COMPASS legacy:
transverse spin phenomena

(as seen from the back stage)

Franco Bradamante
INFN, sezione di Trieste

COMPASS

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

**fixed target experiment
at the CERN SPS**

COMPASS

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

fixed target experiment
at the CERN SPS

PROPOSAL	**March ’96**
RECOMMANDED	**September ’96**
APPROVED	**February ’97**
TAKING DATA	**since 2002**

25 YEARS

our jubilee

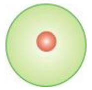
THE STRUCTURE OF THE NUCLEON

Collinear description leading twist

		nucleon polarisation		
		U	**L**	**T**
quark polarisation	**U**	f_1		
	L		g_1	
	T			h_1

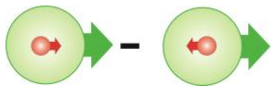
number density $f_1\ (q)$

very well known

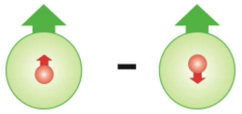


helicity distribution $g_1\ (\Delta q)$

well known



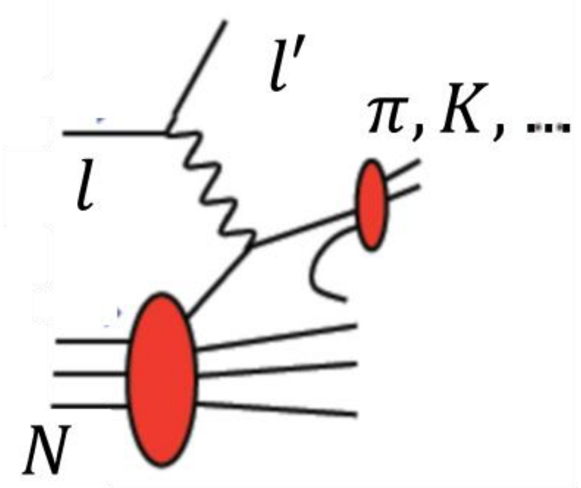
transversity distribution $h_1\ (\Delta_T q)$



- first experimental evidence in 2005
- correlation between the transverse polarisation of the nucleon and the transverse polarisation of the quark
- related to **tensor charge**
- a chirally-odd distribution, not observable in DIS, accessible in SIDIS

SEMI-INCLUSIVE DEEP INELASTIC SCATTERING

hard interaction of a lepton with a nucleon via virtual photon exchange



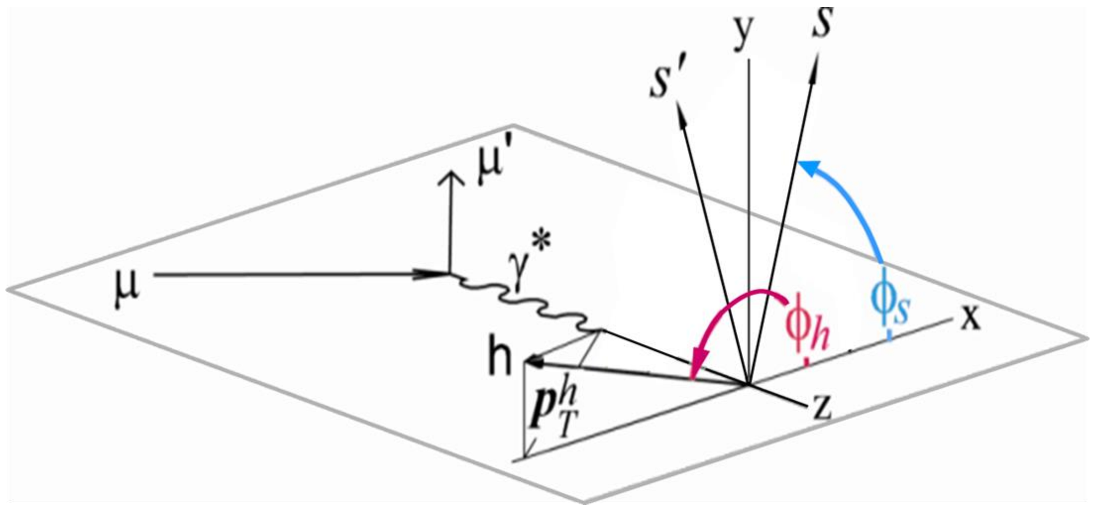
$$x = \frac{Q^2}{2P \cdot q} \qquad y = \frac{P \cdot q}{P \cdot \ell} =_{LAB} \frac{E - E'}{E}$$

$$Q^2 = -q^2 \qquad W^2 = (P + q)^2$$

$$z = \frac{P \cdot P_h}{P \cdot q} =_{LAB} \frac{E_h}{E - E'}$$

$$\sigma^{lN \to lhX} \sim \sum\nolimits_q \sigma^{lq \to lq} \otimes f(x) \otimes D_q^h(z)$$

$$\boldsymbol{p_T^h,\ \phi_h}$$



SIDIS – THE COLLINS ASYMMETRY

Collins effect

→ **azimuthal distribution of the hadrons produced in** $lN^{\uparrow} \rightarrow l' h X$

$$N_h^{\pm}(\Phi_C) = N_h^0 \cdot \left[1 \pm P_T \cdot D_{NN} \cdot A_{Coll} \cdot \sin\Phi_C\right]$$

± refer to the opposite orientation of the transverse spin of the nucleon

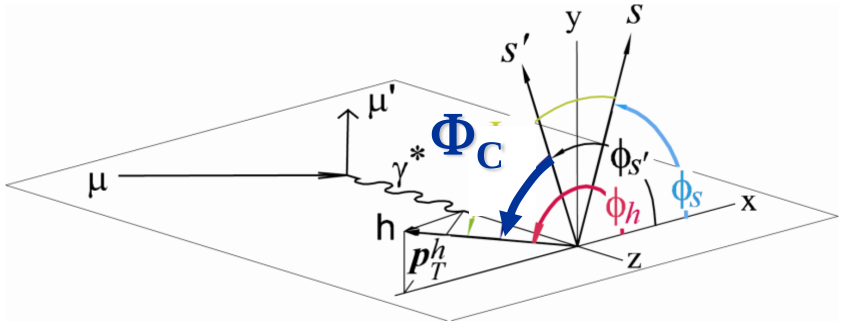
P_T is the target polarisation; D_{NN} is the transverse spin transfer coefficient initial → struck quark

COMPASS

“Collins angle”

$$\Phi_C = \phi_h - \phi_{s'} = \phi_h + \phi_S - \pi$$

$\phi_{h,s',S}$ azimuthal angles of hadron momentum, of the spin of the fragmenting quark and of the nucleon in the GNS



from the azimuthal distribution of the hadrons one measures the “Collins Asymmetry”

$$\boxed{A_{Coll} \propto \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}}$$

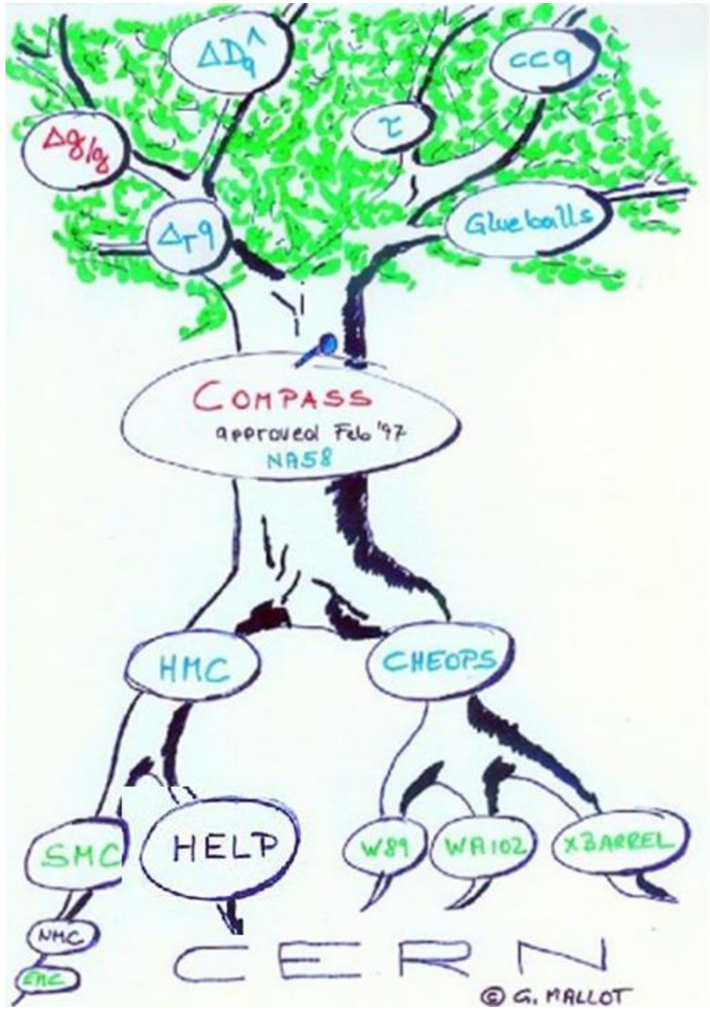
$$\Delta_T q \leftrightarrow h_1^q$$

$$\Delta_T^0 D_q^h \leftrightarrow H_{1\,q}^{\perp h}$$ Collins function

TRANSVERSE SPIN EFFECTS – TRANSVERSITY PDF

HELP proposal (L. Dick, B. Vuaridel, R. Hess, 1993) rejected by CERN:
regarded as black magic

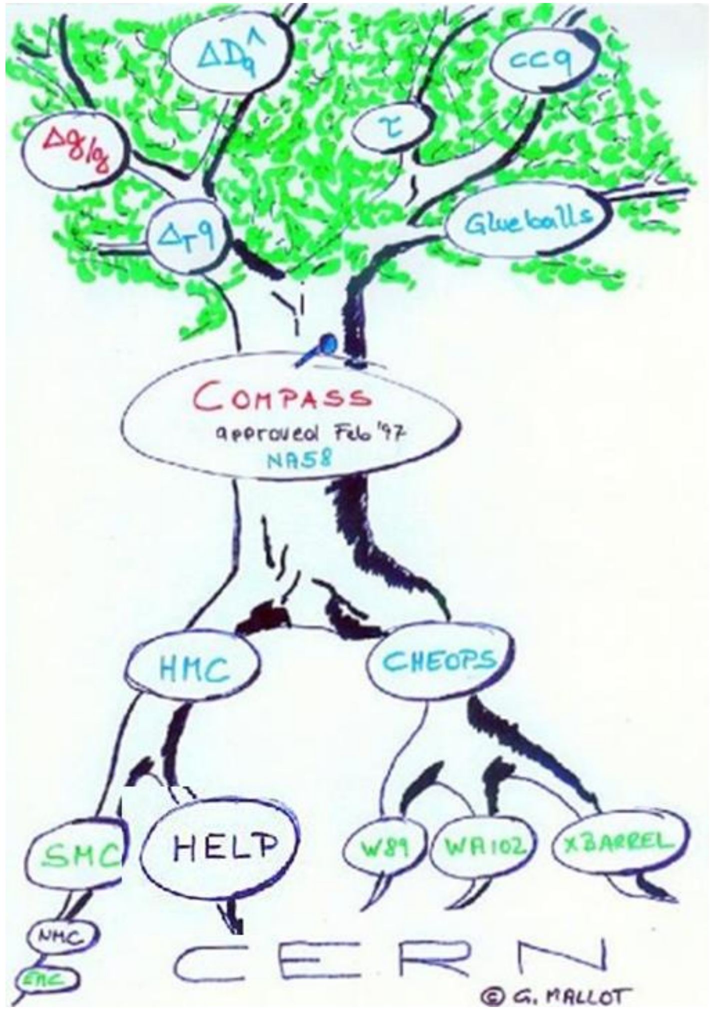
Our Collaboration accepted as a compromise to dedicate
20% of the running time with muon beam to measurements with
transversely polarized nucleon targets



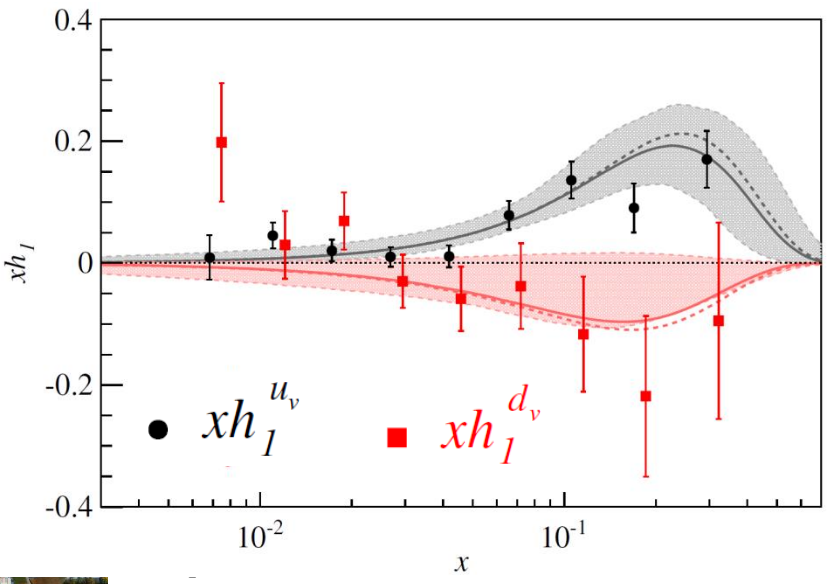
TRANSVERSE SPIN EFFECTS – TRANSVERSITY PDF

HELP proposal (L. Dick, B. Vuaridel, R. Hess, 1993) rejected by CERN:
regarded as black magic

Our Collaboration accepted as a compromise to dedicate
20% of the running time with muon beam to measurements with transversely polarized nucleon targets



Transversity is different from zero
and has been extracted from COMPASS and e^+e^- data
and with "global" fits of COMPASS, HERMES, e^+e^-, …data



A. Martin, F.B., V. Barone, Phys.Rev.D 91, 2015
curves from Anselmino et al., PRD87 2013

TRANSVERSE SPIN EFFECTS – THE SIVERS PDF

in parallel, the Sivers function story

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

....

TRANSVERSE SPIN EFFECTS – THE SIVERS PDF

in parallel, the Sivers function story

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

….

1996: not in our Proposal

IT IS ALSO DIFFERENT FROM ZERO

THE STRUCTURE OF THE NUCLEON

taking into account the quark intrinsic transverse momentum k_T, at leading order
8 TMD PDFs are needed for a full description of the nucleon structure

correlations between parton transverse momentum, parton spin and nucleon spin

nucleon polarisation

quark polarisation	**U**	**L**	**T**
U	f_1		$f_{1T}^{\perp}$
L		g_1	g_{1T}
T	$h_1^{\perp}$	$h_{1L}^{\perp}$	h_1 $h_{1T}^{\perp}$

h_1 **Transversity**

$h_{1T}^{\perp}$ pretzelosity

$f_{1T}^{\perp}$ **Sivers PDF**

g_{1T} worm-gear T
Kotzinian- Mulders

THE STRUCTURE OF THE NUCLEON

taking into account the quark intrinsic transverse momentum k_T, at leading order
8 TMD PDFs are needed for a full description of the nucleon structure

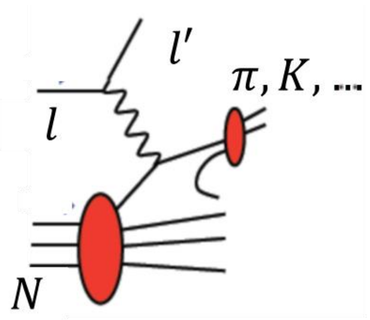
correlations between parton transverse momentum, parton spin and nucleon spin

nucleon polarisation

quark polarisation

	U	**L**	**T**
U	f_1		$f_{1T}^{\perp}$
L		g_1	g_{1T}
T	$h_1^{\perp}$	$h_{1L}^{\perp}$	h_1 $h_{1T}^{\perp}$

SIDIS
gives access
to all of them !



h_1	**Transversity**	$h_{1T}^{\perp}$	pretzelosity
$f_{1T}^{\perp}$	**Sivers PDF**	g_{1T}	worm-gear T Kotzinian- Mulders

