Experimental overview on TMDs at fixed-target experiments

- Introduction to TMDs
- Experiments and results
- Putting them together

Caroline Riedl

Jefferson Lab
Hall A

Photo: Kennecott Utah Copper Mine

April 16–19
Salt Lake City, Utah
The current picture of the proton

Figure courtesy of: “Electron Ion Collider: The Next QCD Frontier. Understanding the glue that binds us all”. arXiv:1212.1701
Correlation between spin and transverse momentum

Transverse Momentum dependent PDFs

TMDs $f(x,k_T)$

$\xi=0$, $t=0$ (collinear) PDFs $q(x)$, 1D

Nucleon tomography

Generalized Parton Distributions

$b = \text{impact parameter}$:

$FT(t \leftrightarrow b) \leftrightarrow H(x,\xi=0,b)$

$k_T=0$
Deep Inelastic Scattering (DIS): $\ell N \to \ell (h)X$

**Example: “spin structure function”**

$$g_1(x, Q^2)$$

Longitudinal momentum- and spin structure of the proton well known.

- Lepton
- Photon
- Virtuality $Q^2$
- Longitudinal direction
- Proton
- Longitudinal momentum fraction of quark
- Inclusive $x, Q^2$
Deep Inelastic Scattering (DIS): $\ell N \rightarrow \ell (h)X$

**Example:** “spin structure function”

$$g_1(x, Q^2)$$ Longitudinal momentum- and spin structure of the proton well known.

<table>
<thead>
<tr>
<th>$x$</th>
<th>$Q^2$</th>
<th>$g_1(x, Q^2) + c$</th>
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<tr>
<td>0.0036</td>
<td>(i = 0)</td>
<td>12.1 - 0.7</td>
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<td>0.0045</td>
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COMPASS PLB 753 (2016) 18
Factorization of DIS cross section

\[ \sigma^\ell p \rightarrow \ell hX = \sum_q (DF \otimes \sigma^\ell q \rightarrow \ell q \otimes FF) \]

- TMD Distribution Functions (DF)
- TMD Fragmentation Functions (FF)

The problem:
- TMD factorization is a 2-scale problem.
  \[ f(x, k_T; Q^2) \]

Collinear factorization is a 1-scale problem.
  \[ f(x; Q^2) \]

courtesy Alexei Prokudin 2015/16

criedl@illinois.edu - TMDs at COMPASS and CLAS

APS 2016, Salt Lake City, April 18, 2016
The SIDIS cross section: 
"harmonic(ϕ, ϕs)⋅DF ⊗ FF"

- \( F_{X,Y,Z} \) = structure function. \( X = \) beam, \( Y = \) target polarization,
  \([Z = \) virtual-photon polarization]. \( X, Y \in \{ U, L, T \} \)

- \( \lambda_e \) = helicity of the lepton beam
- \( S_L \) and \( S_T \) = longitudinal and transverse target polarization
- \( \epsilon \) = ratio of longitudinal and transverse photon fluxes

Unpolarized Longitudinally Transversely

Bacchetta et al., JHEP 02, 093 (2007)
TMD(PDF)s

Legend:
- nucleon moves to the right.
- nucleon (N)
- unpolarized quark (Q)
- quark spin
- quark kT

TMDs surviving integration over kT. “Collinear analysis”

Chiral odd TMDs
→ Chiral symmetry breaking of the QCD nucleon wave function

8 TMD(PDF)s needed at leading twist description.

Analog table for fragmentation functions (capital letters except for UU=D1)

Flavor indices and kinematic dependences skipped for simplicity.

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### Proton “orbitals”

<table>
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<tr>
<th>N</th>
<th>U</th>
<th>L</th>
<th>T</th>
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<tr>
<td>U</td>
<td>f₁</td>
<td>h₁</td>
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<tr>
<td>L</td>
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<tr>
<td>T</td>
<td>f₁T</td>
<td>g₁T</td>
<td>h₁  h₁T</td>
</tr>
</tbody>
</table>

- **Monopole** (S)
- **Dipole** (S, P interference)
- **Quadrupole** (D)

#### H-atom wave function

\[ \psi_{nlm}(r, \theta, \phi) \]

- orbital angular momentum
- spin


- Understand the bound system and its excitation levels.
- Spin-orbit correlations in QCD similar to those in QED (H-atom).
- “Proton (hyper)fine structure”
Naive time-reversal odd TMDs

Reversal of spin- and momentum vectors only

Describe strength of spin-orbit correlations \( \vec{S} \cdot (\vec{P}_1 \times \vec{P}_2) \)

no Lorentz vector under T-odd

\[ \vec{S}_T \cdot (\hat{P} \times \vec{k}_T) \]

Sivers function

\[ \vec{s}_T \cdot (\hat{P} \times \vec{k}_T) \]

Boer-Mulders function

If non-zero: indicate orbital angular momentum (OAM) of partons inside the nucleon.

\[ \vec{s}_T \cdot (\hat{k} \times \vec{P}_{hT}) \]

= chiral-even factor in cross section

Describe strength of spin-orbit correlations

quark spin

nucleon spin

\( \vec{k}_T \)

(longitudinal direction)

Transversity

chiral-odd PDF (spin-spin correlation)

Collins function

chiral-odd FF

\( \vec{S}_T \)

\( \vec{s}_T \)

\( \vec{P} \)
Sivers effect generates distorted distribution of unpolarized quarks in the transversely polarized proton.

\[
A_{UT}(\phi) = \frac{1}{f S_T} \frac{N^{\uparrow}(\phi) - N^{\downarrow}(\phi)}{N^{\uparrow}(\phi) + N^{\downarrow}(\phi)}
\]

