What is the HERMES Experiment?
HERa MEasurement of Spin

- Collaboration of 140 physicists
- 24 Institutions
- 12 Countries

**Original goal:**
Understand the spin structure of the nucleon

**Present goal:**
Understand the nucleon
OUTLINE

- Introduction to polarized DIS
  - Also a bit of history
- The HERMES Detector
- The longitudinal spin Structure of the nucleon
- Going beyond the quark helicity
History of Spin

Stern-Gerlach Experiment 1922

Expectation from Classical Physics

\[ F = \nabla \left( \hat{m} \cdot \overline{B} \right) \]
\[ F = m_B \nabla B \]

\( \hat{m} \) magnetic moment vector
\( \overline{B} \) the magnetic field
\( m_B \) the projection of \( m \) on \( B \)

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History of Spin
Uhlenbeck and Goudsmit 1926

\[ M_s = \frac{g \mu_B}{\hbar} S \]

The hydrogen spectrum

Uhlenbeck Kramer Goudsmit

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Is Spin Important?

Pauli principle …

Particle wavefunction is antisymmetric under interchange of identical particles.

Two particles cannot occupy the same quantum state.

- Half integer SPIN
  - Obey Pauli principle
  - Fermi-Dirac statistics
    - Fermions

- Integer SPIN
  - Don’t care about Pauli principle
  - Bose-Einstein statistics:
    - Bosons
Is Spin Important?

Pauli principle …

- Half integer SPIN

Matter

- Integer SPIN

Forces

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<th>matter constituents spin = 1/2, 3/2, 5/2, …</th>
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<td>g gluon</td>
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How to study the nucleon spin? 
Deep Inelastic Scattering

HERMES is a Fixed target experiment.
The measured quantities in the lab system are $E, E', \theta$. Two are independent.

From $E, E', \theta$ three scaling variables can be computed $Q^2$, $x$, and $y$. Two are independent.

$Q^2 = 4EE' \sin^2 \left( \frac{\theta}{2} \right)$

$x = \frac{Q^2}{2M(E - E')} = \frac{Q^2}{2Mv}$

$y = |E - E'| / E$

with $v = E - E'$

$v$ is the energy of the virtual photon in the lab frame

J Stewart
Deep Inelastic Scattering

Quark Parton Model

- $Q^2$ is the squared 4-momentum of the virtual photon.
- $x$ is the Bjorken scaling variable.
  - The fraction of the total nucleon momentum carried by the struck quark.
- $y$ is the inelasticity.
  - The fraction of the incoming momentum carried by the virtual photon.

- High resolution: $Q^2 > 1 \text{GeV}^2$
- Inelastic: $M_x \neq M^2$ implying $x < 1$

\[ Q^2 = - (k - k')^2 = -q^2 \]
\[ x = \frac{Q^2}{2p \cdot q} = \frac{Q^2}{2Mv} \]
\[ y = \frac{p \cdot q}{p \cdot k} = \frac{\sqrt{E}}{E} \]

and

\[ xy = \frac{Q^2}{(s - M^2)} \]

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**DIS Cross Section**

$$\sigma(\text{ep} \to \text{eX})$$

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2 E'}{2MQ^4 E} L_{\mu\nu}(k,q,s) W^{\mu\nu}(P,q,S)$$

$L_{\mu\nu}$ leptonic part of the cross section
- Independent of the proton structure
- Purely electromagnetic → Calculable in QED

$W^{\mu\nu}$ hadronic part of the cross section
- Contains info on the proton structure
- Not Calculable in QCD

J Stewart
Hadronic Tensor $W^{\mu\nu}$

- Parameterized by structure functions (Lorentz invariance, current conservation, parity, etc.)

\[
W^{\mu\nu} = -g^{\mu\nu} + \frac{P^\mu P^\nu}{v^2} + i\varepsilon^{\mu\nu\lambda\sigma} P^\lambda S^\sigma
\]

Symmetric part $\rightarrow$ Spin independent

QPM:

\[
F_1 = \frac{1}{2} \sum_f e_r^2 (q_r^+ (x) + q_r^- (x)) = \frac{1}{2} \sum_f e_r^2 q_r (x)
\]

momentum distribution of quarks

\[
q_r^+ (x) = \text{Polarized Distribution Function connected to the probability to have a struck quark with the fraction } x \text{ of the nucleon momentum and spin in the same direction as the nucleon.}
\]

\[
\Delta q_r (x) = \bar{q}_r (x) - \bar{q}_r (x)
\]

