Recent HERMES results on polarized semi-inclusive deep-inelastic scattering
Longitudinal double-spin asymmetries in semi-inclusive DIS of electrons and positrons by protons and deuterons

[PRD 99 (2019) 112001]
Access to angular momentum in (SI)DIS

‘pizza quattro stagioni’

[M. Burkardt]
Access to angular momentum in (SI)DIS

\[ \mathcal{L}_q \quad \frac{1}{2} \Delta \Sigma \]
\[ \Delta G \]

'pizza quattro stagioni'

[M. Burkardt]

\[ \text{evolution, high-} p_T \text{ hadrons} \]
\[ [\text{better: polarized pp}] \]
Access to angular momentum in (SI)DIS

\[ \mathcal{L}_q + \Delta g + \frac{1}{2} \Delta \Sigma \]

('pizza quattro stagioni')

(M. Burkardt)

(semi-)inclusive longitudinal double-spin asymmetries

evolution, high-\(p_T\) hadrons

[better: polarized pp]

[better: polarized pp]
The proton spin puzzle and $\Lambda$ polarization in deep-inelastic scattering

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Longitudinal quark polarization in transversely polarized nucleons

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Evidence for a Single-Spin Azimuthal Asymmetry in Semi-inclusive Pion Electroproduction

\[
A_{UL} = \frac{1}{|P_B|} \frac{N^\rightarrow(\phi) - N^\leftarrow(\phi)}{N^\rightarrow(\phi) + N^\leftarrow(\phi)}
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\[ \sim \sin \phi \ ? \]
Final-state interactions and single-spin asymmetries in semi-inclusive deep inelastic scattering

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Received 2 February 2002; accepted 2 February 2002

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\[ \mathcal{L}_q, \frac{1}{2} \Delta \Sigma, \mathcal{L}_g, \Delta G \]

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(semi-)inclusive longitudinal double-spin asymmetries

evolution, high-\(p_T\) hadrons

[better: polarized pp]
Access to angular momentum in (SI)DIS

TMDs? (SIDIS): [better(?): GPDs]

\[ \Delta L_q = \pm 1 \text{ (or 2)} \]

\( \Delta L_q \)

\( \frac{1}{2} \Delta \Sigma \)

\( L_q \)

\( L_g \)

\( \Delta G \)

‘pizza quattro stagioni’

[M. Burkardt]

\( + \)

\( - \)

TMD

(semi-)inclusive longitudinal double-spin asymmetries

evolution, high-\( p_T \) hadrons

[better: polarized pp]
deep-inelastic scattering

\[ e^{-(E, p)} \rightarrow (E', p') \]

inclusive

factorization: parton distributions

Gunar Schnell
deep-inelastic scattering

\[(E, p) \rightarrow (E', p')\]

\[e \rightarrow q\]

\[\gamma^* \rightarrow u, d, u\]

parton distributions

fragmentation functions

semi-inclusive

factorization:
deep-inelastic scattering

- polarized lepton beams
- polarized targets
- large-acceptance spectrometer
- good particle identification (PID)
27.6 GeV polarized $e^+/e^-$ beam scattered off ...

- unpolarized (H, D, He, ..., Xe)
- as well as transversely (H) and longitudinally polarized (pure) H, D & $^3$He gas targets
HERMES polarized target

**Polarization:**
- longitudinal: ~85%
- transversal: ~75%

Fast/frequent spin reversal

- (movable) collimators against synchrotron radiation
- Source for polarized gas: $10^{17}$ atoms/sec
- 0.35 Tesla solenoid

Electron beam

- Coil
- Storage cell: $29 \times 9.8 \times 400$ mm$^3$
- $d < 0.1$ mm Al
- $n = 1-3.5 \times 10^{14}$ atoms/cm$^2$

