HERMES view on the nucleon’s spin & 3d structure
Congratulations!
2022 — so many anniversaries!

- 25 years of COMPASS approval
- 20 years of COMPASS data taking
2022 — so many anniversaries!

- 25 years of COMPASS approval
- 20 years of COMPASS data taking
- 35 years of spin crisis/puzzle
- 30 years of HERA and (conditional) HERMES approval
- 15 years of HERA shutdown
27.6 GeV polarized $e^+/e^-$ beam scattered off...

- unpolarized (H, D, He, ..., Xe) as well as
- transversely (H) or
- longitudinally (H, D, He) polarized pure gas targets
Total number of published HERMES papers: 83
Total number of citations: 10,135
Average citations per paper: 122
2 top-cite 500+ & 9 top-cite 250+
[inspirehep.net as of Aug. 28, 2022]
HERMES publication statistics (08/2022)

- Total number of published HERMES papers: 83
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end of data taking
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Publication schedule for 2012 priority analyses (08/2022)

- despite tremendous drop in analysis manpower, almost all priority analyses identified finished
  - two analyses dropped
  - one still ongoing in advanced state
  - at same time new ideas; partially already published, others ... waiting for manpower
  - only possible thanks to tremendous data-preservation efforts
semi-inclusive one-hadron production (ep→ehX)
semi-inclusive one-hadron production ($e p \rightarrow e h X$)

parton kinematics

fragmentation kinematics

parton polarization

fragmentation fct. selector
Evidence for a Single-Spin Azimuthal Asymmetry in Semi-inclusive Pion Electroproduction

\[
A_{UL} = \frac{1}{|P_B|} \frac{N^\to(\phi) - N^\leftarrow(\phi)}{N^\to(\phi) + N^\leftarrow(\phi)}
\]
Evidence for a Single-Spin Azimuthal Asymmetry in Semi-inclusive Pion Electroproduction

\[ A_{UL} = \frac{1}{|P_B|} \frac{N^\rightarrow(\phi) - N^\leftarrow(\phi)}{N^\rightarrow(\phi) + N^\leftarrow(\phi)} \]

\[ \sim \sin \phi \]
Evidence for a Single-Spin Azimuthal Asymmetry in Semi-inclusive Pion Electroproduction

\[ A_{UL} = \frac{1}{|P_B|} \frac{N^\rightarrow(\phi) - N^\leftarrow(\phi)}{N^\rightarrow(\phi) + N^\leftarrow(\phi)} \]

\[ \sim \sin \phi \]
transverse-momentum distributions (TMDs)

Longitudinal momentum

\[ k^+ = xP^+ \]

Transverse momentum

Partons

Transverse plane

[courtesy of A. Bacchetta, Pavia]
3d spin-momentum structure of the nucleon

\[ \frac{1}{2} \text{Tr} \left[ (\gamma^+ + \lambda \gamma^5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T}^+ + \lambda \Lambda g_1 + \lambda S^i k^i \frac{1}{m} g_{1T} \right] \]

\[ \frac{1}{2} \text{Tr} \left[ (\gamma^+ - s^j i \sigma^{+j} \gamma^5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T}^+ + s^i \epsilon^{ij} k^j \frac{1}{m} h_1^+ + s^i S^i h_1 \right. \]

\[ + s^i (2k^i k^j - k^2 \delta^{ij}) S^j \frac{1}{2m^2} h_{1T}^+ + \Lambda s^i k^i \frac{1}{m} h_{1L}^+ \]

- each TMD describes a particular spin-momentum correlation
- functions in black survive integration over transverse momentum
- functions in green box are chirally odd
- functions in red are naive T-odd
3d spin-momentum structure of the nucleon

\[
\frac{1}{2} \text{Tr} \left[ (\gamma^+ + \lambda \gamma^5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T} + \lambda \Lambda g_1 + \lambda S^i k^i \frac{1}{m} g_{1T} \right]
\]

\[
\frac{1}{2} \text{Tr} \left[ (\gamma^+ - s^j i \sigma^j + \gamma^5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T} + s^i \epsilon^{ij} k^j \frac{1}{m} h_{1T}^{\perp} + s^i S^i h_1 \right]
\]

\[
+ s^i (2k^i k^j - k^2 \delta^{ij}) S^j \frac{1}{2m^2} h_{1T}^{\perp} + \Lambda s^i k^i \frac{1}{m} h_{1L}^{\perp}
\]

- each TMD describes a particular spin-momentum correlation
- functions in black survive integration over transverse momentum
- functions in green box are chirally odd
- functions in red are naive T-odd

<table>
<thead>
<tr>
<th>nucleon pol.</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>f_1</td>
<td></td>
<td>( h_1^{\perp} )</td>
</tr>
<tr>
<td>L</td>
<td>( g_{1L} )</td>
<td>( h_{1L}^{\perp} )</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>( f_{1T}^{\perp} )</td>
<td>( g_{1T} )</td>
<td>( h_1, h_{1T}^{\perp} )</td>
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</tbody>
</table>

- helicity
- quark pol.
- Boer-Mulders
- Sivers
- pretzelosity
- transversity
- worm-gear
- unpolarized quarks: easy - “just” hit them (and count)
- longitudinally polarized quarks: use polarized beam
- unpolarized quarks: easy - “just” hit them (and count)
- longitudinally polarized quarks: use polarized beam

- transversely polarized quarks: need final-state polarimetry, e.g.
## TMDs in hadronization

<table>
<thead>
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</tr>
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<tbody>
<tr>
<td>U</td>
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</tr>
<tr>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>T</td>
<td>T</td>
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**TMDs in hadronization**

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<tr>
<td>L</td>
<td>$G_1$</td>
</tr>
<tr>
<td>T</td>
<td>$D_{1T}$</td>
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- relevant for unpolarized final state
### TMDs in hadronization

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<td>U</td>
<td>$D_1$</td>
<td></td>
<td>$H_1$</td>
</tr>
<tr>
<td>L</td>
<td></td>
<td>$G_1$</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>$D_{1T}$</td>
<td>$G_{1T}$</td>
<td>$H_1$ $H_{1T}$</td>
</tr>
</tbody>
</table>

- **quark pol.**
- **Collins FF:** $H_1 \perp, q \rightarrow h$
- **ordinary FF:** $D_q \rightarrow h$

- Relevant for unpolarized final state
### TMDs in hadronization

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<tr>
<td>U</td>
<td>$D_\perp$</td>
<td>$H_{\perp 1}$</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>$G_1$</td>
<td>$H_{\perp 1L}$</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>$D_{1T}$</td>
<td>$G_{1T}$</td>
<td>$H_1 , H_{1T}$</td>
</tr>
</tbody>
</table>

