Overview of the nucleon spin studies at COMPASS

Nucleon: almost all visible matter

Spin: fundamental quantum number

ICNFP 2013 - Crete, Greece

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Motivation

**Motivation I: Nucleon spin structure**

Where does the proton spin (complex structure in QCD) come from?

\[
\left( \frac{S_z^N}{\hbar} \right) = \frac{1}{2} \Delta \Sigma + L^q_z + \Delta G + L^g_z = \lim_{t \to 0} \int_{-1}^{+1} dx x \left[ H(x, \xi, t) + E(x, \xi, t) \right] + J^g
\]

\[ GPDs \]

- \( \Delta \Sigma = \int_0^1 \Delta u(x) + \Delta \bar{u}(x) + \Delta d(x) + \Delta \bar{d}(x) + \Delta s(x) + \Delta \bar{s}(x) dx \)
- \( \Delta G = \int_0^1 \Delta g(x) dx \)
- \( L^q \) related to TMDs
- \( \Delta \Sigma + L^q \) related to GPDs

**Motivation II: Parton Distribution Functions (PDFs), TMDs and GPDs**

- Mostly studied in polarised Deep Inelastic Scattering (DIS)
- \( q(x), g(x) \)
- \( \Delta q(x), \Delta g(x) \)
- \( \Delta_T q(x) \)
- \( \Delta \Sigma \)
- Transverse Momentum \( k_T \) Dependent PDFs
- Generalized Parton Distributions

\[ \begin{align*}
Q^2 &= -q^2 \\
\nu &= E - E' \\
x &= \frac{Q^2}{2M\nu} \\
y &= \frac{\nu}{E}
\end{align*} \]
Common Muon and Proton Apparatus for Structure and Spectroscopy

Muon programme
- Spin dependent structure function $g_1$
- Gluon polarisation in the nucleon
- Quark polarisation distributions
- Transversity and TMDs
- Vector meson production
- $\Delta$ polarisation

Hadron programme
- Primakoff effect, $\pi$ & K polarisabilities
- Exotic states, glueballs
- (Double) charmed baryons
- Multiquark states

Future: Polarised Drell-Yan physics and DVCS for GPDs
(using $\pi^-$ beam)

Taking data since 2002 using:
- $\mu^+$: Polarised $^6$LiD and NH$_3$ targets
- $\pi^-$: LH$_2$ target
The spectrometer and polarised (longitudinal example) target

Polarised Target Setup: 2006 onwards

Target: \(^6\text{LiD} \ (2002-06) – \text{NH}_3 \ (2007-11)\)

- \(P_T \sim 50\% / 90\%\)
- \(f \text{ (dilution factor)} \sim 40\% / 16\%\)
- \(T \sim 50 \text{ mK} \ \left(\text{\(^3\text{He} / \text{\(^4\text{He}\)}}\right)\)

2002-2004 setup

- \(P \mu \sim 80\\%\)
- 160 GeV/c

\(\pm 180\) mrad

Polarised cells
Leading Order (LO) description of the nucleon structure

(when the intrinsic transverse momentum of quarks, $k_T$, is also taken into account)

8 TMD PDFs are required:

<table>
<thead>
<tr>
<th>Quark Nucleon</th>
<th>Unpolarised</th>
<th>Longitudinal Polarisation</th>
<th>Transverse Polarisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unpolarised</td>
<td>$f_1$</td>
<td></td>
<td>$h_{1L}^\perp$ (Boer Mulders)</td>
</tr>
<tr>
<td></td>
<td>(Unpolarised)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$f_{1T}^\perp$ (Sivers)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal Polarisation</td>
<td>$g_1$ (Helicity)</td>
<td>$h_{1T}^\perp$ (Worm Gear)</td>
<td>$h_1$ (Number density)</td>
</tr>
<tr>
<td>Transverse Polarisation</td>
<td>$f_{1T}^\perp$ (Sivers)</td>
<td>$g_{1T}$ (Worm Gear)</td>
<td>$h_{1T}^\perp$ (Worm Gear)</td>
</tr>
</tbody>
</table>

