TMD measurements at COMPASS

4th Workshop on the QCD Structure
of the Nucleon (QCD-N'16)

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on behalf of the COMPASS Collaboration

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

fixed target experiment at the CERN SPS

wide physics program carried on using both **muon** and hadron beam

luminosity: ~5 · 10^{32} cm^{-2} s^{-1}

beam intensity: $2 \cdot 10^8$ μ^+/spill (4.8s/16.2s)

beam momentum: 160 GeV/*c*

longitudinally polarized muon beam

deuteron (^{6}LID)
2002, 2003, 2004 — L/T

proton (NH_3)
2006 — L
2007 — L/T
2010 — T
2011 — L

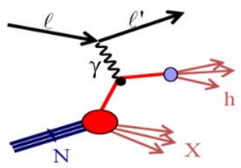
H_2 target
2012

hadron beam
nuclear targets — 2004
LH target — 2008, 2009, 2012
2014
T polarised DY — 2015

Transversely (T) or Longitudinally (L) polarised Target

Accessing Spin and TMD PDFs and FFs

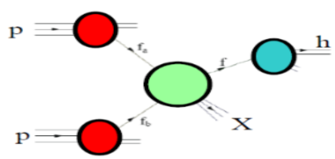
- SIDIS off polarized p, d, n targets



HERMES
COMPASS
JLab

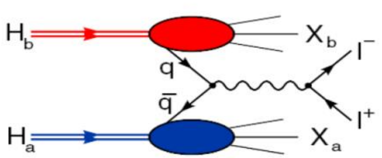
$$\sigma^{\ell p \to \ell' hX} \sim q(x) \otimes \hat{\sigma}^{lq \to lq} \otimes D_q^h(z)$$

- hard polarised pp scattering



RHIC

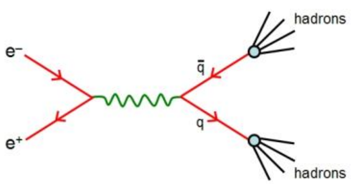
- polarised Drell-Yan



COMPASS
RHIC
FNAL

$$\sigma^{hp \to \mu\mu} \sim \bar{q}_h(x_1) \otimes q_p(x_2) \otimes \hat{\sigma}^{\bar{q}q \to \mu\mu}(\hat{s})$$

- $e^+e^- \to h_1 h_2$



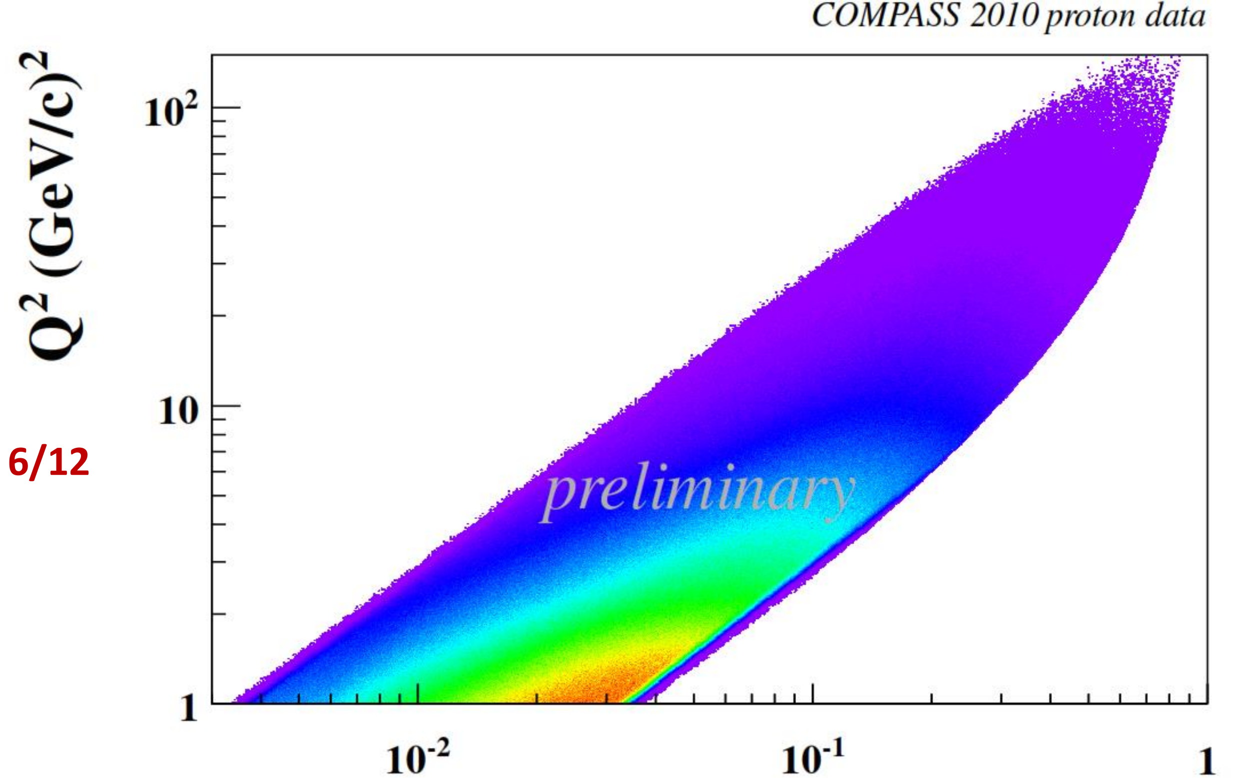
BaBar
Belle
Bes III

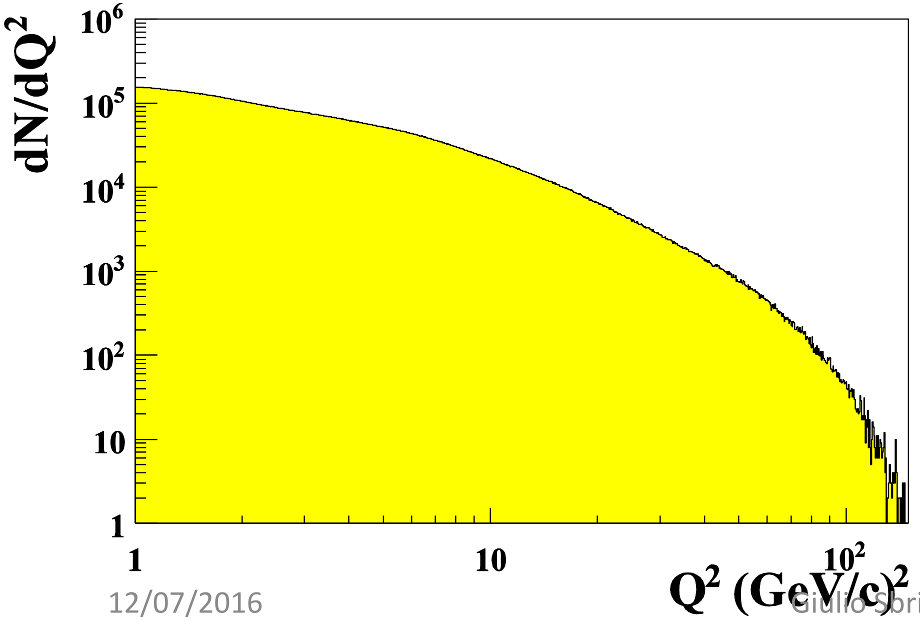
$$\sigma^{e^+e^- \to h_1 h_2} \sim \hat{\sigma}^{\ell\ell \to \bar{q}q}(\hat{s}) \otimes D_q^{h_1}(z_1) \otimes D_{\bar{q}}^{h_2}(z_2)$$

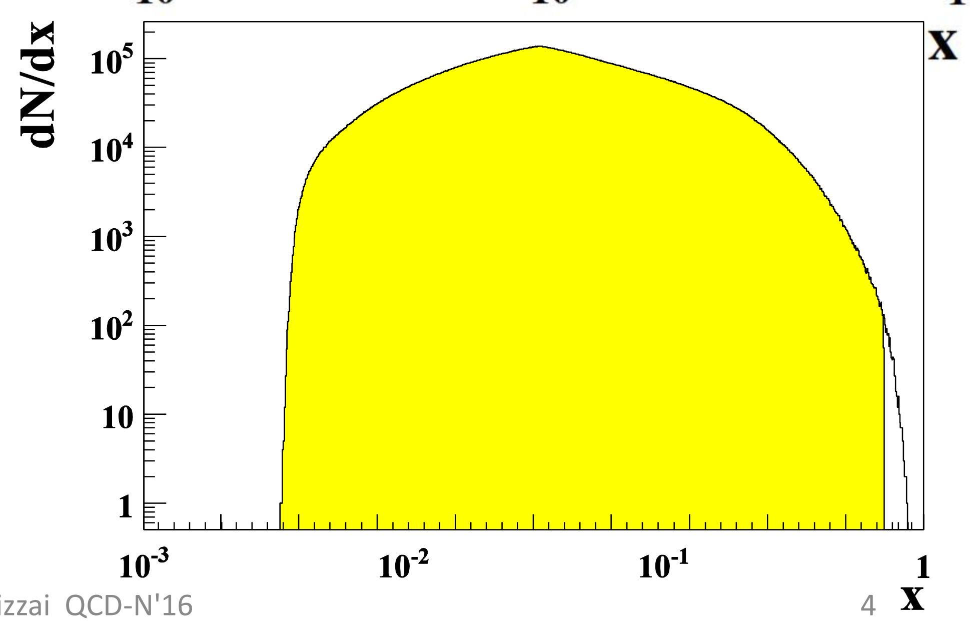
SIDIS event selection

Q2 > 1 (GeV/c)²
0.1 < y < 0.9
W > 5 GeV/c²

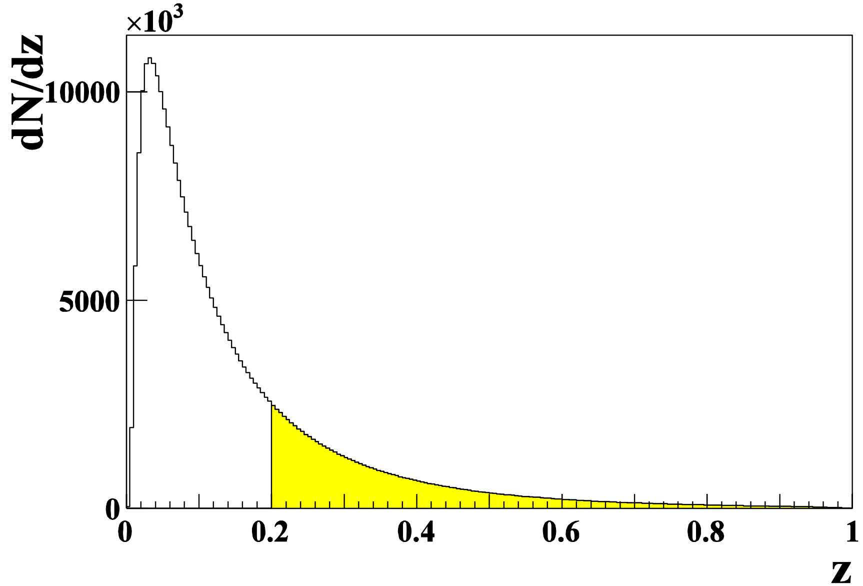
complementary to HERMES and Jlab 6/12

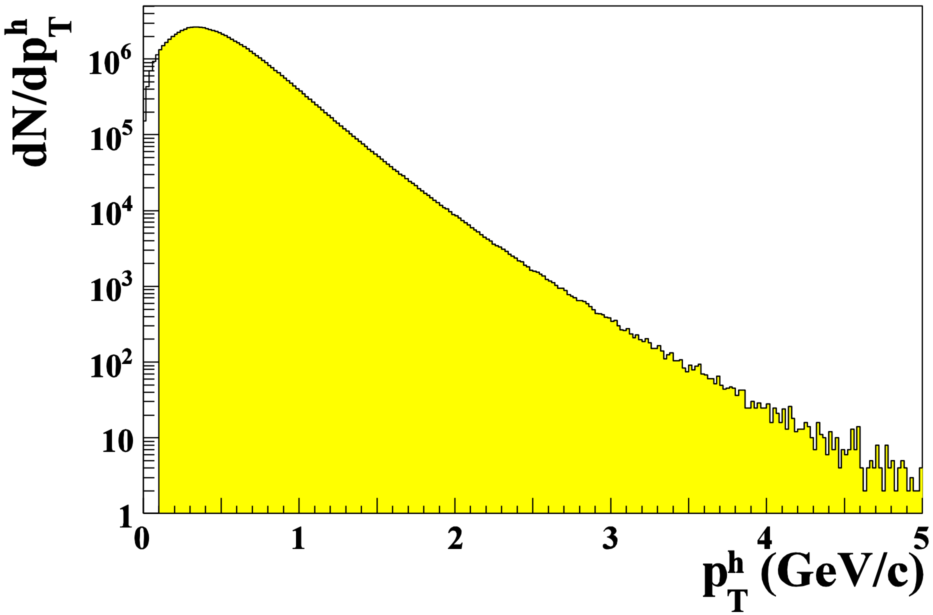






SIDIS event selection

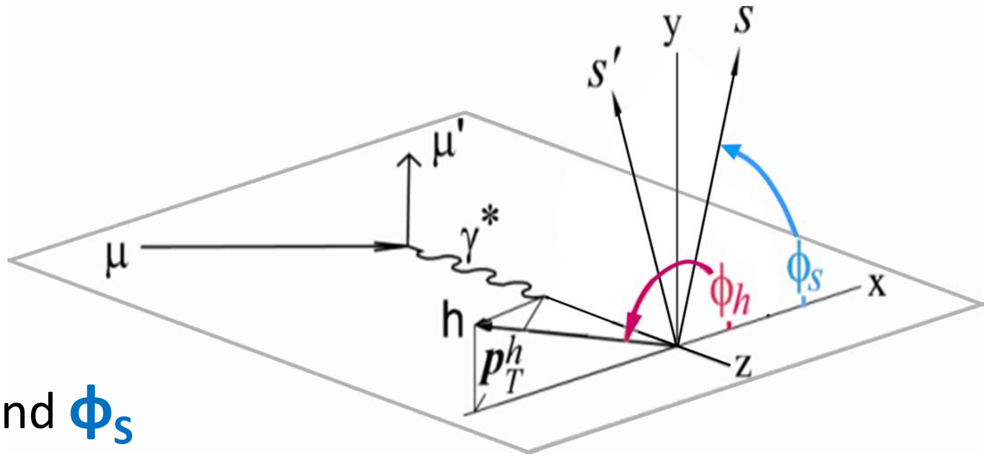




charged hadron selection

$z>0.2$

$p_t^h > 0.1$ GeV/c



definition of the produced hadron and target polarisation azimuthal angles **ϕ_h** and **ϕ_S**

polarised SIDIS azimuthal cross section

"one photon exchange approximation"