- Relevant for unpolarized final state
- Polarized final-state hadrons (e.g., hyperons)
probing TMDs in semi-inclusive DIS

\[ \begin{array}{ccc}
\text{quark pol.} & \text{nucleon pol.} \\
| & | & |
\hline
U & f_1 & h_1^U \\
L & g_{1L} & h_{1L} \\
T & f_{1T} & g_{1T} & h_1, h_{1T} \\
\end{array} \]

\text{in SIDIS*} \) couple PDFs to:

Collins FF: \( H_{1}^\perp q \rightarrow h \)

ordinary FF: \( D_{1}^q \rightarrow h \)

\( \rightarrow \) give rise to characteristic azimuthal dependences

*\) semi-inclusive DIS with unpolarized final state
excluding transverse polarization:

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

\[
\left\{ F^{h}_{UU,T} + \epsilon F^{h}_{UU,L} + \Lambda \sqrt{1 - \epsilon^2} F^{h}_{LL} \right. \\
+ \sqrt{2\epsilon} \left[ \lambda \sqrt{1 - \epsilon} F^{h,\sin \phi}_{LU} + \Lambda \sqrt{1 + \epsilon} F^{h,\sin \phi}_{UL} \right] \sin \phi \\
+ \sqrt{2\epsilon} \left[ \lambda \Lambda \sqrt{1 - \epsilon} F^{h,\cos \phi}_{LL} + \sqrt{1 + \epsilon} F^{h,\cos \phi}_{UU} \right] \cos \phi \\
\left. + \Lambda \epsilon F^{h,\sin 2\phi}_{UL} \sin 2\phi + \epsilon F^{h,\cos 2\phi}_{UU} \cos 2\phi \right\}
\]

\[
F^{h,\text{mod}}_{XY} = F^{h,\text{mod}}_{XY}(x, Q^2, z, P_{h\perp})
\]
excluding transverse polarization:

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

$$\left\{ F_{UU,T}^h + \epsilon F_{UU,L}^h + \lambda \Lambda \sqrt{1 - \epsilon^2} F_{LL}^h \right. $$

$$+ \sqrt{2\epsilon} \left[ \lambda \sqrt{1 - \epsilon} F_{LU}^{h, \sin \phi} + \Lambda \sqrt{1 + \epsilon} F_{UL}^{h, \sin \phi} \right] \sin \phi$$

$$+ \sqrt{2\epsilon} \left[ \lambda \Lambda \sqrt{1 - \epsilon} F_{LL}^{h, \cos \phi} + \sqrt{1 + \epsilon} F_{UU}^{h, \cos \phi} \right] \cos \phi$$

$$\left. + \Lambda \epsilon F_{UL}^{h, \sin 2\phi} \sin 2\phi + \epsilon F_{UU}^{h, \cos 2\phi} \cos 2\phi \right\}$$

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

Beam ($\lambda$) / Target ($\Lambda$) helicities
semi-inclusive DIS

excluding transverse polarization:

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

\[
\begin{align*}
F_{UU,T}^h + \epsilon F_{UU,L}^h + \lambda\Lambda\sqrt{1 - \epsilon^2} F_{LL}^h \\
+ \sqrt{2\epsilon} \left[ \lambda\sqrt{1 - \epsilon} F_{LU}^{h,\sin\phi} + \Lambda\sqrt{1 + \epsilon} F_{UL}^{h,\sin\phi} \right] \sin\phi \\
+ \sqrt{2\epsilon} \left[ \lambda\Lambda\sqrt{1 - \epsilon} F_{LL}^{h,\cos\phi} + \sqrt{1 + \epsilon} F_{UU}^{h,\cos\phi} \right] \cos\phi \\
+ \Lambda\epsilon F_{UL}^{h,\sin2\phi} \sin2\phi + \epsilon F_{UU}^{h,\cos2\phi} \cos2\phi
\end{align*}
\]

double-spin asymmetry:

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

double-spin asymmetry:

\[
A_{LL}^h \equiv \frac{\sigma_{++}^h - \sigma_{+-}^h + \sigma_{--}^h - \sigma_{-+}^h}{\sigma_{++}^h + \sigma_{+-}^h + \sigma_{--}^h + \sigma_{-+}^h}
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\]

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


double-spin asymmetry:

\[
A_{LL}^h \equiv \frac{\sigma_{++}^h - \sigma_{+-}^h + \sigma_{-+}^h - \sigma_{--}^h}{\sigma_{++}^h + \sigma_{+-}^h + \sigma_{-+}^h + \sigma_{--}^h}
\]
semi-inclusive DIS

- excluding transverse polarization:

\[
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\]

\[
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- double-spin asymmetry:

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A_{LL}^h \equiv \frac{\sigma_{++}^h - \sigma_{+-}^h + \sigma_{-+}^h - \sigma_{--}^h}{\sigma_{++}^h + \sigma_{+-}^h + \sigma_{-+}^h + \sigma_{--}^h}
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\]

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

single-spin asymmetry:

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

\begin{align*}
F_{UU,T}^h + \epsilon F_{UU,L}^h + \text{terms not involving transv. polarization} \\
+ S_T \left[ \left( F_{UT,T}^{h,\sin(\phi-\phi_s)} + \epsilon F_{UT,L}^{h,\sin(\phi-\phi_s)} \right) \sin(\phi - \phi_s) \\
+ \epsilon F_{UT}^{h,\sin(\phi+\phi_s)} \sin(\phi + \phi_s) + \epsilon F_{UT}^{h,\sin(3\phi-\phi_s)} \sin(3\phi - \phi_s) \\
+ \sqrt{2\epsilon(1 + \epsilon)} F_{UT}^{h,\sin\phi_s} \sin\phi_s + \sqrt{2\epsilon(1 + \epsilon)} F_{UT}^{h,\sin(2\phi-\phi_s)} \sin(2\phi - \phi_s) \right] \\
+ S_T \lambda \left[ \sqrt{1 - \epsilon^2} F_{LT}^{h,\cos(\phi-\phi_s)} \cos(\phi - \phi_s) \\
+ \sqrt{2\epsilon(1 - \epsilon)} F_{LT}^{h,\cos\phi_s} \cos\phi_s + \sqrt{2\epsilon(1 - \epsilon)} F_{LT}^{h,\cos(2\phi-\phi_s)} \cos(2\phi - \phi_s) \right] \end{align*}
semi-inclusive DIS

