First results on $A_1^p$ and $g_1^p$ at low $x$ and low $Q^2$ from COMPASS

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3 Summary
The COMPASS experiment
Fixed target experiment at the SPS using a tertiary muon beam
Collaboration of around 200 members from 11 countries and 23 institutions
COMPASS spectrometer

- 160/200 GeV $\mu^+$ naturally polarised beam with $P_{\text{beam}} \sim -80\%$

- $^6\text{LiD}$ or $\text{NH}_3$, 1.2 m long, polarised target

- Large acceptance, two staged spectrometer
  - Tracking
  - Calorimetry
  - RICH
Polarised target

\[ N \leftrightarrow \leftrightarrow = a\phi n\bar{n} (1 \pm P_{\text{beam}} P_{\text{target}} f A_{||}) \]

Cancellation of \( a\phi n\bar{n} \) via:

- **flux cancellation**
  - reconstructed beam track or extrapolation must cross all target cells

- **acceptance cancellation**
  - 3 target cells (2, before 2006)
  - polarisation rotation every 24 hours (8h, before 2006)
  - grouping of runs in \( \sim 48 \) h long configurations
  - reversal of “microwave setting” at least once per year

\( ^6\text{LiD} \) (2002–2006): \( f \sim 40\%, P_{\text{target}} \sim 50\% \)

\( \text{NH}_3 \) (2007–2011): \( f \sim 16\%, P_{\text{target}} \sim 85\% \)
Definitions
Deep inelastic scattering event kinematic variables

Global variables:

\[ k_\mu = (E_\mu, k_\mu) \]
\[ k'_\mu = (E'_\mu, k'_\mu) \]
\[ P = (M, 0) \]
\[ q = k_\mu - k'_\mu = (\nu, q) \]
\[ Q^2 = -q^2 \]
\[ \nu = P \cdot q / M = E_\mu - E'_\mu \]
\[ W^2 = M^2 + 2M\nu - Q^2 \]
\[ x = Q^2 / (2M\nu) \]
\[ y = \nu / E_\mu \]

Hadron variables:

\[ p_{\text{lab}} = (E_{\text{lab}}, p_{\text{had}}) \]
\[ z_{\text{had}} = E_{\text{had}} / \nu \]
Spin dependent observables

**Experimental asymmetry**

\[ A_{\text{exp}} = \frac{N \leftarrow - N \Rightarrow}{N \leftarrow + N \Rightarrow} = P_{\text{beam}} P_{\text{target}} f \ A_{\parallel} \]

\( f \): dilution factor (of the target)

**Lepton-nucleon asymmetry**

\[ A_{\parallel} = \frac{d\sigma \leftarrow - d\sigma \Rightarrow}{d\sigma \leftarrow + d\sigma \Rightarrow} = D(A_1 + \eta A_2) \]

\( D \): (virtual photon) depolarisation factor

\( \eta \) - kinematic variable. COMPASS case: \( \eta \sim 0 \Rightarrow A_1 \sim A_{\parallel}/D \)

**Virtual photon-nucleon asymmetry**

\[ A_1 = A_1^{\gamma^*N} = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{g_1 - \gamma^2 g_2}{F_1} \sim \frac{g_1}{F_1} \]

\[ A_2 = \gamma \frac{g_1 + g_2}{F_1} \sim 0 \]

\( \gamma \) - kinematic variable (small at COMPASS)

**Spin dependent structure function \( g_1 \)**

\[ g_1(x, Q^2) = \frac{F_2(x, Q^2)}{2x(1 + R(x, Q^2))} A_1(x, Q^2), \text{ with } R \equiv \sigma_L/\sigma_T \]
Motivation
Motivation for the low $x$, low $Q^2$ studies

- **Low $x$ $\Leftrightarrow$ high parton densities**

- Fixed target experiments $\Leftrightarrow$ **strong correlation**
  
  between $x$ and $Q^2$: low $x \Rightarrow$ low $Q^2$, where pQCD isn’t expected to work

- Some **models, to be confronted with data**, allow a smooth extrapolation to the low-$Q^2$ and high-$Q^2$ regions (resummation, VMD):
  
  B. Badelek et al, B.I. Ermolaev et al.

- $A_1^d$ and $g_1^p$ at low $x$ and low $Q^2$:
  
  ▶ can be measured with **improved precision**
  
  ▶ complement our measurement of $A_1^d$ and $g_1^d$ at low $x$ and low $Q^2$
  
  ▶ $g_1^{NS} = g_1^p - g_1^n$ can be extracted

- The results will be presented also as functions of $\nu$, as requested by theoreticians
Previous COMPASS results
COMPASS published $A_{1}^{p,d}$ data

