Review of COMPASS Spin Physics
- A Personal Selection -

Diffraction 2010
Otranto, September 2010
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ALU Freiburg

* on behalf of the COMPASS collaboration
The Spin of the Nucleon

OUTLINE:
- Helicity distribution of quarks
- ... and gluons
- Transverse spin phenomena

\[ \frac{S_z^N}{\hbar} = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + L^q_z + \Delta G + L^g_z \]

\[ \Phi_{Corr}^{Tw2} (x) = \frac{1}{2} \left\{ f_1 (x) + S_L g_1 (x) \gamma_5 + h_1 (x) \gamma_5 \gamma^1 S_T \right\} n^+ \]

\[ \Delta \Sigma = \Delta u_v + \Delta d_v + \Delta q_s \]

\[ \Delta G \]

\[ h_1, f_{1T}^\perp, ... \]
### Polarized DIS & SIDIS Experiments @ CERN

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<tr>
<td>EMC</td>
<td>$g_1, EJ$</td>
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<td>SMC</td>
<td>$g_1, EJ, B_j$</td>
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<td>COMPASS</td>
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<td>$\Delta G, g_1, \Delta q, TSD, TMD$</td>
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<td>COMPASS-II</td>
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<td>$GPD, TSD, TMD$</td>
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**COMPASS**

**Polarized Target:**
- **2002 – 2006:** $^6$LiD $P_T = 0.5$
- **2007, 2010:** NH$_3$ $P_T = 0.8$

**Polarized $\mu^+$ Beam:** 160 GeV/c $P_B = -0.8$
- with choice of $\mu^+, \mu^-$ 100...200 GeV/c

**Diagram:**
- Length: 50m
- NIMA 577 (2007) 455
Longitudinal Spin Structure
Spin Structure Function $g_1(x, Q^2)$

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

- Very precise data
- Good agreement among Experiments

Deuteron data:
From $\Gamma^1$ @ $Q^2 \to \infty$

**COMPASS:**
- $a_0 = 0.33 \pm 0.03 \pm 0.05$
- $\Delta s + \Delta \bar{s} = 1/3(a_0 - a_8) = -0.08 \pm 0.01 \pm 0.02$
Spin Structure Function \( g_1(x, Q^2) \)

Very precise data
Good agreement among Experiments

Large \( x \) \( \rightarrow \) extra talk:

Dave Gaskell

Deuteron data:

From \( \Gamma^1 \) \( @ \) \( Q^2 \rightarrow \infty \)

COMPASS:

\( a_0 = 0.33 \pm 0.03 \pm 0.05 \)

\( \Delta s + \Delta s = 1/3(a_0 - a_8) \)

\( = -0.08 \pm 0.01 \pm 0.02 \)

What makes up the missing 70%?

- Sea Quarks?
- Polarized Gluons?
- Angular Momentum?
SIDIS Photon-Nucleon Asymmetries

inclusive π K

Leading order analysis

\[ A_{1,p} \]

\[ A_{1,p}^{\pi^+} \]

\[ A_{1,p}^{K^+} \]

\[ A_{1,p}^{\pi^-} \]

\[ A_{1,p}^{K^-} \]

\[ A_{1,d} \]

\[ A_{1,d}^{\pi^+} \]

\[ A_{1,d}^{K^+} \]

\[ A_{1,d}^{\pi^-} \]

\[ A_{1,d}^{K^-} \]

\( x \Delta U \)

\( x \Delta d \)

\( x \Delta S \)

COMPASS preliminary, proton data 2007
HERMES PRD71(2005)
DNS parametrization

COMPASS
HERMES
Flavor symmetry breaking \( \Delta \bar{u} - \Delta \bar{d} \)

Presently only accessible in SIDIS

Considerable asymmetry in the unpolarized case

\[
\int_{0.023}^{0.6} (\Delta \bar{u} - \Delta \bar{d}) \, dx = 0.048 \pm 0.057 \text{(stat)} \pm 0.028 \text{(syst)}
\]

Model predicts naturally symmetry breaking for polarized case
Global NLO QCD Analysis

- Nice data!
- $Q^2$ dependence of $g_1$ data described in QCD
- Limited kinematic range (c.f. Collider)
Inclusive World data
Semi-Inclusive World Data

