Nucleon Spin & Flavor Structure
... and Fragmentation too

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- **Quark Models:**
  how to think about the proton?

- **Deep-Inelastic Scattering:**
  parton distribution functions
  and fragmentation functions

- **The Spin Puzzle**
  and quark polarization

- **Single-Spin Asymmetries:**
  new structures within the proton
  and the fragmentation process
The Wacky World of Quarks
The Quark Model

**Hadrons** are composed of **quarks** with:

1. **flavor:** u,c,t (charge $+\frac{2}{3}$) d,s,b (charge $-\frac{1}{3}$)
2. **color:** R,G,B
3. **spin:** $\frac{1}{2}$

Each hadron observed in nature is **white** ("color singlet")

**Baryons** 3-quark systems, with colors RGB

**Mesons** quark + antiquark with colors CC

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**The spectrum** of observed hadrons is (roughly) explained:

<table>
<thead>
<tr>
<th>Mesons: Spin 0</th>
<th>Mesons: Spin 1</th>
<th>Baryons: Spin 1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+$ $u\bar{d}$</td>
<td>$\rho^+$ $u\bar{d}$</td>
<td>$p$ $uud$</td>
</tr>
<tr>
<td>$\pi^-$ $d\bar{u}$</td>
<td>$\rho^-$ $d\bar{u}$</td>
<td>$n$ $udd$</td>
</tr>
<tr>
<td>$\pi^0$ $u\bar{u} + d\bar{d}$</td>
<td>$\rho^0$ $u\bar{u} + d\bar{d}$</td>
<td>$\Sigma^+$ $uus$</td>
</tr>
<tr>
<td>$K^+$ $u\bar{s}$</td>
<td>$K^{**}$ $u\bar{s}$</td>
<td>$\Sigma^0$ $uds$</td>
</tr>
<tr>
<td>$K^-$ $s\bar{u}$</td>
<td>$K^{**-}$ $s\bar{u}$</td>
<td>$\Sigma^-$ $dds$</td>
</tr>
<tr>
<td>$K^0$ $d\bar{s}$</td>
<td>$K^{*0}$ $d\bar{s}$</td>
<td>$\Lambda$ $uds$</td>
</tr>
<tr>
<td>$\bar{K}^0$ $s\bar{d}$</td>
<td>$\bar{K}^{*0}$ $s\bar{d}$</td>
<td>$\Xi^0$ $uss$</td>
</tr>
<tr>
<td>$\eta$ $u\bar{u} + d\bar{d} + s\bar{s}$</td>
<td>$\phi$ $s\bar{s}$</td>
<td>$\Xi^-$ $dss$</td>
</tr>
<tr>
<td>$\eta'$ $u\bar{u} + d\bar{d} + s\bar{s}$</td>
<td>$\omega$ $u\bar{u} + d\bar{d} + s\bar{s}$</td>
<td></td>
</tr>
</tbody>
</table>

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N.C.R. Makins, NNPSS, July 28, 2006
Hadronic Multiplets

\[ \text{MESONS} = q\bar{q} \]

\[ \text{BARYONS} = qqq \text{ or } \bar{q}qq \]

- **SPIN 0 (\( \uparrow \downarrow \)):**
  - \( u\bar{u} \)
  - \( s\bar{s} \)
  - \( d\bar{d} \)
  - \( K^0 \)
  - \( K^+ \)
  - \( K^- \)

- **SPIN 1/2 (\( \uparrow \downarrow \uparrow \)):**
  - \( u\bar{u}, s\bar{s} \)
  - \( d\bar{d} \)
  - \( \eta, \eta' \)
  - \( \pi^+, \pi^- \)

- **SPIN 1 (\( \uparrow \uparrow \))**
  - \( \rho^+, \rho^- \)
  - \( \omega, \phi \)
  - \( K^{*+}, K^{*-} \)
  - \( \bar{K}^{*0}, K^{*0} \)

- **SPIN 3/2 (\( \uparrow \uparrow \uparrow \))**
  - \( \Omega^- \)
  - \( S\bar{S} \)

- **SPIN 1 (\( \uparrow \uparrow \)):**
  - \( \Sigma^+ \)
  - \( \Sigma^- \)
  - \( \Xi^0 \)
  - \( \Xi^- \)

- **SPIN 1 (\( \uparrow \uparrow \)):**
  - \( \Lambda^0 \)
  - \( \Lambda^0 \)
  - \( \Sigma^0 \)