- Study $\Delta q(x, Q^2)$ and $\Delta g(x, Q^2)$
- Study $\Delta_T q(x, Q^2)$
- Surviving $k_T$ integration
- Contain information about the Orbital Angular Momentum (OAM) of quarks
- Investigated at COMPASS via measurement of spin asymmetries

\[
\Phi_{coll}^{\perp, 2}(x) = \frac{1}{2} \left[ q(x) + S_L y_5 \Delta q(x) + S_L y_5 y' \Delta_T q(x) \right]
\]
COMPASS results with a longitudinally polarised target
Asymmetry measurement (example): $A_1^N := \frac{\Delta \sigma_{\gamma^*N}}{\sigma_{\gamma^*N}} = \frac{\sigma_{\gamma^*N} \uparrow \rho - \sigma_{\gamma^*N} \downarrow \rho}{\sigma_{\gamma^*N} \uparrow \text{unpol}}$

- The number of reconstructed events inside each spin configuration of the target, $N_t$ ($t = u, d, u', d'$), can be used to extract the inclusive $A_1^d / A_1^p$ asymmetries:

$$A_{\text{exp}} = \frac{1}{2} \left( \frac{N_u - N_d}{N_u + N_d} + \frac{N_d' - N_u'}{N_d' + N_u'} \right)$$

$$= f \cdot P_{\mu} \cdot P_T \cdot D \cdot A_1^N$$

$D = \text{Depolarisation factor}$

- Weighting each event with $\omega = (fP_{\mu}D)$:

$$A_1 = \frac{1}{2P_T} \left( \frac{\sum_{i=0}^{N_u} \omega_i - \sum_{i=0}^{N_d} \omega_i}{\sum_{i=0}^{N_u} \omega_i^2 + \sum_{i=0}^{N_d} \omega_i^2} + \frac{\sum_{i=0}^{N_u'} \omega_i - \sum_{i=0}^{N_d'} \omega_i}{\sum_{i=0}^{N_u'} \omega_i^2 + \sum_{i=0}^{N_d'} \omega_i^2} \right)$$

statistical gain:

$$\left\langle \sum_{i=0}^{N_{\text{tot}}} \omega_i^2 \right\rangle$$

$$\left\langle \sum_{i=0}^{N_{\text{tot}}} \omega_i \right\rangle^2$$

$\approx 8 \text{ hr}$

Field rotation

equal acceptance for both cells
Interpretation of $A_1$ in terms of structure functions

$g_1 (polarised structure function)$ is obtained from the measured $A_1$ using:

$$A_1(x, Q^2) = \frac{\sigma_{\gamma^*N} - \sigma_{\gamma^*N}}{\sigma_{\gamma^*N}} \approx \frac{\sum q e_q^2 \Delta q (x, Q^2)}{\sum q e_q^2 q (x, Q^2)} = \frac{g_1(x, Q^2)}{F_1(x, Q^2)} = \frac{g_1(x, Q^2) 2x (1 + R)}{F_2(x, Q^2)}$$

- $\Delta q (x) = q(x)^+ - q(x)^-$
- $q(x) = q(x)^+ + q(x)^-$
- $+ \text{ quark } \uparrow \text{ nucleon}$
- $- \text{ quark } \downarrow \text{ nucleon}$

- $F_2 \rightarrow \text{ SMC parameterisation}$ and $R = \sigma^L/\sigma^T \rightarrow \text{ SLAC parameterisation}$
COMPASS results for $g_1^{d/p}$ and first moments of $g_1^d$

$$\Gamma_1^N(Q_0^2=3\text{(GeV/c)}^2) = \int_0^1 g_1(x)\,dx = 0.0502 \pm 0.0028\text{(stat)} \pm 0.0020\text{(evol)} \pm 0.0051\text{(syst)}$$

$$= \frac{1}{9} \left( 1 - \frac{\alpha_s(Q^2)}{\pi} + O(\alpha_s^2) \right) \left( a_0(Q^2) + \frac{1}{4} a_8 \right) \Rightarrow a_0 = 0.35 \pm 0.03\text{(stat)} \pm 0.05\text{(syst)}$$

$$\Delta \Sigma^{\text{MS}} = 0.33 \pm 0.03\text{(stat)} \pm 0.05\text{(syst)} \quad (\Delta \Sigma^{\text{MS}} = a_0 \text{ @ } Q^2 \to \infty)$$

$$= 0.30 \pm 0.01\text{(stat)} \pm 0.02\text{(syst)} \quad \text{(using world data on } p, n, d)$$

$$\frac{1}{3} (\Delta \Sigma^{\text{MS}} - a_8) = -0.08 \pm 0.01\text{(stat)} \pm 0.02\text{(syst)}$$
Extraction of the quark helicity distributions from Semi-Inclusive DIS (SIDIS)