Polarimeter: 3%
HERMES (1998-2005) schematically

two (mirror-symmetric) halves
HERMES (1998-2005) schematically

Particle ID detectors allow for
- lepton/hadron separation
- dual-radiator RICH: pion/kaon/proton discrimination 2 GeV < p < 15 GeV

two (mirror-symmetric) halves

Gunar Schnell
semi-inclusive DIS

- excluding transverse polarization:

\[
\frac{d\sigma^h}{dx \, dy \, dz \, dP_{h\perp}^2 \, d\phi} = \frac{2\pi \alpha^2}{xyQ^2} \frac{y^2}{2(1 - \epsilon)} \left(1 + \frac{\gamma^2}{2x}\right)
\]

\[
\begin{align*}
F_{UU,T}^h &+ \epsilon F_{UU,L}^h + \lambda \Lambda \sqrt{1 - \epsilon^2} F_{LL}^h \\
+ \sqrt{2\epsilon} \left[ \lambda \sqrt{1 - \epsilon} F_{LU}^{h,\sin \phi} + \Lambda \sqrt{1 + \epsilon} F_{UL}^{h,\sin \phi} \right] \sin \phi \\
+ \sqrt{2\epsilon} \left[ \lambda \lambda \sqrt{1 - \epsilon} F_{LL}^{h,\cos \phi} + \sqrt{1 + \epsilon} F_{UU}^{h,\cos \phi} \right] \cos \phi \\
+ \Lambda \epsilon F_{UL}^{h,\sin 2\phi} \sin 2\phi &+ \epsilon F_{UU}^{h,\cos 2\phi} \cos 2\phi \end{align*}
\]

\[F_{XY}^{h,\text{mod}} = F_{XY}^{h,\text{mod}}(x, Q^2, z, P_{h\perp})\]

Beam (\(\lambda\)) / Target (\(\Lambda\)) helicities

Gunar Schnell
semi-inclusive DIS

- excluding transverse polarization:

\[
\frac{d\sigma^h}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi} = \frac{2\pi\alpha^2}{xyQ^2} \frac{y^2}{2(1 - \epsilon)} \left(1 + \frac{\gamma^2}{2x}\right)
\]

\[
\begin{align*}
F^h_{UU,T} + \epsilon F^h_{UU,L} + \lambda\Lambda\sqrt{1 - \epsilon^2} F^h_{LL} \\
+ \sqrt{2\epsilon} \left[ \lambda\sqrt{1 - \epsilon} F^h_{LU,\sin\phi} + \Lambda\sqrt{1 + \epsilon} F^h_{UU,\sin\phi} \right] \sin\phi \\
+ \sqrt{2\epsilon} \left[ \lambda\Lambda\sqrt{1 - \epsilon} F^h_{LL,\cos\phi} + \sqrt{1 + \epsilon} F^h_{UU,\cos\phi} \right] \cos\phi \\
+ \Lambda\epsilon F^h_{UL,\sin 2\phi} \sin 2\phi + \epsilon F^h_{UU,\cos 2\phi} \cos 2\phi
\end{align*}
\]

- double-spin asymmetry

\[
A^h_{LL} \equiv \frac{\sigma^h_{++} - \sigma^h_{+-} + \sigma^h_{-+} - \sigma^h_{--}}{\sigma^h_{++} + \sigma^h_{+-} + \sigma^h_{-+} + \sigma^h_{--}}
\]

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semi-inclusive DIS

- in experiment extract instead $A_{||}$ which differs from $A_{LL}$ in the way the polarization is measured:

  - $A_{LL}$: along virtual-photon direction
  - $A_{||}$: along beam direction (results in small admixture of transverse target polarization and thus contributions from $A_{LT}$)

- $A_{||}$ related to virtual-photon-nucleon asymmetry $A_1$

\[ A_1^h = \frac{1}{D (1 + \eta \gamma)} A_{||}^h \]

\[ D = \frac{1 - (1 - y) \epsilon}{1 + \epsilon R} \]

\[ \eta = \frac{\epsilon \gamma y}{1 - (1 - y) \epsilon} \]
previous HERMES analysis

