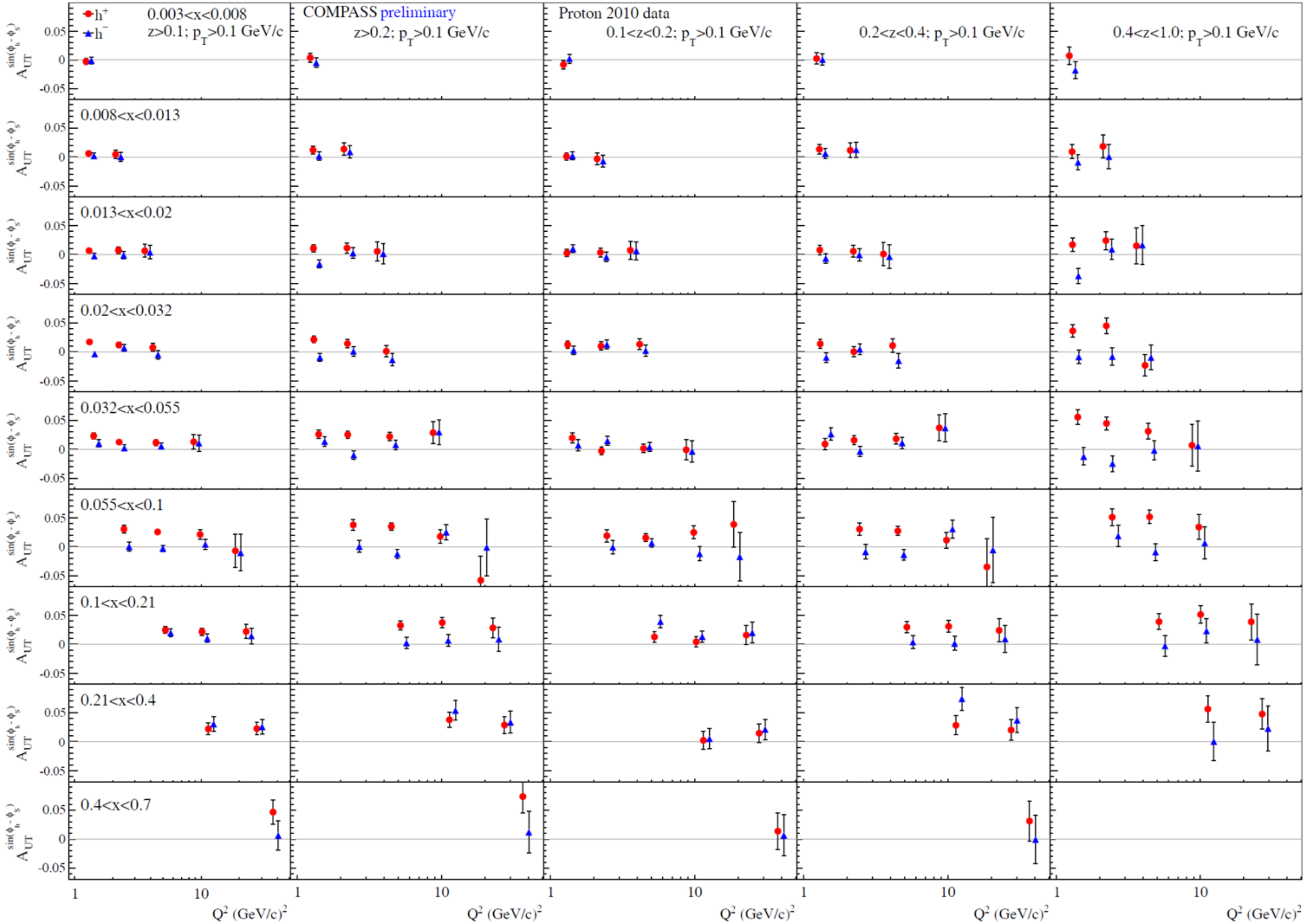
NEW!

Shown for the first time!

3D

- **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 dependency



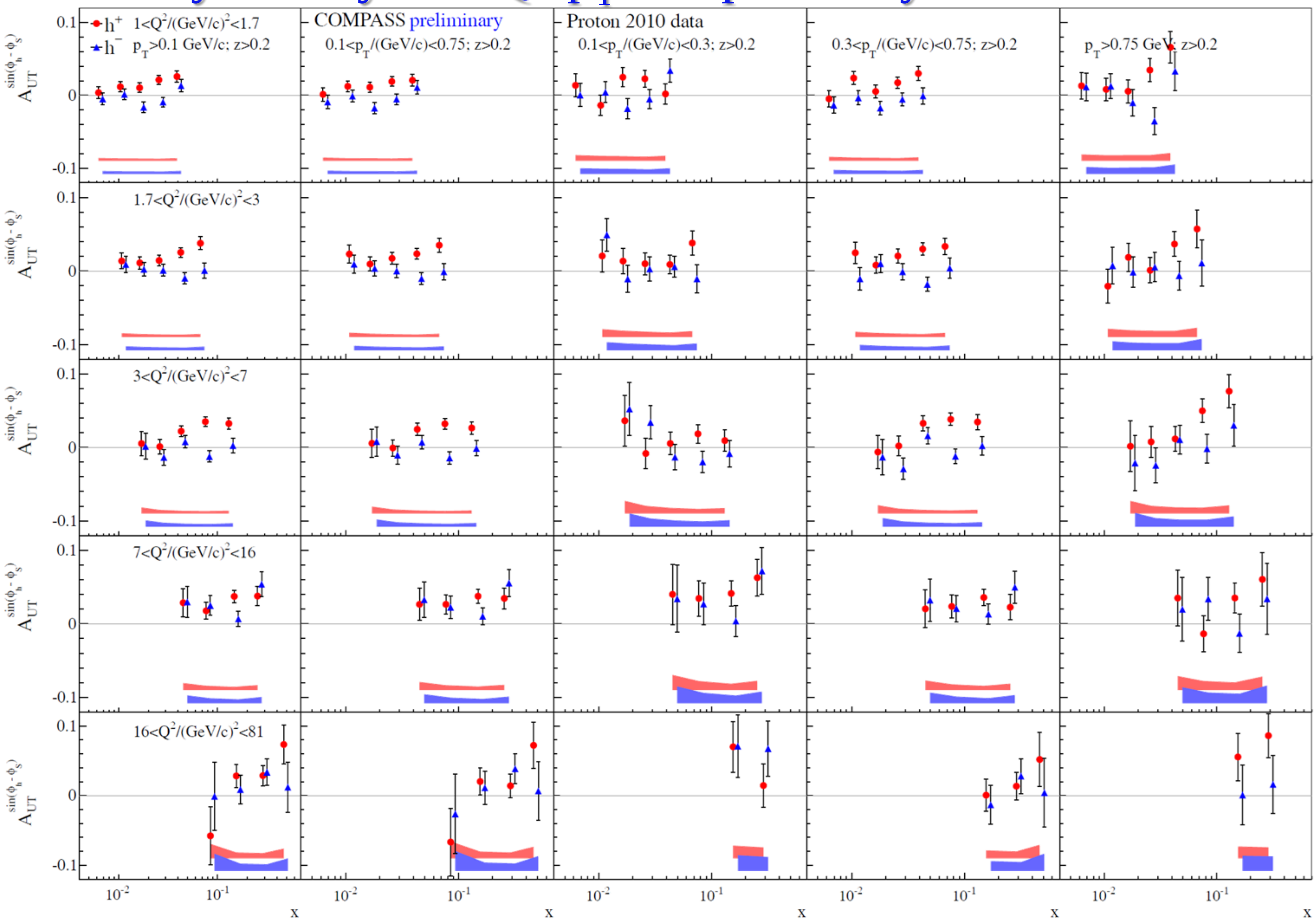
NEW!

Shown for the first time!

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: 4D Q^2-p_T-x dependency at z>0.2



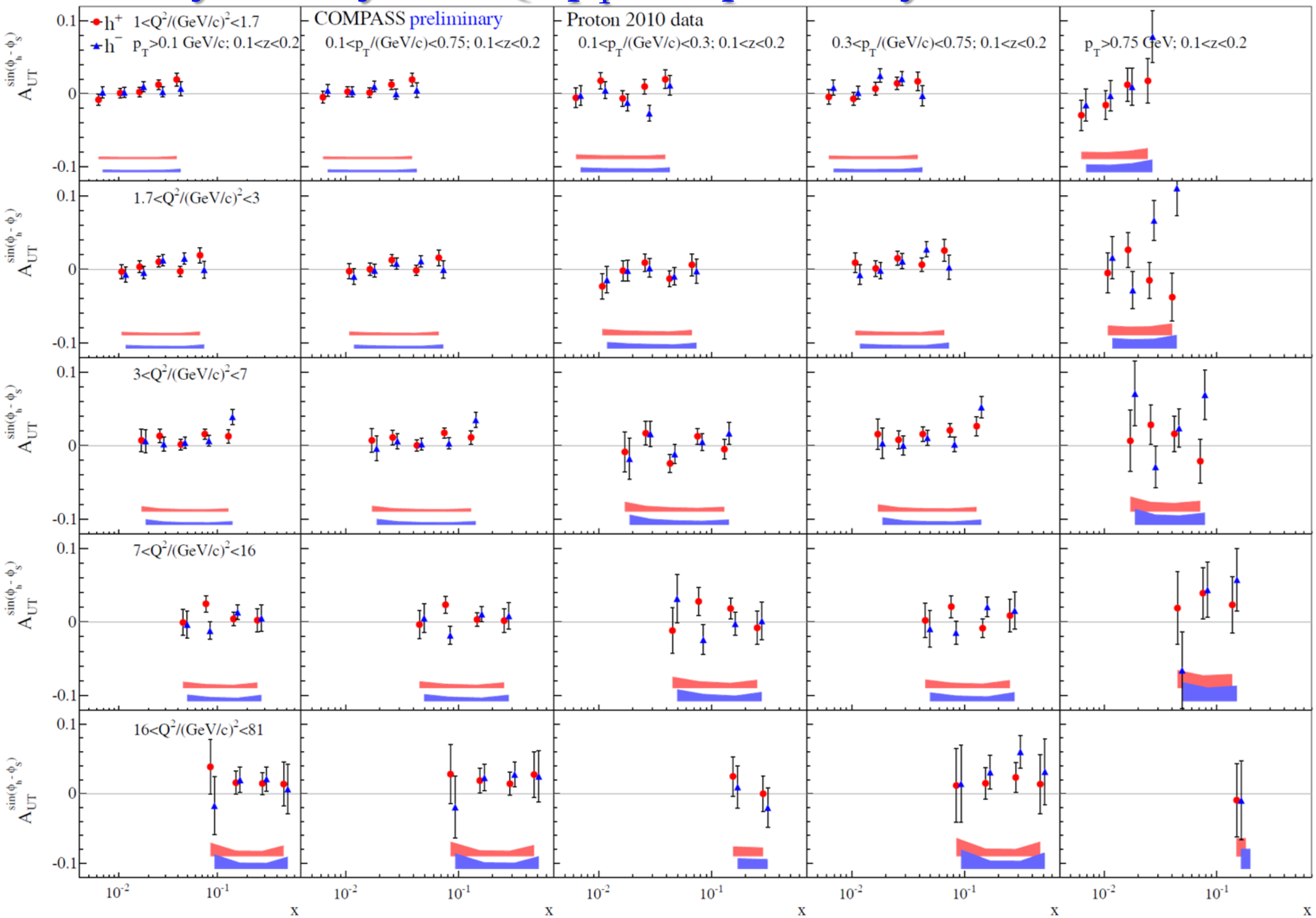
NEW!

Shown for the first time!

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 dependency at 0.1<z<0.2



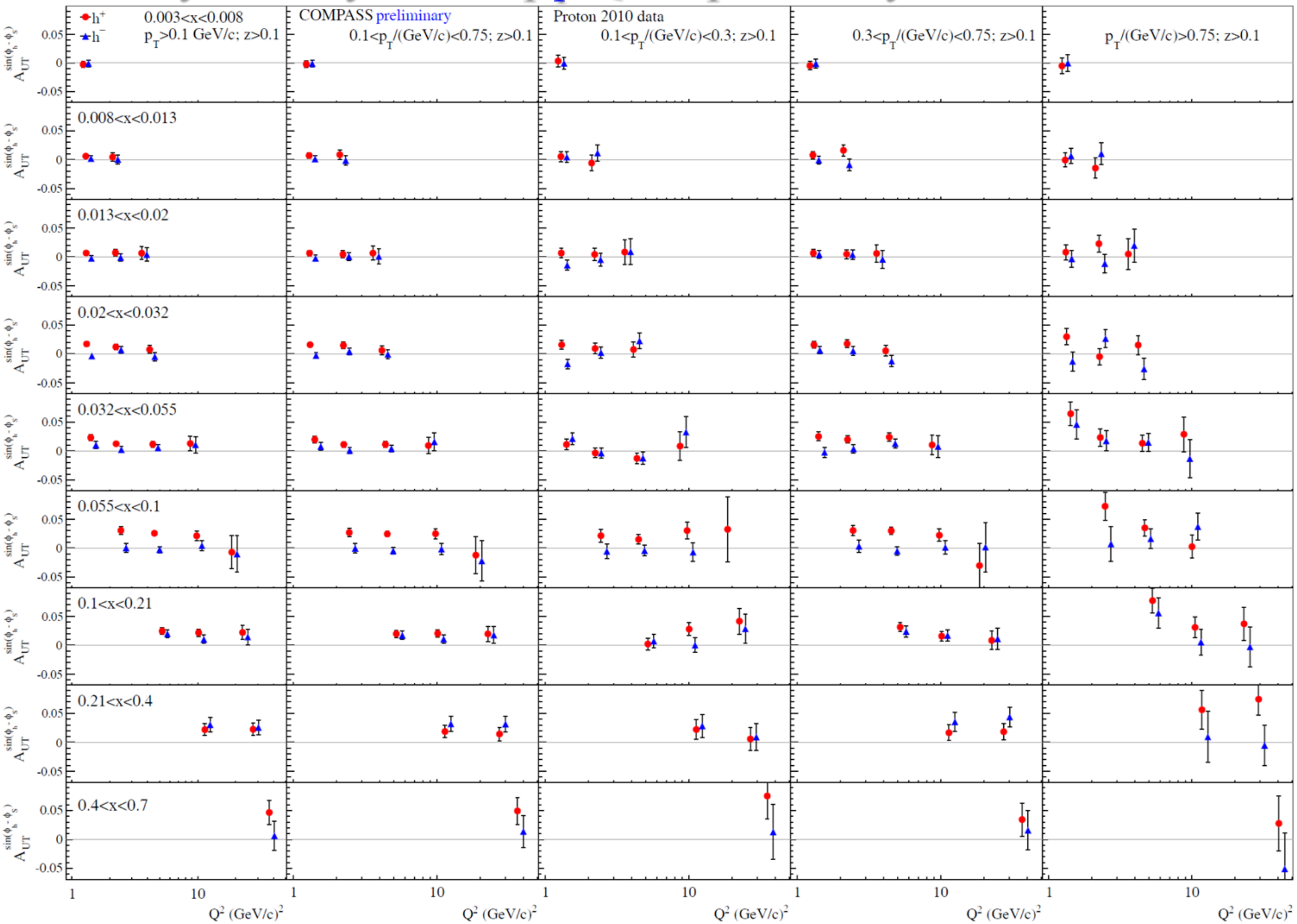
NEW!

Shown for the first time!

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-p_T-Q^2 dependency



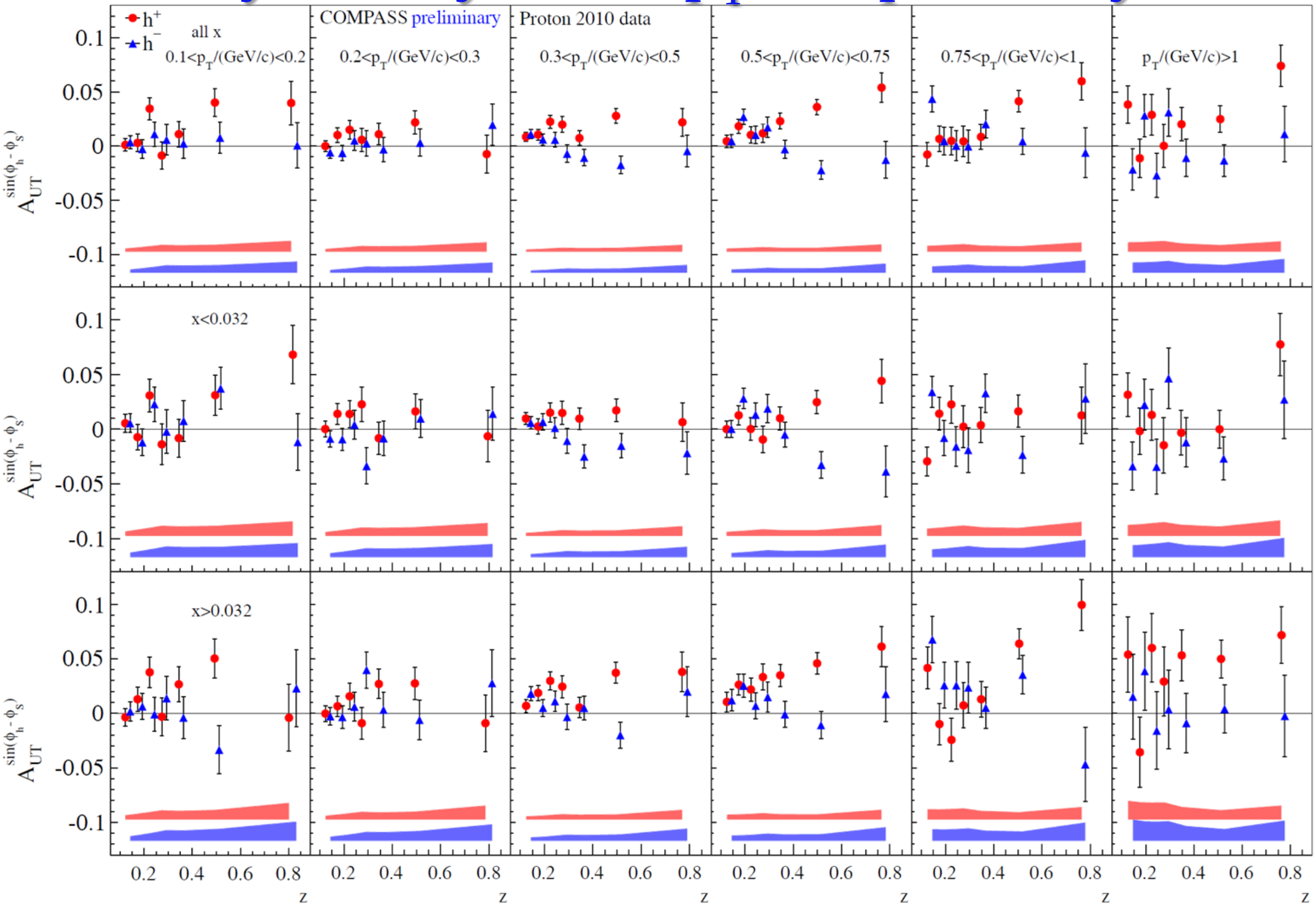
NEW!

Shown for the first time!

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: 3D x-p_T-z dependency



NEW!

