Recent Measurements of Transverse Spin Asymmetries

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Transverse Structure of the Nucleon
Transverse Structure of the Nucleon

in the GPM the information is encoded in the **TMD PDFs** which describe the correlations between transverse momentum and spin of quarks and nucleon spin. 

\[ 8 \text{ at twist 2 for each } q \]

3 of them survive after integration over transverse momenta:

- **number density** \( f_1^q \), well known
- **helicity** \( g_1^q \), known
- **transversity** \( h_1^q \), new

\[ \Delta q, \Delta_T q, \text{ new} \]

ALL OF EQUAL IMPORTANCE!
Transversity PDF

- **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

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

- first measurements in 2005
Transverse Structure of the Nucleon

in the GPM the information is encoded in the **TMD PDFs** which describe the correlations between transverse momentum and spin of quarks and nucleon spin.

\[ 8 \text{ at twist2 for each } q \]

\[
\begin{array}{cccc}
\text{nucleon} & \text{U} & \text{L} & \text{T} \\
\text{U} & f_1 & \text{ } & \text{ } \\
\text{L} & \text{ } & g_1 & g_{1L} \\
\text{T} & h_1 & h_{1L} & h_{1T} \\
\end{array}
\]

other **5 new PDFs** which vanish when integrating over transverse momentum:

all of great interest and \(~\) unknown

two of them are T-odd

**Boer-Mulders** \( h_1 \)

parton transverse spin \( \leftrightarrow \) parton transverse momentum

**Sivers** \( f_{1T} \)

nucleon transverse spin \( \leftrightarrow \) parton transverse momentum
Sivers PDF $f_{1T}^{⊥}$

nucleon transverse spin $\leftrightarrow$ parton transverse momentum

- requires final/initial state interactions to survive time-reversal invariance

- time-reversal invariance implies:

$$f_{1T}^{\perp}|_{\text{SIDIS}} = -f_{1T}^{\perp}|_{\text{DY}} \quad \text{... to be checked, new experiments}$$
Transverse Structure of the Nucleon

in the GPM the information is encoded in the TMD PDFs which describe the correlations between transverse momentum and spin of quarks and nucleon spin

\[ 8 \text{ at twist 2 for each } q \]

how to measure these new PDFs?

either chiral-odd or vanishing when integrating over transverse momentum

\[ \rightarrow \text{ not in DIS} \]
accessing transversity and TMD PDFs

they can be accessed through different processes

**SIDIS**

**HERMES**
**COMPASS**
**Jefferson Lab**
what we know today comes from these measurements

**RHIC**
not easy to disentangle different effects

**Drell-Yan**
no polarised data (yet !)

Anna Martin
why SIDIS

a simple process, a special tool

\[ d\sigma^{\ell p \rightarrow \ell hX} \sim \sum_q e_q^2 f_q(x, k_\perp) \cdot d\sigma^{\ell q \rightarrow \ell q} \cdot D_q^h(z, p_T) \]

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
why SIDIS

de\sigma \over dx \, dy \, d\psi \, dz \, d\phi_h \, dP_{h\perp}^2 =
\frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h \, F_{UU}^{\cos \phi_h} \right\}
\frac{h_L^{\perp} H_L^{\perp}}{h_{LT}^{\perp} H_L^{\perp}}
+ \varepsilon \cos(2\phi_h) \, F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_h \, F_{UL}^{\sin \phi_h}
\frac{h_{LT}^{\perp} H_L^{\perp}}{h_{LT}^{\perp} H_L^{\perp}}
+ 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_e \left[ \sqrt{1-\varepsilon^2} \, F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_h \, F_{LL}^{\cos \phi_h} \right]
\frac{f_{LT}^{\perp} D_{LT}}{f_{LT}^{\perp} D_{LT}}
+ |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]
\frac{h_{LT}^{\perp} H_{LT}^{\perp}}{h_{LT}^{\perp} H_{LT}^{\perp}}
+ \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)}
\frac{h_{LT}^{\perp} H_{LT}^{\perp}}{h_{LT}^{\perp} H_{LT}^{\perp}}
+ \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}
\frac{g_{LT}^{\perp} D_{LT}}{g_{LT}^{\perp} D_{LT}}
+ |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}^{2\phi_h - \phi_S} \right\},