- We have at Leading Order (LO) in QCD:

$$A_{1,(p/d)}^{h}(x,z,Q^2) \approx \frac{\sum_q e_q^2 \Delta q(x, Q^2) D_q^h(z, Q^2)}{\sum_q e_q^2 q(x, Q^2) D_q^h(z, Q^2)}$$

- Unpolarised PDFs ($q(x, Q^2)$) → MRST04
- Fragmentation function of a quark to a hadron ($D_q^h(z, Q^2)$) → DSS parameterisation

- Results for $A_{1,(p/d)}^{h}$ (allows the separate extraction of $\Delta u, \Delta d, \bar{\Delta} u, \bar{\Delta} d, \Delta s$ and $\bar{\Delta} s$):

![Graphs showing A1 distributions for different hadrons and x values]
Quark helicities from SIDIS: $Q^2 = 3 \, (\text{GeV}/c)^2$ and $x < 0.3$

- COMPASS PLB693(2010)227, ○ HERMES, — DSSV

No flavor asymmetry in the polarised sea

- Sea distributions $\sim 0$
- Good agreement with DSSV fits
- Flavour separation until $x \sim 0.004$

Assume $\Delta s = \Delta \bar{s}$

$\Delta s_{\text{(SIDIS)}} = -0.01 \pm 0.01\, (\text{stat.}) \pm 0.01\, (\text{syst.}) \quad @ \, 0.003 < x < 0.3$
The relation between the semi-inclusive asymmetries and $\Delta s$ depends only on the following ratios:

$$R_{UF} = \frac{\int_{0.2}^{0.85} D_d^{K^+}(z) \, dz}{\int_{0.2}^{0.85} D_u^{K^+}(z) \, dz}, \quad R_{SF} = \frac{\int_{0.2}^{0.85} D_s^{K^+}(z) \, dz}{\int_{0.2}^{0.85} D_u^{K^+}(z) \, dz}$$

$R_{UF}$ is varied linearly from 0.13 (DSS) at $R_{SF} = 6.6$ to 0.35 (EMC) at $R_{SF} = 3.4$ (to maintain constant the $K^+$ multiplicity).

- Determination of $R_{SF}$ from hadron multiplicities on the way
A first look on hadron multiplicities

- **Assuming the quark parton model** (leading order):

\[
\frac{dM^h(x, Q^2, z)}{dz} = \sum_q e_q^2 f_q(x, Q^2) D^h_q(z, Q^2) = \frac{\text{hadron yields}}{\text{DIS events yields}}
\]

Data can be used to improve our knowledge on FFs, \( \Delta s(x) \) and \( s(x) \)

Experimental definition

\[
\begin{align*}
Q(x) \int (4D^K_u(z) + 6D^K_d(z)) \, dz + S(x) \int (2D^K_S(z) + 2D^K_d(z)) \, dz \\
= 5Q(x) + 2S(x)
\end{align*}
\]
Direct measurement of $\Delta g/g$ at LO in QCD

There are two methods to tag this process:

- **Open Charm production**
  - $\gamma^*g \rightarrow c\bar{c} \Rightarrow$ reconstruct $D^0$ mesons
  - Hard scale: $M_c^2$
  - No intrinsic charm in COMPASS kinematics
  - No physical background
  - Weakly model dependent
  - Low statistics

- **High-$p_T$ hadron pairs**
  - $\gamma^*g \rightarrow q\bar{q} \Rightarrow$ reconstruct 2 jets or $h^+h^-$
  - Hard scale: $Q^2$ or $\Sigma p_T^2$ [$Q^2 > 1$ or $Q^2 < 1$ (GeV/c)$^2$]
  - High statistics
  - Physical background
  - Strongly model dependent