Bacchetta et al. JHEP 0702:093,2007

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&+S_\parallel\Big[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big]+S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big] \\
&+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) \\
&+\varepsilon\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
&+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},
\end{aligned}
$$

target polarisation

beam polarisation

*14 **independent modulations** in φ_h and φ_S*

polarised SIDIS azimuthal cross section

"one photon exchange approximation"

Bacchetta et al. JHEP 0702:093,2007

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

unpolarised part

$$+S_\parallel\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

$$+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

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

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

$$+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

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

target polarisation

transverse spin dependent part

beam polarisation

$$F=\sum_q PDF_q(x)\otimes FF_q^h(z)$$

OUTLINE

→ Hadron Transverse Momentum (P_T^h) dependent Multiplicities

→ Unpolarised Azimuthal Asymmetries (Boer-Mulders, Cahn effect)

Unpolarised SIDIS

→ Transverse Spin dependent Asymmetries

→ Collins, Sivers

→ P_T^h weighted Sivers asymmetries ***NEW***

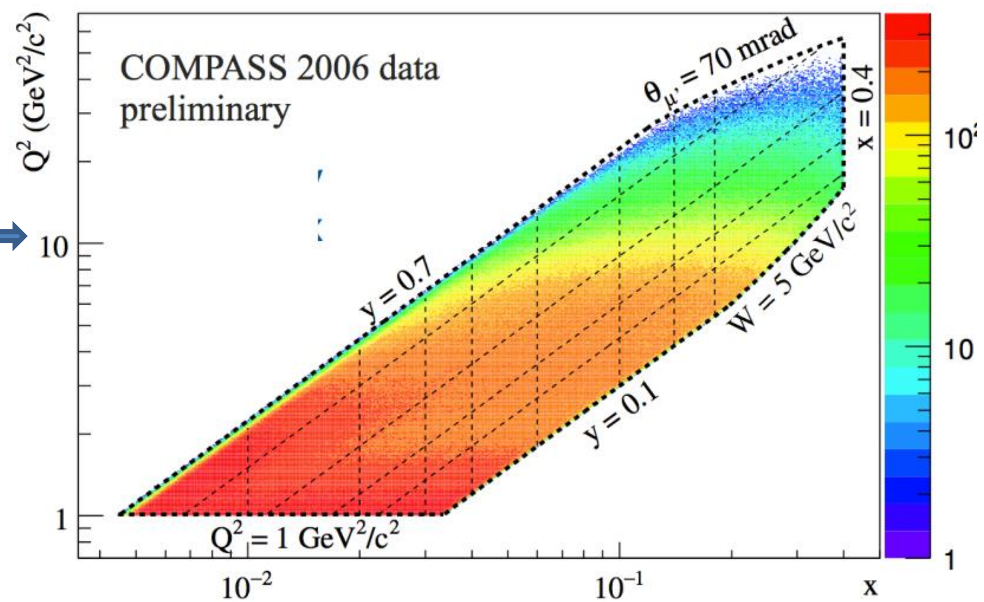
Polarised SIDIS

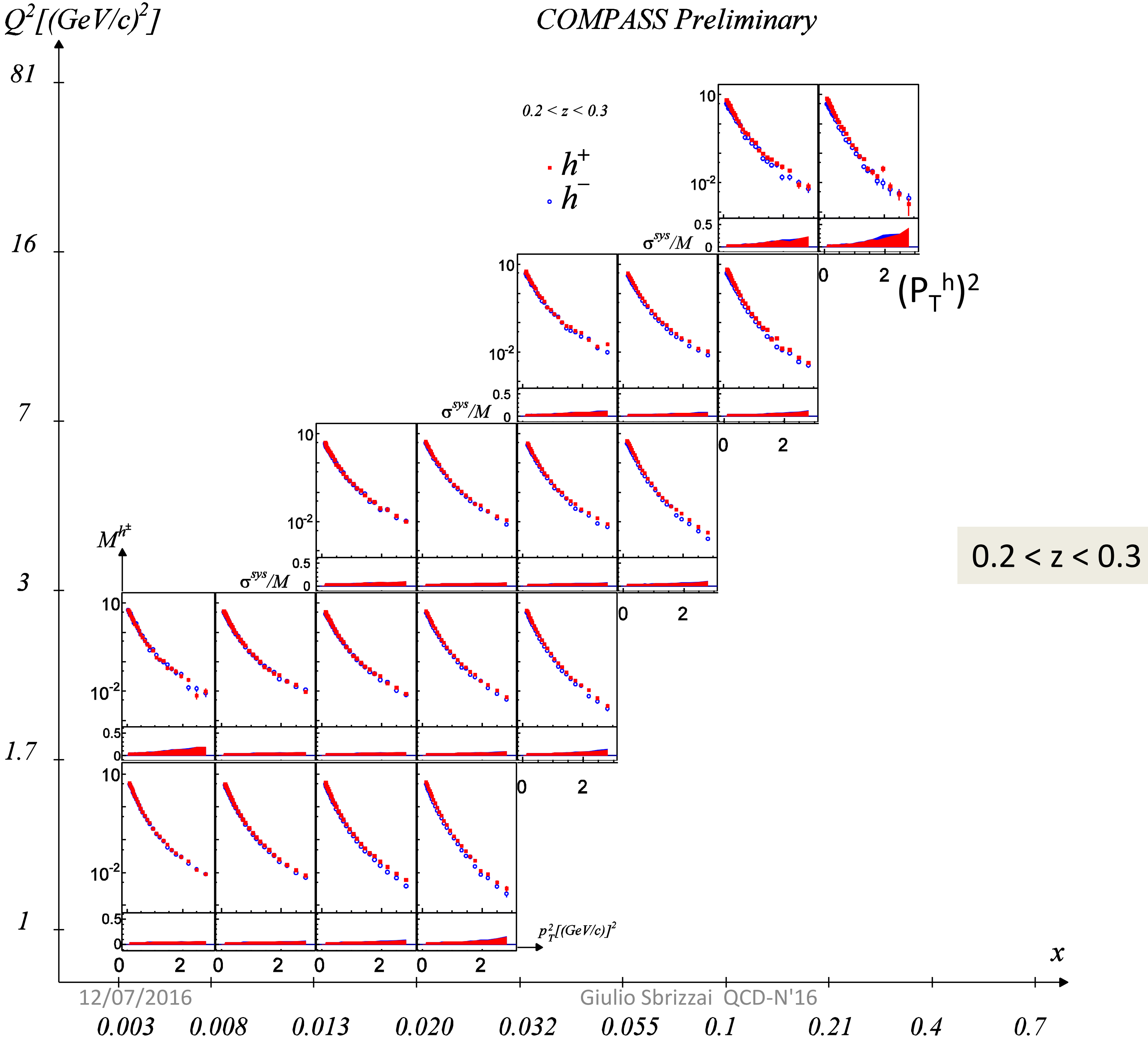
Unpolarised SIDIS

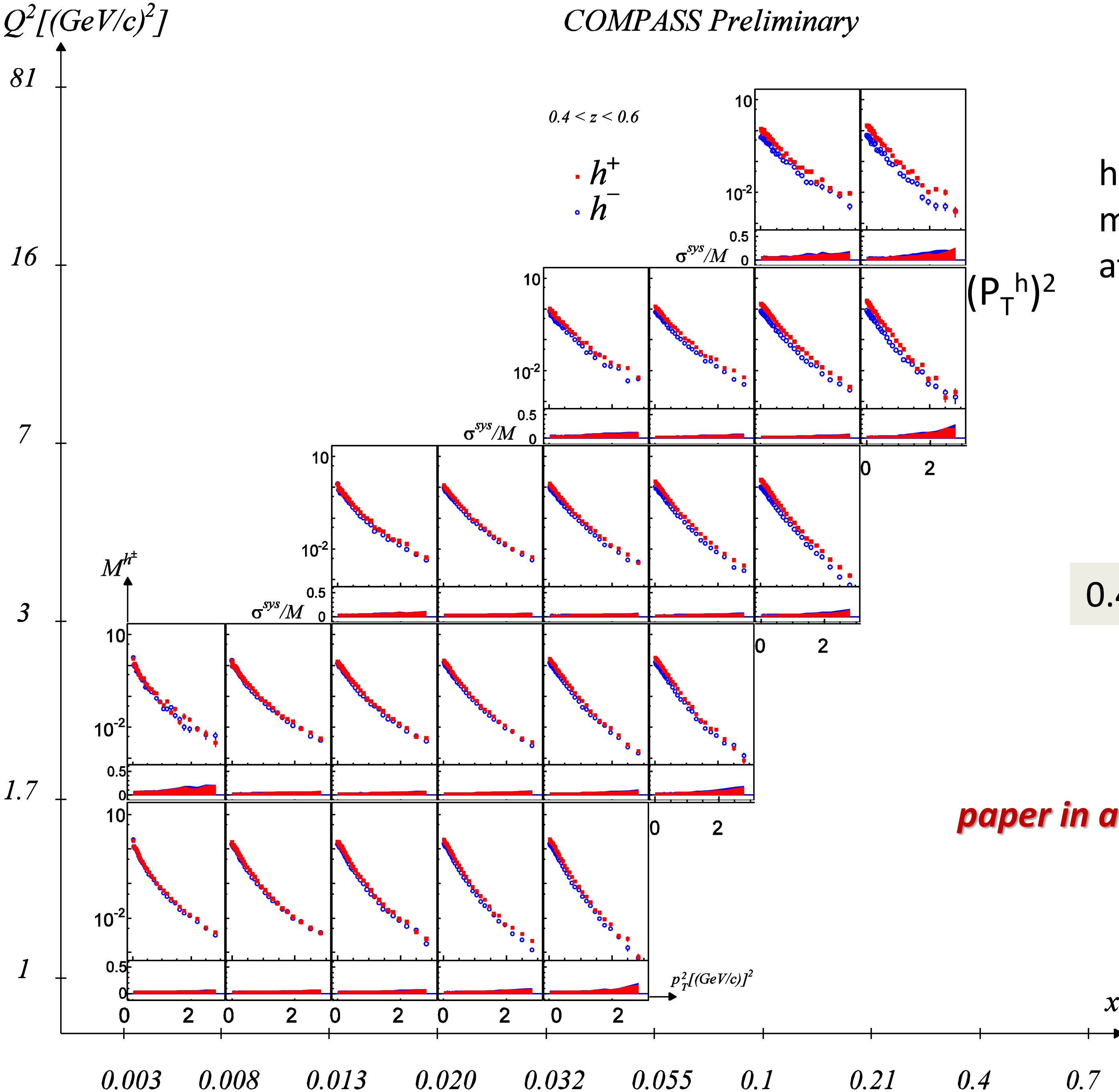
Relevance of unpolarised SIDIS for theTMDs

- The cross-section dependence from P_{hT} results from:
  - intrinsic $k_{\perp}$ of the quarks
  - $p_{\perp}$ generated in the quark fragmentation
  - A Gaussian ansatz for $k_{\perp}$ and $p_{\perp}$ leads to
  - $\langle P_{hT}^2 \rangle = z^2 \langle k_{\perp}^2 \rangle + \langle p_{\perp}^2 \rangle$

Results have been produced
from 2004/2006 deuteron data
multi dimensional analysis performed




COMPASS Preliminary
Q²[(GeV/c)²]
81
16
7
3
1.7
1
0.2 < z < 0.3
h⁺
h⁻
M^{h±}
σ^{sys}/M
(P_T^h)²
p_T²[(GeV/c)²]
x
0.003
0.008
0.013
0.020
0.032
0.055
0.1
0.21
0.4
0.7
0.2 < z < 0.3



