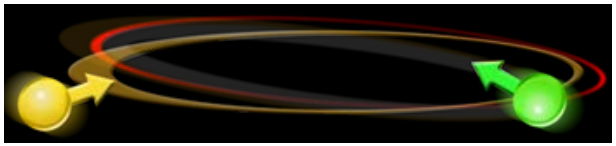
COMPASS studies of the transverse structure of the nucleon

Anna Martin

Trieste University and INFN

on behalf of the COMPASS Collaboration



3D Parton Distributions: path to the LHC

LNF 29/11 - 2/12/2016

COMPASS

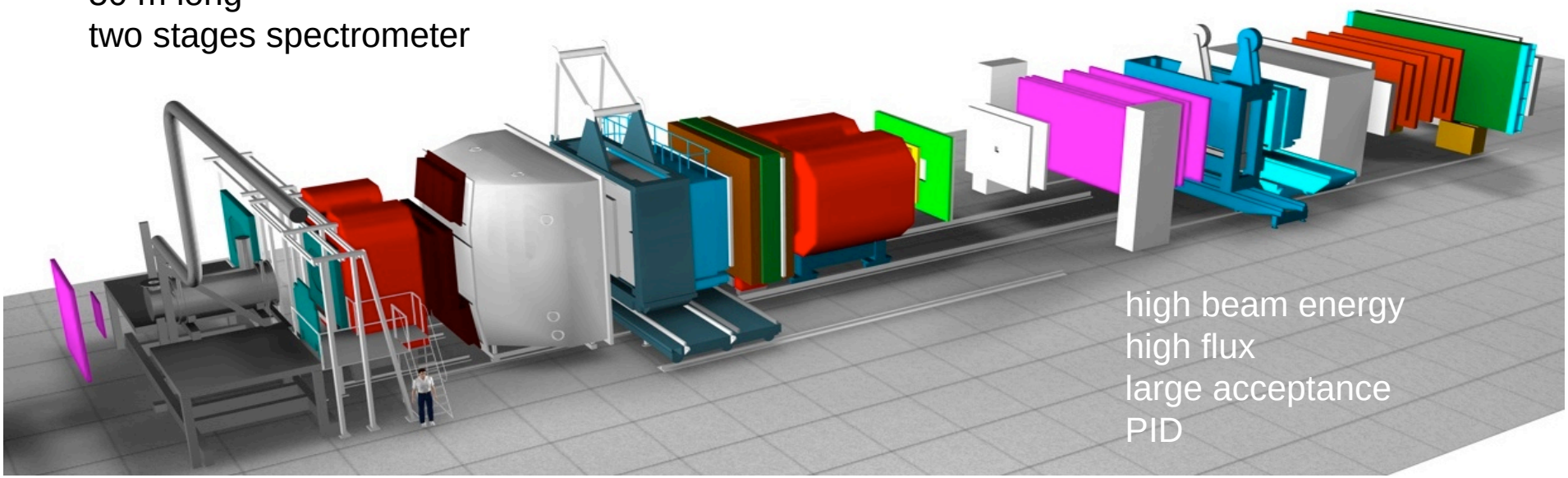
approved in 1997, data taking 2002 → 2018,
plans for beyond 2020 being prepared

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

fixed target experiment at CERN SPS

high energy (160-200 GeV) muon and hadron beams
polarised and unpolarised targets

50 m long
two stages spectrometer



COMPASS

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physics program

- **pion, kaon and proton beams, LH_2 and nuclear targets** 2008, 2009, 2012
  - spectroscopy - looking for exotics
  - pion/kaon polarisability
- **muon beam** - **nucleon structure** SIDIS, DVCS 2002-2007 2010 2011
  - quark and gluon helicities - **longitudinally polarised p and d targets**
  - transversity and TSA - **transversely polarised p and d targets**
  - GPDs - **liquid hydrogen target** [2012] 2016,2017
- **pion beam** - **nucleon structure**
  - Drell-Yan - **transversely polarised p target** [2014] 2015 (2018)

COMPASS

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polarised and unpolarised targets

used or being used to study TMDs

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COMPASS

this talk:

nucleon spin structure from
SIDIS off transversely polarised and unpolarised targets

used or being used to study TMDs

physics program

- **pion, kaon and proton beams, LH_2 and nuclear targets**
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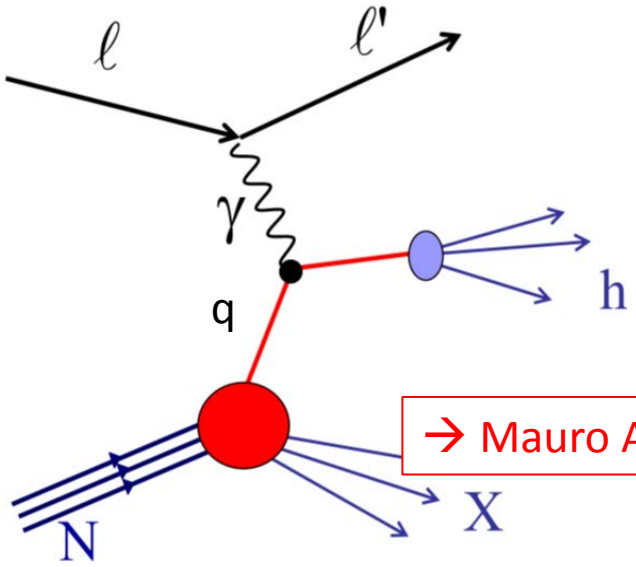
B. Parsamyan

A. Bressan

C. Quintans

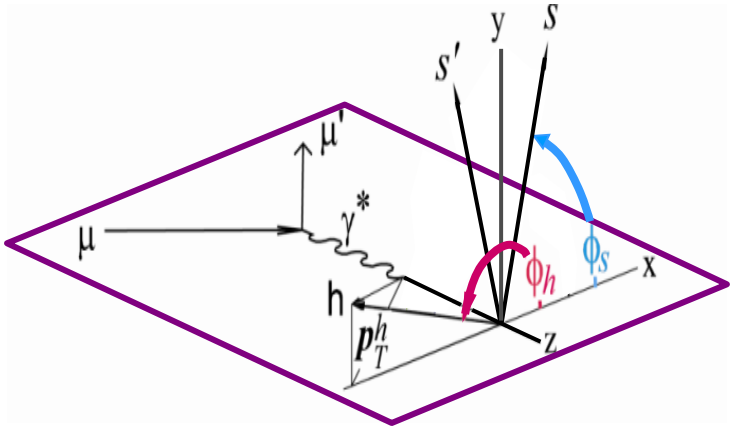
why SIDIS

a simple process, a special tool



→ Mauro Anselmino

$x,\ Q^2;$ $z,\ P_T\ ,$ ϕ_h, ϕ_S



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

why SIDIS

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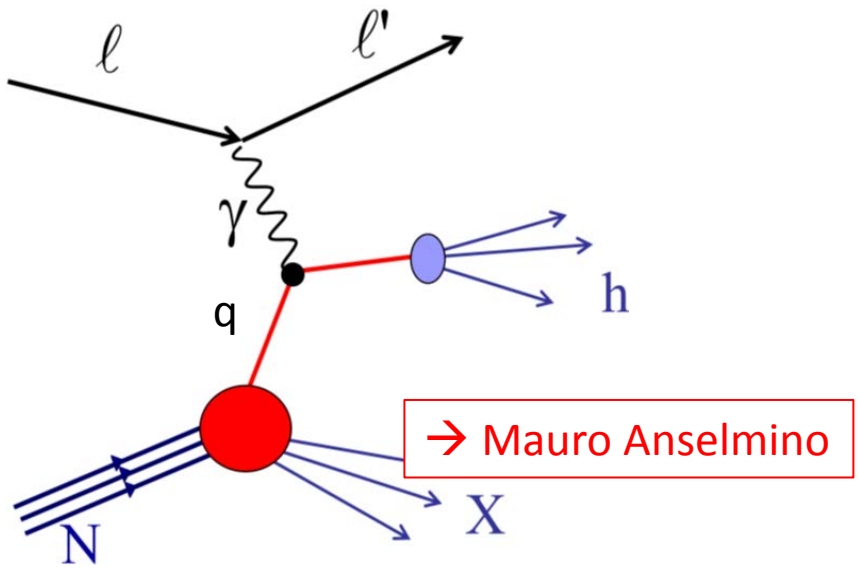


→ Mauro Anselmino

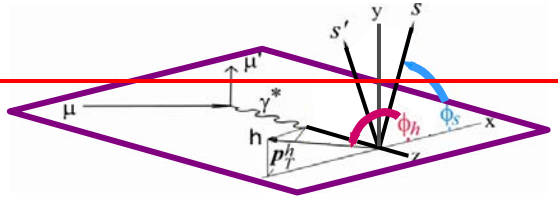
quark \ nucleon	U	L	T	
U	f_1		$f_{1T}^{\perp}$	
L		g_1	g_{1T}	
T	$h_1^{\perp}$	$h_{1L}^{\perp}$	h_1	$h_{1T}^{\perp}$

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

all the TMD PDFs appear in the cross-section
and the different effects can be disentangled

p, n, d targets, final state particle identification
→ flavor separation

why SIDIS



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

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

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

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

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

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

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

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

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

$h_1^\perp H_1^\perp$ $h_{1L}^\perp H_1^\perp$ $f_{1T}^\perp D_1$ $h_{1T}^\perp H_1^\perp$ $h_1 H_1^\perp$ $g_{1T} D_1$

14 azimuthal modulations

measured
at COMPASS, HERMES, JLab

A Bacchetta et al., 2006

why SIDIS

all of them have been measured at COMPASS on p and d with a 160 GeV muon beam

very clear signals for the azimuthal asymmetries on p related to **transversity** and **Sivers PDFs** only

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

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

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

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

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

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

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

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

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

8 azimuthal modulations

A Bacchetta et al., 2006

transversity PDF

$\Delta_{\mathrm{T}} q, h_1^q$

accessing transversity

(single hadron) **Collins asymmetry**

amplitude of the
$sin\,(\phi_h + \phi_S + \pi)$ modulation

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

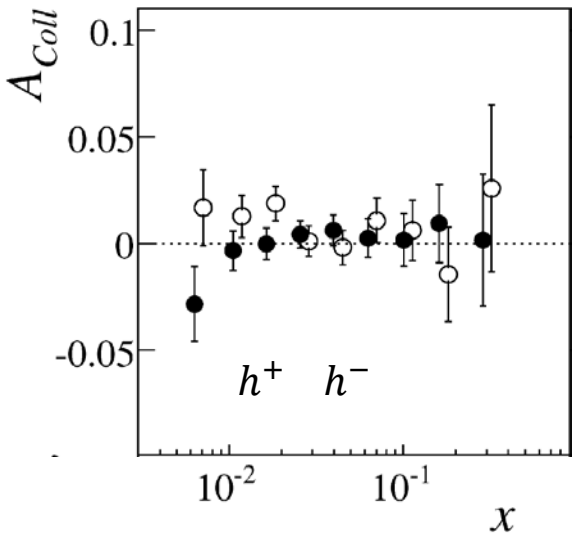
Collins FF
independent information
from $e^+e^- \rightarrow hadrons$

accessing transversity

(single hadron) **Collins asymmetry**

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

final results on deuteron



2002-2004 data
NPB765 2007, PLB673 2009

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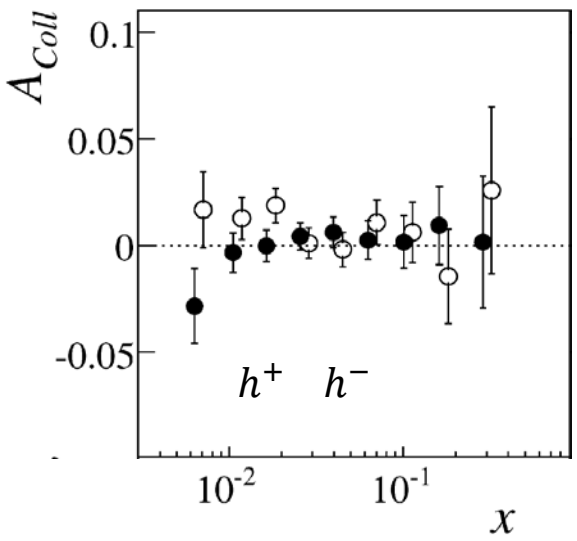

2002-2004 data
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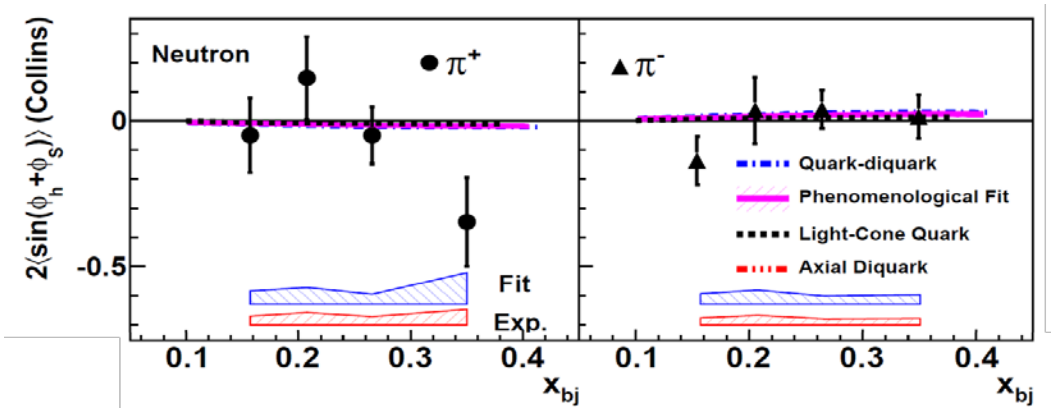
and **neutron**

Jefferson Lab

Hall A PRL107, 2011



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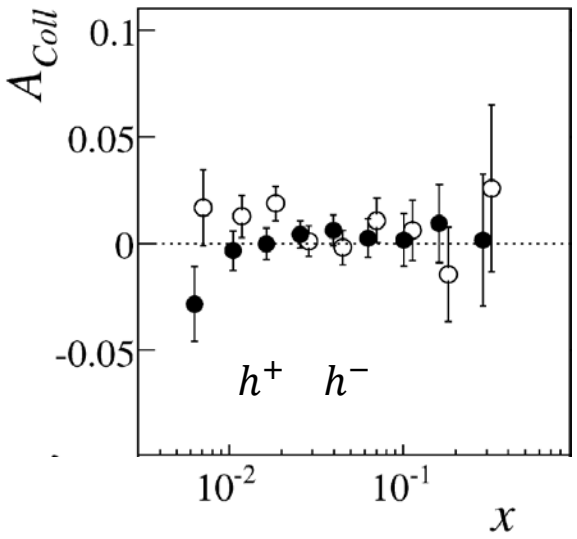

2002-2004 data
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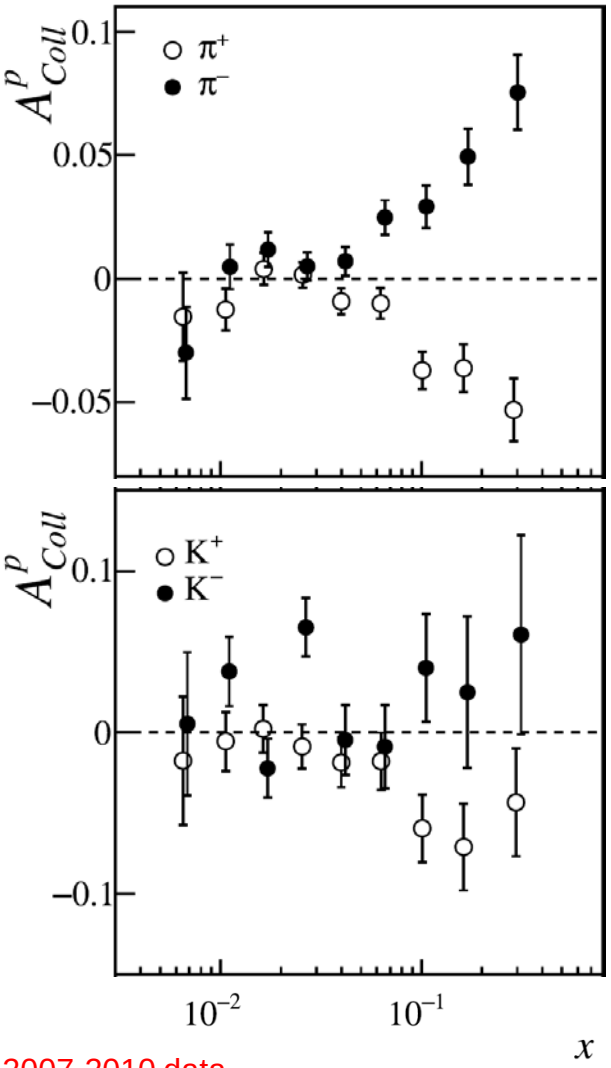
and on proton



2007-2010 data
PLB744 2015

accessing transversity

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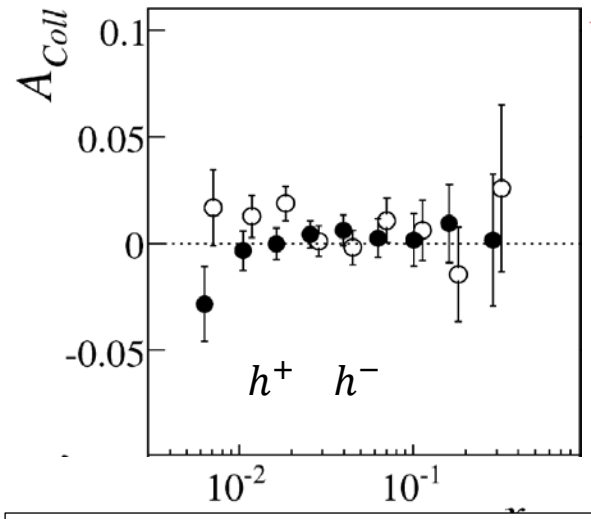
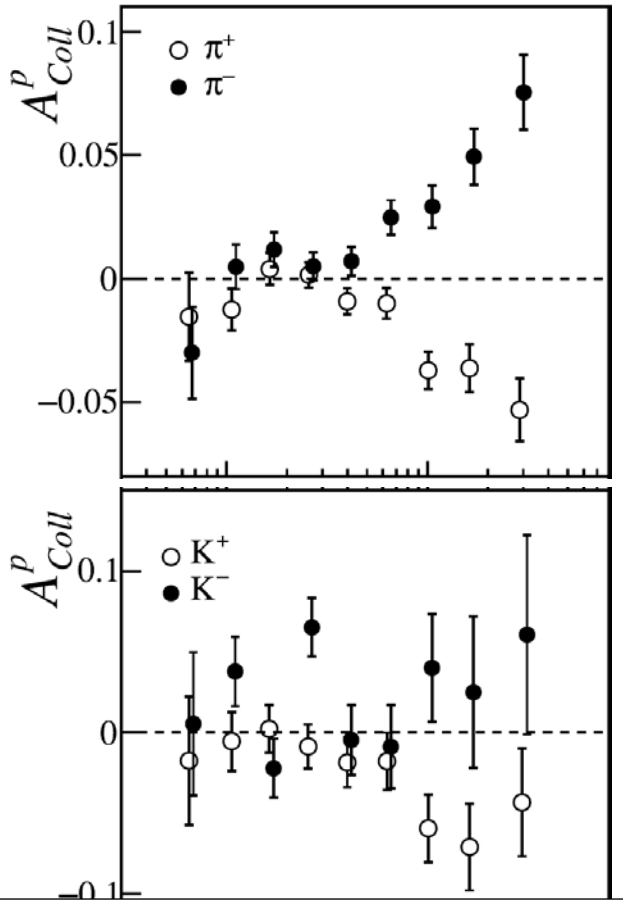
final results on deuteron



and on proton



PLB744 2015

used with the HERMES p data and the corresponding e^+e^- results (Belle) to extract $\boldsymbol{h_1^q}$ and $\boldsymbol{H_{1q}^{\perp}}$

