

Overview of COMPASS results in SIDIS and future plans

**transverse spin and
transverse momentum
nucleon structure**

Anna Martin

Trieste University and INFN
on behalf of the COMPASS Collaboration

IWHSS2018, Bonn, 20 March 2018

The COMPASS logo features the word "COMPASS" in a large, grey, serif font. It is overlaid on a circular diagram of the COMPASS detector, which consists of a blue ring with several red rectangular segments and a red, elongated detector component at the bottom.

Why transverse spin physics at COMPASS

at the time of the COMPASS proposal it was already known that

three collinear quark distribution functions are necessary to describe the structure of the nucleon

ALL 3 OF EQUAL IMPORTANCE

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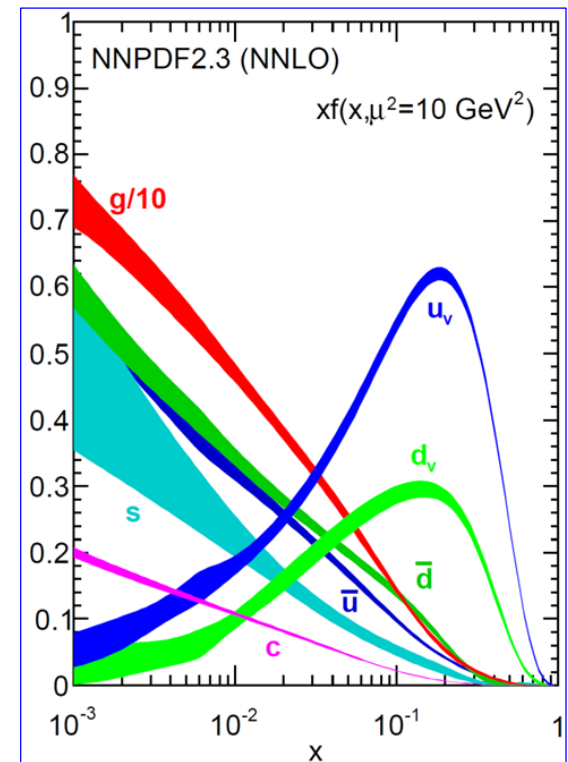
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$$q(x) \text{ or } f_1^q(x)$$



unpolarised PDF

quark with momentum xP in a nucleon
well known



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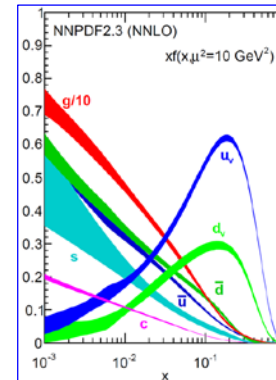
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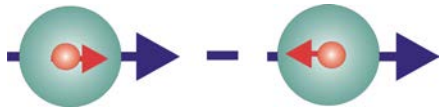


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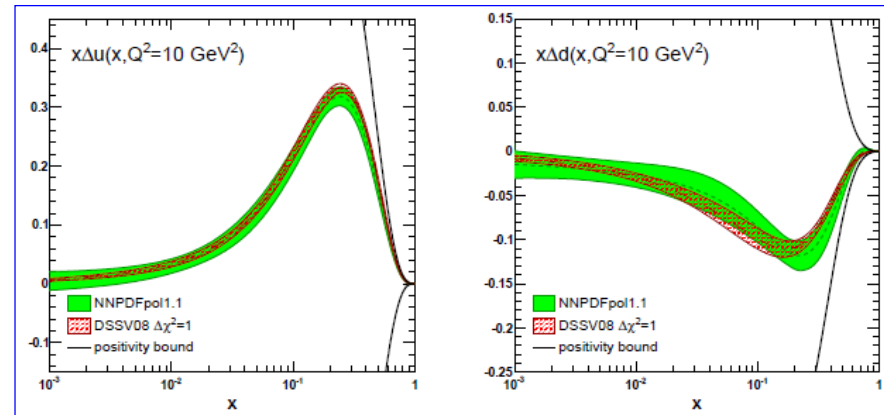
$$\Delta q(x) \text{ or } g_1^q(x)$$



helicity PDF

quark with polarisation parallel to the nucleon
longitudinal polarisation

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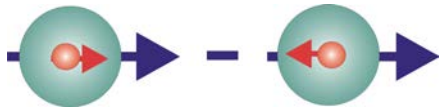
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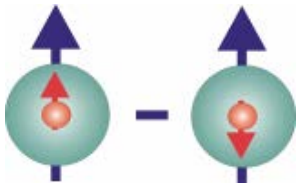
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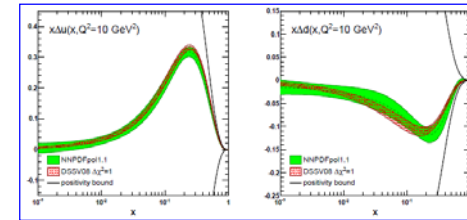
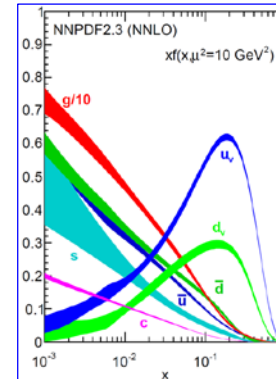
$$\Delta_T q(x) \text{ or } h_1^q(x)$$



transversity PDF

quark with polarisation parallel to the nucleon
transverse polarisation

unmeasured till 2005



ALL 3 OF EQUAL IMPORTANCE

Why transverse spin physics at COMPASS



the main motivation for measurements of

Semi Inclusive Deep Inelastic Scattering off transversely polarised targets was to

access TRANSVERSITY

chiral-odd: observable effects are given only if coupling with
an other **chiral-odd function**, not accessible in inclusive DIS

Why transverse spin physics at COMPASS



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chiral-odd: observable effects are given only if coupling with
an other **chiral-odd function**, not accessible in inclusive DIS

→ proposal to access it via “quark polarimetry”
transverse spin asymmetries in SIDIS:

$$l N^\uparrow \rightarrow l' h X$$

Collins asymmetry

Collins Fragmentation Function

$$l N^\uparrow \rightarrow l' h h X$$

two-hadron asymmetry

Interference Fragmentation Function





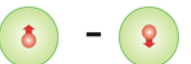



$$l N^\uparrow \rightarrow l' \Lambda X$$

Λ polarisation

Fragmentation Function of $q^\uparrow \rightarrow \Lambda$

recent developments

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

		nucleon polarization		
		U	L	T
quark polarization	U	f_1  <i>unpolarised</i>		f_{1T}^\perp  <i>Sivers</i>
	L		g_1  <i>helicity</i>	g_{1T}  <i>worm gear</i>
	T	h_1^\perp  <i>Boer-Mulders</i>	h_{1L}^\perp  <i>worm gear</i>	h_1  <i>transversity</i> h_{1T}^\perp  <i>pretzosity</i>

recent developments

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

these TMD PDFs describe the different spin-spin and spin- k_T correlations

transversity PDFs

$$(S_{TN} - S_{Tq})$$

Sivers PDFs





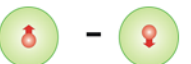



$$(S_{TN} - k_T)$$

Boer-Mulders PDFs

$$(k_T - S_{Tq})$$

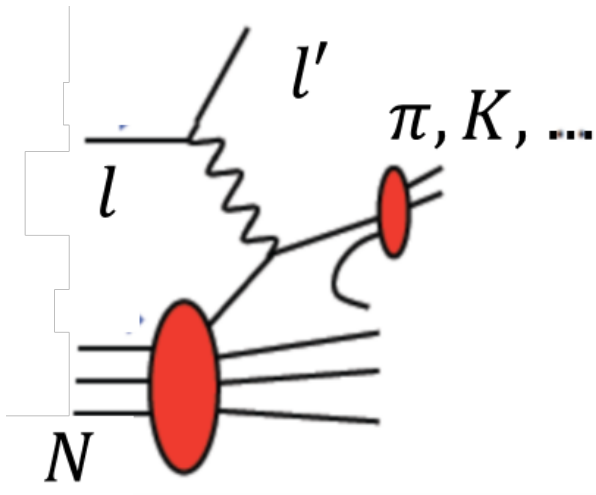
T-odd

their sign depends on the process

		nucleon polarization		
		U	L	T
quark polarization	U	f_1  <i>unpolarised</i>		f_{1T}^\perp  <i>Sivers</i>
	L		g_1  <i>helicity</i>	g_{1T}  <i>worm gear</i>
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Semi-Inclusive Deep Inelastic Scattering

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

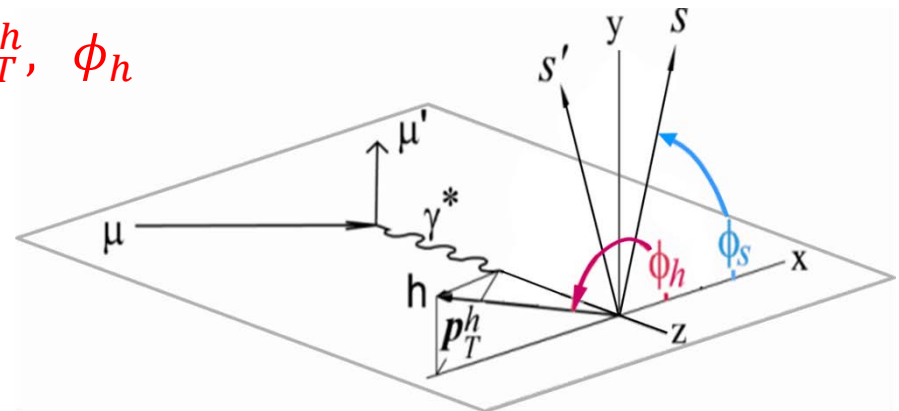


$$x = \frac{Q^2}{2P \cdot q} \quad y = \frac{P \cdot q}{P \cdot \ell} =_{LAB} \frac{E - E'}{E}$$

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

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

P_T^h, ϕ_h



give access to all
the TMD PDFs

$$\sigma^{lN \rightarrow lhX} \sim \sum_q \sigma^{lq \rightarrow lq} \otimes f(x) \otimes D_q^h(z)$$

Semi-Inclusive Deep Inelastic Scattering

- unpolarised targets

- longitudinally polarised targets

- transversely polarised targets

with longitudinally polarised beam

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

$$\frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} f_1 + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} \right.$$

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

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

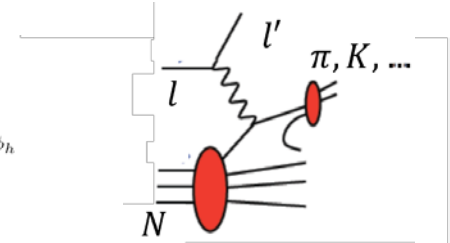
$$+ |S_{\perp}| \left[\sin(\phi_h - \phi_S) \left(F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \right.$$

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

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

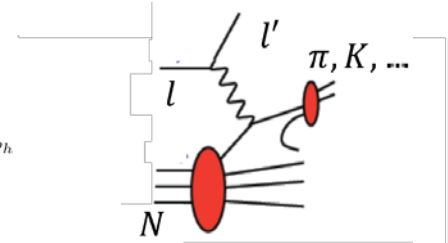
$$+ |S_{\perp}| \lambda_e \left[\sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_S F_{LT}^{\cos\phi_S} \right.$$

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



14 independent azimuthal modulations in the cross-sections
 amplitudes: convolutions of TMD PDFs and Fragmentation Functions

Semi-Inclusive Deep Inelastic Scattering



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14 independent azimuthal modulations in the cross-sections

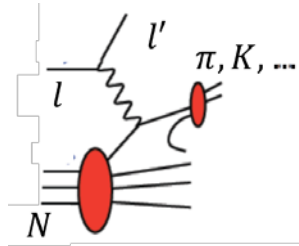
amplitudes: convolutions of TMD PDFs and Fragmentation Functions

to perform flavour separation measurements with

proton and neutron (deuteron) targets and final state particle identification

are needed

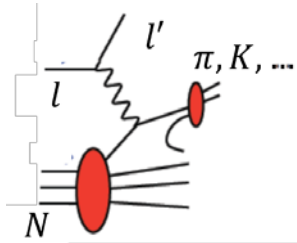
Semi-Inclusive Deep Inelastic Scattering



at COMPASS

μ^+ muon beam, 160 GeV/c, -80% longitudinal polarisation

Semi-Inclusive Deep Inelastic Scattering



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polarised deuteron

unpolarised by
combining opposite
polarisations

2002, 2003, 2004

20% transverse, 80% longitudinal
small acceptance magnet

2006 100% longitudinal

*important results
on helicity and
multiplicities not
shown here*

polarised proton

2007

50% transverse, 50% longitudinal

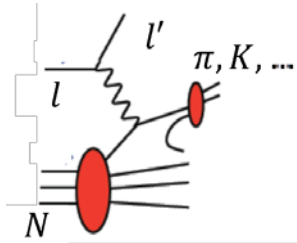
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Semi-Inclusive Deep Inelastic Scattering



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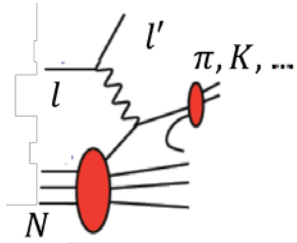
unpolarised proton

2016, 2017

in parallel with DVCS

results soon

Semi-Inclusive Deep Inelastic Scattering



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FUTURE

we have proposed one full year of running with the
transversely polarised deuteron target in **2021** (after the LS2)
to complete the transverse spin program

COMPASS

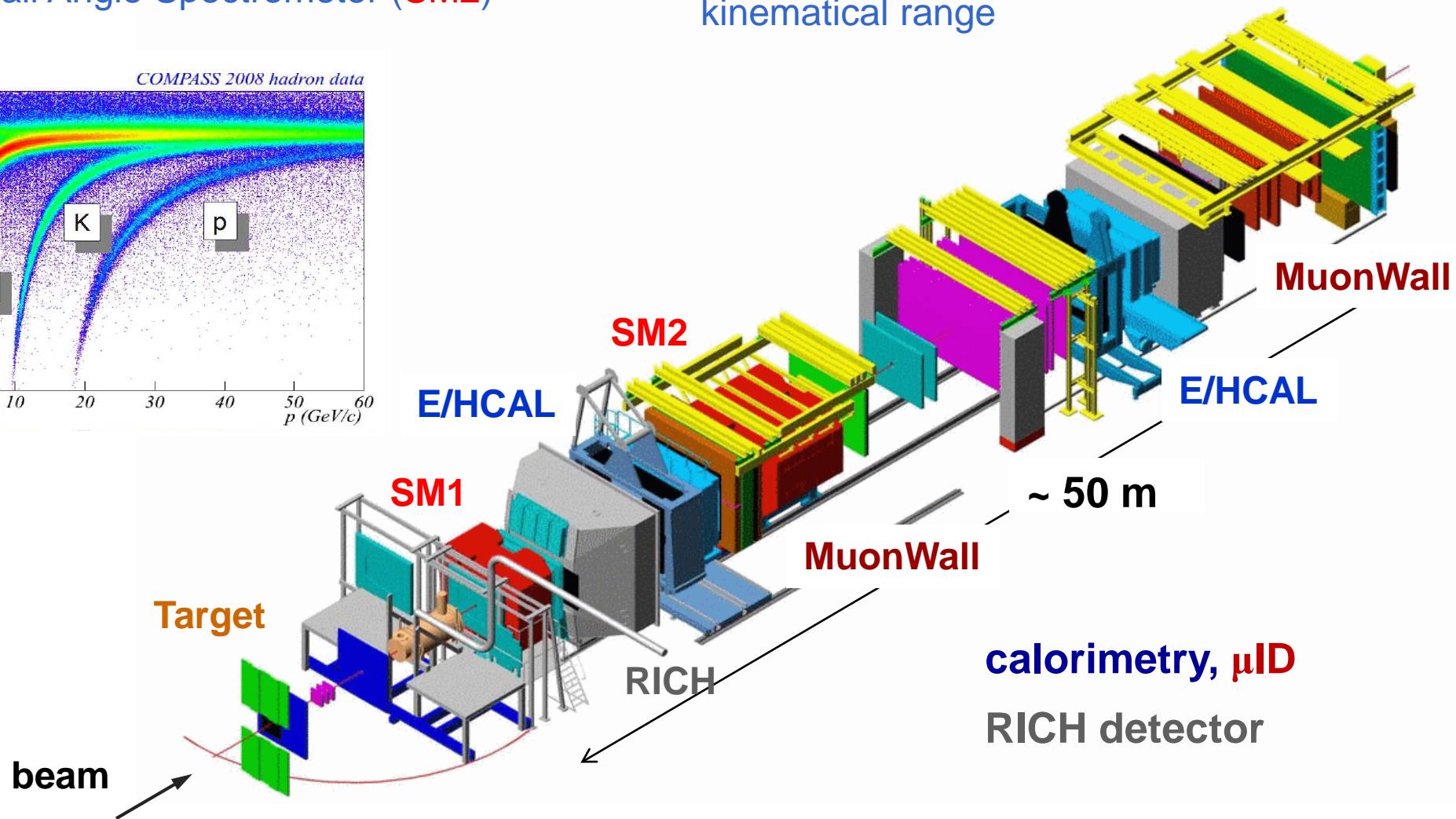
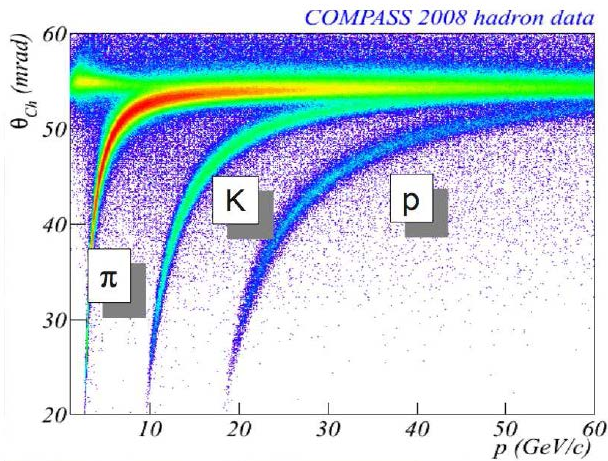


