COMPASS measurements of the P_T weighted Sivers asymmetries

Franco Bradamante
Trieste INFN

on behalf of the COMPASS Collaboration

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the Sivers function

$f_{1T}^{\perp q}$ $\Delta_0^T q$ q_T $\Delta^N f_{q/N\uparrow}$

the most famous of the TMD PDF

a long debate

- **1992 introduced by D. Sivers**
- **1993 J. Collins demonstrate that it must vanish**
- **2002 S. Brodsky et al.: it can be ≠ 0 because of FSI**
- **2002 J. Collins: process dependent, change of sign SIDIS ↔ DY**

....

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....

- **2005 first measurements of the Sivers asymmetry in SIDIS**

$$A_{Siv} \propto \frac{\sum_q e_q^2 \cdot \boldsymbol{f_{1T}^{\perp q}} \otimes D_{1q}^h}{\sum_q e_q^2 \cdot f_1^q \cdot D_{1q}^h}$$

strong signal seen by HERMES for π^+ on protons → $\boldsymbol{f_{1T}^{\perp q} \neq 0}$

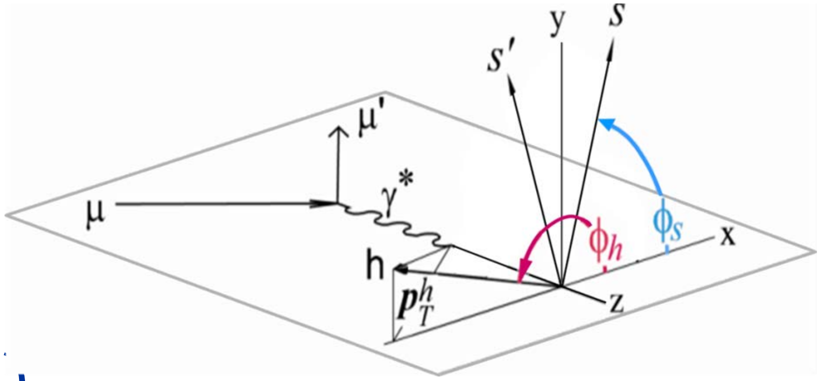
no signal seen by COMPASS for h^+ and h^- on deuterons → $\boldsymbol{f_{1T}^{\perp u} = -f_{1T}^{\perp d}}$

the Sivers asymmetry

appears in SIDIS as a modulation in the

"Sivers angle" $\Phi_S = \phi_h - \phi_S$

ϕ_h azimuthal angle of hadron momentum
ϕ_S azimuthal angle of the spin of the nucleon



$$N_h^{\pm}(\Phi_S) = N_h^0(1 \pm S_T A_{Siv} \sin \Phi_S)$$

$$A_{Siv} \propto \frac{\sum_q e_q^2 \cdot f_{1T}^{\perp q} \otimes D_{1q}^h}{\sum_q e_q^2 \cdot f_1^q \cdot D_{1q}^h}$$

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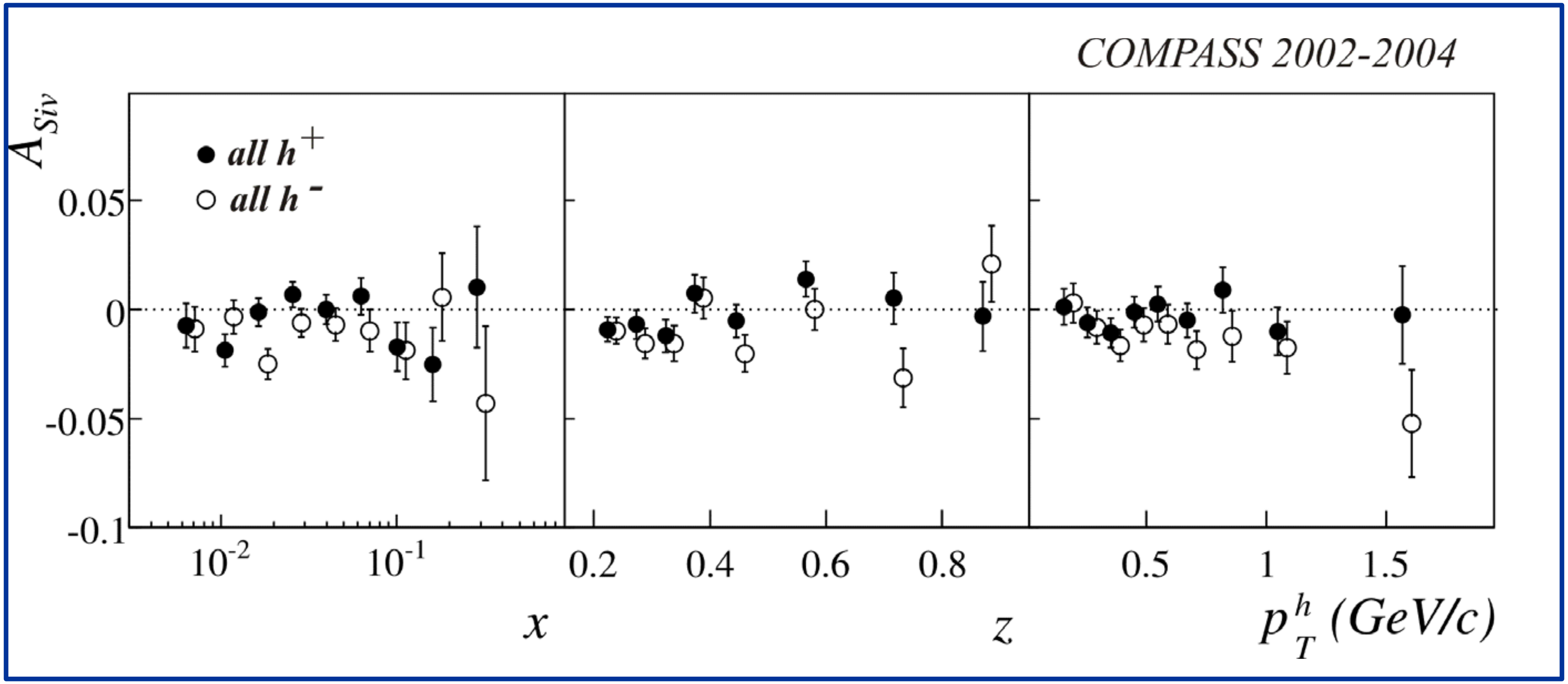
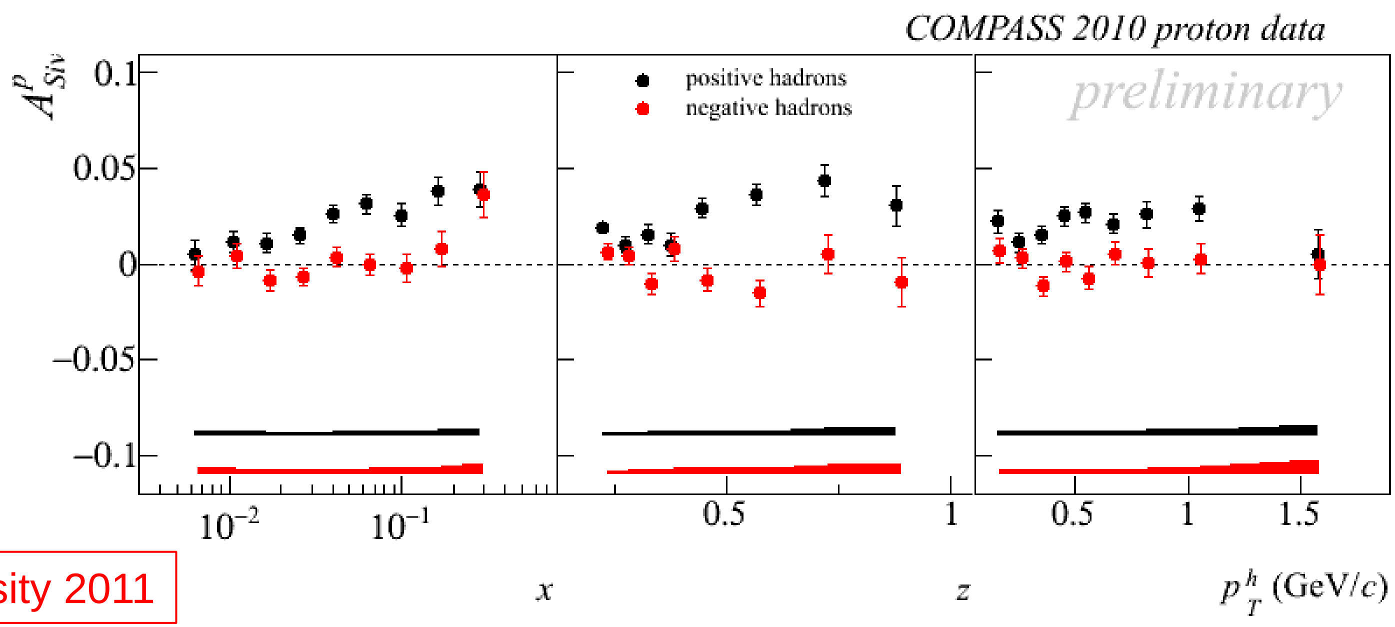
the Sivers asymmetry – deuteron data



final results from 2002-2004 data NPB765 (2007)31

the Sivers asymmetry – proton data

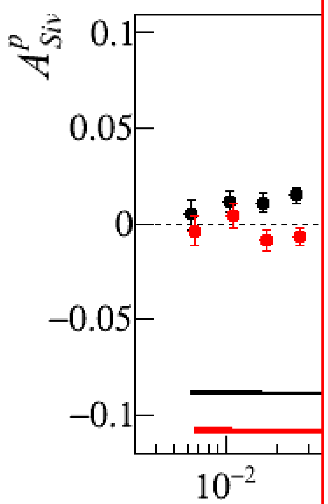


Transversity 2011

published in

PLB 717 (2012) 383 ($h^{\pm}$)