SEMI-INCLUSIVE DEEP INELASTIC SCATTERING cross-section

A. Bacchetta et al JHEP 02 (2007) 093

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

SEMI-INCLUSIVE DEEP INELASTIC SCATTERING cross-section

A. Bacchetta et al JHEP 02 (2007) 093

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\cos\phi_h}\,F_{UU}^{\cos\phi_h} \\
&\quad+\varepsilon\,\overset{h_1^\perp H_1^\perp}{\boxed{\cos(2\phi_h)}}\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&\quad+S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin\phi_h}\,F_{UL}^{\sin\phi_h}+\varepsilon\,\overset{h_{1L}^\perp H_1^\perp}{\boxed{\sin(2\phi_h)}}\,F_{UL}^{\sin 2\phi_h}\right]+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos\phi_h}\,F_{LL}^{\cos\phi_h}\right] \\
&\quad+|\boldsymbol{S}_\perp|\Bigg[\overset{f_{1T}^\perp D_1}{\boxed{\sin(\phi_h-\phi_S)}}\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) \\
&\qquad+\varepsilon\,\underset{h_1 H_1^\perp}{\boxed{\sin(\phi_h+\phi_S)}}\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\overset{h_{1T}^\perp H_1^\perp}{\boxed{\sin(3\phi_h-\phi_S)}}\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\qquad+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin\phi_S}\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin(2\phi_h-\phi_S)}\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] \\
&\quad+|\boldsymbol{S}_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\overset{g_{1T}D_1}{\boxed{\cos(\phi_h-\phi_S)}}\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos\phi_S}\,F_{LT}^{\cos\phi_S} \\
&\qquad+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos(2\phi_h-\phi_S)}\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Big\},
\end{aligned}
$$

SEMI-INCLUSIVE DEEP INELASTIC SCATTERING cross-section

A. Bacchetta et al JHEP 02 (2007) 093

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

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

$$+\,\varepsilon\,\overset{h_1^\perp H_1^\perp}{\boxed{\cos(2\phi_h)}}\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$$+\,S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin\phi_h}\,F_{UL}^{\sin\phi_h}+\varepsilon\,\overset{h_{1L}^\perp H_1^\perp}{\boxed{\sin(2\phi_h)}}\,F_{UL}^{\sin 2\phi_h}\right]+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos\phi_h}\,F_{LL}^{\cos\phi_h}\right]$$

$$+\,|\boldsymbol{S}_\perp|\left[\overset{f_{1T}^\perp D_1}{\boxed{\sin(\phi_h-\phi_S)}}\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)\right.$$

$$+\,\varepsilon\,\underset{h_1 H_1^\perp}{\boxed{\sin(\phi_h+\phi_S)}}\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\overset{h_{1T}^\perp H_1^\perp}{\boxed{\sin(3\phi_h-\phi_S)}}\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

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

$$+\,|\boldsymbol{S}_\perp|\lambda_e\left[\sqrt{1-\varepsilon^2}\,\overset{g_{1T}D_1}{\boxed{\cos(\phi_h-\phi_S)}}\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos\phi_S}\,F_{LT}^{\cos\phi_S}\right.$$

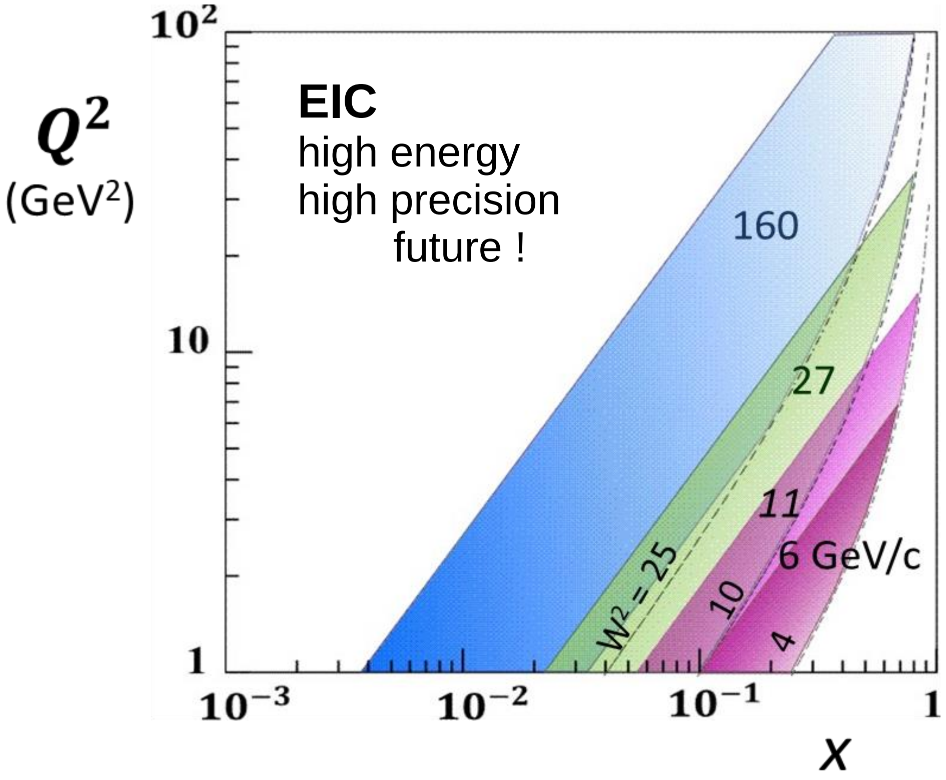
$$\left.\left.+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos(2\phi_h-\phi_S)}\,F_{LT}^{\cos(2\phi_h-\phi_S)}\right]\right\},$$

8 independent azimuthal modulations

leading twist amplitudes
→ convolutions of transversity and TMD PDFs and FFs

TRANSVERSE SPIN EFFECTS – A BIG EXPERIMENTAL EFFORT

SIDIS



EIC
high energy
high precision
future !

COMPASS ongoing

hermes over
results still coming

Jefferson Lab
6 GeV over
11 GeV: to be started
high precision data
24 GeV future

$e^+e^- \rightarrow hadrons$

Fragmentation Functions Collins, DiHadron, ….

BELLE BABAR BESIII

polarized DY

pp → jets

THE COMPASS SPECTROMETER – SIDIS with polarized targets

THE COMPASS SPECTROMETER – SIDIS with polarized targets

designed to

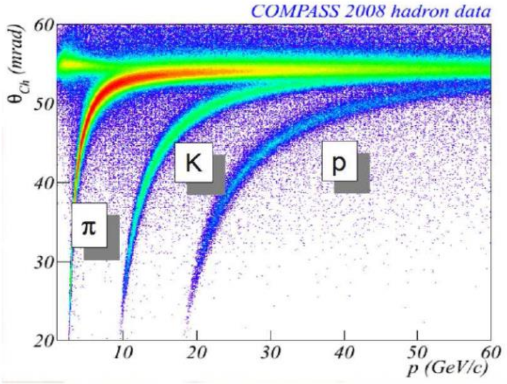
- **use high energy beams**
- **have large angular acceptance**
- **cover a broad kinematical range**

variety of tracking detectors

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

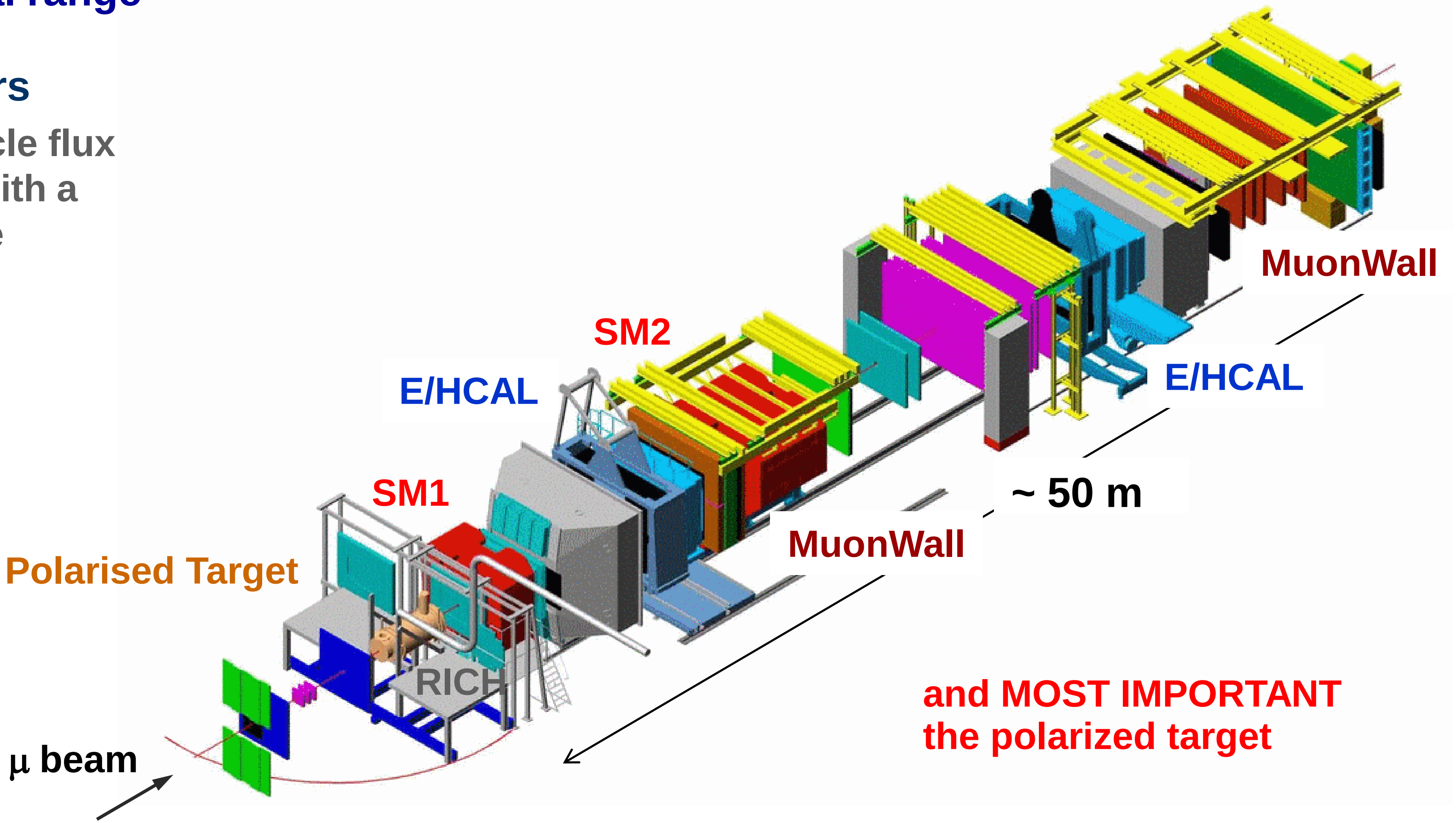
calorimetry, μID

RICH detector



two stages spectrometer

- **Large Angle Spectrometer (SM1)**
- **Small Angle Spectrometer (SM2)**

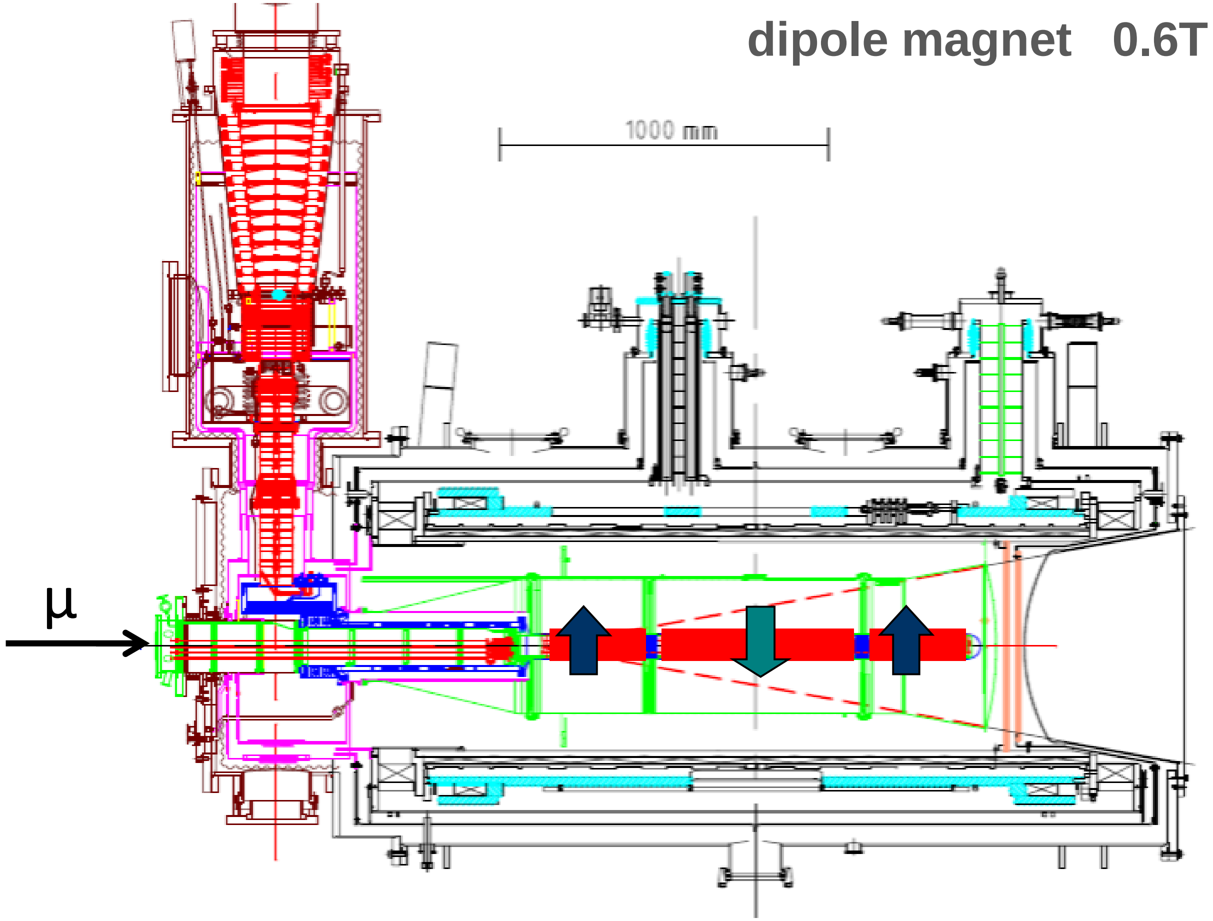


and MOST IMPORTANT the polarized target

The COMPASS polarized target system – SIDIS >2005

^{3}He – ^{4}He dilution refrigerator (T~50mK)

solenoid 2.5T
dipole magnet 0.6T



acceptance > ± 180 mrad

3 target cells
30, 60, and 30 cm long

opposite polarisation

	d (^{6}LiD)	p (NH_3)
polarization	40-50%	90%
dilution factor	40%	16%

no evidence for relevant nuclear effects (160 GeV)

MANY THANKS TO ALAIN

Franco Bradamante

results on Transverse Spin Asymmetries

25 years after the proposal

- **a review of well known results**
- **less known and new results**
- **expected results**

THE DEUTERON DATA - 2002-2004

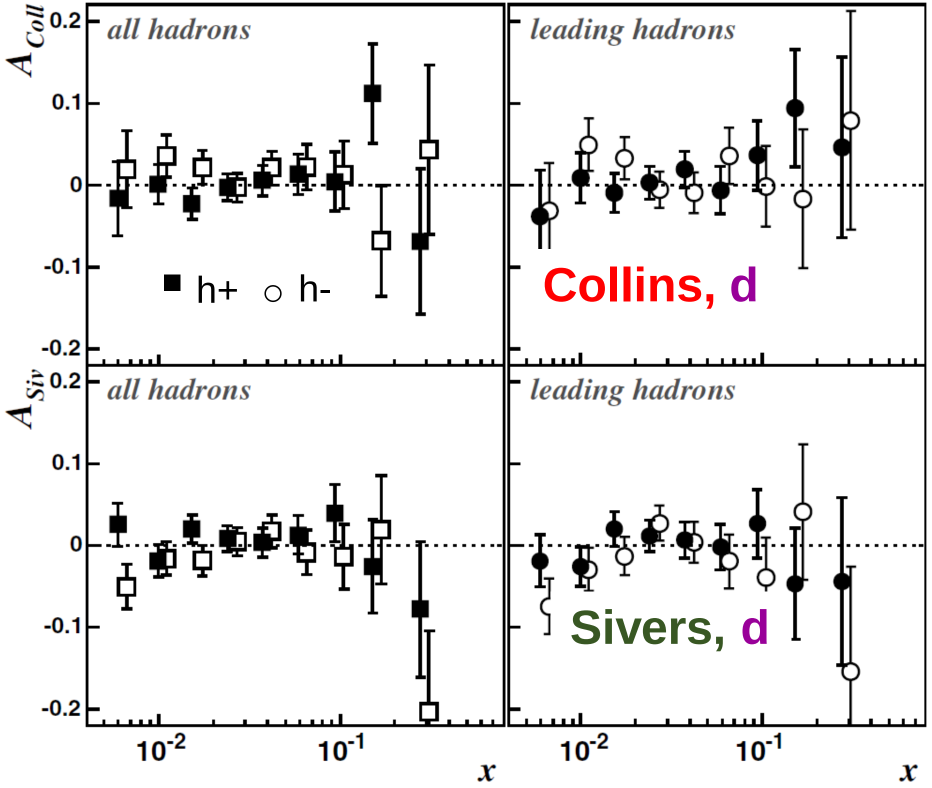
the first SIDIS data with a transversely polarized target in COMPASS were collected
in **2002**: 0.5 effective weeks of data taking
in 2004 first results for the **Collins asymmetry** and for the **Sivers asymmetry**

$$A_{Coll} \sim \frac{\sum_q e_q^2 \, h_1^q \otimes H_{1q}^{\perp}}{\sum_q e_q^2 \, f_1^q \cdot D_{1q}} \qquad A_{Siv} \sim \frac{\sum_q e_q^2 \, f_{1T}^{\perp q} \otimes D_{1q}}{\sum_q e_q^2 \, f_1^q \cdot D_{1q}}$$

first publication in 2005

2002 data

PRL 94, 202002 (2005)



large statistical uncertainties,
compatible with zero

?