- **SPIN 0 (\( \uparrow \downarrow \)):**
  - \( p \)
  - \( n \)

- **SPIN 1/2 (\( \uparrow \downarrow \uparrow \)):**
  - \( u\bar{d} \)
  - \( d\bar{u} \)

- **SPIN 1/2 (\( \uparrow \downarrow \uparrow \)):**
  - \( u\bar{u} \)
  - \( s\bar{s} \)
  - \( d\bar{d} \)
  - \( K^0 \)
  - \( K^+ \)
  - \( K^- \)

- **SPIN 1/2 (\( \uparrow \downarrow \uparrow \)):**
  - \( \eta, \eta' \)
  - \( \pi^+, \pi^- \)

- **SPIN 1 (\( \uparrow \uparrow \)):**
  - \( \rho^+, \rho^- \)
  - \( \omega, \phi \)
  - \( K^{*+}, K^{*-} \)
  - \( \bar{K}^{*0}, K^{*0} \)

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Murray Gell-Mann, 1964:

“A search for stable quarks ... at the highest energy accelerators would help to reassure us of the non-existence of real quarks.”
Electron Scattering and Scaling

Elastic scattering from the proton:

Deep-Inelastic scattering (DIS): at high energies you see ...

\[ Q^2 = |q|^2 - \nu^2 = \text{scale} \]

at which target is probed

\[ \frac{\sigma(Q^2)}{\sigma_{\text{point}}(Q^2)} \]

SLAC, 1969

SLAC, 1969

virtual photon

Energy \( \nu \)

Momentum \( q \)

hard, pointlike constituents!
Parton Distribution Functions

Let’s look inside the proton: **Deep-Inelastic Scattering** (DIS) with high energy beams ⇒ a rich substructure is revealed!

**sea quarks**: virtual quark-antiquark pairs that fluctuate in and out of the vacuum!

**gluons**: carriers of the strong force

\[ \chi \] fraction of proton momentum carried by struck quark

\[ q(x) \] parton distribution function (number density for quark flavor \( q \))

3 constituent quarks of mass \( \approx 350 \text{ MeV} \)

\( \infty \) many current quarks with bare masses \( \approx 5 \text{ MeV} \)

\[ Q^2 = \mu^2 \]

\[ Q^2 = 5 \text{ GeV}^2 \]
Quantum Chromodynamics

The Theory of the Strong Interaction

\[ \mathcal{L}_{\text{QCD}} = -\Psi \left\{ \gamma_\mu \left[ \partial_\mu - \frac{i}{2} g \lambda^a A^a_\mu(x) \right] + M \right\} \Psi - \frac{1}{4} \mathcal{F}^{a}_{\mu\nu} \mathcal{F}^{a}_{\mu\nu} \]

The End.
Bound States in QED and QCD

**QED**
Coupling $\alpha = 1/137$ is weak at relevant scales

- **Perturbation theory** works very well
- **Non-relativistic** quantum mechanics ok
  
e.g. Hydrogen: binding $E = 13.6$ eV $<< M_{\text{elec}} = 511$ keV

**QCD**
Coupling $\alpha_s$ **blows up** at relevant scales!

- **Perturbation theory** impossible
- Bound systems inherently **relativistic**
  
e.g. Proton: Mass $= 938$ MeV $>>$ bare $m_{\text{quark}} = 5$ MeV!
And here’s something else we can’t calculate ...
What Happens in a High Energy Collision

Confinement at Work!

Creation of hadrons from struck quark: the “fragmentation process”
**Fragmentation Functions**

\[ D^h_{q}(z) \]

describe number density of hadrons of type \( h \) and energy-fraction \( z \) produced from a struck quark of flavor \( q \)

**Symmetries:** favored / disfavored FF’s for pions:

\[
D_{\text{fav}}(\text{or } D^+) \equiv D^{\pi^+}_u = D^{\pi^+}_d = D^{\pi^-}_d = D^{\pi^-}_u
\]

\[
D_{\text{dis}}(\text{or } D^-) \equiv D^{\pi^-}_u = D^{\pi^-}_d = D^{\pi^+}_d = D^{\pi^+}_u
\]

\[
D_s \equiv D^{\pi^+}_s = D^{\pi^-}_s = D^{\pi^+}_{\bar{s}} = D^{\pi^-}_{\bar{s}}
\]

(based on charge-conjugation and isospin symmetry)

