Transverse spin azimuthal asymmetries at COMPASS: SIDIS – Multidimensional analysis & Drell-Yan

COMPASS

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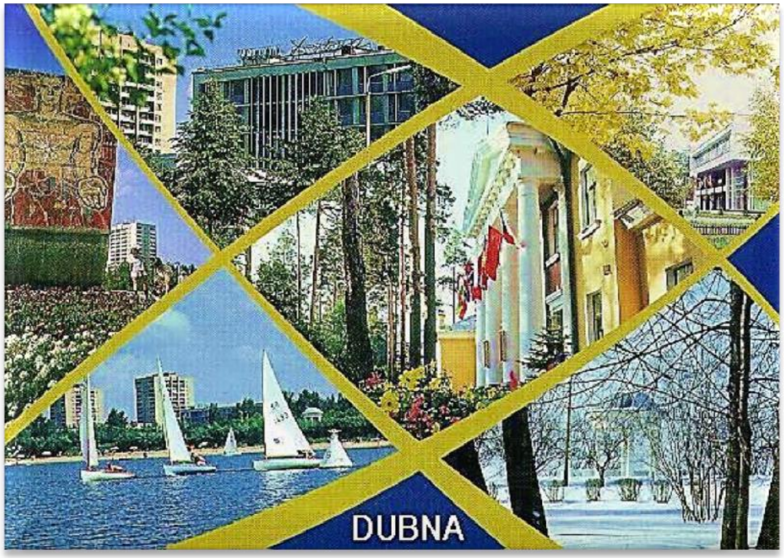
ALMA UNIVERSITAS TAURINENSIS

University of Turin and INFN section of Turin

on behalf of the COMPASS Collaboration

INFN



XVI Workshop on High Energy Physics

DSPIN-15

JINR, Dubna, Russia

September 8 – 12, 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
  - Sivers & Collins asymmetries
  - Beyond Sivers & Collins asymmetries
    - $A_{LT}^{cos(\phi_h-\phi_S)}$ – 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**

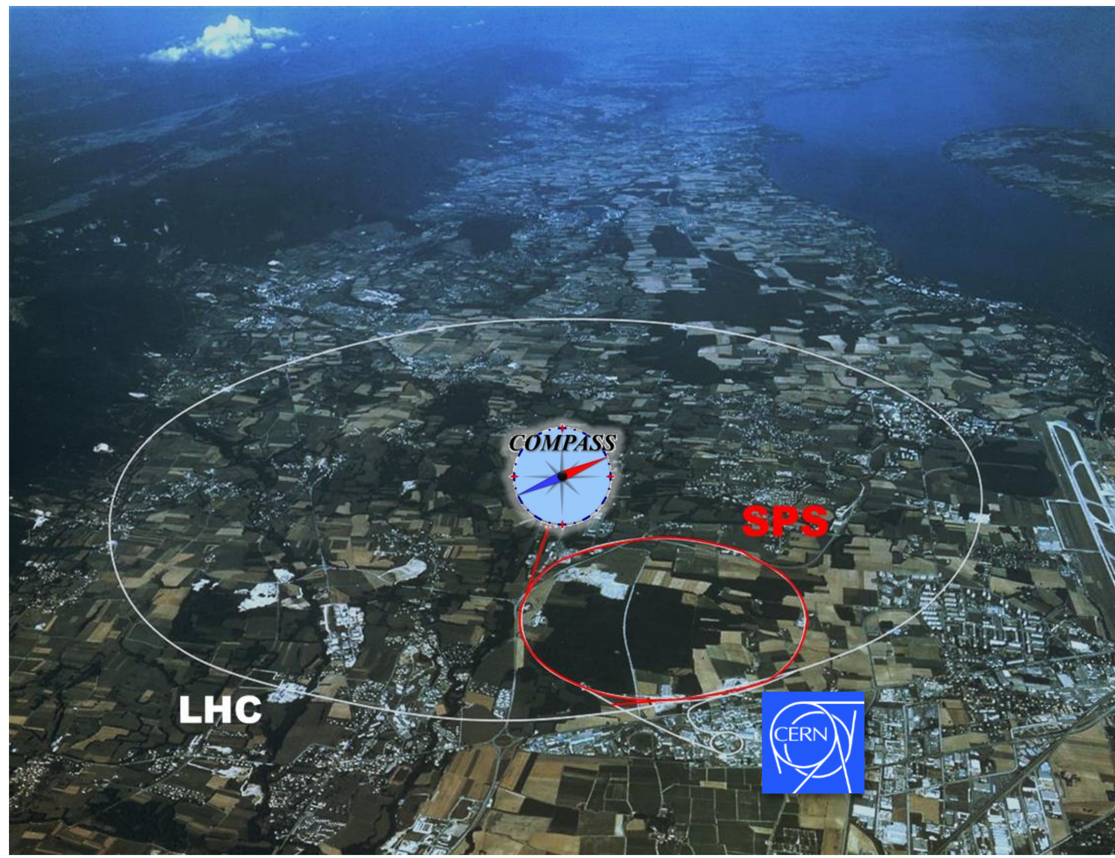
Wide physics program

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

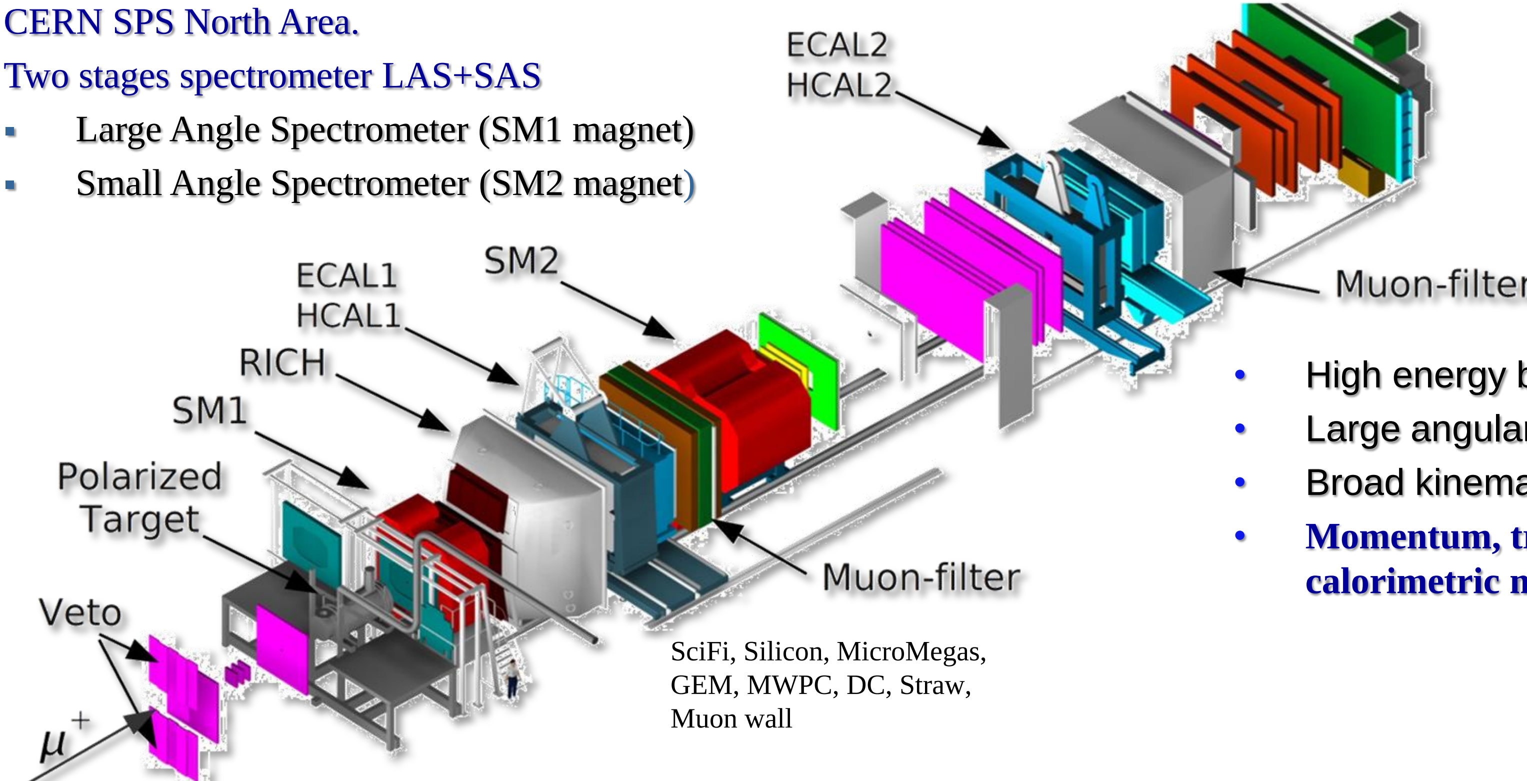
COMPASS experimental setup: Phase I (muon program)

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)



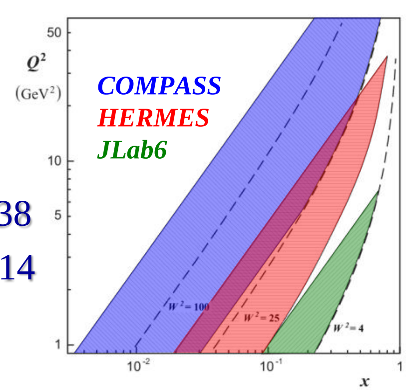
- High energy beam
- Large angular acceptance
- Broad kinematical range
- **Momentum, tracking and calorimetric measurements, PID**

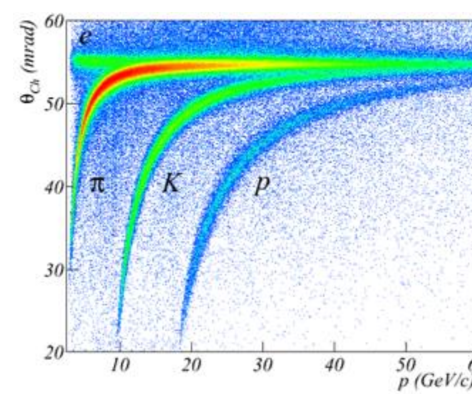
Longitudinally polarized (80%) μ^+ beam:
Energy: 160 GeV/c, Intensity: $2 \cdot 10^8$ μ^+/spill (4.8s).

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





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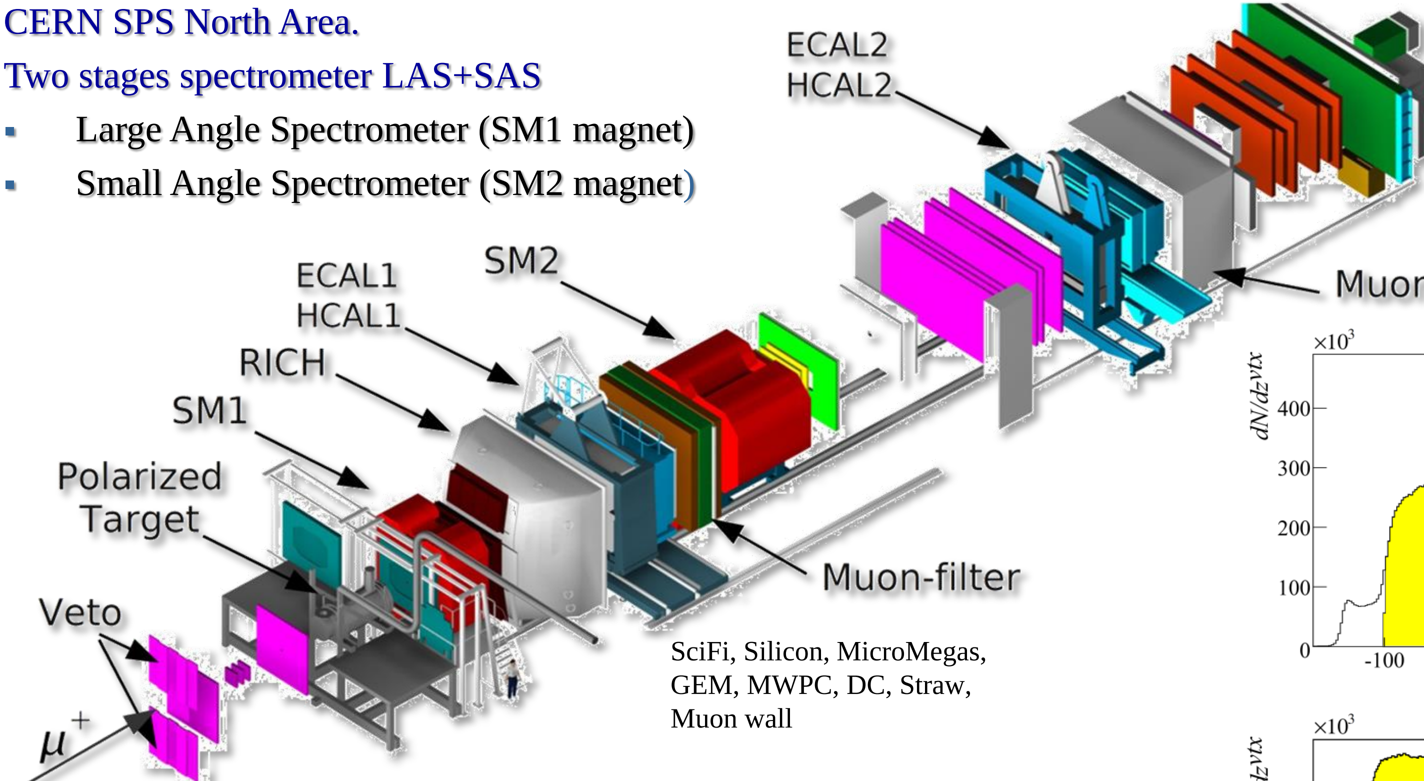

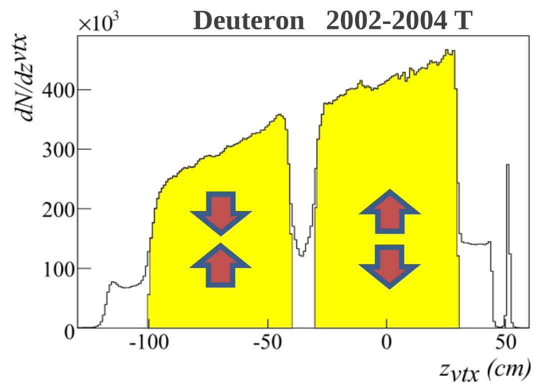

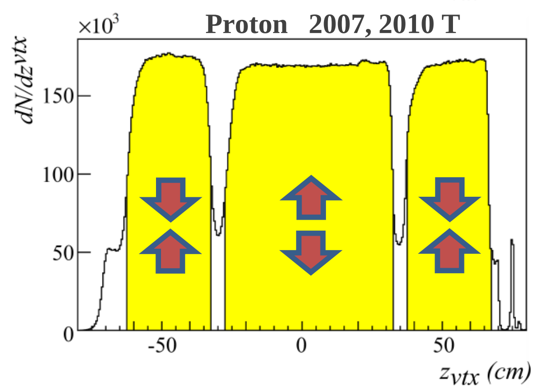

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Data-taking years: 2002-2011

Data is collected simultaneously for the two target spin orientations

Polarization reversal after each ~4-5 days

COMPASS experimental setup: Phase II (DY program)

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

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Two stages spectrometer LAS+SAS

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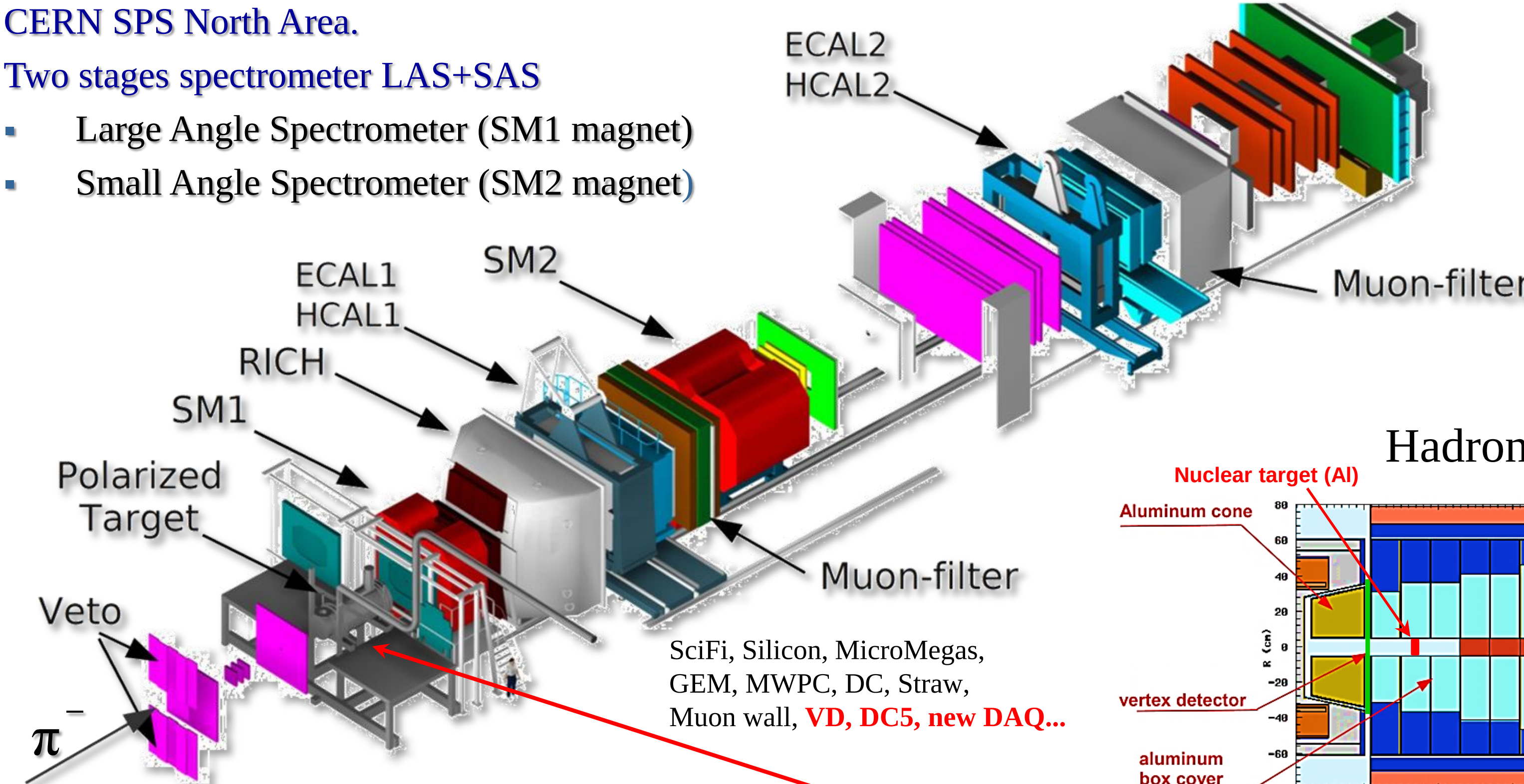
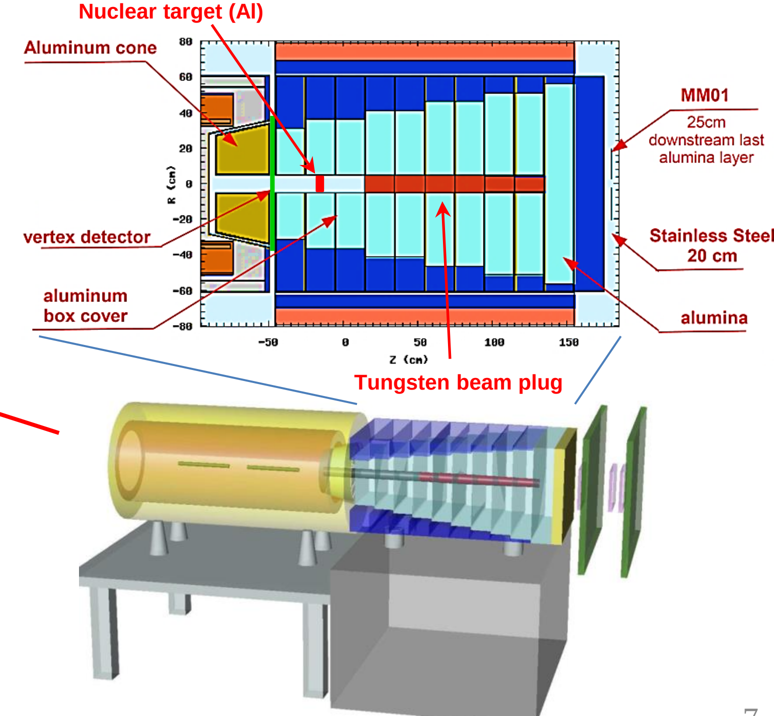


SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon wall, **VD, DC5, new DAQ...**

Hadron absorber



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: 2014 (pilot run) and 2015 – NOW!

COMPASS experimental setup: Phase II (DY program)

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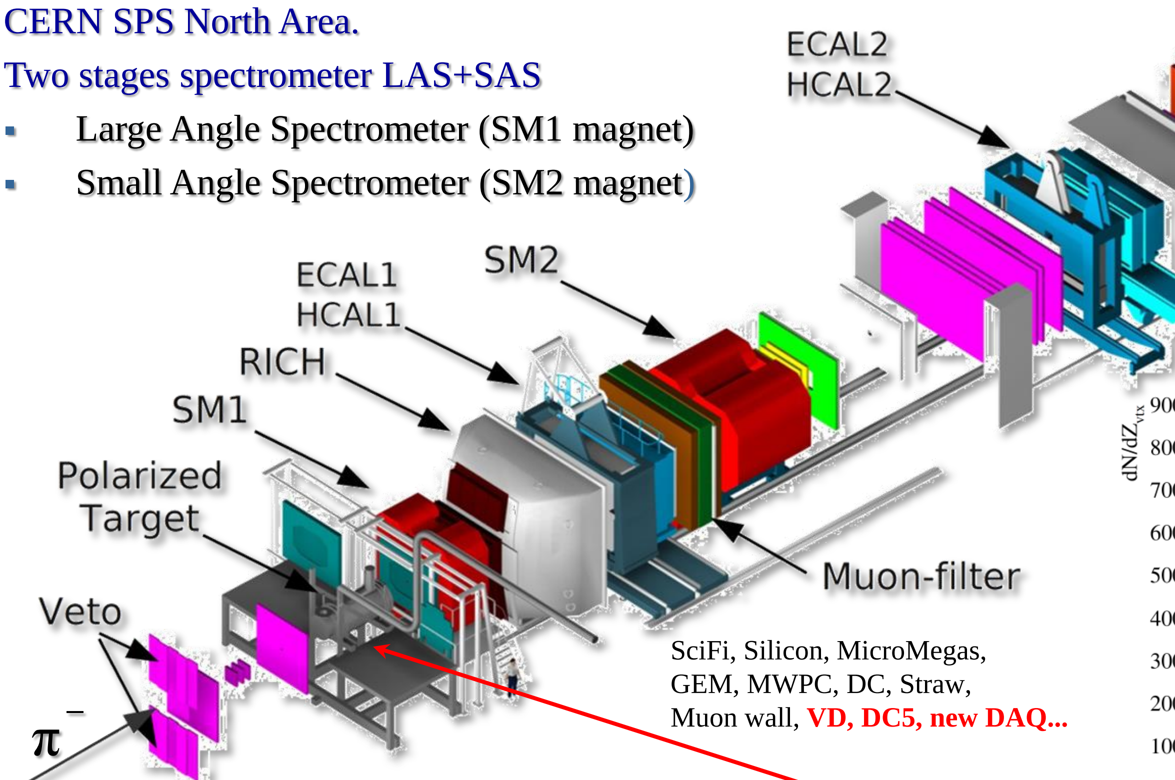

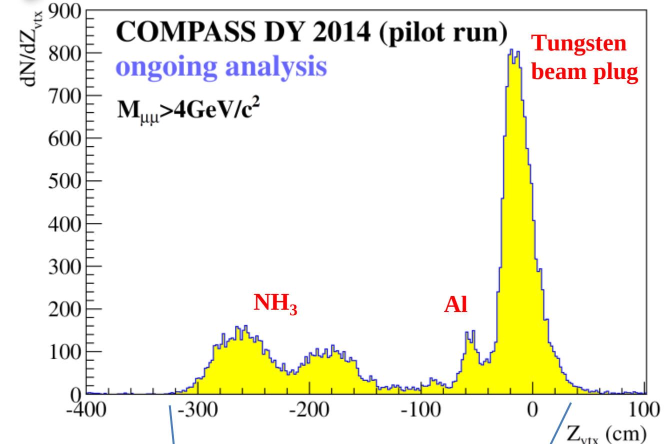

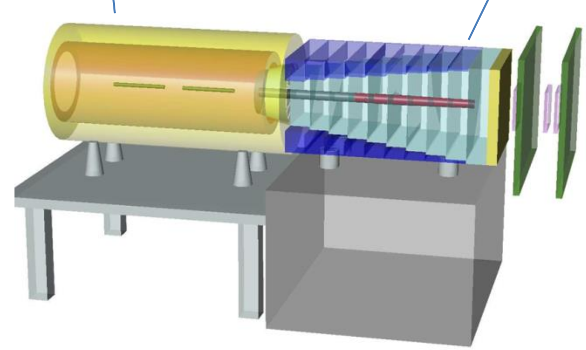

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A.Kotzinian, Nucl. Phys. B441, 234 (1995).
Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel JHEP 0702:093 (2007).