Spin-orbit correlations \( \vec{S} \cdot (\vec{p}_1 \times \vec{p}_2) \) induce observable single-spin asymmetries. Different harmonic modulation for each TMD, e.g. \( \sin(\phi - \phi_S) \)


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SIDIS: polarized muon beams of 160/200 GeV on solid targets
- \( d \rightarrow ({}^6\text{LiD}) \): 2002-2006
- \( p \rightarrow (\text{NH}_3) \): 2007, 2011
- \( d \uparrow ({}^6\text{LiD}) \): 2002-2004
- \( p \uparrow (\text{NH}_3) \): 2006/07, 2010

dilution factor:
\( f=0.22 \) (\( \text{NH}_3 \)), \( f=0.4 \) (\( {}^6\text{LiD} \))

Katharina Schmidt On behalf of the COMPASS Collaboration

Hard Exclusive Measurements at COMPASS

Transversely polarized target
Target material: \( \text{NH}_3 \), \( {}^6\text{LiD} \)

2 magnets: solenoid 2.5 T and dipole 0.5 T

Acceptance:
\( \pm 180 \text{ mrad} \) upstream edge (since 2006)

\( ^3\text{He} - ^4\text{He} \) dilution refrigeration (60mK)

\( \text{dilution refrigerator} (\sim 60\text{mK}) \)
\( \text{superconducting solenoid} (\sim 2.5\text{T}) \)
\( \text{dipole magnet} (\sim 0.5\text{T}) \)
**at Hall B / Jefferson Lab**

- Polarized electrons of 6 / 11 GeV
- Unpolarized and longitudinally polarized targets (2001 / 2005 / 2009)
- Transversely polarized target (CLAS12)
  - Lumi $\sim 10^{34}$cm$^{-2}$sec$^{-1}$

**Hall A at JLab** complementary:
  - very high luminosity vs. very large acceptance at CLAS

**HERMES**: spin experiment at HERA/DESY 1995-2007, polarized electrons of 27.6 GeV on (un)polarized gas targets

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APS 2016, Salt Lake City, April 18, 2016
\[ \text{pt}^2\text{-dependent hadron multiplicities} \]

**negative hadrons**  
(positive hadrons not shown)

\[
\frac{dN^h}{dN^{DIS}} \propto \sum_q e_q^2 q D_q^h
\]

Flavor dependence of spin-independent TMD distribution and fragmentation functions. In total 4,918 data points. Valuable input for TMD evolution studies.

At high-x and high-z:  
\[ h^+h \Rightarrow D_{u}^{\pi^+} > D_{u}^{\pi^-} \]

From: differential multiplicities for \( \pi^+\pi^- \) and \( h^+h^- \) binned in \( x, y, z \).

COMPASS hep-ex/1604.02695, submitted to PLB.

APS 2016, Salt Lake City, April 18, 2016
**Collins asymmetry**

$\ell N^\uparrow \rightarrow \ell hX$

**COMPASS p↑**

**Transversity $\otimes$ Collins**

**Collins Fragmentation Function** describes spin-dependent hadronization of a transversely polarized quark into hadrons.

- $\pi^+ < 0$, $\pi^- > 0$. → favored ($u \rightarrow \pi^+$, $d \rightarrow \pi^-$) & unfavored ($u \rightarrow \pi^-$, $d \rightarrow \pi^+$) Collins FF of similar size but opposite sign.
- HERMES similar → no evolution effect (no $Q^2$ dependence)
- COMPASS $d^↑$ & Hall-A $^3$He: null
- e+e− collider (BELLE and BABAR): confirm trend

**Hall-A neutrons ($^3$He)**

COMPASS PLB 744 (2015) 250 (this plot)
HERMES PLB 693 (2010) 11 (not shown)

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COMPASS PLB 744 (2015) 250 (this plot)
HERMES PLB 693 (2010) 11 (not shown)
Di-hadron asymmetry

\[ \ell N^\uparrow \to \ell h^+h^-X \]

**COMPASS p^\uparrow**

Transversity \(\otimes\) Interference FF

(collinear analysis - no quark kT)

Di-hadron-, or interference FF from interference of different channels of the fragmentation process into the two-hadron system.

- Interference FF \(\approx\) 
  \(\frac{1}{2} \cdot (\text{Collins}[h^+] + (-1) \cdot \text{Collins}[h^-])\)

- Hint at a common physical origin for the **Collins mechanism** & di-hadron fragmentation function

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Sivers asymmetry in SIDIS

COMPASS, HERMES $p^\uparrow$

\[ A_{Si}^p \sim -f_{1T}^+(x, p_T^2) \otimes D_1^{u\rightarrow \pi^+}(z, k_T^2) \]

Negative $u$-quark Sivers function

Null result for negative pions & kaons: positive $d$-quark Sivers function

Pion ($u,\text{anti-d}) < \text{kaon (u, anti-s)}$

"Role of sea quarks non-negligible?"

