The Status of the COMPASS Experiment
– Inclusive and Semi-inclusive Asymmetries –

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– COMPASS experiment
– Inclusive asymmetries
– Semi-inclusive asymmetries
– Upgrade 2006
– Status and outlook
The spin of the nucleon

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

E155
\[ \Delta \Sigma = 0.23 \pm 0.07 \pm 0.19 \]

Gluons important in unpolarized case \( \Delta G \)?

Complete description: orbital angular momenta

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

\( Q^2 = -q^2 \)
\( \nu = E - E' \)
\( x = Q^2 / 2M\nu \)
\( y = \nu / E \)
\( z = E_h / \nu \)

\( p_T \): hadron transverse momentum

• Inclusive cross section

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

\( F_1, F_2, g_1, g_2 \) structure functions
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

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

- spin structure function

\[ g_1 = \frac{1}{2} \sum_q e_q^2 \Delta q(x) = A_1 \cdot \frac{F_2}{2x(1 + R)} \approx \frac{A_{||}}{D} \cdot \frac{F_2}{2x(1 + R)} \]
COMPASS at CERN
COmmon Muon and Proton Apparatus
for Structure and Spectroscopy

Muon beam

Gluon polarisation
Spin dependent structure functions
Polarised quark distributions
Transversity
Lambda polarisation
Vector meson production
DVCS

Hadron beam

Primakoff scattering
Exotic hadrons
- Glueballs
- Hybrids
- Multi-quark states
Charmed hadrons
Spectrometer

Muon beam

160 GeV/c
2 \cdot 10^8 \mu/16.8 \text{ s}
80\% polarisation

Spectrometer

- Two magnets (1 Tm, 4.5 Tm)
- Tracking ($p > 0.5 \text{ GeV/c}$):
  SciFi, Silicon, MicroMega, GEM, MWPC, Drift, Straws, Driftubes
- PID: $\pi$, $k$, $p$ (RICH)
  above 2, 9, 18 GeV/c
- ECAL, HCAL, muon filter

E. Kabuß, PACSPIN07, Vancouver, 30.7.2007
The polarised target

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

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E. Kabuß, PACSPIN07, Vancouver, 30.7.2007

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Method

• to be measured:

\[ A_{\parallel} = \frac{\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\downarrow} + \sigma_{\uparrow\uparrow}} \]

• flux normalization:

\[ A_{\text{exp}} = \frac{N_u - N_d}{N_u + N_d} \]

• acceptance difference:

Polarisation rotation

• take average asymmetry:

\[ \Rightarrow A_{\text{exp}} = \frac{A + A'}{2} = \frac{1}{2} \left( \frac{N_u - N_d}{N_u + N_d} + \frac{N'_d - N'_u}{N'_u + N'_d} \right) \]

\[ \Rightarrow \text{minimization of bias} \]

• experimental asymmetry

\[ A_{\text{exp}} = p_{\mu} p_T \int f \, A_{\parallel} \]

\[ p_{\mu}, p_T \text{ beam and target polarisation} \]

\[ f \text{ dilution factor} \]
Kinematic range

- strong corellation between $x$ and $Q^2$
- inclusive triggers
- semi-inclusive triggers: dominant at low $x$ and $Q^2$
- calorimetric trigger: dominant for $Q^2 > 30 \text{ (GeV/c)}^2$
Inclusive asymmetries
Asymmetry for $Q^2 < 1 \ (GeV/c)^2$

- systematic error mainly due to false asymmetries
- $A_1^d$ is compatible with 0 at small $x$
Comparison with other experiments

- very good agreement with SMC (the only other experiment at low $x$)
- factor 10–20 improvement of statistical errors compared to SMC
$g_1$ structure function ($Q^2 < 1 \text{ (GeV/c)}^2$)

$$g_1 = A_1 \cdot \frac{F_2}{2x(1 + R)}$$

R parametr.: 

$x > 0.12$ SLAC

$0.003 < x < 0.12$ NMC

$x < 0.003$ ZEUS

F2 from SMC parametrisation (extrapolation with JKBB model)
Asymmetry for $Q^2 > 1 \text{ (GeV/c)}^2$

- $88 \cdot 10^6$ events with $x > 0.004$, $0.1 < y < 0.9$
- systematic errors: $p_\mu$ (5%), $p_T$ (5%), $f$ (2–3%), $D$ (6%) $\Rightarrow \delta A_1 \approx 0.1A_1$
- additional contributions from false asymmetries, radiative corrections
Asymmetry for $Q^2 > 1\ (\text{GeV/c})^2$

