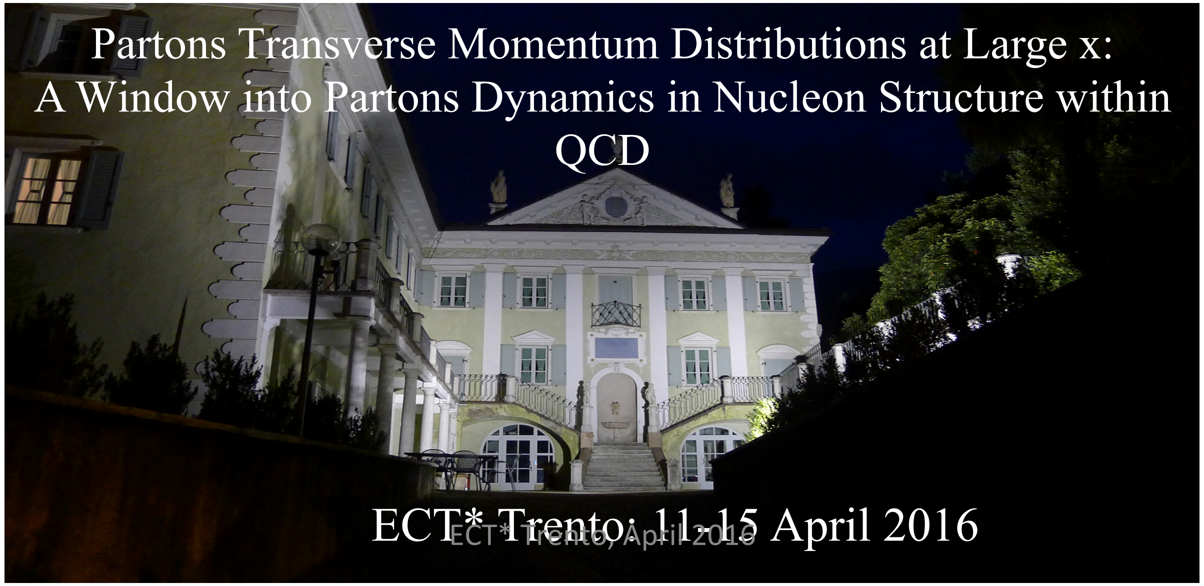
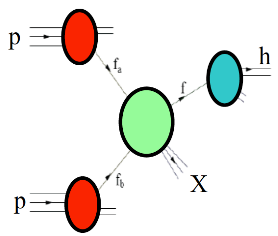
COMPASS Results and TMD Program

Nour Makke, *On behalf of the COMPASS Collaboration*
Trieste University and INFN & ICTP



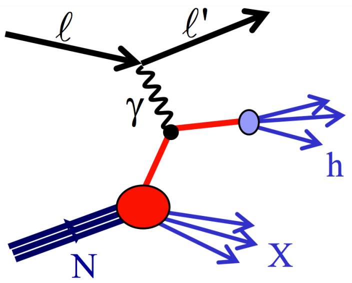
Transverse Momentum Dependent PDFs and FFs

can be assessed in different hard scattering processes



Polarised pp collision

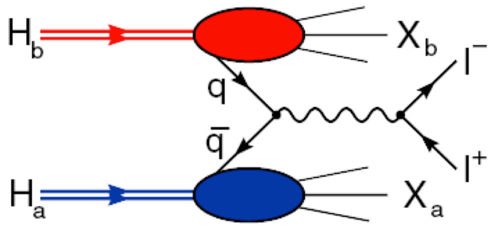
RHIC



SIDIS off transversely polarized targets

HERMES
COMPASS
JLab

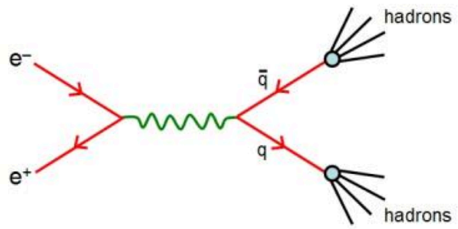
$$\sigma^{lp \to l' hX} \sim q(x) \otimes \hat{\sigma}^{\gamma q \to q} \otimes D_h^q(z)$$



Drell-Yan

CERN (COMPASS) Data taking
Fermilab
RHIC

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



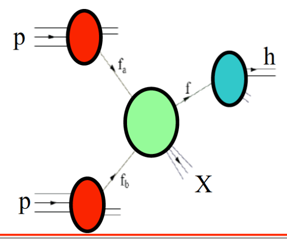
e^+e^- annihilation

BaBar
Belle
Bes III

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

Transverse Momentum Dependent PDFs and FFs

can be assessed in different hard scattering processes



Polarised pp collision

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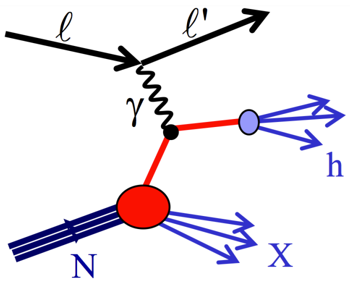

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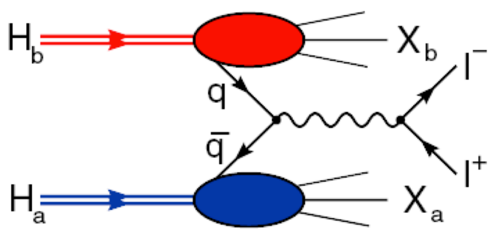

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CERN (COMPASS) Data taking
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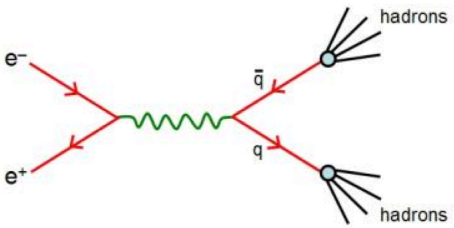

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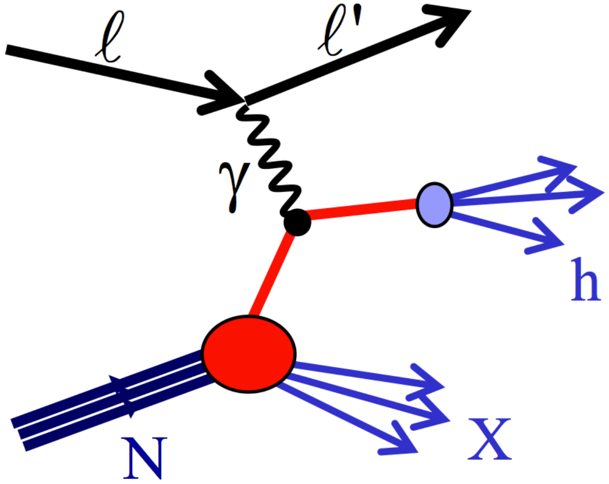
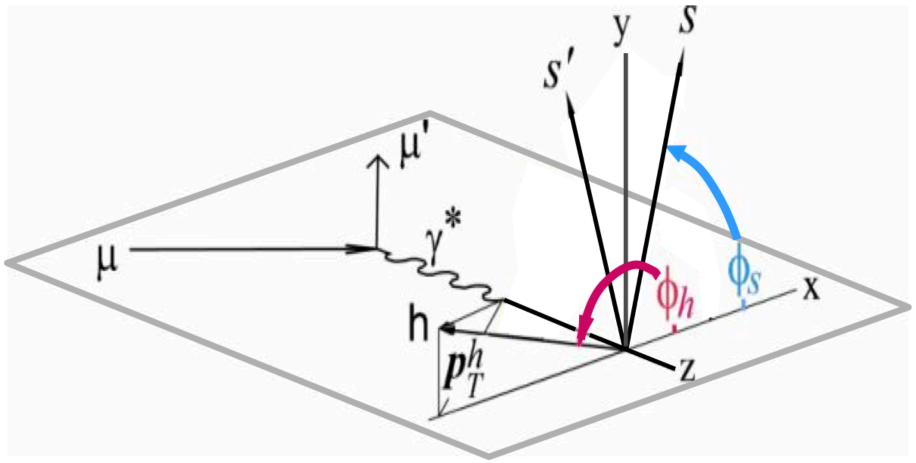
Semi-Inclusive DIS

SIDIS: a powerful tool



- Access universal functions PDFs and FFs
- Allows flavor & charge separation
- Q^2 evolution studies
- Relevant for spin physics kinematics

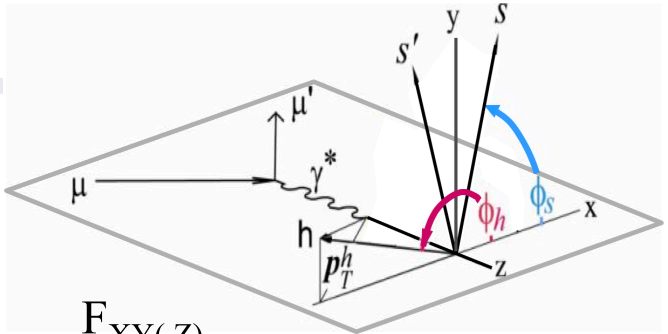


$$d\sigma^{\ell p\to\ell hX} \sim \sum_q e_q^2 f_q(x,\boldsymbol{k}_\perp)\cdot d\sigma^{\ell q\to\ell q}\cdot D_q^h(z,\boldsymbol{p}_T)$$

SIDIS 1h cross-section

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

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



$F_{XY(,Z)}$

X=beam, Y=target, Z=γ^* polarisation

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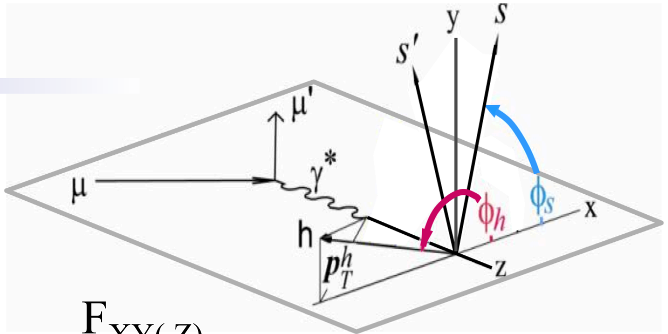
+\cos(2\phi_h)\varepsilon F_{UU}^{\cos(2\phi_h)} + \lambda\sin\phi_h\sqrt{2\varepsilon(1-\varepsilon)}F_{LU}^{\sin\phi_h} + \\
S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{UL}^{\sin\phi_h} + \sin(2\phi_h)\,\varepsilon F_{UL}^{\sin 2\phi_h}\right] + \\
S_L\lambda\left[\sqrt{(1-\varepsilon^2)}F_{LL}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



$F_{XY(,Z)}$
X=beam, Y=target, Z=γ^* polarisation

Longitudinal target polarisation

Transverse target polarisation

18 structure functions F_{XY}

SIDIS 1h cross-section

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

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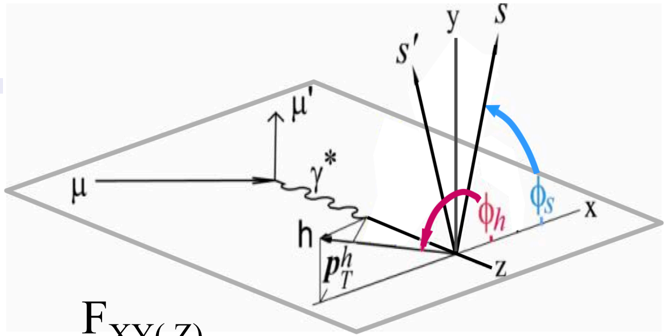
\end{array}\right] + \\
S_T\lambda\left[\begin{array}{l}
\cos\phi_S\left(\sqrt{2\varepsilon(1-\varepsilon)}F_{LT}^{\cos\phi_S}\right) + \\
\cos(\phi_h-\phi_S)\left(\sqrt{(1-\varepsilon^2)}F_{LT}^{\cos(\phi_h-\phi_S)}\right) + \\
\cos(2\phi_h-\phi_S)\left(\sqrt{2\varepsilon(1-\varepsilon)}F_{LT}^{\cos(2\phi_h-\phi_S)}\right)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



$F_{XY(,Z)}$
X=beam, Y=target, Z=γ^* polarisation

Longitudinal target polarisation

Transverse target polarisation

18 structure functions F_{XY}^{Z}

14 different azimuthal modulations

SIDIS 1h cross-section

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

$f_1 \otimes D_1$ $\quad h_1^{\perp} \otimes H_1^{\perp}$

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

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

$h_{1L}^{\perp} \otimes H_1^{\perp}$

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

$g_1 \otimes D_1$

$$S_T \begin{bmatrix} \sin\phi_S \left(\sqrt{2\varepsilon\,(1+\varepsilon)}\,F_{UT}^{\sin\phi_S}\right) + \\ \sin(\phi_h-\phi_S)\left(F_{UT}^{\sin(\phi_h-\phi_S)}\right) + \\ \sin(\phi_h+\phi_S)\left(\varepsilon F_{UT}^{\sin(\phi_h+\phi_S)}\right) + \\ \sin(2\phi_h-\phi_S)\left(\sqrt{2\varepsilon\,(1+\varepsilon)}\,F_{UT}^{\sin(2\phi_h-\phi_S)}\right) + \\ \sin(3\phi_h-\phi_S)\left(\varepsilon F_{UT}^{\sin(3\phi_h-\phi_S)}\right) \end{bmatrix} +$$

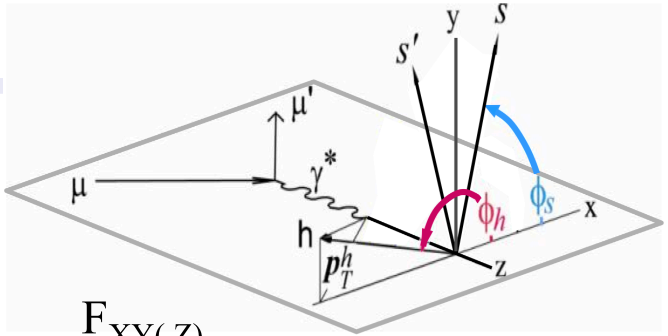
$f_{1T}^{\perp} \otimes D_1$

$h_1 \otimes H_1^{\perp}$

$h_{1T}^{\perp} \otimes H_1^{\perp}$

$$S_T \lambda \begin{bmatrix} \cos\phi_S \left(\sqrt{2\varepsilon\,(1-\varepsilon)}\,F_{LT}^{\cos\phi_S}\right) + \\ \cos(\phi_h-\phi_S)\left(\sqrt{(1-\varepsilon^2)}\,F_{LT}^{\cos(\phi_h-\phi_S)}\right) + \\ \cos(2\phi_h-\phi_S)\left(\sqrt{2\varepsilon\,(1-\varepsilon)}\,F_{LT}^{\cos(2\phi_h-\phi_S)}\right) \end{bmatrix} \Bigg)$$

$g_{1T} \otimes D_1$



$F_{XY(,Z)}$
X=beam, Y=target, Z=γ^* polarisation

18 structure functions F_{XY}^{Z}

14 different azimuthal modulations
∝ PDFs ⊗ FFs

All measured

All TMDs

quark polarization \ nucleon polarization	U	L	T
U	f_1 number density		$f_{1T}^{\perp}$
L		g_1 helicity	g_{1T}
T	$h_1^{\perp}$	$h_{1L}^{\perp}$	h_1 transversity $h_{1T}^{\perp}$

- Can only be assessed in experimental data (measured asymmetries)
- More asymmetries, measured by different experiments in different reactions, at different energies and kinematical ranges expected in the near future towards a global analysis

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

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

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

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

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

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

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

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

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

$$A_{LT}^{\cos(2\varphi_h-\varphi_S)} \propto Q^{-1}\left(g_{1T}^q \otimes D_{1q}^h\right)$$

COMPASS:

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

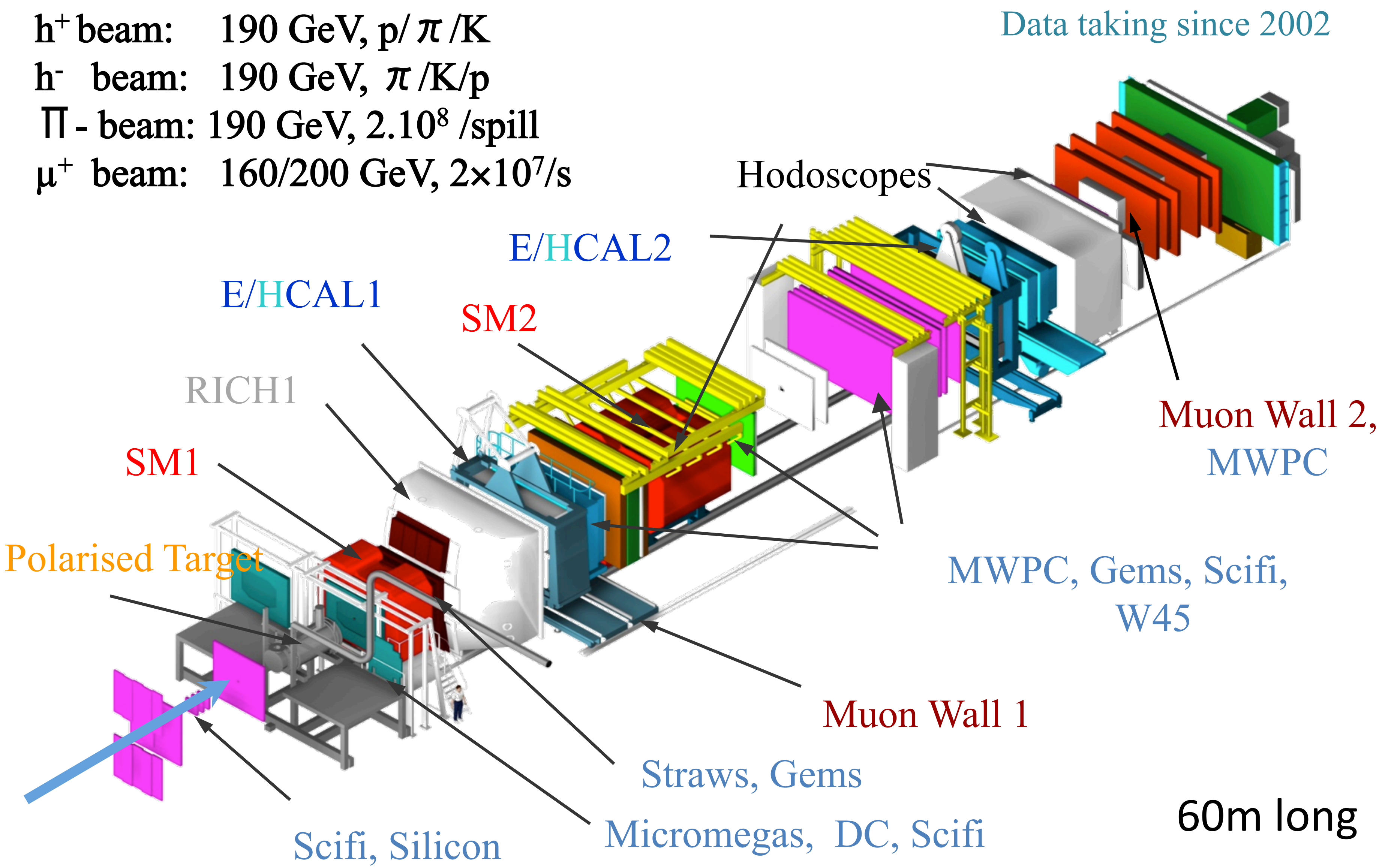
Collaboration
~ 250 physicist
from 24 institutions
of 13 countries

fixed target
experiment at the
CERN SPS

Data taking
since 2002

The COMPASS Experiment

h^+ beam: 190 GeV, p/ π /K
h^- beam: 190 GeV, π /K/p
Π - beam: 190 GeV, 2.10^8 /spill
μ^+ beam: 160/200 GeV, 2×10^7/s



COMPASS measurements

COMPASS measurements of TMD observables in SIDIS using 2002-2010 data

- Transversity
  - **Collins asymmetry on d↑ and p ↑: $h^{\pm}$, $\pi^{\pm}$, $K^{\pm}$**
  - **di-hadron asymmetry on d↑ and p ↑: $h^{\pm}$, $\pi^{\pm}$, $K^{\pm}$**
  - **interplay between Collins and di-hadron asymmetries**

- TMD PDFs
  - **Sivers asymmetry on d↑ and p ↑: $h^{\pm}$, $\pi^{\pm}$, $K^{\pm}$**
  - **other 6 TSA on d↑ and p ↑: only charged hadrons**
  - **Gluon Sivers asymmetry from J/Psi and high p_T hadron pair, on d↑ and p ↑**
  - **azimuthal asymmetries on unpol d, $h^{\pm}$**

- Multiplicities
  - **single hadron vs. p_T^2 on d**
  - **2h on d**

Not all shown; just a selection

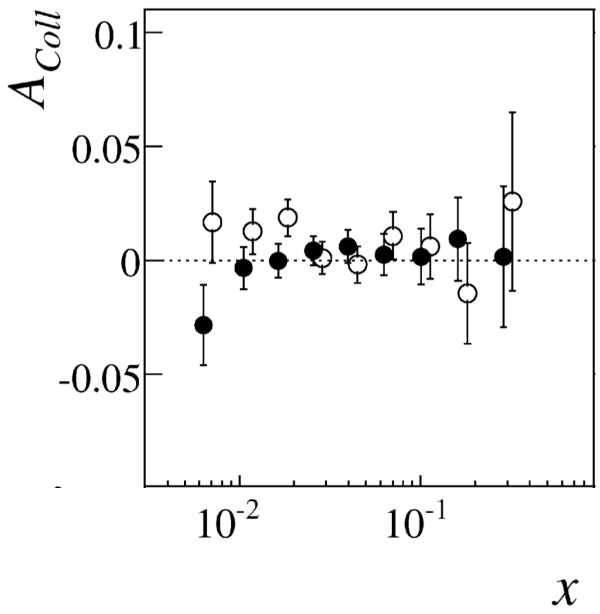
Collins asymmetry $\sim h_1 \otimes H_1^{\perp}$

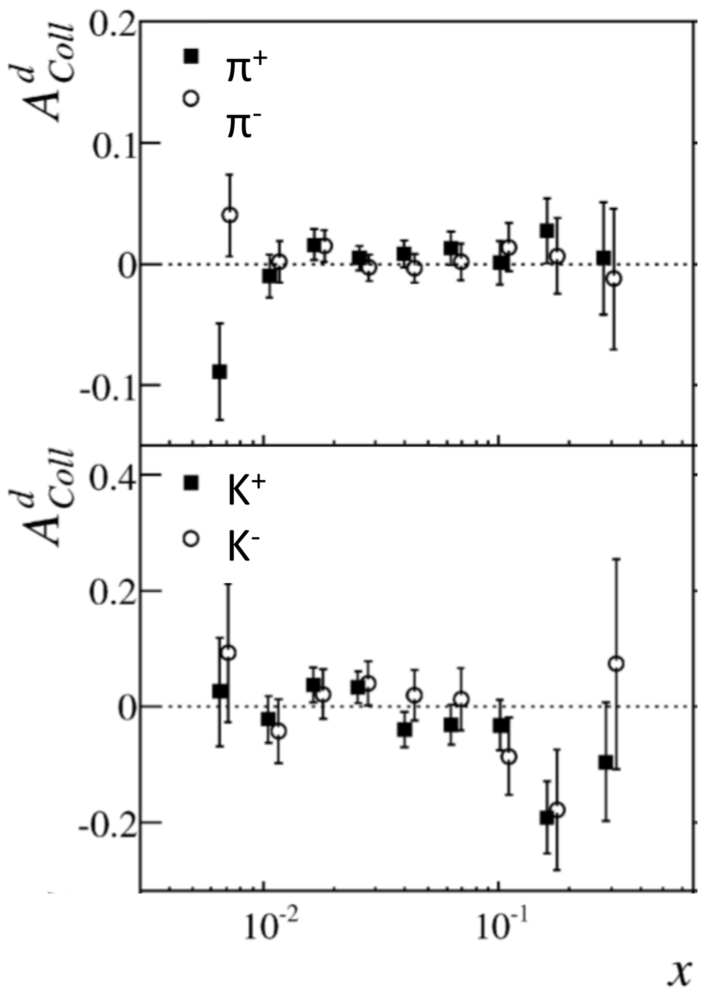
The SIDIS observable to access transversity