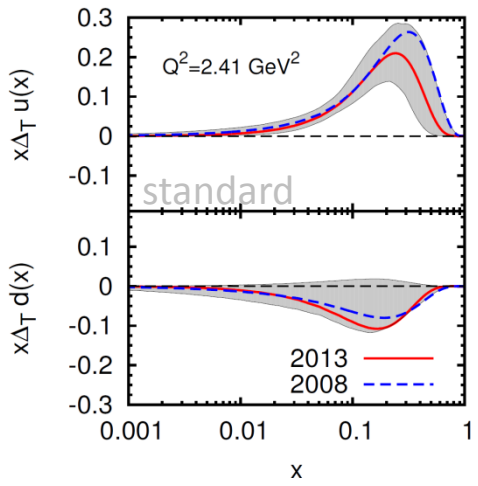
by several groups since 2005

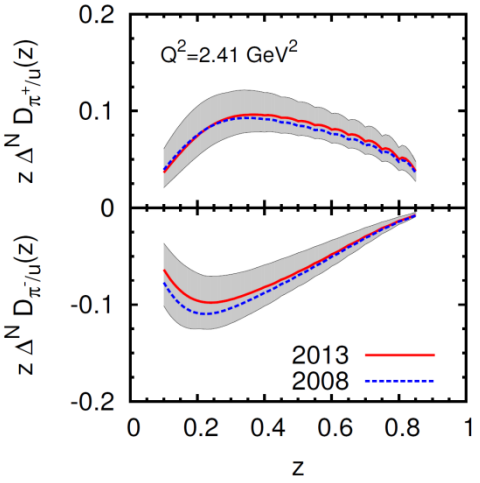
accessing transversity

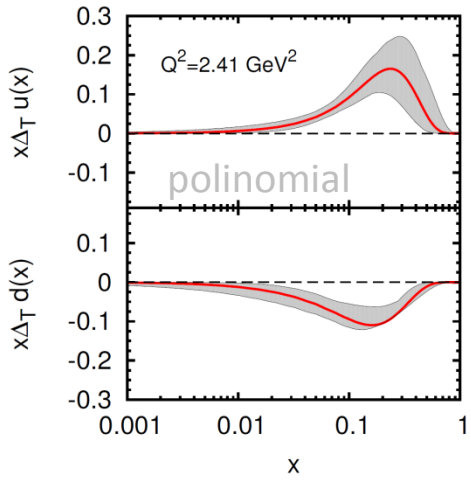
simultaneous fit of SIDIS p & d, and e^+e^- data

very good χ^2

Anselmino et al., PRD87 2013







- $\delta u = 0.39^{+0.18}_{-0.12}$
- $\delta d = -0.25^{+0.30}_{-0.10}$
- $\delta u = 0.31^{+0.16}_{-0.12}$
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accessing transversity

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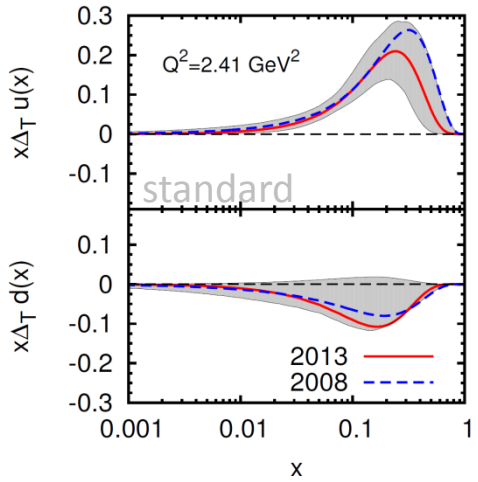

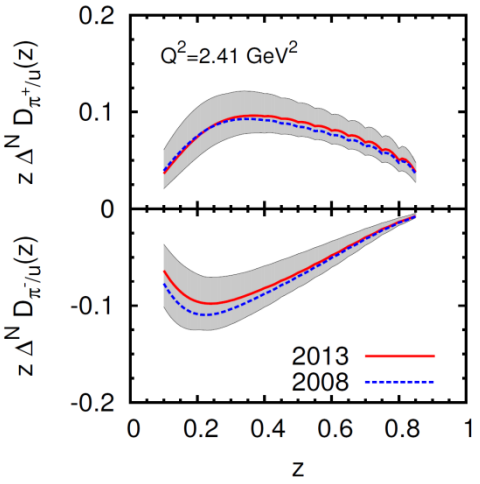

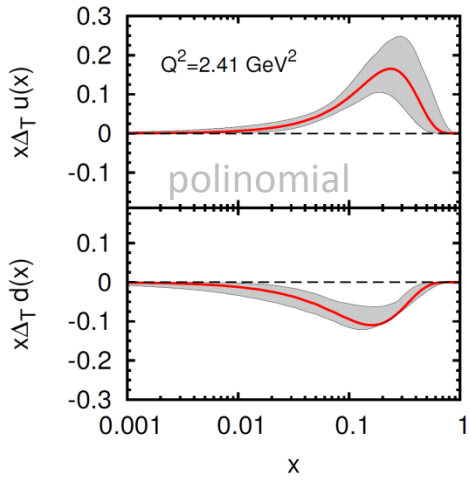

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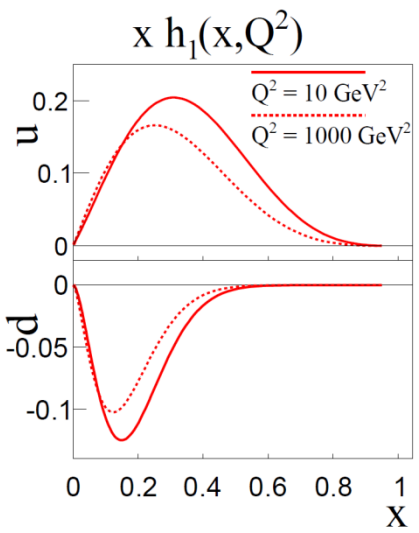
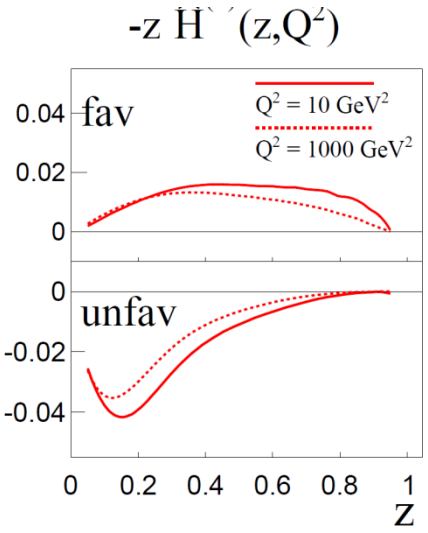
Kang et al, PRD91 2015

$$\delta u^{[0.0065,0.35]} = +0.30^{+0.12}_{-0.08}$$
$$\delta d^{[0.0065,0.35]} = -0.20^{+0.28}_{-0.11}$$

higher order corrections, x z





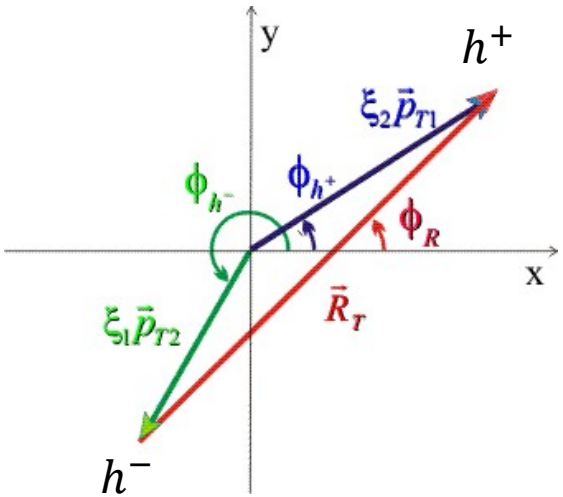
accessing transversity - 2

measurement of the **dihadron asymmetry**

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

DiFF in principle independent of $H_{1q}^{\perp}$
quantitative information from
$e^+e^- \rightarrow$ hadrons

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



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accessing transversity - 2

dihadron asymmetry

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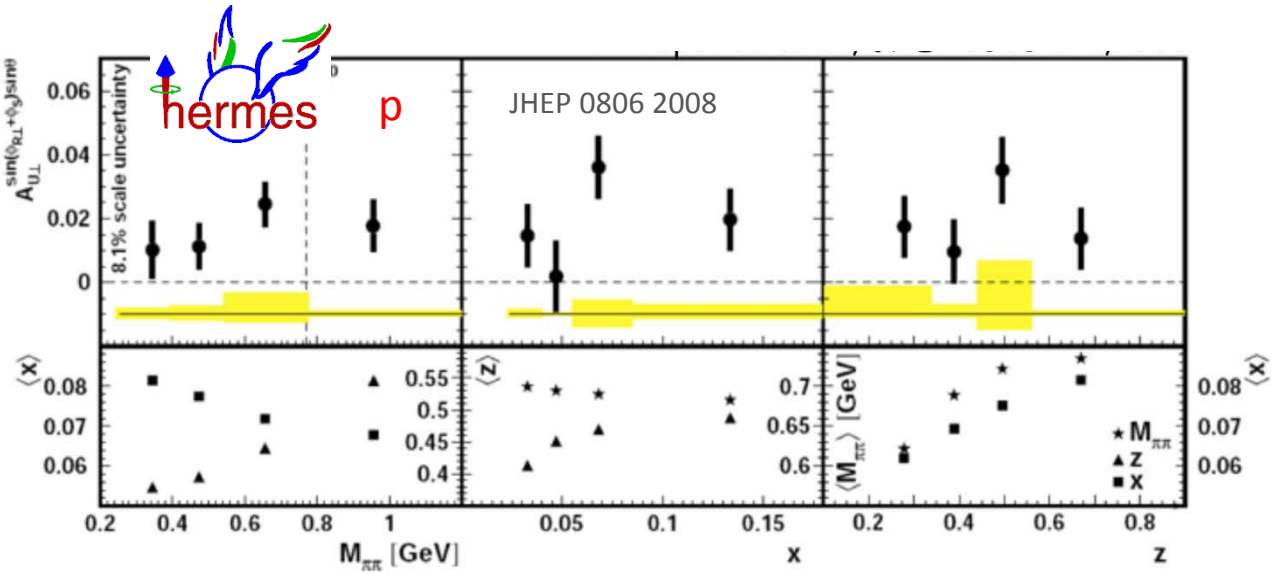

accessing transversity - 2

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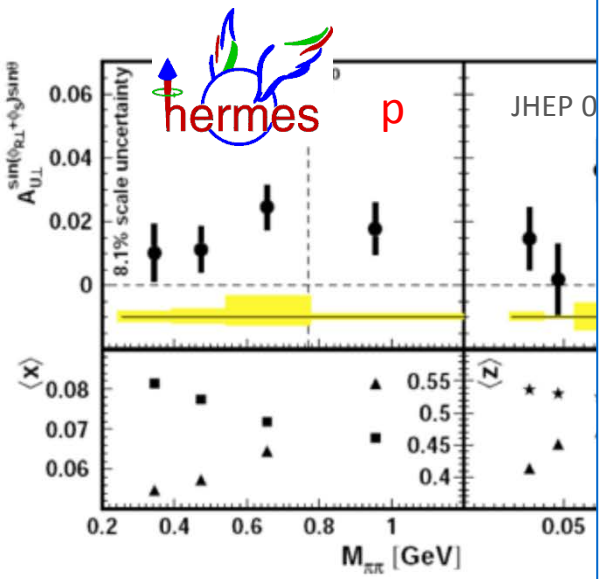
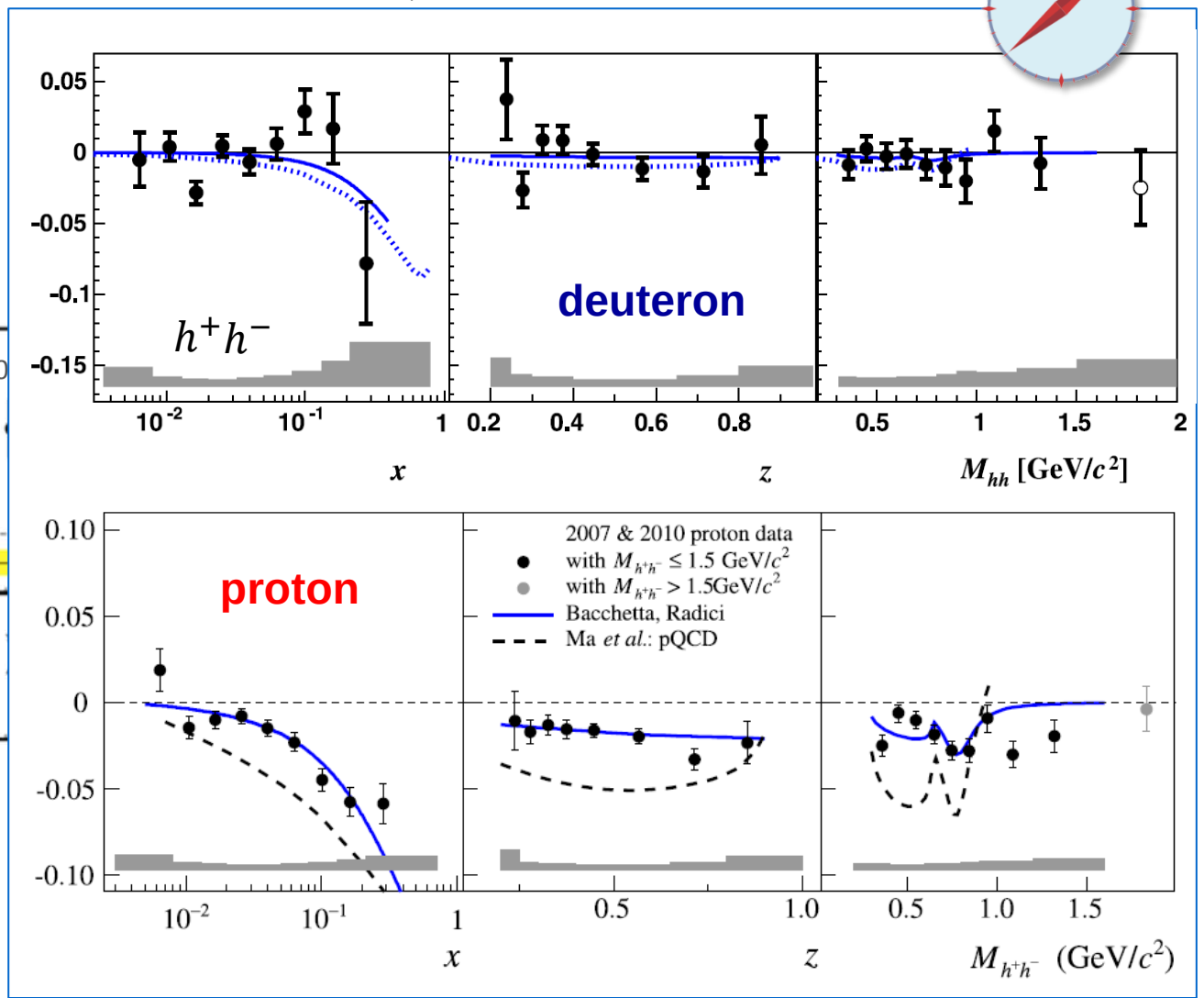
PLB 713 2012, PLB736 2014





accessing transversity - 2

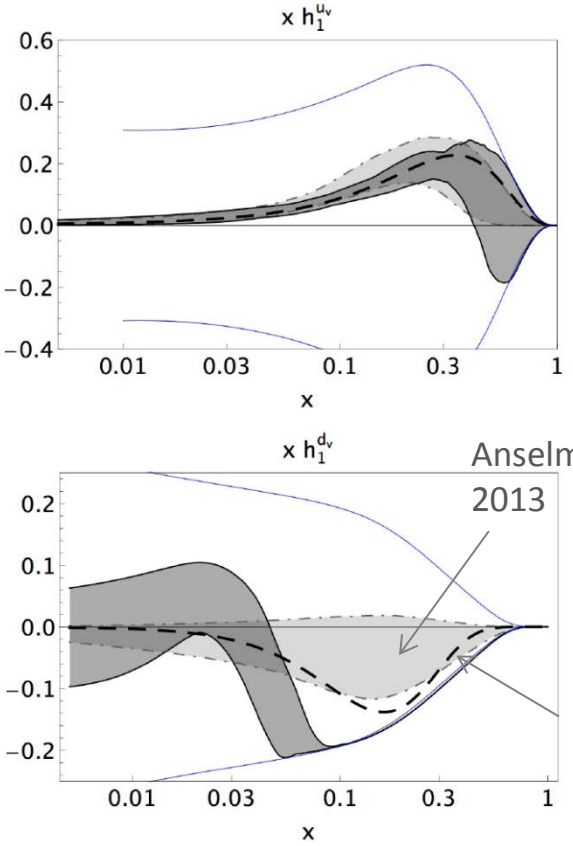
"collinear extraction" of $h_1^{u_v}$ and $h_1^{d_v}$

unpolarised DiFF from PYTHIA
polarised DiFF from Belle
dihadron asymmetries from
HERMES (p) COMPASS (p, d)

linear combinations of $h_1^{u_v}$ and $h_1^{d_v}$
fit with different parametrizations

M. Radici et al JHEP 1505 (2015)

flexible



accessing transversity

point-by-point extraction of transversity
from SIDIS asymmetries measured
on p and d at the same x, Q^2 values
and analysing power from e^+e^- asymmetries,
with no parametrisation of PDFs and FFs

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

accessing transversity

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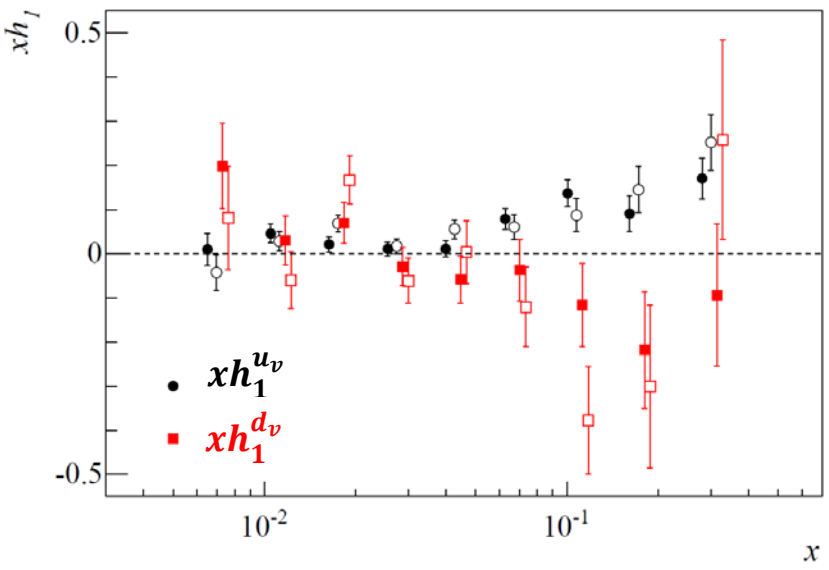
with no parametrisetion of PDFs and FFs

from COMPASS results for
Collins asymmetry ● ■ and
dihadron asymmetries ○ □
and corresponding Belle data



