Polarized Parton Distributions

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

- Some Phenomenological Models
- Quark and Gluon Polarization
- Studies with Polarized \( \Lambda \) Production
- New Structures: Transversity and Friends
Some Phenomenological Models

Non-relativistic Quark Model
Pure valence description of constituent quarks:
\[ \Delta u = +4/3, \quad \Delta d = -1/3 \quad \rightarrow \quad \Delta \Sigma = 1 \]

Relativistic Quark Model
Relativistic current quarks with light masses: orbital angular momentum is important, and accounts for the deficit of $\Delta \Sigma$.
\[ \Delta \Sigma \approx 0.60 - 0.75, \quad L_q = \frac{1}{2}(1 - \Delta \Sigma) \]

Meson Cloud Models
Quark sea generated by cloud of pseudoscalar mesons.
\[ \rightarrow \Delta q_{valence} > 0 \]
\[ \rightarrow \Delta q_{sea} < 0, \quad \text{but ...} \]
\[ \rightarrow \Delta \overline{q} = 0 \]

Large $N_c$ Limit and the Chiral-Quark Soliton Model
Nucleon = chiral soliton in pion field.
\[ \Delta \overline{u} - \Delta \overline{d} \sim N_c^2 \]
\[ \Delta \overline{u} + \Delta \overline{d} \sim N_c \]
\[ \Rightarrow \text{Light sea quarks have significant polarization, but with } \Delta \overline{u} \sim -\Delta \overline{d}. \]
Rho Meson Cloud

**Rho: lightest polarizable meson**

\[ \rho^\pm, n, \Delta^0, \Delta^{++} \]

Fries, Scäfer, PLB 443 (1998) 40

\[ x \left( \Delta \bar{d}(x) - \Delta \bar{u}(x) \right) \]

Miyama, DIS 2001

\[ x \left( \Delta \bar{u}(x) - \Delta \bar{d}(x) \right) \]

\[ \rightarrow \Delta \bar{u} - \Delta \bar{d} < 0 ! \]

**Interference Terms**

Apparent discrepancy with \( \chi \)QSM might be resolved by interference terms ...

\[ \chi \)QSM Prediction \]

Boreskov, Kaidalov EPJC 10 (1999) 143

Calculation in progress: R. Fries, Ch. Weiss

Large contributions indicated ...
In polarized DIS, using polarized lepton beams and polarized nuclear targets, one probes the polarization of the partons in the nucleon.

\[ F_1 = \frac{1}{2} \sum_i e_i^2 q_i \]
\[ g_1 = \frac{1}{2} \sum_i e_i^2 \Delta q_i \]
\[ \Delta q_i = q_i^+ - q_i^- \]

**QCD Fits to** $g_1(x, Q^2)$ **at NLO**

\[ g_1^{(p(n))} = \frac{1}{9} \left( C_{NS} \otimes \left[ \pm \frac{3}{4} \Delta q_3 + \frac{1}{4} \Delta q_8 \right] + C_S \otimes \Delta \Sigma + 2N_f C_g \otimes \Delta g \right) \]

Using $g_1$ measurements on both proton and neutron (deuterium) targets, one can *in principle* separate these polarized PDF's:

\[ \Delta q_3(x, Q^2) = \Delta u - \Delta d, \]
\[ \Delta q_8(x, Q^2) = \Delta u + \Delta d - 2\Delta s, \]
\[ \Delta \Sigma(x, Q^2) = \Delta u + \Delta d + \Delta s, \]
\[ \Delta g(x, Q^2) \]

by exploiting the different $Q^2$-dependent behaviour of each term.

However ...
World data on $F_1^p$

World data on $g_1^p$

December 1998

Preliminary

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$F_1^p$ and $g_1^p$ as a function of $Q^2$.
QCD Fits to $g_1(x, Q^2)$: Challenges

- Precision and range of present polarized data is insufficient to perform a complete separation. Present analyses also use information from hyperon $\beta$-decay to constrain non-singlet matrix elements:

  \[ a_3 = \Delta q_3 = F + D = 1.2601 \pm 0.0025 \text{ (Bj. sum rule)} \]
  \[ a_8 = \Delta q_8 = 3F - D = 0.579 \pm 0.032 \]

  However, expression for $a_8$ depends on assumption of SU(3)-symmetry among hyperons, which is known to be inexact ...

