Spin structure of the nucleon in COMPASS

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19th December 2010, PASC Workshop
The nucleon spin puzzle

Longitudinally polarized DIS
  ★ $A_1, g_1^d$ and the Bjorken sum rule
  ★ Flavour separation
  ★ Gluon polarization

Transversely polarized SIDIS

TMD PDFs from polarized Drell-Yan

GPDs from DVCS

Conclusions
The COMPASS Experiment at CERN

   ★ with polarized muon beam ($\mu^+$ at 160 GeV/c, $\approx$80% polarized) and polarized targets ($^6\text{LiD}$ and $\text{NH}_3$)

♦ Studies of hadron spectroscopy (2008 – 2009)
   ★ with $h^-$ beam at 190 GeV/c (95% $\pi^-$, 4% $K^-$, 1% $\bar{p}$) and unpolarized targets (liquid $H_2$, Ni, Cu, Pb, W)
   ★ with $h^+$ beam at 190 GeV/c (75% $p$, 24% $\pi^+$, 1% $K^+$) and unpolarized liquid $H_2$ target

   ★ GPDs from DVCS: with polarized muon beam ($\mu^\pm$ at 100-190 GeV/c and long unpolarized liquid $H_2$ (1$^{st}$ phase) or transversely polarized $\text{NH}_3$ target (2$^{nd}$ phase)
   ★ TMD PDFs from polarized Drell-Yan: with hadron beam (95% $\pi^-$) and a polarized $\text{NH}_3$ target
The COMPASS spectrometer and target setup includes:

- Polarized target
- Dipole magnets
- RICH
- 350 tracking planes
- Calorimeters

A muon (\(\mu^+\)) beam at 160 GeV with approximately 80% polarization is used for the experiments.

The target spin is reversed every 8 hours. The targets used are \(^6\text{LiD}\) or \(NH_3\).

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**The nucleon spin puzzle**

Nucleon spin: \( \frac{1}{2} = \frac{1}{2} \, \Delta \Sigma + \Delta G + L_Z \)

- Quarks spin
- Gluons spin
- Orbital ang. mom.

- In the quark-parton model, including relativistic corrections, expect \( \Delta \Sigma \approx 0.6 \)

- 1988: EMC measured the quarks contribution to the spin of the nucleon to be very small!

- Present world data:
  \[ \Delta \Sigma = 0.30 \pm 0.01 \text{(stat)} \pm 0.02 \text{(evol)} \]
  \[ \rightarrow \text{COMPASS, PLB 647 (2007) 8-17} \]
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Spin asymmetries in DIS

For its deep inelastic scattering (DIS) programme, COMPASS uses beam and target polarized to measures double spin asymmetries.

\[ Q^2 = -q^2 \]
\[ \nu = E - E' \]
\[ x = \frac{Q^2}{2M\nu} \]
\[ z = \frac{E_B}{\nu} \]

The $\mu$-deuteron/proton asymmetry is measured from the difference between cross-sections from 2 oppositely polarized target cells:

\[ A^{\mu N} = \frac{1}{fP_T P_B} \left( \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \right) \]

This measured asymmetry relates to the longitudinal and transverse $\gamma^*$-deuteron/proton asymmetries: $\frac{A^{\mu N}}{D} \approx A_1$
Longitudinal polarization: inclusive asymmetries

deuteron (2002-2006 data)

proton (2007 data)


COMPASS, PLB 690 (2010) 466-472.