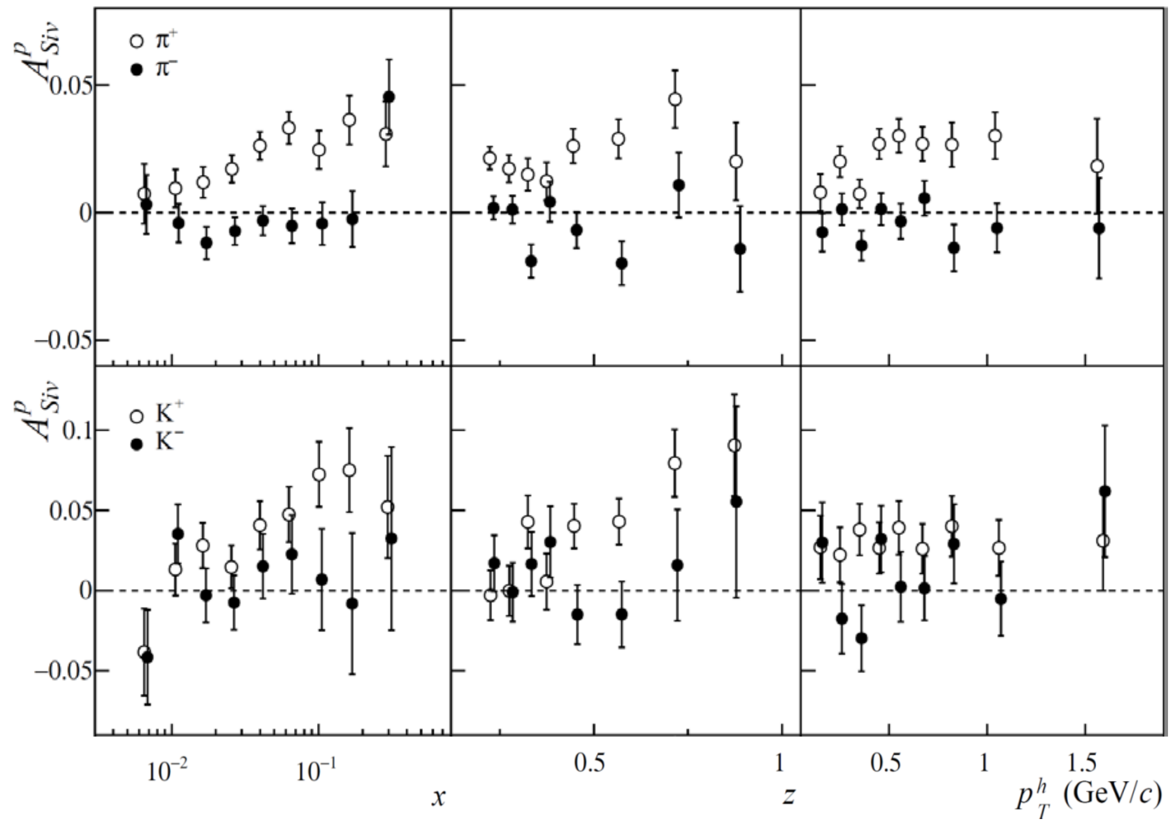
the Sivers asymmetry – proton data



Transversity 2011

published in
PLB 717 (2012) 3

and in PLB 744 (2015) 250



and used, together with HERMES results, for
several extractions of the Sivers function
and studies of the TMD evolution

the Sivers asymmetry

more recent results from 2010 p data

1. **Sivers asymmetry in Q^2 Drell-Yan ranges**

2. **multiD ($x, Q^2; z, P_T$) results for Sivers and other TSA asymmetries**

the Sivers asymmetry

more recent results from 2010 p data

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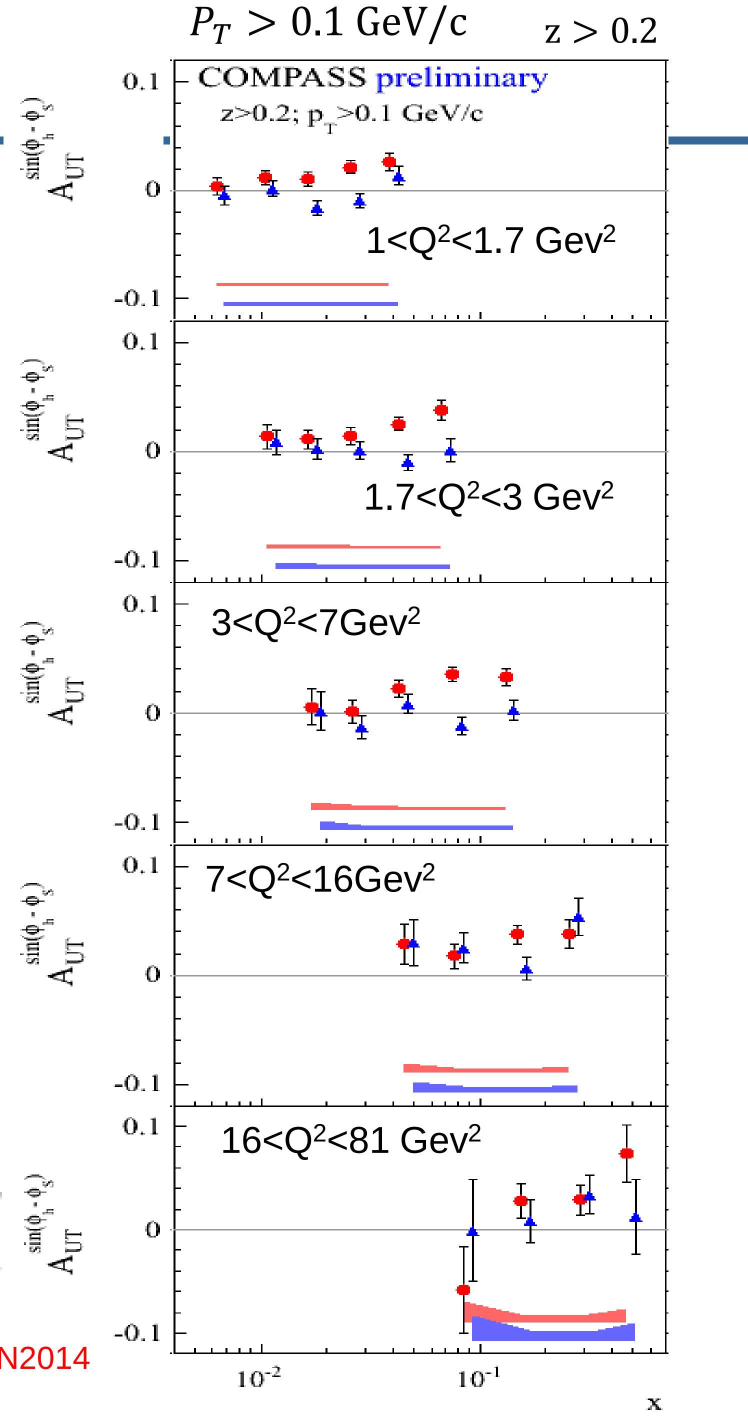


