BNL/RBRC Summer Program on Nucleon Spin
July 14-27, 2010

The structure of the nucleon

---the *hermes* perspective---

Gunar.Schnell @ desy.de
integrated DFs

1D

3D

GPDs

TMDs
integrated DFs

inclusive DIS

semi-inclusive DIS

1D

3D

GPDs

TMDs
Inclusive DIS
\[
\frac{d^2 \sigma(s, S)}{dx \, dQ^2} = \frac{2\pi \alpha^2 y^2}{Q^6} L_{\mu \nu}(s) W^{\mu \nu}(S)
\]
Inclusive DIS

\[
\frac{d^2 \sigma(s, S)}{dx \ dQ^2} = \frac{2\pi \alpha^2 y^2}{Q^6} L_{\mu\nu}(s) W^{\mu\nu}(S)
\]

Lepton Tensor
$$\frac{d^2 \sigma(s, S)}{dx \ dQ^2} = \frac{2\pi\alpha^2 y^2}{Q^6} L_{\mu\nu}(s) W^{\mu\nu}(S)$$

Lepton Tensor

Hadron Tensor

parametrized in terms of

Structure Functions
\[
\frac{d^2 \sigma(s, S)}{d x \ d Q^2} = \frac{2 \pi \alpha^2 y^2}{Q^6} L_{\mu \nu}(s) W_{\mu \nu}(S)
\]

Lepton Tensor

Hadron Tensor

parametrized in terms of Structure Functions

\[
\frac{d^3 \sigma}{d x d y d \phi} \propto \frac{y}{2} F_1(x, Q^2) + \frac{1 - y - \gamma^2 y^2 / 4}{2 x y} F_2(x, Q^2)
\]

\[
- P_l P_T \cos \alpha \left[ \left( 1 - \frac{y}{2} - \frac{\gamma^2 y^2}{4} \right) g_1(x, Q^2) - \frac{\gamma^2 y}{2} g_2(x, Q^2) \right]
\]

\[
+ P_l P_T \sin \alpha \cos \phi \gamma \sqrt{1 - y - \frac{\gamma^2 y^2}{4}} \left( \frac{y}{2} g_1(x, Q^2) + g_2(x, Q^2) \right)
\]
Check the details!
Check the details!

two-photon exchange important?!
Two-photon exchange

- Candidate to explain discrepancy in form-factor measurements
- Interference between one- and two-photon exchange amplitudes leads to SSAs in inclusive DIS off transversely polarized targets
- Sensitive to beam charge due to odd number of e.m. couplings to beam
- Cross section proportional to $S(k \times k')$ - either measure left-right asymmetries or sine modulation
No sign of two-photon exchange consistent with zero

Front view of HERMES detector

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Why measure $F_2$ at HERMES?

- complementary kinematic coverage compared to colliders
- direct info at HERMES kinematics
- higher statistics compared to other fixed target experiments:
  - HERMES: 58 million DIS (P+D)
  - NMC: 9 million DIS (P+D)
Comparison with parameterization by SMC and GD07

GD07: hep-ph0708.3196
Comparison with parameterization by SMC and GD07

Agreement with world data in the overlap region

GD07: hep-ph0708.3196
**F\textsubscript{2}**

- **proton**

New region covered by HERMES

Agreement with world data in the overlap region

Comparison with parameterization by SMC and GD07

**SLAC**
**JLAB**
**HERMES**
**BCDMS**
**NMC**
**H1**
**ZEUS**

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\[ Q^2 \{ \text{GeV}^2 \} \]
$F_2$ deuteron

New region covered by HERMES

Agreement with world data in the overlap region

Comparison with parameterization by SMC


$Q^2$ [GeV$^2$]
Many systematic errors common to proton and deuteron cross sections cancel in ratio.

Normalization uncertainties

Additional normalization uncertainties not included.
Polarized Structure Function $g_1$

A. Airapetian et al., PRD 75 (2007)
Integral of $g_1(x)$

$\int_x^{0.9} g_1(x) \, dx$

$Q^2 = 5 \text{ GeV}^2$

NS

n

d

p

Integral of $g_1(x)$
Saturation close to full integral?

\[
\Delta \Sigma = \frac{1}{\Delta C_S} \left[ \frac{9 \Gamma_1^d}{1 - \frac{3}{2} \omega_D} - \frac{1}{4} a_8 \Delta C_{NS} \right]
\]

\[
\Gamma_1^d = 0.05 \pm 0.05
\]

Theory vs. hyperon-decay data
Integral of $g_1(x)$

Saturation close to full integral?

$$\Delta \Sigma^{\overline{MS}} = 0.330 \pm 0.011_{\text{theory}} \pm 0.025_{\text{exp}} \pm 0.028_{\text{evol}}$$

$$\Delta \Sigma^{\overline{MS}} \equiv \frac{1}{\Delta C_S} \left[ \frac{9 \Gamma_1^d}{1 - \frac{3}{2} \omega_D} - \frac{1}{4} a_8 \Delta C_{NS} \right]$$

$$Q^2 = 5 \text{ GeV}^2$$

Hyperon-decay data
Integral of $g_1(x)$

Saturation close to full integral?

$$\Delta \Sigma \bar{MS} \equiv \frac{1}{\Delta C_S} \left[ \frac{9 \Gamma_1^d}{1 - \frac{3}{2} \omega_D} - \frac{1}{4} a_8 \Delta C_{NS} \right]$$

0.05±0.05

hyperon-decay data

most precise result; only 1/3 of nucleon spin from quarks

$$\Delta \Sigma \bar{MS} \equiv 0.330 \pm 0.011_{\text{theory}} \pm 0.025_{\text{exp}} \pm 0.028_{\text{evol}}$$
Extraction of $g_2$

\[
\frac{\sigma \rightarrow \downarrow(\phi) - \sigma \rightarrow \uparrow(\phi)}{\sigma \rightarrow \downarrow(\phi) + \sigma \rightarrow \uparrow(\phi)} = \Delta \sigma_T = \frac{\Delta \sigma_T}{\overline{\sigma}} =
\]

\[
= -\gamma \sqrt{1 - y - \frac{\gamma^2 y^2}{4}} \left( \frac{y}{2} g_1(x, Q^2) + g_2(x, Q^2) \right)
\]

\[
\frac{\frac{y}{2} F_1(x, Q^2) + \frac{1}{2xy} \left( 1 - y - \frac{\gamma^2 y^2}{4} \right) F_2(x, Q^2)}{A_T}
\]

\[
\cos \phi
\]
Extraction of $g_2$

$$\frac{\sigma_{\downarrow}(\phi) - \sigma_{\uparrow}(\phi)}{\sigma_{\downarrow}(\phi) + \sigma_{\uparrow}(\phi)} = \frac{\Delta \sigma_T}{\bar{\sigma}} = \frac{1}{d(1+\gamma \xi)}$$

$$A_T = -\gamma \sqrt{1 - y - \frac{\gamma^2 y^2}{4}} \left( \frac{y}{2} g_1(x, Q^2) + g_2(x, Q^2) \right) \left[ \frac{y}{2} F_1(x, Q^2) + \frac{1}{2xy} \left( 1 - y - \frac{\gamma^2 y^2}{4} \right) F_2(x, Q^2) \right]$$

Fit to double-spin asymmetry

$$A_2 = \frac{1}{d(1+\gamma \xi)} A_T + \frac{\xi(1+\gamma^2)}{1+\gamma \xi} \frac{g_1}{F_1}$$
Extraction of $g_2$

\[
\frac{\sigma^{\downarrow}(\phi) - \sigma^{\uparrow}(\phi)}{\sigma^{\downarrow}(\phi) + \sigma^{\uparrow}(\phi)} = \frac{\Delta \sigma_T}{\sigma} = -\gamma \sqrt{1 - y - \frac{\gamma^2 y^2}{4}} \left( \frac{y}{2} g_1(x, Q^2) + g_2(x, Q^2) \right) \cos \phi
\]

\[
\frac{y}{2} F_1(x, Q^2) + \frac{1}{2xy} \left( 1 - y - \frac{\gamma^2 y^2}{4} \right) F_2(x, Q^2)
\]

\[
A_2 = \frac{1}{d(1 + \gamma \xi)} A_T + \frac{\xi(1 + \gamma^2)}{1 + \gamma \xi} \frac{g_1}{F_1}
\]

\[
g_2 = \frac{F_1}{\gamma d(1 + \gamma \xi)} A_T - \frac{F_1(\gamma - \xi)}{\gamma(1 + \gamma \xi)} \frac{g_1}{F_1}
\]

fit to double-spin asymmetry

parameterizations

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Results on $A_2$ and $xg_2$.