<table>
<thead>
<tr>
<th>$Q^2 &lt; 1$ (GeV/c)$^2$</th>
<th>$Q^2 &gt; 1$ (GeV/c)$^2$</th>
</tr>
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<tbody>
<tr>
<td>$A_{1}^{d}$</td>
<td>$A_{1}^{p}$</td>
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</tbody>
</table>

\[ A_{1}^{d} \]

\[ A_{1}^{p} \]

\[ Q^2 < 1 \text{ (GeV/c)}^2 \]

\[ Q^2 > 1 \text{ (GeV/c)}^2 \]

\[ A_{1}^{d} \]

\[ A_{1}^{p} \]

$↔$ later in this talk

$↔$ more in M. Wilfert’s talk

$A_{1}^{p}$ and $g_{1}^{p}$ at low $x$ and $Q^2$ (COMPASS)
Data samples
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 vertex
  ("hadron method") - SMC proved there is no bias to the inclusive asymmetries at low $x$

- not a $\mu e$ elastic scattering event

- $Q^2 < 1 \ (\text{GeV/c})^2$

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

- $0.1 < y < 0.9$
Kinematic variables of the final samples

$x$ vs. $Q^2 (\text{GeV}/c)^2$

$\nu (\text{GeV})$

$W (\text{GeV})$
Features of the final samples

\[ \langle Q^2 \rangle \ (\text{GeV}^2/c^2) \ vs \ \langle x \rangle \]

\[ \langle x \rangle \ vs \ \langle \nu \rangle \ (\text{GeV}) \]

\[ \langle f \rangle \ vs \ x \]

\[ \langle D \rangle \ vs \ x \]
Removal of $\mu e$ elastic scattering events

$q\theta^* \equiv \text{charge} \times \text{angle of the track with respect to the virtual photon direction}$

The cut effectively eliminates the $\mu e$ events from the sample.
Double spin longitudinal asymmetry $A_1^p$
Double spin longitudinal asymmetry $A_1^P$

- Obtained giving each event a weight $\omega = f D |P_b|$ to optimize the statistical errors of the results

- Unpolarised radiative corrections (RC), included in the dilution factor, from TERAD

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

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

- Thorough checks on possible sources of false asymmetries $\Rightarrow$ systematic errors smaller than the statistical errors
First COMPASS results for $A_1^p(x)$ at low $x$ and low $Q^2$

The results for the two beam energies are compatible within errors. The systematic errors are smaller than the statistical errors (not shown here). A significant positive asymmetry is observed.
First COMPASS results for $A_1^p(\nu)$ at low $x$ and low $Q^2$

The results for the two beam energies are compatible within errors. The systematic errors are smaller than the statistical errors (not shown here).

A significant positive asymmetry is observed. No significant dependence with $\nu$ is seen.
Spin dependent structure function $g_1^p$
Spin dependent structure function $g_1^p$

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

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

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

- $R \left( \langle x \rangle, \langle Q^2 \rangle \right)$ based on SLAC parameterization, extended to low $Q^2$
  [COMPASS, PLB 647 (2007) 330]
First COMPASS results for $g_1^p(x)$ at low $x$ and low $Q^2$

The results for the two beam energies are compatible within errors. The systematic errors are smaller than the statistical errors (not shown here).

$g_1^p$ is significantly positive.
First COMPASS results for $g_1^p(\nu)$ at low $x$ and low $Q^2$

The results for the two beam energies are compatible within errors. The systematic errors are smaller than the statistical errors (not shown here).

$g_1^p$ is **significantly positive**.

No significant dependence with $\nu$ is seen.
Comparison with previous experiments
The COMPASS results significantly **improve the precision** of the measurement.
Comparison with model
Comparison with model

(VMD contribution and QCD improved parton model extended to low $Q^2$)

\[ g_1(x, Q^2) = g_1^{\text{VMD}}(x, Q^2) + g_1^{\text{part}}(x, Q^2) \]

Parameter \( C \): multiplicative factor relating the VMD contributions and the partonic contributions.

