The Spin Nucleon Structure Investigation at HERMES: Recent Highlights.

Contalbrigo Marco
INFN Ferrara

Baryons2013 Conference
June 25th, 2013 Glasgow
Spin degrees of freedom can explain otherwise surprising phenomena and bring new insights into nuclear matter structure.

Fundamental: do not neglect it!!
Proton spin budget: role of partonic orbital motion?

\[ \Delta \Sigma = 0.33 \pm 0.03 \] from DIS

\[ \Delta G \approx 0.1 \text{ at } 0.02 < x < 0.3 \] from DIS and pp scattering

\[
\frac{1}{2} = \frac{1}{2} \sum_f (q_f^+ - q_f^-) + L_q + \Delta G + L_g
\]
Proton spin budget: role of partonic orbital motion?

\[ \Delta \Sigma = 0.33 \pm 0.03 \text{ from DIS} \]
\[ \Delta G \approx 0.1 \text{ at } 0.02 < x < 0.3 \text{ from DIS and pp scattering} \]

\[ \frac{1}{2} = \frac{1}{2} \sum_f (q_f^+ - q_f^-) + L_q + \Delta G + L_g \]

Single spin asymmetries: BIG (?!?) although suppressed as \( m_q/Q^2 \) in pQCD

\[ p^\uparrow p \rightarrow \pi X \]
\[ \sqrt{s} = 5 \text{ GeV} \]
\[ ANL \]

\[ \sqrt{s} = 62 \text{ GeV} \]
\[ BRAHMS \]

\[ pp \rightarrow \Lambda^\uparrow X \]

\[ \pi p \rightarrow \mu \mu X \]

Phys Rev D75 (2007) 012007

Open Issues: Test Field for QCD

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The Real Experience: 3D!
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: \( f_p^{u}(x,k_T) \), …

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

May explain SSA & Lam-Tung

\[ A_N \]
\[ \sqrt{s} = 20 \text{ GeV} \]
\( p_T < 2 \text{ GeV/c} \)

PDFs \( f_p^{u}(x) \), …
Quantum Phase-space Distributions of Quarks

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TMD PDFs: \( f_{p,u}(x,k_T) \), …

Exclusive Measurements
Momentum transfer to target
Direct info about spatial distribution

GPDs: \( H_{p,u}(x,\xi,t) \), …

May explain SSA & Lam-Tung

PDFs \( f_{p,u}(x) \), …

May solve proton spin puzzle

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

27.6 GeV e+/e- HERA beam

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

Valence and sea

Electron and Hadron ID

Data taking: 95-07

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SIDIS for Transverse Momentum Dependence
The SIDIS Case

### The SIDIS Case

#### quark polarisation

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

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

Involved phenomenology due to the convolution over transverse momentum.

#### TMD factorization for $P_{h\perp} \ll Q$

$$\frac{d^6 \sigma}{dx\,dy\,dz\,d\phi_S\,d\phi \,dP_{h\perp}^2} \propto S_T \left\{ \sin(\phi - \phi_S) F_{UT,T}^{\sin(\phi - \phi_S)} \right\}$$

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

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

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### Leading Twist TMDs

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#### 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.
Leading Twist TMDs

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### 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:

- sign change between DY and SIDIS
  - universality of TMDs

Strict prediction from TMDs + QCD!
Leading Twist TMDs

**quark polarisation**

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First TMD Evidences

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

SIDIS:
\[ e p \rightarrow e' h X \]

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

2005: First evidence from HERMES measuring SIDIS on proton


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

Non-zero Sivers function !!
### Quark polarisation

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**Boer Mulders**
- Consistent with zero
  - PLB 562 (2003) 182
  - PRL 84 (2000) 4047