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3D

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- **Positive h^- amplitude at relatively large x (>0.032) and Q^2 (>7) at intermediate and large z (all p_T)**
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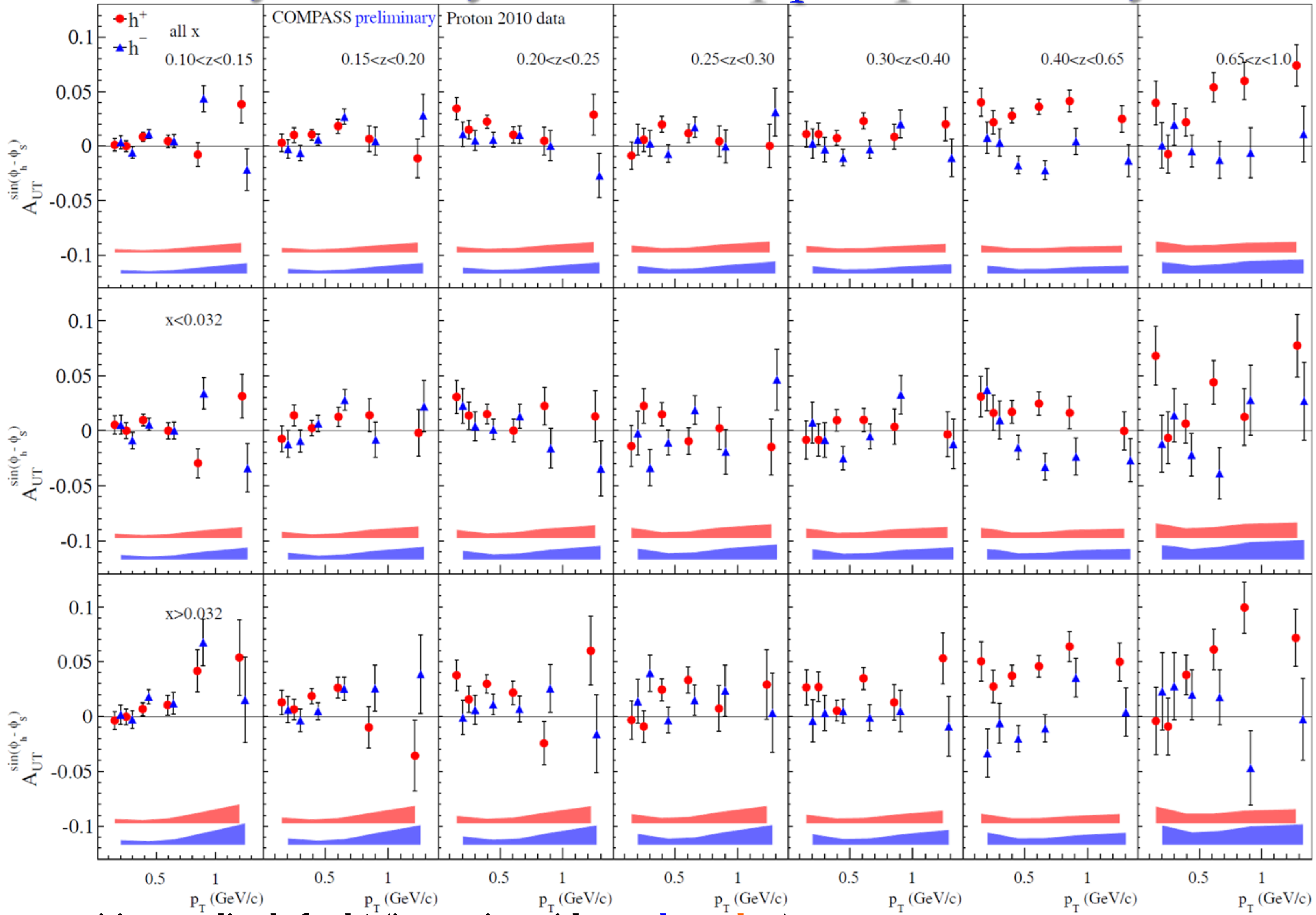
Sivers asymmetry: 3D x-z-p_T dependency



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- **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)**
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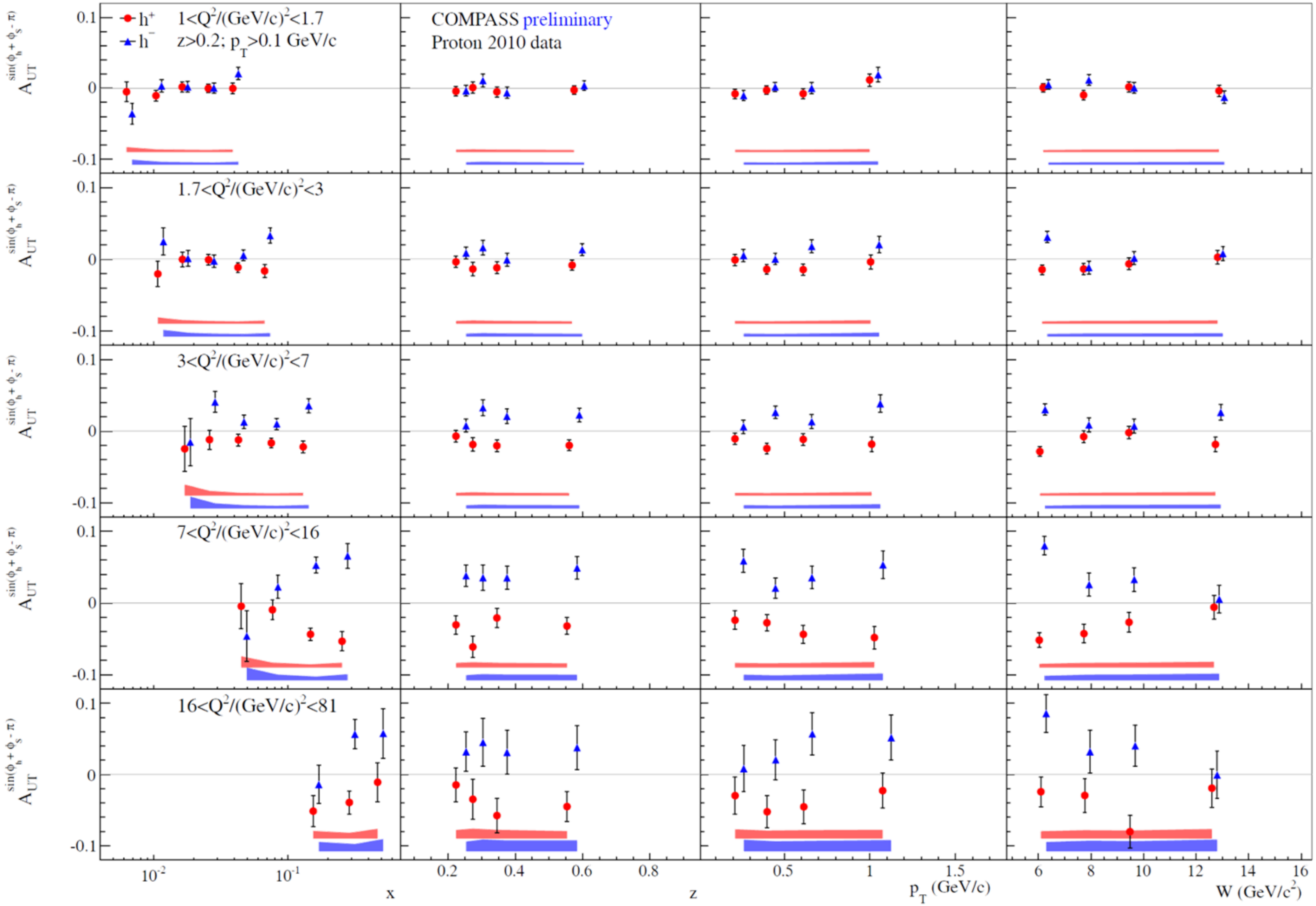


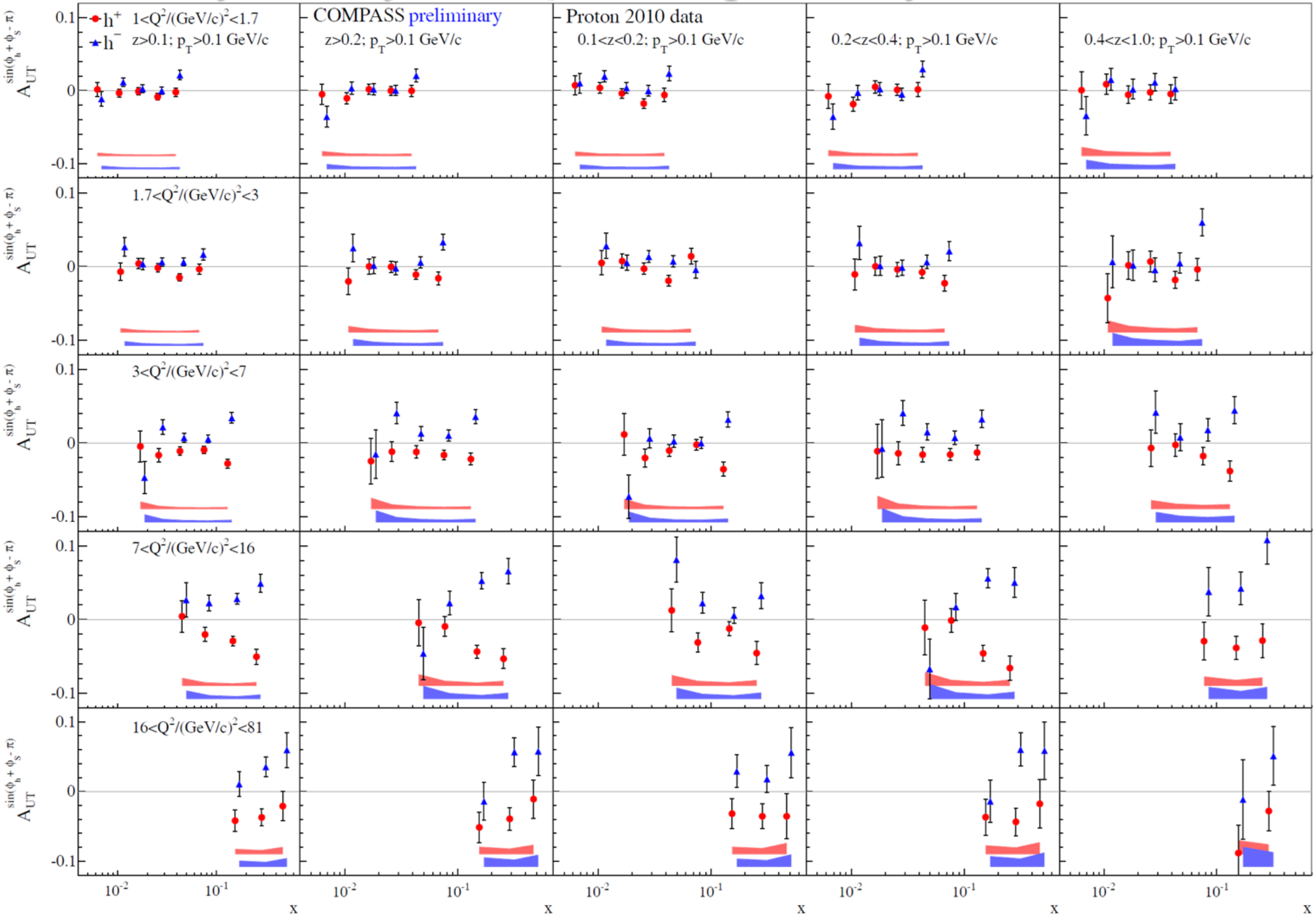
NEW!

Shown for the first time!

2D

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

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



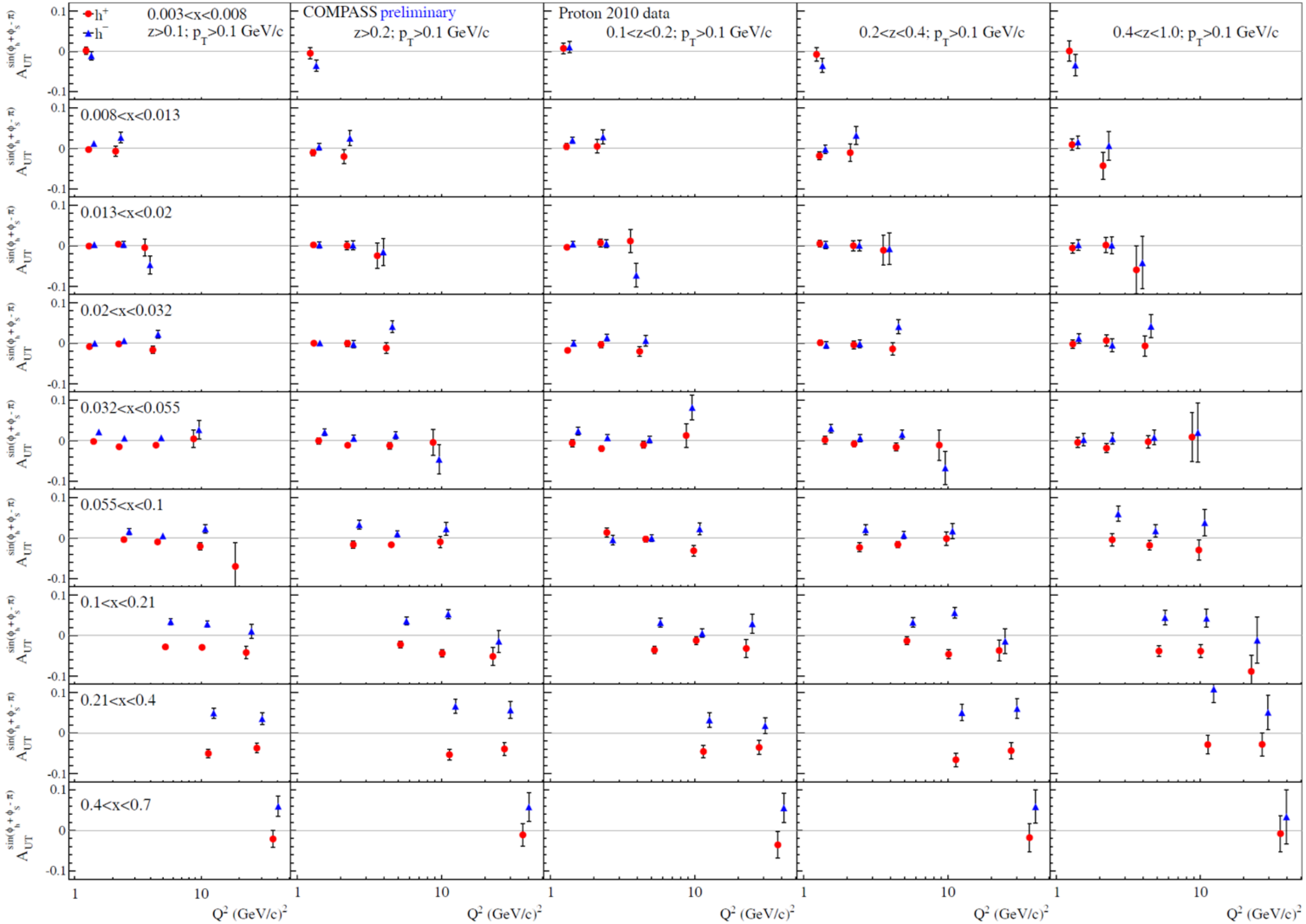
NEW!

Shown for the first time!

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 dependency



NEW!

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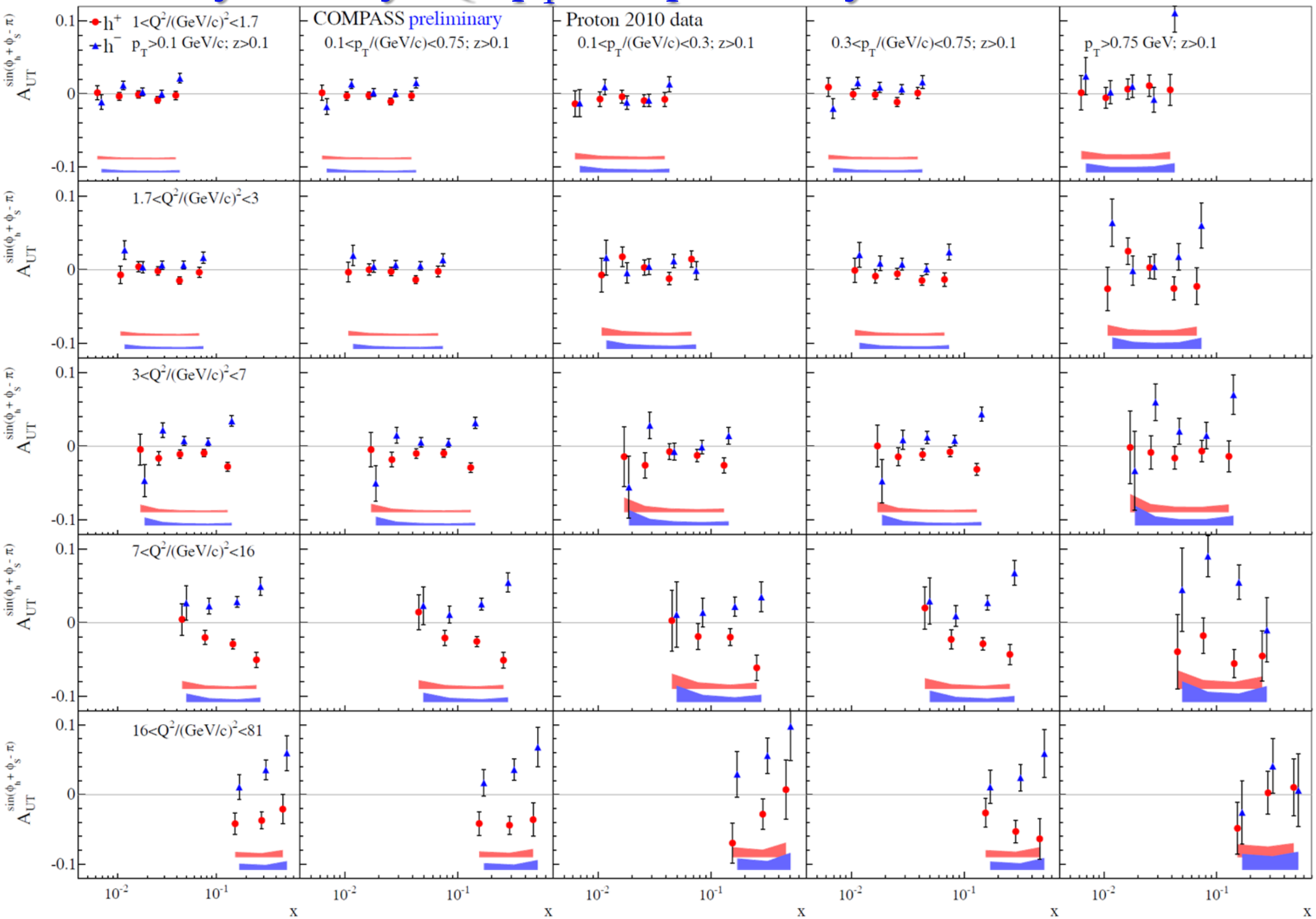
3D

- **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-dependencies. Not clear.**

Collins asymmetry: Q^2-p_T-x dependency at z>0.1



NEW!