- (semi-) inclusive asymmetries used for LO extraction of helicity PDFs
re-analysis of double-spin asymmetries

- revisited [PRD 71 (2005) 012003] $A_1$ analysis at HERMES in order to
- exploit slightly larger data set (less restrictive momentum range)
- provide $A_\parallel$ in addition to $A_1$

$$A_1^h = \frac{1}{D(1 + \eta \gamma)} A_\parallel^h$$

$$D = \frac{1 - (1 - y) \epsilon}{1 + \epsilon R}$$

R (ratio of longitudinal-to-transverse cross-section) still to be measured! [only available for inclusive DIS data, e.g., used in $g_1$ SF measurements]

- correct for D-state admixture (deuteron case) on asymmetry level
- correct better for azimuthal asymmetries coupling to acceptance
- look at multi-dimensional ($x, z, P_{h\perp}$) dependences
- extract twist-3 cosine modulations
azimuthal-asymmetry corrections

\[ \tilde{A}_\parallel^h (x, Q^2, z, P_{h\perp}) = \frac{\int d\phi \sigma^h_{\parallel} (x, Q^2, z, P_{h\perp}, \phi) \xi(\phi)}{\int d\phi \sigma^h_{UU} (x, Q^2, z, P_{h\perp}, \phi) \xi(\phi)} \]

- both numerator and in particular denominator \( \phi \) dependent
- in theory integrated out
- in praxis, detector acceptance also \( \phi \) dependent
- convolution of physics & acceptance leads to bias in normalization of asymmetries

measured

“polarized Cahn” effect etc.

Boer-Mulders and Cahn effects etc.

azimuthal acceptance
azimuthal-asymmetry corrections

both numerator and in particular denominator $\phi$ dependent

in theory integrated out

in praxis, detector acceptance also $\phi$ dependent

convolution of physics & acceptance leads to bias in normalization of asymmetries

implement data-driven model for azimuthal modulations [PRD 87 (2013) 012010] into MC ➔ extract correction factor & apply to data

Boer-Mulders and Cahn effects etc.

“polarized Cahn” effect etc.

measured azimuthal acceptance
double-spin asymmetry $A_{\parallel}$

$$A^h_{\parallel} \equiv \frac{C^h_{\phi}}{f_D} \left[ \frac{L \Leftrightarrow N^h \Leftrightarrow - L \Leftrightarrow N^h \Rightarrow}{L_P, \Rightarrow N^h \Leftrightarrow + L_P, \Leftrightarrow N^h \Rightarrow} \right]_B$$
double-spin asymmetry $A_{||}$ 

$$A_{||}^{h} \equiv \frac{C_{\phi}^{h}}{f_{D}} \left[ \frac{L \leftrightarrow N^{h} \leftrightarrow - L \leftrightarrow N^{h}}{L_{P, \leftrightarrow} N^{h} \leftrightarrow + L_{P, \leftrightarrow} N^{h}} \right]_{B}$$
double-spin asymmetry $A_{\parallel}$

$$A_{\parallel}^h \equiv \frac{C_{\phi}^h}{f_D} \left[ \frac{L \leftrightarrow N \leftrightarrow - L \leftrightarrow N \leftrightarrow}{L_{P,\leftrightarrow} N \leftrightarrow + L_{P,\leftrightarrow} N \leftrightarrow} \right]_B$$

azimuthal correction

nucleon-in-nucleus depolarization factor (0.926 for deuteron due to D-state admixture)
Double-spin asymmetry $A_{||}$

$$A_{||}^h \equiv \frac{C^h_\phi}{f_D} \left[ \frac{L \leftrightarrow N^h \leftrightarrow - L \leftrightarrow N^h \leftrightarrow}{L_{P,\leftrightarrow} N^h \leftrightarrow + L_{P,\leftrightarrow} N^h \leftrightarrow} \right]_B$$