- Consistent with (sparse) world data.
- Low beam polarization during HERA II $\Rightarrow$ small f.o.m.
- In analysis stage: low-$x/Q^2$ data.

**Graphs:**
- Left graph: $A_2$ vs. $x$.
- Right graph: $xg_2$ vs. $x$.

**Data Sources:**
- HERMES preliminary (10.0% scale uncertainty).
- E155 Coll., E143 Coll., SMC Coll.

**Note:**
- $A_2^{ww}$.
Semi-Inclusive DIS
Spin-Momentum Structure of the Nucleon

\[ \frac{1}{2} \text{Tr} \left[ (\gamma^+ + \lambda \gamma^+ \gamma_5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T} + \lambda \Lambda g_1 + \lambda S^i k^i \frac{1}{m} g_{1T} \right] \]

\[ \frac{1}{2} \text{Tr} \left[ (\gamma^+ - s^j i \sigma^{+j} \gamma_5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T} + s^i \epsilon^{ij} k^j \frac{1}{m} h_1^+ + s^i S^i h_1 \right] + s^i (2k^i k^j - k^2 \delta^{ij}) S^j \frac{1}{2m^2} h_{1T} + \Lambda s^i k^i \frac{1}{m} h_{1L} \]

<table>
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<th>quark pol.</th>
<th>U</th>
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<td>(g_{1T})</td>
<td>(h_1, h_{1T}^+)</td>
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- Functions in black survive integration over transverse momentum
- Functions in green box are chirally odd
- Functions in red are naive T-odd
Spin-Momentum Structure of the Nucleon

\[
\frac{1}{2} \text{Tr} \left[ (\gamma^+ + \lambda \gamma^+ \gamma_5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{i j} k^j \frac{1}{m} f_{1T}^1 + \lambda \Lambda g_1 + \lambda S^i k^i \frac{1}{m} g_{1T} \right]
\]

\[
\frac{1}{2} \text{Tr} \left[ (\gamma^+ - s^j i \sigma^{+j} \gamma_5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{i j} k^j \frac{1}{m} f_{1T}^1 + s^i \epsilon^{i j} k^j \frac{1}{m} h_1^1 + s^i S^i h_1 \right]
\]

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

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<td>g_{1T}</td>
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functions in black survive integration over transverse momentum

functions in green box are chirally odd

functions in red are naive T-odd

Twist-2 TMDs

Boer-Mulders

Sivers

pretzelosity

transversity

worm-gear
Strange-quark distributions

- Use isoscalar probe and target to extract strange-quark distributions

- Only need inclusive asymmetries and $K^+K^-$ asymmetries, i.e., $A_{||,d}(x, Q^2)$ and $A_{||,d}^{K^+ + K^-}(x, z, Q^2)$, as well as $K^+K^-$ multiplicities on deuteron

\[
\begin{align*}
S(x) \int D^K_S(z) \, dz & \simeq Q(x) \left[ 5 \frac{d^2 N^K(x)}{d^2 N^{DIS}(x)} - \int D^K_Q(z) \, dz \right] \\
A_{||,d}(x) \frac{d^2 N^{DIS}(x)}{dx \, dQ^2} & = K_{LL}(x, Q^2) \left[ 5 \Delta Q(x) + 2 \Delta S(x) \right] \\
A_{||,d}^{K^\pm}(x) \frac{d^2 N^K(x)}{dx \, dQ^2} & = K_{LL}(x, Q^2) \left[ \Delta Q(x) \int D^K_Q(z) \, dz + \Delta S(x) \int D^K_S(z) \, dz \right]
\end{align*}
\]
Strange-quark distributions

- use isoscalar probe and target to extract strange-quark distributions

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---

Strange-quark distributions

\[ xS(x) \]

- Fit
- CTEQ6L
- $x(u(x)+d(x))$

---

A. Airapetian et al., PLB 666, 446 (2008)
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Strange-quark distributions

- use isoscalar probe and target to extract strange-quark distributions

- only need inclusive asymmetries and \(K^+K^-\) asymmetries, i.e., \(A_{\|,d}(x, Q^2)\) and \(A_{\|,d}^{K^+K^-}(x, z, Q^2)\), as well as \(K^+K^-\) multiplicities on deuteron

Strange-quark distribution softer than (maybe) expected

A. Airapetian et al., PLB 666, 446 (2008)
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Strange-quark distributions

- use isoscalar probe and target to extract strange-quark distributions
- only need inclusive asymmetries and $K^+K^-$ asymmetries, i.e., $A_{||,d}(x, Q^2)$ and $A_{||,d}^{K^+K^-}(x, z, Q^2)$, as well as $K^+K^-$ multiplicities on deuteron

Strange-quark distribution softer than (maybe) expected

A. Airapetian et al., PLB 666, 446 (2008)

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Strange-quark distributions

- use isoscalar probe and target to extract strange-quark distributions

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A. Airapetian et al., PLB 666, 446 (2008)
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Strange-quark distribution softer than (maybe) expected

Strange-quark helicity distribution consistent with zero or slightly positive in contrast to inclusive DIS analyses

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<td>$h_{1L}^\perp$</td>
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<td>$f_{1T}$</td>
<td>$g_{1T}$</td>
<td>$h_1$, $h_{1T}^\perp$</td>
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• smaller range in \((x, Q^2)\) than for \(f_1\)

• data mainly for integrated version of \(g_{1L}\)

• need asymmetries not only binned in \(x\) but also in \(P_{h\perp}\)
only weak if any dependence on $P_{h\perp}$ seen
Transversity distribution

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Chiral-odd transversity involves quark helicity flip

\[
 f_1^q = \quad \text{Diagram 1} \quad g_1^q = \quad \text{Diagram 2} \quad h_1^q = \quad \text{Diagram 3}
\]
Transversity distribution

chiral-odd transversity involves quark helicity flip

\[ f_1^q = \] (diagram)
\[ g_1^q = \] (diagram)
\[ h_1^q = \] (diagram)
chiral-odd transversity involves quark helicity flip

\[ f_1^q = \begin{array}{c}
\uparrow \\
\uparrow \\
\uparrow \\
\end{array} \quad g_1^q = \begin{array}{c}
\rightarrow \\
\leftarrow \\
\rightarrow \\
\end{array} \quad h_1^q = \begin{array}{c}
\uparrow \\
\downarrow \\
\downarrow \\
\end{array} \]
Transversity distribution

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<td>f₁T</td>
<td>g₁T</td>
<td>h₁, h₁⁺T</td>
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chiral-odd transversity involves quark helicity flip

\[
f₁^q = \quad g₁^q = - \quad h₁^q = -
\]

need to couple to chiral-odd fragmentation function:
Transversity distribution

chiral-odd transversity involves quark helicity flip

\[ f_1^q = \begin{array}{c}
\end{array}; \quad g_1^q = \begin{array}{c}
\end{array}; \quad h_1^q = \begin{array}{c}
\end{array} \]

need to couple to chiral-odd fragmentation function:

- transverse spin transfer (polarized final-state hadron)
chiral-odd transversity involves quark helicity flip

\[ f_1^q = \begin{array}{c} \text{+} \\ \text{+} \end{array} \quad g_1^q = \begin{array}{c} \text{+} \\ \text{-} \end{array} \quad h_1^q = \begin{array}{c} \text{+} \\ \text{-} \end{array} \]

need to couple to chiral-odd fragmentation function:

- transverse spin transfer (polarized final-state hadron)
- 2-hadron fragmentation
Transversity distribution

chiral-odd transversity involves quark helicity flip

\[ f_1^q = \quad g_1^q = \quad h_1^q = \]

need to couple to chiral-odd fragmentation function:

- transverse spin transfer (polarized final-state hadron)
- 2-hadron fragmentation
- Collins fragmentation
Transversity distribution (transverse-spin transfer)

\[
\begin{array}{|c|c|c|}
\hline
U & L & T \\
\hline
f_1 & h_1^+ \\
\hline
\end{array}
\]

\[
\begin{array}{|c|c|c|}
\hline
L & g_{1L} & h_{1L}^+ \\
\hline
T & f_{1T}^+ & g_{1T} h_{1}^+, h_{1T}^+ \\
\hline
\end{array}
\]
**Transversity distribution**