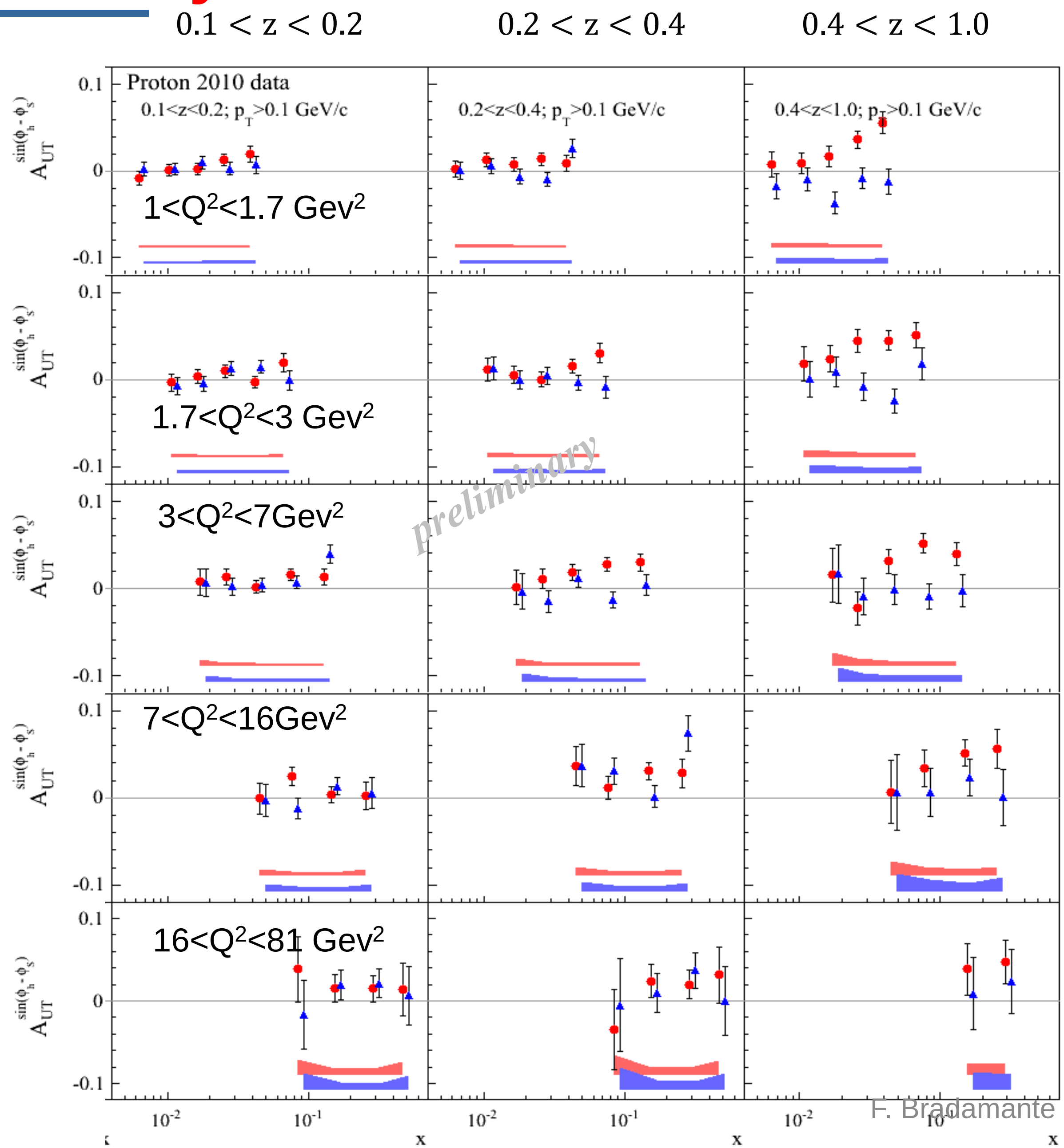
SPIN2014

the Sivers asymmetry

multiD $(x, Q^2; z, P_T)$ results

an example

$P_T > 0.1$ GeV/c



SPIN2014

the Sivers asymmetry

new: weighted asymmetry

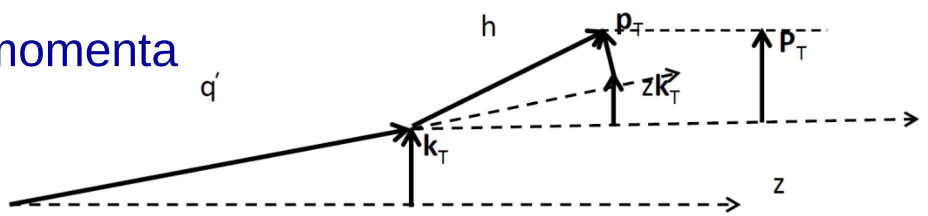
the “standard” Sivers asymmetry

the HERMES and COMPASS results used for several extractions
of the Sivers function and studies of TMD evolution are measurements of

$$A_{Siv} \propto \frac{\sum_q e_q^2 \cdot f_{1T}^{\perp q} \otimes D_{1q}^h}{\sum_q e_q^2 \cdot f_1^q \cdot D_{1q}^h} \qquad N_h^{\pm}(\Phi_S) = N_h^0 (1 \pm S_T A_{Siv} \sin \Phi_s)$$

$\otimes$ convolution over transverse momenta

$$\vec{P}_T = \vec{p}_T + z\vec{k}_T$$



$$f_{1T}^{\perp} \otimes D_1 = \int d^2\vec{P}_T \int d^2\vec{k}_T \int d^2\vec{p}_T \, \delta^2(z\vec{k}_T + \vec{p}_T - \vec{P}_T) \frac{\vec{k}_T \cdot \vec{P}_T}{M P_T} f_{1T}^{\perp} D_1$$

usually solved using the **Gaussian model** for PDFs and FFs

$$f_{1T}^{\perp h}(x, k_T^2, Q^2) = f_{1T}^{\perp h}(x, Q^2) \frac{1}{\pi \langle k_T^2 \rangle_S} e^{-k_T^2/\langle k_T^2 \rangle_S}$$

$$D_1(z, p_T^2, Q^2) = D_1(z, Q^2) \frac{1}{\pi \langle p_T^2 \rangle} e^{-p_T^2/\langle p_T^2 \rangle}$$

the “standard” Sivers asymmetry

possible alternative:

measure P_T weighted asymmetries

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

SIDIS cross-section

$$\frac{d\sigma_{\uparrow\downarrow}^{\ell(l,\lambda)+N(P_N,S)\to\ell(l')+h(P)+X}}{dx\,dQ^2\,d\phi_S\,dz\,d^2P_T} = C\left(x,Q^2\right)\left(\sigma_U \pm S_T\sigma_{Siv} + \cdots\right)$$

$$C\left(x,Q^2\right) = \frac{\alpha^2}{Q^4}\left(1+(1-y)^2\right)$$

$$\boldsymbol{\sigma_U} = \int d^2\vec{P}_T \int d^2\vec{k}_T \int d^2\vec{p}_T\, \delta^2(z\vec{k}_T + \vec{p}_T - \vec{P}_T)\, f_1(k_T^2)\, D_1(p_T^2)$$

$$= \boldsymbol{f_{1T}^{\perp} \cdot D_1}$$

$$\boldsymbol{\sigma_{Siv}} = \int d^2\vec{P}_T \int d^2\vec{k}_T \int d^2\vec{p}_T\, \delta^2(z\vec{k}_T + \vec{p}_T - \vec{P}_T)\, \frac{[\hat{s}_T \times \vec{k}_T]\cdot\vec{P}_T}{M}\, f_{1T}^{\perp}(k_T^2)\, D_1(p_T^2)$$

$\sum_q e_q^2$ *not indicated here*

SIDIS cross-section

$$\sigma_{Siv} = \int d^2\vec{P}_T \int d^2\vec{k}_T \int d^2\vec{p}_T \, \delta^2(z\vec{k}_T + \vec{p}_T - \vec{P}_T) \frac{[\hat{s}_T \times \vec{k}_T] \cdot \vec{P}_T}{M} f_{1T}^{\perp}(k_T^2)\, D_1(p_T^2)$$

…. after some calculation ...

$$\sigma_{Siv} = \sin\Phi_S \int d^2\vec{P}_T P_T F(P_T^2)$$

with $$F(P_T^2) = \int d^2\vec{k}_T \int d^2\vec{p}_T \, \delta^2(\vec{P}_T - z\vec{k}_T - \vec{p}_T) \frac{\vec{P}_T \cdot \vec{k}_T}{M P_T^2} f_{1T}^{\perp}(k_T^2)\, D_1(p_T^2)$$

the integral can not be evaluated **without** parametrizations of Sivers and FFs:
it is the **convolution** which appears in the Sivers asymmetry

$$A_{Siv} \propto \frac{\sum_q e_q^2 \cdot \boldsymbol{f_{1T}^{\perp q}} \otimes D_{1q}^h}{\sum_q e_q^2 \cdot f_1^q \cdot D_{1q}^h}$$

SIDIS cross-section

$$\sigma_{Siv} = \int d^2\vec{P}_T \int d^2\vec{k}_T \int d^2\vec{p}_T\, \delta^2(z\vec{k}_T + \vec{p}_T - \vec{P}_T)\, \frac{[\hat{s}_T \times \vec{k}_T]\cdot \vec{P}_T}{M} f_{1T}^{\perp}(k_T^2)\, D_1(p_T^2)$$

…. after some calculation ...

$$\sigma_{Siv} = \sin\Phi_S \int d^2\vec{P}_T P_T F(P_T^2)$$

the integral can be solved using the Gaussian model

$$f_{1T}^{\perp h}(x, k_T^2, Q^2) = f_{1T}^{\perp h}(x, Q^2)\frac{1}{\pi\langle k_T^2\rangle_S} e^{-k_T^2/\langle k_T^2\rangle_S}$$

$$D_1(z, p_T^2, Q^2) = D_1(z, Q^2)\frac{1}{\pi\langle p_T^2\rangle} e^{-k_T^2/\langle p_T^2\rangle}$$

one gets

$$\sigma_{Siv} = \sin\Phi_S\, a_G\; f_{1T}^{\perp(1)q}\cdot D_{1q}^h$$

i.e.

$$A_{Siv} = a_G \frac{\sum_q e_q^2 \cdot f_{1T}^{\perp(1)q}\cdot D_{1q}^h}{\sum_q e_q^2\cdot f_1^q \cdot D_{1q}^h}$$

with $f_{1T}^{\perp(1)} = \int d^2\vec{k}_T \frac{k_T^2}{2M^2} f_{1T}^{\perp}(k_T^2)$ and $a_G = \frac{\sqrt{\pi}M}{\sqrt{\langle k_T^2\rangle_S + \langle p_T^2\rangle/z^2}}$

weighted cross-section

on the contrary, if we weight with $w = P_T/zM$

$$\sigma_{Siv}^{w} = \sin\Phi_S \int d^2\vec{P}_T P_T \frac{P_T}{zM} F(P_T^2)$$

the integral can be solved and gives

$$\sigma_{Siv}^{w} = \sin\Phi_S \; f_{1T}^{\perp(1)} \cdot D_1$$

where

$$f_{1T}^{\perp(1)} = \int d^2\vec{k}_T \frac{k_T^2}{2M^2} f_{1T}^{\perp}(k_T^2)$$

$$\frac{\sigma_{Siv}^{w}}{\sigma_U} = \sin\Phi_S \frac{2\sum_q e_q^2 \cdot f_{1T}^{\perp(1)q} \cdot D_{1q}^h}{\sum_q e_q^2 \cdot f_1^q \cdot D_{1q}^h} = \sin\Phi_S\, A_{Siv}^{w}$$

without using the **Gaussian model or other parametrisations**

weighted cross-section

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$$\sigma^w_{Siv} = \sin\Phi_S \int d^2\vec{P}_T P_T \frac{P_T}{zM} F(P_T^2)$$