SPIN2004
Trieste

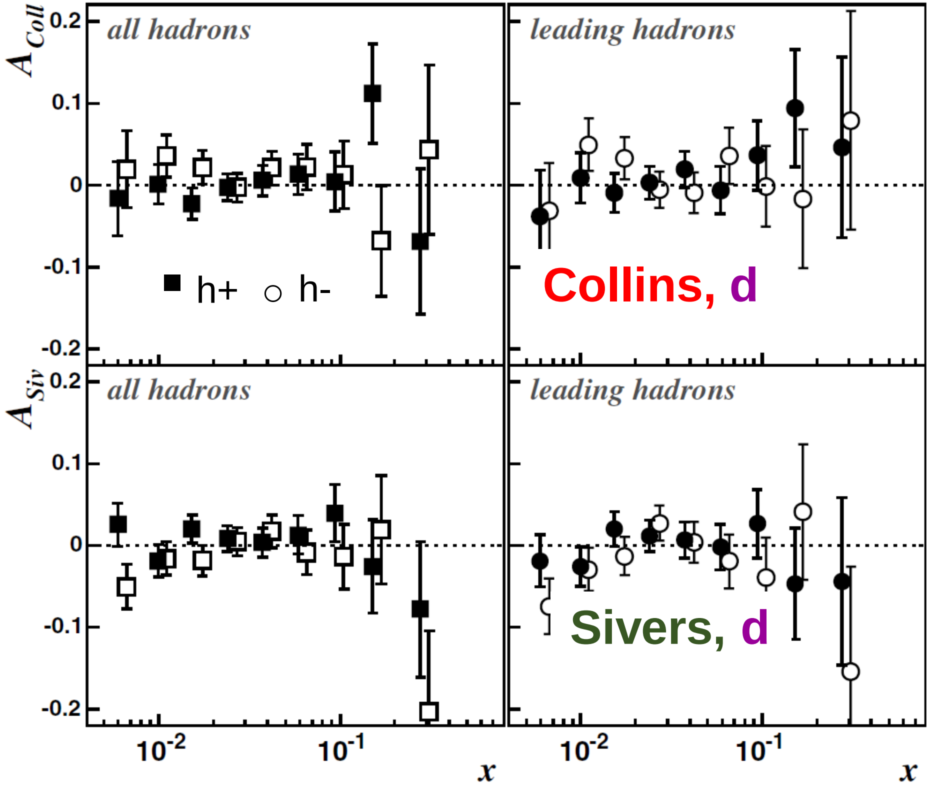
THE DEUTERON DATA - 2002-2004

the first SIDIS data with a transversely polarized target in COMPASS were collected
in **2002**: 0.5 effective weeks of data taking
in 2004 first results for the **Collins asymmetry** and for the **Sivers asymmetry**

first publication in 2005

2002 data

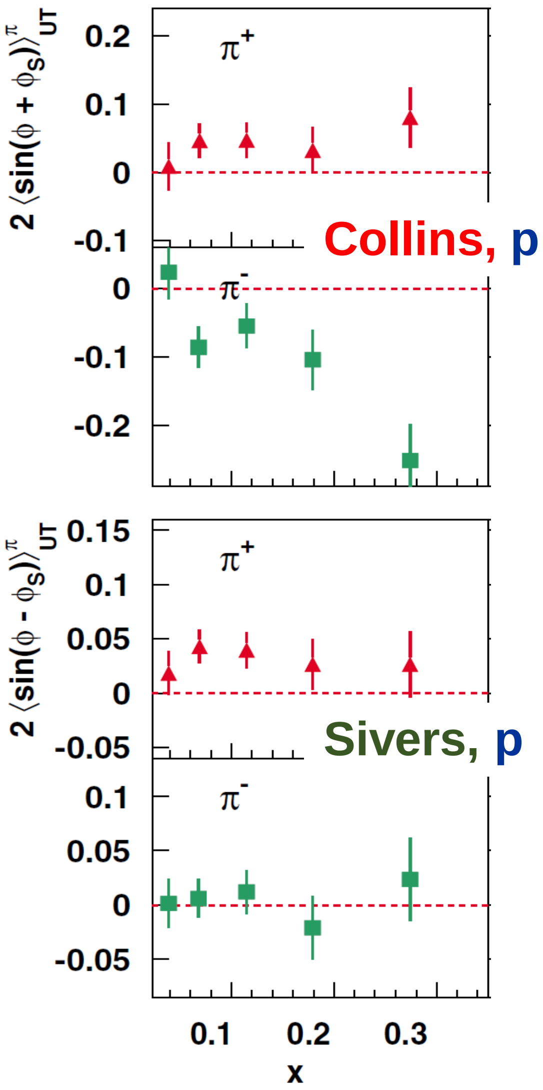
PRL 94, 202002 (2005)



in the mean time, HERMES measurements with a proton target

for the first time clear signals: real effects !

hep-ex/0408013

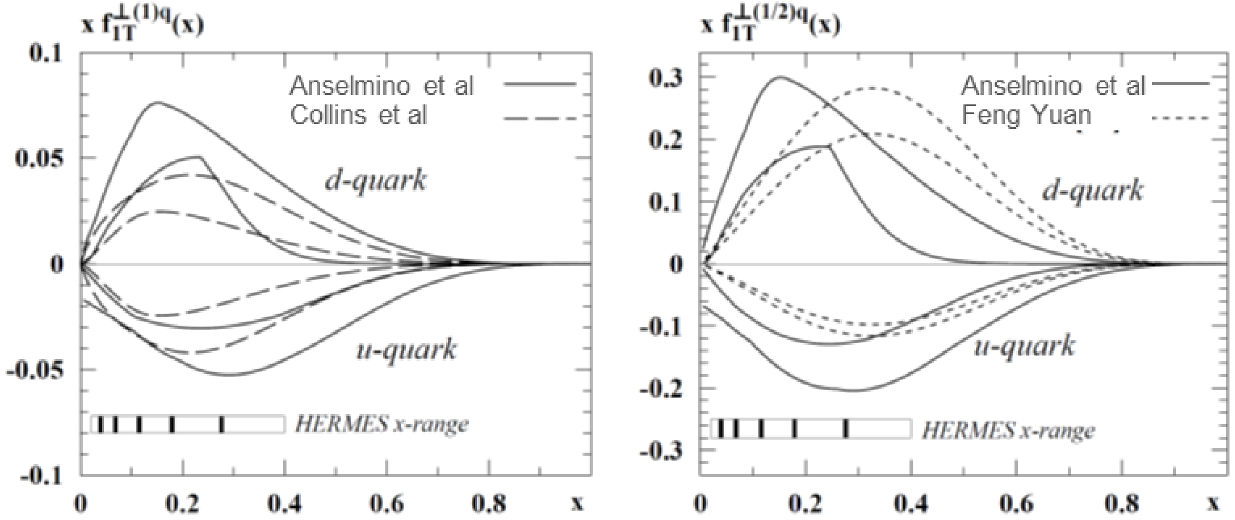


SPIN2004
Trieste

FIRST EXTRACTIONS OF THE NEW PDFs

the first extractions of the **Sivers PDFs** from these p and d Sivers asymmetries came very soon

the HERMES and COMPASS data could be well described



proceedings of
Transversity 2005

confirmation that the COMPASS results could be due to u d quark cancellation

FIRST EXTRACTIONS OF THE NEW PDFs

the first extractions of the **Sivers PDFs** from these p and d Sivers asymmetries came very soon

proceedings of
Transversity 2005

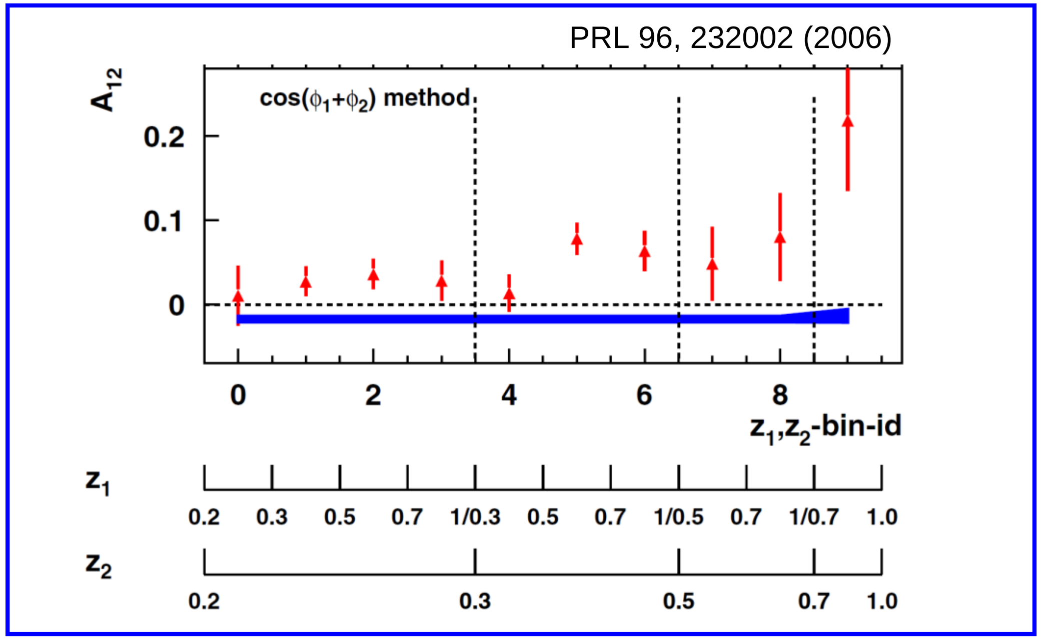
the extraction of the **transversity PDFs** took some more time

the Collins FF was the missing piece
it was qualitatively described by the Artru $^3P_0$ model

$$A_{Coll} \sim \frac{\sum_q e_q^2 \, \boldsymbol{h_1^q} \otimes \boldsymbol{H_{1q}^\perp}}{\sum_q e_q^2 \, f_1^q \cdot D_{1q}}$$

first measurements the Collins- like asymmetry
in $e^+e^- \rightarrow hadrons$ at BELLE

clear independent indication of
non-zero Collins FFs



PRL 96, 232002 (2006)

again indication that the COMPASS results
could be due to u d cancellation

FIRST EXTRACTIONS OF THE NEW PDFs

the first extractions of the **Sivers PDFs** from these p and d Sivers asymmetries came very soon

proceedings of
Transversity 2005

the extraction of the **transversity PDFs** took some more time

the Collins FF was the missing piece
it was qualitatively described by the Artru ${}^3P_0$ model

$$A_{Coll} \sim \frac{\sum_q e_q^2\, \boldsymbol{h_1^q} \otimes \boldsymbol{H_{1q}^\perp}}{\sum_q e_q^2\, f_1^q \cdot D_{1q}}$$

first measurements the Collins- like asymmetry
in $e^+e^- \to hadrons$ at BELLE

to summarize:

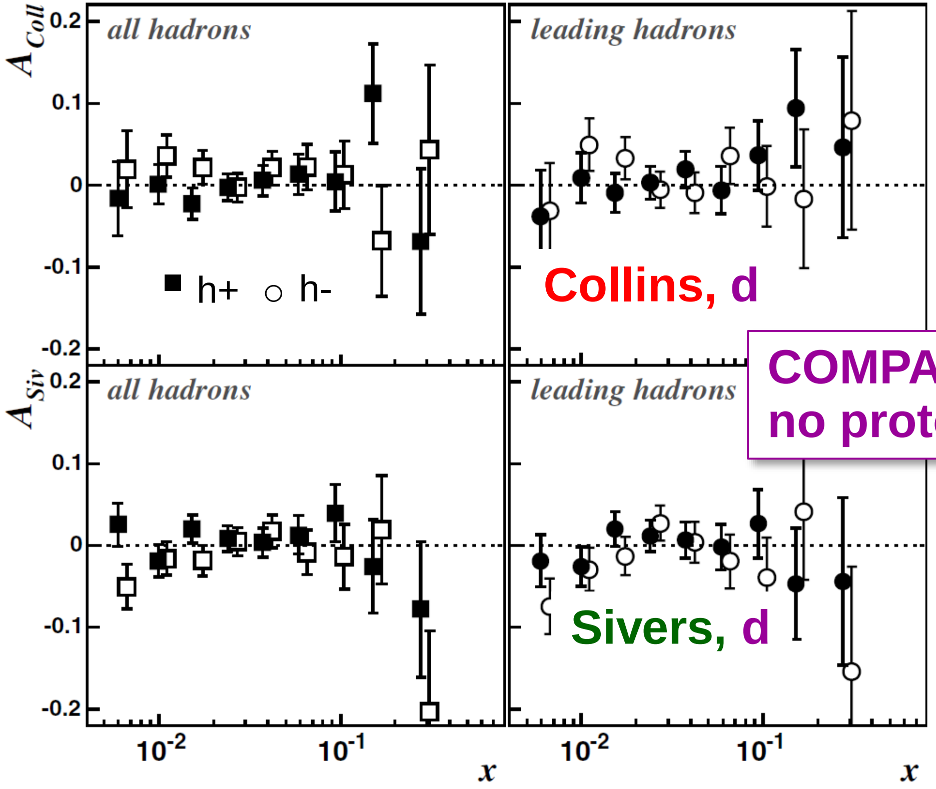
- clear signals of the new transverse spin effects seen at HERMES and Belle
- a consistent picture of transverse spin effects was coming out, which could explain both the HERMES proton and the COMPASS deuteron data

EXPERIMENTAL SITUATION IN 2005

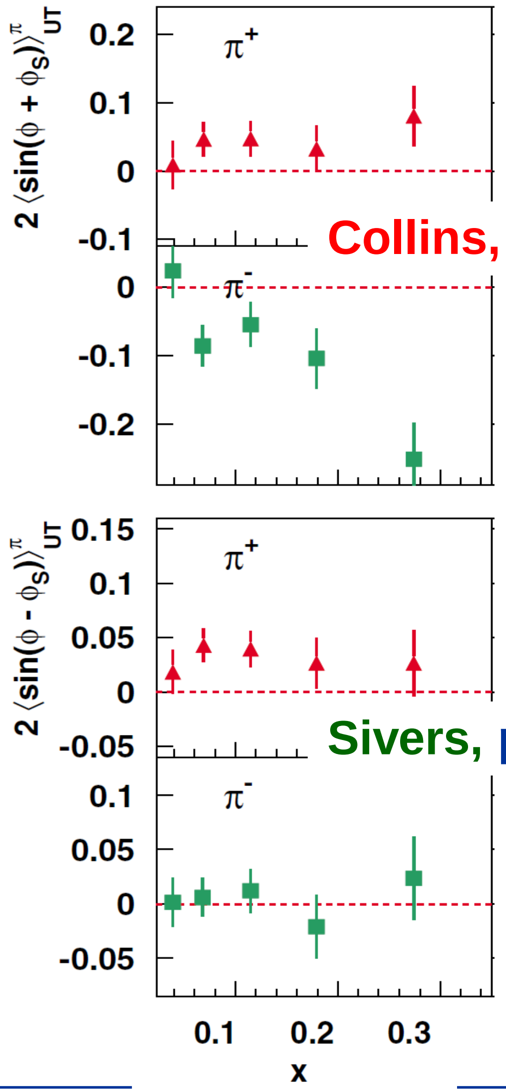
in 2004 first results for the **Collins asymmetry** and for the **Sivers asymmetries**
first publications in 2005

2002 data

PRL 94, 202002 (2005)