h+ / h- difference more pronounced at large x and large z

0.4 < z < 0.6

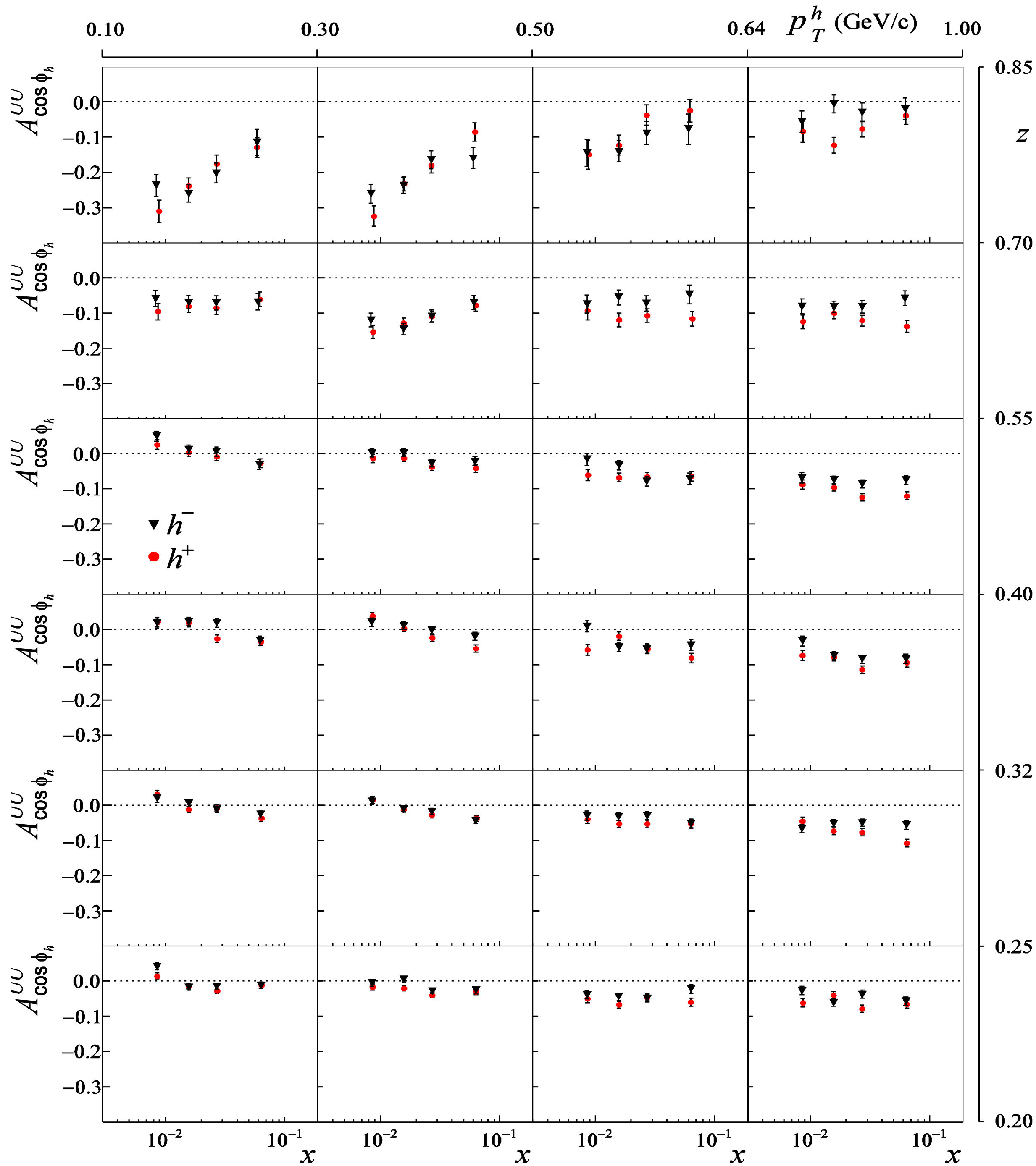
paper in a few months

Unpolarised Azimuthal Asymmetries measured from 2004 deuteron data

$$A^{UU}_{\cos\phi_h} \approx \frac{1}{Q} Cahn + \frac{1}{Q} BM$$

convoluted with the Collins FF

multiD performed both on **cosϕ** → and **cos2ϕ**

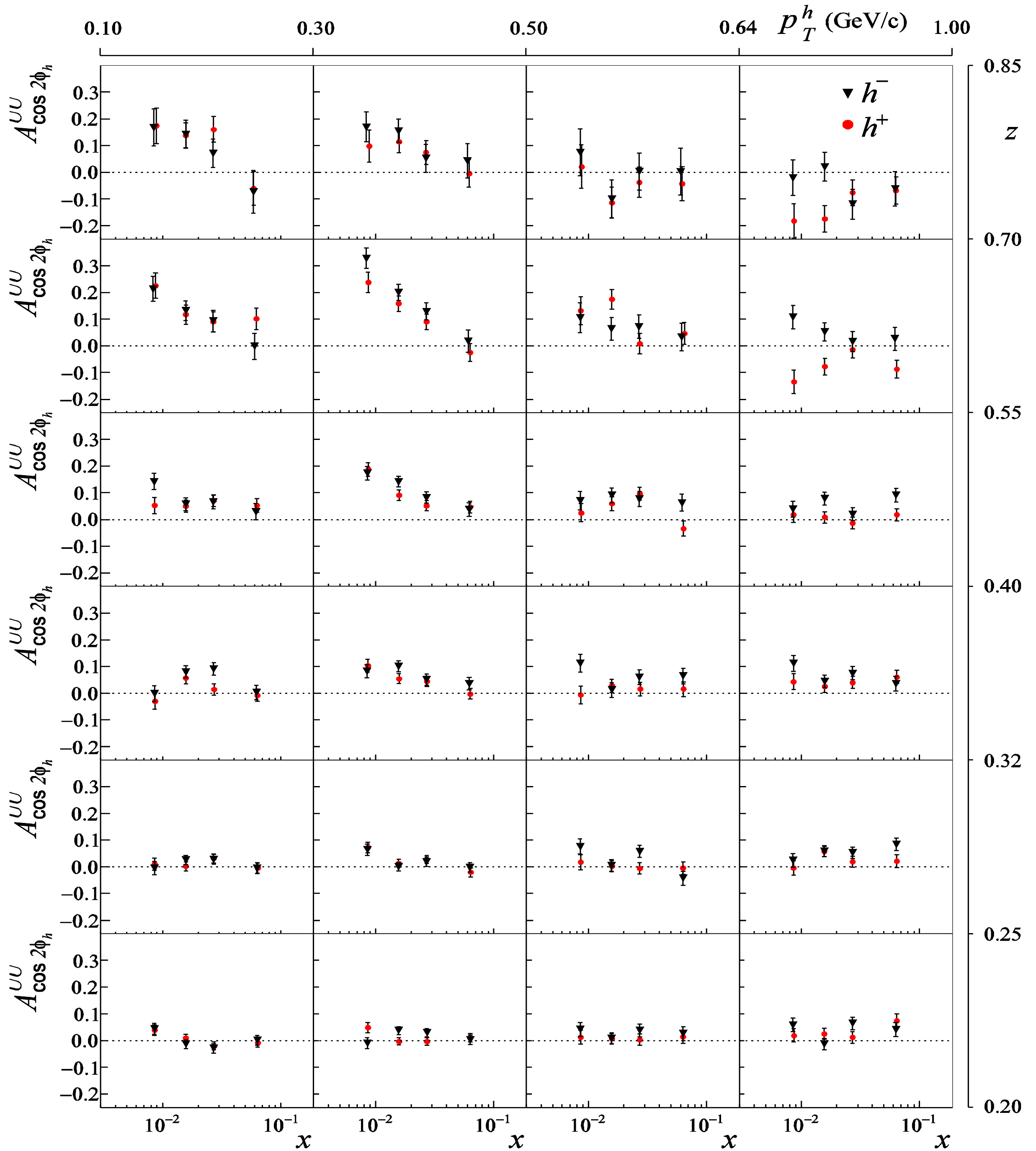


Unpolarised Azimuthal Asymmetries measured from 2004 deuteron data

$$A^{UU}_{\cos 2\phi_h} \approx \frac{1}{Q^2} Cahn + BM$$

convoluted with the Collins FF

multiD performed both on **cosϕ** and **cos2ϕ**



Polarised SIDIS

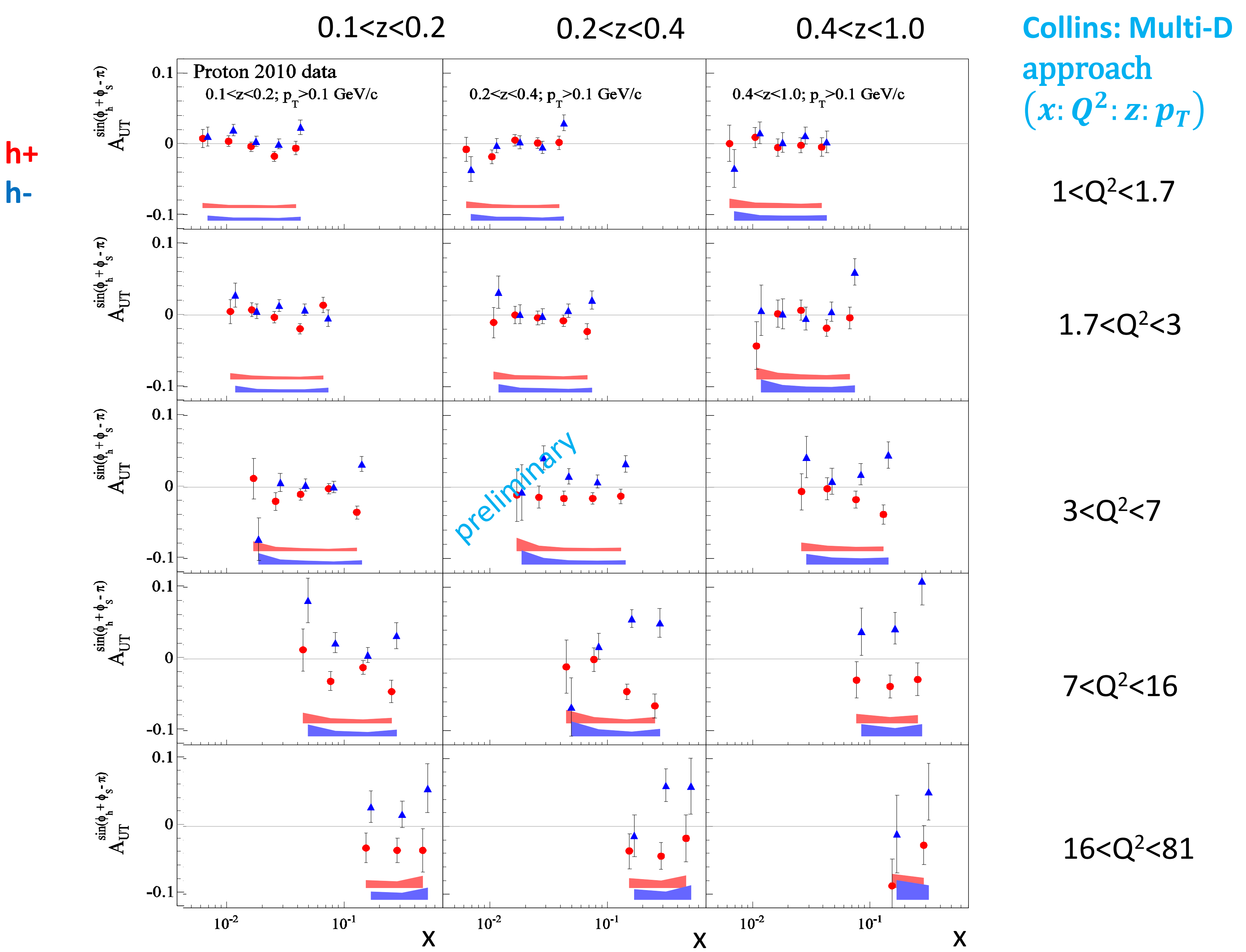
The Collins asymmetry

- *results on deuteron (2002-2004 data) compatible with zero*
  HERMES p + COMPASS p&d + BELLE → extraction of transversity for u and d quarks

- combined **2007** - PLB 692 (2010) 240 - and **2010** - PLB 717 (2012) 376 - PLB 744 (2015) 250
  published measurements on transversely polarised proton
  very good agreement between two independent data set

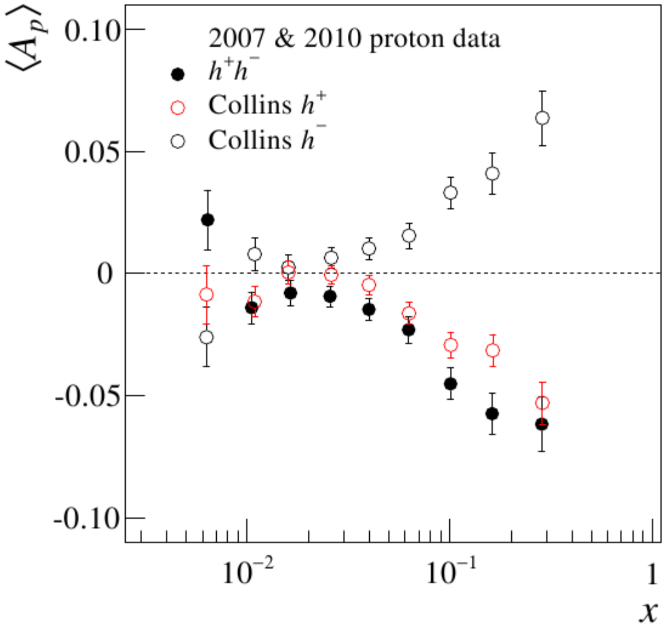
- multi dimensional analysis

- **more recent:**
  - **comparison with di-hadron asymmetries → interplay**



0.1<z<0.2
0.2<z<0.4
0.4<z<1.0
Collins: Multi-D approach
$(x: Q^2: z: p_T)$
h+
h-
Proton 2010 data
0.1<z<0.2; p$_T$>0.1 GeV/c
0.2<z<0.4; p$_T$>0.1 GeV/c
0.4<z<1.0; p$_T$>0.1 GeV/c
$A_{UT}^{\sin(\phi_h+\phi_s-\pi)}$
0.1
0
-0.1
10^{-2}
10^{-1}
x
preliminary
$1<Q^2<1.7$
$1.7<Q^2<3$
$3<Q^2<7$
$7<Q^2<16$
$16<Q^2<81$

Interesting studies comparing with the Di-hadron Transverse Spin Asymmetries



$$lN \rightarrow l'h^+h^-X$$

$$A_{UT}^{\sin\phi_{RS}} \approx \frac{\sum_q e_q^2 \cdot h_1^q(x) \cdot H_{1q}^{\angle}(z, M_{hh}^2)}{\sum_q e_q^2 \cdot f_1^q(x) \cdot D_{1q}^h(z, M_{hh}^2)}$$

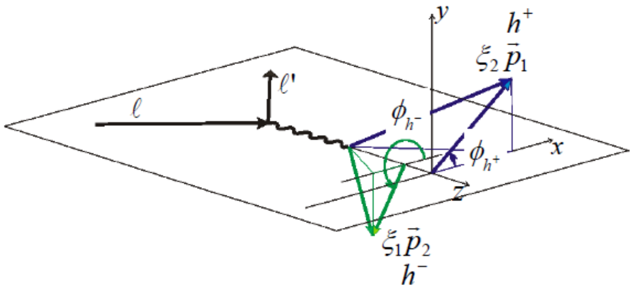
- Collins asymmetry for h+ and for h- :
  "mirror symmetry"
- dihadron asymmetry vs Collins asymmetry:
  only somewhat larger

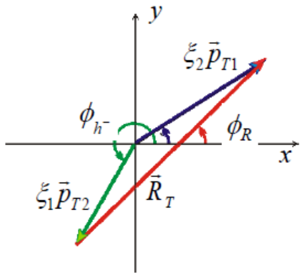
analysis of the single hadron and dihadron asymmetries performed ***on a common data sample*** *(2010 transversely polarised proton)*

standard COMPASS SIDIS sample but wth h^+ h^- at least detected
(each hadron with z >0.1)

