Overview of Experimental Results From HERMES

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INFN Ferrara

QCD Evolution Workshop
May 14, 2011  JLab
Quantum Phase-space Distributions of Quarks

W_p^q(x,k_T,r) “Mother” Wigner distributions

Probability to find a quark q in a nucleon P with a certain polarization in a position r & momentum k

TMD PDFs: f_p^u(x,k_T), ...

GPDs: H_p^u(x,ξ,t), ...

Semi-inclusive measurements
Momentum transfer to quark
Direct info about momentum distribution

GPDs

Exclusive Measurements
Momentum transfer to target
Direct info about spatial distribution

May explain SSA & Lam-Tung

PDFs f_p^u(x), ...

May solve proton spin puzzle

\[ J_q = \frac{1}{2} \Delta \Sigma + L_q = \lim_{t \to 0} \int_{-1}^{1} dx \ x \left[ H(x, \xi, t) + E(x, \xi, t) \right] \]
The HERMES Experiment

27.6 GeV e+/e- HERA beam

Valence and sea

Electron and Hadron ID

Data taking: 95-07

Internal gaseous target:
96-00 (p/d) Lpol
02-05 (p) Tpol
06-07 (p/d) Unpol
Generalized parton distributions

Encompass parton distributions and form factors
longitudinal momentum and transverse spatial position correlated information
Access OAM $L_q = J_q - \frac{1}{2} \Delta \Sigma$ via Ji sum rule

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

- Sensitivity of different final states to different GPDs

- For spin-1/2 target 4 chiral-even leading-twist quark GPDs: $H, E, \tilde{H}, \tilde{E}$

- $H, \tilde{H}$ conserve nucleon helicity,
$E, \tilde{E}$ involve nucleon helicity flip

- DVCS $(\gamma) \to H, E, \tilde{H}, \tilde{E}$

- Vector mesons $(\rho, \omega, \phi) \to H, E$

- Pseudoscalar mesons $(\pi, \eta) \to \tilde{H}, \tilde{E}$
The DVCS Landscape

\[ \frac{d^4 \sigma}{dQ^2 \, d x_B \, dt \, d \phi} \propto (|T_{DVCS}|^2 + |T_{BH}|^2 + I) \]

**HERMES DVCS**

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

**DVCS**

- Bethe-Heitler

**PRL 87 (2010) 182001**

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The DVCS Landscape

![Graphs showing DVCS results](image)

**HERMES DVCS**

- Hydrogen
- Deuterium
- Hydrogen Preliminary

**New**

- Re $\mathcal{H}$
- Im $\mathcal{H}$

**Im (\mathcal{H} - \mathcal{E})**

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

Amplitude Value

Overall -t [GeV$^2$] $x_B$ $Q^2 [GeV^2]$
Kinematic event fitting technique: all 3 particles in the final state detected should satisfy 4-constraints on energy-momentum conservation.

- No requirement for Recoil
- Charged recoil track in acceptance
- Kinematic fit probability > 1%
- Kinematic fit probability < 1%
Leading Twist TMDs

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**quark polarisation**

**Number density and helicity:**
- Focusing here in transverse momentum dependence

**Transversity:**
- Survives transverse momentum integration (missing leading-twist collinear piece)
- Differs from helicity due to relativistic effects and no mix with gluons in the spin-1/2 nucleon

**Off-diagonal elements:**
- Interference between wave functions with different angular momenta: contains information about parton orbital angular motion and spin-orbit effects
- Testing QCD at the amplitude level

**T-odd elements:**
- \( \rightarrow \) sign change between DY and SIDIS
  - universality of TMDs
- Strict prediction from TMDs + QCD!

