COMPASS Legacy

Longitudinal spin structure and gluon polarisation

G.K. Mallot
Historical excursion

• 1987: EMC nucleon spin puzzle

\[ \Delta \Sigma = \Delta u + \Delta d + \Delta s = 0.12 \pm 0.17 \]
\[ \Delta s = -0.19 \pm 0.06 \]

\[ \Gamma_1 = \int_0^1 g_1(x) dx \]

35\textsuperscript{th} anniversary

• 1988/9: axial anomaly may mask quark polarisation
  – Altarelli, Ross; Efremov, Teryaev

\[ a_0 = \Delta \Sigma - n_f \frac{\alpha_S}{2\pi} \Delta G \]
To summarise, let us return to the fit of Fig. 7 and 8. At \( Q^2 = 10 \text{GeV}^2 \) this corresponds to \( \Delta g = 6.3 \) and so the proton helicity is given by

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta g + L_Z
\]

\[
= 0.35 + 6.3 - 6.15
\]

G.G. Ross 1989

Need huge \( \Delta G \approx 6 \)

for \( \Delta \Sigma = 0.7 \)

\[ \rightarrow \text{measure } \Delta G \]
Historical excursion

- 1993: SMC measures deuteron $g_1$
  in agreement with Bjorken sum rule

\[ \Gamma^p_1 - \Gamma^n_1 = \frac{1}{6}g_a \]

- 1995: with new SMC and SLAC $g_1$ data about $\Delta G \approx 2.5$
  needed to restore parton model value $\Delta \Sigma \approx 0.7$
  via axial anomaly

- 1995: HMC and Cheops LoI’s
  - Gluon and quark polarisations, transversity
  - Spectroscopy, pion polarisability
28 March 1995

- Independent LoI’s
- Both require new spectrometer
- Both propose to use same experimental hall

‘Hadron Muon Collaboration’
Spectrometers

SPSLC, June 1995: join forces!
Common Muon and Proton Apparatus for Structure and Spectroscopy

The COMPASS Collaboration

Abstract

We propose to study hadron structure and hadron spectroscopy with high-rate hadron and muon beams and a new spectrometer to be built at the CERN SPS. The experiment can start up in 1999 and a program of physics measurements for an initial period of 5 more years is planned.
The Research Board then discussed the COMPASS proposal. The physics programme was recognised to be of topical interest. The re-design of the spectrometer in order to cope with the available funds was appreciated. In conclusion the Research Board approved the experiment under the conditions spelled out by the SPSC and subject to the availability of funds. Its code number will be NA58.
COMPASS Spectrometer

NIM A577 (2007) 455

\( \mu \) beam
- 160 – 200 GeV, \( \sim \) 80% pol.
- \( 2 \times 10^8 \) /spill

Two stages
- 2 magnets
- tracking
- particle ID
Polarised target

- 2.5 T solenoid, 0.6 T dipole
- ~ 50 mK
- 2 or 3 oppositely pol. cells
- pol. reversal by rotation of magnet field
- $^6$LiD ~ 50%
- NH$_3$ ~ 85%

New large acceptance COMPASS magnet in 2005
Repaiired and instrumented at Saclay
COMPASS magnet at Saclay

Alain Magnon, J. Ball, C. Marchand, JY Rousse, ...
Alain Magnon (1944 – 2022)
Alain Magnon (1944 – 2022)

Merci Alain
Kinematic coverage

- Lowest $x$ data from COMPASS and SMC
Measured asymmetry $A_{\text{exp}}$ yields the virtual photon asymmetry

\[ A_1 \approx \frac{A_{\text{exp}}}{f P_\mu P_T D} \]

and the structure function $g_1$ via

\[ A_1(x, Q^2) = \frac{\sum q e_q^2 \Delta q(x, Q^2)}{\sum q e_q^2 q(x, Q^2)} = \frac{g_1(x, Q^2)}{F_1(x, Q^2)} \]
• **COMPASS** contributes the lowest $x$ and highest $Q^2$ data
• $A_1$ is still positive at lowest $x$ ($Q^2 > 1$ GeV$^2$)
Deuteron for $A_1$ and $g_1$

- COMPASS contributes the lowest $x$ and highest $Q^2$ data
- $A_1$, $g_1$ are compatible with zero at lowest $x$ (c.f. SMC)
Proton and deuteron $g_1(x,Q^2)$

Curve: Compass QCD fit to world data

$W^2 > 10 \text{ GeV}^2$
$g_1$ for small $x$ ($Q^2 < 1 \text{ GeV}^2$)

- $0.006 < Q^2 < 1 \text{ GeV}^2$
- $4 \cdot 10^{-5} < x < 4 \cdot 10^{-2}$
- Spin effects are present even below $x < 10^{-3}$

Curve: phenom. Model by B. Badełek, J. Kwiecinski, B. Ziaja

proton

deuteron

- $0.006 < Q^2 < 1 \text{ GeV}^2$
- $4 \cdot 10^{-5} < x < 2 \cdot 10^{-2}$
- Compatible with zero
Bjorken sum rule

- First moment of $g_1$
  \[ \Gamma_1 = \int_0^1 g_1(x) \, dx \]
- Non-singlet structure function
  \[ g_1^{\text{NS}} = g_1^p - g_1^n \]
- Bjorken sum rule
  \[ \Gamma_1^{\text{NS}} = \frac{1}{6} (\Delta u - \Delta d) = \frac{1}{6} \left| \frac{g_A}{g_V} \right| \]
- COMPASS $\Gamma_1^{\text{NS}}$ corresponds to
  \[ \left| \frac{g_A}{g_V} \right| = 1.29 \pm 0.05_{\text{stat.}} \pm 0.10_{\text{syst.}} \]
- c.f. PDG 2022: $1.2754 \pm 0.0013$