fixed target experiment at the CERN SPS

two stages spectrometer

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

designed to have large angular acceptance and cover a broad kinematical range



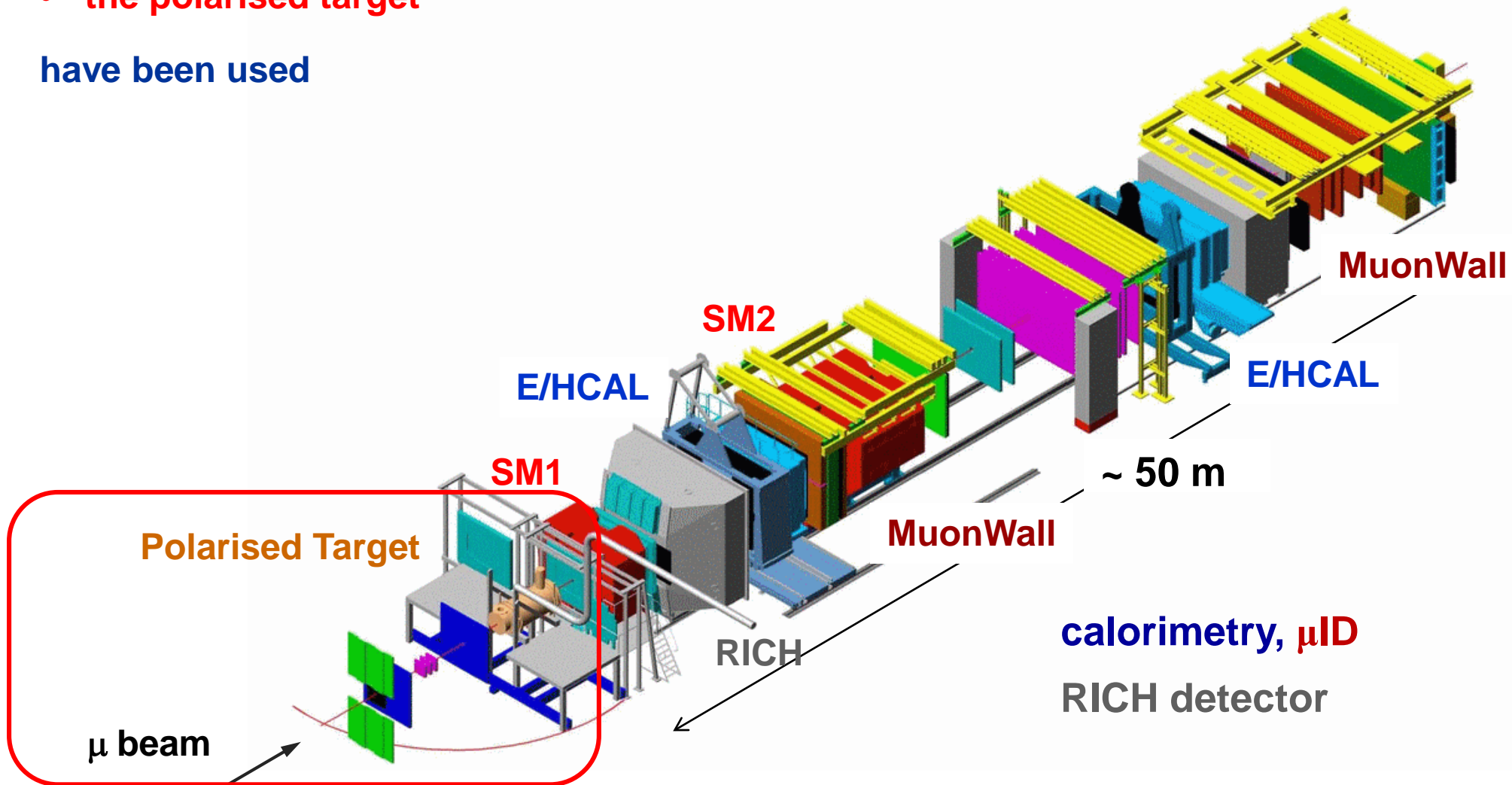
COMPASS



for the measurements described here

- the 160 GeV muon beam
- the polarised target

have been used

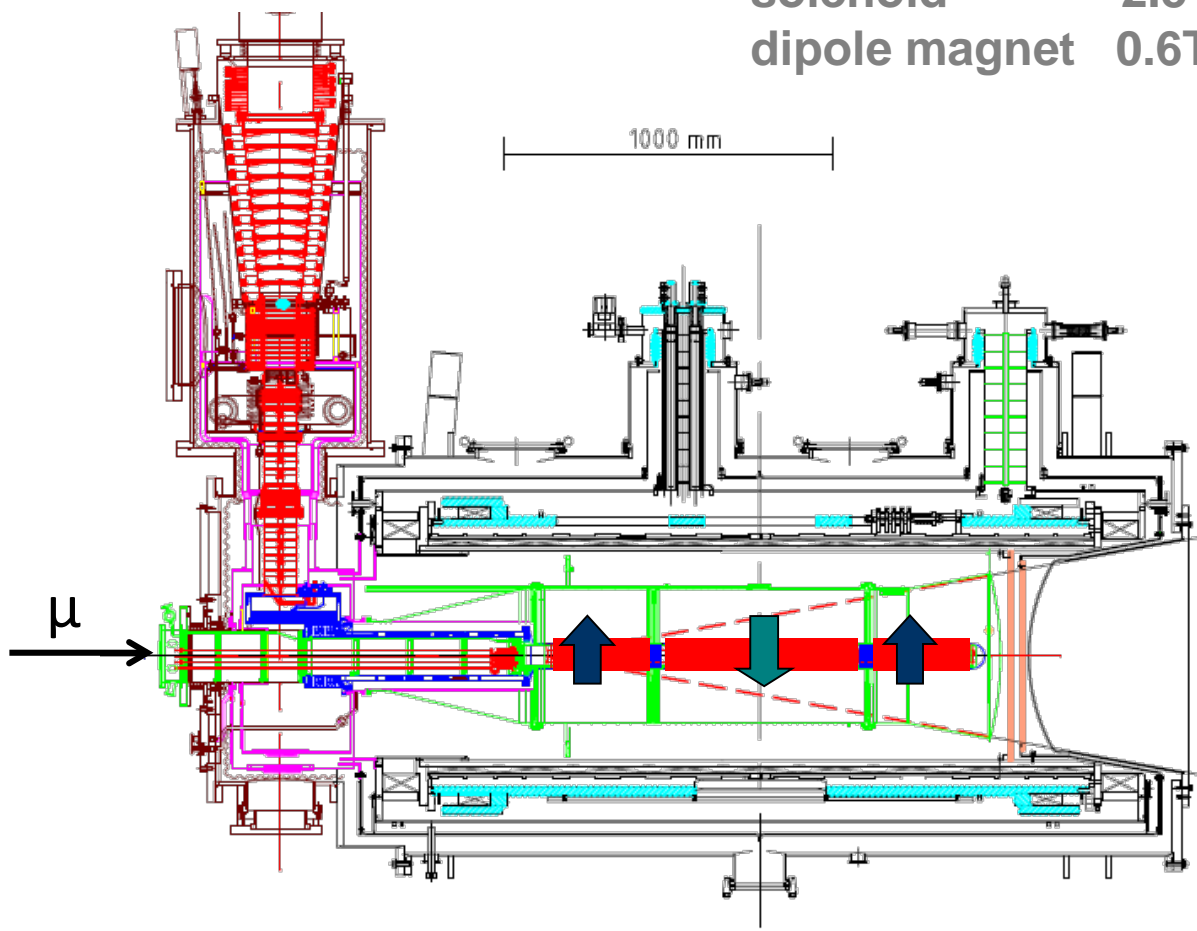




the polarised target system (>2005)

$^3\text{He} - ^4\text{He}$ dilution refrigerator ($T \sim 50\text{mK}$)

solenoid 2.5T
dipole magnet 0.6T



acceptance $> \pm 180$ mrad

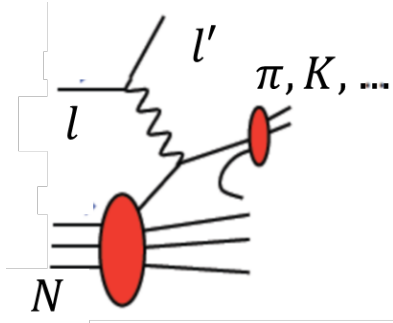
3 target cells in the beam line
30, 60, and 30 cm long

opposite polarisation,
longitudinal or transverse

	d (^6LiD)	p (NH_3)
polarisation	50%	90%
dilution factor	40%	16%

Semi-Inclusive Deep Inelastic Scattering

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



$$x = \frac{Q^2}{2P \cdot q}$$

$$y = \frac{P \cdot q}{P \cdot \ell} =_{LAB} \frac{E - E'}{E}$$

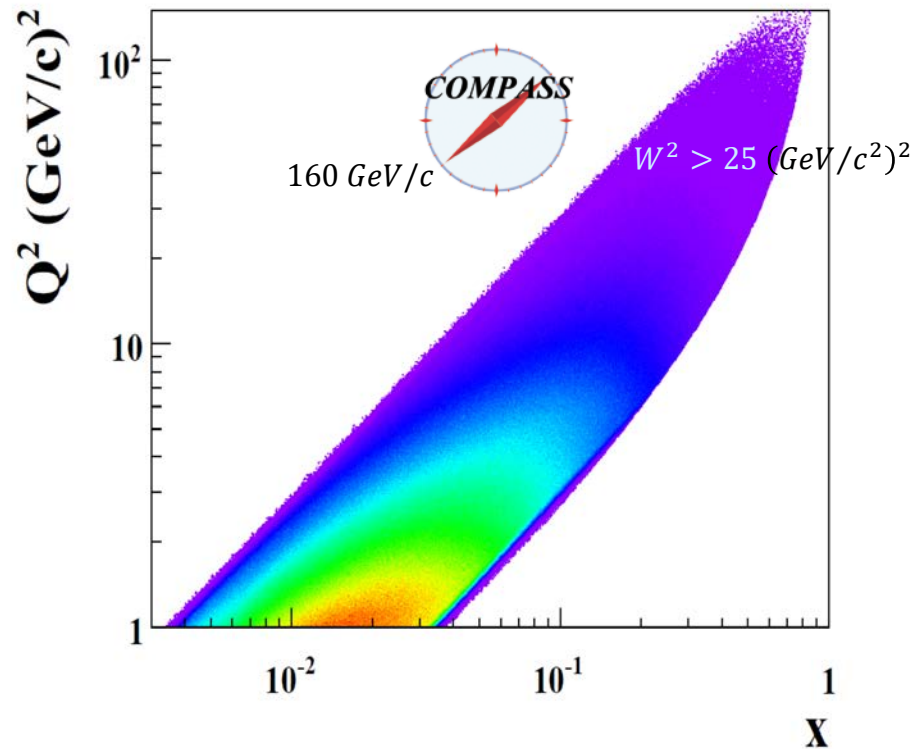
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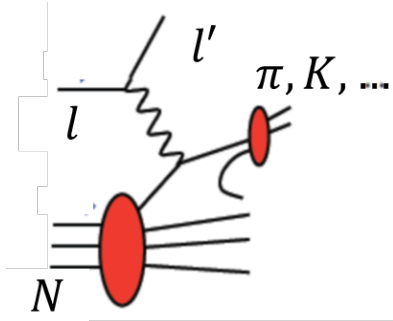
P_T^h, ϕ_h

wide $x - Q^2$ range



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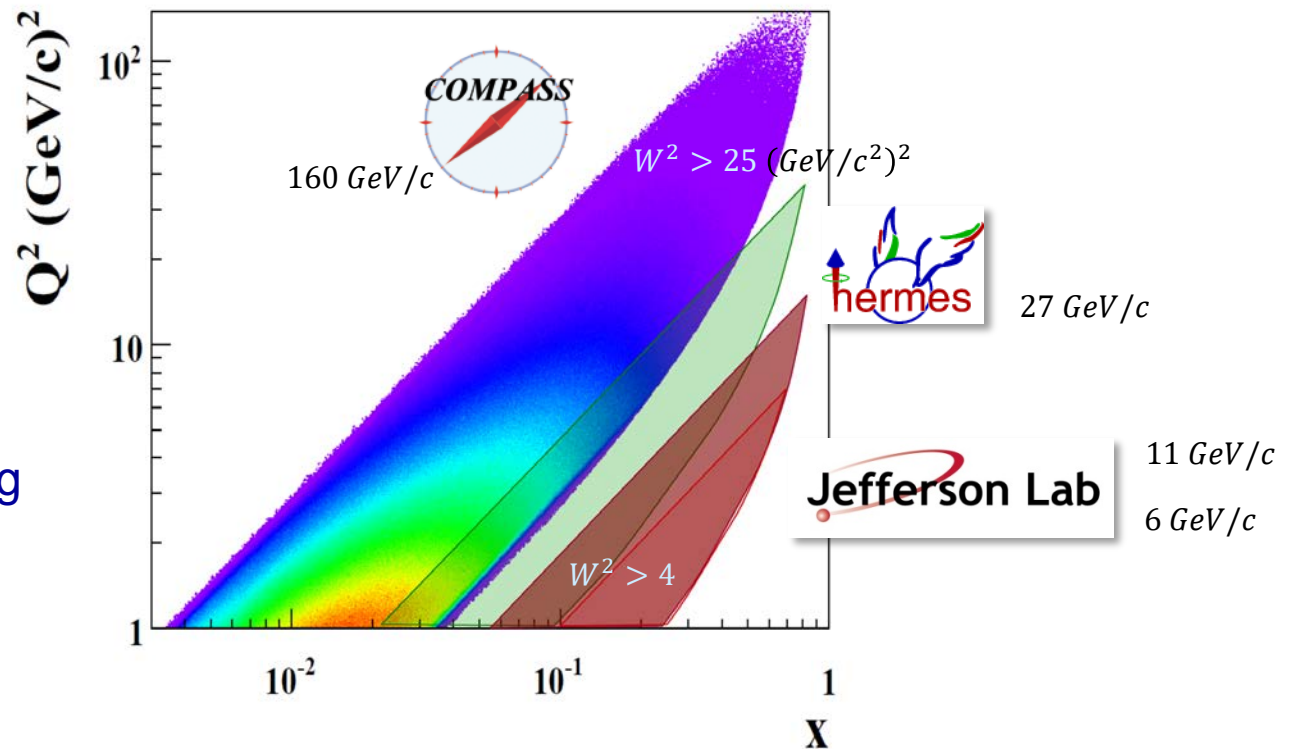
complementary to that of the other experiments

and future **JLab12** experiments

not competitive concerning luminosity,

still a **unique facility**

while EIC is not running



results on TMD PDFs from SIDIS off

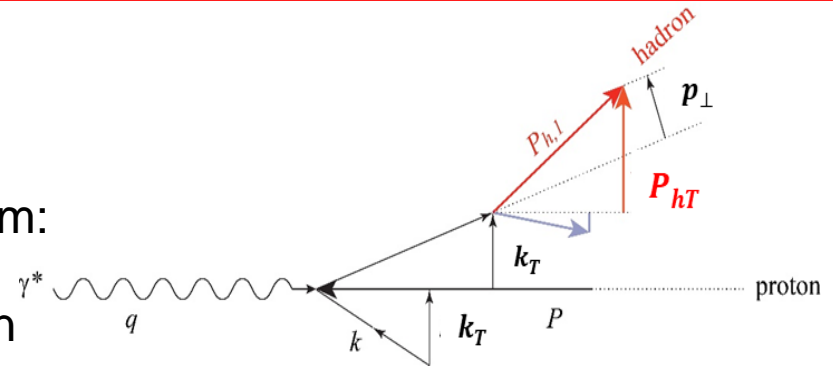
- **unpolarised deuteron**
- longitudinally polarised p and d
- transversely polarised p and d

unpolarised SIDIS

relevance for TMDs:

- the cross-section **dependence on P_{hT}** comes from:
 - intrinsic k_T** of the quarks
 - p_\perp generated in the quark fragmentation

$$\langle P_{hT}^2 \rangle \cong \langle p_\perp^2 \rangle + z^2 \langle k_T^2 \rangle$$



- the **azimuthal modulations** in the unpolarised cross-sections comes from:
 - intrinsic k_T** of the quarks $\cos \phi_h$ modulation
 - Boer-Mulders PDFs** $\cos 2\phi_h$ modulation

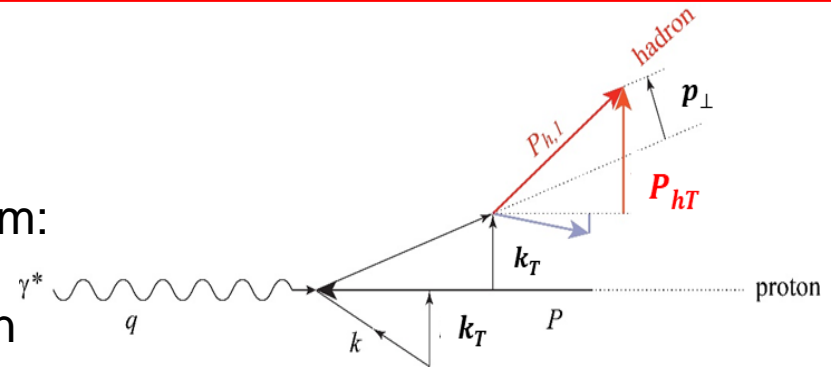
in principle these measurements allow to access k_T distributions and the Boer-Mulders PDFs $h_1^{\perp q}$

unpolarised SIDIS

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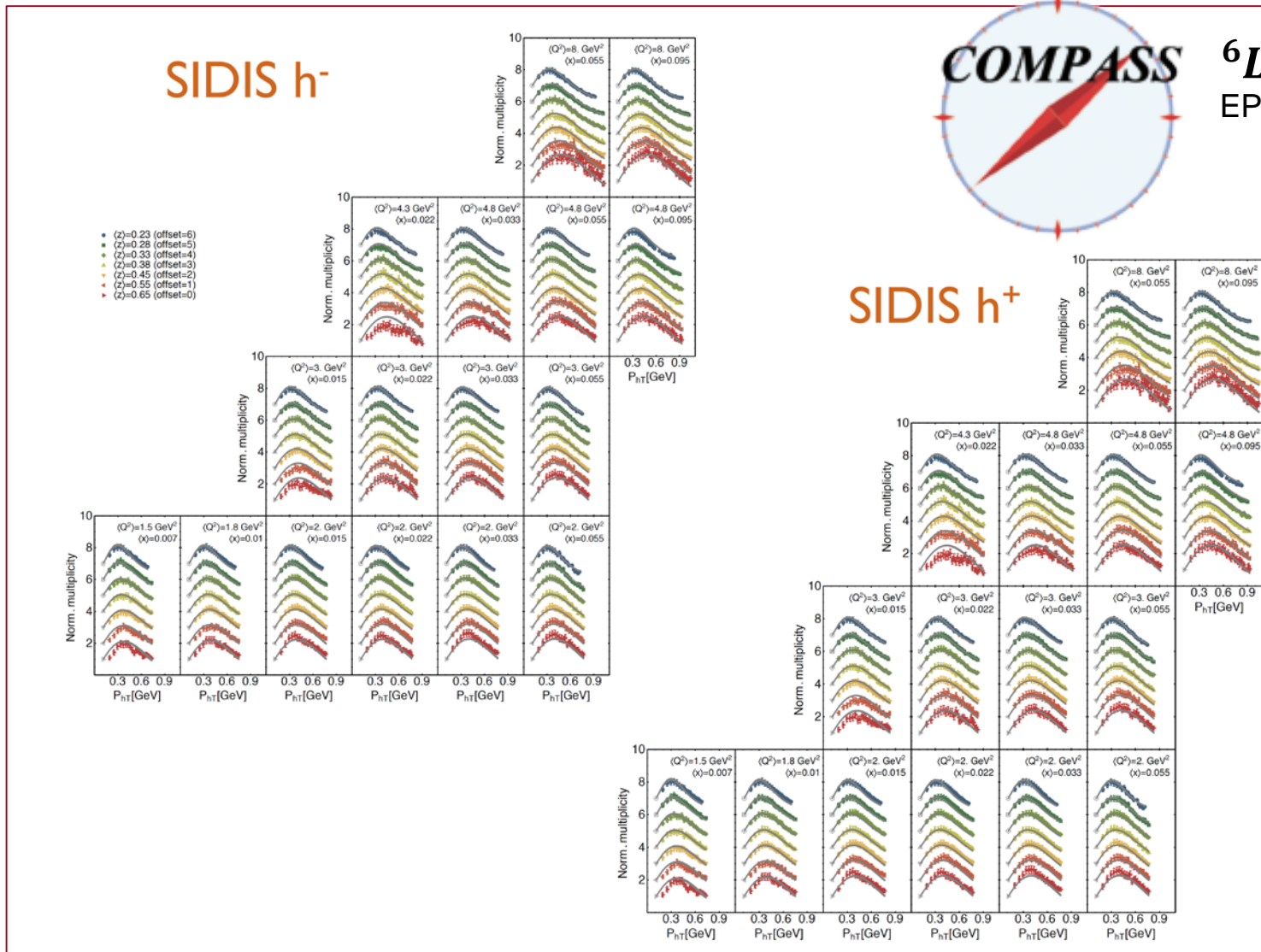
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COMPASS has published results on

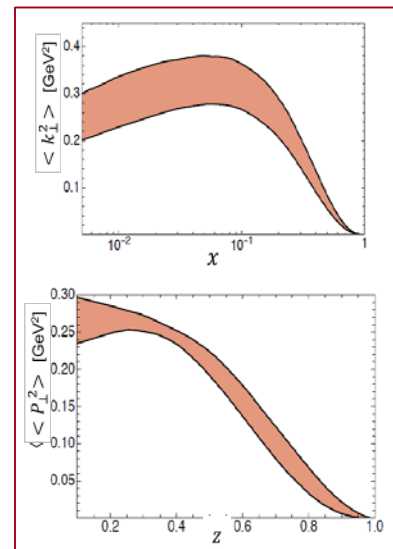
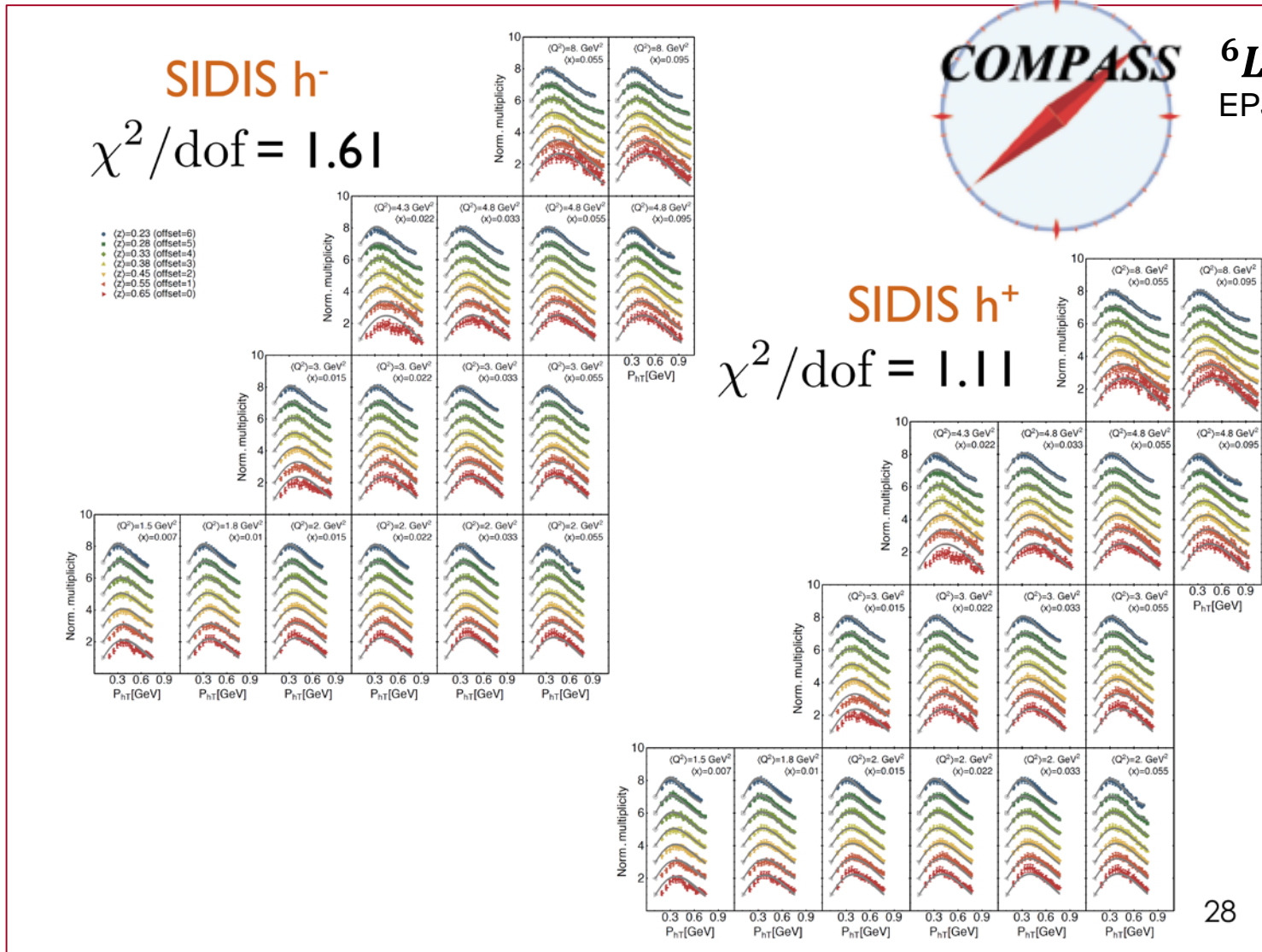
- azimuthal asymmetries and P_{hT} distributions from 2004 ${}^6\text{LiD}$ data NPB 886 (2014)
- P_{hT} distributions from 2004 ${}^6\text{LiD}$ data EPJC 73 (2013)
- P_{hT} distributions from 2006 ${}^6\text{LiD}$ data NEW PRD 97 (2018)

