Nucleon spin and structure studies at COMPASS

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- Nucleon spin: Quark and gluon helicities
- Quark Fragmentation Functions
- Transversity
- Future
COmmon Muon Proton Apparatus for Structure and Spectroscopy

~240 physicists, 12 countries, 24 institutions

Fixed target experiment, multi-purpose set-up.
Secondary ~200 GeV muon and hadron beams from CERN SPS
Various targets
COMPASS at CERN

Results from:

Polarized muon beam & polarized target: d, p: Nucleon spin structure

Hadron beam \( \pi / K / p \) \& LH\( _2 \) or nuclei targets: Meson spectroscopy \( \rightarrow \) Talk of S. Uhl

\( \pi, K \) polarisabilities

Ongoing program:

- Generalized Parton Distributions from DVCS
- Transverse Momentum Dependent distributions from Polarized Drell-Yan

**COMPASS at CERN**

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**NIMA 577 (2007) 455**
Nucleon spin

How is the nucleon spin distributed among its constituents?

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

- \( \Delta \Sigma \) : sum over \( u, d, s, \bar{u}, \bar{d}, \bar{s} \)
- can take non half-integer value:
  - superposition of several spin states

\[ \Delta q = q - q \]

Parton spin parallel or anti parallel to nucleon spin

Past:

- Theory: QPM estimations, with relativistic effects
- \( \Delta \Sigma \sim 0.6 \)
- Experiment: “Spin crisis” in 1988, when EMC measured
  - \( a_0 = \Delta \Sigma = 0.12 \pm 0.17 \) \( \text{MS scheme} \)
- Quark spin contribution \(~ 0?\)

Today:

- Precise world data on polarized DIS
  - \( g_1 + SU_f(3) \)
  - \( a_0 = \Delta \Sigma \sim 0.3 \)
  - Quark spin contribution \sim 30\%

- Confirmed by first results from Lattice QCD on \( \Delta \Sigma_{u,d} \).

Large experimental effort on \( \Delta G \) measurement

- also because \( a_0 = \Delta \Sigma - n_f(\alpha_s/2\pi) \Delta G \) (AB scheme)
Quark and gluon helicity

Quarks and gluons from nucleon, probed with lepton beams

**quarks**
- Deep inelastic scattering
- QCD Leading order

**gluons**
- Photon-gluon fusion: $\gamma g \rightarrow q\bar{q}$

Helicities of partons measured via spin asymmetries using polarized beams and targets

- **Acces $\Delta \Sigma$ et $\Delta G$**: contributions of quark and gluon spin to nucleon spin $\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g$
- **Comparison to lattice QCD calculations**
Gluon helicity $\Delta G/G$ from hadron production

Photon Gluon Fusion

$\mu^+ p \rightarrow \mu^{' h + h} + X$

Results are in agreement with latest fits from NNPDF and DSSV++ using RHIC pp data, which give $\int_{0.05}^{0.2} \Delta g(x) \, dx \approx 0.20$
QCD fits - World data on $g_1^p$ and $g_1^d$

Polarized Deep Inelastic Scattering

$\rightarrow$ Nucleon spin structure functions $g_1$

$\rightarrow g_1(x,Q^2)$ as input to global QCD fits for extraction of $\Delta q_f(x)$ and $\Delta g(x)$

\[
\frac{d g_1}{d \log(Q^2)} \propto -\Delta g(x, Q^2)
\]

However $x$ and $Q^2$ coverage not yet sufficient for precise $\Delta g$

Would need to use constraint from pp data (as DSSV, NNPDF)
COMPASS NLO pQCD fit to $g_1$ DIS world data

- Assume functional forms for $\Delta \Sigma$, $\Delta G$ and $\Delta q^{\text{NS}}$, and assume SU3 symmetry
- Use DGLAP equations, relating $\Delta \Sigma$, $\Delta G$ evolutions.
- Fit $g_1^p$, $g_1^d$, $g_1^n$ DIS world data

- Extract $\Delta \Sigma$ Quarks $\Delta G$ Gluons

→ Solutions $\Delta G > 0$ and $\Delta G < 0$

→ Quark spin contribution:
  $\Delta \Sigma = 0.31 (5)$ at $Q^2 = 3$ (GeV/c)$^2$

  Largest uncertainty comes from the bad knowledge of functional forms.
  Results in fair agreement with other global fits

→ Gluon spin contribution: $\Delta G$ not well constrained, even the sign, using DIS only

  Solution with $\Delta G > 0$ agrees with result from DSSV++ using RHIC pp data
Summary on nucleon spin from COMPASS

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

**Quarks**  \(\frac{1}{2} \Delta \Sigma \sim 0.15\) (3)
- largest uncertainty due to uncertainty on \(\Delta G\)

**Gluons**  \(\Delta G/G\) positive at \(x \sim 0.1\) (PGF)
- agrees with precise RHIC result (\(\Delta G \sim 0.2\) for integral \(0.05 < x < 0.2\))
- Low \(x\) contribution to integral still unknown.

**Orbital momenta**  \(L_q, L_g\)
- Ongoing measurements of GPDs

There exist promising results from lattice QCD calculations:
- Confirm already \(\Delta \Sigma\), and predictions for \(L_u\) et \(L_d\).

