Latest results on longitudinal spin physics at COMPASS

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Outline

Results from longitudinally polarised nucleons:

- $A_1^{d/p}$, $g_1^{d/p}$, and first moments of $g_1^d$
- Semi-inclusive asymmetries and flavour separation
- Hadron multiplicities
- Gluon polarisation at LO in QCD:
  - Open Charm
  - High-$p_T$ hadron pairs
- Gluon polarisation at NLO in QCD:
  - Open Charm
The spectrometer and polarised target

Polarised Target: 2006-2007 setup

Target: $^6$LiD (2002-06) - NH$_3$ (2007)

$P_T \sim 50\% / 90\%$

$f$ (dilution factor) $\sim 40\% / 16\%$

$T \sim 50$ mK ($^3$He / $^4$He)

$P^\mu \sim 80\%$

160 GeV/c

2002-2004 setup

Upstream cell

Downstream cell

$\mu$-beam
Inclusive asymmetries and spin structure functions
Asymmetry measurement: \( A_1^N := \frac{\Delta \sigma_{\gamma^*N}}{\sigma_{\gamma^*N}} = \frac{(\sigma_{\gamma^*N}^{\uparrow} - \sigma_{\gamma^*N}^{\downarrow})}{\sigma_{\gamma^*N}^{\text{unpol}} - \sigma_{\gamma^*N}^{\text{unpol}}(\text{field rotation})} \)

- 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 \( A_1^d / A_1^p \) asymmetries:

\[ A_{\text{exp}} = \frac{1}{2} \left( \frac{N_u - N_d}{N_u + N_d} + \frac{N_{d'} - N_{u'}}{N_{d'} + N_{u'}} \right) \]

\[ = f \cdot P_\mu \cdot P_T \cdot D \cdot A_1 \rightarrow A^{\mu N} \]

\( D = \text{Depolarisation factor} \)

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

\[ A_1 = \frac{1}{2P_T} \left( \sum_{i=0}^{N_u} \omega_i^2 - \sum_{i=0}^{N_d} \omega_i^2 + \sum_{i=0}^{N_{u'}} \omega_i^2 - \sum_{i=0}^{N_{d'}} \omega_i^2 \right) \]

\[ = \frac{(\sum_{i=0}^{N_u} \omega_i - \sum_{i=0}^{N_d} \omega_i)(\sum_{i=0}^{N_{u'}} \omega_i - \sum_{i=0}^{N_{d'}} \omega_i)}{(\sum_{i=0}^{N_u} \omega_i^2 + \sum_{i=0}^{N_d} \omega_i^2) + (\sum_{i=0}^{N_{u'}} \omega_i^2 + \sum_{i=0}^{N_{d'}} \omega_i^2)} \]

Statistical gain:

\[ \frac{\left\langle \sum_{i=0}^{N_{tot}} \omega_i^2 \right\rangle}{\left\langle \sum_{i=0}^{N_{tot}} \omega_i \right\rangle^2} \]
Inclusive asymmetries $A_1^{d/p}$: $Q^2 > 1 \text{ (GeV/c)}^2$

Good agreement between all experimental points

Significant improvement of precision in the low $x$ region: $A_1^d$ compatible with zero for $x < 0.01$

No negative trend for $A_1^d$
Interpretation of $A_1$ in terms of structure functions

$\Delta q(x) = q(x)^+ - q(x)^-$

$q(x) = q(x)^+ + q(x)^-$

+ quark $\uparrow\uparrow$ nucleon

- quark $\uparrow\downarrow$ nucleon

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

$$A_1(x, Q^2) = \frac{\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\downarrow} + \sigma_{\uparrow\uparrow}} \approx \frac{\sum_q e_q^2 \Delta q(x, Q^2)}{\sum_q e_q^2 q(x, Q^2)} = \frac{g_1(x, Q^2)}{F_1(x, Q^2)} = \frac{g_1(x, Q^2) 2x (1 + R)}{F_2(x, Q^2)}$$

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

\[
\Gamma_1^N(Q_0^2=3(\text{GeV}/c)^2) = \int_0^1 g_1(x) \, dx = 0.0502 \pm 0.0028(\text{stat}) \pm 0.0020(\text{evol}) \pm 0.0051(\text{syst})
\]
\[
= \frac{1}{9} \left( 1 - \frac{\alpha_s(Q^2)}{\pi} + O(\alpha_s^2) \right) \left(a_0(Q^2) + \frac{1}{4} a_8\right) \Rightarrow a_0 = 0.35 \pm 0.03(\text{stat}) \pm 0.05(\text{syst})
\]

\[
\Delta \Sigma^{\text{MS}} = 0.33 \pm 0.03(\text{stat}) \pm 0.05(\text{syst}) \quad (\Delta \Sigma^{\text{MS}} = a_0 \ @ Q^2 \to \infty)
\]
\[
(\Delta s + \Delta \bar{s}) = \frac{1}{3}(\Delta \Sigma^{\text{MS}} - a_8) = -0.08 \pm 0.01(\text{stat}) \pm 0.02(\text{syst})
\]
Semi-inclusive asymmetries and flavour separation
Extraction of the quark helicity distributions from SIDIS