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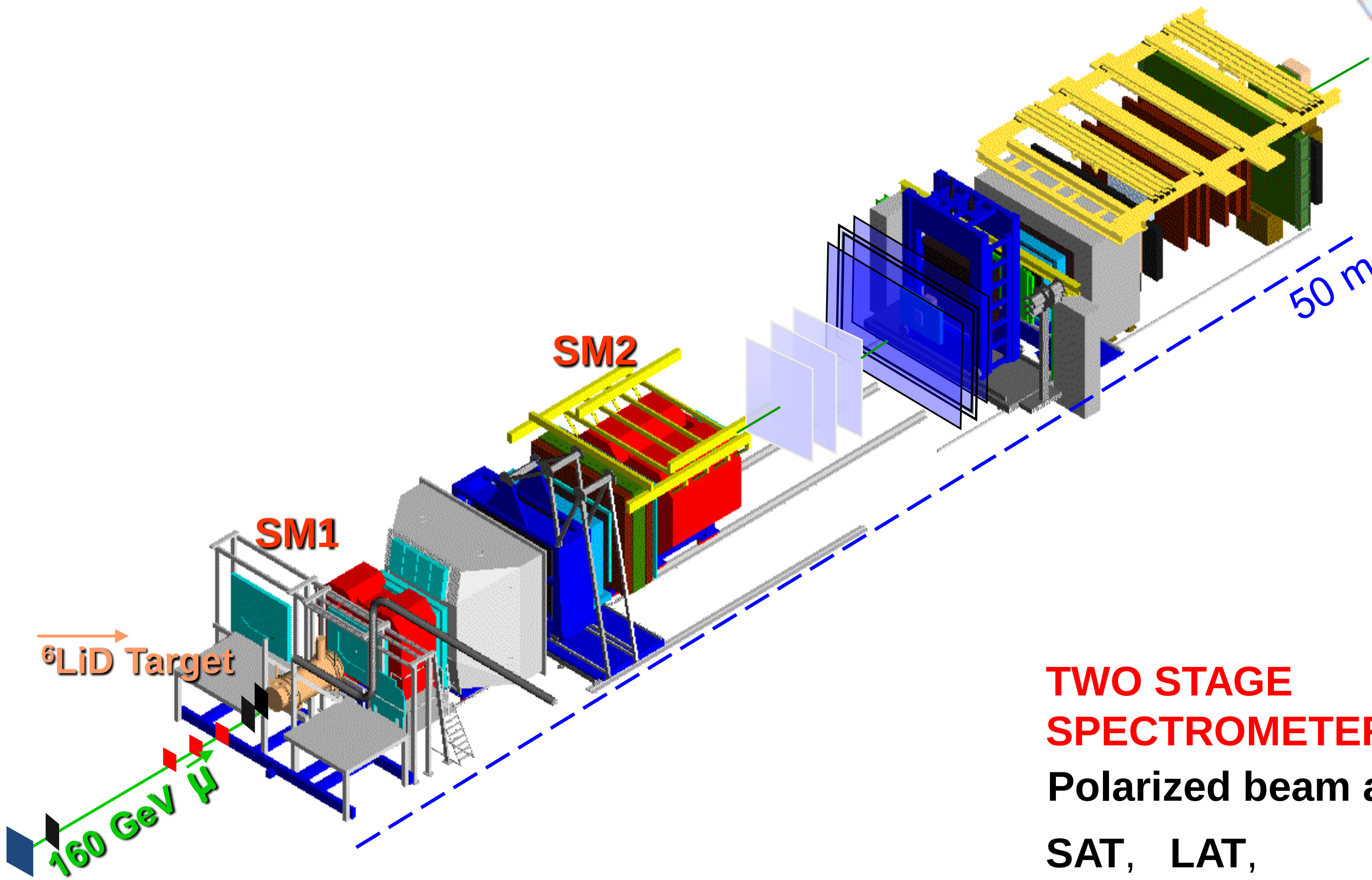
without using the **Gaussian model or other parametrisations**

experimental problems:
- acceptance effects
- weight only the spin dependent part of the cross-section

COMPASS

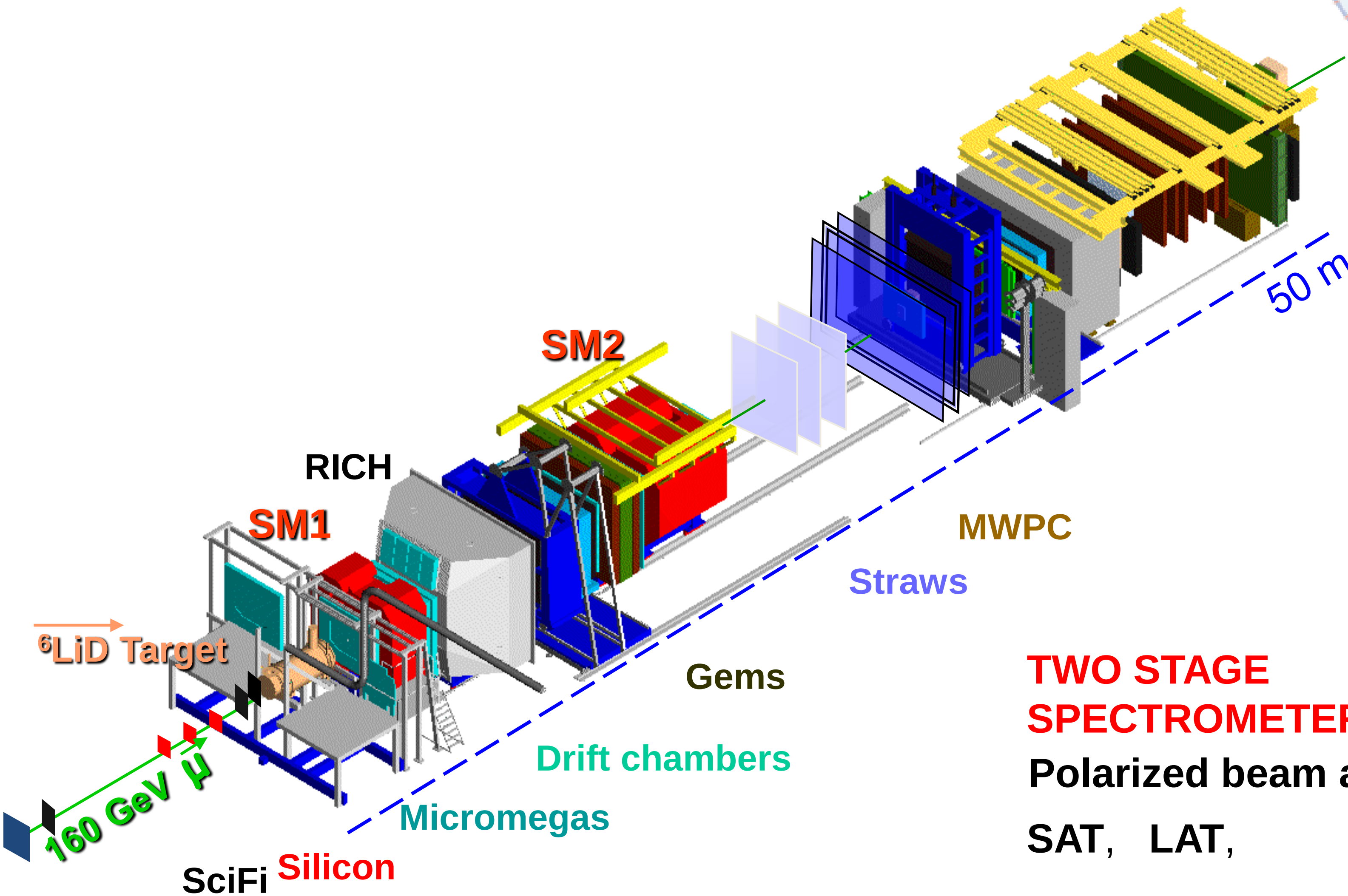


TWO STAGE SPECTROMETER:

Polarized beam and target

SAT, LAT,

COMPASS



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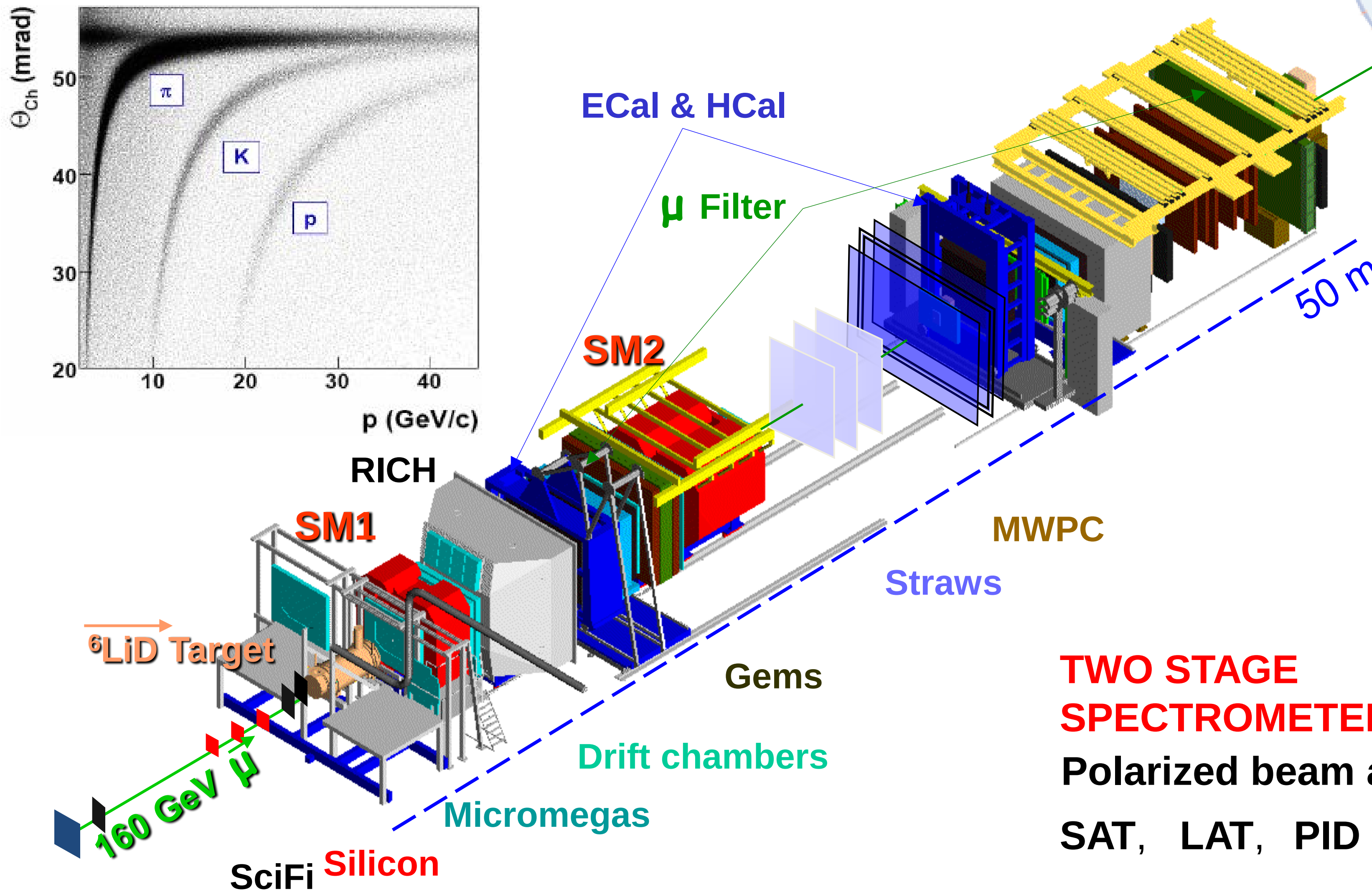
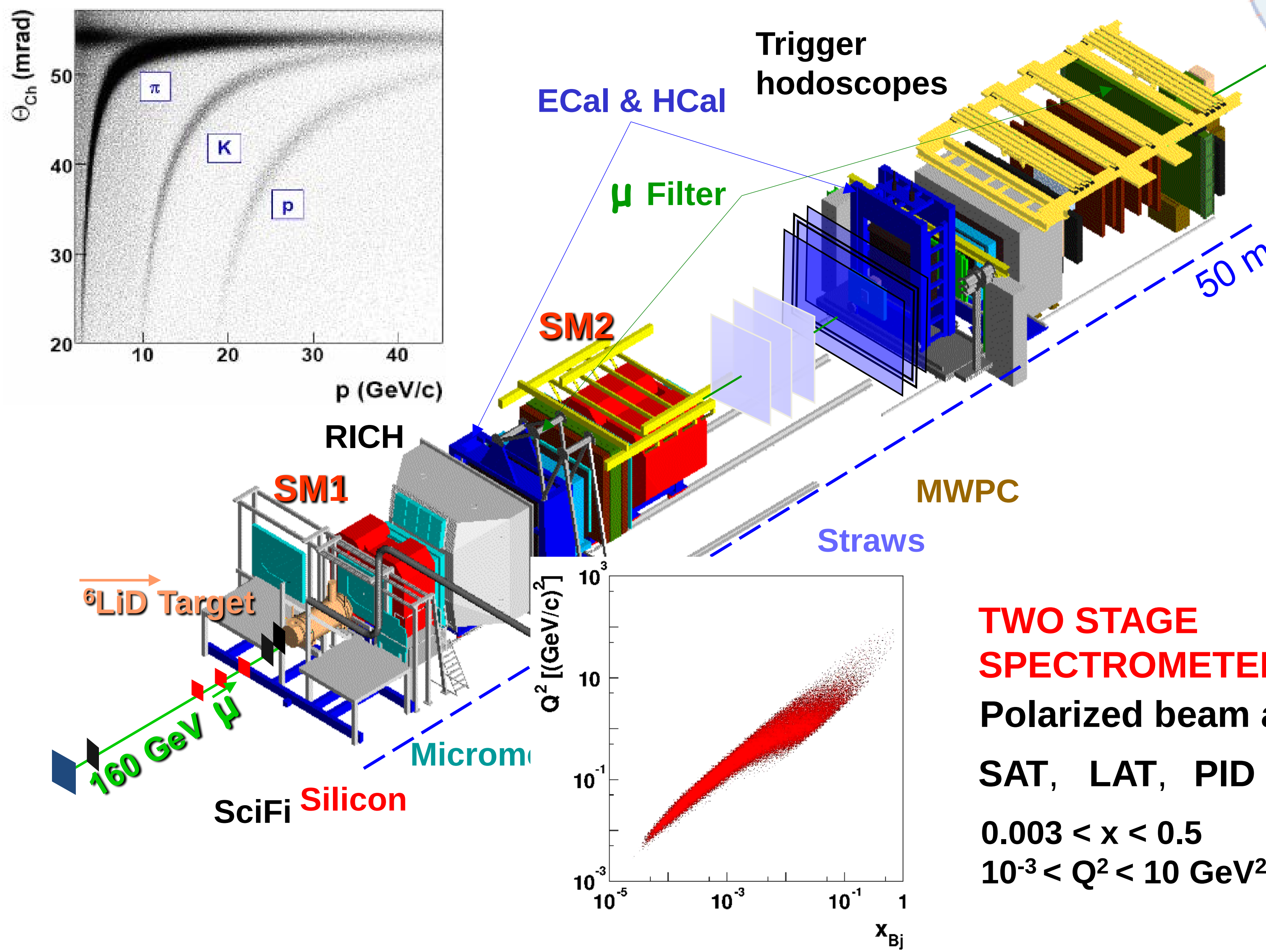


TWO STAGE SPECTROMETER:

Polarized beam and target

SAT, LAT, PID

COMPASS



TWO STAGE SPECTROMETER:

Polarized beam and target

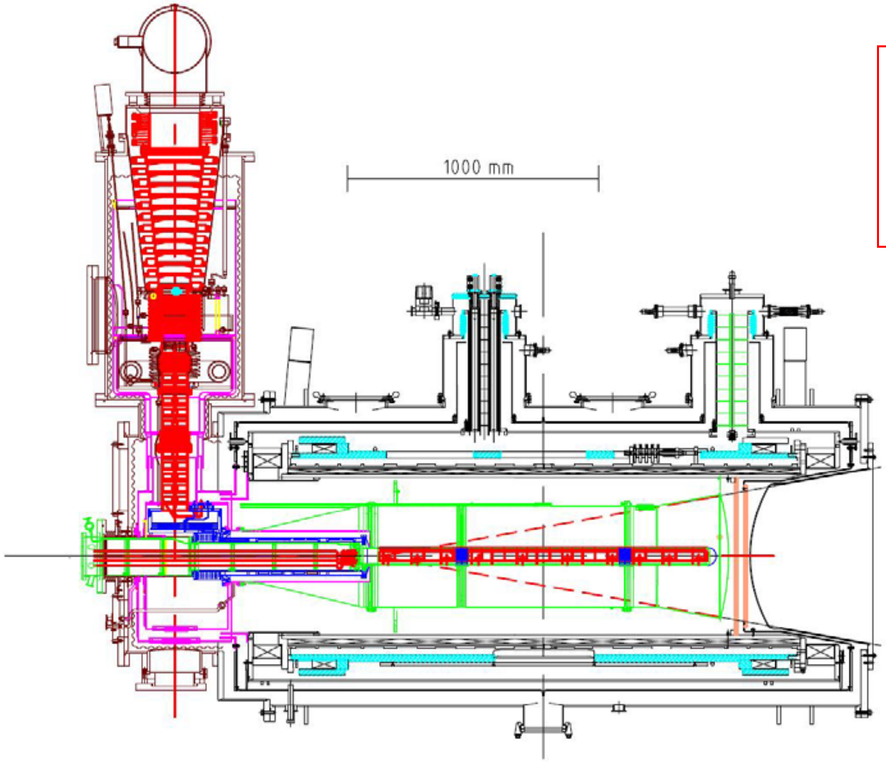
SAT, LAT, PID

$0.003 < x < 0.5$

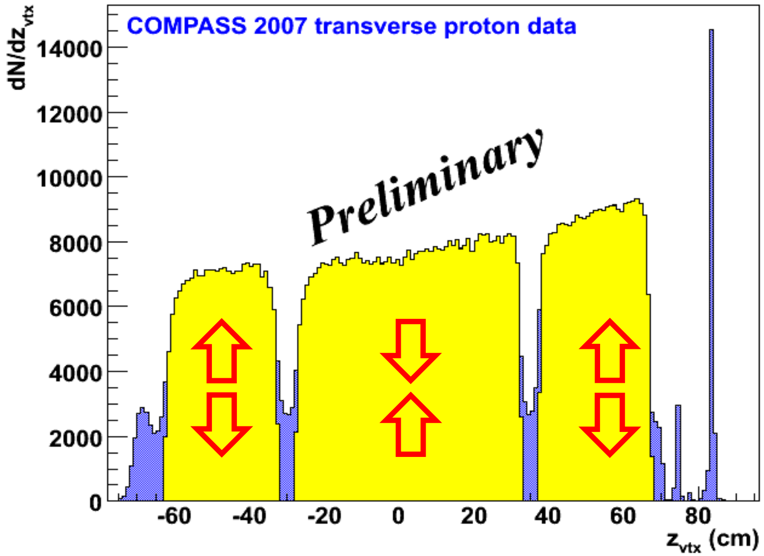
$10^{-3} < Q^2 < 10$ GeV^2

the target system

solid state target operated in frozen spin mode



2007-2010: NH_3 (polarised protons, T)
dilution factor f = 0.14
polarization P_T = 90%



measuring the weighted asymmetries

one period (week)

number of hadrons in sub-period 1

in each φ_{Siv} bin

number of hadrons in sub-period 2

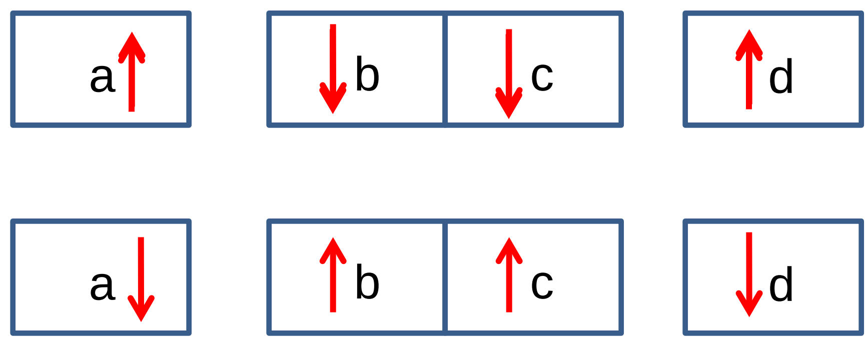
N_1 *cell **a+d** first sub-period*

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:

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

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

measuring the weighted asymmetries

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

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

$$\begin{aligned} \Delta^w &= N_1^w N_2'^w - N_1'^w N_2^w \\ \Sigma^w &= N_1^w N_2'^w + N_1'^w N_2^w \\ \Sigma &= N_1 N_2' + N_1' N_2 \end{aligned}$$

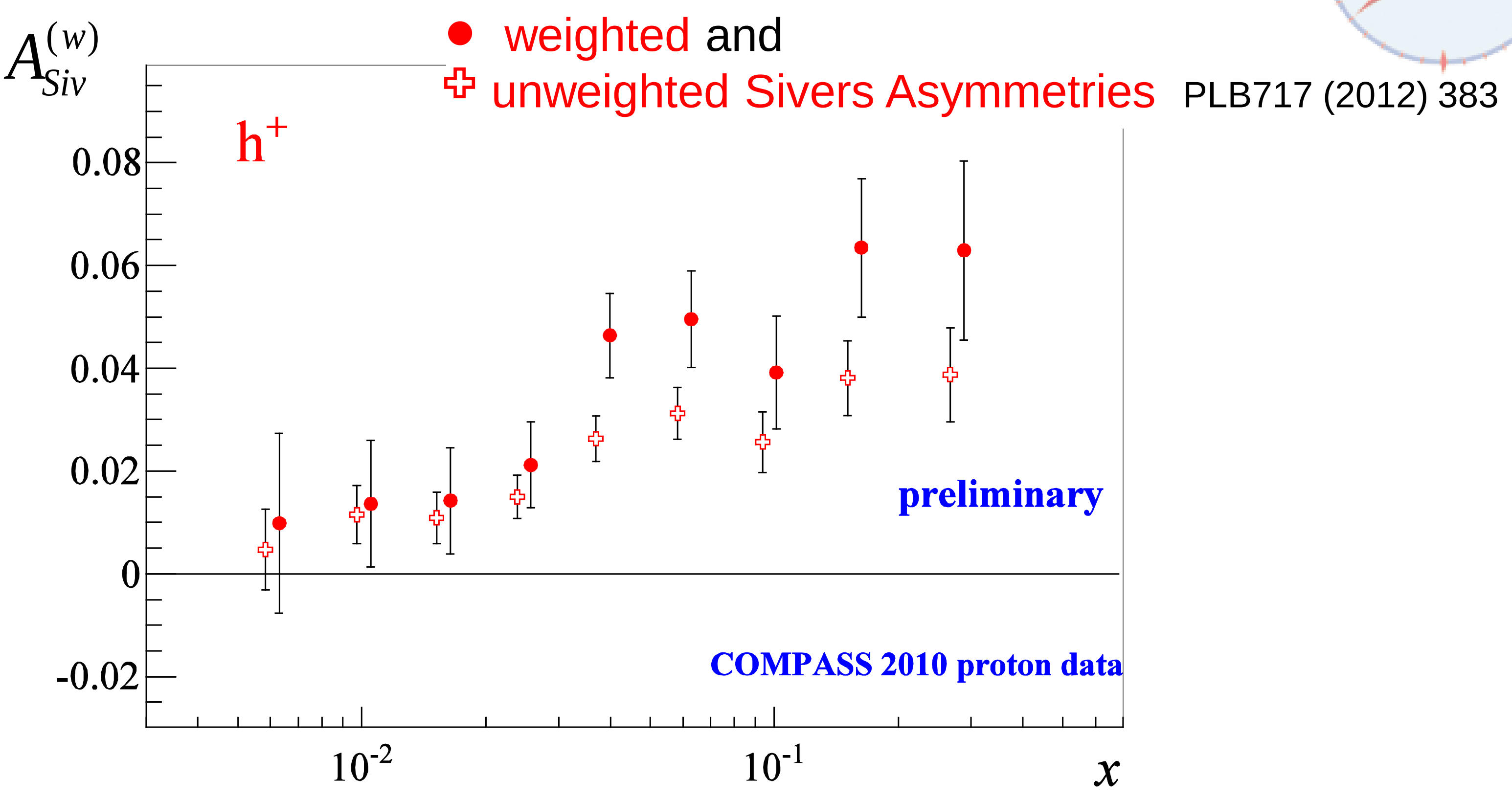
$$\simeq S_T \frac{\sigma_{Siv}^w}{\sigma_U}(\Phi_S) = S_T A_{Siv}^w \sin\Phi_S$$

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

calculated in 16 bins of Φ_S
and fitted using a $p_0 + p_1 \sin\Phi_s$ function

$$\Rightarrow \quad A_{Siv}^w = 2\,\frac{\sum_q e_q^2 \cdot f_{1T}^{\perp(1)q} \cdot D_{1q}^h}{\sum_q e_q^2 \cdot f_1^q \cdot D_{1q}^h}$$

results



$$A_{Siv}^{w} = 2\frac{\sum_q e_q^2 \cdot f_{1T}^{\perp(1)q} \cdot D_{1q}^h}{\sum_q e_q^2 \cdot f_1^q \cdot D_{1q}^h}$$

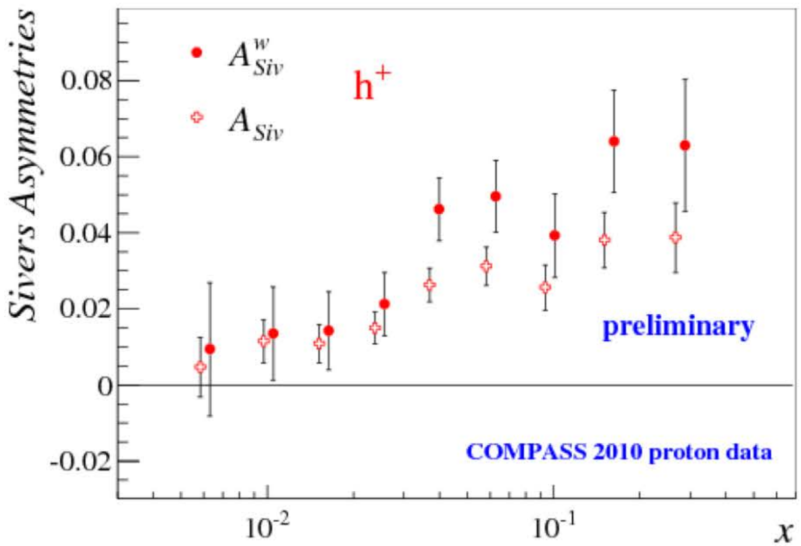
red full points

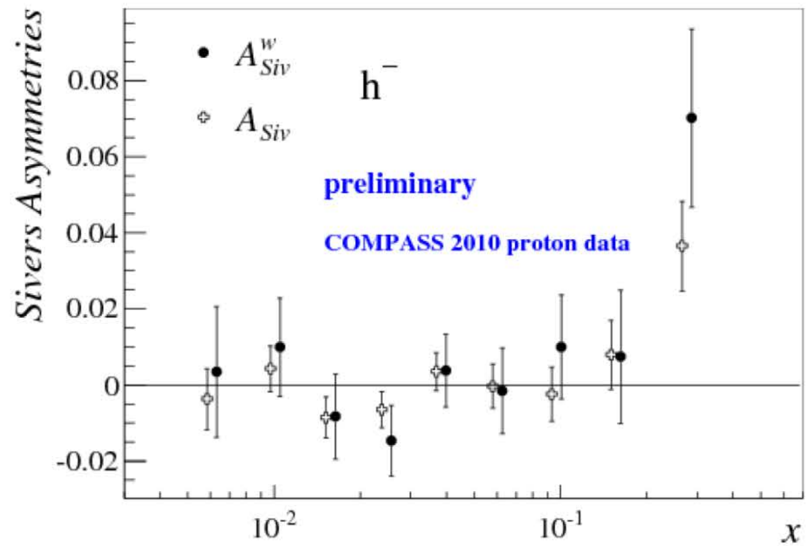
$$A_{Siv} = a_G \frac{\sum_q e_q^2 \cdot f_{1T}^{\perp(1)q} \cdot D_{1q}^h}{\sum_q e_q^2 \cdot f_1^q \cdot D_{1q}^h}$$

red empty crosses

results

● weighted and
✚ unweighted Sivers Asymmetries PLB717 (2012) 383





$$A^w_{Siv} = 2\frac{\sum_q e_q^2 \cdot f_{1T}^{\perp(1)q} \cdot D_{1q}^h}{\sum_q e_q^2 \cdot f_1^q \cdot D_{1q}^h}$$