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**Graphs:**

- **HERMES D+/D**
  - HERMES D+/D\(^+\) (\( \pi, P>4 \text{ GeV, sea corrected} \))

- **D+/D**
  - Hermes (preliminary)

**Note:**

- HERMES preliminary
- stat. errors only

\[ z \equiv E_h/E_q \]
In SIDIS, a **hadron** \( h \) is detected in **coincidence** with the scattered lepton:

**The Distribution Function**

momentum **distribution of quarks** \( q \)
within their proton bound state

\[ \Rightarrow \text{lattice QCD progressing steadily} \]

**The Fragmentation Function**

momentum **distribution of hadrons** \( h \)
formed from quark \( q \)

\[ \Rightarrow \text{not even lattice can help ...} \]
The Spin Puzzle
A particular puzzle: Where does the proton spin come from?

\[ q(x) = q^\uparrow(x) + q^\downarrow(x) \]

\[ \Delta q(x) = q^\uparrow(x) - q^\downarrow(x) \]

only three possibilities

1. **Quark polarization**
   \[ \Delta \Sigma \equiv \int dx \ (\Delta u(x) + \Delta d(x) + \Delta s(x) + \Delta \bar{u}(x) + \Delta \bar{d}(x) + \Delta \bar{s}(x)) \approx 20\% \text{ only} \]

2. **Gluon polarization**
   \[ \Delta G \equiv \int dx \ \Delta g(x) \]

3. **Orbital angular momentum**
   \[ L_z \equiv L_q + L_g \]

In friendly, **non-relativistic** bound states like atoms & nuclei (& constituent quark model), particles are in **eigenstates of L**

Not so for bound, **relativistic Dirac particles** ...

Noble “l” is **not a good quantum number**
Flavor Structure of the Proton

Constituent Quark Model
Pure valence description: proton = $2u + d$

Perturbative Sea
Sea quark pairs from $g \rightarrow q\bar{q}$ should be flavor symmetric:

$$\bar{u} = \bar{d}$$

Non-perturbative models: alternate deg’s of freedom

Meson Cloud Models
Quark sea from cloud of $0^-$ mesons:

$$\bar{d} > \bar{u}$$

Chiral-Quark Soliton Model
- quark degrees of freedom in a pion mean-field
- nucleon = chiral soliton
- one parameter: dynamically-generated quark mass
- expand in $1/N_c$

$$\sim \bar{u}_R u_L \bar{d}_R d_L$$

E866: $d/u > 1$
Spin Structure: SU(6) Proton Wave Function in CQM

The 3 quarks are identical fermions ⇒ \( \psi \) antisymmetric under exchange

\[ \psi = \psi(\text{color}) \times \psi(\text{space}) \times \psi(\text{spin}) \times \psi(\text{flavor}) \]

1 Color: All hadrons are color singlets = antisymmetric

\[ \psi(\text{color}) = 1/\sqrt{6} \ (\text{RGB} - \text{RBG} + \text{BRG} - \text{BGR} + \text{GBR} - \text{GRB}) \]

2 Space: proton has \( l = l' = 0 \rightarrow \psi(\text{space}) = \text{symmetric} \)

3 Spin: \( 2 \otimes 2 \otimes 2 = (3S \oplus 1A) \otimes 2 = 4S \oplus 2_{MS} \oplus 2_{MA} \)

- \( 4S \) symmetric states have spin 3/2, e.g. \( \left| \frac{3}{2}, +\frac{3}{2} \right> = \uparrow\uparrow\uparrow \)

- \( 2_{MS} \) and \( 2_{MA} \) have spin 1/2 and mixed symmetry:
  - S or A under exchange of first 2 quarks only, e.g.

\[
\left| \frac{1}{2}', \frac{1}{2} \right>_{MS} = (\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow - 2\uparrow\uparrow\downarrow)/\sqrt{6} \quad \left| \frac{1}{2}', \frac{1}{2} \right>_{MA} = (\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow)/\sqrt{2}
\]
Flavor: symmetry groups SU(2)-spin and SU(3)-color are exact ...

