Spin structure of the proton at low $x$ and low $Q^2$
in two-dimensional bins from COMPASS

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Motivation

- low $x \leftrightarrow$ high parton densities
- low $x$ and low $Q^2 \leftrightarrow$ transition from the regime of photoproduction to the regime of DIS (described by pQCD)
- $A_1^p$ and $g_1^p$ as functions of $x$ and $\nu$ showed, for the first time, positive spin effects at very low $x$ (cf. $A_1^d \sim 0$ at low $x$, and SMC sample - 150x smaller)
- theoretical predictions for $g_1^p$ as function of two kinematic variables:
    “Spin structure function $g_1(x, Q^2)$ and the DHGHY integral $I(Q^2)$ at low $Q^2$: Predictions from the GVMD model”
    “Comment on the recent COMPASS data on the spin structure function $g_1$”
    “Overview of the spin structure function $g_1$ at arbitrary $x$ and $Q^2$”
    “one can parameterize $g_1$ by the set of variables $x$, $Q^2$ or, alternatively, $\omega \equiv 2pq = 2M(E - E')$, $Q^2$, or $\nu$, $Q^2$”
- COMPASS’ $\sim 7 \times 10^8$ events allow a 2D extraction
- extraction, for the first time, in 4 2D grids: $(x, Q^2)$, $(\nu, Q^2)$, $(x, \nu)$, $(Q^2, x)$
The COMPASS experiment at CERN

COMPASS @ CERN
COmmom Muon Proton Apparatus for Structure and Spectroscopy

- Fixed target experiment at the SPS using a tertiary muon beam
- Collaboration of about 200 members from 11 countries and 23 institutions

- 160/200 GeV $\mu^+$ polarised beam, $P_b \sim -80\%$
- $^6\text{LiD}$ or $\text{NH}_3$, 1.2 m long, polarised target @ 2.5 T and 60 mK, $P_{\text{target}} \sim 50/85\%$

- large acceptance, two staged spectrometer
- tracking, calorimetry, PID

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### Polarised target

<table>
<thead>
<tr>
<th>Material</th>
<th>Dilution factor ((f))</th>
<th>Polarisation ((P_{\text{target}}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{6}\text{LiD})</td>
<td>0.40</td>
<td>50%</td>
</tr>
<tr>
<td>(\text{NH}_3)</td>
<td>0.16</td>
<td>85%</td>
</tr>
</tbody>
</table>

Two 30 cm long target cells polarised in the same direction. One 60 cm long target cell polarised in the opposite direction.

\(^{4}\text{He} - ^{4}\text{He} \text{ Dilution refrigerator (T ~ 50 mK)}\)

#### Vertex coordinate \(z_{PV}\)

- 160 GeV beam (2007)
- 200 GeV beam (2011)

\(\mu\)

\(\mu\)

\(\geq 2006\)
Data samples for the extraction of $A_1^p$ and $g_1^p$

- Longitudinally polarised target (NH$_3$): $676 \times 10^6$ events
  (447 $\times 10^6$ with 160 GeV beam in 2007, 229 $\times 10^6$ with 200 GeV beam in 2011)

- Before, SMC low $x$, low $Q^2$ proton data: 4.5 $\times 10^6$ events
  $\Rightarrow$ The COMPASS data set has 150$\times$ more events than SMC

Main selection criteria:

- at least one additional track (besides the scattered muon) in the interaction point
  ("hadron method") - SMC proved there is no bias to the inclusive asymmetries at
  low $x$

- not a $\mu e$ elastic scattering event

- $Q^2 < 1$ (GeV/c)$^2$

- $x \geq 4 \times 10^{-5}$

- 0.1 $\leq y < 0.9$
Characteristics of the final sample

- $A_P^D$ and $g_1^D$ at low $x$ and $Q^2$ (COMPASS)

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Phase-space coverage of the 2D analysis

\[ (x, Q^2) \]

\[ (\nu, Q^2) \]

\[ (x, \nu) \]

\[ (Q^2, x) \]
Double spin longitudinal asymmetry $A_{1}^{p}$

\[ N \leftrightarrow,\leftrightarrow = a \phi n \bar{\sigma}(1 \pm P_{\text{beam}} P_{\text{target}} \chi D A_{1}^{p}) \]

\[ \frac{N \leftrightarrow,1 \cdot N \leftrightarrow,2}{N \leftrightarrow,1 \cdot N \leftrightarrow,2} \rightarrow 2^{\text{nd}} \text{ ord. eq. on } A_{1}^{p} \]

- Each event is given a weight $\omega = f D|P_{\text{beam}}|$ to optimize the statistical errors

- Unpolarised radiative corrections (RC), included in the dilution factor, from TERAD
  
  [A.A. Akhundov, et al., Fortschr. Phys. 44 (1996) 373]

- Polarised radiative corrections ($A_{1}^{pRC} \leq 0.25 \delta A_{1}^{\text{stat}}$) from POLRAD
  

- Corrected for polarisable $^{14}N$ ($A_{1}^{^{14}N} \leq 0.01 \delta A_{1}^{\text{stat}}$)

- Thorough checks on possible sources of false asymmetries $\Rightarrow$ systematic errors similar to the statistical errors
Spin dependent structure function $g_1^p$