**Transversity:**

\[
\begin{array}{cccc}
N/q & U & L & T \\
\hline
U & D_{1T} & & H_{1L} \\
& Unpolarized & & Collins \\
L & G_{1L} & & H_{1L} \\
T & D_{1T} & G_{1T} & H_{1T} \\
\end{array}
\]
The SIDIS Case

### nucleon polarisation

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- **U**: Number Density
- **L**: Helicity
- **T**: Sivers

### quark polarisation

- **U**: $f_1$
- **L**: $g_1$
- **T**: $h_{1T}^+$

### SIDIS cross section (transversely pol. target):

$$f \otimes D = \int_q e_q^2 d^2 p_T d^2 k_T \ldots w(k_T, p_T) f^q(x, k_T^2) D^q(z, p_T^2)$$

Involved phenomenology due to the convolution over transverse momentum

$$d^6 \sigma = \sum_q \sigma_{ep \rightarrow ehX} = \sum_q DF_{eq \rightarrow eq} \otimes FF$$

Leading Twist

$$S_T \left\{ \sin(\phi - \phi_S) F_{UT,T}^{\sin(\phi - \phi_S)} \right\}$$

Twist

$$h_{1T} \otimes H_1^+$$

$$+ S_T \left\{ \epsilon \sin(\phi + \phi_S) F_{UT}^{\sin(\phi + \phi_S)} + \epsilon \sin(3\phi - \phi_S) F_{UT}^{\sin(3\phi - \phi_S)} \right\}$$

$$g_{1T} \otimes D_1$$

$$+ S_T \lambda_e \left\{ \sqrt{1 - \epsilon^2} \cos(\phi - \phi_S) F_{LT}^{\cos(\phi - \phi_S)} \right\} + \ldots$$

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First TMD Evidences

$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 \otimes H_1^\perp$

SIDIS:
$e p \leftrightarrow e' h X$

$\sigma_{UT}^{\sin(\phi-\phi_S)} \propto f_{1T}^\perp \otimes D_1$

2005: First evidence from HERMES measuring SIDIS on proton


Non-zero transversity !!
Non-zero Collins function !!

Non-zero Sivers function !!
### Leading Twist TMDs

#### Quark polarisation

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**Nucleon polarisation**

- $P_{h_1}$ dependence: Preliminary result
- $P_{h_1}$ dependence: Preliminary result
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**HERMES has access to all of them through specific azimuthal modulations ($\phi, \phi_S$) of the cross-section thanks to the polarized beam and target**

- Indication to be not-zero! Preliminary result
- Different from zero! Preliminary result
- Consistent with zero
- Preliminary result
- Consistent with zero
- Preliminary result

**References**

- PRL 94 (2005) 012002
- PRL 103 (2009) 152002
- PLB 562 (2003) 182
- PRL 84 (2000) 4047
- PRL 94 (2005) 012002
- JHEP 06 (2008) 017
- PLB 693 (2010) 11
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LO interpretation:

\[ M_N^h = \frac{1}{N_N^{DIS}(Q^2)} \frac{dN_N^h(z, Q^2)}{dz} = \sum_q e_q^2 \int dx \ f_{1q}(x, Q^2) D_{1q}(z, Q^2) \]

Correlated systematics cancels

Proton-deuteron asymmetry:

\[ A_{d-p}^h = \frac{M_d^h - M_p^h}{M_d^h + M_p^h} \]

Reflects different flavor content

Correlated systematics cancels

SIDIS data constrain fragmentation at low c.m. energy and bring enhanced flavor sensitivity
Disentanglement of $z$ and $P_{h\perp}$: access to the transverse intrinsic quark $k_T$ and fragmentation $p_T$,

i.e. from gaussian ansatz

$$\langle P_{h\perp}^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle$$

**The $P_{h\perp}$ unintegrated Multiplicities**

Disentanglement of $z$ and $P_{h\perp}$: access to the transverse intrinsic quark $k_T$ and fragmentation $p_T$, i.e. from gaussian ansatz

$$\langle P_{h\perp}^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle$$

**Joosten, DIS 2011**
Indirect indication of a $k_T$ and $p_T$ broadening with c.m. energy:

TMD $Q^2$ evolution
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\[ A_1(x, P_{h\perp}) \]

2D - dependence

Sensitive to differences in transverse momentum dependence of \( g_1 \) and \( f_1 \)

No significant \( P_{h\perp} \) dependence observed
The $A_{LL}^{\cos(2\phi)}$ Asymmetry

\[ \cos(2\phi) \]

\[ p_{h_T} [\text{GeV}] \]