- $A_1^d$ compatible with 0 for $x < 0.05$
- good agreement with previous experiments
- significant improvement at low $x$, no tendency towards negative values
\[ g_1(x) \text{ at measured } Q^2 \]

\[ g_1 = A_1 \cdot \frac{F_2}{2x(1 + R)} \]

COMPASS, \( Q^2 > 1 \text{(GeV/c)}^2 \)

\[ F_2(x, <Q^2>) \]

\[ R(x, <Q^2>) \]
First moment of $g_1$

$$\Gamma_1^N (Q^2 = 3(\text{GeV/c})^2) = \int_0^1 g_1^N dx$$

$$= 0.0502 \pm 0.0028(\text{stat}) \pm 0.0020(\text{evol.}) \pm 0.0051(\text{syst.})$$

- data for $0.004 < x < 0.7$, QCD fit used for extrapolation
- contribution of unmeasured region about 3 %

• using:
  $$\Gamma_1^N = \frac{1}{9}(1 - \frac{\alpha_s(Q^2)}{\pi} + O(\alpha + s^2))(a_0(Q^2) + \frac{1}{4}a_8)$$

  $$a_0(Q^2 = 3(\text{GeV/c})^2) = 0.35 \pm 0.03(\text{stat}) \pm 0.05(\text{syst})$$

• extrapolating towards $Q^2 \to \infty$:
  $$\hat{a}_0 = 0.33 \pm 0.03(\text{stat}) \pm 0.05(\text{syst}) = \Delta \Sigma$$

  $$\Delta s + \Delta \bar{s} = \frac{1}{3}(\hat{a}_0 + a_8) = -0.08 \pm 0.01(\text{stat}) \pm 0.02(\text{syst})$$

- negative strange sea polarisation
QCD analysis

• spin structure function $g_1$

\[ g_1(x, Q^2) = \frac{1}{2} \langle e^2 \rangle [C_{NS} \otimes \Delta q_{NS} + C_S \otimes \Delta \Sigma + 2n_f C_g \otimes \Delta g] \]

• DGLAP equations

\[
\frac{d}{d \ln Q^2} \Delta q_{NS} = \frac{\alpha_s(Q^2)}{2\pi} \Delta P_{qq}^{NS} \otimes \Delta q_{NS}
\]

\[
\frac{d}{d \ln Q^2} \begin{pmatrix} \Delta \Sigma \\ \Delta g \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi} \begin{pmatrix} \Delta P_{qq}^S & 2n_f \Delta P_{qg} \\ \Delta P_{gq} & \Delta P_{gg} \end{pmatrix} \otimes \begin{pmatrix} \Delta \Sigma \\ \Delta g \end{pmatrix}
\]

• input parameterization at $Q_0^2$

\[
(\Delta \Sigma, \Delta q_3, \Delta q_8, \Delta g) = \eta \frac{x^\alpha (1-x)^\beta (1+\gamma x)}{\int_0^1 x^\alpha (1-x)^\beta (1+\gamma x) dx}
\]

with \[ \Delta \Sigma = \Delta u + \Delta d + \Delta s, \Delta q_3 = \Delta u - \Delta d, \Delta q_8 = \Delta u + 2\Delta d - \Delta s \]
QCD fits

- two different approaches
  - numerical integration in \((x,Q^2)\) space (PRD 58 (1998) 112002)
  - solution of DGLAP in space of moments (PRD 70 (2004) 074032)
- fit to world data (except final \(g_1^d\) from HERMES)
- NLO analysis in \(\overline{\text{MS}}\) scheme

\[
\begin{align*}
g_1^d(x) &= 0.01, \\
&= 0.005, \\
&= 0.015, \\
&= 0.02, \\
&= 0.025, \\
&= 0.03
\end{align*}
\]

- well described by two solutions with \(\Delta G > 0\) and \(\Delta G < 0\)
Results for $p$, $d$ and $n$

COMPASS QCD fit, $Q^2 = 3 \text{ (GeV/c)}^2$, $\Delta G > 0$

world data at $Q^2 = 3 \text{ (GeV/c)}^2$ fit with $\Delta G > 0$
Polarised parton distributions

COMPASS QCD fit, $\overline{\mathcal{M}}$, $Q^2=3(GeV/c)^2$, $\Delta G>0$

| $x$ (\Delta u+\Delta \bar{u}) | $x$ (\Delta d+\Delta \bar{d}) | $x$ (\Delta s+\Delta \bar{s}) | $x$ $\Delta G$
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COMPASS range

COMPASS QCD fit, $\overline{\mathcal{M}}$, $Q^2=3(GeV/c)^2$, $\Delta G<0$

| $x$ (\Delta u+\Delta \bar{u}) | $x$ (\Delta d+\Delta \bar{d}) | $x$ (\Delta s+\Delta \bar{s}) | $x$ $\Delta G$
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COMPASS range