- *agreement between results from Collins and dihadron asymmetries*
  gaussian model with G=1 vs collinear case
- $h_1^{d_v}$ *large errors: statistics with d marginal*
- *Collins*
  - *stable results vs different assumptions*
    in particular for evolution

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

accessing transversity

point-by-point extraction of transversity
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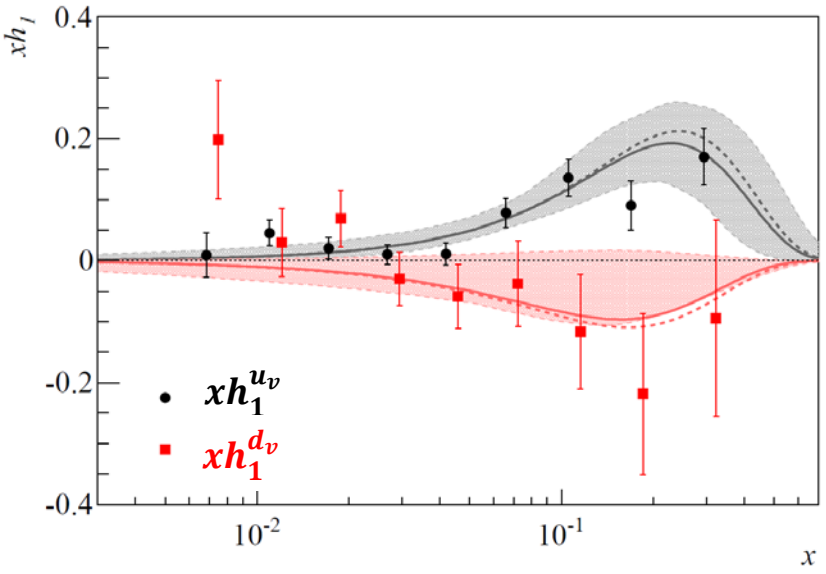

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- *Collins*
  - *stable results vs different assumptions*
    in particular for evolution
  - *agreement with previous extractions*

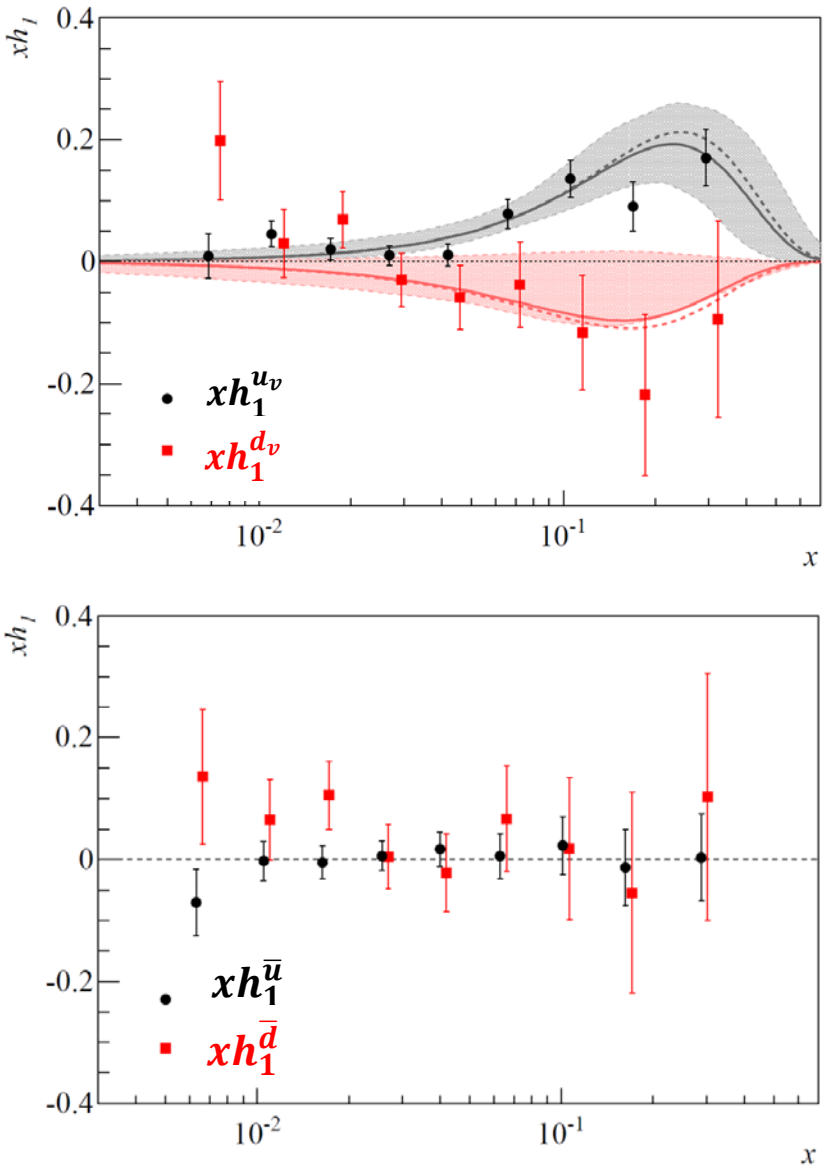
A. M., F. Bradamante, V. Barone PRD 2015

accessing transversity

point-by-point extraction of transversity
from SIDIS asymmetries measured
on p and d at the same x, Q^2 values
and analysing power from e^+e^- asymmetries,
with no parametrisetion of PDFs and FFs

from COMPASS results for
Collins asymmetry ● ■ and
dihadron asymmetries ○ □
and corresponding Belle data

- *agreement between results from Collins and dihadron asymmetries*
  gaussian model with G=1 vs collinear case
- $h_1^{d_v}$ *large errors: statistics with d marginal*
- *Collins*
  - *stable results vs different assumptions*
    in particular for evolution
  - *agreement with previous extractions*
  - *allows extraction of* ***sea quark*** *transversity*



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

accessing transversity

a promising method, to be kept in mind by future experiments

point-by-point extraction of transversity from SIDIS asymmetries measured on p and d at the same x, Q^2 values and analysing power from e^+e^- asymmetries, with no parametrisetion of PDFs and FFs

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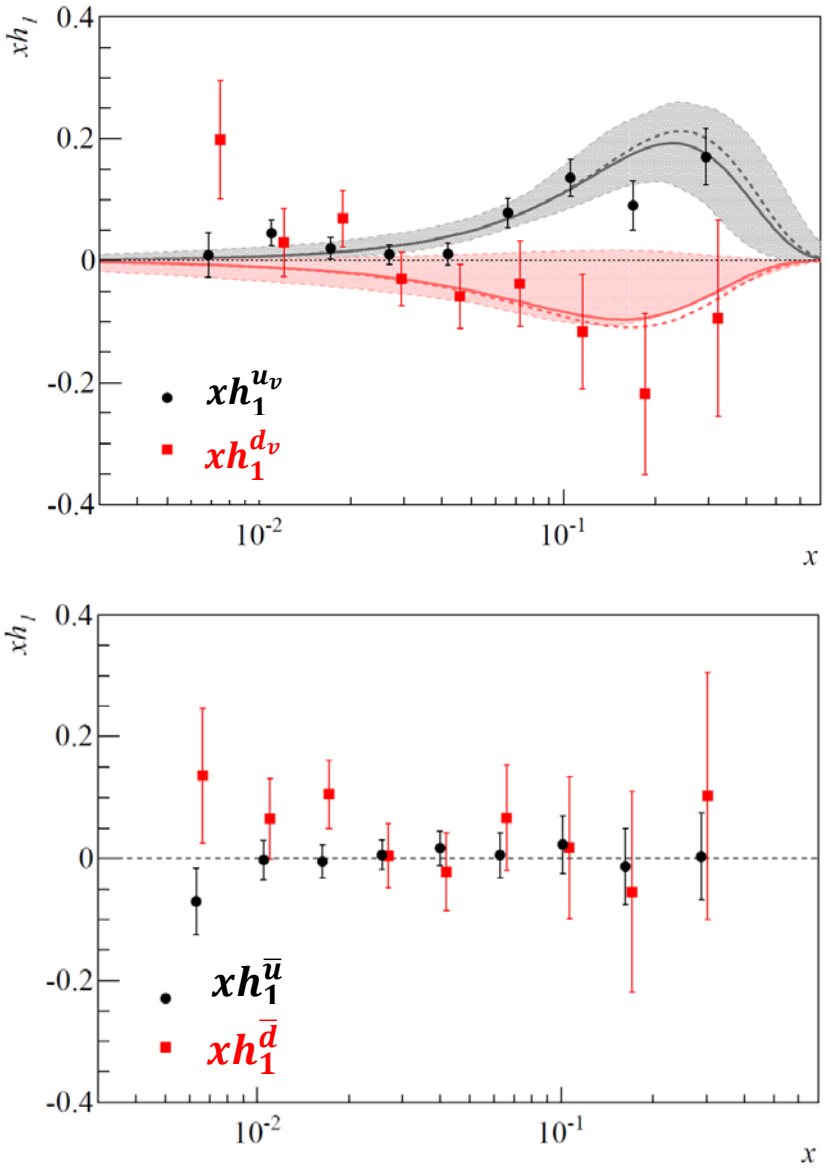


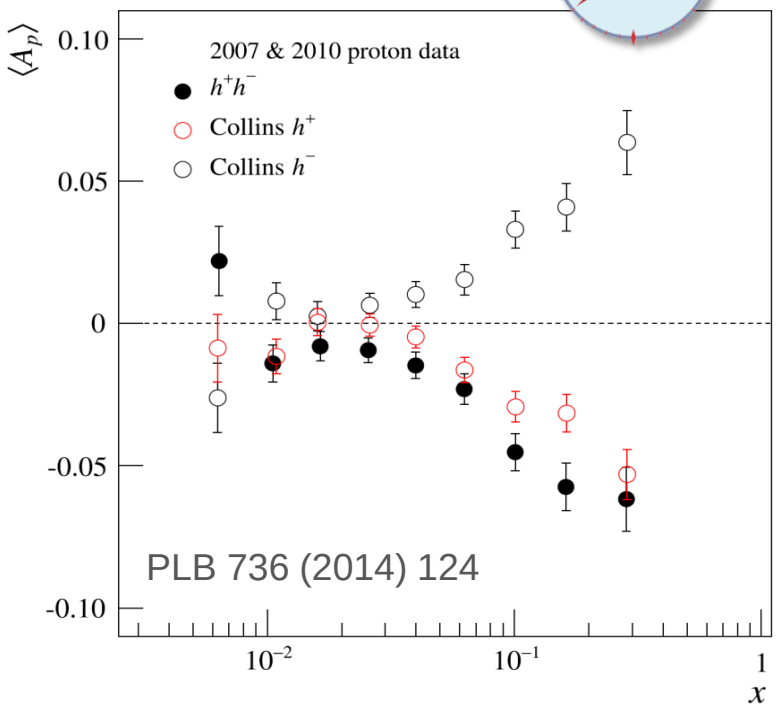
A. M., F. Bradamante, V. Barone PRD 2015

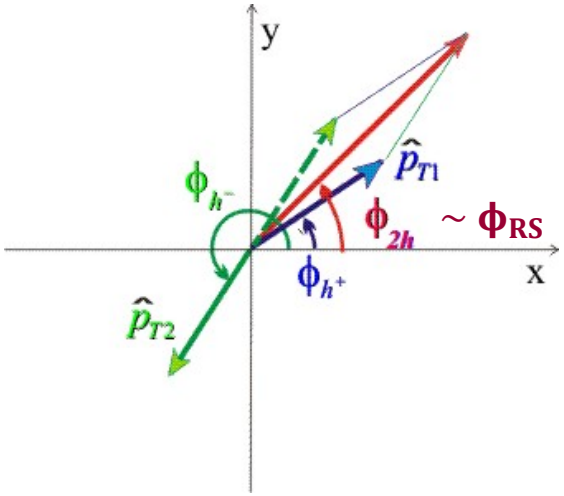
other recent COMPASS results - 1

interplay among dihadron and single hadron asymmetries

- Collins asymmetry for h+ and for h-
  "mirror symmetry"
- dihadron asymmetry
  only somewhat larger than h+ Collins
- meaning of the relevant angles

hints for a common origin
of the Collins FF and DiFF
Como 2013, DSpin2013, PLB736 (2014) 124





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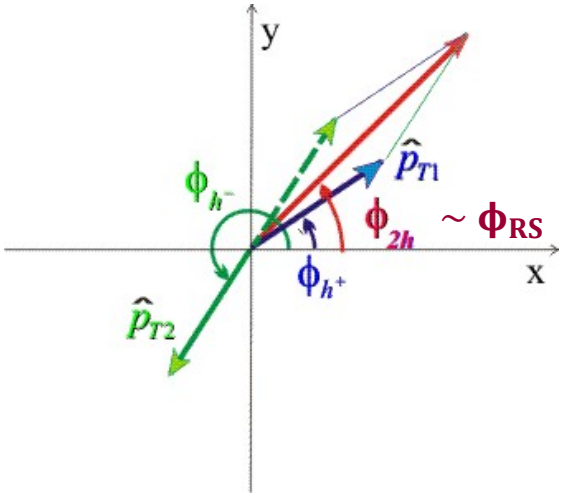
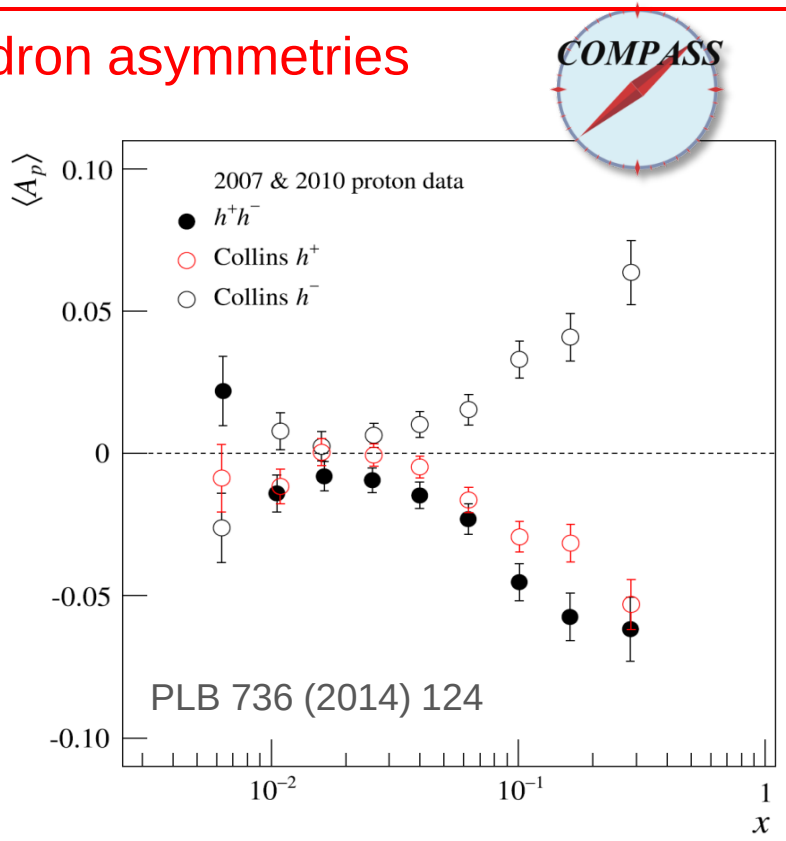




further study: look at
the $\Delta\phi = \phi_1 - \phi_2$ $\quad 1: h^+ \quad 2: h^-$
dependence of the asymmetries
one of the COMPASS studies on final state hadron correlations

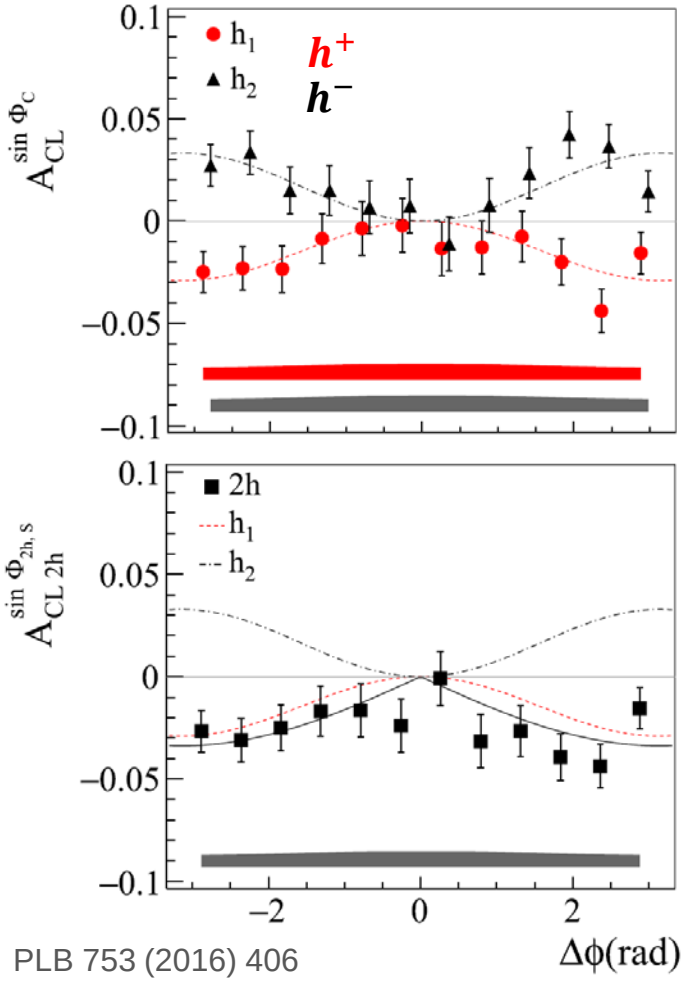
interplay among dihadron and single hadron asymmetries

analitically

$$A_{CL1}^{\sin \Phi_C} = a_1 + a_2 \cos \Delta\phi$$

$$A_{CL2}^{\sin \Phi_C} = a_2 + a_1 \cos \Delta\phi$$

mirror symmetry



PLB 753 (2016) 406

agreement with data if $a_1 = -a_2 = a$

$$A_{CL\,2h}^{\sin \Phi_{2h,S}} = a\sqrt{2(1-\cos \Delta\phi)}$$

agreement with data

a very simple relationships among the asymmetries in the “2h sample”
they are driven by the same elementary mechanism.

ratio of the $\Delta\phi$ integrated 2h and 1h asymmetries: $4/\pi$
slightly larger than h^+

can be studied in e^+e^- ?