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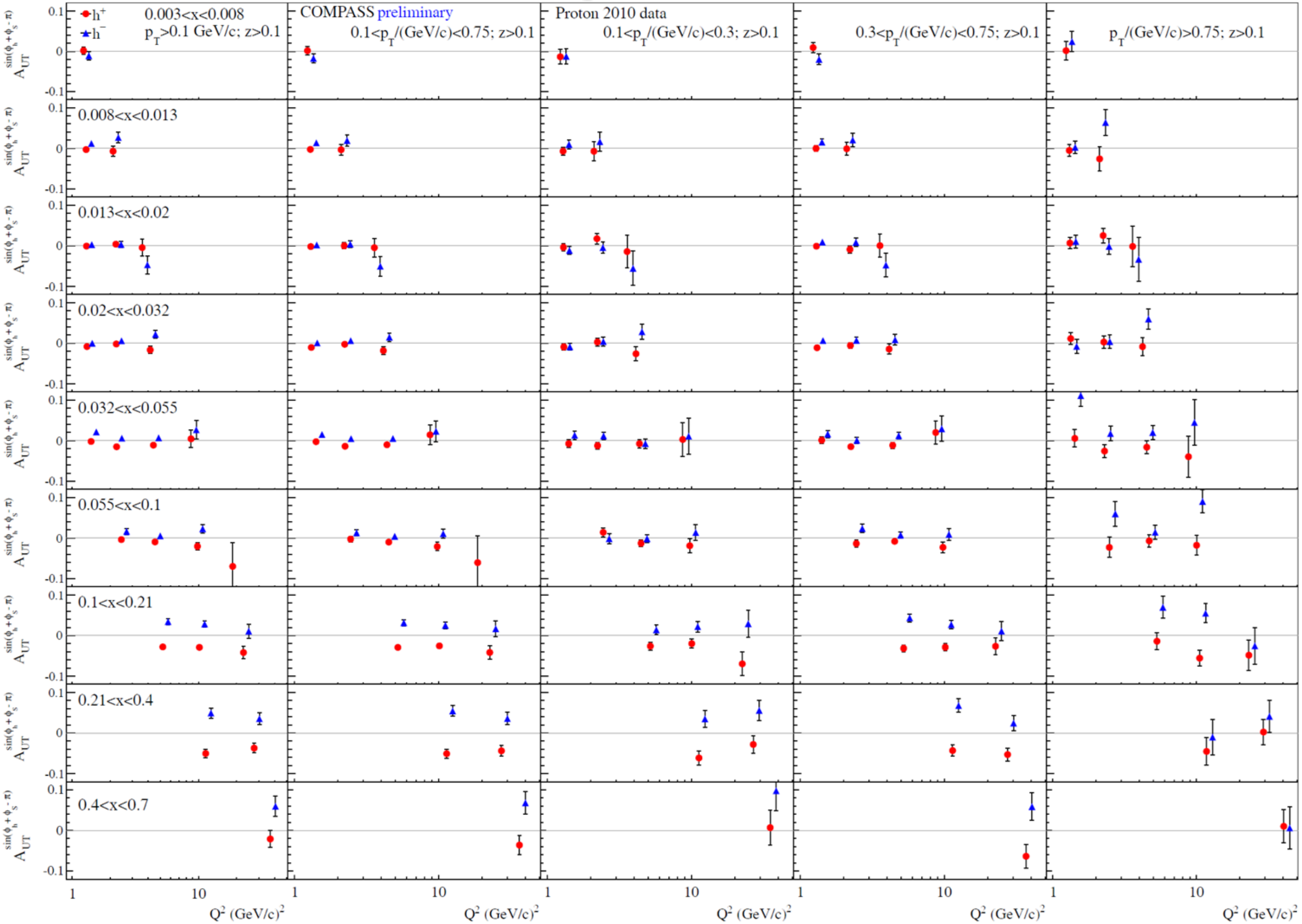
- **Both h^+ and h^- amplitudes are compatible with zero at low x and become sizable (opposite in sign) from x>0.032**
- **Both h^+ and h^- amplitudes tend to increase with x, but with some "irregularities"**
- **Both h^+ and h^- amplitudes tend to increase with p_T**

Collins asymmetry: 3D x-p_T-Q^2 dependency



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3D

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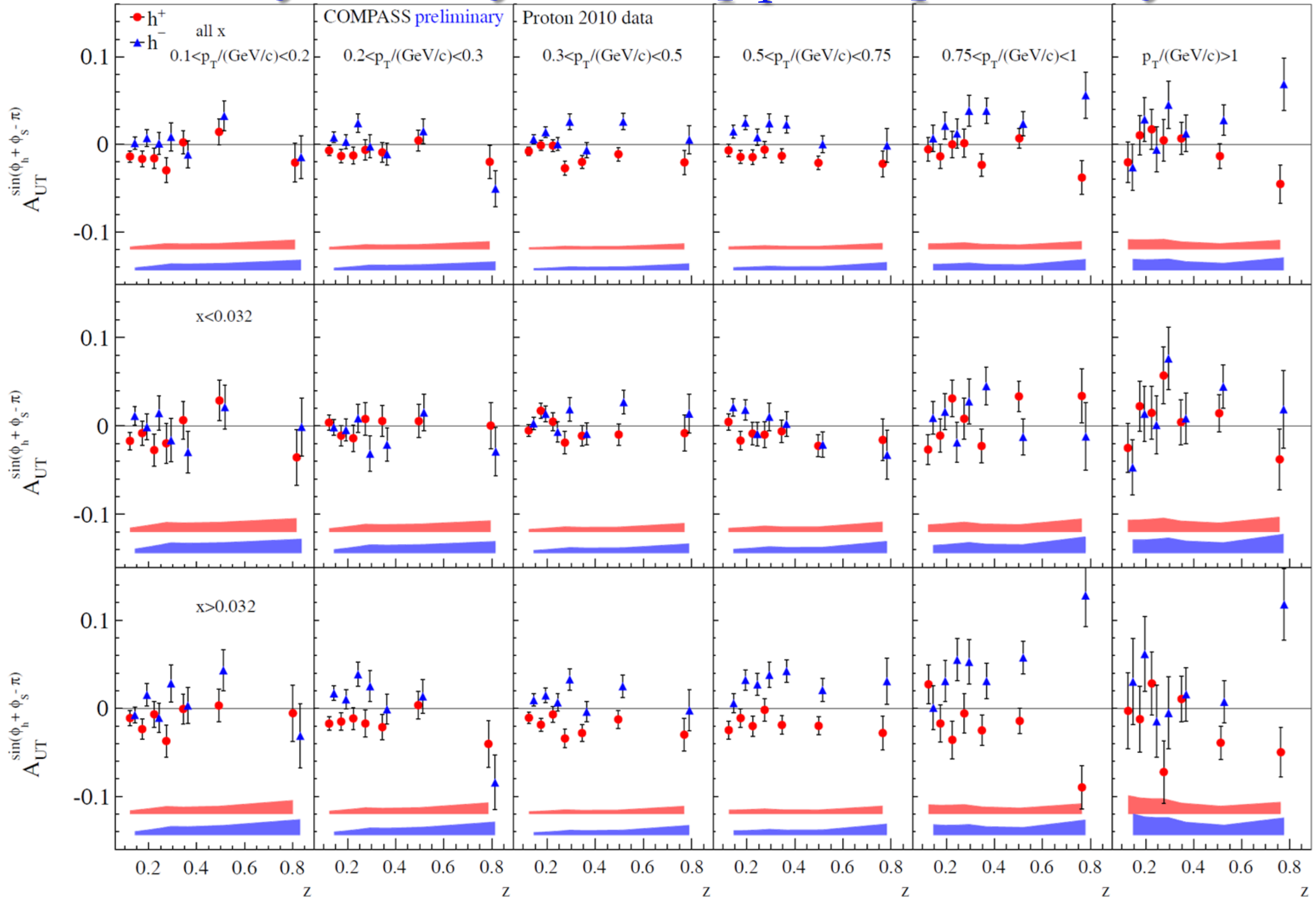
Collins asymmetry: 3D x-p_T-z dependency



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- **Both h^+ and h^- amplitudes tend to increase with x, but with some "irregularities"**
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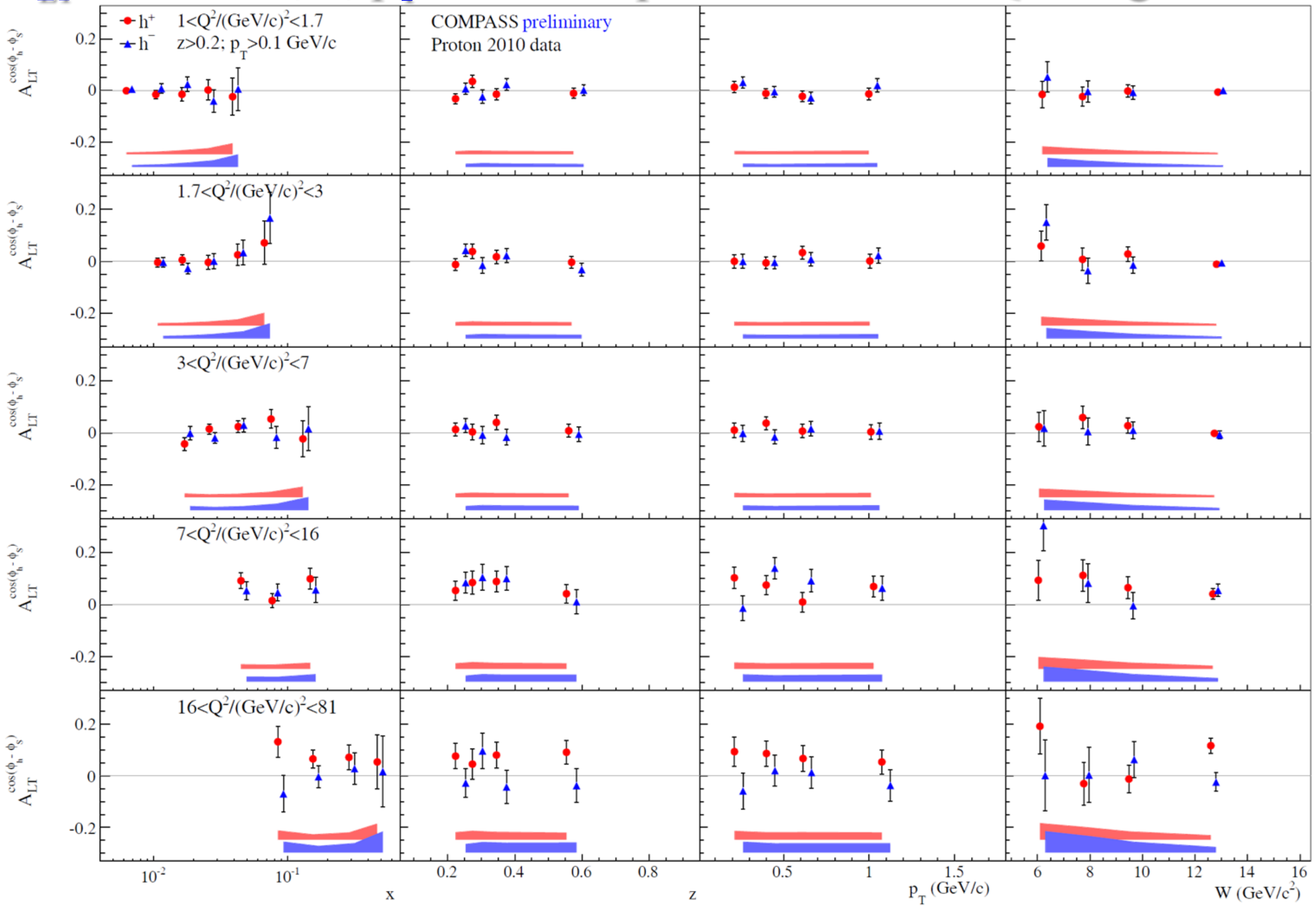
$A_{LT}^{cos(\phi_h-\phi_S)}$: x, z, p_T and W dependencies in 5 Q^2-ranges



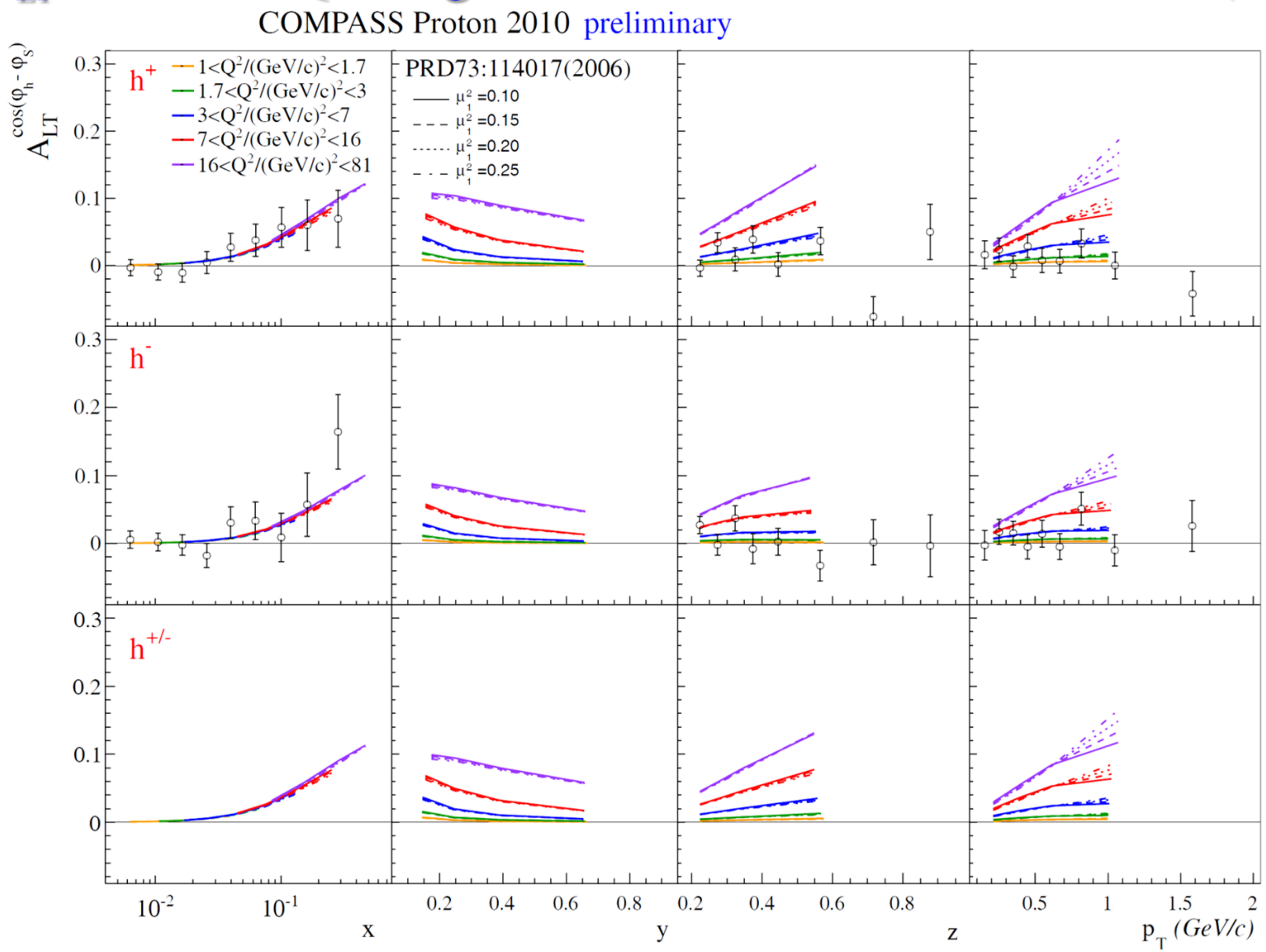
NEW!

Shown for the first time!

2D

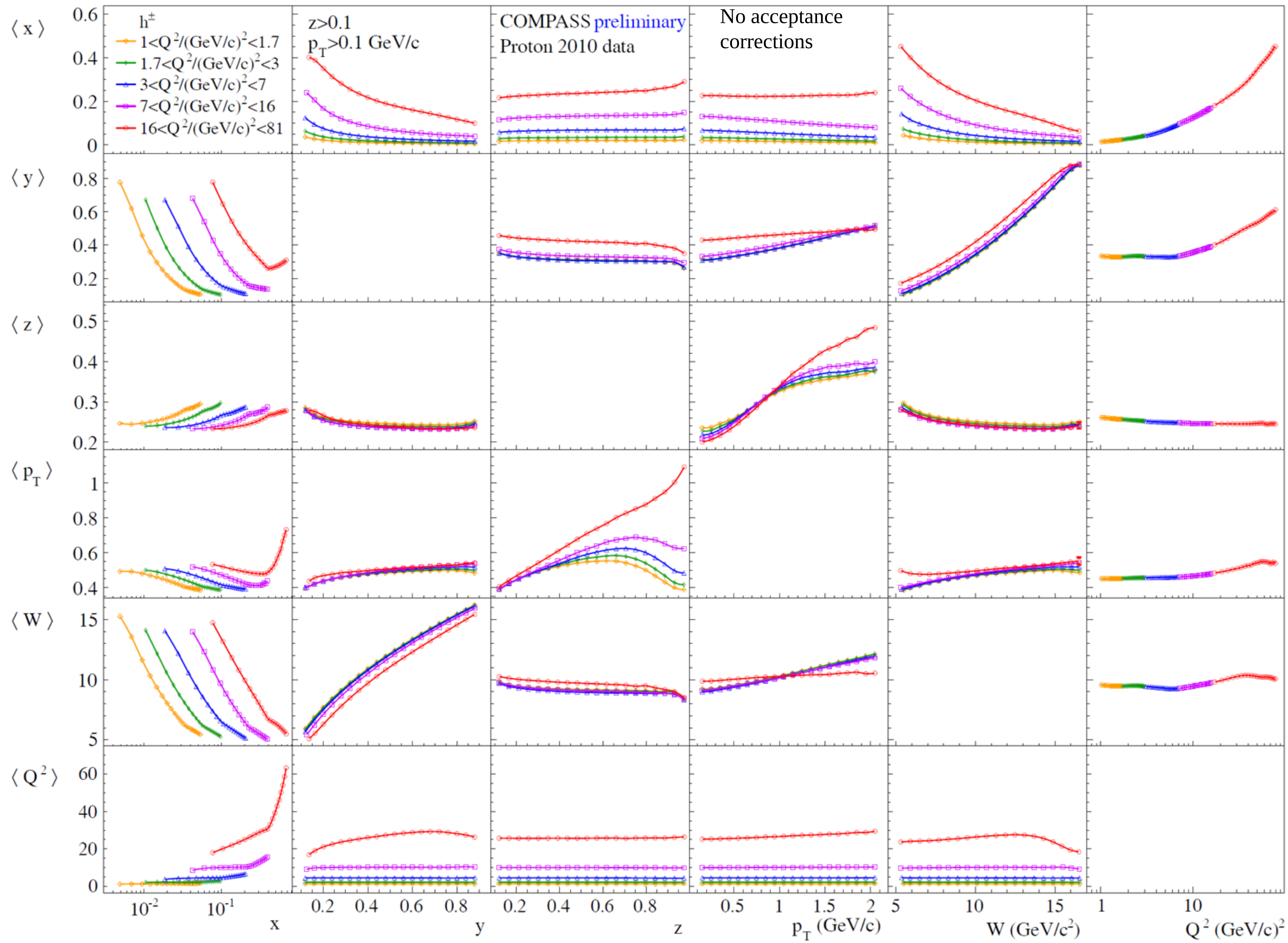
- **Positive amplitude for h^+ at large x (>0.032) and Q^2 (>3)**
- **Signal for negative hadrons is not evident.**