Sivers (COMPASS) < Sivers (HERMES): non-trivial $Q^2$-dependence

Null result (u/d-quark cancellation effects)


Hall-A neutrons ($^3\text{He}$)

Sivers from positive pions off neutron target negative

=> d-quark Sivers negative

COMPASS $d^\uparrow$

Null result (u/d-quark cancellation effects)


Hall A Collaboration PRL 107 (2011) 072003

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**Sivers asymmetry**

Sivers asymmetry

\[ A_{\text{UT}} \] vs. \( P_{hT} \) (GeV)

**COMPASS gluon Sivers**

from photon-gluon fusion →

experimental signature: 2 high-\( p_T \) hadrons

On proton target: Sivers asymmetry negative

\[ A_{\text{PGF}}^{\sin(\phi_{2h-\phi_s})} = -0.26 \pm 0.09 \text{(stat.)} \]

\( +0.08 \text{(syst.) at } \langle x_g \rangle = 0.15 \)

**Herbans**

Sivers asymmetry for gluons on deuterons

**HERMES**

0 0.2 0.4 0.6 0.8 1 1.2

**COMPASS**

**Fig. 15.**

obtained by [69].

**Fig. 16.**

unpolarised data

**HERMES** [30] and **COMPASS** [139] Sivers asymmetry

**Double ratio**

**Leading process (LP) - PGF**

main DIS process

**sin(\( \phi - \phi_s \))**

**sin(\( \phi - \phi_s \))**

**sin(\( \phi - \phi_s \))**

**TMD evolution**

**Fig. 14.**

14 H. Avakian et al.: Experimental results on TMDs - TMDs at COMPASS and CLAS

**APS 2016, Salt Lake City, April 18, 2016**
Spin-dependent Drell-Yan measurement at COMPASS

Universality: naive time-reversal-odd TMDs are expected to have the same magnitude but opposite sign in DY. Crucial test of TMD framework.

Sivers (SIDIS) = −(1)·Sivers (DY)

• First spin-dependent DY measurement. **2015 COMPASS results** soon to come! 2nd year of COMPASS polarized DY planned for 2018.

• STAR at RHIC/BNL: Sivers amplitude in $W^{+}/Z^{0}$ production PRL 116, 132301 (2016): “The current data thus favor theoretical models that include a change of sign for the Sivers function relative to [...] SIDIS measurements, if TMD evolution effects are small.”

• SeaQuest at FNAL: DY w/ polarized target 2018/19

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Phase space of COMPASS Drell-Yan data

- Unique possibility of measuring SIDIS and Drell-Yan observables at the same facility.
- No need to rely on uncertainties of TMD evolution.
- π- on proton probes valence-quark region ★ Sivers function of large magnitude.

COMPASS projections (2015+2018 data)

COMPASS SIDIS in DY range:

- $h^+$ for $1 < Q^2/(\text{GeV/c})^2 < 4$
- $h^-$ for $z > 0.2$

COMPASS Drell-Yan MC
$4 < M_{\mu\mu} < 9 \text{ GeV/c}^2$
(240 days)

(Sivers)$_p \times (f_1)_n$

(BM)$_p \times (BM)_n$

COMPASS Drell-Yan MC
$4 < M_{\mu\mu} < 9 \text{ GeV/c}^2$
(240 days)

invariant di-muon mass

COMPASS DY 2014 (pilot run)

- Total
- $J/\psi$
- Continuum
- $\psi'$
- Combinatorial Bkg

ongoing analysis

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Future Sivers and Collins measurements at CLAS-12

- Transversely polarized HD-Ice target: with negligible nuclear background and small dilution factor. No strong holding field required.

- High luminosity and large acceptance will allow measurements in wide range of $x$, $Q^2$, and $P_{hT}$ and a multi-dimensional analysis: extended mapping in several ($x$, $Q^2$) bins.

- Study of TMD evolution.

- Constraints of higher-twist contributions to resolve the observed mismatch between the signs of the moment of the Sivers function extracted from SIDIS data and twist-3 calculations.


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**SIDIS Boer-Mulders**

**COMPASS d**

COMPASS NPB 886 (2014) 1046

- **Cahn effect** → \(<k_T>\) carried by unpol. quarks in unpol. nucleon. cos\(\phi\) modulation solely from inclusion of non-zero quark \(k_T\).

- \(h^+\) vs. \(h^-\): u-quark dominates & Collins FF has opposite sign of u-quark into positively and negatively charged pions.

- **COMPASS and HERMES**: sizable modulations. Results for unidentified hadrons (h) differ.

**CLAS p**

Small cos\(\phi\) and cos(2\(\phi\)) modulations.

CLAS PRD 80 (2009) 032004

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Cos(nφ) COMPASS vs. HERMES in “almost overlapping kinematics”

COMPASS: 0.02 < x < 0.13, ⟨Q²⟩ = 4 GeV²
HERMES: 0.023 < x < 0.145, ⟨Q²⟩ = 2 GeV²

- Full differential analysis using the complete multidimensional information is mandatory.

For both experiments, bin-by-bin correction for the ratio of the longitudinal to transverse virtual photon flux before making the weighting average (statistical error only) in x and P_{hT}. All results acceptance corrected.
Worm-gear TMD

- Related to parton orbital motion - requires interference between wave functions with OAM difference by 1 unit.
- Worm gear TMDs: no “partner GPD”, unlike other 6 TMDs.

Hall-A n↑ Hall A PRL 108 (2012) 052001 (not shown): neutron result slightly positive for π⁻; ≈0 for π⁺

COMPASS p↑ COMPASS preliminary Proton 2010 data

HERMES p↑ Preliminary result (not shown): positive trend for π⁺ and π⁻


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The systematic uncertainty. The upper band shows the measured Collins fragmentation functions, it can provide a significant.

