New COMPASS Results on Transverse Spin Physics

Franco Bradamante

Trieste University & INFN

On behalf of the COMPASS Collaboration

INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS

37th Course

Probing Hadron Structure with Lepton and Hadron Beams

Erice-Sicily: September 16-24, 2015

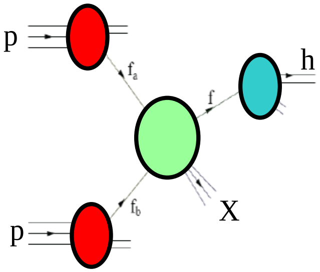
Norbert Nagel

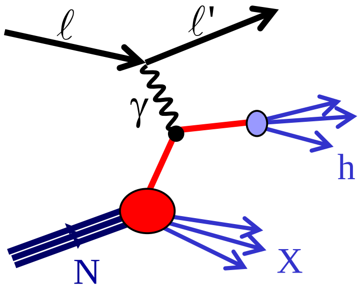
Transverse Spin and Momentum Structure of the Nucleon

a large international theoretical and experimental effort

hard polarised pp scattering

RHIC / BNL



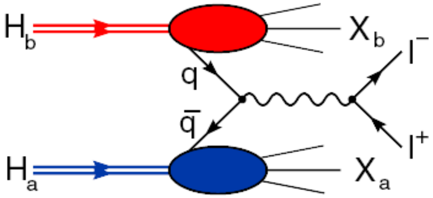


SIDIS off transversely polarised targets

DESY (HERMES)
CERN (COMPASS)
JLab
and ***EIC***

(polarised) Drell-Yan

CERN (COMPASS) TAKING DATA
FUTURE : ***FNAL, JParc, RHIC, JINR, IHEP, GSI***



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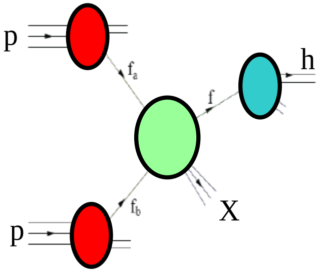

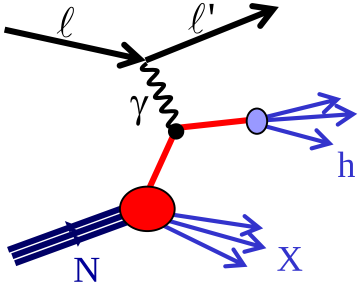

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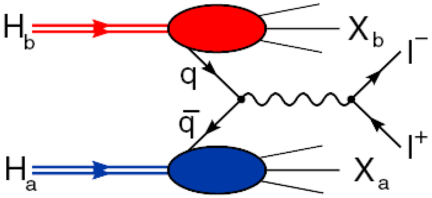
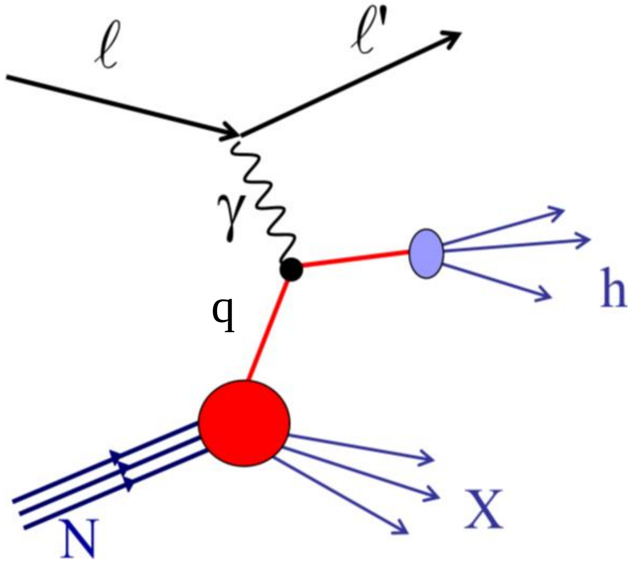
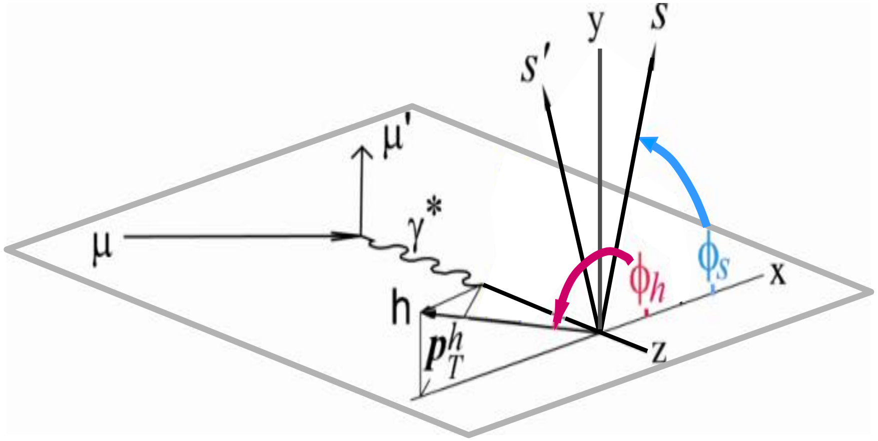


The TMD PDFs can be measured in SIDIS

a simple process, a special tool



$x,\ Q^2;\qquad z,\ P_T^h,\qquad \phi_h,\ \phi_S$

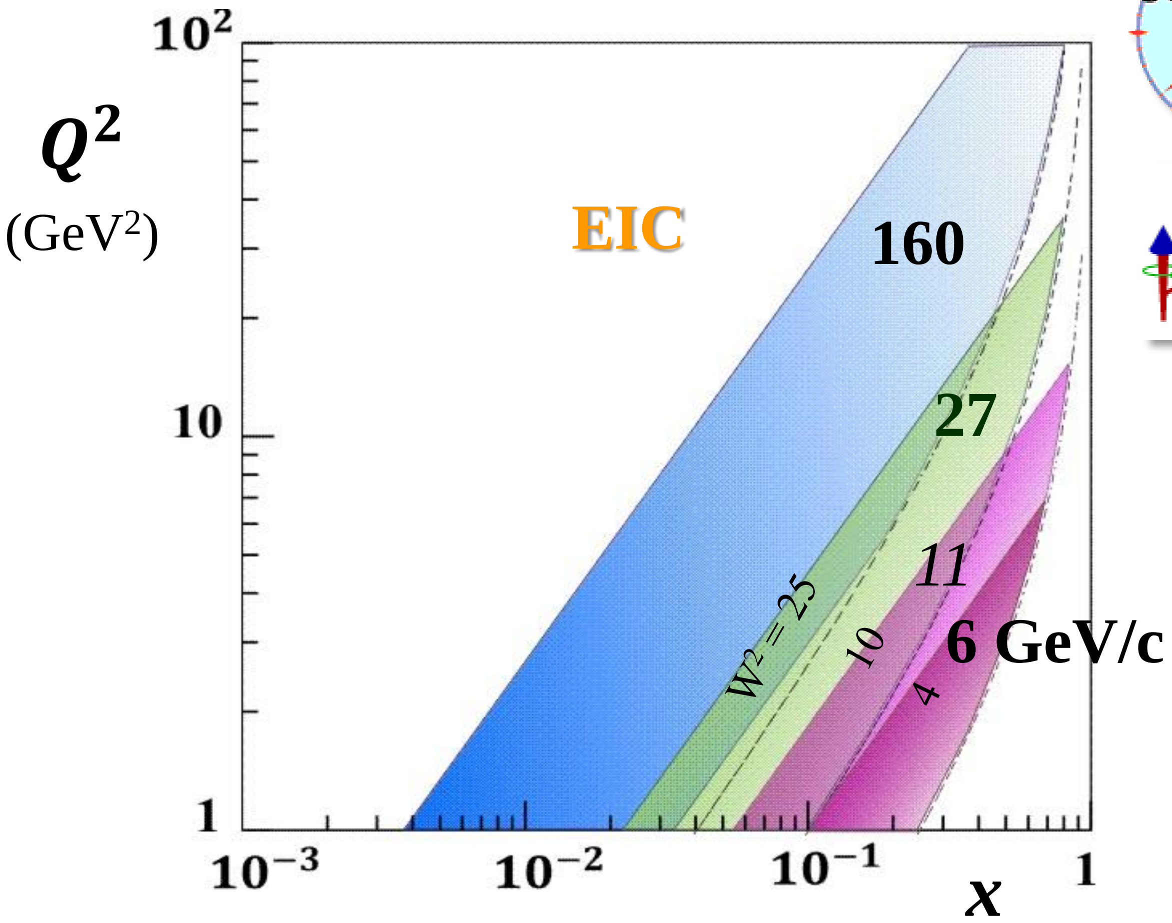


$$d\sigma^{\ell p\to\ell hX} \sim \sum_q e_q^2\, f_q(x,\boldsymbol{k}_\perp)\cdot d\sigma^{\ell q\to\ell q}\cdot D_q^h(z,\boldsymbol{p}_T)$$

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

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

Complementarity of the SIDIS experiments



COMPASS

hermes

Jefferson Lab

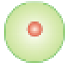
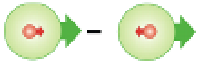
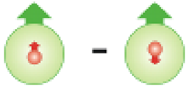
huge activity on TMD Q^2 evolution

Transverse Spin and Momentum Structure of the Nucleon

a large international theoretical and experimental effort

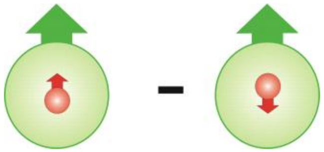
three distribution functions are necessary to describe the quark structure of the nucleon at LO in the **collinear case** **ALL OF EQUAL IMPORTANCE !**

transversity PDF $\Delta_T q$ or h_1 : correlation between the transverse spin of the nucleon and the transverse spin of the quark

		nucleon polarisation		
		U	L	T
	U	f_1  *number density* q		
quark polarisation	L		g_1  *helicity* Δq	
	T			h_1  *transversity*

$\Delta_T q$

Transversity PDF



- **correlation between the transverse spin of the nucleon and the transverse spin of quarks**

- **proposed in ’77** (Ralston & Soper)

- **different properties than helicity**
  - chiral-odd, cannot be measured in inclusive DIS
  - no contribution from the gluons
  - first moment: tensor charge   (being computed on the lattice)

- **first ideas on possible measurements in the 90s (Collins, …)**

- **first measurements in 2005**

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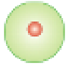
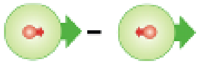
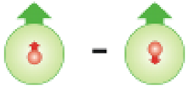
***nucleon** polarisation*

		U	L	T
	U	f_1  *number density* q		
***quark** polarisation*	L		g_1  *helicity* Δq	
	T			h_1  *transversity*

$\Delta_T q$

Transverse Spin and Momentum Structure of the Nucleon

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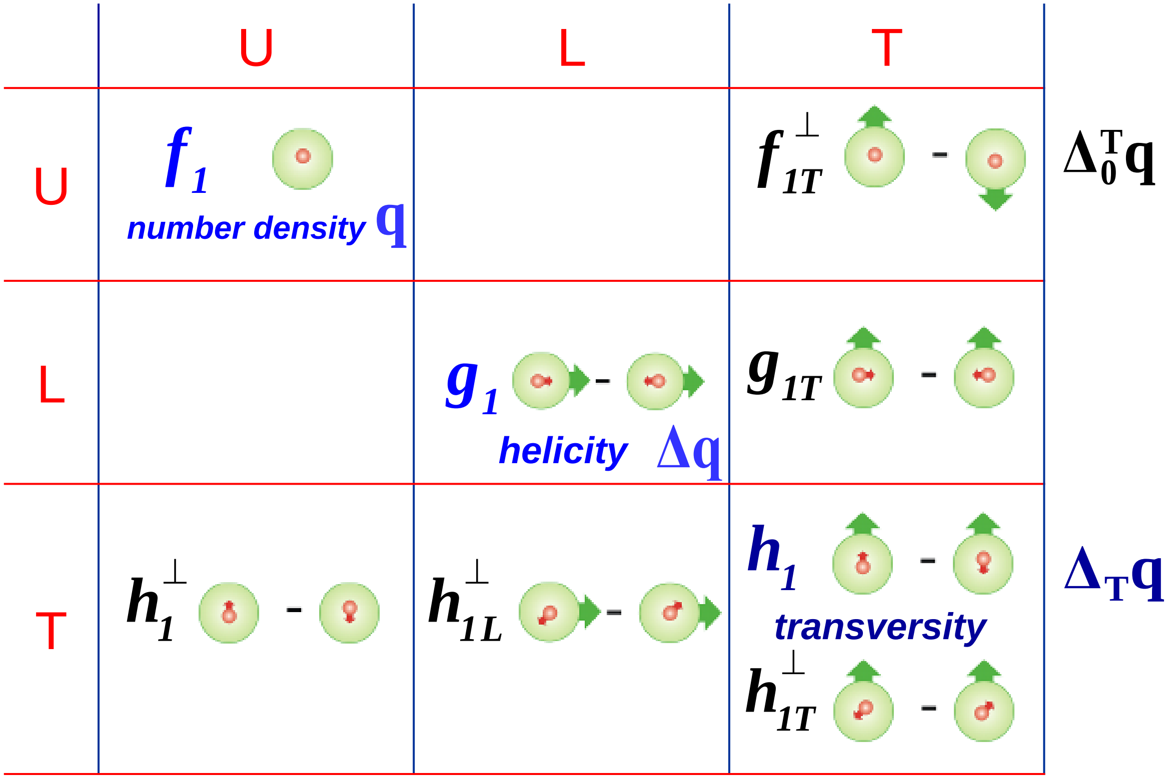
transversity PDF $\Delta_T q$ or h_1 : correlation between the transverse spin of the nucleon and the transverse spin of the quark

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

the new 5 TMD PDFs" vanish when integrating over the transverse momentum



nucleon polarisation

quark polarisation

	U	L	T	
U	f_1 *number density* q		$f_{1T}^{\perp}$ -	$\Delta_0^T q$
L		g_1 - *helicity* Δq	g_{1T} -	
T	$h_1^{\perp}$ -	$h_{1L}^{\perp}$ -	h_1 - *transversity* $h_{1T}^{\perp}$ -	$\Delta_T q$

Transverse Spin and Momentum Structure of the Nucleon

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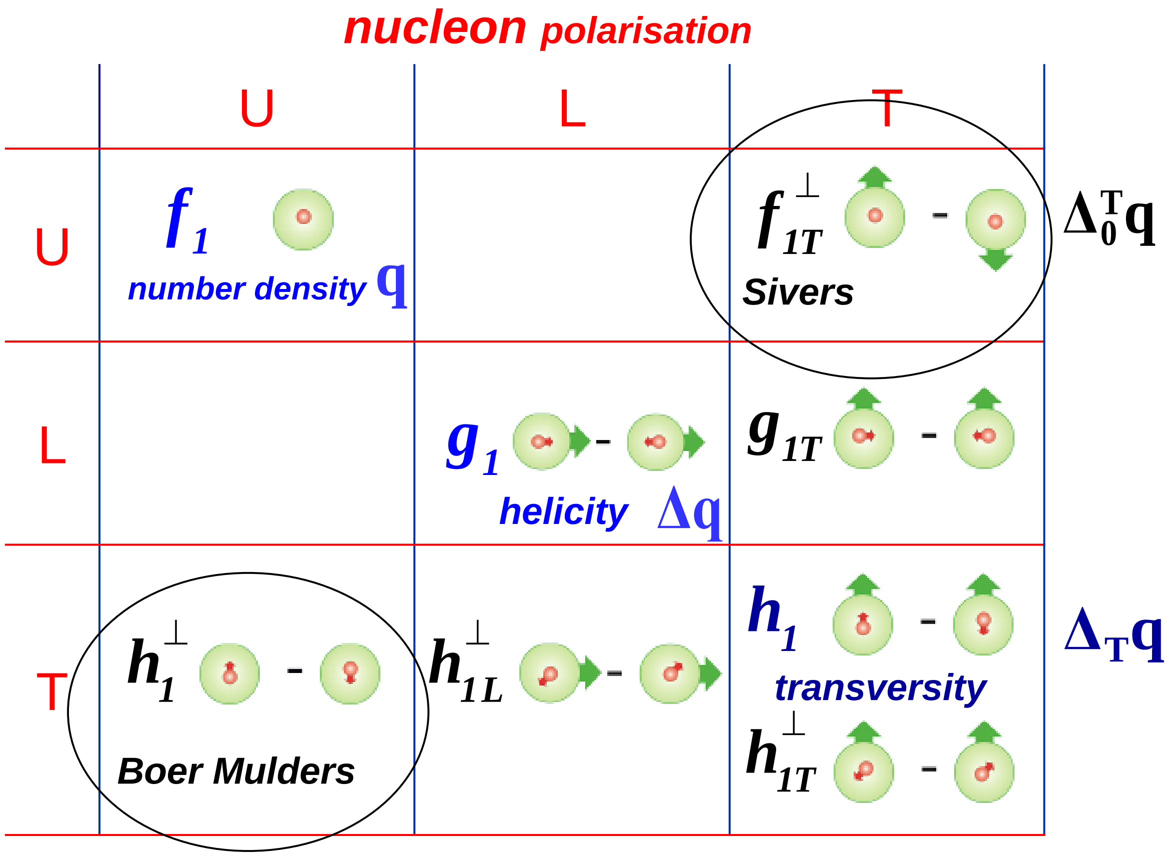
transversity PDF $\Delta_T q$ or h_1 : correlation between the transverse spin of the nucleon and the transverse spin of the quark