- The structure function is obtained in bins of $x$ or $\nu$ according to:

$$g_1^p \left( \langle x \rangle, \langle Q^2 \rangle \right) = \frac{F_2^p \left( \langle x \rangle, \langle Q^2 \rangle \right)}{2x \left[ 1 + R \left( \langle x \rangle, \langle Q^2 \rangle \right) \right]} A_1^p \left( \langle x \rangle, \langle Q^2 \rangle \right)$$

- $F_2^p(\langle x \rangle, \langle Q^2 \rangle)$ from the SMC fit on data or from a model (for low $x$ and $Q^2$)

- $R(\langle x \rangle, \langle Q^2 \rangle)$ based on SLAC parameterization, extended to low $Q^2$
  [COMPASS, PLB 647 (2007) 330]
$A_1^p(x)$ & comparison with previous experiments

- Results for the two beam energies are compatible within errors
- Systematic errors are similar to the statistical errors (not shown here)
- $A_1^p$ is significantly positive
- No dependence on $x$ is seen (nor on $\nu$, not shown here)
- The COMPASS results improve the precision of the measurement
$A_1^p$ and $g_1^p$ at low $x$ and low $Q^2$: results for the grid $(x, Q^2)$

Data: 2007&2011, $\mu^+ p \rightarrow \mu^+ X$

- **no strong dependence** on $x$ or $Q^2$
$A_1^p$ and $g_1^p$ at low $x$ and low $Q^2$: results for the grid $(\nu, Q^2)$

**Data:** 2007 & 2011, $\mu^+ p \rightarrow \mu^+ X$

- **No strong dependence** on $\nu$ or $Q^2$

$A_1^p$ and $g_1^p$ at low $x$ and $Q^2$ (COMPASS)
$A_1^p$ and $g_1^p$ at low $x$ and low $Q^2$: results for the grid $(\nu, x)$

Data: 2007 & 2011, $\mu^+ p \rightarrow \mu^+ X$

- **no strong dependence** on $\nu$ or $x$
$A_1^p$ and $g_1^p$ at low $x$ and low $Q^2$: results for the grid ($Q^2$, $x$)

Data: 2007&2011, $\mu^+ p \rightarrow \mu^+ X$

- no strong dependence on $x$ or $Q^2$
Longitudinal double spin asymmetries $A_1^p$ and the spin dependent structure function $g_1^p$ extracted in 4 two-dimensional grids:

- $(x, Q^2)$
- $(\nu, Q^2)$
- $(x, Q^2)$
- $(Q^2, x)$

- **Positive** spin asymmetries at very low $x$

- **No significant dependence** on studied kinematic variables

BACKUP
To obtain the value of $C$ from (12), the contribution of resonances was evaluated using the preliminary data taken at ELSA/MAMI by the GDH Collaboration [16] at the photoproduction, for $W_i = 1.8$ GeV. The asymptotic part of $g_1$ was parametrized using the GRSV2000 fit for the “standard scenario” of polarized parton distributions with a flavor symmetric light sea, $\Delta u = \Delta d = \Delta s = \Delta \bar{s}$, at the NLO accuracy [9]. The non-perturbative parton distributions, $\Delta p_i^{(0)}(x)$, in the light vector meson component of $g_1$, (3), were evaluated at fixed $Q^2 = Q_0^2$, using, either (i) the GRSV2000 fit, or (ii) a simple, “flat” input:

$$\Delta p_i^{(0)}(x) = N_i (1 - x)^{\eta_i},$$

(13)

with $\eta_u = \eta_d = 3$, $\eta_s = 7$ and $\eta_{\bar{s}} = 5$. The normalization constants $N_i$ were determined by imposing the Bjorken sum rule for $\Delta u_i^{(0)} - \Delta d_i^{(0)}$, and requiring that the first moments of all other distributions are the same as those determined from the QCD analysis [18]. It was checked that the parametrization (13) combined with the unified equations gives a reasonable description of the SMC data on $g_1^{NS}(x, Q^2)$ [19] and on $g_1^p(x, Q^2)$ [5]. This fit was also used to investigate the magnitude of the double logarithmic corrections, $\ln^2(1/x)$, to the spin structure function of the proton at low $x$ [20]. We have assumed $Q_0^2 = 1.2$ GeV$^2$, cf. (1) and (3), in accordance with the analysis of $F_2$ [7,8]. As a result the constant $C$ was found to be $-0.30$ in case (i) and $-0.24$ in case (ii). These values change at most by 13% when $Q_0^2$ changes in the interval $1.0 < Q_0^2 < 1.6$ GeV$^2$.

Fig. 1. Values of $g_1$ for the proton as a function of $x$ and $Q^2$. The asymptotic contribution, $g_1^{AS}$, is marked with broken lines, the VMD part, $g_1^L$, with dotted lines and the continuous curves mark their sum, according to (5).

Fig. 2. Values of $xg_1$ for the proton as a function of $x$ at the measured values of $Q^2$ in the non-resonant region, $x < x_t = Q^2/2M_{\pi^0}(Q^2)$. The upper plot corresponds to the VMD part parameterized using (13), the lower plot corresponds to the GRSV parameterization [9] of the VMD input. The $g_1^{AS}$ in both plots has been calculated using the GRSV fit for standard scenario at the NLO accuracy. The contributions of the VMD and of the $xg_1^{AS}$ are shown separately. Points are the SMC measurements at $Q^2 < 1$ GeV$^2$ [3]; errors are total. The curves have been calculated at the measured $x$ and $Q^2$ values.