Gluon polarisation and other polarised lepton scattering physics

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The spin of the nucleon

Naive parton model:
\[ \Delta \Sigma = \Delta u_v + \Delta d_v = 1 \]

EMC (1988)
\[ \Delta \Sigma = 0.12 \pm 0.09 \pm 0.14 \]

Gluons important in unpolarized case

Complete description: orbital angular momenta

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

- Introduction
- Polarised deep inelastic scattering
- Longitudinal spin structure functions
- Gluon polarisation
  - Open Charm production
  - High $p_T$ hadron pairs
  - $\pi^0$ asymmetries in pp collisions
- Transversity
- Outlook
Deep inelastic scattering

\[ Q^2 = -q^2 \quad x = Q^2 / 2M \nu \]
\[ \nu = E - E' \quad y = \nu / E \]
\[ z = E_h / \nu \]
\[ p_T : \text{hadron transverse momentum} \]
\[ D_q^h(x) : \text{fragmentation function} \]
\[ (\text{from quark } q \text{ into hadron } h) \]

- **Inclusive cross section**

\[
\frac{d^2\sigma}{d\Omega dE'} \sim c_1 F_1(x, Q^2) + c_2 F_2(x, Q^2) + c_3 g_1(x, Q^2) + c_4 g_2(x, Q^2)
\]

- **Spin independent**
- **Spin dependent**

\[ F_1, F_2, g_1, g_2 \] structure functions
Leading order quark distributions

<table>
<thead>
<tr>
<th>Spin averaged distributions</th>
<th>Helicity distributions</th>
<th>Transverse distributions</th>
</tr>
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<tbody>
<tr>
<td>$q(x) = \begin{array}{c} \text{unpolarised} \ \text{quark and nucleon} \ \text{vector–charge:} \end{array}$</td>
<td>$\Delta q(x) = \begin{array}{c} \text{longitudinally polarised} \ \text{quark and nucleon} \ \text{axial–charge:} \end{array}$</td>
<td>$\Delta_T q(x) = \begin{array}{c} \text{transversely polarised} \ \text{quark and nucleon} \ \text{tensor–charge:} \end{array}$</td>
</tr>
</tbody>
</table>

$$
\langle PS | \bar{\psi} \gamma^{\mu} \psi | PS' \rangle = \int_0^1 q(x) - \bar{q}(x) \, dx \\
\langle PS | \bar{\psi} \gamma^{\mu} \gamma_5 \psi | PS' \rangle = \int_0^1 \Delta q(x) + \Delta \bar{q}(x) \, dx \\
\langle PS | \bar{\psi} \sigma^{\mu\nu} \gamma_5 \psi | PS \rangle = \int_0^1 \Delta_T q(x) - \Delta_T \bar{q}(x) \, dx
$$

all three PDFs equally important to describe the nucleon
Spin averaged distributions

- **structure function** $F_2$
  \[ F_2(x) = x \sum_q e_q^2 q(x) \]

- **analysis of $Q^2$ dependence**
  \[
  \begin{align*}
    \frac{dq(x, Q^2)}{d \ln Q^2} &= \frac{\alpha_s(Q^2)}{2\pi} (P_{qq} \otimes q + P_{qg} \otimes G) \\
    \frac{dG(x, Q^2)}{d \ln Q^2} &= \frac{\alpha_s(Q^2)}{2\pi} (P_{gq} \otimes q + P_{gg} \otimes G)
  \end{align*}
  \]
  (DGLAP evolution equations)