Photon-gluon fusion process (PGF)

\[
A_{\mu N}^{\text{PGF}} = \frac{\int d\hat{s} \Delta \sigma_{\text{PGF}} \Delta g(x_g, \hat{s})}{\int d\hat{s} \sigma_{\text{PGF}} g(x_g, \hat{s})} \approx \left(a_{\text{LL}}^{\text{PGF}}\right) \frac{\Delta g}{g}
\]

Obtained from Monte Carlo and parameterised by a Neural Network (to be used on data)
Results on $\Delta g/g$ and $x\Delta g$

**World data at LO**

![Graph showing world data at LO]

**COMPASS Open-Charm at NLO**

![Example of NLO diagrams]

$$\int_0^1 \Delta g \, dx = 0.27 \pm 0.09$$

$$\int_0^1 \Delta g \, dx = -0.34 \pm 0.12$$
COMPASS results with a transversely polarised target
Interpretation of Collins & Sivers asymmetries in terms of TMDs

Collins Angle

\[ A_{\text{Coll}} \approx \sum_q e^2_q \frac{h^q_1 \otimes H^\perp_1}{\sum_q e^2_q f^q_1 \otimes D^h_{1q}} \]

Sivers Angle

\[ A_{\text{Siv}} \approx \sum_q e^2_q \frac{f^\perp_{1T} \otimes D^1_{1q}}{\sum_q e^2_q f^q_1 \otimes D^h_{1q}} \]

measured by fitting the corresponding \((\phi^h, \phi^S)\) distributions \((\sigma^{\text{SIDIS}})\) in different \(x, z, p_T^h\) bins

Collins Angle

\[ \sin(\Phi^h + \Phi^S) \]

Sivers Angle

\[ \sin(\Phi^h - \Phi^S) \]

The “Collins Effect”

\[ h^q_1(x) \otimes H^\perp_1(z, p_T) \]

The “Sivers Effect”

\[ f^\perp_{1T}(x, k_T) \otimes D^1(z) \]

Angle of hadron / initial quark spin

Angle of hadron / final quark spin

sensitive to transversity and spin-orbit effects in fragmentation

sensitive to quark orbital motion

\( \otimes \) denotes convolution over intrinsic quark \( k_T \) & fragmentation \( p_T \)
Results on the Collins asymmetry
(correlation between the hadron \( p_T \) & the quark transverse spin in a transversely polarised nucleon)

Understood as:
- u - d cancellation
- favored/unfavored Collins FF


COMPASS 2007, 2010 proton data
Transversity from Collins asymmetry

Combined analysis of HERMES-proton, COMPASS-deuteron and BELLE FF data:

- $\Delta_T u > 0$ and $\Delta_T d < 0$
  (u quark transversity along nucleon spin)
- Smaller amplitudes than helicity

\[ A^p_{\text{coll}}: \text{COMPASS vs. HERMES} \]

\[ x \Delta_T u(x), x \Delta_T d(x) \]

- Same signal strength, although different $Q^2$ (~ factor of 4)

\[ Q^2=2.41 \text{ GeV}^2 \]

\[ x \Delta_T u(x), x \Delta_T d(x) \]

\[ x \text{ vs. } Q^2 \]

\[ 2013, 2008 \]

\[ 0.001, 1 \]
Results on the Sivers asymmetry
(correlation between the nucleon transverse spin and the quark $k_T$)


COMPASS 2007, 2010 proton data

Understood as:
- u - d cancellation

Large signal for $h^+$
Sivers function and Orbital Angular Momentum (OAM)

(Ji sum rule: $J^q = \frac{1}{2}\Delta \Sigma + L^q = \frac{1}{2}\int_0^1 dx \ x [H^q(x,0,0) + E^q(x,0,0)] = \frac{1}{2} - J^g$)

Combined analysis of HERMES-p and COMPASS-d:

Smaller signal at higher $Q^2$ (COMPASS)

Use SIDIS Sivers asymmetry data to constrain shape.