Boer-Mulders function $h_1^\perp$
correlation between the transverse spin and the transverse momentum of the quark in unpol nucleons

T-odd TMDs

Sivers function $f_{1T}^\perp$
correlation between the transverse spin of the nucleon and the transverse momentum of the quark



nucleon polarisation

quark polarisation

	U	L	T	
U	f_1 *number density* q		$f_{1T}^\perp$ - *Sivers*	$\Delta_0^T q$
L		g_1 - *helicity* Δq	g_{1T} -	
T	$h_1^\perp$ - *Boer Mulders*	$h_{1L}^\perp$ -	h_1 - *transversity* $h_{1T}^\perp$ -	$\Delta_T q$

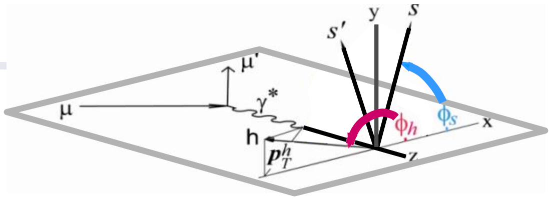
Sivers PDF $f_{1T}^{\perp}$

- correlation between the transverse spin of the nucleon and the transverse momentum of the parton
- introduced in 1992, demonstrated it can be different from zero in 2002
- requires final/initial state interactions
- being T-odd, time-reversal invariance implies:

$$f_{1T}^{\perp}\Big|_{SIDIS} = -f_{1T}^{\perp}\Big|_{DY}$$

… to be checked

SIDIS cross-section



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

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

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

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

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

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

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

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

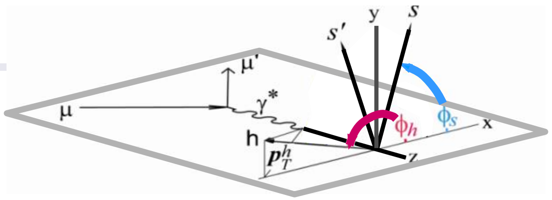
$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\},$$

18 structure functions F_{XY}^{Z}

A Bacchetta et al., 2006

Franco Bradamante

SIDIS cross-section



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

18 structure functions F_{XY}^{Z}

14 different azimuthal modulations

all measured

A Bacchetta et al., 2006

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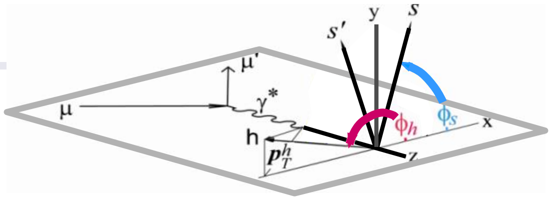
SIDIS cross-section



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

$f_1 \otimes D_1$

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

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

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

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

$g_1 \otimes D_1$

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

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

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

$h_1 \otimes H_1^\perp$

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

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

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

$g_{1T} \otimes D_1$

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

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

18 structure functions F_{XY}^{Z}

14 different azimuthal modulations

all measured

LO: the structure functions are convolutions of TMD PDFs and FFs

A Bacchetta et al., 2006

SIDIS

MAJOR RESULT: in the past 10 years
2 of these new PDF’s have been measured
and shown to be different from zero

by COMPASS and HERMES

the **transversity** PDF

the **Sivers** PDF

A STEP TOWARDS
THE 3-D STRUCTURE OF THE NUCLEON

SIDIS

MAJOR RESULT: in the past 10 years
2 of these new PDF's have been measured
and shown to be different from zero

by COMPASS and HERMES

the transversity PDF amplitude of the sine modulation in $\phi_h + \phi_s - \pi$

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

the Sivers PDF amplitude of the sine modulation in $\phi_h - \phi_s$

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

A STEP TOWARDS
THE 3-D STRUCTURE OF THE NUCLEON

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

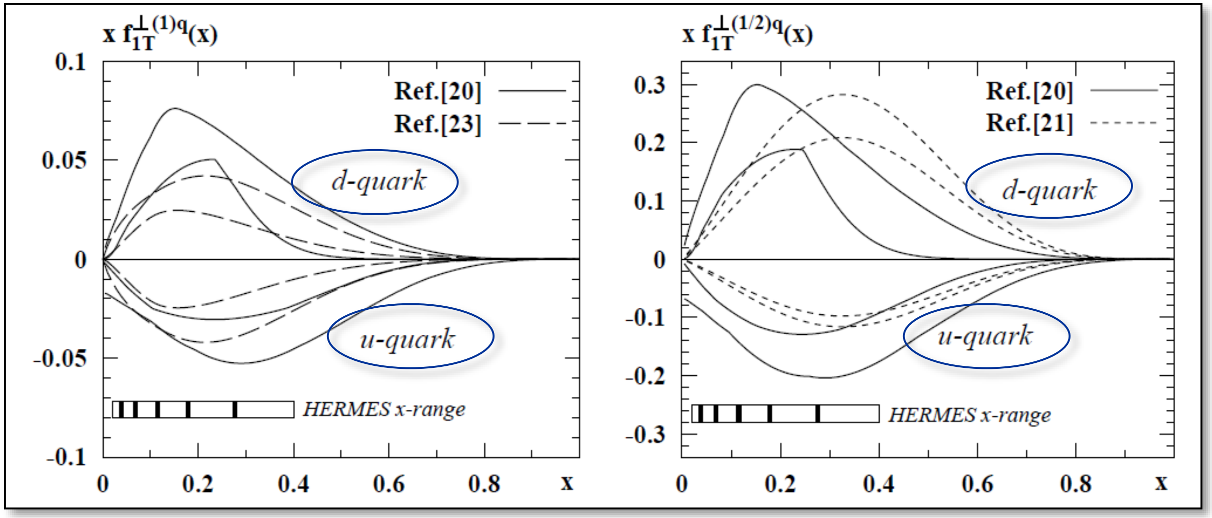
2004: first evidence for non-zero values on proton

compatible with zero on deuteron

data well described by theory

2005: first extractions of the Sivers function

Anselmino et al, proceedings of Transversity2005 hep-ph/0511017



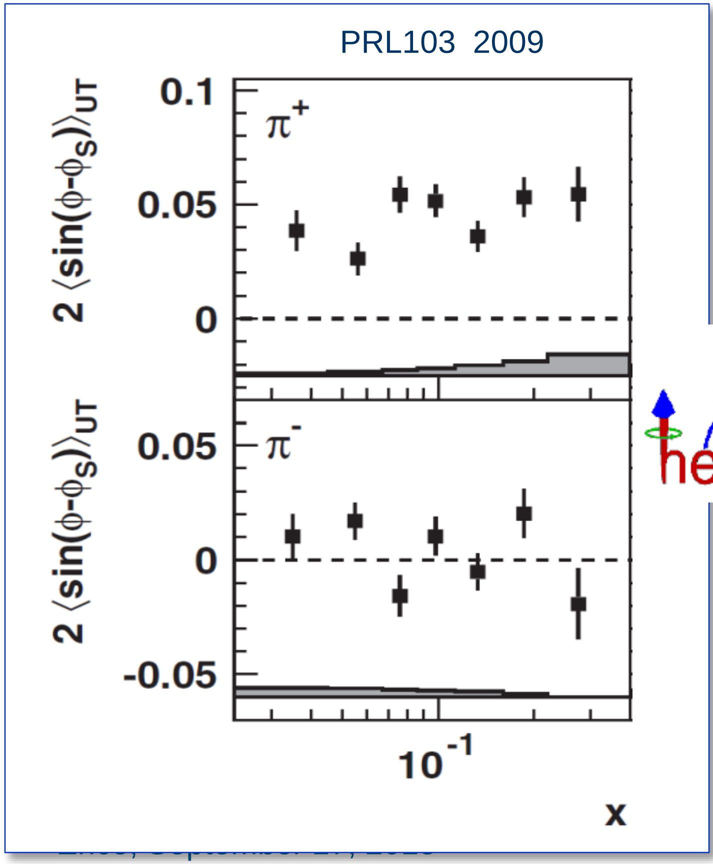
~ opposite
u- and d-quark
contributions

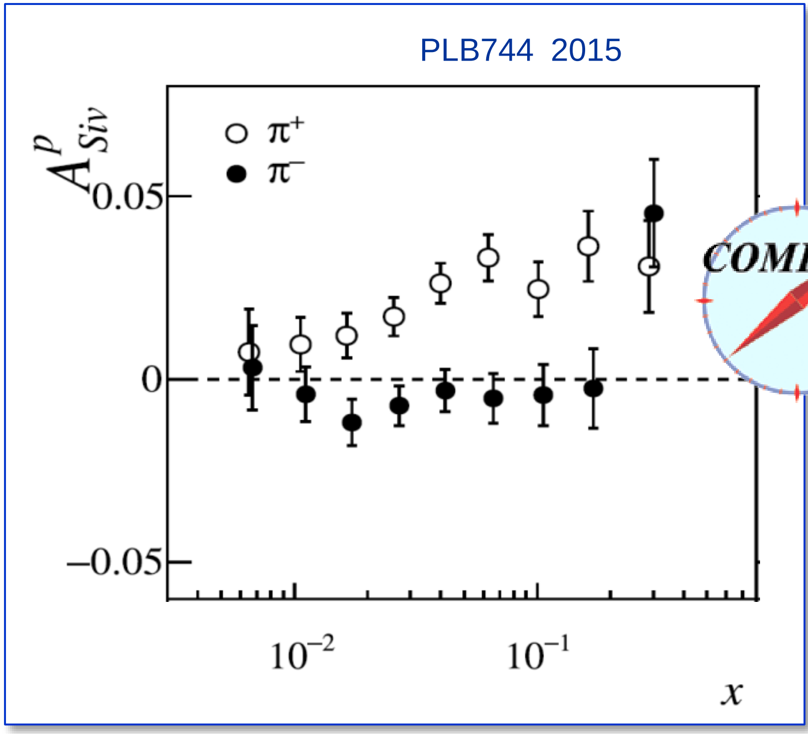
Sivers asymmetry $\sim f_{1T}^{\perp} \otimes D_1$

2004: first evidence for non-zero values on proton

compatible with zero on deuteron

final results on proton $z > 0.2$


PRL103 2009


PLB744 2015

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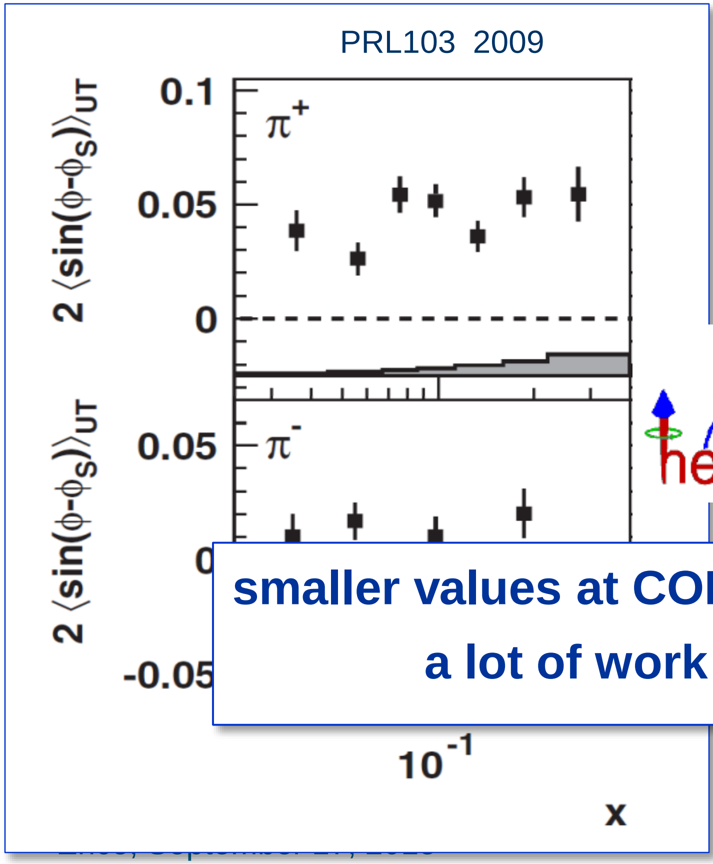
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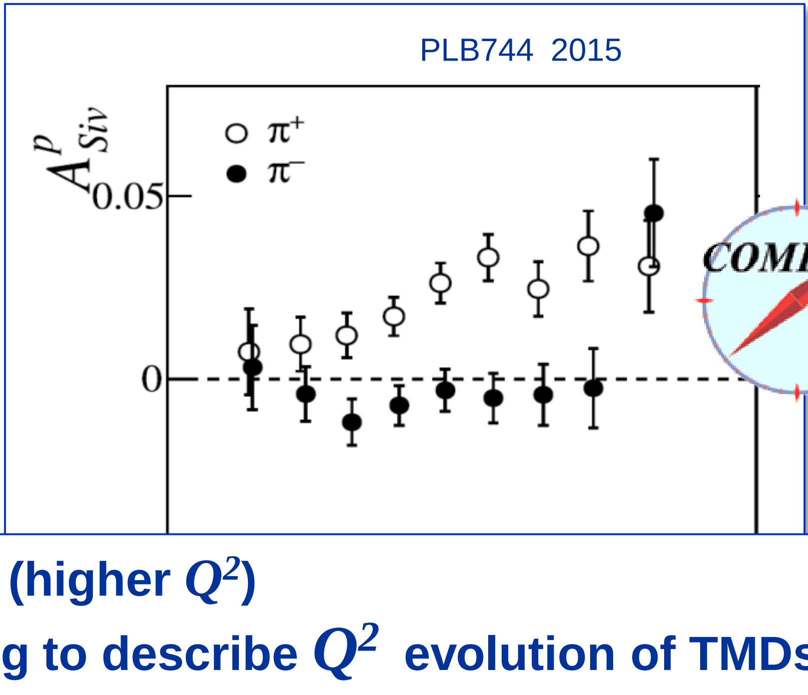

