Longitudinale Spinphysik bei COMPASS

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Outline

1. Introduction
2. Results on $A_1^p$ and $g_1^p$
3. NLO QCD fit
4. Validation of the Bjorken sum rule
5. Identified hadron asymmetries
6. Summary and Outlook
Motivation

Longitudinal spin composition of the nucleon:

\[ S_z = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L \]
\[ \Delta \Sigma = \Delta U + \Delta D + \Delta S \]

- Quark spin \( \Delta \Sigma \) contributes only about 30% to the nucleon spin
- Gluon contribution \( \Delta G \) some experimental constrains available
- Hardly any experimental information on orbital angular momentum \( L \)
Deep Inelastic lepton nucleon Scattering

$\ell N \rightarrow \ell' X$

- Measurement of the nucleon structure
- Scattering of leptons on nucleons
- Kinematic domain with no individual resonances
- Measurement of the spin structure
  - Polarised nucleon
  - Polarised leptons
    - $\rightarrow$ Polarised $\gamma$
  - High energetic beam
SPS proton beam

secondary hadron beam ($\rho, \pi, K$) 150 – 270 GeV/c

tertiary muon beam

400 GeV/c

100 – 200 GeV/c
The COMPASS experiment

**COmmon Muon and Proton Apparatus for Structure and Spectroscopy**

- M2 beamline
- Solid state polarised target (1.2 m)
- Polarised μ beam ($P_b \sim 80\%$)
  - Energy: 160 GeV, 200 GeV
  - Flux: $10^8 \mu/s$

**Spectrometer**

- 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

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Polarised target

- Needed: polarised $p, d$
  → Solid state target
- Polarised via DNP
- High magnetic field: 2.5 T solenoid field
- Low temperature 50 mK
- $^6$LiD (Longitudinal deuteron polarisation: $\sim 50\%$)
- NH$_3$ (Longitudinal proton polarisation: $\sim 90\%$)
- Large geometrical acceptance (180 mrad)
Deep Inelastic lepton nucleon 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:** $p_L$
Polarised Deep Inelastic Scattering

- Absorption of polarised photons
  \[
  \sigma_{1/2} \sim q^+ \\
  \sigma_{3/2} \sim q^-
  \]
- Photon nucleon asymmetry
  \[
  A_1(x, Q^2) = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \approx \frac{\sum_q e_q^2(q(x)^+ - q(x)^-)}{\sum_q e_q^2(q(x)^+ + q(x)^-)}
  \]
- Spin structure function
  \[
  g_1(x, Q^2) = A_1(x, Q^2) \cdot F_1(x, Q^2) \approx \frac{1}{2} \sum_q e_q^2 \Delta q(x)
  \]
**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

\[ N_i = a_i \phi_i n_i \sigma (1 + P_B P_T fDA_1) \]
Acceptance cancellation

- Acceptance changes with Z
- Two/Three target cells, oppositely polarised
- Measuring simultaneously both polarisations
- Flux cancels
- Regular polarisation reversals by field rotation
- Once by repolarisation
Data selection

2007 and 2011 data taking

- Target material: NH$_3$
- Increased beam energy: 160 GeV → 200 GeV
  - Higher $Q^2$
  - Smaller $x$

Event selection

- Kinematic cuts:
  - $Q^2 > 1$ (GeV/c$^2$)
  - $0.1 < y < 0.9$ remove hard to reconstruct/radiative events
  - $0.0025(0.004) < x < 0.7$
  - $W^2 > 10$ (GeV/c$^2$)$^2$
  - Extrapolated beam track crosses all target cells
Data quality studies

- Influence of small detector movements, detector problems ...
- Check mean values of different quantities (e.g. Number of tracks)
- Check stability of $K^0$ mass for all runs
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Inputs to for asymmetry calculation

\[ A_{\text{exp}} = A_1 \cdot P_B \cdot P_T \cdot f \cdot D \]

- **D**: Depolarisation factor
- **f**: Dilution factor
- **P_T**: Target polarisation
- **P_B**: Beam polarisation
- **Calculate average**
Systematic studies