Study of the azimuthal correlations of the two hadrons

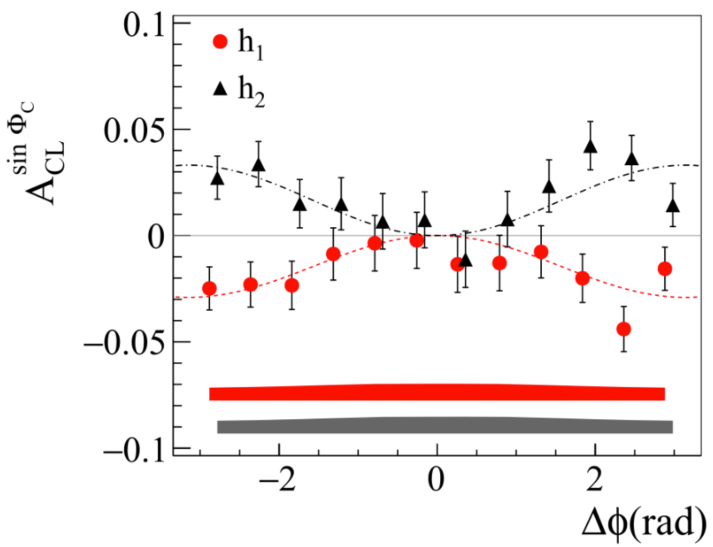
$$\Delta\phi = \phi_{h^+} - \phi_{h^-}$$

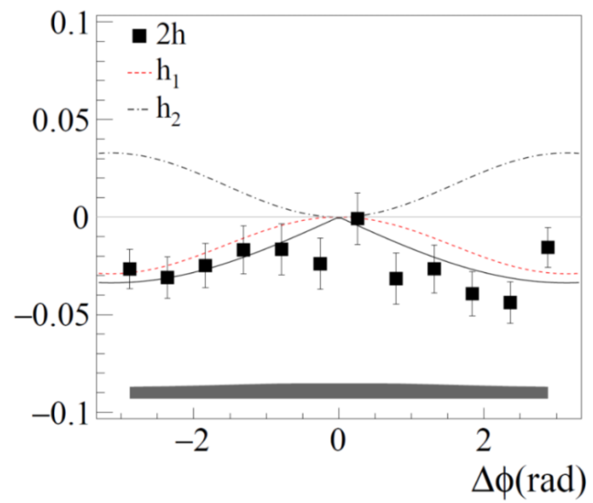




Interesting studies comparing with the Di-hadron Transverse Spin Asymmetries

$$\frac{d\sigma^{h^+h^-}}{d\phi_{h^+}d\phi_{h^-}d\phi_S} = \sigma_U^{h^+h^-} + S_T \cdot \left[\sigma_{1C}^{h^+h^-}\sin(\phi_{h^+}+\phi_S-\pi) + \sigma_{2C}^{h^+h^-}\sin(\phi_{h^-}+\phi_S-\pi)\right]$$





PLB 753 (2016) 406

$$A_{2CL}^{\sin(\phi_{h^-}+\phi_S-\pi)} = -\frac{\sigma_{1C}^{h^+h^-}}{\sigma_U^{h^+h^-}} \cdot (1-\cos\Delta\phi)$$

$$A_{1CL}^{\sin(\phi_{h^+}+\phi_S-\pi)} = \frac{\sigma_{1C}^{h^+h^-}}{\sigma_U^{h^+h^-}} \cdot (1-\cos\Delta\phi)$$

$$A_{2h,CL}^{\sin(\phi_{2h}+\phi_S-\pi)} = \frac{\sigma_{1C}^{h^+h^-}}{\sigma_U^{h^+h^-}} \cdot \sqrt{2\cdot(1-\cos\Delta\phi)}$$

"a common origin"

The Sivers asymmetry

- *results on deuteron (2002-2004 data) compatible with zero*

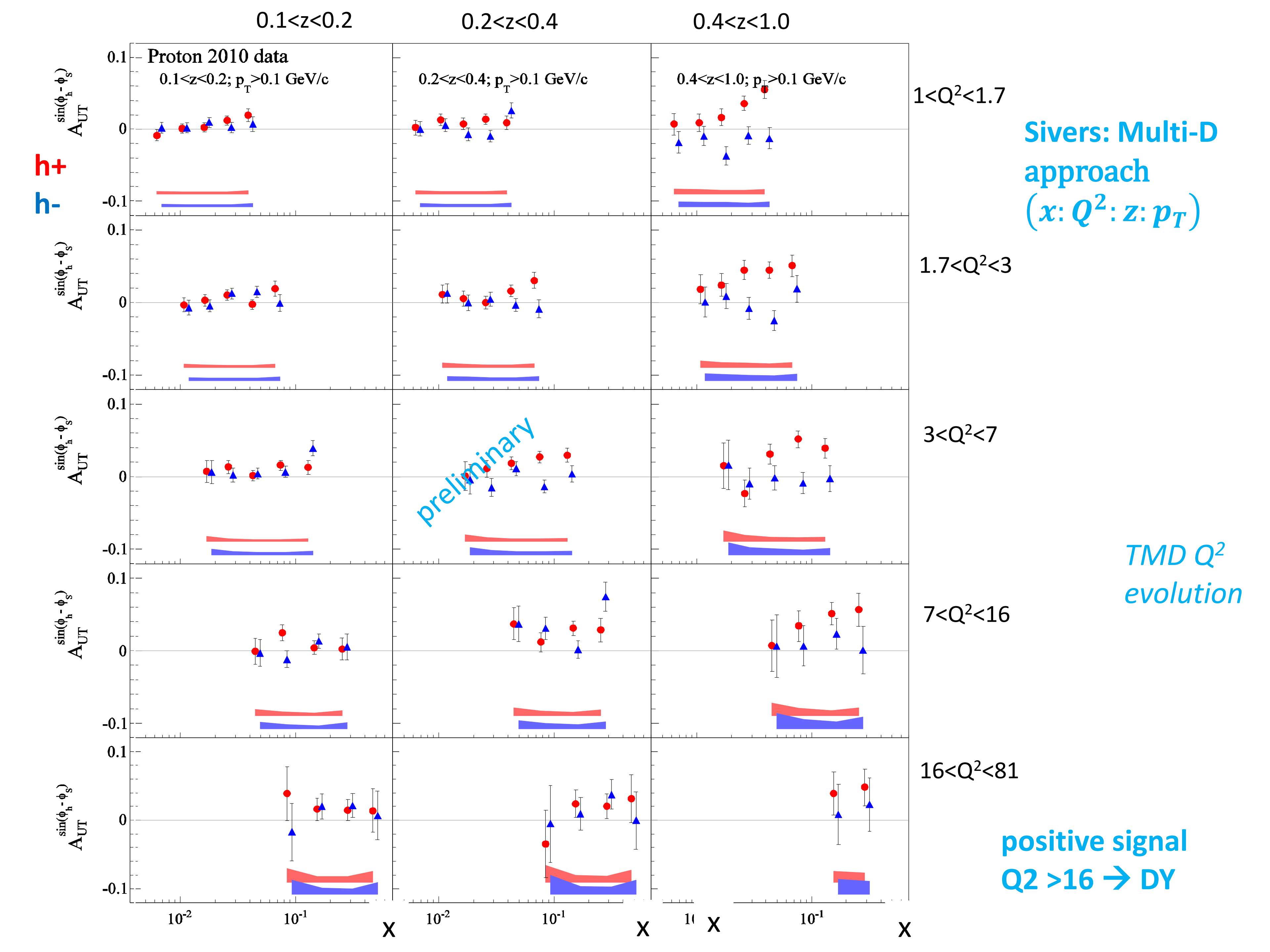
- combined **2007** - PLB 692 (2010) 240 - and **2010** - PLB 717 (2012) 383 - **measurements on proton**

  very good agreement between two independent data set

- multi dimensional analysis

- ***Recent Measurements***

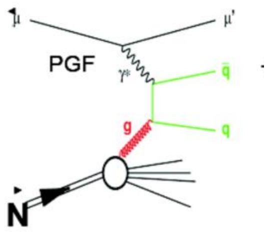
  - Gluon Sivers
  - Sivers from J/ψ
  - Weighted Sivers asymmetries ⟵ **NEW !**



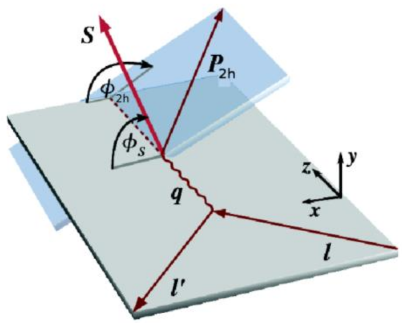
0.1<z<0.2
0.2<z<0.4
0.4<z<1.0
Proton 2010 data
0.1<z<0.2; p_T>0.1 GeV/c
0.2<z<0.4; p_T>0.1 GeV/c
0.4<z<1.0; p_T>0.1 GeV/c
$A_{UT}^{\sin(\phi_h-\phi_s)}$
h+
h-
$1<Q^2<1.7$
$1.7<Q^2<3$
$3<Q^2<7$
$7<Q^2<16$
$16<Q^2<81$
Sivers: Multi-D approach
$(x: Q^2: z: p_T)$
preliminary
TMD Q^2 evolution
positive signal
Q2 >16 → DY
x

Gluon Sivers from high-P_T^h two hadrons pairs

photon-gluon fusion (PGF)



$$\ell + N \rightarrow \ell' + 2h + X$$

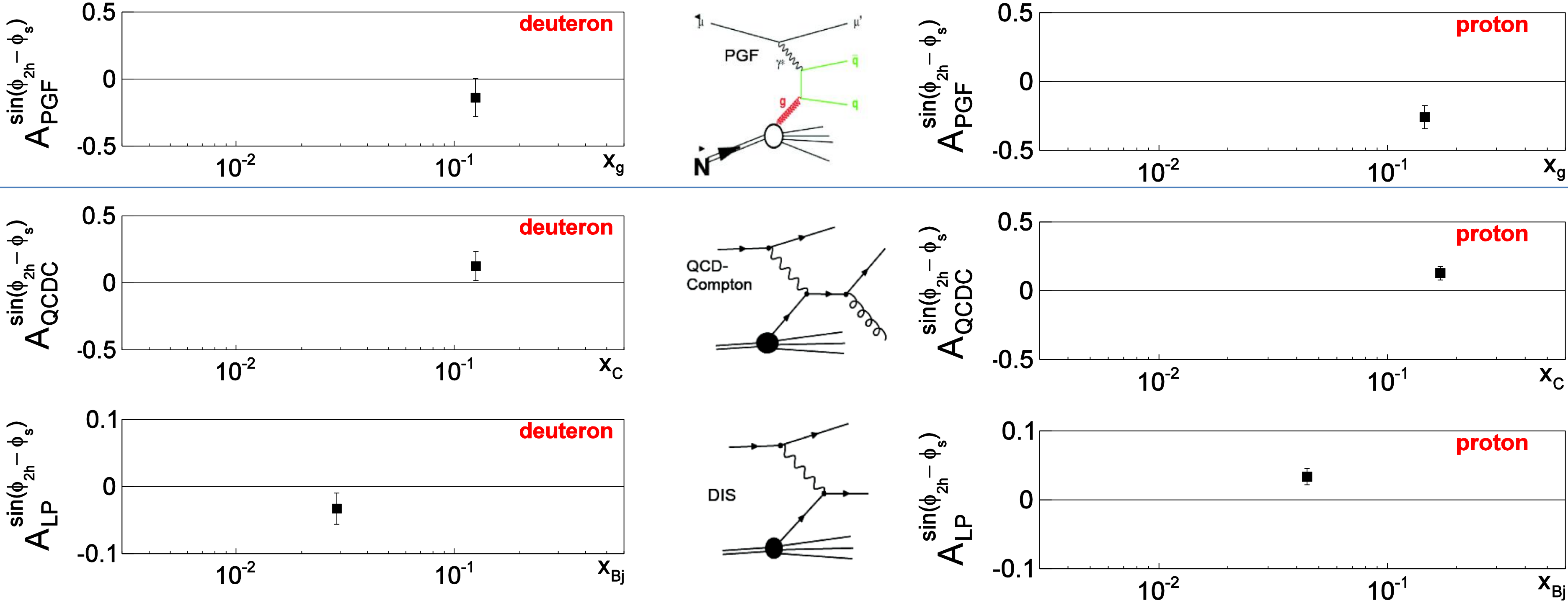


$$\vec{P}_{2h} = \vec{p}_1 + \vec{p}_2$$

$$\phi = \phi_{2h} - \phi_S$$

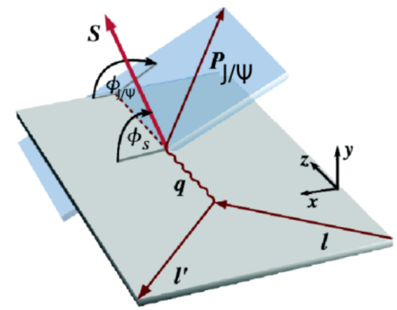
NN MC to tag the different contributing processes

ϕ_{2h} correlated to ϕ_{gluon}



Gluon Sivers from J/ψ

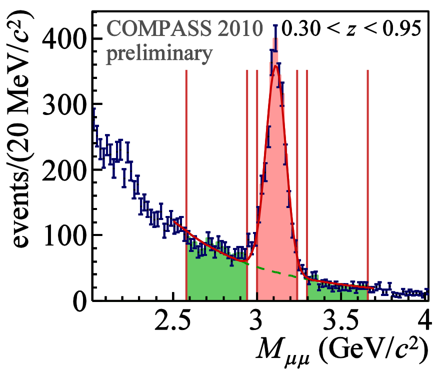
$$\mu^+ + N \to \mu^+ + J/\Psi + X \to 2\mu^+ + \mu^- + X$$