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

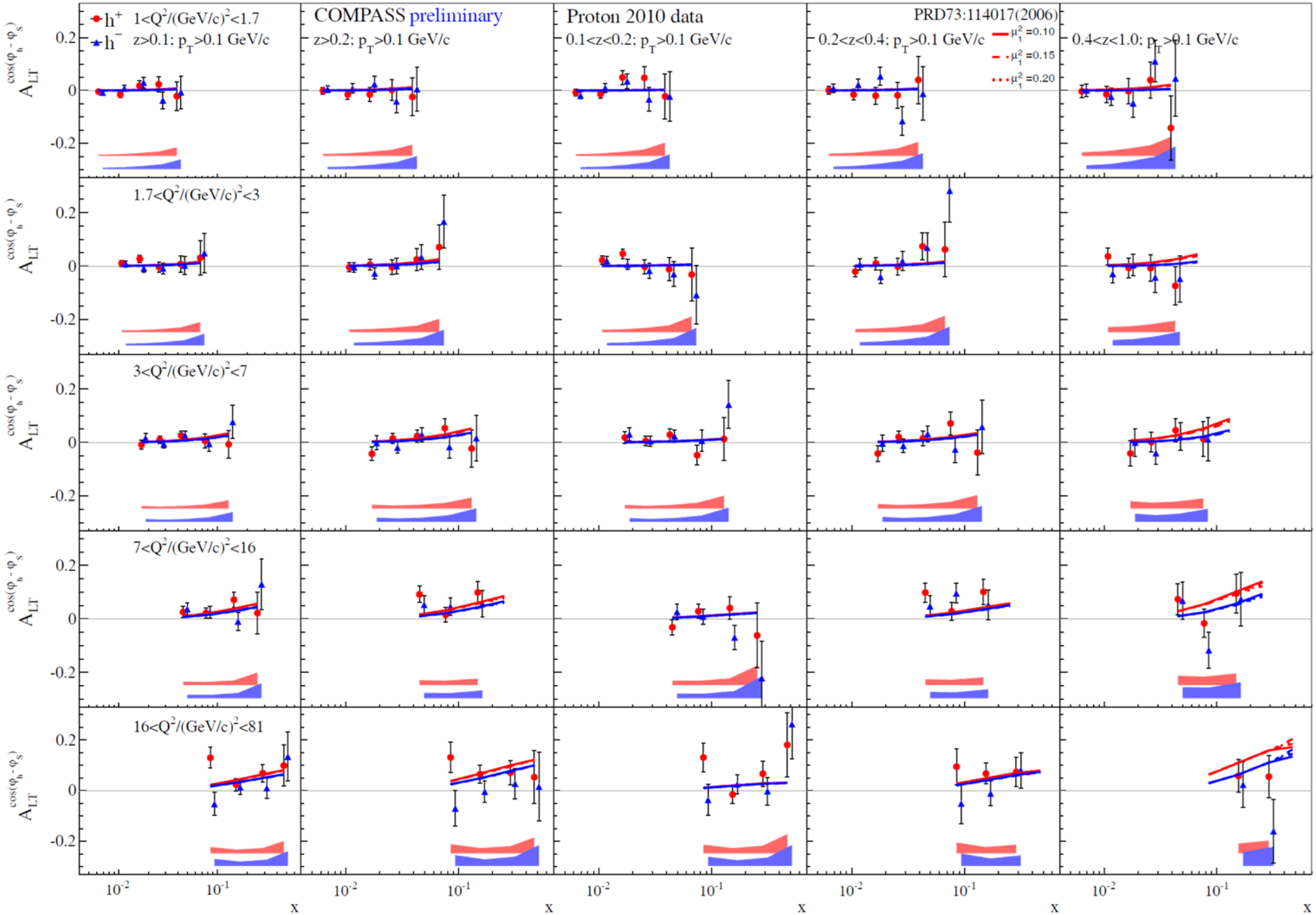


Asymmetry is evaluated in COMPASS specific mean kinematic points extracted from the data.
The predictions show a good level of agreement with the experimentally extracted asymmetry

Kinematical map: z>0.1, p_T>0.1



$A_{LT}^{\cos(\phi_h-\phi_S)}$: 3D Q^2-z-x dependency: Predictions - PRD 73, 114017(2006)



NEW!

Shown for the first time!

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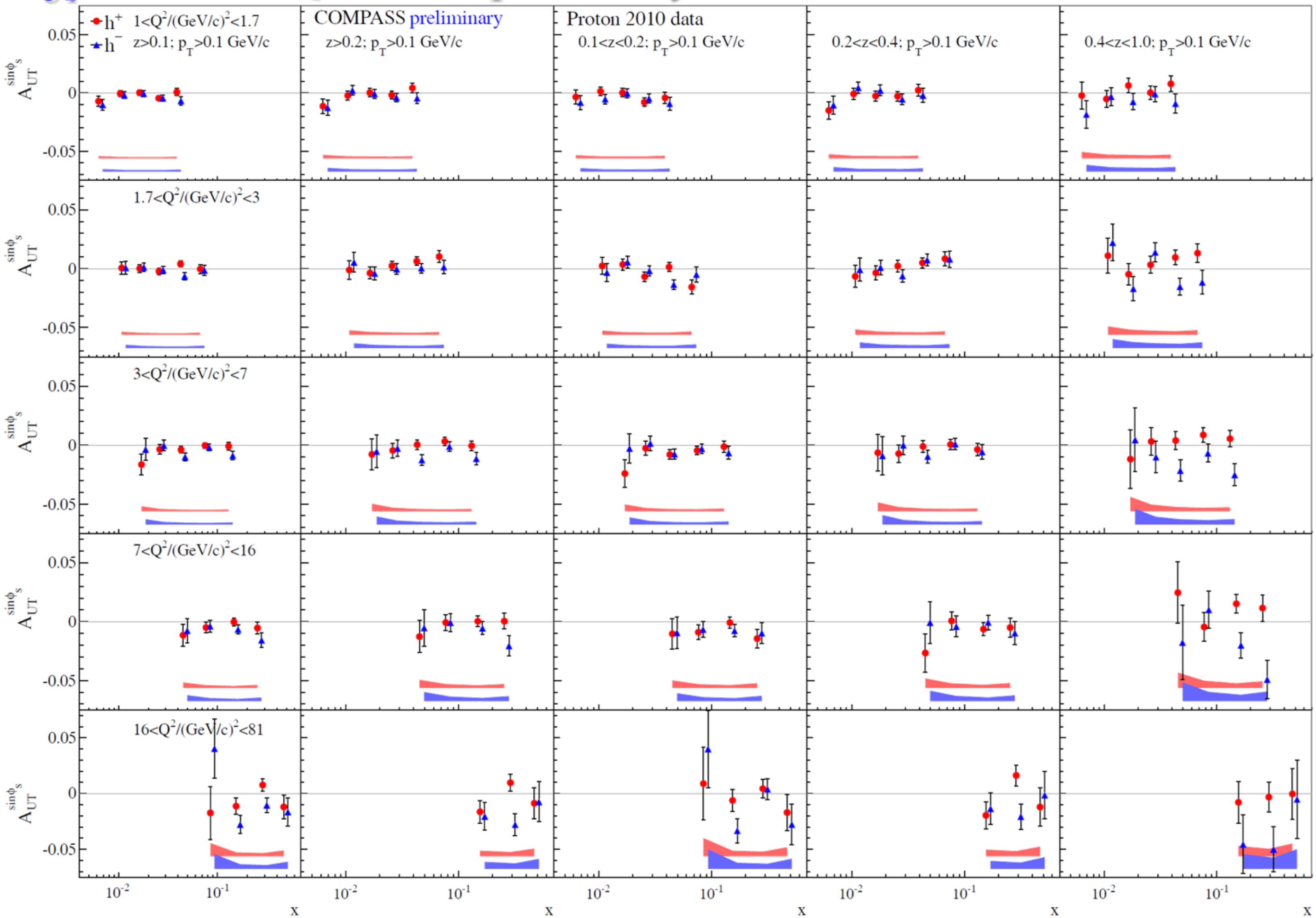
$A_{UT}^{\sin\phi_S}$: 3D Q^2-z-x dependency



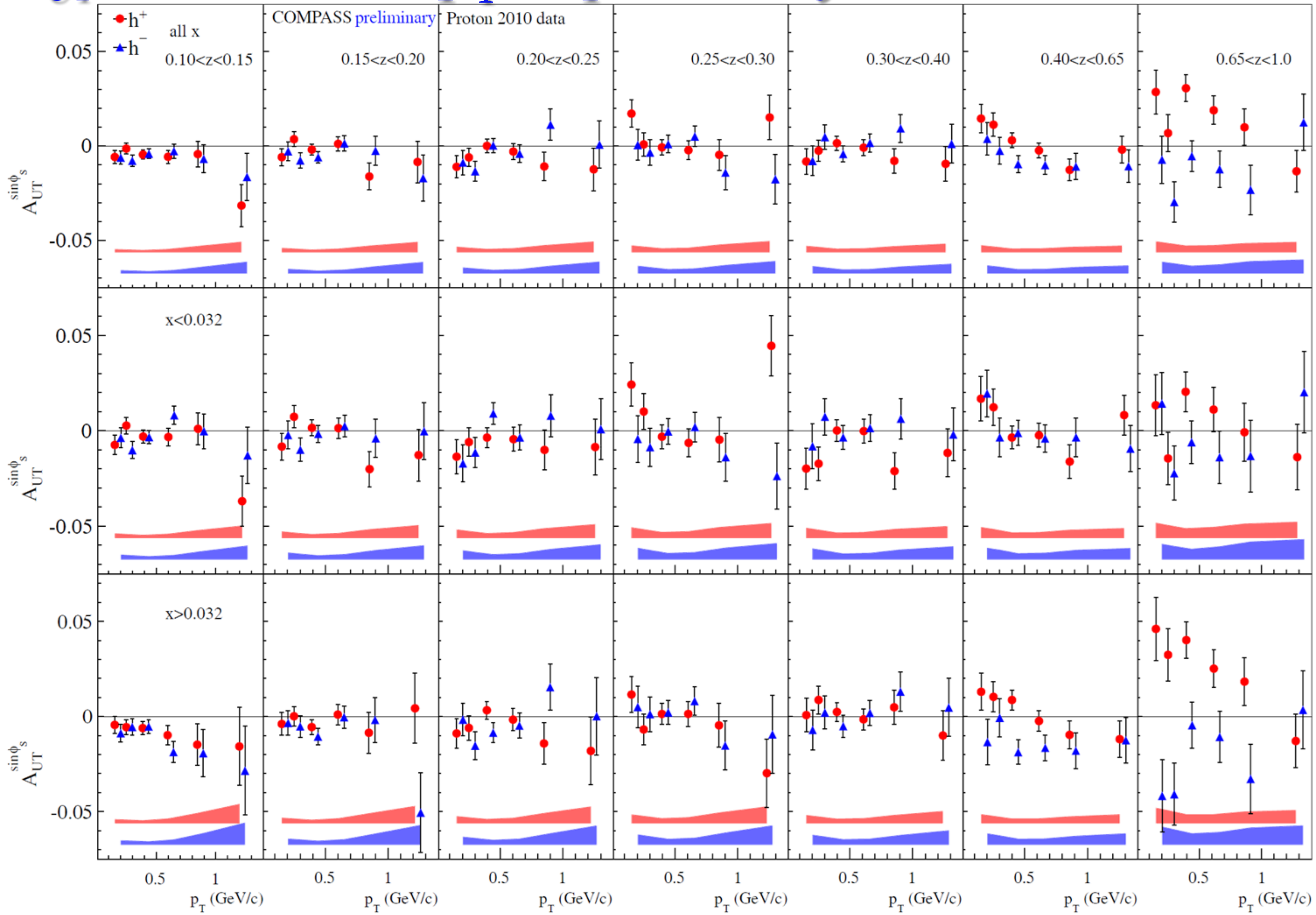
NEW!

Shown for the first time!

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 dependency



NEW!

Shown for the first time!

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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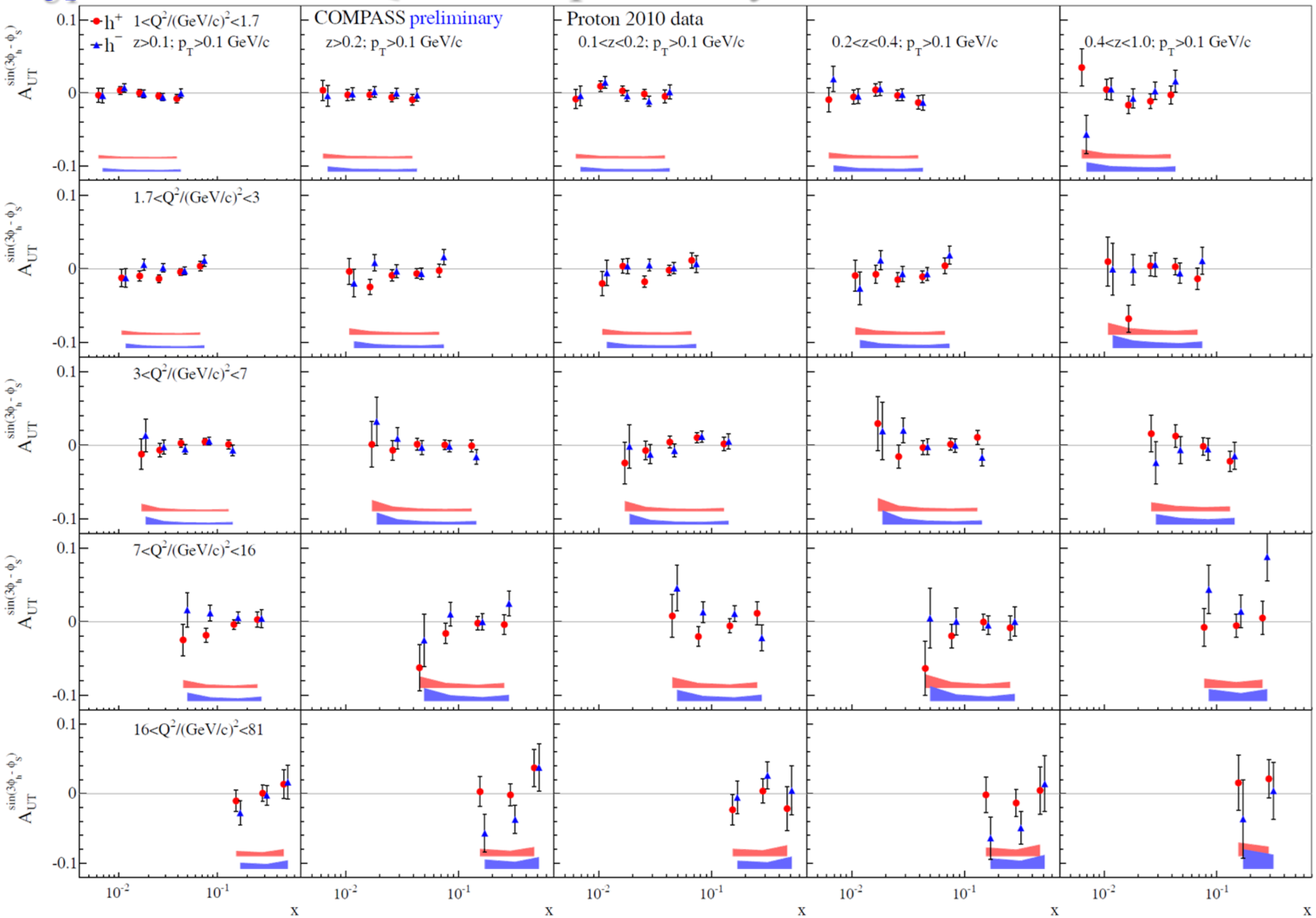
$A_{UT}^{sin(3\phi_h-\phi_S)}$: 3D Q^2-z-x dependency



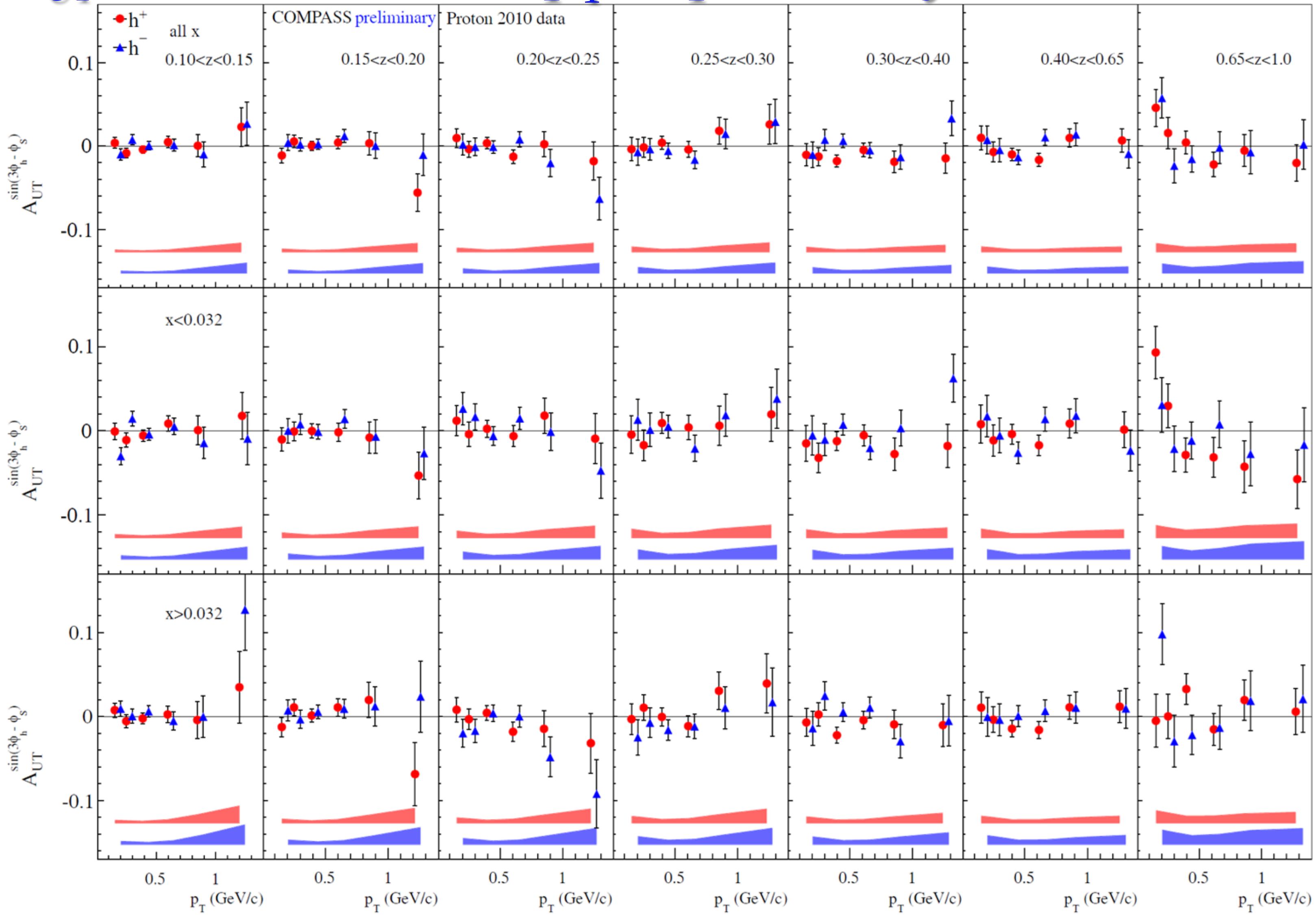
NEW!

Shown for the first time!

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**

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



NEW!