- Significant improvement of precision in the low $x$ region.
- Large asymmetry observed at high $x$, in agreement with other experiments.
Longitudinal spin-dependent \( g_1 \) PDF

\( g_1 \) is obtained from the asymmetry \( A_1 \), for proton or deuteron:

\[
g_1 = A_1 \frac{F_2}{2x(1 + R)}
\]

\( F_2 \rightarrow \) SMC parameterization; \( R = \sigma^L / \sigma^T \rightarrow \) SLAC parameterization

From the 1\(^{st}\) moment of \( g_1^d(x) \):

\[
\Delta \Sigma = a_0 = 0.33 \pm 0.03(\text{stat}) \pm 0.05(\text{syst}) \text{ at } Q^2 = 3 \text{ (GeV/c)}^2
\]

\[
\Delta s + \Delta \bar{s} = \frac{1}{3}(a_0 - a_8) = -0.08 \pm 0.01 \pm 0.02 \text{ at } Q^2 \rightarrow \infty
\]
Combining deuteron and proton data, one can access the non-singlet spin structure function $g_{1NS} = g_1^p - g_1^n$.

According to the Bjorken sum rule the first moment of $g_{1NS}$ is proportional to the ratio of axial and vector coupling constants $g_A/g_V$:

$$\int_{x_{min}}^{1} dx \, g_{1NS}^X(x, Q^2) = \frac{1}{6} \left| \frac{g_A}{g_V} \right| C_{1NS}^X(Q^2)$$

- 92% of the first moment of $g_{1NS}$ comes from the measured region.
- At the lowest accessible $x$ in COMPASS, $\int_{0.004}^{1} dx \, g_{1NS}^X = 0.180 \pm 0.009$.
- The value expected from the Bjorken sum rule is 0.188, taking $|g_A/g_V|$ from neutron $\beta$ decay.
- Validity of the Bjorken sum rule confirmed with 5% statistical precision.
Flavour separation

From a semi-inclusive DIS analysis, using charged kaons and pions identified in the RICH detector, with both deuteron and proton polarized targets, full quarks flavour decomposition (in LO) can be done:

- The curves are predictions from the DSSV fit calculated at NLO (D.Florian, Sassot, Stratmann, Vogelsang, Phys.Rev.D 80 (2009) 034030)
- The flavour asymmetry of the sea helicity distributions $\Delta \bar{u} - \Delta \bar{d}$ is slightly positive, compatible with zero.

PLB 693 (2010) 227-235
Gluon polarization

The direct measurement of $\Delta G$ is of crucial importance for the understanding of the spin puzzle.

Access it via the photon-gluon fusion (PGF) process.

PGF events are selected by analysing:

- Open Charm production
  - Very clean: almost no physics background
  - Low statistics
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- **High \( p_T \) hadron pairs**
  - Large statistics available
  - Very dependent on Monte-Carlo
5 channels with $D^o$ production are studied (data 2002-2007):

- $D^o \rightarrow K\pi$ (untagged)
- $D^*\text{ tagged} : D^o \rightarrow K\pi, K\pi\pi^o, K\pi\pi\pi, \text{sub}(K)\pi$

Weighted events: all factors between $A_{raw}$ and $\Delta G/G$ enter in the weight. The method implies simultaneous extraction of the background asymmetry:

$$A_{raw} = P_t P_b f a_{LL} \frac{S}{S+B} \frac{\Delta G}{G}$$

$$A_{bkg} = \frac{1}{P_t P_b f D} \frac{B}{S+B} A_{raw}$$
In LO and $Q^2 > 1 \text{ (GeV/c)}^2$, besides PGF 2 background processes must be considered: leading processes (LP) and QCD-Compton (QCDC). Generically, the higher the hadrons $p_T$, the larger is the PGF fraction expected.

The fractions $R$ and the analysing powers $a_{LL}$ of each process are calculated from Monte-Carlo. They are parameterized on an event basis by a Neural Network trained on MC.

- Data 2002-2006 were analysed
- Analysis in 3 bins of $x_g$
- The present analysis requires leading hadron with $p_T > 0.7$ and sub-leading with $p_T > 0.4 \text{ GeV/c}$, and uses fractions $R$ and $a_{LL}$ to weight the events.
Open-charm analysis: $\Delta G/G = -0.08 \pm 0.21(\text{stat}) \pm 0.03(\text{syst})$

at $\langle x_g \rangle = 0.11$ and $\langle \mu^2 \rangle = 13$ GeV$^2$.