2004: non-zero values on p by HERMES
Compatible with zero on d by COMPASS

final COMPASS results

NPB765 2007
PLB673 2009





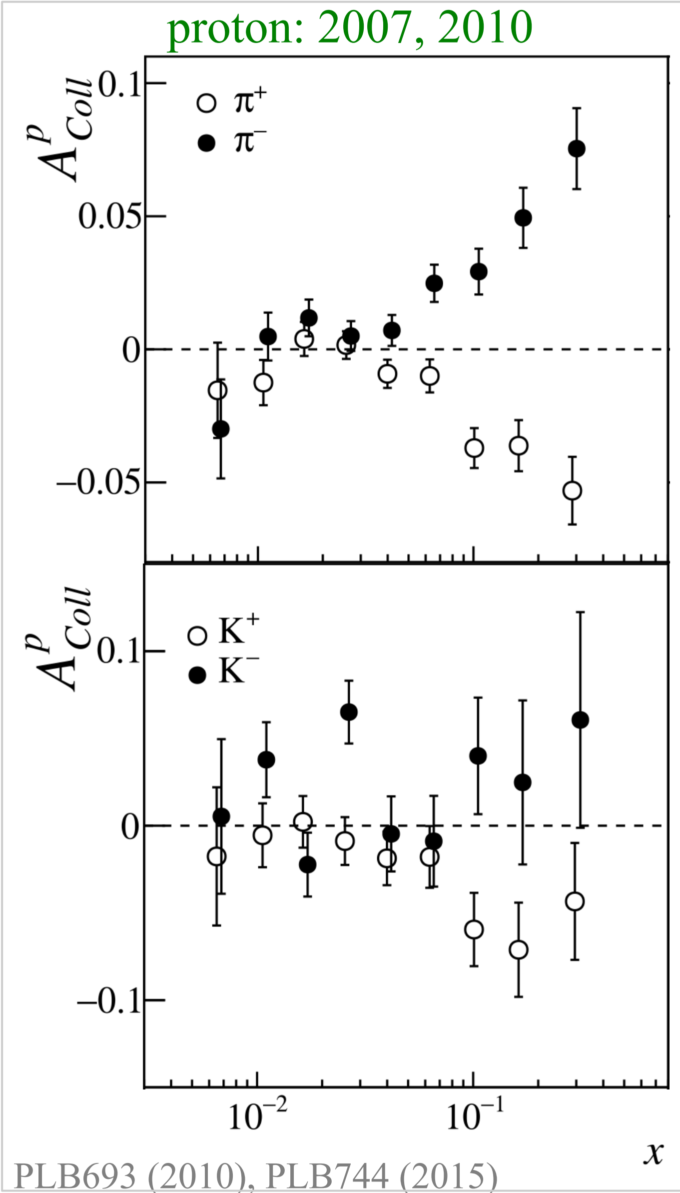
understood as
u-d cancellation

$h_1^u \sim -h_1^d$

Collins asymmetry $\sim h_1 \otimes H_1^\perp$

The SIDIS observable to access transversity

final COMPASS results



clear mirror symmetry for x>0.032

➛ opposite sign for favored & unfavored Collins FFs

negative trend for K^+ w/ increasing x

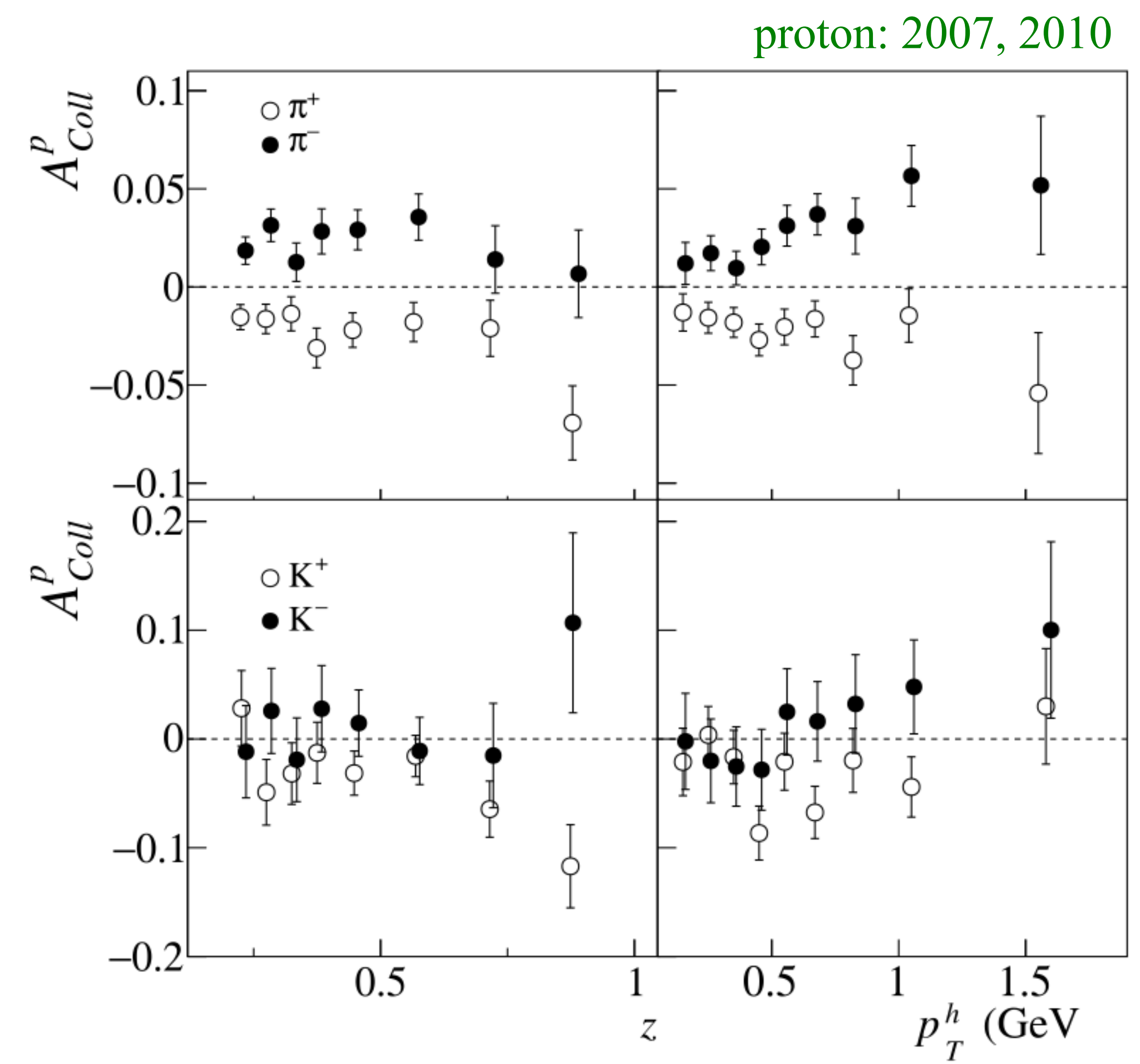
K^- positive on average

K^0 compatible with zero

Collins asymmetry $\sim h_1 \otimes H_1^{\perp}$

The SIDIS observable to access transversity

final COMPASS results



PLB693 (2010), PLB744 (2015)

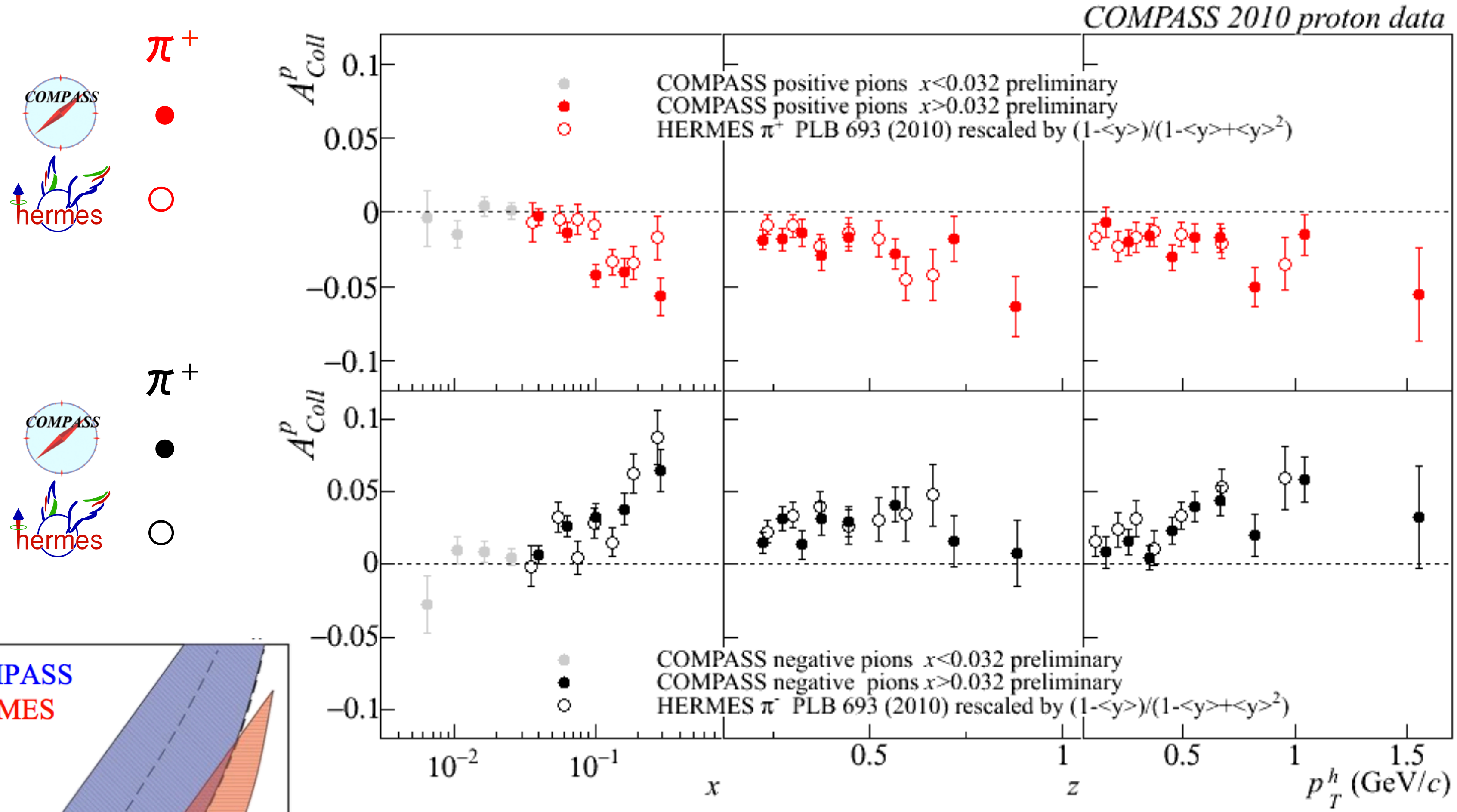
z, p_T dependence at
x > 0.032

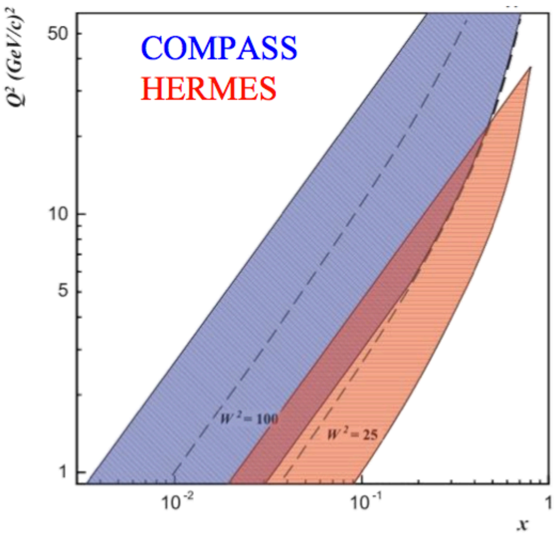
➛ sizeable w/ opposite sign signal for π

➛ although large statistical uncertainties, K^+ negative trend vs. z

➛ in good agreement with HERMES results.

Collins asymmetry: COMPASS vs. HERMES



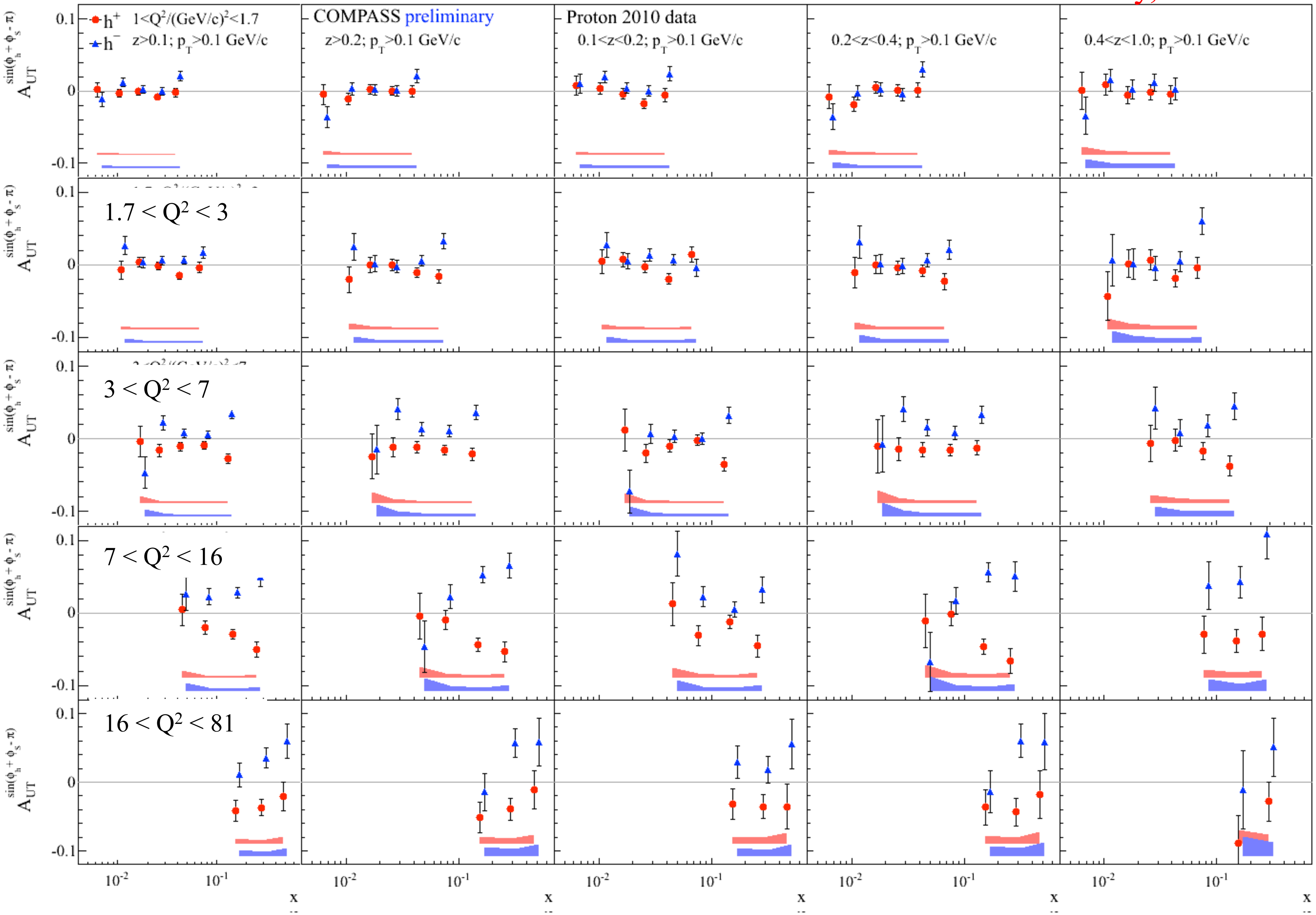


Intriguing observation: Different Q^2 by a factor of ~ 2-3

No Q^2 evolution ?

First extraction within a Multi-D (x:Q^2:z:p_T) approach

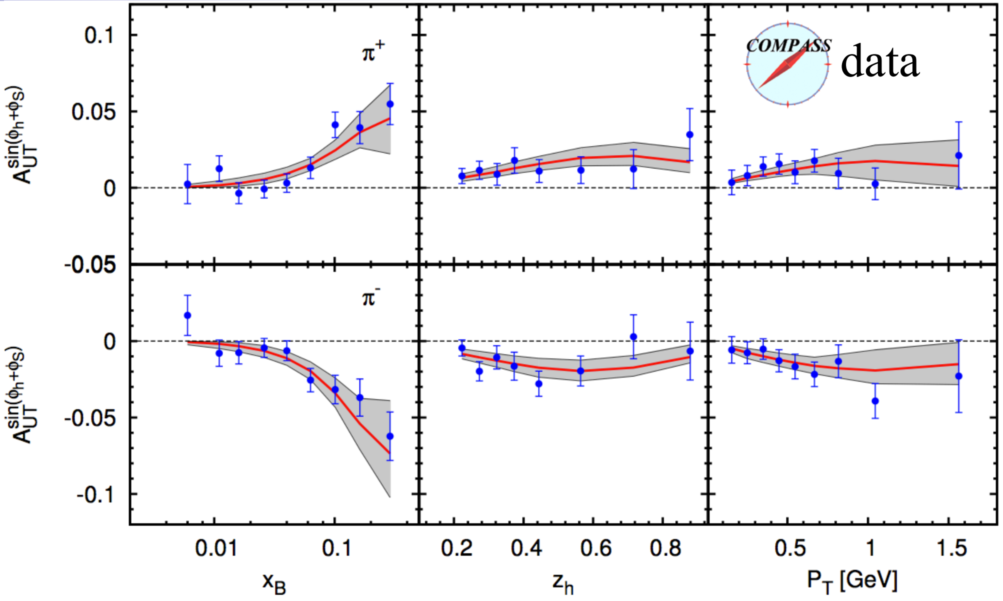
COMPASS Preliminary, SPIN2014



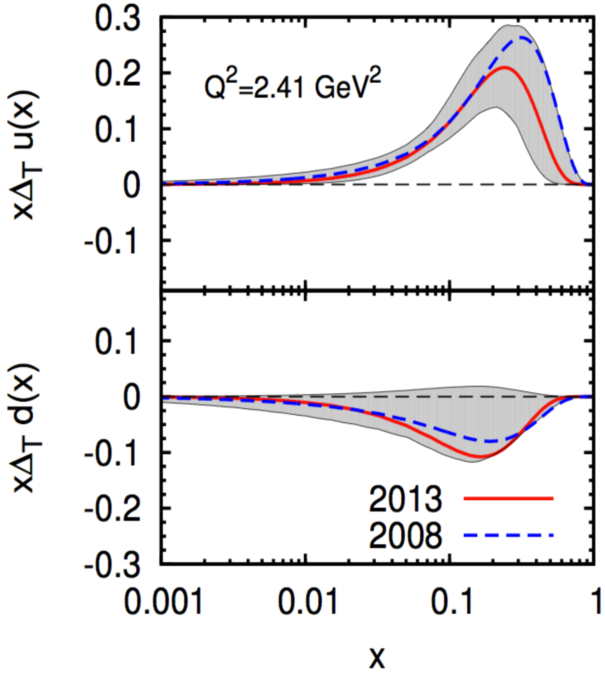
Transversity from Collins asymmetry

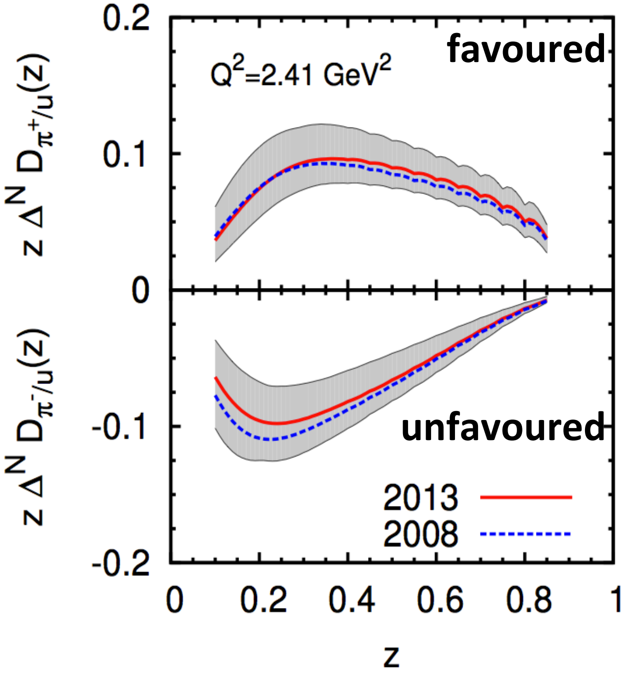
simultaneous fit of data from
HERMES (p)-COMPASS (p & d)-BELLE

transversity PDF and Collins FF



Anselmino et al., PRD 87 (2013)





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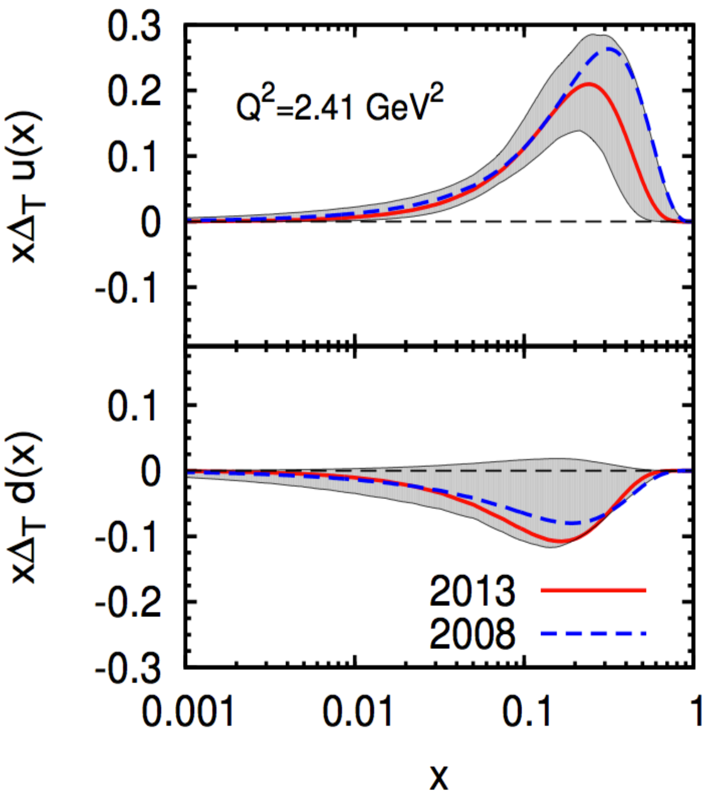
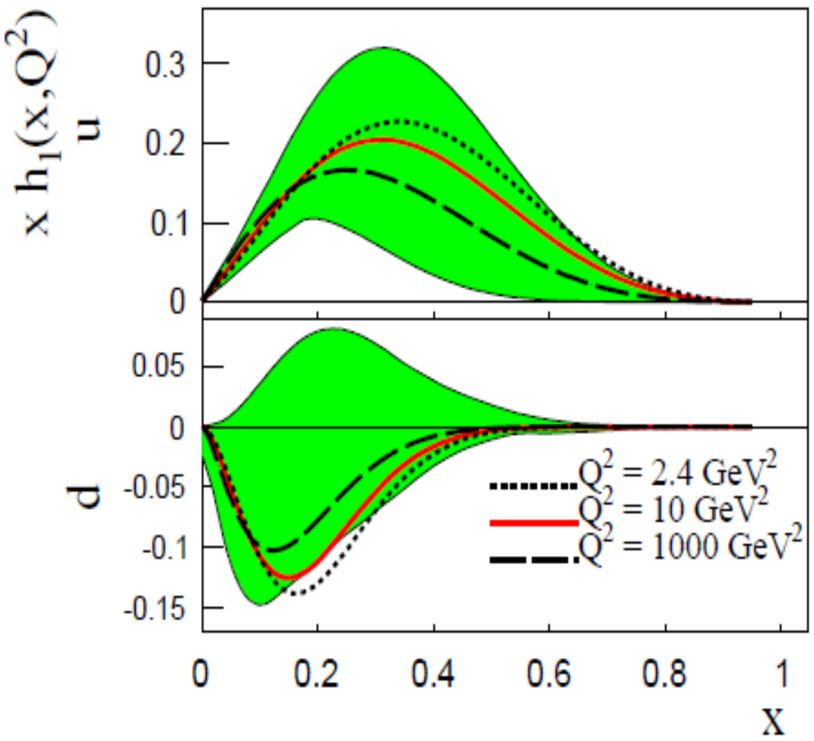