* (transverse-spin transfer)

- non-zero **longitudinal spin transfer** (based on complete HERMES data set)
- statistics much lower for transverse-target data
- spin-transfer already puzzle for longitudinal case
- ➡ no real prospects at HERMES for measuring transversity via spin transfer

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**Twist-2 TMDs**

$U \ U \ L \ T$

$D = \frac{h_{1\perp}}{h_{1\perp} + h_{1T\perp}}$

- HERMES Preliminary
- 1996 - 2007 ($eN \rightarrow e'\Lambda X$)
- NOMAD ($\nu N \rightarrow \mu \Lambda X$)
- E665 ($\mu N \rightarrow \mu'\Lambda X$)
- COMPASS ($\mu N \rightarrow \mu'\Lambda X$)
Transversity distribution (2-hadron fragmentation)

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A. Airapetian et al. [HERMES], JHEP 06 (2008) 017
Transversity distribution
(2-hadron fragmentation)

A. Airapetian et al. [HERMES], JHEP 06 (2008) 017

first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS

---

U  L  T
---
U  $f_1$  $h_1^+$
L  $g_{1L}$  $h_{1L}^+$
T  $f_{1T}^+$  $g_{1T}^+$  $h_1^+, h_{1T}^+$

---

gunar.schnell @ desy.de
Transversity distribution
(2-hadron fragmentation)

A. Airapetian et al. [HERMES], JHEP 06 (2008) 017

- First evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS
- Invariant-mass dependence rules out Jaffe model

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Transversity distribution
(2-hadron fragmentation)

- First evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS
- Invariant-mass dependence rules out Jaffe model
- Difference in magnitude between COMPASS and HERMES

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Transversity distribution (2-hadron fragmentation)

- first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS
- invariant-mass dependence rules out Jaffe model
- difference in magnitude between COMPASS and HERMES
- more amplitudes coming out soon

A. Airapetian et al. [HERMES], JHEP 06 (2008) 017
Transversity distribution
(Collins fragmentation)

- significant in size and opposite in sign for charged pions
- disfavored Collins FF large and opposite in sign to favored one
- leads to various cancellations in SSA observables

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Twist-2 TMDs significant in size and opposite in sign for charged pions.
Disfavored Collins FF large and opposite in sign to favored one leads to various cancellations in SSA observables.

Non-zero transversity
Non-zero Collins function

2005: First evidence from HERMES SIDIS on proton

Transversity distribution
(Collins fragmentation)

- significant in size and opposite in sign for charged pions
- disfavored Collins FF large and opposite in sign to favored one
- leads to various cancellations in SSA observables

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\[ \sin(\phi_S) \]

[A.Airapetian et al., arXiv:1006.4221]
Transversity distribution (Collins fragmentation)

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-0.05 0 0.05 0.1 0.15
2 ($\sin(\phi + \phi_s)_{UT}$)

-0.1 0.1
2 ($\sin(\phi + \phi_s)_{UT}$)

-0.02 0 0.02 0.04 0.06 0.08
2 ($\sin(\phi + \phi_s)_{UT}$)

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significant non-zero amplitudes also for $K^+$

[A.Airapetian et al., arXiv:1006.4221]
Sivers amplitudes for pions

\[ 2\langle \sin(\phi - \phi_S) \rangle_{UT} = -\frac{\sum_q e_q^2 g_1^q(x, p_T^2) \otimes W D_1^q(z, k_T^2)}{\sum_q e_q^2 f_1^q(x, p_T^2) \otimes D_1^q(z, k_T^2)} \]

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Sivers amplitudes for pions

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

\( \pi^+ \) dominated by u-quark scattering:

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

\( \uparrow \) u-quark Sivers DF < 0

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

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

\( \pi^+ \) dominated by u-quark scattering:

\[ \sum_q e_q^2 f_{1T}^{uT}(x, p_T^2) \otimes \mathcal{W} D_1^u \rightarrow \pi^+(z, k_T^2) \]

\[ \sum_q e_q^2 f_1^u(x, p_T^2) \otimes D_1^u \rightarrow \pi^+(z, k_T^2) \]

\( \Uparrow \) u-quark Sivers DF \( < 0 \)

\( \Uparrow \) d-quark Sivers DF \( > 0 \)

(cancelation for \( \pi^- \))
Sivers amplitudes for pions

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

\( \pi^+ \) dominated by \( u \)-quark scattering:

\[ \simeq - \frac{f_{1T}^u \left( x, p_T^2 \right) \otimes \mathcal{W} \ D_1^{u \rightarrow \pi^+} \left( z, k_T^2 \right)}{f_1^u \left( x, p_T^2 \right) \otimes D_1^{u \rightarrow \pi^+} \left( z, k_T^2 \right)} \]

\( L_z^u > 0 \)

Sivers “difference asymmetry”

Transverse single-spin asymmetry of pion cross-section difference:

\[ A_{UT}^{\pi^+ - \pi^-} (\phi, \phi_S) \equiv \frac{1}{ST} \frac{(\sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-}) - (\sigma_{U\downarrow}^{\pi^+} - \sigma_{U\downarrow}^{\pi^-})}{(\sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-}) + (\sigma_{U\downarrow}^{\pi^+} - \sigma_{U\downarrow}^{\pi^-})} \]

\[ \langle \sin(\phi - \phi_S) \rangle_{UT}^{\pi^+ - \pi^-} (\phi, \phi_S) \propto -\frac{4f_{1T}^u v - f_{1T}^d v}{4f_{1T}^u v - f_{1T}^d v} \]
Sivers “difference asymmetry”

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\[ \langle \sin(\phi - \phi_S) \rangle_{UT}^{\pi^+ - \pi^-}(\phi, \phi_S) \propto -\frac{4f_{1T}^{\perp, u_v} - f_{1T}^{\perp, d_v}}{4f_{1}^{u_v} - f_{1}^{d_v}} \]

access to Sivers u-valence distribution

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The kaon Sivers amplitudes

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\[2 \langle \sin(\psi_\phi) \rangle_{UT}^n\]

\[2 \langle \sin(\psi_\phi) \rangle_{UT}^{K^+}\]

\[2 \langle \sin(\psi_\phi) \rangle_{UT}^{K^-}\]

\[2 \langle \sin(\psi_\phi) \rangle_{UT}^\pi^+\]

\[2 \langle \sin(\psi_\phi) \rangle_{UT}^\pi^0\]

\[2 \langle \sin(\psi_\phi) \rangle_{UT}^\pi^-\]

\[x \quad 10^{-1} \quad 0.4 \quad 0.6 \quad z \quad P_{h\perp} [\text{GeV}]\]

\[x \quad 10^{-1} \quad 0.4 \quad 0.6 \quad z \quad P_{h\perp} [\text{GeV}]\]
The kaon Sivers amplitudes

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Quark pol. U, L, T

Nucleon pol. U, f, h, g, L, g, T, f, h, T

Twist-2 TMDs

![Graphs showing the kaon Sivers amplitudes for different kaon species and pion masses.](image)
The kaon Sivers amplitudes

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![Graph showing $2 \langle \sin(\phi - \phi_S) \rangle_{UT}$ for different kaons and pions with $x$, $z$, and $P_{h\perp}$ axes.](image)

gunar.schnell @ desy.de
### The "Kaon Challenge"

$\pi^+ / K^+$ production dominated by scattering off $u$-quarks:

$$\pi^+ / K^+ \propto -\frac{f_{1T}^u(x, p_T^2) \otimes \mathcal{W} D_{1}^{u \rightarrow \pi^+ / K^+}(z, k_T^2)}{f_{1}^u(x, p_T^2) \otimes D_{1}^{u \rightarrow \pi^+ / K^+}(z, k_T^2)}.$$
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The “Kaon Challenge”

$$\pi^+ / K^+$$ production dominated by scattering off u-quarks:

$$\sim - \frac{f_{1T}^u(x, p_T^2) \otimes \mathcal{W} D_1^{u \rightarrow \pi^+ / K^+}(z, k_{T}^2)}{f_1^u(x, p_T^2) \otimes D_1^{u \rightarrow \pi^+ / K^+}(z, k_{T}^2)}$$
The "Kaon Challenge"

\[ \pi^+ / K^+ \] production dominated by scattering off u-quarks: \( \sim - \frac{f_{1T}^u(x, p_T^2) \otimes W D_{1u} \rightarrow \pi^+/K^+}(z, k_T^2)}{f_{1T}^u(x, p_T^2) \otimes D_{1u} \rightarrow \pi^+/K^+}(z, k_T^2)\)