**Different from zero!**
- PRL 94 (2005) 012002
- JHEP 06 (2008) 017
- PLB 693 (2010) 11

**Indication to be not-zero!**
- PRD 87 (2013) 012010

**Hint of non-zero signal**
- Preliminary result

**Consistent with zero**
- Preliminary result

**Different from zero!**
- PRL 103 (2009) 152002

**HERMES has access to all of them through specific azimuthal modulations ($\phi, \phi_3$) of the cross-section thanks to the polarized beam and target.**

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Parton Number Density
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- Number Density
- Helicity
- Sivers
- Worm-gear

(The Baseline)
Parton Number Density

HERA I+II inclusive, jets, charm PDF Fit

$Q^2 = 10 \text{ GeV}^2$

HERAPDF1.7 (prel.)
exp. uncert.
model uncert.
parametrization uncert.

HERAPDF1.6 (prel.)

$x_f$

$10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $1$ $x_f$

$x_g (\sim 0.05)$
$x_S (\sim 0.05)$

June 2011

HERAPDF Structure Function Working Group
**HERA I+II inclusive, jets, charm PDF Fit**

\[ Q^2 = 10 \text{ GeV}^2 \]

- HERAPDF1.7 (prel.)
- exp. uncert.
- model uncert.
- parametrization uncert.
- HERAPDF1.6 (prel.)

\[ x_{u,v} \]

\[ x_S \]

\[ x_S \]

\[ x_{d,v} \]

\[ r_s = \frac{0.5(s + \bar{s})}{\bar{d}}. \]

**ATLAS:** arXiv:1206.4051

\[ Q^2 = 1.9 \text{ GeV}^2, x = 0.023 \]

**HERMES Preliminary with} D_s(z,Q^2)dz=1.27 \langle Q^3 \rangle = 2.5 \text{ GeV}^2**

**Fit**
- CTEQ6L
- \( x(u(x)+d(x)) \)
- CTEQ6.5S-0
- NNPDF21

**HERAPDF Structure Function Working Group**

**June 2011**

\[ 0.4 \]

\[ 0.2 \]

\[ 0 \]

\[ 0.02 \]

\[ 0.6 \]

\[ 0.1 \]

\[ 0.2 \]

\[ 0.3 \]

**ATLAS:** epWZ tree $s$

**COMPASS PRELIMINARY**

\[ 0.18 \]

\[ 0.16 \]

\[ 0.14 \]

\[ 0.12 \]

\[ 0.1 \]

\[ 10^{-2} \]

\[ 10^{-1} \]

\[ x \]

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LO interpretation:

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

Reflects different flavor content

Correlated systematics cancels

Proton-deuteron asymmetry:

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

SIDIS data constrain fragmentation at low c.m. energy and bring enhanced flavor sensitivity

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Disentanglement of z and $P_{h\perp}$: access to the transverse intrinsic quark $k_T$ and fragmentation $p_T$

i.e. from gaussian anstaz

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

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Indication of a $k_T$ and $p_T$ broadening with c.m. energy:

TMD $Q^2$ evolution ≠ DGLAP

SIDIS

$z \sim 0.5$

COMPASS

HERMES

DY

$\pi^- N \rightarrow \mu^+ \mu^- X$

OMEGA

E537

NA3

E444

for comparison:

$E615$, Fig.2.2
$E615$, Fig.2.1

$Q_i = \sqrt{2.4}$ GeV
$Q_f = 5$ GeV
$x = 0.1$

$F_{up/P}$

$F_{Sivers}$

Evolved unpolarized TMDPDF

$F_{up/P}$

$F_{Sivers}$

Evolved Sivers function (Bochum)

$Q_i = \sqrt{2.4}$ GeV
$Q_f = 5$ GeV
$x = 0.1$

$\kappa_T$ (GeV)

$\vec{k}_T$ (GeV)

$\langle p_{h \perp}^2 \rangle$ (GeV$^2$)

$\langle q_T^2 \rangle$ (GeV$^2$)