BJ sum rule tested at 9% level
Flavour singlet axial charge

- BJ SR major contribution from small $x$
  \[ \Gamma_{1}^{NS} = 0.192 \pm 0.007_{\text{stat}} \pm 0.015_{\text{syst}} \]

- EJ SR no contribution from small $x$
  \[ \Gamma_{1}^{N}(Q^2 = 3 \text{ (GeV/c)}^2) = 0.046 \pm 0.002_{\text{stat}} \pm 0.004_{\text{syst}} \pm 0.005_{\text{evol}} \]

- From deuteron ($\Gamma_{1}^{N}$) and SU$_3$:
  \[ a_o \overline{MS} \Delta\Sigma = 0.32 \pm 0.02_{\text{stat}} \pm 0.04_{\text{syst}} \pm 0.05_{\text{evol}} \text{ at 3 GeV}^2 \]
QCD fit to world data

- NLO to world DIS data (2016/18)
- Gluon polarisation hardly constrained, a positive and a negative solution

\[ \Delta G \in [-1.6, 0.5] \text{ at } 3 \text{ GeV}^2 \]
Semi-inclusive DIS results

Additional hadron observed in FS

\[ A_1^h = \frac{\sum_q e_q^2 g_1^q(x, Q^2) D_{1q}^h(z, Q^2)}{\sum_q e_q^2 f_1^q(x, Q^2) D_{1q}^h(z, Q^2)} \]

gives access to flavour information via the fragmentation functions \( D_{1q} \)

\[ z = \frac{E_h}{\nu} \]
Proton: Incl. & semi-incl. $A_1$

- Compass and Hermes data for proton

First kaon data
Deuteron: Incl. & semi-incl. $A_1$

- Compass and Hermes data for deuteron

First kaon data
Polarisation by flavour

LO analysis of 5p+5d asymmetries, DSS FF
Line: NLO DSSV not including these data

5-flavour fit, assuming $\Delta s = \Delta \bar{s}$
‘direct’ $\Delta g$ measurements

$\Delta g$ assessable via photon-gluon fusion (PGF)

- Measure double-spin asymmetry
  - Open charm production (D mesons), PGF is only process in LO scale set by charm quark mass
  - Single hadrons or hadron pairs contributions from LP, QCD-C, PGF
Open charm: $D$ meson samples

- Statistics limited, $D^0 \rightarrow \pi K$ (BR $\sim 4\%$)
- Large combinatorial background
- Drastically reduced in $D^* \rightarrow D^0 \pi_s \rightarrow K \pi \pi_s$ with detected slow $\pi_s$
- Background checked using wrong sign charge combinations
Open charm: \( \langle \Delta g/g \rangle \)

\[
A^{\mu N} = DA^{\gamma N} = a_{LL} \frac{\Delta g}{g}
\]

- **Leading order:** \( \langle \frac{\Delta g}{g} \rangle = -0.06 \pm 0.21 \text{(stat.)} \pm 0.08 \text{(syst.)} \) \( 0.06 < x < 0.22; \langle x \rangle \approx 0.11 \)
- **NLO:** \( a_{LL} \) in NLO using Aroma generator and parton shower

\[
\langle \frac{\Delta g}{g} \rangle^{\text{NLO}} = -0.13 \pm 0.15 \text{(stat.)} \pm 0.15 \text{(syst.)} \quad 0.12 < x < 0.33; \langle x \rangle \approx 0.20
\]

Agrees with NLO fit with negative \( \Delta G \)

Large positive \( \Delta G \) less likely
All-$p_T$ hadrons method $\langle \Delta g / g \rangle$

- Contributions in leading order (gluon)
All-$p_T$ hadrons method

- $0.05 < p_T < 2.5$ GeV; $Q^2 > 1$ GeV$^2$
- Determine contribution and analysing power for the three processes by a NN trained on MC data.
- MC agrees well with measured kinematic distributions
All-$p_T$ hadrons method

- Result:

$$\langle \Delta g/g \rangle = 0.113 \pm 0.038_{\text{stat.}} \pm 0.036_{\text{syst.}}$$

$$\langle x \rangle \approx 0.10, \quad \langle Q^2 \rangle = 3 \text{ GeV}^2$$

- Statistics allows splitting in three $x_g$ bins
Summary of $\Delta g$

- All-$p_T$ agrees well with previous less precise result from high-$p_T$ data
- Compatible with result from open charm
- Large $\Delta G$ ruled out
Conclusion

- Compass united several physics communities since decades, a real success story and highly on-trivial.
- Rewarded by great physics outputs, incl. longitudinal spin structure data 2002-2011.
- Proposal precision for $\langle \Delta g/g \rangle$ of 0.11 in open charm almost reached despite many difficulties.
- Precision from all-$p_T$ even much better, about 0.04.
- COMPASS was the first to rule out a large gluon polarisation in the nucleon! Certainly not 6 (after EMC) nor 2.5 (after SMC, Slac).
- Today we have new, more complicated view on nucleon spin being shared between orbital angular momentum and quark and gluon spins.
- Precise test of Bjorken sum rule
- Quark polarisations $\Delta q$
Thanks for your attention