- The outgoing hadron tags the quark flavour

- Required: fragmentation function of a quark $q$ to a hadron $h$: $D^h_q(z, Q^2)$

\[ z = \frac{E_h}{E_\mu - E'_\mu} \]

- The semi-inclusive asymmetries have the following interpretation (at LO):

\[ A_1^{h(p/d)}(x, z, Q^2) \approx \frac{\sum_q e_q^2 \Delta q(x, Q^2) D^h_q(z, Q^2)}{\sum_q e_q^2 q(x, Q^2) D^h_q(z, Q^2)} \]

- Inputs needed for the extraction of $\Delta q(x, Q^2)$:
  - Unpolarised PDFs (q(x, Q^2)) → MRST04
  - $D^h_q(z, Q^2) → DSS parameterisation$
Inclusive and semi-inclusive spin asymmetries: Deuteron data

- From these asymmetries one can extract: $\Delta u + \Delta d$, $\bar{\Delta}u + \bar{\Delta}d$ and $\Delta s = \bar{\Delta}s$
Inclusive and semi-inclusive spin asymmetries: Proton data

First measurement ever of $A_{1,p}^K$

- Using $A_{1,p}^h$ and $A_{1,d}^h$, we can separately extract: $\Delta u$, $\Delta d$, $\Delta\bar{u}$, $\Delta\bar{d}$, $\Delta s$ and $\Delta\bar{s}$
Quark helicities from SIDIS ( $Q^2 = 3 \text{ (GeV/c)}^2$ and $x < 0.3$ )

- Sea quark distributions $\sim 0$
- Good agreement with DSSSV fits
- Full flavour separation until $x \sim 0.004$

$$\Delta s_{\text{SIDIS}} = -0.01 \pm 0.01 \text{(stat)} \pm 0.01 \text{(syst)} \quad @ \quad 0.003 < x < 0.3$$
**Δs dependence on FFs**

- The relation between the semi-inclusive asymmetries and Δs depends only on the following ratios:

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

- Determination of \( R_{SF} \) from hadron multiplicities on the way

- \( R_{UF} \) 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)
Hadron Multiplicities
A first look on hadron multiplicities

- Assuming the quark parton model (leading order):

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

Experimental definition

X dependence of

\[
\frac{1}{N_{\text{DIS}}} \frac{dN^h}{dzdx}
\]

Obtained from a small part of $^6\text{LiD}$ data
Comparison to parameterisations

- The existence of discrepancies are evident (especially for K)

- Data can be used to improve our knowledge on FFs (also good for $\Delta s$) and also on poorly known PDFs (like $s(x)$)

- It will contribute significantly to our knowledge of the hadronisation process
Gluon Polarisation
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)

$A_{\mu N}^{PGF} = \frac{\int d\hat{s} \Delta \sigma_{PGF} \Delta G(x_G, \hat{s})}{\int d\hat{s} \sigma_{PGF} G(x_G, \hat{s})} \approx \left< a_{\mu N}^{PGF} \right> \frac{\Delta G}{G}$

Obtained from Monte Carlo and parameterised by a Neural Network (to be used on data)
Open Charm
D\(^0\) mass spectra (all samples): 

\[
A_{D^0}^{\text{exp}} = \mathcal{F}_\mu P_T \frac{S}{S+B} A_{\mu N}^{\text{PGF}}
\]

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

Number of D\(^0\):
- Total \(\rightarrow 86250\)
- \(^6\)LiD \(\rightarrow 57400\)
- NH\(_3\) \(\rightarrow 28850\)
\( s/(s+b) \): Obtaining final probabilities for a D^0 candidate

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

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

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

\[
\delta \left( \frac{\Delta G}{G} \right) = \frac{1}{\text{FOM}}
\]
High-$p_T$ hadron pairs
High-\(p_T\) asymmetries (2002-2006): \(Q^2 > 1\) (GeV/c)^2