further results will come from 2016/17 data on LH_2

unpolarised SIDIS – P_{hT} distributions

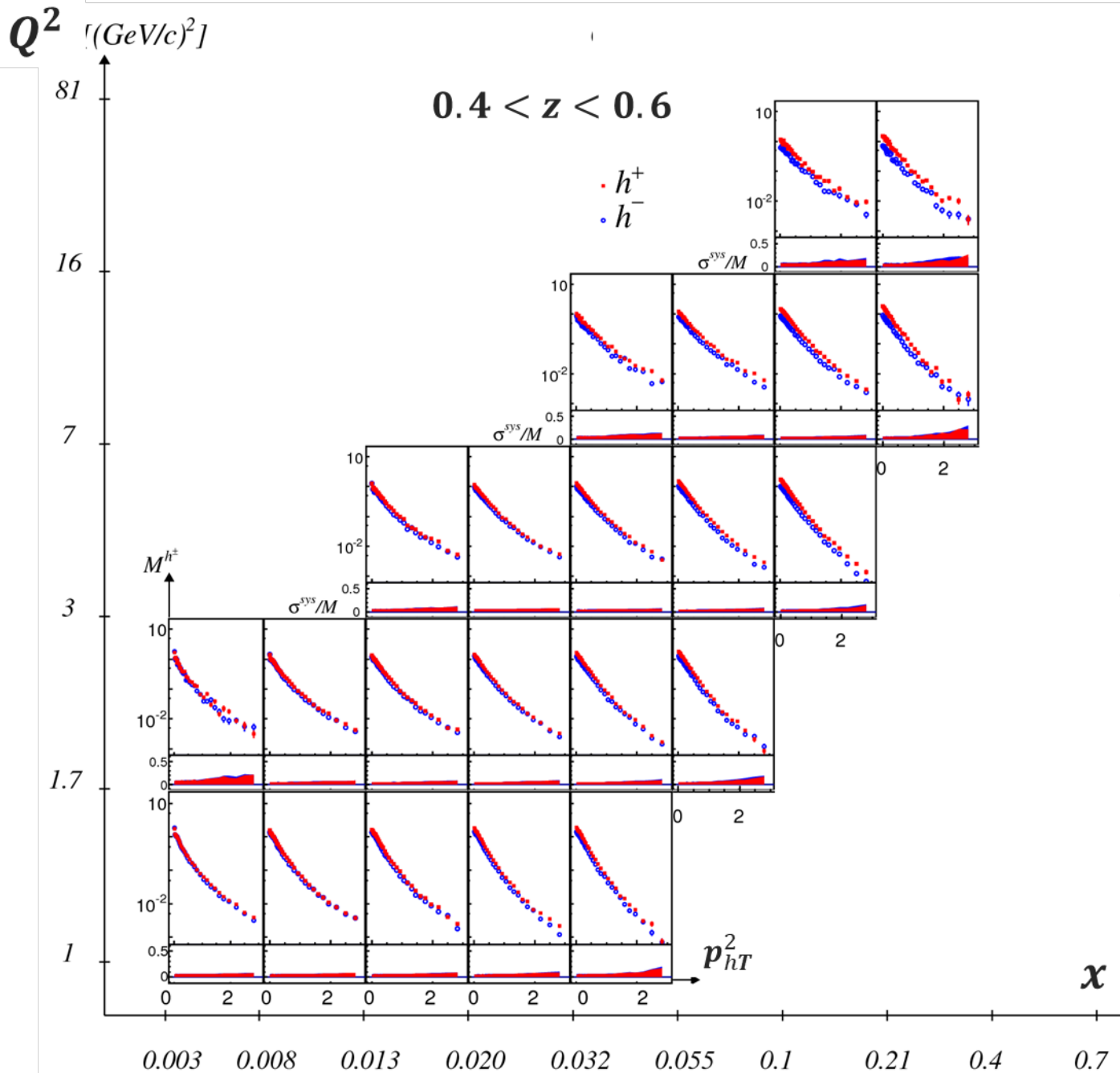


unpolarised SIDIS – P_{hT} distributions



global fit of P_{Th} distributions
 F. Delcarro, Transversity2017 → next talk

unpolarised SIDIS – P_{hT} distributions



**NEW INDEPENDENT
DATA SET**

${}^6\text{LiD}$ 2006 data

increased kinematic and
 P_{hT} range

normalisation: smaller
systematic uncertainty

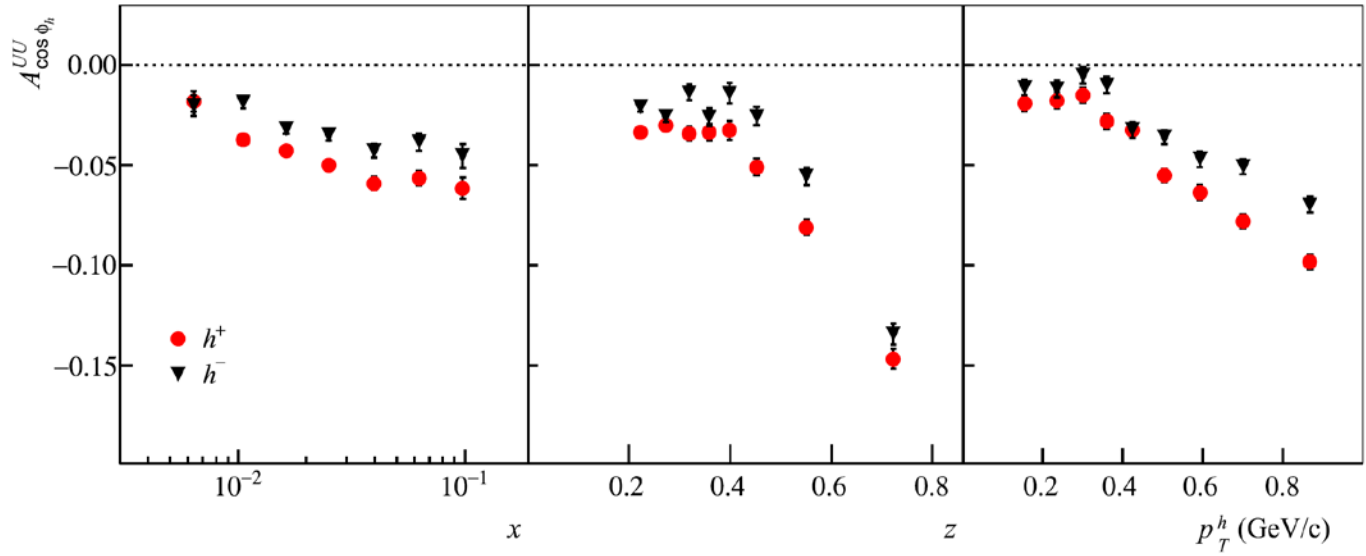
4918 points

PRD 97 (2018) 032006

unpolarised SIDIS - Azimuthal Asymmetries



$\cos \phi_h$



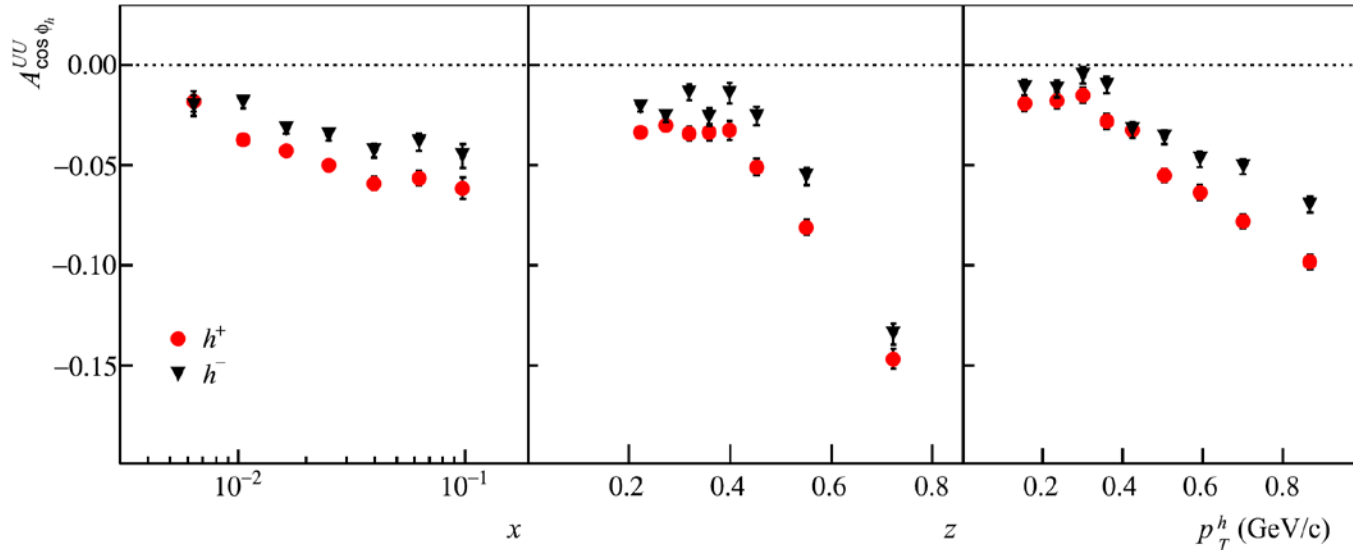
Cahn effect
 BM \otimes Collins FF
 h_1^\perp \otimes H_1

NPB 886 (2014) 1046

unpolarised SIDIS - Azimuthal Asymmetries



$\cos \phi_h$



Cahn effect

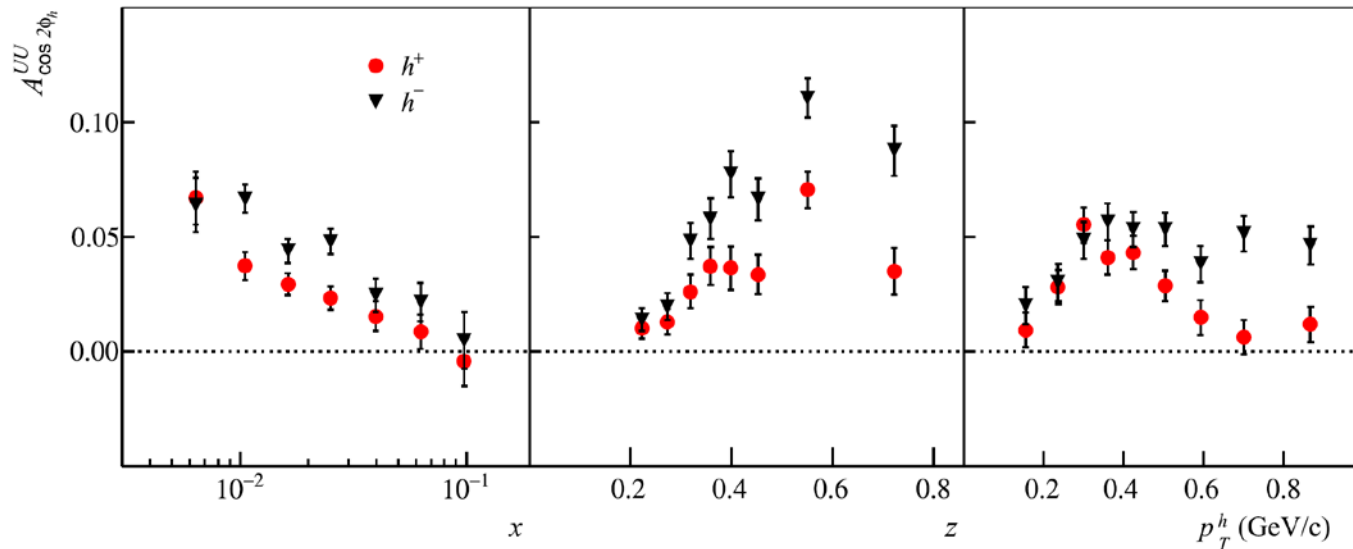
BM \otimes Collins FF

h_1^\perp \otimes H_1

- large asymmetries
- strong kinematical dependences
- different for h^+ and h^-

NPB 886 (2014) 1046

$\cos 2\phi_h$



BM \otimes Collins FF

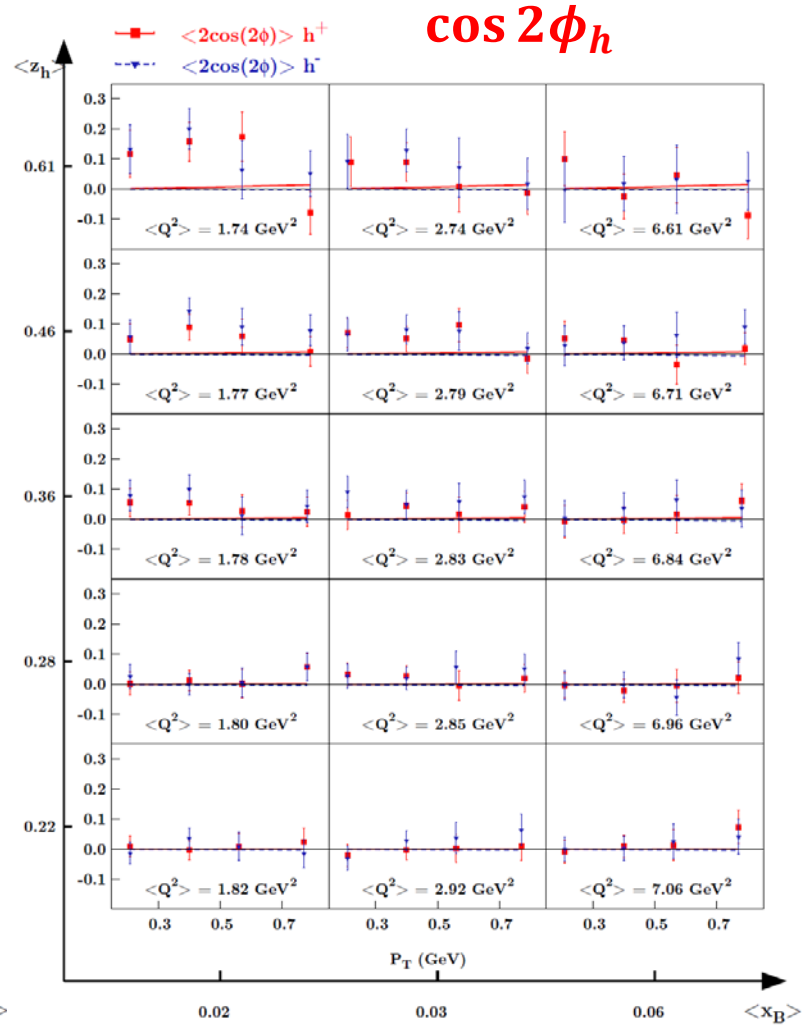
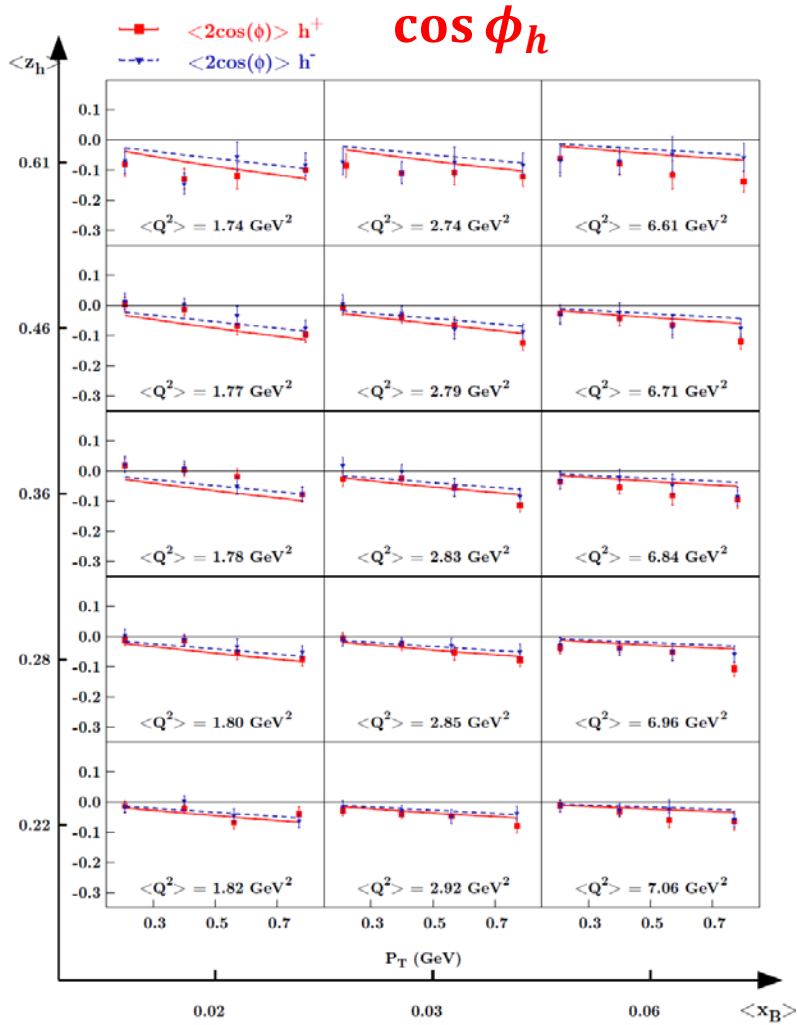
h_{iT}^\perp \otimes H_1

Cahn effect

unpolarised SIDIS - Azimuthal Asymmetries



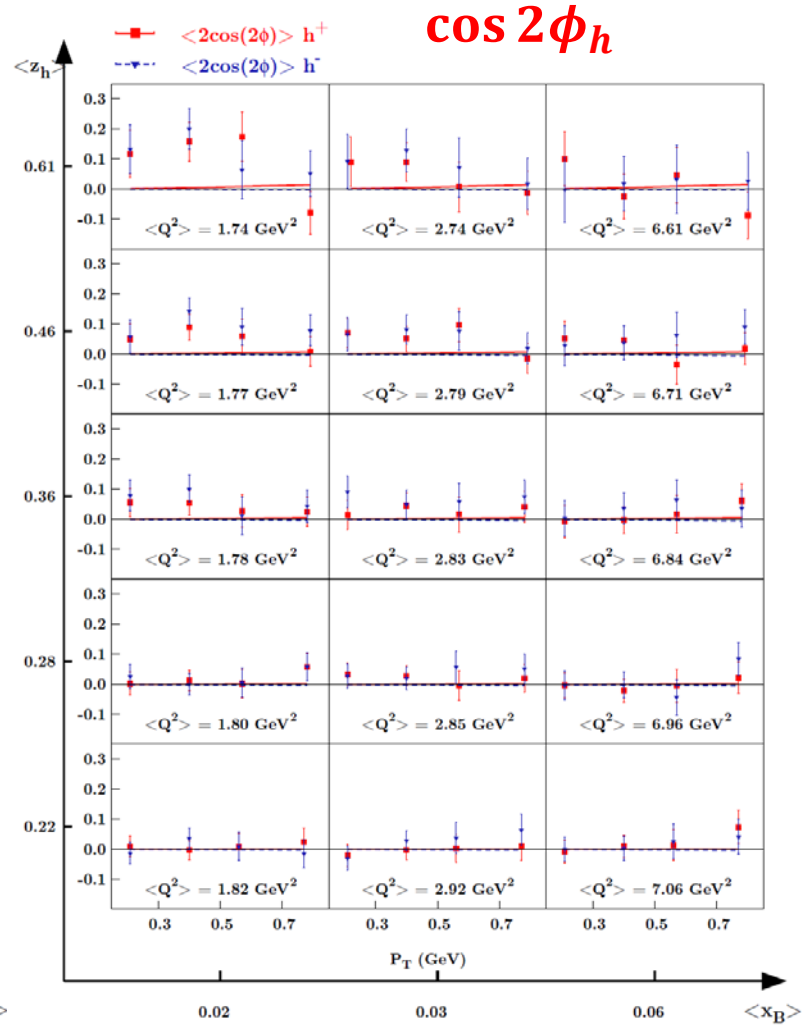
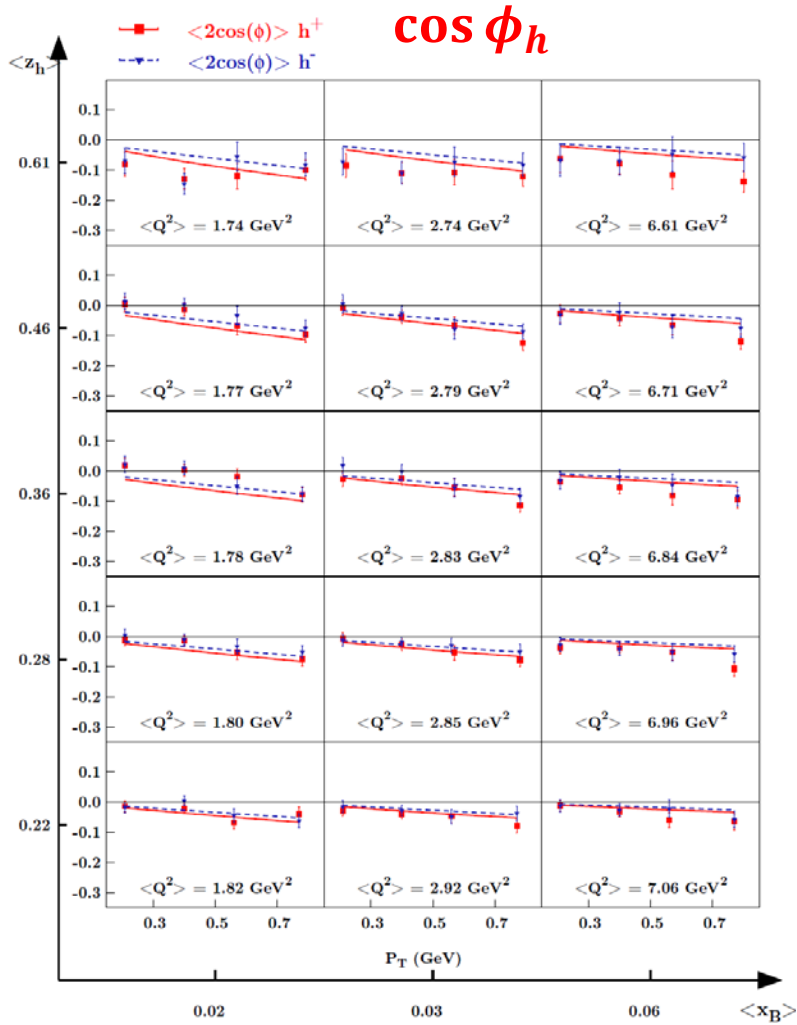
3D (x , z , P_{Th}) analysis