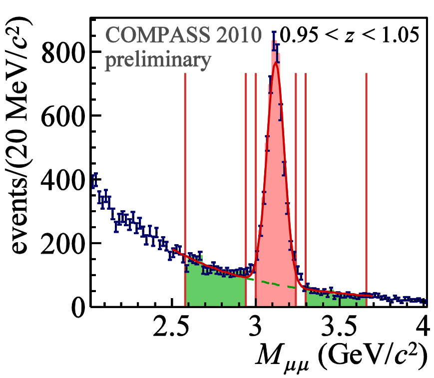


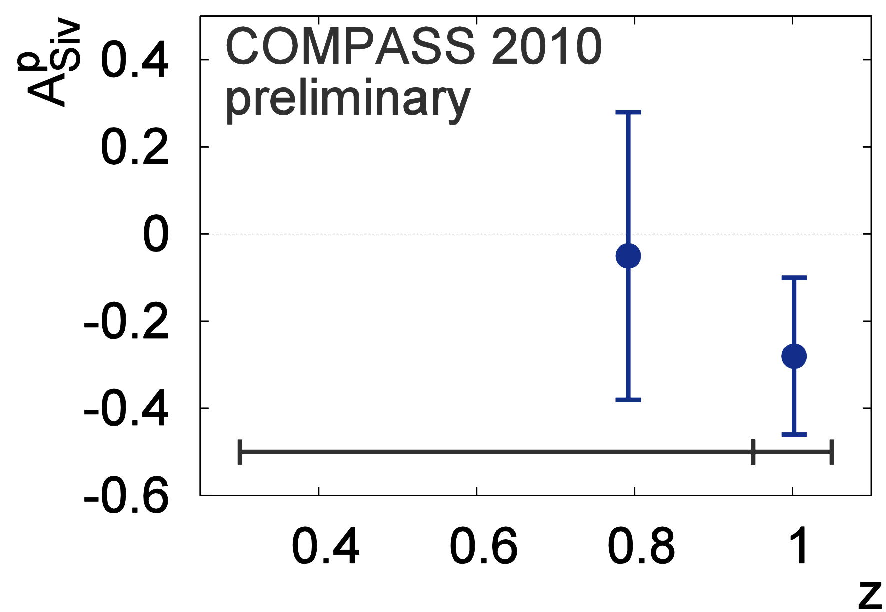
$$\mathbf{P}_{J/\Psi} = \mathbf{p}_{\mu^+} + \mathbf{p}_{\mu^-}$$
$$\phi_{\mu^+\mu^-} = \phi_{J/\Psi} = \phi_g$$

from 2010 transversely polarised proton data
in two z bins 0.30<z<0.95 and 0.95<z<1.05

$$\phi = \phi_{\mu^+\mu^-} - \phi_S$$







New measurement: P_T^h weighted Sivers Asymmetry

A. Kotzinian and P. J. Mulders, PLB 406 (1997) 373
D. Boer and P. J. Mulders, PRD 57 (1998) 5780
J. C. Collins et al. PRD 73 (2006) 014021

$$A_{Siv}^{w} = \frac{1}{M}\frac{\sigma_S^w}{\sigma_U} \qquad \sigma_S^w = \int \sigma_S(P_T^h)\cdot\frac{P_T^h}{z}\,dP_T^h$$

$$\sigma(\varphi_{Siv}) = \sigma_U + \int \sigma_S(P_T^h)\cdot\frac{P_T^h}{z}\,dP_T^h \cdot \sin(\varphi_{Siv})$$

standard Sivers Asymmetry: $A_{Siv} = \frac{\sigma_S}{\sigma_U}$ $\qquad \sigma(\varphi_{Siv}) = \sigma_U + \sigma_S \sin(\varphi_{Siv})$

assuming polarisation = +1 and dilution factor = 1

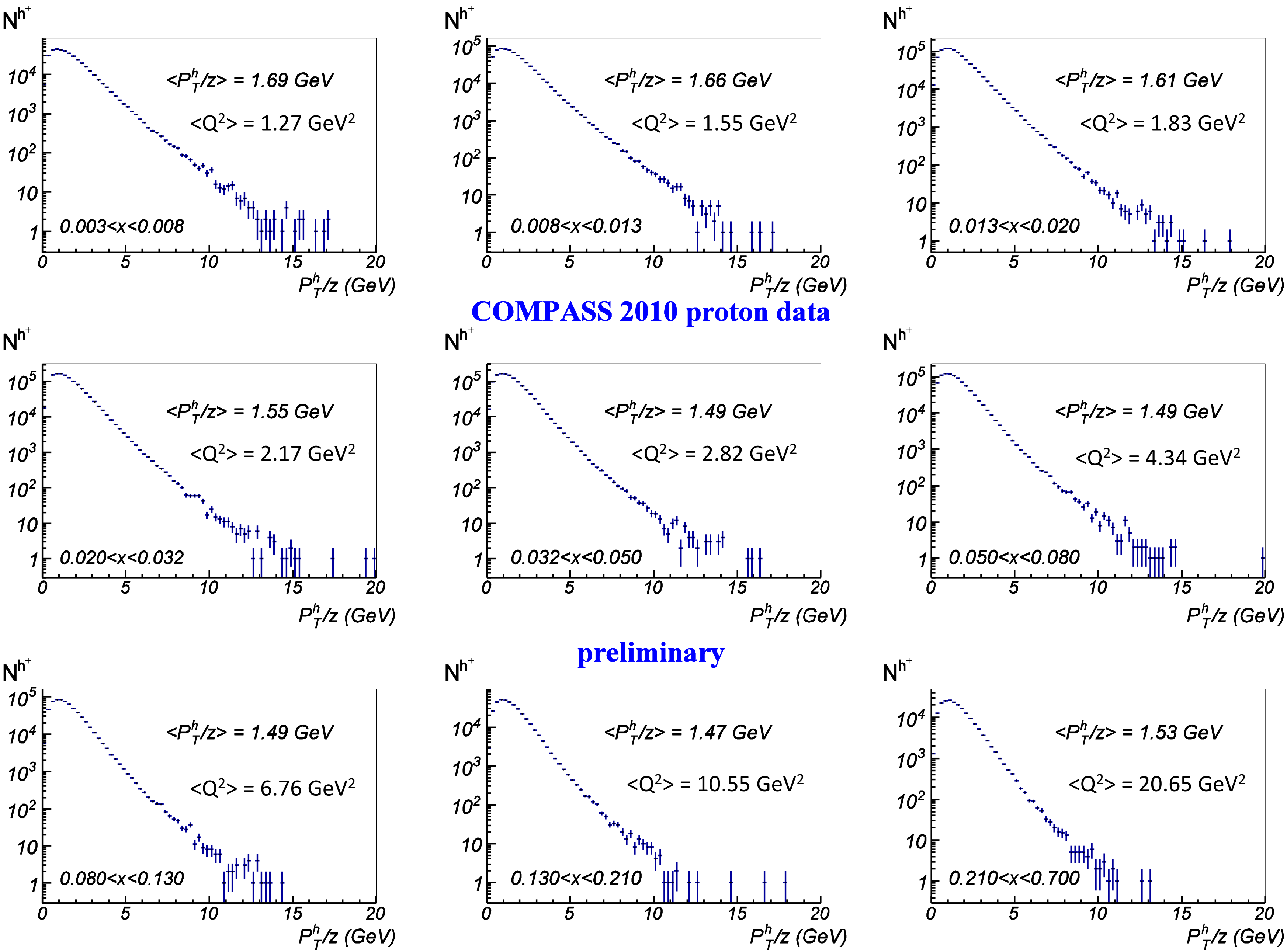
convolution over TM ⟶ product of Sivers (first moment) and FF

$$A_{Siv}^{w} = 2\cdot\frac{\sum_{quarks} e_q^2 \cdot f_{1T,q}^{\perp(1)}(x)\cdot D_{1,q}^h(z)}{\sum_{quarks} e_q^2 \cdot f_{1,q}(x)\cdot D_{1,q}^h(z)}$$

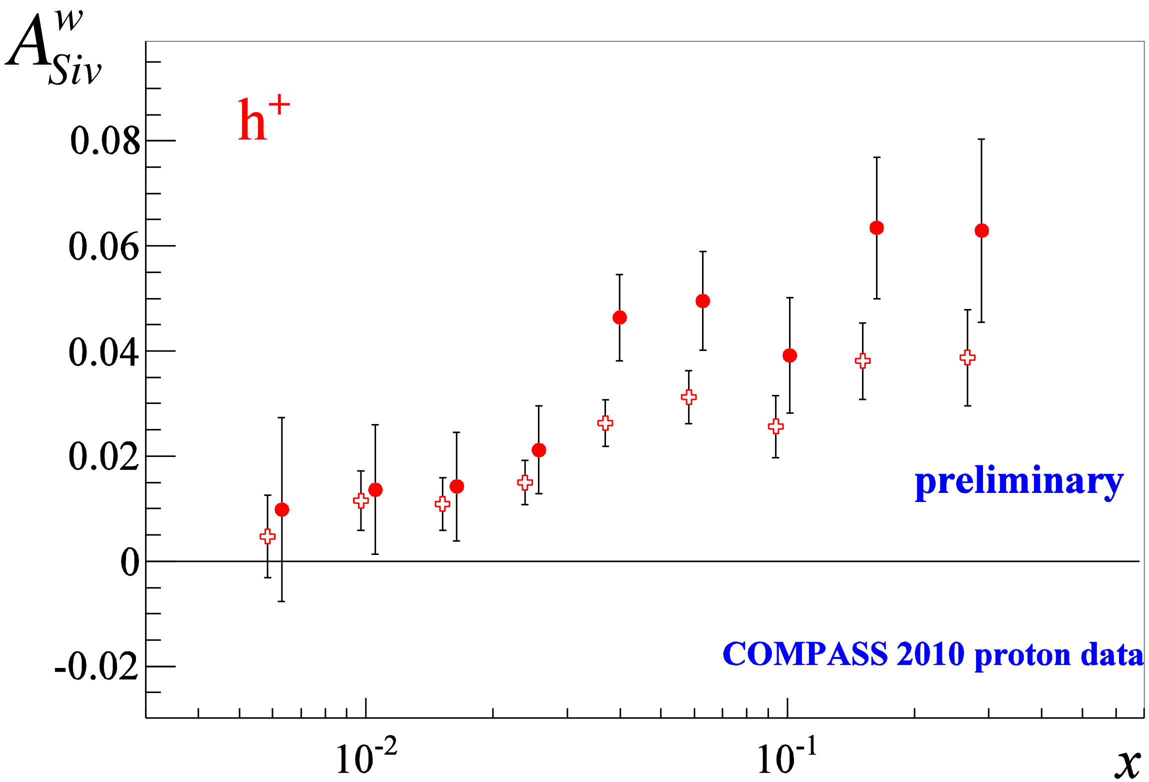
in a ***model independent way*** (no assumption on the shape of PDFs and FFs)

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

The P_T^h/z distributions for each bin of x



Final results ● compared with the standard Sivers Asymmetries ✚ (PLB 717 (2012) 383)



$$A^{w}_{Siv} = 2 \cdot \frac{\sum_{quarks} e_q^2 \cdot f_{1T,q}^{\perp(1)}(x) \cdot D_{1,q}^{h}(z)}{\sum_{quarks} e_q^2 \cdot f_{1,q}(x) \cdot D_{1,q}^{h}(z)}$$

red full points

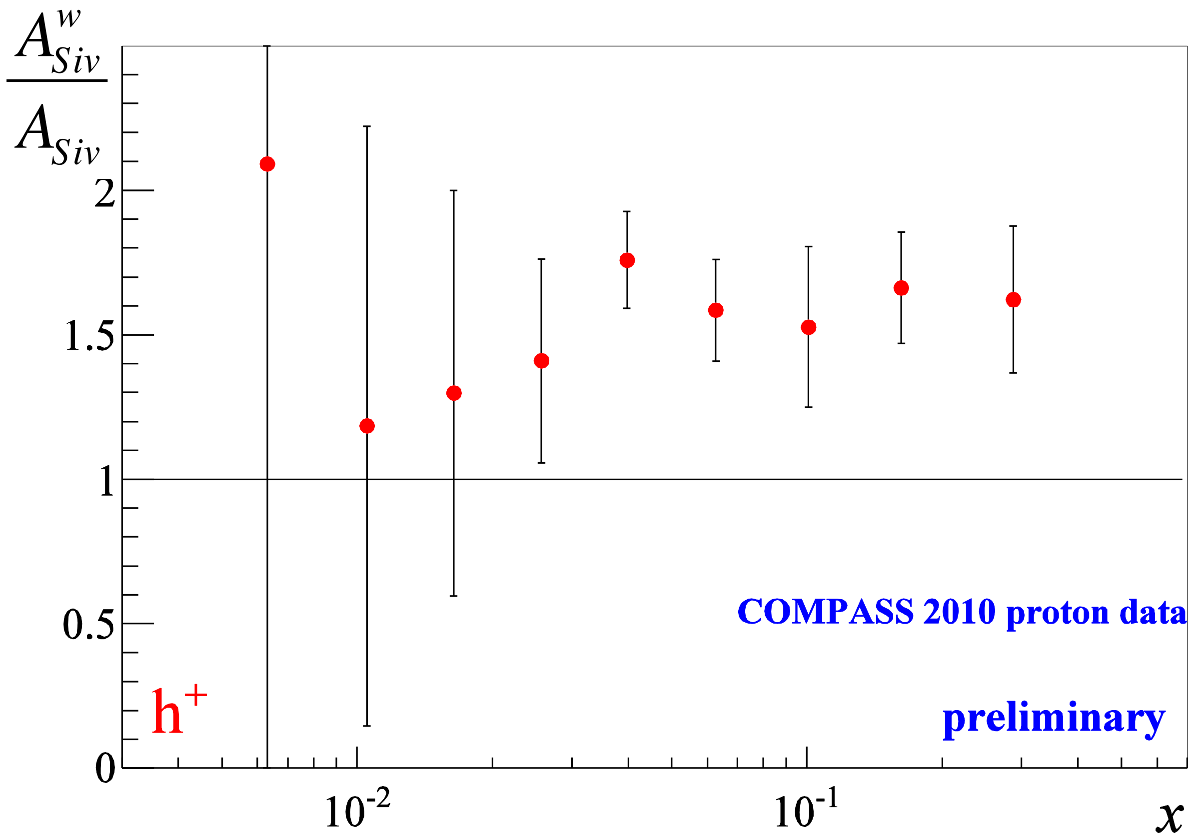
$$A_{Siv} = 2 \cdot a_{Gauss} \frac{\sum_{quarks} e_q^2 \cdot f_{1T,q}^{\perp(1)}(x) \cdot D_{1,q}^{h}(z)}{\sum_{quarks} e_q^2 \cdot f_{1,q}(x) \cdot D_{1,q}^{h}(z)}$$

red empty crosses

Gassian assumption and a_{Gauss}
needed to extract standard Sivers Function

J. C. Collins et al. PRD 73 (2006) 014021 *from the ratio* $\frac{A_{Siv}^{w}}{A_{Siv}}$ *one can measure* $a_{Gauss} \propto \frac{1}{\sqrt{k_{T,Sivers}^{2} + p_{\perp}^{2} / z^{2}}}$