Kang et al, PRD91 (2015)

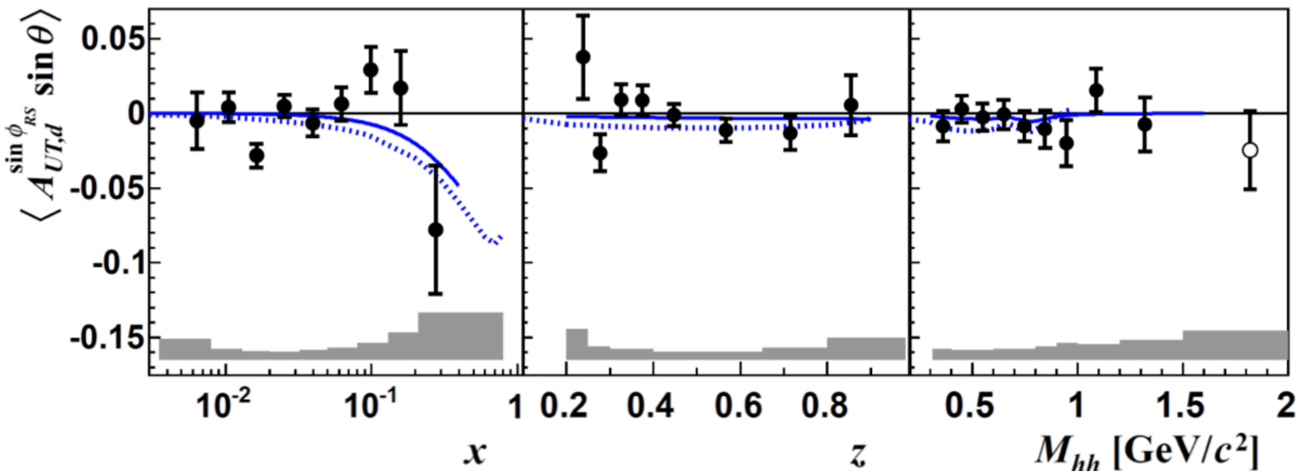


di-hadron asymmetry

alternative way to access transversity

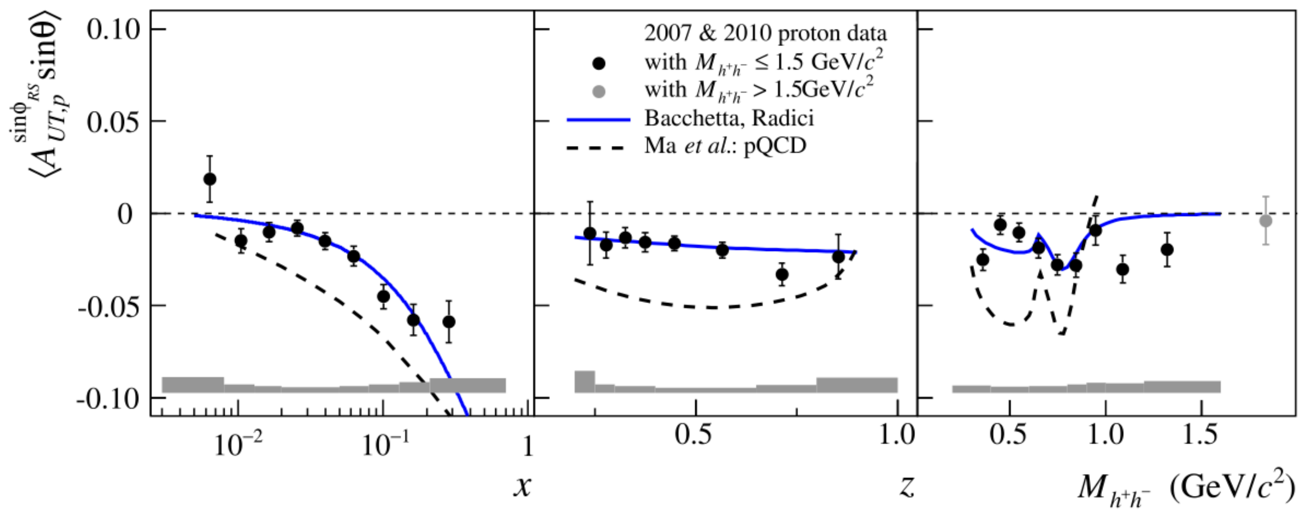
2008: first evidence for non-zero signal on p from HERMES

final COMPASS results



deuteron:
Compatible with zero

PLB 713 (2012)



proton:
same sign and shape
slightly higher
than Collins asymmetry
for h^+

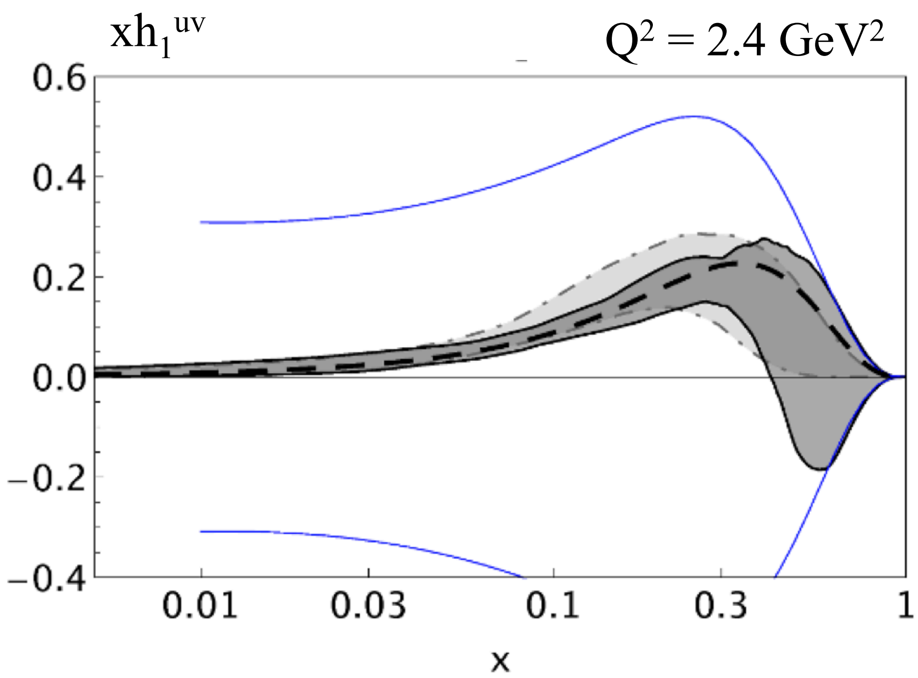
PLB 736 (2014)

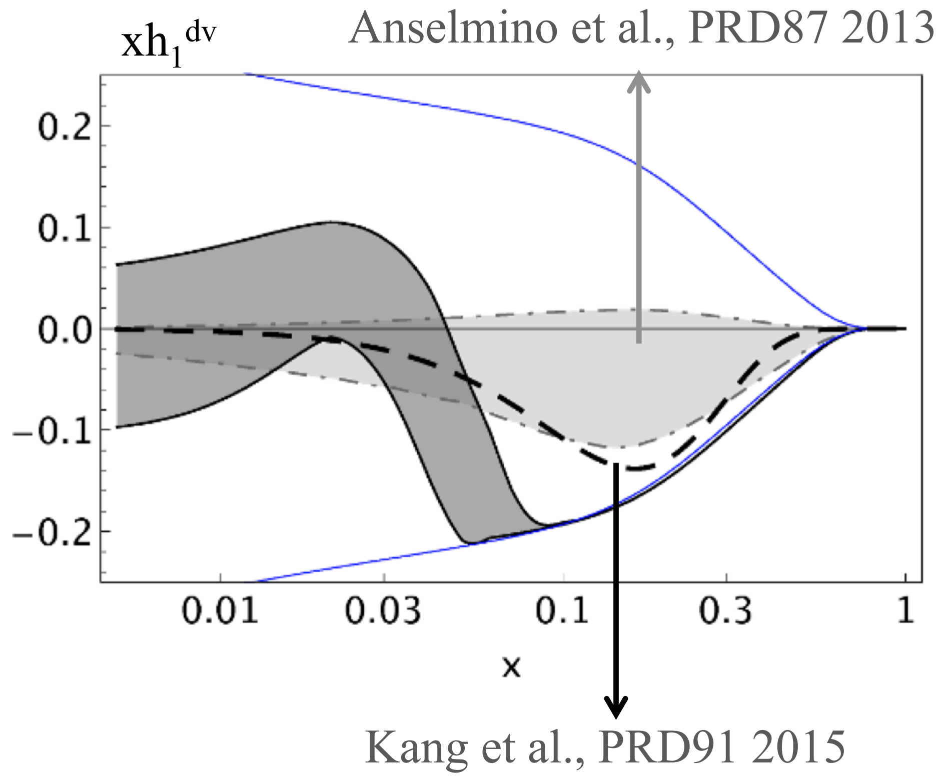
Transversity from di-hadron asymmetry

Fit of linear combinations from Hermes (p)-COMPASS (p & d)-BELLE data

D_q^{2h} from PHYTIA

Radici, Courtoy, Bacchetta, Guagnellia, JHEP 1505 (2015)



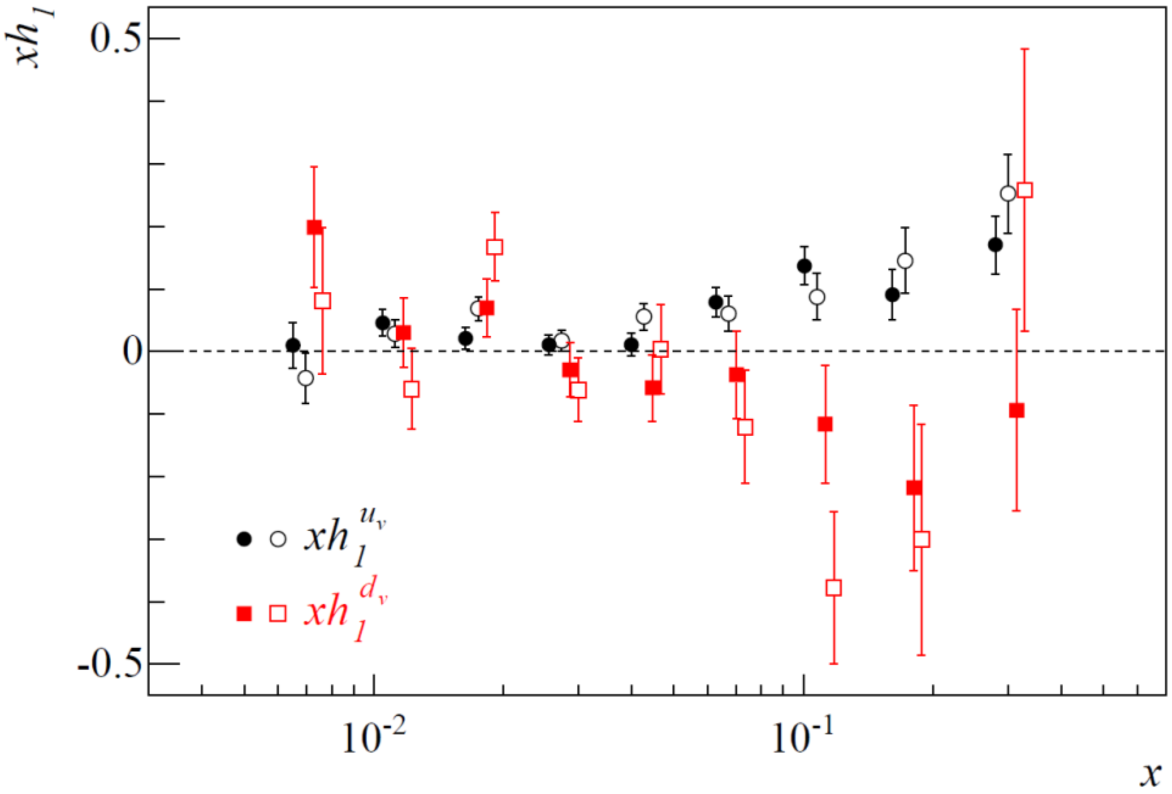


Transversity from Collins and di-hadron asymmetry

point by point extraction

Using the COMPASS p and d asymmetries, and the Belle data to evaluate the analyzing power (reasonable assumptions used)

No use of neither MC nor parameterization



open points: di-hadron
closed points: Collins

Martin, Bradamante, Barone
PRD91 (2015)

New speculations

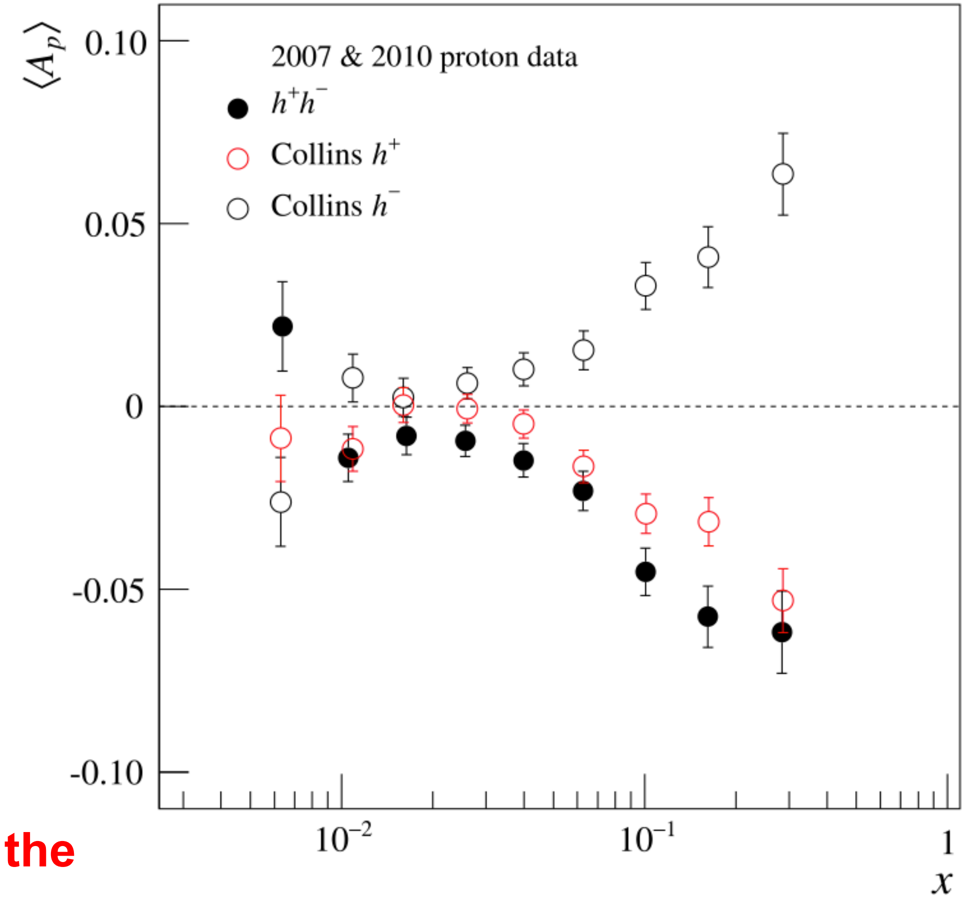
are the Collins and di-hadron asymmetries independent ?

PLB 736 2014

known intriguing final results;

- Collins asymmetry for h+ and for h-
  "mirror symmetry"

- di-hadron asymmetry
  only somewhat larger than h+ Collins



hints for a common origin of the Collins FF and DiFF ?

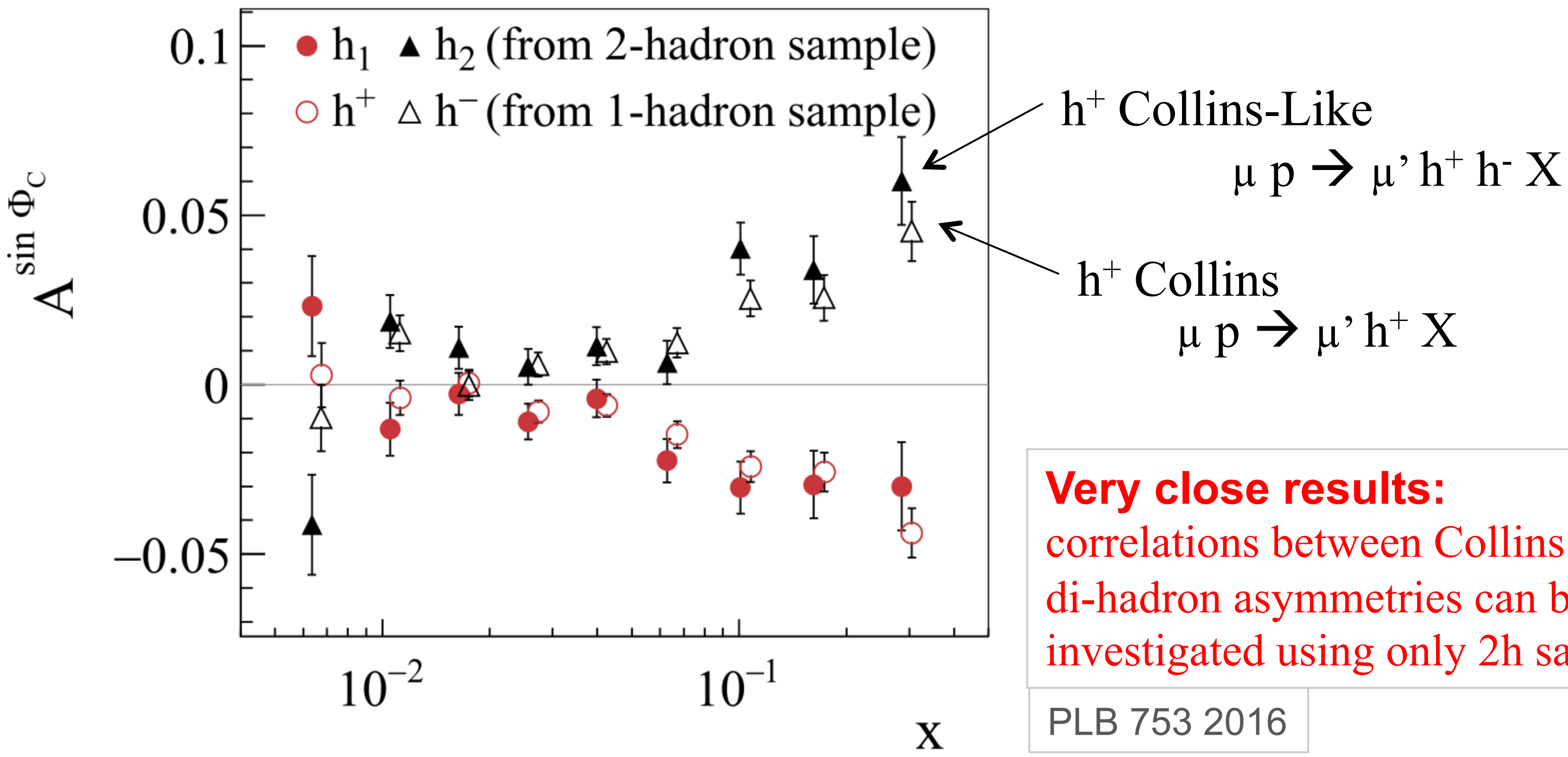
PLB 753 2016

Interplay between Collins and di-hadron asymmetries

1. Study of the dependence of the Collins asymmetry on the detection of other hadrons in the jet?

$\mu\, p \rightarrow \mu'\, h^+ X$ h^+ Collins asymmetry

$\mu\, p \rightarrow \mu'\, h^+ h^- X$ h^+ Collins-Like asymmetry
→ use of 2h sample



Very close results:
correlations between Collins and di-hadron asymmetries can be investigated using only 2h sample.