- **Momentum sum rule** not available. In unpolarized case:

  \[ \int dx \, x \left[ u(x) + d(x) + s(x) + g(x) \right] = 1 \]

  In polarized case, the unknown angular momentum appears:

  \[ \int dx \left[ \frac{1}{2} \Delta \Sigma(x) + \Delta g(x) \right] = \frac{1}{2} - L \]

- The net quark polarization $\Delta \Sigma(Q^2)$ is maximally scheme dependent ...

  Connection between measured $\Gamma_1^p = \int dx \, g_1$ and $\Delta \Sigma$ may involve the gluon polarization.

    \[ \Rightarrow \text{In the } MS \text{ scheme, } \Delta \Sigma \text{ is not conserved.} \]
    \[ \Rightarrow \text{In the AB or JET schemes, } \Delta \Sigma \text{ is conserved:} \]

    \[ \Delta \Sigma(Q^2)_{MS} = \Delta \Sigma_{AB(JET)} - \frac{3\alpha_s(Q^2)}{2\pi} \Delta g(Q^2)_{AB(JET)} \]
First moments at $Q_0^2 = 1 \text{ GeV}^2$:

SMC, PRD 58 (1998) 112002

$\Delta \Sigma_{(MS)} = 0.19 \pm 0.05 \pm 0.04$

$\Delta \Sigma_{(AB)} = 0.38 \pm 0.03 \pm 0.03$

$\Delta g_{(AB)} = 0.99 \pm 1.17 \pm 0.42 \pm 1.43$

Sensitivity to SU(3) symmetry breaking

Consider variation of $a_8$ matrix element from hyperon $\beta$-decay, around SU(3)-symmetric value of $3F - D = 0.58$. In JET scheme:

E.Leader, A.Sidorov, D.Stamenov, hep-ph/0004106

<table>
<thead>
<tr>
<th>$a_8$</th>
<th>$\chi^2$/DOF</th>
<th>$\Delta \Sigma$</th>
<th>$\Delta g$</th>
<th>$\Delta s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.40</td>
<td>0.82</td>
<td>0.34 (\pm) 0.05</td>
<td>0.13 (\pm) 0.14</td>
<td>-0.02 (\pm) 0.01</td>
</tr>
<tr>
<td>0.58</td>
<td>0.83</td>
<td>0.40 (\pm) 0.04</td>
<td>0.57 (\pm) 0.14</td>
<td>-0.06 (\pm) 0.01</td>
</tr>
<tr>
<td>0.86</td>
<td>0.82</td>
<td>0.40 (\pm) 0.06</td>
<td>0.84 (\pm) 0.30</td>
<td>-0.15 (\pm) 0.02</td>
</tr>
</tbody>
</table>

$\Rightarrow$ Gluon and strange quark polarizations are strongly dependent on the SU(3)-symmetry assumption.
In semi-inclusive DIS a hadron $h$ is detected in coincidence with the scattered lepton

$$\begin{align*}
(E, p) &\rightarrow (\nu, Q^2) \\
\gamma &\rightarrow h
\end{align*}$$

**Flavour Tagging**

The flavour content of the final state hadrons is related to the flavour of the struck quark through the agency of the **fragmentation functions** $D^h_q(z, Q^2)$. In LO QCD:

$$A^h_1(x, Q^2) = \frac{\int_{z_{\text{min}}}^{1} dz \sum_q e_q^2 \Delta q(x, Q^2) \cdot D^h_q(z, Q^2)}{\int_{z_{\text{min}}}^{1} dz \sum_q e_q^2 q(x, Q^2) \cdot D^h_q(z, Q^2)}$$

Can rewrite in terms of a **purity matrix** :

$$A^h_1(x, z) = \sum_q P^h_q(x, z) \frac{\Delta q(x)}{q(x)}$$

Purities are *spin-independent*, and may be computed via Monte Carlo.
Quark Polarizations at LO

Not yet included ...