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{aligned}
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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]\\
&+S_T\left[\begin{aligned}&\sin(\phi_h-\phi_S)\left(A_{UT}^{\sin(\phi_h-\phi_S)}\right)\\
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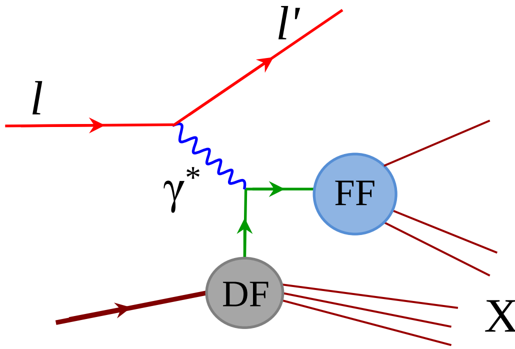

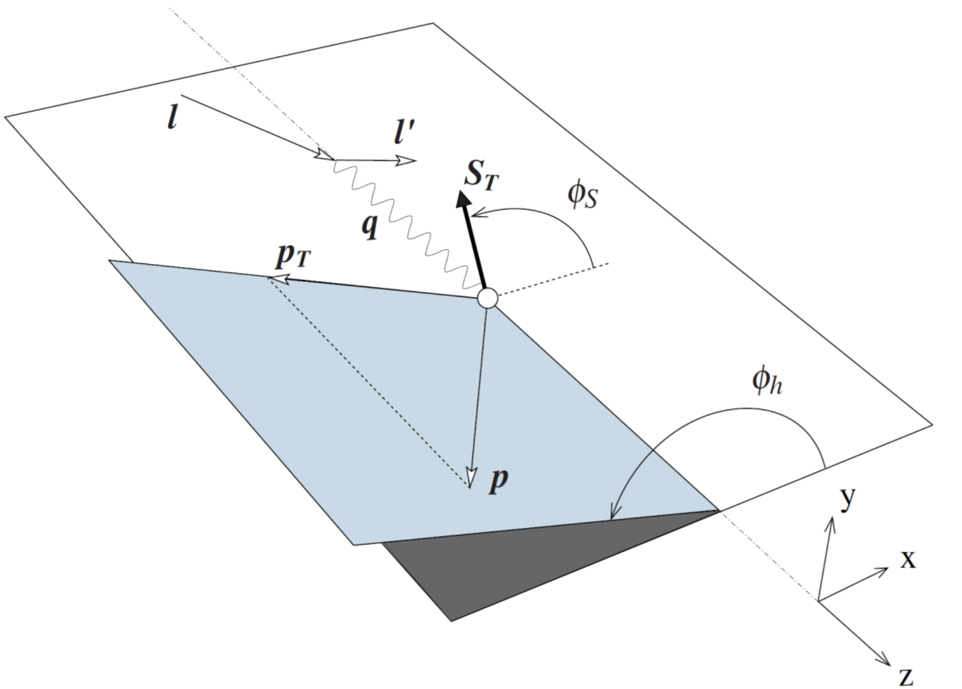

$$A_{U(L),T}^{w(\varphi_h,\varphi_s)} = \frac{F_{U(L),T}^{w(\varphi_h,\varphi_s)}}{F_{UU,T}+\varepsilon F_{UU,L}};\quad \varepsilon=\frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2},\quad \gamma=\frac{2Mx}{Q}$$

SIDIS x-section

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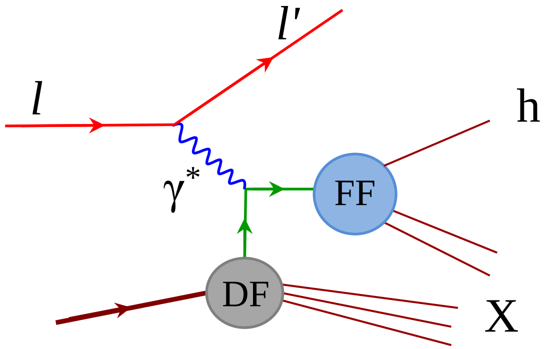
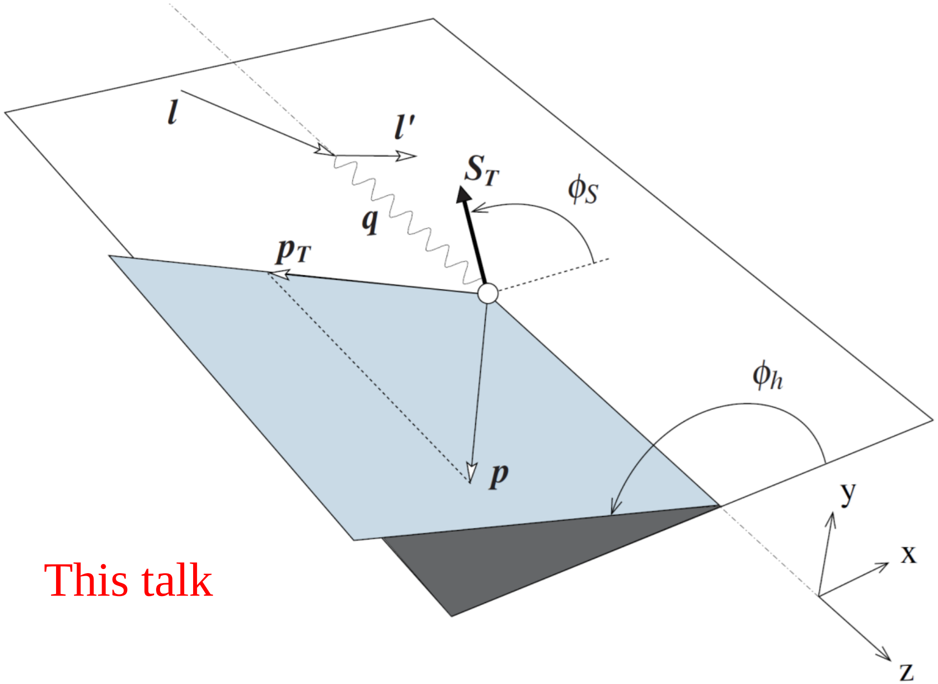
SSA

DSA





This talk

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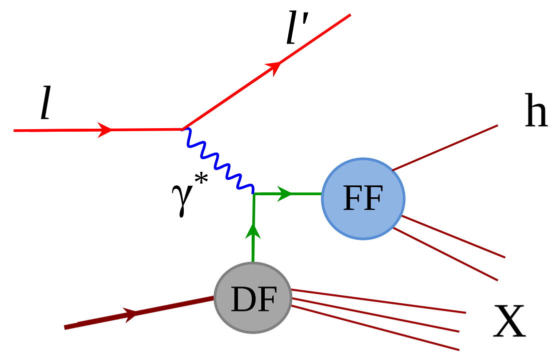
SSA ↑

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

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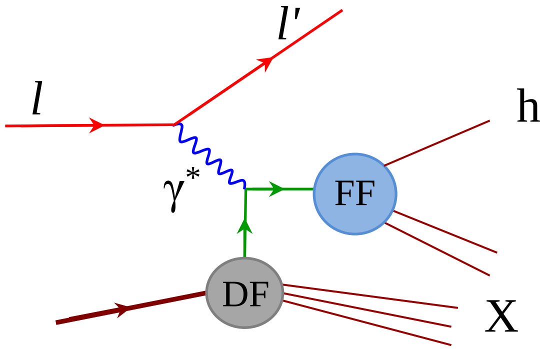

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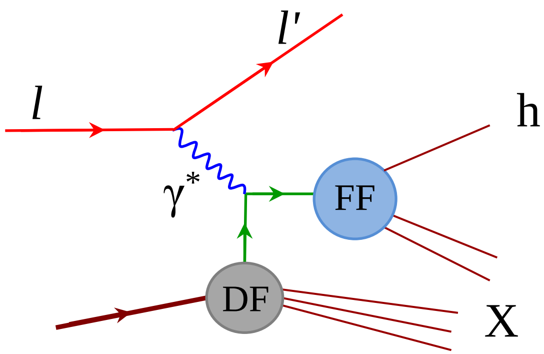


$$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q}\otimes D_{1q}^h$$

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

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

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

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

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

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

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

Twist-2

Twist-3

Outline

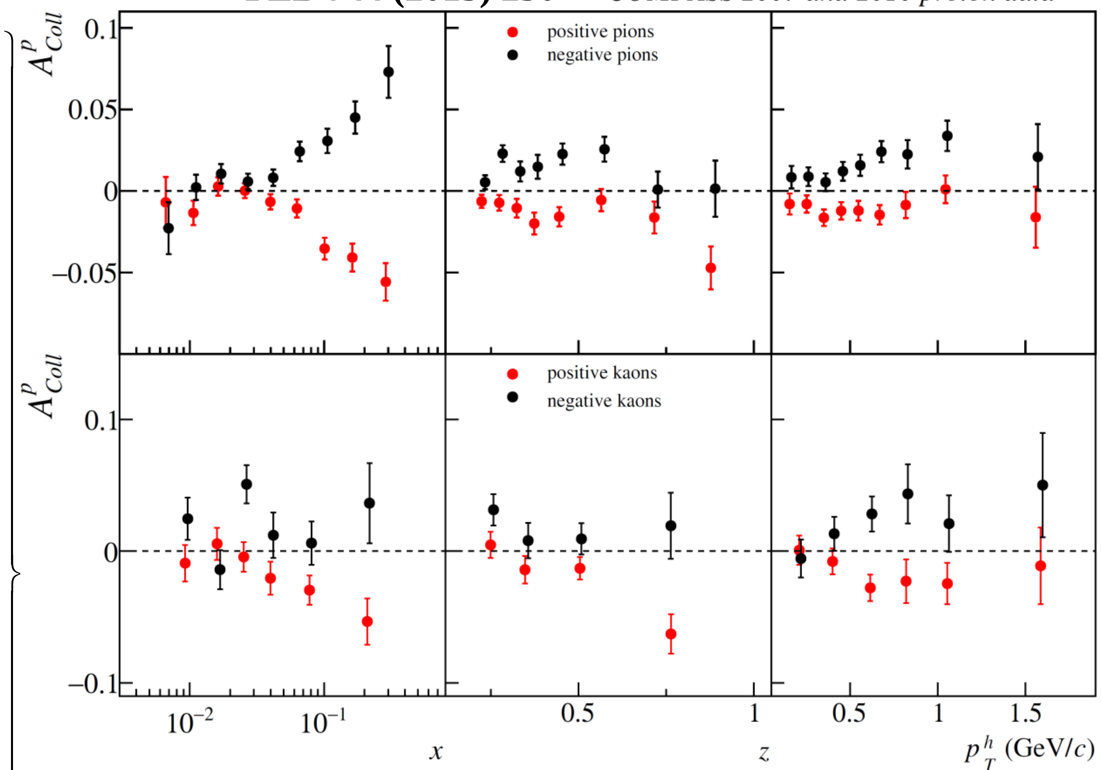
- Introduction
  - COMPASS experiment
  - SIDIS x-section and TSAs
  - Brief review of recent COMPASS results with TSAs
    - COMPASS: SIDIS – Drell-Yan bridge
- COMPASS multidimensional approach
  - COMPASS multidimensional phase-space
- Results for TSAs from multi-D analysis
  - Sivers & Collins asymmetries
  - Beyond Sivers & Collins asymmetries
    - $A_{LT}^{cos(\phi_h - \phi_S)}$ – 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

SIDIS x-section

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

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

PLB 744 (2015) 250 *COMPASS 2007 and 2010 proton data*



- 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

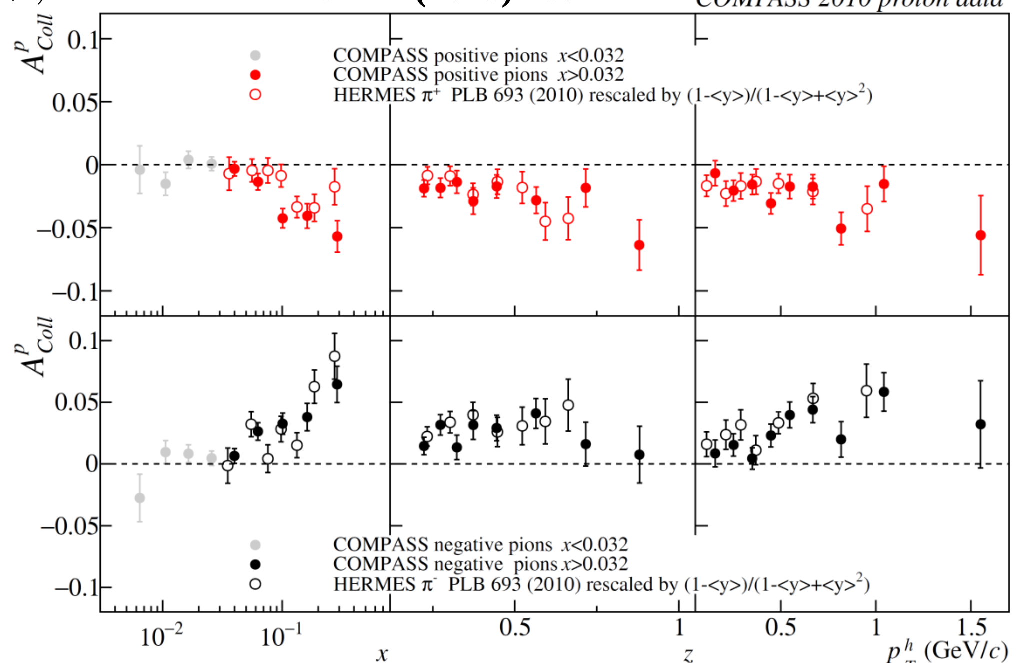
SIDIS x-section

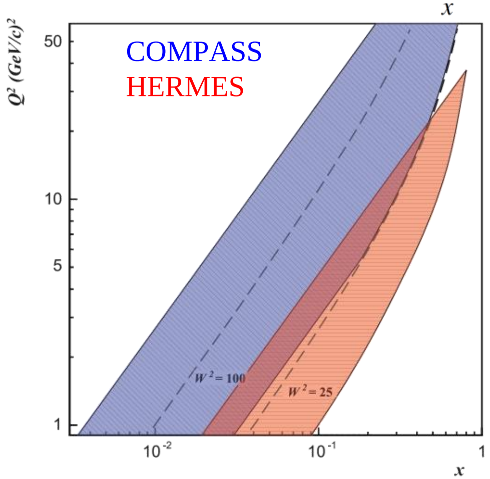
$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$ SSA [twist-2]

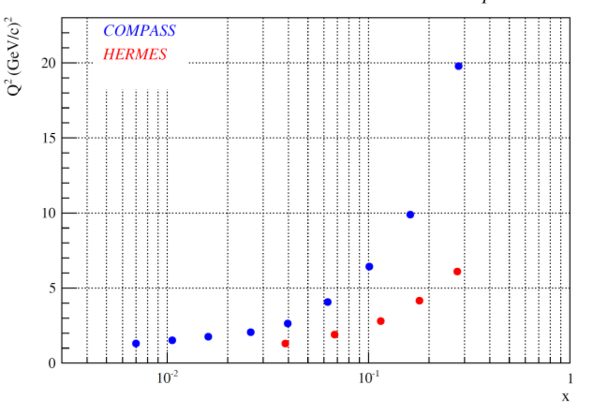
$$\frac{d\sigma}{dxdydzdP_{hT}^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

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

PLB 744 (2015) 250







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

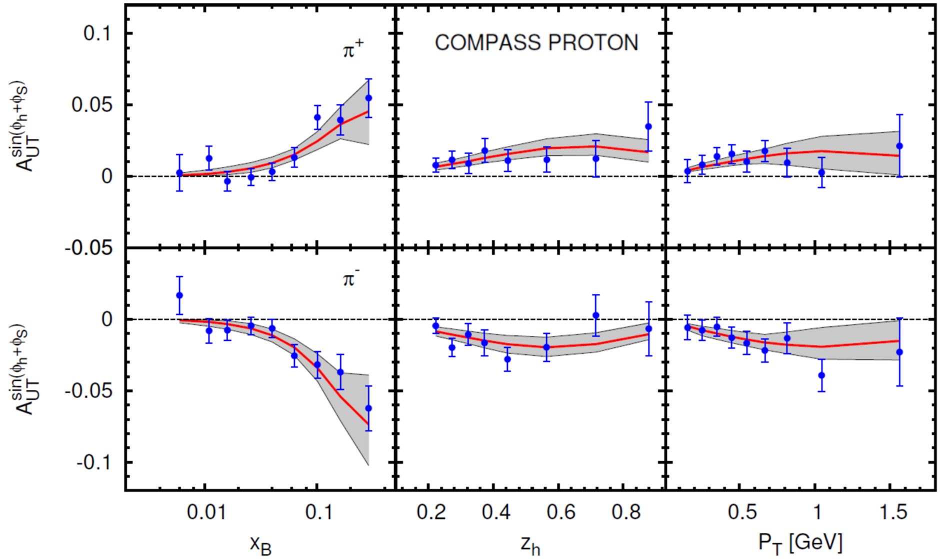
SIDIS x-section

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

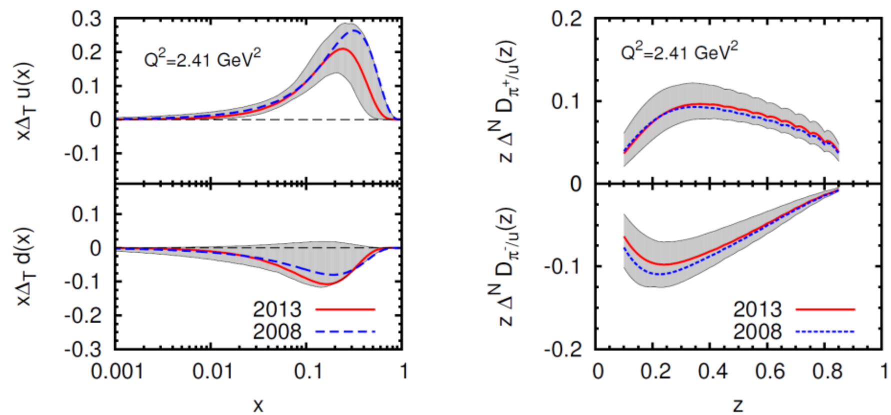
$$\frac{d\sigma}{dx\,dy\,dz\,dP_{hT}^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

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

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



- Global fit of HERMES-COMPASS-BELLE data



- Transversity PDF + Collins FF

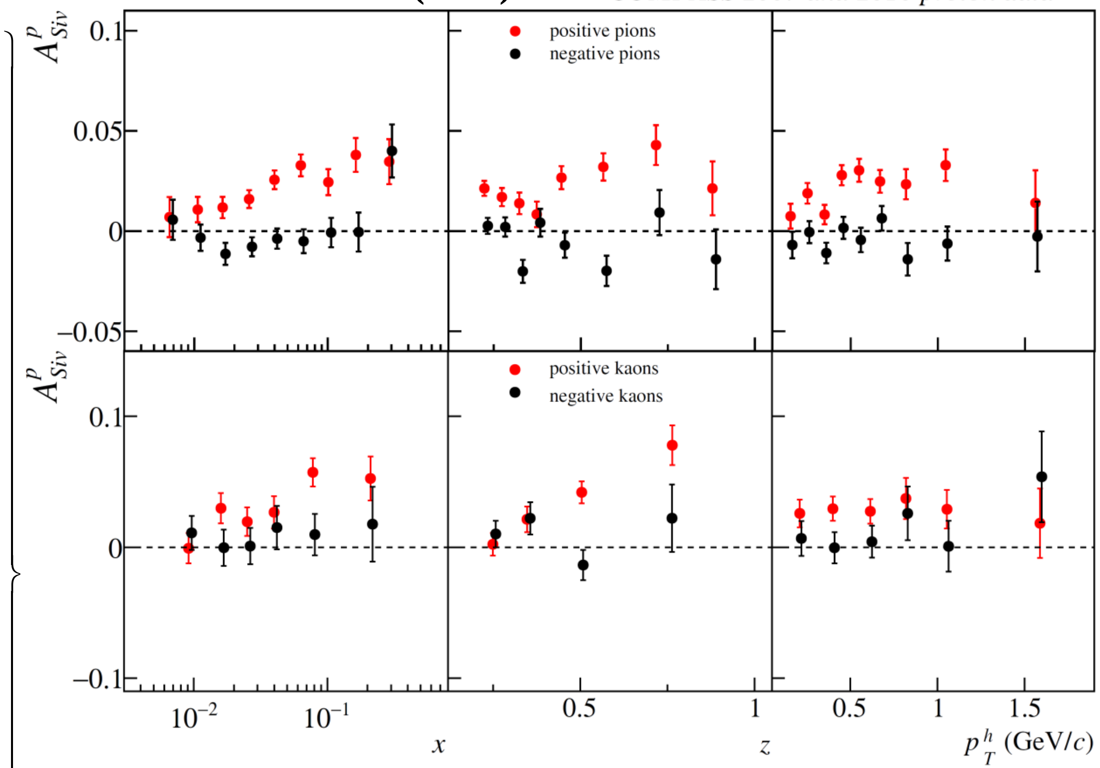
SIDIS x-section

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

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

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

PLB 744 (2015) 250 *COMPASS 2007 and 2010 proton data*



- 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

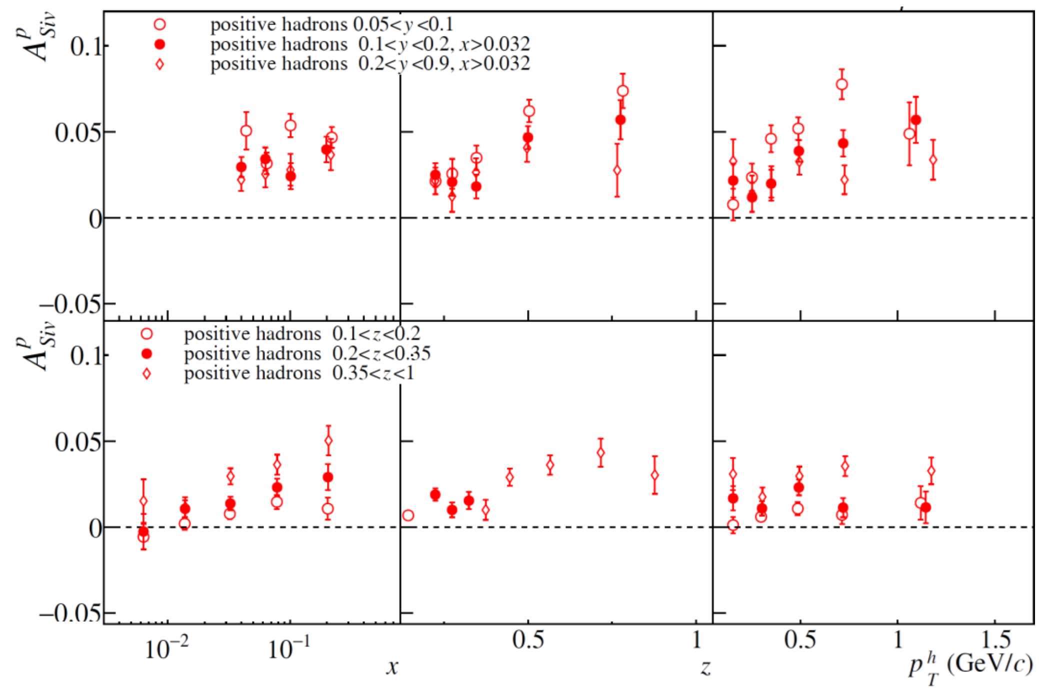
$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$ SSA[twist-2]