PLB744 2015

smaller values at COMPASS (higher Q^2)

a lot of work ongoing to describe Q^2 evolution of TMDs

Sivers function

from COMPASS and HERMES SIDIS data

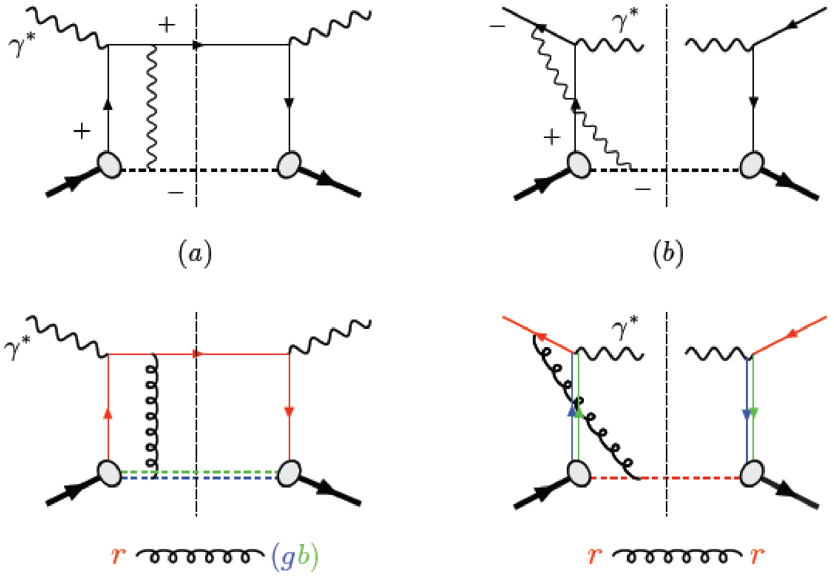
it is clearly different from zero – *in spite it is T-odd*

final state interactions, gauge link

process-dependence of Sivers functions

DIS: "attractive"

D-Y: "repulsive"



$$[f_{1T}^{q\perp}]_{\rm SIDIS} = -[f_{1T}^{q\perp}]_{\rm DY}$$

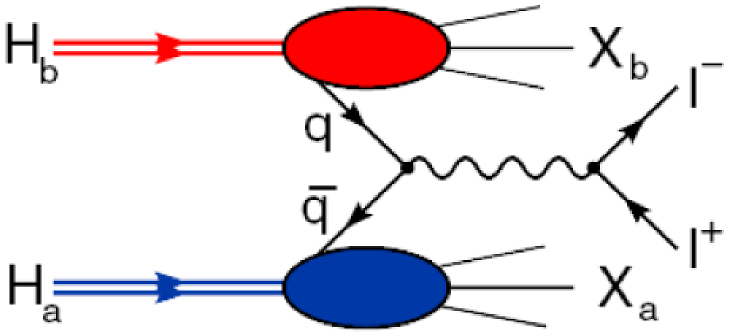
Sivers function

from COMPASS and HERMES SIDIS data

it is cleary different from zero -- in spite it is T-odd

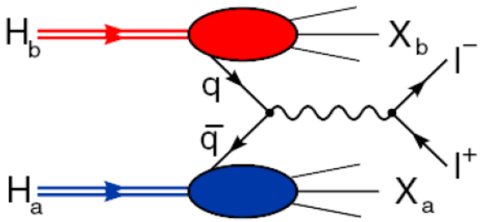
final state interactions, gauge link

change of sign when measured in the **Drell-Yan process**



COMPASS - **data taking ongoing !**
RHIC
FNAL
future: FAIR, JPark, NICA

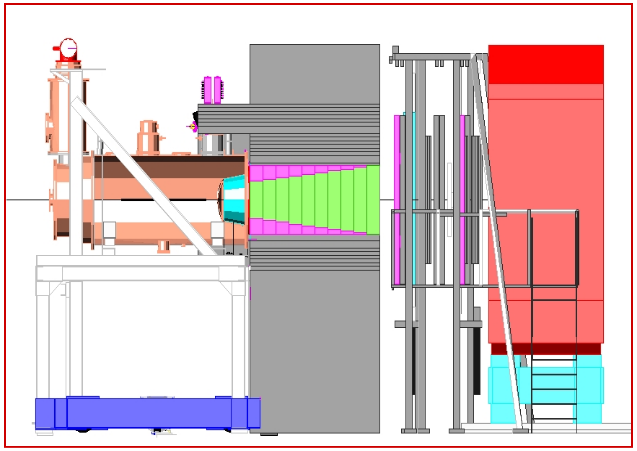
Drell-Yan at COMPASS



190 GeV π^- beam

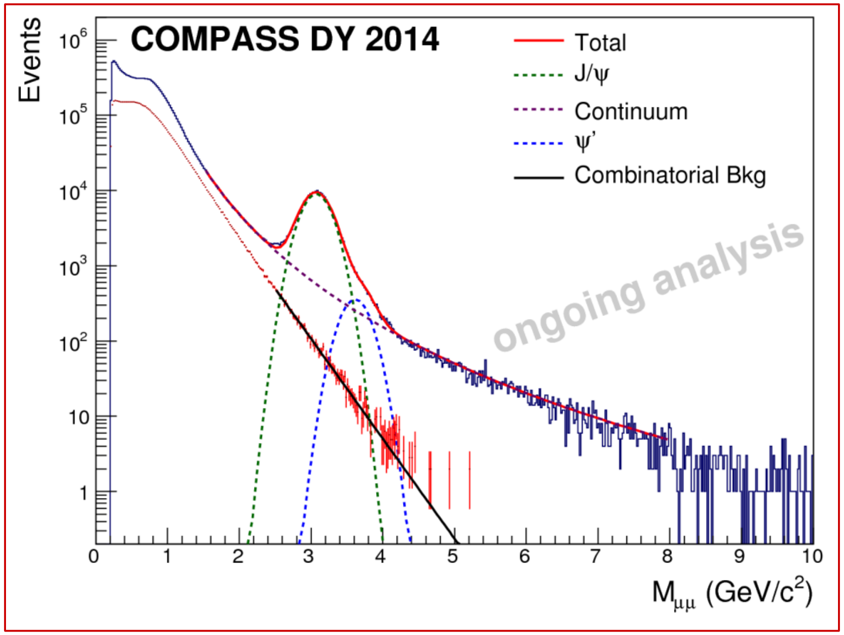
transversely polarised proton (NH3) target

thick hadron absorber



several azimuthal asymmetries

in particular the amplitude of the $\sin\phi_{CS}$ modulation is $\sim \boldsymbol{f_{1/\pi} \otimes f^{\perp}_{1T/p}}$



"golden region" $M_{inv} > 4$ GeV

Drell-Yan run 2015 ongoing

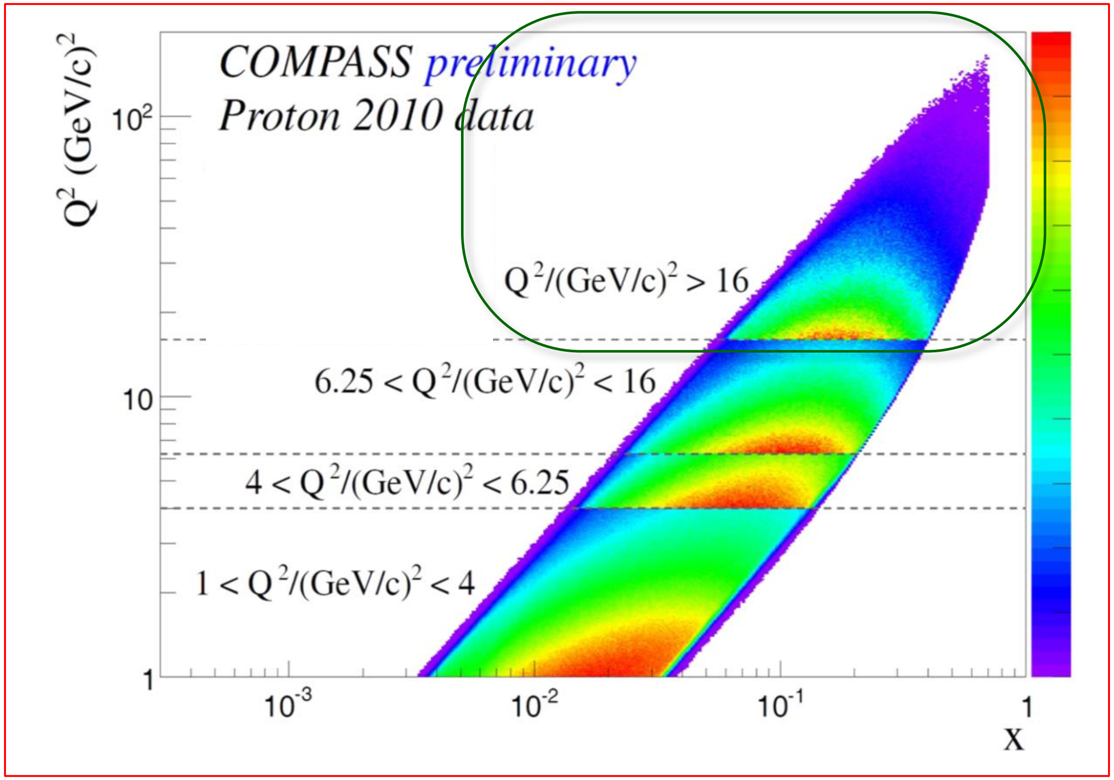
Sivers function still different from zero ? … **Q^2 evolution…**

Sivers asymmetry – Drell-Yan range

COMPASS has measured the TSA in the 4 Q^2 ranges of the "future" Drell-Yan experiment

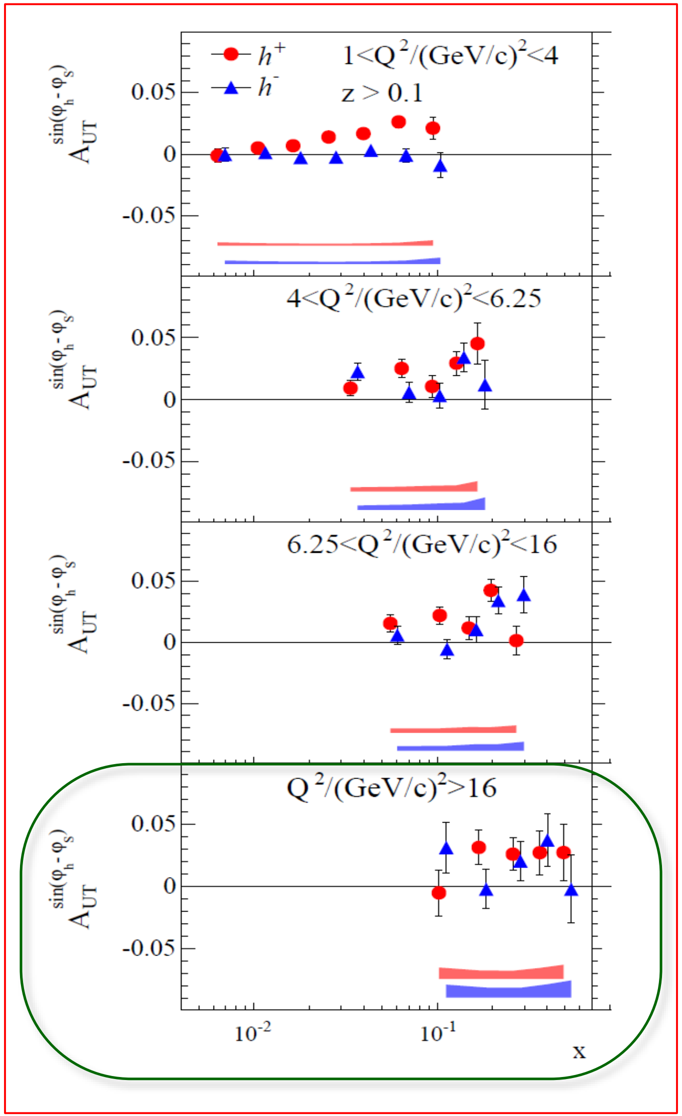
"golden" region: $Q^2 > 16$ GeV^2

Transversity 2014



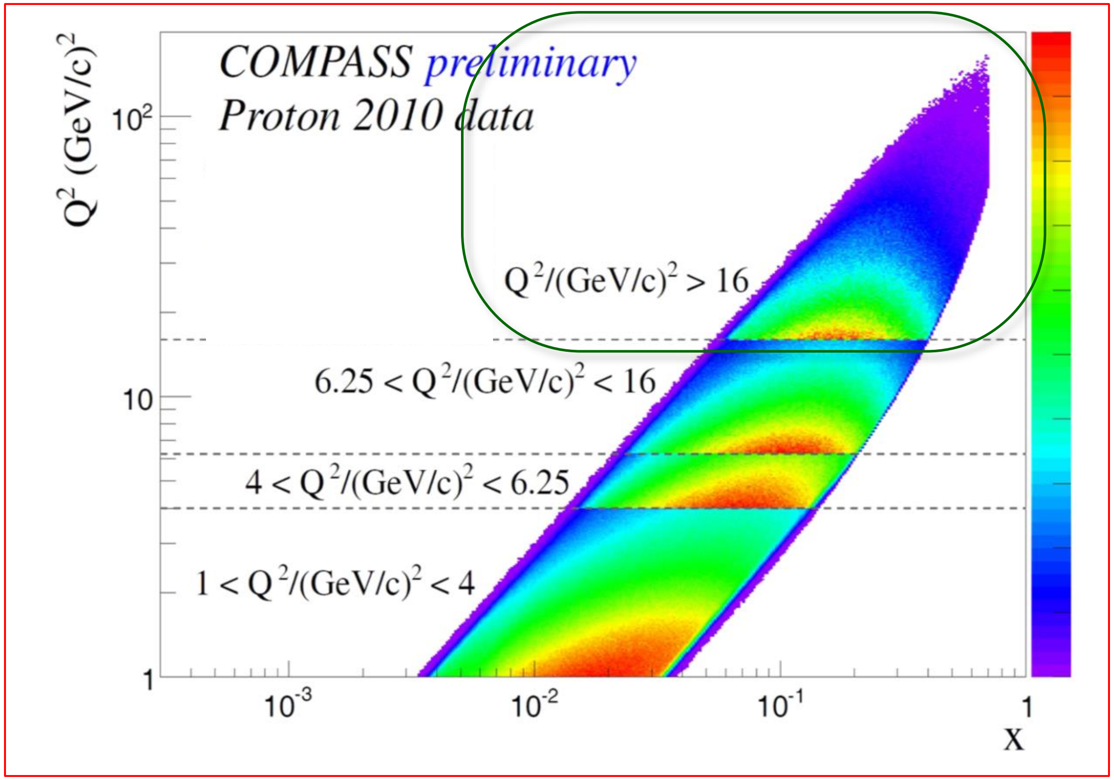
Sivers asymmetry – Drell-Yan range

COMPASS has measured the TSA in the 4 Q^2 ranges of the "future" Drell-Yan experiment



"golden" region: $Q^2 > 16$ GeV^2

Transversity 2014



clearly positive
test of change of sign feasible

SIDIS

MAJOR RESULT: in the past 10 years 2 of these new PDF’s have been measured and shown to be different from zero

by COMPASS and HERMES

the transversity PDF amplitude of the sine modulation in $\phi_h + \phi_s - \pi$

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

the Sivers PDF amplitude of the sine modulation in $\phi_h - \phi_s$

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

A STEP TOWARDS
THE 3-D STRUCTURE OF THE NUCLEON

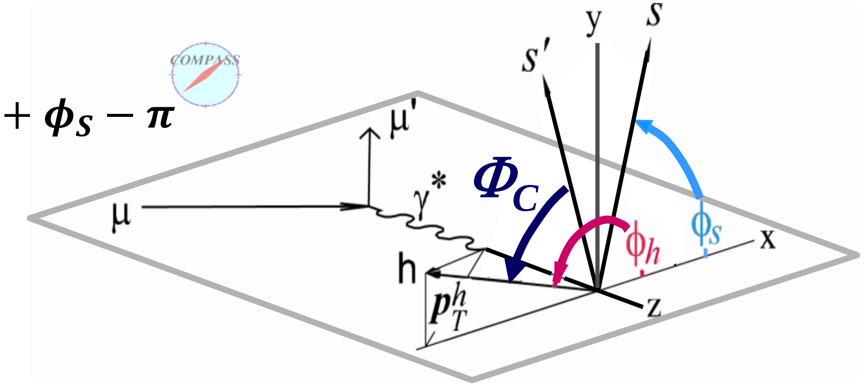
how has TRANSVERSITY been measured

the observable in SIDIS is the "Collins asymmetry"

amplitude of the $\sin\Phi_C$ modulation

in the azimuthal distribution
of the final state hadrons

$$\Phi_C = \phi_h + \phi_S - \pi$$



$$A_{Coll} \approx \frac{\sum_q e_q^2 \; h_1^q \otimes H_{1q}^{\perp}}{\sum_q e_q^2 \; f_1^q \otimes D_q}$$

the best way to access transversity

how has TRANSVERSITY been measured

the observable in SIDIS is the "Collins asymmetry"

amplitude of the $\sin\Phi_C$ modulation

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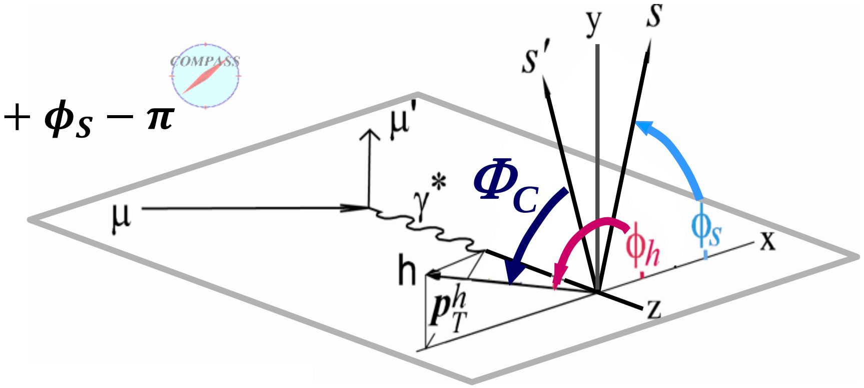
$$\Phi_C = \phi_h + \phi_S - \pi$$



transversity

Collins FF, chiral odd

$$A_{Coll} \approx \frac{\sum_q e_q^2 \; h_1^q \otimes H_{1q}^{\perp}}{\sum_q e_q^2 \; f_1^q \otimes D_q}$$