- small sensitivity to light sea and gluon polarisation

- **quark polarisation:** $\eta_\Sigma = 0.30 \pm 0.01\,(\text{stat}) \pm 0.02\,(\text{evol})$
  (error factor 2 larger without COMPASS)

- **gluon polarisation:** $|\eta_G| \approx 0.2 - 0.3$
Gluon polarisation

- bands correspond to statistical errors
- uncertainty due to parameterization not included
- unpolarised PDFs from MRST
- direct measurements of $\Delta G$ (see talk from N. Doshita)
Semi-inclusive asymmetries
Hadron asymmetries

\[
A_h^1(x) = \frac{\sum_q e_q^2 (\Delta q(x) D_q^h + \Delta \bar{q}(x) D_{\bar{q}}^h)}{\sum_q e_q^2 (q(x) D_q^h + \bar{q}(x) D_{\bar{q}}^h)}
\]

\[
A^+ = \frac{\sigma_{h^+}^{↑↓} - \sigma_{h^+}^{↑↑}}{\sigma_{h^+}^{↑↓} + \sigma_{h^+}^{↑↑}}
\]

\[
A^- = \frac{\sigma_{h^-}^{↑↓} - \sigma_{h^-}^{↑↑}}{\sigma_{h^-}^{↑↓} + \sigma_{h^-}^{↑↑}}
\]

- selection: \( Q^2 > 1 \text{ (GeV/c)}^2, \quad 0.1 < y < 0.9, \quad 0.2 < z < 0.85 \)
- events: \( N^+ = 30 \cdot 10^6, \quad N^- = 25 \cdot 10^6, \quad \text{corr}(N^+, N^-) \approx 20\% \)
Difference asymmetry

\[ A^{+-} = \frac{(\sigma_{h+}^{h+} - \sigma_{h-}^{h-}) - (\sigma_{h+}^{h+} - \sigma_{h-}^{h-})}{(\sigma_{h+}^{h+} - \sigma_{h-}^{h-}) + (\sigma_{h+}^{h+} - \sigma_{h-}^{h-})} \]

- LO analysis: fragmentation functions cancel, for deuteron PID not necessary

\[ A^{\pi^+ - \pi^-}_d(x) = A^{K^+ - K^-}_d(x) = \frac{\Delta u_v(x) + \Delta d_v(x)}{u_v(x) + d_v(x)} \]

- \( A^{+-} \) asymmetry obtained from \( A^+ \) and \( A^- \) asymmetries

\[ A^{+-} = \frac{1}{1 - r} (A^+ - rA^-) \quad \text{with} \quad r = \frac{\sigma_{h+}^{h-} + \sigma_{h}^{h-}}{\sigma_{h+}^{h+} + \sigma_{h}^{h+}} = \frac{\sigma^{h-}}{\sigma^{h+}} = \frac{N^-/a^-}{N^+/a^+} \]
Polarised valence distribution

\[ x(\Delta u_v(x) + \Delta d_v(x)) = \frac{x(u_v(x) + d_v(x))}{(1 + R(x))(1 - 1.5\omega_D)} A^{+-}(x) \]

- evolved to \( Q^2 = 10 \) (GeV/c)^2
- using LO DNS parameterization (PRD 71(2005)094018)
- DNS predicts COMPASS data
- for \( u_v + d_v \)
- MRST04(LO) used

- sea very small at large \( x \), with inclusive asymmetry much better precision

\[ \Delta u_v + \Delta d_v = \frac{36}{5} \frac{g_1^d(x, Q^2)}{1 - 1.5\omega_D} - \left[ 2(\Delta \bar{u} + \Delta \bar{d}) + \frac{2}{5}(\Delta \bar{s} + \Delta \bar{s}) \right] \]
Comparison with other experiments

![Graph showing comparison between different experiments](graph.png)

- **x(Δu_v + Δd_v)**, MRST04
- SMC 98
- HERMES 05
- x(Δu_v + Δd_v), DSN
- COMPASS
Towards polarised sea quarks

• using $\Gamma_1^N$ at $Q^2 = 10 \text{ GeV}/c^2$

$$\Gamma_1^N(Q^2 = 10 \text{ GeV}/c^2) = \frac{1}{9}(a_0 + \frac{1}{4}a_8)$$

$$= 0.051 \pm 0.003^{\text{stat}} \pm 0.003^{\text{evol}} \pm 0.005^{\text{syst}}$$