- strong force is **flavor blind**
- constituent $q$ masses **similar**: $m_u, m_d \approx 350$ MeV, $m_s \approx 500$ MeV

⇒ SU(3)-flavor is **approximate** for $u, d, s$

SU(3)-flavor gives $3 \otimes 3 \otimes 3 = 10_S \oplus 8_{MS} \oplus 8_{MA} \oplus 1_A$

Proton: $\psi(s=1/2)$ from spin $2_{MS}, 2_{MA} \otimes \psi(uud)$ from flavor $8_{MS}, 8_{MA}$

$$|p^\uparrow\rangle = (u^\uparrow u^\downarrow d^\uparrow + u^\downarrow u^\uparrow d^\uparrow - 2u^\uparrow u^\uparrow d^\downarrow + \text{2 permutations})/\sqrt{18}$$

Count the number of quarks with spin up and spin down:

$$\langle p^\uparrow|\hat{N}(u^\uparrow)|p^\uparrow\rangle = \frac{30}{18} = \frac{5}{3} \quad \langle p^\uparrow|\hat{N}(d^\uparrow)|p^\uparrow\rangle = \frac{6}{18} = \frac{1}{3}$$

$$\langle p^\uparrow|\hat{N}(u^\downarrow)|p^\uparrow\rangle = \frac{6}{18} = \frac{1}{3} \quad \langle p^\uparrow|\hat{N}(d^\downarrow)|p^\uparrow\rangle = \frac{12}{18} = \frac{2}{3}$$

Quark contributions to proton spin are:

$$\Delta u = N(u^\uparrow) - N(u^\downarrow) = +\frac{4}{3} \quad \Delta d = N(d^\uparrow) - N(d^\downarrow) = -\frac{1}{3}$$

⇒ $\Delta \Sigma = \Delta u + \Delta d + \Delta s = 1$ **All spin present & accounted for!**

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Baryon Magnetic Moments

\[ \mu_B = \sum_q \mu_q \Delta q \]

where \( \mu_q \sim e_q/m_q \)

- take constituent quark masses
- take \( \mu_u = -2\mu_d \), \( \mu_s = 2\mu_d/3 \)
  and fit \( \mu_d \) to data

Note: \( \mu_B \sim (e_q/m_q)\Delta q \sim |e_q|(\Delta q - \Delta \bar{q}) \)

⇒ observable sensitive to *valence quarks*

Hyperon \( \beta \)-Decay

- parity-violating weak decay
- decay products parallel to spin
- sensitive to \( \sum_q (\Delta q + \Delta \bar{q}) \)

⇒ *Constituent Quark Model lacks sea quarks*
Spin Structure of the Proton

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]

Parton Distribution Functions

unpolarized: \( q(x) = q^\uparrow(x) + q^\downarrow(x) \)
polarized: \( \Delta q(x) = q^\uparrow(x) - q^\downarrow(x) \)

Constituent Quark Model

\[ \Delta u = +\frac{4}{3}, \quad \Delta d = -\frac{1}{3} \rightarrow \Delta \Sigma = 1 \]

Relativistic Quark Model

\[ \Delta \Sigma \simeq 0.60 - 0.75 \]
\[ L_q = \frac{1}{2}(1 - \Delta \Sigma) \]

Polarized Deep-Inelastic Scattering

From NLO-QCD analysis of inclusive DIS measurements + hyperon β-decay ...

- \( \Delta \Sigma = 0.19 \pm 0.07 \quad \text{(MS scheme)} \)
- \( \Delta G = 1.0^{+1.9}_{-0.6} \quad \text{(AB scheme)} \)

\( \rightarrow \) barely constrained, value > 0 favored

The Spin Crisis!
Anti-quark Spin in the Proton Sea

Meson Cloud Models

Li, Cheng, hep-ph/9709293

$0^-$ meson

$\gamma_5$

"valence" "sea"

\[ \Delta q_{\text{valence}} > 0 \]

\[ \Delta q_{\text{sea}} < 0 \]

\[ \Delta \bar{q} = 0 \]

"Higher-order" cloud of vector mesons can generate a small polarization.

Chiral-Quark Soliton Model

Goeke et al, hep-ph/0003324

Light sea quarks polarized:

\[ \Delta \bar{u} \simeq -\Delta \bar{d} > 0 \]

\[ \Delta q_{\text{valence}} > 0 \]

\[ \Delta q_{\text{sea}} < 0 \]

\[ \Delta \bar{q} = 0 \]

Instanton Mechanism

\[ \bar{u}_R u_L \bar{d}_R d_L \] transfers helicity from valence $u$ quarks to $d\bar{d}$ pairs

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Quark Helicity
Distributions $\Delta q(x)$:
Results
Spin-Dependent Deep Inelastic Scattering (DIS)