CERN & DESY
Selected Results from two Global Fits

Quark distributions well determined
Possibility of a node @ x=0.1 in Δg(x)
SIDIS prefer Δs=0
Incl. data require Δs<0 (SU3)
Fits give indication for a node
Direct Access to the Gluon Polarization (SIDIS)

Direct measurement of $\Delta G/G$ in Photon-Gluon-Fusion

$A_{||} = R_{pgf} \langle \hat{a}_{pdf} \rangle \langle \frac{\Delta g}{g} \rangle$

- single charmed meson
  - quasi-real photons
  - MC: AROMA, RAPGAP

- high-$p_T$ hadron pairs (no ID of $\pi$, $K$)
  - $Q^2 > 1$ GeV$^2$ (MC: LEPTO)
  - $Q^2 < 1$ GeV$^2$ (MC: PYTHIA)

- high-$p_T$ single hadron
  - small $Q^2$ (MC: PYTHIA)

Strategies to suppress background:

- $q = c$
  - charm fragmentation:
    - $D^0$, $D^*$ (60%)
    - $D^+$ (20%)
    - $D^+_s$, $\Lambda^+_c$ (10% each)

- Hadrons with large $p_T$
  - $q = u, d, s$
Direct Access to the Gluon Polarization (SIDIS)

Direct measurement of $\Delta G/G$ in Photon-Gluon-Fusion

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- Hadrons with large $p_T$
  - $q = u, d, s$
Summary Gluon Polarization

Presently all Analysis in LO only, NLO coming soon

\[ \Delta G/G = -0.08^{+0.21}_{-0.11} \text{(stat)}^{+0.11}_{-0.11} \text{(sys.)} \]

(Systematic error still under investigations)

COMPASS Open Charm:

\[ \Delta G/G = -0.08^{+0.21}_{-0.11} \text{(stat)}^{+0.11}_{-0.11} \text{(sys.)} \]

(Value supersedes previous publication)
Transverse Spin Structure
Single Hadron Production Cross Section

\[
\frac{d\sigma}{dx \, dy \, dz \, d\phi_h \, dP_{h\perp}^2} \propto \{ F_{UU, T} + \epsilon F_{UU, L} \\
+ \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} \\
+ \epsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \cancel{P_{\text{beam}}} \sqrt{2\epsilon(1-\epsilon)} \sin\phi_h F_{UL}^{\sin \phi_h} \\
+ \cancel{P_L} \sqrt{2\epsilon(1+\epsilon)} \sin\phi_h F_{UL}^{\sin \phi_h} + \epsilon \sin(2\phi_h) F_{UL}^{\sin(2\phi_h)} \\
+ \cancel{P_L} \cancel{P_{\text{beam}}} \sqrt{1 - \epsilon^2} F_{LL} + \sqrt{2\epsilon(1-\epsilon)} \cos\phi_h F_{LL}^{\cos\phi_h} \\
+ |P_T| \sin(\phi_h - \phi_S) (F_{UT, T}^{\sin(\phi_h - \phi_S)} + \epsilon F_{UT, L}^{\sin(\phi_h - \phi_S)}) \\
+ \epsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \epsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \\
+ \sqrt{2\epsilon(1+\epsilon)} \sin\phi_S F_{UT}^{\sin \phi_S} \\
+ \sqrt{2\epsilon(1+\epsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \\
+ |P_T| \cancel{P_{\text{beam}}} \sqrt{1 - \epsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} \\
+ \sqrt{2\epsilon(1-\epsilon)} \cos\phi_S F_{LT}^{\cos \phi_S} \\
+ \sqrt{2\epsilon(1-\epsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \} \}
\]

- General expression
- Valid for
  - SIDIS
  - exclusive reactions
- for entire phase space (TFR, CFR)

A. Kotzinian NPB 441 (1995) 234
Bacchetta et al, JHEP 0702:093, 2007
**Transverse Momentum Dependent PDFs**

<table>
<thead>
<tr>
<th>Nucleon</th>
<th>quark</th>
<th>U</th>
<th>L</th>
<th>T</th>
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<tbody>
<tr>
<td>U</td>
<td>f₁</td>
<td></td>
<td>h₁⁻</td>
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</tr>
<tr>
<td>L</td>
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- Boer-Mulders DF **
- 'Worm-gear 1' DF 
- Transversity DF
- Prezelosity DF

- Sivers DF *
- 'Worm-gear 2' DF

* T-odd
# chiral-odd

Only $f_1$ and $g_1$ measurable in inclusive DIS, all others in SIDIS

A. Bacchetta et al., JHEP 0702 (2007)
The Collins FF \( H_{1,q}^\perp(z, p_T) \) correlates the transverse spin of the fragmenting quark and the transverse momentum \( P_{h\perp} \) of the produced hadron \( h \).