- COMPASS and HERMES results: compatible with zero. COMPASS (deuteron) EPJ C70 (2010) 39
  HERMES (proton π+/-) PRL 84 (2000) 4047
  HERMES (proton π0) PRD 64 (2001) 097101
  HERMES (deuteron) PLB 562 (2003) 182

- CLAS12 measurement will cover wider kinematic range with smaller uncertainties.
Transverse spin asymmetries at COMPASS

\[ \cos \phi_S - S_A \]

\[ \begin{array}{cccc}
-0.02 & -0.01 & -0.1 & 0.04 \\
0.01 & 0.01 & 0.01 & -0.1 \\
-2 & 0 & 0 & 0 \\
10 & 90 & 180 & 270
\end{array} \]

negative hadrons
positive hadrons
negative hadrons
positive hadrons

\[ \sin \phi \]

\[ \sin(3\phi - \rho) \]

\[ P \times S_A \]

\[ \text{COMPASS preliminary Proton 2010 data} \]

\[ \text{COMPASS p↑} \]

\[ A_{UT} \]

\[ \sin(3\phi_S - \rho) \]

Not shown:

\[ \text{COMPASS d↑ Also compatible with zero.} \]

\[ \text{HERMES p↑ Preliminary results: compatible with zero.} \]

\[ \text{Hall-A n↑} \]

\[ \text{Hall-A SoLID: proposal @ JLab 12} \]

“pretzelosity = helicity minus transversity”

\[ \Rightarrow \text{measure of relativistic motion of quarks inside of proton.} \]

\[ \text{CLAS projections} \]

\[ \text{positivity model} \]

\[ \text{CLAS12 projections} \]

\[ \pi^+ \text{ proton} \]
Global analysis of TMD data

- Study kinematic dependences in **multi-dimensional phase-space**
  ⇒ Requires careful choice of ranges and binnings, accounting for experimental acceptances

- **Consistent treatment amongst experiments**
  ⇒ various reactions ↔ address TMD universality
  ⇒ various energy domains ↔ address TMD evolution

- **Experimental challenges**: results must be as-free-as-possible of acceptance and radiative effects, and of events of diffractive meson production.

- **Quark flavor disentanglement**: use different targets, and identify hadrons.

- Prominent: Sivers and Transversity PDFs, and Collins FF.

- More: see Zhongbo Kang’s talk this session.

map of valence-quark region: JLab

Sivers function from HERMES and COMPASS data

M. Anselmino et al., arXiv:1107.4446 [hep-ph]
Outlook: TMD experiments

- **2016/17 (just starting!):** COMPASS-II SIDIS (2016/17) on unpolarized target (LH$_2$)
  - Flavor separation: proton + deuteron data and advanced hadron PID.
  - Mapping in 4 dimensions: x, Q$^2$, p$_T^2$, z; e.g. Boer-Mulders and Cahn-effect
  - Strange-quark distribution function s(x) in so-far uncovered region 0.001 < x < 0.2

- **>2020: “COMPASS-III” ? Discussions have started.**
  - Different energies for Sivers TMD evolution
  - High-precision mapping
  - Tranversity on deuteron target
  - New structure function $\rightarrow$ target fragmentation region?

- **JLab 12**
  Several closely-related proposals approved in all three Halls, providing complementary studies with different systematics.
  **CLAS12:** transversely polarized hydrogen target with access to higher P$_hT$ and Q$^2$ with negligible nuclear background

- **RHIC results:** see Xiaorong Wang, E3.00002

- **TMDs at an Electron-Ion Collider:** see E. Aschenauer’s talk this session.

Connection with GPDs: Sivers function $\leftrightarrow$ GPD $E$
chiral odd: Transversity $\leftrightarrow$ GPD $H_T$, Boer-Mulders $\leftrightarrow$ 2$H_T + E_T$
Summary: TMDs at COMPASS, HERMES & JLab

- The proton structure is being unraveled - similarly exciting situation as in the early 20th century, when the (fine)structure of the hydrogen atom was discovered.

- Huge international effort to measure observables sensitive to the transverse momentum of partons in the nucleon. Parallel effort on the theory side.

- Currently most prominent question: Sivers (et al.) sign switch SIDIS ↔ DY?

- First extraction of TMDs: QCD dynamics is complex.

- Common TMD extraction needed from multi-dimensional observables with high precision →

- COMPASS-II: 2015-18
- JLab12: >=2016
- “COMPASS-III” > 2020?

Thank you to: Harut Avakian, Andrea Bressan, Marco Contalbrigo.
Backup slides
# Table of TMD(PDF)s

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<td>N</td>
<td>$f_1$ number density</td>
<td>$g_1$ helicity</td>
<td>$h_{1\perp}$ Boer-Mulders</td>
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<td>U</td>
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<tr>
<td>T</td>
<td>Sivers</td>
<td>$g_{1T}$ worm-gear</td>
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**Legend**
- Nucleon (N)
- Unpolarized quark (Q)
- Nucleon spin
- Quark spin
- Quark $k_T$

**Chiral odd TMDs**

> Flavor indices and kinematic dependences skipped for simplicity. 8 TMD(PDF)s needed at leading twist description.

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<table>
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<td>“Re(S×P)”</td>
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<tr>
<td>T</td>
<td>$f_1T$</td>
<td>$g_{1T}$</td>
<td>$h_{1T}$</td>
<td>↔ D wave component</td>
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“Im(S×P)” “Re(S×P)”

\[
f(x, k_{\perp}^2)
\]

\[
\frac{k_{\perp i} S_{Ti}}{M} f(x, k_{\perp}^2)
\]

\[
\frac{k_i k_j - \frac{1}{2} k_{\perp}^2 g_{T}^{ij}}{M^2} f(x, k_{\perp}^2)
\]

Monopole

Dipole

Quadrupole
TMD Fragmentation Functions

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<td>$G_{1L}$</td>
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<tr>
<td>T</td>
<td>$H_{1T}$</td>
<td>$G_{1T}$</td>
<td>$H_1$ $H_{1T}$</td>
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</tbody>
</table>

8 functions describing fragmentation of a quark into spin $\frac{1}{2}$ hadron


courtesy A. Prokudin
Naive T-odd TMDs

- **Naive time reversal** (no symmetry of QCD Lagrangian): time-reversal operation without interchange of initial and final states, i.e. reversal of momentum and spin vectors only.