unpolarised SIDIS - Azimuthal Asymmetries



3D (x , z , P_{Th}) analysis



V. Barone,
M. Boglione et al.
PRD91 (2015)

$$A^{\cos \phi} = A^{\cos \phi}|_{\text{Cahn}} + A^{\cos \phi}|_{\text{BM}}$$

$$A^{\cos 2\phi} = A^{\cos 2\phi}|_{\text{BM}}$$

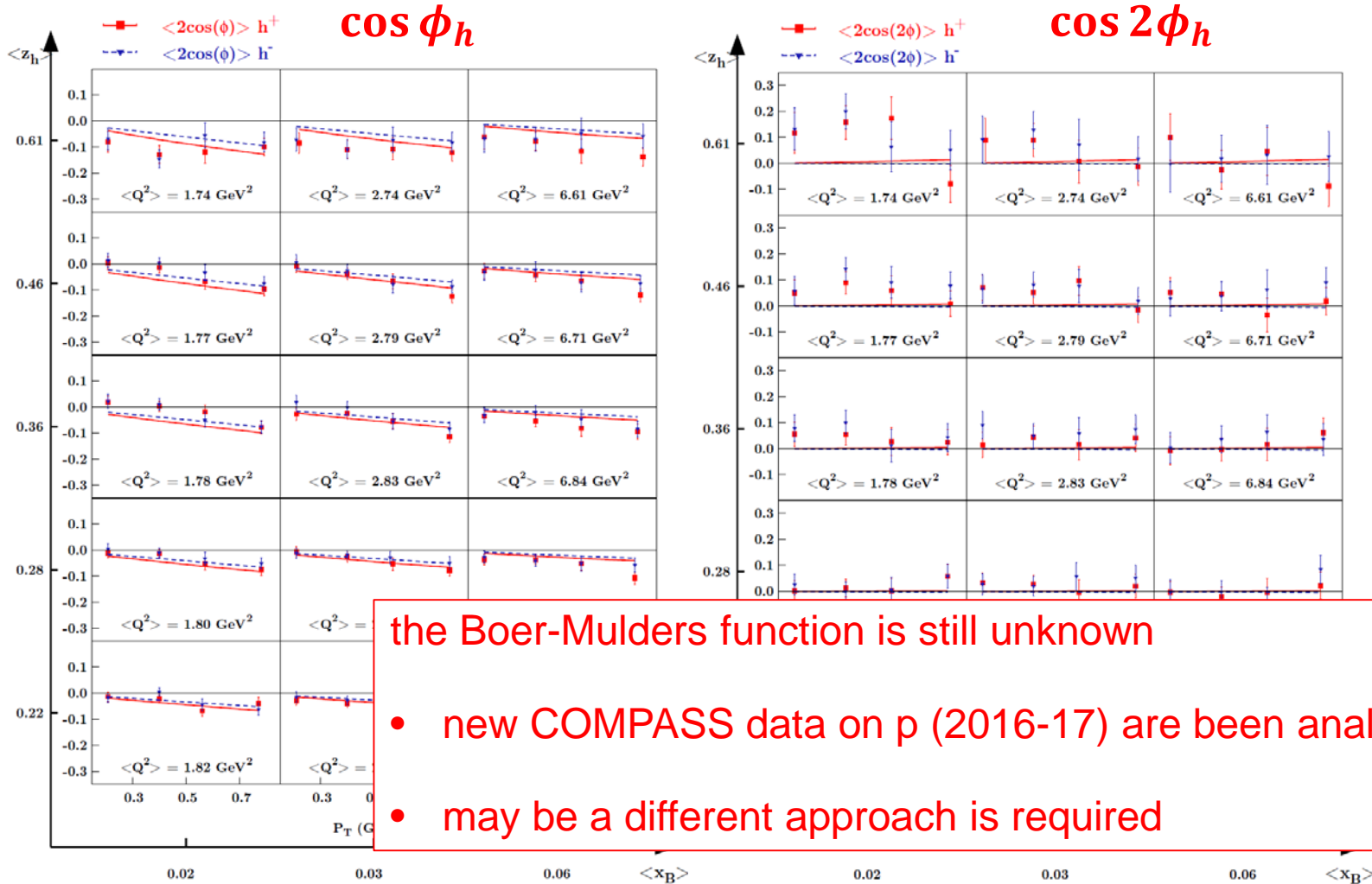
$$\langle k_T^2 \rangle \sim 0.03 - 0.04 \text{ GeV}^2$$

”... indeterminacy on the extraction of the Boer-Mulders function ...”

unpolarised SIDIS - Azimuthal Asymmetries



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the Boer-Mulders function is still unknown

- new COMPASS data on p (2016-17) are being analysed
- maybe a different approach is required

”... indeterminacy on the extraction of the Boer-Mulders function ...”

unpolarised SIDIS - Azimuthal Asymmetries



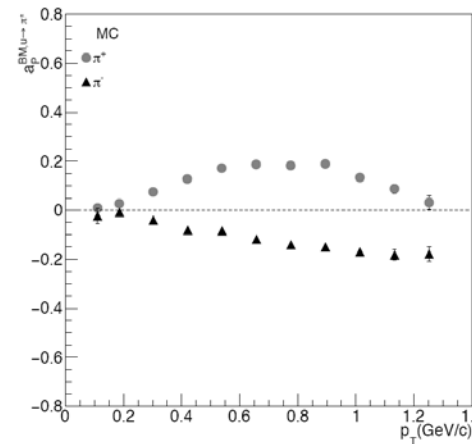
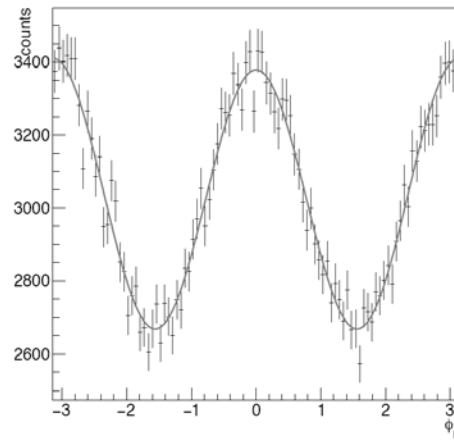
MC for the fragmentation of transversely polarised quarks based on the 3P_0 model

A. Kerbizi et al. arXiv:1802.00962

results introducing a correlation between the quark transverse momentum and its transverse spin

A. Kerbizi et al, DSPIN 2017

ϕ_h
distribution



amplitude of the
 $\cos 2\phi_h$ modulation
vs P_{Th}

should be there!

the Boer-Mulders function is still unknown

- new COMPASS data on p (2016-17) are being analysed
- maybe a different approach is required

results on TMD PDFs from SIDIS off

- unpolarised deuteron
- longitudinally polarised p and d
- transversely polarised p and d

SIDIS off longitudinally polarised nucleons



all possible asymmetries at leading twist have been measured

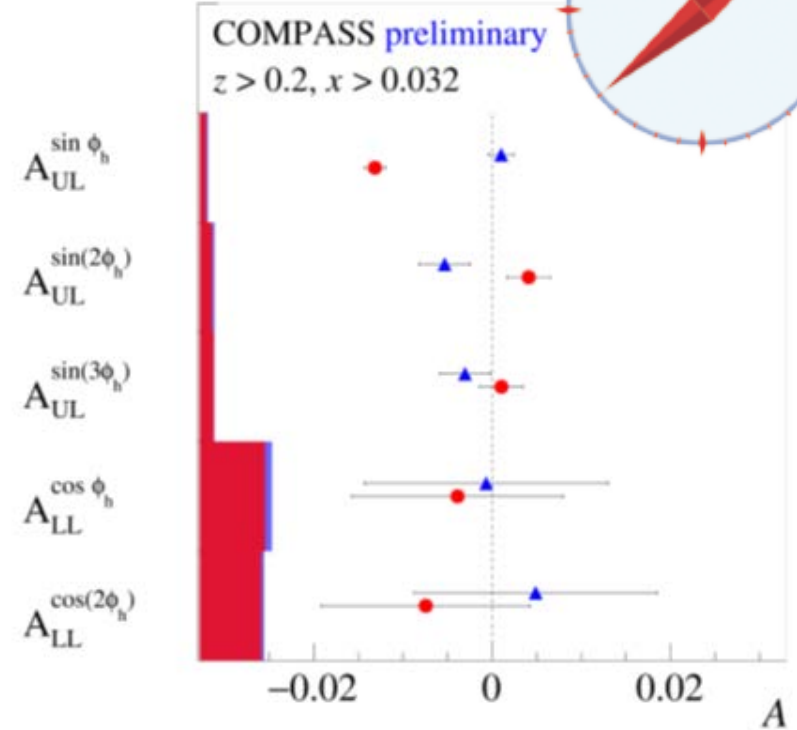
- single hadron on p and d

SPIN2016; EPJC 70 (2010) 39–49, hep-ex/1609.06062

- two hadrons (p)

SPIN2016

no clear signal has been observed



SIDIS off longitudinally polarised nucleons



all possible asymmetries at leading twist have been measured

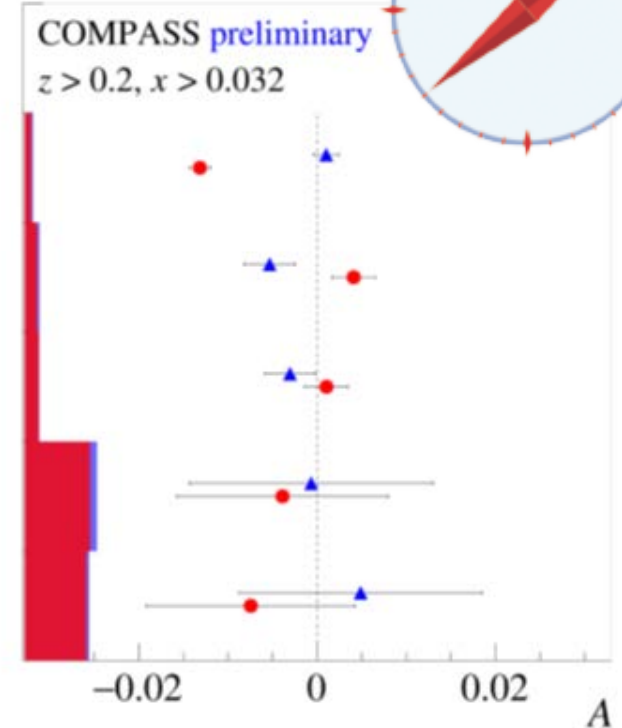
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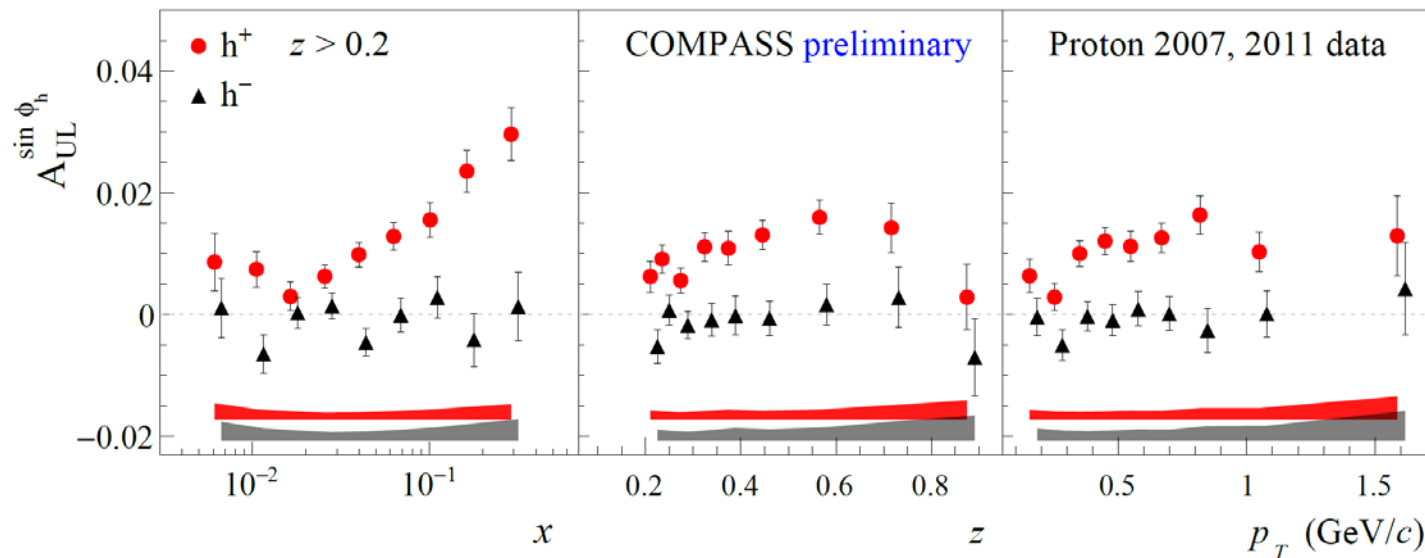
- two hadrons (p)

SPIN2016

no clear signal has been observed



agreement with HERMES, better precision



no clear interpretation in terms of TMD PDFs

results on TMD PDFs from SIDIS off

- **unpolarised deuteron**
- **longitudinally polarised p and d**
- **transversely polarised p and d**

Semi-Inclusive Deep Inelastic Scattering

MAJOR RESULT:

since 2004 two of these new PDFs have been measured

by COMPASS and HERMES

and have been shown to be different from zero



the **transversity** PDF

Collins asymmetry, dihadron asymmetry

the **Sivers** PDF

Sivers asymmetry

**A STEP TOWARDS
THE 3-D STRUCTURE OF THE NUCLEON**

TRANSVERSITY PDFs

Transversity PDF in SIDIS

$$l N^\uparrow \rightarrow l' h X$$

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

H_1^\perp **Collins Fragmentation Function:** left-right asymmetry of hadrons with respect to the transverse spin of the fragmenting quark

amplitude of the modulation $\sin(\phi_h + \phi_s - \pi)$

COMPASS
HERMES
JLab HallA

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COMPASS
HERMES
JLab HallA

$$l N^\uparrow \rightarrow l' h_1 h_2 X$$

$$\text{dihadron asymmetry} \quad \sim h_1 H_1^\chi$$

H_1^χ **Interference / Dihadron Fragmentation Function:** modulation in the azimuthal angle of the 2h production plane

amplitude of the modulation $\sin(\phi_R + \phi_S - \pi)$

COMPASS
HERMES
(STAR in pp)

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COMPASS
HERMES
(STAR in pp)

from $e^+e^- \rightarrow \text{hadrons}$
Belle, BaBar, BES

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COMPASS
HERMES
(STAR in pp)

not independent [COMPASS PLB736 (2014) and MC studies] **but with different properties:**

- Collins asymmetry: higher statistics,
unpolarised FF D_1 known
factorisation in pp ?
- dihadron asymmetry: no convolution on transverse momenta
known evolution, (still) unknown unpolarised FF
factorisation in pp ok

from $e^+e^- \rightarrow \text{hadrons}$
Belle, BaBar, BES

Transversity PDF in SIDIS

$$l N^\uparrow \rightarrow l' h X$$

Collins asymmetry

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

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Belle, BaBar, BES

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COMPASS
HERMES
JLab HallA

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amplitude of the modulation $\sin(\phi_R + \phi_S - \pi)$

COMPASS
HERMES
(STAR in pp)

$$l N^\uparrow \rightarrow l' \Lambda X$$

Λ polarisation

“self-analysing” particle:
fragmenting quark polarisation from Λ polarisation

low statistics

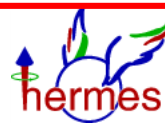
Fragmentation Function of $q^\uparrow \rightarrow \Lambda$ unknown

COMPASS

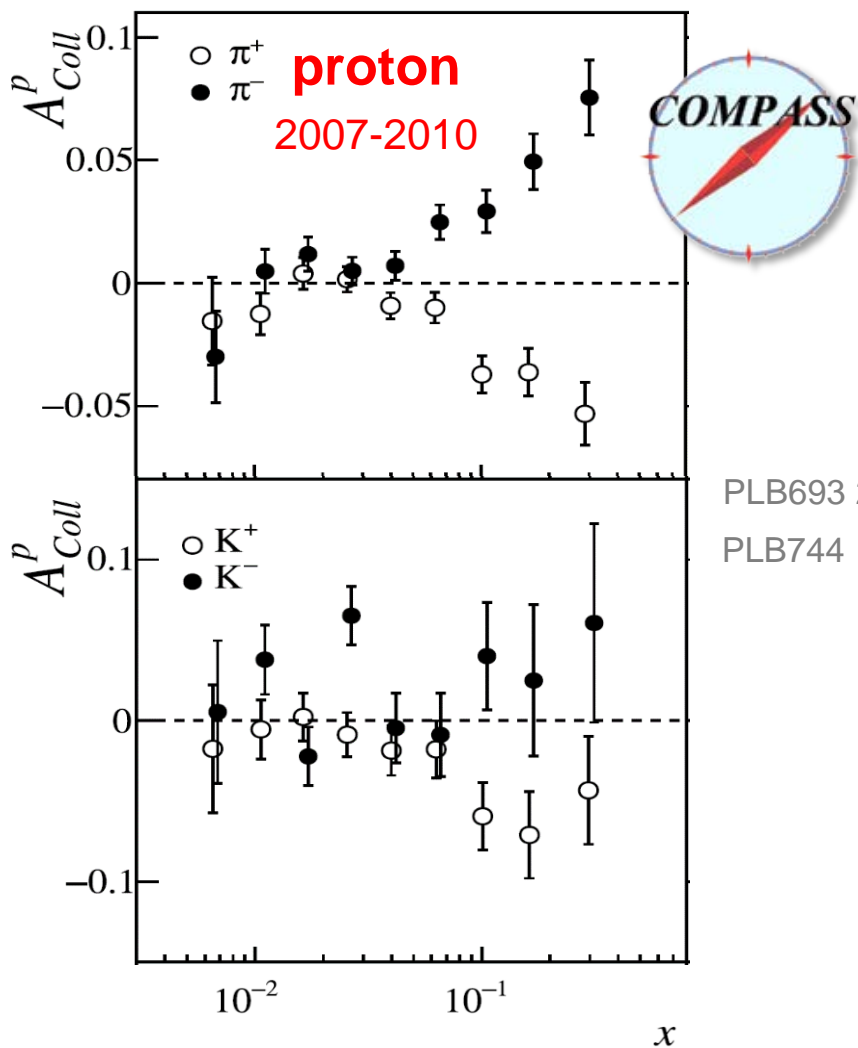
Collins asymmetry

Collins asymmetry

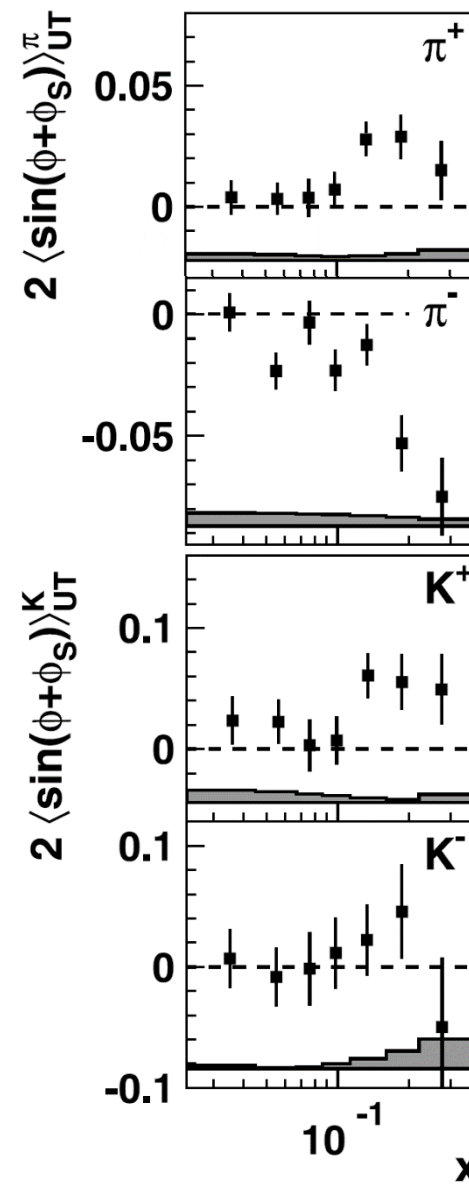
2004: first evidence for non-zero Collins asymmetry on p from HERMES