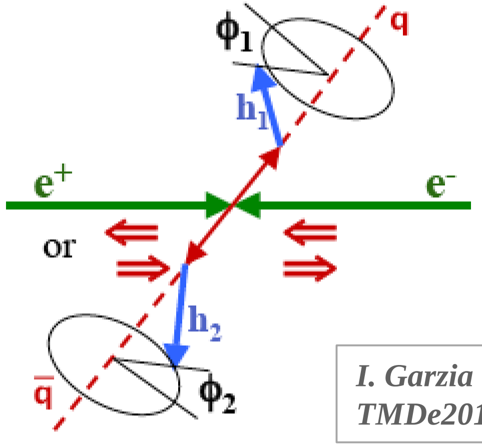
left-right asymmetry
of the hadrons in the hadronization process
of a transversely polarized quark

➔ **QUARK POLARIMETRY**

assessed in e^+e^- annihilation into hadrons

the best way to access transversity

Collins FF – e^+e^- annihilation into hadrons

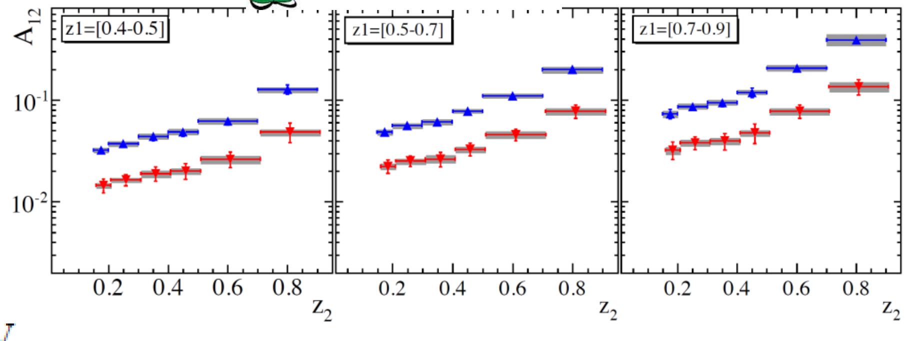


I. Garzia
TMDe2015

$$\approx H_1^\perp \otimes H_1^\perp$$

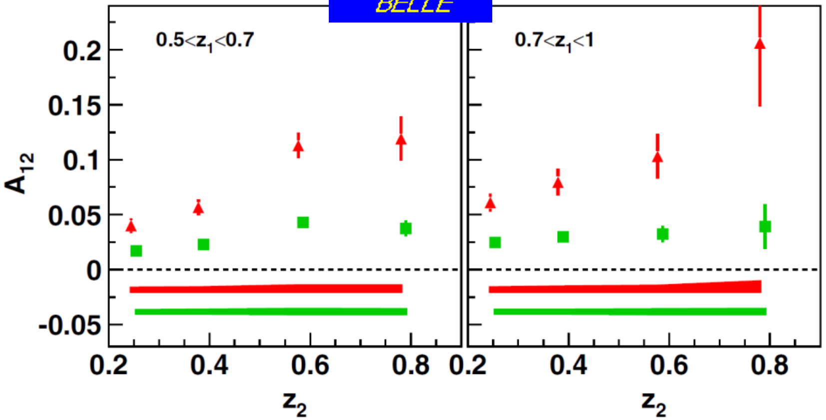
BABAR

PRD90 2014



√s=10.58 GeV

BELLE



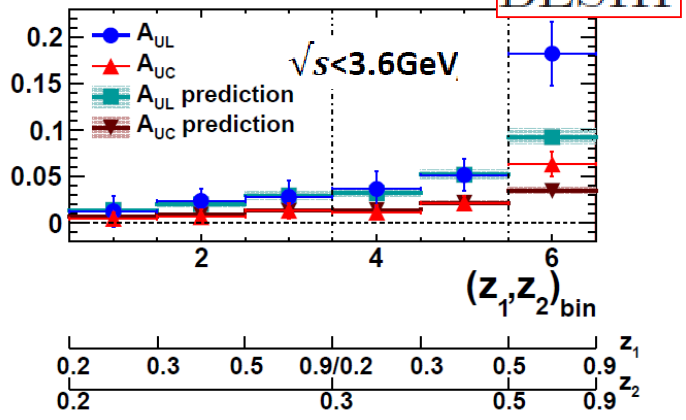
PRD78, 2008 PRD86, 2012

Unlike-sign couples / Like-sign couples

Unlike-sign couples / All charges

arXiv:1507.06824

BESIII

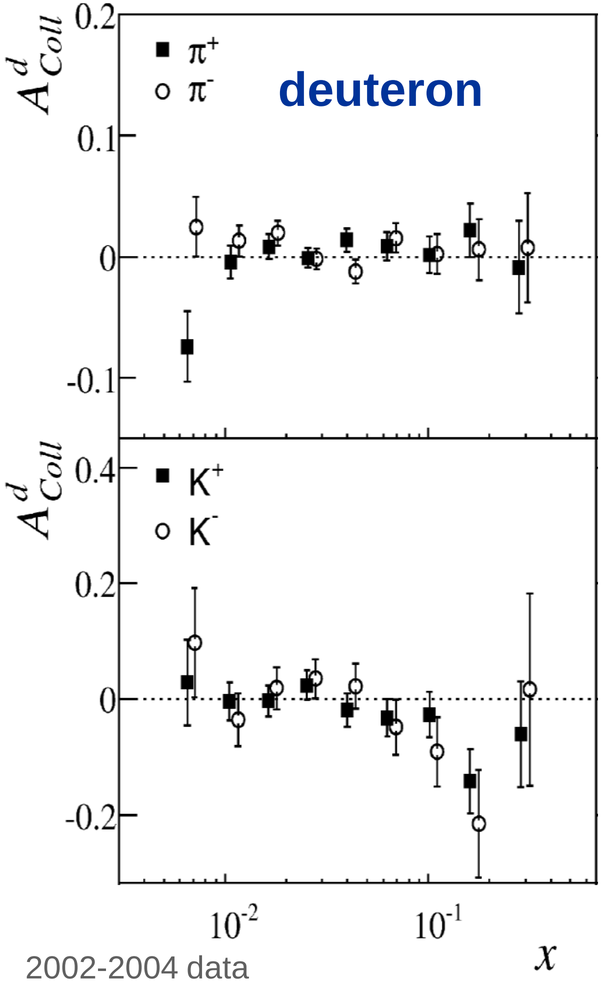


Collins asymmetry

$\sim h_1 \otimes H_1^\perp$

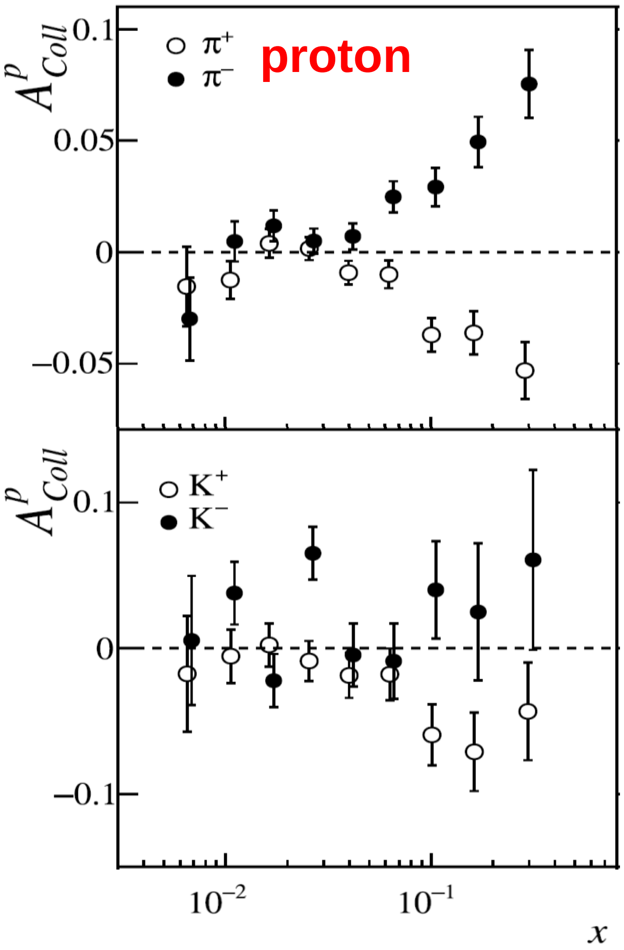
2004: first evidence for non-zero Collins asymmetry on p from HERMES

final COMPASS results



2002-2004 data

NPB765 2007, PLB673 2009



PLB693 2010

PLB744 2015

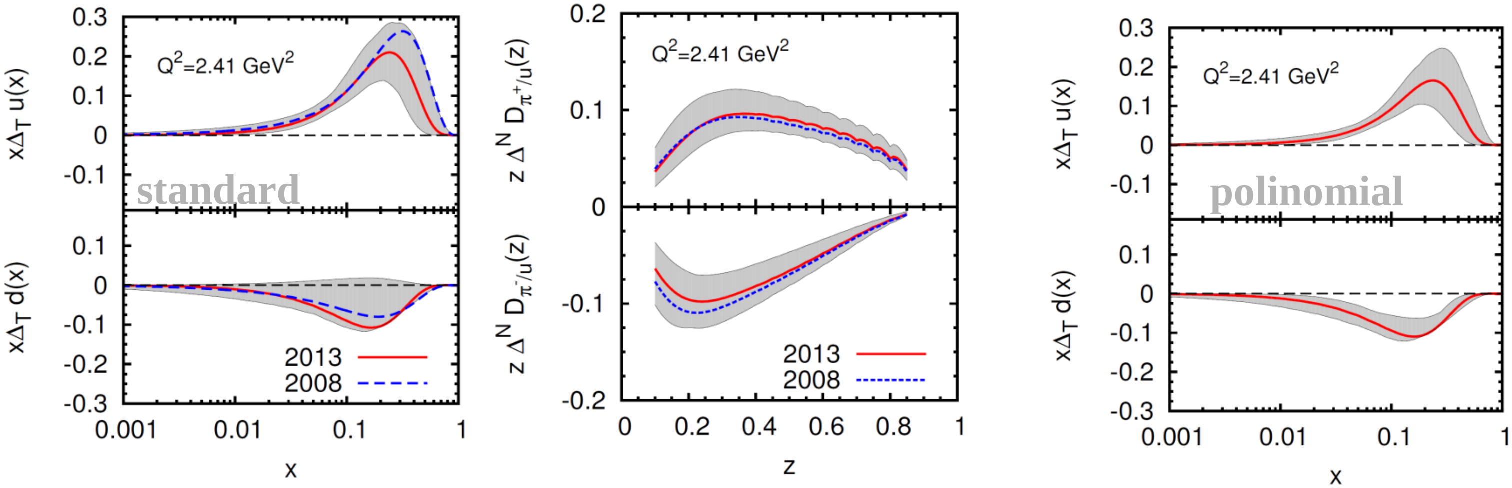
Franco Bradamante

Transversity from SIDIS Collins asymmetry

simultaneous fit of HERMES p, COMPASS p & d, and Belle data
parametrisations of Transversity and Collins functions

very good χ^2

Anselmino et al.,
PRD87 2013



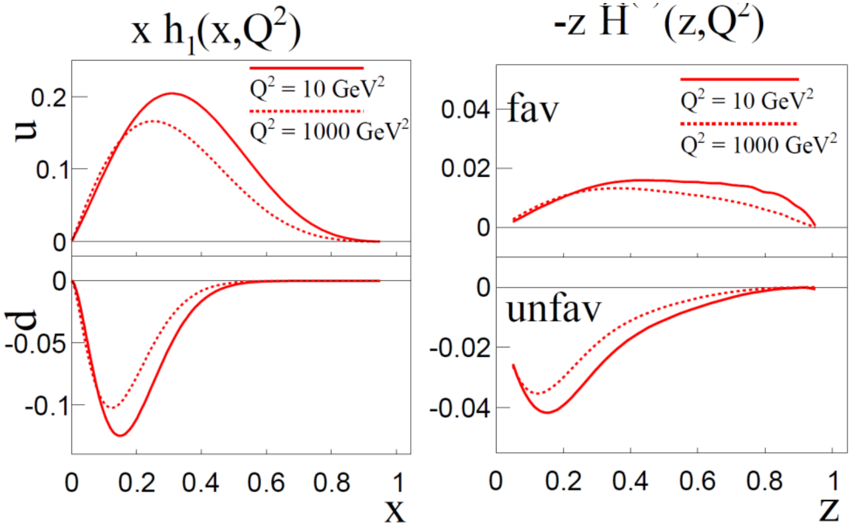
$$\delta u = 0.39^{+0.18}_{-0.12} \qquad \delta d = -0.25^{+0.30}_{-0.10}$$

$$\delta u = 0.31^{+0.16}_{-0.12} \qquad \delta d = -0.27^{+0.10}_{-0.10}$$

Kang et al, PRD91 2015

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

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



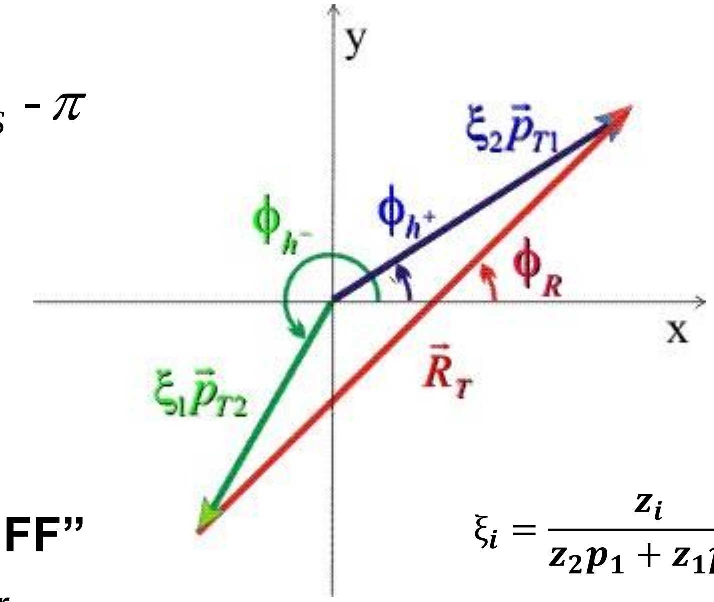
higher order corrections, x z

dihadron asymmetry

alternative way to access **transversity**
in SIDIS off transversely polarised nucleons

dihadron asymmetry

alternative way to access **transversity**
in SIDIS off transversely polarised nucleons



azimuthal asymmetry in $\Phi_{RS} = \phi_R + \phi_S - \pi$

$$N^{\pm}(\Phi_{RS}) = N^0 \cdot \{1 \pm P_T D \cdot A_{RS} \cdot \sin\Phi_{RS}\}$$

$$\xi_i = \frac{z_i}{z_2 p_1 + z_1 p_2}$$

“Interference / Di-hadron FF”