- At leading twist, the existence of a naively T-odd FF arising from final state interaction effects, was predicted by Collins and is now generally known as the Collins effect. In the fragmentation of transversely polarized quarks it is responsible for a left-right asymmetry which is due to a correlation between the spin of the fragmenting quark and the transverse momentum of the produced hadron with respect to the quark direction.

- Final-state interactions are required for non-vanishing signals for the naive-$T$-odd TMDs (measured in SIDIS). The associated single-spin asymmetries are caused by the interference of scattering amplitudes involving a helicity flip of only the nucleon, which has to be compensated by orbital angular momentum of the unpolarized quarks.
Chiral-odd TMDs

• Although fundamental for the nucleon description, transversity has long remained unmeasured due to its chiral-odd nature (in the helicity basis, it corresponds to a quark helicity flip), which prevents its measurement in inclusive DIS: the transversity distribution can only be measured in conjunction with another chiral-odd object.

• One possibility is represented by SIDIS reactions, where at least one final state hadron is detected in coincidence with the scattered lepton, thus conjugating parton distribution with fragmentation functions (for transversity, the Collins FF).

• The TMD distributions for transversely polarized quarks arise from interference between amplitudes with left- and right-handed polarization states, and only exist because of chiral symmetry breaking in the nucleon wave function in QCD. For example, the transversity distribution reflects the quark transverse polarization in a transversely polarized nucleon and is related to the tensor charge of the nucleon.
Collins asymmetry in SIDIS

Fig. 5:
Left: comparison between the Collins asymmetries for pions as a function of $x$, extracted from 2007 and 2010 data taking. Right: the same comparison for the Sivers asymmetries.

Fig. 6:
The Collins asymmetries for charged pions (top), charged kaons (middle) and neutral kaons (bottom) on proton as a function of $x$, $z$ and $p_T$.

PLB 744 (2015) 250
PLB 693 (2010) 11

No effects of evolution (unlike for Sivers case)

Diffractive vector mesons in SIDIS COMPASS data

0.2 < Q^2 < 1.13

0.4 < Q^2 < 1.83

0.6 < Q^2 < 2.5

0.8 < Q^2 < 3.5

Monte Carlo simulation

3.5 < Q^2 < 5.0

5.0 < Q^2 < 7.0

7.0 < Q^2 < 10

10 < Q^2 < 100

Monte Carlo simulation

0.20 < z < 0.50

0.50 < z < 0.60

0.60 < z < 0.65

0.65 < z < 0.70

0.70 < z < 0.75

0.75 < z < 0.85
Angle definitions for di-hadron production

\[ N_{h^+h^-}(x, y, z, M_{h^+h^-}^2, \cos \theta, \phi_{RS}) \propto \sigma_{UU} \left( 1 + f(x, y) P_T D_{nn}(y) A_{UT}^{\sin \phi_{RS}} \sin \theta \sin \phi_{RS} \right) \]

\[ A_{UT}^{\sin \phi_{RS}} = \frac{|p_1 - p_2|}{2M_{h^+h^-}} \frac{\sum_q e_q^2 \cdot h_{1,q}^q(x) \cdot H_{1,q}^\perp(z, M_{h^+h^-}^2, \cos \theta)}{\sum_q e_q^2 \cdot f_{1,q}^q(x) \cdot D_{1,q}(z, M_{h^+h^-}^2, \cos \theta)} \]

experimentally extracted quantity:

\[ A = \langle A_{UT}^{\sin \phi_{RS}} \sin \theta \rangle, \text{ integrated over the angle } \theta. \]

\[ \theta = \text{polar angle of one of the hadrons in the di-hadron rest frame with respect to the di-hadron boost axis} \]

from COMPASS PLB 736 (2014) 124
Sivers asymmetry (HERMES)

\[
2\langle \sin(\phi - \phi_S) \rangle_{UT} = -\frac{\sum \epsilon_{qT}^2 f_{qT}^q(x, p_T^2) \otimes \mathcal{W} D_1^q(z, k_T^2)}{\sum \epsilon_{qT}^2 f_{qT}^q(x, p_T^2) \otimes D_1^q(z, k_T^2)}
\]

- $\pi^+$ dominated by u-quark scattering:
  \[
  -f_{1T}^u(x, p_T^2) \otimes D_1^{u \rightarrow \pi^+}(z, k_T^2)
  \]
- u-quark Sivers function $< 0$
- d-quark Sivers function $> 0$


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Fig. 11: The asymmetries are compared to HERMES results.

The Sivers asymmetries for positive pions and kaons, as a function of $x$.

Fig. 10: The role of sea quarks is non-negligible.

COMPASS PLB 744 (2015) 250

HERMES PRL 103 (2009) 152002
Similarity between p and d results
⇒ indication of same-sign BM for up and down quarks.