- large 2000 data set on Deuterium
- Kaon asymmetries from RICH detector → access to $\Delta s$

Hermes Running 1996-2000

- So far: agreement with Gehrmann, Stirling fit to inclusive data (Gluon A, LO)
- Result insensitive to choice of SU(3)-symmetric sea assumption:

\[
\frac{\Delta q_s}{q_s} \equiv \frac{\Delta u_s}{u_s} = \frac{\Delta d_s}{d_s} = \frac{\Delta s}{s} = \frac{\Delta \bar{u}}{\bar{u}} = \frac{\Delta \bar{d}}{\bar{d}} = \frac{\Delta \bar{s}}{\bar{s}}
\]

\[
\Delta q_s \equiv \Delta u_s = \Delta d_s = \Delta s = \Delta \bar{u} = \Delta \bar{d} = \Delta \bar{s}
\]

There are other possibilities ... 2000 data will permit 4- and 5-parameter fits

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Global Fit with Semi-Inclusive Data

**deFlorian & Sassot 2000**

- Assume isospin / charge conjugation symmetry between fragmentation functions:

  \[
  \begin{align*}
  &\text{FAVOURED} \quad D_1^\pi \equiv D_u^{\pi+} = D_u^{\pi-} = D_d^{\pi-} = D_d^{\pi+} \\
  &\text{DISFAVOURED} \quad D_2^\pi \equiv D_u^{\pi-} = D_u^{\pi+} = D_d^{\pi+} = D_d^{\pi-} \\
  &\text{STRANGE} \quad D_s^\pi \equiv D_s^{\pi+} = D_s^{\pi+} = D_s^{\pi-} = D_s^{\pi-}
  \end{align*}
  \]

- Relax \( F, D \) constraints:

  \[
  \Delta q_3 = (F + D)(1 + \epsilon_{\text{Bj}}) \quad \Delta q_8 = (3F - D)(1 + \epsilon_{\text{SU}(3)})
  \]

- Try 3 choices for \( \int \Delta g @ \mu_0 \):

  1. \( \Delta G|_{\mu_0} < 0.4 \)
  2. \( 0.4 < \Delta G|_{\mu_0} < 0.7 \)
  3. \( \Delta G|_{\mu_0} > 0.7 \) \( \chi^2 \) same for all 3

- 2 scenarios for light quark sea:

  - "+" scenario: \( \delta u = \delta \bar{d} \) at \( \mu_0 \)
  - "-" scenario: \( \delta u = -\delta \bar{d} \)

<table>
<thead>
<tr>
<th>MOMENTS:</th>
<th>( \Delta \Sigma )</th>
<th>( \Delta G )</th>
<th>( \Delta q_{\text{sea}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>@ ( Q^2 = 10 )</td>
<td>0.15 – 0.19</td>
<td>0.8 – 1.8</td>
<td>( \Delta s = -0.06 - -0.07 )</td>
</tr>
</tbody>
</table>

Conclusions:

- SIDIS data \( \Rightarrow \delta u > 0 \) but \( \delta \bar{d} \) unconstrained
  
  \( \Rightarrow \) no \( \chi^2 \) change between + and – scenarios

- \( \Delta s < 0 \) indicated, with \( \epsilon_{\text{Bj}} \approx -2\% \) and \( \epsilon_{\text{SU}(3)} \approx -6\% - 7\% \)
Global Fit with Semi-Inclusive Data

Using inclusive data only ...

dean, Sassot, PRD 62 (2000) 094025

Adding semi-inclusive data ...
Quark Polarization: Future

**HERMES**: data up to 2000

- Pion & Kaon asymmetries
  → $\Delta s$, $\Delta \bar{s}$ sensitivity

**RHIC-spin**: 2002 - ...

- Polarized $W$ production
  → $\Delta \bar{u}$ vs $\Delta \bar{d}$ sensitivity

And further DIS data expected from COMPASS and HERMES Run II

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Longitudinal $\Lambda$ Polarization

$\Lambda$ polarization accessible via angular distribution of decay $p, \pi$

Using polarized beam and unpolarized target, measure longitudinal spin transfer in fragment $\Lambda$ (from struck $q$ to $\Lambda$)

$$ P_\Lambda = P_{\text{beam}} \cdot D(y) \cdot D_{LL'} $$

- Final state $\Lambda$ polarization
- Struck quark polarization
- Spin transfer

$$ D_{LL'} = \frac{\sum e_q^2 q(x) \Delta D_q^\Lambda(z)}{\sum e_q^2 q(x) D_q^\Lambda(z)} = \sum \frac{\Delta D_q^\Lambda(z)}{D_q^\Lambda(z)} \cdot \omega_q^\Lambda(x) \quad \text{"purity"} $$

