Recent results from COMPASS muon scattering measurements

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QCD@Work 2012 – Lecce, 20 June 2011
Outline

- Short overview of the COMPASS experiment
- Introduction to longitudinal spin physics
- Polarised structure functions
- Quark helicity densities
  - digression on fragmentation functions
- Gluon polarisation
The COMPASS experiment at CERN

230 physicists
25 institutes
11 countries
COMPASS spectrometer

60m long

E/HCAL1

SM1

RICH1

Polarised Target

160/200 GeV μ beam

E/HCAL2

Hodoscopes

Muon Wall 2, MWPC

MWPC, Gems, Scifi, W45

Muon Wall 1

Straws, Gems

Micromegas, DC, Scifi

Scifi, Silicon
Experimental programme

**Muon beam**
- Deep inelastic scattering (DIS)
- Semi-inclusive DIS (SIDIS)
- Transversity
- DVCS/GPDs
- Λ polarisation

**Hadron (\(\pi^\pm, K^\pm\)) beams**
- Hadron spectroscopy
- Meson structure
- \(\chi\)PT tests
- Search for exotics
- Drell-Yan
Spin physics

- Strong interaction dynamics $\Rightarrow$ spin structure of hadrons
- It is a testbed for QCD
- At high energies $\Rightarrow$ pQCD + factorisation theorems
- It is a testbed for QFTs in general

In this talk: **Longitudinal spin**

- Mainly deep inelastic lepton scattering
- Spins (polarisations) parallel to the beam momentum
- Longitudinal polarised structure functions
- Longitudinal polarised PDFs of quarks and gluons
Longitudinal spin decomposition

- Simple decomposition of the nucleon spin ($\hbar = 1$)

\[ S_N = \frac{1}{2} \Delta \Sigma + \Delta G + L_z \]

- $S_N = 1/2$: nucleon spin
- $\Delta \Sigma$: quark polarisation
- $\Delta G$: gluon polarisation
- $L_z$: orbital angular momentum

in this talk!
Polarised structure functions

\[
\ell N \rightarrow \ell' (X)
\]

Inclusive inelastic scattering cross section

- **Structure functions:**
  - unpolarised: \( F_1(x, Q^2), F_2(x, Q^2) \)
  - polarised: \( g_1(x, Q^2), g_2(x, Q^2) \)

From longitudinal double-polarisation asymmetry:

\[
A = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \Rightarrow g_1(x, Q^2)
\]

At COMPASS

- polarised muon beam
- polarised proton (NH\(_3\)) and deuteron (\(^6\)LiD) targets
Measurements of $g_1$

**Proton**

- $x g_1(x)$ for $Q^2$ and $x$ in various experiments.

**Deuteron**

- $x g_1(x)$ for $Q^2$ and $x$ in various experiments.
Deep inelastic scattering (DIS)

\[ \ell N \rightarrow \ell' (X) \quad Q^2 > 1 \text{ GeV}^2 \text{ (hard scale)} \]

⇒ Scattering on quasi free partons (Factorisation + pQCD ⇒ parton model)

\[ \text{unpol. } \sigma \Rightarrow F_1(x), F_2(x) \Rightarrow \text{unpol. p.d.f. } q(x) \]

\[ \text{pol. } \sigma \Rightarrow g_1(x), g_2(x) \Rightarrow \text{pol. p.d.f. } \Delta q(x) \]

First moment of \( g_1 \):

\[ \Gamma_1 = \int_0^1 dx \, g_1(x) = \frac{1}{2} \sum_q e_q^2 \int_0^1 dx \left( \Delta q(x) + \Delta \bar{q}(x) \right) \equiv \Delta q \]

⇒ contributions \( \Delta q \) of quarks to the spin
Deep inelastic scattering (DIS)

$\ell N \rightarrow \ell' \ (X)$

$Q^2 > 1 \text{ GeV}^2$ (hard scale)

⇒ Scattering on quasi free partons (Factorisation + pQCD ⇒ parton model)

Relation with axial charges of baryons

(SU(3) flavour symmetry)

$$\Gamma_1^N \equiv \frac{1}{2} (\Gamma_1^p + \Gamma_1^n)$$

$$= \frac{1}{9} C_1^S (Q^2) a_0 + \frac{1}{36} C_1^{NS} (Q^2) a_8$$

▷ $C_1^{S,NS}$ calculable in pQCD

▷ $a_8 = 0.585 \pm 0.025$ from hyperon beta decay

▷ $a_0 = \Delta\Sigma$ in the $\overline{\text{MS}}$ scheme

$$\Rightarrow \Delta\Sigma (Q^2 = 3(GeV/c)^2) = 0.30 \pm 0.01_{\text{stat}} \pm 0.02_{\text{evol}}$$

(PLB 647 (2007) 8)
Bjorken sum rule

- Validity check of this framework
- Measuring $g_1^p$ on a proton target
- Non-singlet combination: $g_1^{NS}(x) = g_1^p(x) - g_1^n(x)$

$$\Gamma_1^{NS} = \int dx \, g_1^{NS}(x) = \frac{1}{6} \left| \frac{g_A}{g_V} \right| C_1^{NS}(Q^2)$$