COMPASS results



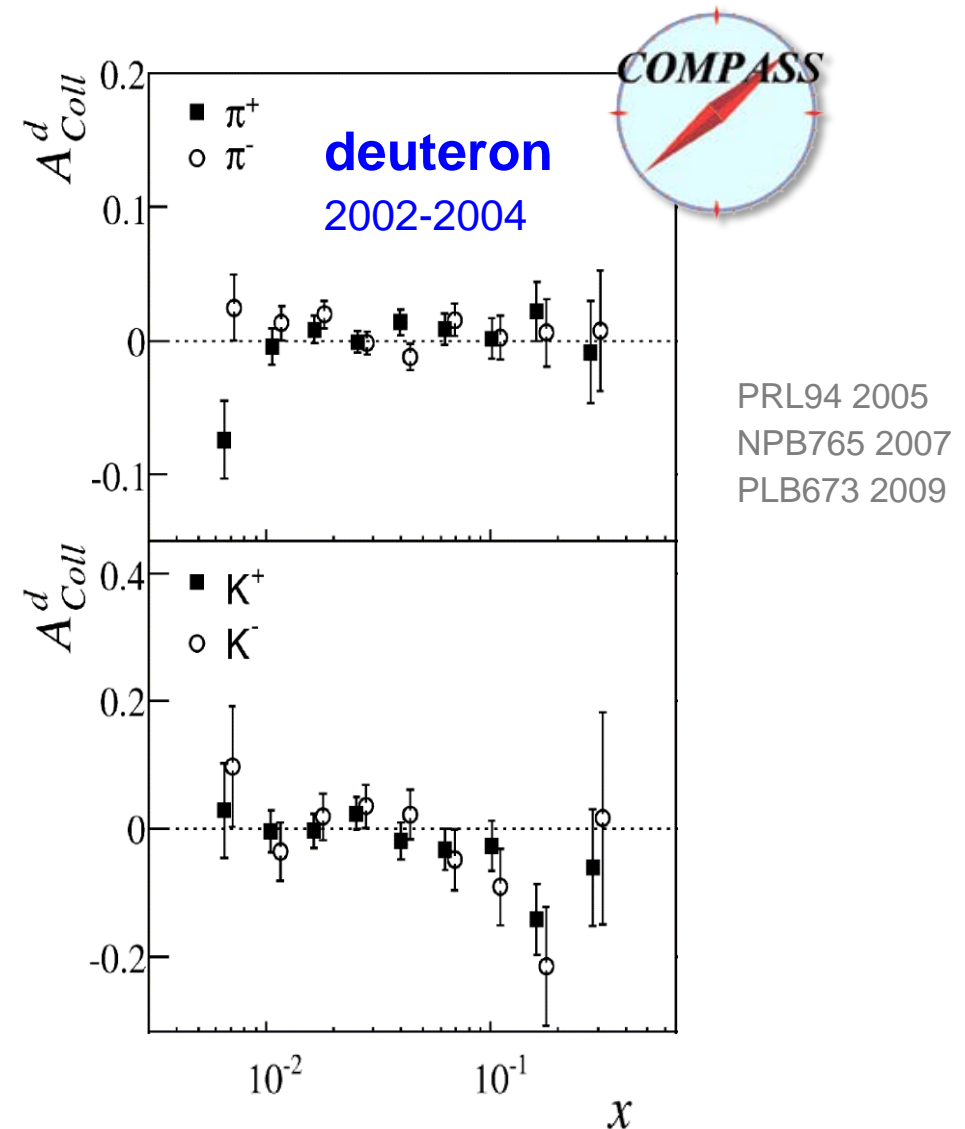
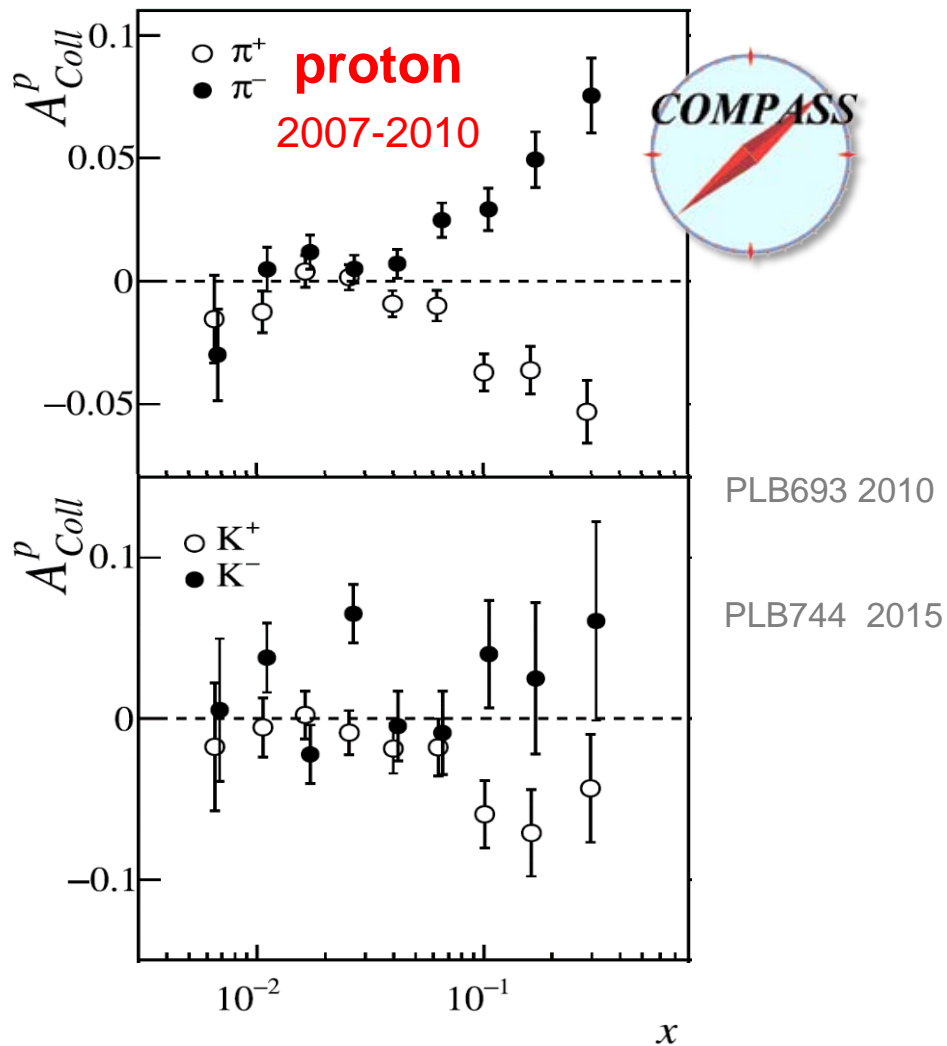
PLB693 2010 final results



Collins asymmetry

COMPASS results

- compatible with zero
- large statistical errors



Collins asymmetry

the only existing d data!

- compatible with zero
- large statistical errors

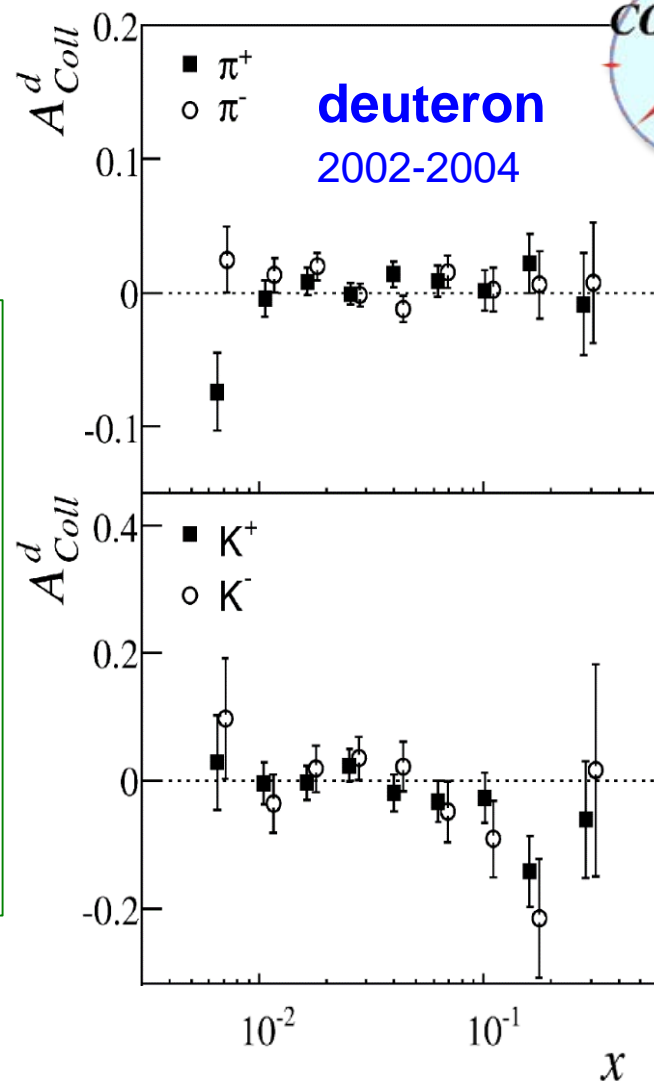
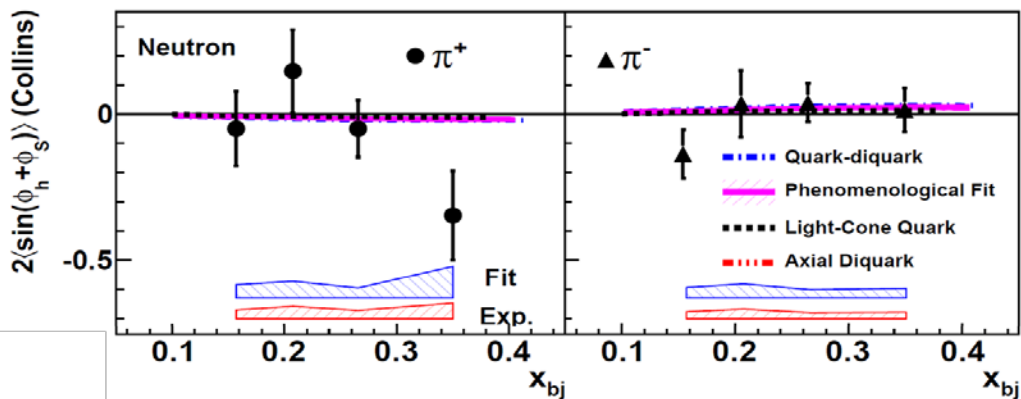


PRL94 2005
NPB765 2007
PLB673 2009

neutron

Jefferson Lab

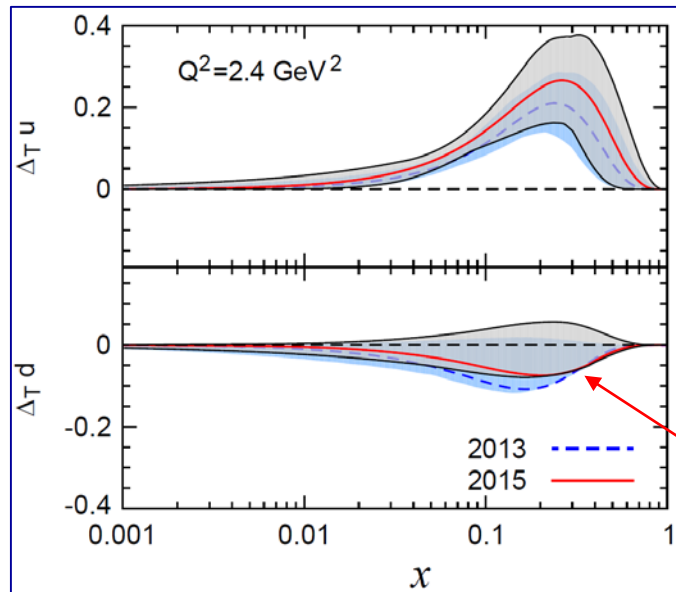
Hall A PRL107, 2011



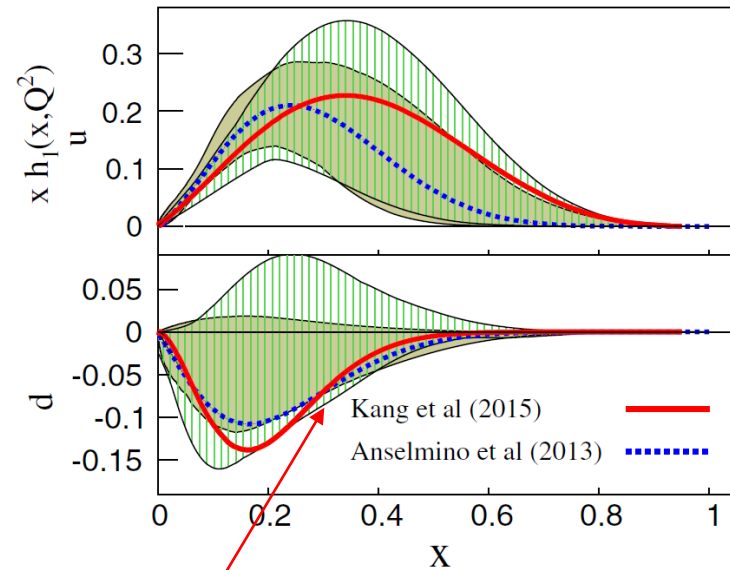
Transversity from Collins asymmetry

fits to HERMES p, COMPASS p and d, e^+e^- data

to estimate the parameters of a given parametrisation of transversity and Collins function



M. Anselmino et al.,
PRD 2015



Soffer Bound

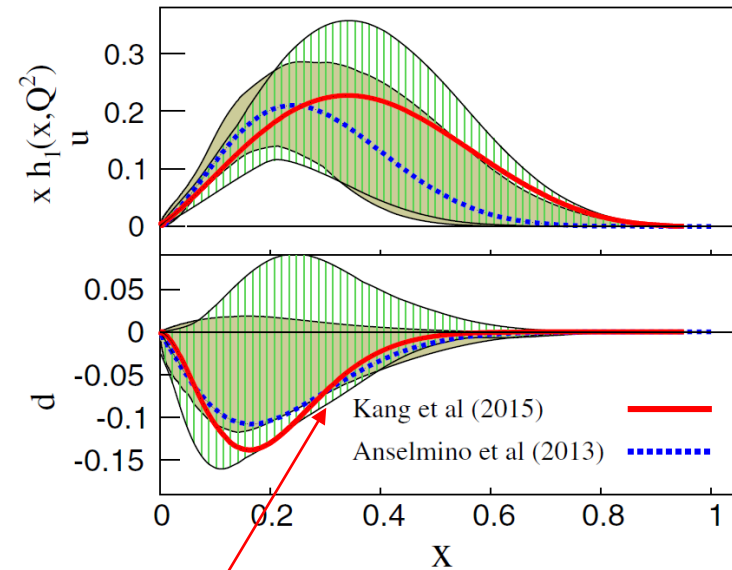
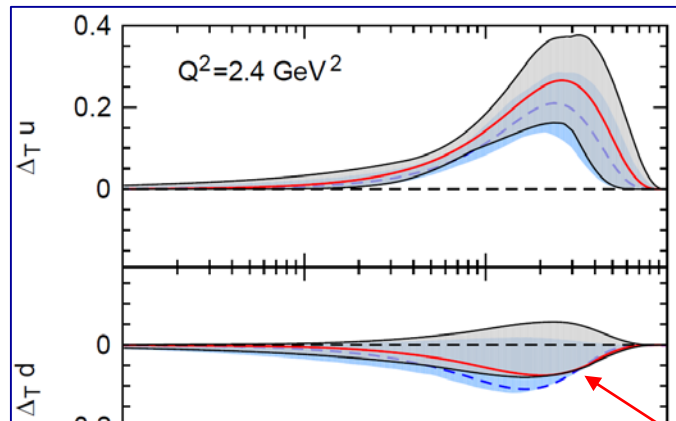
ZB Kang et al.,
PRD 2016

larger uncertainty on $x h_1^d$
due to the low statistics d data

Transversity from Collins asymmetry

fits to HERMES p, COMPASS p and d, e^+e^- data

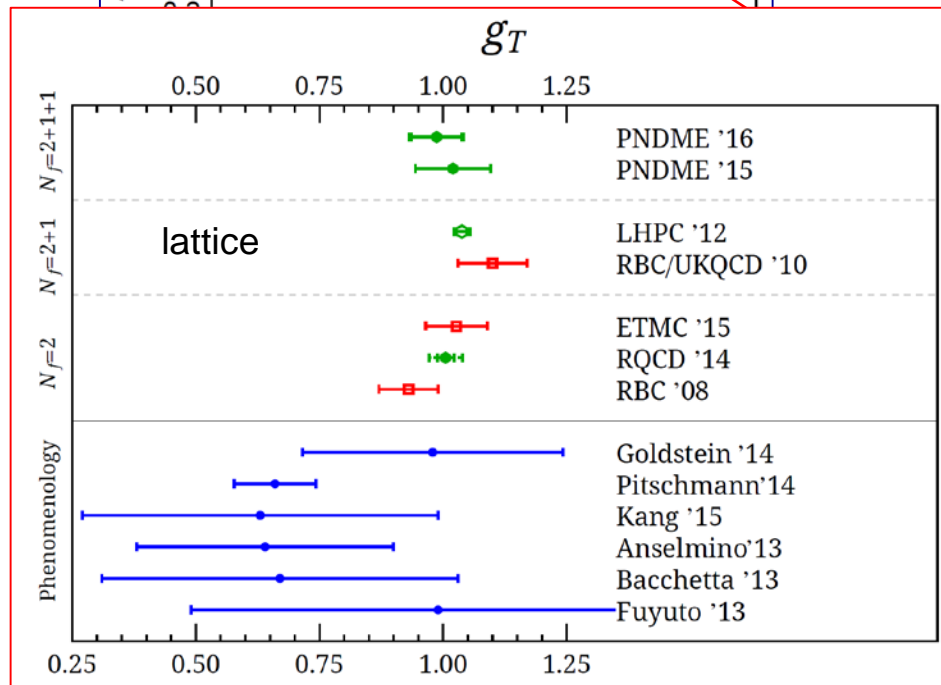
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Soffer Bound

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PRD 2016

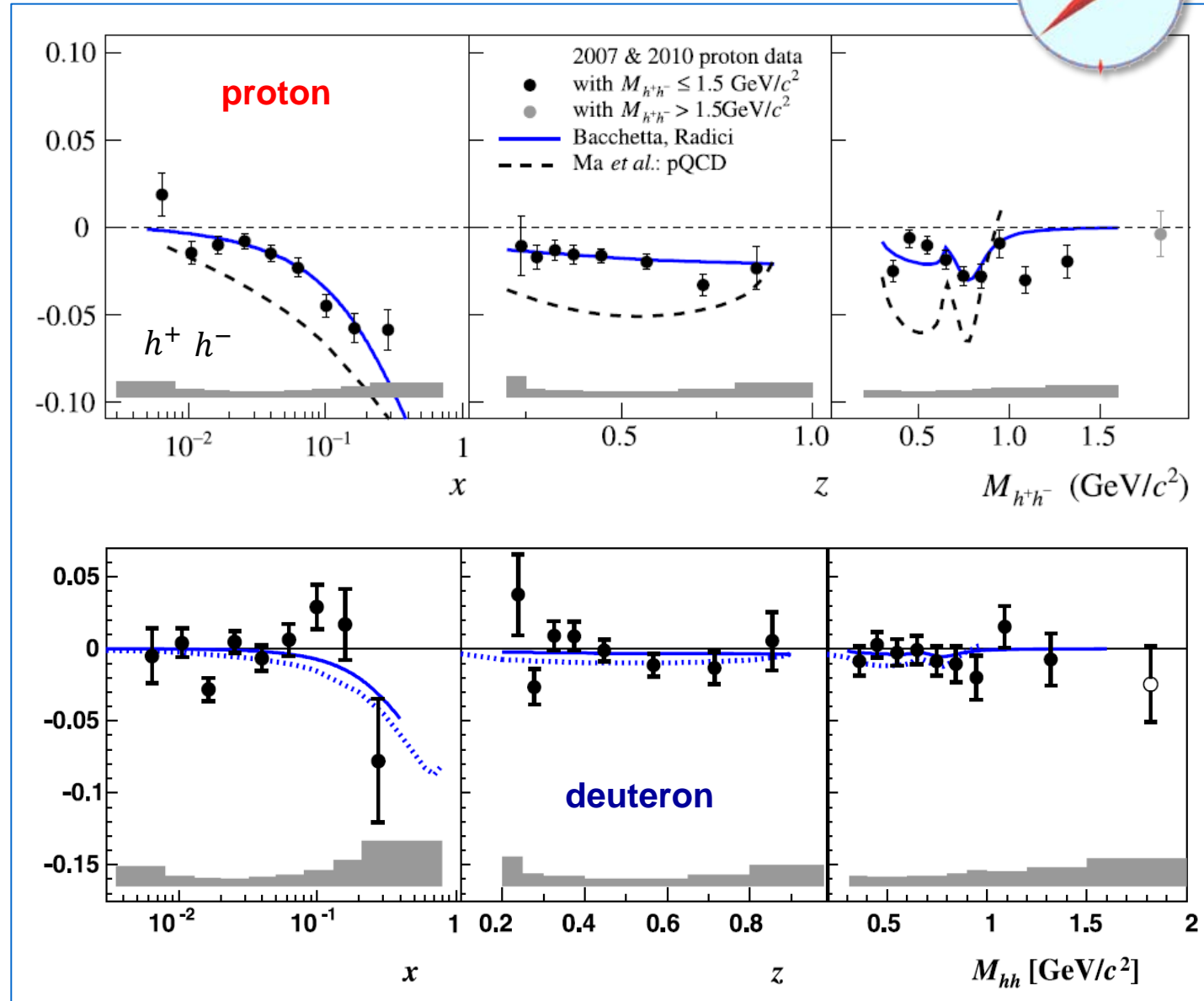
larger uncertainty on xh_1^d
due to the low statistics d data