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3D

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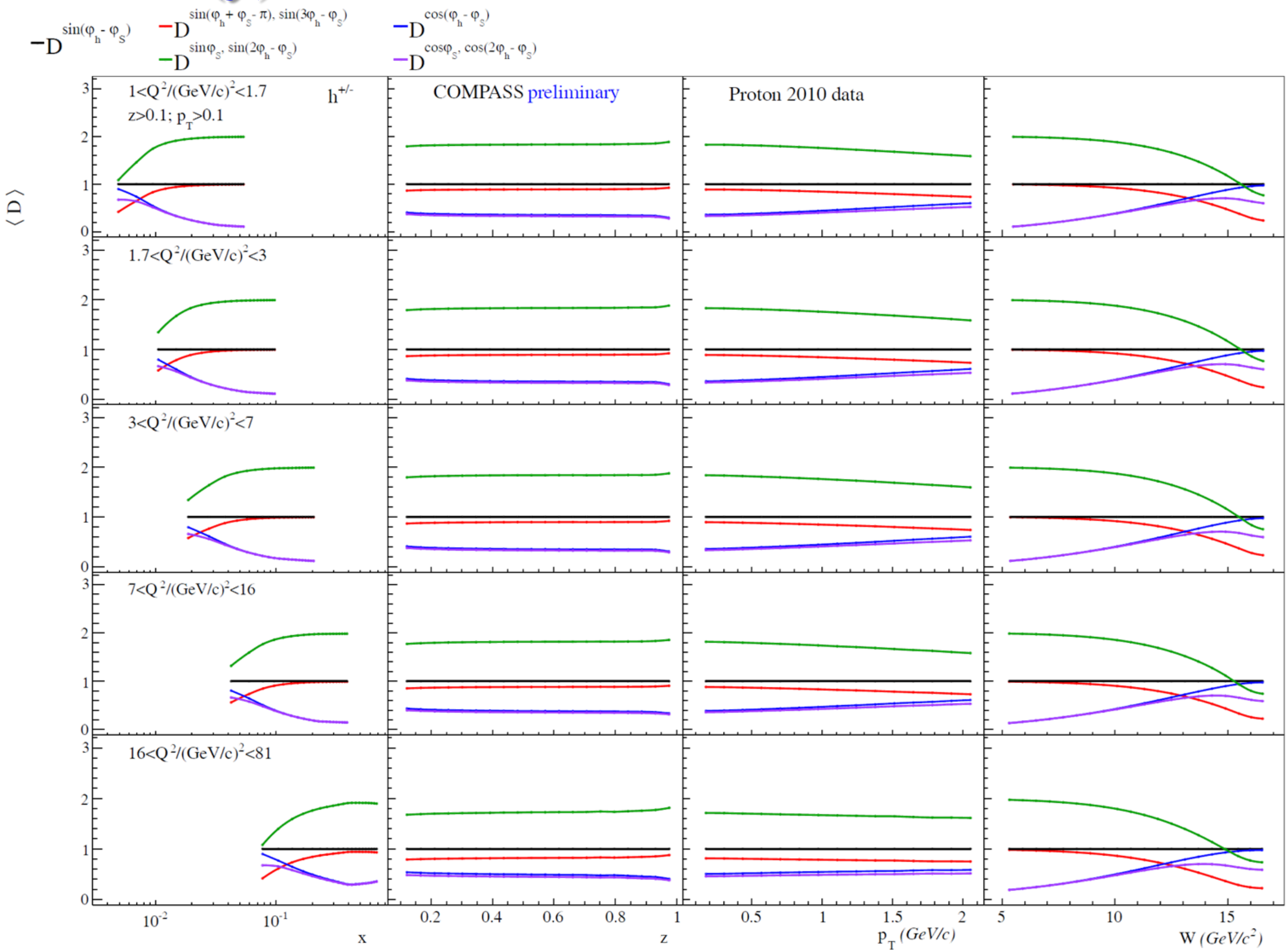
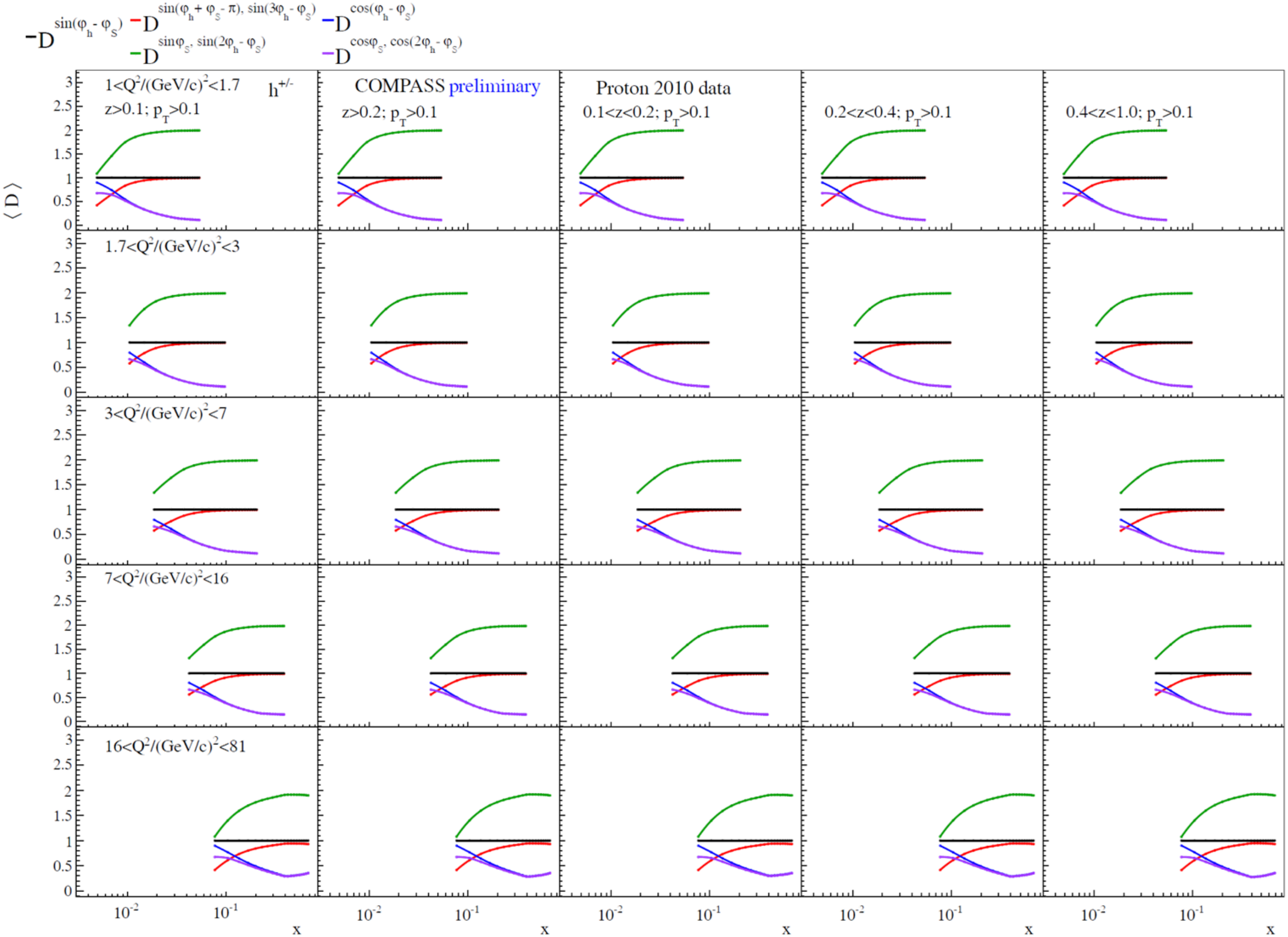
Mean D(y)-factors



Mean D(y)-factors in 3D "Q²-z-x" grid



Mean D(y)-factors are approximately same over z and p_T.

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- **Corrections for *lp* to $\gamma{*}p$ transition**
- Conclusions

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

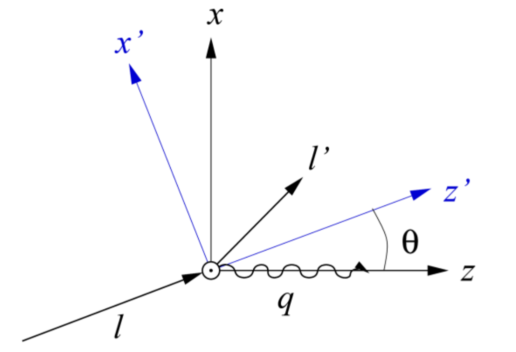
Kotzinian et al.
hep-ph/9808368 (1998)
hep-ph/9908466 (1999)
M. Diehl and S. Sapeta,
Eur. Phys. J. C 41 (2005) 515

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

$$\Bigg[1+\cos\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\right)+\cos2\phi_h\left(\varepsilon A_{UU}^{\cos2\phi_h}\right)+\lambda\sin\phi_h\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\right)$$

$$+\frac{P_T}{\sqrt{1-\sin^2\theta\sin^2\phi_S}}\left[\begin{array}{l}\sin(\phi_h-\phi_S)\left(\cos\theta A_{UT}^{\sin(\phi_h-\phi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\right)\\+\sin(\phi_h+\phi_S)\left(\cos\theta\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\right)\\+\sin(3\phi_h-\phi_S)\left(\cos\theta\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right)\\+\sin\phi_S\left(\cos\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\right)\\+\sin(2\phi_h-\phi_S)\left(\cos\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}+\frac{1}{2}\sin\theta\varepsilon A_{UL}^{\sin2\phi_h}\right)\\+\sin(2\phi_h+\phi_S)\left(\frac{1}{2}\sin\theta\varepsilon A_{UL}^{\sin2\phi_h}\right)\end{array}\right]$$

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



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

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

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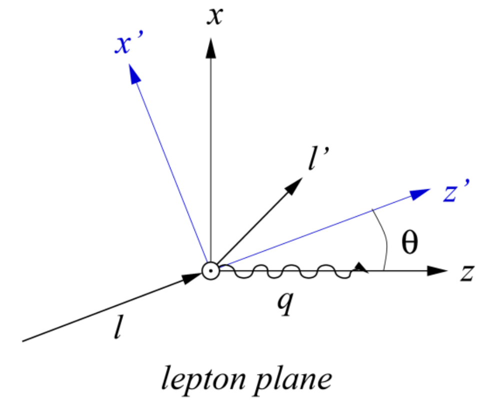
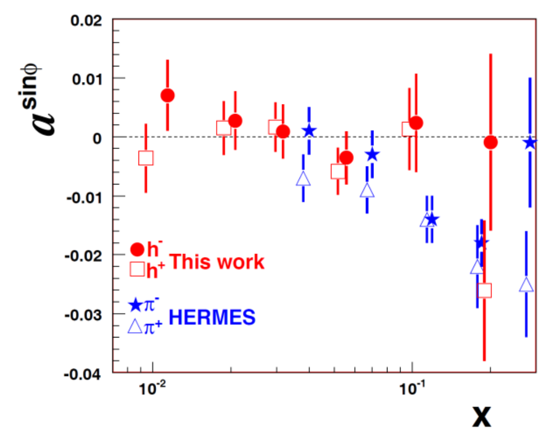
$$+\sin(\phi_h+\phi_S)\left(\cos\theta\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\right)$$
$$+\sin(3\phi_h-\phi_S)\left(\cos\theta\,\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right)$$
$$+\sin\phi_S\left(\cos\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\right)$$
$$+\sin(2\phi_h-\phi_S)\left(\cos\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}+\frac{1}{2}\sin\theta\,\varepsilon A_{UL}^{\sin 2\phi_h}\right)$$
$$+\sin(2\phi_h+\phi_S)\left(\frac{1}{2}\sin\theta\,\varepsilon A_{UL}^{\sin 2\phi_h}\right)\Bigg]$$

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



Eur.Phys.J.C70:39-49,2010



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

Kotzinian et al.
hep-ph/9808368 (1998)
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M. Diehl and S. Sapeta,
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$$\frac{d\sigma}{dx\,dy\,dz\,dP_{hT}^2\,d\phi_h\,d\phi_S} = \left[\frac{\cos\theta}{1-\sin^2\theta\sin^2\phi_S}\right]\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

$$\Bigg[1+\cos\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\right)+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right)+\lambda\sin\phi_h\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\right)$$

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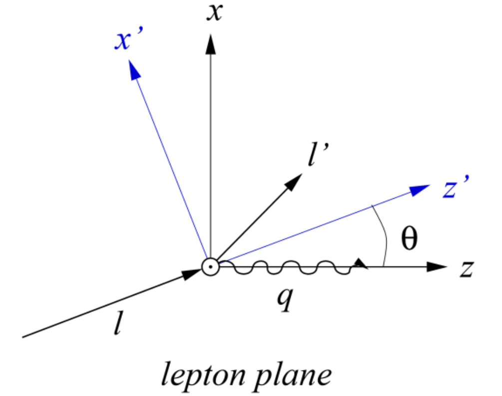
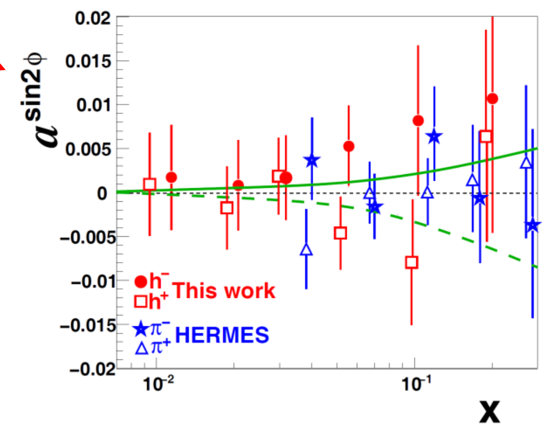
$$+\frac{P_T\lambda}{\sqrt{1-\sin^2\theta\sin^2\phi_S}}\left[\begin{array}{l}\cos(\phi_h-\phi_S)\left(\cos\theta\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\right)\\ +\cos\phi_S\left(\cos\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}+\sin\theta\sqrt{(1-\varepsilon^2)}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



Eur.Phys.J.C70:39-49,2010



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

Kotzinian et al.
hep-ph/9808368 (1998)
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M. Diehl and S. Sapeta,
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$$\frac{d\sigma}{dx\,dy\,dz\,dP_{hT}^2\,d\phi_h\,d\phi_S} = \left[\frac{\cos\theta}{1-\sin^2\theta\sin^2\phi_S}\right]\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

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$$+\sin(2\phi_h-\phi_S)\left(\cos\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}+\frac{1}{2}\sin\theta\,\varepsilon A_{UL}^{\sin 2\phi_h}\right)$$
$$+\sin(2\phi_h+\phi_S)\left(\frac{1}{2}\sin\theta\,\varepsilon A_{UL}^{\sin 2\phi_h}\right)\Bigg]$$

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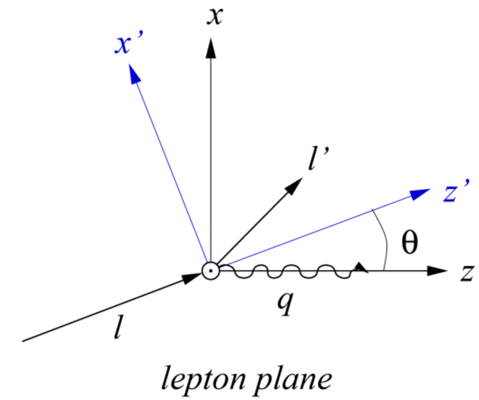
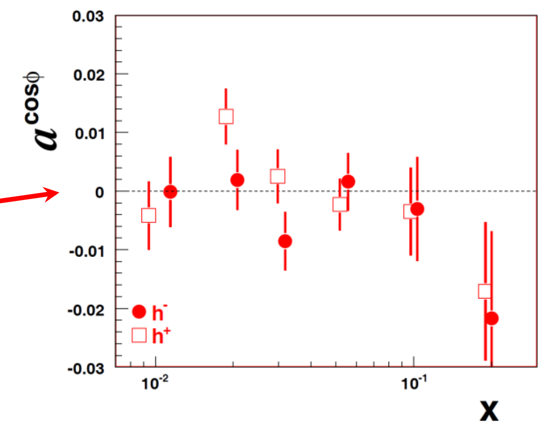
$$+\cos(\phi_h+\phi_S)\left(\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\right)\Bigg]\Bigg]$$



Eur.Phys.J.C70:39-49,2010



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

Kotzinian et al.
hep-ph/9808368 (1998)
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M. Diehl and S. Sapeta,
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$$\Bigg[1+\cos\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\right)+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right)+\lambda\sin\phi_h\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\right)$$

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$$+\sin(3\phi_h-\phi_S)\left(\cos\theta\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right)$$
$$+\sin\phi_S\left(\cos\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\right)$$
$$+\sin(2\phi_h-\phi_S)\left(\cos\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}+\frac{1}{2}\sin\theta\varepsilon A_{UL}^{\sin 2\phi_h}\right)$$
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$$+\frac{P_T\lambda}{\sqrt{1-\sin^2\theta\sin^2\phi_S}}\Bigg[\cos(\phi_h-\phi_S)\left(\cos\theta\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\right)$$
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$$+\cos(2\phi_h-\phi_S)\left(\cos\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\right)$$
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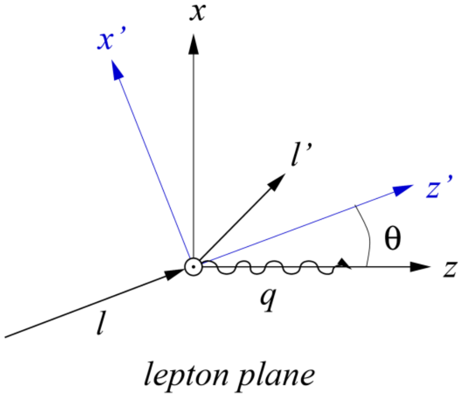
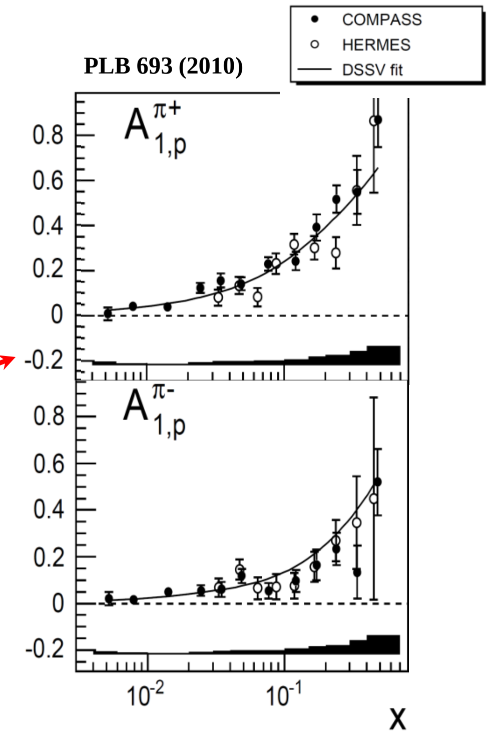