($f : u, d, s, \bar{u}, \bar{d}, \bar{s}$)

\[
g_1 = \frac{1}{2} \sum_f e_r^2 (q_r^+ (x) - q_r^- (x)) = \frac{1}{2} \sum_f e_r^2 \Delta q_r (x)
\]

helicity distribution of quarks
Why do polarized leptons measure quark helicity distributions? Look at the virtual photon cross section.

- Virtual photon can only couple to quarks of opposite helicity
- Select quark helicity by changing target polarization direction
- Different targets give sensitivity to different quark flavors

\[
S_\gamma + S_N = 1 + 1/2 = 3/2 \\
\sigma_{3/2} = -S_q \\
\sigma_{3/2} \sim q^- (x) \\
S_N = S_q \\
\sigma_{1/2} \sim q^+ (x)
\]

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Cross section Asymmetries

\( \sigma_{1/2} \) and \( \sigma_{3/2} \) are roughly the same size so you cannot measure both separately and subtract the results. What you measure is the ratio of sums and differences of cross sections called asymmetries.

\[
A_{\parallel} = \frac{\sigma^{\leftrightarrow} - \sigma^{\Rightarrow}}{\sigma^{\leftrightarrow} + \sigma^{\Rightarrow}}
\]

- Both beam and target helicities are reversed as often as possible.
  - Changes to the beam, target, and detector on time scales longer than the flipping time cancel!
- Enables measuring the effect of very small cross section differences.
  - HERMES few percent
  - CP violation \( 10^{-6} \)
- As the cross section differences are small large statistics are needed.

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Structure Functions and Measured Asymmetries

\[ A_{\parallel} = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \]
\[ A_{\perp} = \frac{\sigma^{\uparrow\leftarrow} - \sigma^{\downarrow\leftarrow}}{\sigma^{\uparrow\leftarrow} + \sigma^{\downarrow\leftarrow}} \]

\[ A_{\parallel} = D(A_1 + \eta A_2) \]
\[ A_{\perp} = d(A_2 + \xi A_1) \]

Virtual Photon Asymmetries

\[ A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{g_1 - \gamma^2 g_2}{F_1} \]
\[ A_2 = \frac{\sigma_{\perp L}}{F_1} = \frac{\gamma (g_1 + g_2)}{F_1} \]

\[ F_1 = \frac{1}{2} \sum_f e_f^2 (q_f^+ (x) + q_f^- (x)) = \frac{1}{2} \sum_f e_f^2 q_f (x) \]
\[ g_1(x) = \frac{1}{2} \sum_f e_f^2 (q_f^+ (x) - q_f^- (x)) = \frac{1}{2} \sum_f e_f^2 \Delta q_f (x) \]

Momentum distribution of the Quarks  
Helicity distribution of the Quarks
The spin structure of the nucleon

Constituent quark model

\[ \Delta u_v = \frac{4}{3}, \quad \Delta d_v = -\frac{1}{3} \]

Include relativistic wavefunction

\[ \Delta \Sigma \approx 0.75 \]

Gluons are important!

Unpolarised structure fct.

\[ \frac{1}{2} = \frac{1}{2} \left( \Delta u_v + \Delta d_v \right) \]

Full description of \( J_q \) and \( J_g \)

Sea quarks

\[ \Delta \Sigma = 1 \]

BUT

1989 EMC measured

\[ \Sigma = 0.120 \pm 0.09 \pm 0.138 \]

Spin Puzzle

\[ \Delta \Sigma \neq \Delta d_v + \Delta d_v + \Delta G + L_q + \Delta G + \Delta L_g \]

Full description of \( J_q \) and \( J_g \)

J Stewart
The HERMES Experiment

Necessary ingredients
- Polarized beam
- Polarized target
- Particle identification
  - Lepton hadron separation
- Large acceptance spectrometer

Additional capabilities
- Hadron identification
- Acceptance at large angles
- Unpolarized heavy targets
Hermes at HERA