Polarized lepton beams incident on polarized nucleon targets

The polarized virtual photon selects certain quark polarizations:

Double spin asymmetries are measured:

\[
A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \approx \frac{g_1}{F_1} = \frac{\sum q e_q^2 \Delta q(x, Q^2)}{\sum q e_q^2 q(x, Q^2)}
\]
In SIDIS, a hadron $h$ is detected in coincidence with the scattered lepton:

**Flavor Tagging:** Flavor content of observed hadron $h$ is related to flavor of struck quark $q$ via the fragmentation functions $D(z)$.

$$A_h^1(x, Q^2) = \frac{\int_{z_{\text{min}}}^{1} dz \sum_q e_q^2 \Delta q(x, Q^2) \cdot D^h_q(z, Q^2)}{\int_{z_{\text{min}}}^{1} dz \sum_q e_q^2 q(x, Q^2) \cdot D^h_q(z, Q^2)}$$

Rewriting ...

$$A_h^1(x, z) = \sum_q P^h_q(x, z) \frac{\Delta q(x)}{q(x)}$$

**Purity matrix** $P^h_q = \text{probability that hadron } h \text{ came from struck quark } q$

Purities are spin-independent ... compute using Monte Carlo tuned to unpolarized data.

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Final \( \Delta q \) Measurement from HERMES Run 1

using polarized data 1996–2000:

\[ A_{1,p}, A_{1,\pi}, A_{1,d}, A_{1,\bar{d}}, A_{1,K} \]

First 5-flavor fit to \( \Delta q(x) \)

No evidence of anti-quark polarization, or flavor-asymmetry thereof

\( x(\Delta u - \Delta \bar{d}) \)

\[ Q^2 = 2.5 \text{ GeV}^2 \]

\( \chi^{QSM} \)

B. Dressler et al., EPJ C14 (2000) 147.
New Analysis: Isoscalar extraction of $\Delta s$

Extract isoscalar combinations of $\Delta q(x)$:

$$\Delta S(x) \equiv \Delta s(x) + \Delta \bar{s}(x)$$

$$\Delta Q(x) \equiv \Delta u(x) + \Delta \bar{u}(x) + \Delta d(x) + \Delta \bar{d}(x)$$

Asymmetries measured form isoscalar deuteron data:

$$\frac{A_d(x)}{A_d^{K^+K^-}(x)} \equiv C_R \left( \frac{P_q}{P_s^{K^+K^-}} \frac{P_s}{P_s^{K^+K^-}} \right) \left( \frac{\Delta Q(x) / Q(x)}{\Delta S(x) / S(x)} \right)$$

- Inclusive purities are simple combinations of unpolarized PDFs.

$$P_q(x) = \frac{5Q(x)}{5Q(x) + 2S(x)}, P_s(x) = \frac{2S(x)}{5Q(x) + 2S(x)}$$

- Kaon purities can be computed from the unpolarized K multiplicity assuming only charge symmetry in fragmentation.

$$D_q^{K^+K^-}(x) = D_{\bar{q}}^{K^+K^-}$$

Excellent agreement -- No MC Dependence
Single-Spin Asymmetries
So what’s next?
Fermilab E704: $p^\uparrow p \rightarrow \pi X$ at 400 GeV

Analyzing Power

$$A_N = \frac{1}{P_{\text{beam}}} \frac{N^\pi_{\text{left}} - N^\pi_{\text{right}}}{N^\pi_{\text{left}} + N^\pi_{\text{right}}}$$

Huge single-spin asymmetry!

- Opposite sign for $\pi^+ = ud\bar{d}$ than for $\pi^- = d\bar{u}$
- Effect larger for forward production
- Observable: $\vec{S}_{\text{beam}} \cdot (\vec{p}_{\text{beam}} \times \vec{p}_\pi)$

Surprising observation! ..... Why?