Azimuthal correction

Luminosities

Nucleon-in-nucleus depolarization factor (0.926 for deuteron due to D-state admixture)
double-spin asymmetry $A_{\parallel}$

\[
A_{\parallel}^h \equiv \frac{C_{\phi}^h}{f_D} \left[ \frac{L \Rightarrow N^h \leftrightarrow - L \Rightarrow N^h \leftrightarrow}{L_P, \Rightarrow N^h \leftrightarrow + L_P, \leftrightarrow N^h \Rightarrow} \right]_B
\]

azimuthal correction

luminosities

nucleon-in-nucleus depolarization factor (0.926 for deuteron due to D-state admixture)

polarization-weighted luminosities
double-spin asymmetry $A_{||}$

\[
A_{||}^h \equiv \frac{C_{\phi}^h}{f_D} \left[ \frac{L \Rightarrow N^h \Leftrightarrow - L \Leftrightarrow N^h}{L_P, \Rightarrow N^h \Leftrightarrow + L_P, \Leftrightarrow N^h} \right]_B
\]

azimuthal correction

luminosities

polarization-weighted luminosities

unfolded for QED radiation to Born level

nucleon-in-nucleus depolarization factor

(0.926 for deuteron due to D-state admixture)
double-spin asymmetry $A_{||}$

\[
A_{||}^h \equiv \frac{C_{\phi}^h}{f_D} \left[ \frac{L \Leftrightarrow N^h \Leftrightarrow - L \Leftrightarrow N^h \Leftrightarrow}{L_P, \Leftrightarrow N^h \Leftrightarrow + L_P, \Leftrightarrow N^h \Leftrightarrow} \right]_B
\]
double-spin asymmetry $A_{||}$

$$A_{||}^h \equiv \frac{C^h_\phi}{f_D} \left[ \frac{L \leftrightarrow N^h \leftrightarrow - L \leftrightarrow N^h \leftrightarrow}{L_P, \leftrightarrow N^h \leftrightarrow + L_P, \leftrightarrow N^h \leftrightarrow} \right]_B$$

- dominated by statistical uncertainties
double-spin asymmetry $A_{||}$

$$A_{||}^h \equiv \frac{C^h_\phi}{f_D} \left[ \frac{L \leftrightarrow N^h - L \leftrightarrow N^h}{L_P, \leftrightarrow N^h} + \frac{L_P, \leftrightarrow N^h}{L_P, \leftrightarrow N^h} \right]_B$$

- dominated by statistical uncertainties
- main systematics arise from
  - polarization measurements [6.6% for hydrogen, 5.7% for deuterium]
  - azimuthal correction [$\mathcal{O}$(few %)]
x dependence of $A_{||}$

- consistent with previous HERMES publication [PRD 71 (2005) 012003]

[arXiv:1810.07054]
$z$ dependence of $A_{||}$ (three $x$ ranges)

- In general, no strong $z$-dependence visible

[arXiv:1810.07054]
dependence of $A_{||}$ (three x ranges)

- again, no strong dependence (beyond on $x$)

[arXiv:1810.07054]
$P_{h\perp}$ dependence of $A_{||}$ (three $x$ ranges)

- again, no strong dependence (beyond on $x$)

- also fit to $A_1$ fit does not favor an additional dependence on $P_{h\perp}$
interlude: dealing with multi-d dependences
multi-d dependences

- TMD cross sections differential in at least 5 variables
  - some easily parametrized (e.g., azimuthal dependences)
  - others mostly unknown
multi-d dependences

- TMD cross sections differential in at least 5 variables
  - some easily parametrized (e.g., azimuthal dependences)
  - others mostly unknown
- one-dimensional binning provide only glimpse of true physics
  - even different kinematic bins can’t disentangle underlying physics dependences
  - e.g., binning in $x$ involves [incomplete] integration(s) over $P_{h\perp}$
multi-d dependences