• combining with $\Gamma_1^N$ and $a_8$

$$\Gamma_v = \int_0^1 (\Delta u_v(x) + \Delta d_v(x))dx$$

• contribution of sea quarks

$$\Delta \bar{u} + \Delta \bar{d} = 3 \Gamma_1^N - \frac{1}{2}\Gamma_v + \frac{1}{12}a_8$$

$$= (\Delta s + \Delta \bar{s}) + \frac{1}{2}(a_8 - \Gamma_v)$$

• disentangle between flavour symmetric $(\Delta \bar{u} = \Delta \bar{d} = \Delta s = \Delta \bar{s})$ and asymmetric $(\Delta \bar{u} = -\Delta \bar{d})$ sea, precision $\delta \Gamma_v < |\Delta s + \Delta \bar{s}|$ needed
Estimate of first moment (LO)

\[ \int_{x}^{0.7} (\Delta u_{v} + \Delta d_{v}) dx \]

SIDIS+DIS, \( Q^{2} = 10 \text{ GeV}^2 \)

- \( \Delta \bar{u} = \Delta \bar{d} = \Delta s = \Delta \bar{s} \)
- \( \Delta \bar{u} = -\Delta \bar{d} \)

\[ \int_{0.006}^{0.7} (\Delta u_{v} + \Delta d_{v}) dx = 0.40 \pm 0.07 \pm 0.05 \]

- contribution from \( 0.7 < x < 1 \) about 0.004 (DNS fit)
- \( \Gamma_{v} \) is 2.5 \( \sigma_{\text{stat}} \) away from flavour symmetric sea scenario
- asymmetric sea favoured
2006 upgrade
2006 Upgrade

- **Polarised target**: large acceptance magnet system
- **RICH1**: central photon detectors replaced by MAPMTs
- new read out using APVs for outer photon detectors
- **RICH wall** (preshower for ECAL1)
- **ECAL1** Electromagnetic calorimeter in first stage
- More **large angle tracking** in first stage
- **DAQ** and **DCS** consolidation and upgrades
- Other small additions
Polarised target magnet

- new target magnet: SMC (70 mrad) $\rightarrow$ COMPASS (180 mrad)
- gain in statistics at least 30%
- field homogeneity of $3 \cdot 10^{-5}$ at Saclay
- $7 \cdot 10^{-5}$ reached in presence of SM1 dipole field
- delicate operation due to short in one correction coil, however reliable
Polarised target microwave cavity

to match larger acceptance: new 3 cell microwave cavity
reduction of false asymmetries
Polarisation of $^6$LiD in 2006: 53.5%, -52%, 56.2% higher and faster than in 2004
RICH upgrade

Inner photon detectors

• read out changed from MWPCs to MAPMTs for the inner quarter
• telescope in front of MAPMT for cost effectiveness and to avoid dead regions
• significant increase in number of photons
• space resolution a bit worse but in total increase in precision
• excellent timing, no dead time, improved efficiency

Outer photon detectors

• new APV readout for the outer 75% of the photon detectors
• reduction of uncorellated background by at least a factor 6
• much smaller dead time
RICH upgrade

Lens system
+ MAPMTs
+ MAD4
+ F1

CsI MWPC
+ APV25S1
+ ADC
RICH1 central photon detectors

- sketch of telescope in front of MAPMT
- single event with 10 ns timing cut
electromagnetic calorimeter (1500 lead glass blocks) in first stage in 2007 included into semi-inclusive and calorimetric triggers
Large angle tracking

large area tracker (drift tubes) with lead converter behind RICH also used as preshower for ECAL1

large area detectors in first stage: straw modules large drift chamber DC4
Data taking 2007

- **Different target material: NH$_3$**
  - fragile and difficult to handle
  - successfully polarised, very long relaxation time ($\sim 4000$ h)
  - magnetic field rotation without polarisation loss
  - FOM factor 2 smaller for proton than for deuteron, partly compensated by 2006 upgrade

- **Main goals:**
  - **longitudinal target polarisation:**
    - flavour separation of PDFs
    - sign of strange sea polarisation at low $x$
    - shape $g_1^p$ at low $x$
  - **transverse target polarisation:**
    - Collins and Sivers asymmetries
    - flavour separation
  - **2007 proton data to complement 2002-2006 deuteron data:**
    - needs stable beam conditions, high intensity, excellent spectrometer performance
  - **started with transversity measurement**
Flavour separated PDFs

with 2007 proton and 2002–2006 deuteron data

COMPASS unique at small $x$
Summary and outlook

• Results from 2002–2004 deuteron data
  – Inclusive and semi-inclusive data discussed
  – First moment of $g_1^d$ and QCD-analysis
  – Valence quark polarisation from difference asymmetry

• 2006 data being analysed

• 2007 proton data taking

• 2008 measurements with hadron beam prepared

• Future plans
  – Measurement of DVCS
    (recoil detector and ECAL studies started)
  – Polarised Drell-Yann measurement
    (beam and target test planned this year)