Belle Babar

$$A_{RS} \approx \frac{\sum_q e_q^2 \; h_1^q \cdot H_q^{\angle}}{\sum_q e_q^2 \; f_1^q \cdot D_q^{2h}}$$

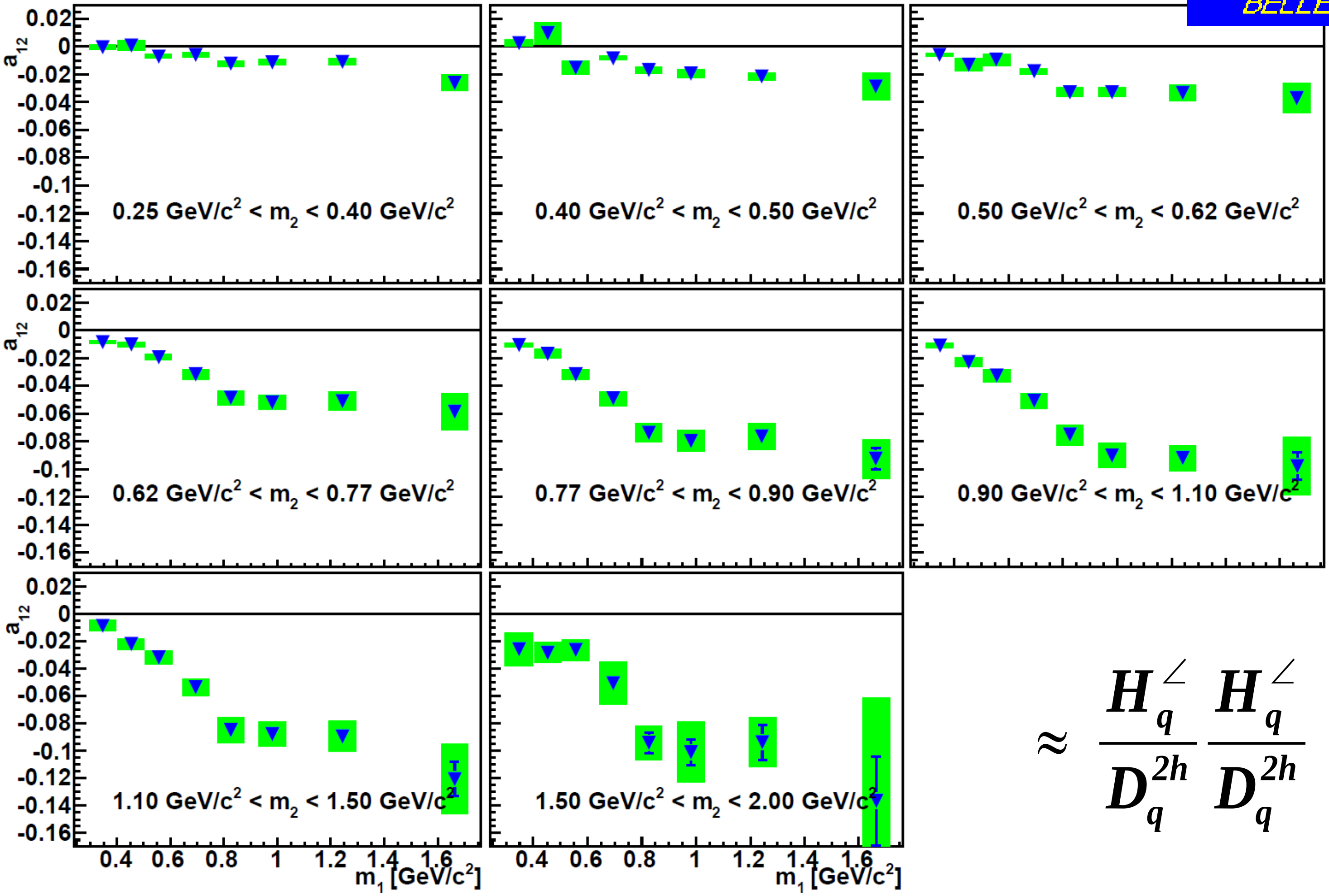
“spin independent di-hadron FF”

being measured at Belle Babar COMPASS

A. Bacchetta, M. Radici, hep-ph/0407345
X. Artru, hep-ph/0207309

dihadron asymmetry

again essential information is coming
from the B-factories

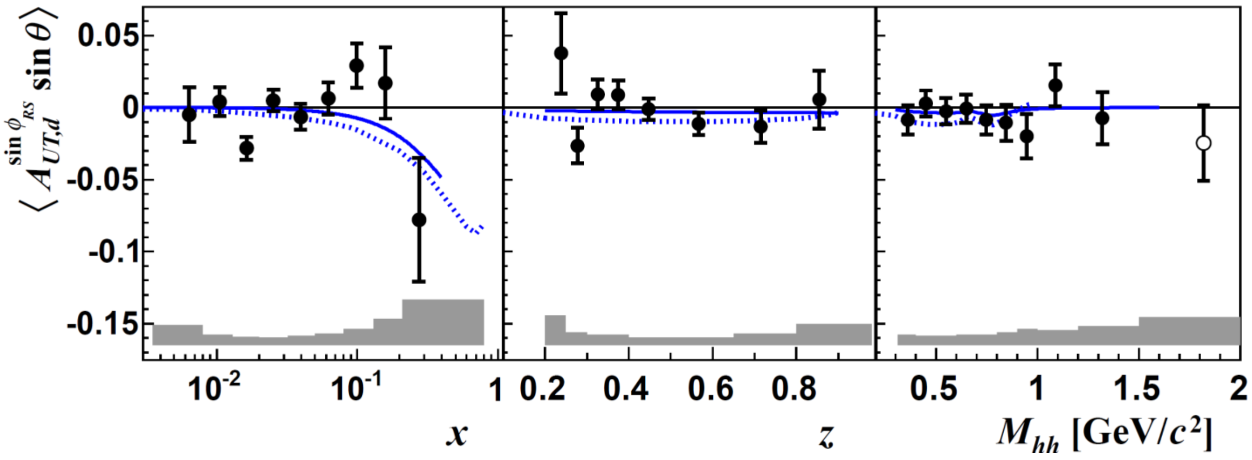


$$\approx \frac{H_q^{\angle}}{D_q^{2h}} \frac{H_q^{\angle}}{D_q^{2h}}$$

dihadron asymmetry

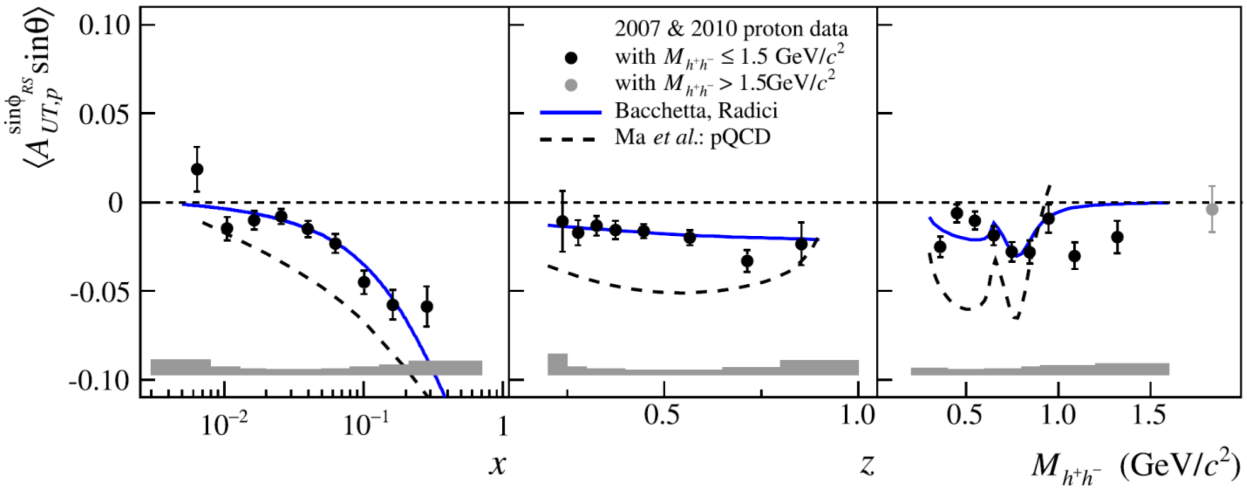
2008: first evidence for non-zero di-h FF on p from HERMES, low statistics

final COMPASS results



deuteron:

compatible with zero



proton:

same sign and shape

slightly higher
than Collins asymmetry
for h^+

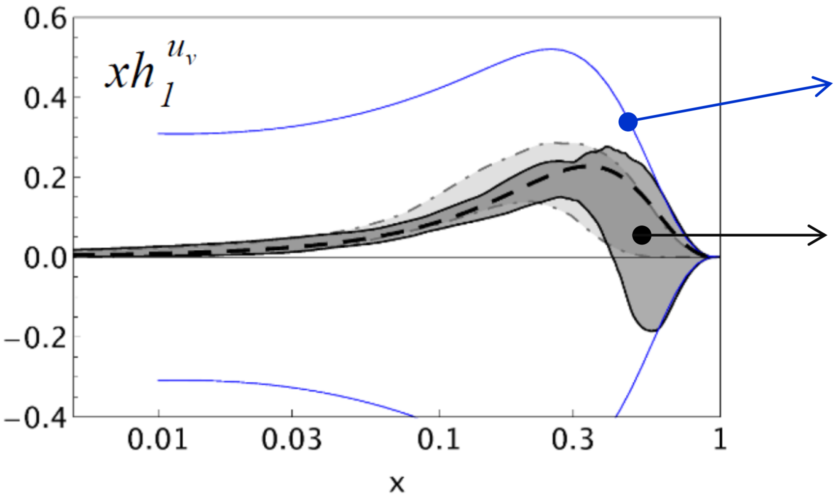
PLB 713 2012, PLB736 2014

Transversity from di-hadron asymmetry

Transversity from di-hadron asymmetry

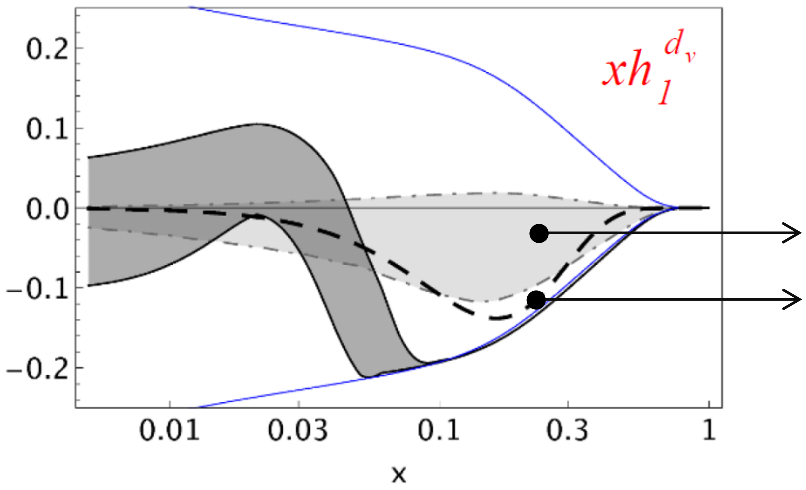
fit of linear combinations from HERMES p, COMPASS p & d, and Belle data

Radici, Courtoy, Bacchetta, Guagnellia, JHEP 1505 2015



Soffer bound

flexible scenario, $Q^2=2.4$ GeV^2



low statistics d data

Anselmino et al., PRD87 2013

Kang et al, PRD91 2015

Transversity from Collins and di-hadron asymmetries

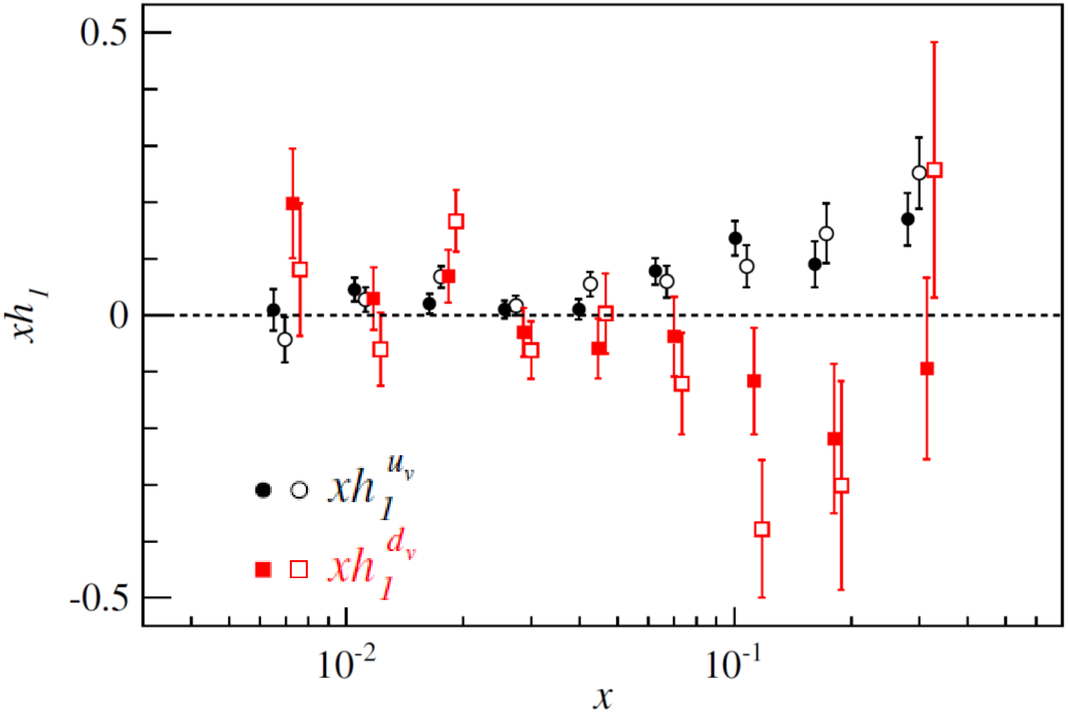
point by point extraction

Transversity from Collins and di-hadron asymmetries

point by point extraction

one can use directly the COMPASS p and d asymmetries,
and the Belle data to evaluate the analysing power
(with some “reasonable” assumptions)

advantage: no MC nor parametrisation is needed



open points: dihadron
closed points: Collins

Martin Bradamante Barone
PRD91 2015

Transversity from Collins and di-hadron asymmetries

New speculations:
are the Collins and the di-hadron asymmetries independent ?