- Most important contribution to the systematic uncertainty:
  - False asymmetries
  - Microwave reversal
  - Fake configuration (same spin orientation)
- Several other tests
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![Graph showing A_{fake} vs. x_{Bj}](image-url)
Results on $A_1^p$

- $x$ dependence of the asymmetry
- Rise towards valence region

$g_1^p(x, Q^2) = F_1(x, Q^2)A_1^p(x, Q^2)$
$A_1^D$ in bins of $x$ and $Q^2$

- $^{14}\text{N}$ correction and pol. rad. corrections included
- New data points at very small $x$
- Good agreement between COMPASS results at 160/200 GeV
Result compared to the world data

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

- DGLAP equations

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

\[ \frac{d}{d \ln Q^2} \left( \begin{array}{c} \Delta q_{\text{Si}} \\ \Delta g \end{array} \right) = \frac{\alpha_s(Q^2)}{2\pi} \left( \begin{array}{cc} \Delta P_{qq}^{\text{Si}} & 2n_f \Delta P_{qg} \\ \Delta P_{gq} & \Delta P_{gg} \end{array} \right) \otimes \left( \begin{array}{c} \Delta q_{\text{Si}} \\ \Delta g \end{array} \right) \]

- Structure function:

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

- \( \Delta q_{\text{Si}} = \Delta U + \Delta D + \Delta S, \Delta q_3 = \Delta U - \Delta D, \Delta q_8 = \Delta U + 2\Delta D - \Delta S \)

- 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 \( \Delta g \)
No $x$ dependence given

Input parametrisation at $Q_0^2 = 1 \text{(GeV/c)^2}$ needed

Guess parametrisation

- Low $x$: $x^\alpha$
- High $x$: $(1 - x)^\beta$
- Allow for a node: $1 + \gamma x$

$$f = \eta \frac{x^\alpha (1 - x)^\beta (1 + \gamma x)}{\int_0^1 x^\alpha (1 - x)^\beta (1 + \gamma x) dx}$$
\[ \chi^2 = \sum_{n=1}^{N_{\text{exp}}} \left[ \sum_{i=1}^{N_n^{\text{data}}} \left( \frac{g^\text{fit}_{n,i} - N_n g^\text{data}_{n,i}}{N_n \sigma_i} \right)^2 + \left( \frac{1 - N_n}{\delta N_n} \right)^2 \right] + \chi^2_{\text{positivity}} \]

- 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 (\( W^2 > 10 \text{ GeV}^2 \))
- Unpolarised parton distributions from MSTW2008
Solutions for parton distributions

- Several equally good solutions
- Two extremes selected
- Systematic studies:
  - Different parametrisations
  - Reference scale $Q_0^2$
  - $\chi^2$ very stable

→ Systematic uncertainty larger than statistical
Statistical uncertainty

- Generation of 1000 sets of pseudo data:
  - Randomise data points according to a normal law
- Fit each data set
- Calculate mean and spread $\rightarrow 1\sigma$ interval

Confidence level 68%

$Q^2 = 3 \text{ (GeV/c)}^2$
Polarised parton distributions

- Quark polarisation \(0.26 < \Delta \Sigma < 0.36\)
- Gluon polarisation \(\Delta G = \int \Delta g(x)dx\) Not well constrained

\("\rightarrow\) Direct measurement
First moments from COMPASS data

\[ \Gamma_{p,n}^{p,n}(Q^2) = \frac{1}{36} \int_0^{x_{min}} g_{1}^{p,n}(x, Q^2) dx = \frac{1}{36} \left[ (a_8 \pm 3a_3) C^{NS}(Q^2) + 3a_0 C^{S}(Q^2) \right] \]

- Evolve \( g_1 \) to \( Q^2 = 3 \text{ (GeV/} c)^2 \)
- Use results from QCD fit
- Calculate contributions from unmeasured region \( (x \to 0, 1) \)

\[ \Gamma_{1}^{P} = 0.139 \pm 0.003_{\text{stat}} \pm 0.009_{\text{syst}} \pm 0.005_{\text{evol}} \]
\[ \Gamma_{1}^{N} = 0.049 \pm 0.003_{\text{stat}} \pm 0.004_{\text{syst}} \pm 0.004_{\text{evol}} \]
Bjorken sum rule from COMPASS measurement

\[
\int_0^1 g_{1NS}(x, Q^2) dx = \frac{1}{6} \left| \frac{g_A}{g_V} \right| C_{1NS}(Q^2)
\]