Dihadron asymmetry

$$A_{2h} \sim \frac{\sum_q e_q^2 h_1^q \cdot H_q^\Delta}{\sum_q e_q^2 f_1^q \cdot D_q^{2h}}$$

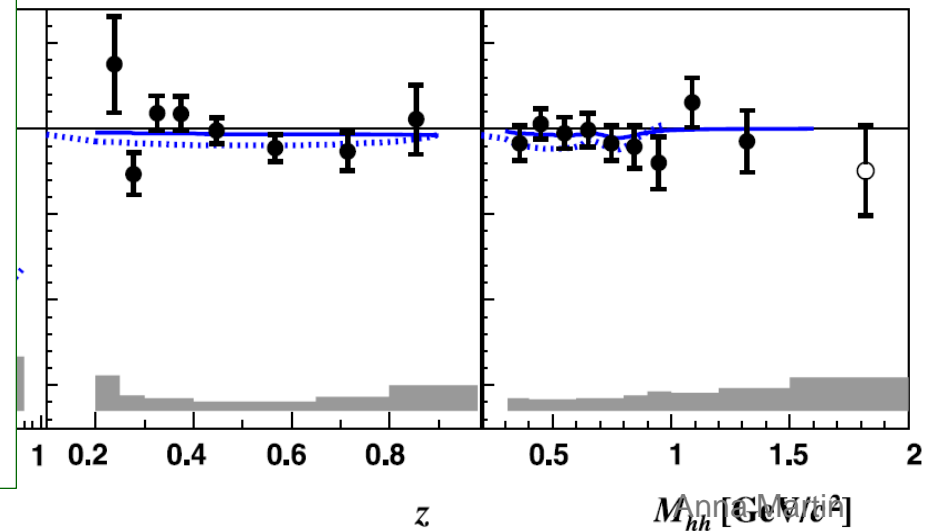
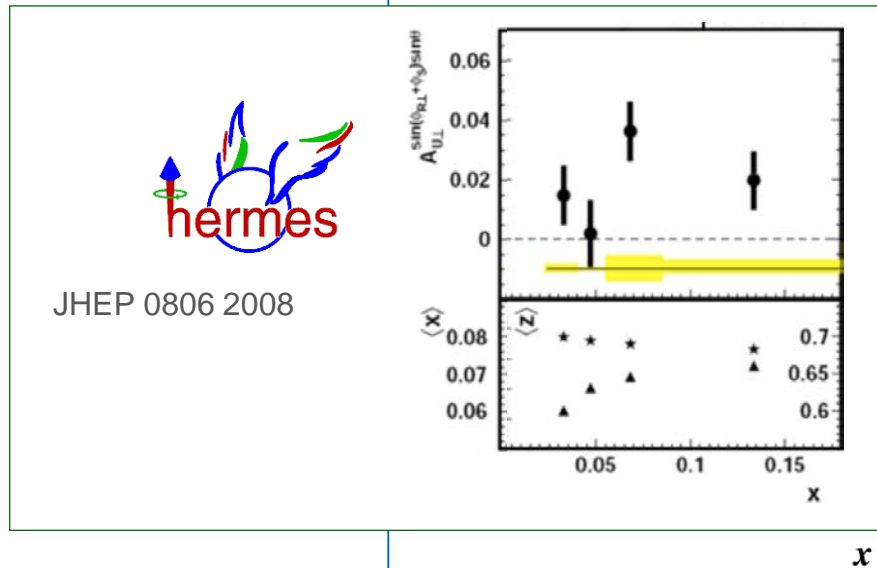
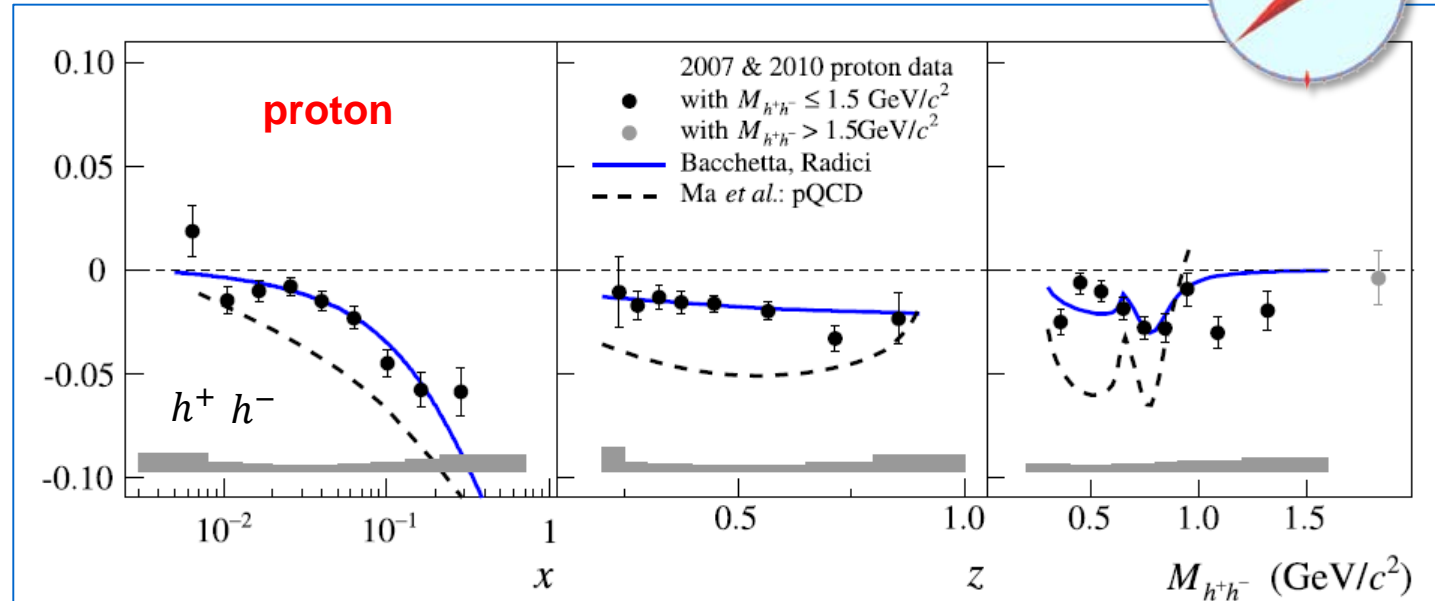
PLB 713 2012, PLB736 2014



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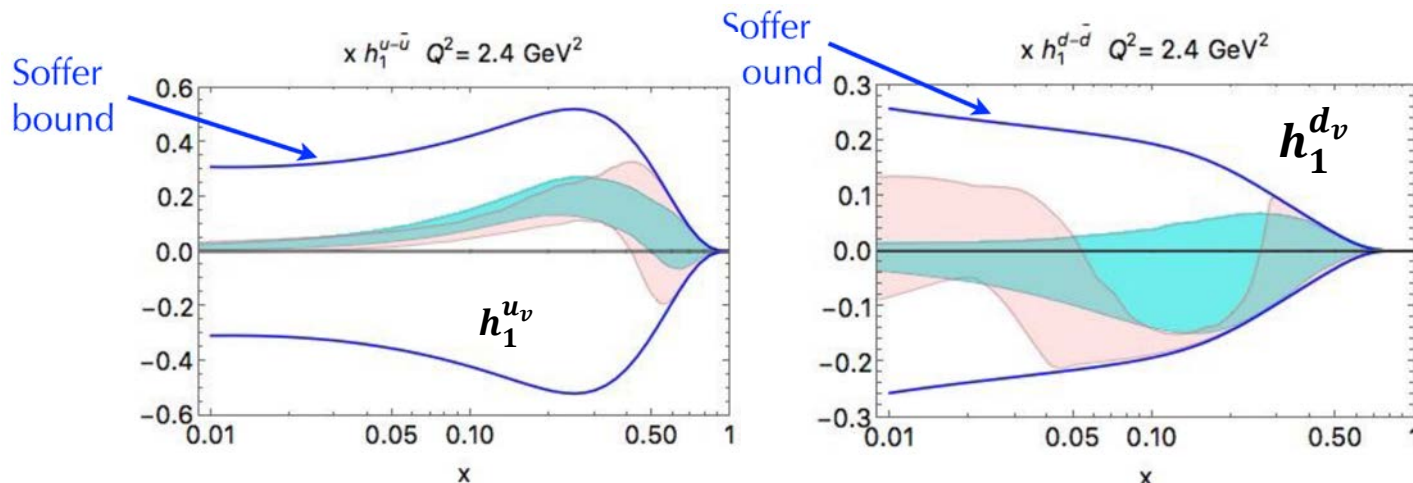
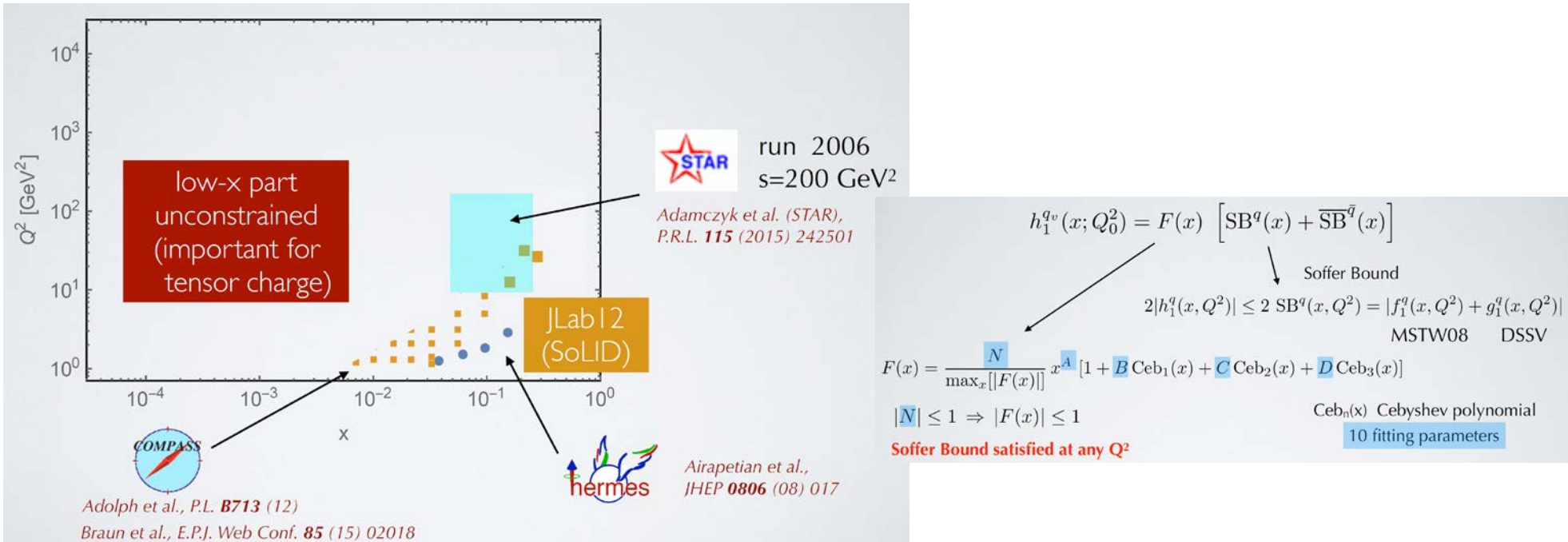
PLB 713 2012, PLB736 2014



Transversity from dihadron asymmetry

from M. Radici and A. Bacchetta, Transversity 2017

“collinear extraction” of $h_1^{u_v}$ and $h_1^{d_v}$



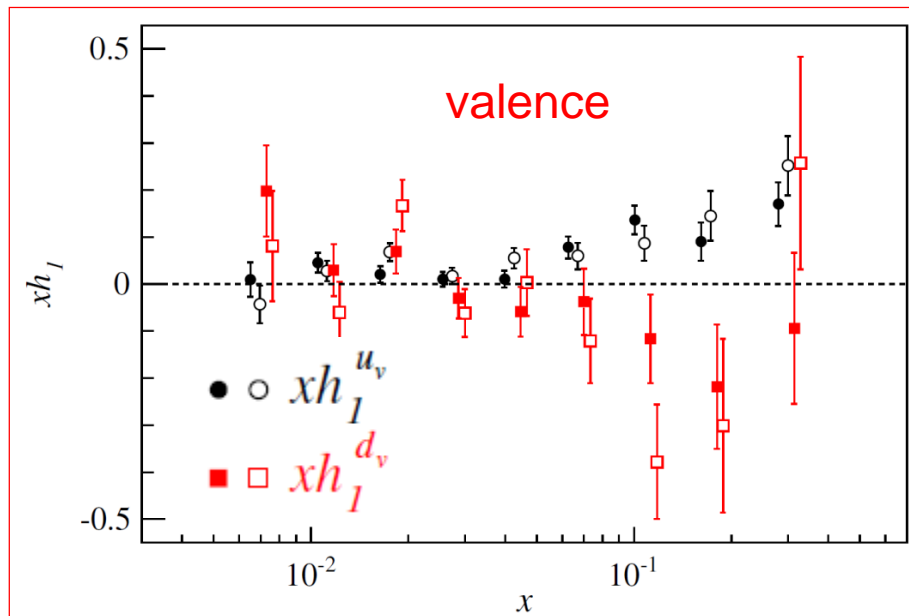
need dihadron multiplicities from RHIC and better deuteron data from COMPASS

Transversity from Collins and dihadron asymmetries

using the COMPASS p and d results (at the same $x - Q^2$ values)
and the Belle data (analysing power)

a direct **point by point extraction of transversity** is possible

advantage: no Monte Carlo nor parametrisation is needed



open points: dihadron

closed points: Collins

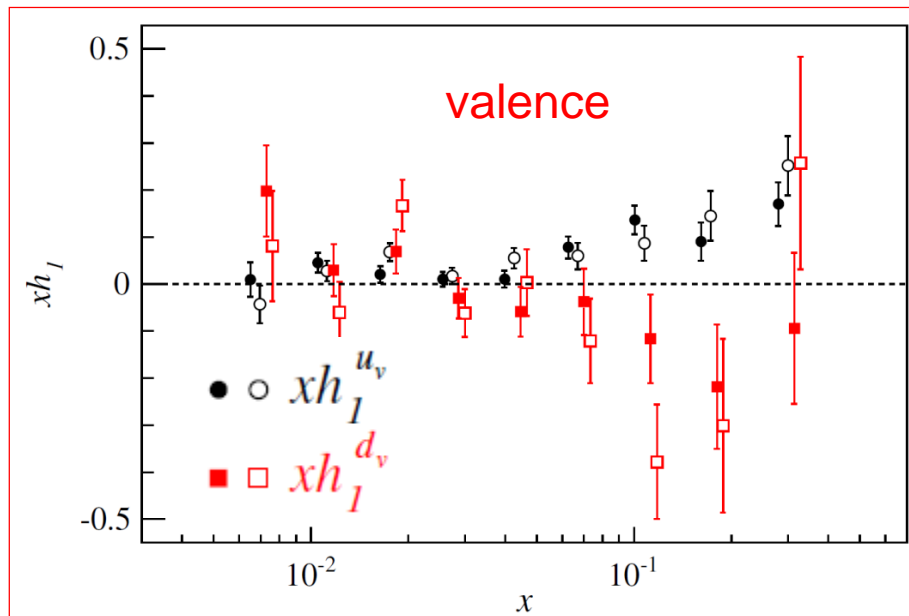
A.M., F. Bradamante, V. Barone PRD 2015

Transversity from Collins and dihadron asymmetries

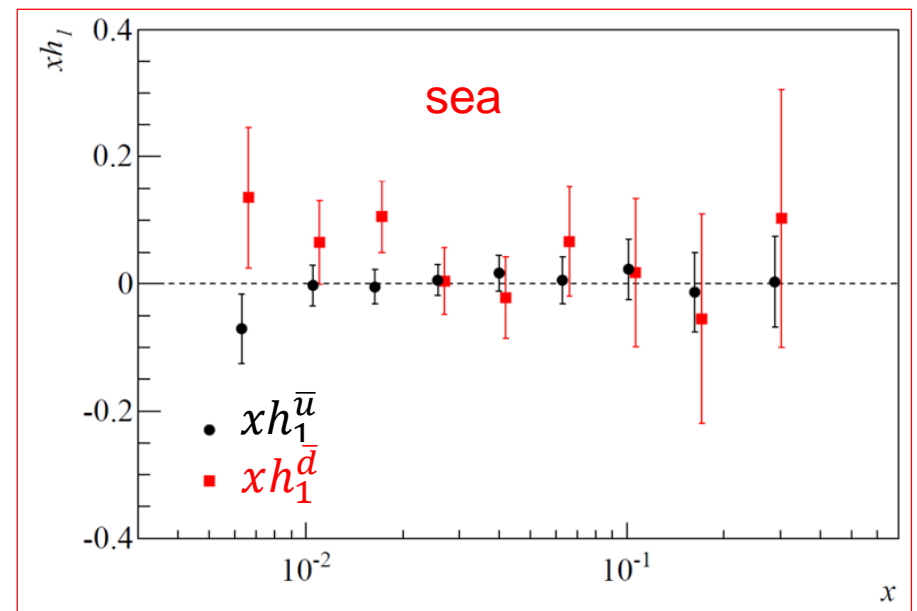
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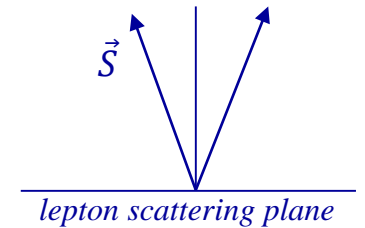


A.M., F. Bradamante, V. Barone PRD 2015

Λ polarisation

in SIDIS off transversely polarised nucleons, the Λ polarisation measured using the “reflected” direction of the nucleon spin i.e. the transverse polarisation of the struck quark if transversity is different from zero can be written as

$$P_{\Lambda} = \frac{\sum_q e_q^2 h_1^q H_1^{\Lambda/q}}{\sum_q e_q^2 f_1^q D_1^{\Lambda/q}}$$



today transversity is somewhat known, while $H_1^{\Lambda/q}$ is completely unknown

with different assumptions,

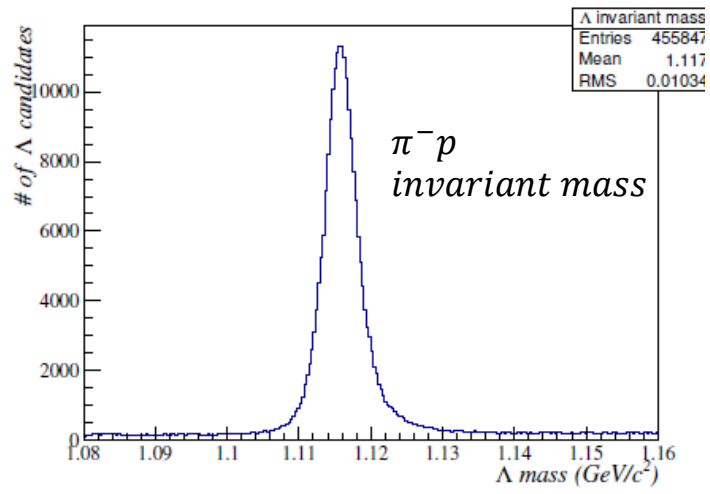
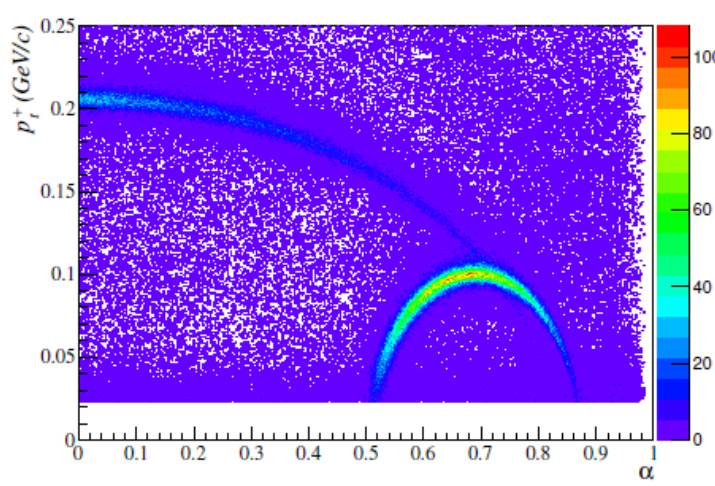
this measurement can give information either on h_1^s or on $H_1^{\Lambda/q} / D_1^{\Lambda/q}$



