COMPASS legacy: transverse spin phenomena

(as seen from the back stage)

Franco Bradamante
INFN, sezione di Trieste
fixed target experiment at the CERN SPS
COMPASS
Common Muon and Proton Apparatus for Structure and Spectroscopy

fixed target experiment at the CERN SPS

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

25 YEARS our jubilee

August 29, 2022
Franco Bradamante
THE STRUCTURE OF THE NUCLEON

Collinear description  leading twist

<table>
<thead>
<tr>
<th>nucleon polarisation</th>
<th>U</th>
<th>L</th>
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<tr>
<td>U</td>
<td>$f_1$</td>
<td></td>
<td></td>
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<tr>
<td>L</td>
<td>$g_1$</td>
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<td>T</td>
<td></td>
<td></td>
<td>$h_1$</td>
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- **number density** $f_1(q)$ 
  very well known

- **helicity distribution** $g_1(\Delta q)$ 
  well known

- **transversity distribution** $h_1(\Delta_T q)$

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

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

\[
\sigma_{lN \rightarrow l'hX} \sim \sum_q \sigma_{lq \rightarrow l'q} \otimes f(x) \otimes D_q^h(z)
\]

\[
p_T^h, \ \phi_h
\]
Collins effect

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

\( \pm \) refer to the opposite orientation of the transverse spin of the nucleon

\( P_T \) is the target polarisation; \( D_{NN} \) is the transverse spin transfer coefficient initial \( \rightarrow \) struck quark

"Collins angle"

\[ \Phi_C = \phi_h - \phi_s, = \phi_h + \phi_S - \pi \]

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

from the azimuthal distribution of the hadrons one measures the "Collins Asymmetry"

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

\( \Delta_T q \leftrightarrow h_1^q \)

\( \Delta_T^0 D_q^h \leftrightarrow H_{1q}^L \) Collins function
HELP proposal (L. Dick, B. Vuaridel, R. Hess, 1993) rejected by CERN: regarded as black magic

Our Collaboration accepted as a compromise to dedicate 20% of the running time with muon beam to measurements with transversely polarized nucleon targets
HELP proposal (L. Dick, B. Vuaridel, R. Hess, 1993) rejected by CERN: regarded as black magic

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

**Transversity is different from zero**

and has been extracted from COMPASS and $e^+e^-$ data

and with “global” fits of COMPASS, HERMES, $e^+e^-$, …data

curves from Anselmino et al., PRD87 2013
in parallel, the Sivers function story

a long debate

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

a long debate

• 1992 introduced by D. Sivers
• 1993 J. Collins demonstrate that it must vanish
• 2002 S. Brodsky et al.: it can be \( \neq 0 \) because of FSI
• 2002 J. Collins: process dependent, change of sign \( \text{SIDIS} \leftrightarrow \text{DY} \)
  ...

1996: not in our Proposal

IT IS ALSO DIFFERENT FROM ZERO
THE STRUCTURE OF THE NUCLEON

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

<table>
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<td>$h_{1LT}$</td>
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$h_1$  Transversity  
$h_{1T}$  pretzelosity  
$f_{1T}$  Sivers PDF  
$g_{1T}$  worm-gear  
Kotzinian-Mulders

Franco Bradamante
THE STRUCTURE OF THE NUCLEON

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

### SIDIS gives access to all of them!

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<tr>
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<td>$h_1^\perp$, $h_1^{\perp L}$, $h_1^{\perp T}$</td>
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$h_1$ Transversity