18 structure functions
14 azimuthal modulations
azimuthal asymmetries

fi Sivers

\[ A_{Siv} \approx \frac{\sum q e_q^2 f_{IT}^{\perp q} \otimes D_1^q}{\sum q e_q^2 f_I \otimes D_1^q} \]

- the Fragmentation Functions must be well known
- convolutions on transverse momenta crucial to know them!
why SIDIS

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

from HERMES, COMPASS and Jefferson Lab experiments

\[ Q^2 \] (GeV\(^2\))

some selected results only …
Sivers asymmetry

amplitude of the modulation in $\phi_h - \phi_S$ $A_{UT}^{\sin(\phi_h - \phi_S)}$

2004: first evidence for non-zero values on proton compatible with zero on deuteron

data well described by theory

first extractions of the Sivers function

~ opposite u- d- quark contributions
Sivers asymmetry

final results on deuteron

COMPASS

2002-2004 data
NPB765 2007, PLB673 2009

and neutron

Jefferson Lab

Hall A  PRL107, 2011

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Sivers asymmetry

1D final results on proton

- clearly positive for $\pi^+$ down to $x \sim 10^{-2}$
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 \( y \)
Sivers asymmetry

final results on proton

\[ z > 0.2 \]

- clearly positive for \( \pi^+ \) down to \( x \sim 10^{-2} \)
Sivers asymmetry

final results on proton

- clearly positive for $\pi^+$ down to $x \sim 10^{-2}$
- $K^+$ asymmetries larger than $\pi^+$ asymmetries
Sivers asymmetry

final results on proton for positive particles vs

\[ A_{SW}^P \]

\[ A_{SW}^P \]

\[ p_T^h \text{ (GeV/c)} \]

\[ x \]

\[ z \]
Sivers asymmetry

final results on proton for positive particles vs

COMPASS asymmetries larger than HERMES asymmetries

$Q^2$ evolution of TMDs?

factor of 3
TMDs evolution

a lot of work in the last few years
still ongoing

new extractions from existing SIDIS data
and predictions for SIDIS experiments at different energies
and polarised Drell-Yan experiments

from small to very large $Q^2$ dependence

multidimensional analysis
Sivers asymmetry

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

Transversity 2014
Sivers asymmetry

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

“golden” range: $Q^2 > 16$ GeV$^2$
Sivers asymmetry

COMPASS has measured the TSA in the 4 \( Q^2 \) ranges of the “future” Drell-Yan experiment

Transversity 2014

“golden” range: \( Q^2 > 16 \text{ GeV}^2 \)

clearly positive

test of change of sign feasible
Sivers asymmetry

complete multidimensional measurements

**optimised** $x$-$Q^2$ $z$-$p_T$ binning

COMPASS preliminary

Proton 2010 data

$Q^2/(GeV/c)^2 > 1$

$16 < Q^2/(GeV/c)^2 < 81$

$7 < Q^2/(GeV/c)^2 < 16$

$3 < Q^2/(GeV/c)^2 < 7$

$1.7 < Q^2/(GeV/c)^2 < 3$

$1 < Q^2/(GeV/c)^2 < 1.7$

COMPASS preliminary

Proton 2010 data

$z$-$p_T$ binning

SPIN2014
Sivers asymmetry

complete multidimensional measurements
Sivers asymmetry

- preliminary results produced for all TSA
- these data allow for useful tests of results from integrated 1D asymmetries
Collins asymmetry
Collins asymmetry

amplitude of the modulation in $\phi_h + \phi_S - \pi$

$A_{Coll} \approx \frac{\sum_q e_q^2 h_q^1 \otimes H_{1q}^\perp}{\sum_q e_q^2 f_q^1 \otimes D_q}$

convolution of transversity with the chiral-odd Collins FF

correlation between transverse spin of the fragmenting quark and transverse momentum of hadrons