PLB 753 2016

Interplay between Collins and di-hadron asymmetries

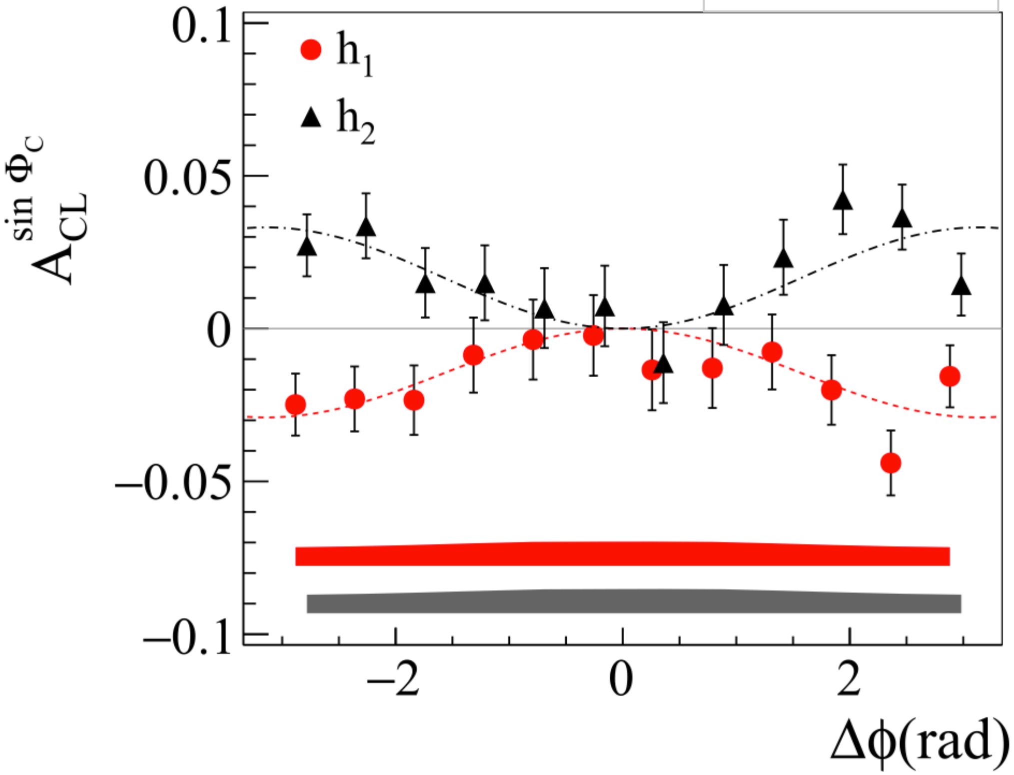
2. Correlations between h^+ and h^- CL asymmetries

as a function of x, they are mirror symmetric

as a function of $\Delta\Phi = \Phi_1 - \Phi_2$
They are expected to be
- mirror symmetric
- maximum at $\Delta\Phi = \pi$

confirmed by data

PLB 753 2016



Interplay between Collins and di-hadron asymmetries

2. Correlations between h$^+$ and h$^-$ CL asymmetries

analytical calculations, *A. Kotzionian, PRD91 2015*

$$\frac{d\sigma^{h_1 h_2}}{d\phi_1 d\phi_2 d\phi_S} = \sigma_U + S_T[\sigma_{C1}\sin(\phi_1+\phi_S-\pi)+\sigma_{C2}\sin(\phi_2+\phi_S-\pi)]$$

Change of variables $(\phi_1,\phi_2) \rightarrow (\phi_{1,2},\Delta\phi)$

$$A_{CL1} = \frac{1}{D_{NN}}\frac{\sigma_{C1}+\sigma_{C2}\cos\Delta\phi}{\sigma_U}$$

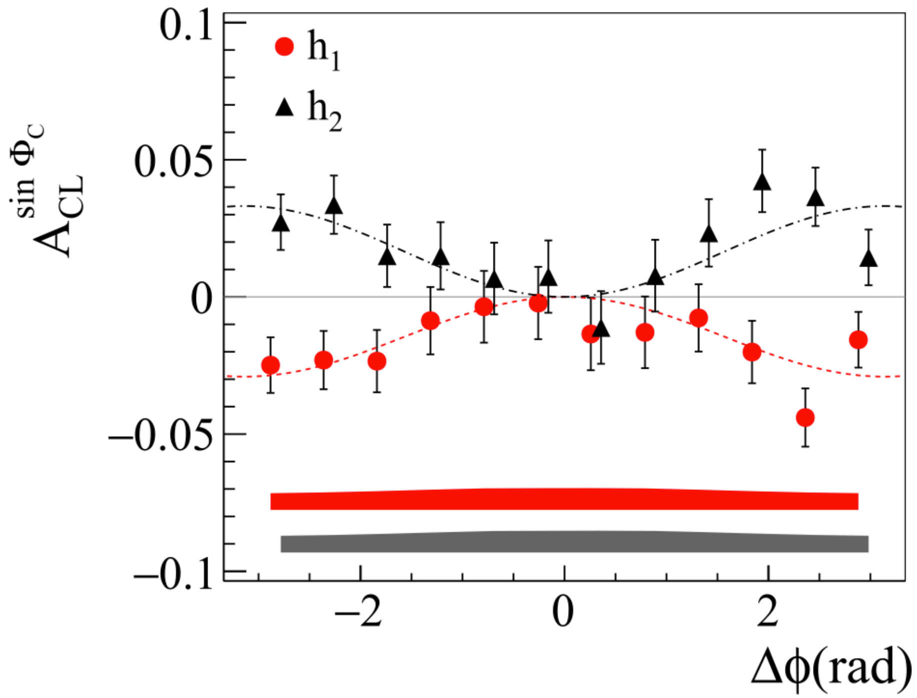
$$A_{CL2} = \frac{1}{D_{NN}}\frac{\sigma_{C2}+\sigma_{C1}\cos\Delta\phi}{\sigma_U}$$

agreement with the data if

$$\sigma_{C2} = -\sigma_{C1} \qquad i.e.$$

$$A_{CL1} = \frac{1}{D_{NN}}\frac{\sigma_{C1}}{\sigma_U}(1-\cos\Delta\phi)$$

$$A_{CL2} = -\frac{1}{D_{NN}}\frac{\sigma_{C1}}{\sigma_U}(1-\cos\Delta\phi) = -A_{CL1}$$



Interplay between Collins and di-hadron asymmetries

2. Correlations between h+ and h- CL asymmetries

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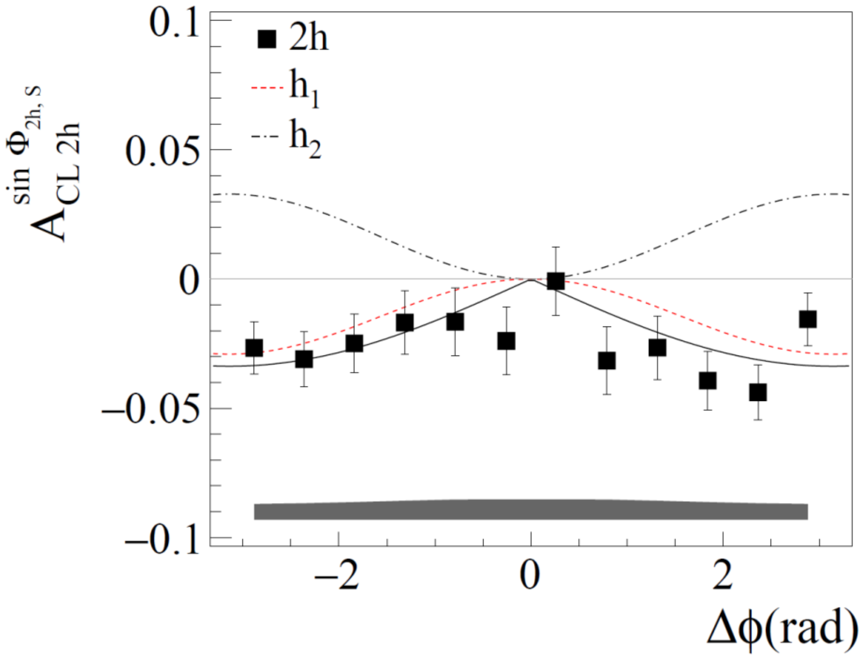
$$\frac{d\sigma^{h_1 h_2}}{d\phi_1 d\phi_2 d\phi_S} = \sigma_U + S_T[\sigma_{C1}\sin(\phi_1+\phi_S-\pi) + \sigma_{C2}\sin(\phi_2+\phi_S-\pi)]$$

$\sigma_{C2} = -\sigma_{C1}$; *Change of variables* $(\phi_1,\phi_2) \to (\Phi_{2h}\ \Delta\phi)$

$$\boxed{A_{2h} = \frac{1}{D_{NN}}\frac{\sigma_{C1}}{\sigma_U}\sqrt{2(1-\cos\Delta\phi)}}$$

a simple relationship between di-hadron and single hadron asymmetries in the 2h sample

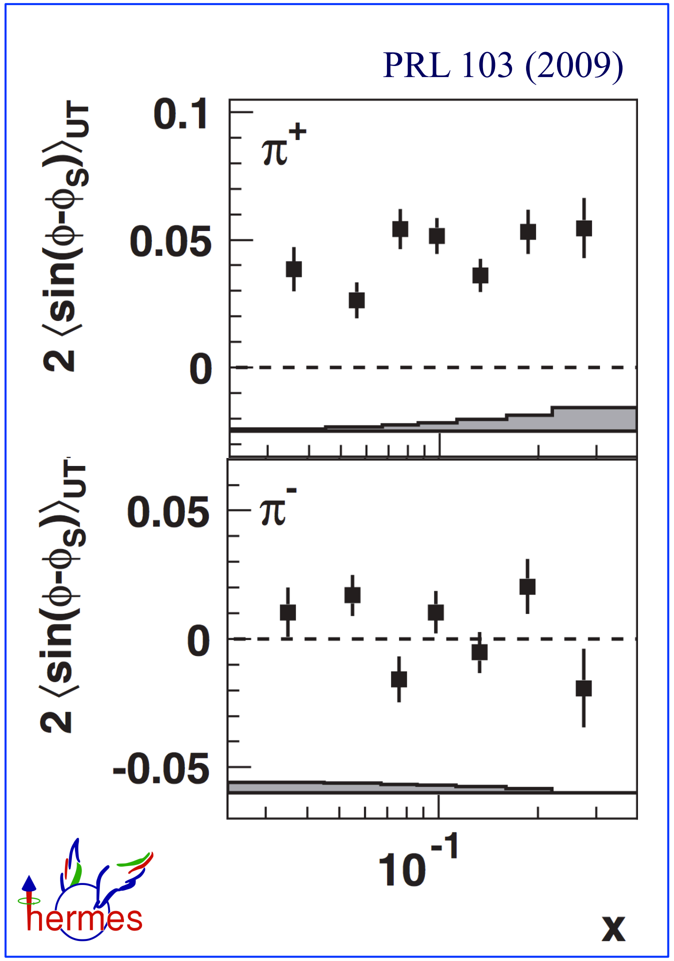


in agreement with data

"a common origin"

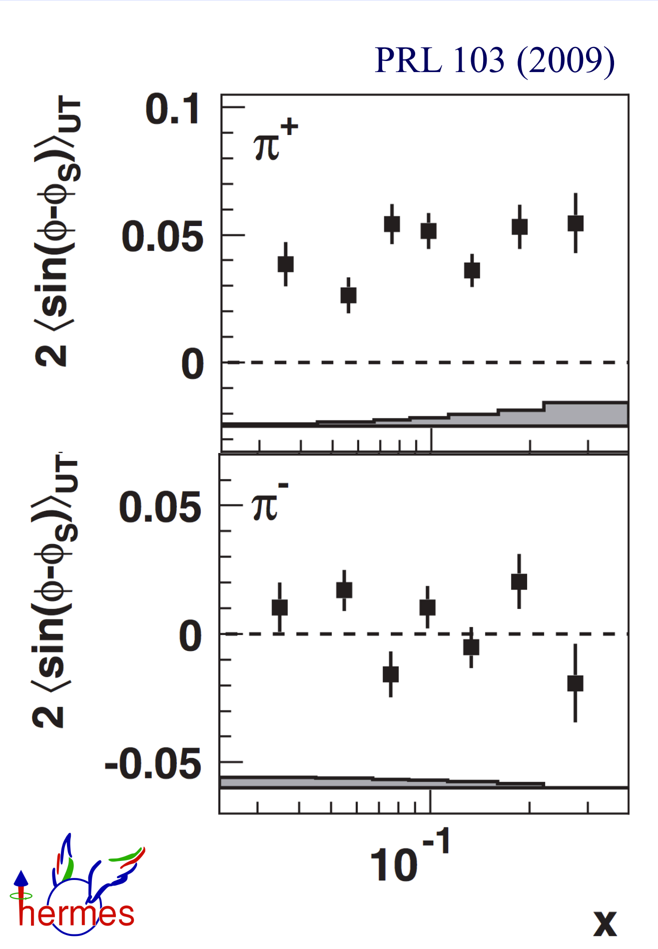
Sivers Asymmetry $\sim f_{1T}^{\perp} \otimes D_1$

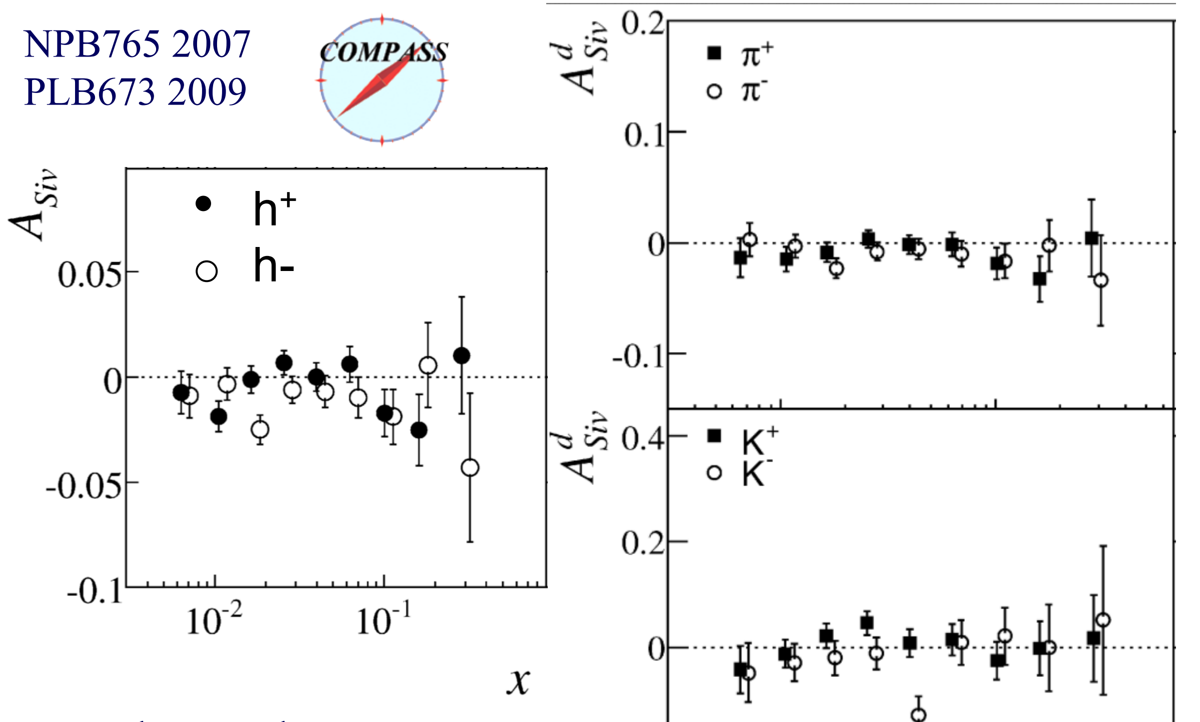
2004: First evidence for non-zero values on p by HERMES



Sivers Asymmetry $\sim f_{1T}^{\perp} \otimes D_1$

2004: First evidence for non-zero values on p by HERMES
Compatible with zero on d by COMPASS (2002-04)





understood as
u-d cancellation

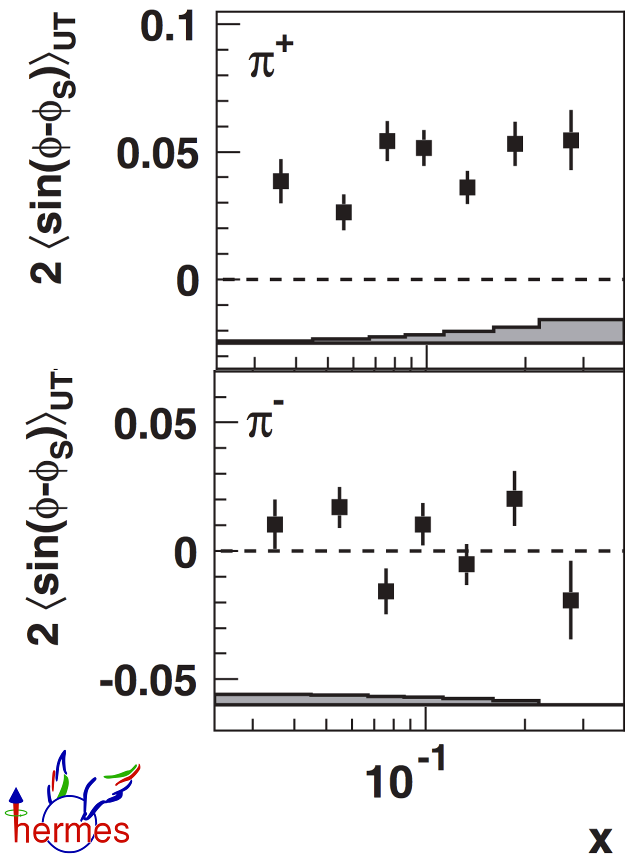
$$f_{1T,u}^{\perp} \approx -f_{1T,d}^{\perp}$$

Sivers Asymmetry $\sim f_{1T}^{\perp} \otimes D_1$

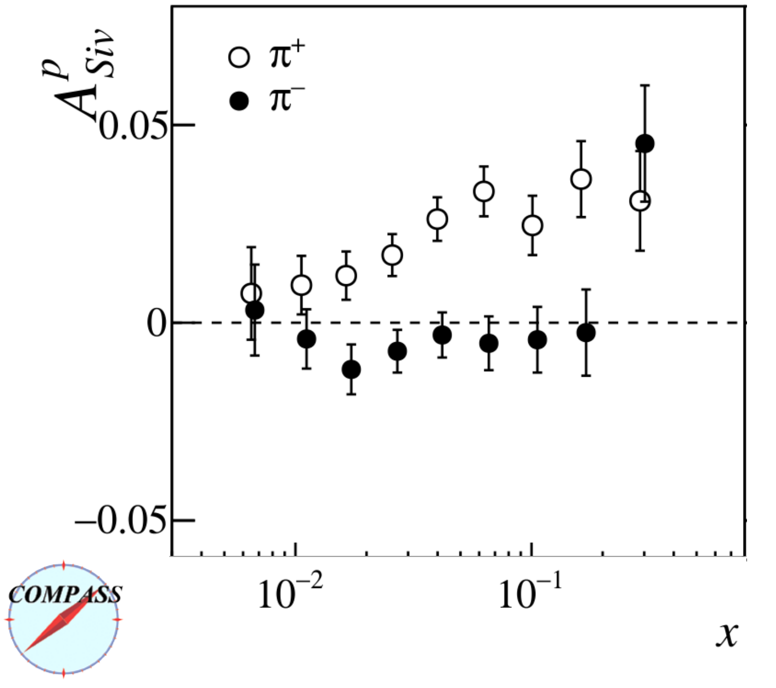
2004: First evidence for non-zero values on p by HERMES
Compatible with zero on d by COMPASS (2002-04)

COMPASS measurements on proton 2007/10

PRL 103 (2009)

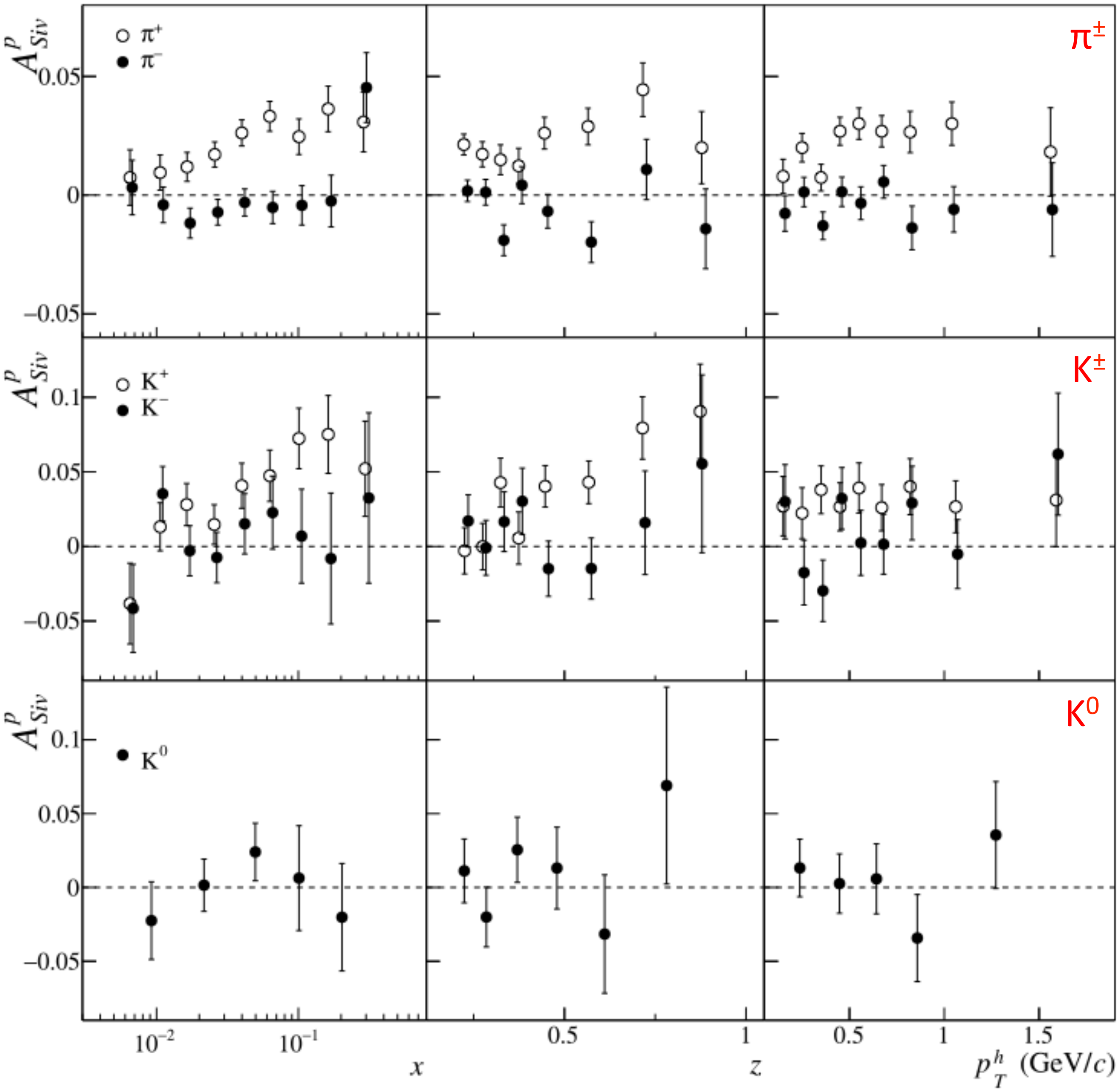


PLB 744 (2015)



clearly positive for π^+ down to x ~ 10^{-2}

Sivers Asymmetry $\sim f_{1T}^{\perp} \otimes D_1$



PLB 744 (2015)

- vs. x, z, p_T
- for π , K, K^0

~ zero asym. for $\pi^-/K^-/K^0$

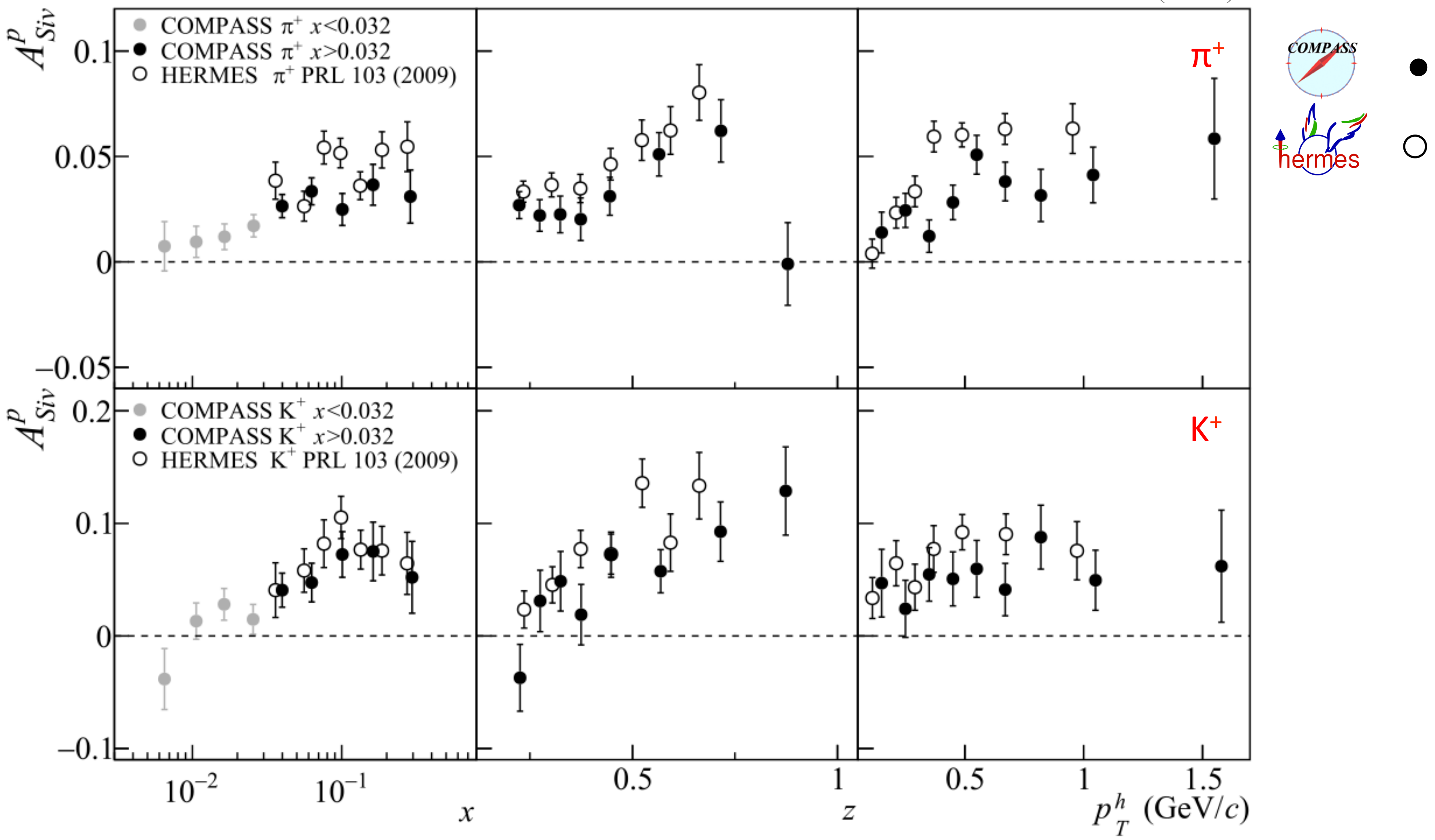
positive signal for π^+/K^+

- over full x
- increase with z

- larger for K^+ than for π^+ as for HERMES
  ➛ non negligible role of sea quarks