$h_1^T$ pretzelosity

$f_1^T$ Sivers PDF

$g_1^T$ worm-gear T Kotzinian-Mulders

Franco Bradamante
\[
\frac{d\sigma}{dx dy d\psi d\phi_h dP^2_{h,\perp}} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} \right.
\]
\[
+ \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} 
\]
\[
+ S_\parallel \left[ \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_h F_{UL}^{\sin \phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin 2\phi_h} \right] + S_\parallel \lambda_e \left[ \sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_h F_{LL}^{\cos \phi_h} \right] 
\]
\[
+ |S_\perp| \left[ \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \right.
\]
\[
+ \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} 
\]
\[
+ \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_S F_{UT}^{\sin \phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} 
\]
\[
+ |S_\perp| \lambda_e \left[ \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_S F_{LT}^{\cos \phi_S} \right.
\]
\[
+ \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right\}.
\]
\[
\frac{d\sigma}{dx\, dy\, d\psi\, dz\, d\phi_h\, dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1 - \varepsilon)} \left(1 + \frac{\gamma_c^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1 + \varepsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} \right.
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+ S_\parallel \left[ \sqrt{2\varepsilon(1 + \varepsilon)} \sin\phi_h F_{UL}^{\sin\phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{2\phi_h} \right] + S_\parallel \lambda_\varepsilon \left[ \sqrt{1 - \varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1 - \varepsilon)} \cos\phi_h F_{LL}^{\cos\phi_h} \right]
\]
\[
+ |S_\perp| \sin(\phi_T - \phi_S) \left(F_{UT,T}^{\sin(\phi_T - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_T - \phi_S)} \right)
\]
\[
+ \varepsilon \sin(\phi_T + \phi_S) \left(F_{UL}^{\sin(\phi_T + \phi_S)} + \varepsilon F_{UL}^{\sin(3\phi_T - \phi_S)} \right)
\]
\[
+ \sqrt{2\varepsilon(1 + \varepsilon)} \sin\phi_S F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1 + \varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{2\phi_h - \phi_S}
\]
\[
+ |S_\perp| \lambda_\varepsilon \left( \sqrt{1 - \varepsilon^2} \cos(\phi_T - \phi_S) F_{LT}^{\cos(\phi_T - \phi_S)} + \sqrt{2\varepsilon(1 - \varepsilon)} \cos\phi_T F_{LT}^{\cos\phi_T} \right)
\]
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+ \sqrt{2\varepsilon(1 - \varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{2\phi_h - \phi_S} \right\}
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\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_T^2_{h\perp}} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ F_{UU,T} + \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_\varepsilon \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_\varepsilon \left[ \sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_h F_{LL}^{\cos\phi_h} \right] \\
\left. \right\} + |S_\perp| \left\{ f_{1T}^+ D_U \right. \\
+ \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \\
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\left. \right\} + |S_\perp| \lambda_\varepsilon \left\{ g_{1T}^+ D_L \right. \\
+ \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} \left. \right\} ,
\]

8 independent azimuthal modulations
leading twist amplitudes
\rightarrow convolutions of transversity and TMD PDFs and FFs
**TRANSVERSE SPIN EFFECTS – A BIG EXPERIMENTAL EFFORT**

**SIDIS**

\[
Q^2 \quad (\text{GeV}^2) \\
X
\]

- **EIC**
  - high energy
  - high precision
  - future!

- **COMPASS**
  - ongoing

- **hermes**
  - over results still coming

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

**e^+ e^- \rightarrow hadrons**

Fragmentation Functions: Collins, DiHadron, …

BELLE, BABAR, BESIII

**polarized DY**

pp \rightarrow jets
THE COMPASS SPECTROMETER — SIDIS with polarized targets

designed to
• use high energy beams
• have large angular acceptance
• cover a broad kinematical range

two stages spectrometer
• Large Angle Spectrometer (SM1)
• Small Angle Spectrometer (SM2)

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

calorimetry, $\mu$ID
RICH detector

and MOST IMPORTANT
the polarized target
The COMPASS polarized target system – SIDIS >2005

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

- solenoid 2.5T
- dipole magnet 0.6T

acceptance > ±180 mrad

3 target cells
30, 60, and 30 cm long

opposite polarisation

- $^6\text{LiD}$ polarization 40-50%
- $^4\text{He}$ dilution factor 40%
- $\text{NH}_3$ polarization 90%
- $\text{NH}_3$ dilution factor 16%

no evidence for relevant nuclear effects (160 GeV)