\( K^+ = |u\bar{s}\rangle \) & \( \pi^+ = |u\bar{d}\rangle \) \( \Rightarrow \) non-trivial role of sea quarks?
The “Kaon Challenge”

\[ K^+ - \pi^+ \]

\[ 2 \langle \sin(\phi - \phi_s) \rangle^{K^+}_{\nu \tau} - 2 \langle \sin(\phi - \phi_s) \rangle^{\pi^+}_{\nu \tau} \]

\[ 10^{-1} \]

\[ \frac{f_{1L}^u(x, p^2_T)}{m} \quad D_{1u}^{u \rightarrow \pi^+/K^+}(z, k^2_T) \]

\[ f_{1T}^u(x, p^2_T) \quad D_{1T}^{u \rightarrow \pi^+/K^+}(z, k^2_T) \]

\[ \frac{f_{1L}^u(x, p^2_T)}{\pi^+} \quad D_{1L}^{u \rightarrow \pi^+/K^+}(z, k^2_T) \]

\[ 2 \langle \sin(\phi - \phi_s) \rangle^{K^+}_{\nu \tau} - 2 \langle \sin(\phi - \phi_s) \rangle^{\pi^+}_{\nu \tau} \]

\[ K^+ = |us\rangle \quad \pi^+ = |ud\rangle \]

\[ \text{non-trivial role of sea quarks?} \]

\[ \text{convolution integrals depend on } k_T \text{ dependence of fragmentation functions} \]
The “Kaon Challenge”

\[
\pi^+ / K^+ \text{ production dominated by scattering off } u\text{-quarks: } \sim - \frac{f_{1T}^u(x, p_T^2) \otimes D_{1u}^{\pi^+ / K^+}(z, k_T^2)}{f_{1T}^u(x, p_T^2) \otimes D_{1u}^{\pi^+ / K^+}(z, k_T^2)}
\]

- \( K^+ = |u\bar{s}\rangle \) & \( \pi^+ = |u\bar{d}\rangle \) \( \rightarrow \) non-trivial role of sea quarks?

- convolution integrals depend on \( k_T \) dependence of fragmentation functions

possible difference in dependences on the kinematics integrated over

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Role of sea quarks

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[A. Airapetian et al., PLB 666, 446 (2008)]

$\sin(\phi-\phi_S)_{\pi^+}^K - 2 \frac{\langle \sin(\phi-\phi_S)_{\pi^+}^K \rangle}{\langle \pi^+ \rangle}$

$K^+ - \pi^+$
### Role of sea quarks

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[A. Airapetian et al., PLB 666, 446 (2008)]

**Figure:**

- **$K^+ - \pi^+$**

- Differences biggest in region where strange sea is most different from light sea

---

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\begin{equation}
\langle \sin(\phi - \phi_S) \rangle_{UT}^{\pi^+ - \pi^-}(\phi, \phi_S) \propto -\frac{4f_{1T,u_v}^\bot - f_{1T,d_v}^\bot}{4f_{1}^u - f_{1}^d}
\end{equation}
Cancelation of FFs

\[
\langle \sin(\phi - \phi_S) \rangle_{UT}^{\pi^+ - \pi^-} (\phi, \phi_S) \propto \frac{4f_{1T}^\perp, u_v - f_{1T}^\perp, d_v}{4f_{1T}^u v - f_{1T}^d v}
\]

should be flat

\[
2 \langle \sin(\phi - \phi_S) \rangle_{UT}^{\pi^+ - \pi^-}
\]

\[
10^{-1} \quad x \quad 0.4 \quad 0.6 \quad z \quad P_{h\perp} [\text{GeV}] \quad 0.5 \quad 1
\]
**Q^2 dependence of amplitudes**

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- separate each x-bin into two Q^2 bins:

- only in low-Q^2 region significant (>90% c.l.) deviation
Q² dependence of amplitudes

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\[
2 \langle \sin(\phi - \phi_s)/u_T \rangle
\]

\[
\langle Q^2 \rangle \ [\text{GeV}^2]
\]

\[
0.1
\]

\[
0
\]

\[
10
\]

\[
10^{-1}
\]

\[
x
\]

\[
\pi^+
\]

\[
Q^2 < \langle Q^2(x_i) \rangle
\]
\( Q^2 \) dependence of amplitudes

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\[
2 \left< \sin(\phi - \phi') \right> \propto \begin{cases} 
\pi^+ & \text{if } Q^2 < \left< Q^2(x_i) \right> \\
\circ & \text{if } Q^2 > \left< Q^2(x_i) \right>
\end{cases}
\]

\[
\left< Q^2 \right> \text{ [GeV}^2]\]

\[
10 \quad 1 \quad 10^{-1} \quad x
\]

\[
\pi^+
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\left< Q^2 \right> \text{ [GeV}^2]\]

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\[ 2 \langle \sin(\phi-\phi_s) \rangle_{ul} \]
\[ \langle Q^2 \rangle_{[GeV^2]} \]
\[ Q^2 < \langle Q^2(x_i) \rangle \]
\[ Q^2 > \langle Q^2(x_i) \rangle \]

\[ \pi^+ \]
\[ K^+ \]

\[ x \]

\[ 10^{-1} \]

gunar.schnell @ desy.de
$Q^2$ dependence of amplitudes

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$2 \langle \sin(\phi - \phi_s) \rangle_{ul}$

- $\cdot$ $Q^2 < \langle Q^2(x_i) \rangle$
- $\cdot$ $Q^2 > \langle Q^2(x_i) \rangle$

$2 \langle \sin(\phi - \phi_s) \rangle_{ut}$

- $\cdot$ $Q^2 < \langle Q^2(x_i) \rangle$
- $\cdot$ $Q^2 > \langle Q^2(x_i) \rangle$

$\langle Q^2 \rangle [\text{GeV}^2]$ vs. $x$

- $\pi^+$
- $K^+$

$\Rightarrow$ hint of $Q^2$ dependence of kaon amplitude
chiral-odd $\rightarrow$ needs Collins FF (or similar)

leads to $\sin(3\phi - \phi_s)$ modulation in $A_{UT}$

data consistent with zero

suppressed by two powers of $P_{h\perp}$ (compared to, e.g., Sivers)

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Pretzelosity

- chiral-odd $\Rightarrow$ needs Collins FF (or similar)
- leads to $\sin(3\phi - \phi_s)$ modulation in $A_{UT}$
- data consistent with zero
- suppressed by two powers of $P_{h\perp}$ (compared to, e.g., Sivers)

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\[\sin(3\phi - \phi_s)\]
Subleading twist I - $\sin(2\phi + \phi_s)$

- arises solely from longitudinal component of target-spin (≤15%)
- no significant non-zero signal observed (except maybe $K^+$)
- suppressed by one power of $P_{h\perp}$ (compared to, e.g., Sivers)
- related to worm-gear $h_{1L}^\perp$
Subleading twist II - \( \sin(2\phi - \phi_s) \)

- no significant non-zero signal observed
- suppressed by one power of \( P_{h\perp} \) (compared to, e.g., Sivers)
- various terms related to pretzelosity, worm-gear, Sivers etc.:

\[
\sigma \propto \mathcal{W}_1(p_T, k_T, P_{h\perp}) \left( x f_{1 T} \tilde{D}_1 - \frac{M_h}{M} h_{1 T} \tilde{H} \frac{\tilde{H}}{z} \right) - \mathcal{W}_2(p_T, k_T, P_{h\perp}) \left[ \left( x h_{T H} + \frac{M_h}{M} g_{1 T} \tilde{G} \frac{\tilde{G}}{z} \right) + \left( x h_{T H} - \frac{M_h}{M} f_{1 T} \tilde{D} \frac{\tilde{D}}{z} \right) \right]
\]