HERMES preliminary

PROTON TARGET
- 0.023 < $x$ < 0.1
- 0.1 < $x$ < 0.6

DEUTERON TARGET
- 0.023 < $x$ < 0.1
- 0.1 < $x$ < 0.6
  - Anselmino et al. $\mu^2=0.10$
  - Anselmino et al. $\mu^2=0.25$

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### Transversity

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First evidence: 2005
The Collins Amplitude

Pion signals fulfill isospin symmetry

Clear & opposite signals for charged pions:

With u-dominance: \( \pi^+(ud) \pi^-(\bar{u}\bar{d}) \)

opposite sign for favored and unfavored Collins

Not in contradiction with Collins at BELLE

\[ e^+e^- \rightarrow h_1h_2X \]

\[ A_{12} \propto H_1^\dagger H_1^\dagger \]

Not enough statistics to exclude twist-4
K$^+$ signal larger than $\pi^+$
role of sea quarks
$k_T$ dependence in FFs
higher twists effects

Peculiar $K^-$
no valence quark in common with proton
Consistent non-zero signals for charged hadrons, but K-
Two Hadron Asymmetries

\[ A_{UT}^{\sin(\phi_{R} + \phi_{S}) \sin \theta} \propto \sum_{q} e_{q}^{2} h_{1}(x, Q^{2}) H_{1}^{<}(z, M_{h}^{2}, Q^{2}) \]

\[ \sum_{q} e_{q}^{2} f_{1}(x, Q^{2}) D_{1}^{<}(z, M_{h}^{2}, Q^{2}) \]

Issue with unknown pp-terms in partial wave expansion

- Survives \( P_{h} \) integration
- Collinear factorization (simple product)
- DGLAP evolution
- Universality

JHEP 06 (2008) 017

COMPASS 2007 transverse proton data
Transversity Signals

\[ l_p \rightarrow l' hX \]

\[ e^+ e^- \rightarrow h_1 h_2 X \]

\[ l_d \rightarrow l' hX \]

Existing data limited to \( x < 0.3 \)

Evolution from high energy colliders

**1st extraction of Transversity!**

\[ A_{UT}^{\sin(\phi+\phi_S)} \propto h_1(x) \otimes H_{1q}^{\perp}(z) \]


**1st collinear extraction!**

\[ x h_1^{u*}(x) - \frac{x}{4} h_1^{d*}(x) \]

Bacchetta et al., PRL 107 (2011)
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**Naïve-T-odd**

Chirally-odd

Spin effect in unpolarized reactions

**The Neglected Effects**
The Azimuthal Modulation

\[ \frac{d^5 \sigma_{ep \rightarrow e' hX}}{dx \, dy \, dz \, d\phi \, dP^2_{h\perp}} \propto \left\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2 \epsilon (1 + \epsilon)} \cos(\phi) F_{UU}^{\cos(\phi)} + \epsilon \cos(2\phi) F_{UU}^{\cos(2\phi)} \right\} \]

Kinematical effect predicted since 1978 by Cahn due to non-zero intrinsic \( k_T \)

Leading-twist contribution introduced by Boer & Mulders in 1998

Till 2008: qualitative agreement with Cahn expectations

- No hadron identification
- No charge separation
- Poor statistics for \( \cos 2\phi \)

**Plots:**
- \( x_F > 0.1 \)
- \( x_F > 0.2 \)

**Equation:**

\[ w_1(y) = (2 - y) \sqrt{(1 - y) / [1 + (1 - y)^2]} \]
Unpolarized Cross-section

$\sigma_{UU}^{\cos(\phi)} \propto \left[ f_1 \otimes D_1 + h_1^\perp \otimes H_1^\perp + \ldots \right]/Q$

Increasing with $z$ and $P_h$

Large difference in hadron charge!

Larger in magnitude for $\pi^+$

$\cos\phi$ large and negative!
cosφ large and negative!

Increasing with $z$ and $P_h$

Large difference in hadron charge!

Larger in magnitude for $\pi^+$

$\cos^2\phi$ non-zero!