COMPASS Collaboration

Como 2013, DSpin2013, PLB 736 2014, SPIN 2014,

CERN-PH-EP/2015-199 hep-ex/1507.07593

interplay

between Collins and di-hadron asymmetries

known intriguing results

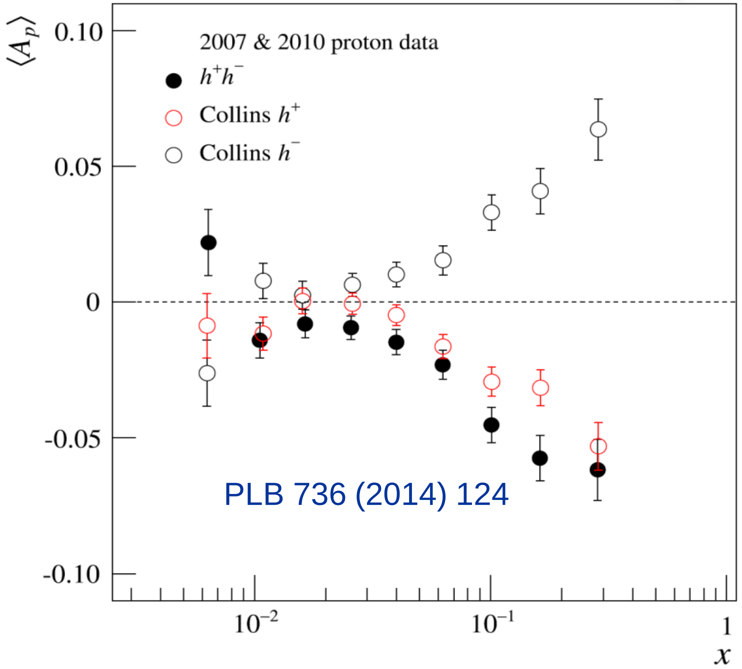
- Collins asymmetry for h^+ and for h^-

  “mirror symmetry”

- di-hadron asymmetry

  only somewhat larger than
  h^+ Collins asymmetry

→ similar analysing powers



PLB 736 (2014) 124

hints for a common origin
of the Collins FF and Di-hFF

interplay between Collins and di-hadron asymmetries

four steps:

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

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

   $\mu p \rightarrow \mu' h^+ h^- X$ → h^+ Collins-Like asymmetry

   → use of the 2h sample

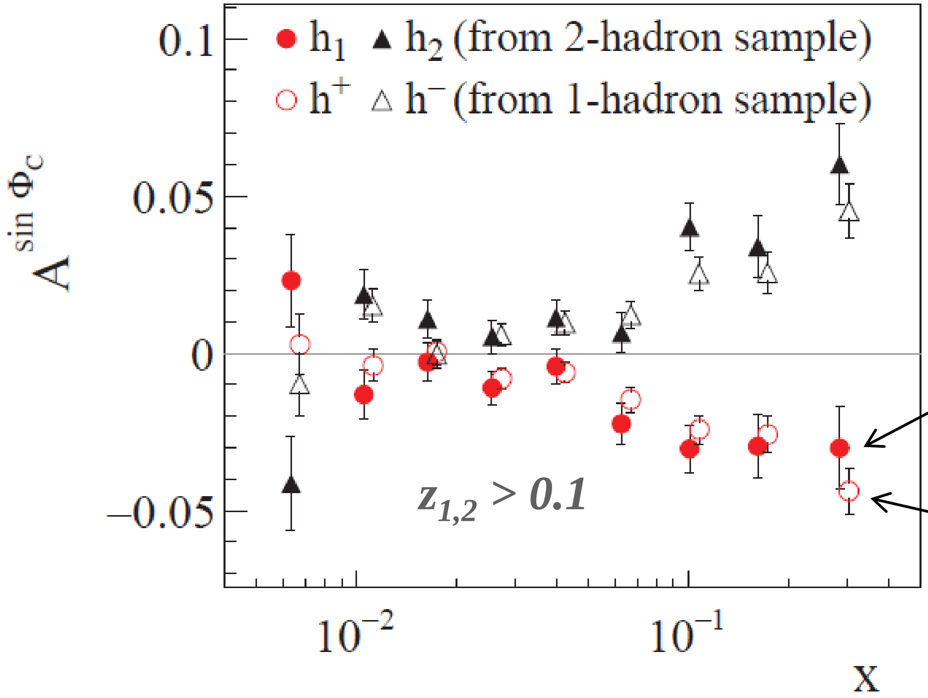
2. Study the correlation between hadron-pair azimuthal angles and between the corresponding asymmetries

3. Investigate the correlations between the h^+ and h^- asymmetries as a function of $\Delta\phi = \phi_{h^+} - \phi_{h^-}$

4. Investigate the correlation between the CL asymmetries and the di-hadron asymmetry

1. Comparison of Collins and CL asymmetries

hep-ex/1507.07593



h^+ Collins-Like

$\mu\, p \rightarrow \mu'\, h^+\, h^-\, X$

h^+ Collins

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

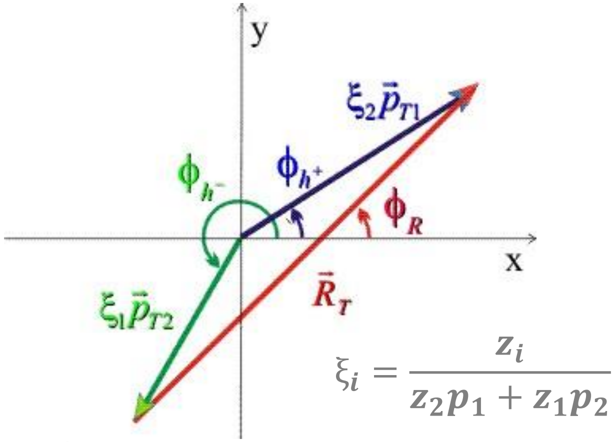
very close results: the “2h” sample can be used to investigate the correlations between Collins and di-hadron asymmetries

interplay between Collins and di-hadron asymmetries

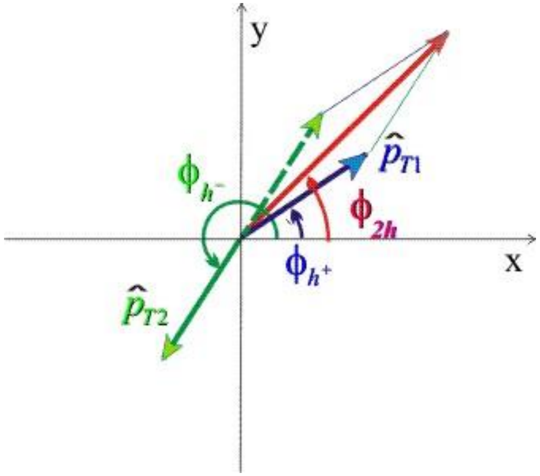
2. Correlation between di-hadron azimuthal angles

$\boldsymbol{\phi_R}$ azimuthal angle of $\vec{R}_T$

$$\boldsymbol{\phi_{2h}} = \frac{1}{2}[\phi_1 + \phi_2 + sign(\Delta\phi) \cdot \pi]$$

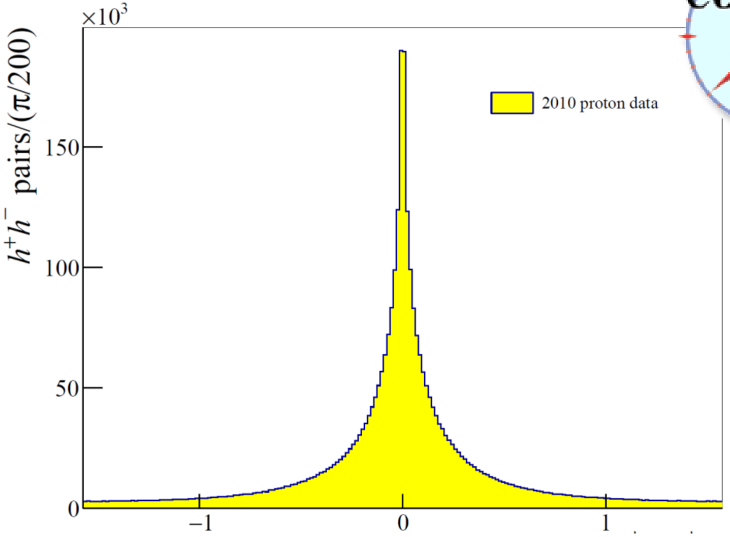


$$\xi_i = \frac{z_i}{z_2 p_1 + z_1 p_2}$$



$$\Delta\phi = \phi_1 - \phi_2$$

$1 = h^+$
$2 = h^-$



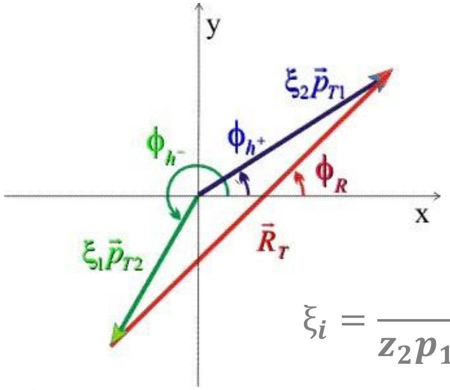
$\boldsymbol{\phi_R - \phi_{2h}}$

PLB 736 (2014) 124

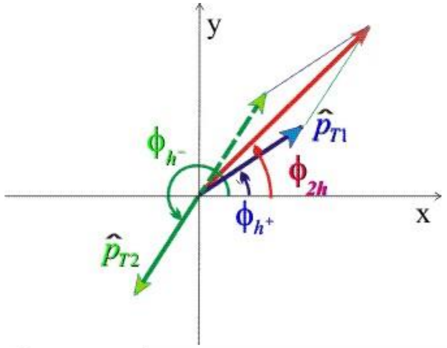
interplay between Collins and di-hadron asymmetries

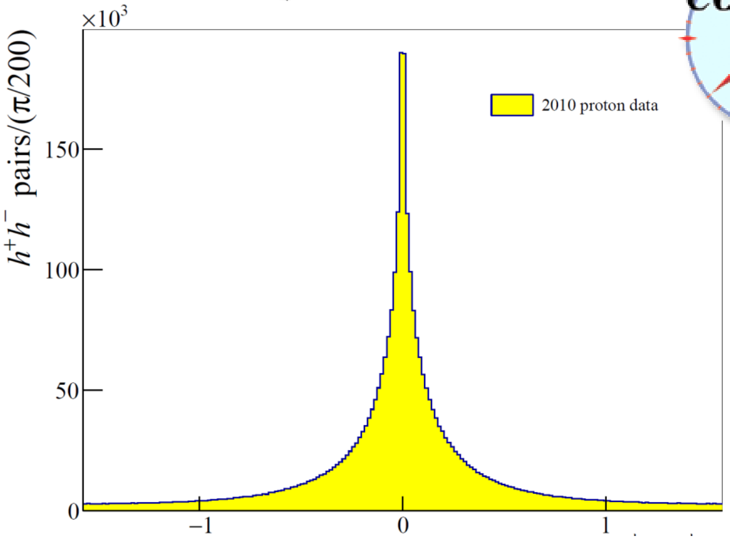
2. Correlation between di-hadron azimuthal angles

Correlation between the corresponding di-hadron asymmetries evaluated using ϕ_R or ϕ_{2h}



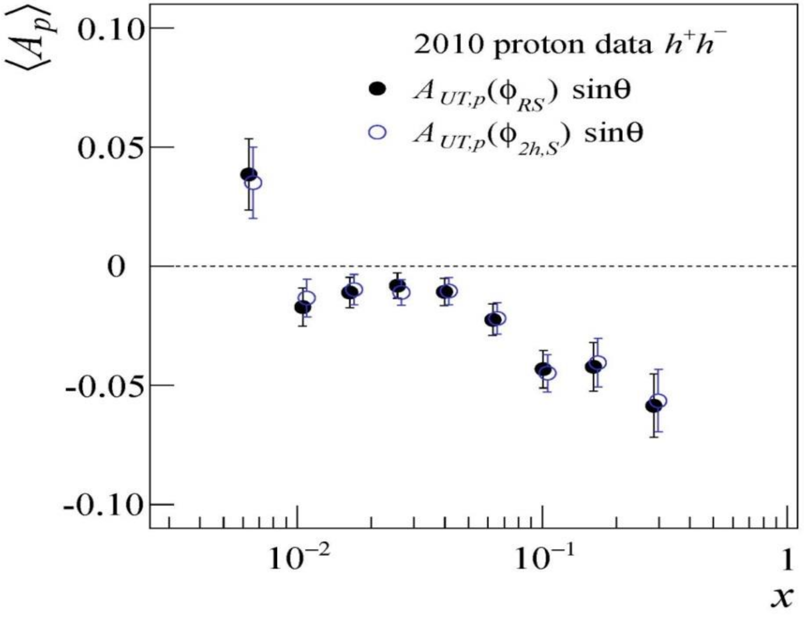
$$\xi_i = \frac{z_i}{z_2 p_1 + z_1 p_2}$$





$\phi_R - \phi_{2h}$

PLB 736 (2014) 124



interplay between Collins and di-hadron asymmetries

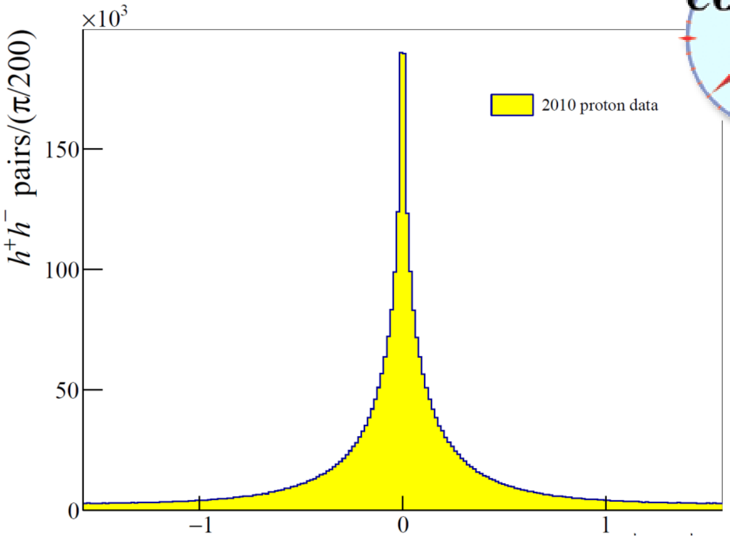
2. Correlation between di-hadron azimuthal angles

Correlation between the corresponding di-hadron asymmetries evaluated using $\boldsymbol{\phi_R}$ or $\boldsymbol{\phi_{2h}}$

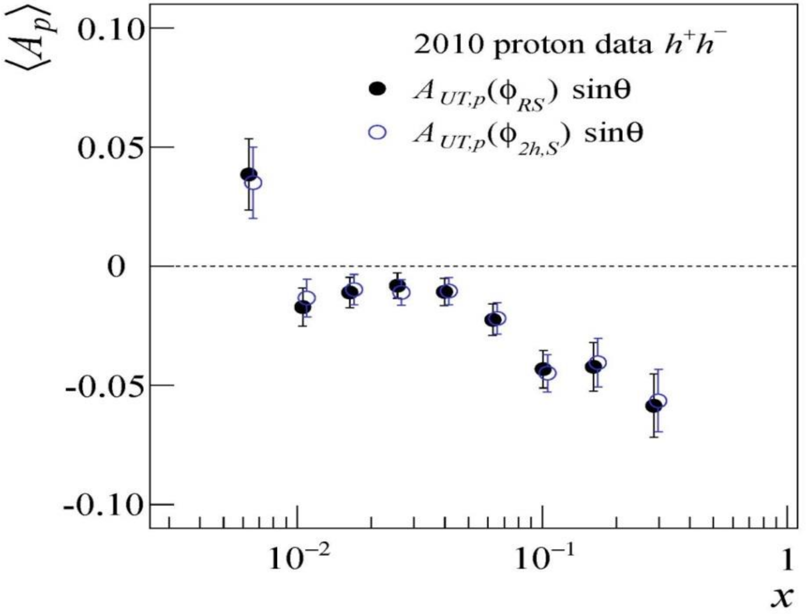
very much the same:

$\boldsymbol{\phi_{2h}}$ can be used to measure the di-hadron asymmetries

$\boldsymbol{\phi_{2h} + \phi_S - \pi}$ is a sort of mean of the Collins angles of h^+ and h^-



