Results on longitudinal spin physics at COMPASS

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30\textsuperscript{th} June 2015

QCD 15

- COMPASS
- Structure functions
- Quark & gluon polarisation
Spin contributions of the nucleon:

\[ S = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L \]
\[ \Delta \Sigma = \Delta u + \Delta d + \Delta s \]

- Measured in DIS
- Quark spin contributes only about 30% to the nucleon spin
- Gluon contribution constrained only for a limited x range
- Hardly any experimental information on orbital angular momentum
M2 beamline

Polarised $\mu$ beam ($P_b \sim 80\%$)
$160 \text{ GeV/c}, 200 \text{ GeV/c}$

Solid state polarised target ($1.2 \text{ m}$)

Two magnets

Tracking ($p > 0.5 \text{ GeV/c}$)
SciFi, Silicon MicroMega, Gem, MWPC, Straws, Drift tubes

PID: RICH($\pi, K, p$)
ECAL, HCAL, muon filters
Polarised target

- Two/Three target cells, oppositely polarised
- 180 mrad geometrical acceptance
- Regular polarisation reversals by field rotation
- LiD (Longitudinal deuteron polarisation: \(\sim 50\%\))
- \(\text{NH}_3\) (Longitudinal proton polarisation: \(\sim 90\%\))
- 2.5 T solenoid field
- Low temperature 50 mK
Deep Inelastic Scattering

- DIS: $\ell + N \rightarrow \ell' + X$
- SIDIS: $\ell + N \rightarrow \ell' + h + X$

**DIS variables**
- Photon virtuality: $Q^2 = -q^2$
- Bjorken scaling variable: $x = \frac{Q^2}{2 \cdot P \cdot q}$
- Relative photon energy: $y = \frac{E - E'}{E}$

**Hadron variables**
- Hadron energy fraction: $z = \frac{E_h}{E - E'}$
- Transverse momentum: $p_T$
- Longitudinal momentum: $p_L$
Absorption of polarised photons
\[ \sigma_{1/2} \sim q^+ \]
\[ \sigma_{3/2} \sim q^- \]
\[ q(x) = q(x)^+ + q(x)^- \]
\[ \Delta q(x) = q(x)^+ - q(x)^- \]

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

Spin structure function
\[
g_1(x, Q^2) = \frac{1}{2} \sum_q e_q^2 \Delta q(x) = A_1(x, Q^2) \cdot F_1(x, Q^2)
\]
Method (idea)

Aim:
\[ A = \frac{\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\downarrow} + \sigma_{\uparrow\uparrow}} \]

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

Needed:
- Flux cancellation
- Acceptance cancellation
  \rightarrow polarisation rotation
  \rightarrow 3 target cells

\[ A_{\text{exp}} = A \cdot P_B \cdot P_T \cdot f \]
\[ A = A_1 \cdot D \]
\[ f: \text{ Dilution factor} \]
\[ D: \text{ Depolarisation factor} \]

Averaging:
\[ A_{\text{exp}} = \frac{A + A'}{2} = \frac{1}{2} \left( \frac{N_u - N_d}{N_u + N_d} + \frac{N_d' - N_u'}{N_u' + N_d'} \right) \]
$A_1^p$ in bins of $x$ and $Q^2$

- $^{14}$N correction and pol. rad. corrections included
- New data point at very small $x$
- Good agreement between COMPASS 2007 and 2011 data
Result compared to the world data

- COMPASS 2011 (200 GeV)
- COMPASS 2007 (160 GeV)
- COMPASS fit at NLO
- New data point at very low $x$
- Input for global QCD fit
- Indirect $\Delta G$ extraction
NLO QCD analyses

- DGLAP equations

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

\[ \frac{d}{d \ln Q^2} \begin{pmatrix} \Delta q_{Si} \\ \Delta g \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi} \begin{pmatrix} \Delta P^S_{qq} \\ \Delta P^g_{qg} \\ 2n_f \Delta P^g_{gg} \end{pmatrix} \otimes \begin{pmatrix} \Delta q_{Si} \\ \Delta g \end{pmatrix} \]

- Structure function:

\[ g_1 = \frac{1}{2} \langle e^2 \rangle \left( C^{Si}(\alpha_s) \otimes \Delta q_{Si} + C^{NS}(\alpha_s) \otimes \Delta q_{NS} + C^g(\alpha_s) \otimes \Delta g \right) \]

- Input parametrisation \( f \) of \( \Delta q_{Si}, \Delta q_3, \Delta q_8, \Delta g \) at \( Q^2_0 = 1 \text{ GeV}^2 \) needed

\[ f = \eta \frac{x^\alpha(1-x)^\beta(1+\gamma x)}{\int_0^1 x^\alpha(1-x)^\beta(1+\gamma x)dx} \]

- Using only inclusive asymmetries quarks and anti-quarks cannot be disentangled e.g. determination of \( \Delta(u + \bar{u}), \Delta(d + \bar{d}), \Delta(s + \bar{s}) \) and \( \Delta g \)

\[ \Delta q_{Si} = \Delta U + \Delta D + \Delta S, \quad \Delta q_3 = \Delta U - \Delta D, \quad \Delta q_8 = \Delta U + 2\Delta D - \Delta S \]
Input and constraints

\[ \chi^2 = \sum_{n=1}^{N_{\text{exp}}} \left[ \sum_{i=1}^{N_{\text{data}}} \left( \frac{g_{1,1}^{\text{fit}} - N_n g_{1,i}^{\text{data}}}{N_n \sigma_i} \right)^2 + \left( \frac{1 - N_n}{\delta N_n} \right)^2 \right] + \chi^2_{\text{positivity}} \]