- Beam Energy: 27.5 GeV
- Electrons and positrons
- Beam current
  - ~50 mA start of fill
  - ~10 mA end of fill
- Polarized (<P> ~53%)
- Can be set at each expt.
- Beam helicity reversible

Online measurement of beam polarization with two Compton polarimeters:

\[ \Delta P_B = 1.8 - 3.4 \% \]
The Polarized Target

- Breit-Rabi Polarimeter
- Holding field and target cell
- Atomic Beam Source
- Hera

Credit: Photo Agency Bilderberg/ Ginter, Peter
The HERMES polarised gas target

**ADVANTAGES:**
- no dilution; all the material is polarised
- no radiation damage
- rapid inversion of polarisation direction every 90s in less than 0.5s

J Stewart
The HERMES target cell

- **Material:** 75µm Al with Drifilm coating + ice
- **Size:** length 40cm, elliptical cross section (21mm x 8.9 mm)
- **Working temperature:** 100K (variable 35K – 300K)
- **Increase of density to free jet ~100 (3 – 5*10^{31} nucl/cm²/s)**
Target Performance

Longitudinal Polarization:
1996-1997 Hydrogen  $|P_T| = 85\%$
1999-2000 Deuterium  $|P_T| = 85\%$

$\rho = 7.6 \times 10^{13}$ nucl./cm$^2$

Transverse Polarization:
2002-2005 Hydrogen  $|P_T| = 0.75\%$

$P_T = \alpha_0 \alpha_r P_a + \alpha_0 (1 - \alpha_r) P_m$

$P_T$ = total target polarization
$\alpha_0$ = atomic fraction in absence of recombination
$\alpha_r$ = atomic fraction surviving recombination
$P_a$ = polarization of atoms
$P_m$ = polarization of recombined molecules

Unpolarized Gases:
→H$^2$, D$^2$, He, N$_2$, Ne, Xe

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The HERMES Spectrometer

- Magnetic spectrometer for momentum measurement.
- Electromagnetic calorimeter for energy measurement and photon detection.
- Relatively large acceptance.
- Excellent particle identification.
The HERMES Spectrometer

Magnetic Spectrometer:
- Kinematic Range: $0.02 \leq x \leq 0.8$ at $Q^2 \geq 1 \text{GeV}^2$ and $W \geq 2 \text{GeV}$
- Top-Bottom symmetric

Particle Identification:
- TRD
- Cherenkov:
- 1.5T dipole field, 0.3 MW walls, Calorimeter
- Threshold Cherenkov is 100 MeV
- 7 drift chambers

Reconstruction:
- $1.0 \pm 2.0\%$, $\theta \leq 1.0$ mrad
- Large acceptance

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Which Particle is Which

Physics requirement: Need lepton hadron separation over wide momentum range

In worst case factor $10^5$ hadron suppression is needed

combined suppression $10^3$

Factor 100 still needed

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The HERMES TRD

Single Module Response

- Pion dE/dx
- Electron dE/dx
- Electron dE/dx + TR

Energy Deposition (keV)

Counts

Counts

0 0.005 0.01 0.015 0.02 0.025 0.03 0.035 0.04 0.045

Electron dE/dx + TR

0 1 0 2 0 3 0 4 0 5 0 6 0 7 0 8 0

Truncated Mean

combining all 6 modules

Pion Rejection Factor

0 10 20 30 40 50 60 70 80

L (cm)

1 10 10^2 10^3 10^4 10^5

0 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08

0 1 0 2 0 3 0 4 0 5 0 6 0 7 0 8 0

Single TRD Module
Which Hadron ($\pi, K, p$) is Which

hadron/positron separation
combining signals from:
TRD, calorimeter, preshower

hadron separation
Dual radiator RICH for $\pi$, $K$, $p$

\[ \cos \Theta = \frac{1}{\beta n} \]
\[ p = \frac{m \beta c}{\sqrt{1 - \beta^2}} \]

J Stewa
From 1996 through 2005 HERMES ran with the polarized H/D target.

- November 2005 the ABS was removed.

- In January 2006 the recoil detector was installed.

- February started data taking.
  - Scintillating fiber detector worked immediately.