PLB 736 (2014) 124



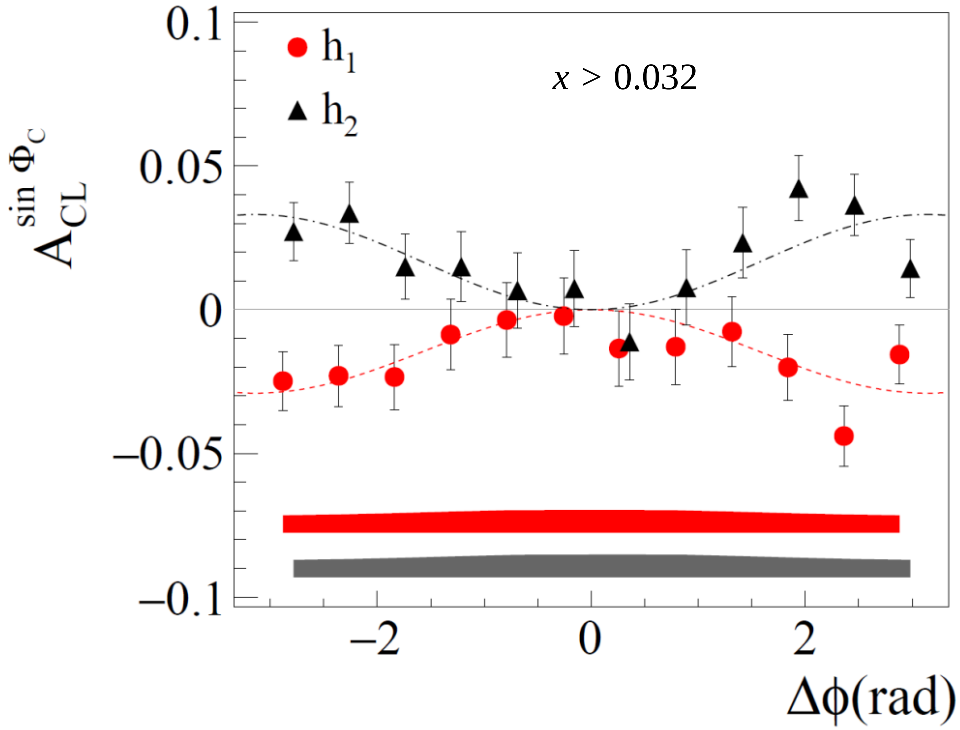
3. Correlations between the h^+ and h^- CL asymmetries

as function of x they are mirror symmetric

as function of $\Delta\boldsymbol{\phi} = \boldsymbol{\phi}_1 - \boldsymbol{\phi}_2$ they are

- mirror symmetric
- maximum at $\Delta\phi = \pi$,
  ~ zero at $\Delta\phi = 0$

hep-ex/1507.07593



3. Correlations between the h^+ and h^- CL asymmetries

analytical calculations (A. Kotzionian, PRD91 2015)

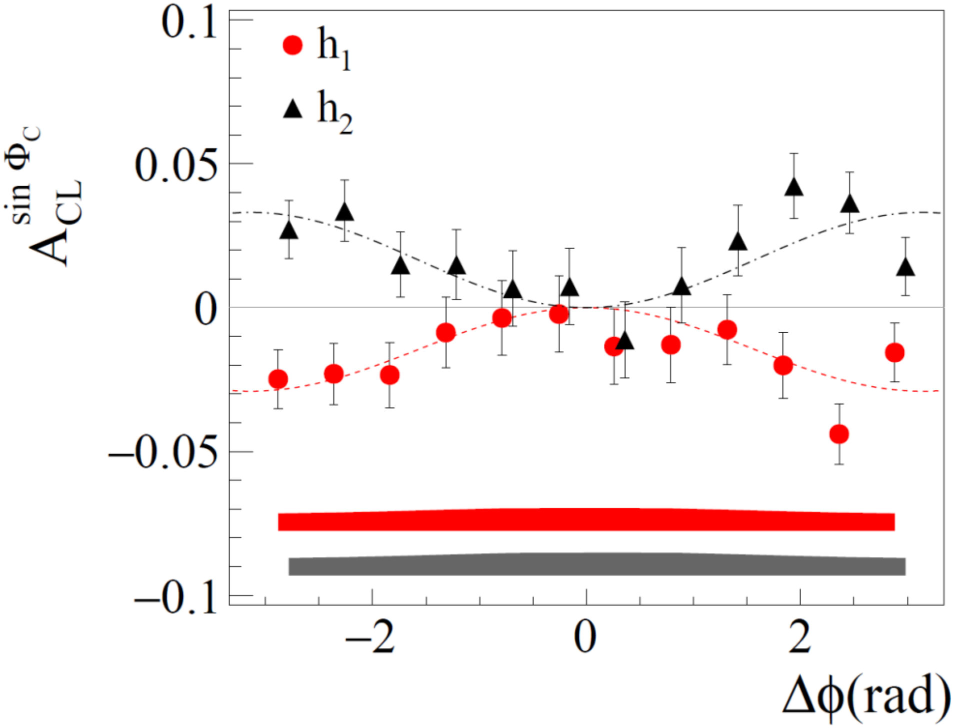
$$\frac{d\sigma^{h_1h_2}}{d\phi_1 d\phi_2 d\phi_S} = \sigma_U + S_T[\sigma_{C1}\sin(\phi_1+\phi_S-\pi) + \sigma_{C2}\sin(\phi_2+\phi_S-\pi)]$$

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

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

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

hep-ex/1507.07593



interplay between Collins and di-hadron asymmetries

3. Correlations between the h^+ and h^- CL asymmetries

analytical calculations (A. Kotzionian, PRD91 2015)

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

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

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

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

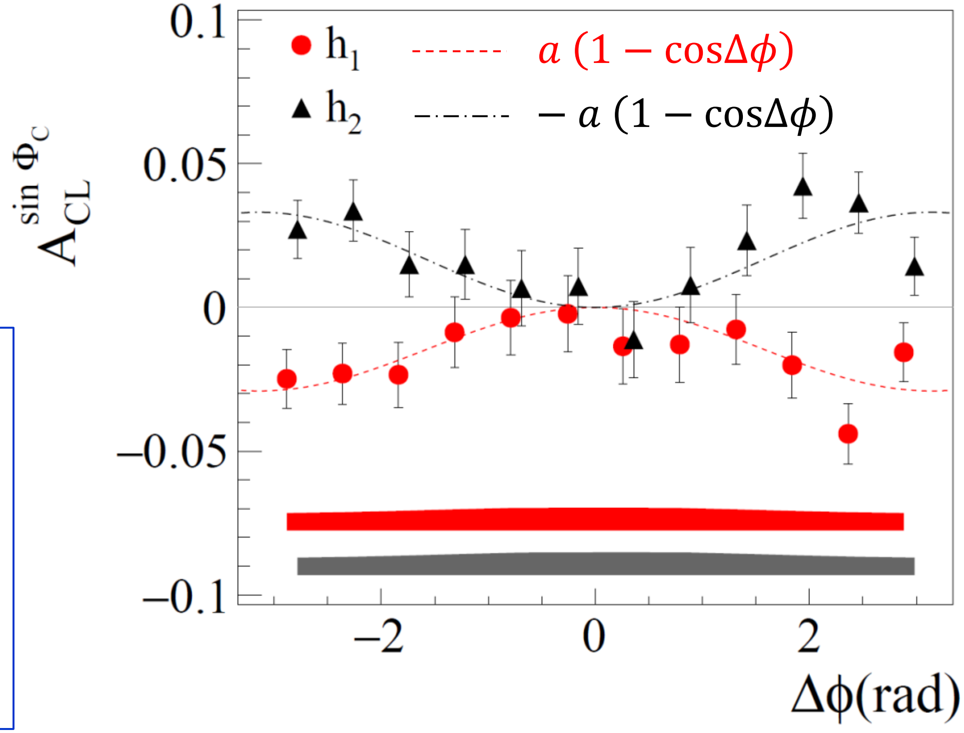
agreement with the data if

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

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

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

hep-ex/1507.07593



4. Correlation between the CL and di-h asymmetries

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

- $\sigma_{C2} = -\sigma_{C1}$
- *change of variables* $(\phi_1,\phi_2) \rightarrow (\phi_{2h}, \Delta\phi)$

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

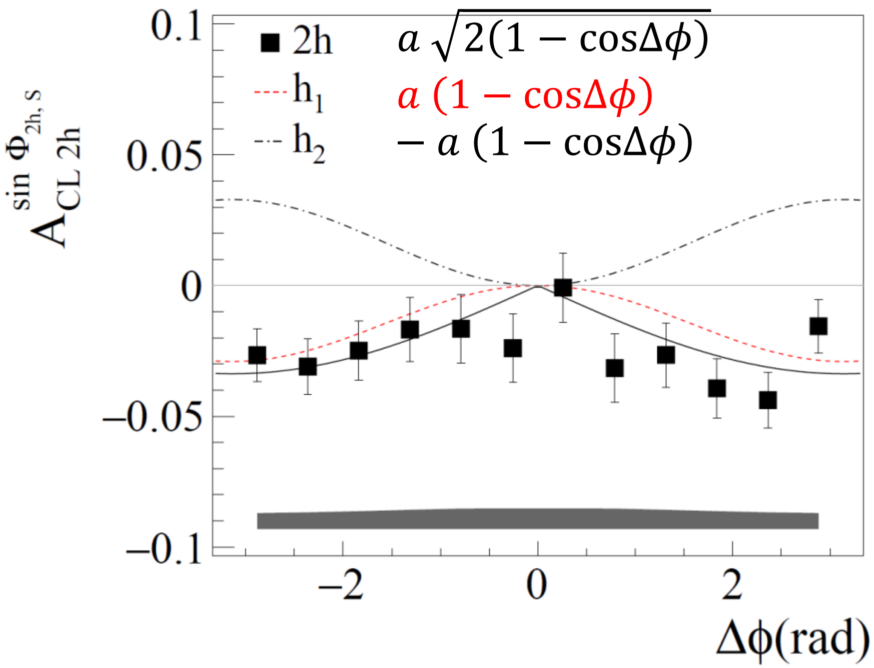
a very **simple relationship** between di-hadron and single hadron asymmetries in the 2h sample

in agreement with data

ratio of the integrals: 4/π

slightly larger than h^+

“a common origin”



Other important COMPASS results

on Transverse Spin Asymmetries

preliminary results:

- **full multidimensional analysis** (x, Q^2, z, p_T)
- **gluon Sivers PDF from**
  - **high** p_T **pairs**
  - **J/Ψ production**
- **…**

and different new analysis ongoing

and on TMD observables in unpolarised SIDIS

Relevance of unpolarised SIDIS for TMDs

The cross-section dependence on $\boldsymbol{p_{Th}}$ comes from:

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

gaussian ansatz: $\left\langle \boldsymbol{p_{Th}}^{\boldsymbol{2}} \right\rangle = \langle p_\perp{}^{\boldsymbol{2}} \rangle + \boldsymbol{z}^{\boldsymbol{2}} \langle k_{\boldsymbol{T}}{}^{\boldsymbol{2}} \rangle$

The azimuthal modulations in the unpolarized cross-sections comes from:

- **intrinsic $\boldsymbol{k_T}$ of the quarks**
- **Boer-Mulders PDF**

combined analysis should allow to disentangle the different effects

Relevance of unpolarised SIDIS for TMDs

The cross-section dependence on p_{Th} comes from:

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

gaussian ansatz: $\left\langle \boldsymbol{p_{Th}}^2 \right\rangle = \langle p_\perp{}^2 \rangle + \boldsymbol{z}^2 \langle k_{\boldsymbol{T}}{}^2 \rangle$

The azimuthal modulations in the unpolarized cross-sections comes from:

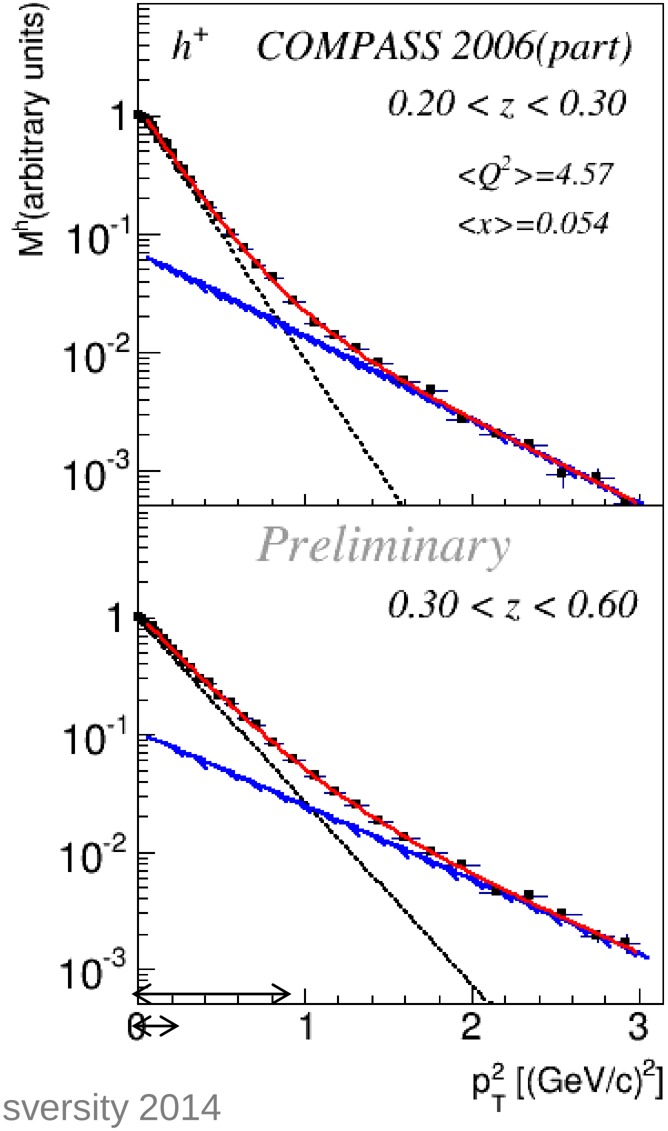
- **intrinsic $\boldsymbol{k_T}$ of the quarks**
- **Boer-Mulders PDF**

combined analysis should allow to disentangle the different effects

COMPASS

- **has produced results on $^6\boldsymbol{LiD}\ (\sim\boldsymbol{d})$ from 2004/6 data**
- **will measure SIDIS on LH_2 in parallel with DVCS**

unpolarised SIDIS – p_{Th} distributions

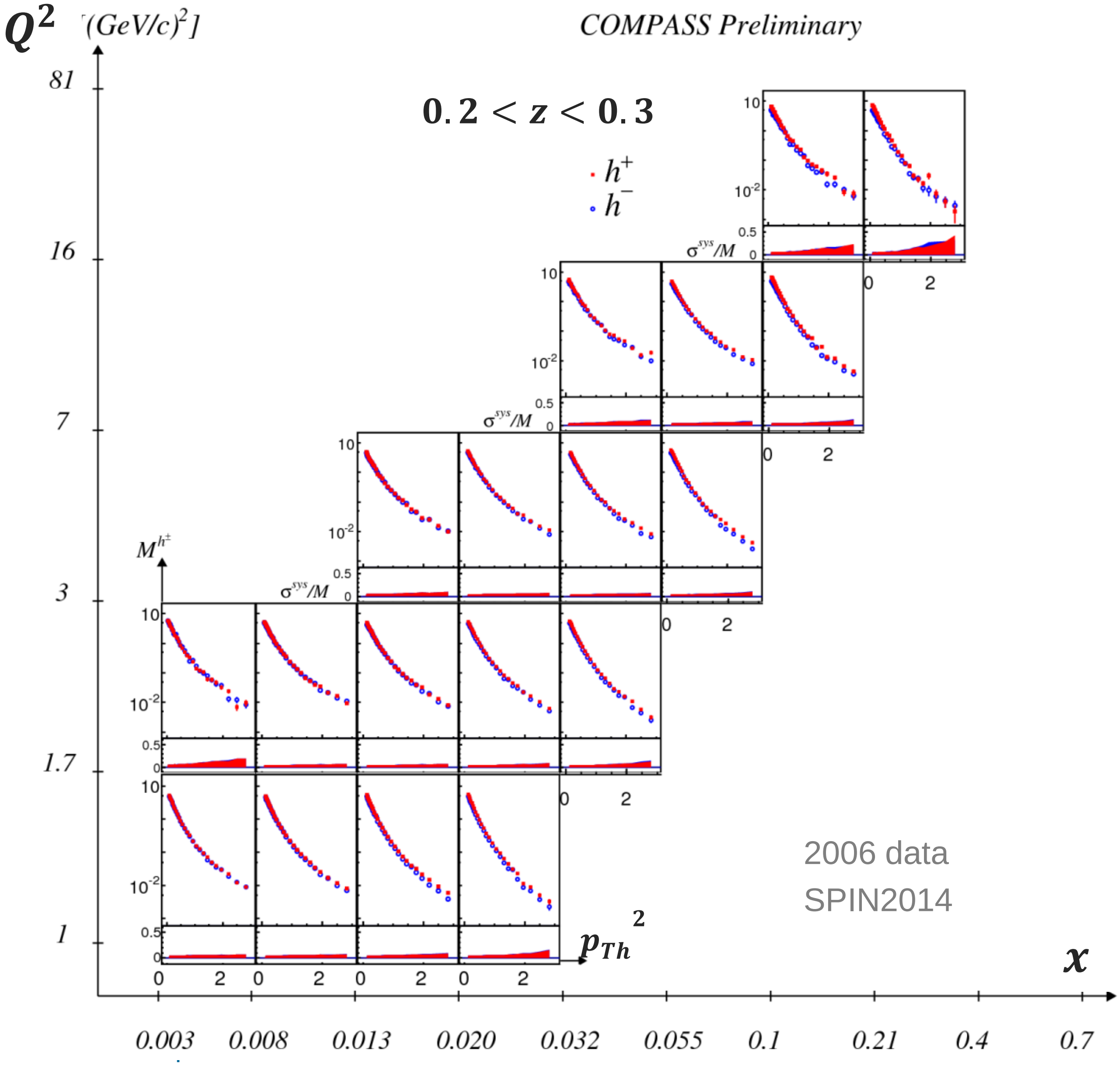


Fit distributions with

- **1 exponential for $p_{Th}^{\ 2}$ ∈ [0.05, 0.68]**
- **2 exponentials for $p_{Th}^{\ 2}$ ∈ [0.05, 3]**