\( x \) - nucleon pol.
\( f_1 \) - quark pol.
\( h_{1 L} \) - various terms related to pretzelosity, worm-gear, Sivers etc.
**Subleading twist III - \( \sin(\phi_s) \)**

- significant non-zero signal observed for negatively charged mesons
- must vanish after integration over \( P_{h\perp} \) and \( z \), and summation over all hadrons

**Graphical Representation**

- Various graphs showing distributions of \( 2 \langle \sin(\phi_s) \rangle u^\perp \) for different mesons (\( \pi^+ \), \( \pi^0 \), \( \pi^- \), \( K^+ \), \( K^- \))
- HERMES PRELIMINARY
- 7.3% scale uncertainty

**Equation**

\[
\sim \left( x f_{T D} - M_{h h} \right) \left( x h_{T H} + M_{h h} \right) - W(p_{T}, k_{T}, P_{h\perp})
\]

**Additional Information**

- \( \sin(\phi_s) \)
- \( x \) range: \( 10^{-1} \) to 0.6
- \( z \) range: 0 to 1
- \( P_{h\perp} \) range: 0.5 to 1 GeV

**Contact Information**

gunar.schnell @ desy.de

**Articles**

Subleading twist III - $\sin(\phi_s)$

- significant non-zero signal observed for negatively charged mesons
- must vanish after integration over $P_{h\perp}$ and $z$, and summation over all hadrons

HERMES

PRELIMINARY

7.3% scale uncertainty

$\propto \left( x_f T^1 - M_{h^1} \tilde{H} \right) - W \left( p_{T}, k_{T}, P_{h\perp} \right) \left[ (x_h T^1 H^1_{\perp} + M_{h^1} \tilde{G} \perp z) - (x_h \perp T^1 H^1_{\perp} - M_{h^1} M_f \perp T^1 \tilde{D} \perp z) \right]$
significant non-zero signal observed for negatively charged mesons

- must vanish after integration over \( P_{h\perp} \) and \( z \), and summation over all hadrons

\[
\sin(\phi_s) \quad \text{Subleading twist III} \quad \text{[Phys. Lett. B682 (2010) 345]}
\]

\[
\begin{align*}
\text{ep} & \rightarrow \text{en} \pi^+ \\
\text{e}^+ \text{p}^\uparrow & \rightarrow \text{e}^+ X
\end{align*}
\]

\[
A_{UT, l} \times \sin(\phi_s) \quad \text{[Phys. Lett. B682 (2010) 351]}
\]

\[
\langle Q^2 \rangle \quad \text{GeV}^2 \quad \text{Elastic fraction}
\]

\[
\begin{align*}
\text{6.6\% scale uncertainty} \\
\text{6.6\% scale uncertainty}
\end{align*}
\]
**Subleading twist III - sin(\(\phi_s\))**

- significant non-zero signal observed for negatively charged mesons
- must vanish after integration over \(P_{h\perp}\) and \(z\), and summation over all hadrons
- various terms related to transversity, worm-gear, Sivers etc.:

\[
\alpha \left( x_f T D_1 - \frac{M_h}{M} h_1 \tilde{H} \right) \\
- \mathcal{W}(p_T, k_T, P_{h\perp}) \left[ \left( x_h T H_1^\perp + \frac{M_h}{M} g_{1T} \tilde{G}^\perp \right) \\
- \left( x_h T H_1^\perp - \frac{M_h}{M} f_{1T} \tilde{D}^\perp \right) \right]
\]
Subleading twist III - $\sin(\phi_s)$

HERMES PRELIMINARY
7.3% scale uncertainty

$2 \langle \sin(\phi_s) \rangle_{U_T}$

$\pi^+$

$\pi^0$

$\pi^-$

$K^+$

$K^-$

$2 \langle \sin(\phi_s) \rangle_{U_T}$

$\langle Q^2 \rangle$ [GeV$^2$]

$Q^2$ dependence seen in signal for negative pions

$Q^2 > \langle Q^2(x_i) \rangle$

$Q^2 < \langle Q^2(x_i) \rangle$
Worm-Gear $g_{1T}$

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**Worm-Gear g_{1T}**

![Graph showing E06010 Preliminary $^3$He $A_{LT}$ Cos($\phi_h - \phi_s$)]

- **chiral even**

**gunar.schnell @ desy.de**

BNL/RBRC “Summer Spin” - July 2010
**Worm-Gear $g_{1T}$**

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- **chiral even**
- **first direct evidence for worm-gear $g_{1T}$ from JLab**

---

gunar.schnell @ desy.de

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- **Worm-Gear** $g_{1T}$

- chiral even
- first direct evidence for worm-gear $g_{1T}$ from JLab
- HERMES results on $A_{LT}$ coming out soon
Multi-dimensional analyses

kinematic dependences often don’t factorize
bin in as many independent variables as possible:

Example: Collins amplitudes in x-z and z-P

HERMES PRELIMINARY 2002-2005
Lepton Beam Asymmetries — 8.1 % scale uncertainty

gunar.schnell @ desy.de
Modulations in spin-independent SIDIS cross section

\[
\frac{d^5 \sigma}{dx \, dy \, dz \, d\phi_h \, dP^2_{h\perp}} = \frac{\alpha^2}{x y Q^2} \left( 1 + \frac{2 \gamma^2}{2x} \right) \left\{ A(y) \, F_{UU,T}^{UU} + B(y) \, F_{UU,L}^{UU} + C(y) \cos \phi_h F_{UU}^{\cos \phi_h} + B(y) \cos 2\phi_h F_{UU}^{\cos 2\phi_h} \right\}
\]

leading twist
\[ F_{UU}^{\cos 2\phi_h} \propto C \left[ \frac{2(\hat{P}_{h\perp} \cdot \vec{k}_T)(\hat{P}_{h\perp} \cdot \vec{p}_T) - \vec{k}_T \cdot \vec{p}_T}{MM_h} \right] \]

next to leading twist
\[ F_{UU}^{\cos \phi_h} \propto \frac{2M}{Q} \left[ \frac{\hat{P}_{h\perp} \cdot \vec{p}_T}{M_h} \times h_1^\perp H_1^\perp - \frac{\hat{P}_{h\perp} \cdot \vec{k}_T}{M} \times f_1 D_1 \right] \]

CAHN EFFECT

Interaction dependent terms neglected

Boer-Mulders effect

Implicit sum over quark flavours

gunar.schnell @ desy.de
Extraction of cosine modulations

- **Fully differential analysis**
in \((x, y, z, P_{h \perp}, \phi)\)

- **Multi-dimensional unfolding**: correction for finite acceptence, QED radiation, kinematic smearing, detector resolution

\[
n_{\text{EXP}} = S \cdot n_{\text{BORN}} + n_{\text{Bg}}
\]

\[
n_{\text{BORN}} = S^{-1} \left[ n_{\text{EXP}} - n_{\text{Bg}} \right]
\]

includes the events smeared into the acceptance

probability that an event generated with a certain kinematics is measured with a different kinematics
Extraction of cosine modulations

\[ \langle \cos \phi_h(x_b) \rangle \approx \frac{\int_{0.3}^{0.85} dy \int_{0.2}^{0.75} dz \int_{0.05}^{0.75} dP_{h\perp}^2 \sigma^{A\pi}(\omega_{x_i=x_b}) \langle \cos \phi \rangle_{x_i=x_b}}{\int_{0.3}^{0.85} dy \int_{0.2}^{0.75} dz \int_{0.05}^{0.75} dP_{h\perp}^2 \sigma^{A\pi}(\omega_{x_i=x_b})} \]

First y bin

Kinematic bin number

projection
opposite sign for charged pions (as expected for BM effect?!), with larger magnitude for $\pi^-$
opposite sign for charged pions (as expected for BM effect?!), with larger magnitude for $\pi^-$

prediction including Cahn effect does not describe data
Cahn effect?

BOER-MULDERS EFFECT

CAHN EFFECT

Interaction dependent terms neglected

\[ F_{UU}^{\cos \phi_h} \approx \frac{2M}{C} \left\{ \begin{array}{l}
- \frac{\vec{P}_{h_\perp} \cdot \vec{P}_T}{M_h} x \ h_1^+ H_1^+ \\
- \frac{\vec{P}_{h_\perp} \cdot k_T}{M} x \ f_1 D_1 + \ldots
\end{array} \right. \]

no dependence on hadron charge expected
Cahn effect?