- Full detector operations since September 2006.
  - 20M DIS in 2007
  - 20M DIS in 2006
    - Recoil only for part of data.
Recoil Detector Overview

Photon Detector
- 3 layers of Tungsten/Scintillator
- PID for higher momentum
-detects $\Delta^+ \rightarrow p\pi^0$

Scintillating Fiber Detector
- 2 Barrels
- 2 Parallel- and 2 Stereo-Layers in each barrel
- 10° Stereo Angle
-Momentum reconstruction & PID

Silicon Detector
- 16 double-sides sensors
- $10 \times 10$ cm$^2$ active area each
- 2 layers
- Inside HERA vacuum
-Momentum reconstruction & PID

1 Tesla Superconducting Solenoid

Target Cell

J Stewart

Target Cell

HERA Beam
Back to inclusive physics

Measuring $g_1$
How to measure cross section asymmetries

\[ \sigma(\theta, E') \leftrightarrow \sigma(x, Q^2) \]

\[ \sigma(x, Q^2) \propto \frac{N(\Delta x, \Delta Q^2)}{L} \]

Cut: because of radiative corrections

\[ A_\parallel = \frac{1}{P_b P_t} \frac{N \rightarrow L \rightarrow -N \rightarrow L \rightarrow}{N \leftarrow L \rightarrow -N \leftarrow L \rightarrow} \]

Cut: exclude resonance region

Resolve quark structure

Spectrometer acceptance
World Data on $g_1/F_1$

Proton

Data shown at measured $<Q^2>$: 0.02-58 GeV$^2$

$$A_{\parallel} = \frac{1}{P_b P_t} \frac{N \rightarrow L \rightarrow -N \rightarrow L \rightarrow}{N \rightarrow L \rightarrow -N \rightarrow L \rightarrow}$$

$$\frac{g_1}{F_1} = \frac{1}{1 + \gamma^2} \left[ \frac{A_{\parallel}}{D} + (\gamma + \eta) A_2 \right]$$
Model-independent unfolding

- detector smearing
- QED radiative effects

\[ S_{ij} = \frac{\partial \sigma^{\text{meas}}}{\partial \sigma^{\text{born}}} = \frac{\partial N^{\text{meas}}}{\partial N^{\text{born}}} \]

\[ = \frac{N(i, j)_{\leftarrow\rightarrow}}{N^{\text{born}}(j)_{\leftarrow\rightarrow}} \]

- kinematic migration inside acceptance for each spin state
- j=0 bin: kinematic migration into the acceptance

- systematic correlations between bins fully unfolded
- resulting (small) statistical correlations known

smearing within acceptance
World Data on $xg_1(x,Q^2)$

- $g_1^p > g_1^d > g_1^{^3\text{He}}$
- Very precise proton data
- The most precise deuteron data

$$g_1^d = \frac{1}{2} \left( 1 - \frac{3}{2} w_d \right) (g_1^p + g_1^n)$$

- 0.021-0.9 measured range:
  $$\int g_1^p = 0.1246 \pm 0.0032 \pm 0.0074$$
  $$\int g_1^d = 0.0452 \pm 0.0015 \pm 0.0017$$

$\Delta \Sigma = 0.33$
World data on $g_1$

$g_1^p(x,Q^2) + C(x)$

- **SMC**: $x = 0.0063 (+7.5)$
- **EMC**: $x = 0.0141 (+6.2)$
- **E143**: $x = 0.0245 (+5.2)$
- **E155**: $x = 0.0346 (+4.5)$
- **HERMES**: $x = 0.0490 (+4.0)$
- **x = 0.0775 (+3.5)**
- **HERMES**: $x = 0.122 (+3.0)$
- **HERMES**: $x = 0.173 (+2.5)$
- **x = 0.245 (+2.0)**
- **BB**: $x = 0.346 (+1.5)$
- **GRSV**: $x = 0.490 (+1.0)$
- **x = 0.735 (+0.5)**

$g_1^d(x,Q^2) + C(x)$

- **COMPASS**: $x = 0.0063 (+8.1)$
- **SMC**: $x = 0.0063 (+8.1)$
- **HERMES**: $x = 0.0141 (+6.7)$
- **E155**: $x = 0.0245 (+5.6)$
- **E143**: $x = 0.0346 (+4.8)$
- **E155**: $x = 0.0490 (+4.2)$
- **E143**: $x = 0.0775 (+3.7)$
- **HERMES**: $x = 0.122 (+3.2)$
- **HERMES**: $x = 0.173 (+2.7)$
- **HERMES**: $x = 0.245 (+2.2)$
- **BB**: $x = 0.346 (+1.6)$
- **GRSV**: $x = 0.490 (+1.1)$
- **AAC**: $x = 0.735 (+0.5)$
Semi-Inclusive Deep Inelastic Scattering