The Collins FF is given by the following equation:

\[
A_{Coll} \propto \frac{\sum_q e_q^2 h_1^q(x) \cdot H_{1,q}^\perp(z, p_T)}{\sum_q e_q^2 f^q(x) \cdot D_q^h(z)}
\]

The Collins interference amplitude is given by:

\[
A_{Coll} = \frac{A_{UT}^{\sin \phi}}{D_{NN} \cdot f \cdot P}
\]

where

\[
\phi_C = \phi_h - \phi_s - \pi
\]
Collins FF and Transversity distribution function are sizeable

\( \pi^- \) asymmetries unexpectedly large

Large contribution from unfavoured FF

\[ H_{1\perp q}^{\text{unf}} \approx -H_{1\perp q}^{\text{fav}} \]
Two Hadron Interference FF

Alternative: couple $h^q_1(x)$ to chiral odd 2-hadron interference FF $H_1^{zq}$

$$A_{Coll} \propto \sum_q e_q^2 h^q_1(x) \cdot H_1^{zq}(z, M_T^2)$$

Cross-section asymmetry:

$$\frac{\Delta \sigma}{\sigma} \propto A_{RS} \sin \phi_{RS} \sin \theta$$

$$\phi_{RS} = \phi_R + \phi_S - \pi; \quad \sin \theta \simeq 1$$

COMPASS 2007 transverse proton data

h⁺ h⁻ pairs
Transversity DF and Collins FF from a Global Fit

- Indication for large contribution from unfavoured FF

\[ H_{1\perp}^{\text{unf}} \approx -H_{1\perp}^{\text{fav}} \]

- Extraction based on Belle, COMPASS, HERMES data @ \( Q^2 = 2.4 \text{ (GeV/c)}^2 \)

Anselmino et al.
\[ A_{Siv} \propto \frac{\sum_q e_q^2 f_{1T}^{q\perp}(x, p_T^h/z) \cdot D_q^h(z)}{\sum_q e_q^2 f_q^q(x, p_T^h/z) \cdot D_q^h(z)} \]

\[ \frac{\Delta \sigma}{\sigma} \propto A_{Siv} \sin \Phi_S \]

\[ \Phi_S = \phi_h - \phi_S \]
Sivers Asymmetries

Experimental evidence for orbital momentum of the quarks

- COMPASS $\pi$ and K /deuteron
- HERMES /proton

used to extract Sivers function

Anselmino et al.
Kinematic Effects

COMPASS 2007 proton data

positive hadrons

negative hadrons

$A_{SIV}^p$

$W > 7.5 \text{ GeV/c}^2$

$W < 7.5 \text{ GeV/c}^2$

preliminary

Dependance on hadronic mass?
Unpolarized target

COMPASS 2004$^6$LiD (part)

$A_D \cos 2\phi$

$p^+$ preliminary

$A_D \cos 2\phi$

$Cahn$ effect

Boer-Mulders

QCD (first order)

Barone, Prokudin, Ma
Outlook – COMPASS II

Upgrade existing COMPASS Spectrometer @ CERN/SPS

DVCS & DVMP Measurements
Transverse Imaging
Beam Charge & Spin asymmetry
GPD H
later GPD E

Drell-Yan Measurements
Sivers PDF
Boer Mulders PDF
Test of factorization approach

PDFs and Fragmentation s(x)
Kaon FF

Chiral Perturbation Theory → Jan Friedrich's presentation

Proposal submitted to CERN (2010-05-17)
Presently under discussion at SPSC
Data taking can start 2012

CERN-SPSC-2010-014/SPSC-P-340
... later, during lunch break, you may practice
Recent fit (dominated by HERMES, COMPASS $p$ not yet in)