- **with transverse target polarization:**

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

\[
\left\{ F_{UU,T}^h + \varepsilon F_{UU,L}^h + \text{terms not involving transv. polarization} \right. \\
\left. + S_T \left[ \left( F_{UT,T}^{h,\sin(\phi-\phi_s)} + \varepsilon F_{UT,L}^{h,\sin(\phi-\phi_s)} \right) \sin(\phi - \phi_s) \right. \\
+ \varepsilon F_{UT}^{h,\sin(\phi+\phi_s)} \sin(\phi + \phi_s) + \varepsilon F_{UT}^{h,\sin(3\phi-\phi_s)} \sin(3\phi - \phi_s) \\
+ \sqrt{2\varepsilon(1+\varepsilon)} F_{UT}^{h,\sin\phi_s} \sin\phi_s + \sqrt{2\varepsilon(1+\varepsilon)} F_{UT}^{h,\sin(2\phi-\phi_s)} \sin(2\phi - \phi_s) \\
\left. + S_T \lambda \left[ \sqrt{1-\varepsilon^2} F_{LT}^{h,\cos(\phi-\phi_s)} \cos(\phi - \phi_s) \right. \\
+ \sqrt{2\varepsilon(1-\varepsilon)} F_{LT}^{h,\cos\phi_s} \cos\phi_s + \sqrt{2\varepsilon(1-\varepsilon)} F_{LT}^{h,\cos(2\phi-\phi_s)} \cos(2\phi - \phi_s) \right] \right\}
\]
2d kinematic phase space

current and future data for Sivers asymmetries (selection):

- COMPASS $h^\pm$: $P_{hT} < 1.6$ GeV
- COMPASS Drell-Yan
- HERMES $\Delta^{0,\ast}$, $K^\pm$: $P_{hT} < 1$ GeV
- JLab Hall-A $\pi^\pm$: $P_{hT} < 0.45$ GeV
- STAR W bosons
- JLab 12 (upcoming)
- STAR Drell-Yan (upcoming)
- LHC-FT Drell-Yan (proposed)
2d kinematic phase space

current and future data for Sivers asymmetries (selection):

- COMPASS: $h^\pm$: $P_{hT} < 1.6$ GeV
- COMPASS: Drell-Yan
- HERMES: $\pi^\pm$, $K^\pm$: $P_{hT} < 1$ GeV
- JLab Hall-A: $\pi^\pm$: $P_{hT} < 1$ GeV
- JLab 12 (upcoming): $\pi^\pm$
- STAR: charged mesons
- STAR: neutral pions
- LHC-FT Drell-Yan (proposed)

Scattered lepton:

- $Q^2 > 1$ GeV$^2$
- $W^2 > 10$ GeV$^2$
- $0.023 < x < 0.6$
- $0.1 < y < 0.95$

Detected hadrons:

- $2$ GeV $< |P_{h\perp}| < 15$ GeV: charged mesons
- $4$ GeV $< |P_{h\perp}| < 15$ GeV: (anti)protons
- $|P_{h\perp}| > 2$ GeV: neutral pions
- $P_{h\perp} < 2$ GeV
- $0.2 < z < 0.7$ (1.2 for the “semi-exclusive” region)

Table 3. Restrictions on selected kinematics variables. The upper limit on $z$ of 1.2 applies only to the analysis of the $z$ dependence.
2d kinematic phase space

current and future data for Sivers asymmetries (selection):

- **COMPASS** $h^\pm$: $P_{ht} < 1.6$ GeV
- **COMPASS** Drell-Yan
- **HERMES** $\pi^\pm, K^\pm$: $P_{ht} < 1$ GeV
- **JLab Hall-A** $\pi^\pm$: $P_{ht} < 0.46$ GeV
- **STAR** W bosons
- **JLab 12** (upcoming)
- **STAR** Drell-Yan (upcoming)
- **LHC-FT** Drell-Yan (proposed)

2d ($x$-$Q^2$) kinematic space not the only relevant one for SIDIS interpretation
current vs. target fragmentation

virtual-photon—nucleon c.m.s

incoming / scattered lepton

virtual photon

target nucleon

hadron formation

hadron

final-state hadrons

virtual photon

K^+

Λ

Π^−

Π^0

Π^+

target nucleon

y_h < 0

y_h = 0

y_h > 0

y_h \equiv \frac{1}{2} \ln \frac{P^+_h}{P^-_h}

P^\pm_h \ldots \text{light-cone momenta}
current vs. target fragmentation

virtual-photon—nucleon c.m.s

\[ y_h \equiv \frac{1}{2} \ln \frac{P_h^+}{P_h^-} \]

\( P_h^\pm \) ... light-cone momenta
current vs. target fragmentation

selected hadrons at HERMES mainly forward-going in photon-nucleon c.m.s.
Longitudinal double-spin asymmetries in semi-inclusive deep-inelastic scattering of electrons and positrons by protons and deuterons


(The HERMES Collaboration)
re-analysis of longitudinal 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 $A_1$

\[
A_1^h = \frac{1}{D(1 + \eta \gamma)} A_\parallel^h, \quad D = \frac{1 - (1 - y)\varepsilon}{1 + \varepsilon R}
\]

$R$ (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
■ 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 $A_1$

$$A_1^h = \frac{1}{D(1 + \eta \gamma)} A_\parallel^h. \quad D = \frac{1 - (1 - y)\epsilon}{1 + \epsilon R}$$

R (ratio of longitudinal-to-transverse cross-sec'n) 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 ... consistent with zero
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 $A^h_{\parallel}$

$$A^h_{\parallel} \equiv \frac{C^h_{\phi}}{f_D} \left[ \frac{L \Rightarrow N^h \Leftrightarrow - L \Leftrightarrow N^h}{L \Rightarrow N^h \Leftrightarrow + L \Leftrightarrow N^h} \right]_B$$

azimuthal correction
double-spin asymmetry $A_{ll}$

$$A^h_{ll} \equiv \frac{C^h_{\phi}}{f_D} \left[ \frac{L \leftrightarrow N^h \leftrightarrow L \leftrightarrow N^h}{L_P \leftrightarrow N^h \leftrightarrow L_P \leftrightarrow N^h} \right]_B$$

azimuthal correction

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

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

azimuthal correction

luminosities

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

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

- **Azimuthal correction**
- **Luminosities**
- **Polarization-weighted luminosities**
- **Nucleon-in-nucleus depolarization factor**
  (0.926 for deuteron due to D-state admixture)
double-spin asymmetry $A_{||}$

\[ A_{||}^h \equiv \frac{C_h^\phi}{f_D} \left[ \frac{L \Leftrightarrow N_h^h - L \Leftrightarrow N_h^h}{L_P,\Leftrightarrow N_h^h + L_P,\Leftrightarrow N_h^h} \right] \]

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 $A_{\parallel}$

\[
A^h_{\parallel} \equiv \frac{C^h_{\phi}}{f_D} \left[ \frac{L \Rightarrow N^h_{\Leftrightarrow} - L \Leftrightarrow N^h_{\Rightarrow}}{L_P, \Rightarrow N^h_{\Leftrightarrow} + L_P, \Leftrightarrow N^h_{\Rightarrow}} \right]_B
\]

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

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

- dominated by statistical uncertainties
- main systematics arise from
  - polarization measurements [6.6% for hydrogen, 5.7% for deuterium]
  - azimuthal correction [$O(\text{few }\%)$]
azimuthal-asymmetry corrections

\[ \tilde{A}_h^h(x, Q^2, z, P_{h\perp}) = \frac{\int d\phi \, \sigma_h^h (x, Q^2, z, P_{h\perp}, \phi) \, \xi(\phi)}{\int d\phi \, \sigma_{UU}^h (x, Q^2, z, P_{h\perp}, \phi) \, \xi(\phi)} \]

- 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

\[ \tilde{A}_h(x, Q^2, z, P_{h\perp}) = \frac{\int d\phi \; \sigma_h(x, Q^2, z, P_{h\perp}, \phi) \; \xi(\phi)}{\int d\phi \; \sigma_{UU}(x, Q^2, z, P_{h\perp}, \phi) \; \xi(\phi)} \]

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

measured

“polarized Cahn” effect etc.