Note: In Mulders notation, $\Delta D(z) = G_1(z)$

$\rightarrow$ fragmentation analogue of $g_1(x)$
**SPIN TRANSFER** \( \vec{q} \to \vec{\Lambda} \)

\[
D_{LL'} = \sum \omega_q(x) \frac{G_{1,q}^\Lambda(z)}{D_{1,q}^\Lambda(z)}
\]

... **IF** \( q \) helicity conserved in fragmentation ...

\[
\Rightarrow \frac{G_{1,q}^\Lambda}{D_{1,q}^\Lambda} \sim \frac{\Delta q^\Lambda}{q^\Lambda}
\]

* i.e. directly related to quark polarization in \( \Lambda \)

---

**SCENARIO 1** **NRQM** : \( \Delta u^\Lambda = \Delta d^\Lambda = 0, \quad \Delta s^\Lambda = 1 \)

**SCENARIO 2** **Burkardt & Jaffe** : \( \Delta u^\Lambda = \Delta d^\Lambda \approx -0.2 \)

**SCENARIO 3** **"extreme"** : equal polariz\( n \) of flavours \( \Delta u^\Lambda \approx \Delta d^\Lambda \approx \Delta s^\Lambda \)

(e.g. if \( \exists \) sizable contrib\( s \) from decays of heavier hyperons)

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*deFlorian, Stratmann, Vogelsang, PRD 57 (1988) 5811*

N.C.R. Makins, Santorini 2001
Influence of Heavy Hyperon Decays

Heavier Hyperons at E665

Ashery, Lipkin, PLB 469 (1999) 263

LEP Analyses


OPAL and ALEPH data on $P_\Lambda$ confronted with Monte Carlo models:

- simple SU(3)-symmetric hyperon spin structure
- hyperons not containing primary $q$ unpolarized
- perfect helicity conservation of primary $q$

\[ \begin{array}{c}
\text{OPAL} \\
\hline
-0.1 & 0 & 0.1 & 0.2 & 0.3 & 0.4 & 0.5 & 0.6 & 0.7 & 0.8 & 0.9 & 1 \\
0 & 0.1 & 0.2 & 0.3 & 0.4 & 0.5 & 0.6 & 0.7 & 0.8 & 0.9 & 1 & \end{array} \]

\[ \begin{array}{c}
\text{ALEPH data} \\
\hline
\text{Jetset (corrected)} \\
\text{Jetset range} \\
\text{Herwig (corrected)} \\
\end{array} \]
**Spin Structure as \( x \to 1 \)**

- **Gribov-Lipatov relation**

\[ q_h(x) \propto D_{q}^{h}(z) \]

endpoint easy to see:

\[ z_{A} \to 1 \]

\( A \) carries all energy of struck quark

\[ x_{A} \to 1 \]

struck quark carries all energy of \( A \)

1. **Quark-Diquark Model**

\[ \psi_{D}(x, k_{\perp}) \sim \exp \left[ \frac{1}{8\beta_{D}^{2}} \left( \frac{m_{q}^{2} + k_{\perp}^{2}}{x} + \frac{m_{D}^{2} + k_{\perp}^{2}}{1 - x} \right) \right] \]

... as \( x \to 1 \), VECTOR diq config \( \psi_{D} \) suppressed

\[ \frac{d}{u} \to 0 \quad \frac{F_{2}^{n}}{F_{2}^{p}} \to \frac{1}{4} \]

\[ \frac{\Delta u}{u} \to 1 \quad \frac{\Delta d}{d} \to -\frac{1}{3} \]

2. **pQCD Model**

\( x \to 1 \) wavefn obtained from "normal" wavefn by exchange of large invariant mass gluons from spectator \( q \)'s ... propagators \( \sim \frac{1}{p^{2}} \) small

\( \to \) small couplings, perturbative methods possible

\[ \frac{d}{u} \to \frac{1}{5} \quad \text{thus} \quad \frac{F_{2}^{n}}{F_{2}^{p}} \to \frac{3}{7}, \quad \frac{\Delta q}{q} \to 1 \text{ for } u \text{ and } d \]