(PLB 690 (2010) 466–472)
Longitudinal spin decomposition

Simple decomposition of the nucleon spin ($\hbar = 1$)

$$S_N = \frac{1}{2} \Delta \Sigma + \Delta G + L_z$$

- $S_N = 1/2$: nucleon spin
- $\Delta \Sigma$: quark polarisation
- $\Delta G$: gluon polarisation
- $L_z$: orbital angular momentum

How do different flavours contribute?
$\Delta q$’s from SIDIS

Semi-inclusive DIS (SIDIS): $\ell N \rightarrow \ell' h (X)$

At LO in QCD:

$$A^h(x, z) = \frac{\sigma_{h}^{\uparrow\uparrow} - \sigma_{h}^{\uparrow\downarrow}}{\sigma_{h}^{\uparrow\uparrow} + \sigma_{h}^{\uparrow\downarrow}} \quad (z = \frac{E_h}{E_\gamma})$$

$h = \pi^+, \pi^-, K^+, K^- \ldots$

$z > 0.2$ to suppress target fragmentation

$z < 0.85$ to suppress diffractive production

- Need to identify hadrons
- RICH detector at COMPASS
Deuteron SIDIS asymmetries

PLB 680 (2009) 217-224

$A_{1,d}^{\pi^+}$

$A_{1,d}^{\pi^-}$

$A_{1,d}^{K^+}$

$A_{1,d}^{K^-}$

COMPASS

HERMES
Proton SIDIS asymmetries

PLB 693 (2010) 227-235


First kaon SIDIS asymmetries on a proton target
Flavour separation

\[ A^h(x, z) = \frac{\sum_q e_q^2 (\Delta q(x) D^h_q(z) + \Delta \bar{q}(x) D^h_{\bar{q}}(z))}{\sum_q e_q^2 (q(x) D^h_q(z) + \bar{q}(x) D^h_{\bar{q}}(z))} \]

Using:

- MRST unpolarised p.d.f.  
- DSS fragmentation functions  
- \( \Delta s = \Delta \bar{s} \)

For each \( x \) value:

- 4 SIDIS measurements on \( d \) +
- 4 SIDIS measurements on \( p \) +
- 2 inclusive measurements

10 data points

\( \Delta u, \Delta \bar{u}, \Delta d, \Delta \bar{d}, \Delta s (= \Delta \bar{s}) \)

\( \Rightarrow \) 5 unknowns
Flavour separation

$\Delta u$

$\Delta d$

$\Delta \bar{u}$

$\Delta \bar{d}$

$\Delta s$

$\Delta\bar{s}$

- : SIDIS fit
- : DIS asymmetries (only valence)
Curve: DSSV (NLO)
The $\Delta S$ puzzle

Strangeness contribution to long. spin:

$$\Delta S = \int dx \left[ \Delta s(x) + \Delta \bar{s}(x) \right]$$

From inclusive measurements:

$$\Delta S = -0.08 \pm 0.01_{\text{stat.}} \pm 0.02_{\text{syst.}}$$

- $\Gamma_1 = \int g_1(x)$
- SU(3) flavour symmetry + axial charges of baryons (from $\beta$ decay meas.)

From SIDIS:

$$\Delta S = -0.02 \pm 0.02_{\text{stat.}} \pm 0.02_{\text{syst.}}$$

- Fragmentation functions $D_q^h$?
- Strong dependence on the ratio:
  $$R_{SF} = \frac{D_{s}^{K^{+}}}{D_{u}^{K^{+}}}$$

$\Delta s(x)$ vs. $R_{SF}$

DSS

EMC

Lecce, 20/6/2012

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Fragmentation functions (FFs)

- $D^{h}_{q,g}$: mean number of $h$'s emitted in the hadronisation of a parton
- Universal quantities describing hadronisation
- Enter every process with hadrons detected in the final state
- Mostly measured at $e^{+}e^{-}$ colliders
  - At the $Z^{0}$ mass scale $\Rightarrow$ far from fixed target SIDIS scales
  - Mostly sensitive to singlet combinations
    \[ D_{\Sigma} = D_{u} + D_{\bar{u}} + D_{d} + D_{\bar{d}} + D_{s} + D_{\bar{s}} + \ldots \]
- Can be extracted from lepton SIDIS data
  - Measuring the hadron production yield in DIS events
  - Relevant observables: “hadron multiplicities”

\[ M^{h}(x, Q^{2}, z) \equiv \frac{d\sigma^{h}_{DIS}/dz}{\sigma_{DIS}} \]
Measurement of FFs

- Simple formula at LO:

\[
M^h(x, Q^2, z) = \frac{\sum q e_q^2 (q(x, Q^2) D^h_q(z, Q^2) + \bar{q}(x, Q^2) D^h_{\bar{q}}(z, Q^2))}{\sum q e_q^2 (q(x, Q^2) + \bar{q}(x, Q^2))}
\]