J. C. Collins et al. PRD 73 (2006) 014021



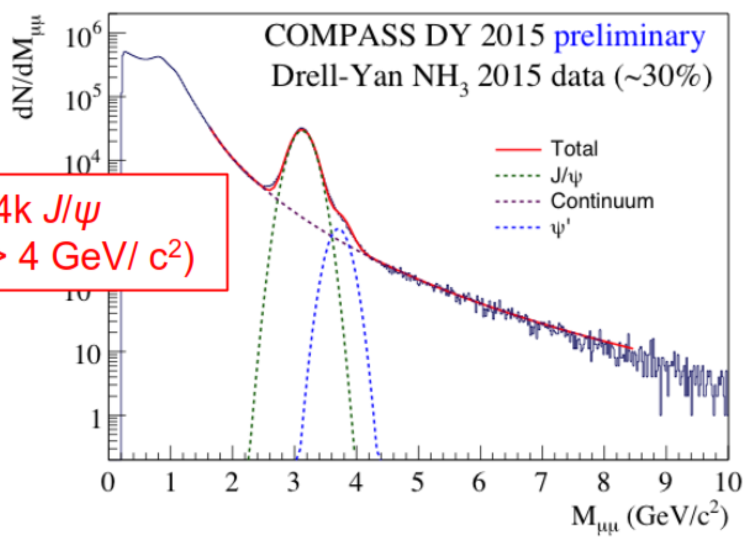
Special: plots from Drell-Yan 2015 polarised proton data

Pion beam on transversely polarized nucleon

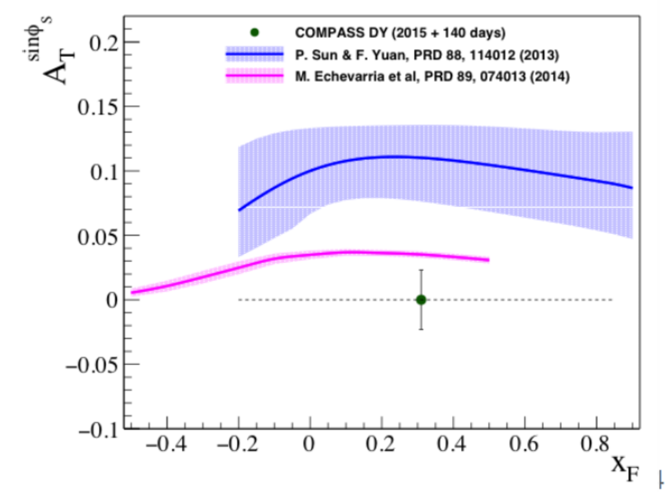
COMPASS assets

- SIDIS and DY experiments: large acceptance, same kinematic region
- Unique hadron beam (π, K, p) with valence antiquarks
- Polarized target

2015 data, 644k *J/ψ*
18k HM ($M_{\mu\mu}$ > 4 GeV/ c^2)



Projection 2 years (2015+2018 data)



Conclusions and Outlook

Many important results produced by COMPASS to investigates TMDs in SIDIS

higher statistics data on transversely polarised d data still needed

DY data promising, more results soon to come

New data in the near future

2016-2017 unpolarised SIDIS on p, in parallel with DVCS

COMPASS III ….

backup

the COMPASS spectrometer

- high energy beams
- large angular acceptance
- broad kinematical range

two stages spectrometer

Large Angle Spectrometer (SM1)

Small Angle Spectrometer (SM2)

variety of tracking detectors

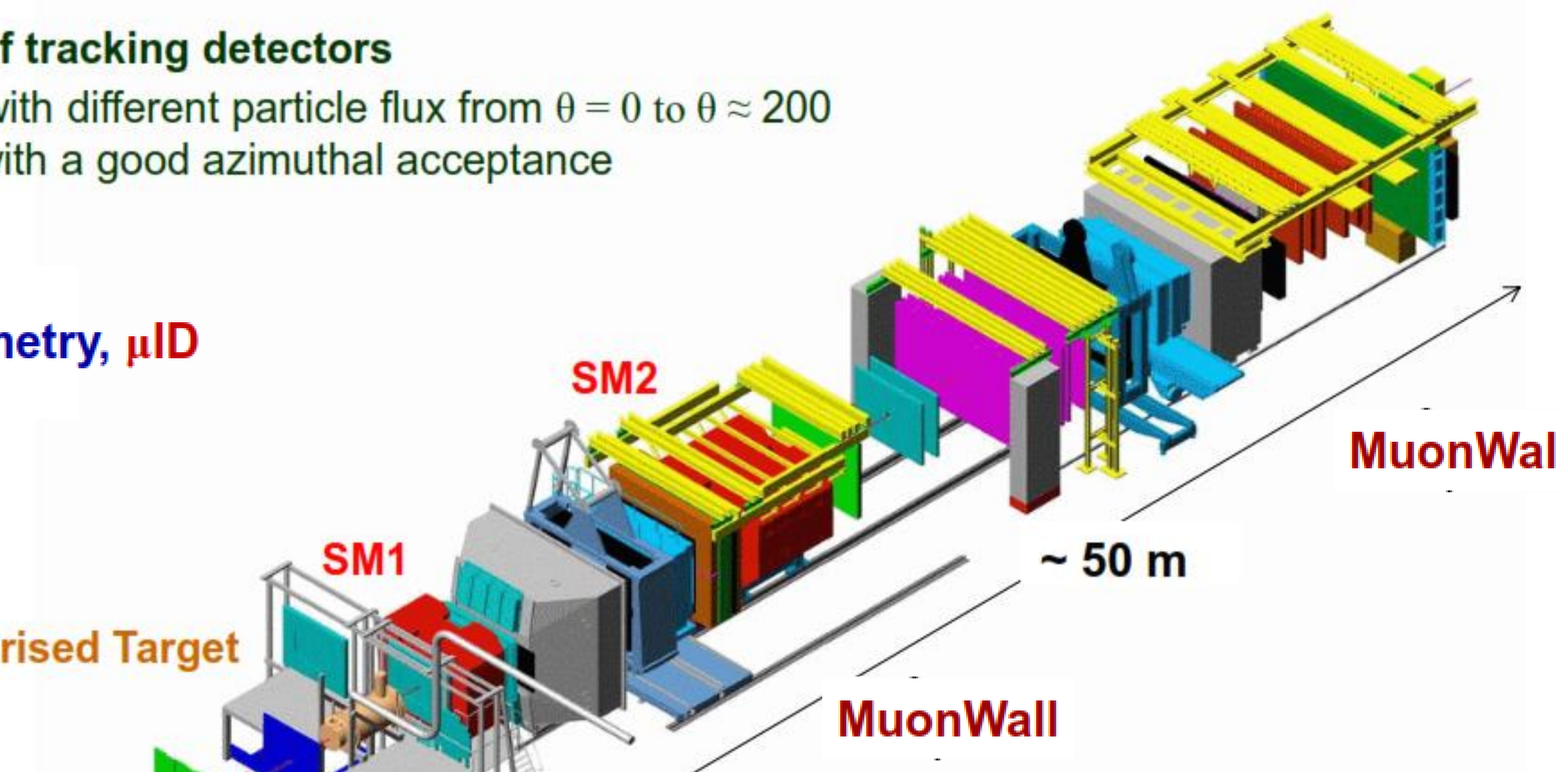
to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad with a good azimuthal acceptance

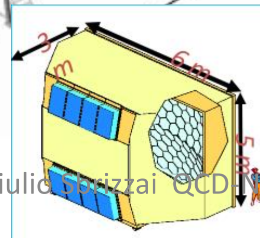
calorimetry, μID

RICH

Polarised Target

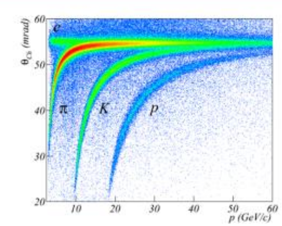
μ beam





Hadron identification: $\pi^{\pm}$ $K^{\pm}$

based on RICH-1 response (likelihood algorithm)

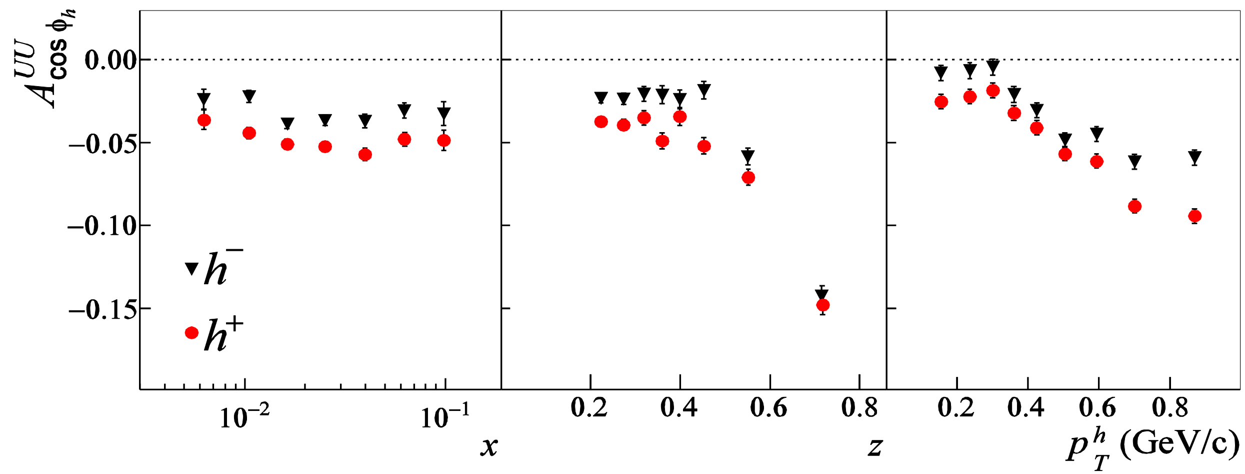


Cherenkov thresholds
π ~ 3 GeV/c
K ~ 9 GeV/c
p ~ 18 GeV/c

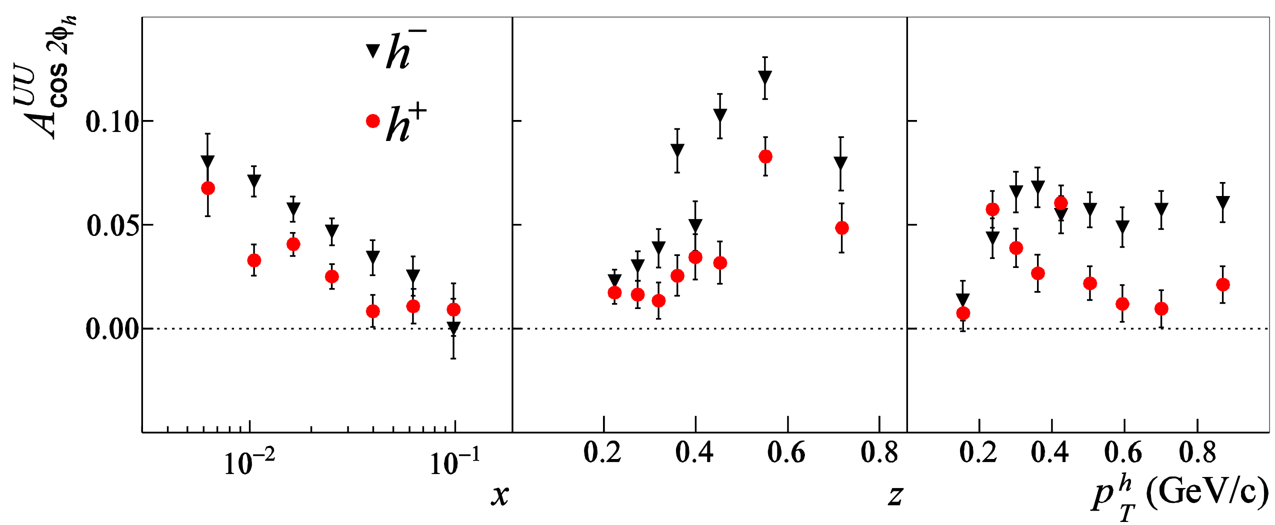
Unpolarised Azimuthal Asymmetries measured from 2004 deuteron data

$$A^{UU}_{\cos\phi_h} \approx \frac{1}{Q} Cahn + \frac{1}{Q} BM$$

cosϕ



cos2ϕ



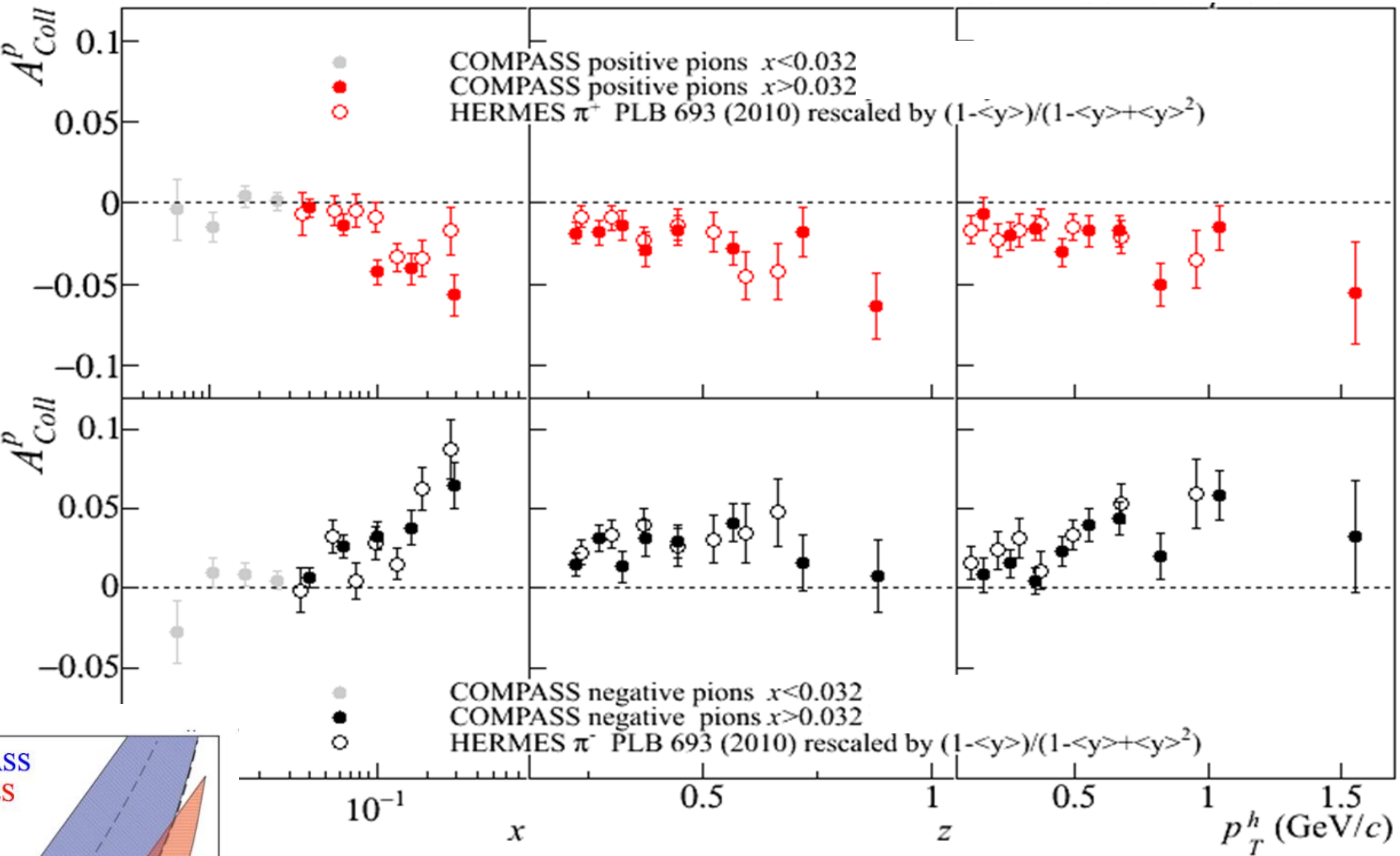
$$A^{UU}_{\cos 2\phi_h} \approx \frac{1}{Q^2} Cahn + BM$$