$\frac{d\sigma_{UU}(P_{h \perp})}{dz \, dP_{h \perp}^2} = \frac{d\sigma_{UU}(0)}{dz \, dP_{h \perp}^2} e^{-P_{h \perp}^2/P_{h \perp}^2}$

arXiv: 1003.2190

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# Transversity

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First evidence: 2005

(The Collinear Missing Piece)
Non zero pion signals
Fulfill isospin symmetry

Clear & opposite signals for charged pions:

With u-dominance: \( \pi^+ (u\bar{d})\) \(\pi^- (\bar{u}d)\)
opposite sign for favored and unfavored Collins

Not in contradiction with Collins at BELLE

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

\[
A_{12} \propto H_1^\perp H_1^\perp
\]
$\langle \sin (\phi + \phi_S) \rangle_{\text{UT}}$ for $h_1 \otimes H_1^\perp$

Consistent results at different $Q^2$

- No higher twists
- No strong evolution

$\pi^+$ 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

$K^+$ 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
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**The TMD Challenge**

- **Naïve-T-odd Non-trivial gauge link**
- **Process dependence**

**Sivers**
The Sivers Amplitude @ HERMES

Pion electro-production on proton:

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

Peculiar kaon signals:
The Sivers Signals

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Signals of TMD evolution?

HERMES vs COMPASS Comparison

Different Q^2 for same x range
The Sivers Signals

Signals of TMD evolution?

From SIDIS to pp collisions:

TMDs fact. $p_T << Q$

Collinear fact. $M << p_T$

Sign mismatch!
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
Inclusive Hadron SSA @ HERMES

No scattered beam detected → $p_T$, $x_F$ with respect to e beam (not q-vector)

- $A_{UT}$ 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 $\sin(\phi)$

$$A(x_F, p_T, \phi) = \frac{\sigma_{UT}(x_F, p_T, \phi)}{\sigma_{UU}(x_F, p_T)} = A_{UT} \sin(\phi - \phi_S) \sin(\phi)$$

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# Cahn & Boer-Mulders

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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

Cahn PLB 78 (1978)
Boer & Mulders PRD 57 (1998)

ZEUS 96

Non perturbative contribution

\[ \left( f_1 \otimes D_1 \right) / Q \]
The Azimuthal Modulation

Kinematical effect predicted since 1978 by Cahn due to non-zero intrinsic $k_T$

Leading-twist contribution introduced by Boer & Mulders in 1998

SIDIS: qualitative agreement with Cahn expectations till 2008

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

DY: violation of Lam-Tung relation
cosφ large and negative!

Increasing with z and $P_h$

Large difference in hadron charge!

Larger in magnitude for $\pi^+$

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

$\cos \phi$ large and negative!

Increasing with $z$ and $P_h$

Large difference in hadron charge!

Larger in magnitude for $\pi^+$

$$\sigma_{UU}^{\cos(\phi)} \propto \left[ f_1 \otimes D_1 + h_1^\perp \otimes H_1^\perp + \ldots \right] / Q$$
cos2\(\phi\) non-zero!

Difference in hadron charge!

Positive for \(\pi^-\)

Negative for \(\pi^+\)
**Unpolarized Cross-section**

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

- **cos2\(\phi\) non-zero!**

  - Difference in hadron charge!
  - Positive for \(\pi^-\)
  - Negative for \(\pi^+\)

- **Mild flavor dependence of \(k_T\) expected**
  - Hint of non-zero Boer-Mulders
  - Quark d vs u contribution?
  - DATA support Boer-Mulders of same sign for u and d

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Contalbrigo M.

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Striking difference versus pions!