- **extraction of $q(x)$ and $g(x)$**
  $q(x)$ and $G(x)$ well known

\[ x = 0.000050, i = 21 \]
\[ x = 0.000080, i = 20 \]
\[ x = 0.000130, i = 19 \]
\[ x = 0.000200, i = 18 \]
\[ x = 0.00032, i = 17 \]
\[ x = 0.000500, i = 16 \]
\[ x = 0.000800, i = 15 \]
\[ x = 0.0013, i = 14 \]
\[ x = 0.0020, i = 13 \]
\[ x = 0.0032, i = 12 \]
\[ x = 0.0050, i = 11 \]
\[ x = 0.013, i = 10 \]
\[ x = 0.020, i = 9 \]
\[ x = 0.032, i = 8 \]
\[ x = 0.050, i = 7 \]
\[ x = 0.080, i = 6 \]
\[ x = 0.13, i = 6 \]
\[ x = 0.18, i = 5 \]
\[ x = 0.25, i = 4 \]
\[ x = 0.40, i = 1 \]
\[ x = 0.65, i = 0 \]
Polarised deep inelastic scattering
Polarised deep inelastic scattering

- absorption of polarised photons (QPM)

\[ q(x) = q(x)^+ + q(x)^- \]
\[ \Delta q(x) = q(x)^+ - q(x)^- \]

+ quark ↑↑ nucleon

- quark ↓↑ nucleon

- photon nucleon asymmetry

\[ A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \approx \frac{\sum_q e_q^2 (q(x)^+ - q(x)^-)}{\sum_q e_q^2 (q(x)^+ + q(x)^-)} = \frac{g_1(x)}{F_1(x)} \]

- experimental asymmetry

\[ A_{\text{exp}} = \frac{N^\uparrow \downarrow - N^\uparrow \uparrow}{N^\uparrow \downarrow + N^\uparrow \uparrow} = p_B \ p_T \ f \ A_1 \]
Polarised distributions

- **longitudinal spin structure**

\[
g_1(x) = \frac{1}{2} \sum_{q}^{2N_f} e_q^2 \Delta q(x)
\]

- **moments**

\[
a_q = \int_0^1 \Delta q(x) \, dx \quad \text{contribution of quarks } q
\]

\[
a_0 = a_u + a_d + a_s \quad \text{contribution all quarks}
\]

- **E155 QCD analysis**

**axial charge** \( a_0 (= \Delta \Sigma) \)

\[
a_0 = 0.23 \pm 0.07 \, \text{(sta)} \pm 0.19 \, \text{(sys&th)}
\]

**first moment of \( \Delta G(x) \)**

\[
a_g = 0.99 \pm 1.17 \, \text{(sta)} +0.42 \, \text{(sys)} +1.43 \, \text{(th)}
\]
Experiments
COMPASS at CERN

Muon beam

160 GeV/c
2 \cdot 10^8 \mu/16.8 \ s
78\% \ Polarisation

Spectrometer

- Two stages:
  SM1 1Tm, SM2 4.5Tm
- Tracking:
  SciFi, Silicon, MicroMega, GEM, MWPC, Drift, Straws, Driftubes
- PID: RICH, ECAL, HCAL, muon filter
The polarised target

- Reconstructed interaction vertices

- target material: $^6\text{LiD}$
- polarisation: $> 50\%$
- dilution factor: $\sim 0.4$
- **Dynamic Nuclear Polarization**
- solenoid field: 2.5 T
- $^3\text{He}/^4\text{He}$: $T_{\text{min}} \approx 50 \text{ mK}$
- two 60 cm long target cells with **opposite polarisation**
- 2006 new solenoid with 180 mrad acceptance
HERMES at DESY

- atomic beam source: frequent spin flips

- positron identification: TRD, preshower + calorimeter

- PID: dual radiator RICH for $2 < p < 20$ GeV

- acceptance: $40 < \theta < 220$ mrad
Experiments at JLAB

E99-117

CLAS

- **measurement** of $A^p_1$ and $A^d_1$ for $0.2 < x < 0.6$
- **kinematic range:**
  $1.4 \text{ GeV}^2 < Q^2 < 4.5 \text{ GeV}^2$, $W > 2 \text{ GeV}$

**electron beam:**
5.7 GeV, 80% polarisation

**$^3\text{He}$ target:** 40% polarisation

**kinematic range:**
$2.7 \text{ GeV}^2 < Q^2 < 4.8 \text{ GeV}^2$, $W > 2 \text{ GeV}$
$g_1$ at low $x$ (COMPASS)

- high statistics $A_1^d$ at low $x$ for $Q^2 > 1$ GeV$^2$
- COMPASS systematically above SMC at low $x$
- $xg_1$ points at measured $Q^2$
- QCD fit to world data: $\Delta \Sigma = 0.202^{+0.042}_{-0.077} \rightarrow 0.237^{+0.024}_{-0.029}$
Final $g_1$ data (HERMES)