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SSA’s at high-energies

Now confirmed at STAR at much higher energies

T-odd observables

SSA observables \( \sim \vec{J} \cdot (\vec{p}_1 \times \vec{p}_2) \) \( \Rightarrow \text{odd} \) under naive time-reversal

Since QCD amplitudes are T-even, must arise from interference between spin-flip and non-flip amplitudes with different phases

Can’t come from perturbative subprocess xsec:

- \( q \) helicity flip suppressed by \( m_q/\sqrt{s} \)
- need \( \alpha_s \)-suppressed loop-diagram to generate necessary phase

At hard (enough) scales, SSA’s must arise from soft physics: T-odd distribution / fragmentation functions
SSA’s at high-energies

Now confirmed at STAR at much higher energies

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\( \Rightarrow \) odd under naive time-reversal

Since QCD amplitudes are T-even, must arise from interference between spin-flip and non-flip amplitudes with different phases

Suppressed in pQCD hard-scattering

• q helicity flip suppressed by \( m_q / \sqrt{s} \)

• need \( \alpha_s \)-suppressed loop-diagram to generate necessary phase

Must be a new, spin-orbit structure either in the fragmentation process or within the proton itself

At hard (enough) scales, SSA’s must arise from soft physics: T-odd distribution / fragmentation functions
E704 Possible Mechanism #1: The “Collins Effect”

Need an ordinary distribution function ... transversity

\[ q(x) \quad \Delta q(x) \quad h_1(x) \]

... with a new, T-odd “Collins” fragmentation function

\[ H_1^\perp(z, p_T) \]

spin-orbit in fragmentation!

E704 effect:

\[ h_1(x) \otimes H_1^\perp(z, p_T) \]
Transversity: The Third Structure Function

Proton Matrix Elements

- **Vector charge**
  \[ \langle PS | \bar{\psi} \gamma^\mu \psi | PS \rangle = \int_0^1 dx \, q(x) - \overline{q}(x) \rightarrow \# \text{ valence quarks} \]

- **Axial charge**
  \[ \langle PS | \bar{\psi} \gamma^\mu \gamma_5 \psi | PS \rangle = \int_0^1 dx \, \Delta q(x) + \Delta \overline{q}(x) \rightarrow \text{net quark spin} \]

- **Tensor charge**
  \[ \langle PS | \bar{\psi} \sigma^{\mu\nu} \gamma_5 \psi | PS \rangle = \int_0^1 dx \, \delta q(x) - \delta \overline{q}(x) \rightarrow ??? \]

Forward Helicity Amplitudes

- **$q(x)$**
  \[ q(x) \sim \]

- **$\Delta q(x)$**
  \[ \Delta q(x) \sim \]

- **$\delta q(x)$**
  \[ \delta q(x) \sim \]

... but in transverse basis ...

(optical theorem applied to DIS)

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Properties of Transversity

- In Non-Relativistic Case, boosts and rotations commute: $\delta q(x) = \Delta q(x)$ ... but bound quarks are highly relativistic in nature

- No Gluons
  - Angular momentum conservation: $\Lambda - \lambda = \Lambda' - \lambda'$
  - $\Rightarrow$ transversity has no gluon component
  - $\Rightarrow$ different $Q^2$ evolution than $\Delta q(x)$

- Chiral Odd
  - Helicity flip amplitudes occur only at $O(m_q/Q)$ in inclusive DIS ...
  - but they are observable in e.g. semi-inclusive reactions
Properties of Transversity

• In Non-Relativistic Case, boosts and rotations commute:
  ... but bound quarks are highly *relativistic* in nature

\[ \delta q(x) = \Delta q(x) \]

• No Gluons

Angular momentum conservation: \( \Lambda - \lambda = \Lambda' - \lambda' \)
  \[ \Rightarrow \text{transversity has } \text{no gluon} \text{ component} \]
  \[ \Rightarrow \text{different } Q^2 \text{ evolution} \text{ than } \Delta q(x) \]

• Chiral Odd

Helicity flip amplitudes occur only at \( \mathcal{O}(m_q/Q) \) in inclusive DIS ...

\[ m_q \]

\[ \text{tensor charge} = \text{"pure valence" object} \]

\[ \rightarrow \text{promising for LQCD comparison?} \]
E704 Possible Mechanism #2: The “Sivers Effect”

Need the ordinary fragmentation function $D_1(z)$

... with a new, $T$-odd “Sivers” distribution function $f_{1T}^T(x, k_T)$

Phenomenological model of Meng & Chou:

Forward $\pi^+$ produced from orbiting valence-$u$ quark by recombination at front surface of beam protons

E704 effect:

$\pi^+$

$D_1(z)$
Functions surviving on integration over Transverse Momentum

Distribution Functions

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

\[ f_{1T} = \quad g_{1T} = \quad h_{1T} = \]

\[ h_{1L} = \]

\[ f_1 = \quad \frac{\Delta q(x)}{q(x)} \quad \text{transversity } \delta q(x) \]

Sivers

Fragmentation Functions

\[ D_1 = \quad G_1 = \quad H_1 = \]

\[ D_{1T} = \quad G_{1T} = \quad H_{1T} = \]

\[ H_{1L} = \]

Polarizing FF

Collins

The others are sensitive to intrinsic \( k_T \) in the nucleon & in the fragmentation process.