**For \( A \): Both models predict** \( \frac{\Delta q_{A}^{\Lambda}}{q_{A}^{\Lambda}} \to 1 \text{ for all flavours!} \)

N.C.R. Makins, Santorini 2001
Spin Structure as $x \rightarrow 1$

HERMES 1996-2000 PRELIMINARY

- pQCD (Ma)
- Diquark (Ma)
- Diquark, u+d (Boros)
- naive CQM
- u+d+s
- SU(3)$_f$(BJ)

Longitudinal spin transfer $D^\Lambda$

Hermes

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A complete description of the momentum and spin structure of the nucleon at leading twist requires the third parton distribution \( \delta q(x) \).

### Transversity

\[
f_1 = \begin{array}{c}
\text{\hspace{1cm}}
\end{array}
\quad g_{1L} = \begin{array}{c}
\text{\hspace{1cm}}
\end{array}
\quad h_1 = \begin{array}{c}
\text{\hspace{1cm}}
\end{array}
\]

**transversity:**

\[
h_1(x) \sim \delta q(x)
\]

### Helicity Flip Amplitudes

\[
\left\| q \right\| - \left\| 2 \right\| \sim \text{Im}\left\{ \begin{array}{c}
\text{\hspace{1cm}}
\end{array}\right\}
\]

\[
f_1 \sim \begin{array}{c}
\text{\hspace{1cm}}
\end{array}
\quad g_1 \sim \begin{array}{c}
\text{\hspace{1cm}}
\end{array}
\quad h_1 \sim \begin{array}{c}
\text{\hspace{1cm}}
\end{array}
\]

Target not in helicity eigenstate

⇒ **transversity basis**
In Non-Relativistic Case...

In the absence of relativistic effects, boosts and rotations commute:

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

Tensor Charge of the Nucleon

Fundamental matrix elements:

- Axial charge
  \[ \Delta q(\mu) = \langle PS | \bar{\psi} \gamma^\mu \gamma_5 \psi | PS \rangle = \int_0^1 dx \, g_1(x) + \bar{g}_1(x) \]

- Tensor charge
  \[ \delta q(\mu) = \langle PS | \bar{\psi} \sigma^{\mu\nu} \psi | PS \rangle = \int_0^1 dx \, h_1(x) - \bar{h}_1(x) \]

\[ \Rightarrow \] tensor charge is pure valence object ... promising for comparison with lattice QCD

No Gluons

Angular momentum conservation

\[ \Rightarrow \Lambda - \lambda = \Lambda' - \lambda' \]

Different \( Q^2 \) evolution than \( g_1 \).

Chiral Odd

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

but they are observable in e.g. semi-inclusive reactions
From perturbative QCD considerations, it was expected that transverse spin effects would be \textbf{small}: $\sim \frac{m_q}{\sqrt{s}}$ ...

$$A_N(p^\uparrow p \rightarrow \pi X) \sim \int h_1(x_a)f_1(x_b)D_1^\pi(x_c) \hat{a}_{ab} \frac{d\sigma}{dt}(a^\uparrow b \rightarrow cd)$$

with helicity flip in subprocess asymmetry:

$$\hat{a}_{ab} = \frac{d\sigma(a^\uparrow b \rightarrow cd) - d\sigma(a^\downarrow b \rightarrow cd)}{d\sigma(a^\uparrow b \rightarrow cd) + d\sigma(a^\downarrow b \rightarrow cd)}$$

\textbf{No large effects possible:}

- $q$ helicity flip vanishes in the limit $m_q = 0$
- $\hat{a}_{ab}$ arises from \textbf{interference} between a non-flip and a single-flip helicity amplitude ... and no imaginary phases possible at Born level.
Sivers Effect

Chou-Yang Model

Valence quarks = relativistic Dirac particles in central potential

- relativistic quarks in eigenstates of $J$, which is shared between $L$ and $S$
- symmetrized wavefunction
  \[ \Delta u = +4/3, \Delta d = -1/3 \]
- forward $\pi^+$ produced directly from orbiting $u_v$ quark at front surface of beam proton