- High statistics measurement of $A_{1p}^p$ and $A_{1d}^d$
- New method for smearing corrections (rad. corr. and resolution)
- Statistical correlations between $x$ bins
- Improvement of integrals in the measured range
$g_1$ at high $x$ (JLAB)

- E99-117 result for $A_1^n$

- $A_1^n > 0$ at $x > 0.5$

- combining with $A_1^p$ results: $\Delta u/u > 0$, but $\Delta d/d < 0$

- pQCD expectation: $\Delta u/u = \Delta d/d = 1$ at high $x$

- hint for quark orbital angular momentum
Recent AAC03 analysis using all published data except final HERMES
Valence quark distributions well determined, antiquark distribution larger errors
Polarised gluon distribution not determined
Gluon polarisation
**ΔG/G measurement in DIS**

- **Photon gluon fusion**

  \[ A_{\gamma N}^{PGF} = \frac{\int d\hat{s} \Delta \sigma_{PGF} \Delta G(x_g, \hat{s})}{\int d\hat{s} \sigma_{PGF} G(x_g, \hat{s})} \approx \langle a_{LL}^{PGF} \rangle \frac{\Delta G}{G} \]

  (\text{analyzing power})

- **Methods**

  - **Open charm production**
    \[ \gamma g \rightarrow c\bar{c} \rightarrow D^0 \rightarrow \pi K \quad \text{BR: 4%} \]
    scale: \( m_c^2 \)
    clean channel, limited statistics

  - **High \( p_T \) hadron pairs**
    \[ \gamma g \rightarrow q\bar{q} \rightarrow 2 \text{ jets or } H^+H^- \]
    scale: \( Q^2 \) or \( \Sigma p_T^2 \)
    oppositely charged hadrons pairs with large \( p_T \) and \( \Delta \Phi \approx \pi \)
$\Delta G$ from open charm

$D^*$ tagging: $D^* \rightarrow D^0 \pi_{\text{slow}} \rightarrow (K\pi)\pi_{\text{slow}}$

- No decay vertex reconstruction
- Kaon identification by RICH essential
- Cut on mass difference $M_{K\pi\pi} - M_{K\pi} - M_\pi$
Mass spectra

**D* candidates 2003**

- Effective signal
  \[ S_{\text{eff}} = \frac{S}{1 + S/B} \]

**D^0 candidates 2003**

- Experimental asymmetry
  \[ A_{\text{exp}} = p_\mu p_T f a_{LL} \frac{S}{S + B} \frac{\Delta G}{G} \]

- No physics background

- 1500 D^0 from D*

COMPASS preliminary
Extraction of $\Delta G/G$

- needs $\langle \alpha_{LL}^{\text{PGF}} \rangle$
calculated from MC

- AROMA generator

- good description of
data distributions by MC

- preliminary result
at $\langle x_g \rangle = 0.15$ (RMS 0.08)
from 2002+2003

$$\Delta G/G = -1.08 \pm 0.73 \text{ (stat)}$$

- improvements with 2004 data
and additional channels
High $p_T$ hadron pairs ($Q^2 > 1$ GeV$^2$)

- contributions to experimental asymmetry

\[
\frac{A_{\parallel}}{D} = R_{\text{PGF}} \langle \frac{A_{\text{PGF}}^{\parallel}}{D} \rangle \frac{\Delta G}{G} + \left( R_{\text{QCDC}} \langle A_{\text{QCDC}}^{\parallel} \rangle + R_{\text{LO}} \langle A_{\text{LO}}^{\parallel} \rangle \right) A_1^d
\]