Boer-Mulders and Cahn effects etc.

azimuthal acceptance
x dependence of $A_{||}$

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

[HERMES, PRD 99 (2019) 112001]
3-dimensional binning

- first-ever 3d binning provides transverse-momentum dependence
3-dimensional binning

- **first-ever 3d binning** 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

![Graphs showing 1d and 3d binning](image)
hadron-charge difference asymmetries

\[ A_{1}^{h^{+} - h^{-}}(x) \equiv \frac{(\sigma_{1/2}^{h^{+}} - \sigma_{1/2}^{h^{-}}) - (\sigma_{3/2}^{h^{+}} - \sigma_{3/2}^{h^{-}})}{(\sigma_{1/2}^{h^{+}} - \sigma_{1/2}^{h^{-}}) + (\sigma_{3/2}^{h^{+}} - \sigma_{3/2}^{h^{-}})} \]
hadron-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:
  \[ A_{1,d}^{h^+ - h^-} \overset{\text{LO LT}}{=} \frac{g_{1u}^{u} + g_{1d}^{d}}{f_{1u}^{u} + f_{1d}^{d}} \]
- assuming also isospin symmetry in fragmentation:
  \[ A_{1,p}^{h^+ - h^-} \overset{\text{LO LT}}{=} \frac{4g_{1u}^{u} - g_{1d}^{d}}{4f_{1u}^{u} - f_{1d}^{d}} \]
- can be used to extract valence helicity distributions
hadron-charge difference asymmetries

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

[arXiv:1810.07054]
hadron-charge difference asymmetries

- no significant hadron-type dependence for deuterons
- deuteron results (unidentified hadrons) consistent with COMPASS
- valence distributions consistent with JETSET-based extraction:
Azimuthal single- and double-spin asymmetries in semi-inclusive deep-inelastic lepton scattering by transversely polarized protons

The HERMES Collaboration


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7Physics Division, Argonne National Laboratory, Argonne, Illinois 60439-2808, U.S.A.
8DESY, 15738 Zeuthen, Germany
9Joint Institute for Nuclear Research, 141980 Dubna, Russia
10Deceased

Significant non-vanishing Fourier amplitude

<table>
<thead>
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<tr>
<td>cos (φ − φs)</td>
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Azimuthal single- and double-spin asymmetries in semi-inclusive deep-inelastic lepton scattering by transversely polarized protons

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5DESY, 22603 Hamburg, Germany
6DESY, 15738 Zeuthen, Germany
7Joint Institute for Nuclear Research, 14198 Dubna, Russia
8Decayed.

Azimuthal modulation | Significant non-vanishing Fourier amplitude
--- | ---
\( \sin (\phi + \phi S) \) | \([\text{Collins}]\)
\( \sin (\phi - \phi S) \) | \([\text{Sivers}]\)
\( \sin (3\phi - \phi S) \) | \([\text{Pretzelsometry}]\)
\( \sin (2\phi - \phi S) \) | \([\text{Worm-germ}]\)
\( \cos (\phi - \phi S) \) | \([\text{Collins}]\)
\( \cos (\phi + \phi S) \) | \([\text{Sivers}]\)
\( \cos (2\phi - \phi S) \) | \([\text{Worm-germ}]\)
\( \cos (2\phi + \phi S) \) | \([\text{Worm-germ}]\)
\( \cos (\phi + \phi S) \)
\( \cos (\phi - \phi S) \)

\( \pi^+ \quad \pi^- \quad K^+ \quad K^- \quad p \quad \pi^0 \quad \bar{p} \)

90% 95%
Azimuthal single- and double-spin asymmetries in semi-inclusive deep-inelastic lepton scattering by transversely polarized protons

The HERMES Collaboration


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8Joint Institute for Nuclear Research, 141980 Dubna, Russia

Article funded by SCOAP³.

Significant non-vanishing Fourier amplitude

<table>
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<th>Azimuthal modulation</th>
<th>( \pi^+ )</th>
<th>( \pi^- )</th>
<th>( K^+ )</th>
<th>( K^- )</th>
<th>( p )</th>
<th>( \pi^0 )</th>
<th>( \bar{p} )</th>
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<tr>
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<tr>
<td>( \sin (2\phi + \phi S) )</td>
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<tr>
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Due to the more limited precision of the antiproton and neutral-pion data, such three-dimensional kinematic binning was not feasible. They were thus analyzed as functions of two kinematic variables. A few of those asymmetry amplitudes that are found to be inconsistent with zero at 95% (90%) confidence. Antiprotons and pions are considered to be inconsistent with zero if the Student’s t-test established this for at least \( \cos (\phi) \) or avoiding cancelation effects from integrating over kinematic dependences. In the case of those is based on the one-dimensional projections and hence restricted effects. They are also of limited value for phenomenology. Instead, the results for all asymmetries were tested against the NULL hypothesis using the two-sided Student’s t-test. The asymmetry results binned in three dimensions were used, where available, to increase the robustness of the Student’s t-test by using 64 data points individually (cf. tables and figures). The latter two should significantly increase the reliability of uncertainties resulting from an unspecified degree of statistical and systematic correlation.
Sivers amplitudes for pions

- **high-z data** probes region of increased flavor sensitivity to struck quark (but also where contributions from exclusive vector-meson production becomes significant)

- only last z bin shows indication of sizable $\rho^0$ contribution (decaying into charged pions)
**Sivers amplitudes**

**pions vs. (anti)protons**

Similar-magnitude asymmetries for (anti)protons and pions — consequence of u-quark dominance in both cases?

\[
2\langle \sin(\phi - \phi_S) \rangle_{UT} = -\frac{\sum_q e_q^2 f_{1T}^q(x, p_T^2) \otimes \mathcal{W}}{\sum_q e_q^2 f_1^q(x, p_T^2) \otimes D_1^q(z, k_T^2)} \\
\approx -c \frac{f_{1T,u}^1(x, p_T^2)}{f_{1u}^1(x, p_T^2)}
\]

[A. Airapetian et al., JHEP12(2020)010]
Sivers amplitudes
multi-dimensional analysis

- 3d analysis: 4x4x4 bins in (x, z, $P_{h\perp}$)
Table:

<table>
<thead>
<tr>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>$f_1$</td>
<td>$h_1^+$</td>
</tr>
<tr>
<td>L</td>
<td>$g_{1L}$</td>
<td>$h_{1L}^L$</td>
</tr>
<tr>
<td>T</td>
<td>$f_{1T}$</td>
<td>$g_{1T}$, $h_{1T}^T$</td>
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</tbody>
</table>

**Sivers amplitudes**

**multi-dimensional analysis**

- 3d analysis: 4x4x4 bins in $(x, z, P_{h\perp})$
- reduced systematics
- disentangle correlations
- isolate phase-space region with large signal strength

Figure 15. Sivers SFA for $\pi^+$ extracted simultaneously in bins of $x$, $z$, and $P_{h\perp}$, presented as a function of $x$. Systematic uncertainties are given as bands, not including the additional scale uncertainty of 7.3% due to the precision of the target-polarization determination. Overlaid is a phenomenological fit to previously available data, with the three lines corresponding to the central value of the fit and the fit uncertainty.