COMPASS had no proton data

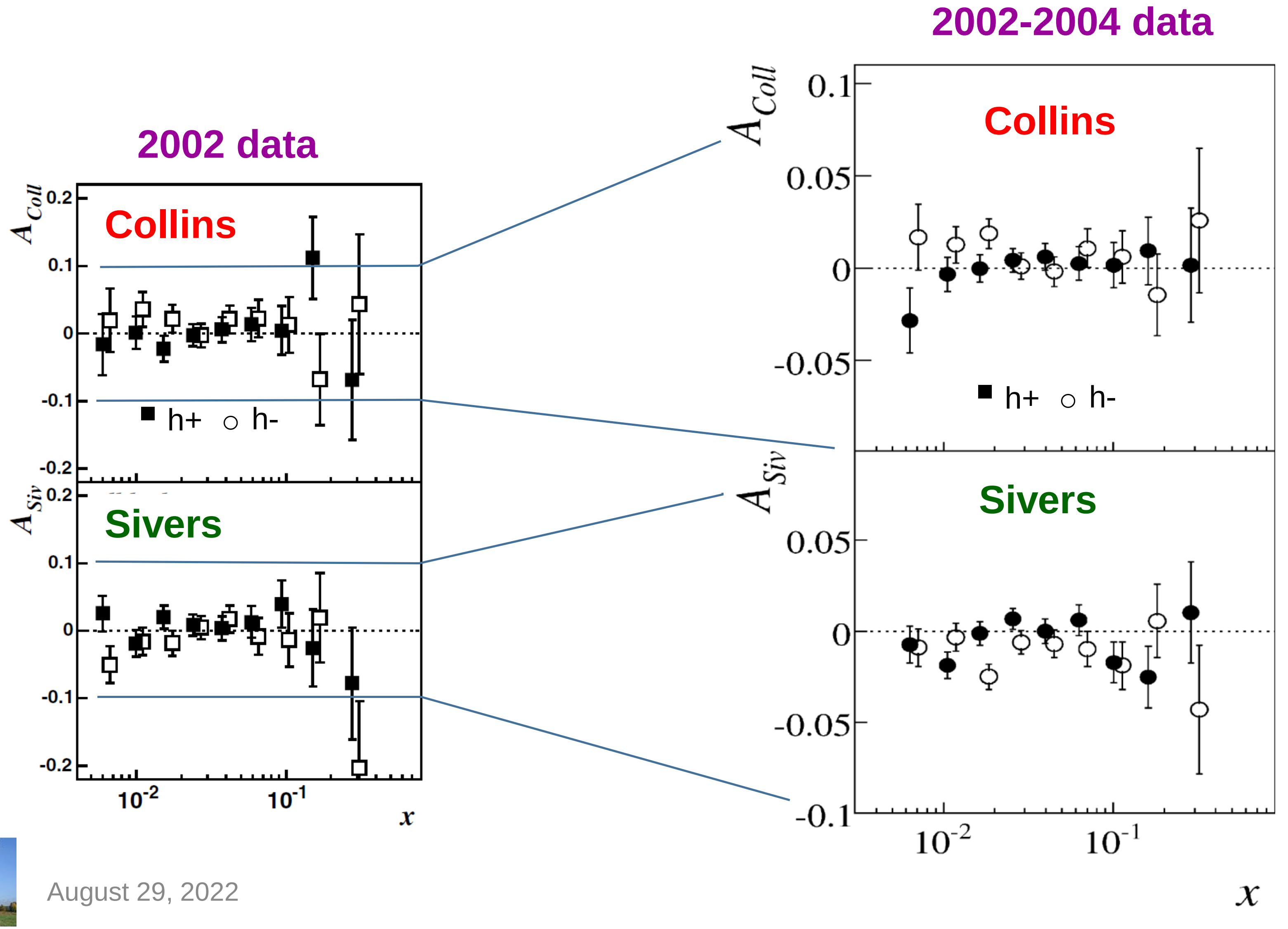


HERMES had no deuteron data

more data were needed !

THE DEUTERON DATA

2002: ~0.5 effective weeks of data taking, published in 2005
2003: 2 weeks of data taking
2004: 2 weeks of data taking

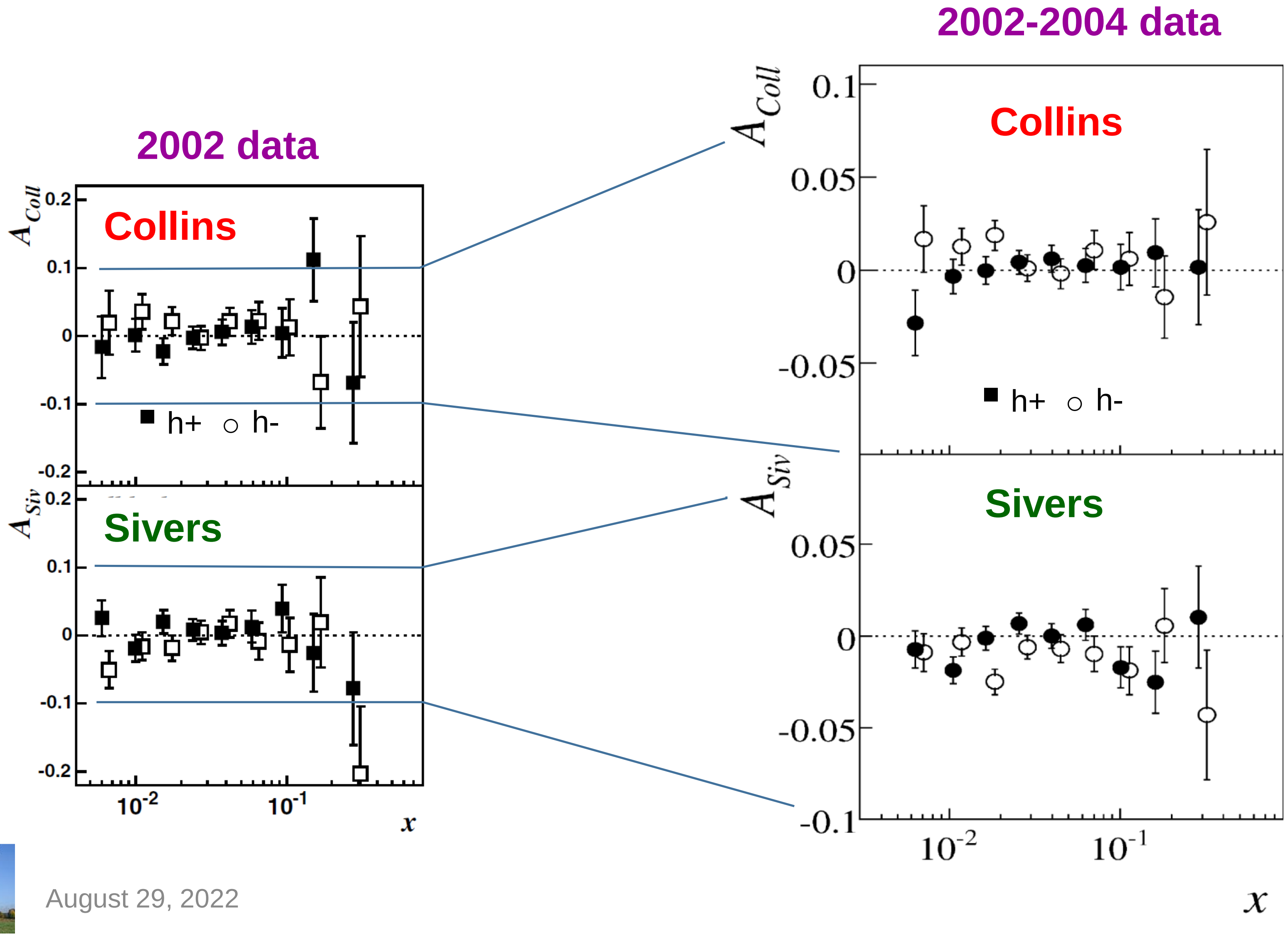


final results for deuteron
published in 2007 NPB 765 (**2007**) 31

a more precise measurement of zero;
still, large statistical uncertainties

THE DEUTERON DATA

2002: ~0.5 effective weeks of data taking, published in 2005
2003: 2 weeks of data taking
2004: 2 weeks of data taking



final results for deuteron
published in 2007 NPB 765 (**2007**) 31

a more precise measurement of zero;
still, large statistical uncertainties

the only existing deuteron data

→ ***run 2022 ongoing !***

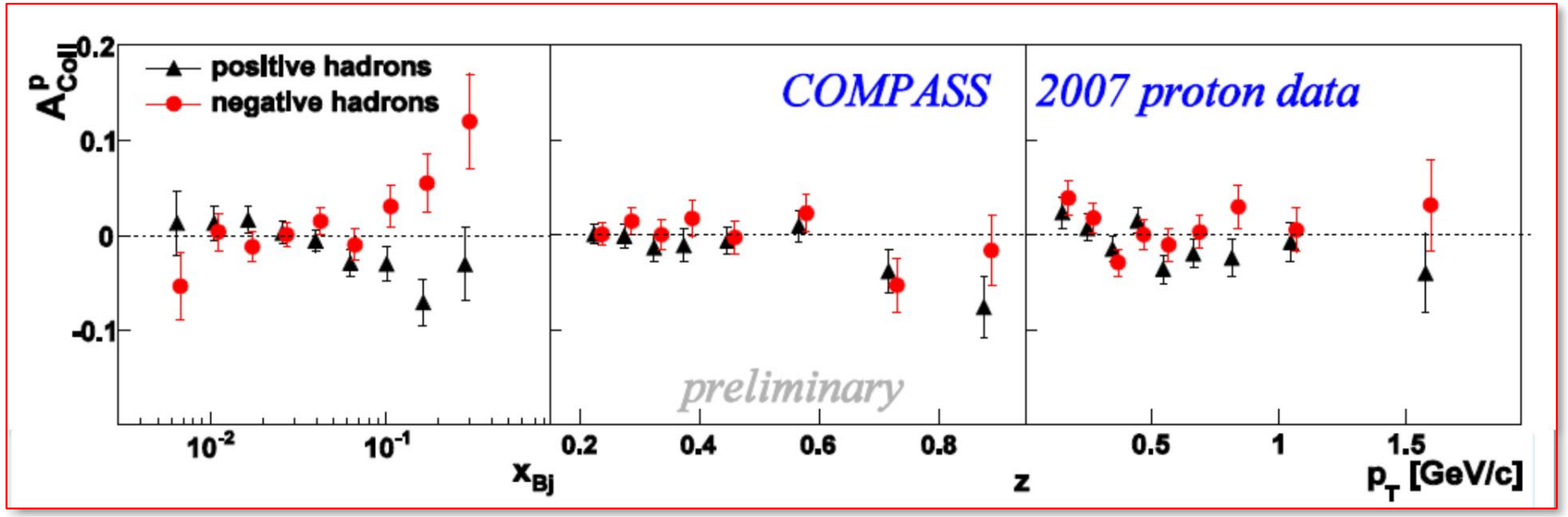
JLab6: He3,
statistically limited

THE 2007 PROTON DATA

in 2007 first (short) **COMPASS run with transversely polarized protons** (NH3)

preliminary results (half of the data): Transversity 2008

COLLINS ASYMMETRY
different from zero and
COMPATIBLE WITH HERMES !

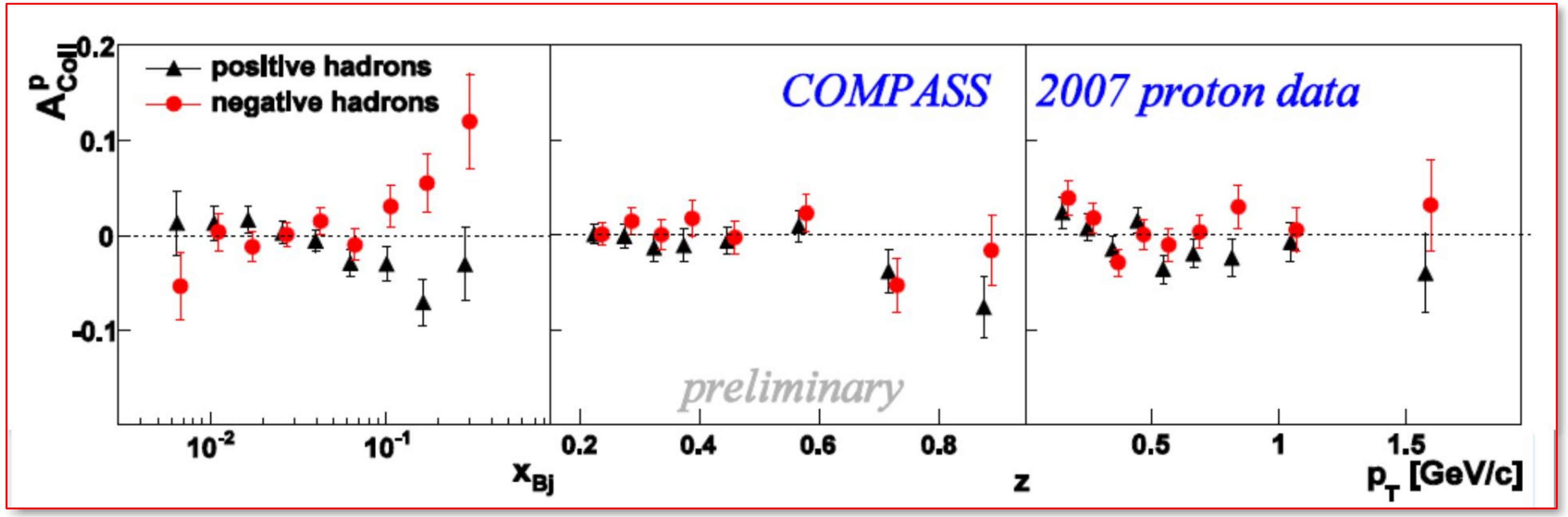


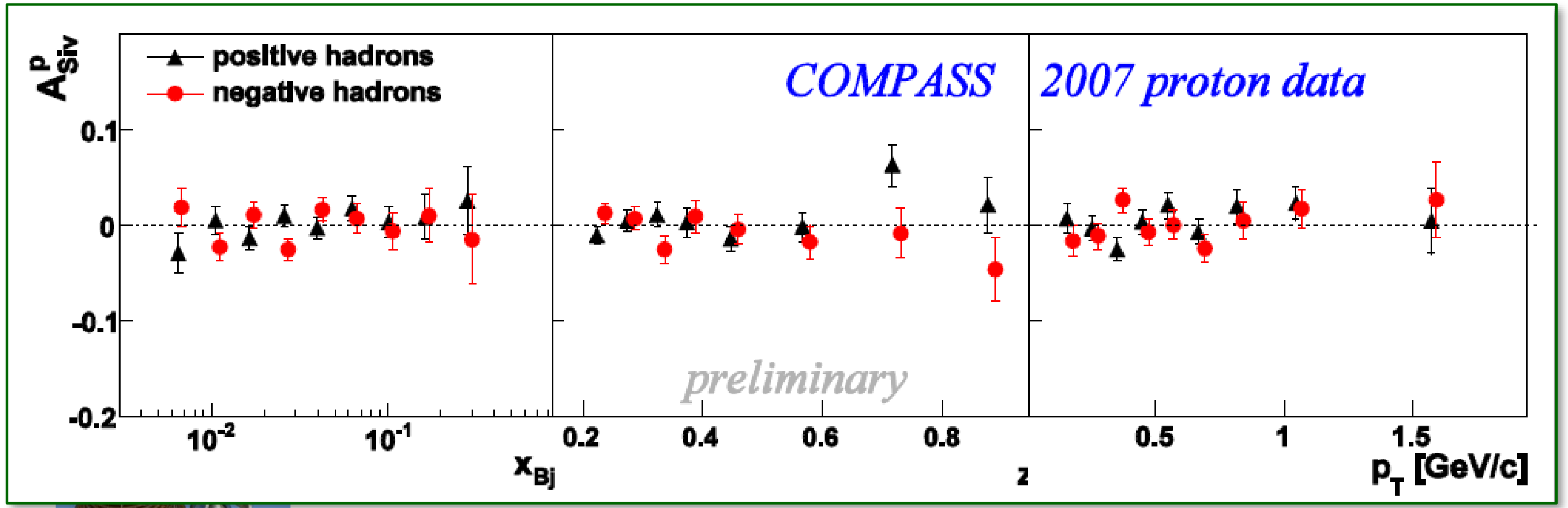
THE 2007 PROTON DATA

in 2007 first (short) **COMPASS run with transversely polarized protons** (NH3)

preliminary results (half of the data): Transversity 2008

COLLINS ASYMMETRY
different from zero and
COMPATIBLE WITH HERMES !