MANY THANKS TO ALAIN

Franco Bradamante
results on
Transverse Spin Asymmetries

25 years after the proposal
• a review of well known results
• less known and new results
• expected results
the first SIDIS data with a transversely polarized target in COMPASS were collected in 2002: 0.5 effective weeks of data taking in 2004 first results for the Collins asymmetry and for the Sivers asymmetry

first publication in 2005

large statistical uncertainties, compatible with zero
the first SIDIS data with a transversely polarized target in COMPASS were collected in 2002: 0.5 effective weeks of data taking in 2004 first results for the Collins asymmetry and for the Sivers asymmetry

first publication in 2005

2002 data

PRL 94, 202002 (2005)

in the mean time, HERMES measurements with a proton target for the first time clear signals: real effects!

Collins, d

Sivers, d

hep-ex/0408013
the first extractions of the Sivers PDFs from these p and d Sivers asymmetries came very soon

the HERMES and COMPASS data could be well described

confirmation that the COMPASS results could be due to u d quark cancellation
the first extractions of the Sivers PDFs from these p and d Sivers asymmetries came very soon

the extraction of the transversity PDFs took some more time

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

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

clear independent indication of non-zero Collins FFs

again indication that the COMPASS results could be due to u d cancellation
FIRST EXTRACTIONS OF THE NEW PDFs

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

The extraction of the transversity PDFs took some more time.

The Collins FF was the missing piece.

It was qualitatively described by the Artru $^3P_0$ model.

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

First measurements the Collins-like asymmetry in $e^+e^- \rightarrow \text{hadrons}$ at BELLE.

to summarize:

• clear signals of the new transverse spin effects seen at HERMES and Belle

• a consistent picture of transverse spin effects was coming out, which could explain both the HERMES proton and the COMPASS deuteron data.
in 2004 first results for the **Collins asymmetry** and for the **Sivers asymmetries**

**FIRST PUBLICATIONS IN 2005**

**EXPERIMENTAL SITUATION IN 2005**

**2002 data**

- **COMPASS** had no proton data
- **HERMES** had no deuteron data

**more data were needed !**
THE DEUTERON DATA

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

THE DEUTERON DATA

2002 data

Collins

Sivers

2002-2004 data

Collins

Sivers

final results for deuteron
published in 2007

NPB 765 (2007) 31

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

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2002 data

Collins

Sivers

2002-2004 data

Collins

Sivers

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

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

the only existing deuteron data

run 2022 ongoing!

JLab6: He3,
statistically limited
THE 2007 PROTON DATA

in 2007 first (short) COMPASS run with transversely polarized protons (NH3)
preliminary results (half of the data): Transversity 2008

COLLINS ASYMMETRY
different from zero and
COMPATIBLE WITH HERMES !
THE 2007 PROTON DATA

in 2007 first (short) COMPASS run with transversely polarized protons (NH3)
preliminary results (half of the data): Transversity 2008

COLLINS ASYMMETRY
different from zero and
COMPATIBLE WITH HERMES!

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

UNEXPECTED RESULT

no panic but NIGHTMARES
A_2 splitting
S meson
superluminal neutrinos
Close scrutiny of the collected data revealed some systematics, "fairly long and sometimes difficult analysis."


Collins asymmetry: preliminary result confirmed \( \sigma_{\text{syst}} \approx 0.5 \sigma_{\text{stat}} \)

Sivers asymmetry:
positive hadrons exhibit an average asymmetry of 0.03 somewhat smaller than HERMES but definitely non zero \( \sigma_{\text{syst}}^+ \approx 0.8 \sigma_{\text{stat}}^+ \pm 0.01 \)

\( \rightarrow \) necessity of a longer and better data taking
Necessity of a longer and better data taking:
request for 1 year of data taking with transversely polarized p

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

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

Year 2010 entirely dedicated to proton running
and the 2010 run was quite successful

Preliminary results shown at Transversity 2011 in Losini
First results published in 2012
THE PROTON DATA – Sivers asymmetry

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

Sivers asymmetry
all COMPASS proton data

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

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

Sivers asymmetry
all COMPASS proton data

comparison with HERMES

smaller values at COMPASS: TMD evolution …
**Sivers function** extractions from SIDIS data (COMPASS, HERMES, Jlab)