Proton is dominated by $u$-quark scattering. Figure 17 compares the Sivers asymmetries for both protons and antiprotons with those for positive pions. Within the available precision an almost surprising agreement of proton and $\pi^+$ asymmetries is visible. Also the asymmetries for antiprotons are very similar, however, the present measurement is plagued by large uncertainties.

In order to investigate slightly more the nature of proton and antiproton production at HERMES, figure 18 depicts the ratio of their raw production rates, e.g., yields not corrected for instrumental effects. The sudden increase of the proton-over-antiproton ratio towards very low $z$ might indicate the onset of target fragmentation, while in most of the $z$ range studied here the ratio exhibits a behavior consistent with current fragmentation. In particular, with increasing $z$ the production of antiprotons, which have no valence quarks in common with the target nucleons, is increasingly suppressed compared to protons. A second qualitative argument supporting the hypothesis of dominance of current fragmentation is the sign of the Sivers asymmetry for protons. The current jet is dominated by $u$-quark.
Sivers amplitudes
multi-dimensional analysis

- 3d analysis: 4x4x4 bins in (x, z, P_{h\perp})
- reduced systematics
- disentangle correlations
- isolate phase-space region with large signal strength
- allows more detailed comparison with calculations
- accompanied by kinematic distribution to guide phenomenology

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
U & L & T \\
\hline
U & f_1 & h_T^+ \\
L & g_{1L} & h_{1L} \\
T & f_{1T} & g_{1T} h_1, h_{1T} \\
\hline
\end{tabular}
\end{table}

[A. Airapetian et al., JHEP12(2020)010]
worm-gear II

- quark-helicity asymmetry in transversely polarized nucleon
- evidences from
  - $^3\text{He}$ target at JLab
  - H target at COMPASS & HERMES

![Graphs and tables showing experimental data and analyses.](image-url)
new HERMES results on Collins amplitudes

- first-ever results for (anti-)protons consistent with zero

vanishing Collins effect for (spin-1/2) baryons?

<table>
<thead>
<tr>
<th>U</th>
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<td>$g_{1L}$</td>
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<td>$f_{1T}$</td>
<td>$g_{1T}$</td>
<td>$h_1, h_{1T}^T$</td>
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</table>

[A. Airapetian et al., JHEP12(2020)010]
new HERMES results on Collins amplitudes

- first-ever results for (anti-)protons consistent with zero
  - vanishing Collins effect for (spin-1/2) baryons?
- analysis now performed in 3d, both including or not including kinematic “depolarization” prefactor
new HERMES results on Collins amplitudes

- first-ever results for (anti-)protons consistent with zero
  ➞ vanishing Collins effect for (spin-1/2) baryons?
- analysis now performed in 3d, both including or not including kinematic “depolarization” prefactor
- high-z region with larger quark-flavour sensitivity, with increasing amplitudes for positive pions and kaons
- quadrupole deformation in momentum space
- chiral-odd \( \Rightarrow \) needs Collins FF (or similar)
- \( ^1\text{H}, ^2\text{H} \& ^3\text{He} \) data from various experiments consistently small/vanishing
- cancelations? pretzelosity=zero? or just the additional general suppression of the asymmetry by two powers of \( P_{h\perp}/M_N \)

\[
\begin{array}{|c|c|c|}
\hline
U & L & T \\
\hline
f_1 & h_L^+ & L \\
\hline
g_{1L} & h_{1L}^+ & T \\
\hline
f_{1T} & g_{1T} & h_1, h_{1T} \\
\hline
\end{array}
\]

**Figure 19.** Pretzelosity SFA for charged mesons (left: pions; right: kaons) presented either in bins of \( x, z \), or \( P_{h\perp} \). Data at large values of \( z \), marked by open points in the \( z \) projection, are not included in the other projections. Systematic uncertainties are given as bands, not including the additional scale uncertainty of 7.3% due to the precision of the target-polarization determination.

**Figure 20.** Pretzelosity SFA for \( \pi^0 \) (left), protons, and antiprotons (right) presented either in bins of \( x, z \), or \( P_{h\perp} \). Data at large values of \( z \), marked by open points in the \( z \) projection, are not included in the other projections (no such high-\( z \) points are available for antiprotons due to a lack of precision). Systematic uncertainties are given as bands, not including the additional scale uncertainty of 7.3% due to the precision of the target-polarization determination.

\[ \left( \sin(3\phi - \phi_S) / \epsilon \right)_{U\perp} \]
surprises: subleading twist, e.g., $<\sin(\phi_s)>_{UT}$

- clearly non-zero asymmetries
- opposite sign for charged pions (Collins-like behavior)
- striking $z$ dependence and in particular magnitude
- similar observation at COMPASS
Beam-helicity asymmetries for single-hadron production in semi-inclusive deep-inelastic scattering from unpolarized hydrogen and deuterium targets

The HERMES Collaboration

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subleading twist II - $\langle \sin(\phi) \rangle_{LU}$

HERMES 3d analysis

most comprehensive presentation; use 1d binning for discussion
\[
\frac{M_h}{M_Z} h_1^\perp \tilde{E} \oplus x g^\perp D_1 \oplus \frac{M_h}{M_Z} f_1 \tilde{G}^\perp \oplus x e H_1^\perp
\]

- p & d targets
- $\pi, K, p & \bar{p}$ final-state h
- SIDIS and high-z transition regions

[HERMES, PLB 797 (2019) 134886]
\[
\frac{M_h}{M_Z} h_1^+ \tilde{E} + x g_1^+ D_1 + \frac{M_h}{M_Z} f_1 \tilde{G}_1^+ + xeH_1^+
\]
subleading twist II - $<\sin(\phi)>_{LU}$

\[
\frac{M_h}{M_Z} h^\perp_1 \tilde{E} \oplus x g^\perp D_1 \oplus \frac{M_h}{M_Z} f^\perp_1 \tilde{G} \oplus x e H^\perp_1
\]