SIVERS ASYMMETRY
compatible with zero, also for positive hadrons
AT VARIANCE WITH HERMES

UNEXPECTED RESULT

no panic but NIGHTMARES

A_2 splitting
S meson
superluminal neutrinos

THE 2007 PROTON DATA

Close scrutiny of the collected data revealed some systematics

" **fairly long and sometimes difficult analysis** "

Final results, all 2007 data: Phys. Lett. B 692 (2010) 240

Collins asymmetry: preliminary result confirmed $\sigma_{syst} \simeq 0.5\,\sigma_{stat}$

Sivers asymmetry:

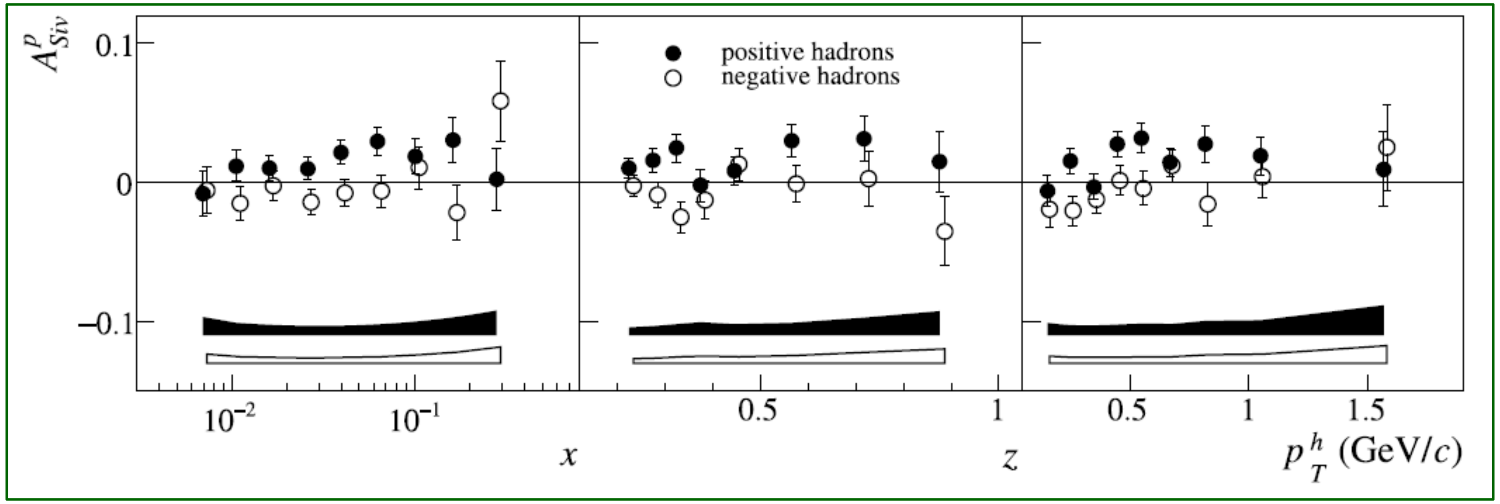
positive hadrons exhibit an average asymmetry of 0.03

somewhat smaller than HERMES

but

definitely non zero

$$\boldsymbol{\sigma^{+}_{syst} \simeq 0.8\,\sigma^{+}_{stat} \pm 0.01}$$



→ **necessity of a longer and better data taking**

THE 2010 PROTON DATA

Necessity of a longer and better data taking:

request for 1 year of data taking with transversely polarized p

“Transverse spin structure and Drell-Yan measurements at COMPASS”
FB talk at New opportunities in the physics landscape at CERN,
May 2009

Addendum 2 to the COMPASS Proposal
CERN-SPSC-2009-025 SPSC-M-769
SPSLC-P-297 Add. 2, 21 June 2009

THE 2010 PROTON DATA

Necessity of a longer and better data taking:

request for 1 year of data taking with transversely polarized p

“Transverse spin structure and Drell-Yan measurements at COMPASS”
FB talk at New opportunities in the physics landscape at CERN,
May 2009

Addendum 2 to the COMPASS Proposal
CERN-SPSC-2009-025 SPSC-M-769
SPSLC-P-297 Add. 2, 21 June 2009

Many thanks to Elke

Year 2010 entirely dedicated to proton running

and the 2010 run was quite successful

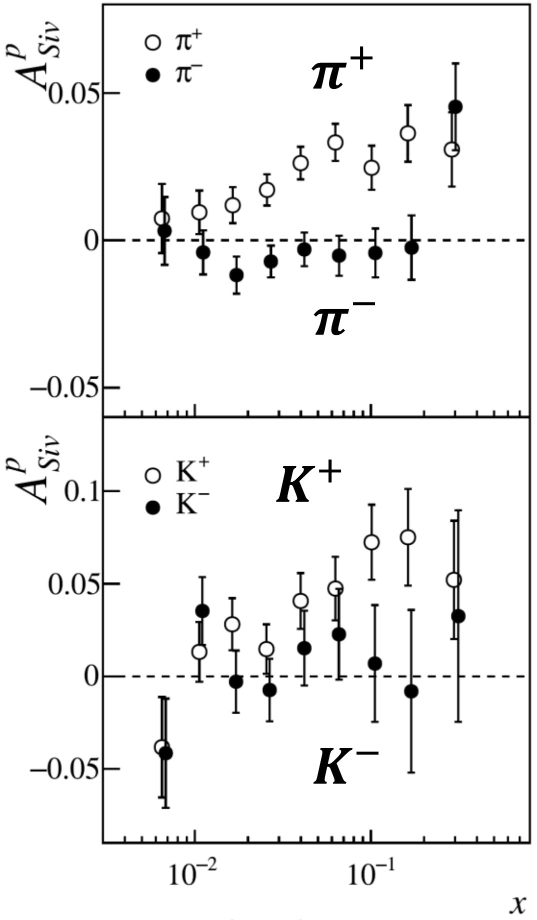
Preliminary results shown at Transversity 2011 in Losini
First results published in 2012

THE PROTON DATA – Sivers asymmetry

2007 half year, 2010 one year of data taking - **the signals are there!**

Sivers asymmetry

all COMPASS proton data



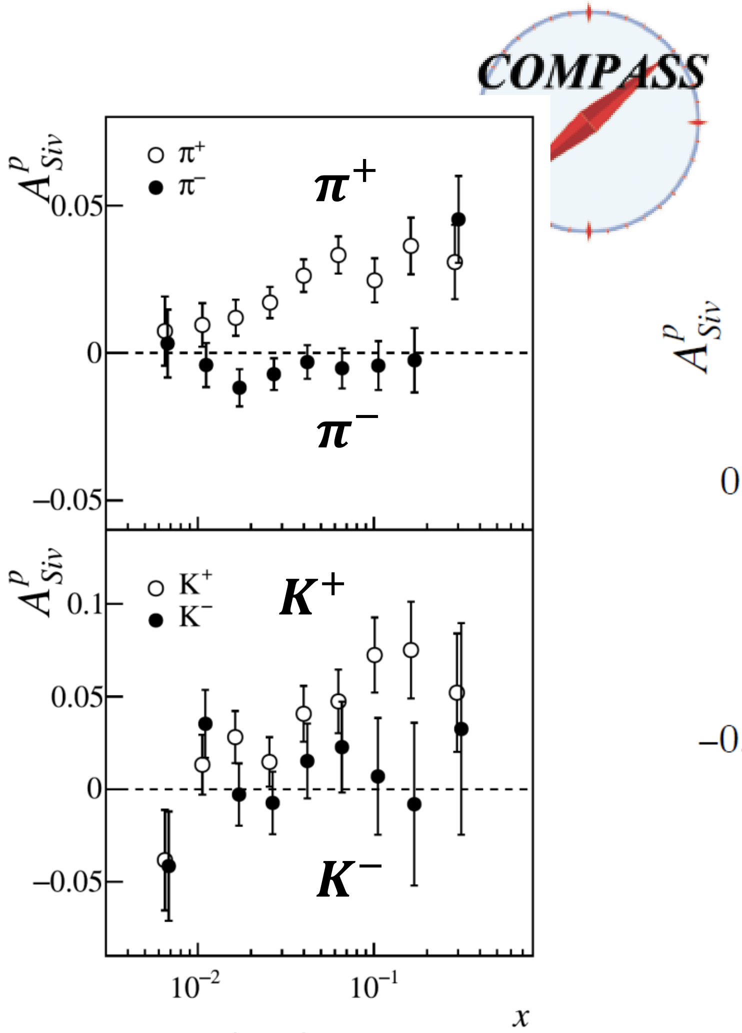
PLB 744 (2015) 250
PLB 717 (2012) 383

THE PROTON DATA – Sivers asymmetry

2007 half year, 2010 one year of data taking - **the signals are there!**

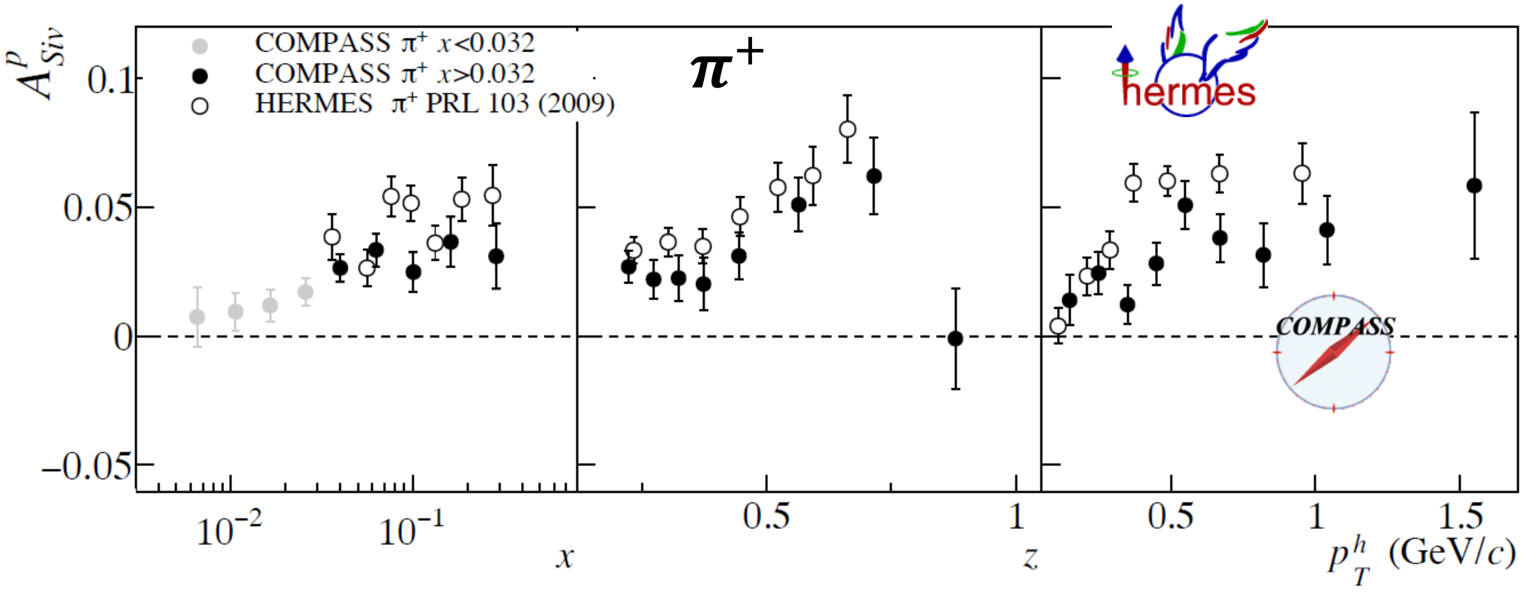
Sivers asymmetry

all COMPASS proton data



PLB 744 (2015) 250
PLB 717 (2012) 383

comparison with HERMES

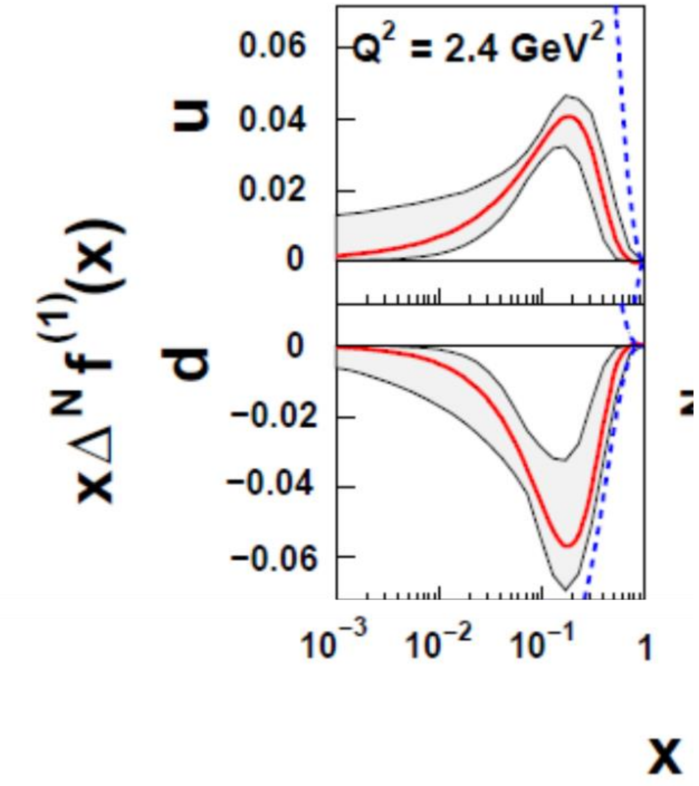


smaller values at COMPASS:
TMD evolution …

THE SIVERS FUNCTION

Sivers function extractions from SIDIS data (COMPASS, HERMES, Jlab)

→ **u and d: clearly different from zero**

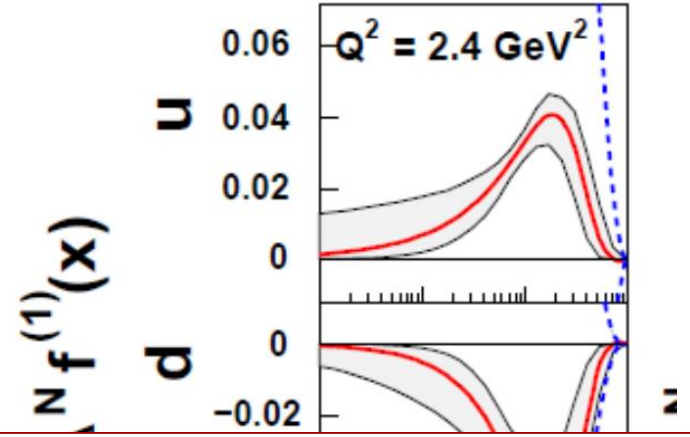


M. Anselmino et al
Eur. Phys. J. A **39**, 89–100 (2009)

THE SIVERS FUNCTION

Sivers function extractions from SIDIS data (COMPASS, HERMES, Jlab)

→ **u and d: clearly different from zero**



9–100 (2009)

… pseudouniversality J. C. Collins, Phys. Lett. B536 (2002) 43.

proposal to measure it in pion-induced Drell-Yan muon pair production at COMPASS

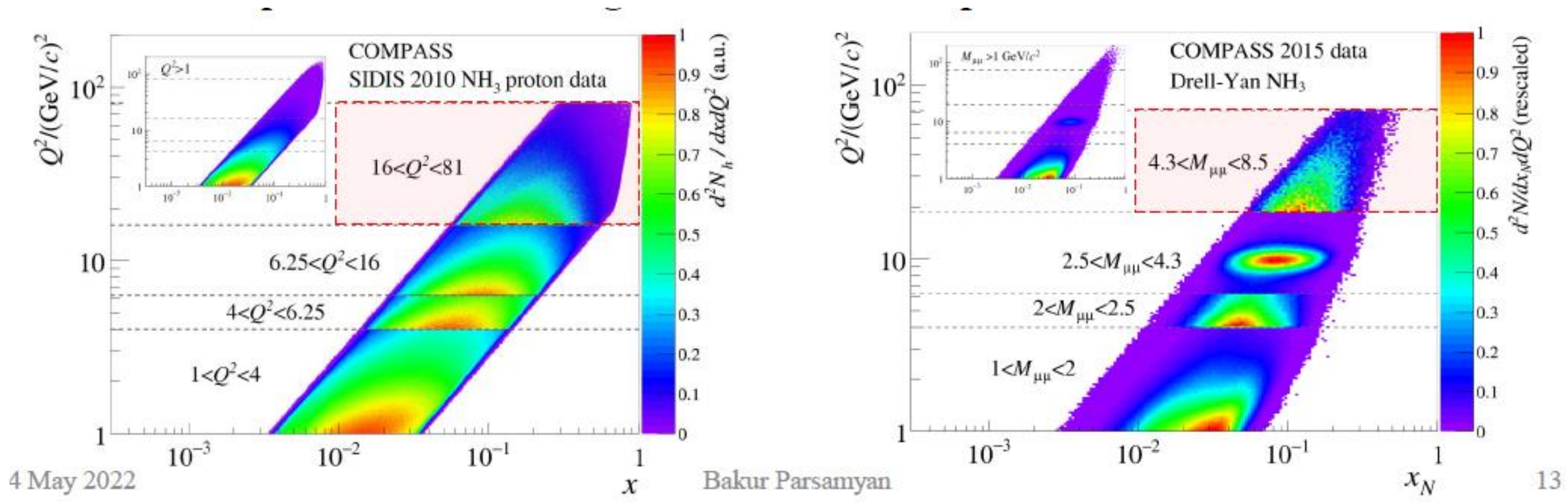
CERN-SPSC-2010-014
SPSC-P-340
May 17, 2010 COMPASS II proposal: DY and DVCS (2015-2018 runs)