- Monte Carlo for $R$, $\langle A_{\text{LL}} \rangle$
- data selection

Current fragmentation: $x_F > 0.1$ and $z > 0.1$
Radiative corrections/ photon polarisation: $0.1 < y < 0.9$
High $p_T$: $p_{T,1}, p_{T,2} > 0.7$ GeV and $p_{T,1}^2 + p_{T,2}^2 > 2.5$ GeV$^2$
\[ \Delta G/G \text{ for } Q^2 > 1 \text{ GeV}^2 \]

- 2002/03 data

\[ A_{||}/D = -0.015 \pm 0.080(\text{stat.}) \pm 0.013(\text{syst.}) \]

- Monte Carlo sample generated with LEPTO reasonable agreement with data

- additional \( x \) cut \( \Rightarrow A_1^d \) small, LO and QCDC neglected

\[ \langle A_{LL}^{PGF} \rangle = -0.75 \pm 0.05 \quad R_{PGF} = 0.33 \pm 0.07, \langle x_g \rangle = 0.13 \text{ (RMS 0.08)} \]

\[ \Delta G/G = 0.06 \pm 0.31(\text{stat.}) \pm 0.06(\text{syst.}) \]

- only 10\% of statistics at \( Q^2 > 1 \text{ GeV}^2 \)

- single hadron analysis started

- expectation for 2002-2004: \( \delta(\Delta G/G) = 0.22 \)
\( \Delta G/G \) for \( Q^2 < 1 \text{ GeV}^2 \)

- Much more statistics but additional background from resolved photon processes

- Data selection same as for large \( Q^2 \)

\[
A_{\parallel}/D = 0.002 \pm 0.019(\text{stat.}) \pm 0.003(\text{syst.})
\]

- MC simulation with PYTHIA compared to data (blue points)
Contributions to asymmetry

- Resolved photons: polarised PDFs in deuteron and photon needed
- Photon non-perturbative part unknown: estimate using unpolarised contribution

$$\Delta G/G(x_g = 0.095^{+0.08}_{-0.04}, \mu^2 = 3 \text{ GeV}^2) = 0.024 \pm 0.089(\text{stat.}) \pm 0.057(\text{syst.})$$

- systematic error includes exp. syst., MC syst. and estimate of photon contribution
$\Delta G/G$ measurements in DIS

$\Delta G/G$ is small or has a node around $x_g \approx 0.1$
\[ \Delta G/G \text{ from pp collider} \]

**RHIC: \( \vec{p} \vec{p} \) at 200 GeV**

- Longitudinal and transverse polarisation for PHENIX and STAR
- Transverse polarisation for BRAHMS
- Run 5 just finished successfully, results from run 3 and 4

**Methods**
- Cleanest channel
  - Prompt photons: \( qg \rightarrow q\gamma \)
  - Needs high luminosity
- Up to now: \( qg \rightarrow qg \)

- Pionproduktion, jets
- Other contributions:
  - \( gg \rightarrow gg \)
  - \( gg \rightarrow q\bar{q} \)
• analysis of 2 jet events at mid rapidity

PHENIX

• analysis of $\pi^0$ production
• first prompt photons
**PHENIX results**

**π⁰ production**

![Graph of π⁰ production](image)

- **PHENIX Data**
- **KKP FF**
- **Kretzer FF**

**Δσ/σ (%)**

![Graph showing Δσ/σ (%)](image)

**π⁰ asymmetries**

![Graph showing π⁰ asymmetries](image)

- **π⁰ A_L from pp at √s=200 GeV**
- **run3+4 combined (PHENIX preliminary)**
- **GRSV-max**
- **GRSV-std**

- Scaling error of ~65% is not included.