HERMES & CLAS

opposite behavior at HERMES/CLAS of negative pions in z projection due to different x-range probed
subleading twist II - $\langle \sin(\phi) \rangle_{LU}$

\[
\frac{M_h}{M_Z} h_1^+ \tilde{E} \oplus x g_1^+ D_1 \oplus \frac{M_h}{M_Z} f_1^+ \tilde{G} \oplus x e H_1^+ 
\]

HERMES & CLAS

- opposite behavior at HERMES/CLAS of negative pions in z projection due to different x-range probed
- CLAS more sensitive to $e(x)$Collins term due to higher x probed?
subleading twist II - $\langle \sin(\phi) \rangle_{LU}$

\[
\frac{M_h}{M_z} h_1^+ \tilde{E} \oplus x g_1^+ D_1 \oplus \frac{M_h}{M_z} f_1 \tilde{G}^+ \oplus x e H_1^+
\]

consistent behavior for charged pions / hadrons at HERMES / COMPASS for isoscalar targets
HERMES continues producing results long after its shut-down

- latest pub’s providing 3d presentations of longitudinal & transverse SSA & DSA
- completes the TMD analyses of single-hadron production
- several significant leading-twist spin-momentum correlations (Sivers, Collins, worm-gear) but no sign for pretzelosity => clear dipole but no quadrupole deformations
- surprisingly large twist-3 effects
- by now, basically all asymmetries (except one: $A_{UL}$) extracted simultaneously in three or even four dimensions — a rich data set on transverse-momentum distributions
- complementary to data from other facilities
- equally important are studies of generalized parton distributions (see DVCS summary in backup) and many other results not related to 3d structure (e.g., nuclear effects)
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**References:**
- PRD 87 (2013) 074029
- PRD 87 (2013) 012010
- PRD 99 (2019) 112001
- PRL 84 (2000) 4047
- PRD 64 (2001) 097101
- PLB 562 (2003) 182
- JHEP 12(2020)010
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- JHEP 12(2020)010
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- PLB 693 (2010) 11
- JHEP 12(2020)010
backup slides
deeply virtual Compton scattering (DVCS)
- beam polarization $P_B$
- beam charge $C_B$
- here: unpolarized target (many more modulations for polarized targets)

Fourier expansion for $\phi$:

$$|T_{BH}|^2 = \frac{K_{BH}}{P_1(\phi)P_2(\phi)} \sum_{n=0}^{2} c_n^{BH} \cos(n\phi)$$

Calculable in QED (using form-factor measurements)
• beam polarization $P_B$
• beam charge $C_B$
• here: unpolarized target
  (many more modulations for polarized targets)

Fourier expansion for $\phi$:

$$|T_{BH}|^2 = \frac{K_{BH}}{P_1(\phi)P_2(\phi)} \sum_{n=0}^{2} c_n^{BH} \cos(n\phi)$$

$$|T_{DVCS}|^2 = K_{DVCS} \left[ \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{DVCS} \sin(n\phi) \right]$$
• beam polarization $P_B$
• beam charge $C_B$
• here: unpolarized target
  (many more modulations
  for polarized targets)

**Fourier expansion for $\phi$:**

$$|T_{BH}|^2 = \frac{K_{BH}}{P_1(\phi)P_2(\phi)} \sum_{n=0}^{2} c_n^{BH} \cos(n\phi)$$

$$|T_{DVCS}|^2 = K_{DVCS} \left[ \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{DVCS} \sin(n\phi) \right]$$

$$I = \frac{C_B K_I}{P_1(\phi)P_2(\phi)} \left[ \sum_{n=0}^{3} c_n^{I} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{I} \sin(n\phi) \right]$$

**DVCS**
• beam polarization $P_B$
• beam charge $C_B$
• here: unpolarized target (many more modulations for polarized targets)

Fourier expansion for $\phi$:

$$|T_{BH}|^2 = \frac{K_{BH}}{P_1(\phi)P_2(\phi)} \sum_{n=0}^{2} c_n^{BH} \cos(n\phi)$$

$$|T_{DVCS}|^2 = K_{DVCS} \left[ \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{DVCS} \sin(n\phi) \right]$$

$$I = \frac{C_B K_I}{P_1(\phi)P_2(\phi)} \left[ \sum_{n=0}^{3} c_n^{I} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{I} \sin(n\phi) \right]$$

bilinear ("DVCS") or linear in GPDs
Beam-charge asymmetry:
GPD $H$

Beam-helicity asymmetry:
GPD $H$

Transverse target spin asymmetries:
GPD $E$ from proton target

Longitudinal target spin asymmetry:
GPD $\tilde{H}$

Double-spin asymmetry:
GPD $\tilde{H}$
Beam-charge asymmetry:  
GPD $H$

Beam-helicity asymmetry:  
GPD $H$

Transverse target spin asymmetries:  
GPD $E$ from proton target

Longitudinal target spin asymmetry:  
GPD $\tilde{H}$

Double-spin asymmetry:  
GPD $\tilde{H}$

however, no cross-section measurement so far at HERMES kinematics!
non-vanishing twist-3
subleading twist I - $\langle \sin(\phi) \rangle_{UL}$

- theory done w.r.t. virtual-photon direction
- experiments use targets polarized w.r.t. lepton-beam direction
subleading twist I - $\langle \sin(\phi) \rangle_{UL}$

- theory done w.r.t. virtual-photon direction
- experiments use targets polarized w.r.t. lepton-beam direction

⇒ mixing of longitudinal and transverse polarization effects

[Diehl & Sapeta, EPJ C 41 (2005) 515], e.g.,

$$
\begin{pmatrix}
\langle \sin \phi \rangle_{UL} \\
\langle \sin(\phi - \phi_S) \rangle_{UT} \\
\langle \sin(\phi + \phi_S) \rangle_{UT}
\end{pmatrix}
= 
\begin{pmatrix}
\cos \theta_{\gamma^*} & -\sin \theta_{\gamma^*} & -\sin \theta_{\gamma^*} \\
\frac{1}{2} \sin \theta_{\gamma^*} & \cos \theta_{\gamma^*} & 0 \\
\frac{1}{2} \sin \theta_{\gamma^*} & 0 & \cos \theta_{\gamma^*}
\end{pmatrix}
\begin{pmatrix}
\langle \sin \phi \rangle_{UL} \\
\langle \sin(\phi - \phi_S) \rangle_{UT} \\
\langle \sin(\phi + \phi_S) \rangle_{UT}
\end{pmatrix}
$$

$$\cos \theta_{\gamma^*} \approx 1, \sin \theta_{\gamma^*} \text{ up to 15% at HERMES energies}$$
subleading twist $I - \langle \sin(\phi) \rangle_{UL}$

- theory done w.r.t. virtual-photon direction
- experiments use targets polarized w.r.t. lepton-beam direction