Sivers Idea

Consider dependence of parton densities on intrinsic $k_T$:

\[
A_N \sim \int f_{1T}^\perp(x_a, k_{Ta}) f_1(x_b, k_{Tb}) D_{1}^\pi(x_c, k_{Tc}) \frac{d\sigma}{dt}(ab \to cd)
\]

- Unknown soft dynamics absorbed into $f_{1T}^\perp$ ... hard subprocess merely transmits the asymmetry to large transverse momentum by kinematics.
- Intrinsic $k_T$ introduces hadronic scale $M$ into the problem: transverse effects of order $p_T/M$ (not just $p_T/s$)

New structure function: $f_{1T}^\perp(x, k_T)$

- disappears on integration over $k_T$
- odd under time reversal ... requires initial state interactions between colliding hadrons
Collins Effect and Transversity

There is another possible explanation ... the E704 single-spin asymmetry could be due to:

- **Sivers Effect:**
  - T-odd distribution function $f_{1T}^{n}$

- **Collins Effect:**
  - T-odd fragmentation function $H_{1}^{1}$

Collins Effect

In this case, $A_{N} \sim h_{1}(x) H_{1}^{1}(z)$

⇒ access to transversity!

How to separate?

**Single Spin Asymmetries in DIS**
The Collins Effect in the String Fragmentation Model

- **chiral-odd** like $h_1(x)$ ... chiral-odd distribution and fragmentation functions appear in pairs in DIS cross-section
- **T-odd** ... one T-odd function required to produce single-spin asymmetry in semi-inclusive DIS

The Collins function is indicative of phase coherence in fragmentation
⇒ generate interference between non-flip and single-flip amplitudes
T-Odd Functions

Spin Spin Azimuthal Asymmetry: \( \sigma \sim \vec{S}_1 \cdot (\vec{p}_1 \times \vec{p}_2) \sim \sin \phi \)

\[ \negrightarrow \text{ODD under time reversal} \]

\[ \phi = -\pi/2 \quad \text{DOWN} \]
\[ \phi = +\pi/2 \quad \text{UP} \]

\[ \hat{T} \text{ transforms } \phi \text{ to } -\phi \]

But elementary QCD processes are \( \hat{T} \)-invariant ...

can build \( \hat{T} \)-odd term in xsec \( \sim \sin \phi \) from **interference**

**TOY EXAMPLE**

Any amplitude \( A = \langle f | \hat{H} | i \rangle \) for \( \hat{T} \)-invariant \( \hat{H} \) satisfies
\[ A^*(-\phi) = A(\phi) \]

① No spin flip \[ A_1 = \langle S_1 = \uparrow | \hat{H} | \phi, S_2 = \uparrow \rangle \sim e^{i\phi} \]

② Spin flip \[ A_2 = \langle S_1 = \uparrow | \hat{H} | \phi, S_2 = \downarrow \rangle \sim 1 \]

... suppose \( \exists \text{PHASE SHIFT} e^{i\delta} \text{ between amplitudes} ... \)

\[ \sigma \sim |A_1 + e^{i\delta} A_2|^2 = 2 + 2\text{Re}(e^{i\delta} A_1^* A_2) = 2 + \cos \delta \cos \phi - \sin \delta \sin \phi \]

- \( e^{i\delta} \Rightarrow \text{scattering phase shift, from final / initial state interactions} \)
- ... but in high energy \( \pi \) production, surely **many** amplitudes contribute

significant \( \hat{T} \)-odd frag\( ^n \) function \[ \text{phase coherence in fragmentation!} \]

N.C.R. Makins, Santorini 2001
SMC: Azimuthal Asymmetry

\[ A_N = \frac{1}{P_T f D_{NN}} \frac{1}{\langle \sin \phi_c \rangle} \frac{N(\phi_c) - N(\phi_c + \pi)}{N(\phi_c) + N(\phi_c + \pi)} \]

\[ d\sigma \sim (1 + A_N \sin \phi_c) d\phi_c \]

Using transversely polarized target
Spin-Azimuthal Asymmetry

Longitudinal target spin asymmetry:

\[ A(\phi) = \frac{1}{P} \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)} \]

Effect observable even with longitudinally polarized target
⇒ good promise for future transverse target program
at HERMES

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\[ A_{UL}^{\sin \phi} \] Behaviour

\[ A_{UL}^{\sin \phi} = \langle \sin \phi \rangle \] moment of longitudinal target asymmetry
→ related to product of \( h_1(x) \) and \( H_1^+(z) \)

Red squares (blue circles) = \( \pi^+ (\pi^-) \).