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

Unpolarized cross-section: any precision measurement should account for these effects

\[
\sigma_{UU}^{\cos(2\phi)} \propto h_1^\perp \otimes H_1^\perp + \left[ f_1 \otimes D_1 + \ldots \right]/Q^2
\]
Exclusivity
EXCLUSIVE-DIS FOR TRANSVERSE POSITION DEPENDENCE
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

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

- 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 (\( \gamma \)) \( \rightarrow \) \( H, E, \tilde{H}, \tilde{E} \)

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

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

First measurement of DVCS beam asymmetry $\text{Im}(H)$

$$\frac{d^4\sigma}{dQ^2\, dx_B\, dt\, d\phi} \propto \left( |\mathcal{T}_{\text{DVCS}}|^2 + |\mathcal{T}_{\text{BH}}|^2 + \mathcal{I} \right)$$
First measurement of DVCS asymmetry on a transverse target $\text{Im}(H-E)$

\[ J_q = \lim_{\xi \to 0} \int dx_1 \left[ H_q(x, \xi, t) + E_q(x, \xi, t) \right] \]

\[ \frac{d^4\sigma}{dQ^2\, dx_B\, dt\, d\phi} \propto \left( |T_{\text{DVCS}}|^2 + |T_{\text{BH}}|^2 + I \right) \]
The HERMES DVCS Legacy

The most complete DVCS asymmetry measurement set:

A. Airapetian et al, JHEP 11 (2009)

A. Airapetian et al, JHEP10 (2012) 042

A. Airapetian et al, JHEP 07 (2012)


A. Airapetian et al, JHEP 06 (2008)


A. Airapetian et al, JHEP 06 (2010)

A. Airapetian et al, JHEP 07 (2012) 032
A. Airapetian et al, JHEP 07 (2012) 032

Re $\mathcal{H}$

Im $\mathcal{H}$
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 %
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- Pseudoscalar mesons \( (\pi, \eta) \to \tilde{H}, \tilde{E} \)
Hard Exclusive $\rho^0$ Meson Production

Meson SDMEs
EPJC 62 (2009) 659-694

Photon SDMEs

$$r_{\lambda V \mu \nu}^{\eta} = \frac{1}{2N} \sum_{\lambda \gamma \mu \nu}^N F_{\lambda V} \chi_{N}^{\prime} \lambda_{N} \lambda_{N} \sum_{\lambda \gamma \mu \nu}^N F_{\mu V}^{*} \chi_{N}^{\prime} \mu_{\gamma} \lambda_{N}$$

Helicity Amplitudes

$$F_{\lambda V \lambda \gamma} = T_{\lambda V \lambda \gamma} + U_{\lambda V \lambda \gamma}$$

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 are the fundamental quantities to be compared with theory

EPJC 71 (2011) 1609

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Hard Exclusive Meson Production

Omega SDMEs

A: $\gamma_L \rightarrow VM_L$ & $\gamma_T \rightarrow VM_T$

B: Interference
$\gamma_L \rightarrow VM_L$ & $\gamma_T \rightarrow VM_T$

C: $\gamma_T \rightarrow VM_L$

D: $\gamma_L \rightarrow VM_T$

E: $\gamma_T \rightarrow VM_T$

Phi SDMEs

A: $\gamma_L \rightarrow \phi_L$

B: Interference $\gamma_L \rightarrow \phi_L$ & $\gamma_T \rightarrow \phi_T$

C: $\gamma_T \rightarrow \phi_L$

D: $\gamma_L \rightarrow \phi_T$

E: $\gamma_T \rightarrow \phi_T$

SDMEs

HERMES Preliminary

proton

deuteron

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HERMES has been a precursor experiment for TMDs and GPDs

Data-taking closed in 2007 but analysis still ongoing

Many innovative results in both fields and recently

- Hadron multiplicities on a pure H target (→ I. Lehman)
- Full-differential analysis of SIDIS unpolarized asymmetries (→ L. Pappalardo)
- DVCS with recoil detection  (→ I. Brodsky)

Several preliminary results close to be published

- Beam spin asymmetry in the semi-inclusive kaon sector (→ V. Zagrebelnyy)
- Inclusive hadron and Semi-inclusive di-hadron analysis on a transverse target  (→ L. Pappalardo)
- Complete decomposition of the transverse target asymmetries (→ L. Pappalardo)
- Associated DVCS (→ M. Murray)
- Exclusive vector-meson production (→ A. Movsisyan)