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

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

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 $x - z - p_T - Q^2$

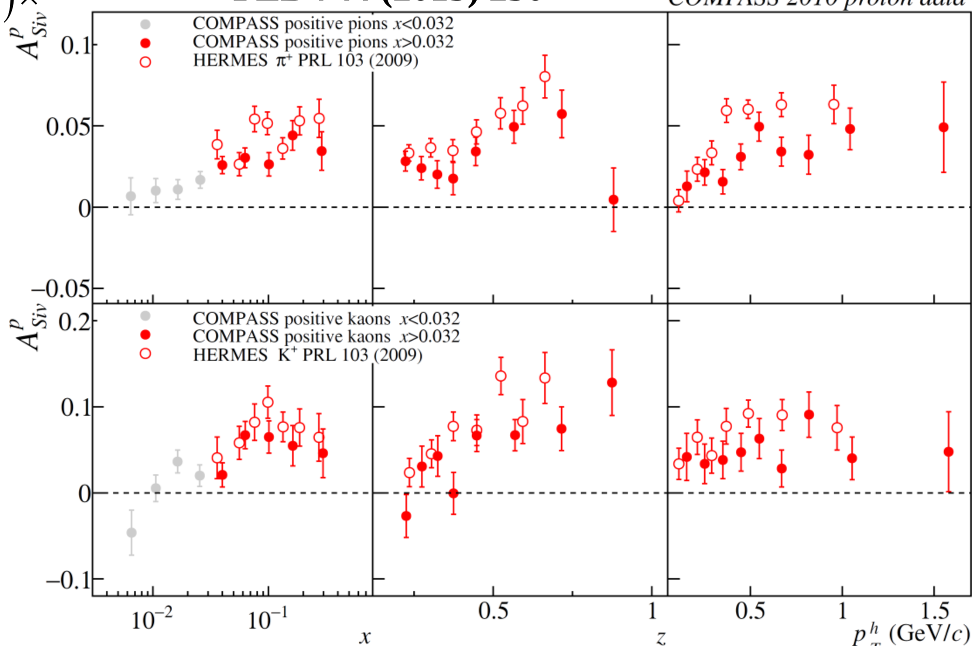
SIDIS x-section

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

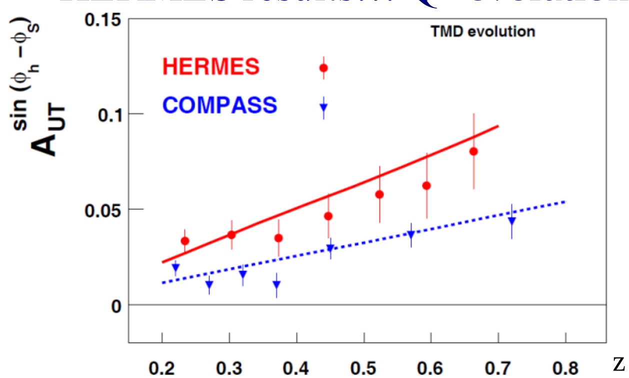
$$\frac{d\sigma}{dx\,dy\,dz\,dP_{hT}^2\,d\varphi_h\,d\psi}=\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

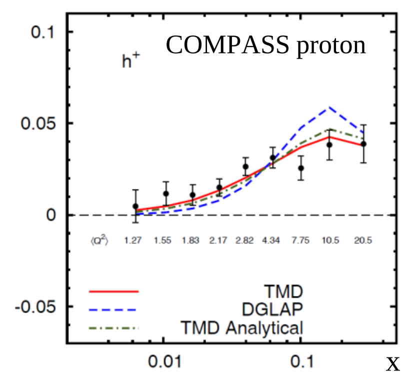
$$\left\{\begin{array}{l}
1+\cos\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\right)+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right)\\
+\ \lambda\sin\phi_h\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\right)\\
+\ S_L\left[\sin\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\right)+\sin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

PLB 744 (2015) 250



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





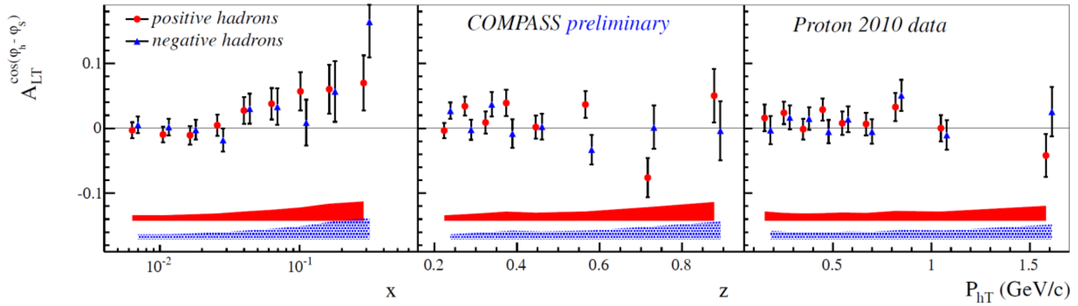
S. M. Aybat, A. Prokudin, T. C. Rogers **PRL 108 (2012) 242003**
M. Anselmino, M. Boglione, S. Melis **PRD 86 (2012) 014028**

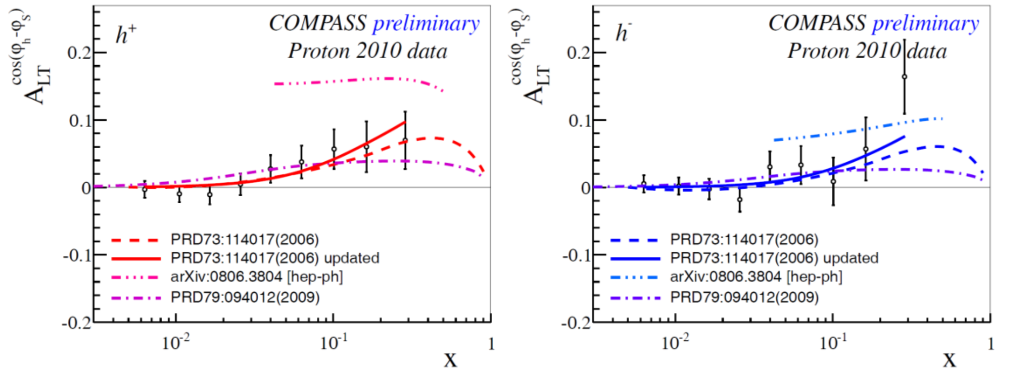
SIDIS x-section

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

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

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



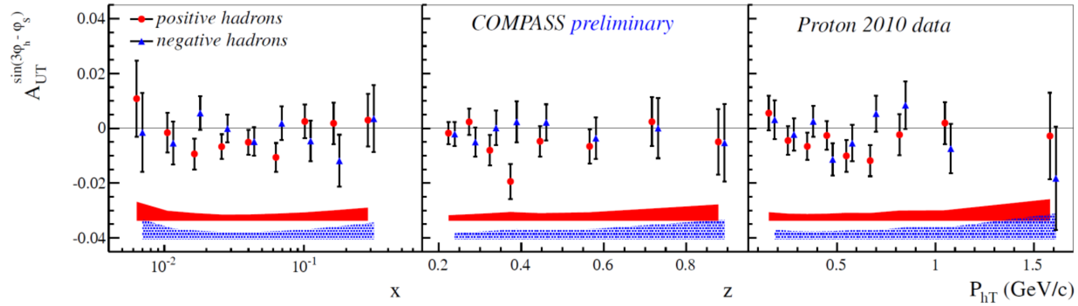


- Gives access to g_{1T} "twist-2" PDF (Kotzinian-Mulders or worm-gear-T)
- Visible signal for h^+ (*preliminary* confirmation also by HERMES)
- In agreement with several model predictions
- Compatible with zero on deuteron

SIDIS x-section

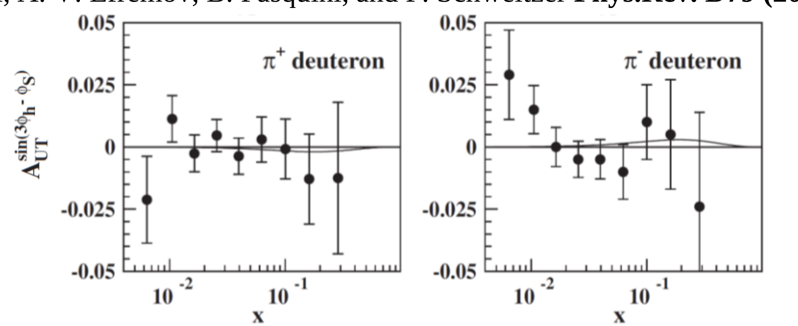
$$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} \quad \mathrm{SSA}\left[\text{twist-2}\right]$$

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

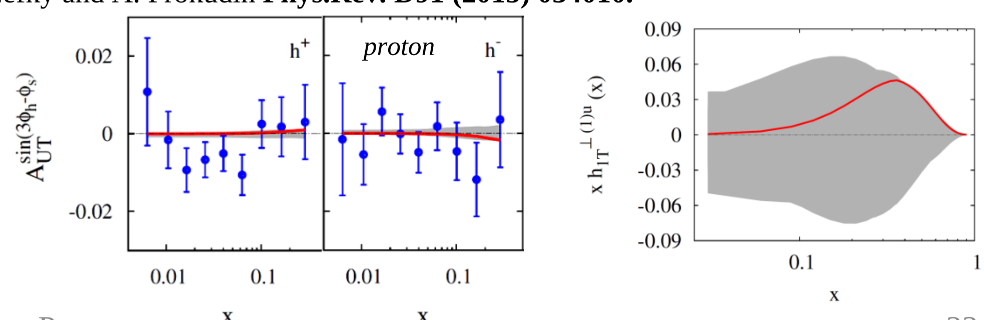


- All compatible with zero within uncertainties (P/D)
- Suppressed by a factor of ~$|p_T|^2$ w.r.t the Collins and Sivers amplitudes

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.**



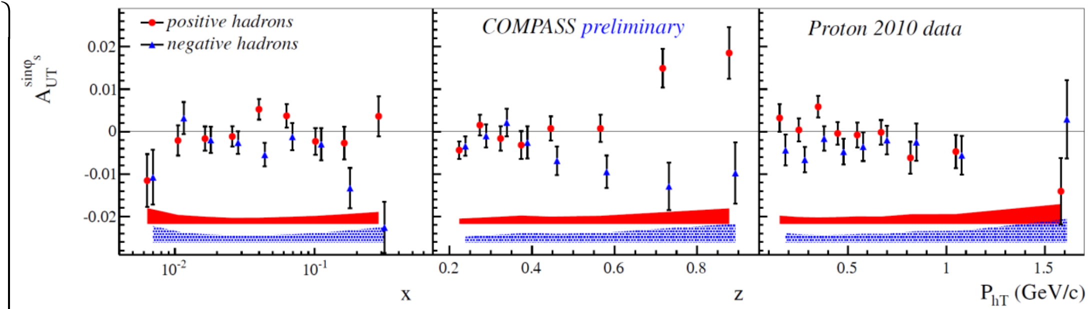
SIDIS x-section

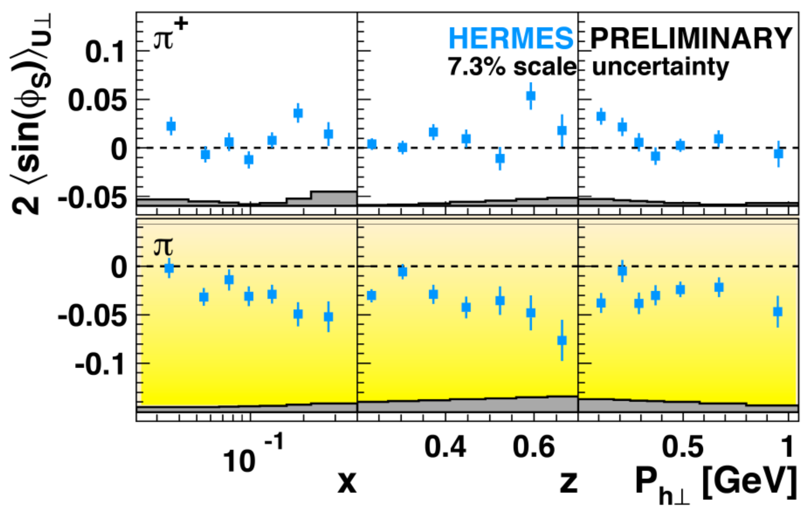
$$A_{UT}^{\sin(\phi_S)} \overset{WW}{\propto} Q^{-1}\left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right)$$

SSA [higher-twist]

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

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





- 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

SIDIS x-section

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

SSA [higher-twist]

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

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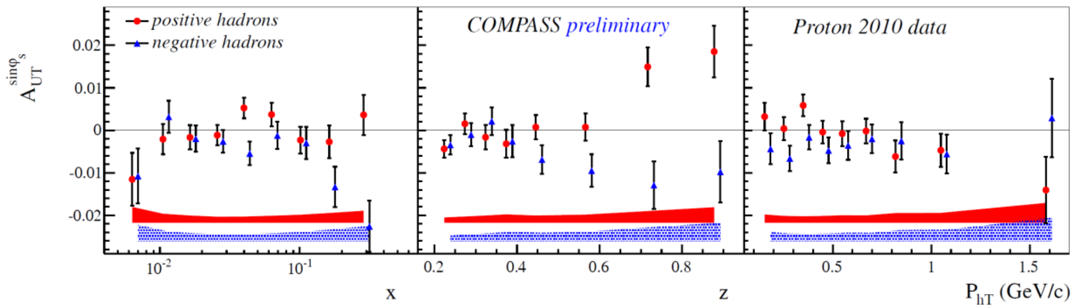
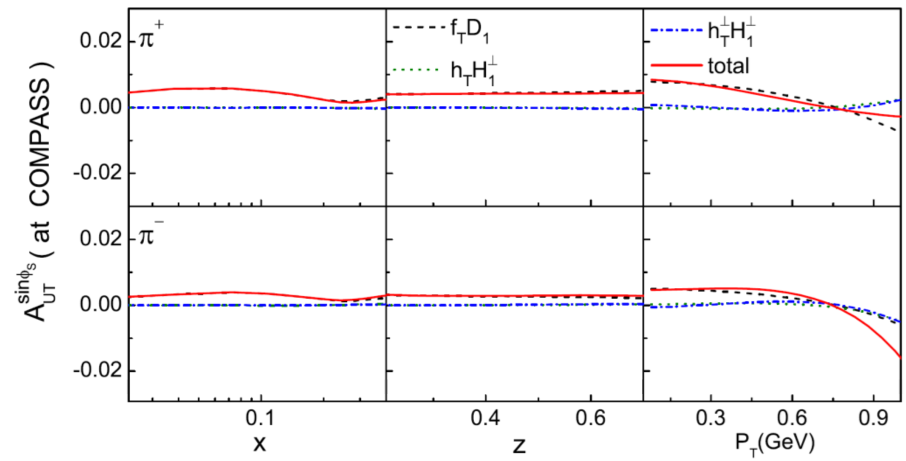
+\ \cos(2\phi_h-\phi_S)\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\right)
\end{array}\right]
\end{array}\right\}$$



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

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

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

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

SSA / DSA [higher-twist]

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

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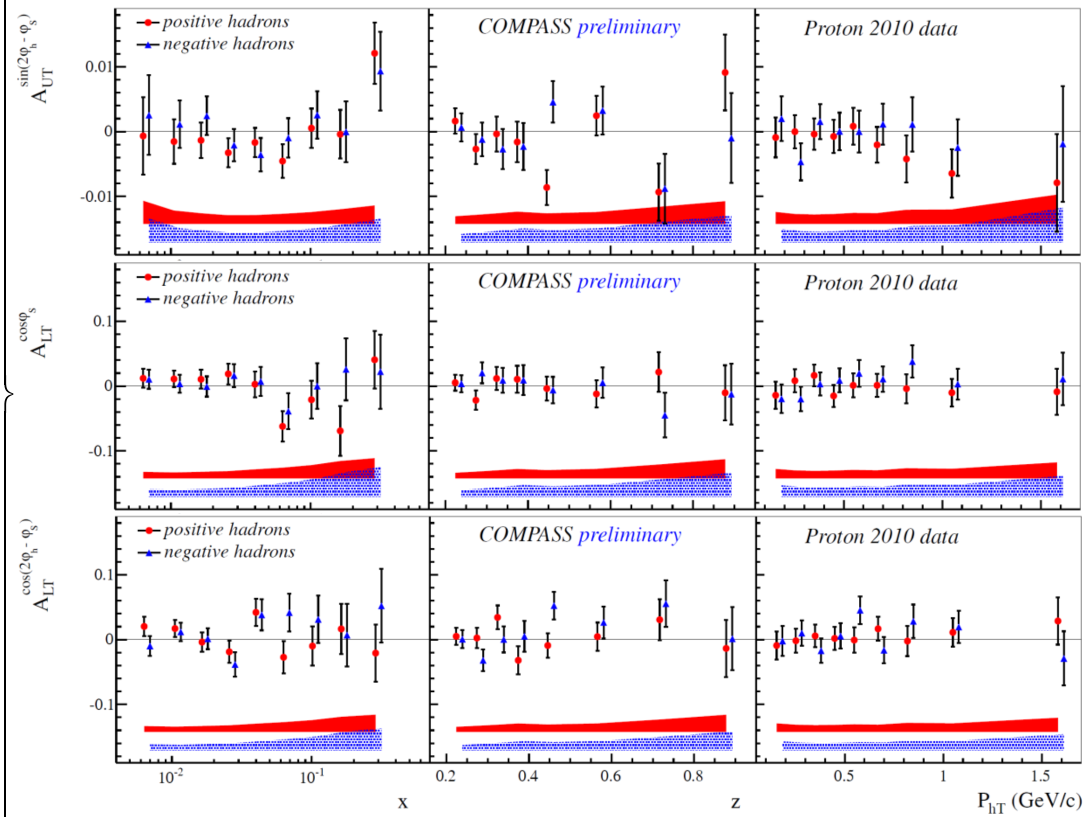
+\ \sin(3\phi_h-\phi_S)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right)\\
+\ \sin\phi_S\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\right)\\
+\ \sin(2\phi_h-\phi_S)\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\right)
\end{array}\right]\\
+\ S_T\lambda\left[\begin{array}{l}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



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

SIDIS x-section

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

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

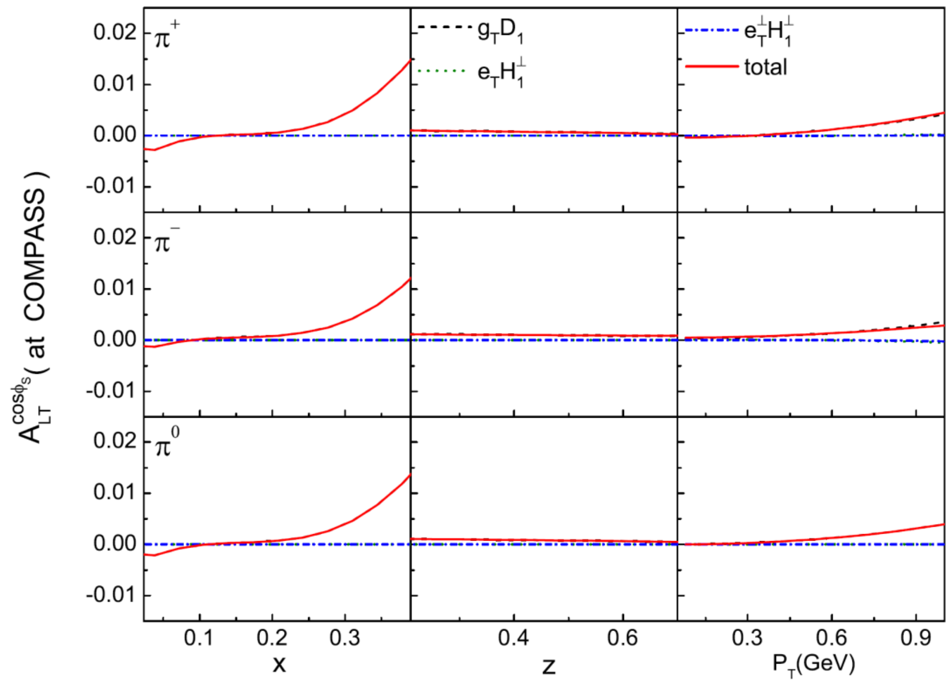
$$A_{UT}^{\sin(2\phi_h-\phi_S)} \overset{WW}{\propto} Q^{-1}\left(h_{1T}^{\perp q}\otimes H_{1q}^{\perp h}+f_{1T}^{\perp q}\otimes D_{1q}^{h}+\ldots\right)$$

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

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

SSA / DSA [higher-twist]

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



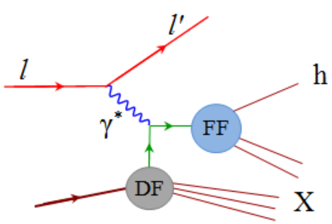
- All compatible with zero within uncertainties (P/D)

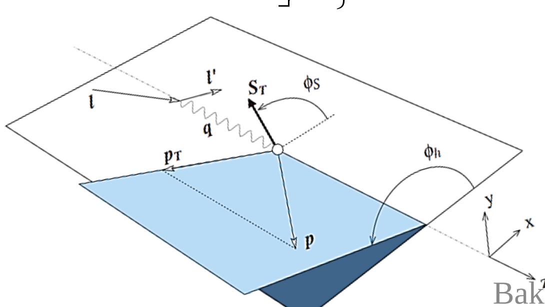
COMPASS bridge

SIDIS x-section

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

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



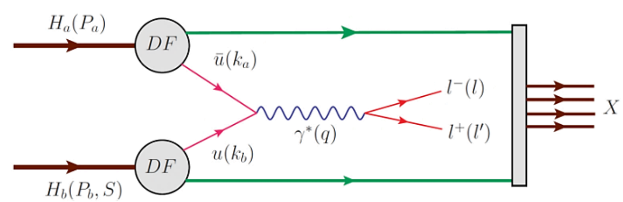


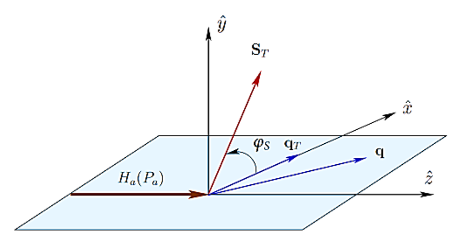
DY x-section

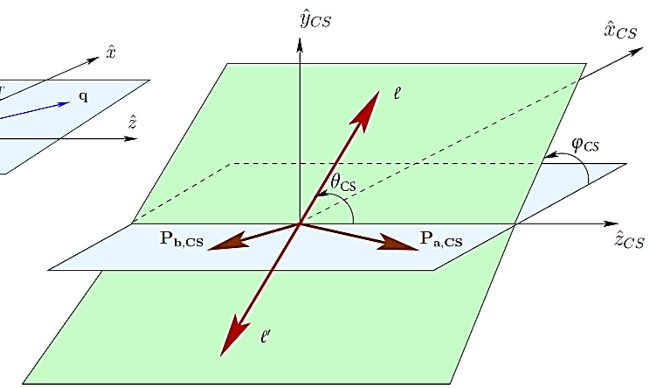
LO single polarized

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2}F_U^1\times$$

$$\left\{\begin{aligned}
&1+\cos^2\theta+\sin^2\theta\cos 2\varphi_{CS}A_U^{\cos 2\varphi_{CS}}\\
&+S_L\sin^2\theta A_L^{\sin 2\varphi_{CS}}\sin 2\varphi_{CS}\\
&+S_T\left[\begin{aligned}
&\left(1+\cos^2\theta\right)\sin\varphi_S A_T^{\sin\varphi_S}\\
&+\sin^2\theta\left(\begin{aligned}&\sin(2\varphi_{CS}+\varphi_S)A_T^{\sin(2\varphi_{CS}+\varphi_S)}\\&+\sin(2\varphi_{CS}-\varphi_S)A_T^{\sin(2\varphi_{CS}-\varphi_S)}\end{aligned}\right)
\end{aligned}\right]
\end{aligned}\right\}$$







TMDs accessed in SIDIS and DY

SIDIS

$$A_{UU}^{\cos\phi_h} \propto Q^{-1}\left(f_1^q \otimes D_{1q}^h - h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots \right)$$

$$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + Q^{-1}\left(f_1^q \otimes D_{1q}^h + \ldots \right)$$

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

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

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

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

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

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

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

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Single polarized DY (LO)

$$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,\mathrm{p}}^{\perp q}$$

$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,\mathrm{p}}^{\perp q}$$

$$A_T^{\sin(2\varphi_{CS} - \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,\mathrm{p}}^q$$

$$A_T^{\sin(2\varphi_{CS} + \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,\mathrm{p}}^{\perp q}$$

