Spin, TMDs and DVCS at COMPASS

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on behalf of the COMPASS collaboration

- Longitudinal spin
  Gluon and quark helicity distributions
- Transverse spin &
  Transverse Momentum Dependent quark distributions
- Future measurements at COMPASS-II

ICHEP, International Conference High Energy Physics,
Paris, France, 2010, July 22-28
**COMPASS**

Fixed target experiment at the CERN SPS:
Use secondary muon or hadron beams. 220 physicists from 26 institutes

**Nucleon spin structure**

Polarized muon beam:
160 GeV $\mu^-$, $P_B=80\%$

Polarized target:
$^6$LiD $P_T=50\%$ 2002-2006
$NH_3$ $P_T=80\%$ 2007

**Meson spectroscopy**

Hadron beam:
190 GeV $\pi/p$ LH$_2$ 2008-2009

Polarized muon beam:
160 GeV $\mu^-$, $P_B=80\%$
Polarized target:
$^6$LiD $P_T=50\%$ 2002-2006
$NH_3$ $P_T=80\%$ 2007

Dipole 1
Dipole 2
$\mu$ filter
RICH
ECal
HCal
MWPC
Straws
Micromegas
Drift chambers
SciFi
GEMs

DIS events
$0.003 < x < 0.5$
$10^{-3} < Q^2 < 10 (GeV/c)^2$

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How is the nucleon spin distributed among its constituents?

Nucleon Spin \[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_{q,g} \]

- Quark \( \Delta q = \vec{q} - \vec{q} \)
- Gluon \( \Delta G \)
- Orbital momentum \( L_{q,g} \)

Parton spin parallel or anti parallel to nucleon spin

Theory: QCD, Ellis-Jaffe sum rule assuming \( \Delta s = 0 \), \( \Delta \Sigma \approx 0.6 \)

Experiment: World data on polarized DIS \( g_1 + SU_f(3) \rightarrow a_0 \approx 0.3 \)

QCD (\( \overline{\text{MS}} \) scheme) \( a_0 = \Delta \Sigma \)

→ “Spin crisis” 1988, EMC measured \( a_0 = 0.12 \pm 0.17 \)

QCD (AB scheme) \( a_0 = \Delta \Sigma - n_f (\alpha_s/2\pi) \Delta G \)

- For \( a_0 \approx 0.3 \), need \( \Delta G \approx 2.5 \) to restore \( \Delta \Sigma \approx 0.6 \). (Then \( L_z \approx 2.3 \))
- \( \Delta G \) enters in the spin \( \frac{1}{2} \) sum rule

→ motivated direct measurements of gluon polarization \( \Delta G \)
**ΔG/G Measurement- Photon Gluon fusion PGF**

Need:
- a process sensitive to gluon distribution → Photon Gluon Fusion
- measure longitudinal spin asymmetry of cross sections → incident polarized lepton beam and polarized nucleon target.

At leading order

\[ A_{||} = R_{PGF} \langle a_{LL} \rangle \langle \Delta G/G \rangle \]

Two signatures for PGF:

- \( q=c \) open charm \( c \rightarrow D^0 \rightarrow K \pi \)
  - Clean signature of PGF
  - pQCD scale \( \mu^2 = 4 (m_c^2 + p_T^2) \)
  - Combinatorial background & limited statistics → Difficult experiment

- \( q=u,d,s \) high \( p_T \) hadron pair \( q \bar{q} \rightarrow h \bar{h} \)
  - High statistics
  - pQCD scale \( Q^2 \) or \( \Sigma p_T^2 \)
  - Physical background, better described for high \( Q^2 \)
Results for $\Delta G/G$ direct measurements

All measurements compatible with 0 for $0.04 < x < 0.2$

Also in agreement with RHIC results on double spin asymmetry in polarized pp reactions, which probe same kinematical range

Direct measurements exclude values for the integral of $\Delta G$ as large as 1 or 2
Spin structure functions - world data

\[ \sigma_{DIS}^{\text{inclusive}} \propto g_1(x) \propto \frac{1}{2} \sum q^2 (\Delta q(x) + \Delta \bar{q}(x)) \]

Polarized PDFs

Polarized DIS

From first moment of \( g_1 \), at \( Q^2 \to \infty \):

- \( \Delta \Sigma = 0.30 \pm 0.01 \) (stat.) \( \pm 0.02 \) (evol.) All data
- \( \Delta s + \Delta \bar{s} = -0.08 \pm 0.01 \pm 0.02 \) Compass data alone

Input to global QCD fits \( \Rightarrow \) Extract \( \Delta q_f(x) \) and \( \Delta G(x) \) through \( Q^2 \) evolution
$\Delta G(x)$ from global QCD analysis of polarized DIS data $g_1(x,Q^2)$

Use $Q^2$ evolution of spin dependent gluon and singlet quark distribution.