High $p_T$ analysis: $\Delta G/G = 0.125 \pm 0.060(\text{stat}) \pm 0.063(\text{syst})$

at $\langle x_g \rangle = 0.094$ and $\langle \mu^2 \rangle = (\langle Q^2 \rangle) = 3.4$ GeV$^2$. 

![Graph showing $\Delta g/g$ vs. $x_g$]
At leading order, 3 PDFs are needed to describe the structure of the nucleon in the collinear approximation.

But if one takes into account also the quarks intrinsic transverse momentum $k_T$, 8 PDFs are needed:
Sivers: the $f_{1T}^{+}(x, k_{T}^{2})$ function describes the distortion of the probability distribution of a non-polarized quark when inside a transversely polarized nucleon.

Boer-Mulders: the $h_{1}^{+}(x, k_{T}^{2})$ function describes the correlation between the transverse spin and the transverse momentum of a quark in an unpolarized hadron.

Transversity: results from the integration over $k_{T}^{2}$ of $h_{1}(x, k_{T}^{2})$.

The last 2 are chiral-odd – as a consequence, they can only be observed convoluted with another chiral-odd object.

→ in SIDIS, the PDF is convoluted with a fragmentation function.
Transverse Polarization

The transverse momentum dependent (TMD) PDFs of the nucleon carry important information about the nucleon spin dynamics, that can be revealed from SIDIS in a transversely polarized target.

\[ \rightarrow 8 \text{ azimuthal asymmetries} \] that can be measured at once.

\[ \phi_h : \text{azimuthal angle of the outgoing hadron momentum} \]

\[ \phi_S : \text{azimuthal angle of the initial quark spin} \]
Collins effect: a quark moving "horizontally" and polarized "upwards" emits the leading meson preferentially on the "left" side of the jet (Collins FF).

The Collins asymmetry is proportional to the convolution of the transversity PDF \( h_1(x) \) with the Collins FF.

Collins angle: \( \phi_C = \phi_h + \phi_S - \pi \)

- Identified hadron Collins asymmetries in agreement with theory predictions.
- Agreement with previous measurements from HERMES and BELLE – both transversity and Collins FF are non-zero!
- Same asymmetries measured in COMPASS with deuteron target are zero – in deuteron there is cancellation between u and d quark contributions.
Another azimuthal modulation that can be extracted from SIDIS is the Sivers effect, measured to be non-zero by HERMES.

Sivers angle: $\phi_{Siv} = \phi_h - \phi_S$

- Non-zero Sivers asymmetry for $h^+$, measured on proton target.
- Sivers asymmetry measured on deuteron is compatible with zero.
- HERMES measures larger asymmetries – COMPASS result still to be understood.
- 2010 data on proton target to be analysed soon.
TMD PDFs, like Sivers, can be accessed not only from SIDIS but also from the Drell-Yan process (DY).

The spin asymmetry is given by the convolution of structure function with fragmentation function.

Because Sivers is T-odd, it is expected that:

\[ f_{1T}^{+}(DY) = -f_{1T}^{+}(SIDIS) \]

The experimental check of this relation is a crucial test of QCD. The same is true for Boer-Mulders.
The COMPASS programme is expected to be completed in 2011, a year for data-taking with muon beam on longitudinally polarized proton target.

A new proposal for further spin studies in COMPASS was delivered to the SPS committee in May 2010 (CERN-SPSC-2010-014).

The proposal was recommended for approval in September 2010.
COMPASS has the unique opportunity to study, with the same spectrometer, TMD PDFs both from SIDIS and from polarized DY processes, thanks to a multipurpose spectrometer:

- Availability of both muon and pion beams
- Unique polarized NH$_3$ target, well suited for transversity studies
- Wide angular acceptance and a muon detection system
- Measurement requires large hadron absorber downstream of the target, and a dimuon trigger.

\[
\pi^- p^\uparrow \rightarrow \mu^+ \mu^- X
\]

The COMPASS phase-space covers the proton quarks valence region ($x_p > 0.1$), for high mass Drell-Yan events ($4. < M_{\mu\mu} < 9.$ GeV/c$^2$).