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APS 2016, Salt Lake City, April 18, 2016
HERMES worm-gear and pretzelosity

\[ 2 \langle \cos(\phi - \phi_S) \rangle_{L} \]

\[ 2 \langle \sin(3\phi - 3\phi_S) \rangle_{U} \]

\[ x, z, P_{h\perp} [\text{GeV}] \]

HERMES PRELIMINARY 8.0% scale uncertainty

HERMES PRELIMINARY 7.3% scale uncertainty
COMPASS

= COnmon Muon and Proton Apparatus for Structure and Spectroscopy

Main CERN site

Geneva, Switzerland /
Prevesettin, France
The COMPASS transversely polarized NH$_3$ target
Hall-C
Super High Momentum Spectrometer (SHMS)
unpolarized SIDIS, hadron ID

Hall-B
CLAS12 H,D polarized targets up to $10^{35} \text{ cm}^{-2} \text{s}^{-1}$
“complete” acceptance, hadron ID

Hall-A
Spectrometer Pair, polarized $^3\text{He}$ target
up to to $10^{38} \text{ cm}^{-2} \text{s}^{-1}$ hadron ID

SOLID $^3\text{He}, \text{NH}_3$ polarized targets
up to $10^{36} \text{ cm}^{-2} \text{s}^{-1}$ large acceptance, pion ID

slide courtesy M. Contalbrigo
FIG. 12: The $p_T^2$-dependence of the $\langle \cos \phi \rangle$ taken at $Q^2 = 2(\text{GeV/c})^2$, $x = 0.30$ and $z = 0.21$ obtained from two different detector acceptance regions (triangles and squares). Full markers correspond to the data before the acceptance correction and the empty markers show acceptance corrected $\langle \cos \phi \rangle$. The two data sets are shifted equally along the $x$-axis in opposite directions from their central values for visibility. Error bars are statistical only.

FIG. 13: Same as Fig. 12 except for $\langle \cos^2 \phi \rangle$.

The systematic uncertainties on the acceptance were estimated from the variation in the absolute cross sections obtained using each of six CLAS sectors separately to detect the electron (pion) and then integrating over the pion (electron) wherever else it appeared. This uncertainty was estimated bin-by-bin and reflects the ability of Monte Carlo to describe the detector non-uniformities. The uncertainty increases at low polar scattering angle, and therefore low-$Q^2$ for electrons and low-$p_T^2$ for pions, where the azimuthal acceptance of CLAS is reduced.
The path of the Wilson lines depends on the space-time structure of the process in which the TMDs are embedded. The Wilson lines required for Drell-Yan production point to the past, whereas those appearing in the parton distributions for SIDIS point to the future. This reflects the fact that the gluon interactions shown in figure 8 strike a parton before the hard scattering in the Drell-Yan case and after the hard scattering in SIDIS.

**Initial-state interactions**

Drell Yan

**Final-state interactions**

SIDIS

If it were not for the gluon exchange represented by the Wilson line, the Sivers modulation would be zero.

M. Diehl, arXiv:1512.01328
Angular dependence of the Drell-Yan cross section

“no spin” (spin integrated)

“Naive Drell-Yan” in collinear (kT=0) qqbar annihilation:

\[
\frac{d\sigma}{d\Omega} \propto 1 + \cos^2 \theta
\]

(1+cos^2\theta) “naive DY”+ kT + higher O(\alpha_s)
(presence of gluons will cause quarks to have kT):

\[
\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2 \theta + \mu \sin(2\theta) \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos(2\phi)
\]

1 - \lambda = 2\nu

Lam-Tung relation

- Basic derivation from structure-function formalism.
- Consequence of spin-\(\frac{1}{2}\) nature of quarks.
- Expected to be valid also in the presence of QCD corrections.

C.S. Lam and W.K. Tung, PRD 18 (1978) 2447
Angular dependence of the Drell-Yan cross section

“with spin” (transversely polarized target)

Measure magnitude of azimuthal modulations in cross section: “Single-Spin Asymmetries” SSA

$$d\sigma(\pi^- p^\uparrow \to \mu^+ \mu^- X) = 1 + \overline{h}_1 \otimes \overline{h}_1 \cos(2\phi)$$

$$+ |S_T| \overline{f}_1 \otimes \overline{f}_{1T} \sin \phi_S$$

$$+ |S_T| \overline{h}_1 \otimes h_{1T} \sin(2\phi + \phi_S)$$

$$+ |S_T| \overline{h}_1 \otimes h_1 \sin(2\phi - \phi_S)$$
Why a meson beam?

Drell-Yan \[ \sigma_{\text{DY}} \propto f_{\bar{u}|\pi} \otimes f_{u|p} \]

- **Flavor sensitive**: meson is specific \( qqbar \) compound  
  - pi-minus on proton: selectively probes u-quark Sivers distribution of the proton  
  - no cancellation effects by opposite-sign u- and d-quark Sivers contributions

- Creation of **large-mass di-lepton from valence quarks**: large \( x \)  
  Proton-induced DY generates di-lepton from sea-quark object with small \( x \).

- Mesons as alternative probe to **test meson structure** and **nuclear models** (not accessible in DIS)

See also: W.-C. Chang and D. Dutta, arXiv:1306.3971,
Transversely polarized NH$_3$ target & Hadron absorber

1. Long. pol.: DNP & 2.5T solenoid
2. Trans. pol: 0.6T dipole

Ammonia beads immersed into liquid helium; dilution factor: $f=0.22$

Vertex detector to improve resolution of
- mass & angle of virtual photon
- vertex position.

$^6$Li absorber
to prevent flooding of very upstream detectors with charged particles from capture of spallation neutrons ($\Rightarrow \gamma \Rightarrow e^+e^-$).

To minimize multiple scattering of muons and to maximize stopping power for hadrons.