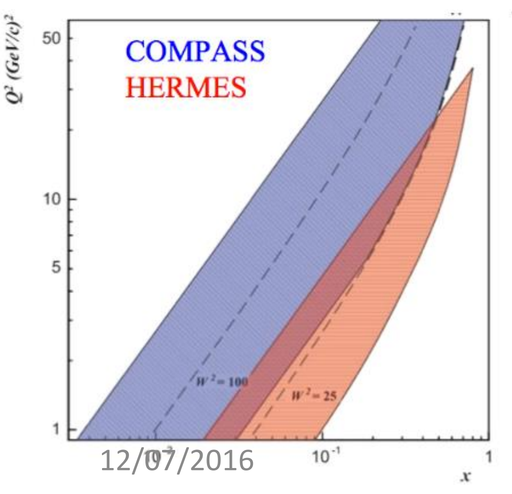
multi dimensional analysis performed to further investigate the interesting dependencies found

COMPASS and HERMES results

π^+

π^-



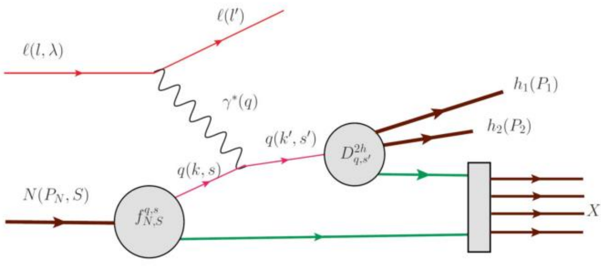


negligible Q^2 evolution? (Q^2 factor 2 or 3 larger in COMPASS)

Interesting studies comparing with the Di-hadron Transverse Spin Asymmetries

$A_{UT}^{\sin\phi_{RS}}$

$lN \to l'h^+h^-X$

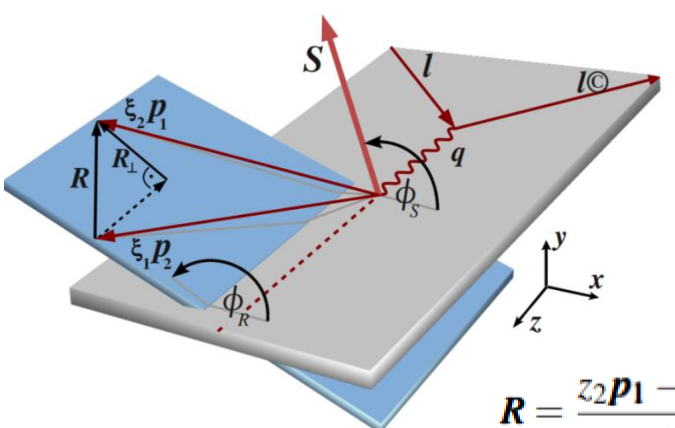


$$N_{h^+h^-}(\phi_{RS}) = N_h^0\left[1 \pm fP_T D_{NN} A_{UT}^{\sin\phi_{RS}} \sin(\phi_{RS})\right]$$

on ***oppositely charged hadrons pairs***

$$A_{UT}^{\sin\phi_{RS}} \approx \frac{\sum_q e_q^2 \cdot h_1^q(x) \cdot H_{1q}^{\angle}(z, M_{hh}^2)}{\sum_q e_q^2 \cdot f_1^q(x) \cdot D_{1q}^h(z, M_{hh}^2)}$$

collinear !

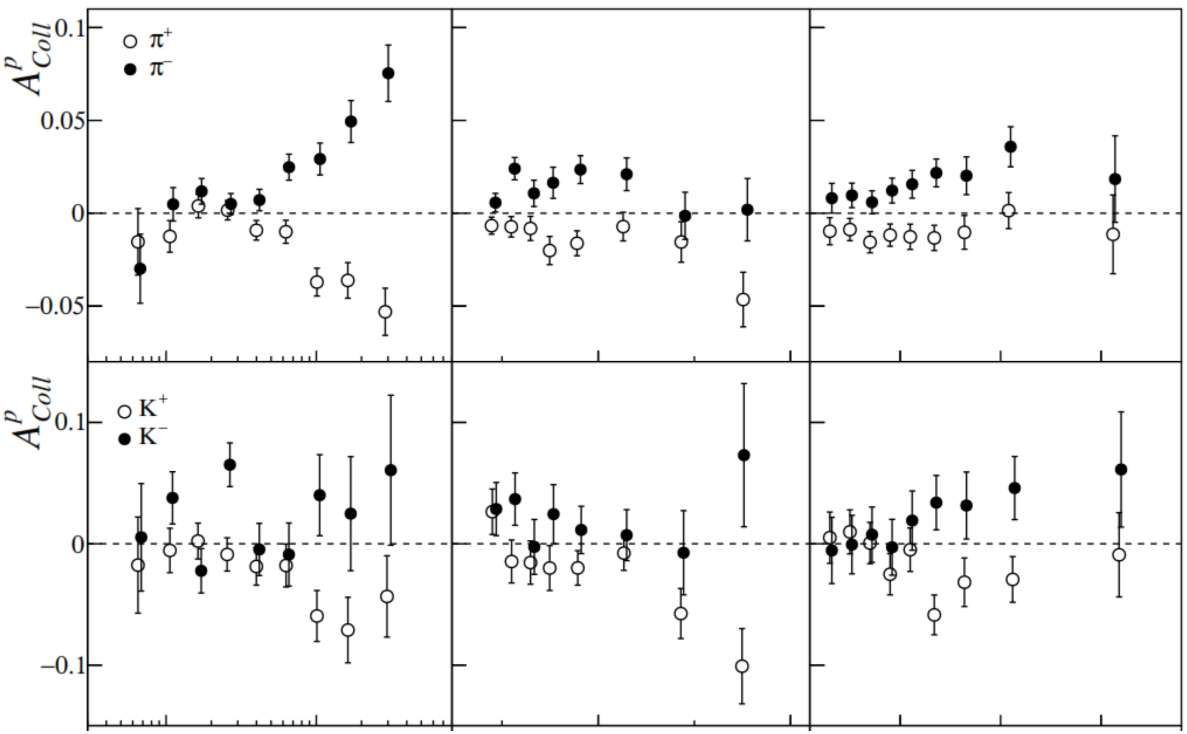


$$R = \frac{z_2 p_1 - z_1 p_2}{z_1 + z_2}$$

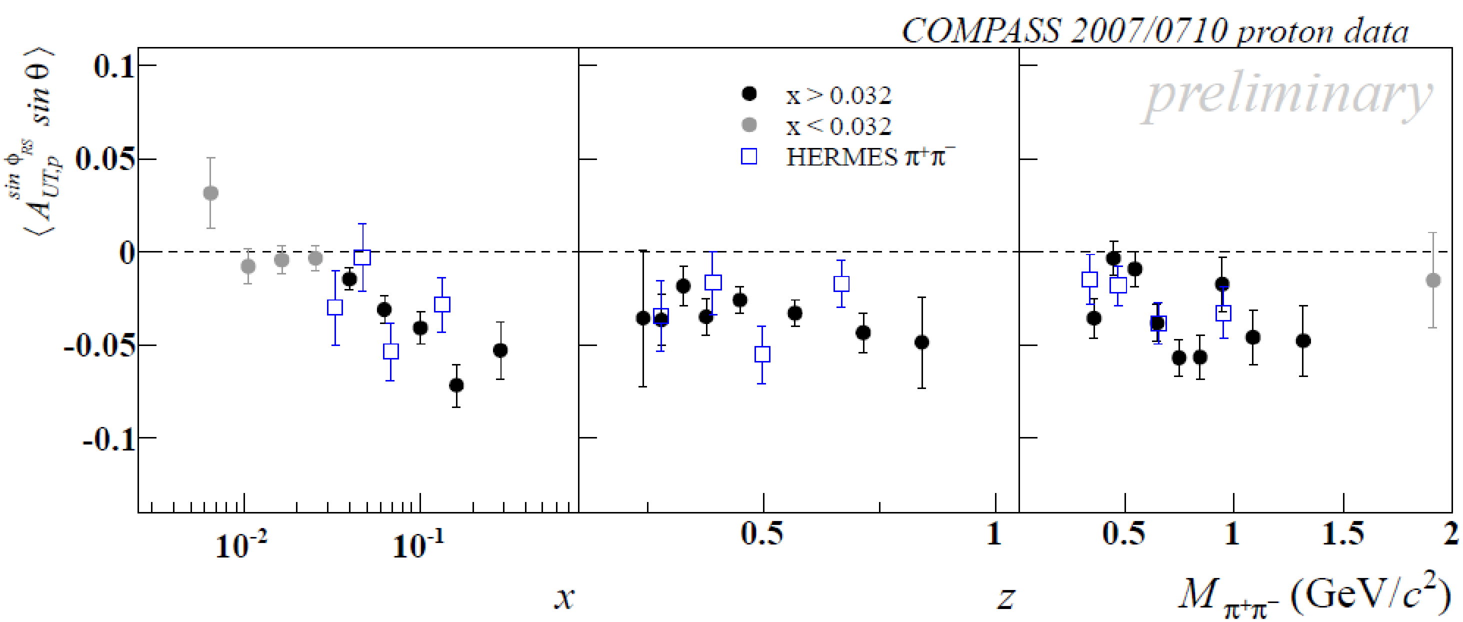
the azimuthal distribution of the hadrons pairs shows a modulation in the azimuthal angle:

$$\phi_{RS} = \phi_R + \phi_S - \pi$$

2002-2004 deuteron *(compatible with zero)* + 2007 proton data published in 2012 PLB 713 (2012) 10

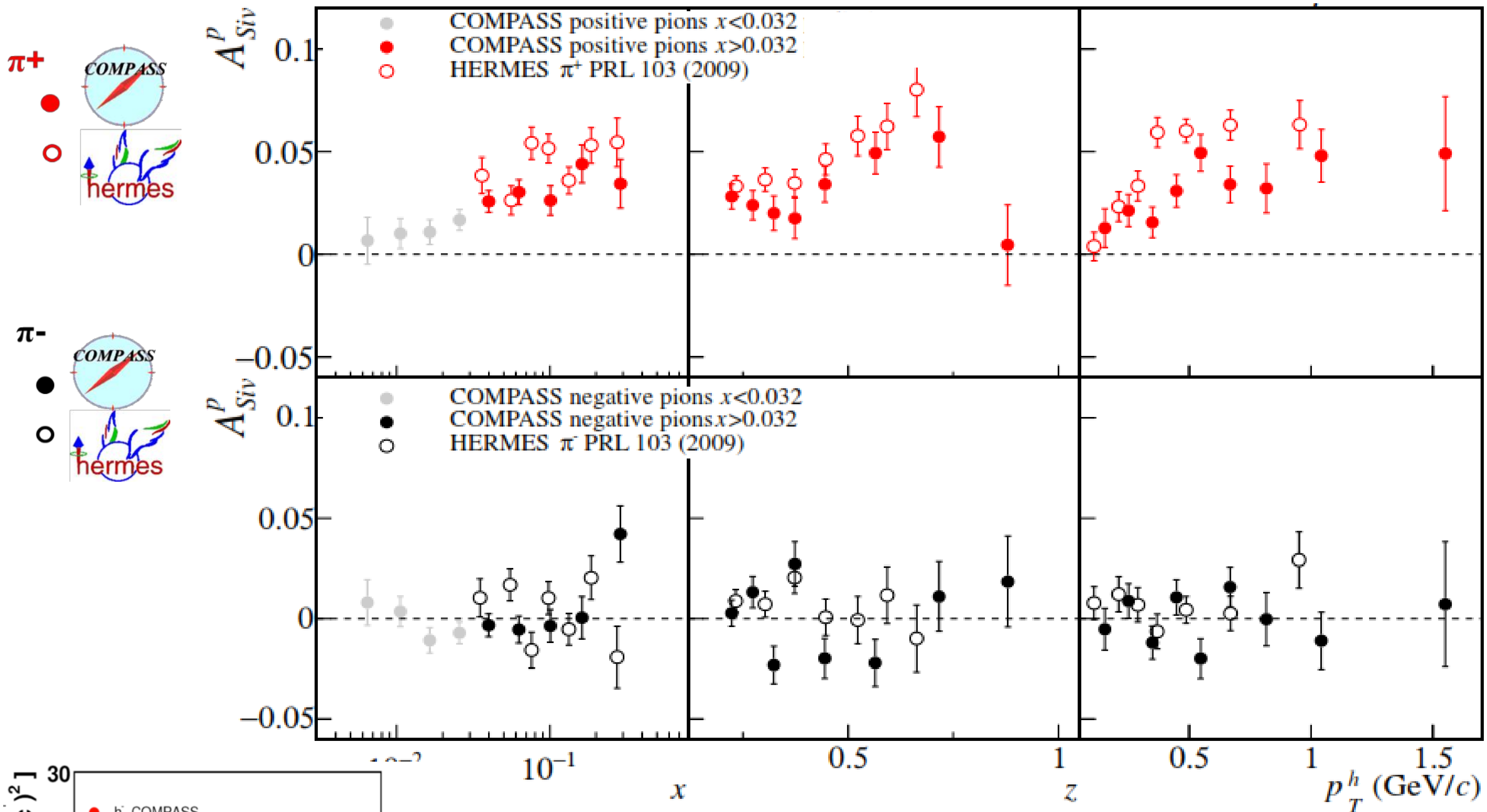


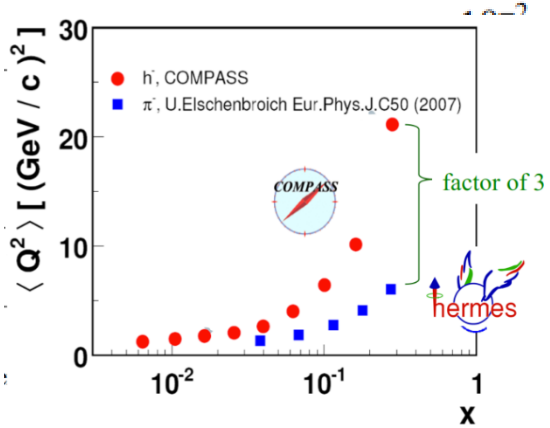
A^p_{Coll}
π+
π−
K+
K−
0.1
0.05
0
−0.05
−0.1