Classical String $+ 3P_0$
mechanism
of Collins effect
Artru, Czyzewski, Yabuki ZP C73 1997

can be (has been) accessed in

$e^+ e^- \rightarrow q \bar{q} \rightarrow h_1 h_2 X$
Collins asymmetry

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

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

2004: non-zero values on proton compatible with zero on deuteron

first evidence that both $h_1$ and Collins FF different from zero

first $e^+e^-$ measurements from Belle

“global” fits

→ first extractions of $h_1$ and Collins FF
Collins asymmetry

final results on deuteron

2002-2004 data
NPB765 2007, PLB673 2009

and neutron

Hall A  PRL107, 2011

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Collins asymmetry

1D final results on proton

\[ 2 \langle \sin(\phi_s + \phi_0) \rangle_{ut} \]

\[ \pi^+ \]

\[ \pi^- \]

\[ K^+ \]

\[ K^- \]

phase \( \pi \) in Collins angle definition
Collins asymmetry

charged pions

Q² evolution of Collins FF?
Collins FF

PRD78, 2008 PRD86, 2012

Unlike-sign couples / Like-sign couples
Unlike-sign couples / All charges

\( \sqrt{s} = 10.58 \text{ GeV} \)
Collins FF

\( \pi \pi \Rightarrow \text{non-zero asymmetries, increase with } z_1, z_2 \)

\( \pi K \Rightarrow \text{asymmetries compatible with zero} \)

\( KK \Rightarrow \text{non-zero asymmetries, increase with } z_1, z_2 \)

Transversity2014

Belle Preliminary

BABAR Preliminary

DIS2015

BESIII Preliminary

\( \sqrt{s} < 3.6 \text{GeV} \)

\((z_1, z_2) \text{ bin}\)
Transversity

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

very good $\chi^2$
Transversity

simultaneous fit of HERMES p, COMPASS p & d, and Belle data

parametrisations of Transversity and Collins functions

very good $\chi^2$

Anselmino et al., PRD87 2013

Kang et al., PRD91 2015

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

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

higher order corrections, x z
Transversity

from COMPASS p & d and Belle data, point by point extraction

- evolution: the same for Collins and unpolarised FF
- convolution on $k_T$ neglected

Martin Bradamante Barone PRD91 2015

curves from Anselmino et al., PRD87 2013

[Graph of valence and sea curves]
Transversity

alternative channels to access transversity in SIDIS

• Δ production, measurement of transverse polarisation difficult: low statistics (see COMPASS d)

• hadron pair production, measurement of the di-hadron asymmetry easier / done
**dihadron asymmetry**

Independent channel to access transversity in SIDIS off transversely polarised nucleons

**Collins**

\[ A_{Coll} \approx \frac{\sum_q e_q^2 h_1^q \otimes H_{1q}}{\sum_q e_q^2 f_1^q \otimes D_q} \]

"Collins FF"

*Belle Babar*

**dihadron**

\[ A_{RS} \approx \frac{\sum_q e_q^2 h_1^q \cdot H_q}{\sum_q e_q^2 f_1^q \cdot D_q^{2h}} \]

"Interference / Di-hadron FF"

*Belle Babar*

"Spin independent di-hadron FF"

*being measured at Belle Babar COMPASS*
dihadron asymmetry

HERMES proton
first evidence for
non-zero dihadron FF,
same sign of Collins
asymmetry for $\pi^+$
**dihadron asymmetry**