- no dependence on hadron charge expected
- prediction off from data
- sign of Boer-Mulders in $\cos\phi$ modulation or “real” twist-3?

HERMES preliminary

$A_{\cos\phi,0}^D$
Difference of pion amplitudes

charge-symmetric contributions (e.g., Cahn) cancel
Target (in)dependence of cosine modulations

\[ 2(\cos(\phi_h))_{uu} / k_1(y) \]

\[ 2(\cos(2\phi_h))_{uu} / k_2(y) \]

\[ \langle Q^2 \rangle_{[\text{GeV}^2]} \]

\[ x \quad 0.4 \quad 0.6 \quad 0.8 \]

\[ y \quad 0.4 \quad 0.6 \quad 0.8 \]

\[ z \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad P_{h\perp} \quad [\text{GeV}] \]

HERMES preliminary
Target (in)dependence of cosine modulations

\[ 2 \cos(\phi_h)_{UU} / k_1(y) \]

\[ 2 \cos(2\phi_h)_{UU} / k_2(y) \]

\[ \langle Q^2 \rangle \text{ [GeV}^2\rangle \]

\[ x \quad 0.4 \quad 0.6 \quad 0.8 \]

\[ y \quad 0.4 \quad 0.6 \]

\[ z \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \]

\[ P_{h \perp} \text{ [GeV]} \]

HERMES preliminary
plenty of data on proton and deuteron targets available

standard Jetset does not describe HERMES data
even after tuning difficult to describe $K^+$ and $K^-$ simultaneously

need multiplicities and fragmentation functions not only binned in $z$ but also in $P_{h\perp}$ coming soon
plenty of data on proton and deuteron targets available

standard Jetset does not describe HERMES data

even after tuning difficult to describe $K^+$ and $K^-$ simultaneously

need multiplicities and fragmentation functions not only binned in $z$ but also in $P_{h\perp}$ ➔ coming soon
Momentum density & FFs

- plenty of data on proton and deuteron targets available
- standard Jetset does not describe HERMES data
- even after tuning difficult to describe $K^+$ and $K^-$ simultaneously
- need multiplicities and fragmentation functions not only binned in $z$ but also in $p_{h\perp}$ coming soon

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plenty of data on proton and deuteron targets available

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need multiplicities and fragmentation functions not only binned in $z$ but also in $p_{h\perp}$ coming soon

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Momentum density & FFs

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(for the afternoon discussion:)

effect of exclusive VM production on multiplicities

HERMES Preliminary

- excl. VM subtracted
- excl. VM included

proton target

$Q^2 = 2.5 \text{ GeV}^2/c^2$
Back to the beginning of Sivers effect

\begin{equation}
p^\uparrow p \rightarrow \pi X
\end{equation}
Back to the beginning of Sivers effect

\[ \sqrt{s} = 4.9 \text{ GeV} \]

\[ \sqrt{s} = 6.6 \text{ GeV} \]

\[ \sqrt{s} = 19.4 \text{ GeV} \]

\[ \sqrt{s} = 62.4 \text{ GeV} \]

Measurement of \( A_N \) in \( p p \)-scattering for different center of mass energies:

- 1976
- 2002
- 1991
- 2008

\[ 4.9 \text{ GeV} \]
\[ 6.6 \text{ GeV} \]
\[ 19.4 \text{ GeV} \]
\[ 62.4 \text{ GeV} \]

Only two models consistently describing the data:

- TMDs (Transverse Momentum Dependent)
- high-twist correlations

Interpretation not yet completely satisfactory

All available models predict \( A_N \) goes to zero at high \( p_T \) values.

BUT: not yet DATA at such kinematic region

All available data coming from \( p p \) scattering

**MOTIVATION**

Alejandro López Ruiz

Universiteit Gent

Florence/DIS 10

SSA in inclusive hadron production at HERMES

ANL

BNL

FNAL

RHIC
Inclusive hadron electro-production

\[ e p^\uparrow \rightarrow hX \]

lepton beam going into the page
Inclusive hadron electro-production

- scattered lepton undetected
- lepton kinematics unknown

$$e p^\uparrow \rightarrow h X$$

\[ \vec{S}_N \]
\[ \vec{p}_h \]

lepton beam going into the page
Inclusive hadron electro-production

- scattered lepton undetected ➞ lepton kinematics unknown
- dominated by quasi-real photo-production (low $Q^2$) ➞ hadronic component of photon relevant?

$e p \uparrow \rightarrow h X$

lepton beam going into the page
Inclusive hadron electro-production

- scattered lepton undetected
  ➞ lepton kinematics unknown

- dominated by quasi-real photo-production (low $Q^2$)
  ➞ hadronic component of photon relevant?

- cross section proportional to $S_N \left( k \times p_h \right) \sim \sin \phi$
Inclusive hadron electro-production

- scattered lepton undetected ➔ lepton kinematics unknown
- dominated by quasi-real photo-production (low $Q^2$) ➔ hadronic component of photon relevant?
- cross section proportional to $S_N (k \times p_h) \sim \sin \phi$

$$A_{UT}(p_T, x_F, \phi) = A_{UT}^{\sin \phi}(p_T, x_F) \sin \phi$$

lepton beam going into the page

This is what we measure!
Inclusive hadron electro-production

- scattered lepton undetected
  - lepton kinematics unknown

- dominated by quasi-real photo-production (low $Q^2$)
  - hadronic component of photon relevant?

- cross section proportional to $S_N (k \times p_h) \sim \sin \phi$

\[
A_{UT}(p_T, x_F, \phi) = A_{UT}^{\sin \phi}(p_T, x_F) \sin \phi \\
A_N = \frac{\int_{0}^{2\pi} d\phi \ \sigma_{UT} \sin \phi - \int_{0}^{\pi} d\phi \ \sigma_{UT} \sin \phi}{\int_{0}^{2\pi} d\phi \ \sigma_{UU}} \\
= -\frac{2}{\pi} A_{UT}^{\sin \phi}
\]

this is what we measure!
$x_F$ dependence of $A_{UT} \sin \phi$ amplitude

$A_{UT}^{\sin \phi}$

$e^\pm p^\uparrow \rightarrow \pi^\pm + X$  HERMES preliminary

$A_{UT}^{\sin \phi}$

$e^\pm p^\uparrow \rightarrow K^\pm + X$

8.8% scale uncertainty

$A_{UT}^{\sin \phi}$

$e^\pm p^\uparrow \rightarrow \pi^- + X$

$e^\pm p^\uparrow \rightarrow K^- + X$

$\langle p_T \rangle [\text{GeV}]$

$0.1$ $0.2$ $0.3$ $0.4$ $0.5$

$0.5$ $1.0$

$0.1$ $0.2$ $0.3$ $0.4$ $0.5$

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$x_F$ dependence of $A_{UT} \sin \phi$ amplitude

- opposite in sign to pp
- increasing amplitudes
$x_F$ dependence of $A_{UT} \sin \phi$ amplitude

- opposite in sign to pp
- increasing amplitudes

increasing $p_T$
$p_T$ dependence of $A_{UT} \sin \phi$ amplitude

increasing amplitudes with turnover
$p_T$ dependence of $A_{UT} \sin \phi$ amplitude

Increasing amplitudes with turnover

Sign change
PT dependence of \( A_{UT} \sin \phi \) amplitude

behavior and size similar to SIDIS Sivers
Inclusive hadrons in pp & ep

- factorization intricate
- sign in ep opposite to pp and to prediction (see talk by Jian)
- so far results for charged pions and kaons only
  - plan to have $K_S$, $\pi^0$ and $\eta$
  - data with beam polarization allows extraction (and model prediction) of $A_{LT}$
What else to expect on (semi-)inclusive hadron production
What else to expect on (semi-)inclusive hadron production

\[
\frac{2M}{Q} C \left[ -\frac{\hat{h} \cdot k_T}{M_h} \left(x e H_1^+ + \frac{M_h}{M} f_1 \frac{\tilde{G}^+}{z} \right) + \frac{\hat{h} \cdot p_T}{M} \left(x g^+ D_1 + \frac{M_h}{M} h_1^+ \frac{\tilde{E}}{z} \right) \right]
\]
What else to expect on (semi-)inclusive hadron production

\[ \frac{2M}{Q} C \left[ -\hat{h} \cdot k_T \left( x e H_1^+ + \frac{M_h}{M} f_1 \frac{\tilde{G}^+}{z} \right) + \hat{h} \cdot p_T \left( x g^+ D_1 + \frac{M_h}{M} \hat{h}_1^+ \frac{\tilde{E}}{z} \right) \right] \]

transverse force on transversely pol. quarks [M. Burkardt]
Introduce the unit vector structure functions appearing in eq. (2.7). To have a compact hadronic tensor and using the equation-of-motion constraint.