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

\[
\begin{align*}
A_1^d(x) &= \frac{\Delta G}{G}(x_g) \left[ a_{LL}^{PGF,inc} \frac{\sigma^{PGF,inc}}{\sigma_{Tot,inc}} \right] + A_1^{LO}(x_C) \left[ a_{LL}^{C,inc} \frac{\sigma^{C,inc}}{\sigma_{Tot,inc}} \right] + A_1^{LO}(x_{Bj}) \left[ D \frac{\sigma^{LO,inc}}{\sigma_{Tot,inc}} \right] \\
A_{LL}^{2h}(x) &= \left( \frac{A^{exp}}{fP_{\mu}P_T} \right) \left[ a_{LL}^{PGF,inc} \frac{\sigma^{PGF}}{\sigma_{Tot}} \right] + A_1^{LO}(x_C) \left[ a_{LL}^{C} \frac{\sigma^{C}}{\sigma_{Tot}} \right] + A_1^{LO}(x_{Bj}) \left[ D \frac{\sigma^{LO}}{\sigma_{Tot}} \right]
\end{align*}
\]

high-\(p_T\) hadron pairs \((p_{T1} / p_{T2} > 0.7 / 0.4\) GeV/c) \(\Rightarrow\) enhancement of the PGF contribution
World measurements of $\Delta G/G$ at LO in QCD

- The gluon polarisation was obtained directly from the data, at LO, and was found to be compatible with zero.

$\Delta G/G$ is small in $x_G \in [0.07, 0.2]$

$\Delta G/G$ (high-$p_T$, $Q^2 > 1$) = $0.125 \pm 0.060$ (stat) $\pm 0.063$ (syst) \@ $\langle x_G \rangle = 0.09^{+0.08}_{-0.04}$

$\Delta G/G$ (Open Charm) = $-0.081 \pm 0.213$ (stat) $\pm 0.094$ (syst) \@ $\langle x_G \rangle = 0.11^{+0.11}_{-0.05}$
NLO results from Open Charm
NLO corrections to the analysing power $a_{LL}$

- **Virtual corrections**
- **Gluon bremsstrahlung corrections**
- **LO: PGF**
- **NLO: PGF**
- **NLO: bg**
Distributions of $a_{LL}$ and $x_G$ at LO and NLO in QCD

Analysing power

NLO

LO

Preliminary

Gluon momentum fraction

LO

NLO

Preliminary
ΔG/G result at NLO in QCD → first world measurement

\[ \frac{\Delta G}{G} = -0.20 \pm 0.21 \text{ (stat)} \pm 0.09 \text{ (syst)} \quad @ \langle x_G \rangle = 0.28^{+0.19}_{-0.10}, \quad \langle \mu^2 \rangle = 13\text{ (GeV/c)}^2 \]

Only experimental: theoretical uncertainties associated with \( a_{LL} \) are still under study!
Open Charm results for $x\Delta G$

Using the LO and NLO parameterisations of $xG$ corresponding to the ones used in the calculations of $a_{LL}$, we obtain the following results from $\Delta G/G$ (the comparison of the LO point with the QCD fits is justified by $xG(LO) \approx xG(NLO)$):

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

$$\int_0^1 \Delta G\,dx = -0.34 \pm 0.12$$
SPARES
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: $|g_{A}/g_{V}| = 1.269 \pm 0.003$)
Q^2 dependence of g_1(x, Q^2) for DGLAP evolution

- The kinematic range is still limited (compared to the unpolarised F_2)
  
  additional data from colliders is required!

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

- Δs comes out negative and Δg is small (< 0.5) — Still with large uncertainties
Comparison of $\Delta s$ with $\Delta \bar{s}$

$\Delta s - \Delta \bar{s}$ is compatible with 0 $\rightarrow$ $\Delta s = \Delta \bar{s}$ is assumed in the analysis
\( \Delta \bar{u} - \Delta \bar{d} \): Flavour asymmetry?

- The considerable asymmetry observed for \((\bar{u} - \bar{d})\) is not verified in the polarised case:
  - \( \Delta \bar{u} - \Delta \bar{d} \) is slightly positive but compatible with zero!
Data vs Monte Carlo: Comparison of $Q^2$ and hadron variables

Monte Carlo (PS on): LEPTO generator with PDFs from MSTW2008LO

The impact of this tuning is included in the systematic error
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:

$$\Delta G/G = 0.024 \pm 0.089 \text{ (stat)} \pm 0.057 \text{ (syst)} \quad \rightarrow \quad \text{Phys. Lett. B 633 (2006) 25 - 32}$$
AROMA with PS-ON versus COMPASS data

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

\[ \sigma(D^{*\pm}) = 1.8 \pm 0.4 \text{ nb} \]
within $20 \text{ GeV} < E_D < 80 \text{ GeV}$
$D^*/D^-$ asymmetry:

$$A(X) = \frac{d\sigma^{D^+}(X) - d\sigma^{D^*}(X)}{d\sigma^{D^+}(X) + d\sigma^{D^*}(X)}$$
Unpolarised gluon distribution in LO: $Q^2 = 13 \text{ (GeV/c)}^2$

- MSTW2008 LO
- GRV98 LO
- MRST98 LO

Unpolarised gluon distribution in NLO: $Q^2 = 13 \text{ (GeV/c)}^2$

- MSTW2008 NLO, $m_\chi = 1.5$
- CTEQ6 (central value)
- MRST2002 NLO
- MRST98 NLO