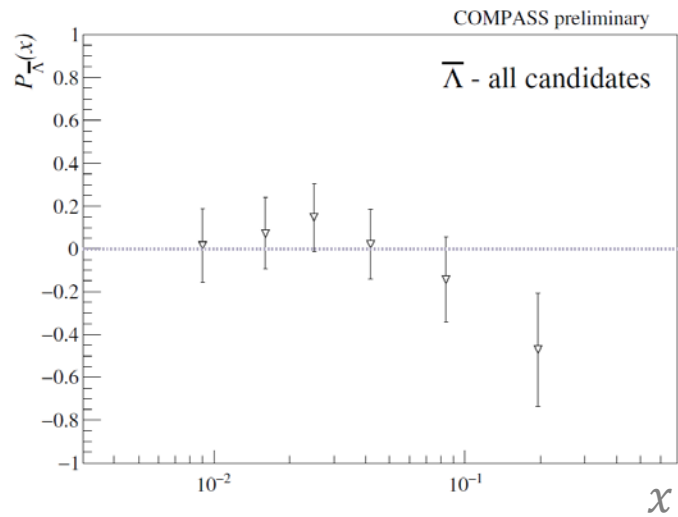
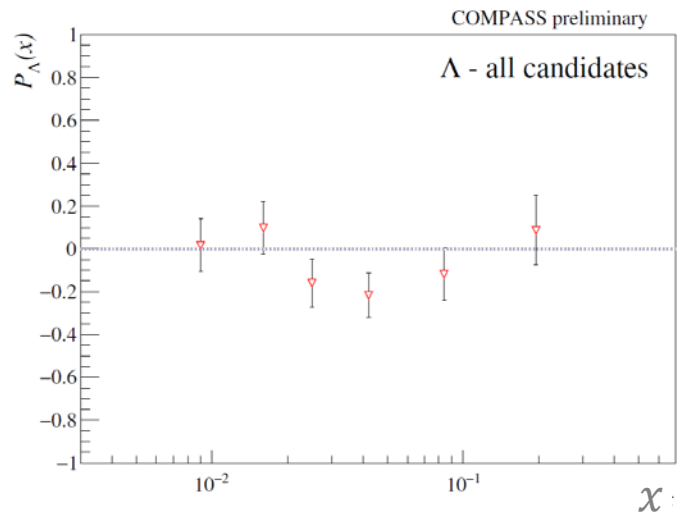
$\Lambda/\bar{\Lambda}$ polarisation

new results from the complete proton data set (2007 and 2010)

$Q^2 > 1 \text{ (GeV/c)}^2$



~300k Λ (~150k $\bar{\Lambda}$)



Sivers function

it is the most famous of the TMD parton distribution functions

requires final/initial-state interactions

quark rescattering via soft gluon exchange

should change sign from SIDIS to DY (important test !!)

in SIDIS it appears in the **Sivers asymmetry**, i.e. in the amplitude of the sine modulation in $\phi_h - \phi_s$

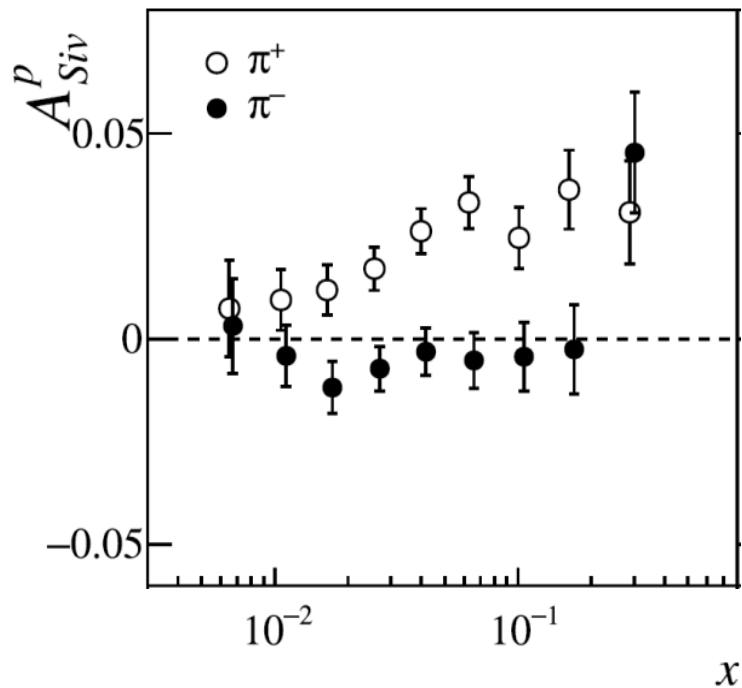
$$f_{1T}^\perp \otimes D_1$$



Sivers asymmetry

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

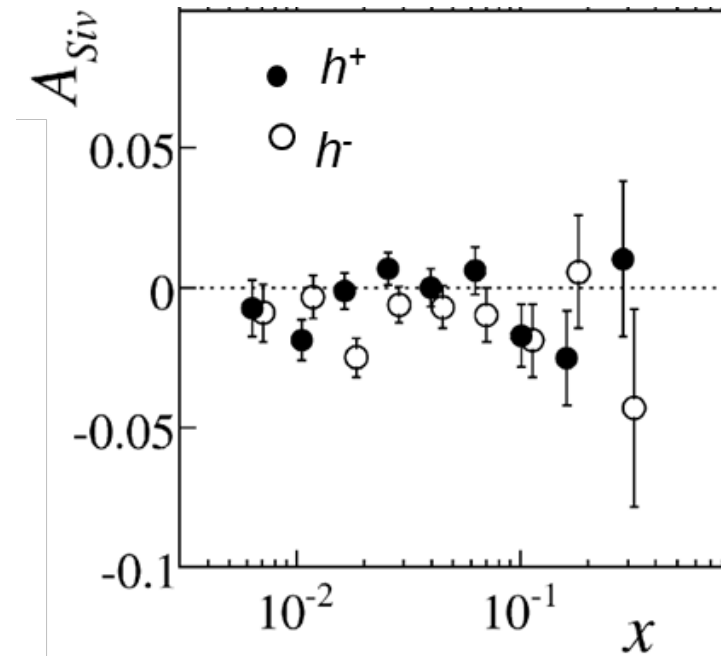
proton



clearly positive for h^+
down to $x \sim 10^{-2}$

PLB 2010, 2012

deuteron



compatible with zero

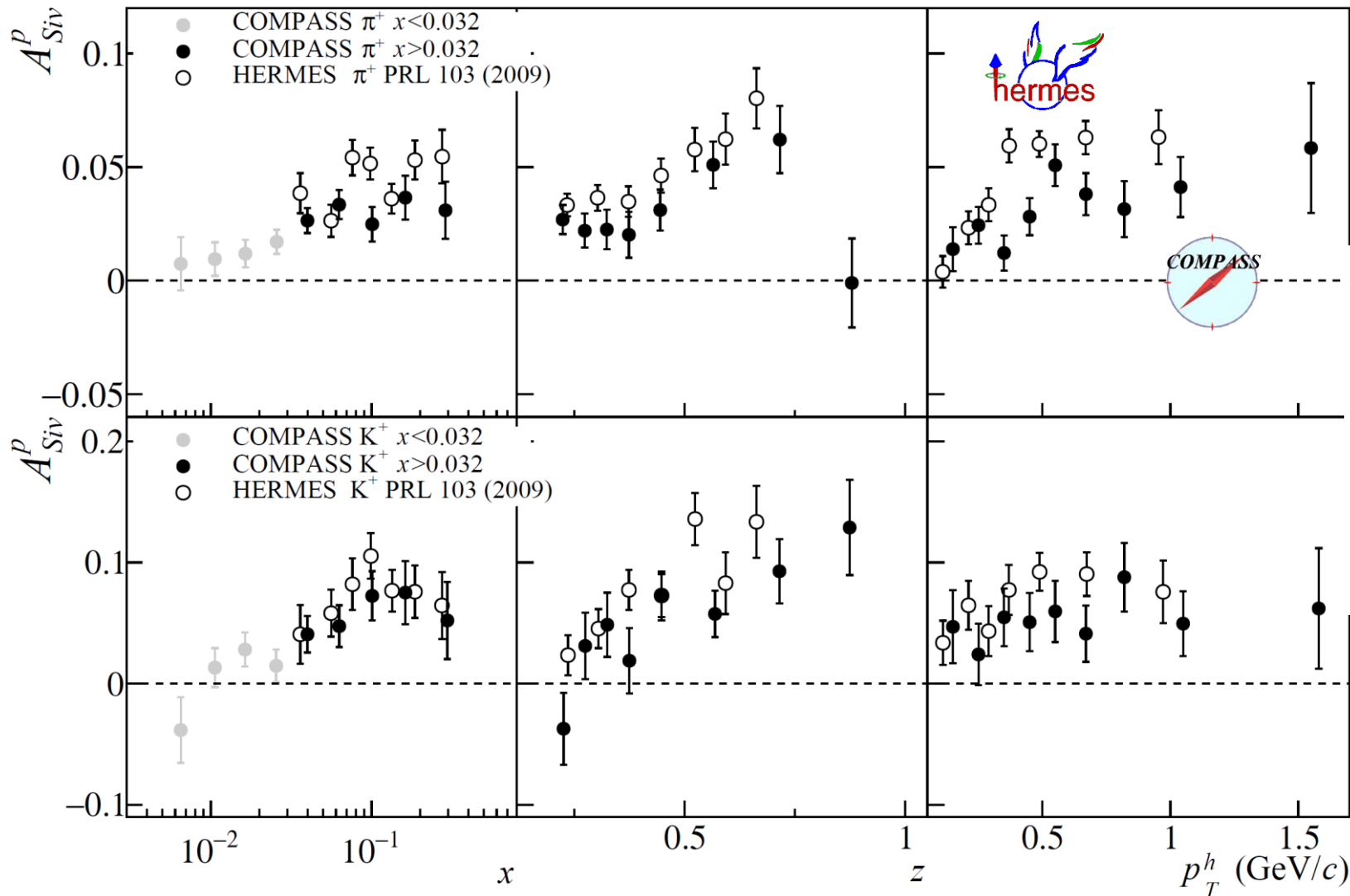
2002-2004 data
NPB765 2007, PLB673 2009

Sivers asymmetry

final results on proton for positive particles



vs



somewhat higher at HERMES
→ Q^2 evolution

K^+ asymmetries larger than π^+ asymmetries

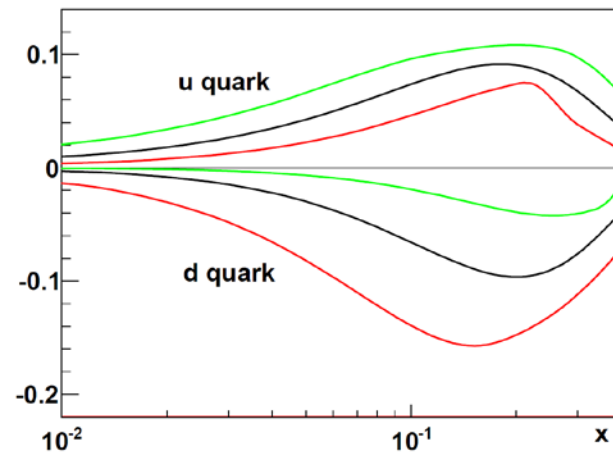
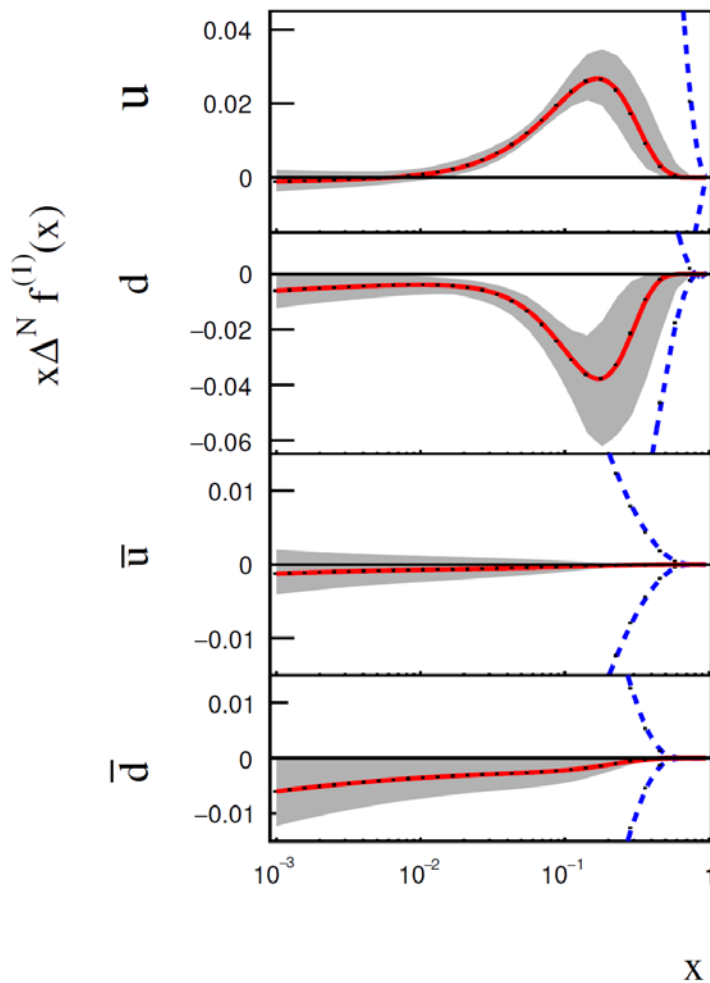


Sivers function from SIDIS data

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

fits to p and d COMPASS and p HERMES data
with different parametrizations, different evolutions

Anselmino et al., JHEP04 2017

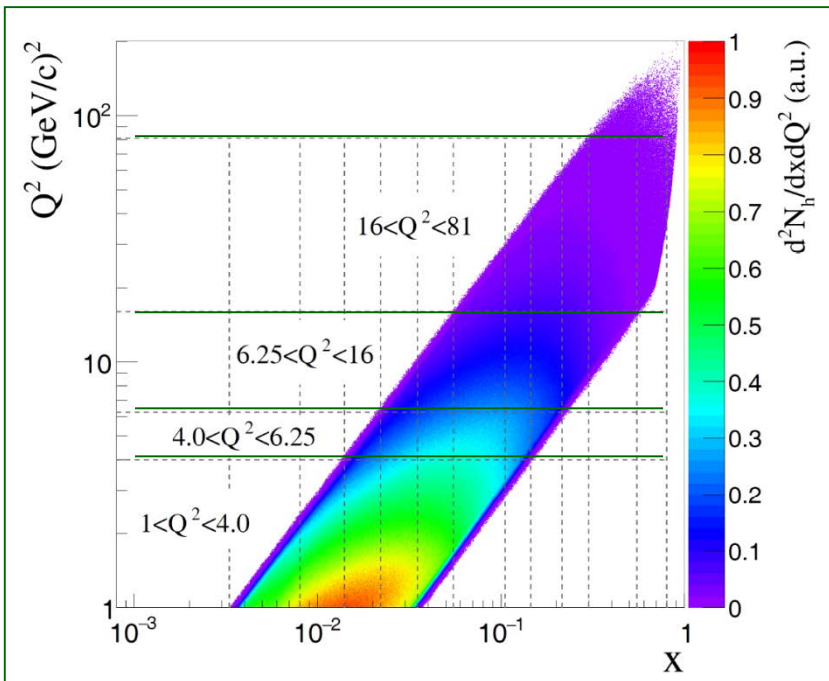


Sun and Yuan
PRD88 2013

clearly different from zero,
opposite sign for u and d quarks
larger uncertainties for the d-quark

important results

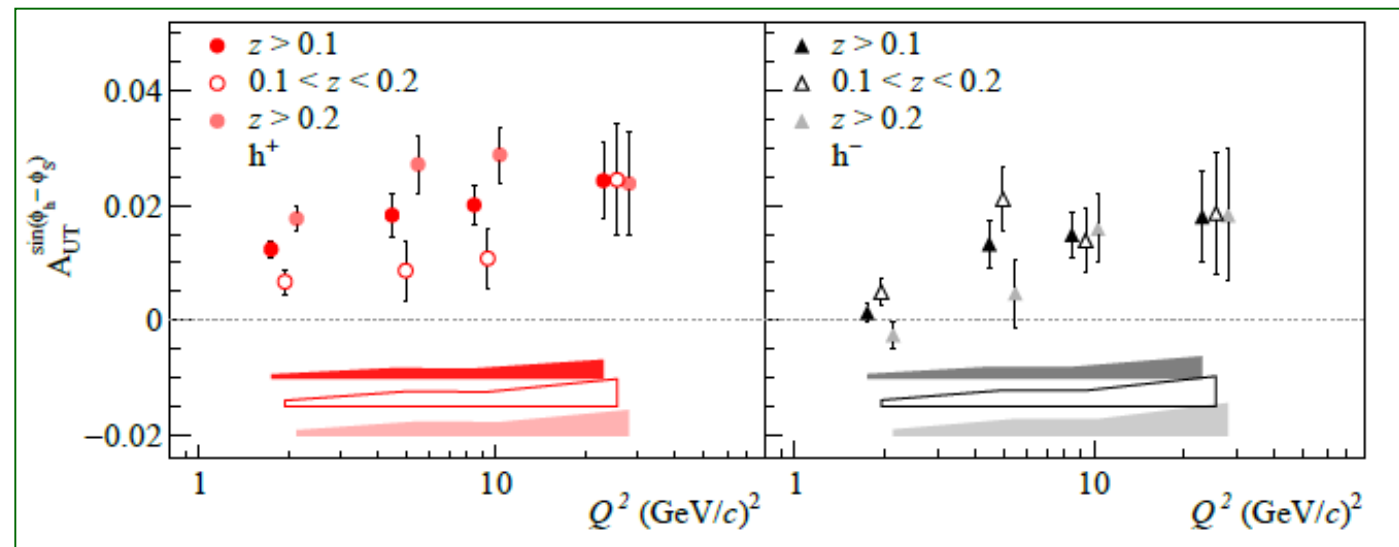
Sivers asymmetry in SIDIS



direct measurement in the
Drell-Yan Q^2 range at COMPASS
no evolution SIDIS \rightarrow DY

PBL770 2017

clearly positive:
test of change
of sign feasible



the weighted Sivers asymmetry



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

convolution

→ non negligible uncertainties in extractions
 \vec{k}_T !

a possible way out: use of the P_T weighted asymmetries

obtained by weighting the spin dependent part of the cross-section

$$w = P_T / zM$$

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

easier to extract $f_{1T}^{\perp(1)q}$

weighted asymmetries proposed a 20 years ago ... reconsidered recently (Sivers)

A. Kotzinian and P. J. Mulders, PLB 406 (1997) ,..., Z.-B. Kang et al., Phys.Rev. D87 (2013)

preliminary results by HERMES in 2005

the weighted Siverts asymmetry

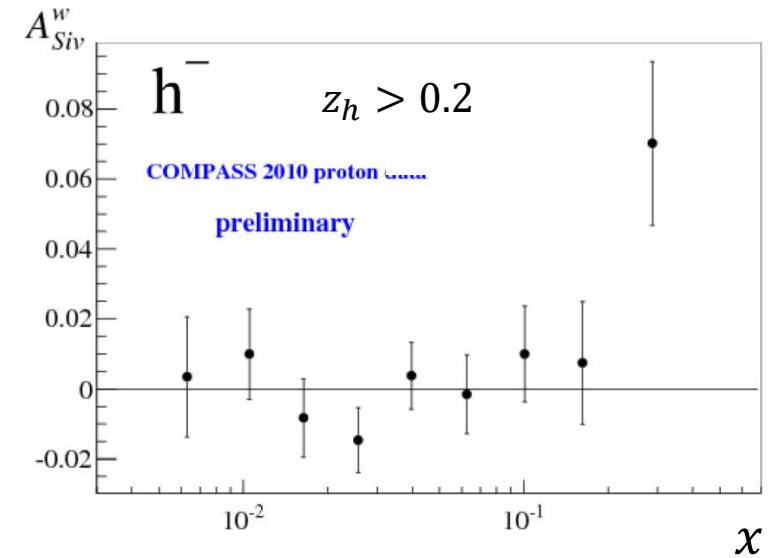
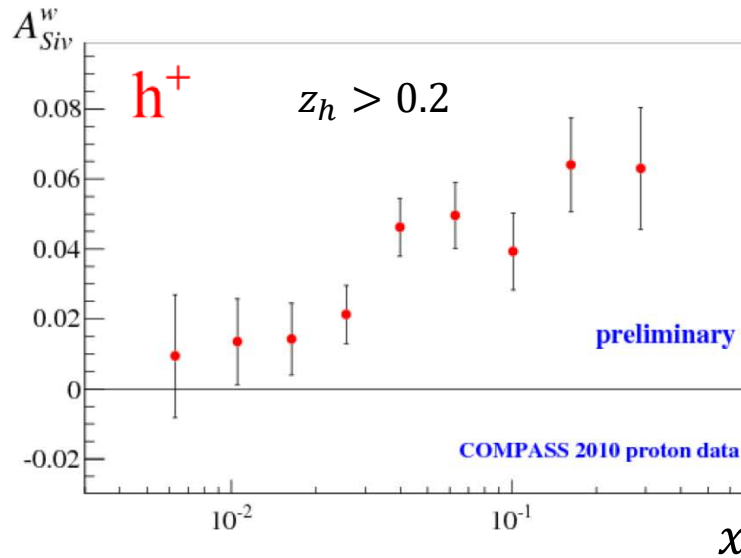
$$w = P_T/zM$$



$$A_{Siv}^w(x) = 2 \frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x) \int D_{1q}(z) dz}{\sum_q e_q^2 x f_1^q(x) \int D_{1q}(z) dz}$$

assuming
u-dominance:

$$A_{Siv}^w(x) \sim 2 \frac{f_{1T}^{\perp(1)u}(x)}{f_1^u(x)}$$



SPIN2016

the weighted Siverts asymmetry

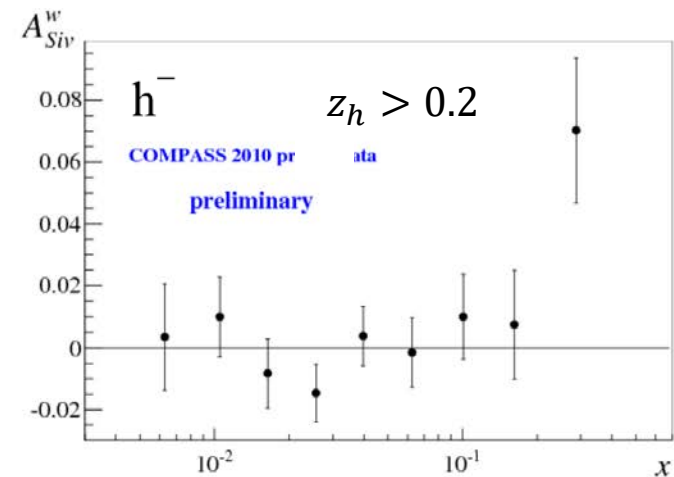
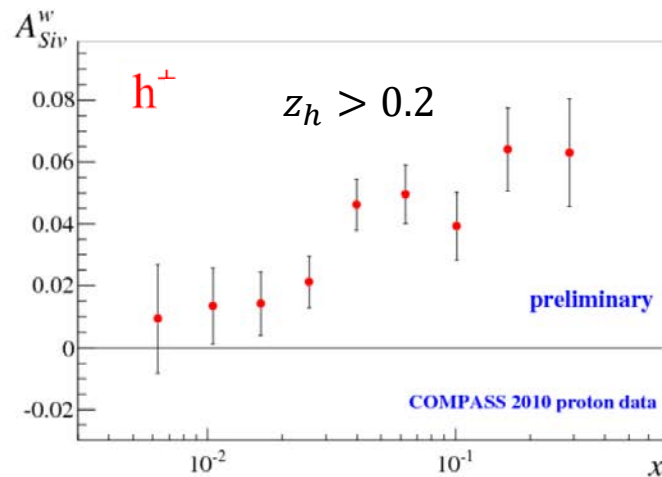
$$w = P_T/zM$$



$$A_{Siv}^w(x) = 2 \frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x) \int D_{1q}(z) dz}{\sum_q e_q^2 x f_1^q(x) \int D_{1q}(z) dz}$$