interplay among dihadron and single hadron asymmetries

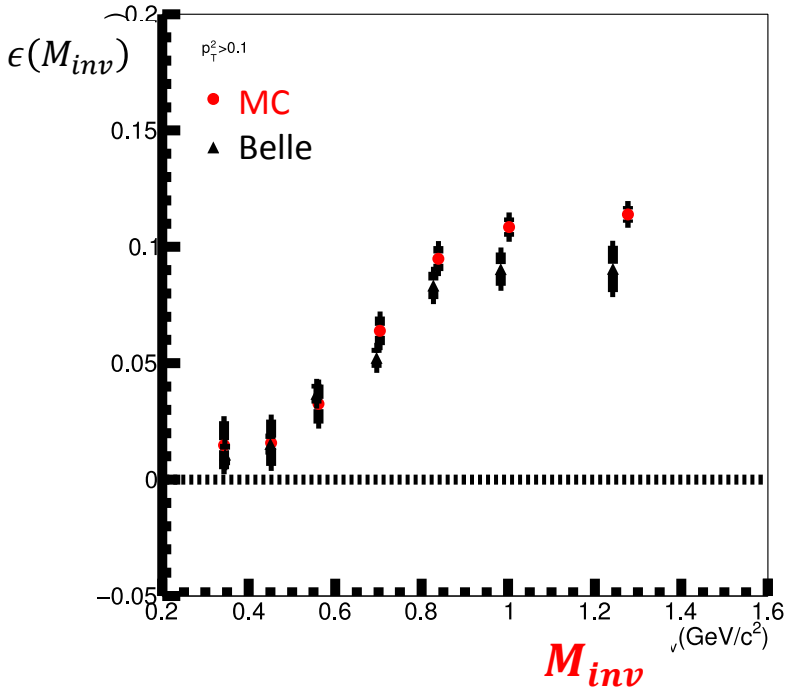
new: preliminary results from a Monte Carlo code for transversely polarized quark jet based on the string fragmentation and including, for the first time, the $^3P_0$ mechanism

only one free parameter for spin effects

→ X. Artru

results in good qualitative agreement with 1h and 2h asymmetries at COMPASS and Belle:

- h^+ *and* h^-*:*
  - *mirror symmetry as in COMPASS*
  - a_P *in agreement with what obtained from Belle data*
- $\pi^+\pi^-$ *in good agreement with Belle*



- $\epsilon(M_{inv}) = \langle a_P^{u\to\pi^+\pi^-}\rangle a_P^{u\to\pi^+\pi^-}(M_{inv})$
- $z_h > 0.1,\ p_T^2 > 0.1\ (GeV/c)^2$ for each pion

A. Kerbizi talk at SPIN2016

interplay among dihadron and single hadron asymmetries

new: preliminary results from a Monte Carlo code for transversely polarized quark jet based on the string fragmentation and including, for the first time, the $^3P_0$ mechanism

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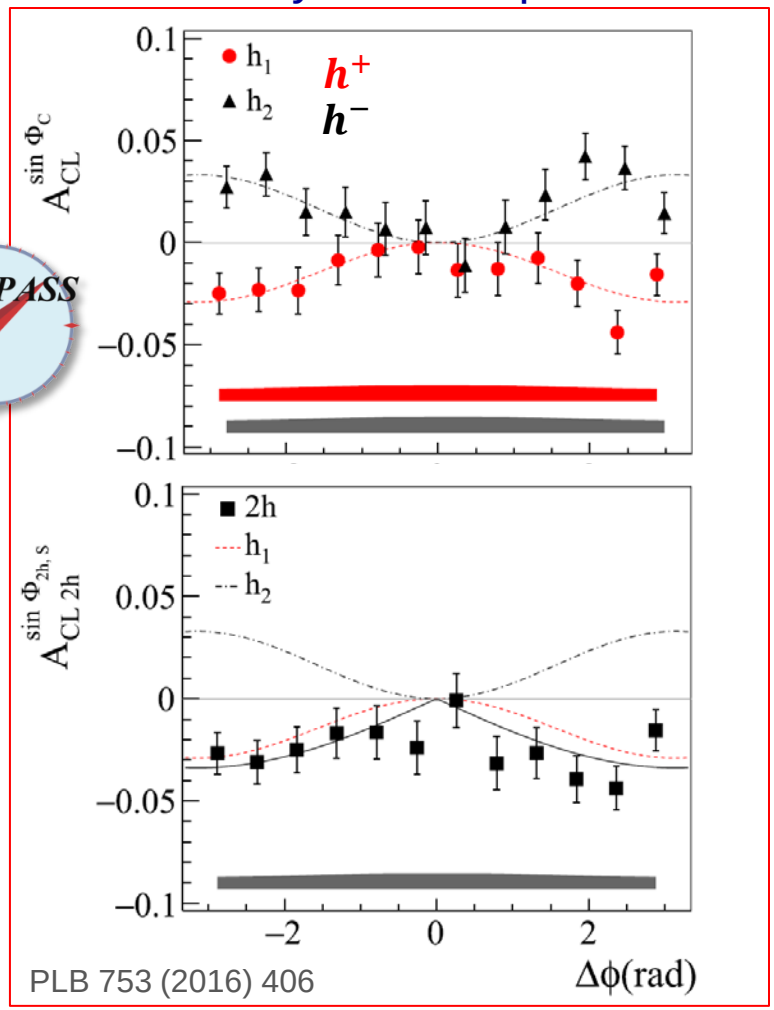
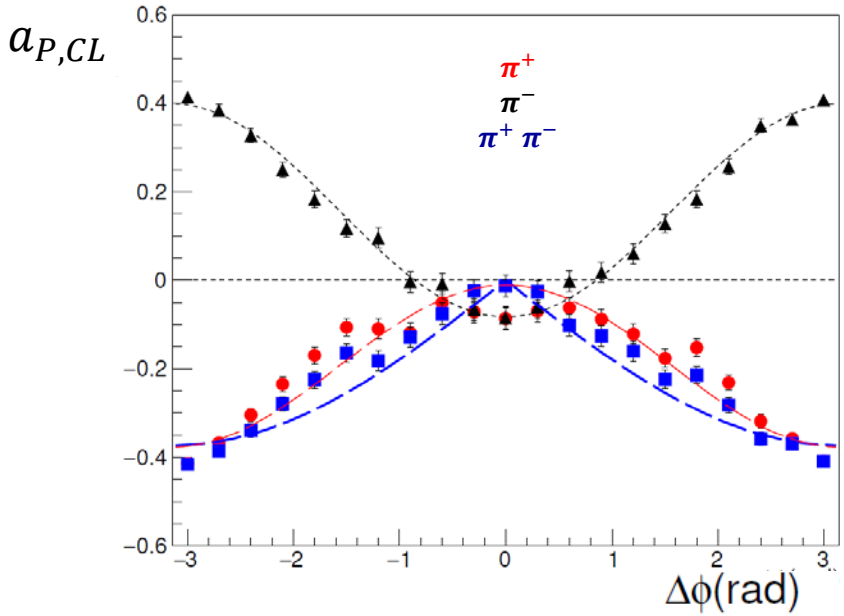


PLB 753 (2016) 406

1h and 2h a_p obtained as COMPASS asymmetries
from the same sample of generated events

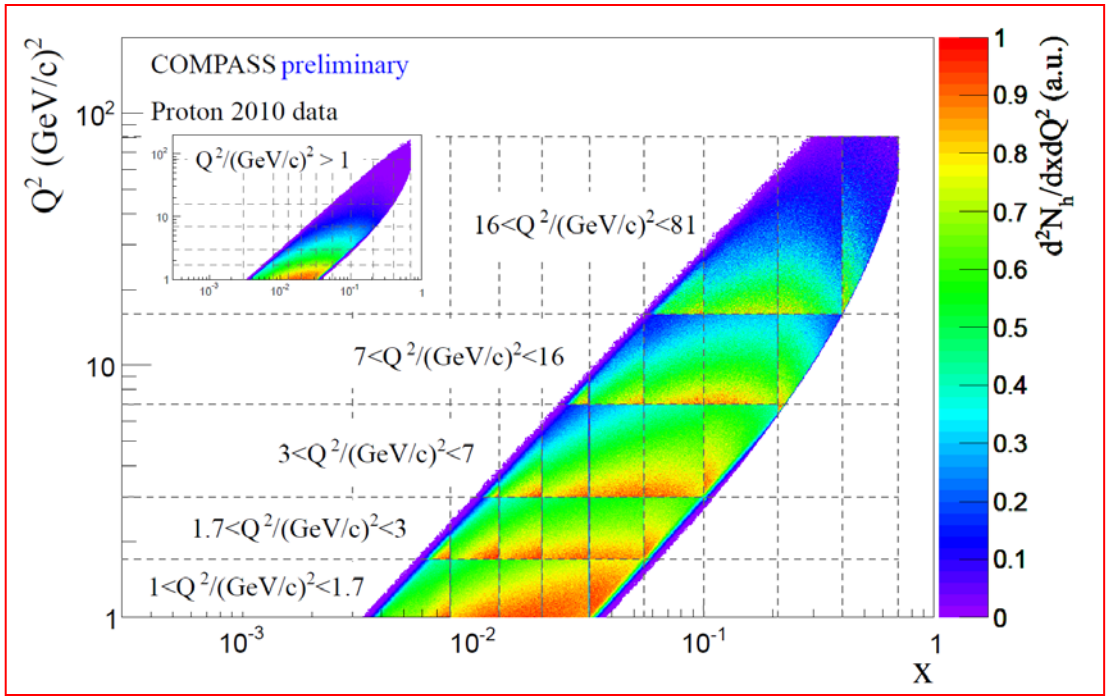
A. Kerbizi talk at SPIN2016



very encouraging results

other recent COMPASS results - 2

multidimensional measurements of the Collins asymmetry

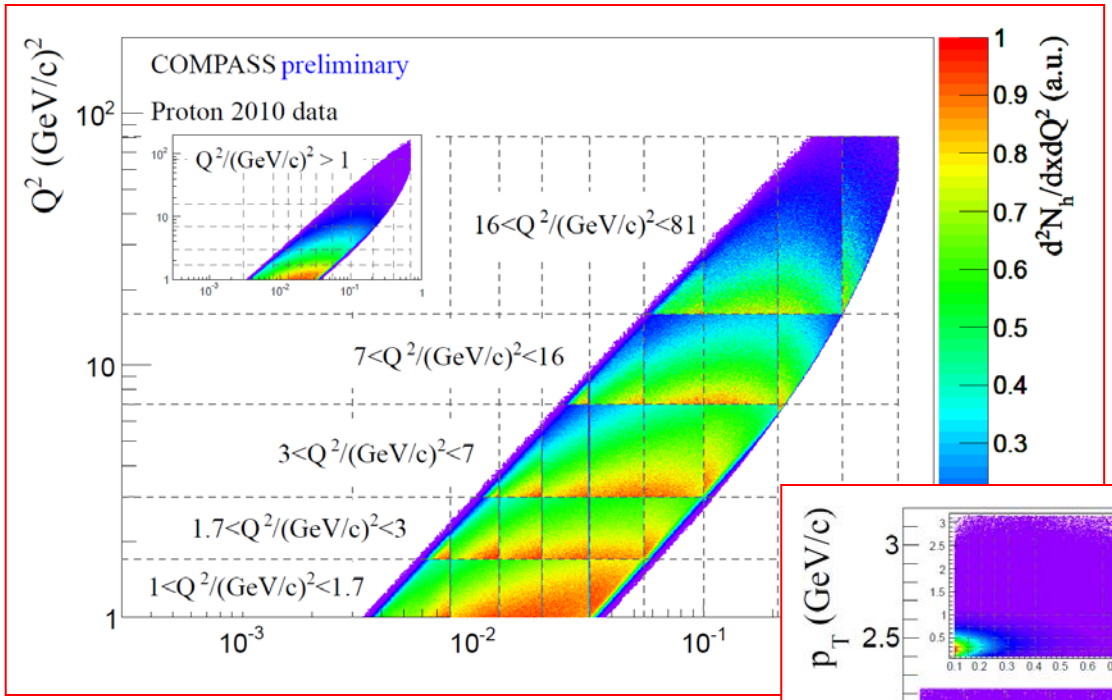


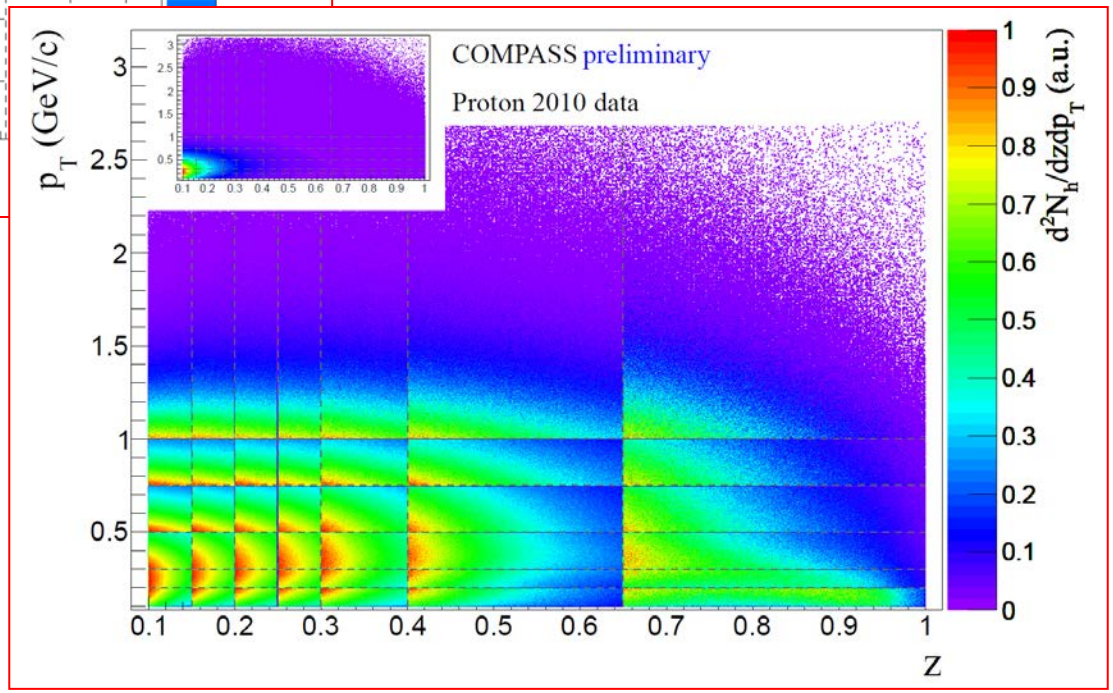
SPIN2014

x-Q^2 z-p_T binning

other recent COMPASS results - 2

multidimensional measurements of the Collins asymmetry





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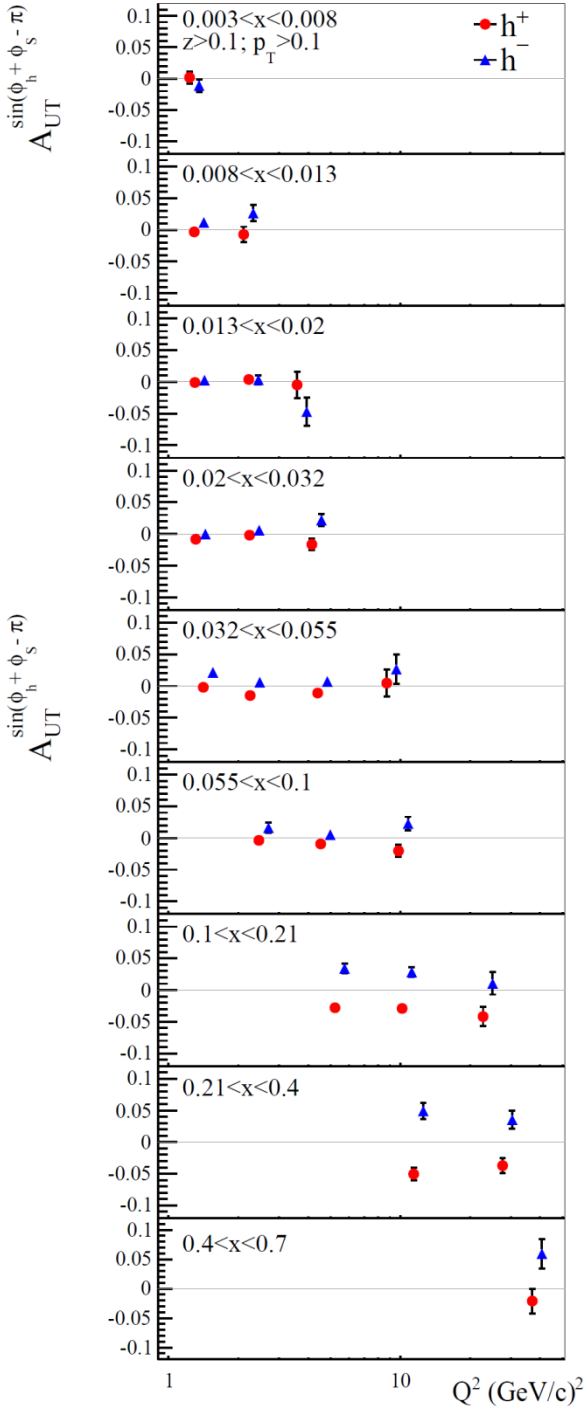
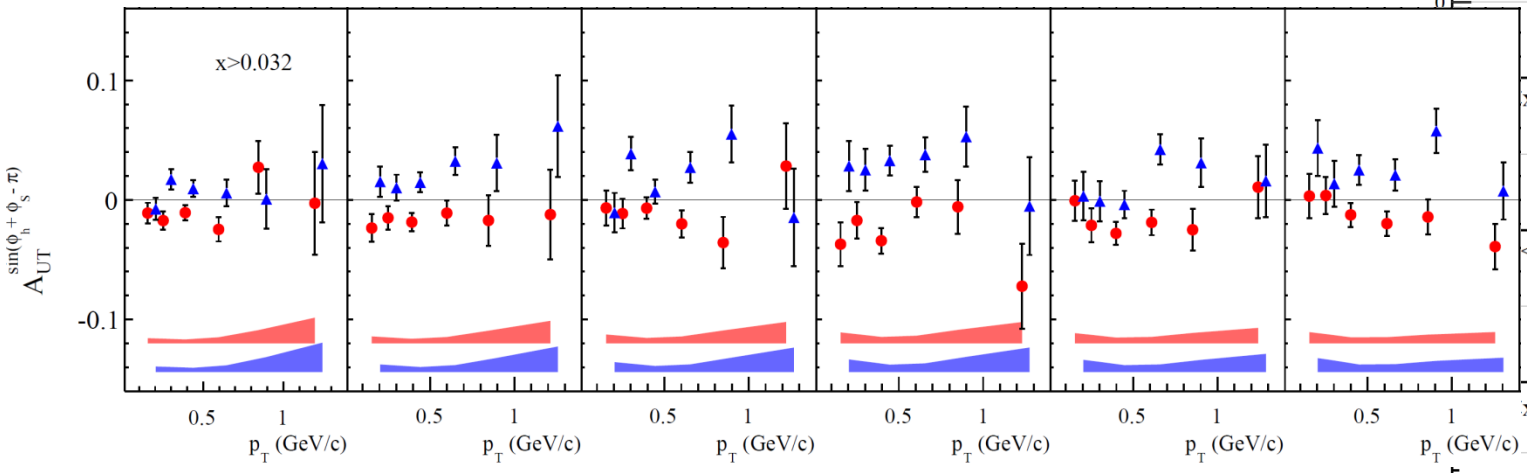
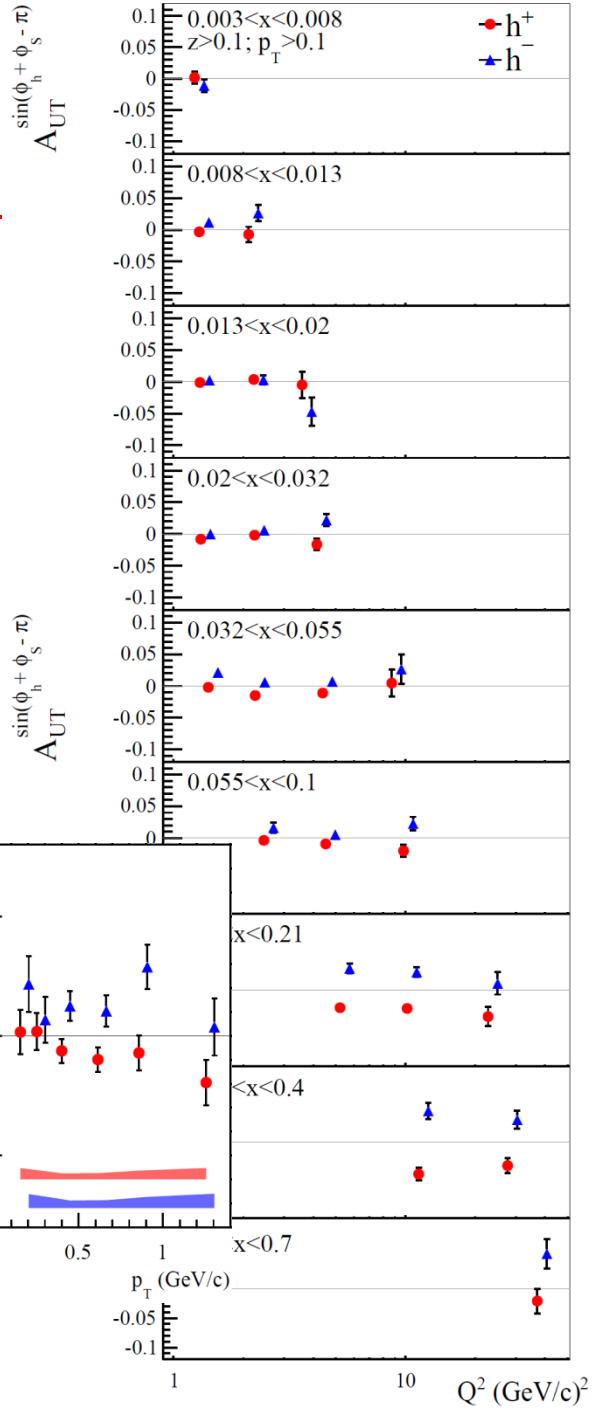