Nucleon TMD PDFs accessed in SIDIS and DY

COMPASS

SIDIS

$$A_{UU}^{\cos\phi_h} \propto Q^{-1}\left(f_1^q \otimes D_{1q}^h - h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots\right)$$

$$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + Q^{-1}\left(f_1^q \otimes D_{1q}^h + \ldots\right)$$

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

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

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

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

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

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

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Single polarized DY (LO)

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$$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$$

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

Nucleon TMD PDFs accessed in SIDIS and DY

COMPASS

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

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

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

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

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

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

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

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

Single polarized DY (LO)

$$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$$

$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$$

$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^q$$

$$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$$

Boer-Mulders

Boer-Mulders

Sivers

Transversity

Pretzelosity

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

Nucleon TMD PDFs accessed in SIDIS and DY

COMPASS

SIDIS

$$A_{UU}^{\cos\phi_h} \propto Q^{-1}\left(f_1^q \otimes D_{1q}^h - h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots \right)$$

$$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + Q^{-1}\left(f_1^q \otimes D_{1q}^h + \ldots \right)$$

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

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

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

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

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

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

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

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

Single polarized DY (LO)

$$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$$

$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$$

$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^q$$

$$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$$

Boer-Mulders

Boer-Mulders

Sivers

Transversity

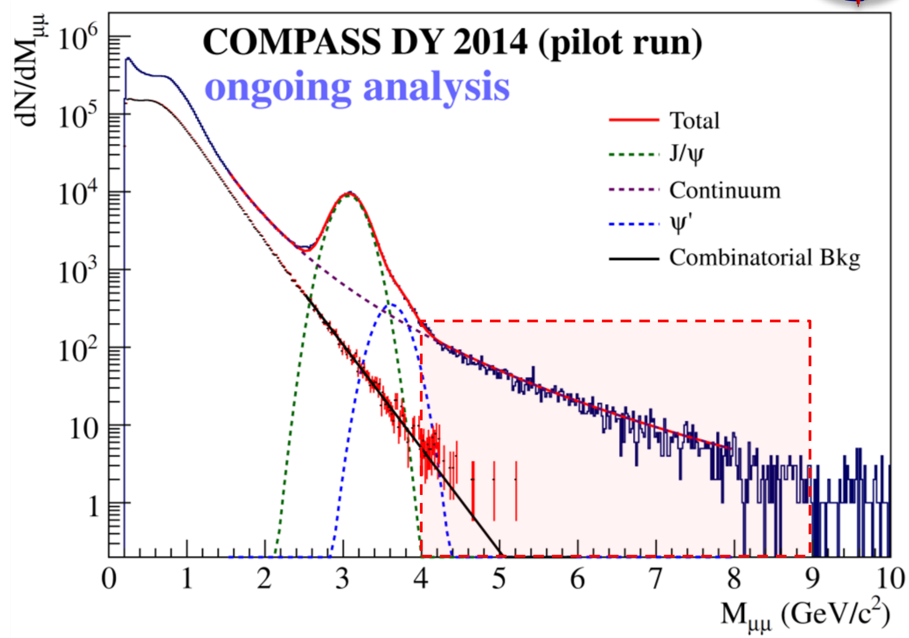
Pretzelosity

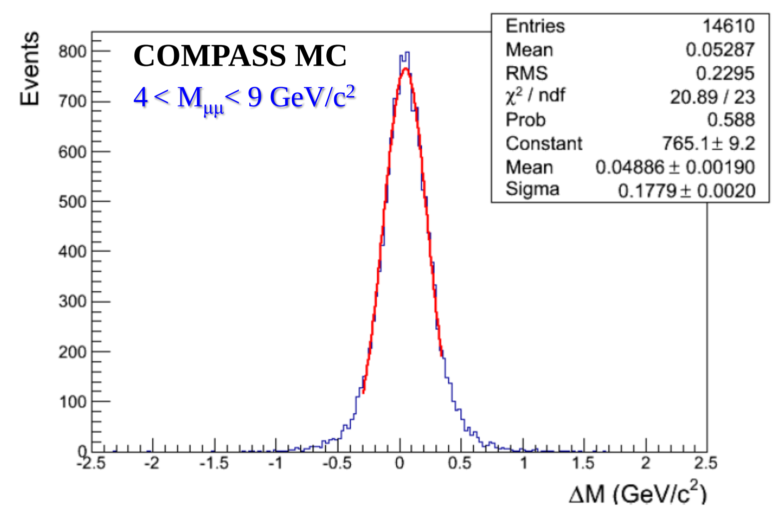
All the answers are encoded in the data... In few years many new asymmetries measured by different experiments in different reactions, at different energies and kinematical ranges will wait for a "global analysis"…

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





Good mass resolution $\Delta M \approx 0.18$ GeV/c^2

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

Four Q^2(or mass)-ranges:

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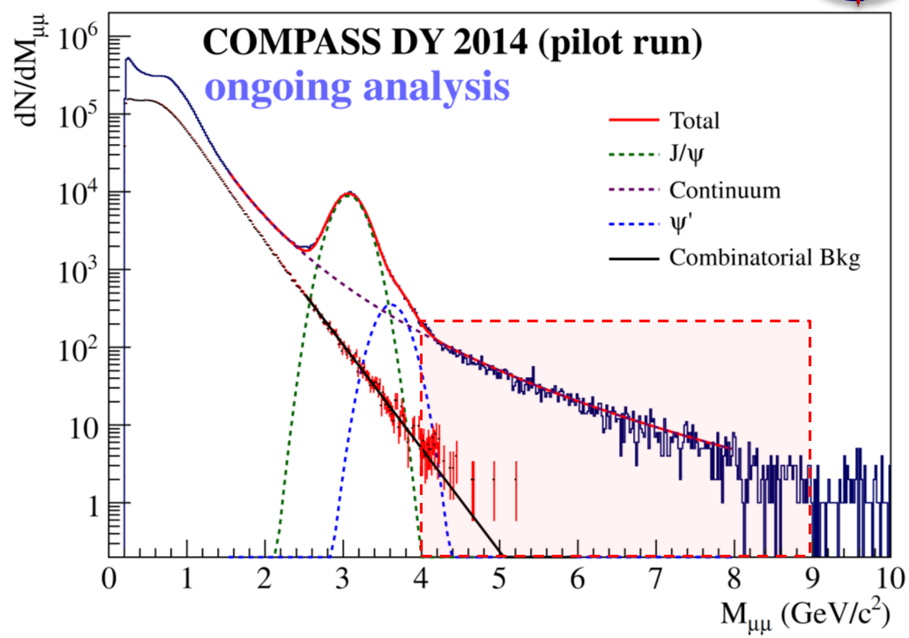

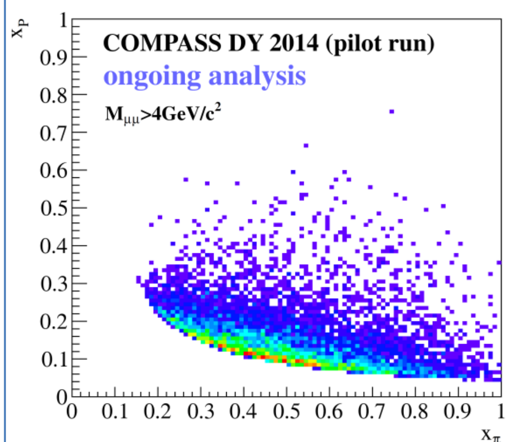

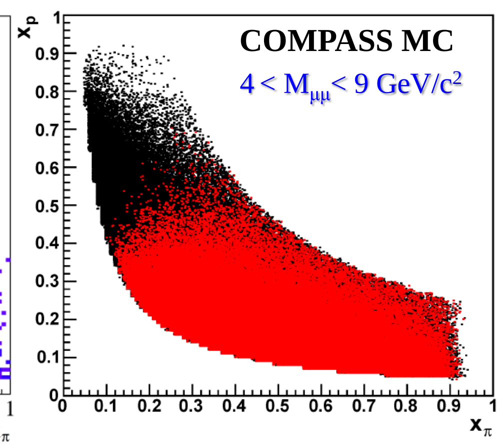

COMPASS x_P:x_π phase-space

Accepted events are in the valence quark range ($x > 0.1$)

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

Four Q²(or mass)-ranges:

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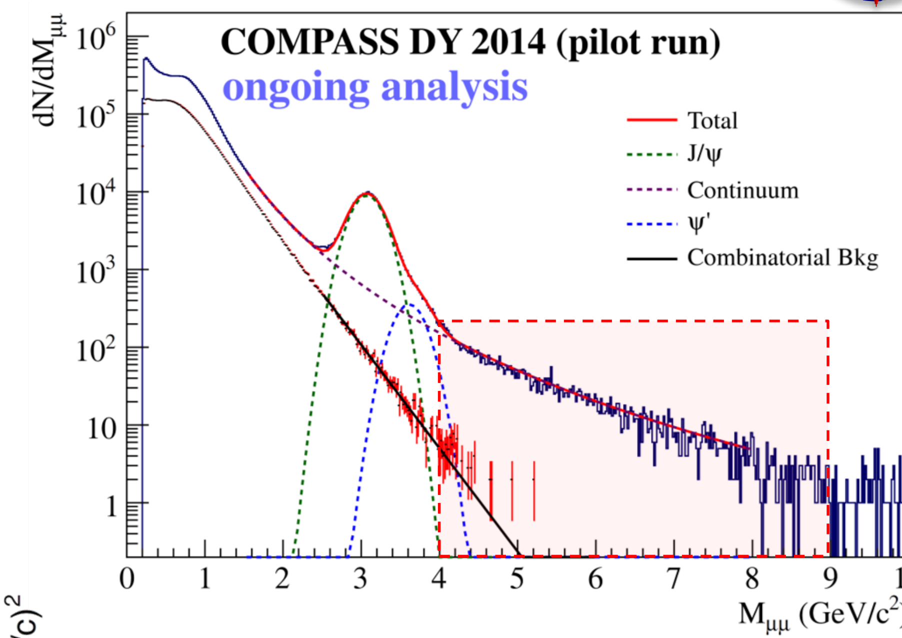
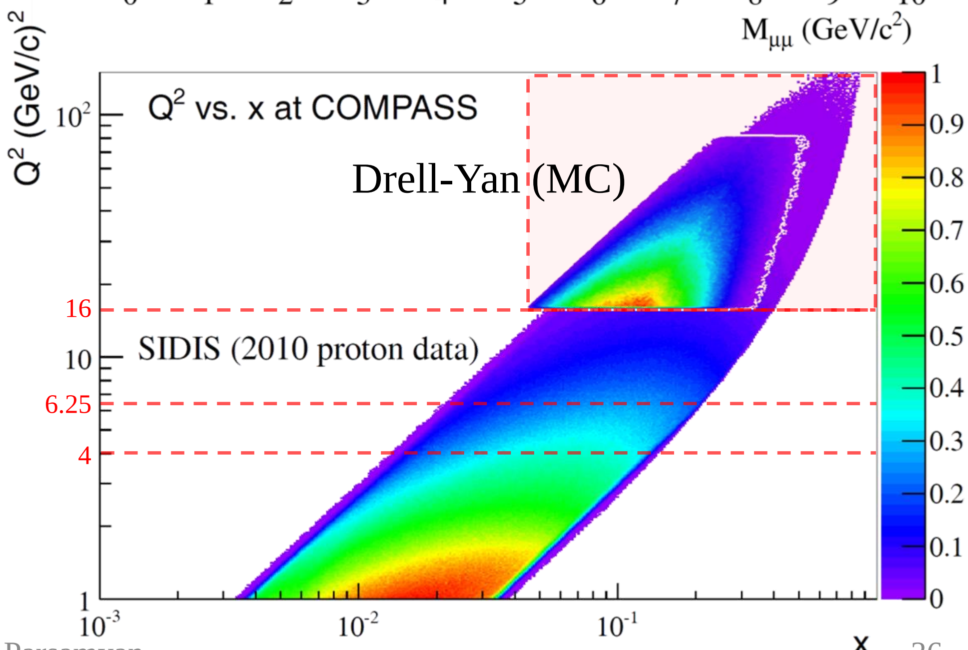
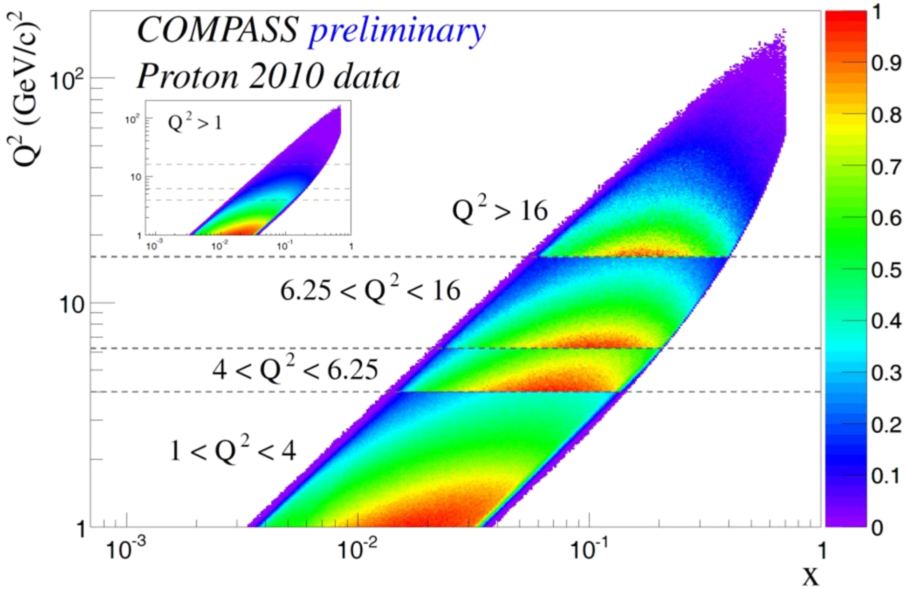
- $Q^2/(\mathrm{GeV}/c)^2 > 16$ "High mass"
  - Beyond J/ψ peak
  - Negligible background
  - Low cross-section
  - Valence region → largest asymmetries

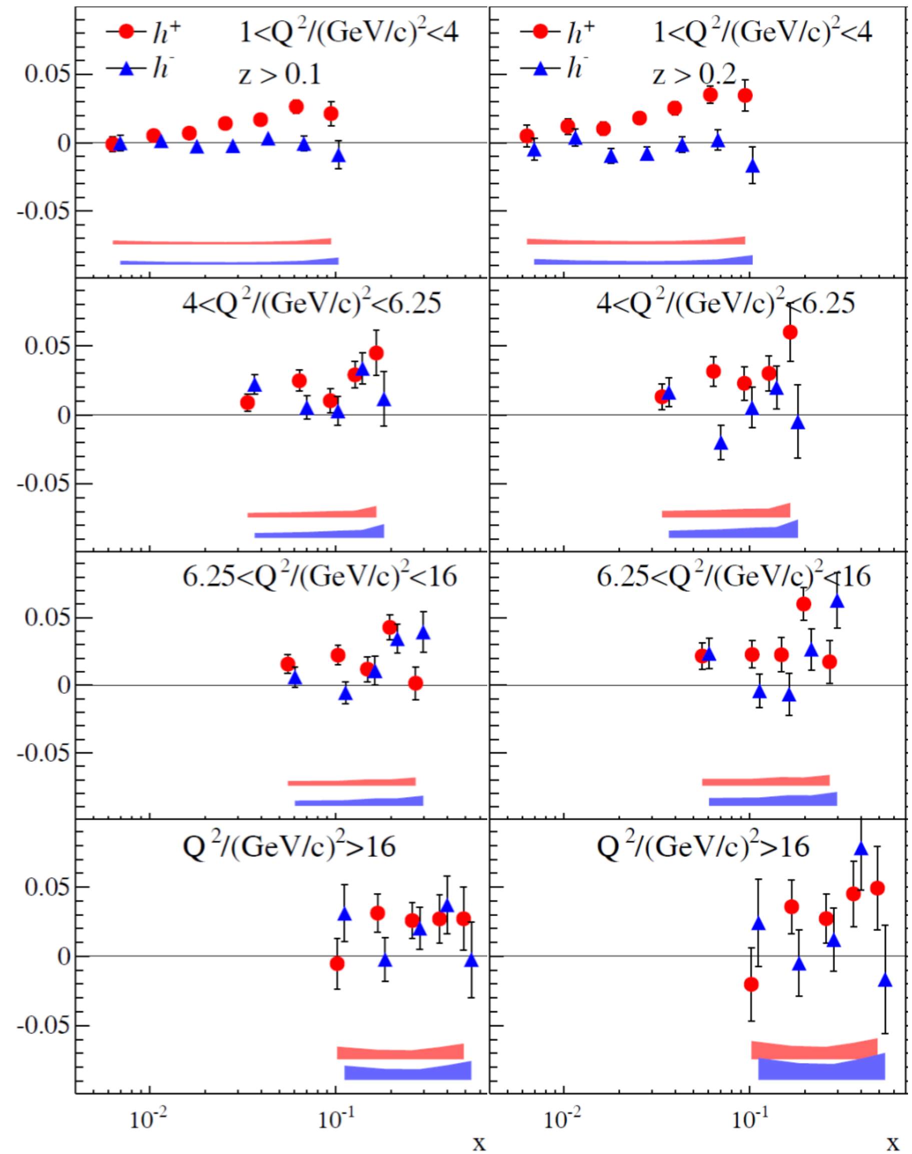




Sivers asymmetry in Drell-Yan Q^2 ranges

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





Towards 3D…

Four Q^2-ranges:

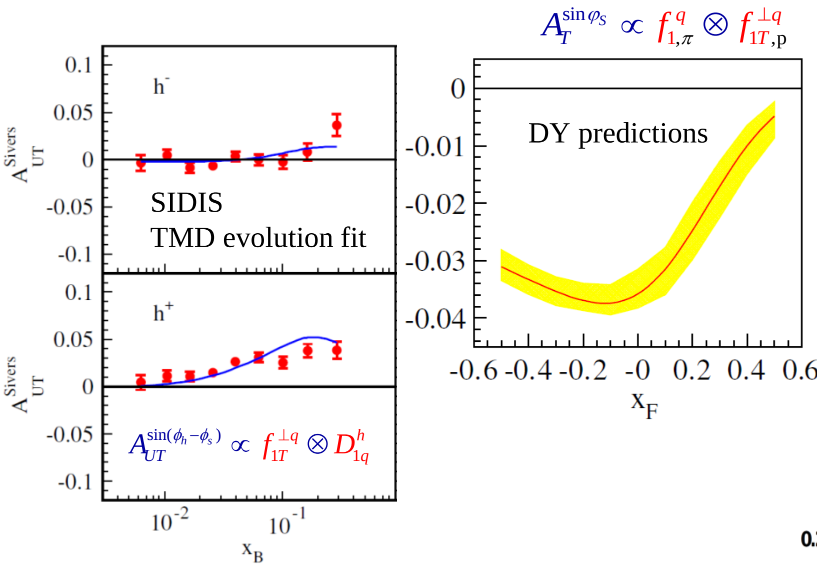
- $1 < Q^2/(GeV/c)^2 < 4$ "Low mass"
- $4 < Q^2/(GeV/c)^2 < 6.25$ "Intermediate"
- $6.25 < Q^2/(GeV/c)^2 < 16$ "J/ψ range"
- $Q^2/(GeV/c)^2 > 16$ "High mass range"

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

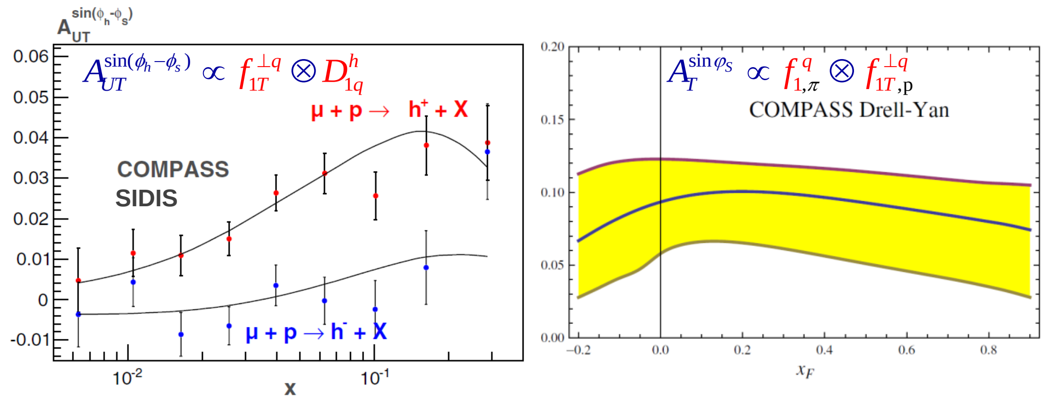
- $z \in [0.2; 1.0]$ – standard selection (cuts)
- $z \in [0.1; 1.0]$ – Extended region: Low z ($z \in [0.1; 0.2]$) + std. selection (cuts)

TSAs in SIDIS and Drell-Yan: fits, predictions

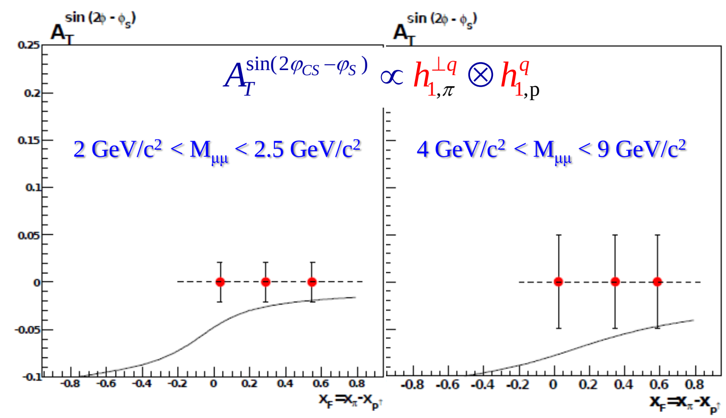
M.G. Echevarria, A.Idilbi, Z.B. Kang and I. Vitev,
"QCD Evolution of the Sivers Asymmetry"
PRD 89 074013 (2014)

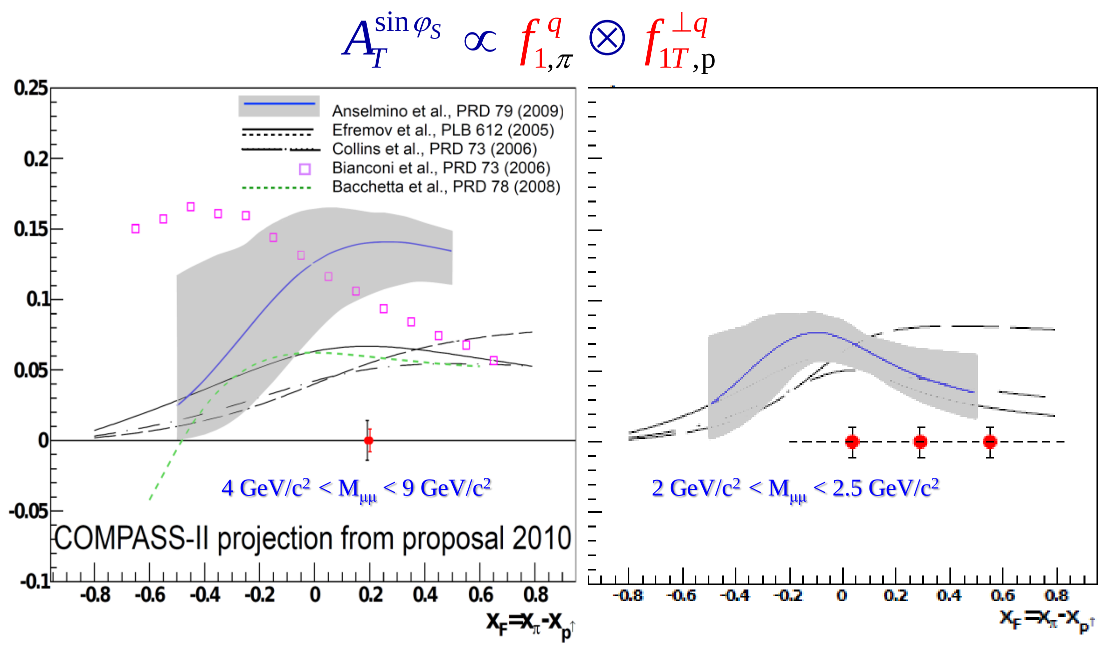


P. Sun and F. Yuan,
"Transverse momentum dependent evolution: Matching SIDIS processes to Drell-Yan and W/Z boson production".
PRD 88 11, 114012 (2013)