Possibility to estimate the orbital angular momentum from $E^q$
COMPASS future
COMPASS future I (2015): TMDs from polarised Drell-Yan

DRELL-YAN PROCESS

\[ \sigma_{\text{DY}} \propto f_{\bar{u}/\pi^-} \otimes f'_{u/P} \]

- Convolution of 2 TMDs \textit{(no FF involved)}:

- Test of the TMD universality factorization approach \textit{(for the description of SSA)}:

\[ f_{1T}^+ \mid_{\text{DY}} = - f_{1T}^+ \mid_{\text{DIS}} \quad \& \quad h_1^+ \mid_{\text{DY}} = - h_1^+ \mid_{\text{DIS}} \]

- Study the production mechanism and the polarisation of $J/\Psi$

Main modifications in the spectrometer

- Large acceptance in the valence region where large single spin asymmetries (SSA) are expected

Clean access to 4 azimuthal modulations
\textit{(Boer-Mulders, Sivers, Pretzelosity and Transversity)}
COMPASS future II (2016, 2017): GPDs and nucleon tomography

- Measurement of 4 generalised parton distributions (GPDs) for quarks: $H, E, \tilde{H}, \tilde{E}(x, \xi, t)$
  - Contain normal PDF and elastic form factor as limiting cases: $q(x) = H(x,0,0)$ and $F(t) = \int dx H(x, \xi, t)$
  - Correlates transverse spatial and longitudinal momentum degrees of freedom (nucleon tomography)
  - Access the OAM of quarks via the Ji sum rule

- The GPD $H$ will be determined by studying the azimuthal dependence of the DVCS cross-section (combining the data of $\mu^+$ and $\mu^-$ beams on a liquid hydrogen target):

- For the cases of $\xi = 0$, we have a purely transverse $\Delta^2$:

Deeply Virtual Compton Scattering (DVCS)

Tomography!
**Summary**

- **Gluon contribution to the nucleon spin:**
  - All measurements point to zero or small contribution

- **Quark contribution to the nucleon spin:**
  - Extraction for all flavours from SIDIS *(more knowledge on FF is needed for Δs)*
  - A global contribution of 30% was measured with high precision

- **Transversity and TMDs**
  - Precise results on Collins and Sivers asymmetries

- **Exciting future program in preparation** *(polarised Drell-Yan and DVCS):*
  - 3D imaging of the nucleon
  - **OAM**
    - $L_q$
    - $L_g$
    - $1/2 \Delta \Sigma$
    - $\Delta G$
    - $J_q$
    - $J_g$

  ![3D imaging of the nucleon](image)
The polarised beam

Naturally polarised muon beam: $P_\mu \sim 80\%$

- beryllium target
- 500 mm long
- $\pi$ and $K$ produced

Primary beam:
- protons (400 GeV)
- $\sim 10^{13}$ p / spill
- spill: 4.8 / 16.8 s

Secondary beam:
- $\sim 96\% \pi$
- 500 m long decay pipe

Tertiary beam $\mu^+$:
- Focusing and momentum selection (160 GeV)
- BMS - momentum measurement
- $2 \times 10^8 \mu^+$/spill

SPS

M2 beam line

Hadron absorber

COMPASS target
Inclusive asymmetries $A_1^{d/p}$: $Q^2 > 1 \text{ (GeV/c)}^2$
Q² dependence of g₁(x, Q²) for DGLAP evolution

- ΔΣ and ΔG can be extracted from Next-to-Leading Order (NLO) fits to the g₁ data (g₁ ∝ ΔΣ and ΔG), using their Q² evolution obtained from the DGLAP equations:

\[
\frac{d}{d\ln Q^2} \Delta q^{NS} = \Delta P_{qq}^{NS} \otimes \Delta q^{NS}
\]

\[
\frac{d}{d\ln Q^2} \left( \frac{\Delta q^S}{\Delta g} \right) = \begin{pmatrix} \Delta P_{qq}^S & \Delta P_{gg}^S \\ \Delta P_{gq}^S & \Delta P_{gg}^S \end{pmatrix} \otimes \begin{pmatrix} \Delta q^S \\ \Delta g \end{pmatrix}
\]

- (Δu + Δ̄u) and (Δd + Δ̄d) are well constrained by the data (LSS PRD 80 2009)

- Despite of the higher Q² measurements by COMPASS, the kinematic coverage is not yet sufficient for ΔG
Bjorken sum rule

- According to the Bjorken sum rule the first moment of the non-singlet spin structure function, $g_{1}^{NS}$, is proportional to the ratio of axial and vector coupling constants $g_{A}/g_{V}$:

$$\int_{0}^{1} g_{1}^{NS}(x, Q^2) dx = \frac{1}{6} \left| \frac{g_{A}}{g_{B}} \right| C_{1}^{NS}(Q^2)$$