multidimensional measurements of the Collins asymmetry

relevant data to test the parametrisations of h_1^q and $H_{1q}^{\perp}$ obtained from the fits of the integrated asymmetries





other recent COMPASS results - 3

coming soon:

new results on Λ polarisation

an independent way to access transversity

one of the first proposed methods

h_1^q $H_1^{\Lambda/q}$ $e^+e^- \rightarrow \Lambda^\uparrow \bar{\Lambda}^\uparrow X$

$$\mathcal{P}_y^{h^\uparrow} = \hat{a}_T(t) \frac{\sum_{q,\bar{q}} e_q^2 \, \Delta_T q(x,Q^2) \, \Delta_T D_{h/q}(z,Q^2)}{\sum_{q,\bar{q}} e_q^2 \, q(x,Q^2) \, D_{h/q}(z,Q^2)}$$

other recent COMPASS results - 3

coming soon:

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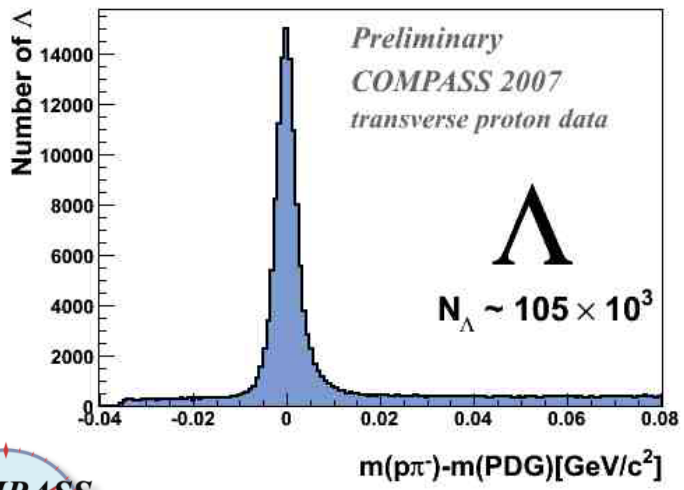
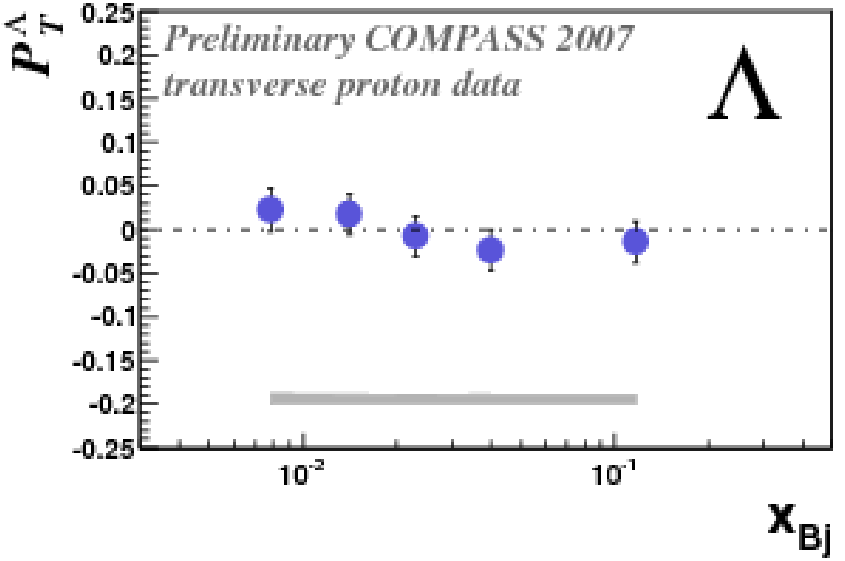
$$\mathcal{P}_y^{h\uparrow} = \hat{a}_T(t)\,\frac{\sum_{q,\bar{q}} e_q^2\,\Delta_T q(x,Q^2)\,\Delta_T D_{h/q}(z,Q^2)}{\sum_{q,\bar{q}} e_q^2\,q(x,Q^2)\,D_{h/q}(z,Q^2)} \qquad \begin{matrix} h_1^q & H_1^{\Lambda/q} \end{matrix} \qquad e^+e^- \to \Lambda^\uparrow \bar{\Lambda}^\uparrow X$$





analysis of 2010 proton data started - expected statistics: x 2

accessing transversity

COMPASS has produced and is producing many interesting results

and new “pioneering” analysis have been started

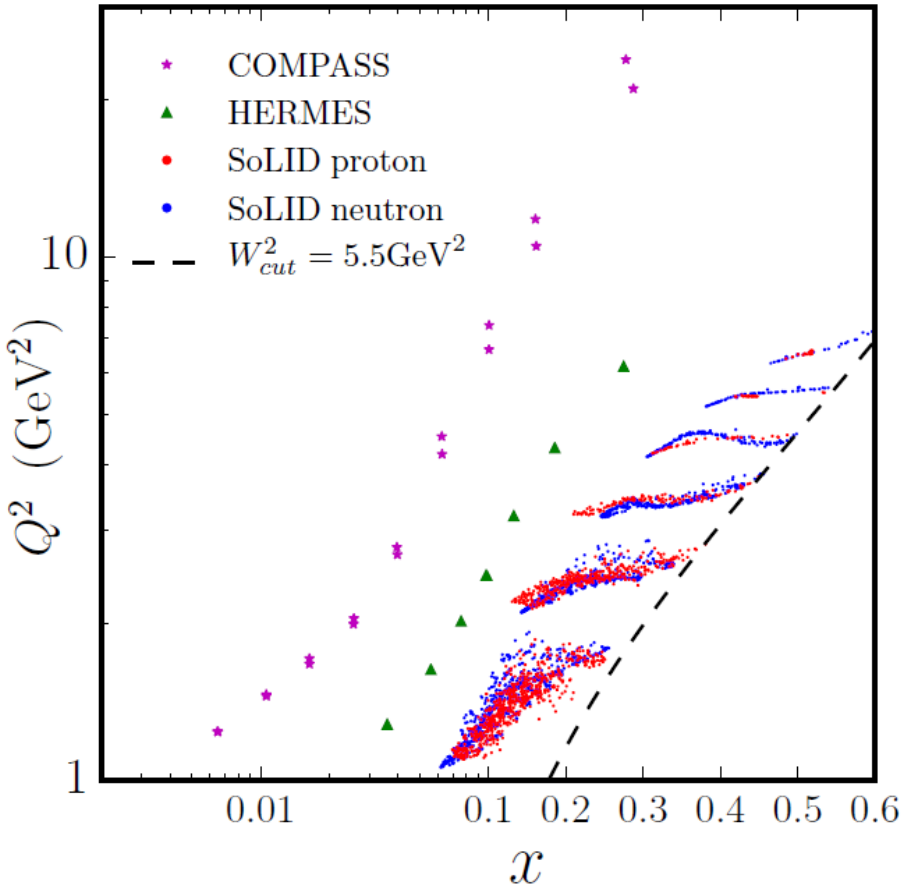
main limitation of existing data:

statistics, in particular for transversely polarised d

new data needed soon!

one more year of data taking with transversely polarised d at COMPASS

an enormous amount of data will come from **JLab12** experiments
and later on from **EIC**



Z. Ye et al. JLAB-THY-16-2328

COMPASS:

no competition on precision!

smaller x, factor > 5 in Q^2, …

the kinematical region is relevant and new d data coming soon are needed

one more year of data taking with transversely polarised d at COMPASS

A. Bressan,
COMPASS beyond 2020 Workshop, CERN, March 2016

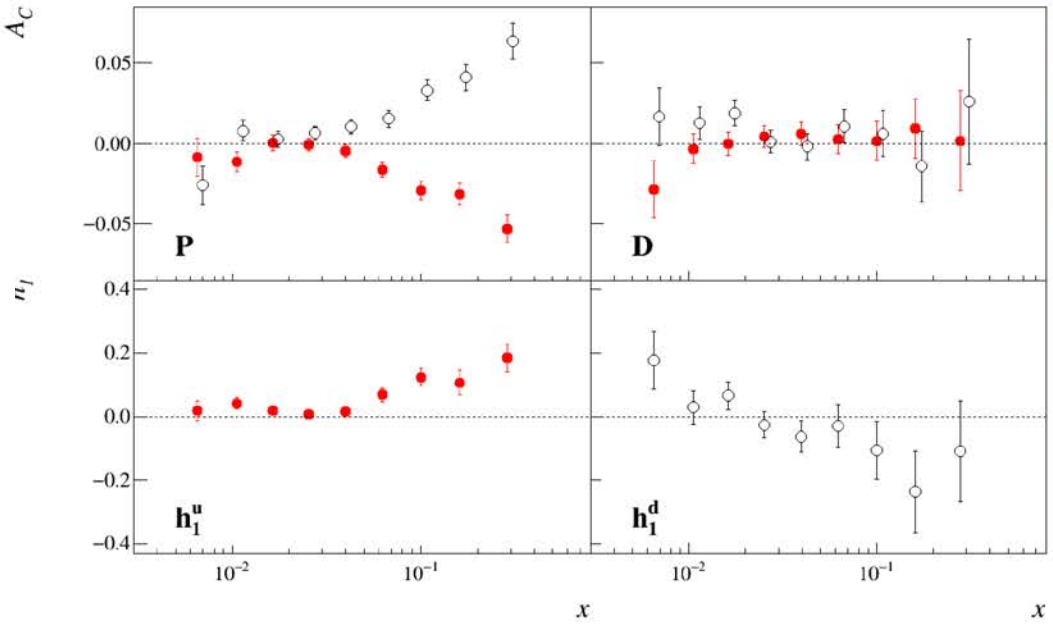
New deuteron data

- Benchmark: extraction from Collins asymmetries

present:

Collins asymmetry

transversity
point-to-point extraction
PRD 91 (2015) 014034



one more year of data taking with transversely polarised d at COMPASS

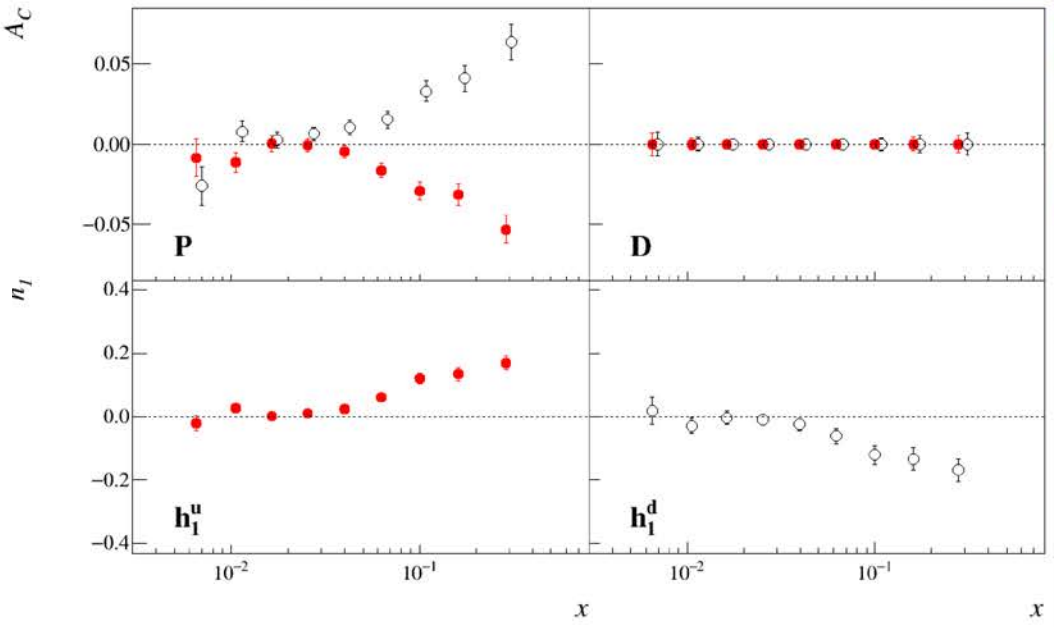
New deuteron data

- 1 full year (same as 2010). We also gain from $\frac{f_p P_{pT}}{f_D P_{DT}} = \frac{0.155 \times 0.8}{0.40 \times 0.5} = 0.6$

after 1 year of d

Collins asymmetry

transversity



THIS IS A MEASUREMENT THAT WILL IMPACT OUR KNOWLEDGE, KEY MEASUREMENT FOR THIS OR NEXT PHASE

Sivers function

accessing the Sivers function

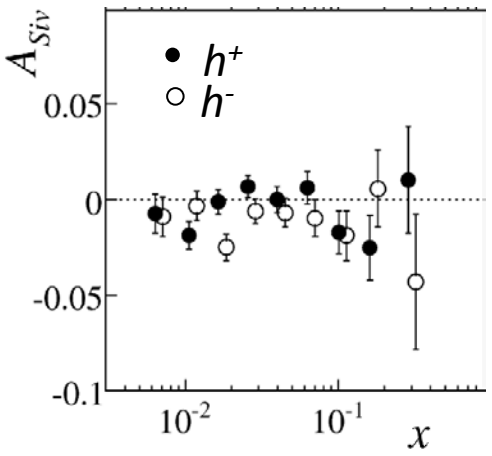
Sivers asymmetry $A_{Siv} \sim \dfrac{\sum_q e_q^2 \, f_{1T}^{\perp\, q} \otimes D_{1q}}{\sum_q e_q^2 \, f_1^q \cdot D_{1q}}$

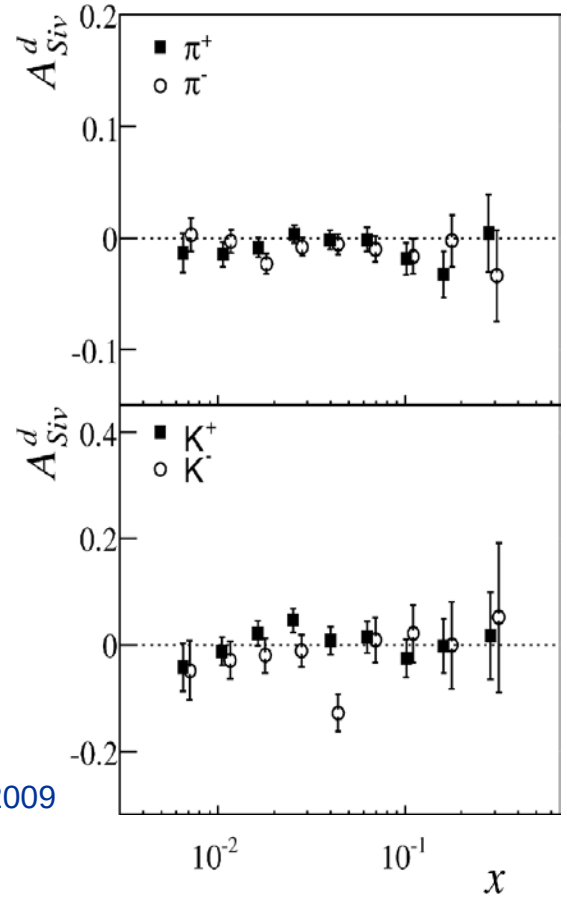
amplitude of the $sin\,(\phi_h - \phi_S)$ modulation

accessing the Sivers function

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

final results on deuteron





2002-2004 data
NPB765 2007, PLB673 2009

accessing the Sivers function

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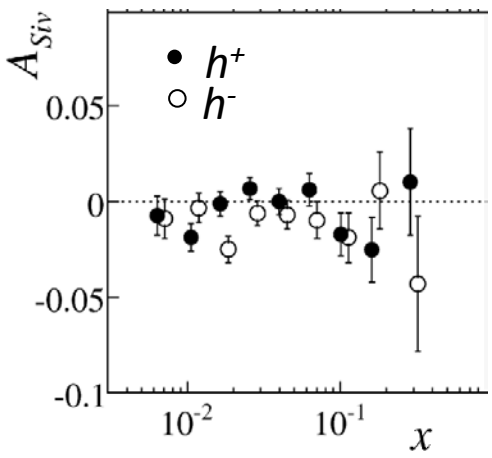
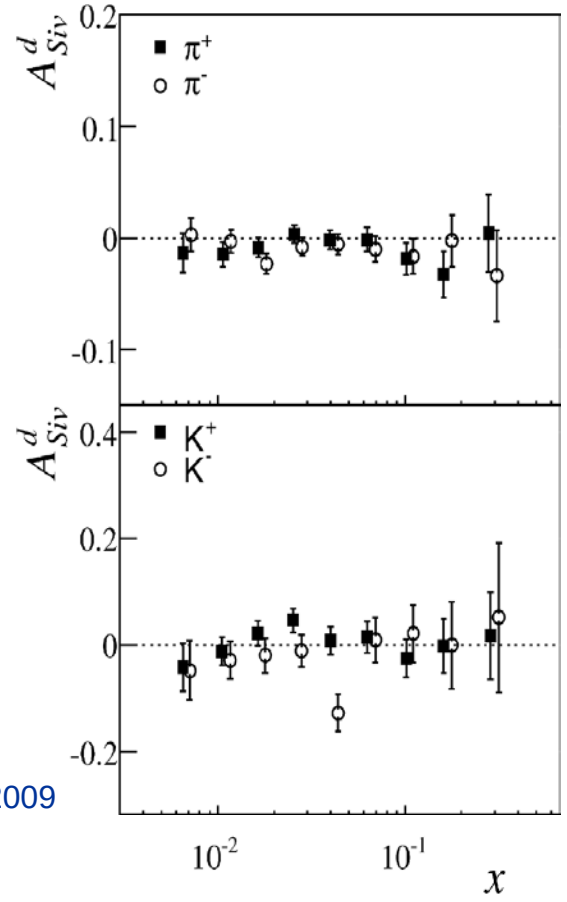
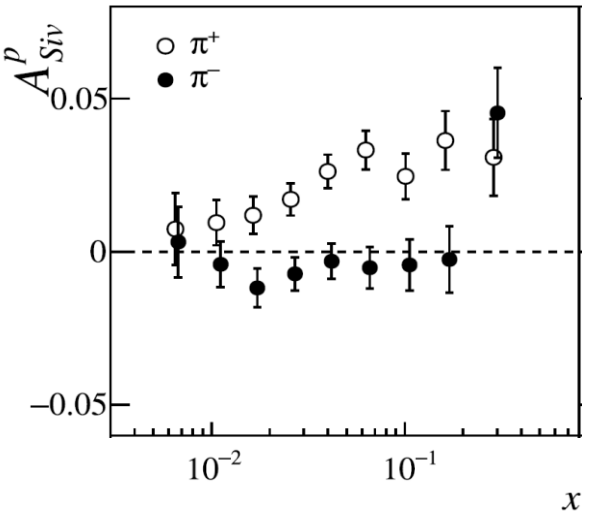