A. N. Sissakian,
Phys. Part.Nucl. 41, 64-100 (2010)





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

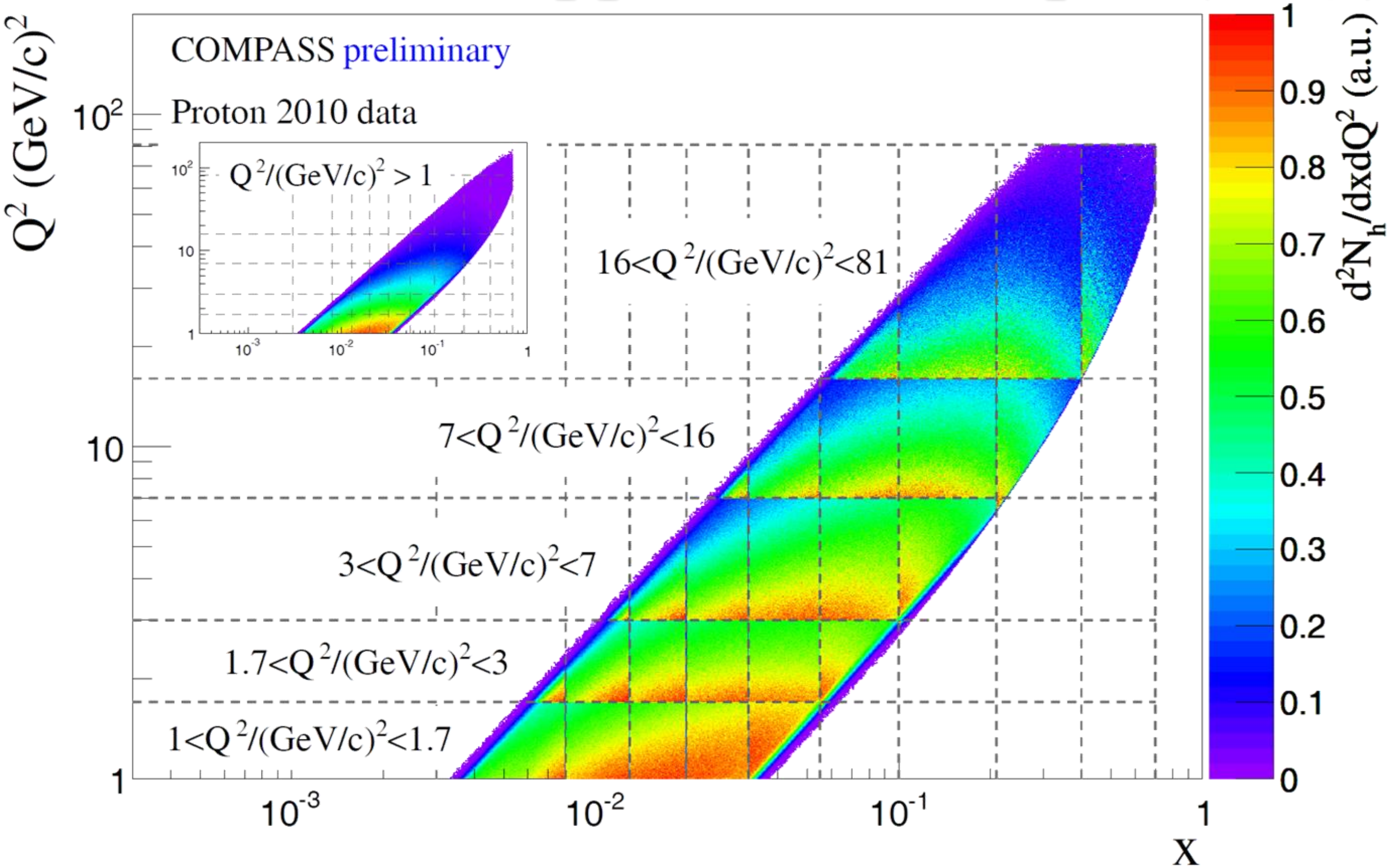
Multidimensional approach concept I (x:Q^2)

- 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)



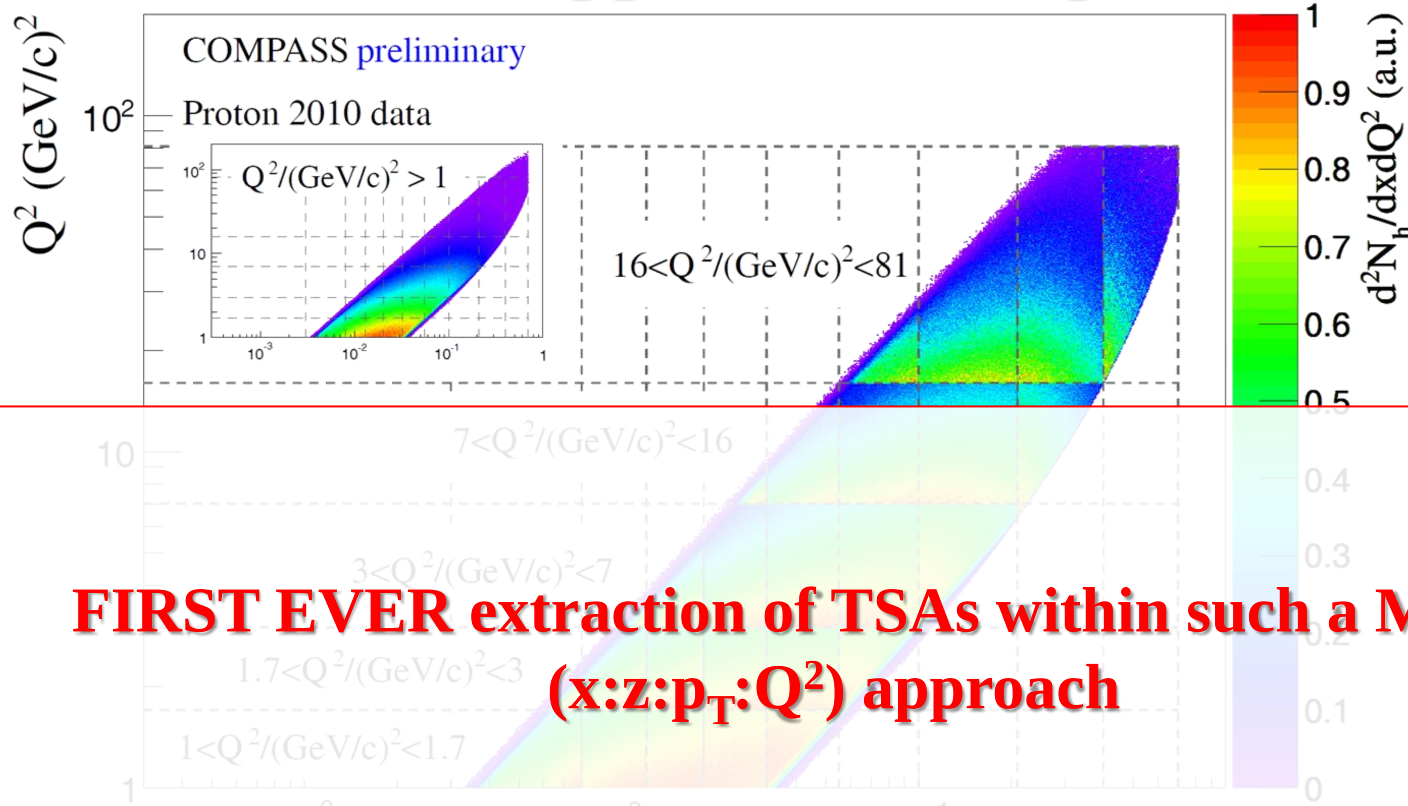
Q² ranges:
- $1 < Q^2 < 1.7$
- $1.7 < Q^2 < 3$
- $3 < Q^2 < 7$
- $7 < Q^2 < 16$
- $16 < Q^2 < 81$

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

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 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:

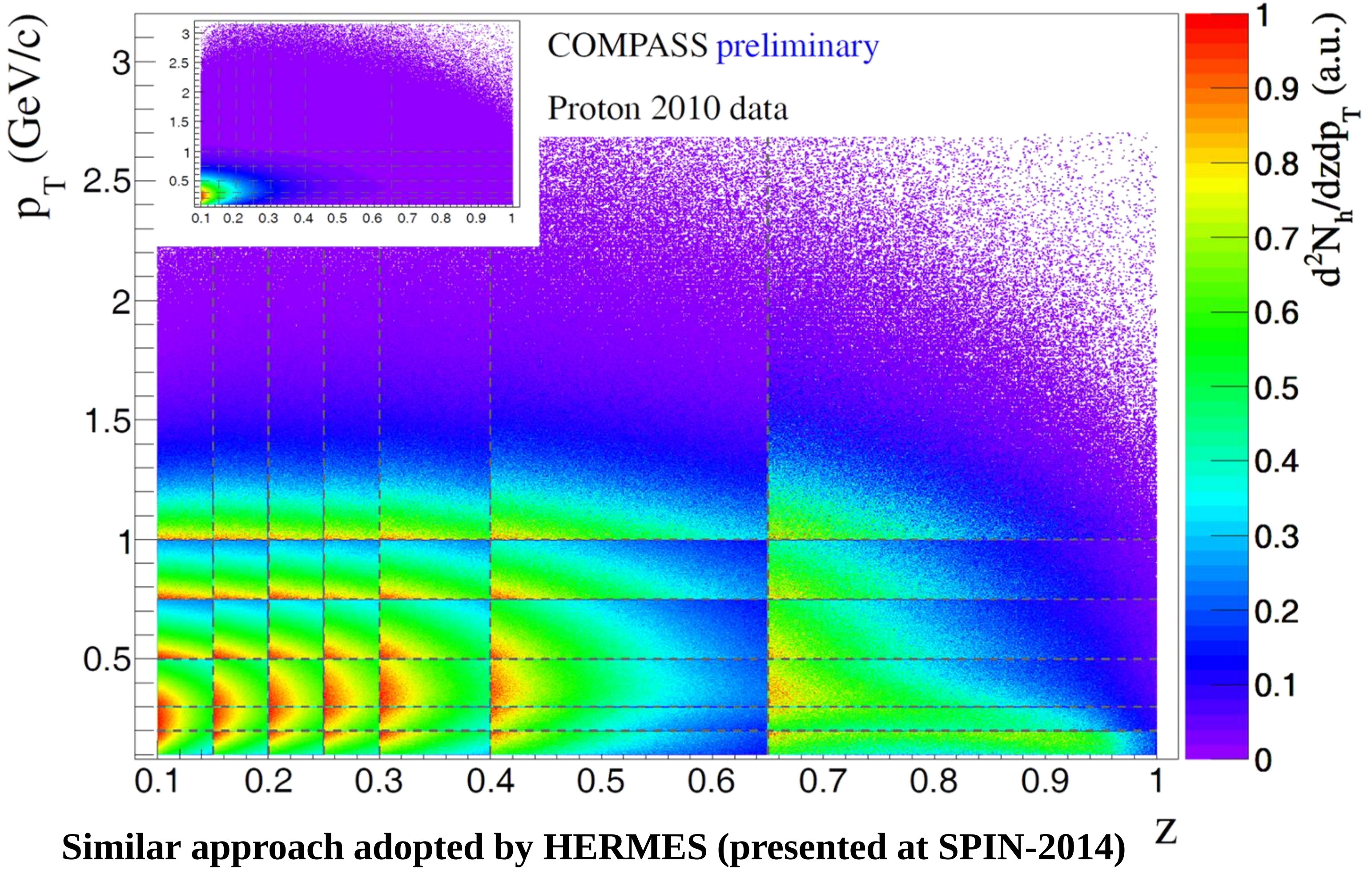
- **all x**
- **$x<0.032$**
- **$x>0.032$**

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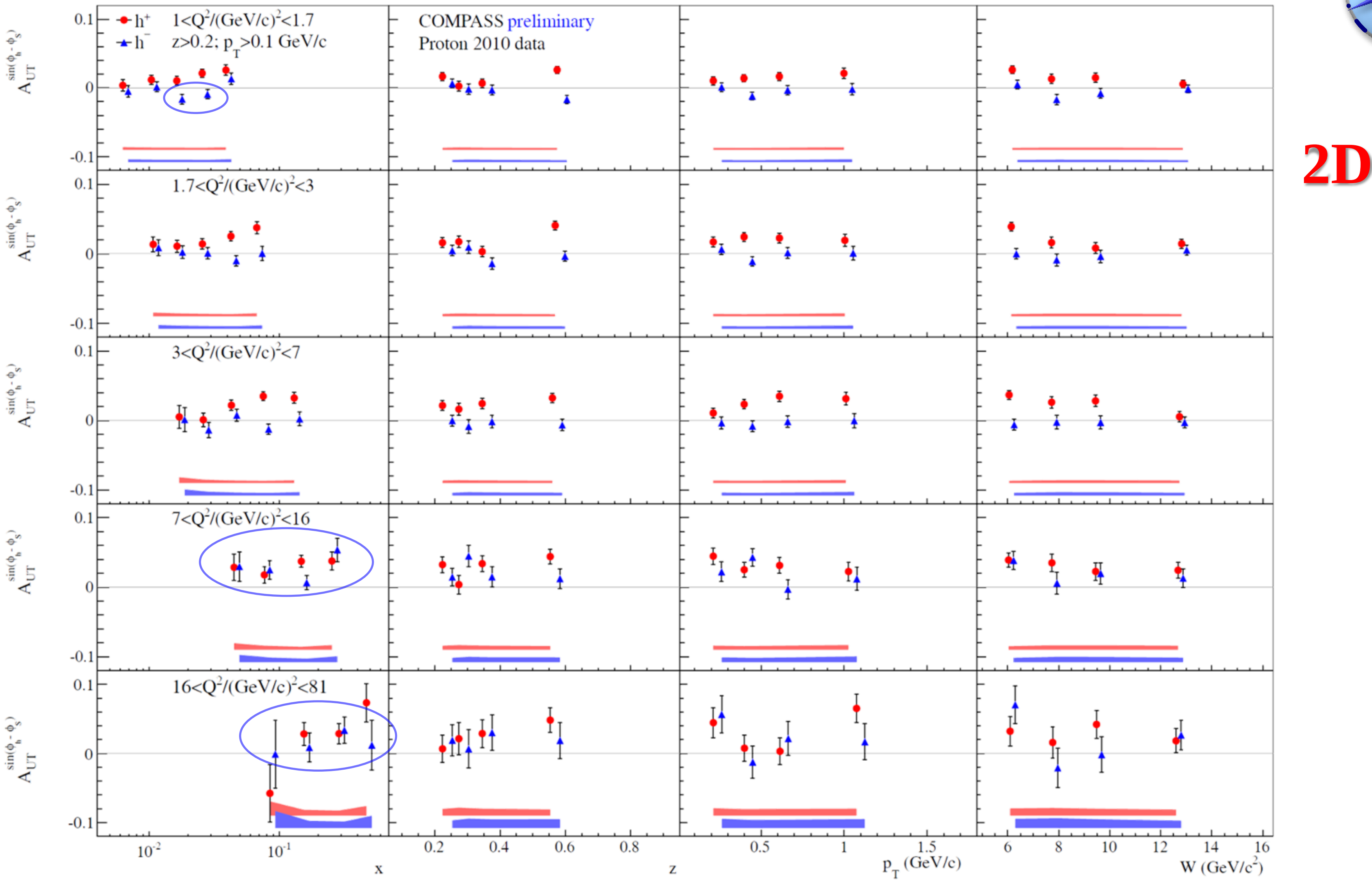
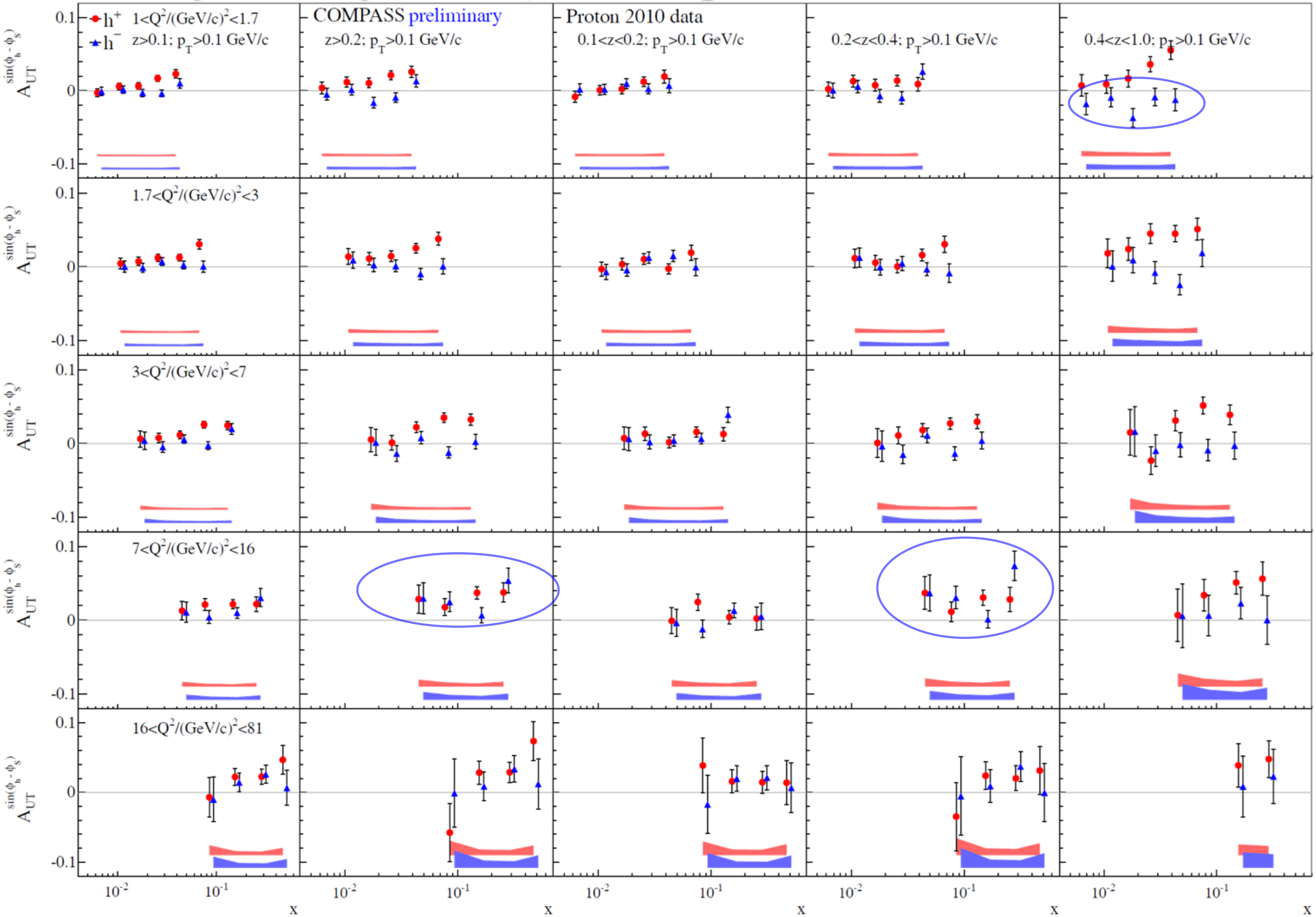
Sivers asymmetry: x, z, p_T and W dependences in 5 Q^2-ranges