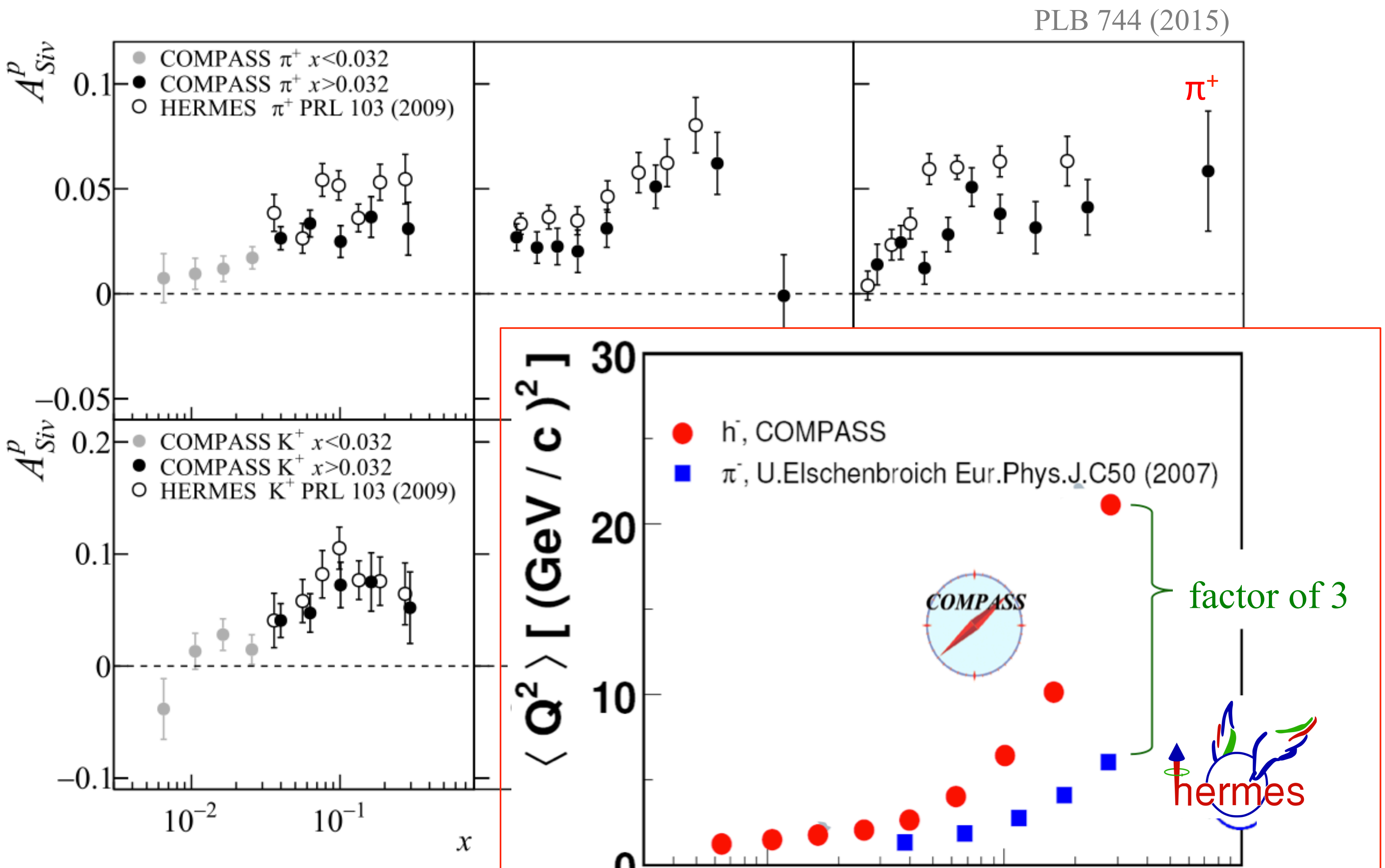
Sivers Asymmetry: COMPASS vs. HERMES

PLB 744 (2015)



COMPASS asymmetries smaller than HERMES asymmetries…

Sivers Asymmetry: COMPASS vs. HERMES



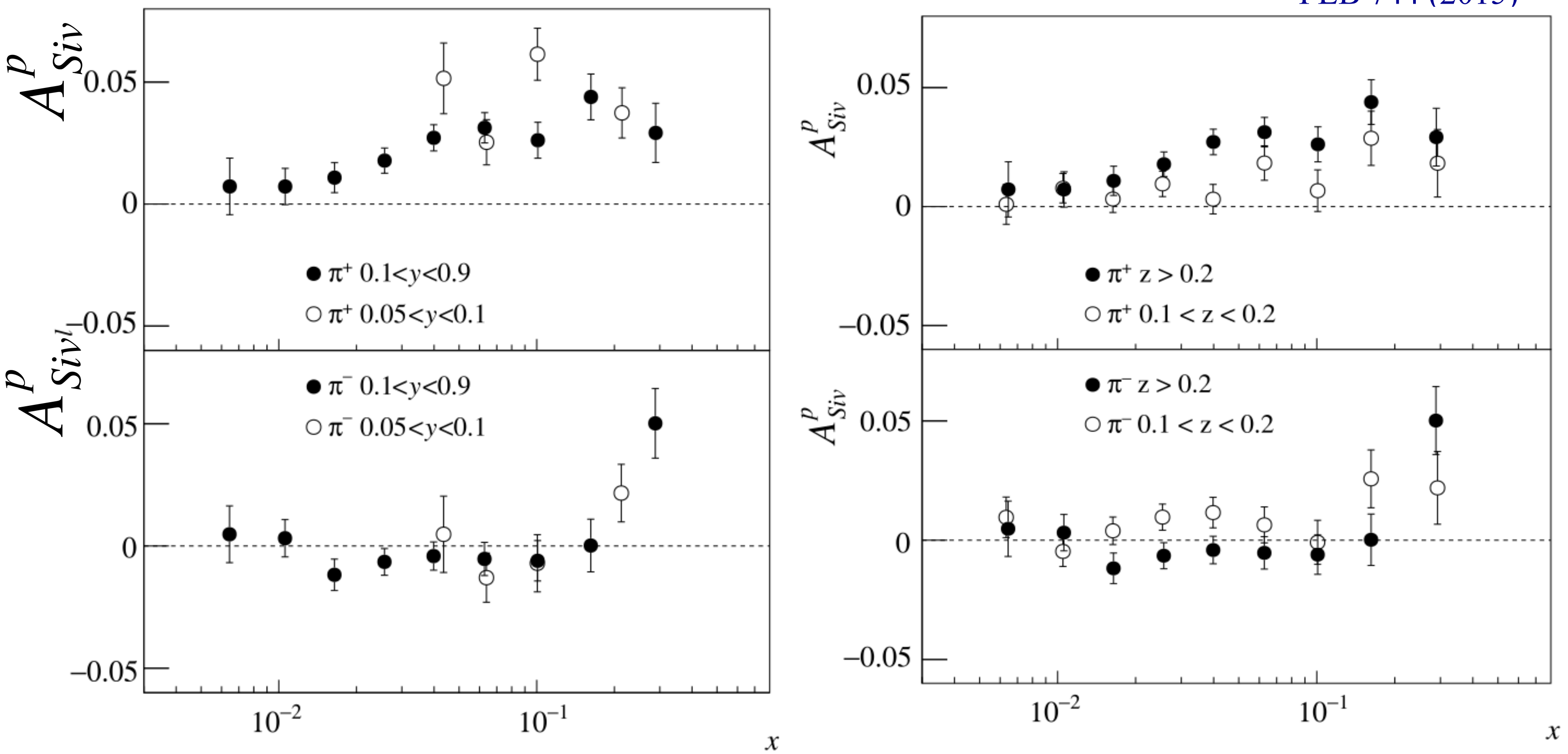
COMPASS asymmetries smalle

TMD Q^2 evolution

Sivers Asymmetry $\sim f_{1T}^{\perp} \otimes D_1$

Sivers in extended kinematic ranges low y / low z

PLB 744 (2015)

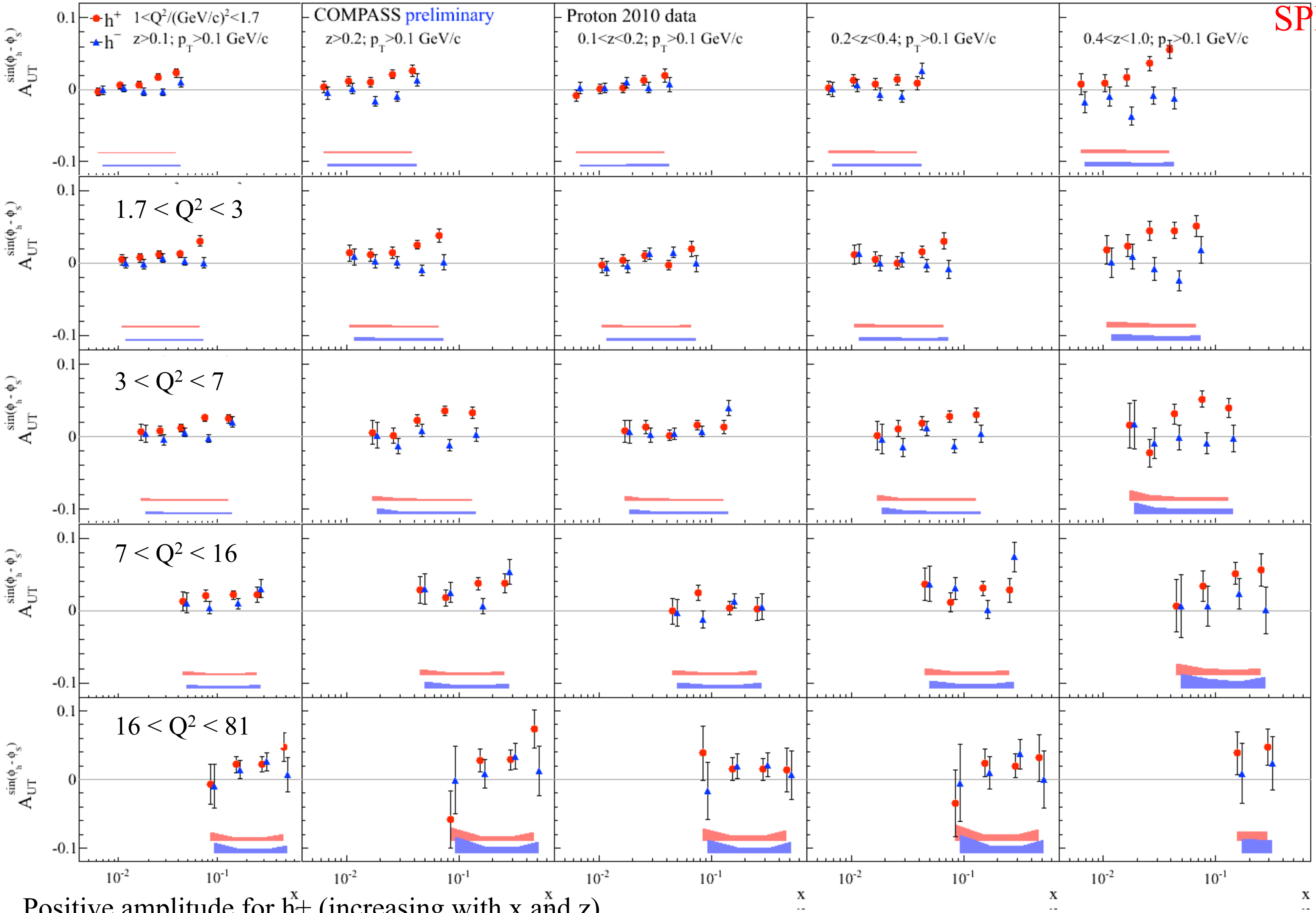


- increase of π^+ asym. at low y
- smaller values for π^+
- Positive signal for π^-

look into asymmetries
in a full multidimensional phase-space over $x - z - p_T - Q^2$

First extraction within a Multi-D (x:Q^2:z:p_T) approach

COMPASS Preliminary
SPIN2014

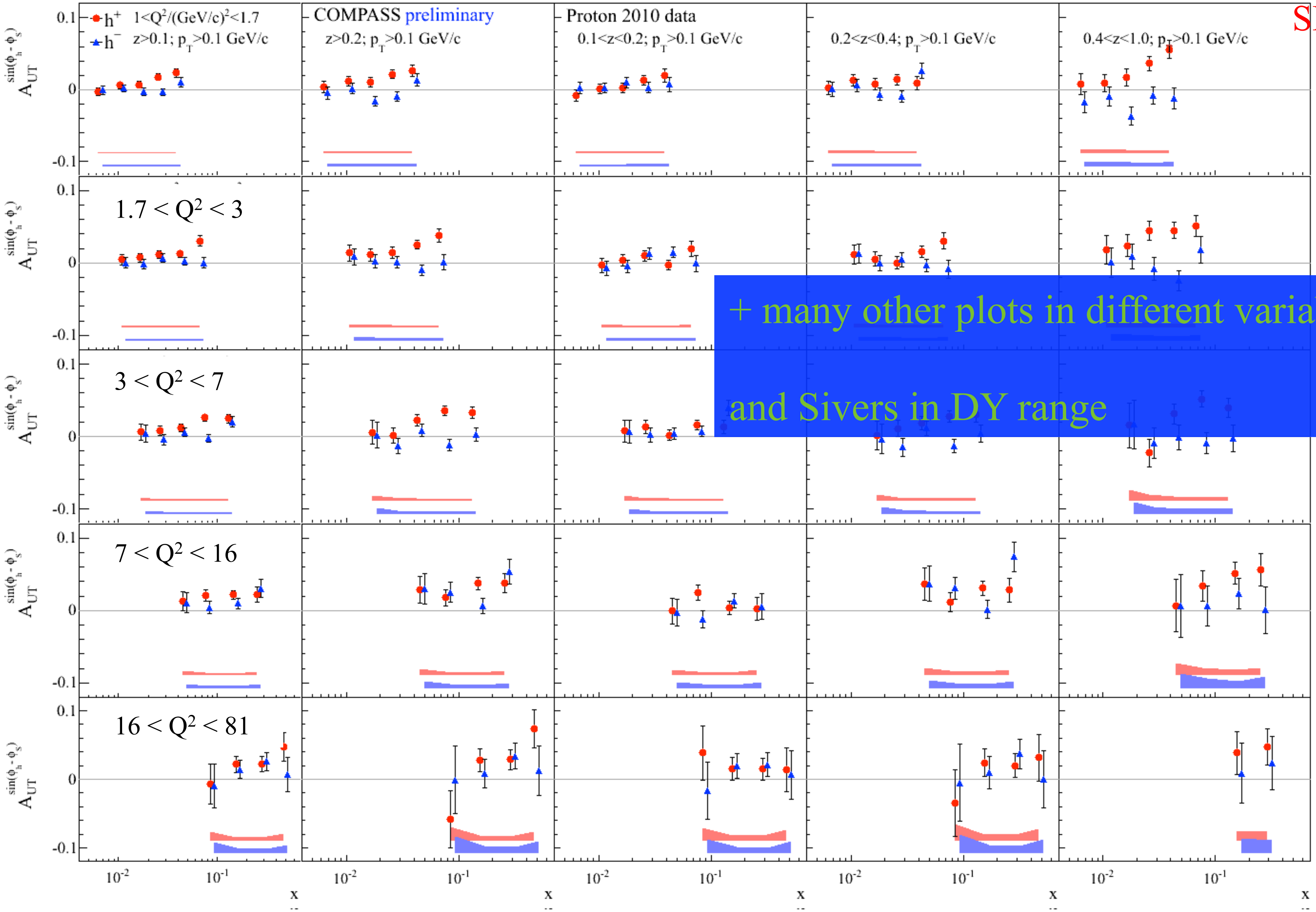


Positive amplitude for h+ (increasing with x and z)

Positive amplitude for h^- at relatively large x (>0.032) and Q2 (>7) at intermediate and large z

First extraction within a Multi-D (x:Q^2:z:p_T) approach

COMPASS Preliminary
SPIN201



+ many other plots in different variable

and Sivers in DY range

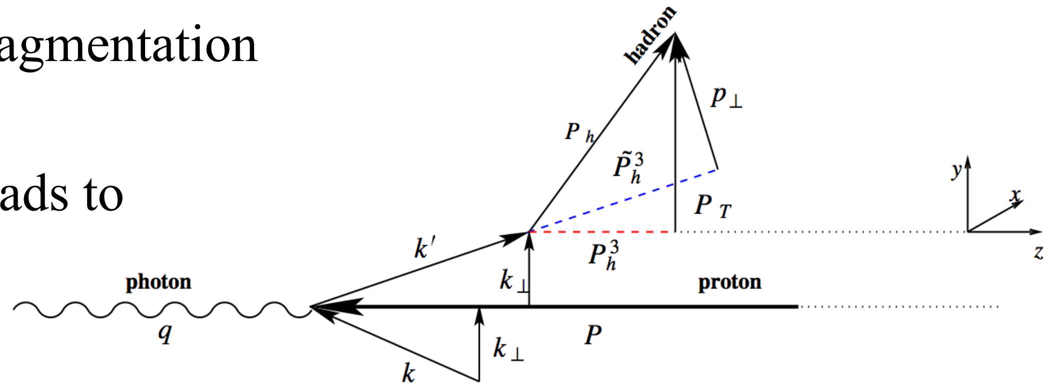
Relevance of Unpolarized SIDIS for TMDs

The cross-section dependence on p_T 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

$$<p_T^2> = <p_\perp^2> + z^2<k_\perp^2>$$



PRD 71, 074006, (2005)

The azimuthal modulations in the unpolarized cross-section result from

- intrinsic $k_\perp$ of the quarks
- The Boer-Mulders PDF
- …

Combined analysis allow to disentangle the different effects

Complicated measurements where one has to correct for the apparatus acceptance

Relevance of Unpolarized SIDIS for TMDs

The cross-section dependence on p_T results from:

- intrinsic $k_\perp$ of the quarks
- $p_\perp$ generated in the quark fragmentation

A Gaussian ansatz for $k_\perp$ *and* $\mathrm{p}_\perp$ leads to

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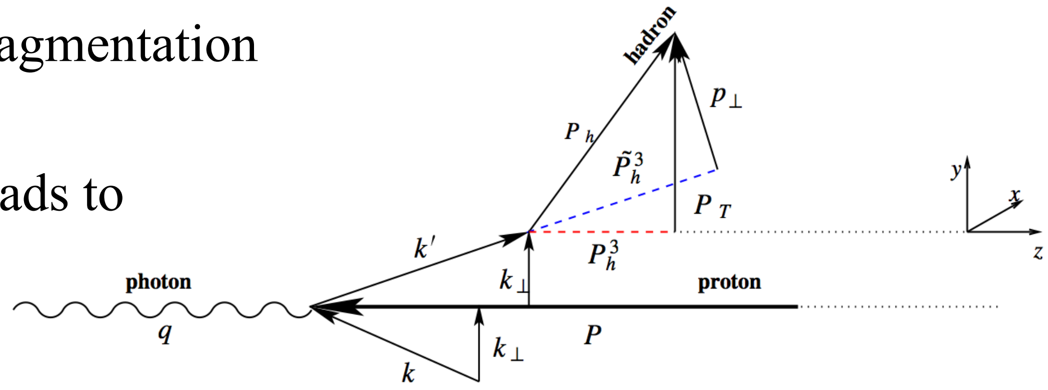


PRD 71, 074006, (2005)

The azimuthal modulations in the unpolarized cross-section result from

- intrinsic $k_\perp$ of the quarks
- The Boer-Mulders PDF
- …

COMPASS

- has produced results on d from 2004/6 data
- will measure SIDIS on LH_2 in parallel with DVCS

Cahn/Boer-Mulders from azimuthal asymmetries

SIDIS cross-section for unpolarized nucleon

$$\frac{d\sigma}{dx_B dy dz_h dP_T^2 d\phi} = \frac{\pi\alpha^2}{Q^2 x_B y}\left\{(1+(1-y)^2)F_{UU} + 2(2-y)\sqrt{1-y}F_{UU}^{\cos\phi}\cos\phi + 2(1-y)F_{UU}^{\cos(2\phi)}\cos(2\phi)\right\}$$

$$F_{UU}^{\cos\phi} = -2\sum_q e_q^2 x \int d^2\boldsymbol{k}_\perp \frac{(\boldsymbol{k}_\perp \cdot \boldsymbol{h})}{Q} f_q(x, k_\perp) D_q(z, p_\perp)$$

Cahn effect
kinematical effect due to quark intrinsic transverse momentum

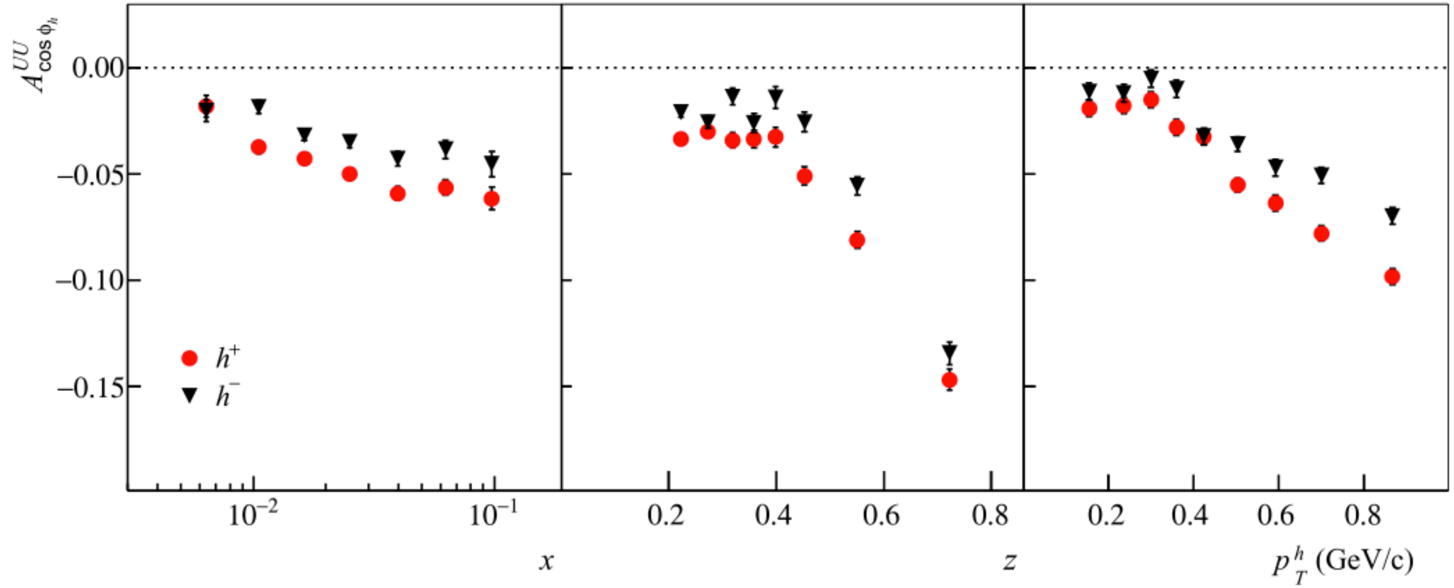
$$+ \sum_q e_q^2 x \int d^2\boldsymbol{k}_\perp \frac{k_\perp}{Q} \frac{P_T - z(\boldsymbol{k}_\perp \cdot \boldsymbol{h})}{p_\perp} \times \Delta f_{q^\uparrow/p}(x, k_\perp) \Delta D_{h/q^\uparrow}(z, p_\perp).$$