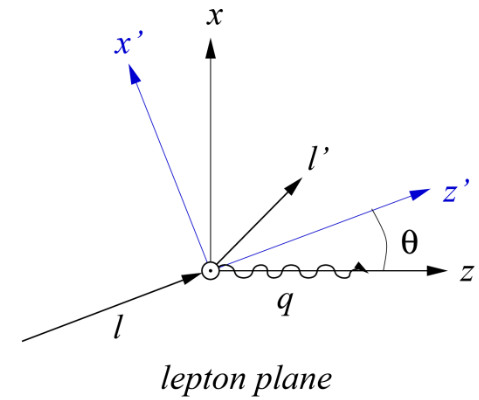


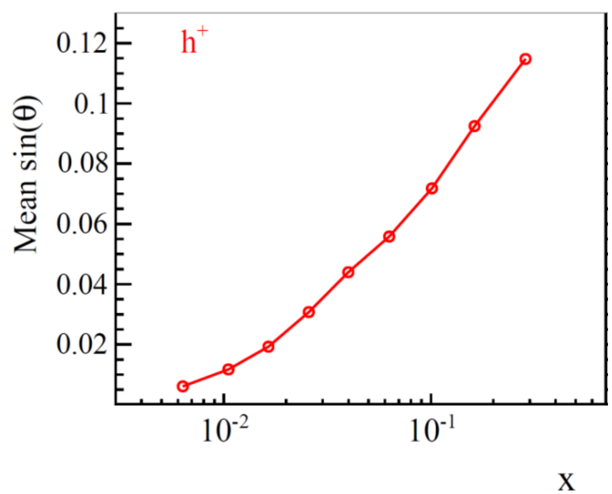
Mixing of the "T" and "L" amplitudes

With good approximation:

$$A_T \approx A_{T,\mathrm{fit}} - C(\varepsilon) A_L$$

TSA	$C(\varepsilon,\theta)$ - factor	Contributing LSA
$A_{UT}^{\sin(\phi_h-\phi_s)}$	$\sin\theta \frac{\sqrt{2\varepsilon(1+\varepsilon)}}{2}$	$A_{UL}^{\sin\phi_h}$
$A_{UT}^{\sin(\phi_h+\phi_s)}$	$\sin\theta \frac{\sqrt{2\varepsilon(1+\varepsilon)}}{2\varepsilon}$	$A_{UL}^{\sin\phi_h}$
$A_{UT}^{\sin(2\phi_h-\phi_s)}$	$\sin\theta \frac{\varepsilon}{2\sqrt{2\varepsilon(1+\varepsilon)}}$	$A_{UL}^{\sin 2\phi_h}$
$A_{LT}^{\cos(\phi_h-\phi_s)}$	$\sin\theta \frac{\sqrt{2\varepsilon(1-\varepsilon)}}{2\sqrt{(1-\varepsilon^2)}}$	$A_{LL}^{\cos\phi_h}$
$A_{LT}^{\cos\phi_s}$	$\sin\theta \frac{\sqrt{(1-\varepsilon^2)}}{\sqrt{2\varepsilon(1-\varepsilon)}}$	A_{LL}
$A_{UT}^{\sin(3\phi_h-\phi_s)}$, $A_{UT}^{\sin\phi_s}$, $A_{LT}^{\cos(2\phi_h-\phi_s)}$	–	–

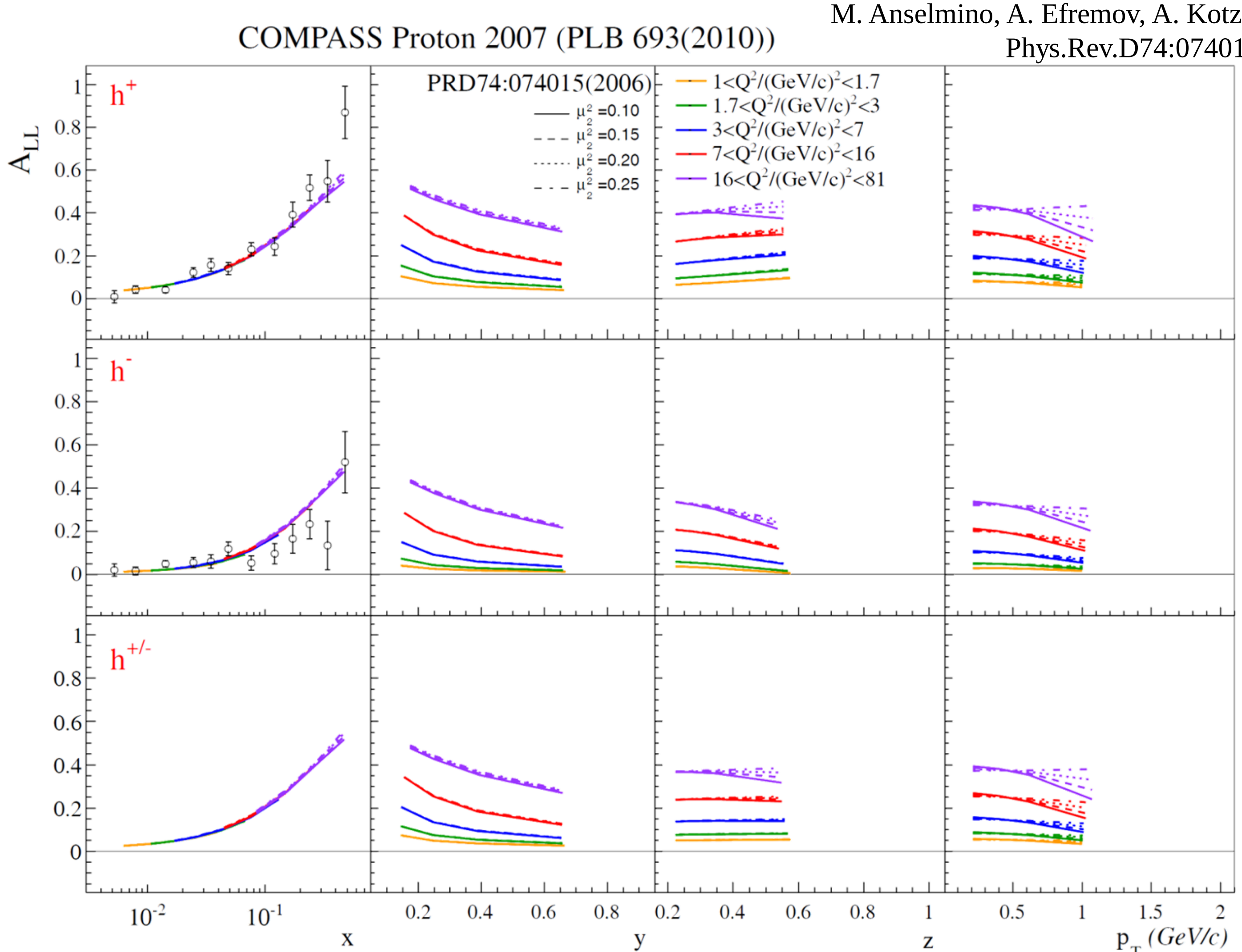




Mean sinθ is small at COMPASS kinematics.
Maximal reached value is ~ 0.18 and the mean is around 0.05 (cosθ ~1.0).

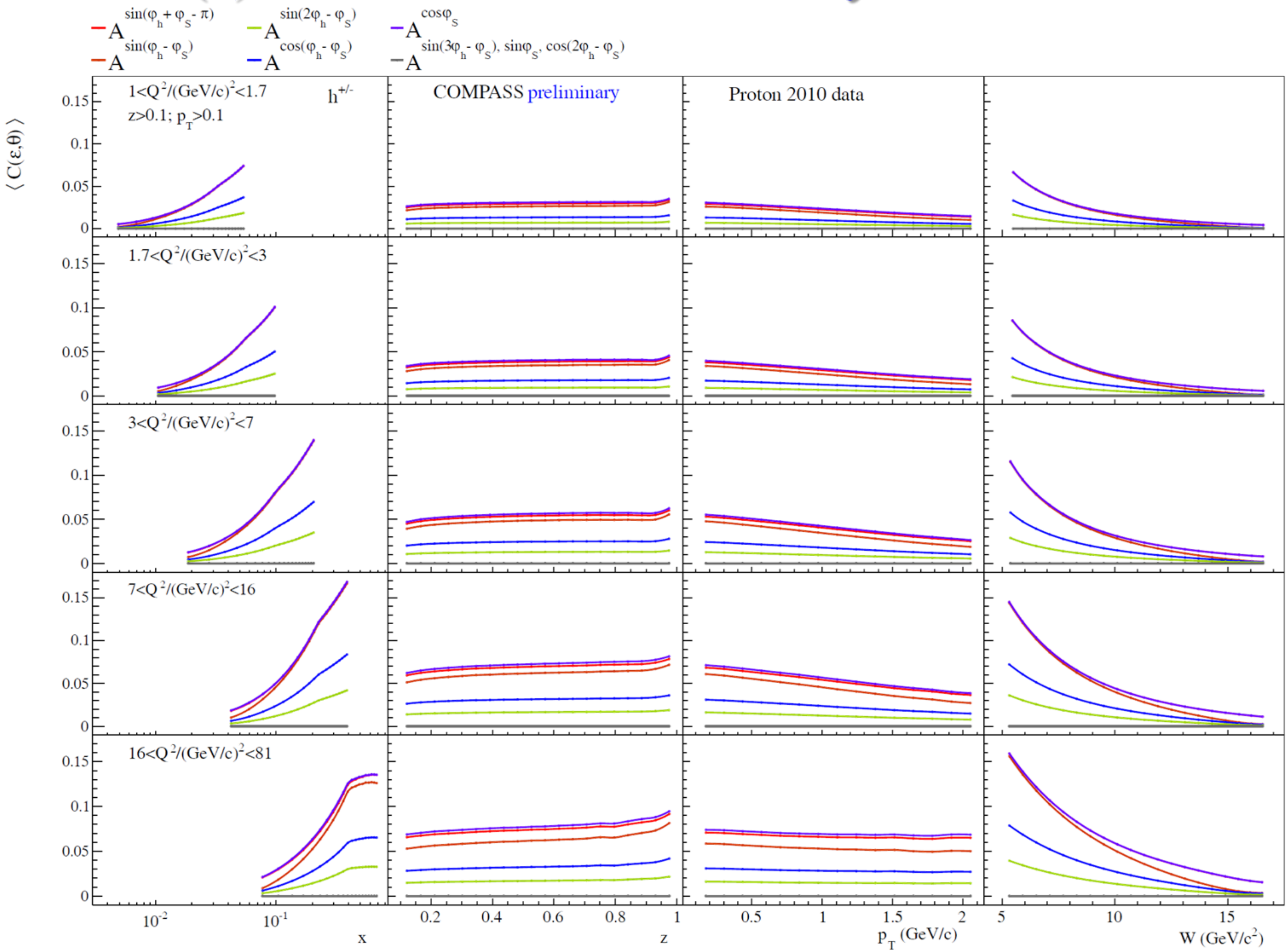
A_{LL} evaluated according to the PRD **74,** 074015 (2006)

M. Anselmino, A. Efremov, A. Kotzinian, and B. Parsamyan
Phys.Rev.D74:074015 (2006)

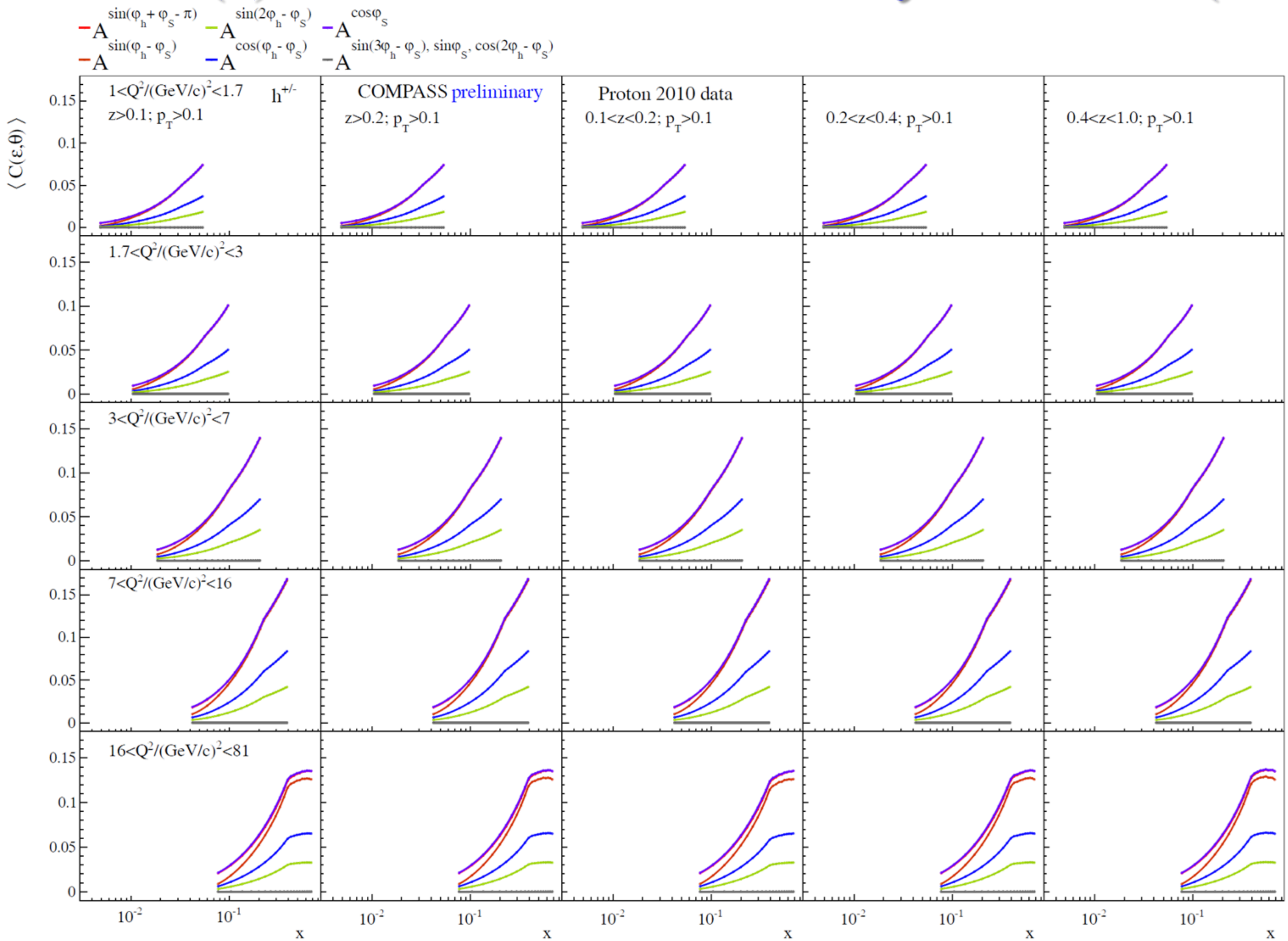


Asymmetry is evaluated in COMPASS specific mean kinematic points extracted from the data. Good level of agreement, which allows us to use the predicted z and P_{hT} – dependencies in $A_{LT}^{\cos(\phi_S)}$-*correction.*

Mean c(ε)-factors for different asymmetries



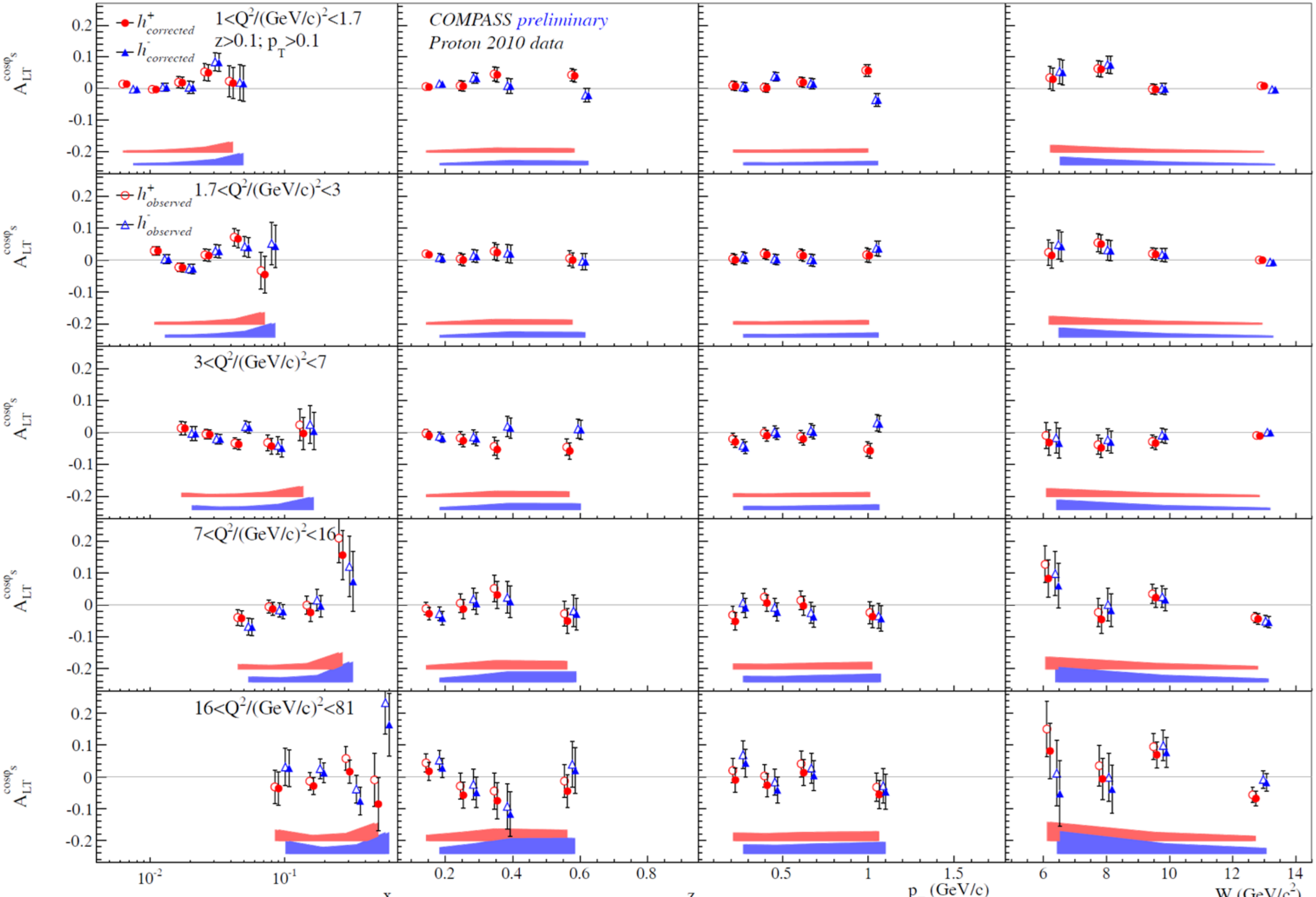
Mean c(ε)-factors for different asymmetries (3D)



Mean c(ε)-factors are approximately same over z and p_T.