Lack of polarized data
Fits not so well constrained, however some results

COMPASS NLO fit of $g_1$ data:
2 solutions with $|\Delta G| = 0.2 - 0.3$

DSSV NLO fit of $g_1$ and $\vec{p}\vec{p}$ data
(different scale)

De Florian, Sassot, Stratmann, Vogelsang
Consequence for nucleon spin

\[ \Delta G = \int \Delta g(x) dx \] not large, both from direct measurements (essentially PGF + RHIC) and \( g_1 \) QCD fit: \( |\Delta G| < 0.35 \)

\[ \Delta \Sigma = a_0 + \left( \frac{3\alpha_s}{2\pi} \right) \Delta G \]
\[ \text{within 0.06 for } \Delta G \text{ within } \pm 0.35 \text{ at } Q^2 = 3 \]

\[ \rightarrow \Delta \Sigma \sim 0.30 \text{ small (≠ predictions)} \]

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

possible scenarios:

\[
\begin{align*}
\frac{1}{2} 0.3 + 0.35 + 0.0 \\
\frac{1}{2} 0.3 + 0.0 + 0.35 \\
\frac{1}{2} 0.3 - 0.35 + 0.7
\end{align*}
\]
Non Singlet structure function and Bjorken sum rule

Non-singlet combination: \( g_1^p(x) - g_1^n(x) \)

The first moment provides a test of the Bjorken sum rule, a fundamental result of QCD derived from current algebra.

\[
\int_0^1 g_1^{NS}(x) \, dx = \frac{1}{6} \left| \frac{g_A}{g_V} \right| C^{NS}
\]

Fit to COMPASS data: \( g_A/g_V = 1.28 \pm 0.07 \text{(stat)} \pm 0.10 \text{(syst)} \)

PDG value:
1.268 ± 0.003
LO Helicity quark distributions

- Full flavour decomposition down to $x \sim 0.004$
- Sea quark distributions $\sim$ zero
- Good agreement with previous global fits to $g_1$ inclusive data, except for $\Delta s$.

However, for $\Delta s$:
- Large uncertainty on strange quark fragmentation functions.
- New global fits (DSSV) suggest negative contribution at lower $x$, in agreement with both inclusive result and semi inclusive data.
Transversity - Collins and Sivers asymmetries

• Transversely polarized target

• Measure simultaneously several azimuthal asymmetries of outgoing hadron in SIDIS $\mu p \rightarrow \mu p h$

\[
\begin{align*}
\text{Collins: } & \text{Outgoing hadron direction & quark transverse spin} \\
\text{Sivers: } & \text{nucleon spin & quark transverse momentum}
\end{align*}
\]

\[
A_{\text{Coll}} = \frac{\sum q e_q^2 \cdot \Delta T q \cdot \Delta D^h_q}{\sum q e_q^2 \cdot q \cdot D^h_q}
\]

Collins fragmentation function

\[
A_{\text{Siv}} = \frac{\sum q e_q^2 f_{1Tq} \cdot \perp D^h_q}{\sum q e_q^2 \cdot q \cdot D^h_q}
\]

note: $\Delta T q$ also measured using
- "Two hadron” fragm. fct.
- lambda Transverse. Polarization
Transversity: Collins Asymmetry on proton

COMPASS data compared to predictions from Anselmino et al., based on fit of HERMES-p and COMPASS-d data, and BELLE FF.

• Large signals in valence region as seen by HERMES, opposite for + and - hadrons
• Data support assumption of weak $Q^2$ dependence in this energy range

Several combined analyses of HERMES p and COMPASS d data:

• $\Delta_T^u > 0$ and $\Delta_T^d < 0$

• Do not saturate
  Soffer bound

• Smaller than helicity

Ex: M. Anselmino et al. arXiv:0812.4366
Transversity via “two hadron”

as an alternative for $\Delta_T u$ and $\Delta_T d$

- Confirms non zero effect at large $x$; larger than Collins asymmetry

- (Smaller) signal was also seen in HERMES in different phase space; difficult to describe both simultaneously A. Bacchetta et al., Mah et al.
Sivers Asymmetry - proton

Comparison with predictions from Anselmino et al., based on fit of Hermes-p and Compass-d data