1st downstream COMPASS detector

Vertex detector + absorber surrounded by 2m of iron-free concrete on each side.

steel alumina

W beam plug

$^6$Li absorber

Ammonia beads immersed into liquid helium; dilution factor: $f=0.22$

1. Long. pol.: DNP & 2.5T solenoid
2. Trans. pol: 0.6T dipole

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$^6$Li absorber
to prevent flooding of very upstream detectors with charged particles from capture of spallation neutrons ($\Rightarrow \gamma \Rightarrow e^+e^-$).
The recovered space between target and spectrometer, the new hadron absorber was mounted, together with concrete shielding structure. The full setup is shown in Fig. 1, except for the beamline CEDARS which were used for beam particle tagging, set on kaons and antiprotons.

The cells of NH$_3$ material that constitute the polarizable target are cylindrical with 2 cm radius and 55 cm length each. There is 20 cm space between cells, since the vertex resolution along the beamline is degraded by the presence of the hadron absorber. In the beamline there are other non-polarizable targets: one aluminum cylinder 7 cm long is placed 27 cm upstream of the beam plug, inserted deep inside the hadron absorber. The tungsten beam plug itself acts as a target. Although its total length amounts to 120 cm, primary Drell-Yan interactions in tungsten come from the 20-40 cm most upstream part only.

**2.1.1 Hardware upgrades for the Drell-Yan experiment at COMPASS**

As it was already said above in order to make a successful Drell-Yan experiment at COMPASS a number of hardware upgrades has been performed. In more detail they are described in the "Hardware for Drell-Yan" Section of this document. Here we would like to bring only the list of upgrades, ordered according to the corresponding element position along the beam line, which looks as follows:

- upgraded CEDAR's system, main goal is to improve rate capability and thermal stability;
- COMPASS Polarised Target Superconducting Magnet, new CERN-standard Magnet Control System (MCS) and Magnet Safety System (MSS);
- COMPASS Polarised Target with renewed cryogenic system and newly produced micro-wave cavity designed to host new 2-cells proton-free polarised target holder;
- New scintillating fiber based high-rate-capable Vertex Detector placed in between the COMPASS PT and the Hadron Absorber (HA) with the goal to improve the di-muon event vertex resolution, degraded by the multiple scattering in HA;
- Hadron Absorber with the incorporated tungsten beam plug designed to stop a secondary hadrons flux over the spectrometer and to absorb non interacted in the PT hadron beam;
- DC05 Large Area Drift Chamber constructed to substitute the poorly performing Straw tube module #2;
- Completely new COMPASS DAQ system both hardware and software wise, designed to improve data taking stability and trigger rate capability.

**2.2 Preliminary analysis of 2014 data**

The 2014 DY data taking started on October 6 and lasted until December 15 2014, the period of beam availability. The first half of the running period was devoted to the commissioning of all parts of the new setup, to the beam tuning, and to the trigger related studies. The new DAQ system was also used for the first time in

![Graph showing vertex position for events with M$_{\mu^+\mu^-}$>4GeV](image)

**Target for COMPASS Drell-Yan run (2015)**

**2015 polarized running:**

- **Period 1:**
  - week 1: 55cm
  - week 2: 55cm
  - week 3: 55cm
  - week 4: 55cm

- **Period 2:**
  - week 1: 55cm
  - week 2: 55cm
  - week 3: 55cm
  - week 4: 55cm

**COMPASS DY 2014 ongoing analysis**

![Graph showing vertex position for events with M$_{\mu^+\mu^-}$>4GeV](image)
Existing COMPASS Drell-Yan data

- 2014: unpolarized proton (mass 1), unpolarized aluminum (mass 27), unpolarized tungsten (mass ~183)

- 2015: transversely polarized proton, unpolarized aluminum, unpolarized tungsten

- Scatter off different targets and record data at the same time.

Events with oppositely charged di-muon events ($M\mu+\mu->4GeV$):

- W: 65%
- Al: 2%
- NH3: 32%
2014 data (DY pilot run) - preliminary

- ~ 2 weeks of stable data taking
- Average beam intensity: 7.3x10^7 particles /s (up to nominal 10^8/s)
- No target polarization, no (usage of) vertex detector
- Statistics (NH_3 M_μ⁺μ⁻>4GeV): ~7k di-muon events (~9% of 2015 data); ~200k J/ψ.

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```
### COMPASS di-muon kinematics

**Continuum:**
- Drell-Yan
- Open charm/bottom decays
- Combinatorial background

**Combinatorial background:**
- From pion / kaon decays.
- Estimated from like-sign muons.

<table>
<thead>
<tr>
<th>$M_{\mu\mu}$ [GeV]</th>
<th>&lt;2</th>
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</table>

**Figure:**
- COMPASS DY 2014
- Events vs $M_{\mu\mu}$ (GeV/c$^2$)
- Continuum: Total, $J/\psi$, Continuum, $\psi$, Combinatorial Bkg

**Table Notes:**
- ✔: Clean
- ✗: >50% background
- ✗: <10% background
- -: Not applicable

---

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APS 2016, Salt Lake City, April 18, 2016
COMPASS di-muon kinematics

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$d\sigma(\pi^- p^\uparrow \rightarrow \mu^+ \mu^- X) =$

$= 1 + \overline{h_1} \otimes h_1 \cos(2\phi)$

$+ |S_T| \overline{f_1} \otimes \overline{f_{1T}} \sin \phi_S$

$+ |S_T| \overline{h_1} \otimes h_{1T} \sin(2\phi + \phi_S)$

$+ |S_T| \overline{h_1} \otimes h_1 \sin(2\phi - \phi_S)$

beam target
pion proton

COMPASS Drell-Yan projections (2015+2018 data)

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APS 2016, Salt Lake City, April 18, 2016
We then use Eq. (43) to express the transverse spin asymmetry for DY production as:

\[ A_T = \frac{dN_{\text{DY}}}{dy_{\text{DY}}} \left( \frac{1 - \cos^2 \theta}{2} \right) \sin \phi \]

where \( \theta \) is the invariant mass of the lepton pair, and \( \phi \) is the azimuthal angle.