\[ \sum \left( \frac{\hat{h} \cdot k_T}{M_h} \left( x e H_1^+ + \frac{M_h}{M} f_1 \frac{\tilde{G}^+}{z} \right) + \frac{\hat{h} \cdot p_T}{M} \left( x g^+ D_1 + \frac{M_h}{M} h_1^+ \frac{\tilde{E}}{z} \right) \right) \]

What else to expect on (semi-)inclusive hadron production

Transverse force on transversely polarized quarks [M. Burkardt]

- Large data set on p and d on tape
What else to expect on (semi-)inclusive hadron production

transverse force on transversely pol. quarks [M. Burkardt]

- large data set on p and d on tape
- RICH allows extraction of amplitudes for kaons as well
What else to expect on (semi-)inclusive hadron production

\[ \frac{2M}{Q} C \left[ -\frac{\hat{h} \cdot k_T}{M_h} \left( xe H_1^+ + \frac{M_h}{M} f_1 \frac{\tilde{G}^+}{z} \right) + \frac{\hat{h} \cdot p_T}{M} \left( xg^1 D_1 + \frac{M_h}{M} h_1^+ \frac{\tilde{E}}{z} \right) \right] \]

transverse force on transversely pol. quarks [M. Burkardt]

- large data set on p and d on tape
- RICH allows extraction of amplitudes for kaons as well
- work on \( p_{h\perp} \)-weighted (Sivers/Collins) asymmetries ongoing

\[ \text{CLAS HERMES} \]

\[ \text{e}^+ \text{p} \to \text{e}^+ \pi^+ \text{X} \]
Exclusive reactions
Probing GPDs in Exclusive Reactions

\[ \int dx H^q(x, \xi, t) = F_1^q(t) \]
\[ \int dx E^q(x, \xi, t) = F_2^q(t) \]

\[ H^q(x, \xi = 0, t = 0) = q(x) \]
\[ \tilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x) \]

Form factors

Transverse distribution of quarks in space coordinates

Parton Distribution Functions
Quark longitudinal momentum fraction distribution in the nucleon

GPDs
Correlation between transverse position and longitudinal momentum fraction of quark in the nucleon

unpolarized | polarized
---|---
no nucleon hel. flip | \( H \) | \( \tilde{H} \)
nucleon hel. flip | \( E \) | \( \tilde{E} \)

(+ 4 more chiral-odd functions)

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Probing GPDs in Exclusive Reactions

Ji relation (1996)

\[ J_q = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx x (H_q(x, \xi, t) + E_q(x, \xi, t)) \]

Moments of certain GPDs relate directly to the total angular

\[ \int dx H_q(x, \xi, t) = F_1^q(t) \]
\[ \int dx E_q(x, \xi, t) = F_2^q(t) \]

\[ H_q(x, \xi = 0, t = 0) = q(x) \]
\[ \tilde{H}_q(x, \xi = 0, t = 0) = \Delta q(x) \]

Form factors

Transverse distribution of quarks in space coordinates

no nucleon hel. flip | polarized | polarized
---|---|---
| \( H \) | \( \tilde{H} \) |
nucleon hel. flip | polarized | polarized
| \( E \) | \( \tilde{E} \) |

(\( +4 \) more chiral-odd functions)
\( \rho^0 \) SDMEs from HERMES

[A. Airapetian et al., arXiv:0901.0701]

**Target-polarization independent SDMEs**

\[
\begin{align*}
1 - r_{00}^0 & = A: \gamma_L^* \to \rho_L^0 \\
2 r_{1-1}^0 & = A: \gamma_T^* \to \rho_T^0 \\
-2 \text{Im} r_{1-1}^0 & = B: \text{Interference } \gamma_L^* \to \rho_L^0 \text{ & } \gamma_T^* \to \rho_T^0 \\
2 \sqrt{2} \text{Re} r_{10}^0 & = C: \gamma_T^* \to \rho_L^0 \\
2 \sqrt{2} \text{Im} r_{10}^0 & = C: \gamma_L^* \to \rho_L^0 \\
2 \text{Re} r_{10}^0 & = D: \gamma_L^* \to \rho_T^0 \\
-2 \text{Re} r_{10}^0 & = D: \gamma_T^* \to \rho_T^0 \\
1/\sqrt{2} r_{00}^0 & = E: \gamma_T^* \to \rho_T^0 \\
-1/\sqrt{2} r_{00}^0 & = E: \gamma_L^* \to \rho_T^0 \\
\sqrt{2} r_{11}^0 & = E: \gamma_T^* \to \rho_T^0 \\
-\sqrt{2} r_{11}^0 & = E: \gamma_L^* \to \rho_T^0 \\
\sqrt{2} \text{Im} r_{1-1}^0 & = E: \gamma_T^* \to \rho_T^0 \\
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\text{Im} r_{1-1}^0 & = E: \gamma_T^* \to \rho_T^0 \\
\end{align*}
\]
\( \rho^0 \) SDMEs from HERMES

[A. Airapetian et al., arXiv:0901.0701]

helicity non-flip much larger than helicity-flip and double helicity-flip

target-polarization independent SDMEs

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$\rho^0$ SDMEs from HERMES

[A. Airapetian et al., arXiv:0901.0701]

1. $\gamma^0 \rightarrow \rho^0_L$
2. $\gamma^0_T \rightarrow \rho^0_T$
3. Interference $\gamma^0_L \rightarrow \rho^0_L$ & $\gamma^0_T \rightarrow \rho^0_T$
4. $\gamma^0_L \rightarrow \rho^0_L$
5. $\gamma^0_T \rightarrow \rho^0_T$

**transverse** SDMEs

**target-polarization independent SDMEs**

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R^0 SDMEs from HERMES

[A. Airapetian et al., arXiv:0906.5160]

**Results**

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- **Results**
  - **A**: $\gamma^* \rightarrow \rho^0_L$
  - **B**: Interference $\gamma^* \rightarrow \rho^0_L$ & $\gamma^* \rightarrow \rho^0_T$
  - **C**: $\gamma_T \rightarrow \rho^0_L$
  - **D**: $\gamma_L \rightarrow \rho^0_T$
  - **E**: $\gamma_T \rightarrow \rho^0_T$

**target-polarization independent SDMEs**

- **GPD E**
  - **dominant transitions**
    - $\gamma^* \rightarrow \rho^0_L$
    - $\gamma^* \rightarrow \rho^0_T$
    - $\gamma_T \rightarrow \rho^0_L$
    - $\gamma_T \rightarrow \rho^0_T$

**SDME values**

- **single spin flip**
  - $\gamma^* \rightarrow \rho^0_T$
- **double spin flip**
  - $\gamma_T \rightarrow \rho^0_T$

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$\rho^0$ SDMEs from HERMES

A. Airapetian et al., arXiv:0906.5160

$e^+ p \rightarrow e^' \rho^0 L p$

$e^+ p \rightarrow e^' \rho^0 T p$

$A_{L, T}^{\text{UT}} \sin (\phi')$

Transverse $\rho^0$

Longitudinal $\rho^0$

 Overall $Q^2$ [GeV$^2$] $x_B$ $-t'$ [GeV$^2$]

Dominant transitions

- $\gamma^* \rightarrow \rho^0_L$
- $\gamma^* \rightarrow \rho^0_T$

Single spin flip

- $\gamma^* \rightarrow \rho^0_L$
- $\gamma^* \rightarrow \rho^0_T$

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- $\gamma^* \rightarrow \rho^0_T$

“Transverse” SDMEs

SDME values

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production is described by four types of GPDs: 
structure of the nucleon and the produced meson. In the case of polarized cross section, where the contribution of asymmetry is proportional to $\sin \phi$.

Fig. 2 to generalized parton distributions (GPDs) information about the structure of the nucleon because of its relation.

The exclusive electroproduction of longitudinal vector mesons by longitudinal target. From the spin density matrix elements, the leading-twist term in the single-spin asymmetry can be obtained from measurements of the transverse target-spin asymmetry in exclusive electroproduction.