The cross section can be expressed as a convolution of a distribution function and a fragmentation function.

\[ Q^2 = -q^2 = -(k - k')^2 \]

\[ \nu = E - E' \]

\[ x = \frac{Q^2}{2M\nu} \]

\[ Z = \frac{E_{\text{had}}}{\nu} \]

Flavor tagging

The cross section can be expressed as a convolution of a distribution function and a fragmentation function.

\[ \sigma^{ep \rightarrow eh} \sim \sum_q DF^{p \rightarrow q} \otimes \sigma^{eq \rightarrow eq} \otimes FF^{q \rightarrow h} \]

J Stewart
Fragmentation

proton

electron

J Stewart
Fragmentation
Fragmentation

J Stewart
Fragmentation

proton → electron

J Stewart
Fragmentation
Fragmentation

proton → electron

J Stewart
Fragmentation

J Stewart
**Fragmentation**

**Fragmentation functions:**

\[ FF_{q \rightarrow h}(z) \]

The probability that if a quark \( q \) was struck that a hadron \( h \) is formed with a fraction \( z \) of the energy of the virtual photon.
Normal lund string model is used to simulate the fragmentation process.

- Need to tune the model to the data.
- The fragmentation process cannot be calculated theoretically.

\[
\begin{align*}
\pi^+ & \quad \Delta^+ & \quad K \\
K^- & \quad \phi & \quad + & \quad \eta
\end{align*}
\]

\[\text{Favored: struck quark is in the formed hadron} \quad \pi^+ = ud\]

\[D_{\pi^+}^u (z, Q^2) \quad \text{J Stewart}\]

\[\text{Unfavored} \quad D_{\pi^+}^u (z, Q^2)\]
Quark Polarizations

Correlation between detected hadron and the struck quark allows flavor separation.

Inclusive DIS $\rightarrow \Delta \Sigma$

Semi-inclusive $\rightarrow \Delta u, \Delta \bar{u}, \Delta d, \Delta \bar{d}, \Delta s$

$$A_1^h(x, Q^2) = \frac{\sigma_{1/2}^h - \sigma_{3/2}^h}{\sigma_{1/2}^h + \sigma_{3/2}^h} \sum_f e_f^2 Q_f(x, Q^2) \int dz D_f^h(z, Q^2) \sim \sum_f e_f^2 q_f(x, Q^2) \int dz D_f^h(z, Q^2) \sim \sum_f e_f^2 q_f(x, Q^2) \int dz D_f^h(z, Q^2) \frac{\Delta q(x)}{q(x)} P_q^h(x, z)$$

Linear System in $\vec{Q}$

$$\vec{A} = (A_{1, p}(x), A_{1, d}(x), A_{1, p}^\pi(x), A_{1, d}^\pi(x), A_{1, d}^{K^+}(x))$$

$\vec{Q} = \left( \begin{array}{c} \Delta u \quad \Delta d \quad \Delta \bar{u} \quad \Delta \bar{d} \quad \Delta s \quad \Delta \bar{s} \end{array} \right)$

$\vec{A} = P \vec{Q}$

J Stewart
The Measured Hadron Asymmetries

DEUTERIUM

\( K^- = \bar{u}s \) is an all sea object and \( A_{1,d}^{K^-} \approx 0 \)

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J Stewart

Meas. hadron multiplicities $\frac{N^h}{N^{DIS}}$

$\chi$

Detector model

DIS generator (LEPTO)

Hadronisation (JETSET)

Purities $P^h_q(x)$

$\Delta q$

$q$

J Stewart
The image contains a graph titled "Purities." The graph plots the purity of various quarks (u, d, s) for different hadrons (π, K) as a function of x. The axes are labeled "Purity" and "x." The graphs show different data points for protons and neutrons.