→ mixing of longitudinal and transverse polarization effects

[Diehl & Sapeta, EPJ C 41 (2005) 515], e.g.,

$$
\begin{pmatrix}
\langle \sin\phi \rangle_{UL} \\
\langle \sin(\phi-\phi_S) \rangle_{UT} \\
\langle \sin(\phi+\phi_S) \rangle_{UT}
\end{pmatrix}
= 
\begin{pmatrix}
\cos\theta_{\gamma^*} & -\sin\theta_{\gamma^*} & -\sin\theta_{\gamma^*} \\
\frac{1}{2} \sin\theta_{\gamma^*} & \cos\theta_{\gamma^*} & 0 \\
\frac{1}{2} \sin\theta_{\gamma^*} & 0 & \cos\theta_{\gamma^*}
\end{pmatrix}
\begin{pmatrix}
\langle \sin\phi \rangle^{q} \\
\langle \sin(\phi-\phi_S) \rangle_{UT} \\
\langle \sin(\phi+\phi_S) \rangle_{UT}
\end{pmatrix}
$$

→ need data on same target for both polarization orientations!
subleading twist I - $\langle \sin(\phi) \rangle_{UL}$

$$\langle \sin \phi \rangle^q_{UL} = \langle \sin \phi \rangle^l_{UL} + \sin \theta \gamma \left( \langle \sin(\phi + \phi_S) \rangle^l_{UT} + \langle \sin(\phi - \phi_S) \rangle^l_{UT} \right)$$

- experimental $A_{UL}$ dominated by twist-3 contribution
- correction for $A_{UT}$ contribution increases the longitudinal asymmetry for positive pions
- consistent with zero for $\pi^-$
subleading twist I - $\langle \sin(\phi) \rangle_{UL}$

$$\langle \sin \phi \rangle_{UL}^q = \langle \sin \phi \rangle_{UL}^l + \sin \theta \gamma_s \left( \langle \sin(\phi + \phi_S) \rangle_{UT}^l + \langle \sin(\phi - \phi_S) \rangle_{UT}^l \right)$$

- experimental $A_{UL}$ dominated by twist-3 contribution
- in contrast to WW-type approximation [1807.10606]
  (both COMPASS and HERMES data)
subleading twist I - $\langle \sin(\phi) \rangle_{UL}$

$$\langle \sin \phi \rangle^q_{UL} = \langle \sin \phi \rangle^l_{UL} + \sin \theta_{\gamma^*} \left( \langle \sin(\phi+\phi_S) \rangle^l_{UT} + \langle \sin(\phi-\phi_S) \rangle^l_{UT} \right)$$

- experimental $A_{UL}$ dominated by twist-3 contribution
- in contrast to WW-type approximation [1807.10606] (for both COMPASS and HERMES data)
- sizable also for new CLAS neutral-pion data
subleading twist II - $<\sin(\phi)>_{LU}$

\[
\frac{M_h}{M_Z} h_1^+ \tilde{E} \oplus x g^1 D_1 \oplus \frac{M_h}{M_Z} f_1 \tilde{G}^+ \oplus x e H_1^+
\]

- naive-T-odd Boer-Mulders (BM) function coupled to a twist-3 FF
- signs of BM from unpolarized SIDIS
- little known about interaction-dependent FF
- little known about naive-T-odd $g^\perp$; singled out in $A_{LU}$ in jet production
- large unpolarized $f_1$, coupled to interaction-dependent FF
- twist-3 $e$ survives integration over $P_h^\perp$; here coupled to Collins FF
  - $e$ linked to the pion-nucleon $\sigma$-term
  - interpreted as color force (from remnant) on transversely polarized quarks at the moment of being struck by virtual photon

- all terms vanish in WW-type approximation
subleading twist III - $\langle \sin(\phi_s) \rangle_{UT}$

- vanishes in inclusive limit, e.g. after integration over $P_{h\perp}$ and $z$, and summation over all hadrons
- tested to permille level at HERMES:

subleading twist III - $<\sin(\phi_s)>_{UT}$

- vanishes in inclusive limit, e.g. after integration over $P_{h\perp}$ and $z$, and summation over all hadrons
- various contributing terms related to transversity, worm-gear, Sivers etc.:

$$\propto \left( x f_T^+ D_1 - \frac{M_h}{M} h_1 \frac{\tilde{H}}{z} \right)$$

$$- \mathcal{W}(p_T, k_T, P_{h\perp}) \left[ \left( x h_T H_1^+ + \frac{M_h}{M} g_{1T} \frac{\tilde{G}^+}{z} \right) \right.$$

$$- \left( x h_T H_1^+ - \frac{M_h}{M} f_{1T} \frac{\tilde{D}^+}{z} \right) \right]$$

- non-vanishing collinear limit:

$$F_{UT}^{\sin(\phi_s)}(x, Q^2, z) = \int d^2 P_{h\perp} F_{UT}^{\sin(\phi_s)}(x, Q^2, z, P_{h\perp}) = -x \frac{2M_h}{Q} \sum_q e_q^2 h_q \frac{\tilde{H}^q(z)}{z}$$
vanishes in inclusive limit, e.g. after integration over $P_{h\perp}$ and $z$, and summation over all hadrons

various contributing terms related to transversity, worm-gear, Sivers etc.:

\[
\propto \left( x f_T^+ D_1 - \frac{M_h}{M} h_1 \frac{\tilde{H}}{z} \right)
- \mathcal{W}(p_T, k_T, P_{h\perp}) \left[ \left( x h_T H_1^+ + \frac{M_h}{M} g_{1T} \frac{\tilde{G}}{z} \right) - \left( x h_T^+ H_1 - \frac{M_h}{M} f_{1T}^+ \frac{\tilde{D}}{z} \right) \right]
\]

non-vanishing collinear limit:

\[
F_{UT}^{\sin(\phi_S)}(x, Q^2, z) = \int d^2 P_{h\perp} F_{UT}^{\sin(\phi_S)}(x, Q^2, z, P_{h\perp}) = -x \frac{2M_h}{Q} \sum_q e_q^2 h_1 \frac{\tilde{H}^q(z)}{z}
\]
subleading twist III - $\langle \sin(\phi_s) \rangle_{UT}$

Figure 27. The $2 \langle \sin(\phi_s) \rangle_{UT}$ as a function of $x$. The $Q^2$ region for each bin was divided into the two regions above (squares) and below (circles) the average $Q^2$ of that bin. The average $Q^2$ is given in the bottom for all bins separately for the two $Q^2$ regions. The error bars represent statistical uncertainties only.