- TMD cross sections differential in at least 5 variables
  - some easily parametrized (e.g., azimuthal dependences)
  - others mostly unknown
- one-dimensional binning provide only glimpse of true physics
  - even different kinematic bins can’t disentangle underlying physics dependences
    - e.g., binning in x involves [incomplete] integration(s) over $P_{h\perp}$
- further complication: physics (cross sections) folded with acceptance
  - NO experiment has flat acceptance in full multi-d kinematic space
multi-d dependences

\[
\frac{N^+(x) - N^-(x)}{N^+(x) + N^-(x)} = \frac{\int d\omega \epsilon(x, \omega) \Delta\sigma(x, \omega)}{\int d\omega \epsilon(x, \omega) \sigma(x, \omega)}
\]

- measured cross sections / asymmetries often contain “remnants” of experimental acceptance $\epsilon$
multi-d dependences

\[
\frac{N^+(x) - N^-(x)}{N^+(x) + N^-(x)} = \frac{\int d\omega \, \epsilon(x, \omega) \Delta \sigma(x, \omega)}{\int d\omega \, \epsilon(x, \omega) \sigma(x, \omega)} \neq \frac{\int d\omega \, \Delta \sigma(x, \omega)}{\int d\omega \, \sigma(x, \omega)}
\]

- measured cross sections / asymmetries often contain “remnants” of experimental acceptance \( \epsilon \)
multi-d dependences

\[
\frac{N^+(x) - N^-(x)}{N^+(x) + N^-(x)} = \frac{\int d\omega \epsilon(x, \omega) \Delta \sigma(x, \omega)}{\int d\omega \epsilon(x, \omega) \sigma(x, \omega)} \neq A(x, \langle \omega \rangle)
\]

- measured cross sections / asymmetries often contain "remnants" of experimental acceptance $\epsilon$
- difficult to evaluate precisely in absence of good physics model
- general challenge to statistically precise data sets
- avoid 1d binning/presentation of data
- theorist: watch out for precise definition (if given!) of experimental results reported ... and try not to treat data points of different projections as independent
3-dimensional binning

- 3d dependences provides transverse-momentum dependence
3-dimensional binning

- 3d dependences provides transverse-momentum dependence
- but also extra flavor sensitivity, e.g.,
  - \( \pi^- \) asymmetries mainly coming from low-\( z \) region where disfavored fragmentation large and thus sensitivity to the large positive up-quark polarization

\[ \begin{array}{c}
\text{1d} \\
\text{3d}
\end{array} \]

[arXiv:1810.07054]
charge-difference asymmetries

\[ A_{1}^{h^+ - h^-}(x) \equiv \frac{(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}) - (\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-})}{(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}) + (\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-})} \]
charge-difference asymmetries

\[ A_{1}^{h^{+}-h^{-}}(x) \equiv \frac{\left( \sigma_{1/2}^{h^{+}} - \sigma_{1/2}^{h^{-}} \right) - \left( \sigma_{3/2}^{h^{+}} - \sigma_{3/2}^{h^{-}} \right)}{\left( \sigma_{1/2}^{h^{+}} - \sigma_{1/2}^{h^{-}} \right) + \left( \sigma_{3/2}^{h^{+}} - \sigma_{3/2}^{h^{-}} \right)} \]

- at leading-order and leading-twist, assuming charge conjugation symmetry for fragmentation functions:

\[ A_{1,d}^{h^{+}-h^{-}} \overset{\text{LO LT}}{=} \frac{g_{1}^{u,v} + g_{1}^{d,v}}{f_{1}^{u,v} + f_{1}^{d,v}} \]
charge-difference asymmetries

\[ A_{1}^{h^+ - h^-}(x) \equiv \frac{(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}) - (\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-})}{(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}) + (\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-})} \]

- at leading-order and leading-twist, assuming charge conjugation symmetry for fragmentation functions:

\[ A_{1,d}^{h^+ - h^-} \overset{LO\ LT}{=} \frac{g_{1uv}^{u} + g_{1}^{d\nu}}{f_{1uv}^{u} + f_{1}^{d\nu}} \]