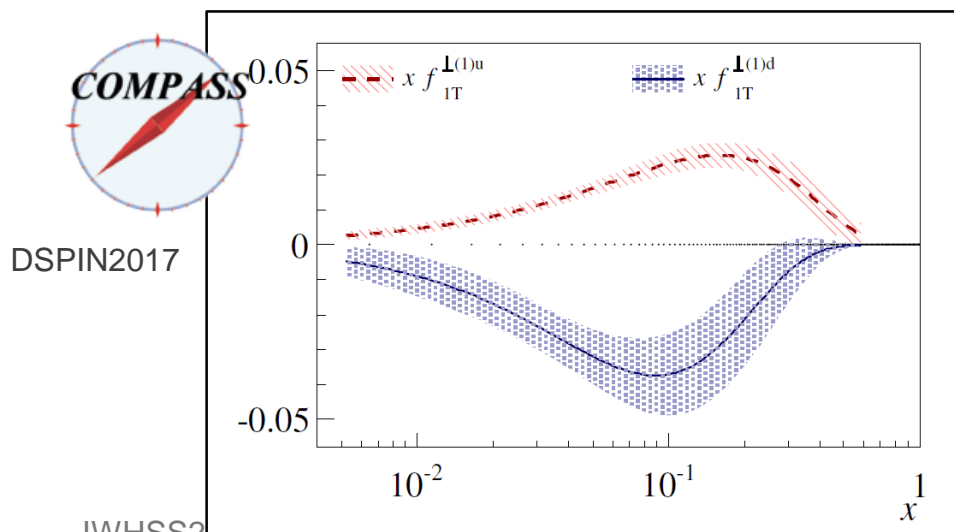
assuming
u-dominance:

$$A_{Siv}^w(x) \sim 2 \frac{f_{1T}^{\perp(1)u}(x)}{f_1^u(x)}$$



used to extract the u- and d-quark Siverts functions

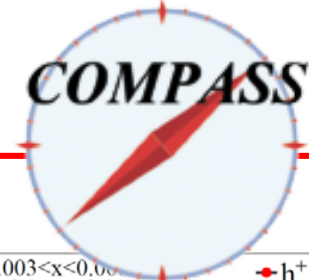
assuming that the Siverts functions of all the sea quarks are zero and $f_{1T}^{\perp(1)q} = a_q x^{b_q} (1-x)^{c_q}$, $q = u_v, d_v$



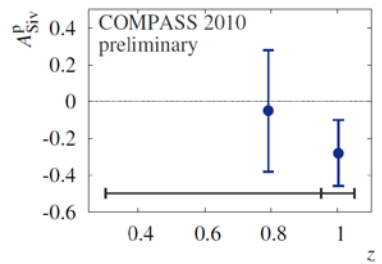
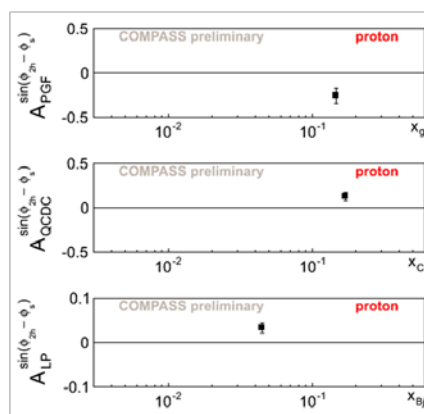
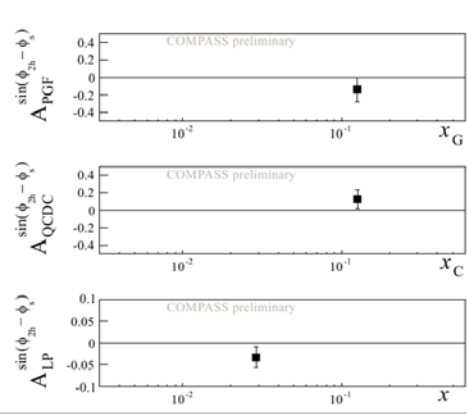
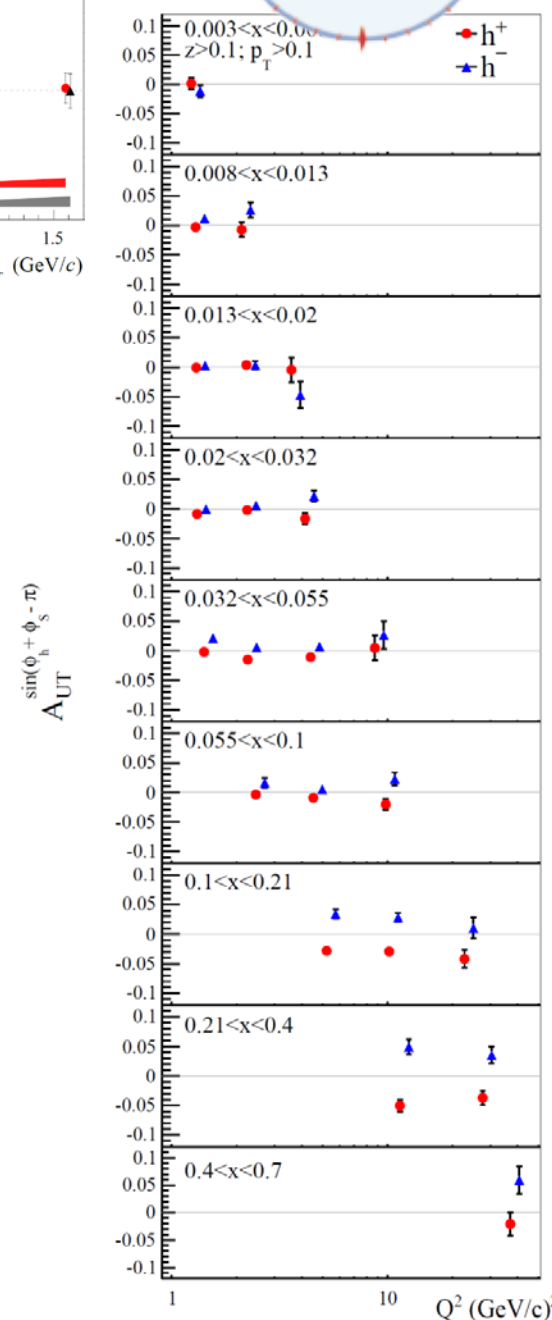
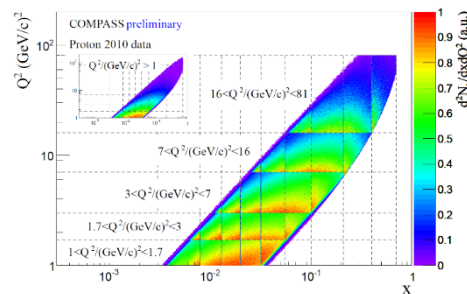
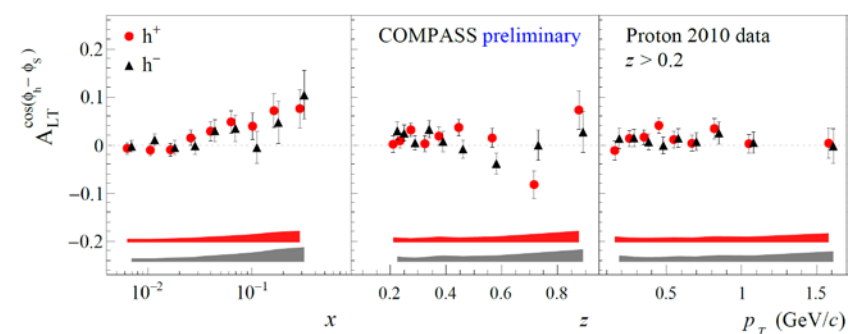
in agreement with previous extractions,
minimum of $f_{1T}^{\perp(1)d_v}$ at smaller x

used to calculate the weighted Drell-Yan
asymmetry → R. Longo

other transverse spin results



- other TSAs beyond Collins and Sivers
- multidimensional analysis of proton TSAs
- gluon Sivers related TSAs: high P_{Th} pairs and J/Ψ production



future

near future, soon after the CERN Long Shutdown 2, in 2021



COMPASS has proposed

one year of run with 160 GeV muons to measure

SIDIS off transversely polarised deuteron

to better constrain the d quark TMD PDFs

the missing piece of information in the exploratory investigation of TMDs

we will further investigate

a kinematic range that only COMPASS can cover, as long as EIC will not start
sensitive to valence, sea and gluon contribution

complementary to JLAB12 (higher Q^2 , lower x):

from the comparison with JLab12, we will obtain information on
evolution, higher twist effects, target fragmentation region

near future, soon after the CERN Long Shutdown 2, in 2021

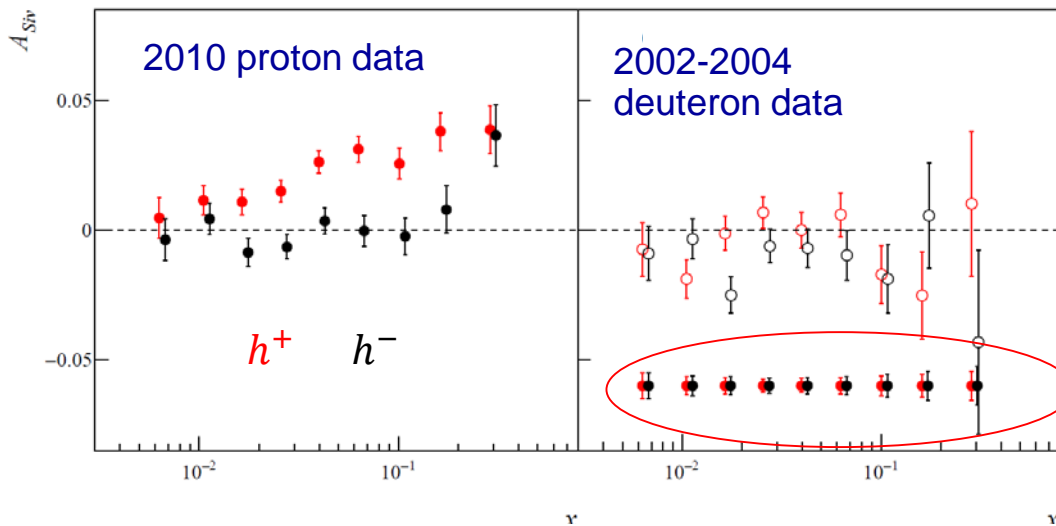


in one year of run with the transversely polarised deuteron (^6LiD) target
all the deuteron asymmetries will be measured with a statistical uncertainty
~0.6 times the statistical uncertainty of the 2010 p asymmetries



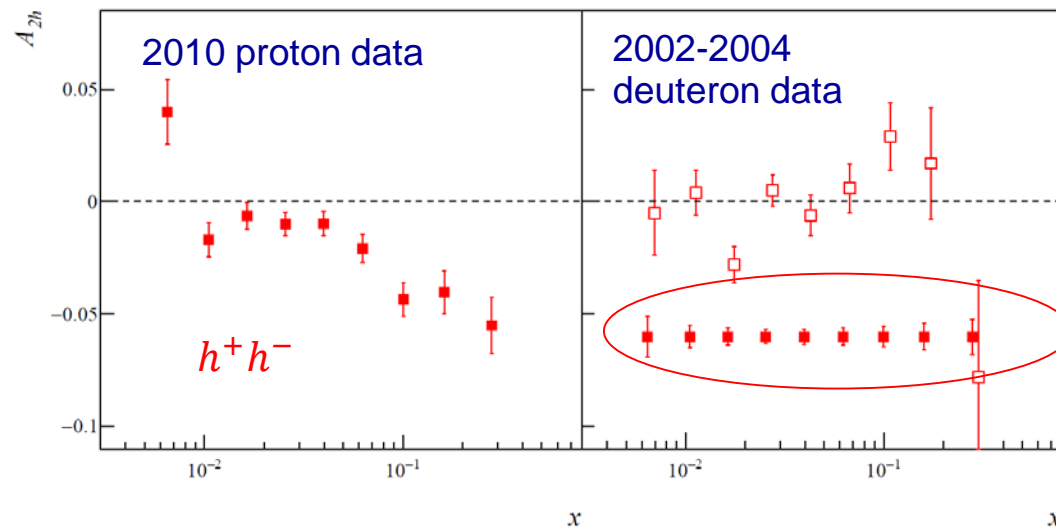
near future, soon after the CERN Long Shutdown 2, in 2021

in one year of run with the transversely polarised deuteron (^6LiD) target
all the deuteron asymmetries will be measured with a statistical uncertainty
 ~ 0.6 times the statistical uncertainty of the 2010 p asymmetries



Sivers asymmetry

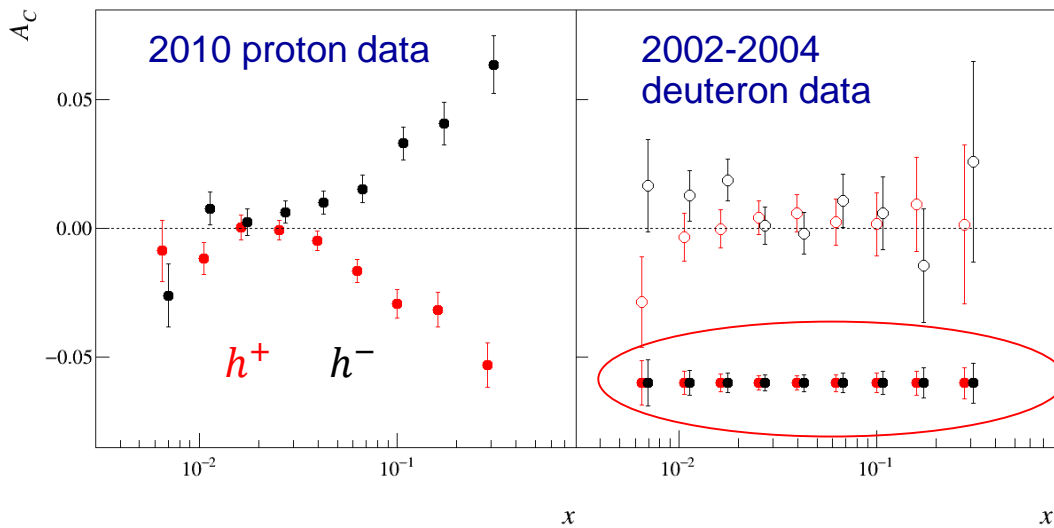
projected errors
from 2021 deuteron data



dihadron asymmetry

projected errors
from 2021 deuteron data

near future, soon after the CERN Long Shutdown 2, in 2021

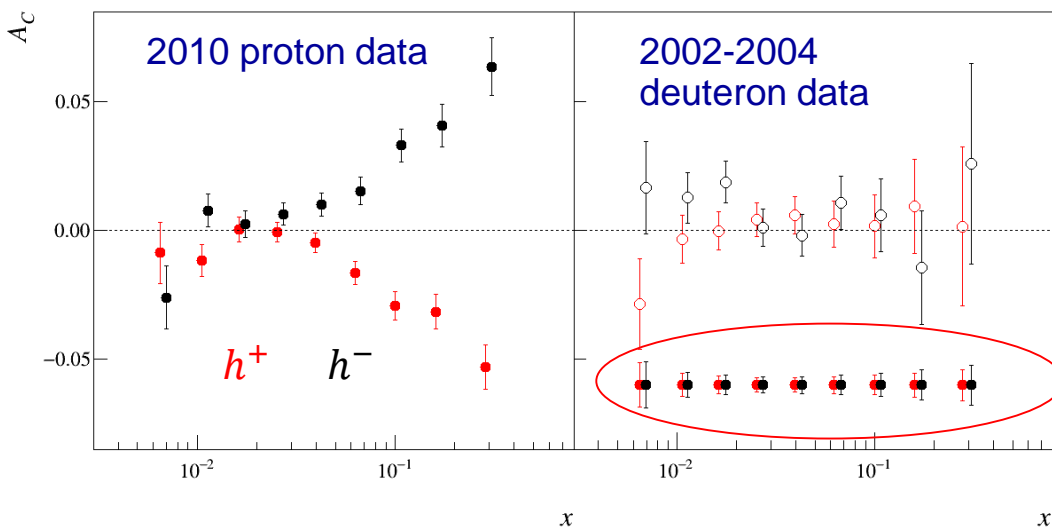


Collins asymmetry

projected errors
from 2021 deuteron data



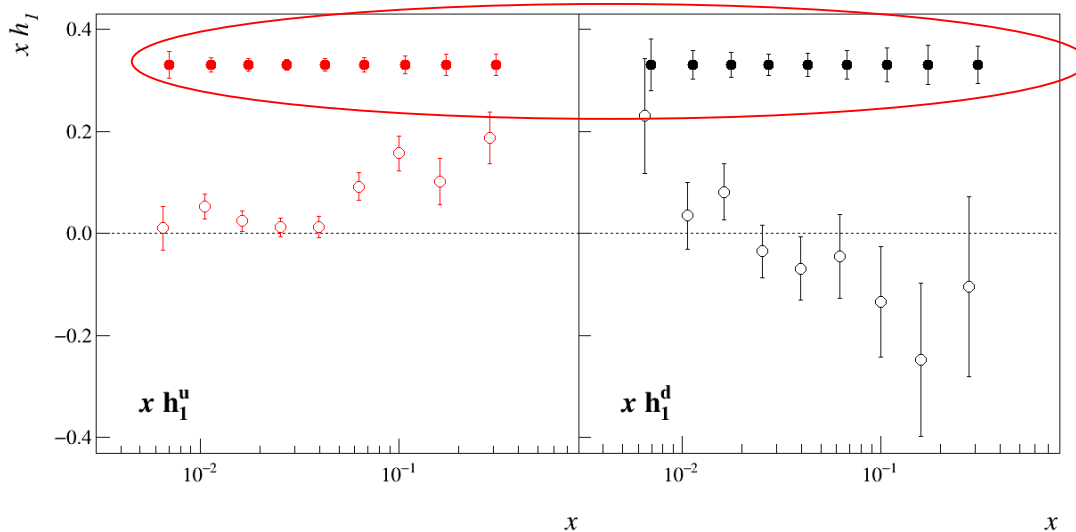
near future, soon after the CERN Long Shutdown 2, in 2021



Collins asymmetry

projected errors from 2021 deuteron data

we also estimated the expect improvement on the transversity PDFs with point-by-point extraction



2010 proton data
2021 deuteron data

2010 proton data
2002-2004 deuteron data

error on $h_1^{d_v}$ smaller by a factor 2 to 4

→ considerable improvement in the knowledge of the tensor charge in the COMPASS x range: **statistical uncertainty ~ twice smaller**

Conclusions

SIDIS measurements, and COMPASS, gave and are giving fundamental contributions to the understanding of the transverse structure of the nucleon
Sivers PDF, transversity, all TMDs, Collins and dihadron FFs

new important results are coming from measurements different processes
Drell-Yan, pp hard scattering, e^+e^-

future SIDIS experiments:

precision measurements will be performed at new facilities

JLab12 and later on EIC

in the mean time, COMPASS will contribute more to the “exploratory” phase with

- new measurements of transverse spin asymmetries from existing data
new ideas and tests
- more precise studies of unpolarised SIDIS using the LH₂ 2016/17 data
many open questions
- hopefully the 2021 run with transversely polarised deuteron and 160 GeV muon beam
the missing piece, to complete our program

Thank you