Difference in hadron charge!

Positive for $\pi^-$

Negative for $\pi^+$

\[
\sigma_{UU}^{\cos(\phi)} \propto \left[ f_1 \otimes D_1 + h_1^\perp \otimes H_1^\perp + \ldots \right]/Q
\]

\[
\sigma_{UU}^{\cos(2\phi)} \propto h_1^\perp \otimes H_1^\perp + \left[ f_1 \otimes D_1 + \ldots \right]/Q^2
\]
Difference in pion charge

\[ \sigma_{UU}^{\cos(\phi)} \propto \left[ f_1 \mathcal{O}_1 + h_1^\perp \otimes H_1^\perp + \ldots \right] / Q \]

\[ \sigma_{UU}^{\cos(2\phi)} \propto h_1^\perp \otimes H_1^\perp + \left[ f_1 \mathcal{O}_1 + \ldots \right] / Q^2 \]

\[ \sigma_{UT}^{\sin(\phi + \phi_S)} \propto h_1 H_1^\perp \]

Mild flavor dependence of \( k_T \) expected

From \( A_{UT} \): Collins favored \((u \rightarrow \pi^+)\) and unfavored \((u \rightarrow \pi^-)\) fragmentation opposite in sign

With u-dominance
Collins makes the difference!
Hint of non-zero Boer-Mulders

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Quark d vs u contribution?
DATA support Boer-Mulders of same sign for u and d
Kaon Signals

Striking difference versus pions!

- Role of the sea
- Strange Collins
- Sub-leading twists

$\sigma^{\sin(\phi+\phi_S)}_{UT} \propto h_1 H_1^\perp$

Unpolarized cross-section: any precision measurement should account for these effects.
The SIDIS $\cos(2\phi)$ Dependence

**Issue:** are $\pi^+$ DATA consistent?

\[ O_{UU}^{\cos(2\phi)} \propto h_1^\perp \otimes H_1^\perp + \left[ f_1 \otimes D_1 + \ldots \right] / Q^2 \]

arXiv: 0912.5194

Can be explained by large uncertainty on Cahn $k_T$ evolution
- $k_T$ cutoff
  and neglected HT effects

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**The SIDIS $\cos \phi$ Dependence**

Significant difference in hadron charge might signal $h_1^\perp \otimes H_1^\perp$

$\sigma_{UU}^{\cos(\phi)} \propto \left[ f_1 \otimes D_1 + h_1^\perp \otimes H_1^\perp + \ldots \right]/Q$

Issue: much lower than expected ??

Expectations largely sensitive on $<k_T>$ and $k_T$ cutoff

**HERMES Proton-$\pi^+$**

num+cuts
analyt

arXiv: 1106.6177

**HERMES preliminary**

**COMPASS$^6$LiD (25% of 2004 data)**

preliminary
**Sivers**

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*Number Density*  
*Boer-Mulders*  
*Helicity*  
*Transversity*  
*Worm-gear*  
*Pretzelosity*

**Naïve-T-odd**  
Non-trivial gauge link  
Process dependence  
(The TMD Challenge)
Pion electro-production on proton:

- Clear signal for $\pi^+$ and for pion difference
- Isospin symmetry fulfilled

The Sivers Amplitude

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P. R. L., 103 (2009) 152002
No evidence for twist-4 $(1/Q^2)$ contribution

HERMES vs COMPASS comparison: are data consistent?

PRL 103 (2009) 152002

COMPASS 2010 proton data

arXiv:1112.4423
The Sivers Challenges

Coverage at large $p_T$ and relation with twist-3 collinear approach

Sivers effect from SIDIS to Drell-Yan:
Sign change as a crucial test of TMDs factorization

Sivers effect from SIDIS to pp:
A possible candidate to explain SSA

Sivers from SIDIS and collinear twist-3 as candidates for SSA explanation
The Inclusive Hadron SSA

The Inclusive Hadron SSA

Sivers effect from SIDIS to pp:
Sign mismatch between SIDIS and pp SSA?