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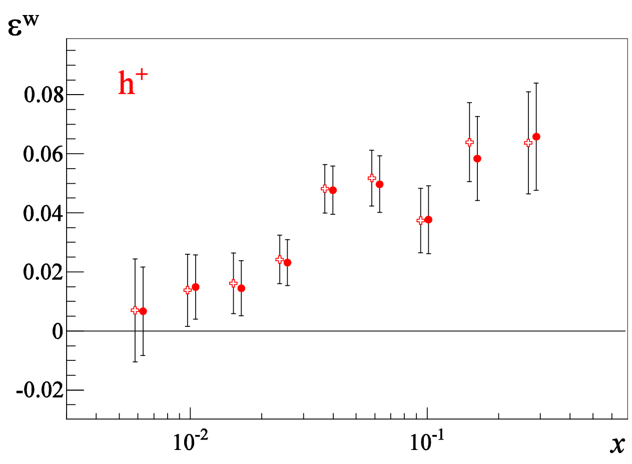
red empty crosses

weighted asymmetries - systematics

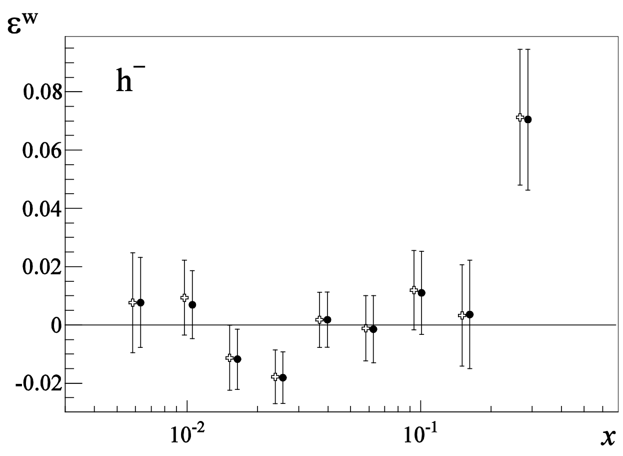
no evidence for systematic effects

acceptance



crosses are asymmetries extracted with Method 1

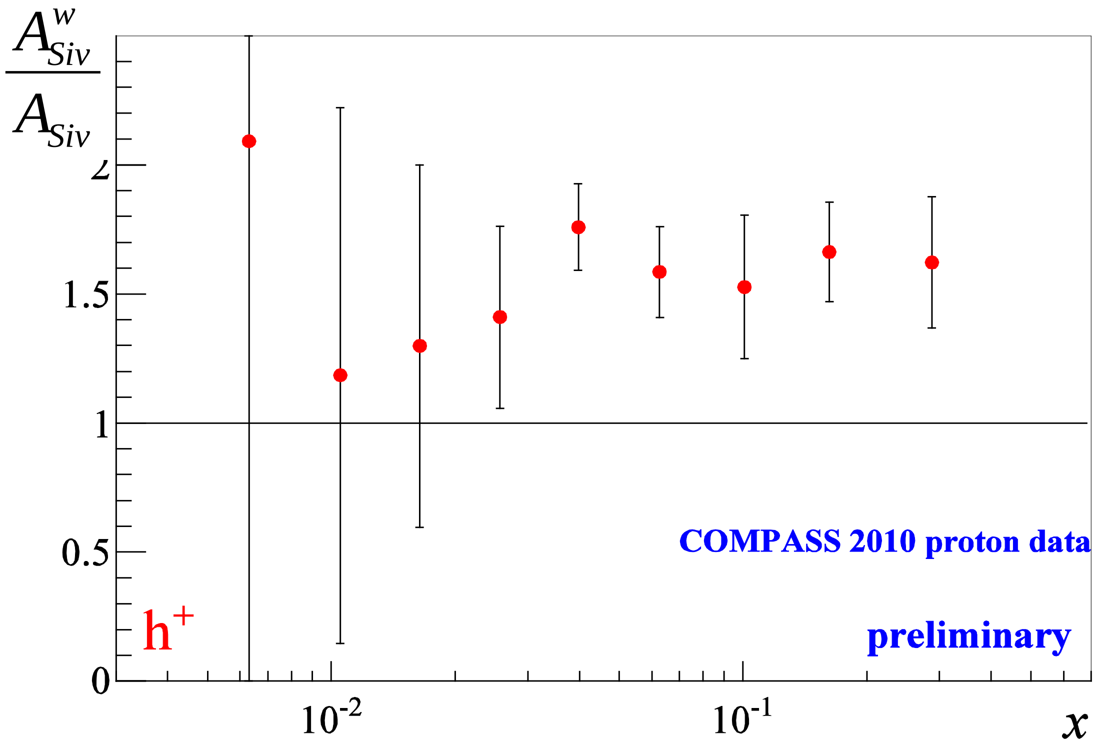
full points are the asymmetries corrected for the acceptance



the results as function of x are very similar for both h+ and h-

results

from the ratio $\frac{A^{w}_{Siv}}{A_{Siv}}$ *one gets information on* $a_G = \frac{\sqrt{\pi} M}{\sqrt{\langle k_T^2 \rangle_S + \langle p_T^2 \rangle / z^2}}$



$$A^{w}_{Siv} = 2 \frac{\sum_q e_q^2 \cdot f_{1T}^{\perp(1)q} \cdot D^h_{1q}}{\sum_q e_q^2 \cdot f_1^q \cdot D^h_{1q}}$$

red full points

$$A_{Siv} = a_G \frac{\sum_q e_q^2 \cdot f_{1T}^{\perp(1)q} \cdot D^h_{1q}}{\sum_q e_q^2 \cdot f_1^q \cdot D^h_{1q}}$$

red empty crosses

P_T weighted Sivers asymmetries at COMPASS

the measurement is feasible and the results are interesting

the method will be further refined in order to

get more direct information on the Gaussian model

apply it to other asymmetries

backup

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: $\sim 5 \cdot 10^{32}$ 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	L/T	
	2003		
	2004		
proton (NH_3)	2006	L	
	2007	L/T	
	2010	T	
	2011	L	
H_2 target	2012		

Transversely (T) or Longitudinally (L) polarised Target

hadron beam

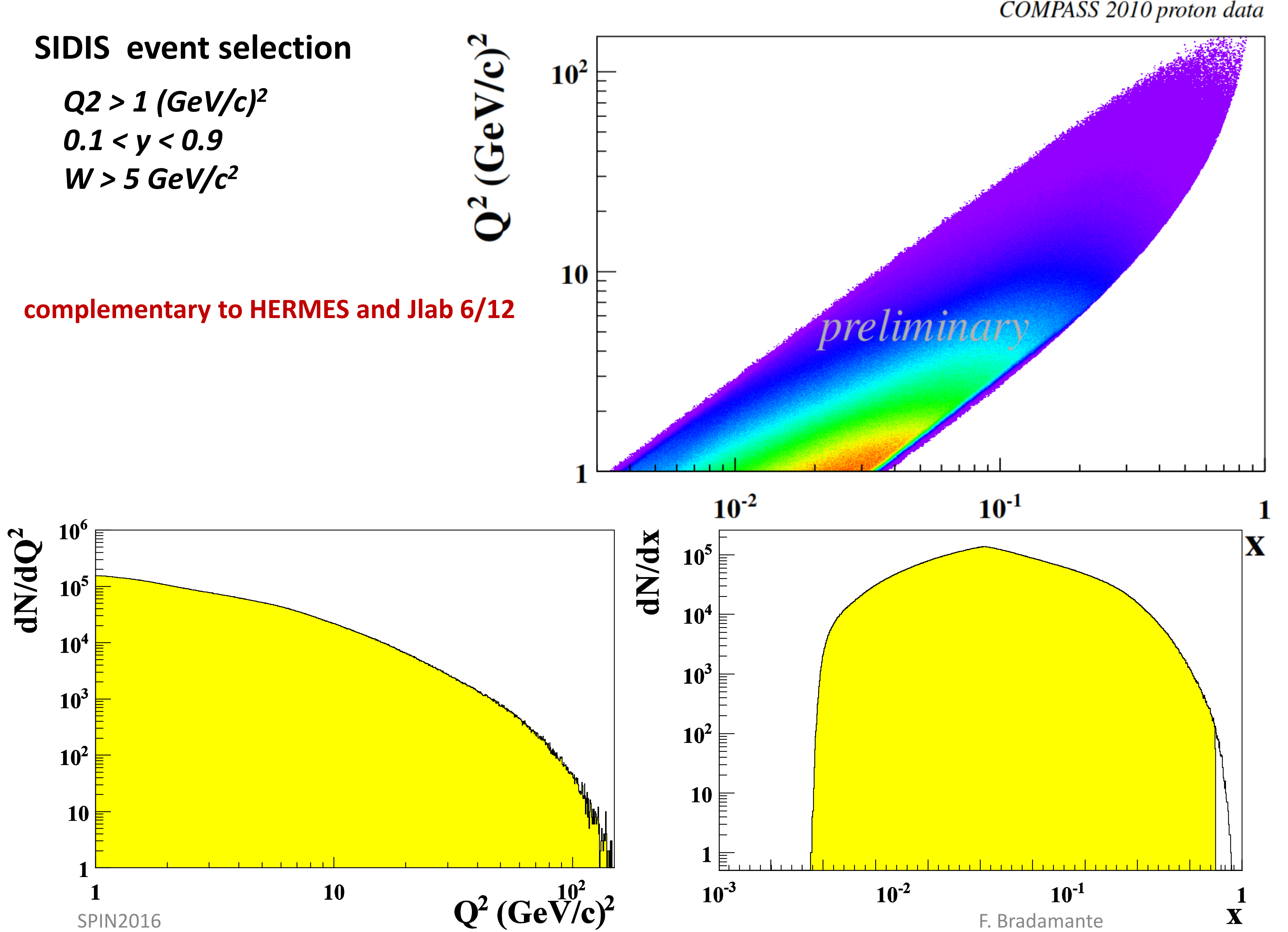
nuclear targets	2004
LH target	2008
	2009
	2012
	2014
T polarised DY	2015