- **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)**

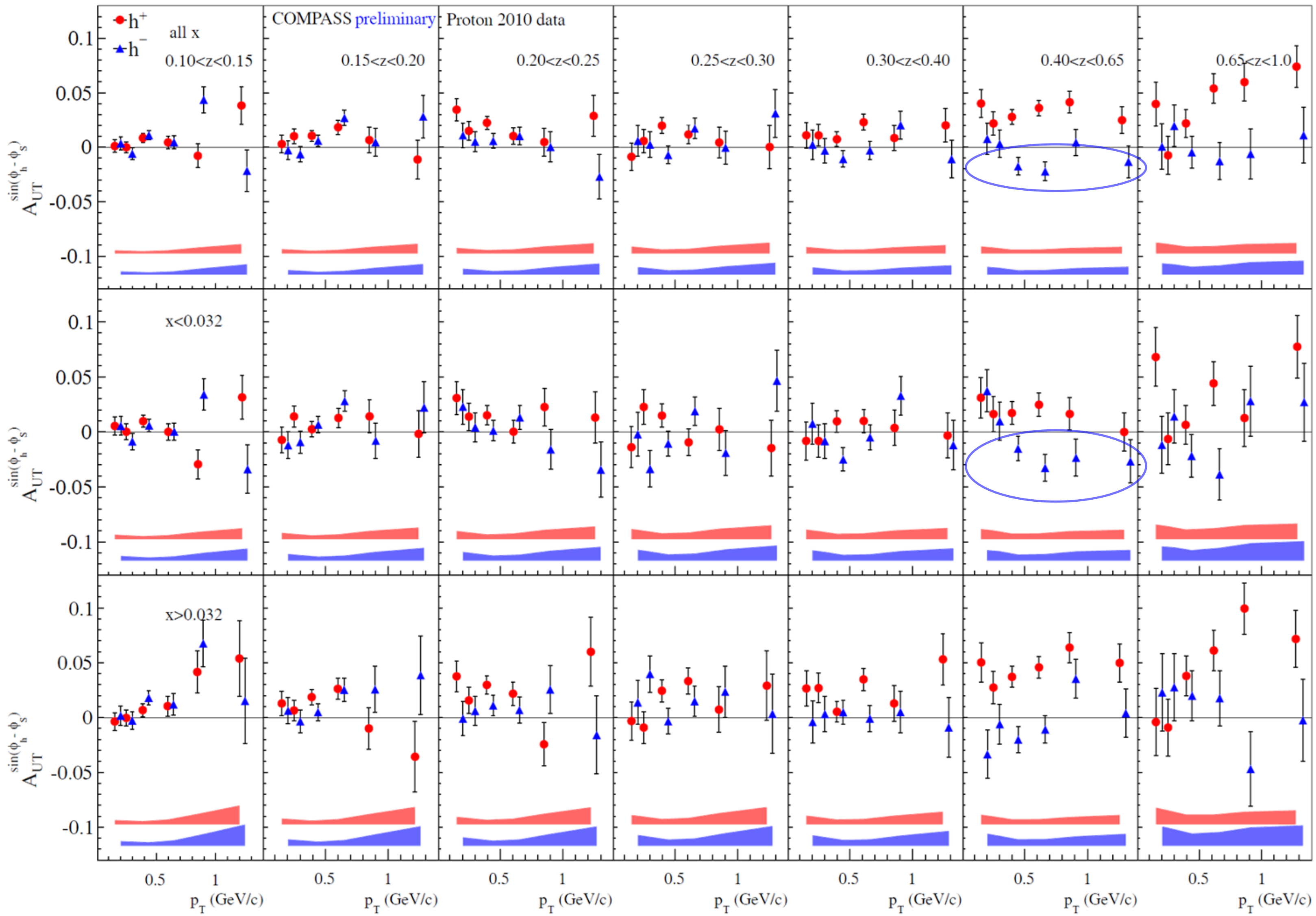
Sivers asymmetry: 3D Q^2-z-x dependence

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**

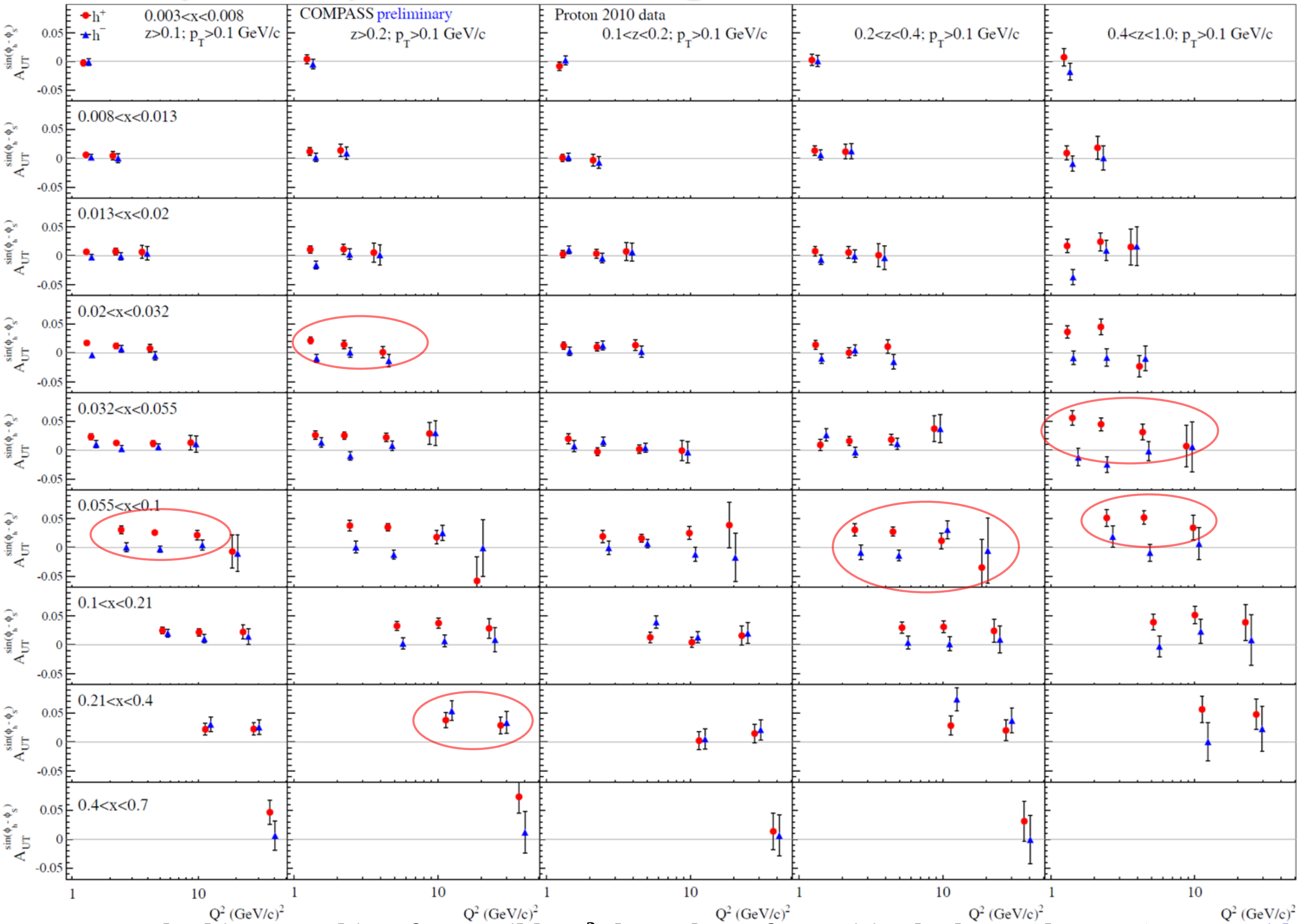
Sivers asymmetry: 3D x-z-p_T dependence



3D

- **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)**

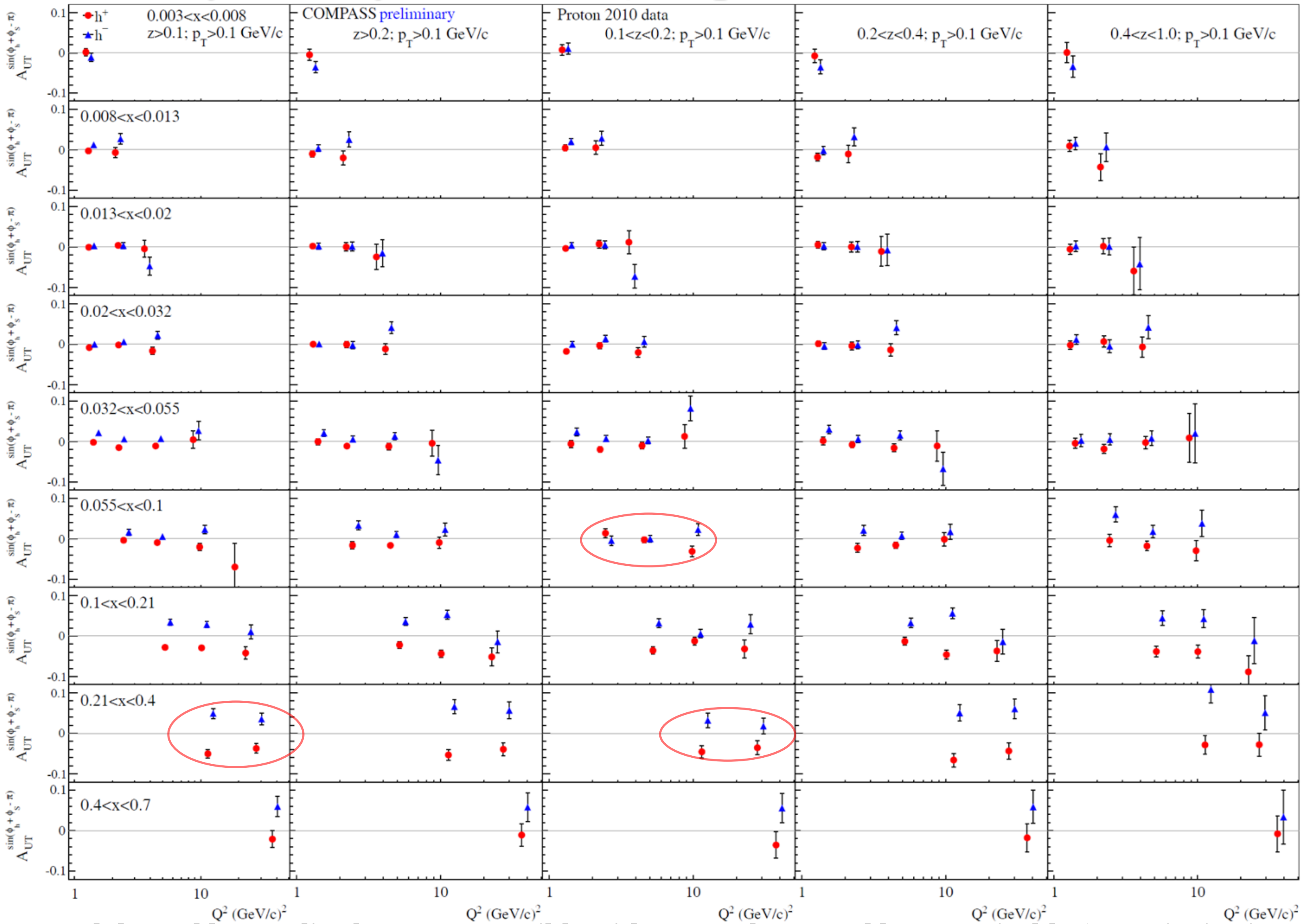
Sivers asymmetry: 3D x-z-Q^2 dependence



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**

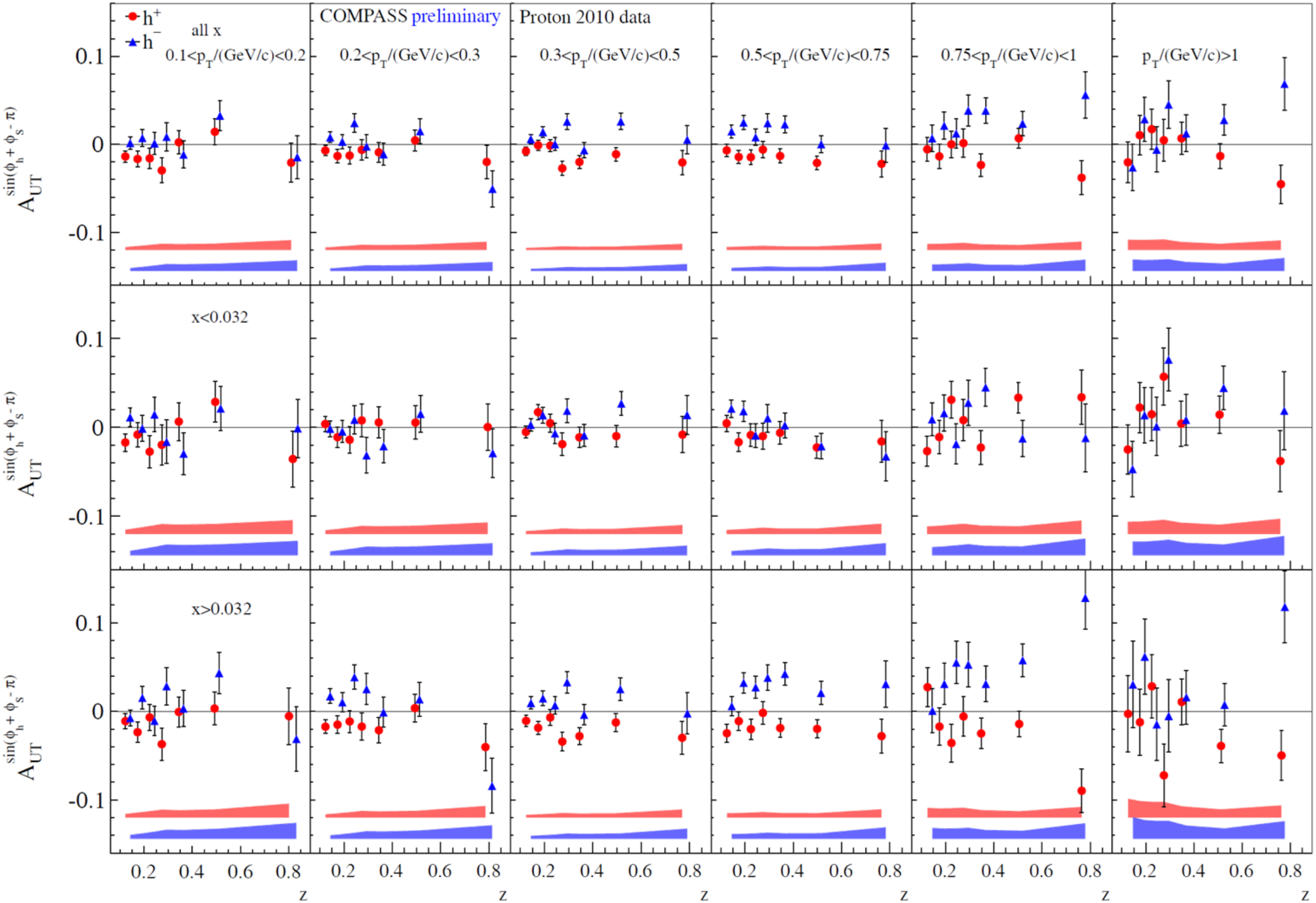
Collins asymmetry: 3D x-z-Q^2 dependence



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.**

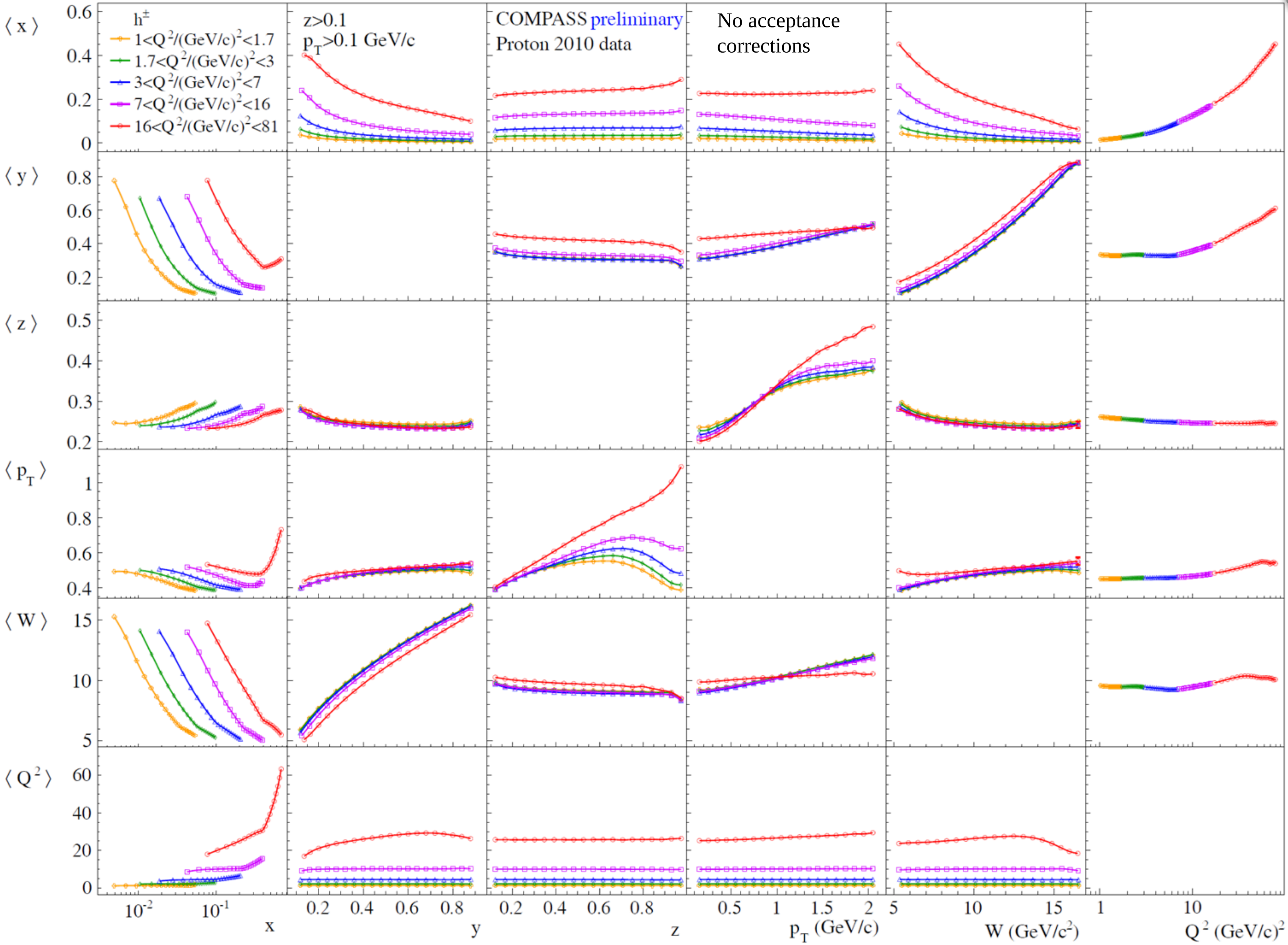
Collins asymmetry: 3D x-p_T-z dependence



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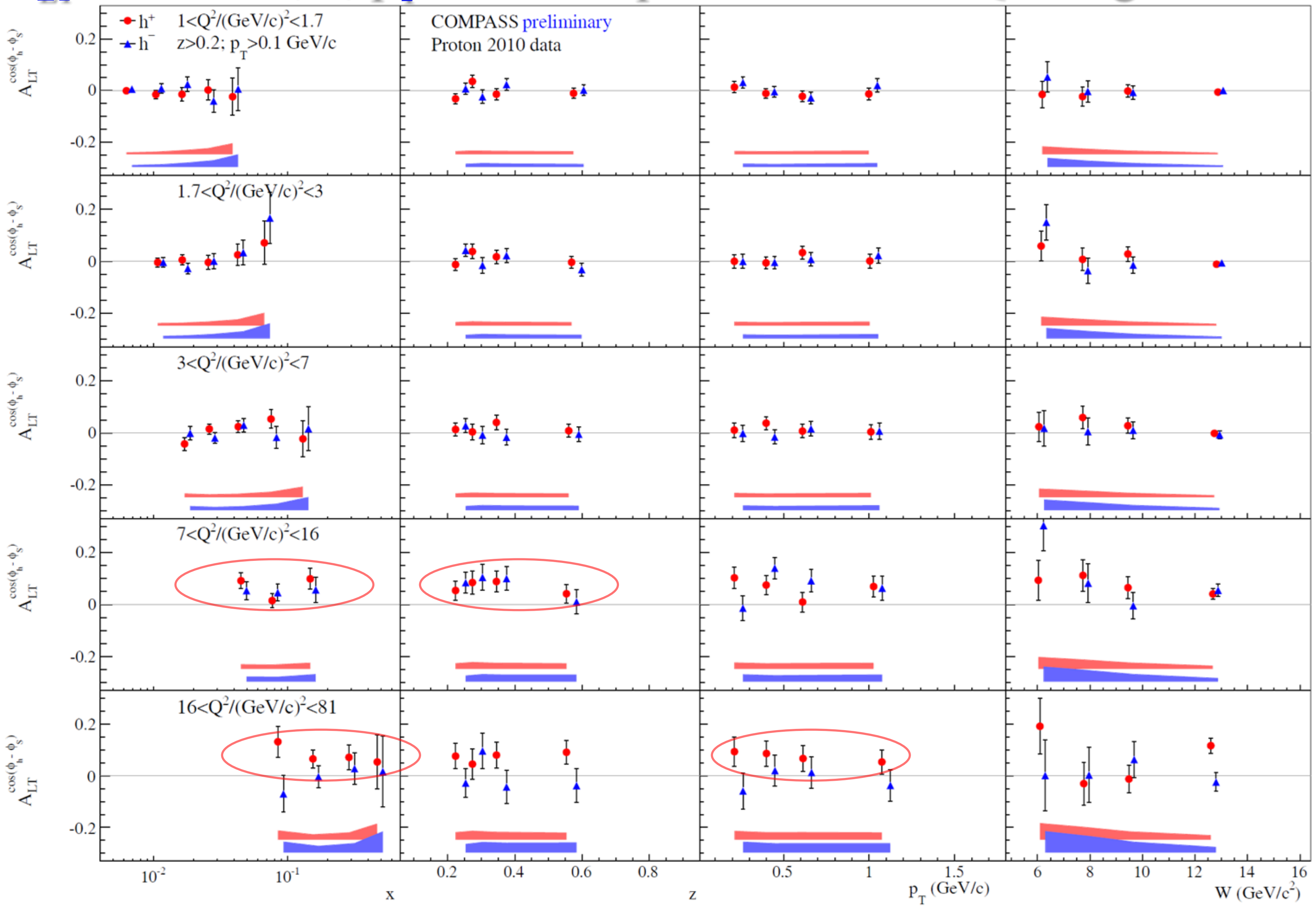
$A_{LT}^{cos(\phi_h-\phi_S)}$: x, z, p_T and W dependences in 5 Q^2-ranges

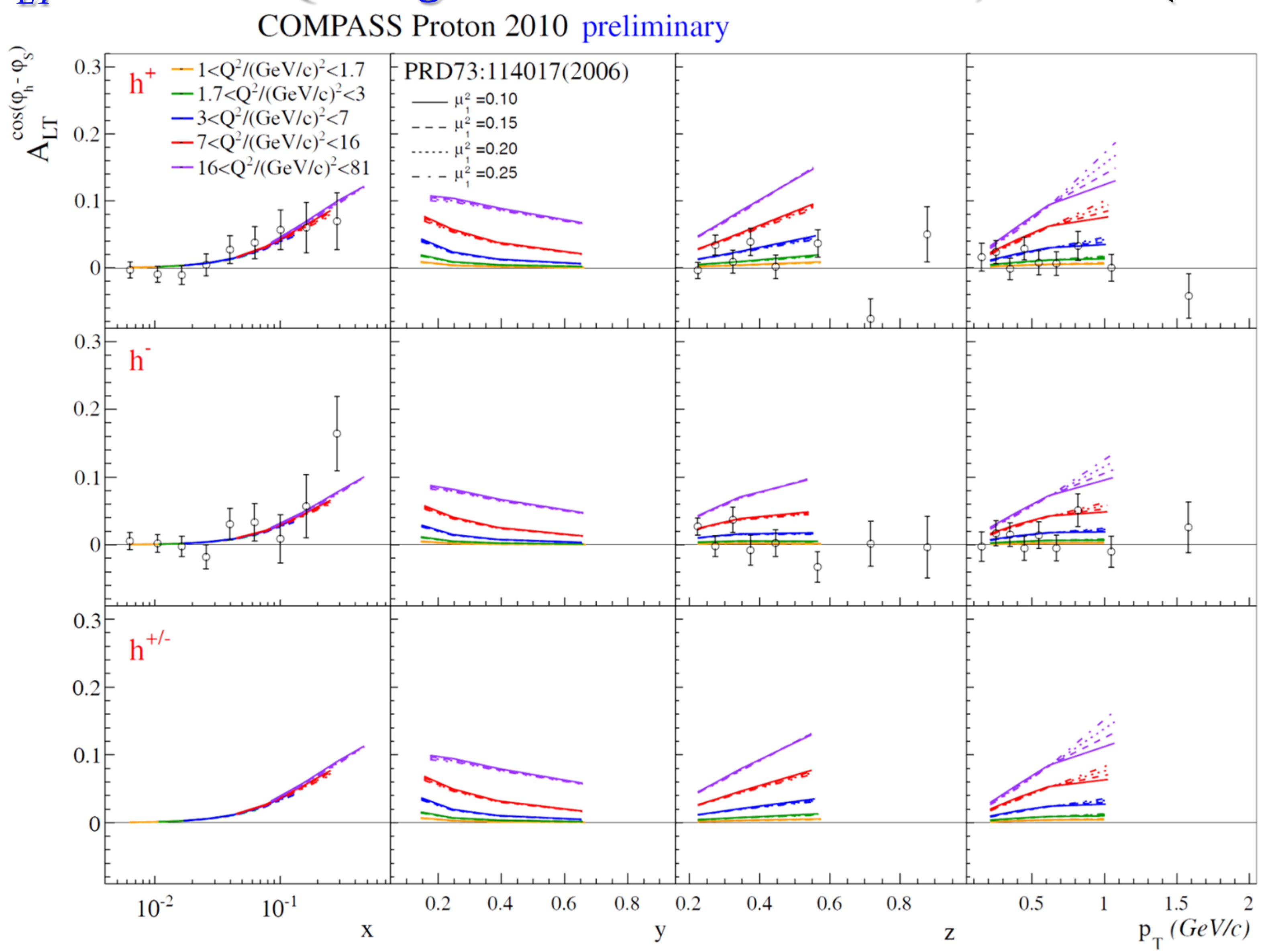


2D

- **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)

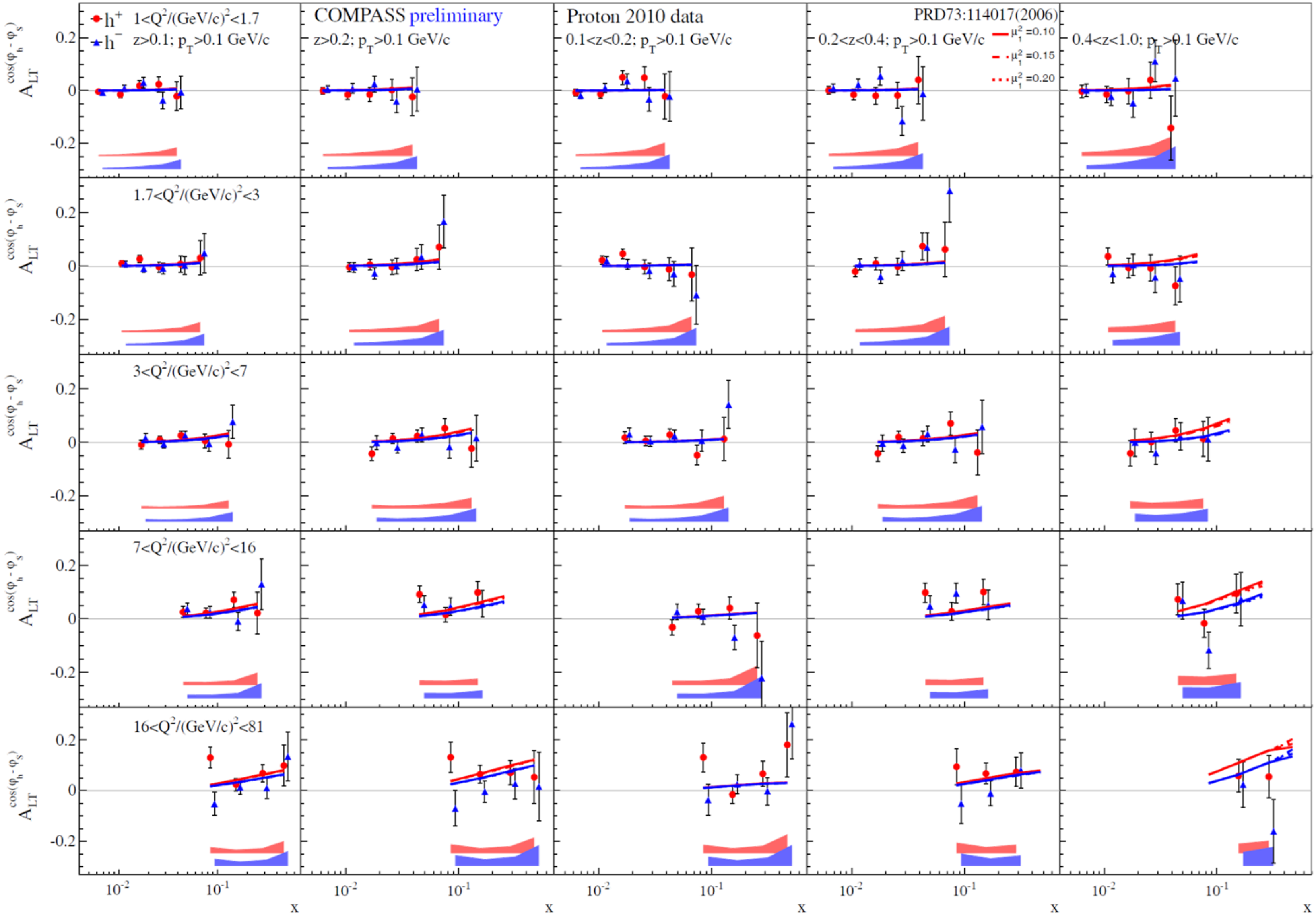
COMPASS



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 Q^2-z-x dependence: Predictions - PRD 73, 114017(2006)