**HERMES proton**
- first evidence for non-zero dihadron FF, same sign of Collins asymmetry for $\pi^+$

**COMPASS deuteron:**
- compatible with zero proton:
  - same sign and shape slightly higher than Collins asymmetry for $h^+$
dihadron FF

\[ a_{12} \approx \frac{H_q^\perp H_q^\perp}{D_{2h}^{2h} D_{2h}^{2h}} \]

\[ 0.25 \text{ GeV/c}^2 < m_2 < 0.40 \text{ GeV/c}^2 \]

\[ 0.40 \text{ GeV/c}^2 < m_2 < 0.50 \text{ GeV/c}^2 \]

\[ 0.50 \text{ GeV/c}^2 < m_2 < 0.62 \text{ GeV/c}^2 \]

\[ 0.62 \text{ GeV/c}^2 < m_2 < 0.77 \text{ GeV/c}^2 \]

\[ 0.77 \text{ GeV/c}^2 < m_2 < 0.90 \text{ GeV/c}^2 \]

\[ 0.90 \text{ GeV/c}^2 < m_2 < 1.10 \text{ GeV/c}^2 \]

\[ 1.10 \text{ GeV/c}^2 < m_2 < 1.50 \text{ GeV/c}^2 \]

\[ 1.50 \text{ GeV/c}^2 < m_2 < 2.00 \text{ GeV/c}^2 \]
Transversity from 2h asymmetries

Bacchetta Courtoy Radici JHEP 1303 2013

$D_{q_{2h}}$ from PYTHIA
HERMES p, COMPASS p and d, Belle data
$\rightarrow$ linear combinations of transversity for u and d valence quark
fit with parametrisations $\rightarrow$ transversity PDFs

$\times h_1^{u\nu}(x) \times h_1^{d\nu}(x)/4$

Data HERMES
Data COMPASS

$\times h_1^{u\nu}(x) + x h_1^{d\nu}(x)$

Data COMPASS

$\times h_1^{u\nu}(x)$

Data HERMES
Data COMPASS

Flexible

Anselmino et al 2013
Transversity from 2h asymmetries

also possible: point-to-point extraction

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

• no MC nor parametrisation is needed
• the same technique used for the Collins asymmetries

open points: dihadron
closed points: Collins

further confirmation that $k_T$ is not so relevant in this case

Martin Bradamante Barone
PRD91 2015
dihadron asymmetry - new ideas
dihadron asymmetry - new ideas

Gliske, Bacchetta, Radici  PRD90 2014, P.R.D91 2015

new partial wave expansion for fragmentation functions

• it gives a consistent framework for fragmentation into final states of any polarization
• shows that the two-hadron SIDIS cross sections, at any twist, can be derived from single-hadron SIDIS cross section
• two-hadron SIDIS cross section is given up to subleading twist, including the dependence upon the transverse momentum of involved particles

\[
D_1 = \sum_{\ell=0}^{\ell_{\text{max}}} \sum_{m=-\ell}^{\ell} P_{\ell,m}(\cos \theta) \cos (m(\phi_{R\perp} - \phi_p)) \\
\times D_1^{\ell,m}(z, M_h, |p_T|),
\]

\[
H_1^{\perp} = \sum_{\ell=0}^{\ell_{\text{max}}} \sum_{m=-\ell}^{\ell} P_{\ell,m}(\cos \theta) e^{im(\phi_{R\perp} - \phi_p)} \\
\times H_1^{\perp\ell,m}(z, M_h, |p_T|),
\]

not easy …

⇒ HERMES
dihadron asymmetry  -  new ideas

interplay between dihadron and single hadron asymmetries

known intriguing results

• Collins asymmetry for h+ and for h- "mirror symmetry"
• dihadron asymmetry
  only somewhat larger than h+ Collins

→ first studies of the correlations between
the relevant azimuthal angles and the
 corresponding asymmetries  $\phi_R \sim \phi_{2h}$

hints for a common origin of the Collins FF and DiFF
Como 2013, DSpin2013, PLB736 2014
interplay between single hadron and dihadron asymmetries

new: Collins like and di-hadron asymmetries vs \( \Delta \phi = \phi_1 - \phi_2 \)
using the events with at least 2 oppositely charged hadrons (2h sample):
Trannsversity2014, SPIN2014

the asymmetries are expected to be specular and maximum at \( \Delta \phi \simeq \pi \)