2002-2004 data
NPB765 2007, PLB673 2009

final results on proton

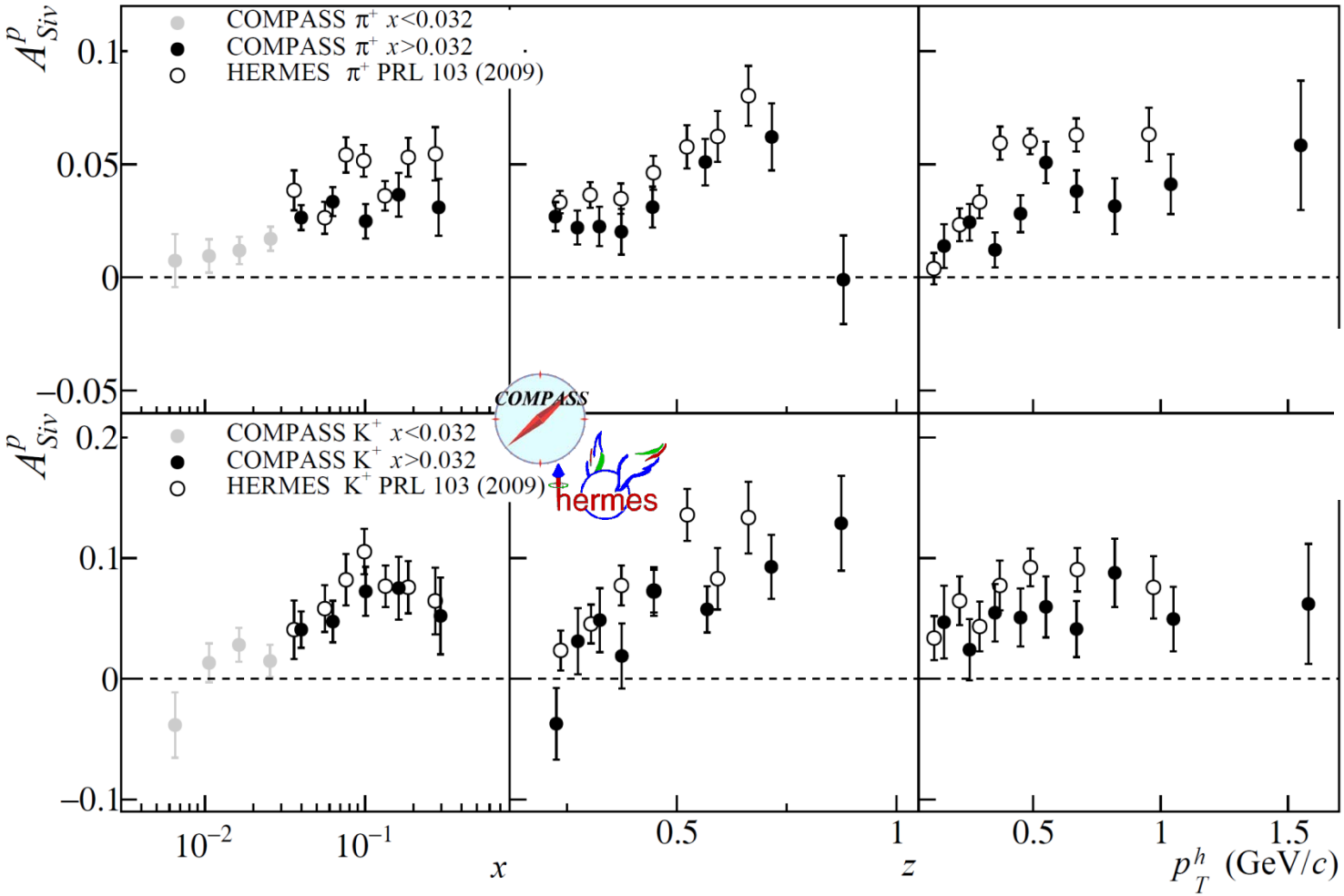


clearly positive for π^+
down to $x \sim 10^{-2}$

accessing the Sivers function

Sivers asymmetry

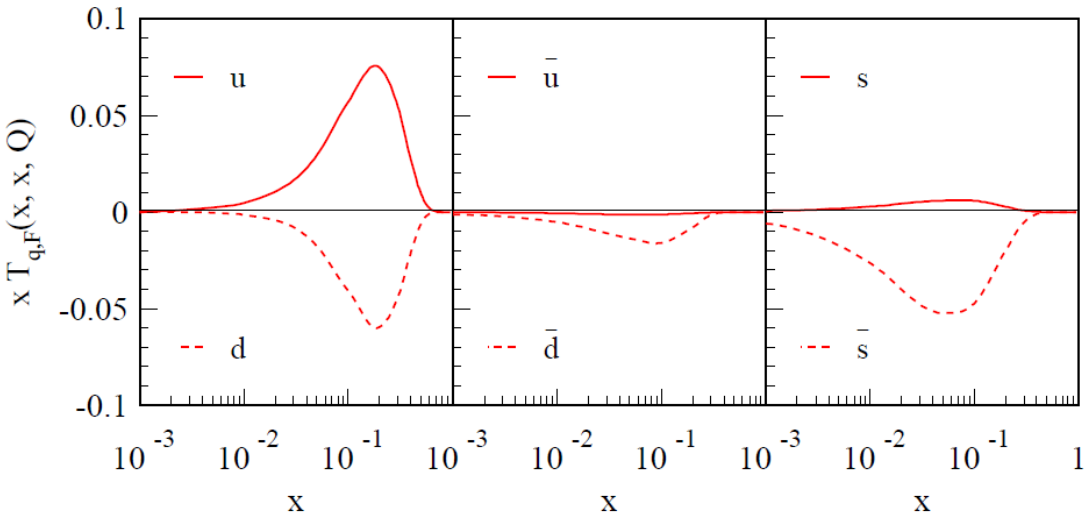
final results on proton for positive particles  vs 



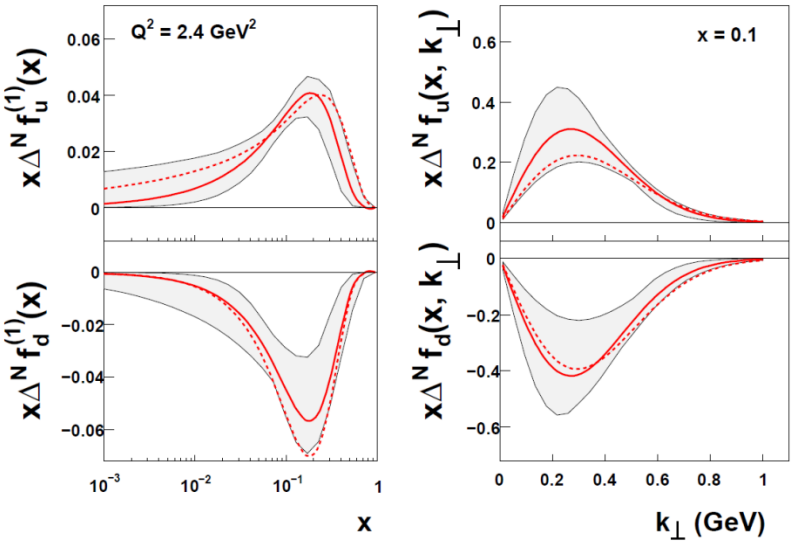
K^+ asymmetries larger than π^+ asymmetries

accessing the Sivers function

fits to COMPASS and HERMES data since 2005



Echevarria et al
Phys.Rev. D89 (2014)



Anselmino et al
Eur.Phys.J. A39 (2009)

accessing the Sivers function

point-by-point extraction ~ transversity case

from p and d Sivers asymmetries measured at the same x, Q^2 values

in the Gaussian model

pions

$$\boldsymbol{xf_{1T}^{\perp(1)u_v}} = \frac{1}{5G\rho_\pi(1-\beta_\pi^{(1)})}\left[xf_p^{\pi^+}\boldsymbol{A_p^{\pi^+}} - xf_p^{\pi^-}\boldsymbol{A_p^{\pi^-}} + \frac{1}{3}\left(xf_d^{\pi^+}\boldsymbol{A_d^{\pi^+}} - xf_d^{\pi^-}\boldsymbol{A_d^{\pi^-}}\right)\right]$$

similar expressions for $\boldsymbol{xf_{1T}^{\perp(1)d_v}}$ and $\boldsymbol{xf_{1T}^{\perp(1)\bar{u}} - xf_{1T}^{\perp(1)\bar{d}}}$ from **pion**

and for $\boldsymbol{xf_{1T}^{\perp(1)u_v}}$ and $\boldsymbol{xf_{1T}^{\perp(1)d_v}}$ from **kaon** p and d asymmetries

independent extraction of $\boldsymbol{xf_{1T}^{\perp(1)u_v}}$ and $\boldsymbol{xf_{1T}^{\perp(1)d_v}}$
from π and from K Sivers asymmetries

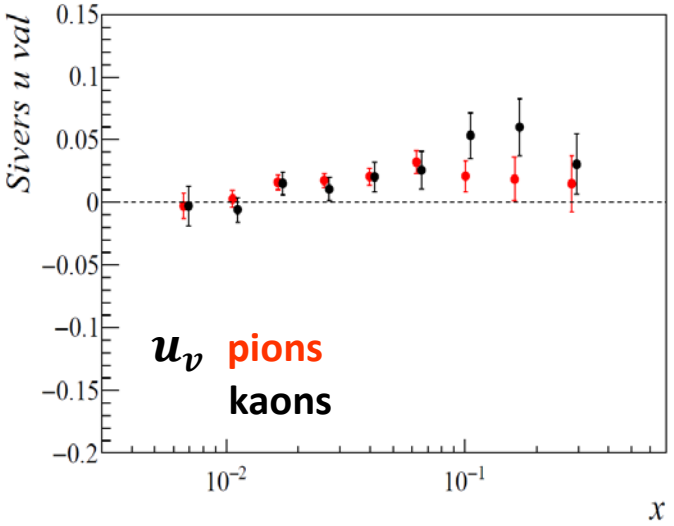
A. M., F. Bradamante, V. Barone, SPIN2016

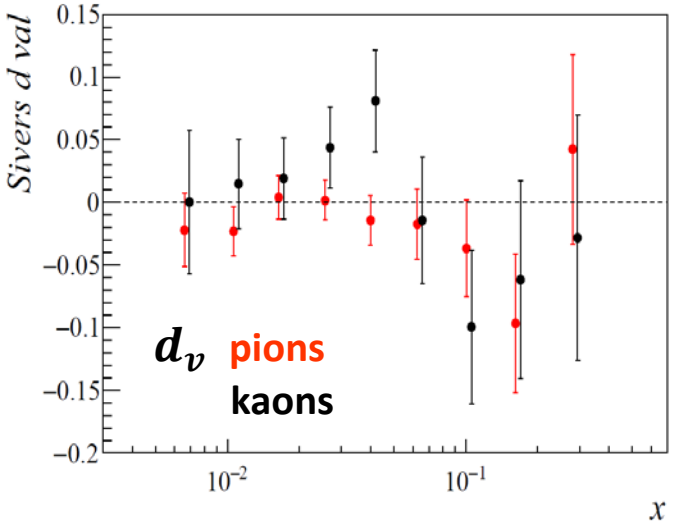
accessing the Sivers function

point-by-point extraction

from p and d Sivers asymmetries measured at the same x, Q^2 values

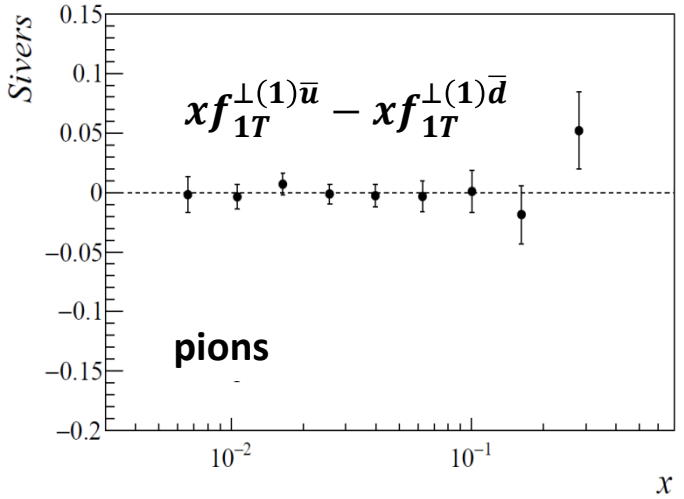
using COMPASS results





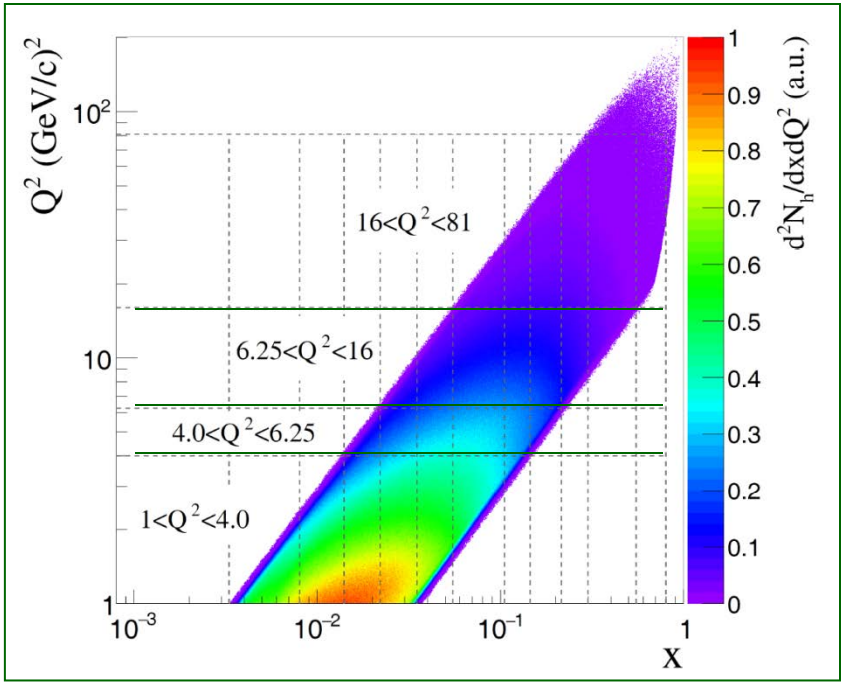
- similar values and uncertainties pions and kaons
- large statistical uncertainties for d_v
- results compatible with recent parametrisations

result for $f_{1T}^{\perp(1)\bar{u}} - f_{1T}^{\perp(1)\bar{d}}$ compatible with zero



A. M., F. Bradamante, V. Barone, SPIN2016

further results of the Sivers asymmetry



Drell-Yan Q^2 range at COMPASS

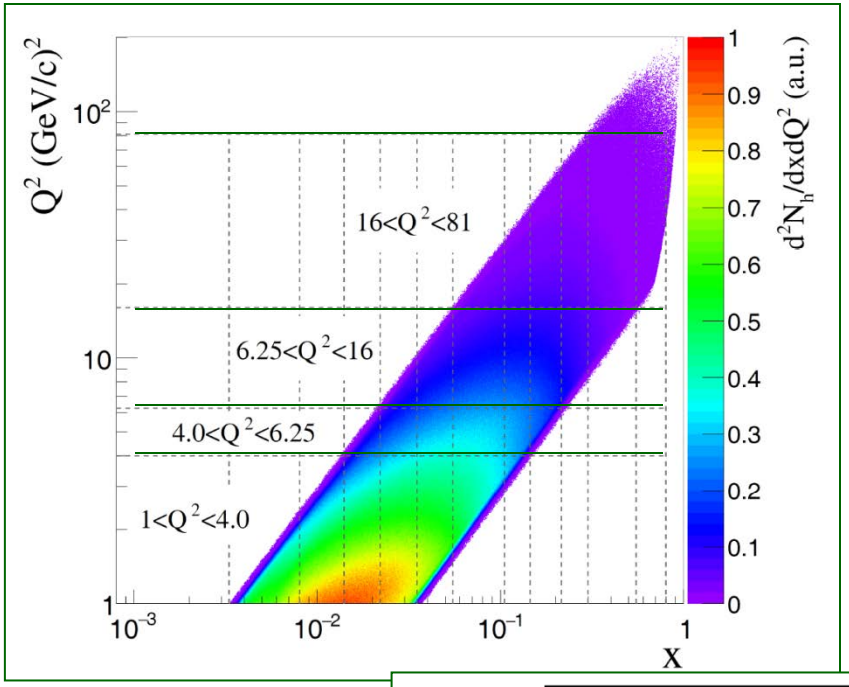
no evolution SIDIS → DY

4 Q^2 bins

11 x bins

z, P_T^h binning

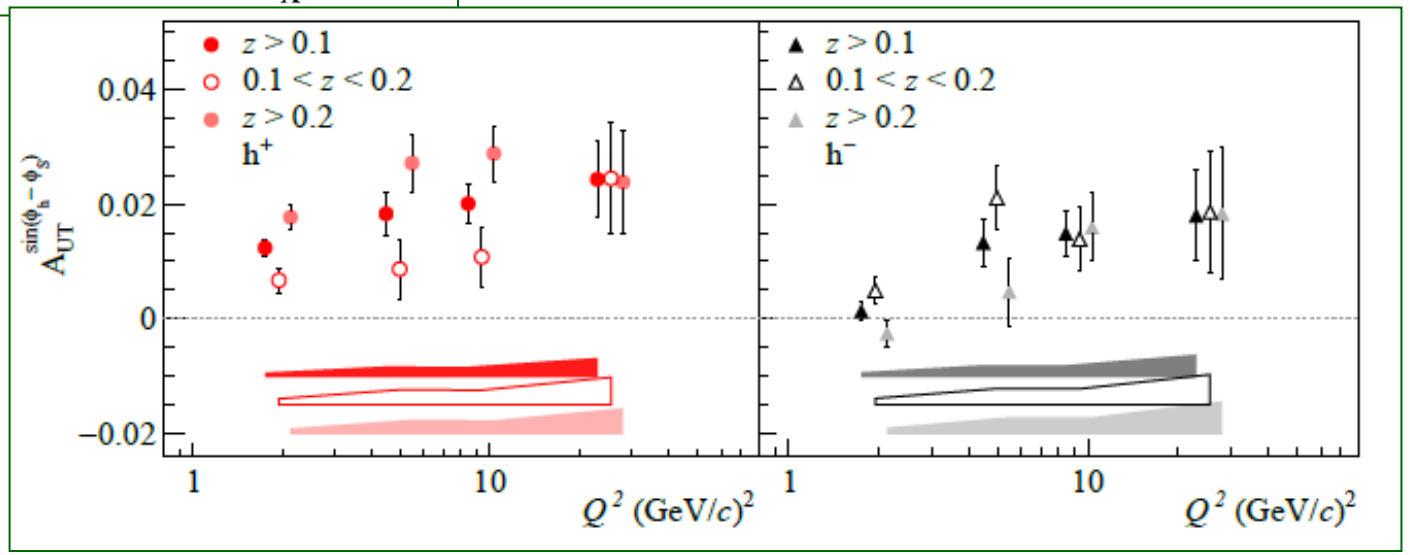
further results of the Sivers asymmetry



Drell-Yan Q^2 range at COMPASS

no evolution SIDIS → DY

more results in the paper
arXiv:1609.07374 [hep-ex]



further results of the Sivers asymmetry

preliminary results have already been recently produced for

- multidimensional measurements of the Sivers asymmetry

- gluon Sivers asymmetries

  J/Ψ

  high P_T^h hadron pairs

new preliminary results (QCD'N2016, SPIN2016)

- $\boldsymbol{P_T}$ **- weighted asymmetries**

P_T 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

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

proposed a long time ago …

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

reconsidered recently

Zhong-Bo Kang et al., Phys.Rev. D87 (2013)
….