The sign change for the Sivers functions between the SIDIS processes to Drell-Yan and W/Z boson production is along the Collins-Soper axis.

The COMPASS Collaboration at CERN will use a 190 GeV proton beam in the main injector. There are two proposals corresponding to either a polarized proton or a polarized deuteron target.

The Single Spin asymmetry defined in the literature; see, e.g., Refs. [63, 83] and follow the Collins-Soper axis.

QCD evolution of the Sivers asymmetry

M.G. Echevarria et al., PRD 89 074013 (2014)

Transverse momentum dependent evolution: Matching SIDIS processes to Drell-Yan and W/Z boson production.
COMPASS SIDIS Sivers in DY kinematic range

- $h^+$ for $1 < Q^2/(GeV/c)^2 < 4$
- $h^-$ for $z > 0.2$, $p_T > 6.25/(GeV/c)$

COMPASS preliminary
Proton 2010 data

$S_{\phi-h}\sin(\Delta T_A)$

$Q^2/(GeV/c)^2 > 16$

$W (GeV/c^2)$

$x$, $z$, $p_T (GeV/c)$
Unpolarized Drell-Yan cross section

\[ \frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2 \theta + \mu \sin(2\theta) \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos(2\phi) \]

1 - \lambda = 2\nu

Lam-Tung relation

Boer and Mulders 1998: distribution function of the unpolarized nucleon with intrinsic \( k_T \) dependence.
- Describes correlation between quark transverse spin and momentum.
- Induces \( \cos(2\Phi) \) modulation of the DY cross section.
Lam-Tung in proton- and pion-induced DY

\[ 1 - \lambda = 2\nu \]

- Proton-induced Drell-Yan (E866)
  - consistent with LT-relation
  - no \( \cos(2\phi) \) dependence
  - no \( p_T \) dependence

- Pion-induced Drell-Yan (NA10, E615)
  - violates LT-relation
    (independent of nucleus: no nuclear effect)
  - large \( \cos(2\phi) \) dependence
  - strong with \( p_T \)

**One candidate to explain LT violation:**
BM function

- Pionic DY probes BM (valence), target=proton
- Protonic DY probes BM (sea), target=proton

BM (sea) \( \ll \) BM (valence)

**study of spin-orbit correlations**

see also: P. E. Reimer, arXiv:0704.3621
Spin-orbit correlations from Drell Yan?

- **Boer and Mulders 1998**: distribution function of the unpolarized nucleon with intrinsic $k_T$ dependence.
  - Describes correlation between quark transverse spin and momentum.
  - Induces $\cos(2\Phi)$ modulation of the DY cross section.

- **Other theoretical interpretations**:
  - QCD higher-twist effect causes change of virtual-photon polarization from transversely ($\lambda=1$) to longitudinally ($\lambda=-1$) polarized for $x_n \rightarrow 1$?
    - Data taken at different $\sqrt{s}$: pion: 11 GeV and 16 GeV; proton: 39 GeV.
    - Such effect should be seen in E906/SeaQuest data.
  - Spin correlations between annihilating quark and anti-quark?
  - Glauber gluons, QCD instantons, ...

More measurements in wider kinematic range, and kaon/anti-proton beams will help to differentiate the interpretations.
EMC effect in Drell Yan

\[ \frac{\sigma^{pA}_{pA}}{\sigma^{pd}_{pd}} \approx \frac{u_A(x)}{u_N(x)} \]

Modification of quark distributions in the nuclear medium

E772: PRL 64 (1990) 2479
E866: PRL 83 (1999) 2304
EMC effect in Drell Yan

- EMC effect: many models with different input physics. DIS data sufficient as probe?
- DY: no excess pions! Traditional meson-exchange model?
- Contemporary models: large effects for anti-quarks as x increases.
Flavor-dependent EMC effect in pion-induced DY

- Flavor-dependent modification of quark distributions in the nuclear medium?
- Distinguish between different nuclear models
- Cloet, Bentz, Thomas (CBT) model: isovector mean field in a N≠Z nucleus affects u- and d-quarks differently

\[
\frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}
\]

\[
\frac{\sigma^{DY}(\pi^+ + A)}{\sigma^{DY}(\pi^- + A)} \approx \frac{d_A(x)}{4u_A(x)}
\]

Dutta, Peng, Cloet, Gaskell, arXiv:1007.3916
Flavor-dependent EMC effect in pion-induced DY

\[
\frac{\sigma^{DY}(\pi^+ + A)}{\sigma^{DY}(\pi^- + A)} \approx \frac{d_A(x)}{4u_A(x)}
\]

\[
\frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}
\]

Important new information from COMPASS-II Drell-Yan data with pion beams

160 GeV pion beam @\(Q^2=25\) GeV^2

Previously unseen effect

\(x_1 = 0.5\)

Such an effect favors the CBT Model over the N=Z approximation.
Sivers from positive pions off neutron target negative

=> d-quark Sivers negative

Hall A Collaboration PRL 107 (2011) 072003