- Positivity: \(|\Delta g(x)| < g(x)\) and \(|\Delta(q(x) + \bar{q}(x))| < q(x) + \bar{q}(x)\)
- Overall: 11 free parameters and 495 data points \((W^2 > 10 \text{ GeV}^2)\)
- MSTW2008
Systematic studies

- Remarks on the previously published fit:
  - No systematic uncertainties
- Study impact of:
  - Different parametrisations
  - Reference scale $Q_0^2$
- $\chi^2$ very stable

→ Larger uncertainty compared to statistical one
Polarised parton distributions

- Quark polarisation $0.26 < \Delta \Sigma < 0.36$
- Gluon polarisation $\Delta G = \int \Delta g(x)dx$ Not well constrained → Direct measurement
Bjorken sum rule from COMPASS measurement

\[ \frac{1}{2} \int_{0}^{1} g_{NS}^{1}(x, Q^2) \, dx = \frac{1}{2} \int_{0}^{1} (g_{1}^{p}(x, Q^2) - g_{1}^{n}(x, Q^2)) \, dx = \frac{1}{6} \left| \frac{g_{A}}{g_{V}} \right| C_{NS}^{1}(Q^2) \]

- Non-singlet spin structure function
  \[ g_{NS}^{1} = g_{1}^{p} - g_{1}^{n} = 2 \left[ g_{1}^{p} - \frac{g_{1}^{d}}{1 - 3/2 \omega_D} \right], \omega_D = 0.05 \]

- \( g_{NS}^{1} \) determined from COMPASS data only
  - 2007 & 2011 proton data
  - 2002 - 2004 deuteron data

- \( \left| \frac{g_{A}}{g_{V}} \right| = 1.2701 \pm 0.0020 \) obtained from neutron \( \beta \)-decay.

- Aim: Verification of the Bjorken sum rule
Non-singlet structure function

- Calculate \( g_1^{NS} \)
- Perform NLO QCD fit
  - Fit only \( \Delta q_3 \)
  - 3 parameters needed
- Evolve \( g_1^{NS} \) to \( Q^2 = 3 \text{ (GeV/c)}^2 \)
- Extrapolation used for unmeasured region \((x \rightarrow 0, 1)\)
- 94\% in measured range
- Verification of the Bjorken sum rule:
  
  \[
  g_A / g_V = 1.22 \pm 0.05_{\text{(stat.)}} \pm 0.10_{\text{(syst.)}}
  \]
Access to the gluon polarisation

- Contribution from three processes to the cross section

\[ A_{LL}^h = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} = \alpha \cdot A_{1}^{LO}(x_{Bj}) + \beta \cdot A_{1}^{LO}(x_{C}) + \gamma \cdot \Delta g/g(x_g) \]

\[ A_{1}^{LO} = \frac{\sum_i e_i^2 \Delta q_i}{\sum_i e_i^2 q_i} \]

- From model
- Simultaneous extraction
Method

- Reanalysis with new method (PLB 718 (2013) 922)
- Treat all processes in the same footing
- Factors $\alpha, \beta, \gamma$ depend on: $a_{LL}^i, R_i$
- Use Neural Network to disentangle the processes
  $\rightarrow$ Events are counted 3 times
- Compare expected and observed number of events
  $\rightarrow$ Minimise the $\chi^2$
- Expected Number of events depends on:
  $a_{LL}^i, R_i, A_1^{LO}, \Delta g/g$, acceptance, unpol. cross section, flux
Neural Network

- NN is trained on MC to parametrise $R_i, a^i_{LL}, x_c, x_g$
- Input parameters: $x_{Bj}, Q^2, p_T, p_L$
- High $p_T$: Clean source of PGF/QCDC
- Low $p_T$: Clean source of LP
Neural Network

- NN is trained on MC to parametrise $R_i$, $a_{LL}^i$, $x_c$, $x_g$
- Input parameters: $x_{Bj}$, $Q^2$, $p_T$, $p_L$

- High $p_T$: Clean source of PGF/QCDC
- Low $p_T$: Clean source of LP
Monte Carlo

- Important variables estimate by MC: $R_i, a_{LL}^i, x_c, x_g$
- Good MC description important
- Reasonable description of the data
- Some improvements possible
- COMPASS high $p_T$ tuning
Results

- Assuming $A_{1}^{QCDC}(x_c) = A_{1}^{LP}(x_{Bj})$ for $x_c = x_{Bj}$
- $\Delta g/g = 0.113 \pm 0.038 \pm 0.035$
  - $\langle Q^2 \rangle \approx 3(\text{GeV}/c)^2$, $\langle x_g \rangle \approx 0.10$
- Best combined uncertainty
- Good statistic $\rightarrow$ 3 $x_g$ bins
- First direct measurement of a positive $\Delta g/g$
Summary

- New measurement of $A_1^P$ and $g_1^P$ at 200 GeV/c
  - NLO QCD fit of world data
  - Update on the Bjorken sum rule from COMPASS data only
- Extraction of $\Delta G$ in LO
  - Reanalysis of COMPASS deuteron data
  - New method to extract $\Delta g/g$
  - Reduction of statistical and systematic uncertainties
  - Positive value of $\Delta g/g$ measured