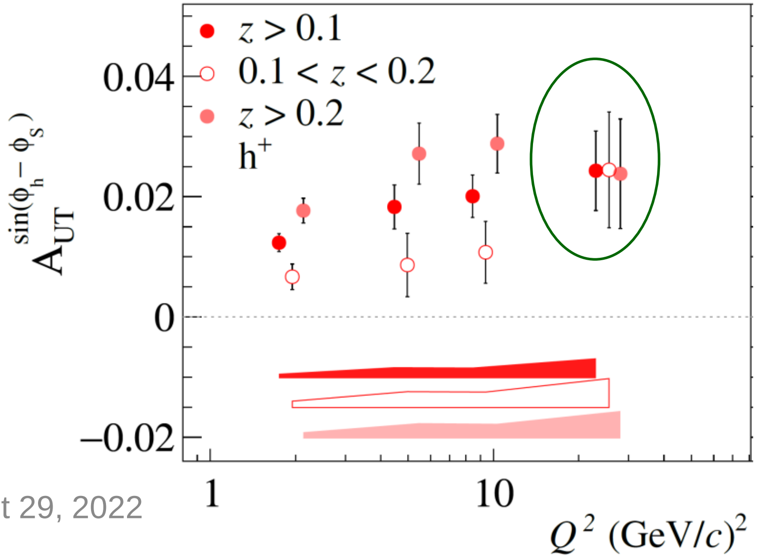
THE PROTON DATA – Sivers asymmetry

to make easier the comparison with DY, avoiding Q^2 evolution problems, we have measured the Sivers asymmetry in Q^2 bins

SIDIS

DY





PLB 770 (2017) 138

COMPASS DY run 2015 + 2018

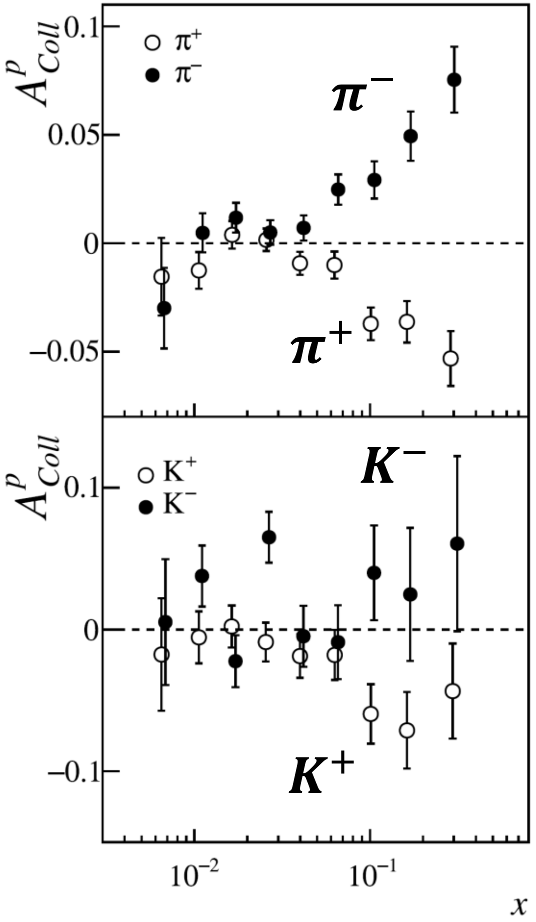
new results at DIS2022
→ Jan Matousek

THE PROTON DATA – Collins asymmetry

2007 half year, 2010 one year of data taking - the signals are there!

Collins asymmetry

all COMPASS proton data



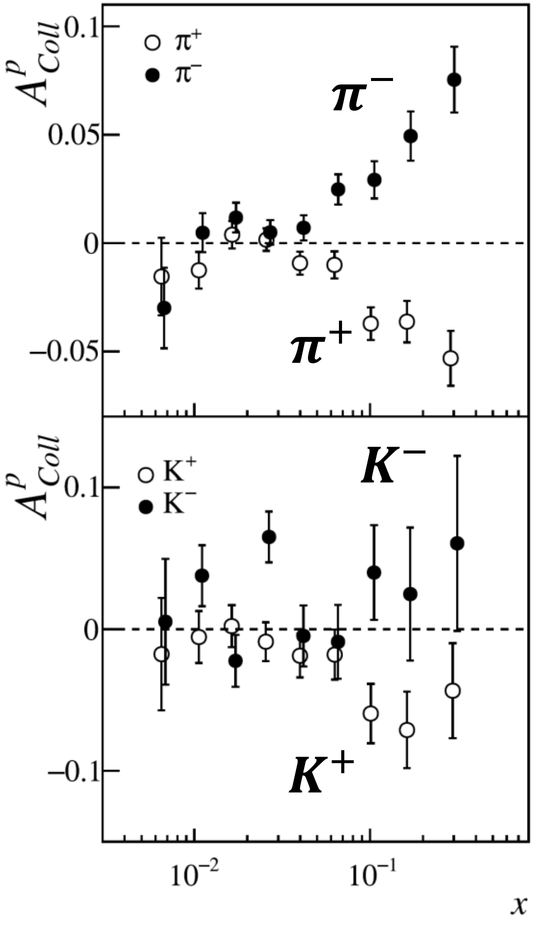
PLB 744 (2015) 250
PLB 717 (2012) 376

THE PROTON DATA – Collins asymmetry

2007 half year, 2010 one year of data taking - the signals are there!

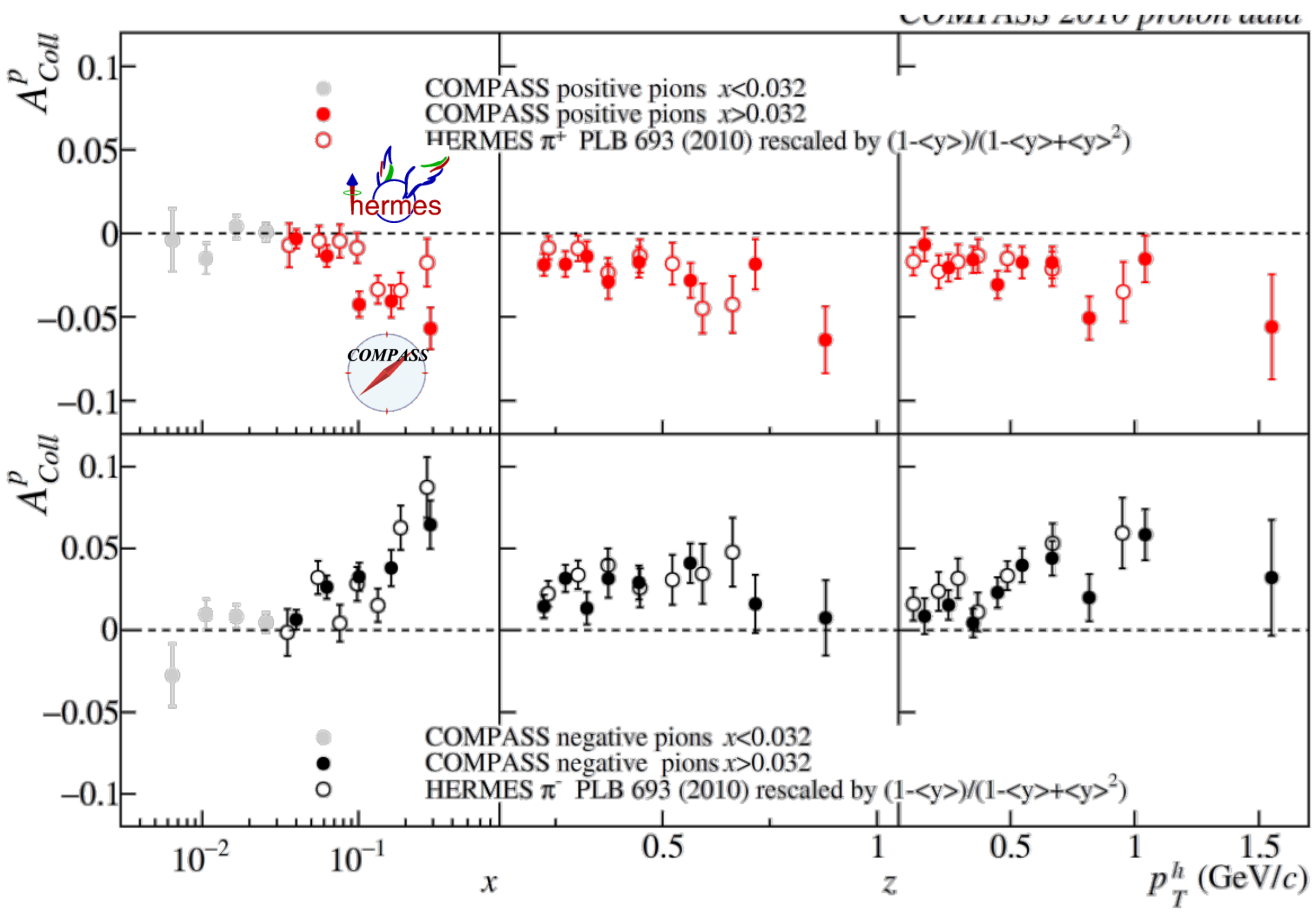
Collins asymmetry

all COMPASS proton data



PLB 744 (2015) 250
PLB 717 (2012) 376

comparison with HERMES



π^+

π^-

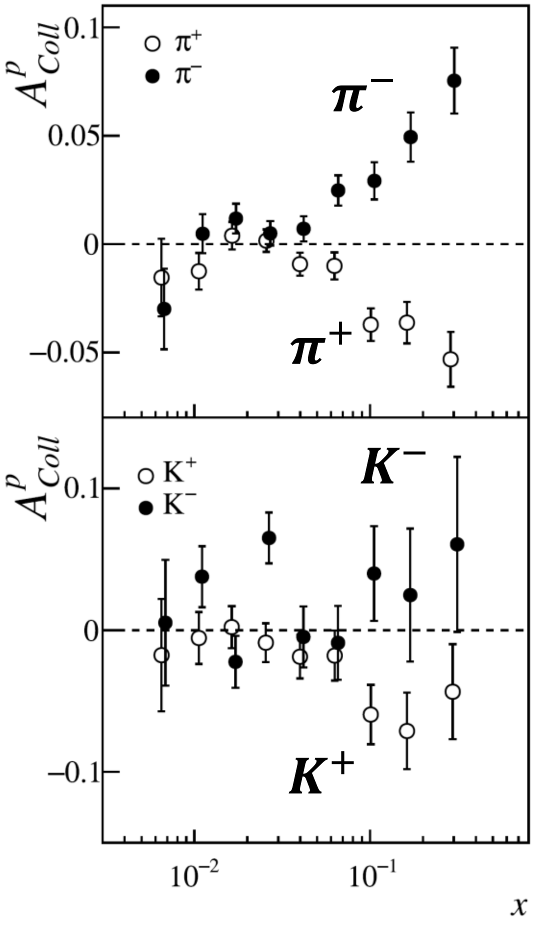
very good agreement !

THE PROTON DATA – Collins asymmetry

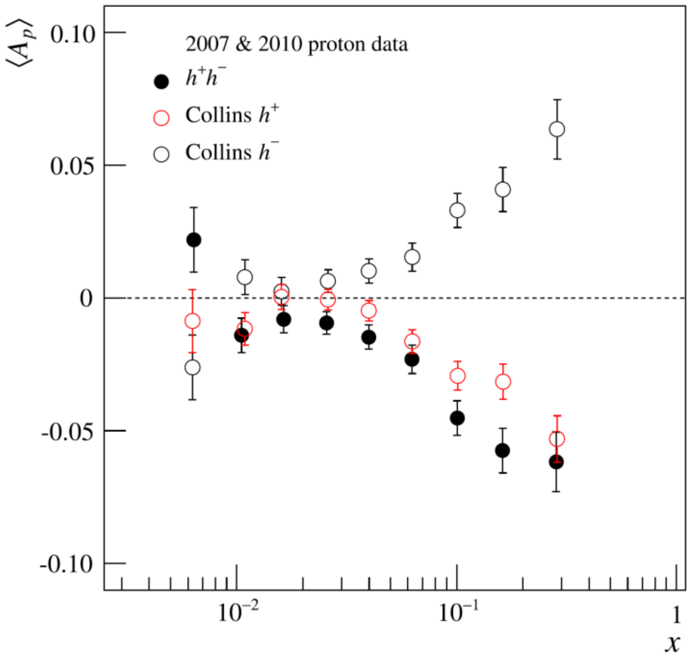
2007 half year, 2010 one year of data taking - the signals are there!

Collins asymmetry

all COMPASS proton data



PLB 744 (2015) 250
PLB 717 (2012) 376



- **di-hadron asymmetry**

PLB 736 (2014) 124

study of the interplay between Collins and di-hadron asymmetries – not independent COMPASS, PLB 753 (2016) 406