1.63 +- 0.09

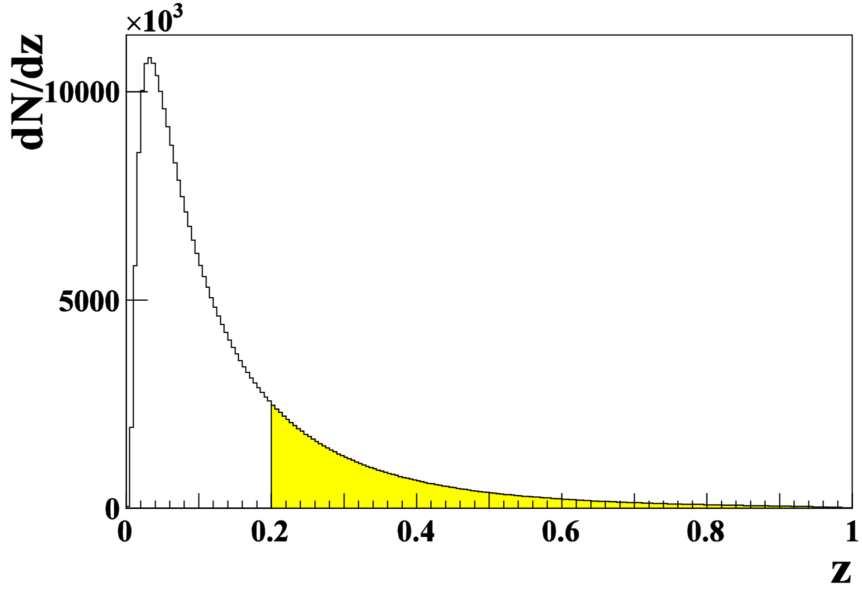
SIDIS event selection

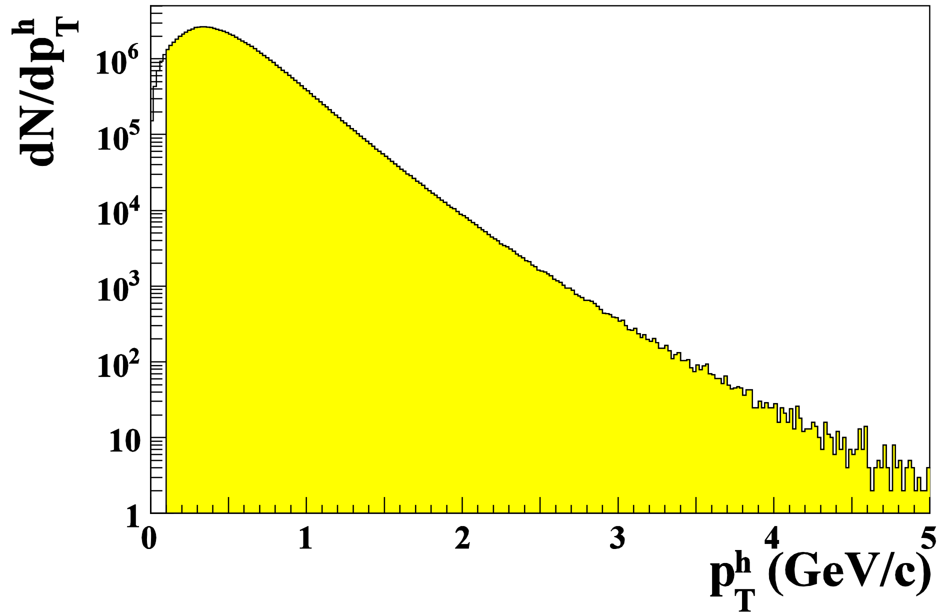
Q2 > 1 (GeV/c)²
0.1 < y < 0.9
W > 5 GeV/c²

complementary to HERMES and Jlab 6/12



SIDIS event selection

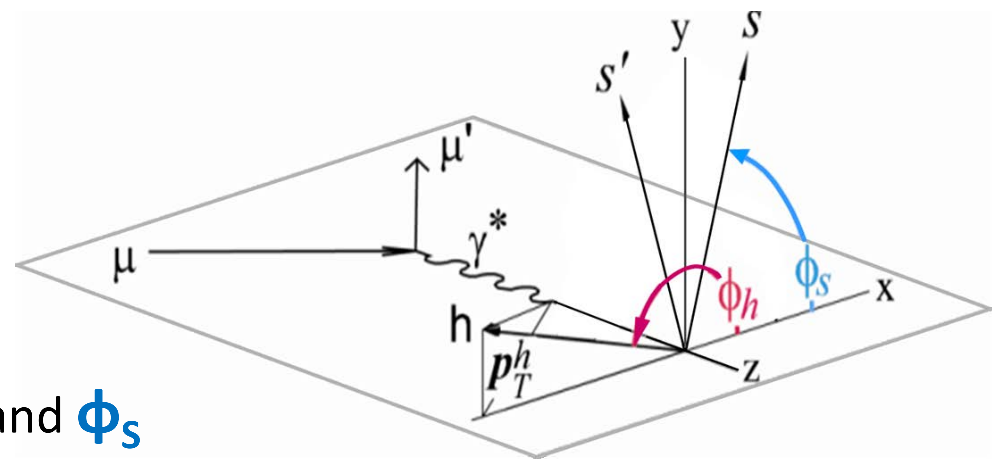




charged hadron selection

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

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

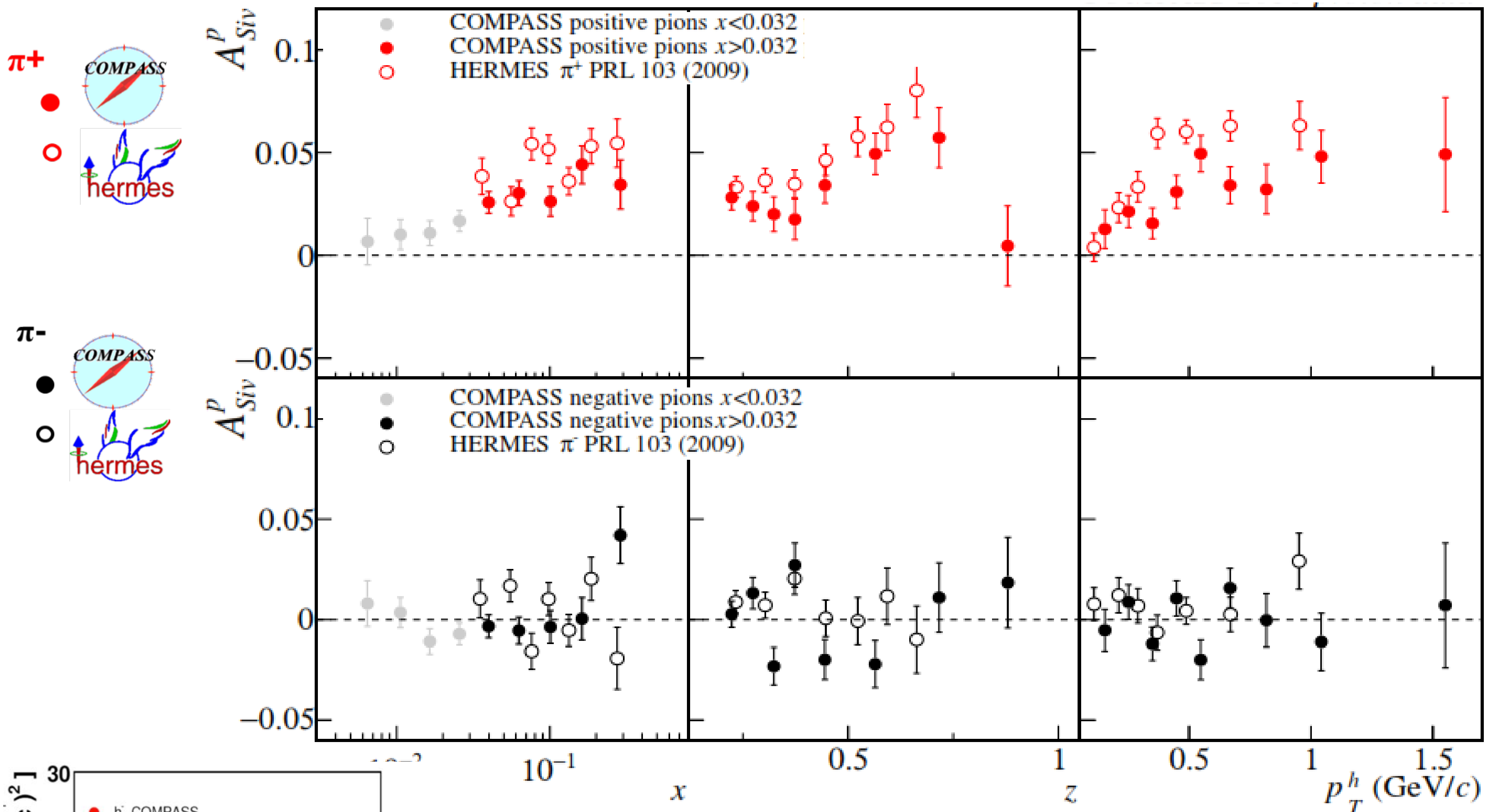
pretzelosity

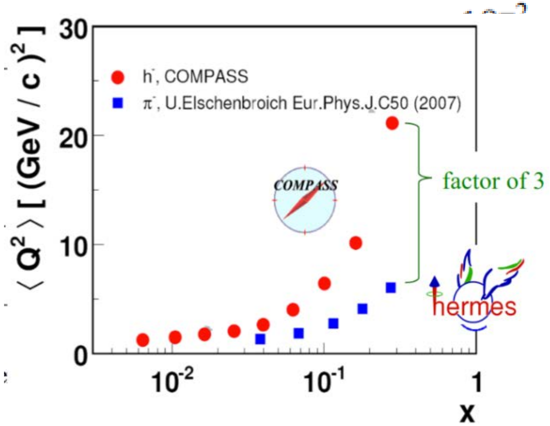
worm-gear

higher twist effects

all of them measured and
found to be compatible with zero

COMPASS and HERMES results





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

F. Bradamante

$\frac{P_T}{z}$ in each bin of x