Key observations:
- $\pi^+$ comes mainly from u quarks.
- $K^+$ comes mainly from u quarks.
- $\pi^-$ is sensitive to d quarks.
- $K^-$ is sensitive to s quarks.

The graph also includes notes for clarity:
- "$\pi^+$ comes mainly from u quarks" indicated by a speech bubble.
- "$K^+$ comes mainly from u quarks" indicated by a speech bubble.
- "$\pi^-$ sensitive to d quark" indicated by a speech bubble.
- "$K^-$ sensitive to s quark" indicated by a speech bubble.

The graph is attributed to J Stewart.
Polarized Quark Densities

\[ \Delta q(x) = \bar{q}(x) - \tilde{q}(x) \]

\( \Delta u(x) > 0 \)

- Polarized parallel to the proton

\( \Delta d(x) < 0 \)

- Polarized anti-parallel to the proton

\( \Delta u(x) \) and \( \Delta d(x) \)

- Good agreement with LO-QCD fit

\( \Delta \bar{u}(x) \) and \( \Delta \bar{d}(x) \sim 0 \)

- No indication for \( \Delta s \leq 0 \)

\[ -0.028 \pm 0.033 \pm 0.009 \]

In the measured range
Unpolarized data on sea shows the Gottfried sum rule is broken

\[ \overline{d} - \overline{u} > 0 \]

Reanalyze polarized data: Fit for \( \hat{Q} = \left( \frac{\Delta u}{u}, \frac{\Delta d}{d}, \frac{\Delta \overline{u} - \Delta \overline{d}}{\overline{u} - \overline{d}}, \frac{\Delta s}{s} \right) \)

Polarized data favor a symmetric sea \( \Delta \overline{d} - \Delta \overline{u} \), but large uncertainties

J Stewart
The HERMES Experiment
Hamburg, Germany

Measuring the spin structure of the proton

How do the quark and gluon constituents of the proton conspire to produce

\textit{SPIN }1/2 ?

... exchanges polarized photons ... with a polarized proton target

Only 30\% of the proton's spin is produced by the quarks

Where is the other 70\% ?

GLUONS?
The Spin Puzzle

Measured both in inclusive and semi-inclusive polarized DIS

\[ \Delta G \] small

Leading order measurement using high pt hadrons

Indications

\[ \Delta G \] small

Both transverse target data and GPDs sensitive to L

Transversity

Unmeasured!
Distribution Functions

**Leading Twist**

- 3 distribution functions survive the integration over transverse quark momentum

<table>
<thead>
<tr>
<th>unpolarized DF</th>
<th>Helicity DF</th>
<th>Transversity DF</th>
</tr>
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<tbody>
<tr>
<td>$q(x) = \bar{q}(x) + \bar{q}(x)$</td>
<td>$\Delta q = \bar{q}(x) - \bar{q}(x)$</td>
<td>$\delta q = q^\uparrow(x) - q^\downarrow(x)$</td>
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- $F_1(x)$
- $g_1(x)$
- Transversity DF

Quark Correlation Matrix

**HERMES 1996-2000**

2002-2005
Properties of the Transversity DFs

- For non-relativistic quarks $\delta q(x) = \Delta q(x)$
  - $\delta q(x)$ probes the relativistic nature of the quarks

- Due to Angular Momentum Conservation
  - Different QCD evolution
  - No gluon component

- $\delta\Sigma(x) = \sum_q [\delta q(x) - \delta\bar{q}(x)]$
  - Predominately sensitive to valence quarks

- Bounds
  - $|\delta q(x)| \leq q(x)$
  - Soffer Bound: $|\delta q(x)| \leq [q(x) + \Delta q(x)]$

- T-even
- Chiral odd
  - Not measurable in inclusive DIS
**Measuring Transversity**

\[
\sigma_{ep\rightarrow eh} \sim \sum_{q} DF_{p\rightarrow q} \otimes \sigma_{eq\rightarrow eq} \otimes FF_{q\rightarrow h}
\]

- Need a chiral odd fragmentation function: ‘Collins FF’
- Transverse quark polarization affects transverse hadron momentum
- Observed asymmetry in azimuthal angle about lepton scattering plane

- Forbidden
- Need chiral odd fragmentation function
Azimuthal angles and asymmetries