analytical calculations:
A. Kotzionian, PRD91 2015

\[
\frac{d\sigma^{h_1 h_2}}{d\phi_1 d\phi_2 d\phi_S} = \sigma_U^{h_1 h_2} + S_T \left[ \sigma_{C_1}^{h_1 h_2} \sin(\phi_1 + \phi_S - \pi) \cdot \right.
\]

\[
\left. + \sigma_{C_2}^{h_1 h_2} \sin(\phi_2 + \phi_S - \pi) \right]
\]

\[
A^{\sin(\phi_1+\phi_S-\pi)}_{CL1} = \frac{1}{D_{NN}} \frac{\sigma_U^{h_1 h_2} + \sigma_{C_2}^{h_1 h_2} \cos \Delta \phi}{\sigma_U^{h_1 h_2}}
\]

\[
A^{\sin(\phi_2+\phi_S-\pi)}_{CL2} = \frac{1}{D_{NN}} \frac{\sigma_{C_1}^{h_1 h_2} + \sigma_{C_2}^{h_1 h_2} \cos \Delta \phi}{\sigma_U^{h_1 h_2}}
\]

good agreement with data if
\[
\sigma_{C_1}^{h_1 h_2} = -\sigma_{C_2}^{h_1 h_2}
\]
interplay between single hadron and dihadron asymmetries

\[ \sigma_{C_1}^{h_1 h_2} = -\sigma_{C_2}^{h_1 h_2} \]

\[ A_{CL1}^{\sin(\phi_1 + \phi_S - \pi)} = \frac{1}{D_{NN}} \frac{\sigma_{C_1}^{h_1 h_2}}{\sigma_U^{h_1 h_2}} \cdot (1 - \cos \Delta \phi) \]

\[ A_{CL2}^{\sin(\phi_2 + \phi_S - \pi)} = -A_{CL1}^{\sin(\phi_1 + \phi_S - \pi)} \]

mirror symmetry
interplay between single hadron and dihadron asymmetries

\[
\sigma_{C1}^{h_1h_2} = -\sigma_{C2}^{h_1h_2}
\]

\[
\begin{align*}
A_{CL1}^{\sin(\phi_1 + \phi_S - \pi)} &= \frac{1}{D_{NN}} \frac{\sigma_{CL1}^{h_1h_2}}{\sigma_{C1}^{h_1h_2}} \cdot (1 - \cos \Delta \phi) \\
A_{CL2}^{\sin(\phi_2 + \phi_S - \pi)} &= -A_{CL1}^{\sin(\phi_1 + \phi_S - \pi)}
\end{align*}
\]

rewriting the cross-section in terms of \(\phi_{2h}\) and \(\Delta \phi\) one easily obtains

\[
A_{2h,CL}^{\sin(\phi_{2h} + \phi_S - \pi)} = \frac{1}{D_{NN}} \frac{\sigma_{CL}^{h_1h_2}}{\sigma_{C1}^{h_1h_2}} \cdot \sqrt{2(1 - \cos \Delta \phi)}
\]

a very simple relationship between dihadron and single hadron asymmetries in the 2h sample in agreement with data

ratio of the integrals: \(4/\pi\)

slightly larger than \(h^+\)

it would be interesting to perform the corresponding studies in \(e^+e^-\)
Transversity in pp
Transversity in pp

inclusive pion production $p^+ p \rightarrow \pi X$

one of the most famous measurements
and one of the motivations for the last 20 years of studies of transverse spin effects

large spin effects confirmed at RHIC
still not clear how large is the contribution of transversity

Drell-Yan:
convolution of $u$ and $\bar{u}$ ($d$ and $\bar{d}$) transversity distributions $\rightarrow$ difficult
still …
Transversity in pp

hadrons inside a jet

Collins asymmetry

\[ \phi_C = \phi_S - \phi_H \]

“the first statistically significant non-zero Collins asymmetries measured in hadronic collisions”