COMPASS



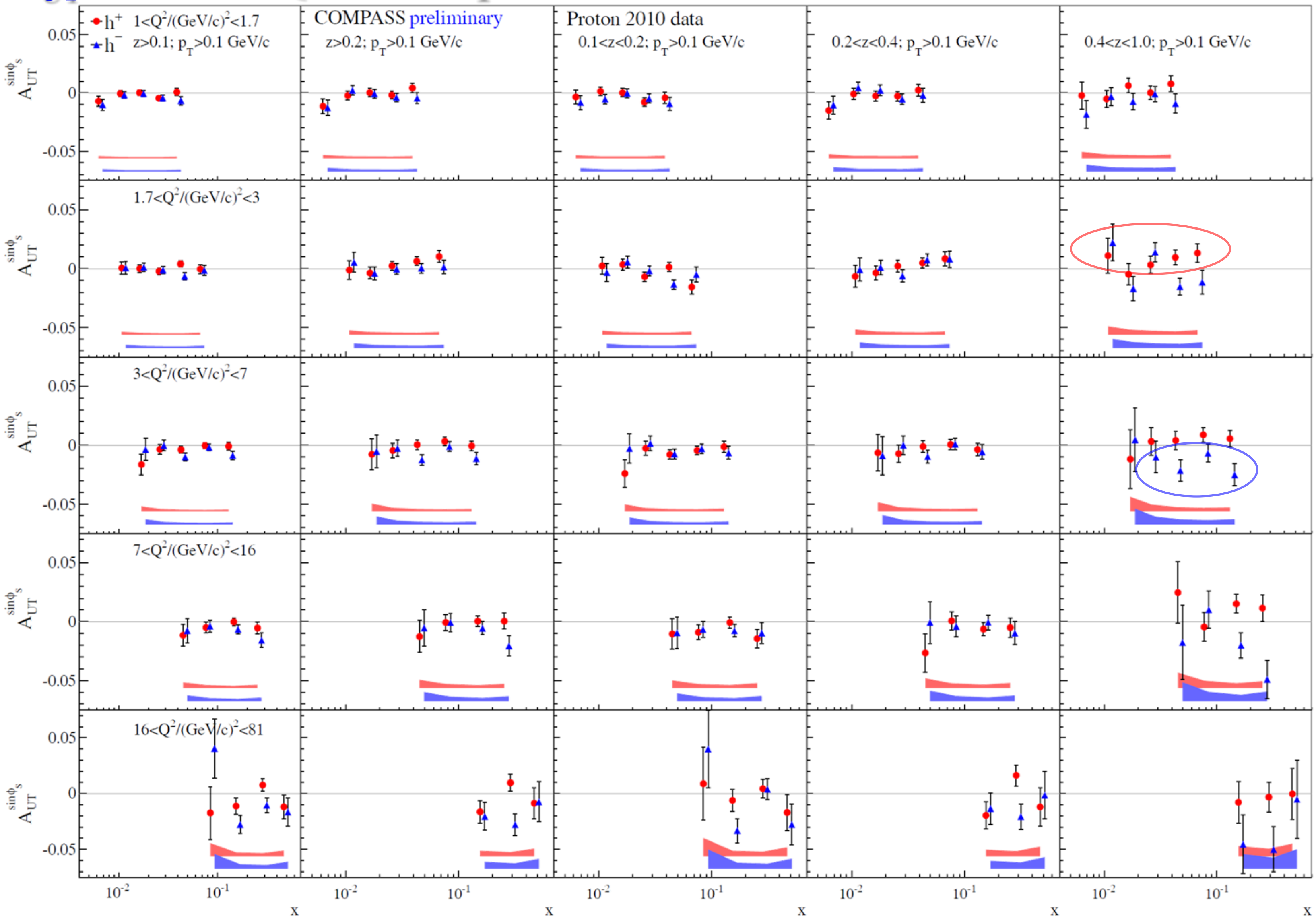
3D

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.

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
  - Sivers & Collins asymmetries
  - Beyond Sivers & Collins asymmetries
    - $A_{LT}^{\cos(\phi_h-\phi_s)}$ – 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

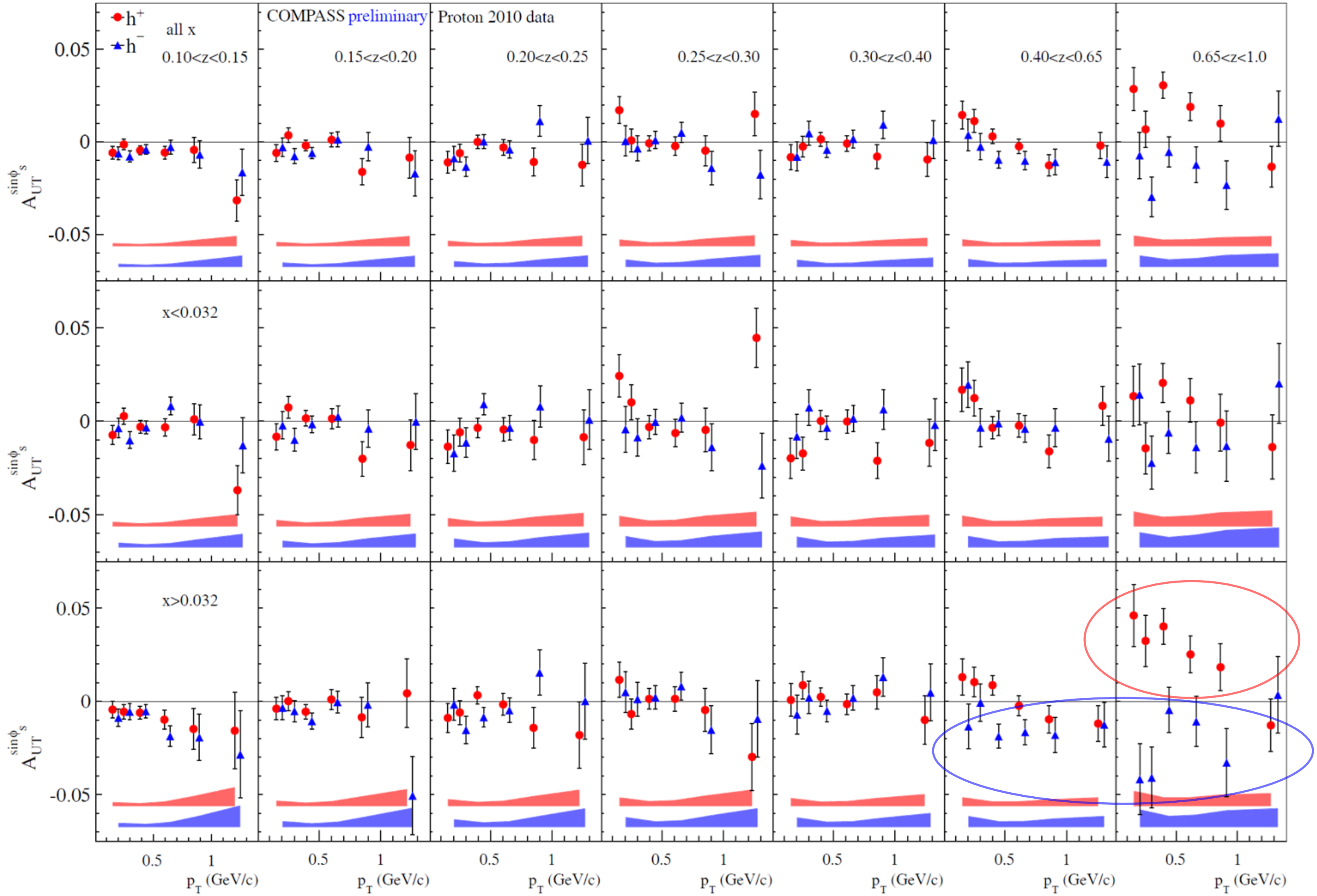
$A_{UT}^{\sin\phi_S}$: 3D Q^2-z-x dependence



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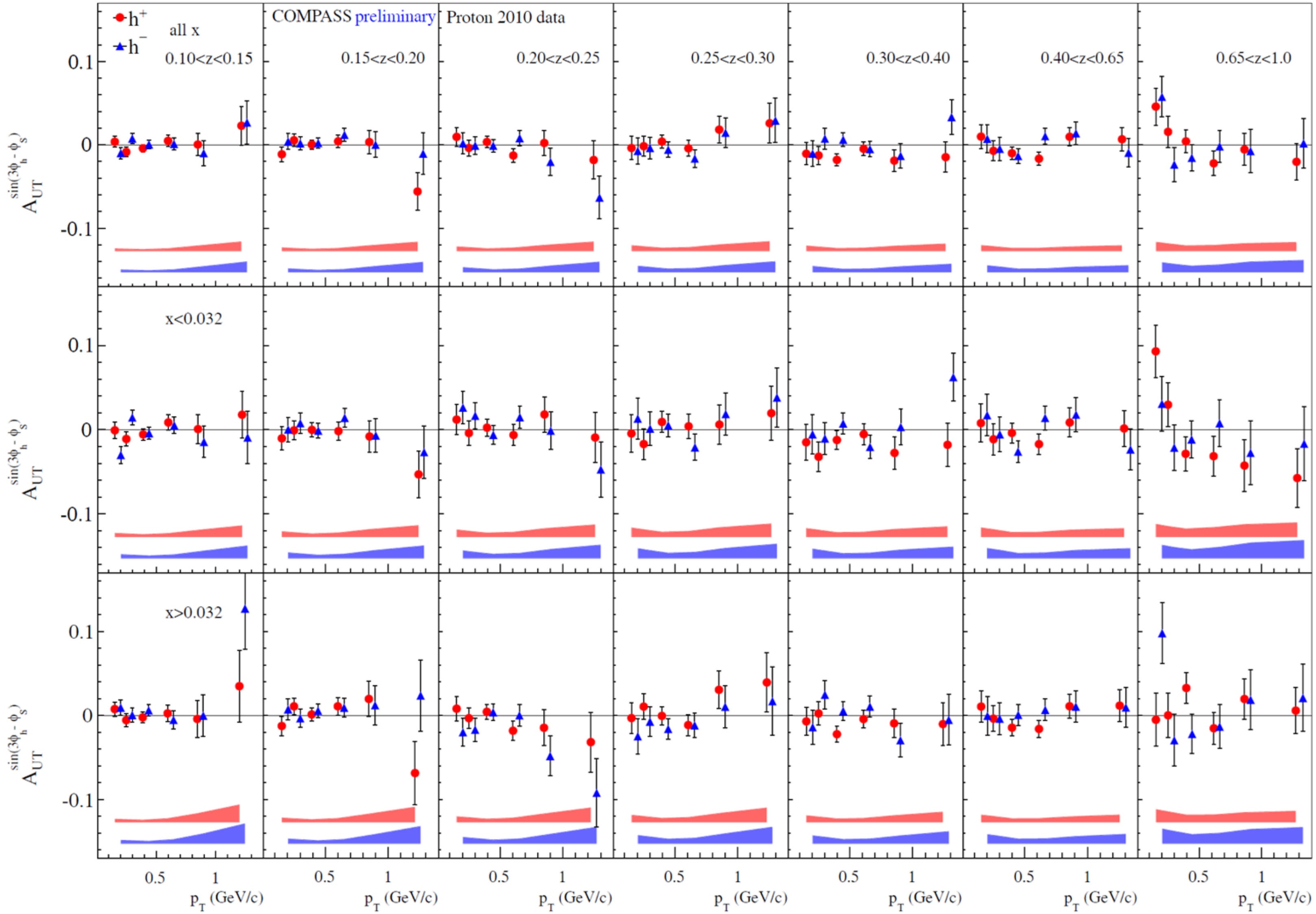
$A_{UT}^{\sin(3\phi_h-\phi_S)}$: 3D x-z-$p_T$ dependence



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

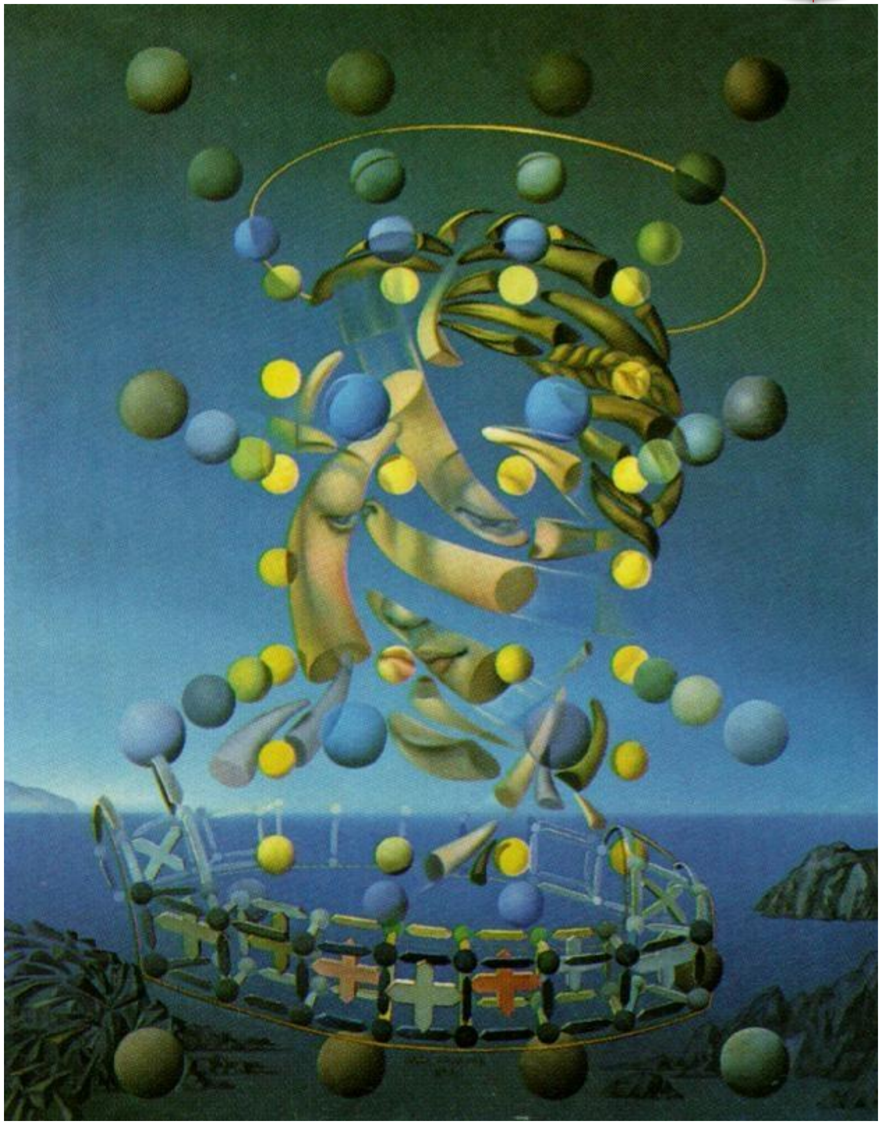
- First ever extraction of transverse spin asymmetries in multidimensional grids:
  - 2D – Q^2:x; Q^2:z; Q^2:p_T; Q^2:W
  - 3D – Q^2:z:x (x:z:Q^2); Q^2:p_T:x (x:p_T:Q^2)
  - 4D – z:Q^2:p_T:x; p_T:Q^2:z:x
  - 3D – x:z:p_T (x:p_T:z);
- TSAs for *unidentified* charged hadrons have been extracted from COMPASS 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”

Raphael *“Madonna del Prato”*

“1D”



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

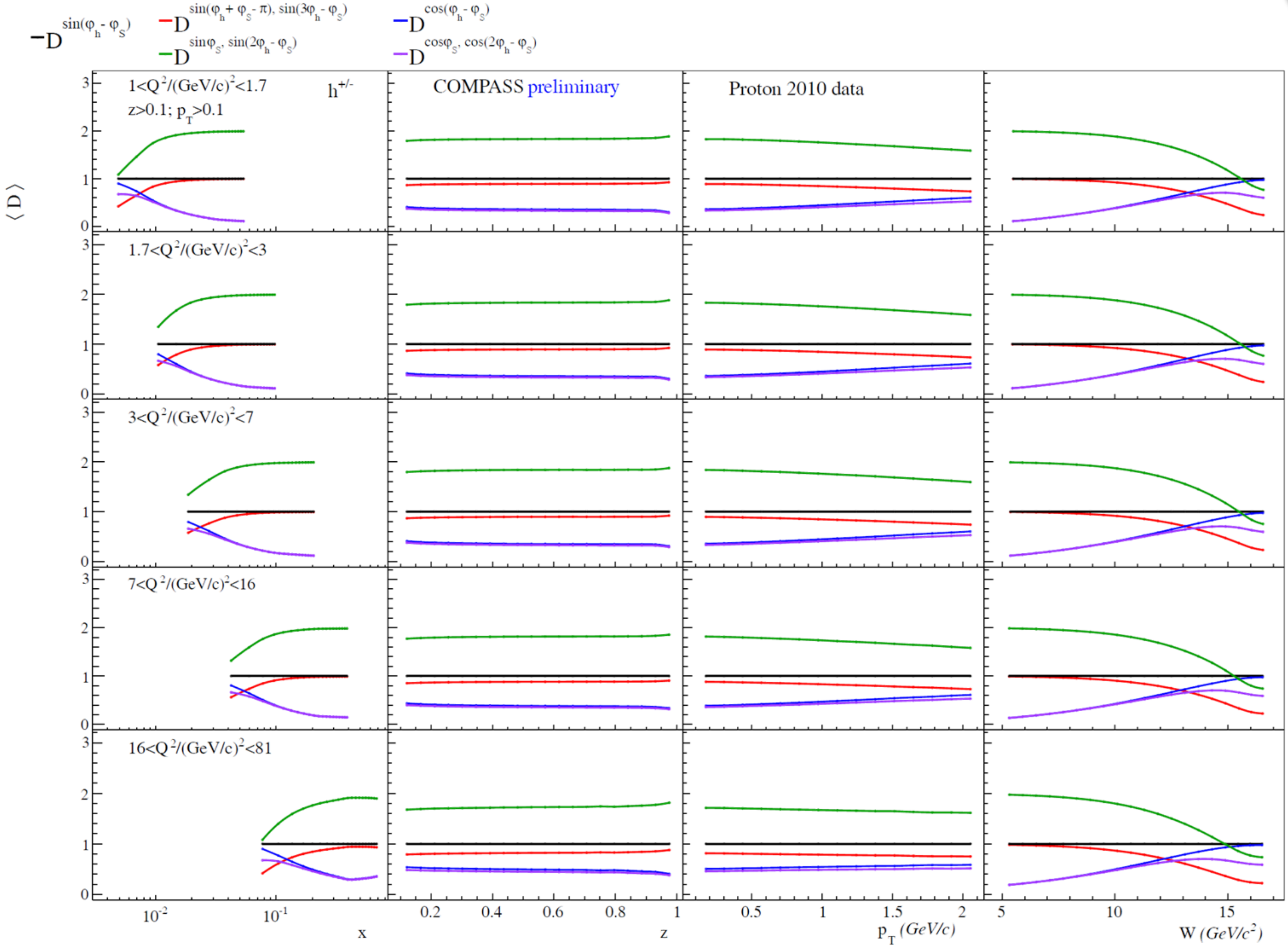
"Nature" *"multi-D" with available statistics*