\[ g_{Tq,F}(x,x) = - \int d^{2}k_{\perp} \frac{|k_{\perp}|^{2}}{M} f_{1T}^{q}(x,k_{\perp}^{2}) \mid_{\text{SIDIS}} \]

Persistent with energy

Asymptotic 1/\(p_{T}\) not reached
Issues on factorization

arXiv: 0801.2990

T3 correlator from pp
Sivers moment from SIDIS

arXiv: 1103.1591
Inclusive Hadron SSA in SIDIS

- $A_{UT}$ is vanishing at low $p_T$
- $Q^2$ increases with $p_T$ approaching DIS regime
- Study transition from perturbative to non-perturbative regime

Non-zero signals for positive hadrons resembling Sivers

Sivers modulation $\sin(\phi - \phi_S)$ can survives as $\sin(\phi)$

$$A(x_F, p_T, \phi) = \frac{\sigma_{UT}(x_F, p_T, \phi)}{\sigma_{UU}(x_F, p_T)} = A_{UT} \sin(\phi)$$
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<td>Boer-Mulders</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>$g_1$</td>
<td>$h_{1L}^L$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Helicity</td>
<td></td>
<td>Worm-gear</td>
</tr>
<tr>
<td>T</td>
<td>$f_{1T}^+$</td>
<td>$g_{1T}^+$</td>
<td>$h_L^L$</td>
</tr>
<tr>
<td></td>
<td>Sivers</td>
<td>Worm-gear</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transversity</td>
<td>Pretzelosity</td>
<td></td>
</tr>
</tbody>
</table>

Sensitive to the D-wave component and the non-spherical shape of the nucleon.
Statistical power of existing data is not enough to observe significant signals

\[ h_{1T}^{1q}(x) = g_1^q(x) - h_1^q(x) \]

no-gluon models

\[ |h_{1T}^{1q}(x)| + |h_1^q(x)| \leq f_1^q(x) \]

positivity bound
### Worm Gear

#### Proton wave-components with different OAM

#### The only T-even and chirally-even off-diagonal TMD

<table>
<thead>
<tr>
<th>N/q</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
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<tr>
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<td>( f_1 )</td>
<td>Helicity</td>
<td>( h_{LT} )</td>
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<tr>
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<td>Number Density</td>
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<td>( g_1 )</td>
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<td>( h_{LT} )</td>
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</tbody>
</table>
The $A_{LT}^{\cos(\psi - \psi_S)}$ Asymmetry

$\gamma_{1T} \otimes D_1$

**Hint of non-zero signals**

Statistics not enough to investigate relations supported by many theoretical models:

$$g_{1T}^q = -h_{1L}^q$$  
(supported by Lattice QCD and first data)

$$g_{1T}^{(1)}(x) \approx x \int_{x}^{1} \frac{dy}{y} g_{1}^{q}(y)$$  
(Wandura-Wilczek type approximation)

From light-cone constituent quark model:

arXiv: 0903.1271
Statistics not enough to investigate relations supported by many theoretical models:

\[ g_{1T}^q = -h_{1L}^q \] (supported by Lattice QCD and first data)

\[ h_{1L}^{q(1)}(x) \approx -x^2 \frac{1}{y^2} \int dy \ h_1^q(y) \] (Wandura-Wilczek type approximation)

---

PLB 562 (2003) 182

Contalbrigo M. QCD Evolution, 14th May 2012, JLab
Non zero

Negligible contribution from transverse target spin (w.r.t. virtual photon):

\[ F_{UL}^{\sin(\phi)} \underset{WW}{\propto} \left[ h_{1L}^\perp \otimes H_1^\perp + g_{1L}^\perp \otimes H_1^\perp + \ldots \right] / Q \]