COMPASS 2007/0710 proton data
preliminary
x > 0.032
x < 0.032
HERMES π+π−
$\langle A_{UT,p}^{\sin\phi_{RS}} \sin\theta \rangle$
0.1
0.05
0
-0.05
-0.1
10^{-2}
10^{-1}
0.5
1
1.5
2
x
z
$M_{\pi^+\pi^-}$ (GeV/c^2)

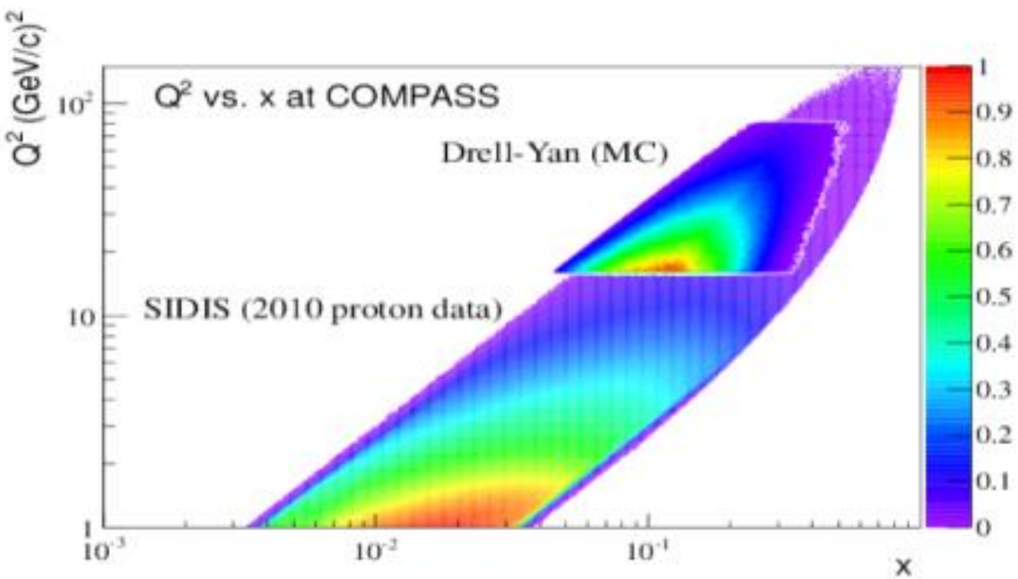
COMPASS and HERMES results





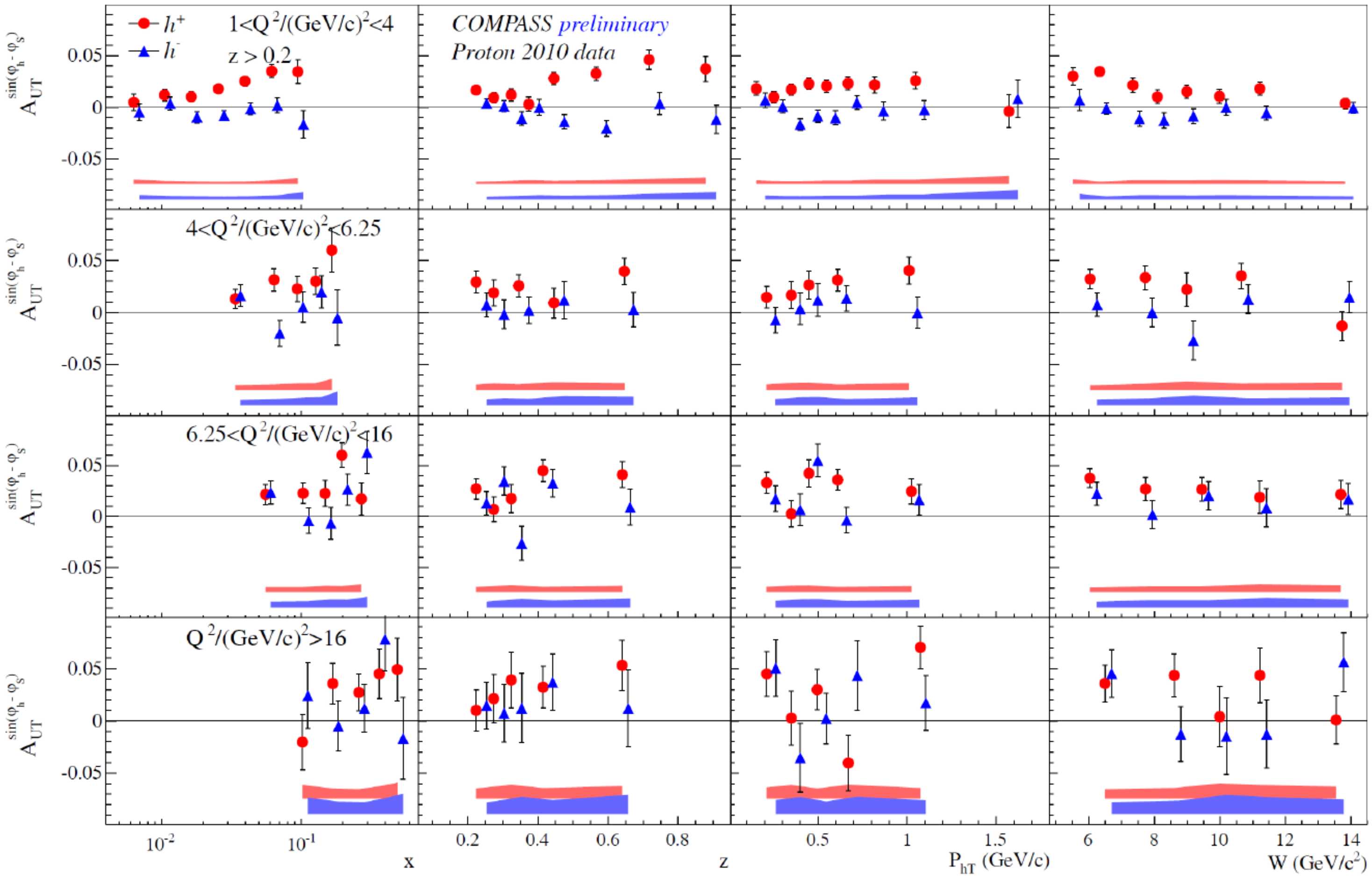
TMD Q^2 evolution? (Q^2 factor 2 or 3 larger in COMPASS) fundamental QCD prediction $$f_{1T}^{\perp}(SIDIS) = -f_{1T}^{\perp}(DY)$$

COMPASS is taking Drell-Yan data with transversely polarised target (full year dedicated)



superposition DY – SIDIS kinematical region at COMPASS

Sivers in DY range



one period (week)

number of hadrons in sub-period 1

in each φ_{Siv} bin

number of hadrons in sub-period 2

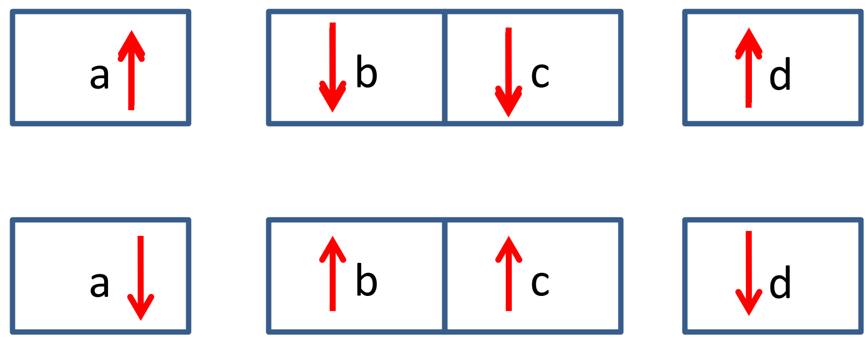
N_1 *cell **a+d** first sub-period*

N_2 *cell **b+c** first sub-period*

N_1' *cell **a+d** second sub-period*

N_2' *cell **b+c** second sub-period*

data taking period (target transverse polarisation reversal)



weighted counts are defined as:

$$N_1^w = \sum_{k=1}^{N_1} \frac{P_{T,k}^h}{z_k \cdot M_{\mathrm{Pr}}}$$

and the same for $N_2^w, N_1^w{}', N_2^w{}'$

Since **only the spin dependent part of the cross section is weighted** we used different method from the standard ones (DR, UML)

First method implemented:

$$\Delta^w = N_1^w - N_1'^w + N_2'^w - N_2^w$$

$$\Sigma = N_1 + N_1' + N_2' + N_2$$

$$R'(\Phi_{Siv}) = \frac{\Delta^w}{\Sigma}$$

$$R'(\Phi_{Siv}) \simeq \bar{S}_T \cdot \epsilon^w \sin \Phi_{Siv}$$

→ calculated in 16 bins of ϕ_{Siv} and fitted using a $p_0 + p_1 \sin(\phi_{Siv})$ function

assuming ***azimuthal acceptance*** *to be* ***the same for the two sub-periods***

$$\epsilon^w = \frac{\sigma_{0S,I}^w}{\sigma_{U,I}} = 2A_{Siv}^{(1)}$$

The method chosen **to extract the final results** is

$$R(\Phi_{Siv}) = \frac{\Delta^w}{\sqrt{\Sigma^w \Sigma}}$$

$$\Delta^w = N_1^w N_2'^w - N_1'^w N_2^w$$

$$\Sigma^w = N_1^w N_2'^w + N_1'^w N_2^w$$

$$\Sigma = N_1 N_2' + N_1' N_2$$

quantity calculated in each bin of ϕ_{Siv}

Azimuthal acceptance cancels if the Reasonable Assumption holds

$$a_1 a_2' = a_1' a_2$$

Other transverse spin dependent asymmetries

just a reminder

there are also other 6 modulations related to different TMDs
they all have been measured at COMPASS

$$
\begin{aligned}
&+ |\boldsymbol{S}_\perp| \Big[\sin(\phi_h - \phi_S) \Big(F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h - \phi_S)} \Big) \\
&\quad + \varepsilon \sin(\phi_h + \phi_S)\, F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S)\, F_{UT}^{\sin(3\phi_h - \phi_S)} \\
&\quad + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin(2\phi_h - \phi_S)\, F_{UT}^{\sin(2\phi_h - \phi_S)} \Big] \\
&+ |\boldsymbol{S}_\perp| \lambda_e \Big[\sqrt{1-\varepsilon^2}\, \cos(\phi_h - \phi_S)\, F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos\phi_S\, F_{LT}^{\cos\phi_S} \\
&\quad + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos(2\phi_h - \phi_S)\, F_{LT}^{\cos(2\phi_h - \phi_S)} \Big] \Big\},
\end{aligned}
$$

sivers
collins

pretzelosity

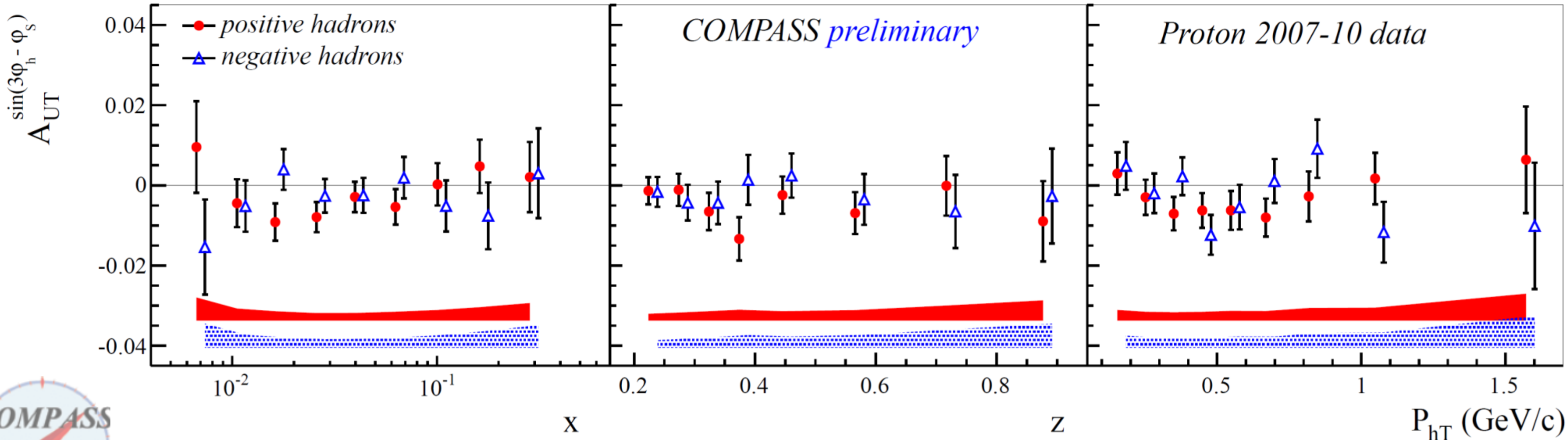
worm-gear

higher twist effects

all of them measured and
found to be compatible with zero

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

sensitive to the D-wave component
non spherical shape of the nucleon



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