Boer-Mulders PDF
correlation between transverse spin and transverse momentum of quarks inside unpolarized proton

$$F_{UU}^{\cos 2\phi}|_{BM} = -\sum_q e_q^2 x \int d^2\boldsymbol{k}_\perp \frac{P_T(\boldsymbol{k}_\perp \cdot \boldsymbol{h}) + z_h[k_\perp^2 - 2(\boldsymbol{k}_\perp \cdot \boldsymbol{h})^2]}{2k_\perp p_\perp} \times \Delta f_{q^\uparrow/p}(x, k_\perp) \Delta D_{h/q^\uparrow}(z, p_\perp).$$

Only Boer-Mulders contribution
+ Cahn effect (twist 4, $1/Q^2$)

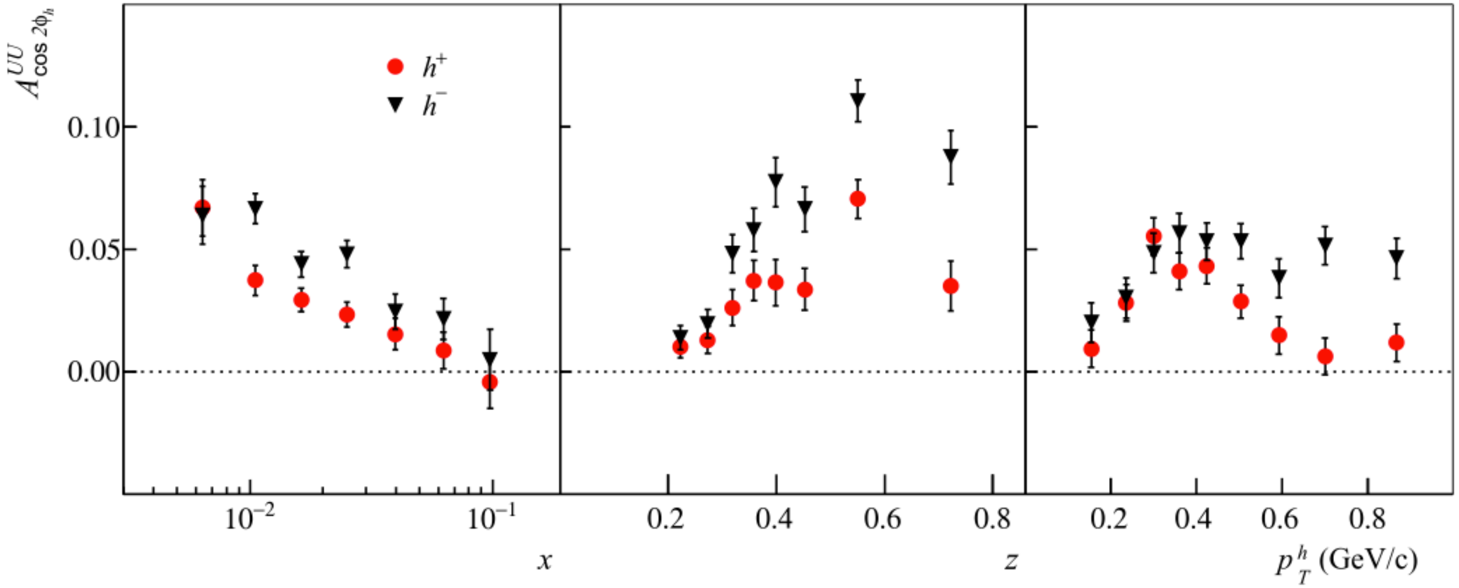
x, z, p_T dependencies



Large, negative
Larger for h^+

Strong kinematic dependencies z,p_T

Almost constant
up to z ~ 0.5
up to p_T ~ 0.4



Large, positive
Larger for h^+

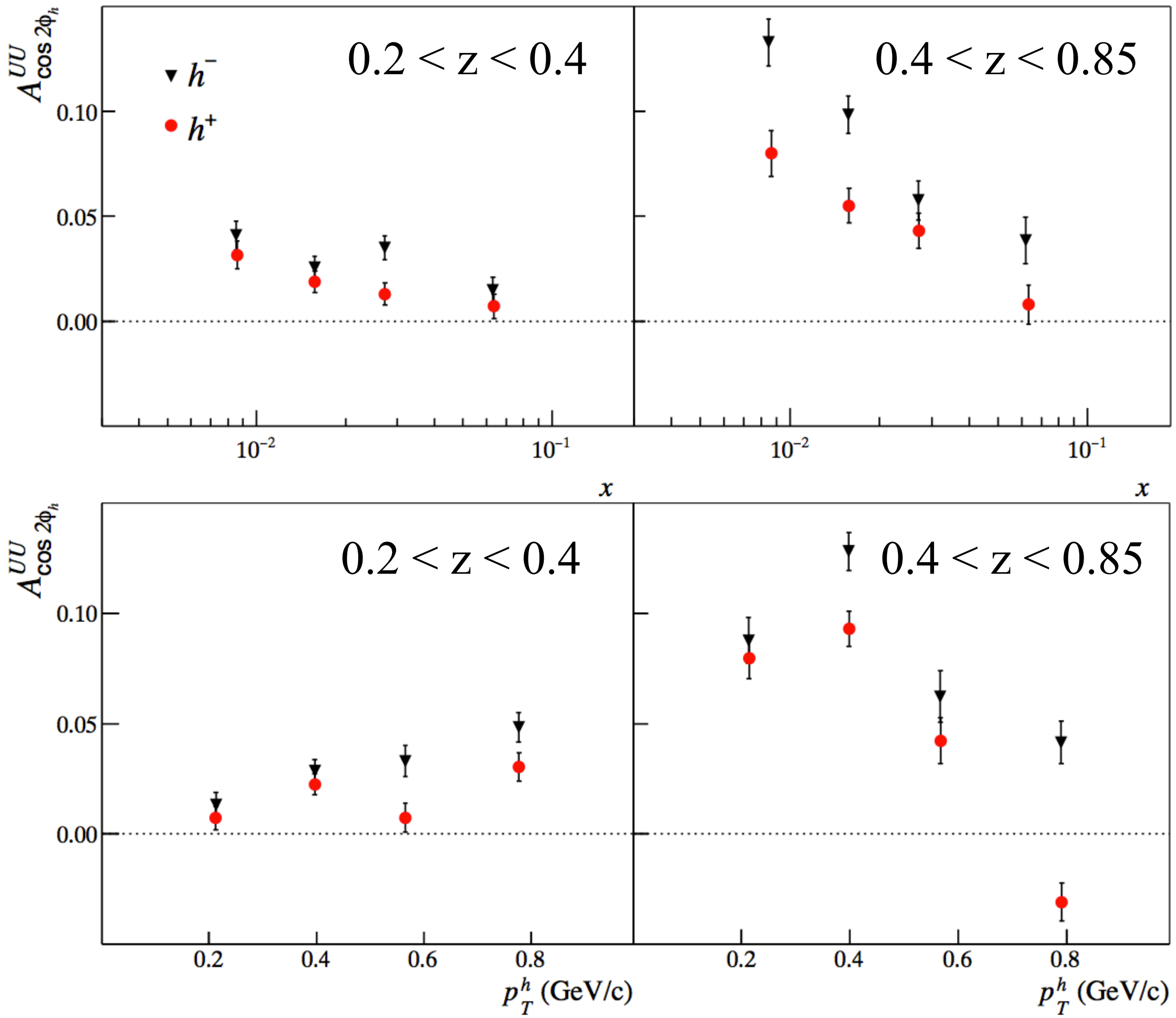
Strong kinematic dependencies z,p_T

Increases
up to z ~ 0.6
up to p_T ~ 0.4

NPB886 2014

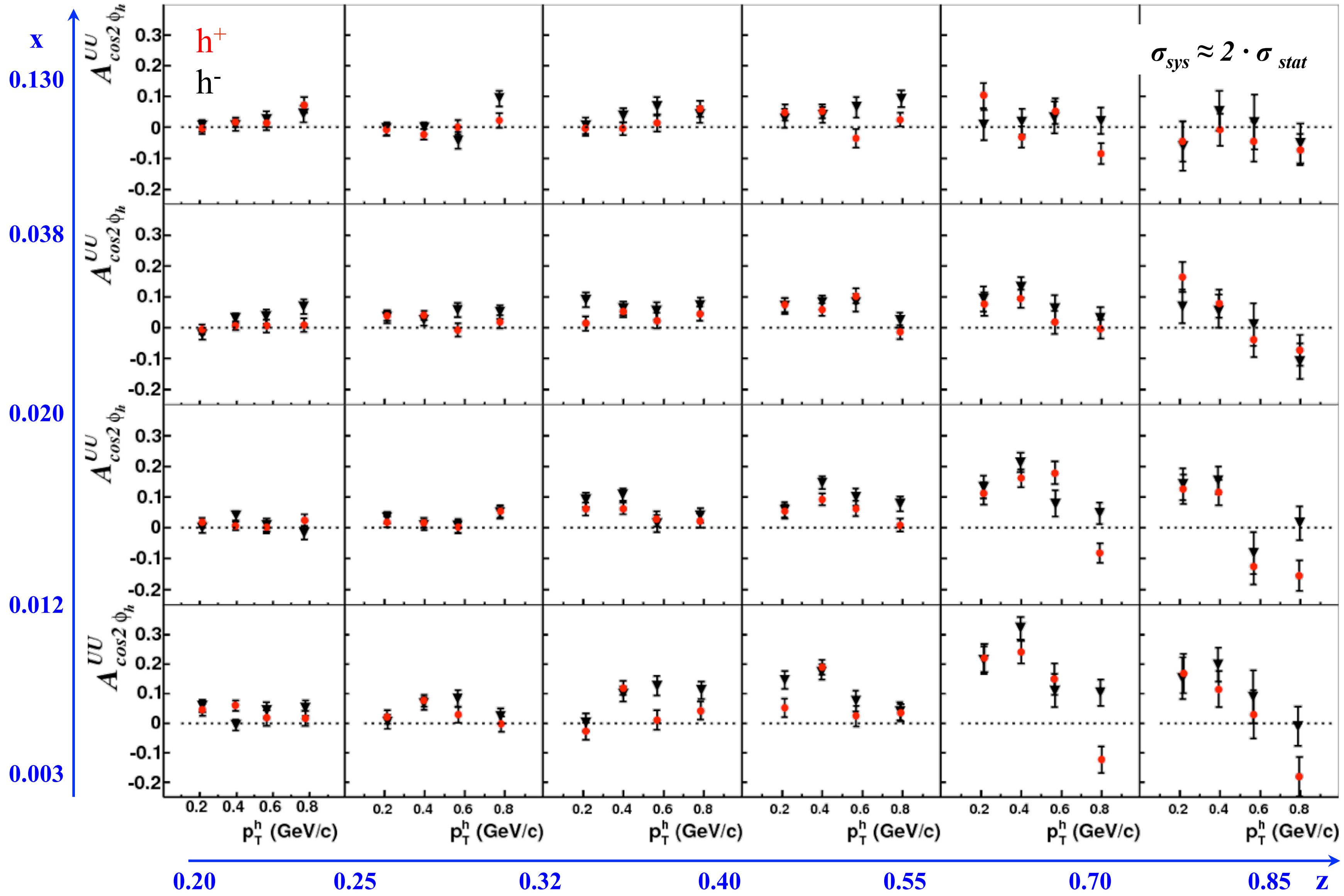
$A_{UU}^{\cos 2\Phi}$ asymmetry: x and p_T dependencies

CERN-PH-EP-2014-009



⇒ Different x and p_T^2 dependencies for different z regimes …

$A_{UU}^{\cos 2\Phi}$ asymmetry: x and p_T dependencies

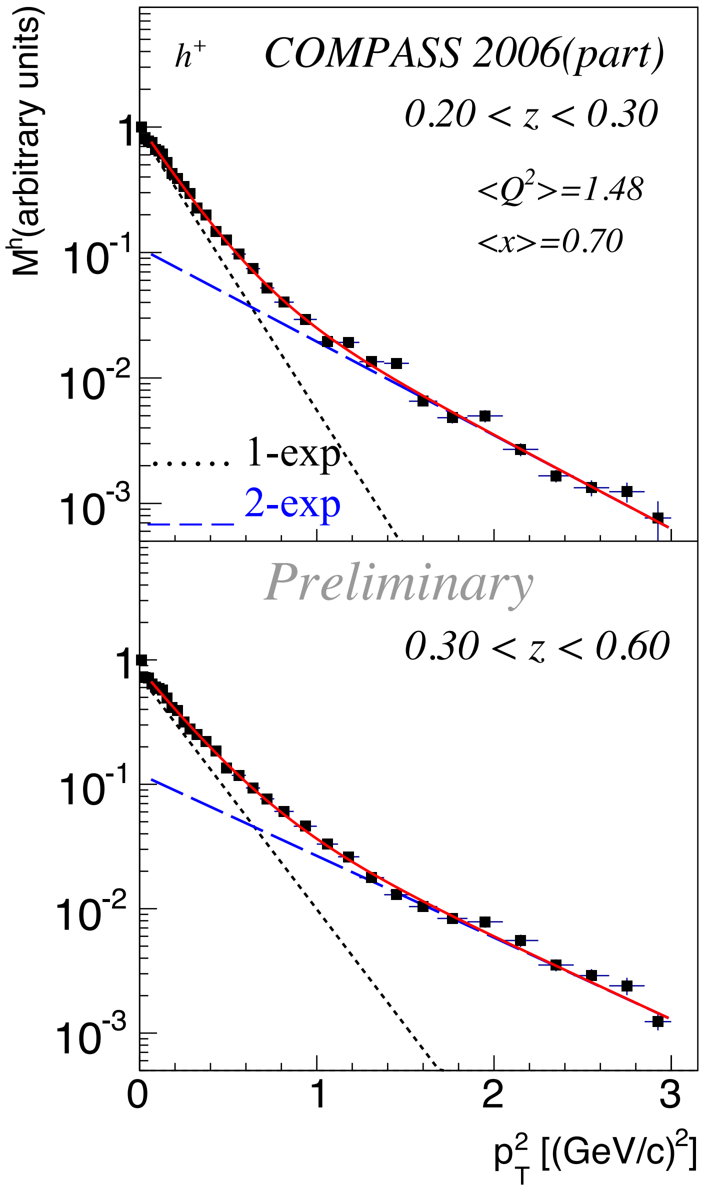


Barone et al., PRD91 2015

p_T trend arises at large z and low x

hard work to extract BM and $k_\perp$, multiplicities used…

h^+ distributions vs. p_T^2



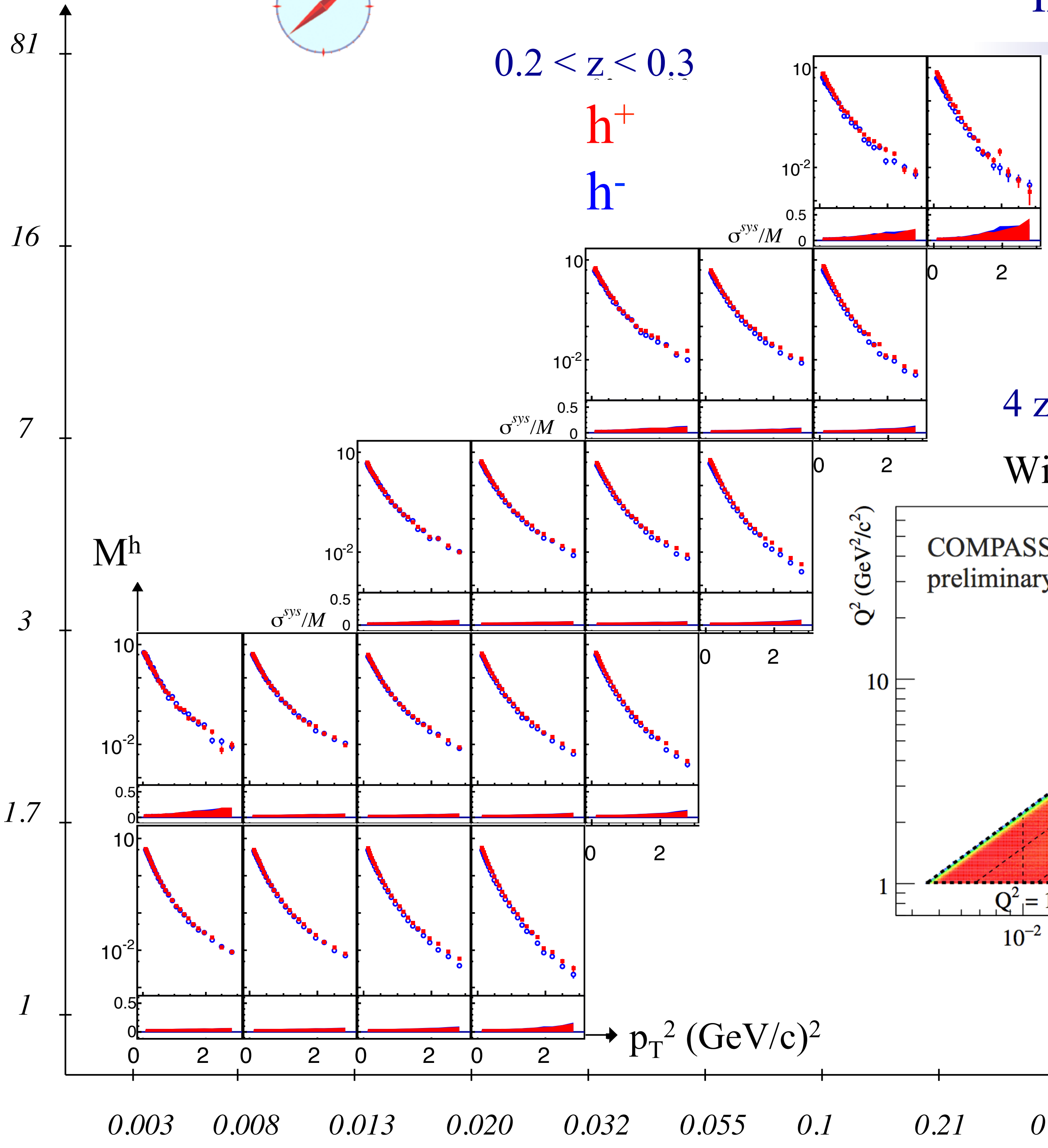
Fit multiplicities with

- 1 exponential for $p_T^2 \in [0.05, 0.68]$
- 2 exponentials for $p_T^2 \in [0.05, 3]$