- QCD fit of COMPASS data using $\Delta q^{NS} = |g_{A}/g_{V}| x^{\alpha}(1 - x)^{\beta}$:

$$\left| \frac{g_{A}}{g_{V}} \right| = 1.28 \pm 0.07 \text{(stat)} \pm 0.10 \text{(sys)}$$  

( PDG value: $|g_{A}/g_{V}| = 1.269 \pm 0.003$ )
D⁰ mass spectra (all samples): \[ A_{D^0}^{\exp} = f P_\mu P_T \frac{S}{S+B} A_{\mu N}^{\text{PGF}} \]

- **Wrong Charge Combination of Kπ pairs:** Example of a background model used for the multidimensional kinematic parameterisation (performed by a Neural Network) of S/(S+B)

Number of D⁰:
- Total → 86250
- \(^6\text{LiD}\) → 57400
- \(\text{NH}_3\) → 28850
s/(s+b): Obtaining final probabilities for a D⁰ candidate

- **Events with small \( [s/(s+b)]_{NN} \)**
  - Mostly combinatorial background is selected

\[
s/(s+b) \text{ is obtained from a fit to these spectra (correcting all events with the corresponding values of } [s/(s+b)]_{NN} \text{)}
\]

- **Events with large \( [s/(s+b)]_{NN} \)**
  - Mostly Open Charm events are selected

\[
\delta \left( \frac{\Delta g}{g} \right) = \frac{1}{\text{FOM}}
\]
$x_g$ from Open Charm
**AROMA with PS-ON versus COMPASS data**

- Differential cross section for $D^*$ meson production ($D_{K\pi}^0$ (2004) from $D^{*+}$ and $D^{*-}$ COMPASS data):

  \[
  \sigma(D^{*\pm}) = 1.8 \pm 0.4 \text{ nb}
  \]
  within $20 \text{ GeV} < E_D < 80 \text{ GeV}$
Intrinsic charm models

High-$p_T$ asymmetries (2002-2006): $Q^2 > 1 \text{ (GeV/c)}^2$

- Two samples are considered (fractions of the processes are estimated from MC):

\[
A_{d}^{d}(x) = \frac{\Delta g}{g}(x_g)\left(a_{\text{LL}}^{\text{PGF, inc}} \frac{\sigma^{\text{PGF, inc}}}{\sigma^{\text{Tot, inc}}}ight) + A_{1}^{\text{LO}}(x_C)\left(a_{\text{LL}}^{\text{C, inc}} \frac{\sigma^{\text{C, inc}}}{\sigma^{\text{Tot, inc}}}ight) + A_{1}^{\text{LO}}(x_{Bj})\left(D \frac{\sigma^{\text{LO, inc}}}{\sigma^{\text{Tot, inc}}}ight)
\]

\[
A_{2h}^{2h}(x) = \frac{A_{\text{exp}}^{\text{exp}}}{f \mu_P \mu_T}(x_g)\left(a_{\text{LL}}^{\text{PGF}} \frac{\sigma^{\text{PGF}}}{\sigma^{\text{Tot}}}ight) + A_{1}^{\text{LO}}(x_C)\left(a_{\text{LL}}^{\text{C}} \frac{\sigma^{\text{C}}}{\sigma^{\text{Tot}}}ight) + A_{1}^{\text{LO}}(x_{Bj})\left(D \frac{\sigma^{\text{LO}}}{\sigma^{\text{Tot}}}ight)
\]

high-$p_T$ hadron pairs ($p_{T1} / p_{T2} > 0.7 / 0.4 \text{ GeV/c}$) $\Rightarrow$ enhancement of the PGF contribution
**High-$p_T$ analysis:** $Q^2 < 1 \text{ (GeV/c)}^2$

2002-2004 Preliminary:

$\Delta G/G = 0.016 \pm 0.058 \text{ (stat)} \pm 0.055 \text{ (syst)}$

2002-2003 Published:

$\Delta G/G = 0.024 \pm 0.089 \text{ (stat)} \pm 0.057 \text{ (syst)}$  