- u and d: clearly different from zero

THE SIVERS FUNCTION

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

→ u and d: clearly different from zero


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

CERN-SPSC-2010-014
SPSC-P-340
to make easier the comparison with DY, avoiding $Q^2$ evolution problems, we have measured the Sivers asymmetry in $Q^2$ bins

COMPASS DY run 2015 + 2018

new results at DIS2022

→ Jan Matousek
THE PROTON DATA – Collins asymmetry

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

Collins asymmetry
all COMPASS proton data

PLB 744 (2015) 250
PLB 717 (2012) 376
THE PROTON DATA – Collins asymmetry

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

Collins asymmetry
all COMPASS proton data

very good agreement!

comparison with HERMES

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

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THE PROTON DATA – Collins asymmetry

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

Collins asymmetry
all COMPASS proton data

study of the interplay between Collins and di-hadron asymmetries – not independent
well reproduced by the $^3P_0$ model

COMPASS, PLB 753 (2016) 406

A. Kerbizi et al. PRD97 (2018) no.7, 074010
further results of Collins asymmetries in SIDIS off p and d, and e+e- data

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

fits of di-hadron asymmetries
SIDIS off p and d, e+e-, and pp data
fits of Collins asymmetries in SIDIS off p and d, and e⁺e⁻ data

point by point extraction using COMPASS p and d asymmetries, and e⁺e⁻ data
no Soffer bound; no Monte Carlo nor parametrisations needed
fits of Collins asymmetries in SIDIS off p and d, and e^+e^- data

work still ongoing …

it is clear the

• u- and d-quark transversity PDFs have opposite sign

• d-quark PDF much worse determined than u-quark PDF because of the scarcity of deuteron (neutron) data

→ 2022 COMPASS run
run 2022 - expectation

many thanks to Gunar and Daniel
several other measurements have been performed

- other TSA
- multidimensional measurements of TSAs \((x, Q^2, z, P_T)\) bins
- Sivers asymmetry in \(Q^2\) bins
  - in particular for the COMPASS Drell-Yan measurement
- \(P_T\) - weighted Sivers asymmetries
  - no convolution, important tests, extraction of the Sivers function
- transversity induced \(\Lambda/\bar{\Lambda}\) polarization
- TSAs for high \(P_T\) pairs from PGF events
- \(J/\Psi\) Sivers asymmetry

- \(\rho^0\) TSAs - new
THE PROTON DATA

$\rho^0$ TSAs

\[ \text{COMPASS preliminary} \]

- indication for positive asymmetry opposite to $\pi^+$ as expected
- large at small $P_T$

Sivers Asymmetry
- indication for positive asymmetry similarly to $\pi^0$ as expected

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

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several other measurements have been performed

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- TSAs for high \(P_T\) pairs from PGF events
- \(J/\Psi\) Sivers asymmetry
- \(\rho^0\) TSAs

and other new measurements are ongoing

- the \(g_2\) structure function
- ....

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

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

It has not been easy to make these measurements, but for sure it has been a lot of fun
COMPASS has given a relevant contribution to the study of the transverse structure of the nucleons with the Transverse Spin Asymmetries in SIDIS.

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

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

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

Much more will surely come from the next generation facilities SOLID EIC ....
thank you !
THE PROTON DATA

- other TSAs

\[ A_{UT}^{\sin \phi_s} \]

subleading twist similar to HERMES results

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

pretzelosity

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

worm-gear T Kotzinian- Mulders

August 29, 2022
• transversity induced $\Lambda/\bar{\Lambda}$ polarization

\[
S_{\Lambda(\bar{\Lambda})} = \frac{\sum_q e_q^2 h_i^q H_{1,q}^{\Lambda(\bar{\Lambda})}}{\sum_q e_q^2 f_1^q D_{1,q}^{\Lambda(\bar{\Lambda})}}
\]
THE PROTON DATA

- TSAs for high $P_T$ pairs from PGF events

PLB 772 (2017) 854

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THE PROTON DATA

• $J/\Psi$ Sivers asymmetry

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