Present data not in fit
- COMPASS signal < HERMES signal
- Possible W dependence

Comparison with calculations of Arnold et al., which are in agreement with Hermes-p data.
Example of one azimuthal asymmetry

Unpolarized target.

\[ \cos(2\phi) \] modulation comparison with theory

V. Barone, A. Prokudin, B. Q. Ma

Sensitivity to Transverse Momentum Distributions
Future QCD studies at COMPASS II

COMPASS-II proposal submitted to CERN SPSC, June 2010

• **GPD (Generalized Parton Distributions)** \( \mu p \rightarrow \mu p \gamma \)
  by exclusive reactions **DVCS** (Deep Virtual ComptonScattering) and **DVMP** (Meson production),
  2 year 'beam charge and spin asymmetry' measurement

• **Polarized Drell-Yan** \( \pi p^\uparrow \rightarrow \mu^+ \mu^- X \)
  Sivers & Boer-Mulders
  Transverse Momentum Dependent distributions
  2 years transversely polarised proton target
  Test of factorization approach
Generalized Parton Distributions

- Unified description of form factors and parton distribution functions
- Transverse imaging = nucleon tomography and (in far future) sensitivity to the quark angular momentum

Kinematic domain: intermediate between HERA and JLab \(10^{-2} < x_B < 10^{-1}\)

Ex: Beam charge & spin asymmetry in DVCS process (interfering with BH):

First signal of DVCS&BH from 2009 short test run, compared to simulations
Measurement of unpolarized PDfs

- In parallel to the DVCS/DVMP program, get (for free) SIDIS data on LH$_2$ target

- Extract strange quark PDF $s(x)$ as well as quark fragmentation functions from kaon multiplicities

Short term goal: LO analysis from COMPASS data alone integrated over z

Longer term goal: provide p and K multiplicities as fct of x, z for global QCD analyses
Polarized Drell-Yan \( \pi^- p \uparrow \rightarrow \mu^+ \mu^- X \)
transversely polarised NH\(_3\) target

\( \sigma^{DY} \propto f_{u|\pi^-} \otimes f_{u|p} \)

→ Transverse Momentum Dependent (TMD) parton distribution functions

Sivers and Boer Mulders fct will be measured:
- in Drell-Yan process
- in \( \mu p \) SIDIS process

Expect opposite sign
→ Test of factorization approach

\( 4 < M_{\mu^+\mu^-} < 9 \text{ GeV} \)

COMPASS DY beam test 2009

Ex: \( A_{UT} \) asymmetry in Drell-Yan process

Anselmino et al.

Bacchetta et al

COMPASS proj.
2 years
**COMPASS (Spin) Summary**

- **Gluon polarization**
  - High $p_T$: at LO, $\Delta G/G \sim 0$ at $x \sim 0.1$ two independent & precise results
  - Charm: at LO, $\Delta G/G = -0.08 \pm 0.21 \pm 0.11$

- **Quark helicity**: extraction at LO for all flavours
  $\Delta s \sim 0$ from SIDIS in measured region

- **Transversity:**
  - Collins and Sivers deuteron, compatible $\sim 0$
  - Collins proton: Signal in valence region, for pos. and neg. Hadrons
    Extract $\Delta_T u > 0$ and $\Delta_T d < 0$
  - Sivers proton: Signal for positive hadrons; possible $W$ dependence

And exciting future program in preparation

2010       Precision measurement on Transverse Spin (Sivers)
2011       Longitudinal Spin
2012 & beyond: New proposal COMPASS II
Spares
Exclusive $\rho^o$ - Transverse Target SSA

- Asymmetry on proton sensitive to GPD $E$, part of Ji sum rule on $L_q$
- Flip of nucleon helicity (and not of quark). Overall helicity not conserved
- Angular momentum conservation $\rightarrow$ transfer of orbital angular momentum

Asymmetry compatible with 0

In agreement with Goloskokov & Kroll prediction
- For $\rho^o$, value of 0.02 in EPJC 59 (2009); hep-ph/08094126
- For $\omega$, larger value expected: 0.10
- $\rho^o$: Asymmetry on deuteron measured to be 0 by COMPASS
\[
\int_{0.004}^{0.3} (\Delta \bar{u} - \Delta \bar{d}) dx = 0.052 \pm 0.035 \text{(stat.)} \pm 0.013 \text{(syst.)}
\]

Flavour asymmetry not as large as in unpolarized case:

\[
\int_{0}^{1} (\bar{u} - \bar{d}) dx = 0.118 \pm 0.012
\]