Mulders & Tangerman, NPB 461 (1996) 197

Functions Odd under naive Time Reversal

One T-odd function required to produce single-spin asymmetries in SIDIS

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The Leading-Twist Sivers Function: Can it Exist in DIS?

A T-odd function like $f_{1T}^{\perp}$ must arise from interference ... but a distribution function is just a forward scattering amplitude, how can it contain an interference?

Brodsky, Hwang, & Schmidt 2002

\[ \text{can interfere with} \]

\[ \text{and produce a T-odd effect!} \]

\[ \text{(also need } L_z \neq 0) \]

It looks like higher-twist ... but no, these are soft gluons = “gauge links” required for color gauge invariance

Such soft-gluon reinteractions with the soft wavefunction are final (or initial) state interactions ... and may be process dependent! → new universality issues

e.g. Drell-Yan
Transversity $h_1(x)$

Collins Function $H_{1\perp}(z, p_T)$

T-Odd observables require interference between a spin-flip and a non-flip amplitude

Favored / Disfavored Frag Functions

$D_{\text{fav}} \equiv D^{u\rightarrow\pi^+} = D^{d\rightarrow\pi^-} = \ldots$

$D_{\text{dis}} \equiv D^{u\rightarrow\pi^-} = D^{d\rightarrow\pi^+} = \ldots$

Sivers Function $f_{1T}(x, k_T)$

Photo-Album of our New Friends!
In Search of T-Odd Functions:
HERMES Run 2
Switched from longitudinal to **transverse** target polarization in 2002 ... 
Measure dependence of pion production on **two azimuthal angles**

Electron beam defines scattering plane

Target spin transverse to beam

Azimuthal angles measured around $q$ vector ...

$\phi_S = \text{target spin orientation}$

$\phi_h = \text{pion ("hadron") direction}$
Separating the Collins & Sivers Mechanisms

Collins mechanism

\[ \delta q(x) \otimes H_1^\perp(z, k_T) \Rightarrow \sin(\phi_h + \phi_S) \]

Sivers mechanism

\[ f_{1T}(x, k_T) \otimes D_1(z) \Rightarrow \sin(\phi_h - \phi_S) \]

Measure azimuthal moments of SIDIS xsec to separate the mechanisms

Thanks to linear polarization of photon ...

Sivers: \( (\phi_h - \phi_S) \)

angle of pion relative to initial quark spin

Collins: \( (\phi_h + \phi_S) = \pi + (\phi_h - \phi_S) \)

angle of pion relative to final quark spin
SSA Results 1: Collins Effect
**Collins Moments for \( \pi^+ \pi^- \) from 2002–2004 \( H \uparrow \) Data**

- First evidence for non-zero Collins function ... and transversity!
  - Positive for \( \pi^+ \) ...
  - Negative and larger for \( \pi^- \) ...

- Systematic error bands include acceptance and smearing effects, and contributions from unpolarized \( \langle \cos(2\phi) \rangle \) and \( \langle \cos(\phi) \rangle \) moments

It exists!
The Collins function exists! ➞ **spin-orbit** correlations in $\pi$ formation

*Is the Artru mechanism responsible?*
Why are the Collins $\pi^-$ asymmetries so large?

**DIS on proton target always dominated by **$u$-quark scattering**

- $A_{\text{Col}}^{\pi^+} \sim \delta u \ H_{1,favored}^\perp$ ... expect: positive
- $A_{\text{Col}}^{\pi^-} \sim \delta u \ H_{1,disfavored}^\perp$ ... expect: $\sim$ zero

Data indicate **disfavored** CollinsFF is **large & negative**!