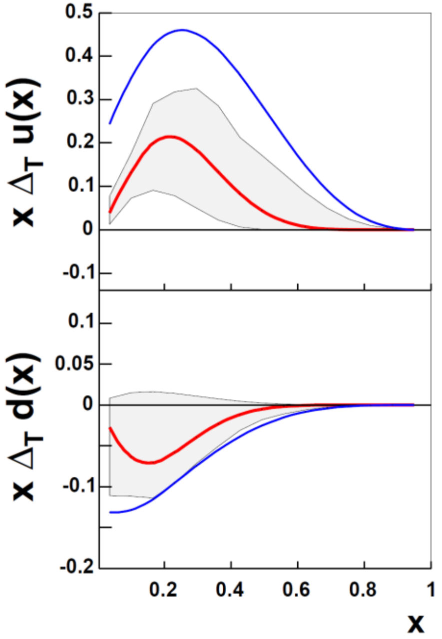
well reproduced by the $^3P_0$ model

A. Kerbizi et al. PRD97 (2018) no.7, 074010

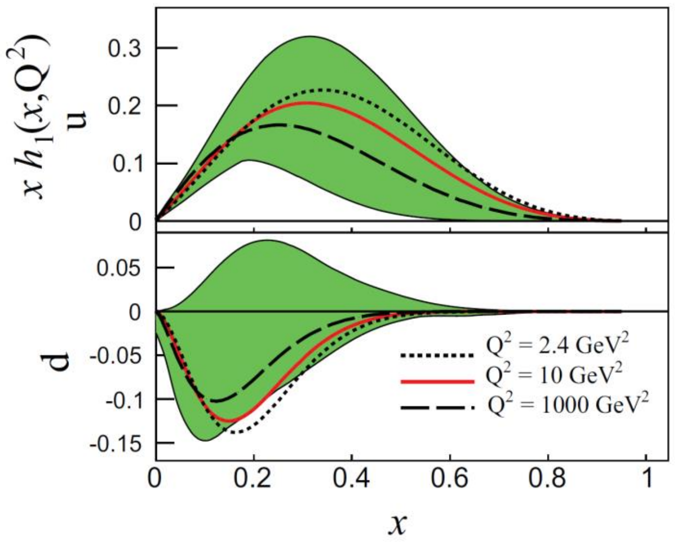
TRANSVERSITY

fits of **Collins asymmetries** in SIDIS off p and d, and e^+e^- data

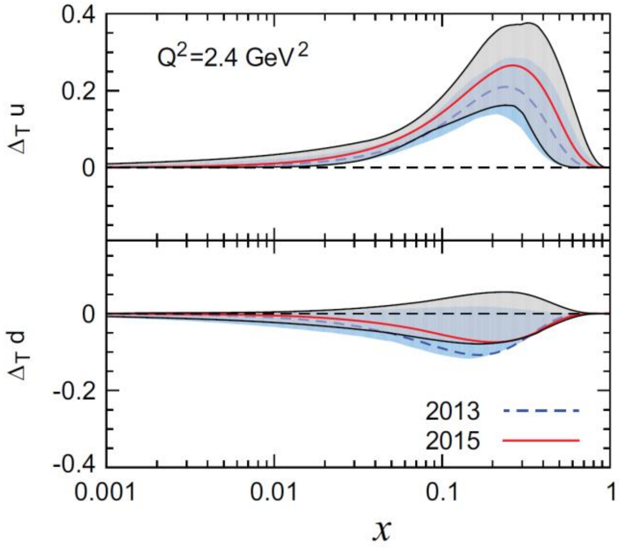
Anselmino et al PRD **2007**



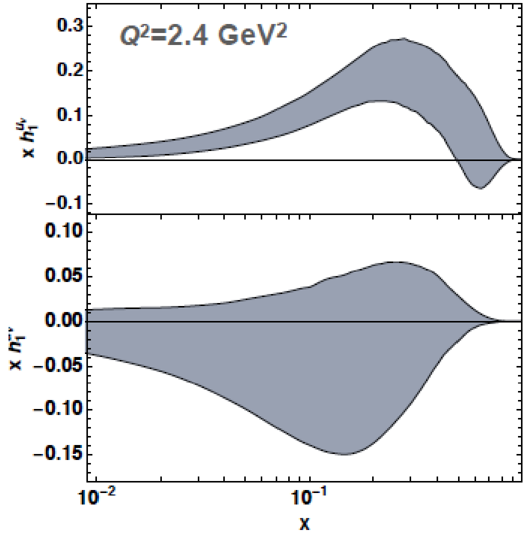
Z.-B. Kang et al. PRD **2016**



M. Anselmino et al.PRD **2015**



Radici Bacchetta PRL **2018**

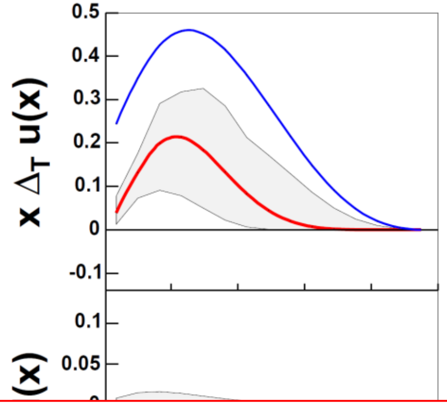


fits of **di-hadron asymmetries**
SIDIS off p and d , e^+e^-, and pp data

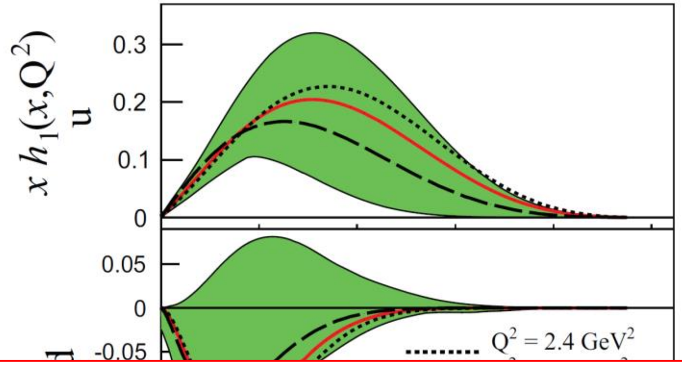
TRANSVERSITY

fits of **Collins asymmetries** in SIDIS off p and d, and e^+e^- data

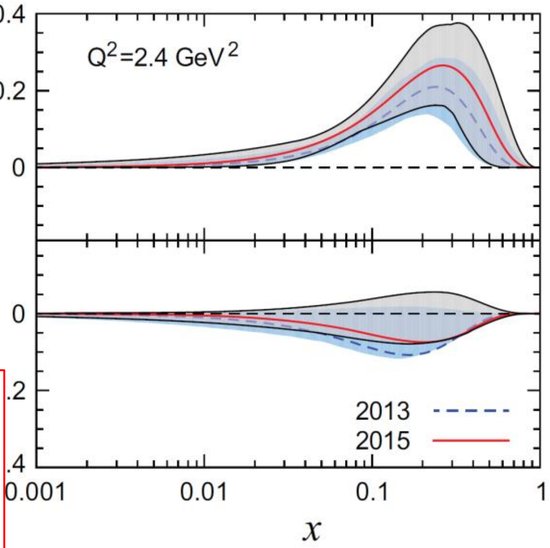
Anselmino et al PRD **2007**



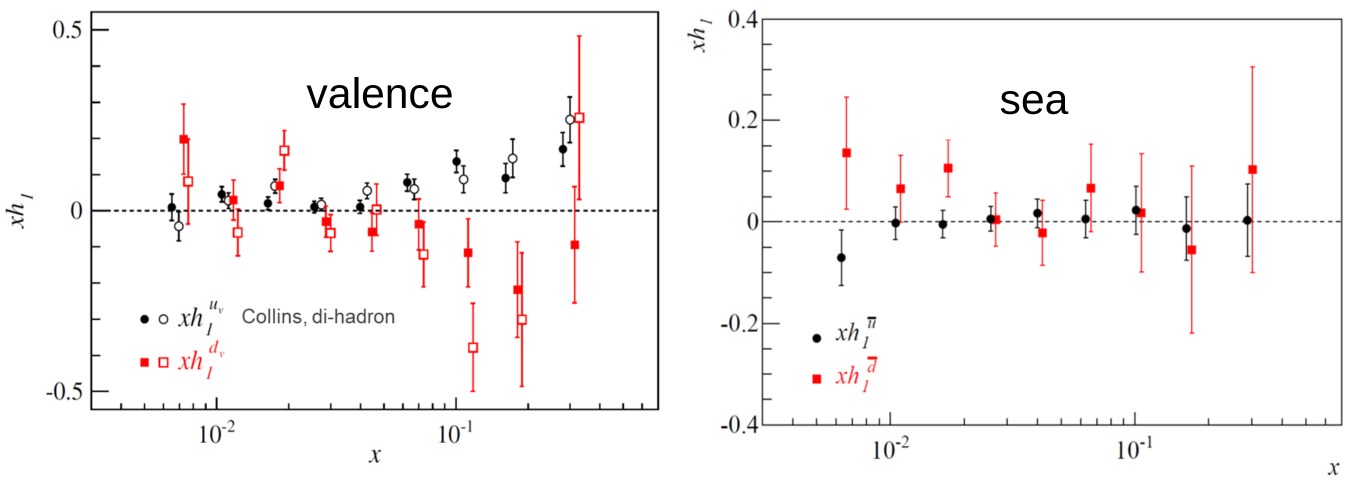
Z.-B. Kang et al. PRD **2016**



M. Anselmino et al.PRD **2015**



A. Martin, F. B., V. Barone PRD 2015



point by point extraction

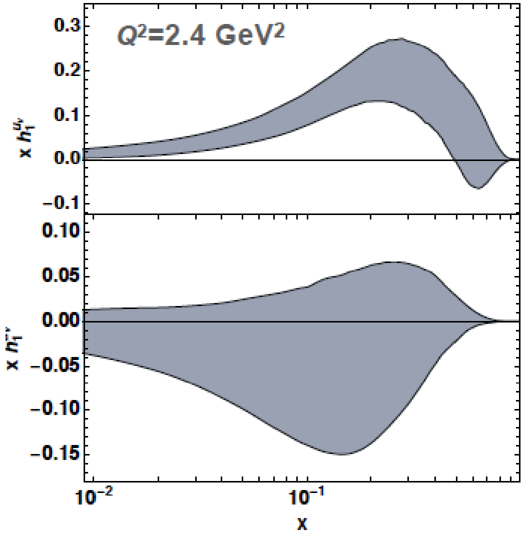
using COMPASS p and d asymmetries, and e^+e^- data

no Soffer bound; no Monte Carlo nor parametrisations needed

ymmetries

$^+e^-$, and pp data

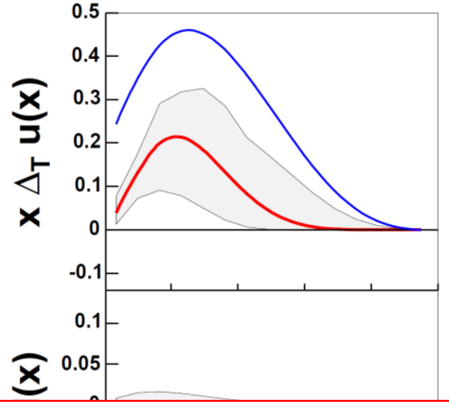
Radici Bacchetta PRL **2018**



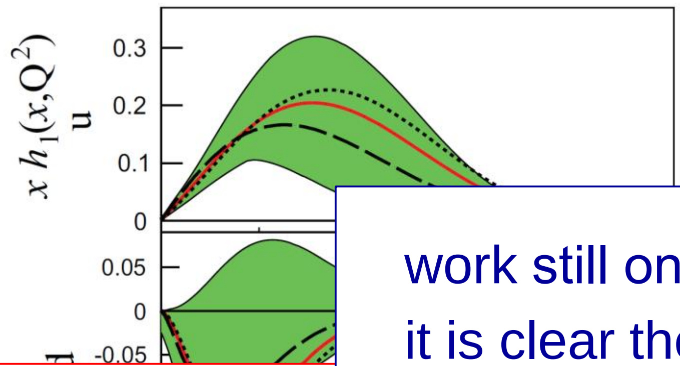
TRANSVERSITY

fits of **Collins asymmetries** in SIDIS off p and d, and e$^+$e$^-$ data

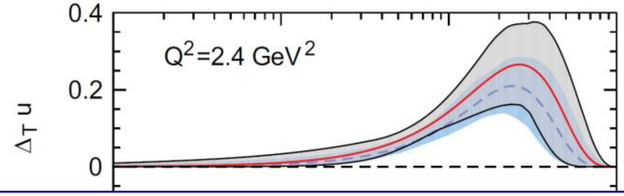
Anselmino et al PRD **2007**

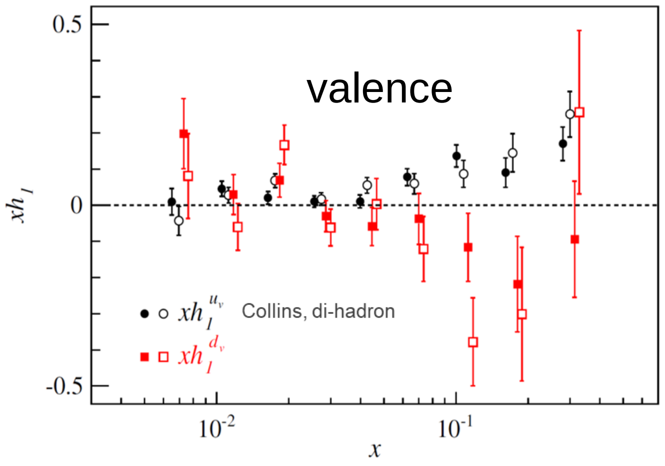


Z.-B. Kang et al. PRD **2016**

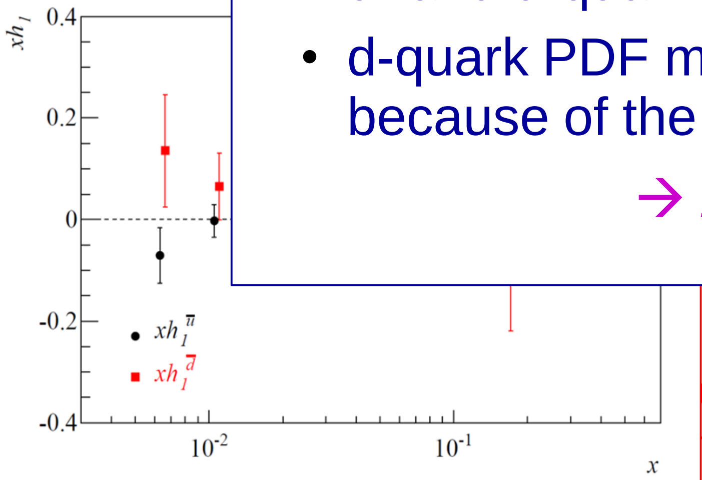


M. Anselmino et al.PRD **2015**





A. Martin,



point by point extraction
using COMPASS p and d asymmetries, and e$^+$e$^-$ data
no Soffer bound; no Monte Carlo nor parametrisations needed

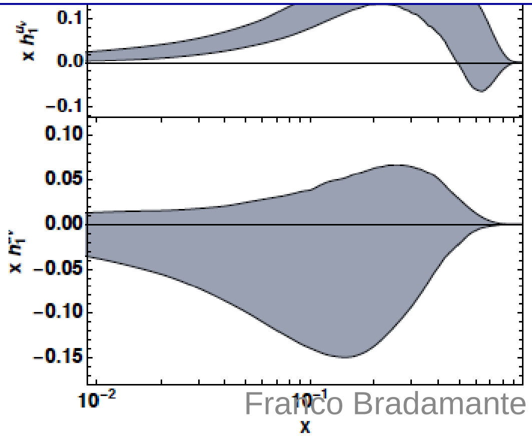
work still ongoing …

it is clear the

- u- and d-quark transversity PDFs have opposite sign
- d-quark PDF much worse determined than u-quark PDF because of the scarcity of deuteron (neutron) data

→ *2022 COMPASS run*

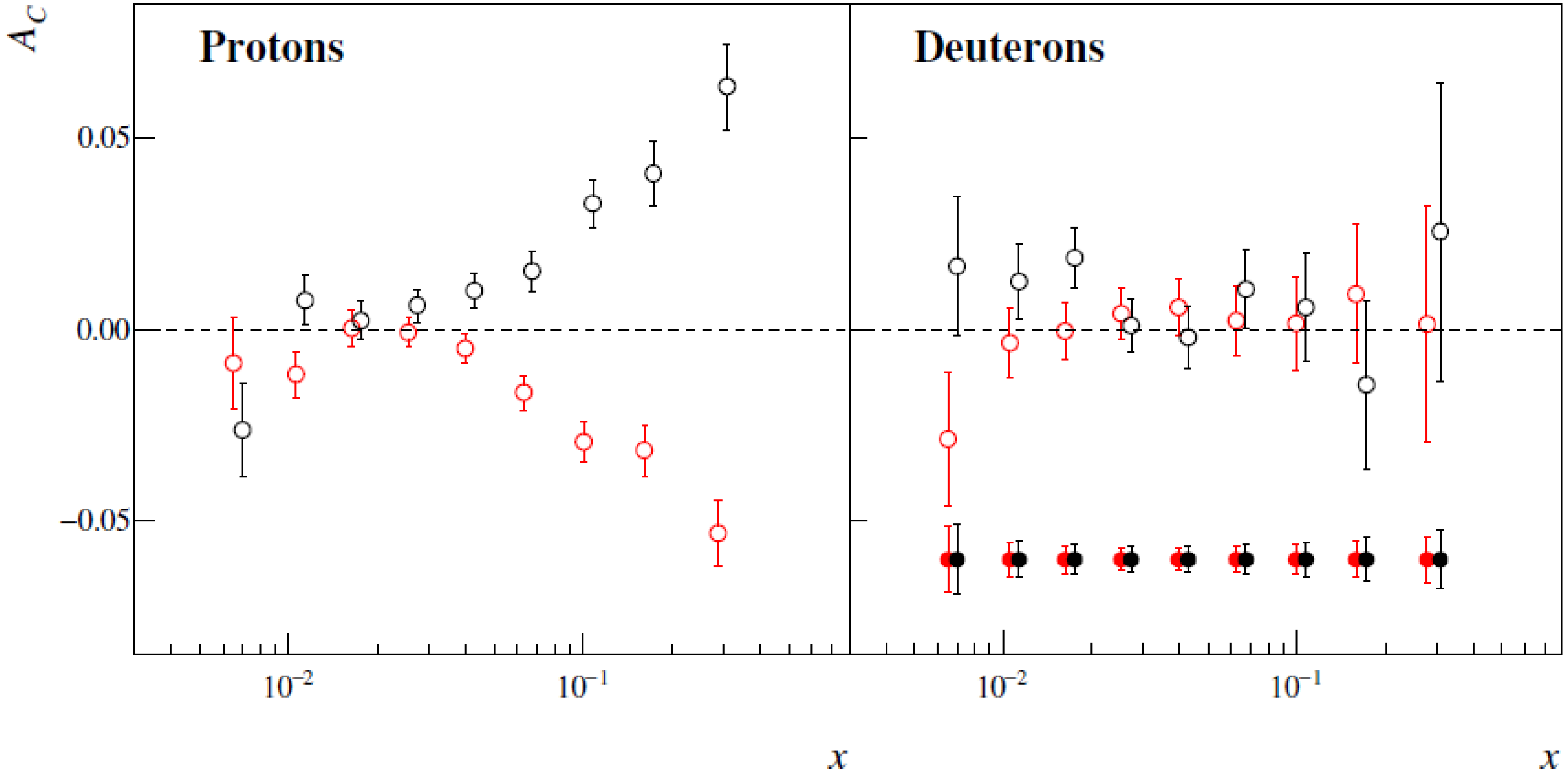
ymmetries
$^+$e$^-$, and pp data



THE DEUTERON DATA

run 2022 - expectation

CERN{SPSC{2017{034
SPSC-P-340-ADD-1
April 5, 2018



many thanks to Gunar and Daniel

THE PROTON DATA

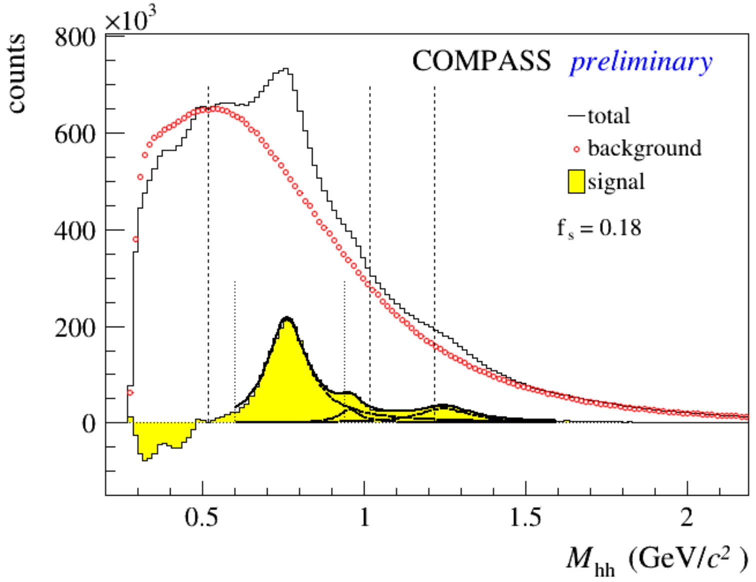
several other measurements have been performed