Need 2-exponentials to describe the p_T^2 shape of the COMPASS data

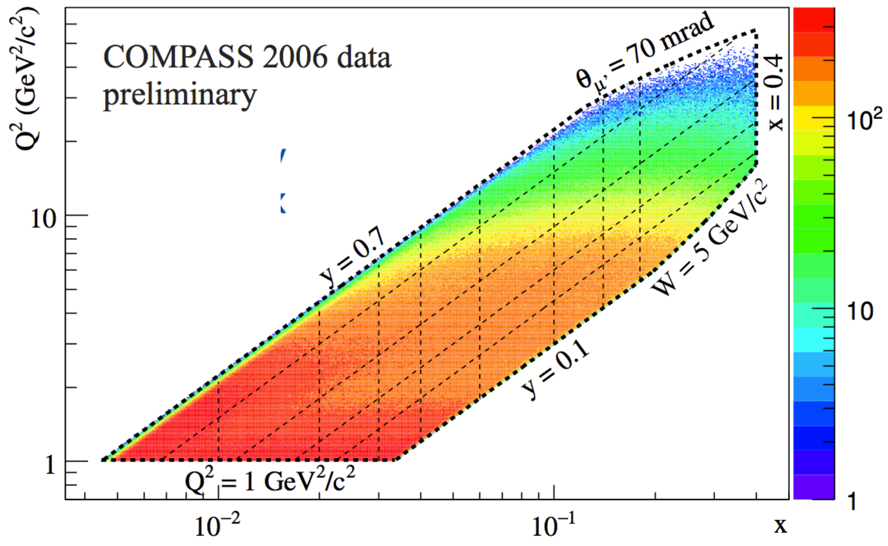
SPIN2014 *COMPASS Preliminary*

$h^{\pm}$ Multiplicities vs. p_T^2



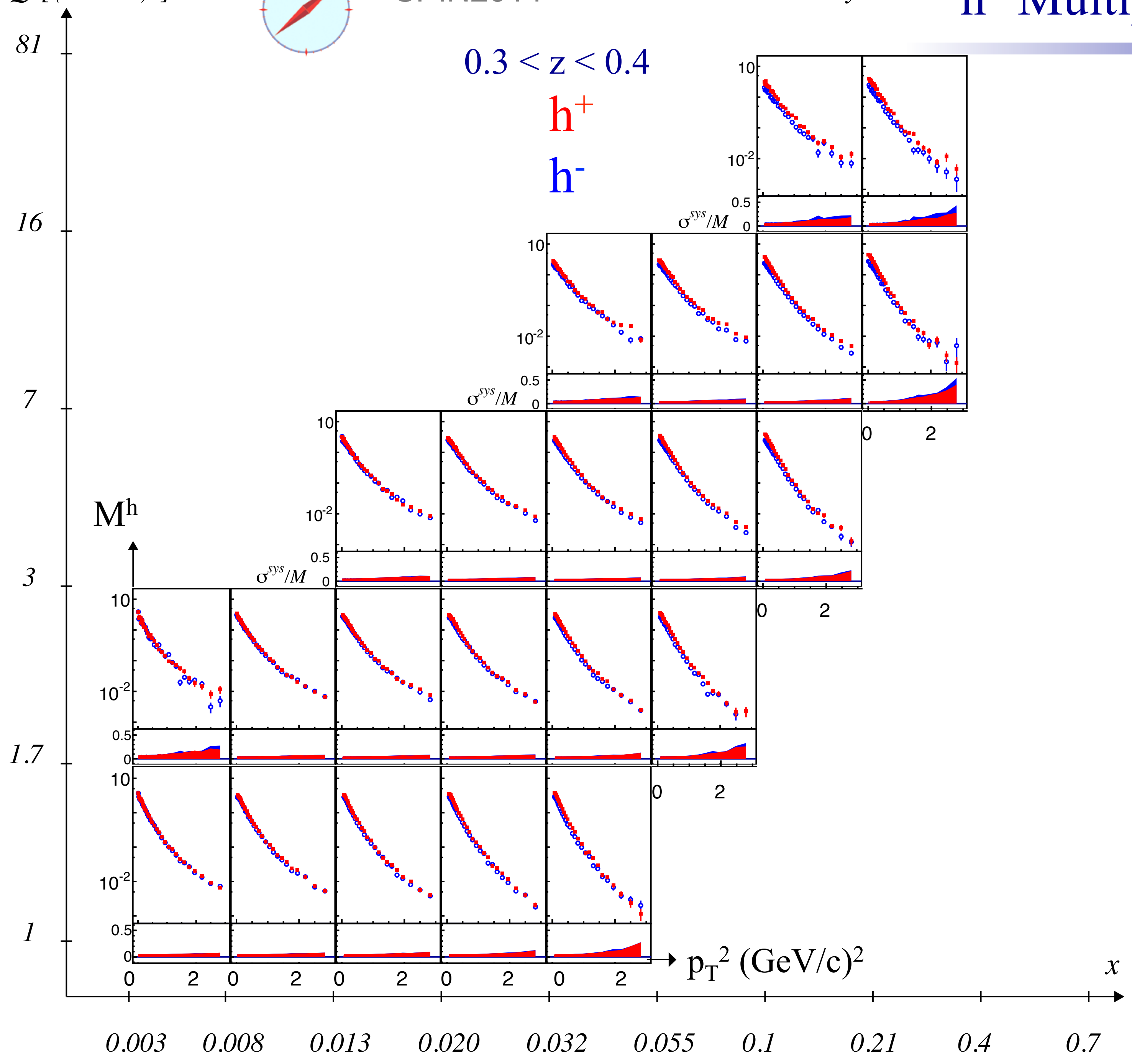
4 z ranges

Wide (x:Q^2; 9:5 bins) kin. range

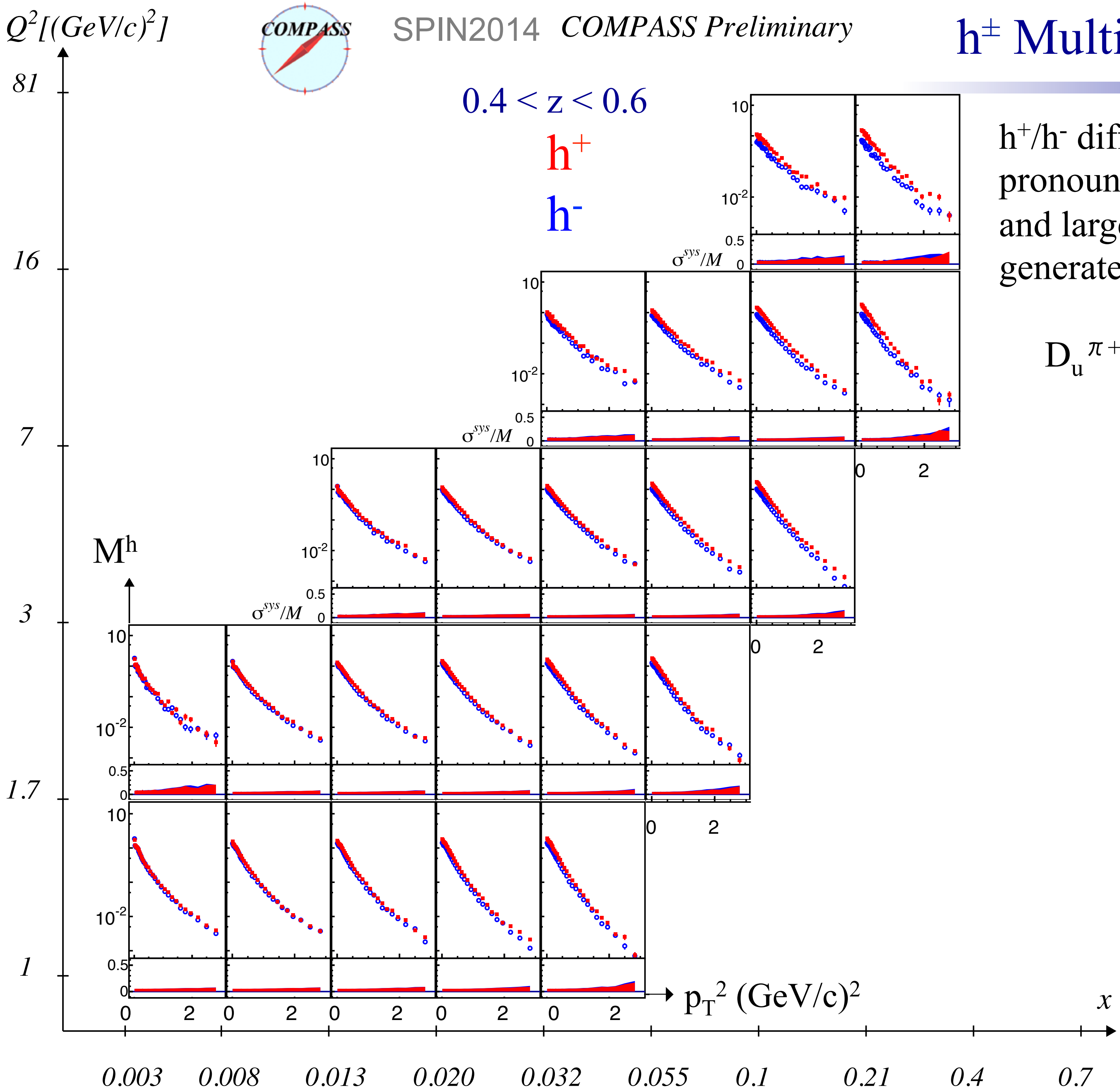


SPIN2014 *COMPASS Preliminary*

$h^{\pm}$ Multiplicities vs. p_T^2



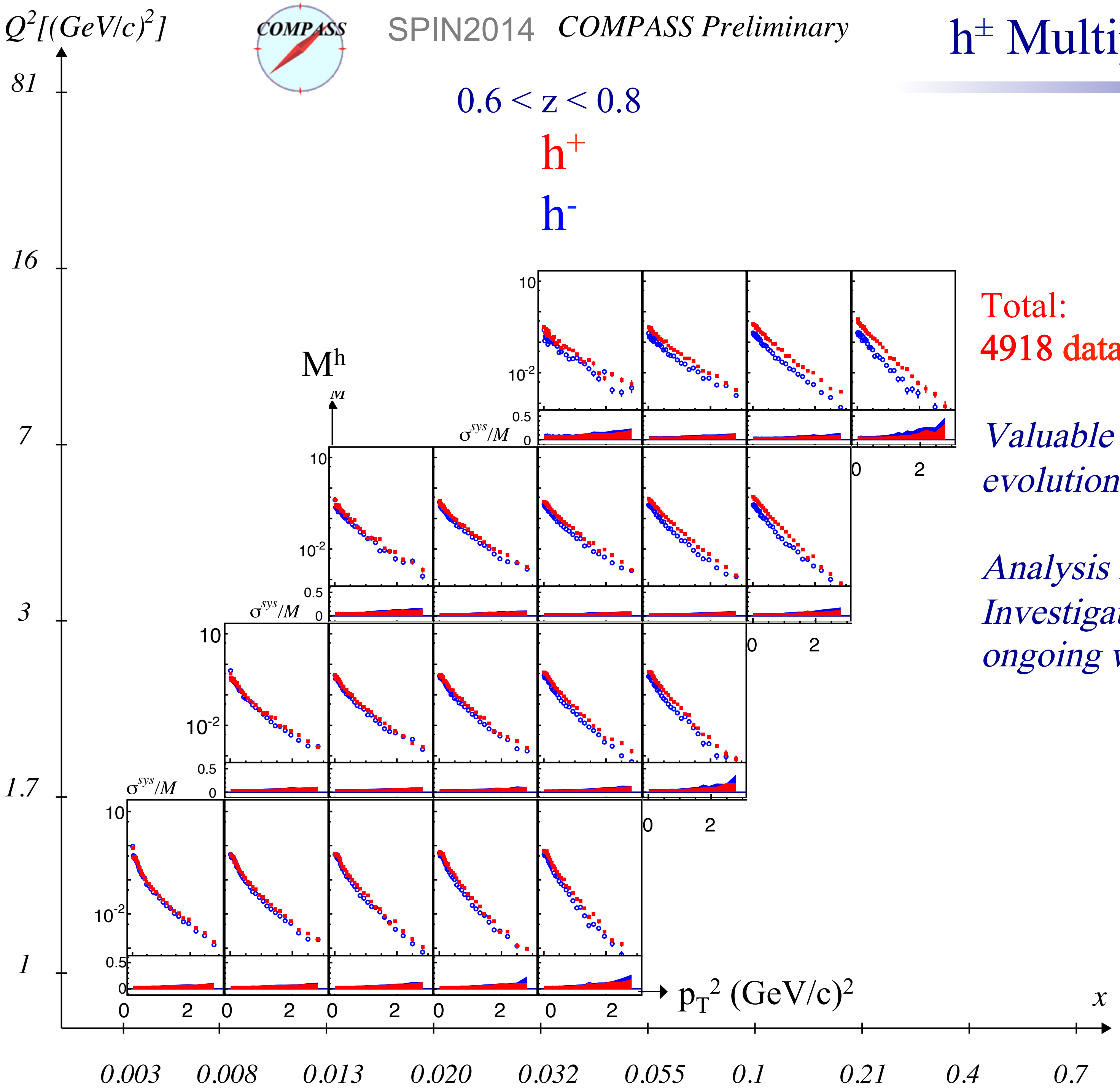
$h^{\pm}$ Multiplicities vs. p_T^2



h^+/h^- difference more pronounced at high x and large z ⇔ generated by FFs

$D_u^{\pi+} >>> D_u^{\pi-}$

$h^{\pm}$ Multiplicities vs. p_T^2



Total:
4918 data points

Valuable input for TMD evolution studies

Analysis finalized,
Investigating 1-exp fit of data
ongoing work on publication

di-hadron (h^+h^-) multiplicities

Transversity from di-hadron asymmetry

$$A_{UT}^{sin\phi_{RS}} \propto \frac{\sum_q e_q \cdot \Delta_T q(x) \cdot H_{1,sp}^{2h}(z, M^{2h})}{\sum_q e_q \cdot q(x) \cdot \boxed{D_q^{2h}(z, M^{2h})}}$$

needed for transversity extraction

Yet, spin-averaged di-hadron FF evaluated from MC simulation

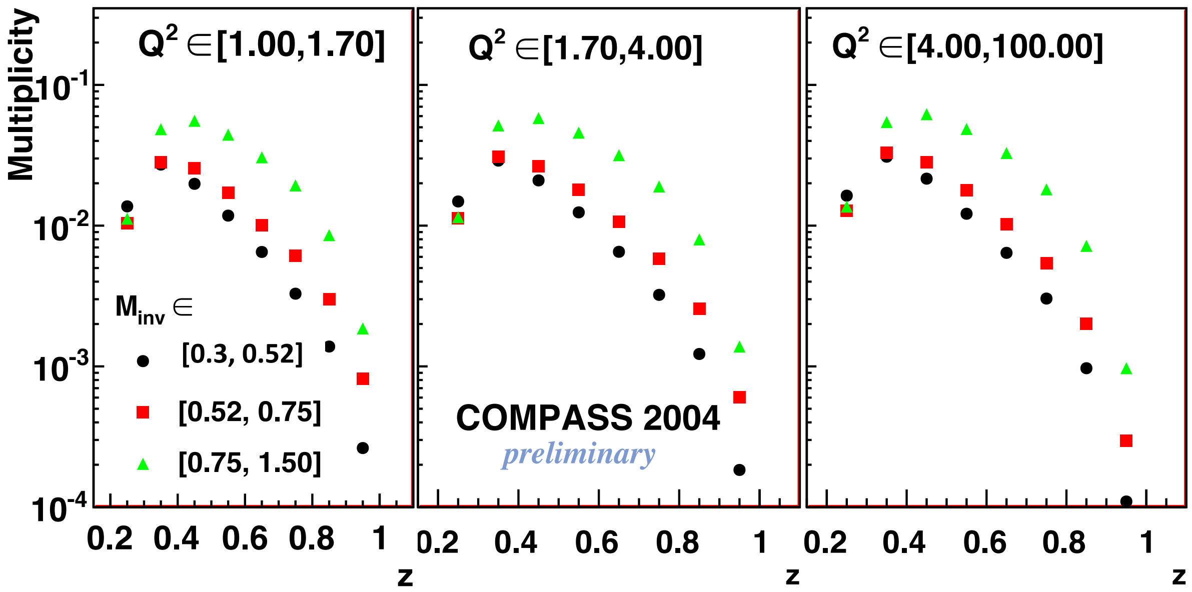
lack of experimental data !!

➡ First extraction in (M_{inv}, z , Q^2) simultaneously by COMPASS

- Normalized yield of final state hadron pairs
- Correction for acceptance effects required

$$M^{2h}(Q^2, z, M_{inv}) \propto q(Q^2) \cdot D_q^{2h}(Q^2, z, M_{inv})$$

di-hadron (h^+h^-) multiplicities



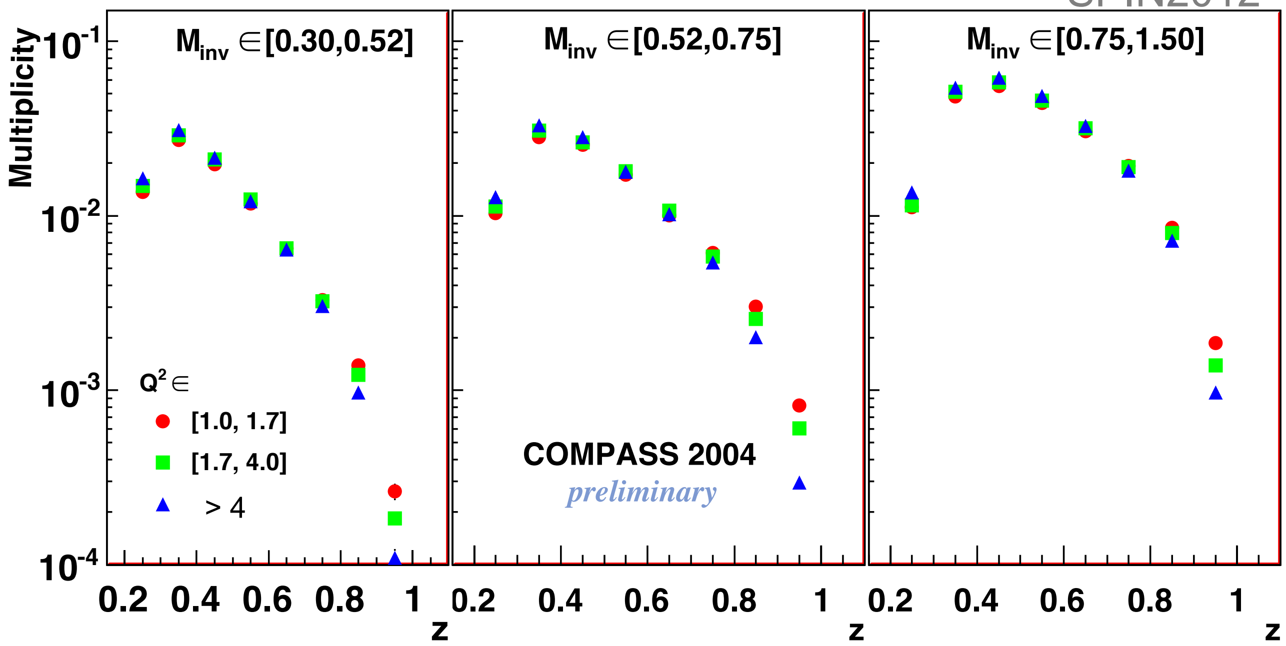
First attempt using data collected in 2004

Next measurement on d using 2006 and/or on p using 2016/17 data

SPIN2012

➡ Significant z, M_{inv} dependence

➡ Weaker dependence upon Q^2



Summary and Outlook I

Many important results produced by COMPASS to investigate transversity and TMDs in SIDIS

higher statistics data on transversely polarised d data still needed

More results coming "soon" from already collected data

transv. pol. p: weighted asymmetries, p_T and Bessel ongoing
unpol d: azimuthal asymmetries, 2h multiplicities
2014-2015: Transversely polarized DY (M. Chiosso's talk)

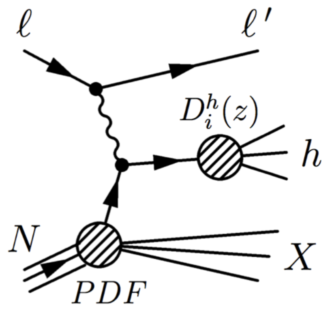
New data in the near future

2016-2017 unpolarised SIDIS on p, in parallel with DVCS
2018 to be discussed having in hand the performances in the previous years

Future: proposals for new measurements being prepared – COMPASS III ?

FF in the collinear case

Very good knowledge of PDFs and FFs is a key element for a precise determination of polarized quantities, e.g. polarization of quarks in



$$\int d^2\mathbf{k}_\perp f_1^q(x, k_\perp) = f_1^q(x)$$

$$\int d^2\mathbf{p}_\perp D_1^q(z, p_\perp) = D_1^q(z)$$

- Longitudinally polarized nucleon

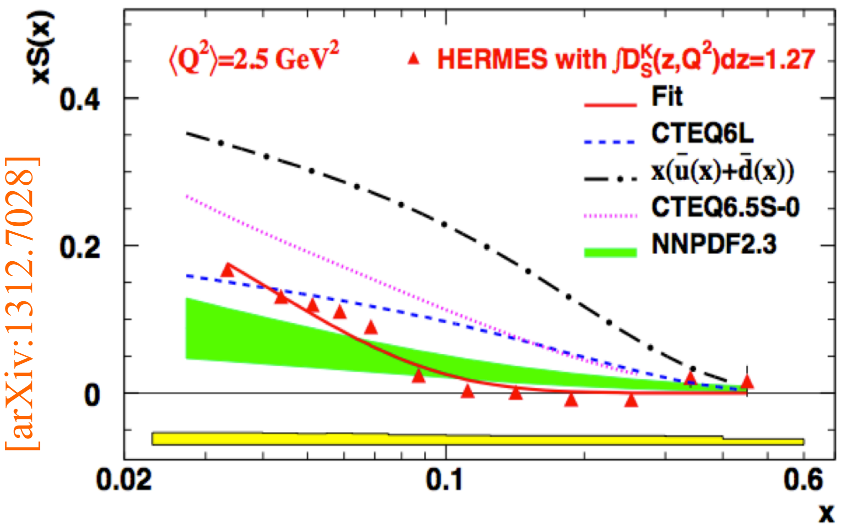
$$A_{LL}^h(x,z) = \frac{\sum_f \Delta q_f(x) D_{q_f}^h(z)}{\sum_f q_f(x) D_{q_f}^h(z)}$$

Large uncertainties in the strange sector

unpolarized PDF

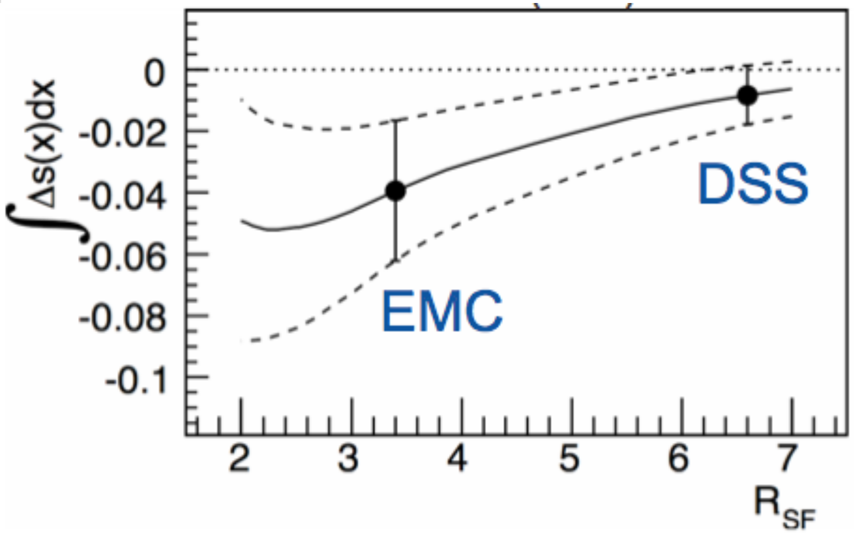
polarized PDF

poor knowledge of S(x)



[arXiv:1312.7028]

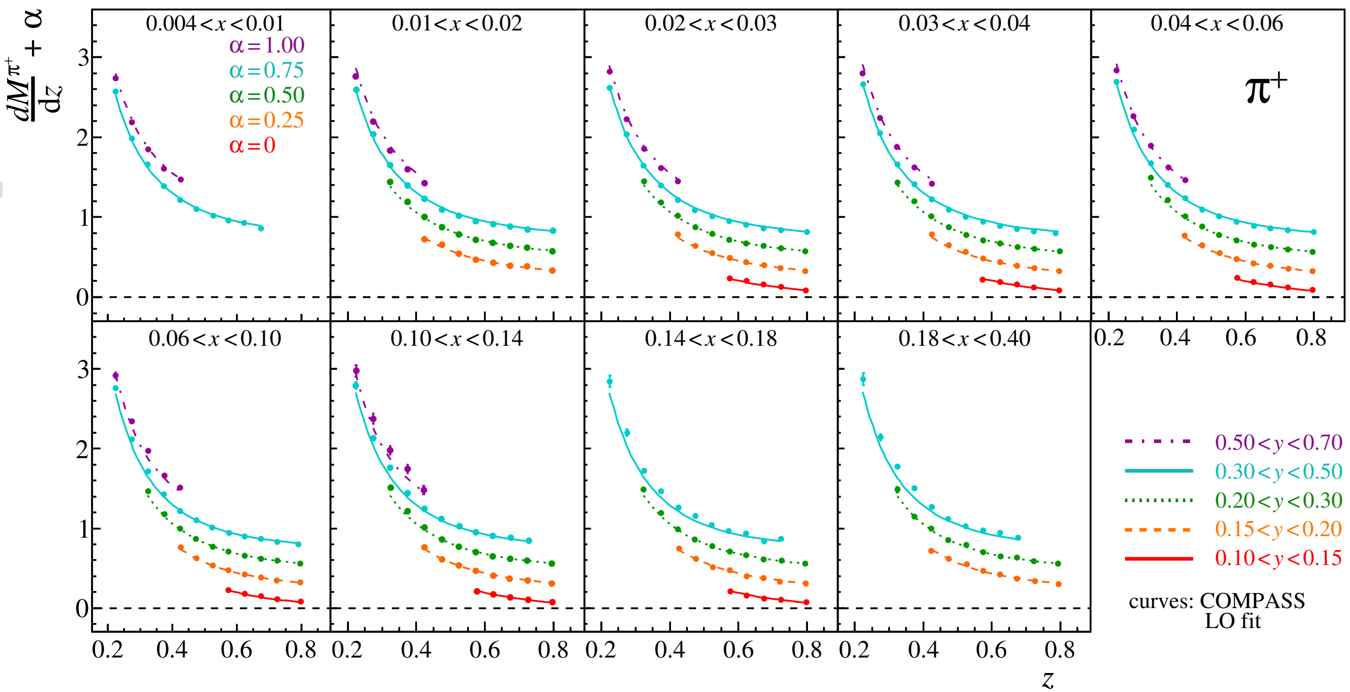
strong dependence of ΔS on FFs parameterizations