Original Predictions of Collins

- Effect should peak at \( x \approx 0.3 \) (valence region)
- Effect should be stronger for \( \pi^+ \) than \( \pi^- \) (\( u \)-quark dominance)
- Effect should grow with \( p_T \) and peak at \( p_T \approx 1 \text{ GeV/c} \)

Future Measurements of Transversity

This effect is essentially a transverse one ... the fact that it is already visible using a longitudinally polarized target ⇒ good promise for future transverse target programs, e.g. at HERMES and COMPASS.
Azimuthal Asymmetry in the Chiral Quark Soliton Model

Charged Pion Asymmetry $A_{UL}$

New: Neutral Pion Asymmetry

Calculation:

- only favoured fragmentation functions $D_{1/a}/\pi$ and $H_{1/La}/\pi$
- $\langle H_{1/L}^z(z)/z \rangle \approx \langle H_{1/L}^z(z) \rangle/\langle z \rangle$ with $\langle z \rangle = 0.41$
- $\langle P_{h\perp} \rangle \approx \langle p_T \rangle \approx 0.4$ GeV
- GRV parametrization for $f_1^a(x)$
- $h_1$ calculated in chiral soliton model

N.C.R. Makins, Santorini 2001
Size of Collins Function

- **DELPHI**
  
  \[
  \pi \xrightarrow{Z^0} \pi
  \]
  
  Transverse \(q, \bar{q}\) polarization small but ANTI-CORRELATED (@ \(\sim\) 50 % level)
  
  \[
  \left| \frac{H_1^\perp}{D_1} \right| = 6.3 \pm 1.7 \%
  \]

- **HERMES / SMC**
  
  Efremov et al., hep-ph/0108213
  
  Fit experimental data for \(H_1^\perp\), taking \(h_1(x)\) from Chiral Quark Soliton Model (\(\chi\)QSM)
  
  \[
  \left| \frac{H_1^\perp}{D_1} \right| = \begin{cases} 
  6.1 \pm 0.9 \pm 0.8 \% & \text{(HERMES)} \\
  10 \pm 5 \% & \text{(SMC)}
  \end{cases}
  \]

- **E704**
  
  Boglione & Mulders, PRD 60 (1999) 054007
  
  Fit experimental data, assuming ONLY Collins effect contributes
  
  \[
  \left| \frac{H_1^\perp}{D_1} \right| = 7.6 \%
  \]

There seems to be general agreement
(although results depend on \(z\)-range over which averaging performed)

What about the Sivers Function?

- Note: fit to E704 assuming ONLY Sivers effect contributes:
  
  \[
  \left| \frac{f_{1T}^\perp}{f_1} \right| = 8.3 \% \quad \text{("max" size)}
  \]

- **MORE DATA NEEDED** ... e.g. DIS w transverse target
  
  \[A_{UT} \text{ has term } \sim f_{1T}^\perp D_1 \sin(\phi_h^l + \phi_s^l)\]

N.C.R. Makins, Santorini 2001
Summary

Quark & Gluon Polarization

- **Semi-inclusive** data critical to constraining $\Delta \bar{u}$, $\Delta \bar{d}$
  - $\rightarrow$ some indication already that $\Delta \bar{u} > 0$
  - $\rightarrow$ wait: HERMES analysis of 2000 data ... new data
    upcoming from RHICspin, COMPASS, HERMES Run II

- **Gluon polarization** not constrained by $g_1$ data
  - $\rightarrow$ need direct meas. of photon-gluon-fusion process
    wait: RHICspin, COMPASS, SLAC, HERMES Run II

- Longitudinal spin transfer in $\Lambda$ production high $z$ may provide
  information on $\Delta q^\Lambda / q^\Lambda$ as $x \rightarrow 1$

New Structures

- **Transversity**: first data on $h_1$ in rather good agreement with models

- First clear evidence of T-odd **Collins Fragmentation Func**t
  $\rightarrow$ strong phase coherence in fragmentation?

- More data required to constrain **Sivers Function** $f_{1T}^{\perp}$
  $\rightarrow$ sensitive to orbital angular momentum?