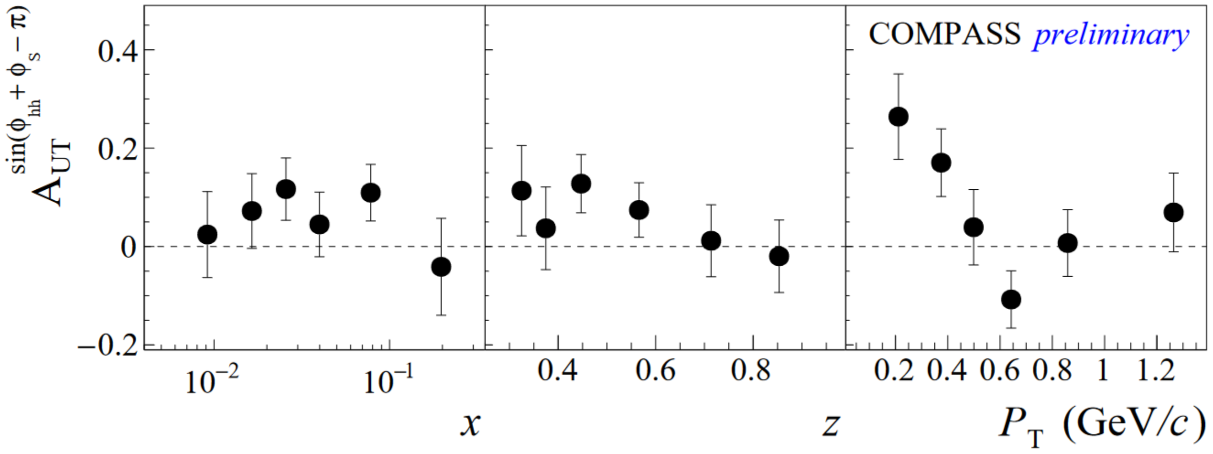
- other TSA
- multidimensional measurements of TSAs $(x, Q^2, z, P_T)\ bins$
- Sivers asymmetry in Q^2 bins
  - in particular for the COMPASS Drell-Yan measurement PLB 770 (2017) 138
- P_T - weighted Sivers asymmetries
  - no convolution, important tests, extraction of the Sivers function NPB 940 (2019) 34
- transversity induced $\Lambda/\bar{\Lambda}$ polarization PLB 824 (2022) 136834
- TSAs for high P_T pairs from PGF events PLB 772 (2017) 854
- J/Ψ Sivers asymmetry

- **ρ^0 TSAs - new**

THE PROTON DATA

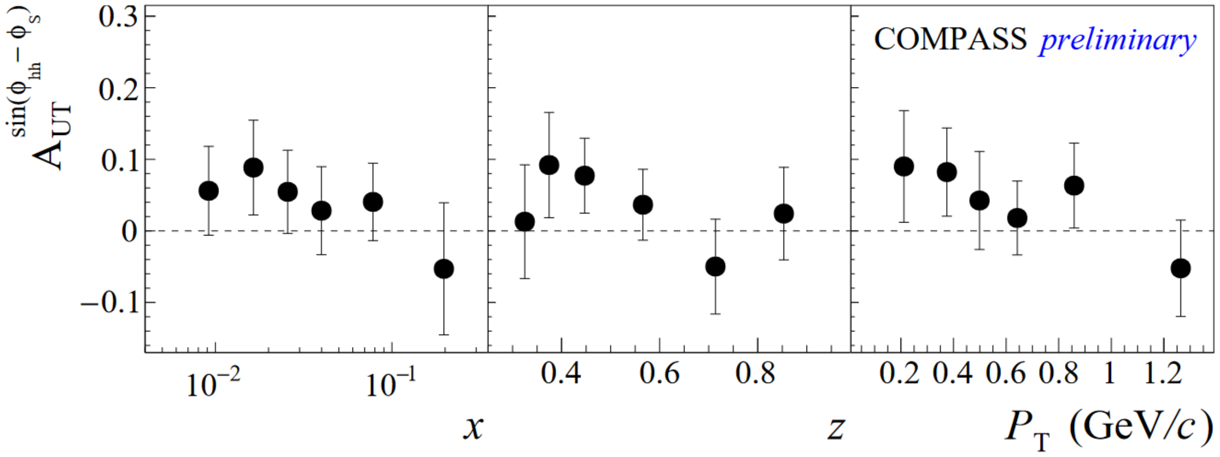
ρ^0 TSAs





COLLINS ASYMMETRY

- indication for positive asymmetry
  opposite to π^+ as expected
- large at small P_T



SIVERS ASYMMETRY

- indication for positive asymmetry
  similarly to π^0 as expected

only statistical uncertainties
$\sigma_{syst} = 0.3\sigma_{stat}$

paper in preparation

THE PROTON DATA

several other measurements have been performed

- *other TSA*
- multidimensional measurements of TSAs $(x, Q^2, z, P_T)\ bins$
- Sivers asymmetry in Q^2 bins

  in particular for the COMPASS Drell-Yan measurement PLB 770 (2017) 138
- P_T - weighted Sivers asymmetries

  no convolution, important tests, extraction of the Sivers function NPB 940 (2019) 34
- *transversity induced* $\Lambda/\bar{\Lambda}$ *polarization* *PLB 824 (2022) 136834*
- *TSAs for high* P_T *pairs from PGF events* *PLB 772 (2017) 854*
- J/Ψ *Sivers asymmetry*
- ρ^0 *TSAs*

and other new measurements are ongoing

- the g_2 structure function
- ….

all these measurements will be repeated with the new deuteron data,
which we are collecting this year

SUMMARY

COMPASS has given a relevant contribution to the study of the transverse structure of the nucleons with the Transverse Spin Asymmetries in SIDIS

It has not been easy to make these measurements, but for sure
it has been a lot of fun

SUMMARY

COMPASS has given a relevant contribution to the study of the transverse structure of the nucleons with the Transverse Spin Asymmetries in SIDIS

It has not been easy to make these measurements, but for sure
it has been a lot of fun

The results have come and are coming, they have been very interesting,
sometimes unexpected and anyway NEW

Our 2022 deuteron run will conclude the exploratory phase of these
transverse spin phenomena carried out by HERMES and COMPASS

Much more will surely come from the next generation facilities

- **SOLID**
- **EIC**
- **….**

thank you !

THE PROTON DATA

- **other TSAs**

$A_{UT}^{\sin\phi_s}$

subleading twist
similar to HERMES results

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

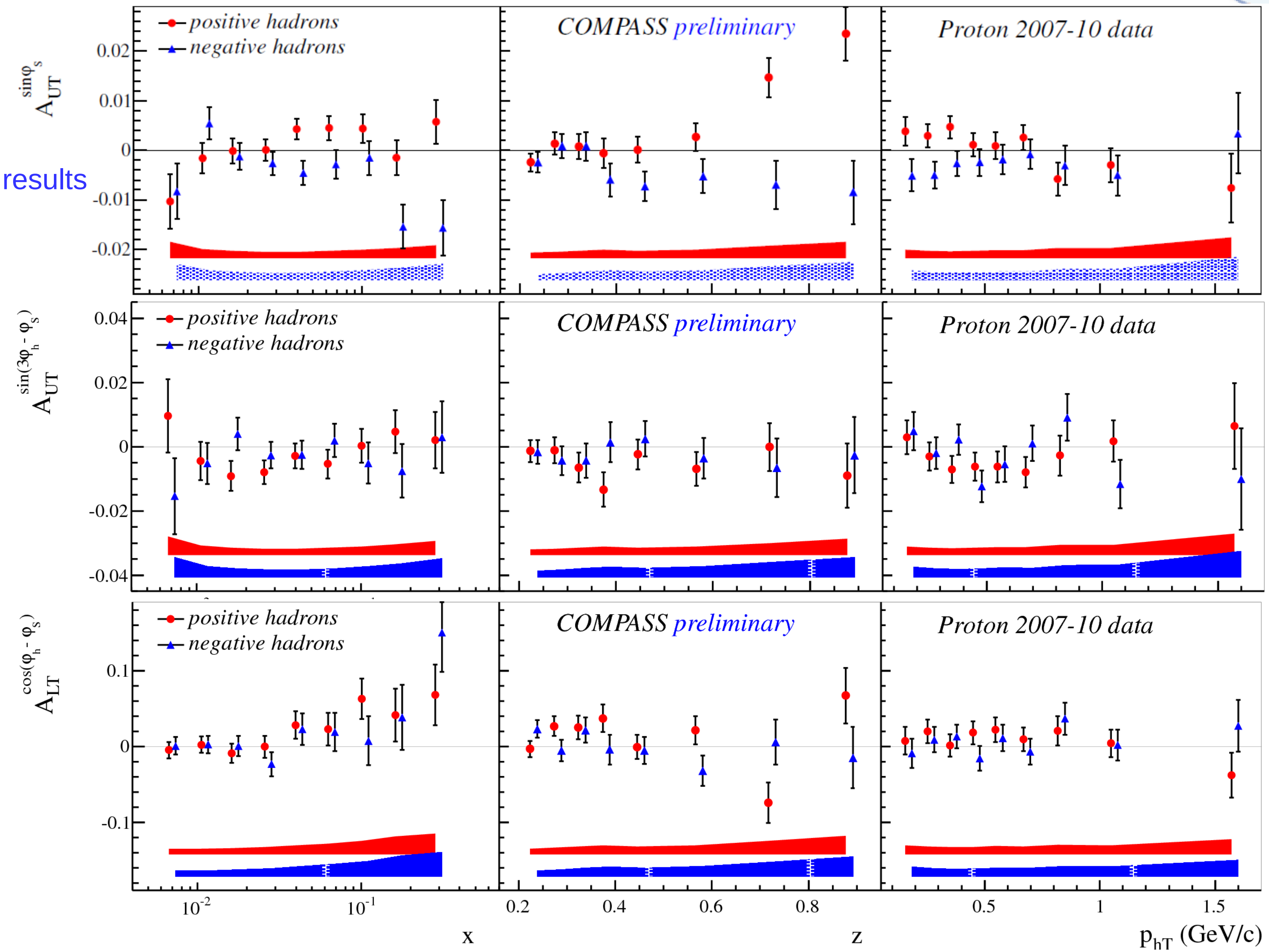
$h_{1T}^{\perp} \otimes H_1^{\perp}$

pretzelosity

$A_{UT}^{\cos(\phi_h-\phi_s)}$

$g_{1T} \otimes D_1$

worm-gear T
Kotzinian- Mulders

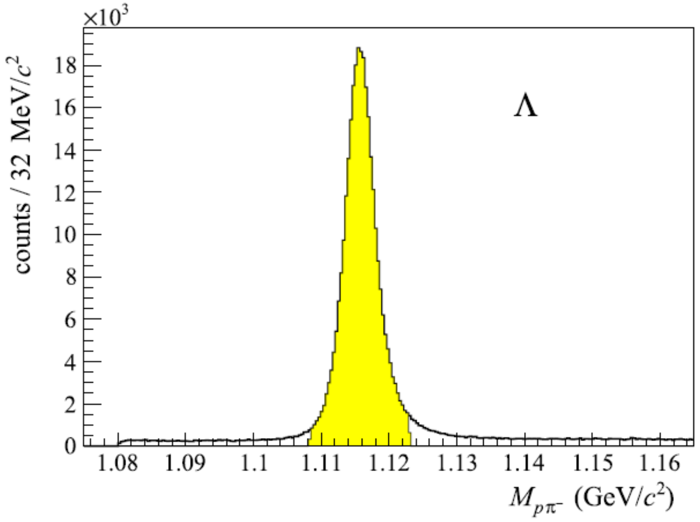


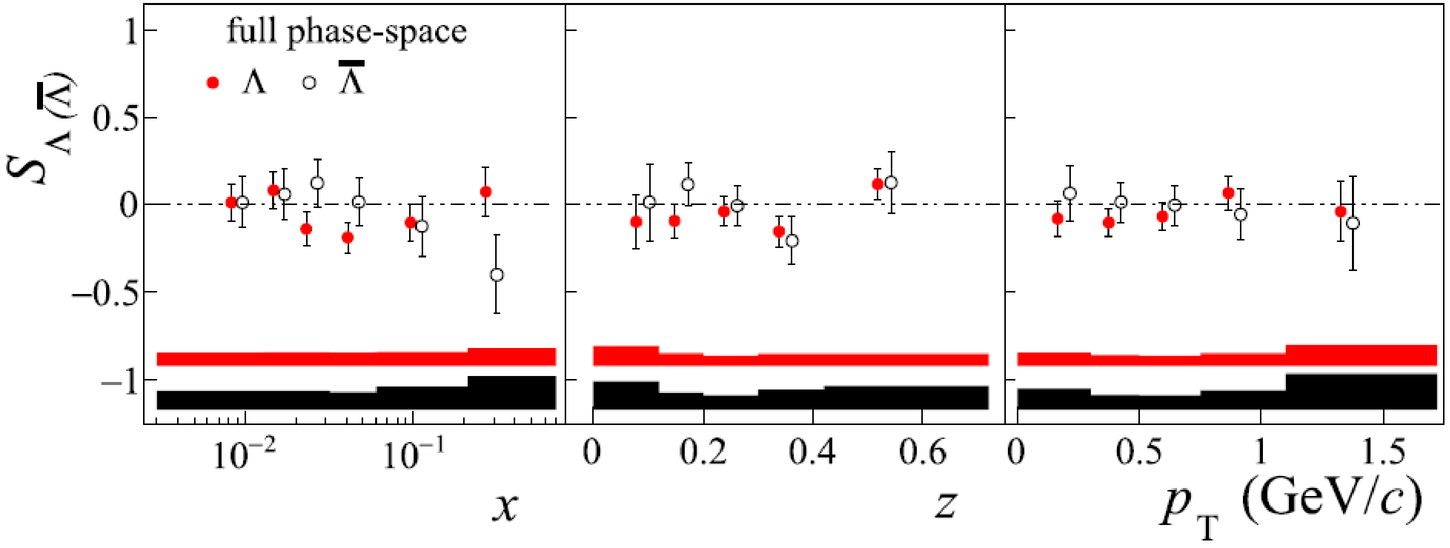
THE PROTON DATA

- **transversity induced $\Lambda/\bar{\Lambda}$ polarization**

PLB 824 (2022) 136834

$$S_{\Lambda(\bar{\Lambda})} = \frac{\sum_q e_q^2 h_1^q H_{1,q}^{\Lambda(\bar{\Lambda})}}{\sum_q e_q^2 f_1^q D_{1,q}^{\Lambda(\bar{\Lambda})}}$$





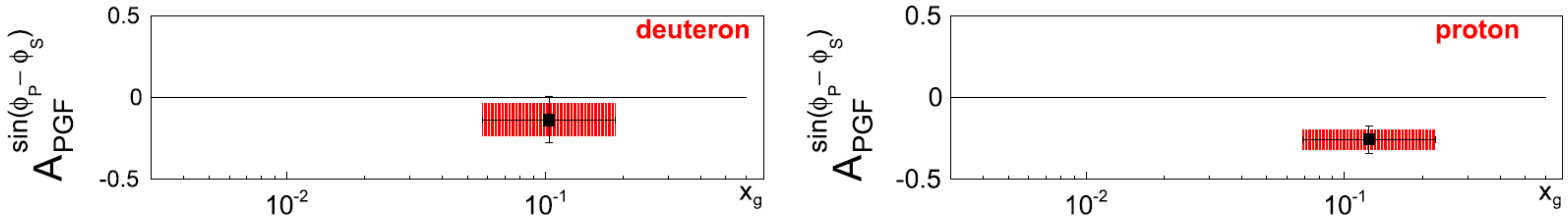
305 000 Λs, 154000 $\bar{\Lambda}$s.

THE PROTON DATA

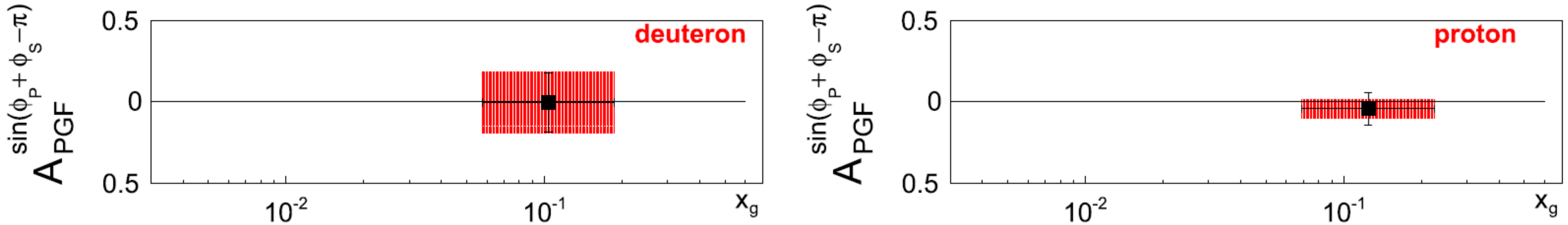
- **TSAs for high P_T pairs from PGF events**

PLB 772 (2017) 854

Sivers-like



Collins-like



THE PROTON DATA

- J/Ψ **Sivers asymmetry**