- assuming also isospin symmetry in fragmentation:

\[ A_{1,p}^{h^+ - h^-} \overset{LO\ LT}{=} \frac{4g_{1uv}^{u} - g_{1}^{d\nu}}{4f_{1uv}^{u} - f_{1}^{d\nu}} \]
charge-difference asymmetries

\[ A_{1}^{h^+ - h^-}(x) \equiv \frac{\left(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}\right) - \left(\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-}\right)}{\left(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}\right) + \left(\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-}\right)} \]

- at leading-order and leading-twist, assuming charge conjugation symmetry for fragmentation functions:

\[ A_{1,d}^{h^+ - h^-} \overset{\text{LO LT}}{=} \frac{g_{1uv}^u + g_{1dv}^d}{f_{1uv}^u + f_{1dv}^d} \]

- assuming also isospin symmetry in fragmentation:

\[ A_{1,p}^{h^+ - h^-} \overset{\text{LO LT}}{=} \frac{4g_{1uv}^u - g_{1dv}^d}{4f_{1uv}^u - f_{1dv}^d} \]

- can be used to extract valence helicity distributions
charge-difference asymmetries

- no significant hadron-type dependence for deuterons
- deuteron results (unidentified hadrons) consistent with COMPASS

![Graphs showing charge-difference asymmetries](arXiv:1810.07054)
charge-difference asymmetries

- No significant hadron-type dependence for deuterons
- Deuteron results (unidentified hadrons) consistent with COMPASS
- Valence distributions consistent with JETSET-based extraction:

\[ A_{1,d}^{\pi^+ - \pi^-} \]

\[ A_{1,d}^{\pi^+,\pi^-} \]

\[ A_{1,d}^{K^+,K^-} \]

\[ x \cdot g_{1}^{u,v} \]

\[ x \cdot g_{1}^{d,v} \]
azimuthal modulations

- twist-3 various contributions
- most prominent: “polarized Cahn effect”

\[ xg_L^\perp D_1 \oplus \frac{M_h}{M_z} g_1 \tilde{D}^\perp \oplus x e_L H_1^\perp \oplus \frac{M_h}{M_z} h_1^\perp \tilde{E} \]

- the only one surviving WW-type approximations
azimuthal modulations

- twist-3 ☛ various contributions
- most prominent: “polarized Cahn effect”
- cosine modulations largely consistent with zero
Several longitudinal double-spin asymmetries in SIDIS have been presented that extend the analysis of previous HERMES publications to include also transverse-momentum dependence and for the first time also a 3d binning.

- Provide $A_{||}$ in addition to $A_1$

- Within precision of the measurements, the virtual-photon-nucleon asymmetries display no significant dependence on $z$ and $P_{h\perp}$

- Hadron-charge difference asymmetries in agreement with COMPASS

- Used for LO, leading-twist extraction of valence helicity PDFs

- $\cos \phi$ moments of semi-inclusive double-spin asymmetry compatible with zero
backup
caused by the convolution of the azimuthal moments of the nucleus and is explained in Section and Table.

Born and smeared Monte Carlo simulations according to i.e., unfolded for radiative and detector smearing, using that the enclosed quantity is corrected to Born level,licity configuration.

the parallel (antiparallel) experimental beam/target he-

rized in Table

publications on longitudinal double-spin asymmetries [same data set and procedure presented in prior HERMES are around 53% (84%).

Kinematical Requirements

Year Type Gas Type Hadron Type Hadron Momentum

<table>
<thead>
<tr>
<th>Year</th>
<th>Beam Type</th>
<th>Target Gas</th>
<th>Hadron Type</th>
<th>Hadron Momentum</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>e⁺</td>
<td>H</td>
<td>π±</td>
<td>4–13.8 GeV</td>
</tr>
<tr>
<td>1997</td>
<td>e⁺</td>
<td>H</td>
<td>π±</td>
<td>4–13.8 GeV</td>
</tr>
<tr>
<td>1998</td>
<td>e⁻</td>
<td>D</td>
<td>π±, K±</td>
<td>2–15 GeV</td>
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