- **Good description of cross section with NLO QCD**
- **Small asymmetries observed**
- **Favours standard GRSV or smaller gluon distribution**

E. Kabuš, PIC05, Prague, 9.7.2005
Transversity
Transversity

- transversity not measurable in inclusive DIS as quark helicity must flip ⇒ SIDIS

- polarisation of struck quark measured e.g. by azimuthal asymmetry of produced hadrons ⇒ Collins–Effect
  \[ \Delta D = \uparrow - \downarrow \]

- azimuthal asymmetries also due to quark transverse momenta ⇒ Sivers–Effect

- other possibility to measure transversity uses interference in the angle between two hadrons

E. Kabuš, PIC05, Prague, 9.7.2005
Collins and Sivers effect

Using a transversely polarized target allows to disentangle Collins and Sivers–Effect.

\[
A_T^h = \frac{1}{|S_T|} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}
\]

\[
\sim \sin(\phi + \phi_S - \pi) \frac{\sum_i e_i^2 \Delta_T q_i(x) \Delta_T D_{q_i}^h(z)}{\sum_i e_i^2 q_i(x) D_{q_i}^h(z)} \quad \text{Collins–Effect}
\]

\[
+ \sin(\phi - \phi_S) \frac{\sum_i e_i^2 f_{1T}^i(x) D_{q_i}^h(z)}{\sum_i e_i^2 q_i(x) D_{q_i}^h(z)} \quad \text{Sivers–Effect}
\]

- \(\Delta_T q(x)\) transversity DF
- \(f_{1T}^i(x)\) Sivers DF
- \(q(x)\) unpolarized DF
- \(\Delta_T D_{q_i}^h(z)\) Collins FF
- \(D_{q_i}^h(z)\) unpolarized FF
• Collins asymmetries positive for $\pi^+$, negative for $\pi^-$ $\implies$ unexpected for $\pi^-$

• Sivers asymmetries positive for $\pi^+$ and zero for $\pi^-$ $\implies$ hint for $L_z$
COMPASS results

**All Hadrons**  **Leading hadrons**

**Collins**

**Sivers**

- Collins and Sivers asymmetries for positive hadrons (closed symbols) and negative hadrons (open symbols)
- **asymmetries small**: cancellation in deuteron?
- more statistics from 2003 and 2004, **proton target (NH₃)** in 2006
Measurement of Collins fragmentation function

- Access to $\Delta D^h_q(z)$ in $e^+e^-$ collisions

- Method: Hadrons pairs in opposite jets

$$\sigma \sim A \cdot \Sigma D^h_1(z_1)D^h_2(z_2)$$

- Transverse momenta included

$$\sigma \sim \ldots + B \cdot \cos(\phi_1 + \phi_2)\Delta_T D^h_1(z_1)\Delta_T D^h_2(z_2)$$

- BELLE: 8 GeV $e^-$ + 3.5 GeV $e^+$

- Off resonance data: $e^+e^- \rightarrow q\bar{q}$ $q=(u,d,s,c)$

- Use unlike and like sign $\pi\pi$ pairs

- Determination of double ratios $\Longrightarrow$ cancellation of acceptance
Two different methods used

Significant asymmetry rising with $z$

observation of Collins FF
Single spin asymmetries from RHIC

- Collins and Sivers not distinguishable

\[ A(\pi_0) > 0 \text{ at } x_F > 0 \]

\[ A(\pi_0) = 0 \text{ at } x_F < 0 \]

\[ \pi^0, h^+, h^− \]

PHENIX Preliminary

A = 0 for \(x_F \approx 0\)

E. Kabuß, PIC05, Prague, 9.7.2005
Results from Brahms

- Results for pions and protons

\[ A(\pi^+) > 0, \quad A(\pi^-) < 0 \text{ at } x_F > 0 \]
\[ A(\pi^-) \approx 0 \text{ at } x_F < 0 \]
\[ A(p) \approx 0 \]
Spin physics is a very active field

Many new results from COMPASS, HERMES, JLAB, RHIC and BELLE

Gluon polarisation measured with several methods
  ⇒ more statistics needed

New precise data for the longitudinal spin structure functions
  ⇒ improvement of polarised PDFs

New puzzling results from all experiments on transversity

Many more results on semi-inclusive DIS, single spin asymmetries, $\rho$ meson production, $\Lambda$ polarisation ...

Plans:
- COMPASS: more data from 2004, data taking continues on 2006
- RHIC: run 5 just finished
- HERMES: more data from 2005, measurements of GPDS e.g. via DVCS 2006/2007