COMPASS has sensitivity to measure Sivers, Boer-Mulders, transversity and pretzelosity PDFs from Drell-Yan.
**TMD PDFs from DY@COMPASS**

**DY 4. – 9. GeV/c²**

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**Sivers**

M. Anselmino et al,
PRD79 (2009) 054010

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**Boer-Mulders**

B. Zhang et al,

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**BM ⊗ pretzelosity**

A.N.Sissakian et al,
Phys.Part.Nucl.41: 64-100, 2010

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**BM ⊗ transversity**

A.Efremov et al, in preparation

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TMDs and GPDs

**TMD PDFs:** adding information about intrinsic transverse momentum dependence or

**GPDs:** adding information about the transverse distance of the constituent quark

are 2 "complementary" ways to improve our knowledge about the nucleon structure.

They are related via Fourier transform. They both allow to access information about the quarks orbital angular momentum – although their interpretation is difficult.

4 GPDs: $H$, $E$, $\tilde{H}$ and $\tilde{E}$ for each quark flavour and gluons.

They depend on 3 variables: $x$, $\xi = \frac{x B}{2 - x B}$ and $t$.

GPDs have no direct probabilistic interpretation.
**DVCS with unpolarized target**

Using $\mu^{+\downarrow}$ and $\mu^{-\uparrow}$ beams on a long (2.5m) unpolarized liquid $H_2$ target, one can do transverse imaging (tomography) of the nucleon.

Access the GPD $h$ from Deeply Virtual Compton Scattering (DVCS).

$$\mu p \rightarrow \mu' p \gamma (\mu' \rho \rho)$$

$$d\sigma^{DVCS} / dt \approx exp(-Bt)$$

$$B \approx \langle r^2 \rangle / 2$$

- Measurement requires a large recoil proton detector, and large coverage electromagnetic calorimetry.
- Main priority is DVCS. Meson production will be studied in parallel.
- 2 competing processes: DVCS and Bethe-Heitler. Low $x_B$: BH; High $x_B$: DVCS; intermediate $x_B$: interference DVCS-BH.
- BH is well-known: used as reference process.
In a 2\textsuperscript{nd} phase of the measurement: use a transversely polarized target (NH\textsubscript{3}), inside a large Recoil Proton Detector.

\[ \text{Access GPD E: from measured azimuthal asymmetries} \]
COMPASS takes data since 2002, for studies both on the nucleon spin structure and on hadron spectroscopy.

COMPASS results on spin physics give an important contribution to our understanding:

- The most precise data on $A_1$ at the low $x_{Bj}$ region, with impact in the determination of $g_1^d$ and $g_1^p$.
- A direct measurement of the gluon polarization, with a result compatible with zero, within errors, in the measured $x_g$ range.
- Collins and Sivers asymmetries on deuteron target compatible with zero – understood now to be due to cancellation between u and d quark contributions.
- Sizable Collins asymmetry on proton target – access to the transversity PDF.
- Positive Sivers asymmetry for $h^+$ on proton target, but difficult systematics – still to be understood.

⇒ Data from 2010 (transverse pol.) and 2011 (longitudinal pol.) still to be analysed!
A proposal for new spin studies in COMPASS was recommended for approval by the CERN Scientific Committee in September 2010:

- Study of TMD PDFs from polarized Drell-Yan – It can be the first ever polarized Drell-Yan experiment.

- Drell-Yan COMPASS phase-space (in the proton’s valence quarks region) seems to be very favorable to access TMDs, according to theory predictions.

- Study of GPDs from DVCS – the COMPASS measurement will be in an intermediate $x$ range, not covered by any other experiment in the near future.

- DVCS process using unpolarized proton target in a 1$^{st}$ phase, to constrain GPD H, and do transverse imaging of the nucleon. Use of a transversely polarized proton target in a 2$^{nd}$ phase, to constrain GPD E.

Thank you!