P_T weighted Sivers asymmetry

only existing data:

preliminary results by HERMES

Acta Phys.Polon. B36 (2005) 209

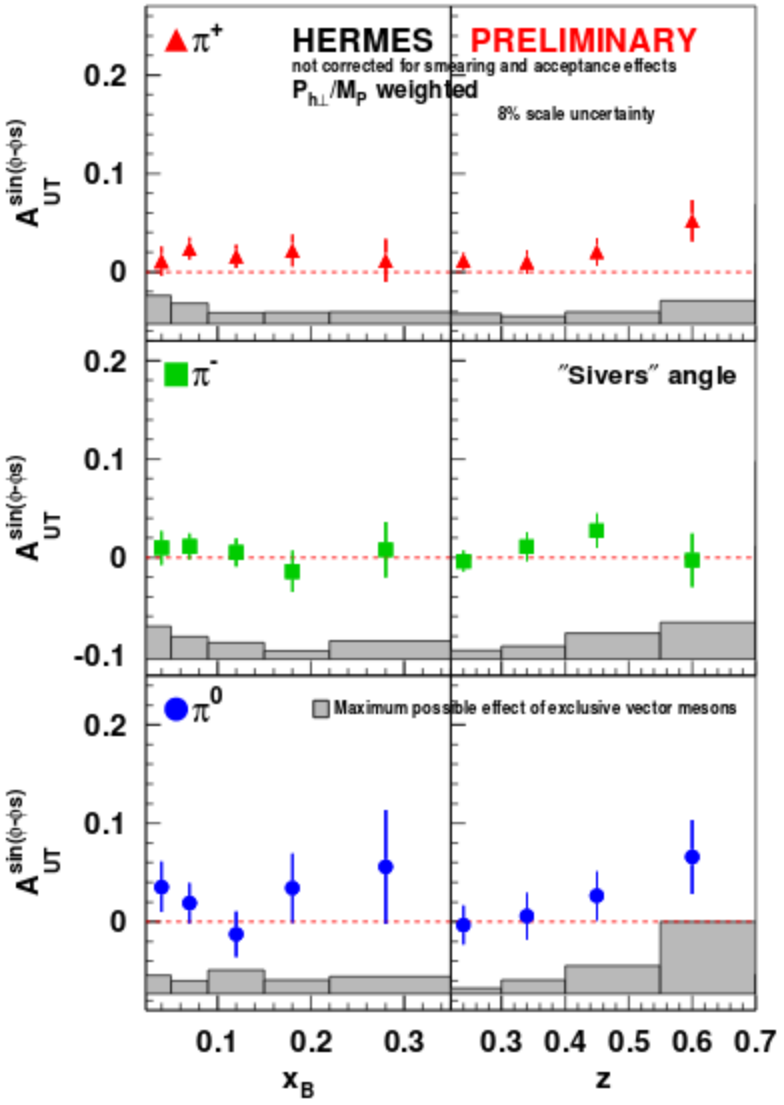
used to extract the Sivers function

A.V. Efremov et al., Phys.Lett. B612 (2005) 233

A. Bacchetta et al., Eur.Phys.J. A45 (2010) 373

…

$w = P_T/M$

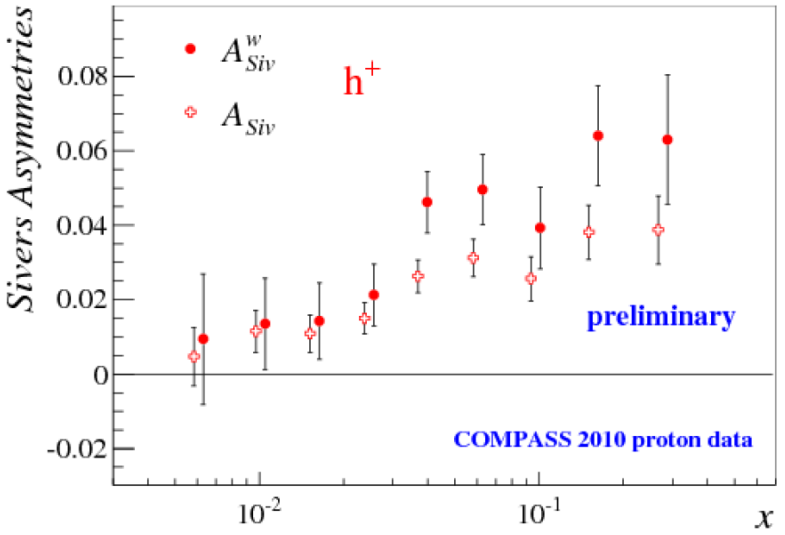


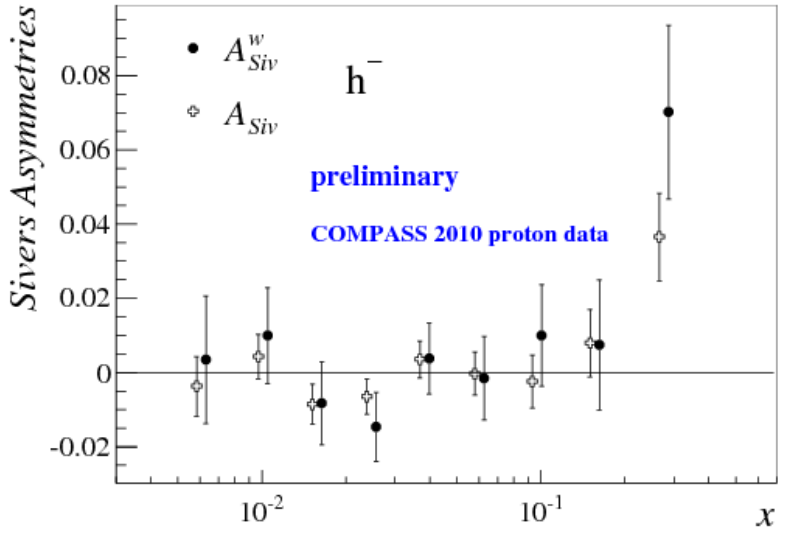
P_T weighted Sivers asymmetry

NEW: COMPASS results

proton only!

$w = P_T/zM$





P_T weighted Sivers asymmetry

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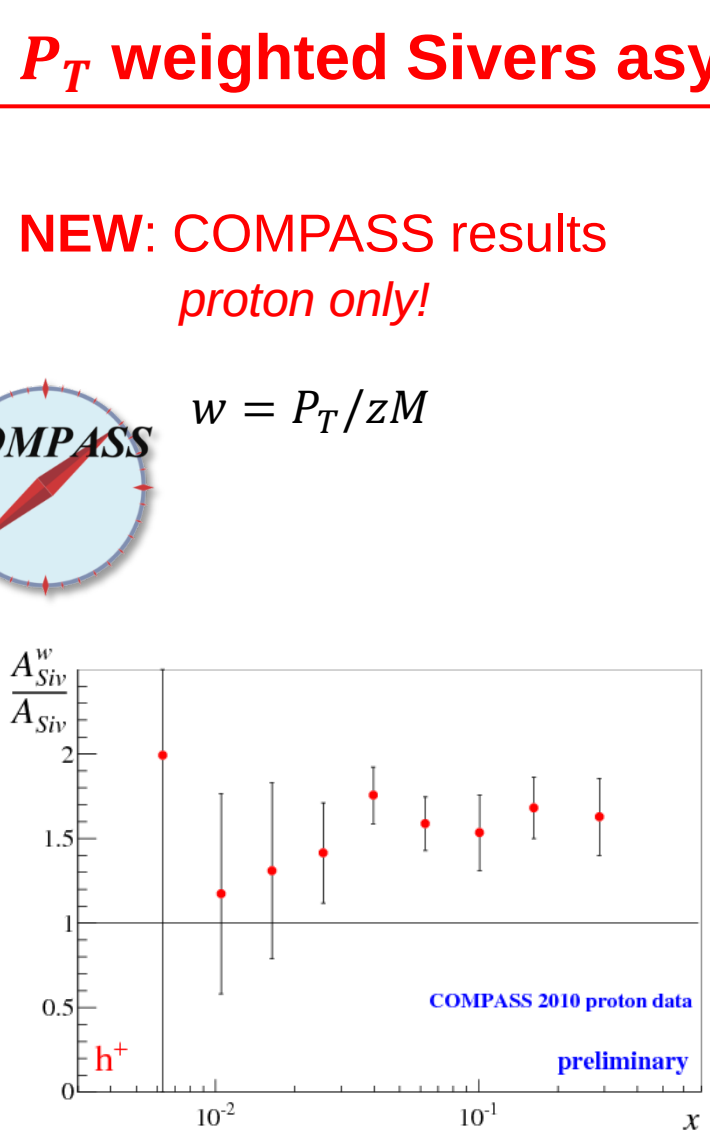
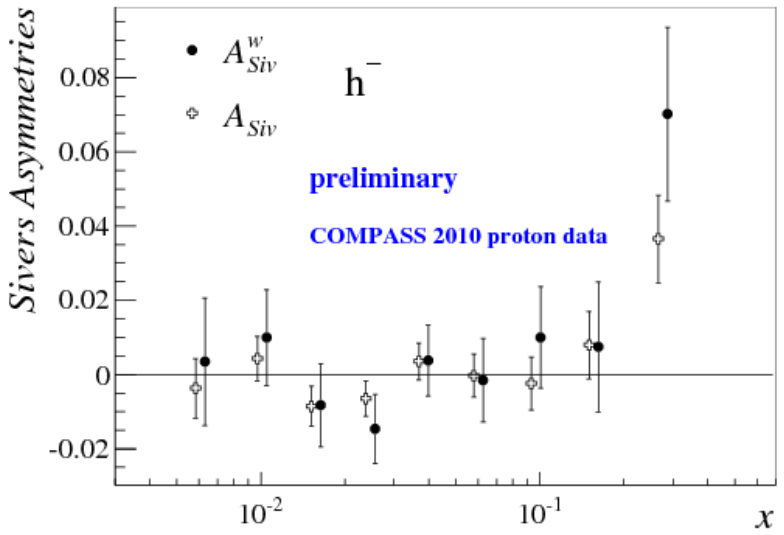




look promising!
plans to publish soon

unpolarised SIDIS

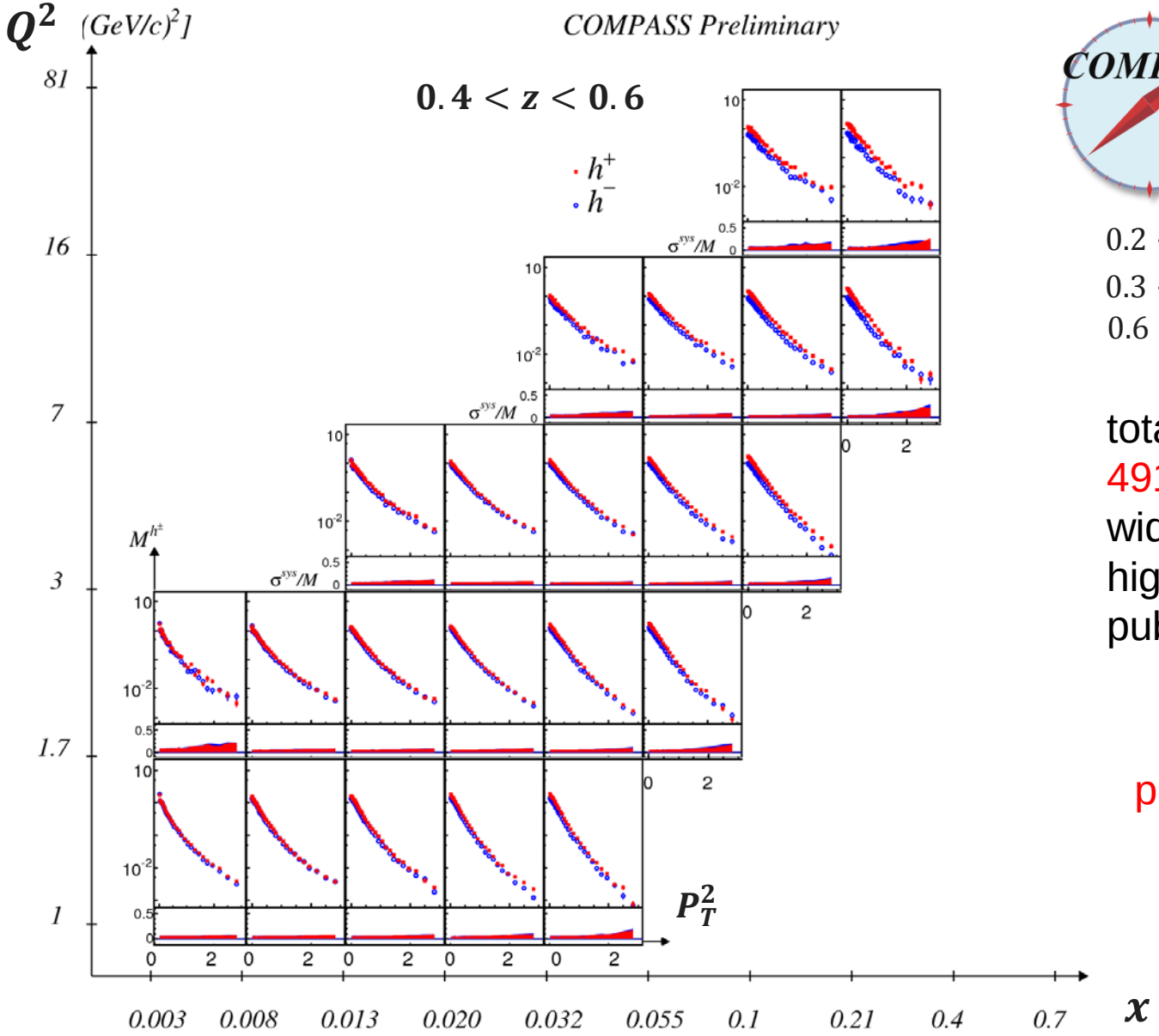
allows to

- access k_T *multiplicities vs* P_T
  cos ϕ *asymmetries*
- study the Boer-Mulders function cos 2ϕ *asymmetries*

a lot of data from COMPASS, on d (^{6}LiD) only

and from HERMES (p and d) and JLab

unpolarised SIDIS – P_T^2 distributions



COMPASS

2006 d data
SPIN2014

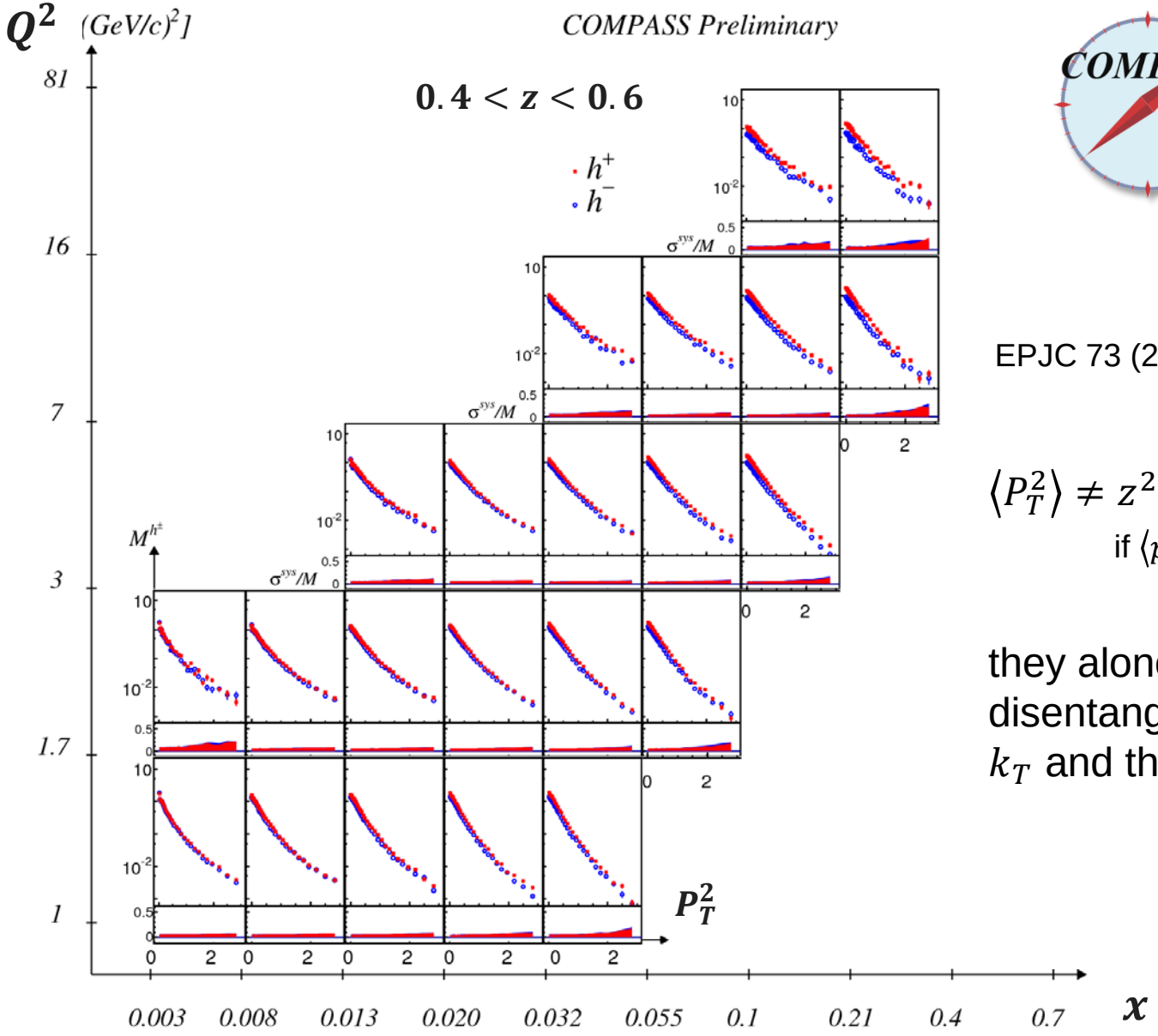
$0.2 < z < 0.3$
$0.3 < z < 0.4$
$0.6 < z < 0.8$

total:
4918 data points
wider kinematic range, higher precision than published results