STAR Preliminary

SPIN2014
Transversity in $pp$

hadrons inside a jet

di-hadron asymmetry

$$\phi_{RS} = \phi_S - \phi_R$$

SPIN2014

STAR Preliminary

“results are at much higher $Q^2$ and sample a different mixture of quark flavors than SIDIS” complementary input
other SIDIS transverse spin asymmetries

\[
\frac{f_{1T} D_1^T}{f_{1T} D_1^T} + |S_\perp| \left[ \begin{array}{c}
\sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \\
+ \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \\
+ \sqrt{2 \varepsilon (1 + \varepsilon)} \sin \phi_S F_{UT}^{\sin \phi_S} + \sqrt{2 \varepsilon (1 + \varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \\
+ |S_\perp| \lambda_e \left[ \begin{array}{c}
\sqrt{1 - \varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2 \varepsilon (1 - \varepsilon)} \cos \phi_S F_{LT}^{\cos \phi_S} \\
+ \sqrt{2 \varepsilon (1 - \varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \\
\end{array} \right] \right]
\]

all of them (and more …) have been measured on p / d / n by COMPASS, HERMES, JLab

preliminary results for multidimensional analysis also produced at COMPASS and HERMES (SPIN2014)
other SIDIS transverse spin asymmetries

measured on p (HERMES, COMPASS) 
d (COMPASS) and n (JLab)

 proton

\[
\begin{align*}
\sin(3\phi_s - \phi_s) = & \frac{M}{Q} (h^{q}_1 \otimes H^{q}_1 + f^{q}_1 \otimes D^{q}_1 + \cdots) \\
\cos(\phi_s) = & \frac{M}{Q} (g^{q}_1 \otimes D^{q}_1 + \cdots)
\end{align*}
\]
other SIDIS transverse spin asymmetries

\[ A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h \]

"Worm Gear" PDF

same trend
other SIDIS transverse spin asymmetries

\[ A_{UT}^{\sin \phi_s} \propto \frac{M}{Q} \left( h_1^q \otimes H_{1q}^h + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots \right) \]

considerably larger at HERMES

as expected
Gluon Sivers function
Gluon Sivers function

1. measurement of the "Sivers" asymmetry in \( lp \rightarrow l'hhX \)
   \[ \phi_P - \phi_S, \quad P = p_1 + p_2 \]

2. extraction of the asymmetries for Photon-Gluon Fusion, Leading Process and QCD Compton using NN trained on MC data

the sample with PGF events is enhanced by selecting DIS events with at least 2 hadrons with large \( p_T \) \( (p_{T1} > 0.7, \quad p_{T2} > 0.4 \text{ GeV/c}) \)
Gluon Sivers function

\[
A_{PGF}^{\sin(\phi_2 - \phi_s)} = -0.14 \pm 0.15 \text{(stat.)} \pm 0.06 \text{(syst.)} \quad \langle x_G \rangle = 0.13
\]

\[
A_{PGF}^{\sin(\phi_2 - \phi_s)} = -0.26 \pm 0.09 \text{(stat.)} \pm 0.08 \text{(syst.)} \quad \langle x_G \rangle = 0.15
\]

PHENIX results from proton-proton collisions with $\sqrt{s} = 200\text{GeV}$ for the observable $A_N$ sensitive to the gluon Sivers function give values compatible with zero.
TSA $A_N$ in $lp \rightarrow hX$ processes
TSA $A_N$ in $lp \rightarrow hX$ processes

motivation:

direct test of the validity of the TMD factorization in $lp \rightarrow hX$ 
→ understanding TSA in $pp^{\uparrow} \rightarrow hX$ 

M. Anselmino et al PRD 81 2010
TSA $A_N$ in $lp \rightarrow hX$ processes

phenomenological interpretation in progress
many new SIDIS results, not all easy to explain

the SIDIS data collected in so far are unique
and the analysis are not yet over

more information is still hidden in the data and has to be extracted
from SIDIS at COMPASS, HERMES, JLab experiments
pp at RHIC
e^+e^- at Belle / Babar / BES
while waiting for the results of the new complementary measurements
and experiments
at COMPASS too!