Map out solution space ... find $H_{\text{disfavored}} \approx -H_{\text{favored}}$
Interpretation of Collins Results

Lund model + $^3P_0$ hypothesis once more:

Subleading pion heads out of page

leading $\pi^+ = u\bar{d}$

Leading $\pi^+$ = favored transition, heads into page

Subleading particle (prob $\pi^-$) = disfavored transition, heads out of page

Perhaps $H_{\text{dis}} \approx -H_{\text{fav}}$ is not only reasonable, but likely?
Collins Global Fit: HERMES (H target) & COMPASS (D target)

Efremov, Goeke, Schweitzer, hep-ph/0603054

Take $h_1(x)$ from Chiral-Quark Soliton Model:

Fit $K_T$-integrated **favored** and **unfavored** Collins FF to HERMES data:

$H_{1}^{\text{fav}} = H_{1}^u/\pi^+ = H_{1}^d/\pi^- = ...$

$H_{1}^{\text{unf}} = H_{1}^u/\pi^- = H_{1}^d/\pi^+ = ...$

$B_{\text{Gauss}}(z) \equiv 1/\sqrt{1 + z^2\langle p_{h_1}^2\rangle/\langle K_{H_1}^2\rangle}$

Also find $H_{1}^{\text{fav}} \approx -H_{1}^{\text{unf}}$

Gives good fit to COMPASS!

(a) $2\langle B_{\text{Gauss}} H_{1}^{(1/2) \text{fav}} \rangle$

(b) $2\langle B_{\text{Gauss}} H_{1}^{(1/2) \text{unf}} \rangle$

HERMES preliminary

HERMES preliminary

COMPASS data

COMPASS data
Fit **BELLE** $z$-dependent results to

$$H_1^\perp(1/2)a(z) = C_a z D_1^a(z)$$

$C_{\text{fav}} = 0.15$, $C_{\text{unf}} = -0.45$

and so $H_1^{\text{fav}} \approx -H_1^{\text{unf}}$

Resulting Collins FF also fit **HERMES** data well
SSA Results 2:
Sivers Effect
Sivers Moments for $\pi^+\pi^-$ from 2002–2004 $H^\uparrow$ Data

**It exists too!**

- First evidence for non-zero Sivers function!
- $\Rightarrow$ presence of non-zero quark orbital angular momentum!
- Positive for $\pi^+$ ...
  Consistent with zero for $\pi^-$ ...
- Systematic error bands include acceptance and smearing effects, and contributions from unpolarized $<\cos(2}\phi)>$ and $<\cos(\phi)>$ moments.
For convenience: \( q_T(x) \equiv f_{1T}^{q}(x) \)

Fit HERMES \( A_{UT} \) to Sivers function of form:
\[
\frac{u_T^{(1/2)}(x)}{u(x)} = (S_u x(1-x)), \quad \frac{d_T^{(1/2)}(x)}{u(x)} = (S_d x(1-x))
\]

- assume no antiquark Sivers func: \( \bar{q}_T(x) = 0 \)
- unpolar PDFs = GRV-LO, unpolar FFs = Kretzer

\( S_u = -0.81 \pm 0.07, \quad S_d = 1.86 \pm 0.28 \)

Fits COMPASS deuterium data well!

**But a surprise!** \( S_d \gg S_u \! \)!

e.g., large-\( N_C \) expectation: \( u_T(x) \approx -d_T(x) \)

Hmm ... \( S_u \) actually reflects \( u_T \pm \bar{d}_T/4 \)

... \( S_d \) actually reflects \( d_T + 4u_T \)

**Could Sivers (and L) be large for antiquarks?**
**Sivers Moments for Kaons from 2002–2004 Data**

**HERMES PRELIMINARY 2002-2004**

- Effect about **equal** for $K^- = s\bar{u}$ and $\pi^- = d\bar{u}$ → note: same antiquark ...
- Effect **seems larger** for $K^+ = u\bar{s}$ than $\pi^+ = u\bar{d}$ at $x \approx 0.1$ ...

→ **significant antiquark** Sivers functions? and strongly flavor-dependent?

Large 2005 data set still to be added!
Quark and gluon polarization

- **Quark polarization** is positive, but much lower than CQM / bag model expectations.
- **Anti-quark** polarization consistent with zero within measured range, including improved verification of $\Delta s \approx 0$.
- Data coming in from COMPASS and RHIC-Spin on $\Delta G$ ... so far a modest, positive value favoured ...

Collins fragmentation function

- Opposite sign and similar magnitude to favored function.
- Sign of effect supports $^3P_0$ picture of color string breaking.
- Result now confirmed by new data from BELLE, + successful global analyses including COMPASS data.

Sivers effect is non-zero in DIS!

- Successful global analysis of HERMES (H) & COMPASS (D).
- ... and suggests large antiquark contributions to orbital $L$.
- Latest HERMES data on Kaon production seem to support this ...