EPJC 73 (2013) 2531

plus HERMES, JLab

unpolarised SIDIS – P_T^2 distributions



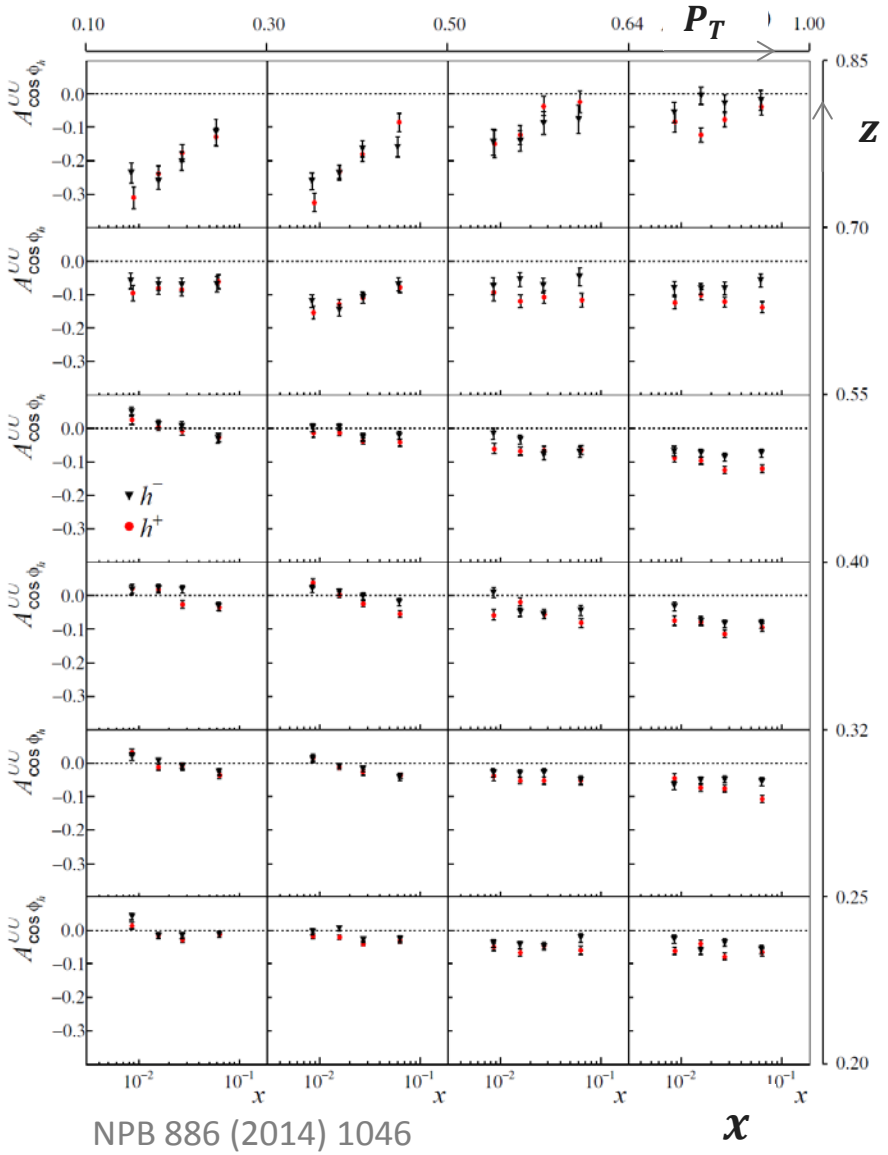
EPJC 73 (2013) 2531

$$\langle P_T^2 \rangle \neq z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle$$

if $\langle p_T^2 \rangle$ const

they alone do not allow to disentangle the k_T and the p_T contributions

unpolarised SIDIS – azimuthal asymmetries



NPB 886 (2014) 1046

$A_{cos\phi}$, "Cahn asymmetry" → k_T

- strong x, z, P_T dependence
- difficult to explain it

- small value of k_T
- presence of further twist-3 terms ?
- non-zero Boer-Mulders effect ? *

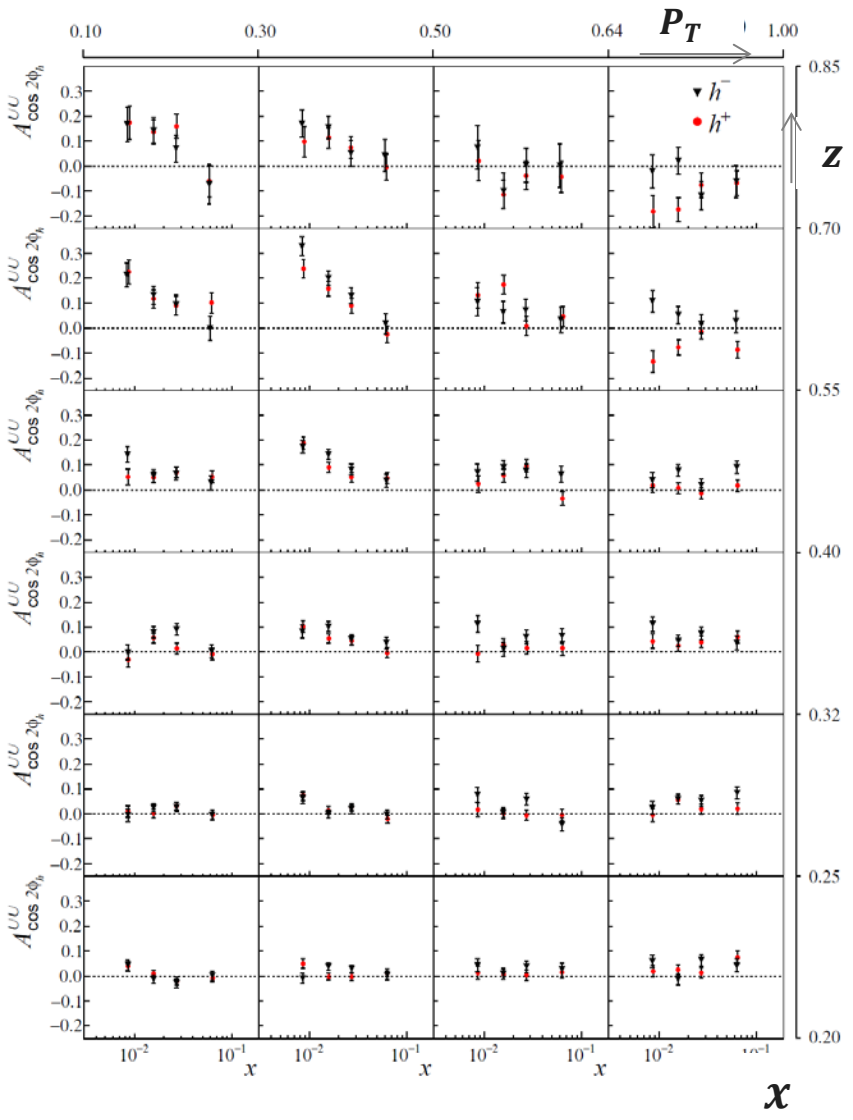
(*) with HERMES data
V. Barone et al.
Phys.Rev. D91 (2015)

unpolarised SIDIS – azimuthal asymmetries

$A_{cos2\phi}$ → Boer-Mulders function

- strong x, z, P_T dependence

other higher-twist effects ? *



still a lot to be done

NPB 886 (2014) 1046

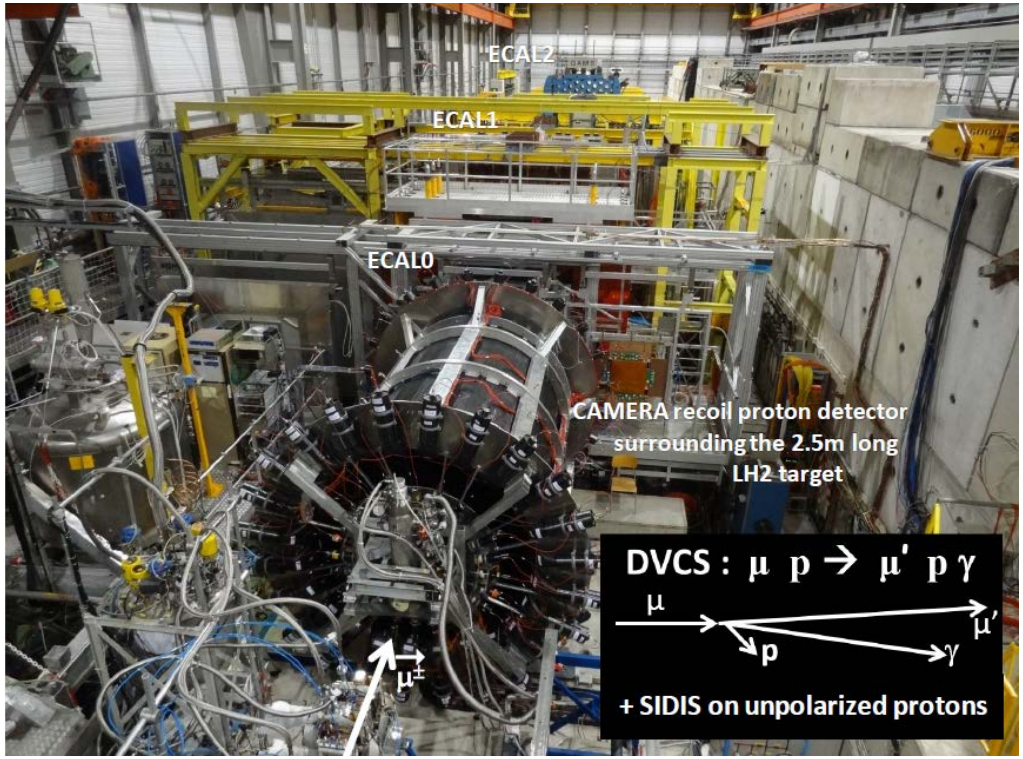
unpolarised SIDIS – near future

data from 2016-17 runs, collected in parallel with DVCS

- LH_2 target
- about the same phase space as in 2004

and

- smaller systematic uncertainties



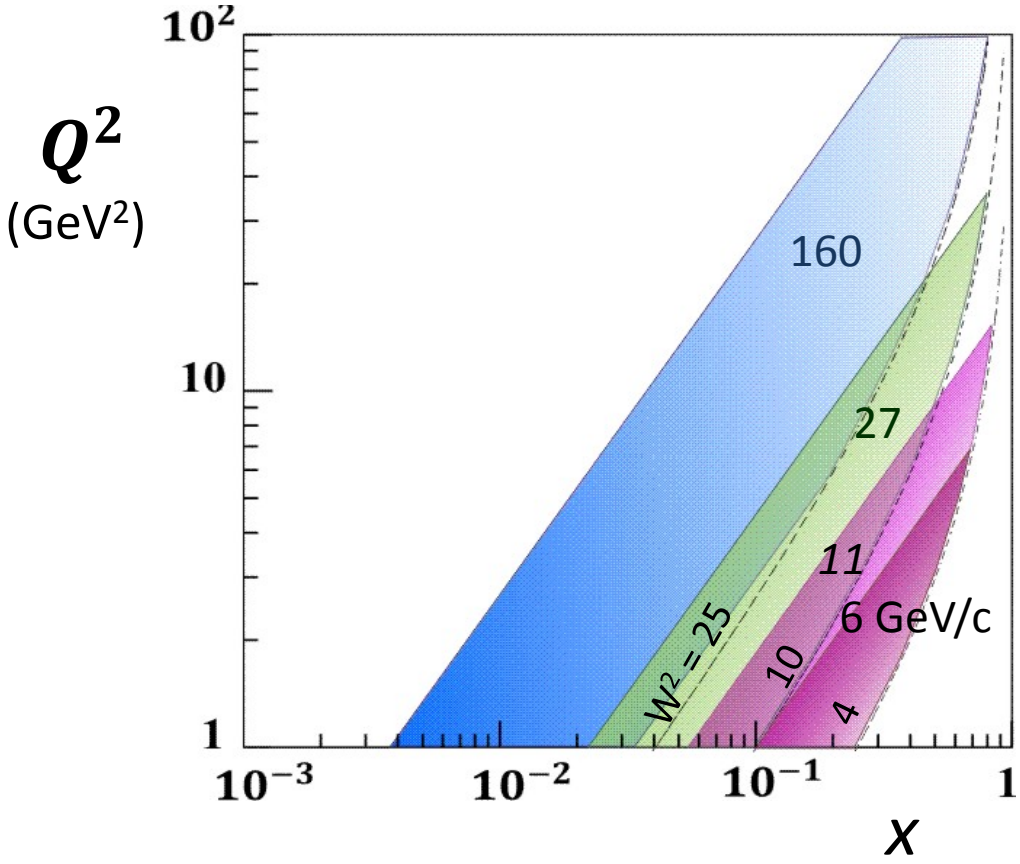
summary

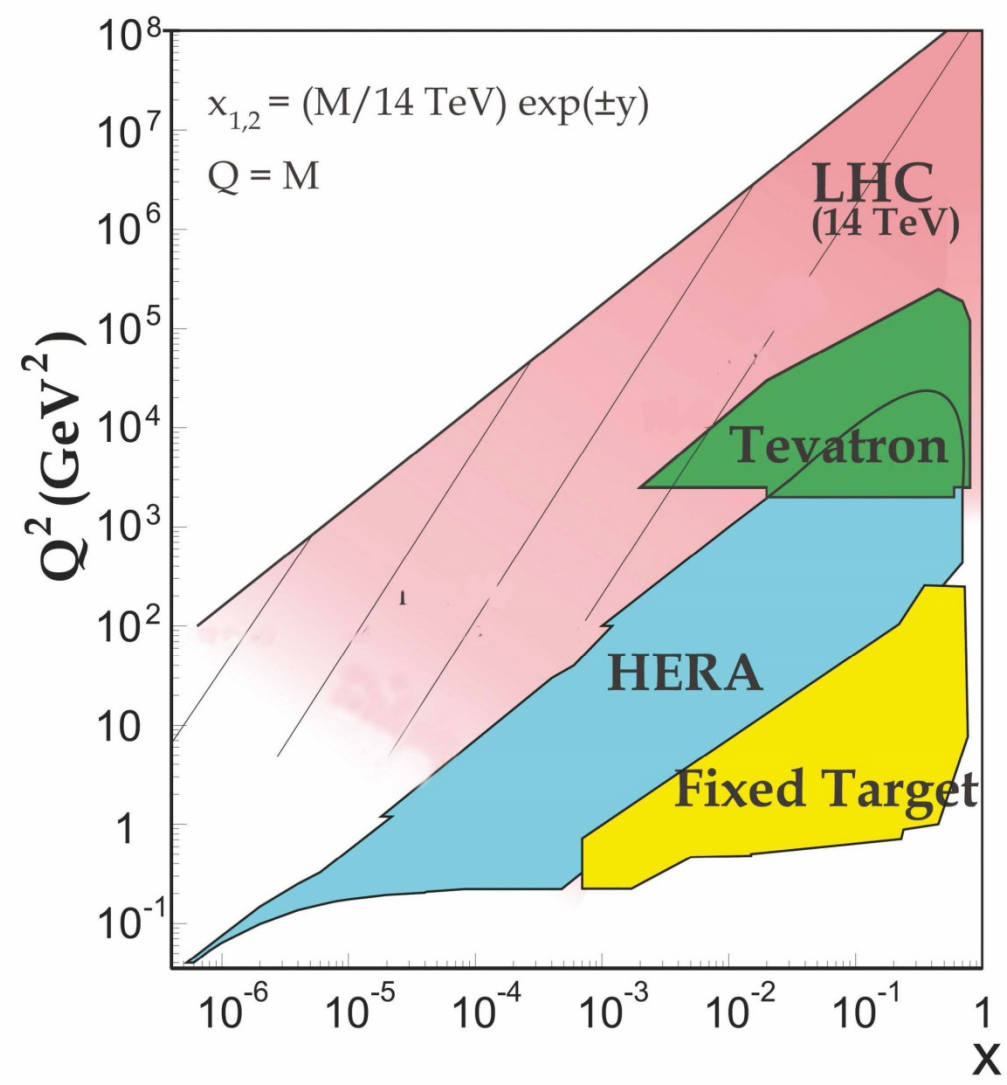
SIDIS experiments, and COMPASS, have given fundamental contributions to the study of the transverse spin and transverse momentum structure of the nucleon

much more will be learned measuring SIDIS at the new facilities
with extremely high precision measurements

in the mean time more can be learned at COMPASS,
performing relevant measurements using
existing data Λ polarisation, weighted asymmetries, fragmentation …
and new data LH_2, and hopefully d↑

new ideas are coming out !


Q^2
(GeV²)
10^2
10
1
10^{-3}
10^{-2}
10^{-1}
1
x
160
27
11
6 GeV/c
$W^2 = 25$
10
4


$x_{1,2} = (M/14\ TeV)\ exp(\pm y)$
Q = M
LHC
(14 TeV)
Tevatron
HERA
Fixed Target
$Q^2\ (GeV^2)$
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x

accessing the Sivers function

direct point-by-point extraction of the Sivers PDFs
from p and d Sivers asymmetries measured at the same x, Q^2

in the Gaussian model

$$A_{Siv}^{h}(x,z,Q^2) = G\, z\, \frac{\sum_q e_q^2 \cdot x\, f_{1T}^{\perp(1)q}(x,Q^2) \cdot D_{1q}^{h}(z,Q^2)}{\sum_q e_q^2 \cdot x f_1^q(x,Q^2) \cdot D_{1q}^{h}(z,Q^2)}$$

$$f_{1T}^{\perp(1)q} = \int d^2\vec{k}_T \frac{k_T^2}{2M^2} f_{1T}^{\perp q}(k_T^2) \qquad G = \frac{\sqrt{\pi}M}{\sqrt{z^2\langle k_T^2\rangle_S + \langle p_T^2\rangle}} \simeq \frac{\pi M}{2\langle P_T\rangle}$$

from data, assumed to be constant

and with the usual assumptions on fav/unfav FFs

pions

$$x f_{1T}^{\perp(1)u_v} = \frac{1}{5G\rho_\pi(1-\beta_\pi^{(1)})}\left[x f_p^{\pi^+} A_p^{\pi^+} - x f_p^{\pi^-} A_p^{\pi^-} + \frac{1}{3}\left(x f_d^{\pi^+} A_d^{\pi^+} - x f_d^{\pi^-} A_d^{\pi^-}\right)\right]$$

similar expressions for $x f_{1T}^{\perp(1)d_v}$ and $x f_{1T}^{\perp(1)\bar{u}} - x f_{1T}^{\perp(1)\bar{d}}$ from **pion**

and for $x f_{1T}^{\perp(1)u_v}$ and $x f_{1T}^{\perp(1)d_v}$ from **kaon** p and d asymmetries

A. M., F. Bradamante, V. Barone, SPIN2016

further results on the Sivers asymmetry

already published:

TSA vs z and p_T in different x ranges

vs x and p_T in different z ranges

vs x and z in different p_T ranges

or in extended kinematical ranges

low z / low y