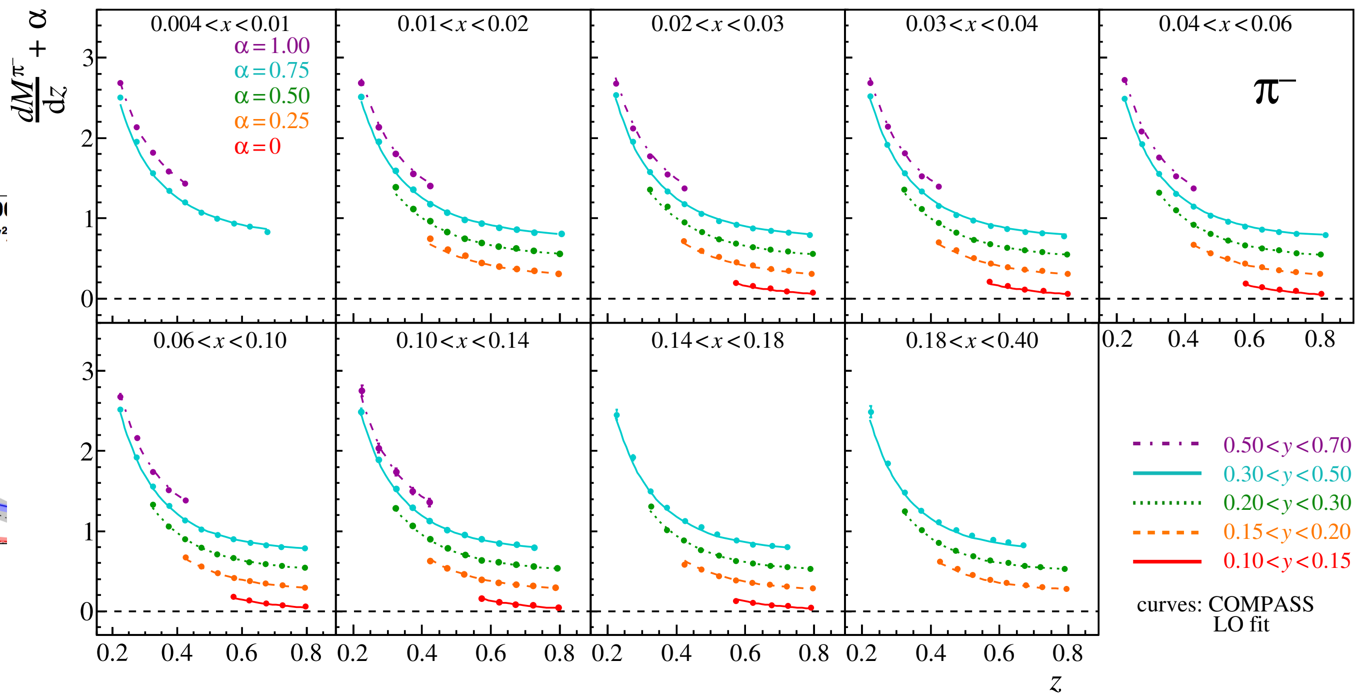


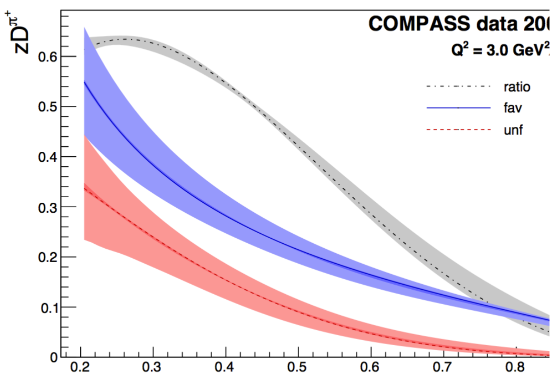
PLB 693 (2010) 227–235

Multiplicities of charged pions

- COMPASS extracted $\pi^{\pm}$ multiplicities
- Publication is out arXiv:1604.02695
- LO FFs fit from only COMPASS data
- Results agree with world data



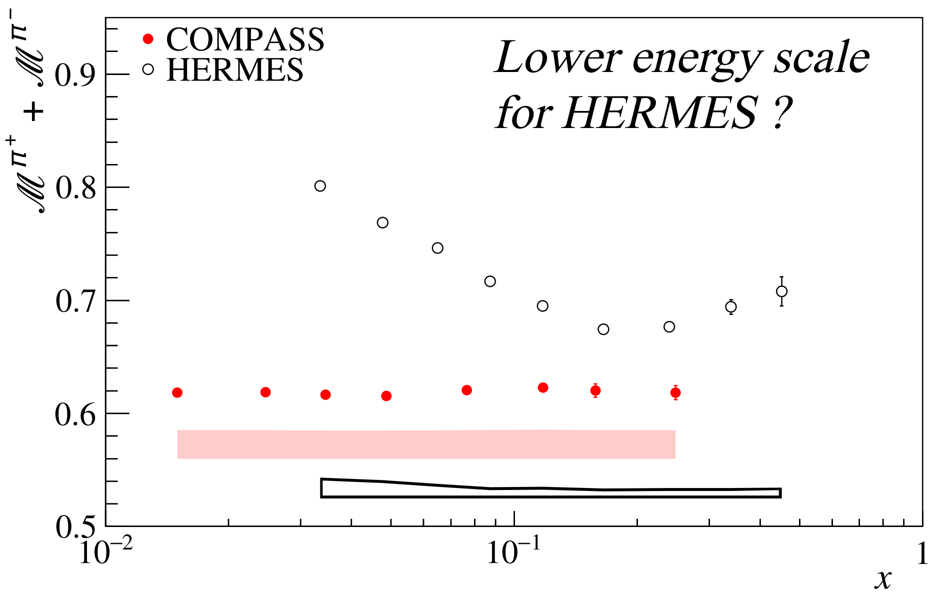


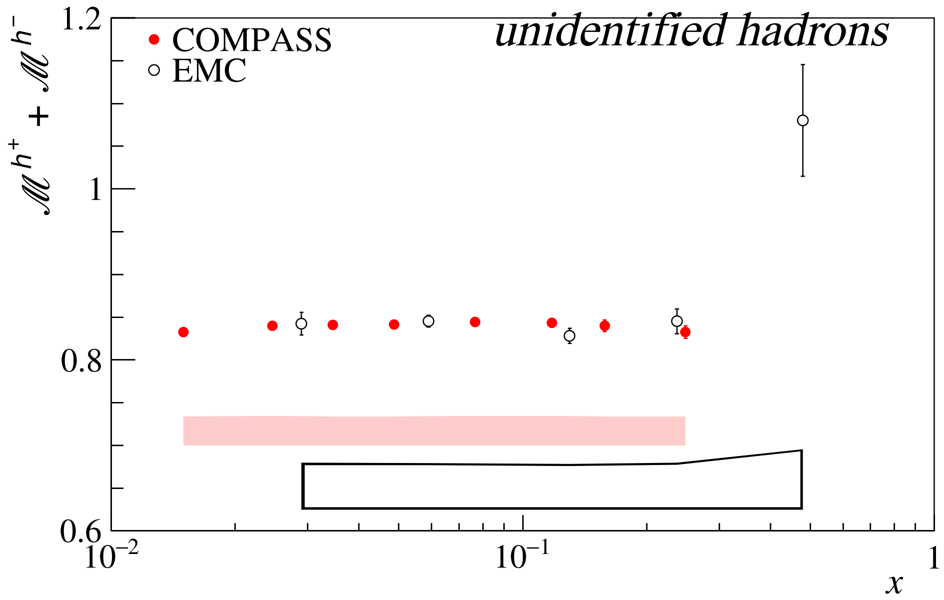


Pion multiplicity sum

- Interesting observations can be made when studying π multiplicity
- For isoscalar target:
  - $M^{\pi^+ + \pi^-} = D_{fav} + D_{unf} + \frac{2S}{5Q+2S}(D_{unf} - D_{fav}) \approx D_{fav} + D_{unf}$
  - $D(z,Q^2)$ → obtained multiplicity sum is effectively independent of x
  - In fixed target experiment x and Q^2 are correlated. But Q^2 dependence of z integrated FF is weak
  - $\int_{0.2}^{0.85} M^{\pi^+ + \pi^-} dz$ vs. x expected to be almost flat

arXiv:1604.02695

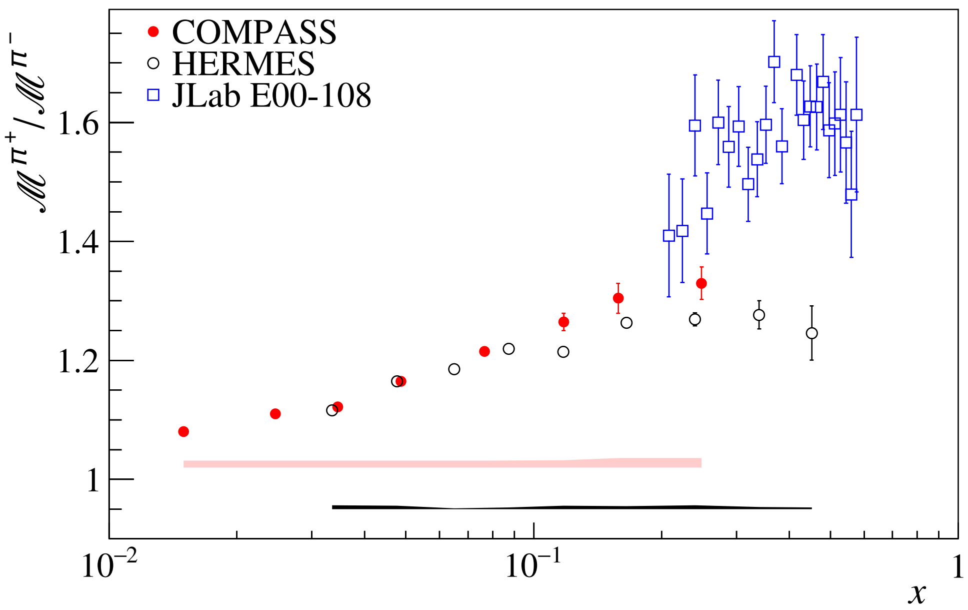


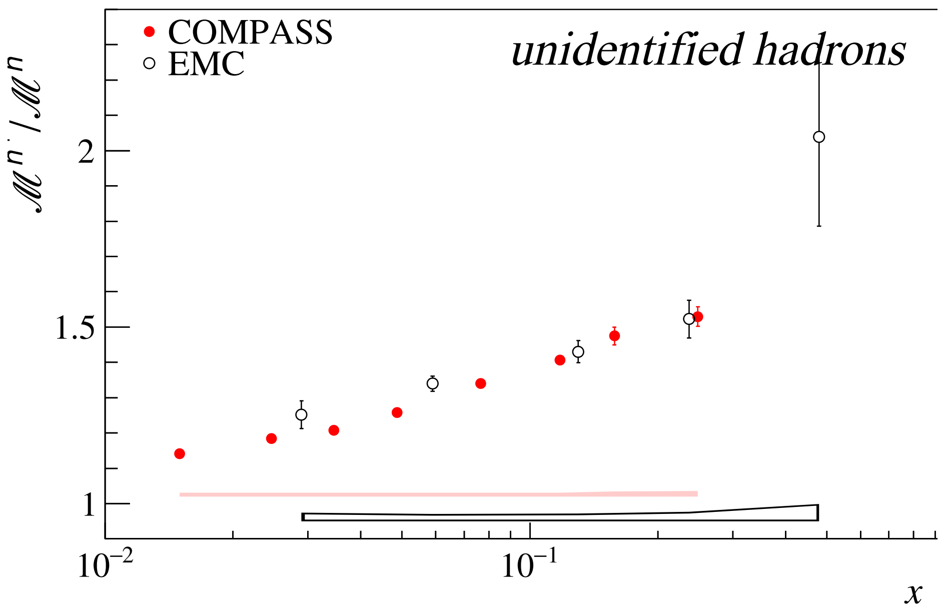


Pion multiplicity ratio

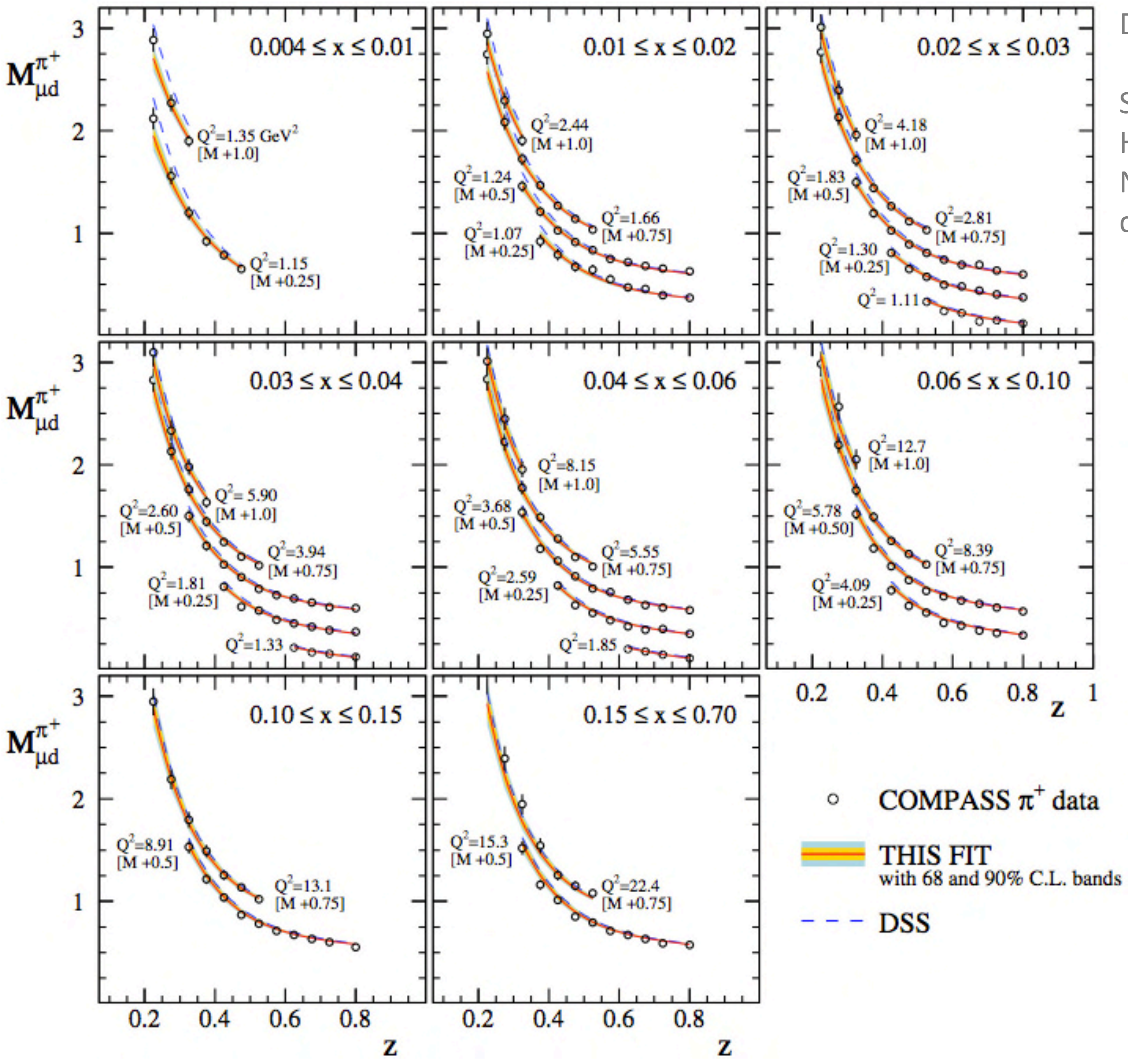
- The ratio of (π^+/π^-) or (h^+/h^-) is interesting to study due to significant cancellation of experimental systematic errors
- Here a good agreement between HERMES and COMPASS is seen
- As previously there is a good agreement between COMPASS and EMC data for unidentified hadrons

arXiv:1604.02695





q→ π DSS FFs fit: COMPASS



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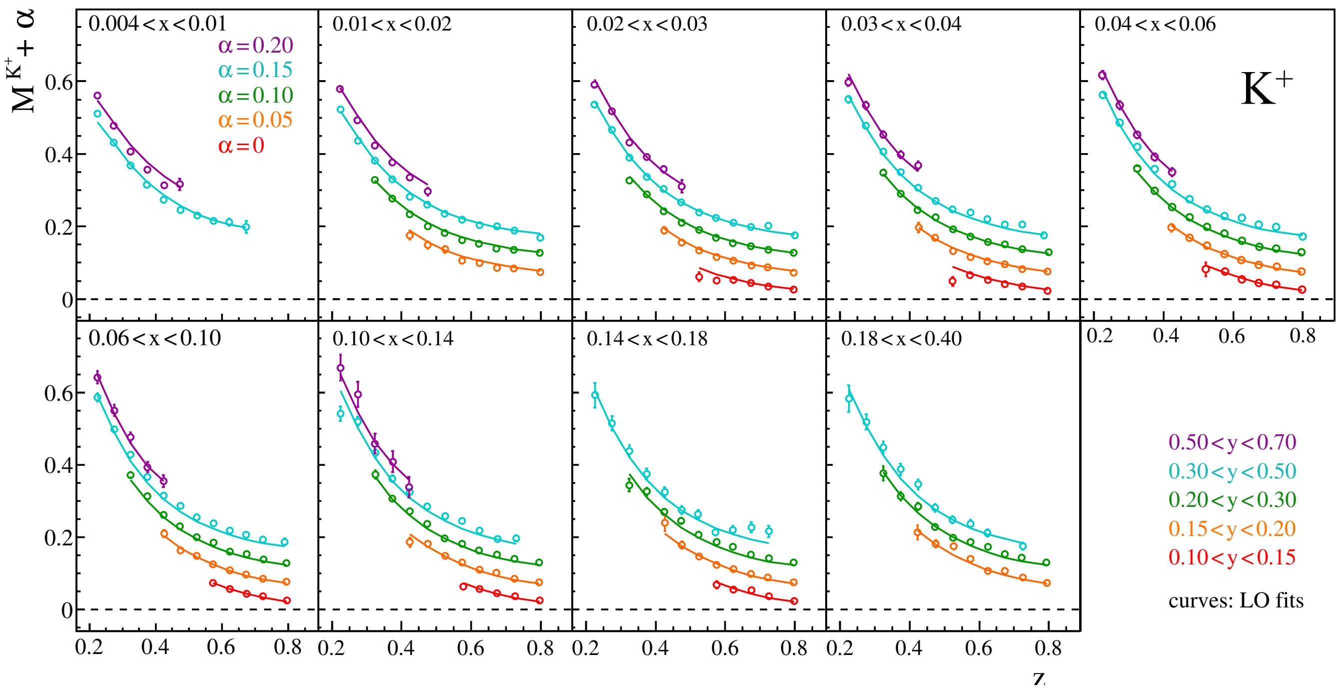
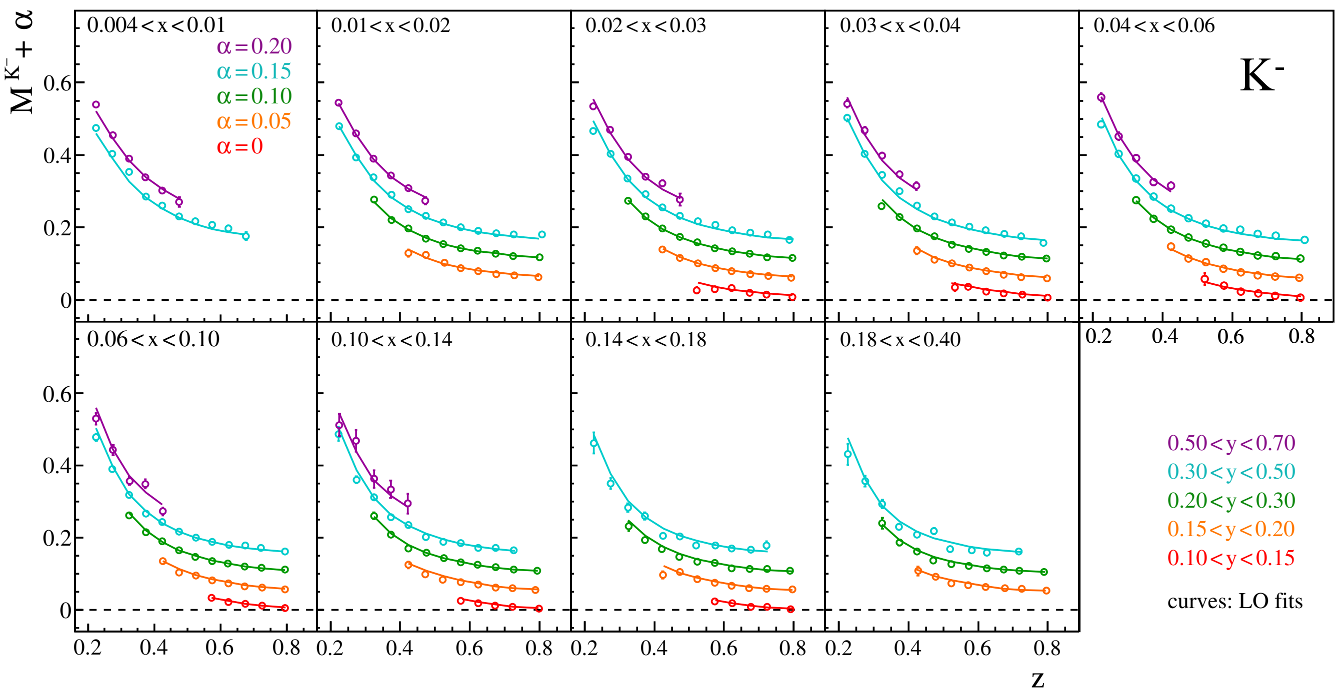
SIDIS data from COMPASS and HERMES
No tension between the two data sets.

Multiplicities of charged kaons

- Urgently needed to extract quark into kaon
- Simlar studies on kaon multiplicity sum and extraction of strange quark distribution





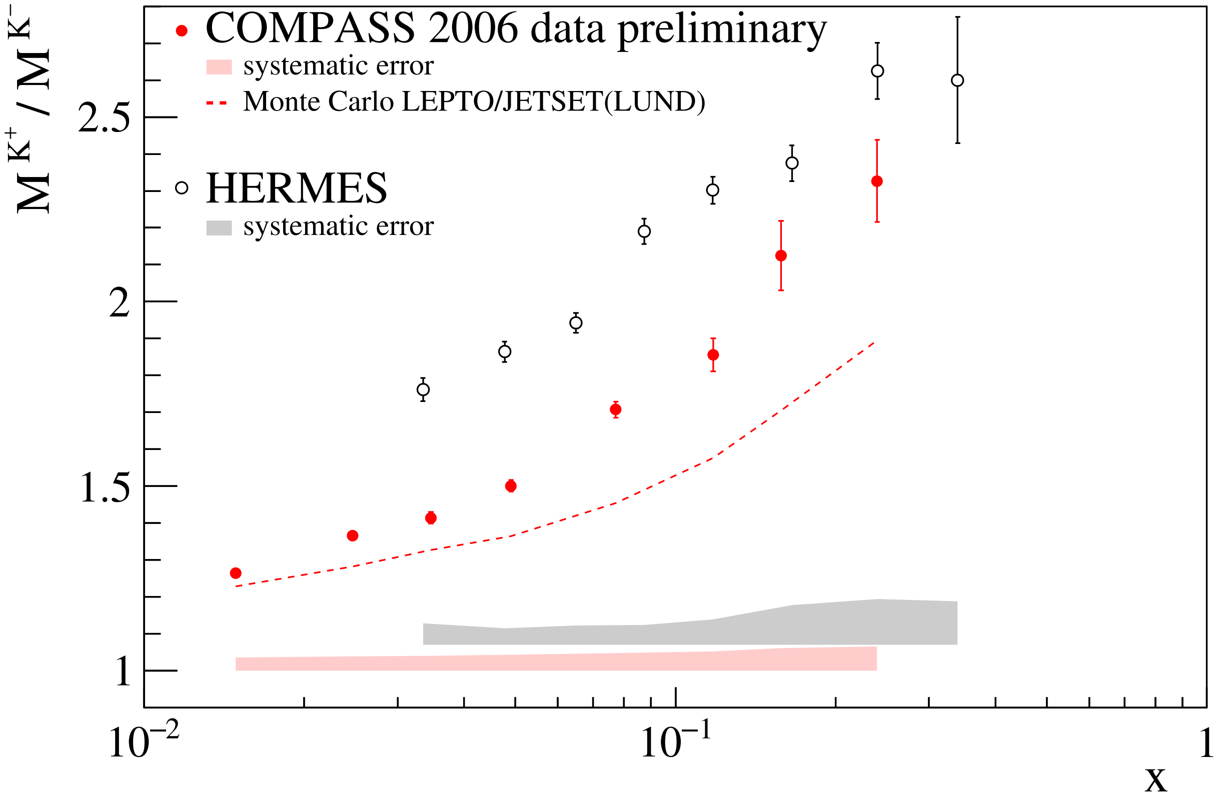
Kaon multiplicity ratio

- π case, there is a good agreement between COMPASS and HERMES for the π^+/π^- multiplicity ratio

  Despite the difference in the shape of π multiplicity sum

- K case: clear discrepancy between COMPASS and HERMES even for the K^+/K^- multiplicity ratio

- DSS next fit of Kaon FF



Summary and Outlook - II

COMPASS measured $h^{\pm}$, $\pi^{\pm}$,$K^{\pm}$ multiplicities in the wide kinematic range

Publication of h±, π ± is out arXiv:1604.02695

Other measurements on Longitudinal structure function (not covered here)