(Wandura-Wilczek type approximation)
The $A_{LU}^{\sin(\phi)}$ Asymmetry

Non zero
Negligible contribution from transverse target spin (w.r.t. virtual photon):

$$F_{UL}^{\sin(\phi)} \propto \frac{e \otimes H_1^\perp + \ldots}{Q}$$

(Wandura-Wilczek type approximation)
The $A_{\sin(\psi_S)}^{UT}$ Asymmetry

Non zero
Higher-twist term with manifest $Q^2$ dependence:

$$F_{UL}^{\sin(\phi)} \propto \left[ h_1 \otimes H_1^\perp + \ldots \right]/Q$$

(Wandura-Wilczek type approximation)
The SIDIS Cross-section

\[
\frac{d^6 \sigma}{dx \, dy \, dz \, d\phi_s \, d\phi \, dP_{h\perp}^2} \propto \left\{ F_{UU,T} + \varepsilon F_{UU,L} \right\} \\
+ \left\{ \sqrt{2\varepsilon(1+\varepsilon)} \cos(\phi)F_{UU}^{\cos(\phi)} + \varepsilon \cos(2\phi)F_{UU}^{\cos(2\phi)} \right\} + \lambda_e \left\{ \sin(\phi)F_{LU}^{\sin(\phi)} \right\}
\]

\[
S_T \left\{ \sin(\phi - \phi_s)(F_{UT,T}^{\sin(\phi-\phi_s)} + \varepsilon F_{UT,L}^{\sin(\phi-\phi_s)}) + \varepsilon \sin(\phi + \phi_s)F_{UT}^{\sin(\phi+\phi_s)} + \varepsilon \sin(3\phi - \phi_s)F_{UT}^{\sin(3\phi-\phi_s)} \right\} + \\
S_T \left\{ \sqrt{2\varepsilon(1+\varepsilon)} \sin(\phi_s)F_{UT}^{\sin(\phi_s)} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi - \phi_s)F_{UT}^{\sin(2\phi-\phi_s)} \right\} + \\
S_T \lambda_e \left\{ \sqrt{1-\varepsilon^2} \cos(\phi - \phi_s)F_{LT}^{\cos(\phi-\phi_s)} + \left( \sqrt{2\varepsilon(1-\varepsilon)} \cos(\phi_s)F_{LT}^{\cos(\phi_s)} + \cos(2\phi - \phi_s)F_{LT}^{\cos(2\phi-\phi_s)} \right) \right\}
\]

\[
+S_L \left\{ \sqrt{2\varepsilon(1+\varepsilon)} \sin(\phi)F_{UL}^{\sin(\phi)} + \varepsilon \sin(2\phi)F_{UL}^{\sin(2\phi)} \right\} + S_L \lambda \left\{ \sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos(\phi)F_{LL}^{\cos(\phi)} \right\}
\]
\[
\frac{d^6 \sigma}{dx \ dy \ dz \ d\phi_s d\phi \ dP^2_{h\perp}} \propto \left\{ F_{UU,T} + \varepsilon F_{UU,L} \right\} + \left\{ \sqrt{2\varepsilon(1+\varepsilon)} \cos(\phi)F_{UU}^{\cos(\phi)} + \varepsilon \cos(2\phi)F_{UU}^{\cos(2\phi)} \right\} + \lambda_\ell \left\{ \sin(\phi)F_{LU}^{\sin(\phi)} \right\} \\
S_T \left\{ \sin(\phi - \phi_S)\left( F_{UT,T}^{\sin(\phi-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi-\phi_S)} \right) + \varepsilon \sin(\phi + \phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon \sin(3\phi - \phi_S)F_{UT}^{\sin(3\phi-\phi_S)} \right\} + \\
S_T \lambda_\ell \left\{ \sqrt{1-\varepsilon^2} \cos(\phi - \phi_S)F_{LT}^{\cos(\phi - \phi_S)} + \left( \sqrt{2\varepsilon(1-\varepsilon)} \cos(\phi_S)F_{LT}^{\cos(\phi_S)} + \cos(2\phi - \phi_S)F_{LT}^{\cos(2\phi - \phi_S)} \right) \right\} + \\
S_L \left\{ \sqrt{2\varepsilon(1+\varepsilon)} \sin(\phi)F_{UL}^{\sin(\phi)} + \varepsilon \sin(2\phi)F_{UL}^{\sin(2\phi)} \right\} + S_L \lambda_\ell \left\{ \sqrt{1-\varepsilon^2}F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos(\phi)F_{LL}^{\cos(\phi)} \right\}
\]
The Higher-twist Terms