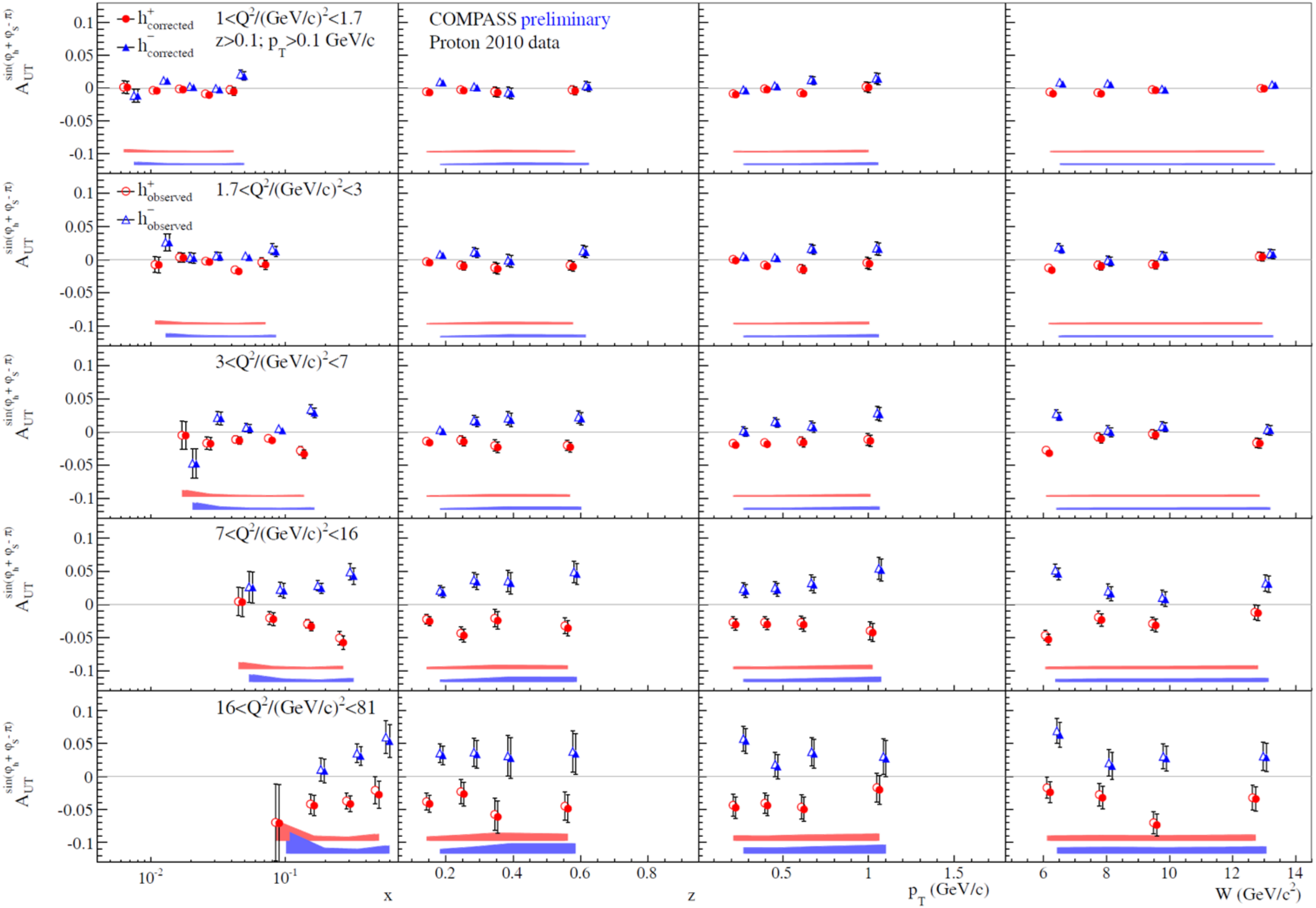
$A_{LT}^{\cos\phi_S}$ corrected for A_{LL}-contribution using A_{LL} from PRD **74,** 074015(2006)

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



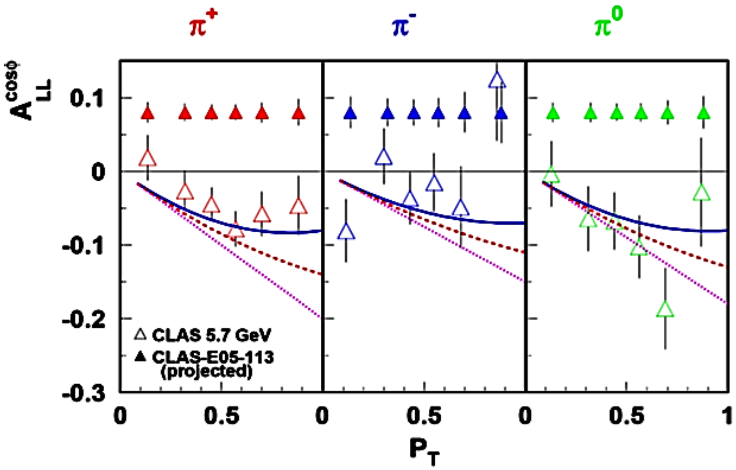
As expected, at large *x* the corrections become sizable. Asymmetry is compatible with zero.

Collins corrected for constant "L"-contribution (set to 0.05)



Even at large *x* and even for chosen large L-amplitude the corrections are small.

Predictions for $A_{LL}^{\cos\phi_h}$ LSA which mixes with $A_{LT}^{\cos(\phi_h - \phi_S)}$

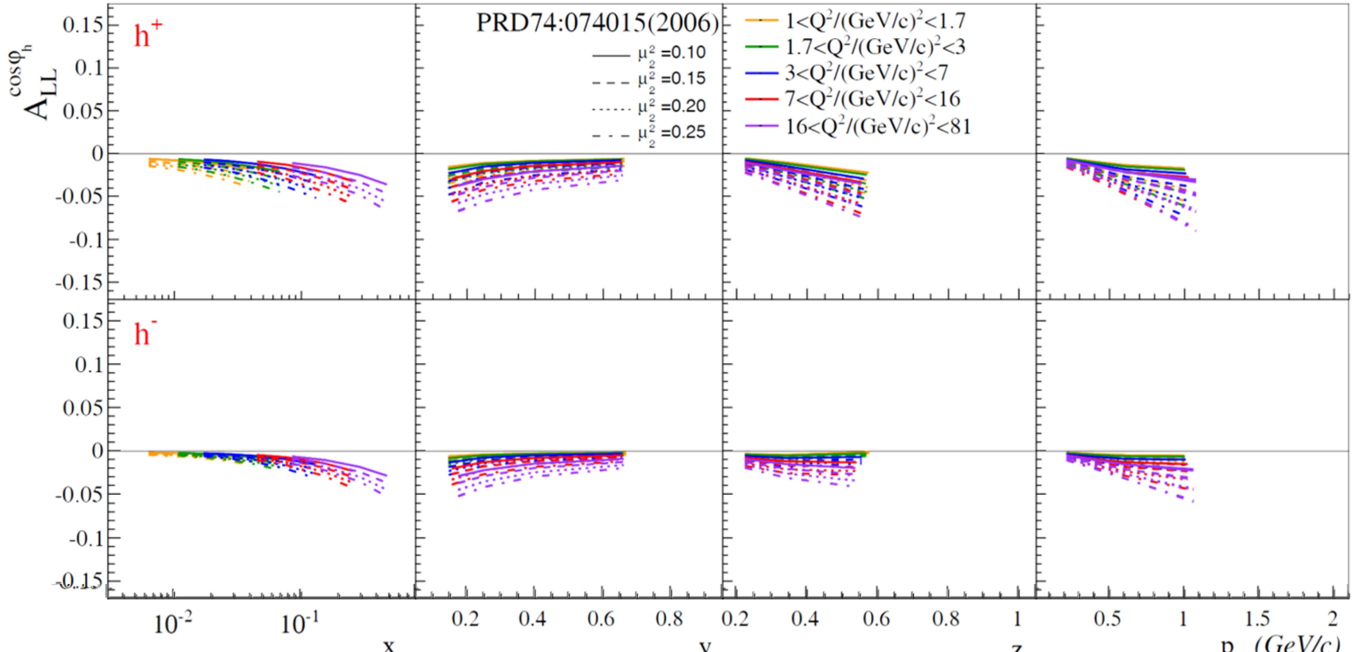


Longitudinal Cahn effect

***Kotzinian et al.* Phys. Rev. D 74,** 074015 (2006)

Model prediction are in a good agreement with JLab data

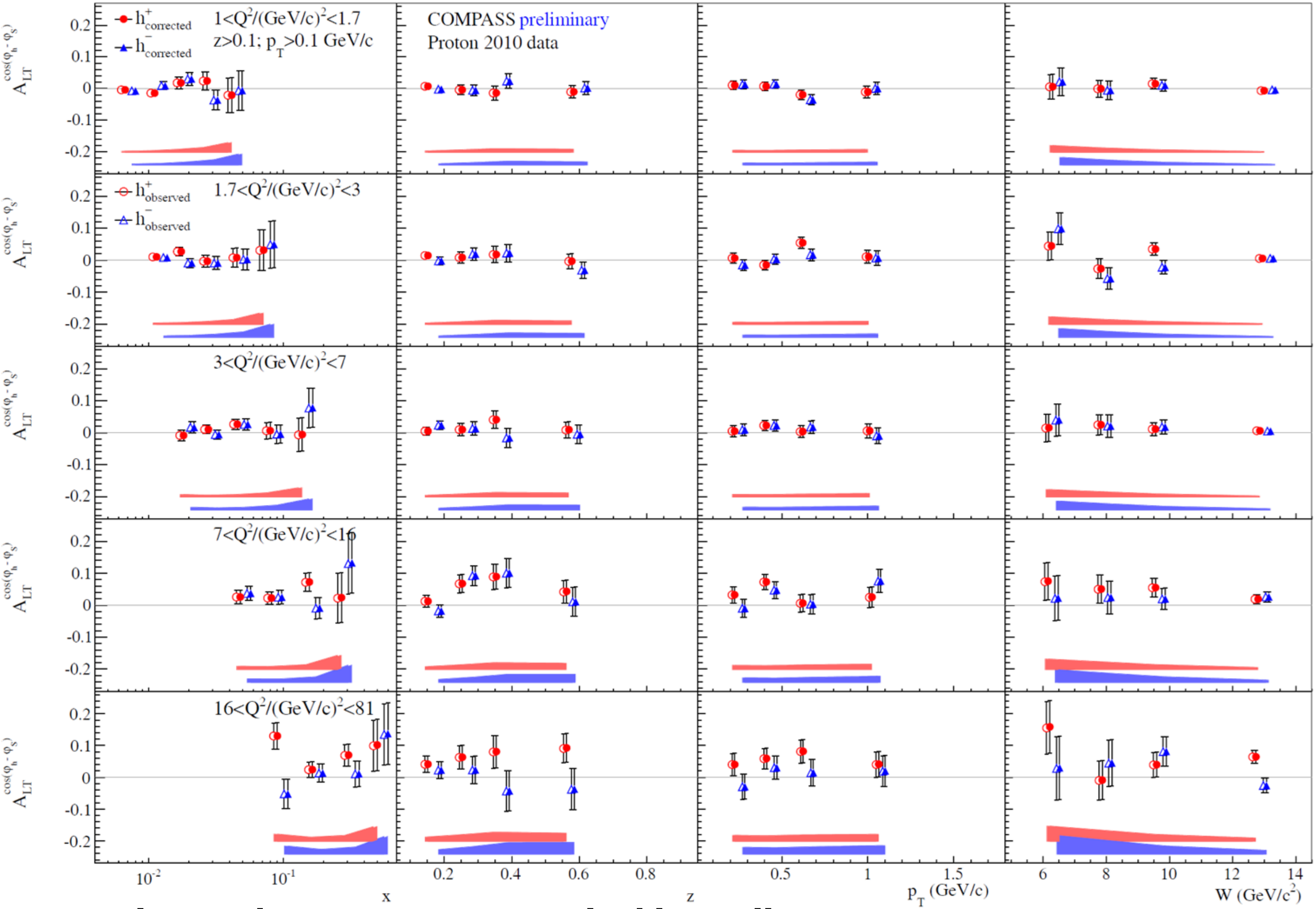
COMPASS Proton



Predictions for the $A_{LL}^{\cos\phi_h}$ asymmetry are evaluated using COMPASS specific mean kinematic points extracted from the data

$A_{LT}^{\cos(\phi_h - \phi_S)}$ corrected for $A_{LL}^{\cos\phi_h}$–contribution

$A_{LL}^{\cos\phi_h}$ according to Phys.Rev.D74:074015 (2006)



Even at large *x* the corrections are negligibly small.

Outline

- Introduction
  - SIDIS x-section and TSAs
  - Brief review of recent COMPASS results with TSAs
- COMPASS multidimensional approach NEW
  - COMPASS multidimensional phase-space
- Results for TSAs NEW (Shown for the first time!)
  - 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
  - Mean depolarization factors
- Corrections for *lp* to $\gamma^{*}p$ transition
- **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!

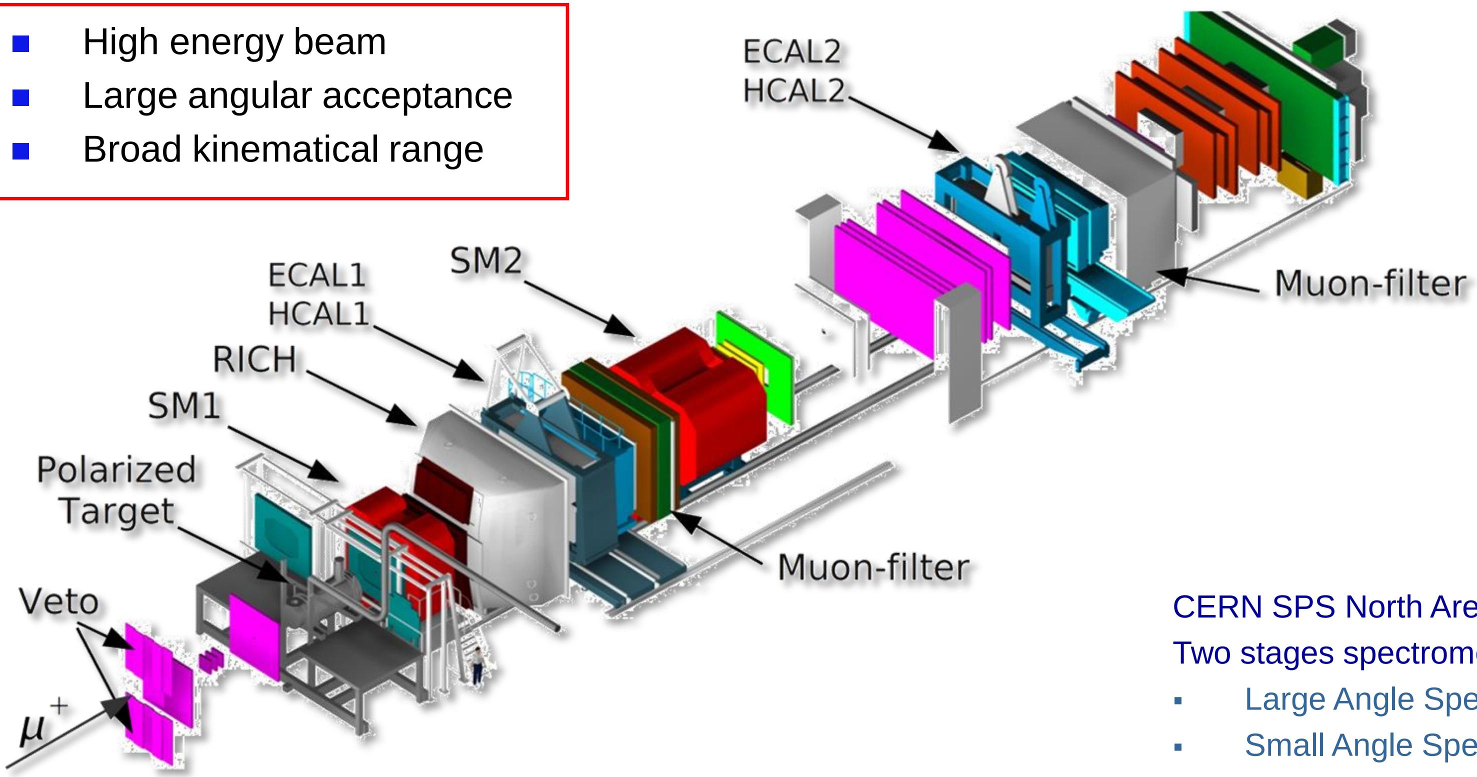
Thank you!

Spare slides

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)

Longitudinally polarized μ^+ beam (160 Gev/c).

Longitudinally or Transversely polarized ^{6}LiD or NH_3 target

Momentum, tracking and calorimetric measurements, PID

Hadron & Muon high energy beams.

Beam rates: 10^8 muons/s, $5 \cdot 10^7$ hadrons/s.

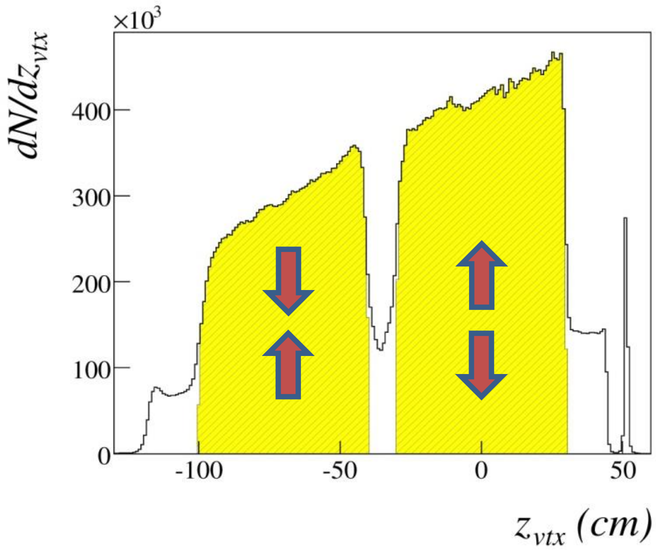
COMPASS Polarized target system

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

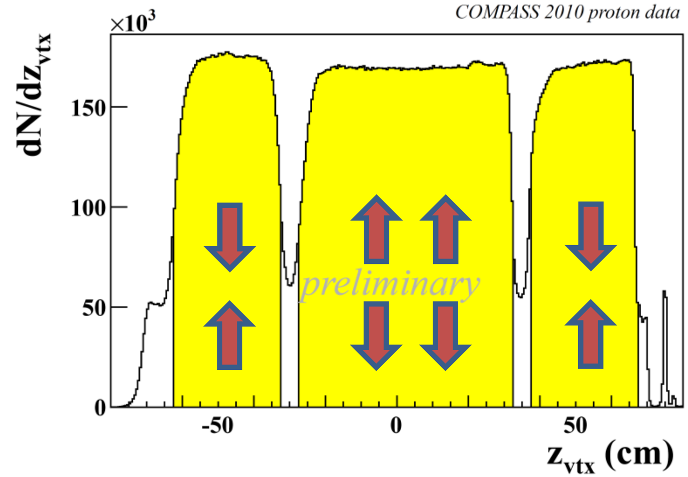


Data is collected simultaneously for the two target spin orientations
Polarization reversal after each ~4-5 days

Years 2007 and 2010

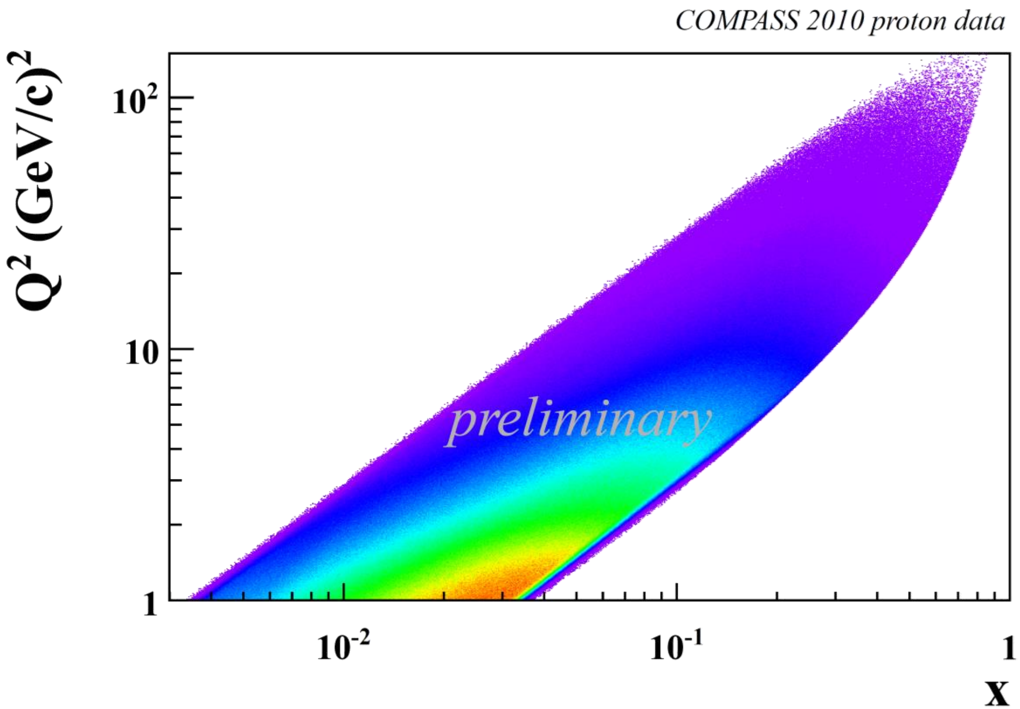
Proton - NH_3:

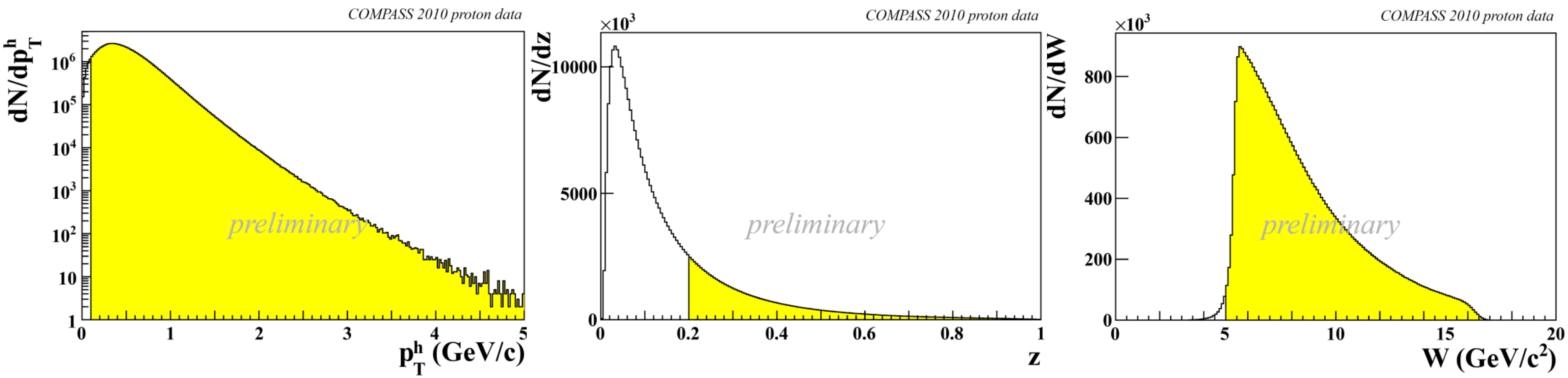
- Three cells system (30 cm,60cm, 30cm)
- Polar angle acceptance – 180 mrad (new magnet in 2006)
- Target Polarization ±90%
- dilution factor f = 0.14



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





Multi-D x:Q^2

Q^2 ranges:

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

5 Q^2-ranges

z ranges:

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

25 z-P_{hT} combinations

p_T ranges:

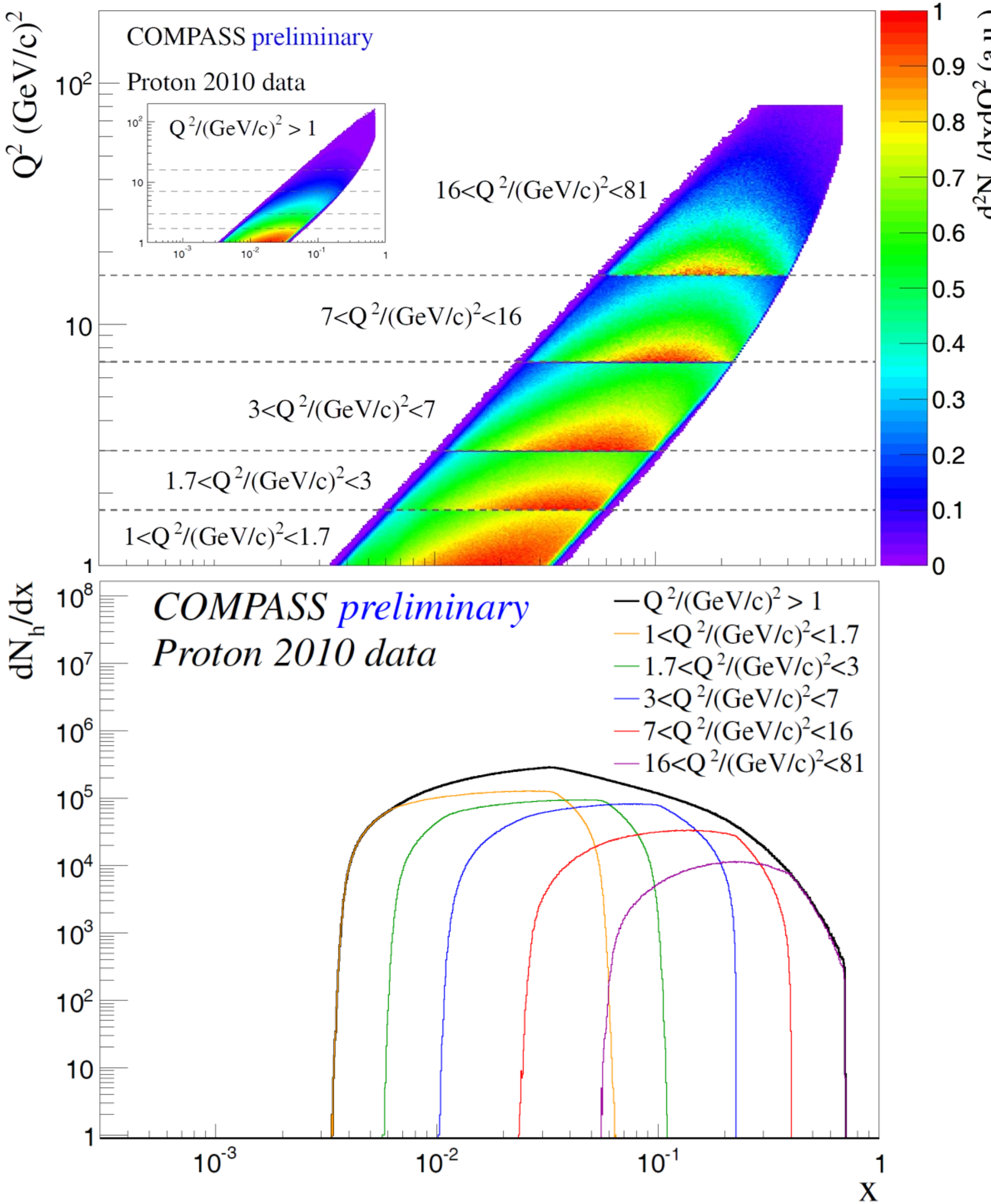
- $p_T > 0.1$
- $0.1 < p_T < 0.75$
- $0.1 < p_T < 0.3$
- $0.3 < p_T < 0.7$
- $p_T > 0.75$

x ranges:

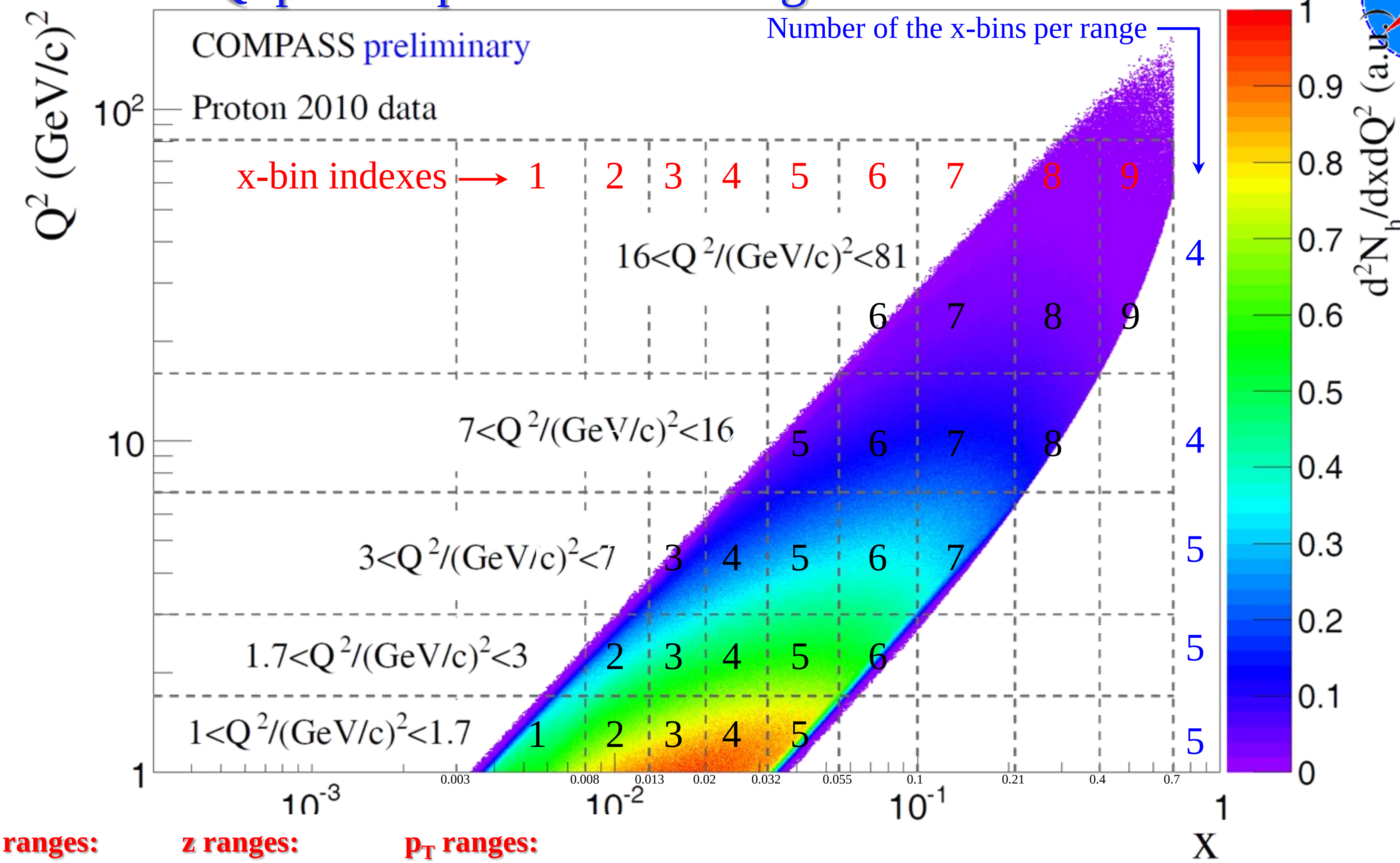
- all x
- x>0.032 ⇨ **2D z:p_T (7x6 bins)**
- x>0.032

x bins:

0.003, 0.008, 0.013, 0.02, 0.032, 0.055, 0.10, 0.21, 0.40, 0.7



Multi-D x:Q^2 phase-space and binning

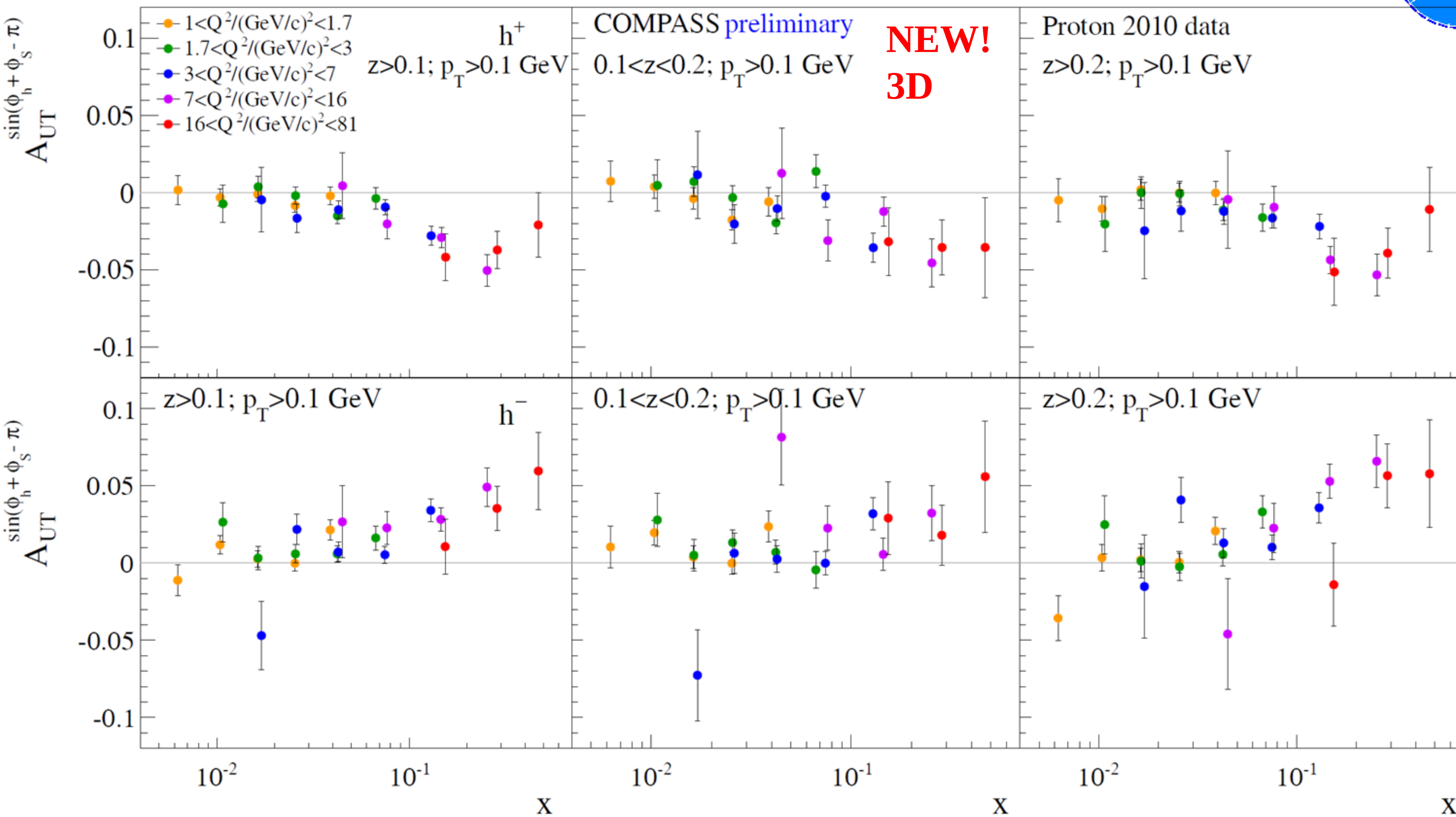


Q^2 ranges:	**z ranges:**	**p_T ranges:**
$1 < Q^2 < 1.7$	$z > 0.1$	$p_T > 0.1$
$1.7 < Q^2 < 3$	$z > 0.2$	$0.1 < p_T < 0.75$
$3 < Q^2 < 7$	$0.1 < z < 0.2$	$0.1 < p_T < 0.3$
$7 < Q^2 < 16$	$0.2 < z < 0.4$	$0.3 < p_T < 0.7$
$16 < Q^2 < 81$	$0.4 < z < 1.0$	$p_T > 0.75$

x bins:

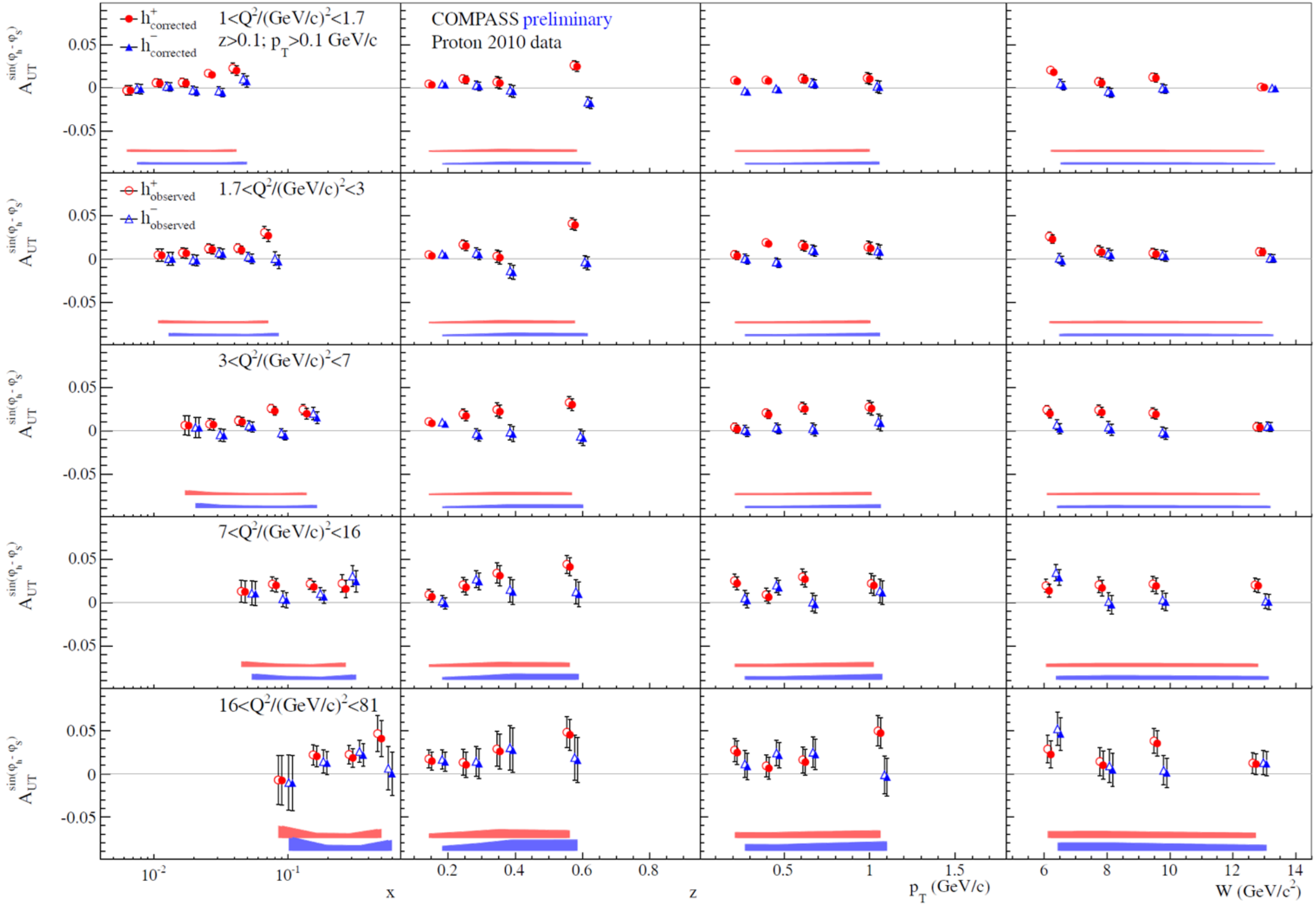
0.003, 0.008, 0.013, 0.02, 0.032, 0.055, 0.10, 0.21, 0.40, 0.7

Collins asymmetry: x-dependency in 5 Q^2-ranges and different z



- **No clear evidences for possible Q^2-dependence**

Sivers corrected for constant "L"-contribution (set to 0.05)



Even at large *x* and even for chosen large L-amplitude the corrections are small.