- hint of $Q^2$ dependence seen in signal for negative pions

\[ Q^2(x_i) \exp \left( \frac{1}{2} \right) \sin(\phi_s) \]
devil in the details &
lessons learnt on the way
mixing of target polarizations

- theory done w.r.t. virtual-photon direction
- experiments use targets polarized w.r.t. lepton-beam direction

⇒ mixing of longitudinal and transverse polarization effects

\[
\begin{pmatrix}
\langle \sin \phi \rangle_l \\
\langle \sin(\phi - \phi_S) \rangle_l \\
\langle \sin(\phi + \phi_S) \rangle_l
\end{pmatrix}
= \begin{pmatrix}
\cos \theta \gamma^* \\
-\sin \theta \gamma^* \\
-\sin \theta \gamma^* \\
\end{pmatrix}
\begin{pmatrix}
1/2 \\
\sin \theta \gamma^* \cos \theta \gamma^* \\
0
\end{pmatrix}
\begin{pmatrix}
\langle \sin \phi \rangle_q \\
\langle \sin(\phi - \phi_S) \rangle_q \\
\langle \sin(\phi + \phi_S) \rangle_q
\end{pmatrix}
\]

\( \cos \theta \gamma^* \approx 1, \sin \theta \gamma^* \text{ up to } 15\% \text{ at HERMES energies} \)
TMD factorization: a 2-scale problem

\[ Q^2 = P_{h\perp}^2 \]

lowest x bin

\[
\begin{align*}
0.2 < z < 0.28 & \quad 0.28 < z < 0.37 & \quad 0.37 < z < 0.49 & \quad 0.49 < z < 0.7 \\
0.0 < P_h < 0.23 & \quad 0.23 < P_h < 0.36 & \quad 0.36 < P_h < 0.54 & \quad 0.54 < P_h < 2.0 \\
0.023 < x < 0.072
\end{align*}
\]
TMD factorization: a 2-scale problem

lowest x bin

\[ Q^2 = P_{h\perp}^2 \]
\[ Q^2 = 2P_{h\perp}^2 \]
\[ Q^2 = 4P_{h\perp}^2 \]

disclaimer: coloured lines drawn by hand
TMD factorization: a 2-scale problem

highest x bin

\[ Q^2 = P^2_{h\perp} \]
\[ Q^2 = 2 P^2_{h\perp} \]
\[ Q^2 = 4 P^2_{h\perp} \]

disclaimer: coloured lines drawn by hand
TMD factorization: a 2-scale problem

highest x bin

\[ Q^2 = P_{h\perp}^2 / z^2 \]
\[ Q^2 = 2 P_{h\perp}^2 / z^2 \]
\[ Q^2 = 4 P_{h\perp}^2 / z^2 \]

disclaimer: coloured lines drawn by hand
TMD factorization: a 2-scale problem

\[ Q^2 = \frac{P^2_{h\perp}}{z^2} \]

all other x-bins included in the Supplemental Material of JHEP12(2020)010
hadron production at HERMES

- forward-acceptance favors current fragmentation
- backward rapidity populates large-$P_{h\perp}$ region [as expected]
**hadron production at HERMES**

- forward-acceptance favors current fragmentation
- backward rapidity populates large-$P_{h\perp}$ region [as expected]
- rapidity distributions available for all kinematic bins (e.g., highest-$x$ bin protons)
The sign of the Sivers asymmetry for protons. The current jet is dominated by qualitative argument supporting the hypothesis of dominance of current fragmentation is common with the target nucleons, is increasingly suppressed compared to protons. A second particular, with increasing towards very low corrected for instrumental e.

Asymmetries for antiprotons are very similar, however, the present measurement is plagued precision an almost surprising agreement of proton and proton is dominated by central value of the fit and the fit uncertainty.

A phenomenological fit \[ \text{uncertainty of } 7.3\% \text{ due to the precision of the target-polarization determination.} \]

Overlaid is a Figure 15 HERMES

In order to investigate slightly more the nature of proton and antiproton production nucleon pol.

\[ \text{Sivers amplitudes} \]

\[ \text{multi-dimensional analysis} \]

\[ \text{Gunar Schnell} \]

\[ [A. \text{Airapetian et al., arXiv:2007.07755}] \]

[Figure 15 HERMES]

Systematic uncertainties are given as bands, not including the additional scale boundaries are indicated by dashed lines.

\[ \text{multi-d dependence and kinematical distribution should facilitate analyses within TMD formalism} \]
Sivers amplitudes
pions vs. kaons

somewhat unexpected if dominated by scattering from $u$-quarks:

$$\tilde{n} \approx - \frac{f_{1T}^u(x, p_T^2) \otimes W D_{1}^{u \to \pi^+/K^+} (z, k_T^2)}{f_{1}^u(x, p_T^2) \otimes D_{1}^{u \to \pi^+/K^+} (z, k_T^2)}$$
Sivers amplitudes
pions vs. kaons

somewhat unexpected if dominated by scattering from u-quarks:

\[ A_{\text{Siv}} \sim - \frac{f_{1T}^u(x, p_{T}^2) \otimes W D_{1}^{u \rightarrow \pi^+ / K^+}(z, k_{T}^2)}{f_1^u(x, p_{T}^2) \otimes D_{1}^{u \rightarrow \pi^+ / K^+}(z, k_{T}^2)} \]

larger amplitudes seen also by COMPASS

[PLB 744 (2015) 250]
somewhat unexpected if dominated by scattering from u-quarks:

\[ A_{Siv}(x) \approx - \frac{f_{1T}^u(x, p_T^2) \otimes_{\lambda W} D_{1u}^{\pi^+/K^+}(z, k_T^2)}{f_{1u}^u(x, p_T^2) \otimes D_{1u}^{\pi^+/K^+}(z, k_T^2)} \]

surprisingly large K⁻ asymmetry for \(^3\)He target (but zero for K⁺?!)
Sivers amplitudes
pions vs. (anti)protons

similar-magnitude asymmetries for (anti)protons and pions
 consequence of $u$-quark dominance in both cases?

possibly, onset of target fragmentation only at lower $z$
Sivers amplitudes
pions vs. (anti)protons

similar-magnitude asymmetries for (anti)protons and pions
⇒ consequence of u-quark dominance in both cases?

possibly, onset of target fragmentation only at lower $z$

Figure 16
Sivers SFA for protons (upper row) and antiprotons (lower row) presented either in bins of $x$, $z$, or $P_{h\perp}$. Data at large values of $z$, marked by open points in the $z$ projection, are not included in the other projections (no such high-$z$ points are available for antiprotons due to a lack of precision). Systematic uncertainties are given as bands, not including the additional scale uncertainty of 7.3% due to the precision of the target-polarization determination.

Figure 17
Comparison of Sivers SFA for positive pions and protons (upper plot) or antiprotons (lower plot) presented either in bins of $x$, $z$, or $P_{h\perp}$. Data at large values of $z$, marked by open points in the $z$ projection, are not included in the other projections (no such high-$z$ points are available for antiprotons due to a lack of precision). Systematic uncertainties are given as bands, not including the additional scale uncertainty of 7.3% due to the precision of the target-polarization determination.