\[ \frac{d^6 \sigma}{dx \, dy \, dz \, d\phi_S d\phi \, dP_{h \perp}^2} \propto \left\{ F_{UU,T} + \varepsilon F_{UU,L} \right\} \]

\[ + \left\{ \sqrt{2\varepsilon(1 + \varepsilon)} \cos(\phi) F_{UU}^{\cos(\phi)} + \varepsilon \cos(2\phi) F_{UU}^{\cos(2\phi)} \right\} + \lambda_\ell \left\{ \sin(\phi) F_{LU}^{\sin(\phi)} \right\} \]

\[ S_T \left\{ \sin(\phi - \phi_S)(F_{UT,T}^{\sin(\phi - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi - \phi_S)}) + \varepsilon \sin(\phi + \phi_S) F_{UT}^{\sin(\phi + \phi_S)} + \varepsilon \sin(3\phi - \phi_S) F_{UT}^{\sin(3\phi - \phi_S)} \right\} + \]

\[ S_T \left\{ \sqrt{2\varepsilon(1 + \varepsilon)} \sin(\phi_S) F_{UT}^{\sin(\phi_S)} + \sqrt{2\varepsilon(1 + \varepsilon)} \sin(2\phi - \phi_S) F_{UT}^{\sin(2\phi - \phi_S)} \right\} \]

\[ S_T \lambda_\ell \left\{ \sqrt{1 - \varepsilon^2} \cos(\phi - \phi_S) F_{LT}^{\cos(\phi - \phi_S)} + \sqrt{2\varepsilon(1 - \varepsilon)} \cos(\phi_S) F_{LT}^{\cos(\phi_S)} + \cos(2\phi - \phi_S) F_{LT}^{\cos(2\phi - \phi_S)} \right\} \]

\[ + S_L \left\{ \sqrt{2\varepsilon(1 + \varepsilon)} \sin(\phi) F_{UL}^{\sin(\phi)} + \varepsilon \sin(2\phi) F_{UL}^{\sin(2\phi)} \right\} + S_L \lambda_\ell \left\{ \sqrt{1 - \varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1 - \varepsilon)} \cos(\phi) F_{LL}^{\cos(\phi)} \right\} \]
HERMES has been a precursor experiment for TMDs and GPDs

Many innovative results in both fields

Data analysis still ongoing

Several preliminary results close to be published

New results on queue

- beam spin asymmetry in the semi-inclusive kaon sector
- semi-inclusive di-hadron analysis
- exclusive reactions
Hard Exclusive $\rho^0$ Meson Production

Meson SDMEs
EPJC 62 (2009) 659-694

Photon SDMEs

\[ r^\eta_{\lambda V \mu V} = \frac{1}{2N} \sum_{\lambda_\gamma \mu \gamma' \lambda_N' \lambda_N} F_{\lambda V} \chi'_{\lambda_N} \lambda_\gamma \lambda_N \sum_{\lambda_\gamma' \mu \gamma} F^*_{\mu V} \chi_{\lambda_N'} \mu \gamma \lambda_N \]

They form a basis for the SDMEs
Re-derived SDMEs consistent with published ones
[A. Airapetian et al. EPJC 62 (2009) 659]
Enhanced sensitivity for polarized SDMEs

Helicity Amplitudes

\[ F_{\lambda V \lambda_\gamma} = T_{\lambda V \lambda_\gamma} + U_{\lambda V \lambda_\gamma} \]

Helicity amplitudes are the fundamental quantities to be compared with theory

EPJC 71 (2011) 1609
Hard Exclusive $\rho^0$ Meson Production

\[ A_{UT}^\gamma(\phi, \phi_3) = \frac{\text{Im} \ n_{00}^{00}}{\nu_{00}^{00}} \]

[PLB679(2009)]

\[ e^+ p^0 \rightarrow e' \rho_L^0 p \]

\[ \langle Q^2 \rangle = 2.0 \text{ GeV}^2 \]
\[ \langle x \rangle = 0.09 \]
\[ \langle t' \rangle = 0.13 \text{ GeV}^2 \]