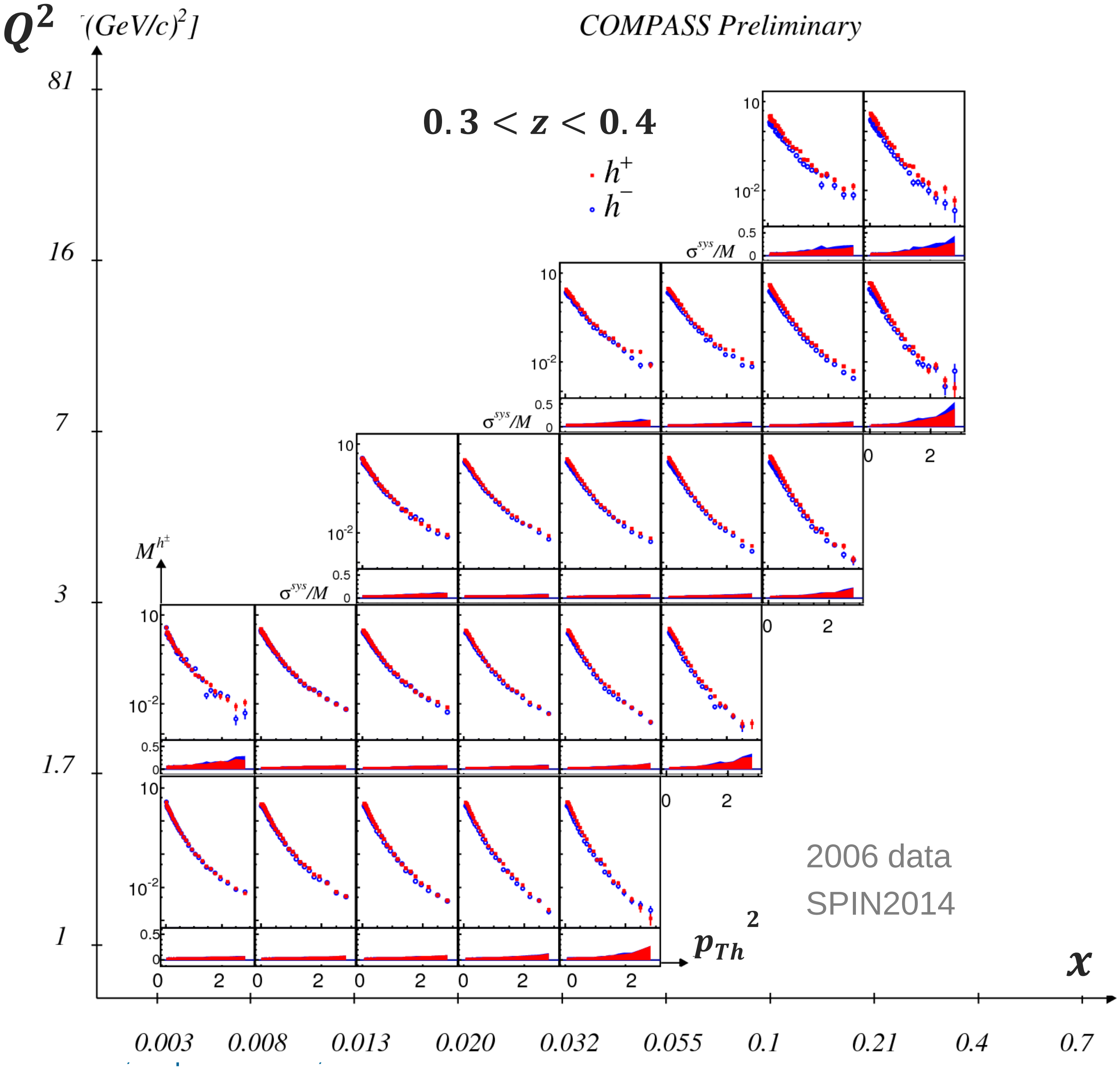
Need 2 exponentials to describe the $p_{Th}^{\ 2}$ shape of the COMPASS data

unpolarised SIDIS – p_{Th} distributions



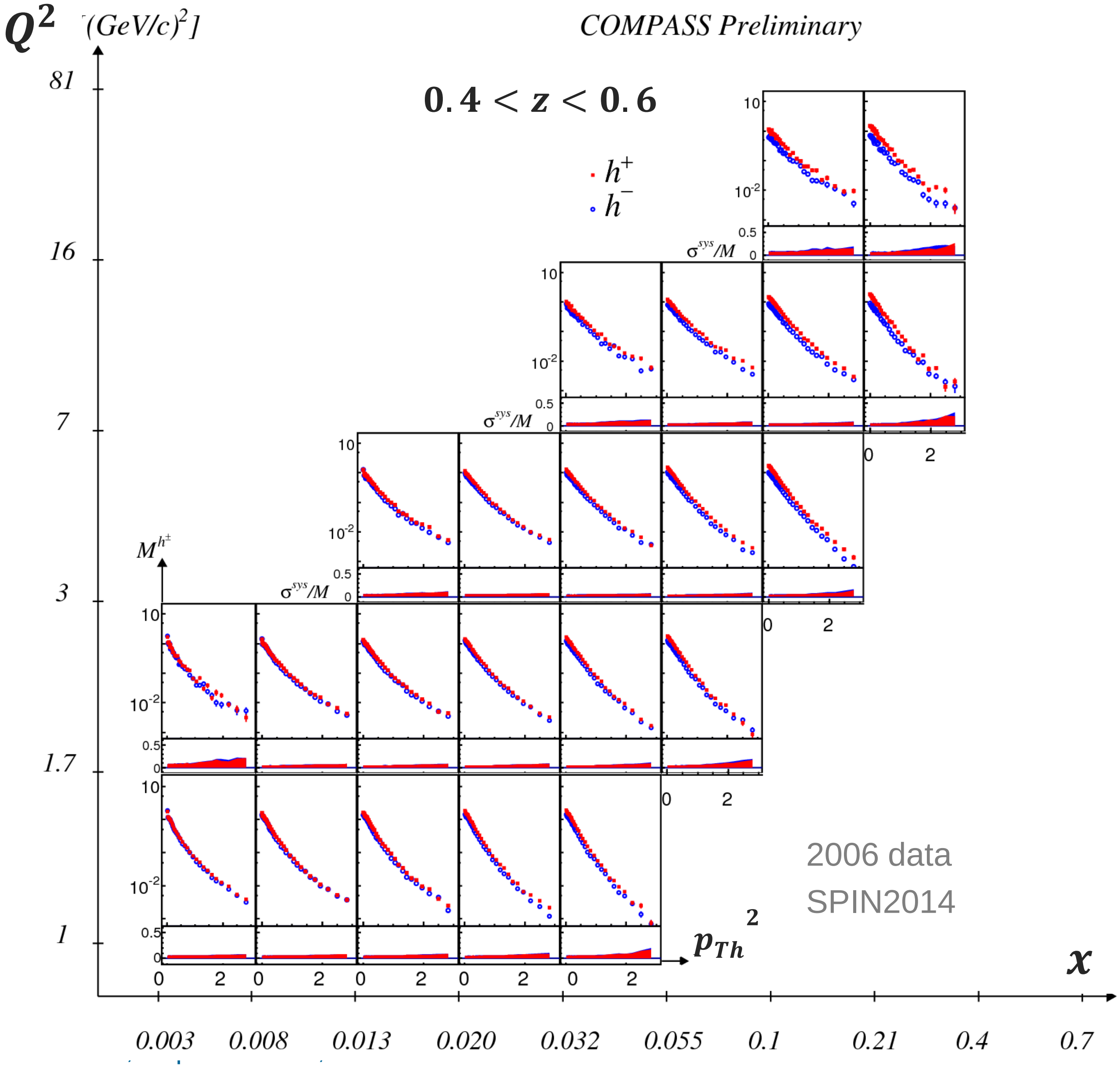
2006 data
SPIN2014

unpolarised SIDIS – p_{Th} distributions



2006 data
SPIN2014

unpolarised SIDIS – p_{Th} distributions



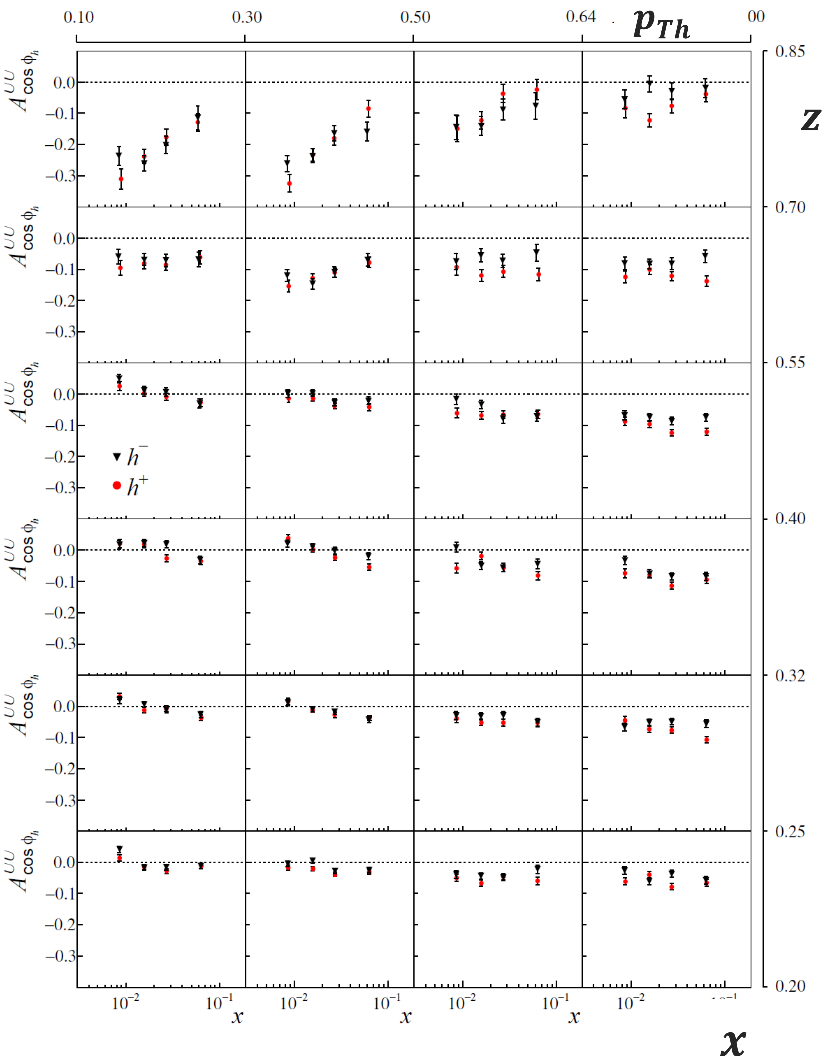
2006 data
SPIN2014

total:
4918 data points

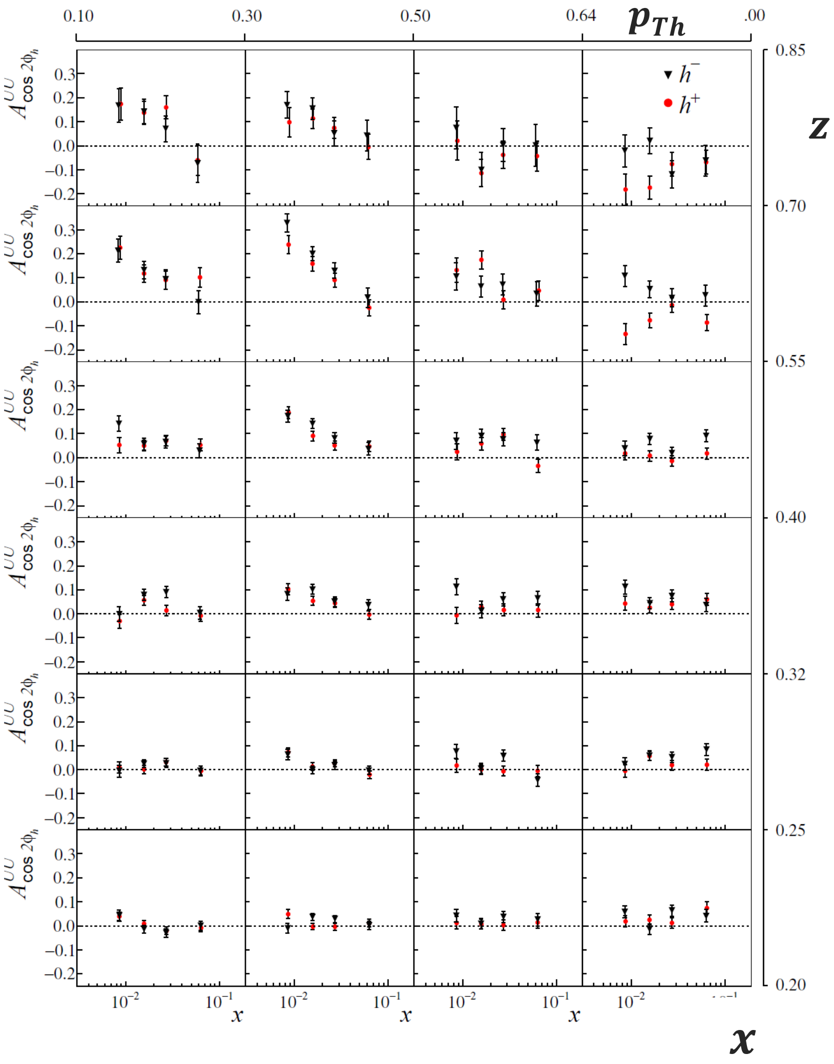
unpolarised SIDIS - azimuthal modulations

unpolarised SIDIS - azimuthal modulations

$\cos\phi_h$



$\cos 2\phi_h$



CONCLUSIONS & OUTLOOK

In the GPM new PDF's have been introduced which allow to understand the many transverse spin phenomena known since decades

COMPASS has given a decisive contribution to establish their properties

The Sivers function is presently being measured by COMPASS in the first Drell-Yan experiment on a polarized proton target

first test of sign change of a T-odd PDF from SIDIS to Drell-Yan

Many results on unpolarized SIDIS cross-section

k_T **vs** $p_\perp$ **Boer-Mulders PDF**

future data on LH target

Interplay between Collins and di-hadron FF's

same structure functions ➔ same origin

COMPASS-II ➔ COMPASS-III ?

Thank you !