Beam and scattered lepton define the scattering plane

Target spin transverse to the beam

Measure azimuthal angles around $q$ referenced to the scattering plane

Hadron production plane defined from $q$ and the hadron momentum

$\phi_h$ angle between hadron prod. plane and scattering plane

$\phi_s$ angle between proton spin and scattering plane
Quark photon interaction preserves spin component out of plane and reverses component in plane

\[
\pi + (\varphi_h - \varphi_S)
\]

angle of hadron relative to \textit{final} quark spin (Collins)

\[
(\varphi_h + \varphi_S)
\]

angle of hadron relative to \textit{initial} quark spin (Sivers)

\[
A_{\text{coll}} \propto h_1^1(x)H_1^\perp(z)
\]

\[
A_{\text{Sivers}} \propto f_{1T}^\perp(x)D_1(z)
\]
**Sivers Function**

\[ \sigma_{ep\rightarrow eh} \sim \sum_q DF_{p\rightarrow q} \otimes \sigma_{eq\rightarrow eq} \otimes FF_{q\rightarrow h} \]

- Distribution function
  - Naïve T-ODD
  - Chiral even

- A remnant of the quark transverse momentum can survive the photo-absorption and the fragmentation process

- Can be inherited in the transverse momentum component
  - influence azimuthal distribution

- Non-vanishing Sivers function requires quark orbital angular momentum

- Cross section depends on the angle between the target spin direction and the hadron production plane

\[ A_{UT} \sim \sin(\phi_h - \phi_S) \sum_q e_q^2 f_{1T}^{(1/2)}(x) D_1^q(z) \]

J Stewart
Single target-spin asymmetry

$$A^h_{UT}(\phi, \phi_s) = \frac{1}{|S_T|} \frac{N^\uparrow_h(\phi, \phi_s) - N^\downarrow_h(\phi, \phi_s)}{N^\uparrow_h(\phi, \phi_s) + N^\downarrow_h(\phi, \phi_s)} =$$

$$= A^\text{Collins}_{UT} \sin(\phi + \phi_s) + A^\text{Sivers}_{UT} \sin(\phi - \phi_s)$$

angle of $h$ to final $\phi$

amplitudes fit simultaneously
(prevents mixing effects due to acceptance)
Sivers moments

$$A_{Sivers} \propto f_{1T}^\perp(x) D_1(z)$$

**Sivers moment:**

$$\pi^+ > 0 \quad \pi^- \sim 0$$

**K^+ > 0 \quad K^- \sim 0**

**K^+ > \pi^+**

- sea quarks important

**non-zero orbital angular momentum in p-wave fct.**

- $L_q$ ??
Collins moments

\[ A_{\text{coll}} \propto h_1(x) H_1^\perp(z) \]

- Collins moment:
  \( \pi^+ > 0 \quad \pi^- < 0 \)

- \( \pi^- \) unexpected large
  - role of unfavoured FF
    \[ H_{\text{fav}} = - H_{\text{unfav}} \]

- first data for Collins-FF available from Belle
  - extraction of \( h_1 \) from Hermes asymmetries

- \( K^+ > 0 \quad K^- > 0 \)
  - \( K^+ \) and \( \pi^+ \) consistent with u-quark dominance
  - \( K^- \) and \( \pi^- \) complicated sea quark contr.
Generalized Parton Distributions

Analysis of **hard exclusive processes** leads to a new class of parton distributions.

Cleanest example: Deeply Virtual Compton scattering

**DVCS**

Four new distributions = “GPDs”

- Helicity conserving: $H(x, \xi, t), E(x, \xi, t)$
- Helicity flip: $\tilde{H}(x, \xi, t), \tilde{E}(x, \xi, t)$

“Femto-photography” of the proton

*Fourier transform of $t$-dependence …*

$x$: average quark momentum fraction

$\xi$: “skewing parameter” = $x_1 - x_2$

$t$: 4-momentum transfer $^2$

**Spatial distribution** of partons
Summary

- Quark helicity distributions are now well measured.
  - Inclusive using NLO fits (sea assumption)
  - Semi-inclusive data using flavor tagging
- Gluon polarization extracted using leading order extraction from high pt hadrons.
- Transversity data now being analyzed. Clear signal is seen.
- Large DVCS data set collected for the GPD determination.
- First steps toward understanding angular momentum.