Raphael *"Madonna del Prato"*

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

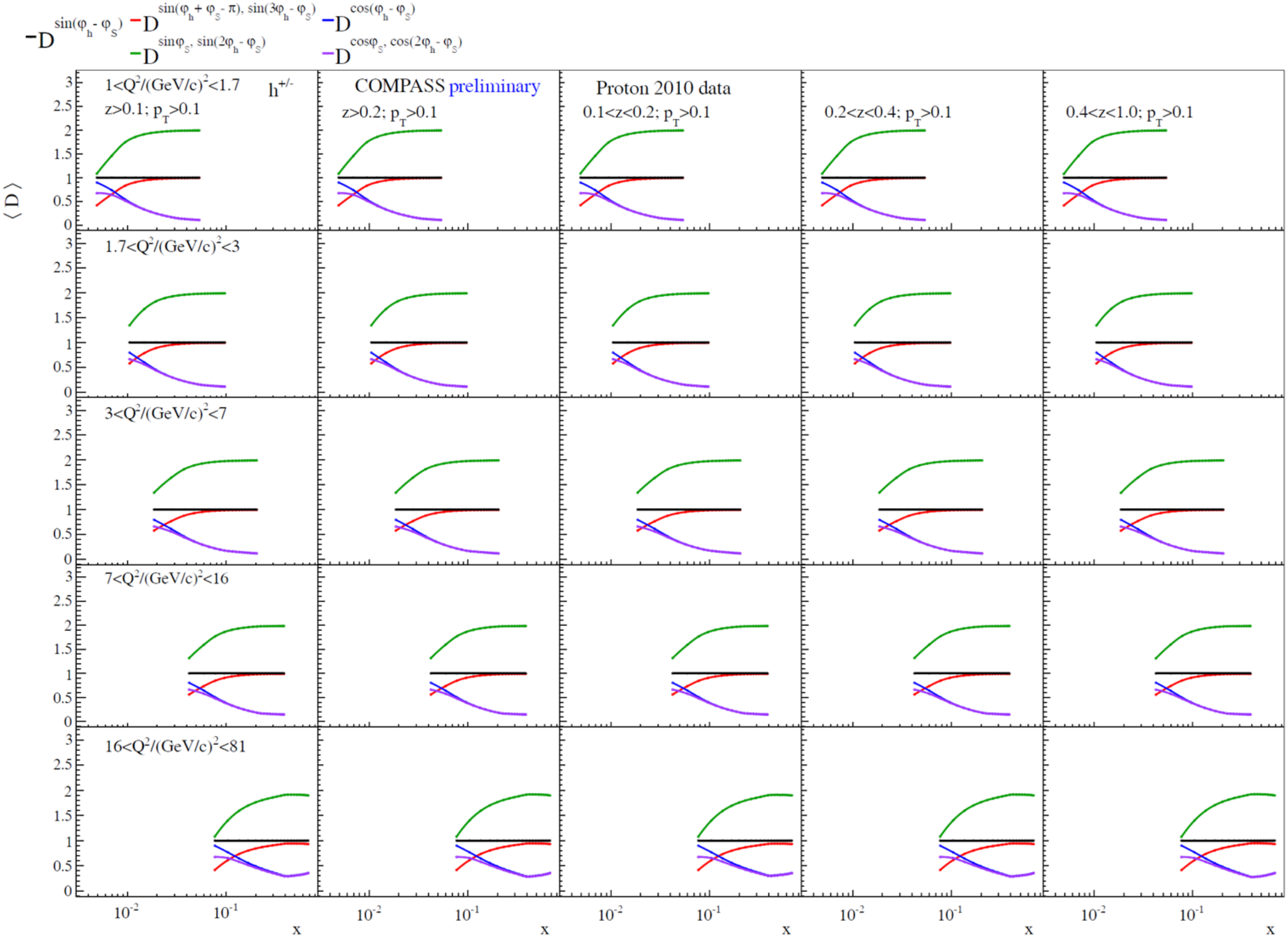
Spare slides

Mean D(y)-factors



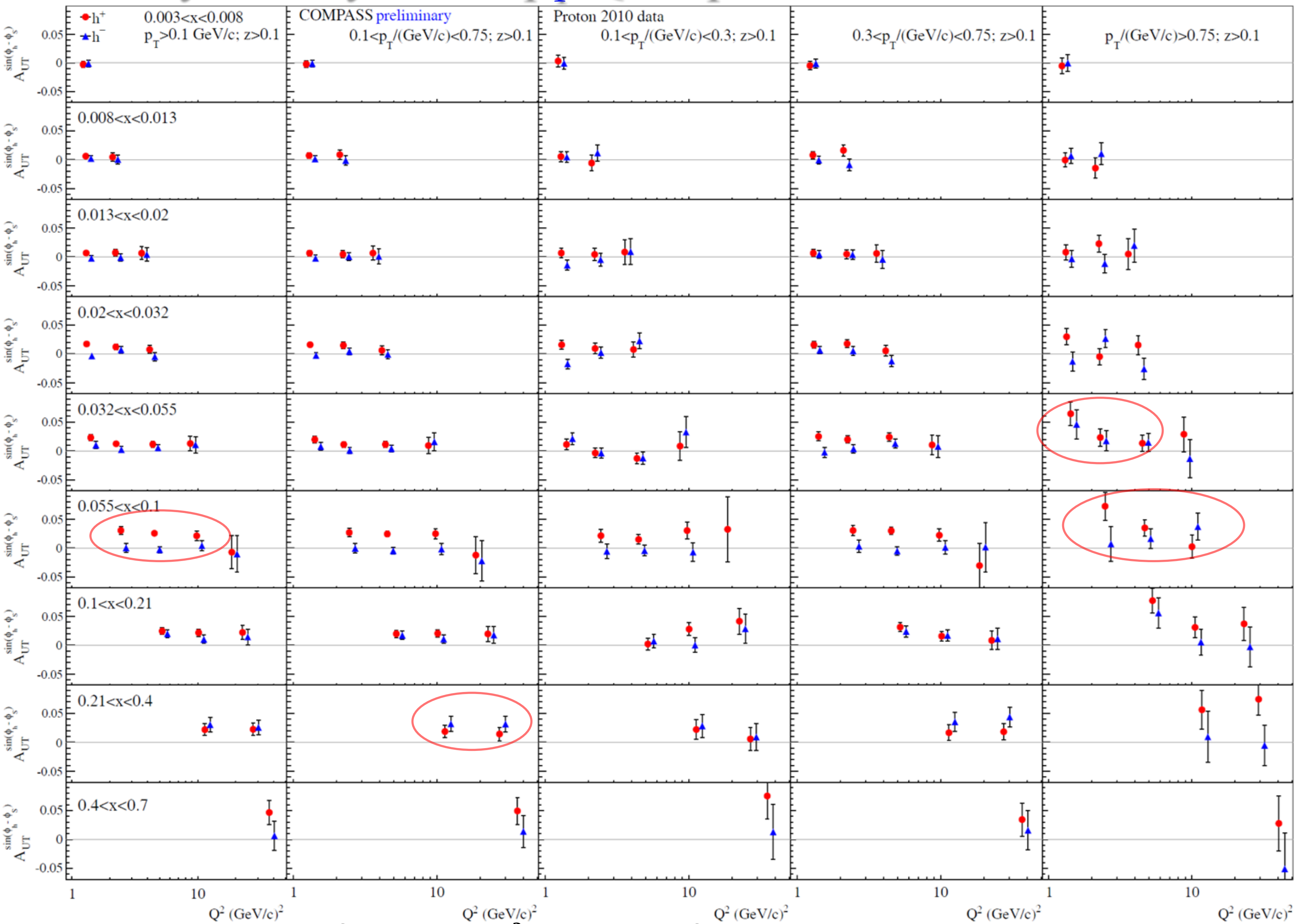
Mean D(y)-factors in 3D "Q²-z-x" grid

COMPASS



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

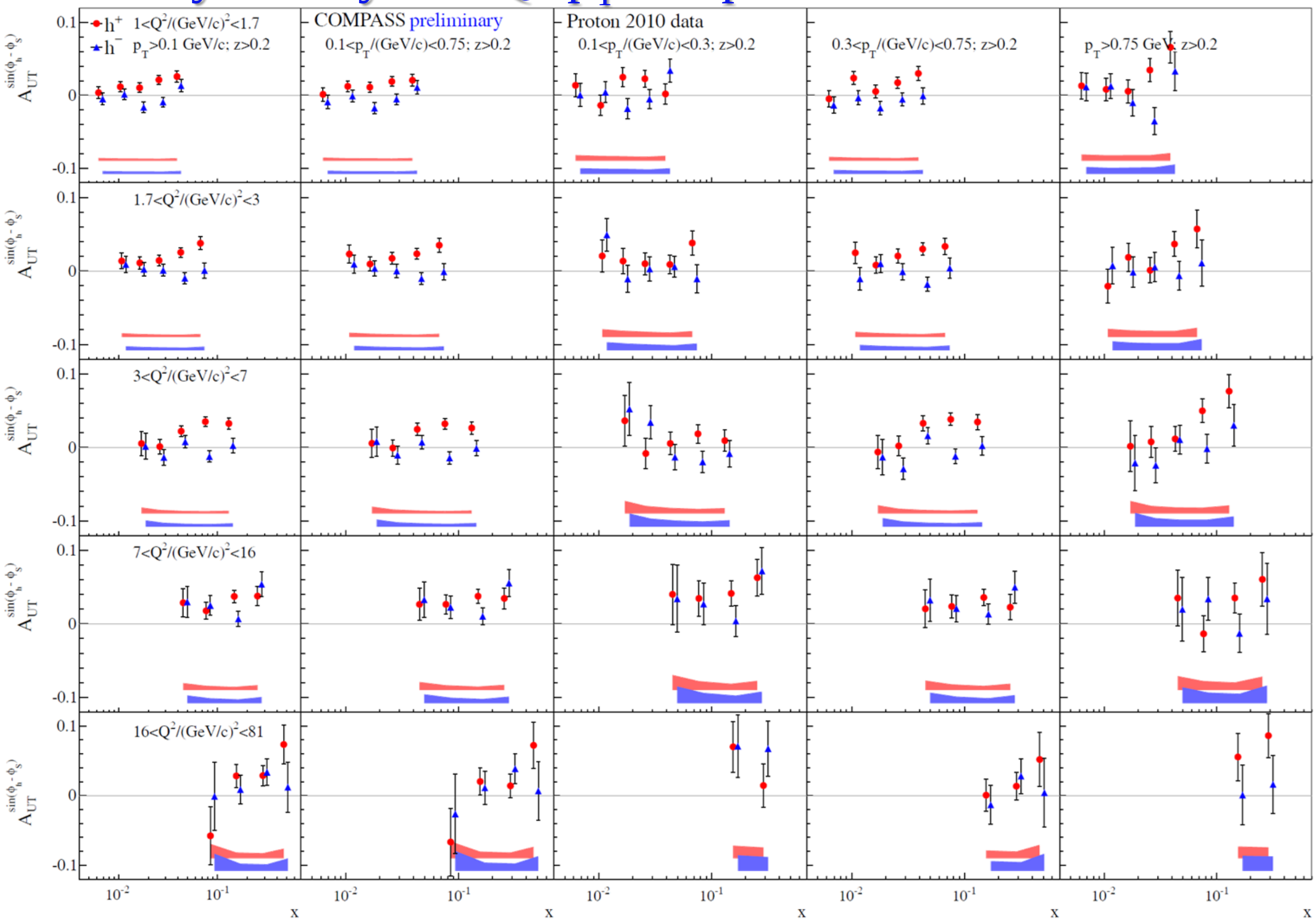
Sivers asymmetry: 3D x-p_T-Q^2 dependence



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**

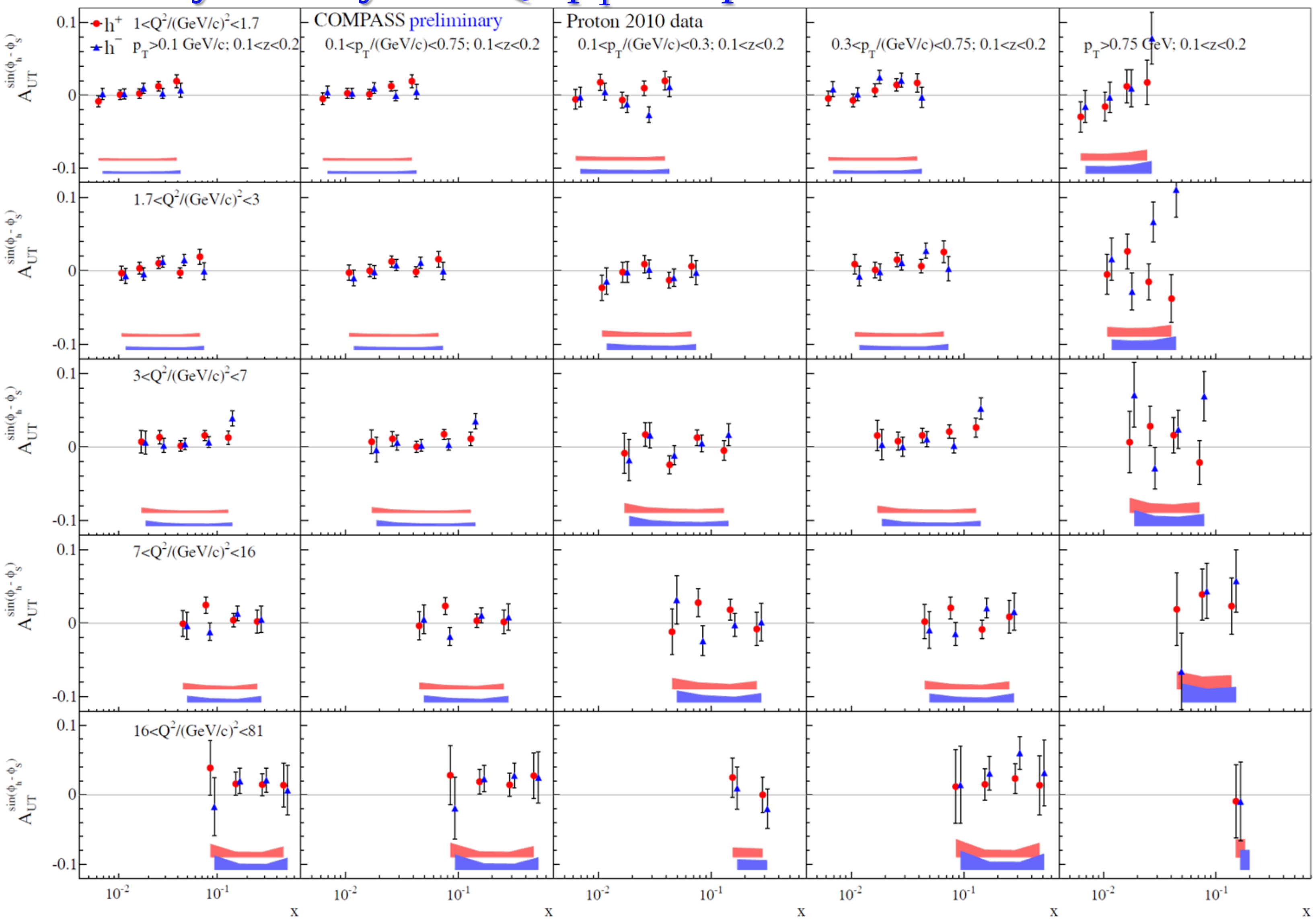
Sivers asymmetry: 4D Q^2-p_T-x dependence at z>0.2



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

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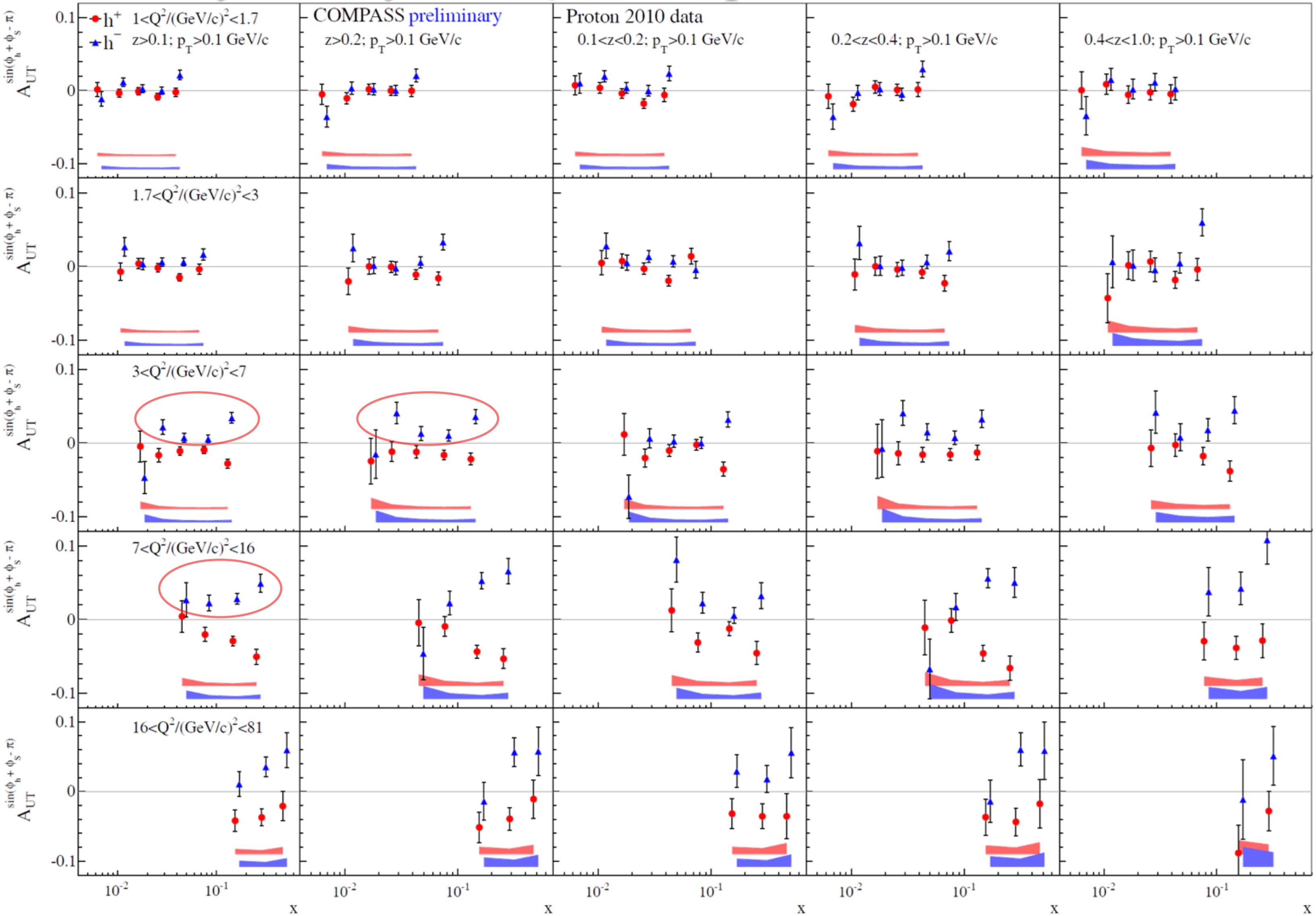
Collins asymmetry: 3D Q^2-z-x dependence



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.**

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

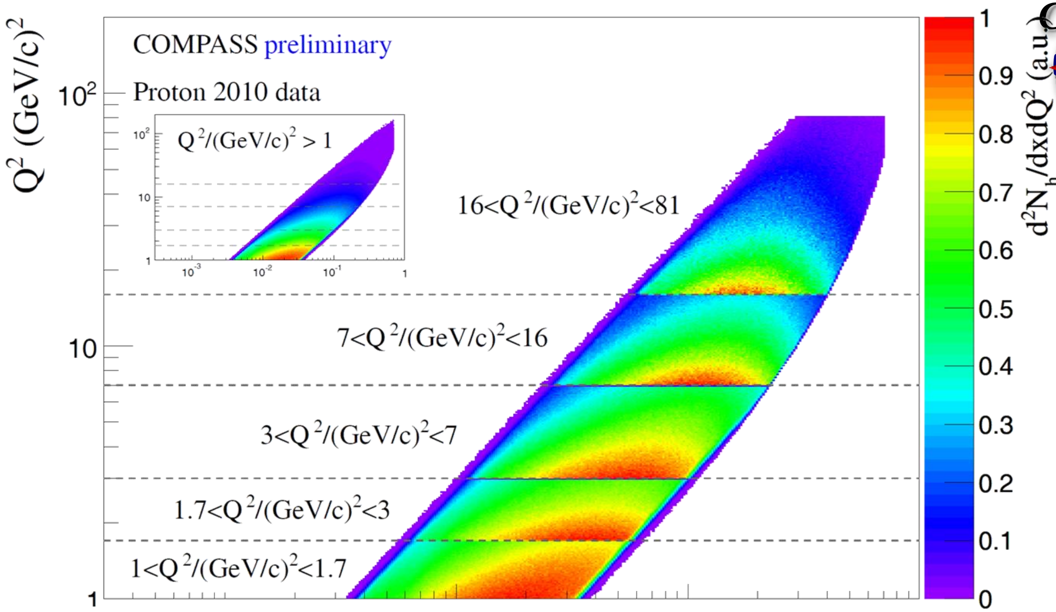
p_T ranges:
- $p_T > 0.1$
- $0.1 < p_T < 0.75$
- $0.1 < p_T < 0.3$
- $0.3 < p_T < 0.7$
- $p_T > 0.75$

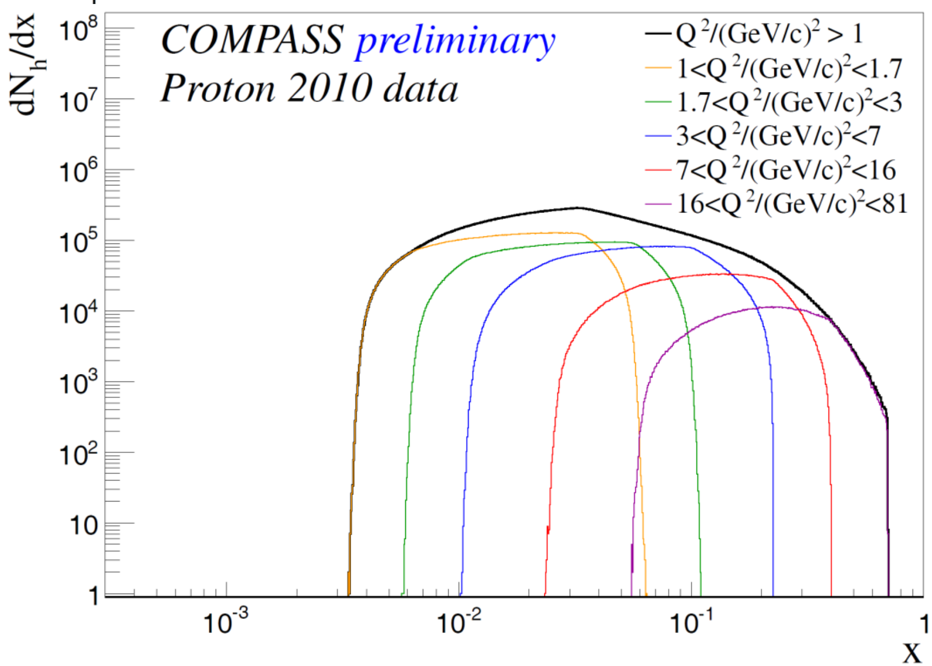
25 z-P_{hT} combinations

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

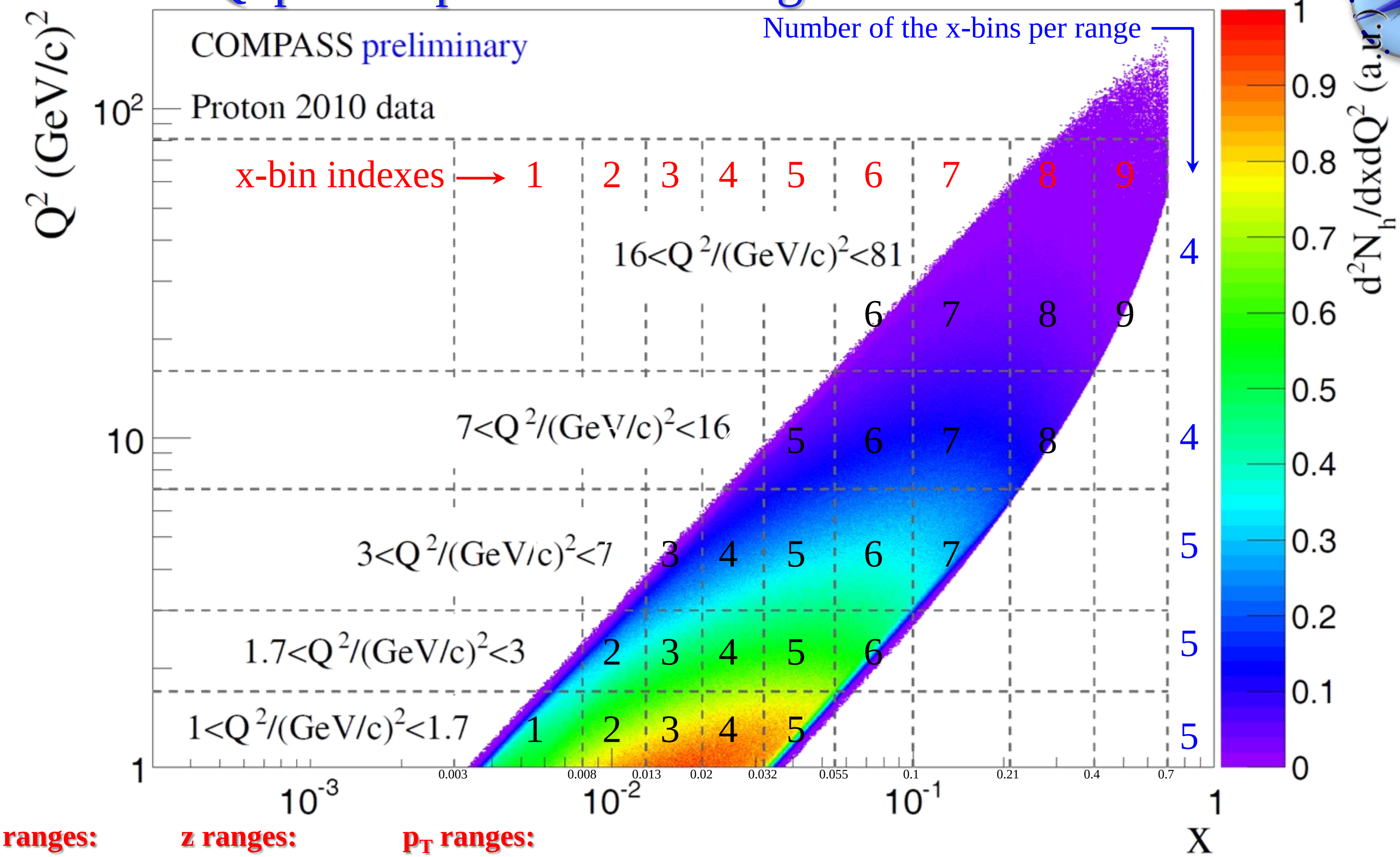
x bins:

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





Multi-D x:Q² phase-space and binning



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

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

x bins:

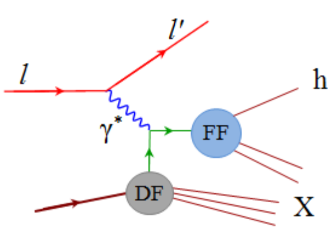
0.003, 0.008, 0.013, 0.02, 0.032, 0.055, 0.10, 0.21, 0.40, 0.7

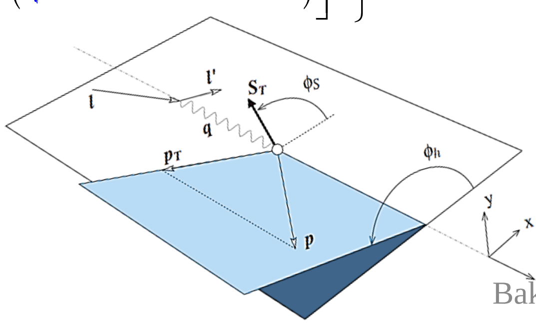
SIDIS x-section

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

$$\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

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





DY x-section

LO single polarized

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2}F_U^1\times$$

$$\left\{\begin{array}{l}
1+\cos^2\theta+\sin^2\theta\cos 2\varphi_{CS}A_U^{\cos 2\varphi_{CS}}\\
+S_T\left[\begin{array}{l}
\left(1+\cos^2\theta\right)\sin\varphi_S A_T^{\sin\varphi_S}\\
+\sin^2\theta\left(\begin{array}{l}
\sin(2\varphi_{CS}-\varphi_S)A_T^{\sin(2\varphi_{CS}-\varphi_S)}\\
+\sin(2\varphi_{CS}+\varphi_S)A_T^{\sin(2\varphi_{CS}+\varphi_S)}
\end{array}\right)
\end{array}\right]
\end{array}\right\}$$