- Preliminary COMPASS results:

Comparison with the DSS parametrisation:

- For \(\pi\): fair agreement
- For \(K\): disagreement!
- To be confirmed: analysis ongoing...
- Dependence on \(s(x)\)?
Longitudinal spin decomposition

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$$S_N = \frac{1}{2} \Delta \Sigma + \Delta G + L_z$$

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Gluon polarisation

- Sensitivity to gluon PDFs needed
- Direct measurement from Photon-Gluon Fusion

Cleanest channel: open charm \((\ell N \rightarrow \ell' D(\ast) X)\)
- High \(p_T\) hadron production
- Scaling violation of PDFs (“indirect”)
- Global fits of all PDFs to different observables
Gluon polarisation: open charm

- Double-spin asymmetry in $D^0/D^*$ production

\[
\frac{\Delta g}{g} = \frac{1}{P_T P_B f a_{LL} \frac{S}{S+B}} A_{raw}
\]

- Disadvantage: low statistics
- Preliminary NLO extraction from COMPASS data
- $a_{LL}$ and $x_g$ change going to NLO
Gluon polarisation: high $p_T$ hadrons

- All “processes” contribute

- At low $Q^2$: > 50% contribution from resolved photons
- Stronger dependence on MC
- Larger statistics than in open charm

▶ HERMES: JHEP 08 (2010) 130
▶ COMPASS: hep-ex/1202.4064 (submitted to PLB)
Gluon polarisation: global fits

- Measure $\Delta g$ sensitive observables
- E.g. $A^h(p_T)$: double polarisation asymmetry of hadron production ($\gamma d \rightarrow h X$)
- Fit them together with other observables within the same framework: factorisation + pQCD

- First feasibility check: measurement $d\sigma^h/dp_T$
- Fair agreement with pQCD calculations
- Improvement by resummation of NLL terms
  (see D. De Florian, W. Vogelsang, PRD 71 (2005) 114004)
Nucleon spin puzzle

\[ S_N = \frac{1}{2} \Delta \Sigma + \Delta G + L_z \]

- Simple expectation (constituent quark models): \( \Delta \Sigma \approx 0.6 \)
- Direct measurements: \( \Delta \Sigma \approx 0.3 \)
- Large \( \Delta G \) could be the solution
- Direct measurements: small \( \Delta G \)
- But the \( x_g \) range of measurements is limited (0.05 – 0.3)
- Maybe better go for global fits (an EIC would be important)
- Intense activity on \( L_z \): transverse spin, GPDs...
Summary

▶ Review of longitudinal spin results from COMPASS
▶ Measurement of polarised structure functions
  ▶ quark contribution to the nucleon spin ($\Delta \Sigma$)
  ▶ check of Bjorken sum rule
▶ Flavour separation of polarised quark PDFs
▶ Preliminary results on fragmentation functions
▶ Status report on $\Delta G/G$
Asymmetry measurement

- Two types of target cells: \( u \) \( d \)
- Two field orientations: \(+\) \(-\) \(\Rightarrow 4\) measurements

\[
N_i = \phi_i \ n_i \ a_i \ \sigma_{\text{unpol}} \ (1 + P_B \ P_T \ f \ D \ A_1)
\]

- \( \phi \): flux
- \( n \): no. of target nucleons
- \( a \): acceptance
- \( f \): dilution factor
- \( D \): depolarisation factor (depends on kinematics and \( R = \sigma_L/\sigma_T \))

\[
\begin{align*}
\phi_u &= \phi_d \\
n_+ &= n_- \\
\left( \frac{a_u}{a_d} \right)_+ &= \left( \frac{a_u}{a_d} \right)_-\\
\frac{N_{+u} \ N_{-d}}{N_{+d} \ N_{-u}} &= \frac{(1 + P_B \ P_T \ f \ D \ A_1)^2}{(1 - P_B \ P_T \ f \ D \ A_1)^2}
\end{align*}
\]

\( w = f \ P_B \ D \) known for each event \(\Rightarrow\) used for weighting
Extraction of $g_N^1$

- $g_N^1$ of the nucleon:
  \[ g_N^1 = \frac{g_1^d}{(1 - 1.5\omega_D)}, \quad \omega_D = 0.05 \pm 0.01 \]

- $g_1^d$ of the deuteron:
  \[ g_1^d = \frac{F_2^d}{2x(1+R)}A_1^d, \quad R = \frac{\sigma^L}{\sigma^T}, \quad A_1^d = \frac{\sigma^T_0 - \sigma^T_2}{2\sigma^T} \]

- What we measure is:
  \[ A^d = D \left( A_1^d + \eta A_2^d \right) \]
  \[ A_2^d \text{ is small (measured at SLAC)} \Rightarrow A_1^d \simeq A_d/D \text{ (}D\text{ depends on } R) \]
From PVS: $e^-$ and $\nu$

Negative $\Delta s$ seems favoured

S. F. Pate et al.,
Phys. Rev. C 78 (2008), 015207