The COMPASS data favour \( C \in [0, +4] \), i.e. a VMD contribution to \( g_1 \) of the same sign of the partonic contribution.
Summary
Summary

- $A_1^p$ and $g_1^p$ measured for $0.001 < Q^2 < 1 \text{ (GeV/c)}^2$, $4 \times 10^{-5} < x < 4 \times 10^{-2}$, and $14 < \nu < 194 \text{ GeV}$, in bins of $x$ or in bins of $\nu$

- Total statistics **150 times larger** than SMC

- Results from data at 160 GeV and 200 GeV are **compatible**

- Results of $A_1^p$ and $g_1^p$ are **significantly positive**

- $A_1^p(x)$ results are compatible with the model of Badelek et al. (1999) for $C \in [0, +4]$, i.e. they favour a VMD contribution to $g_1$ of the same sign as the partonic one.
Spin independent and spin dependent DIS cross sections

For a longitundinally/transversely polarised proton target (with spin ⇒ and ⇐ / ↑ and ↓) and a longitundinally polarised lepton beam (with spin →):

\[
\begin{align*}
\text{Unpolarised differential cross-section} & \quad \left( \frac{d^2 \sigma \Rightarrow}{d\Omega dE'} + \frac{d^2 \sigma \Leftarrow}{d\Omega dE'} \right) = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \left[ 2 \sin^2 \frac{\theta}{2} F_1(x, Q^2) + \frac{M}{\nu} \cos^2 \frac{\theta}{2} F_2(x, Q^2) \right] \\
\text{Longitudinal differential cross-section asymmetry} & \quad \left( \frac{d^2 \sigma \Rightarrow}{d\Omega dE'} - \frac{d^2 \sigma \Leftarrow}{d\Omega dE'} \right) = \frac{4\alpha^2 E'^2}{M\nu Q^2 E} \left[ (E + E' \cos \theta) g_1(x, Q^2) - 2xM g_2(x, Q^2) \right] \\
\text{Transverse differential cross-section asymmetry} & \quad \left( \frac{d^2 \sigma \uparrow}{d\Omega dE'} - \frac{d^2 \sigma \downarrow}{d\Omega dE'} \right) = \frac{4\alpha^2 E'^2}{M\nu Q^2 E} \sin \theta \left[ g_1(x, Q^2) + \frac{2E}{\nu} g_2(x, Q^2) \right]
\end{align*}
\]

\(g_2\) term suppressed relative to \(g_1\) term ⇒ At COMPASS, a longitundinally polarised muon beam and a longitundinally polarised target with protons allow the measurement of \(g_1(x, Q^2)\)

\(A_1^p\) and \(g_1^p\) at low \(x\) and \(Q^2\) (COMPASS)
Removal of $\mu e$ elastic scattering events for 2007 data

$q \theta^*$: charge $\times$ angle of the track with respect to the virtual photon direction

The cut effectively eliminates the $\mu e$ events from the sample.
Removal of $\mu e$ elastic scattering events for 2011 data

$q \theta^*$: charge $\times$ angle of the track with respect to the virtual photon direction

The cut effectively eliminates the $\mu e$ events from the sample.
Polar angle of the scattered muon in the laboratory frame

$\mu_0^2$ $\theta$ $A_p^1$ and $g_1^p$ at low $x$ and $Q^2$ (COMPASS)

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Model details

(VMD contribution and QCD improved parton model extended to low $Q^2$)

\[ g_1(x, Q^2) = g_1^{VMD}(x, Q^2) + g_1^{part}(x, Q^2). \] (4)

\[ g_1^{VMD}(x, Q^2) = \frac{pq}{4\pi} \sum_{\nu=\rho,\omega,\phi} \frac{m_\nu^4 \Delta \sigma_\nu(W^2)}{\gamma_\nu^2(Q^2 + m_\nu^2)^2}. \] (5)

\[ \Delta \sigma_\nu = \frac{\sigma_{1/2} - \sigma_{3/2}}{2}, \] (6)

\[ \frac{pq}{4\pi} \sum_{\nu=\rho,\omega} \frac{m_\nu^4 \Delta \sigma_\nu}{\gamma_\nu^2(Q^2 + m_\nu^2)^2} = C \left[ \frac{4}{9} (\Delta u_\nu^0(x) + 2 \Delta \bar{u}^0(x)) + \frac{1}{9} (\Delta d_\nu^0(x) + 2 \Delta \bar{d}^0(x)) \right] \]

\[ \times \frac{m_\rho^4}{(Q^2 + m_\rho^2)^2}, \] (7)

\[ \frac{pq}{4\pi} \frac{m_\phi^4 \Delta \sigma_\phi}{\gamma_\phi^2(Q^2 + m_\phi^2)^2} = C \frac{2}{9} \Delta s_\phi^0(x) \frac{m_\phi^4}{(Q^2 + m_\phi^2)^2}, \] (8)

\[ \Delta p_j^0(x) = C_j (1-x)^{\eta_j}. \] (3)