The values for this asymmetry are shown in Fig. 2. Ultimately, these studies will help to understand the origin of hermes.

The inner error bars represent the statistical uncertainties. The full error bars represent the total uncertainties.
\[ \rho^0 \] SDMEs from HERMES

[A. Airapetian et al., arXiv:0906.5160]
$\rho^0$ SDMEs from HERMES

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The polar and azimuthal angles of the decay production plane and the transverse part of the nucleon spin, because it has been shown that the helicity being reversed periodically. The net polarization was taken with positive helicity.

Ultimately, these studies will help to understand the origin of charged particle production in exclusive processes.

In this Letter, measurements of exclusive electroproduction on a transversely polarized hydrogen target. Spin density matrix elements for this process were determined from the measured production plane and the transverse part of the nucleon spin, because it has been shown that the helicity being reversed periodically. The net polarization was taken with positive helicity.

The polar and azimuthal angles of the decay production plane can conveniently be described using the polar and azimuthal angles $\phi_S$. At leading twist, the amplitude for the production of longitudinally polarized mesons is tantamount to selecting longitudinal helicities.

The asymmetry for the production of longitudinally polarized mesons is defined with respect to the hadron production plane. Figure 1.

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In this Letter, measurements of exclusive elec
\[
\frac{d^4 \sigma}{dQ^2 \, dx_B \, dt \, d\phi} = \frac{y^2}{32(2\pi)^4} \sqrt{1 + \frac{4M^2x_B^2}{Q^2}} \left( |\mathcal{T}_{\text{DVCS}}|^2 + |\mathcal{T}_{\text{BH}}|^2 + I \right)
\]
Azimuthal asymmetries in DVCS

Cross section:
\[
\sigma(\phi, \phi_S, P_B, C_B, P_T) = \sigma_{UU}(\phi) \cdot \left[1 + P_B A_{LU}^{DVCS}(\phi) + C_B P_B A_{LU}^T(\phi) + C_B A_C(\phi) + P_T A_{UT}^{DVCS}(\phi, \phi_S) + C_B P_T A_{UT}^T(\phi, \phi_S)\right]
\]

Azimuthal asymmetries:

- **Beam-charge asymmetry** \( A_C(\Phi) \):
  \[
three{\phi}{\phi_S}{P_B}{C_B}{P_T}\]
  \[
d\sigma(e^+, \phi) - d\sigma(e^-, \phi) \propto \text{Re}[F_1 \mathcal{H}] \cdot \cos \phi
\]

- **Beam-helicity asymmetry** \( A_{LU}^I(\Phi) \):
  \[
three{\phi}{\phi_S}{P_B}{C_B}{P_T}\]
  \[
d\sigma(e^{\rightarrow}, \phi) - d\sigma(e^{\leftarrow}, \phi) \propto \text{Im}[F_1 \mathcal{H}] \cdot \sin \phi
\]

- **Transverse target-spin asymmetry** \( A_{UT}^I(\Phi) \):
  \[
  \sigma(\phi, \phi_S) - \sigma(\phi, \phi_S + \pi) \propto \text{Im}[F_2 \mathcal{H} - F_1 \mathcal{E}] \cdot \sin(\phi - \phi_S) \cos \phi \\
  + \text{Im}[F_2 \mathcal{H} - F_1 \xi \mathcal{E}] \cdot \cos(\phi - \phi_S) \sin \phi
  \]

\((F_1, F_2)\) are the Dirac and Pauli form factors

\((\mathcal{H}, \mathcal{E})\ldots\) Compton form factors involving GPDs \(H, E, \ldots\)
Beam-charge asymmetry

constant term
\[ \propto - A_C^{\cos \phi} \]

\[ \propto \Re[F_1 H] \]

[higher twist]

[gluon leading twist]

Resonant fraction:
\[ ep \rightarrow e\Delta^+ \gamma \]


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Beam-charge asymmetry

2-D analysis

Figure 5: The $\cos(n\phi)$ amplitude ($n=0$–$3$) of the beam-charge asymmetry $A_C$, extracted from the 1996–2005 hydrogen data as a function of $-t$ for three $x_B$ ranges. The error bars (bands) represent the statistical (systematic) uncertainties.
Beam-spin asymmetry

\[ \alpha \text{Im}[F_1 H] \]

[higher twist]

Resonant fraction:

\[ ep \rightarrow e\Delta^+ \gamma \]


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Figure 3. The first (second) row shows the $\sin \phi$ amplitude of the beam-helicity asymmetry $A_{LU,I}$ sensitive to the interference term (squared DVCS term), extracted from the 1996–2005 hydrogen data as a function of $-t$ for three $x_B$ ranges. Correspondingly, the third row shows the $\sin(2\phi)$ amplitude of $A_{LU,I}$. The error bars (bands) represent the statistical (systematic) uncertainties. Not included is a 2.8% scale uncertainty due to the beam polarization measurement.

Summary

Previously unmeasured charge-difference and charge-averaged beam-helicity asymmetries in hard electroproduction of real photons from an unpolarized proton target are extracted from data taken with electron and positron beams. The $\sin \phi$ amplitudes of these beam-helicity asymmetries are sensitive to the interference term (twist-2) and to the squared $1+D$ analysis.
Transverse target-spin asymmetry

A. Airapetian et al., JHEP 0806:066, 2008

\[ \sin(\phi - \phi_S) \cos \phi \propto -A_{UT} \]

\[ \propto \text{Im}[F_2 \mathcal{H} - F_1 \mathcal{E}] \]

\[ \propto \text{Im}[F_2 \tilde{\mathcal{H}} - F_1 \xi \tilde{\mathcal{E}}] \]


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Transverse target-spin asymmetry

A. Airapetian et al., JHEP 0806:066, 2008


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### DVCS Overview

(A) Beam-charge asymmetry:  
\( \text{GPD } H \)

(B) Beam-helicity asymmetry:  
\( \text{GPD } H \)

(C) Transverse target spin asymmetry:  
\( \text{GPD } E \) from proton target

(D) Longitudinal target spin asymmetry:  
\( \text{GPD } \tilde{H} \)

(E) Double-spin asymmetry:  
\( \text{GPD } \tilde{H} \)

#### HERMES DVCS

| \( A_C \) | \( A_{C}^{\cos(0\phi)} \) | \( A_{C}^{\cos \phi} \) | \( A_{C}^{\cos(2\phi)} \) | \( A_{C}^{\cos(3\phi)} \) | \( \sin \phi \) | \( A_{LU,I}^{\sin \phi} \) | \( A_{LU,DVCS}^{\sin(2\phi)} \) | \( A_{LU,I}^{\sin(\phi-\phi_1)} \) | \( A_{UT,I}^{\sin(\phi-\phi_1)} \) | \( A_{UT,DVCS}^{\sin(\phi-\phi_1) \cos \phi} \) | \( \cos(\phi-\phi_1) \sin \phi \) | \( A_{UT,I}^{\cos(\phi-\phi_1) \sin \phi} \) |
|----------|----------------|----------------|----------------|----------------|----------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Hydrogen | Deuterium | Preliminary |

![Graph showing HERMES DVCS measurements](image)

- Re(\( H \))
- Im(\( H \))
- Re(\( \tilde{H} \))
- Im(\( \tilde{H} - E \))
- Im(\( \tilde{H} \))

**Amplitude Value**

-0.3 -0.2 -0.1 0 0.1 0.2 0.3

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detection of recoiling proton
... still to come ...

- **purpose**: tag exclusive events
- **reduce semi-inclusive DIS and resonance background**

**kinematic fitting**

- No Recoil requirement
- Positive track in Recoil
- Fit probability $< 1$
- Fit probability $> 1$

**HERMES 2007 data**

$M_X^2$ [GeV$^2$/c$^4$]

Purpose: to tag exclusive events with small momenta, large polar angles.

Missing azimuthal angle vs. missing momentum for kinematic fitting.
... still to come ...

- purpose: tag exclusive events
- reduce semi-inclusive DIS and resonance background

\[ A_{LT} \text{ pre-recoil era} \]
\[ A_{LU} \text{ with RD} \]
\[ A_{C} \text{ with RD} \]
\[ \text{Associated DVCS } A_{LU} / A_{C} \]