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

- \( g_{1NS} \) 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 ($x \to 0, 1$)
- 94% in measured range
- Verification of the Bjorken sum rule:
$$\left| \frac{g_A}{g_V} \right|_{\text{NLO}} = 1.22 \pm 0.05\text{(stat.)} \pm 0.10\text{(syst.)}$$
Hadron Asymmetries

\[ A_1^h(x, z) = \frac{\sum_q e_q^2 (\Delta q(x) D_q^h(z) + \Delta \bar{q}(x) D_{\bar{q}}^h(z))}{\sum_q e_q^2 (q(x) D_q^h(z) + \bar{q}(x) D_{\bar{q}}^h(z))} \]

- Calculate asymmetry for hadrons ($\pi^\pm$, $K^\pm$)
- Particle identification needed
- Use the RICH detector
- Determine identification efficiencies
- Access to all helicity distributions $\Delta q(x), \Delta \bar{q}(x)$
- Dependence on fragmentation functions $D_q^h(z)$
The RICH detector

- Using the Cherenkov effect
- Ring projected on photo detectors
- Likelihood method for identification
Momentum dependence of the Cherenkov angle
Efficiency determination - method I

- Needed: Known particle ID without RICH information
- Use:
  - $K^0 \rightarrow \pi^+\pi^-$
  - $\phi \rightarrow K^+K^-$
  - $\Lambda \rightarrow \pi^-p$
- Weak decays of $K^0/\Lambda$: secondary vertex seen
  $\rightarrow$ Cleaner sample
- Strong decays of $\phi$: secondary vertex not seen
  $\rightarrow$ Larger background
Assumption: Efficiency depends mainly on particle momentum and entry angle.

- Strong momentum dependence: 13 bins ($10 - 50 \text{ GeV}/c$)
- Weak angular dependence: 4 bins ($0 - 0.3 \text{ rad}$)

Tag one of the decay particles using the RICH (e.g. $\pi^-$ from $K^0$ decay)

ID of the second particle known (must be $\pi^+$)

Check the answer from the RICH (Identified as $\pi/K/p/no\text{ID}$)
Fit of the invariant mass spectra

Fit simultaneously all five histograms

Constrain on $N(\text{all}) = N(\pi) + N(K) + N(p) + N(\text{noID})$

$\rightarrow$ Efficiency between 0% and 100%

Efficiency $\epsilon(\pi^+ \rightarrow K^+) = N(\pi \rightarrow K)/N(\text{all})$

- $N(\text{all})$ constrained by first histogram (all particles)
- $N(\pi \rightarrow K)$ from third histogram ($\pi$ identified as $K$)
Purity determination

- Coverage in the angle $\theta$ and momentum $p$
- Only one $x$-bin shown
- So far: RICH efficiency $\rightarrow$ detector property
- Needed: Purity/Contaminations $\rightarrow$ physics quantity
- Determined by:
  - Number of true hadrons
  - Number of Identified hadrons
  - RICH efficiency
Purity results
First results

- First very preliminary results
- Unfolding: $A_{1,\text{true}} = \left(Q^T\right)^{-1} A_{1,\text{id}}$
- 2011: Take into account protons
- Small correction
- No correlations calculated so far
- Systematic studies ongoing
Summary and Outlook

- New measurement of $A_1^p$ and $g_1^p$ at 200 GeV
  - NLO QCD fit of world data
  - Update on the Bjorken sum rule from COMPASS data only
  - Verification of the Bjorken sum rule

- Identified hadron asymmetries
  - Method for extracting RICH efficiencies
  - Determination of the hadron purities
  - First results on the asymmetry

- Outlook
  - Further work on the identified hadron asymmetries
  - Extraction of polarised PDFs for each flavour