\(\rightarrow\) The main question raised in ‘Nucleon spin crisis’ resolved:
- Quark spin represents a non zero fraction (0.3) of nucleon spin
  (from measurements and from lattice QCD calculations)
- The hypothesis of very large \(\Delta G\) (2 to 3, associated to \(L \sim -2\) ou -3) rejected
  (COMPASS 2005)
- Puzzle still pending: share between \(\Delta G\) and \(L\) not known
Quark helicities from semi-inclusive DIS

\[ l \rightarrow p \rightarrow l h^{+/-} x \]

Outgoing hadron tags quark flavor (quark fragmentation functions)

Leading order extraction of quark helicities from spin asymmetries:

- COMPASS
  - PLB693(2010)227, using DSS quark FFs
- HERMES
  - PRD71(2005)012003
  - DSSV at NLO

\[ \mathbf{l} \rightarrow \mathbf{p} \rightarrow l h^{+/-} X \]

\( Q^2 = 3 \text{ (GeV/c)}^2 \)

- Full flavour separation \( \rightarrow x \sim 0.004 \)
- Sea quark distributions \( \sim \) zero
- Good agreement with global fits

What about \( \Delta s ? \) Integral is found negative from \textit{inclusive} data (with SU3) while here from \textit{semi-inclusive} data, \( x > \sim 0.005 \), \( \Delta s \) is compatible with zero.

\textbf{NB:} - The extraction assumes quark Fragmentation Functions known (DSS here)
  - No measurement at lower \( x \)
Quark Fragmentation Functions (FF)

**FFs**: - Non perturbative object; needed to describe various reactions
- Strange quark FF = largest uncertainty in $\Delta s$ extraction from polarized SIDIS. Data exist from $e^+e^-$ and pp reactions, but unsufficient and at too high $Q^2$

→ Measure $\pi$, K, p multiplicities in **SIDIS** $\mu^+d \rightarrow \mu^+h^\pm X$

\[
dM^h(x, Q^2, z) = \frac{\sum_q e_q^2 f_q(x, Q^2) D_q^h(z, Q^2)}{\sum_q e_q^2 f_q(x, Q^2)}
\]

PDFs depend on $x$, while FFs depend on $z$

Data obtained in a fine binning in $x$, $z$, $Q^2$

→ Constitute an input to global NLO QCD analyses to extract quark FFs
COMPASS $\pi$ and $K$ multiplicities vs z in (x,y) bins

- ~360 data points for $\pi$ and 360 for $K$
- Strong z dependance
- $M_{\pi^+} \sim M_{\pi^-}$ and $M_{K^+} > M_{K^-}$

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Quark FFs from COMPASS LO fits

**Pions**

Assuming 2 independent FFs: $D_{\text{fav}}^\pi$ and $D_{\text{unf}}^\pi$

- As expected, $D_{\text{fav}}^\pi > D_{\text{unf}}^\pi$.
- COMPASS results ~agree with DSS and LSS NLO fits (not shown here)

**Kaons**

Assuming 3 independent FFs: $D_{\text{fav}}^K$, $D_{\text{unf}}^K$, $D_{\text{str}}^K$

- $D_{\text{fav}}^K > D_{\text{unf}}^K$.
- $D_{\text{fav}}^K$ and $D_{\text{unf}}^K$ larger than DSS and LSS NLO fits (which do not include these kaon data)
- $D_{\text{str}}^K$ (not shown, not constrained enough by the fit)
Sum of $z$ integrated multiplicities $\pi^+ + \pi^- \, \& \, K^+ + K^-$

For isoscalar target, simple dependence on FFs:

$$M^{\pi^+ + \pi^-} = (1 - 2S/(5Q+2S)) \ D_{fav} + D_{unf}$$

At high $x$, $\sim$no $x$ dependence expected

$$5M^{K^+ + K^-} = \ D_Q^K + S/Q \ D_S^K$$

where:

$$\begin{cases}
Q = u + \bar{u} + d + \bar{d}, \\
S = s + \bar{s}, \\
D_Q^K = 4D^K_{fav} + 6D^K_{unf}
\end{cases}$$

COMPASS pion data:
- significantly below HERMES ones
- no $x$ dependence
  (as in EMC h, but not shown here)

COMPASS kaon data:
- significantly above HERMES ones
- agree with MC simulation (LUND)
- Indicate smaller $D_S^K$, and larger $D_Q^K$
**Transversity- Collins and Sivers asymmetries**

- Access via SIDIS, transversely polarized target
  \[ \mu p^\uparrow \rightarrow \mu h^{+/-} X \]

- Measure simultaneously several azimuthal asymmetries, out of which:
  - **Collins**: Outgoing hadron direction & **quark transverse spin**
  - **Sivers**: Nucleon spin & **quark transverse momentum** \( k_T \)

  Sivers function = one of the TMDs = Transverse Momentum Dependent PDFs

At LO:

**Collins**

\[
A_{\text{Coll}} = \frac{\sum_q e_q^2 (\Delta T q \otimes \Delta T) D_h^q}{\sum_q e_q \cdot q \otimes D_h^q}
\]

Collins TMD fragmentation function, depends on spin, and hadron \( p_T \)

**Sivers**

\[
A_{\text{Siv}} = \frac{\sum_q e_q^2 \cdot f_{1Tq} \otimes D_h^q}{\sum_q e_q \cdot q \otimes D_h^q}
\]

Unpolarized quark TMD fragmentation function

**Note**: \( \Delta T q \) also measured in SIDIS using “Two hadron” fragmentation function
Collins asymmetry $\rightarrow$ Transversity $\Delta_T u$ $\Delta_T d$

- Large signal for proton target. (compatible with zero for deuteron target)
- Same signal strength seen by HERMES and COMPASS, although different $Q^2$ (times 4)

Several combined analyses of polarized SIDIS data
HERMES $p$, COMPASS $p$ and $d$, and BELLE FF

- $\Delta_T u > 0$ and $\Delta_T d < 0$
- Smaller than helicity
- Derived also from di-hadron

Nb: Asymmetry also measured for $\pi$ and $K$

PLB 744 (2015) 250

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M. Anselmino et al., RRD87 (2013) 094019
Sivers asymmetry → Sivers function

Correlation between Nucleon spin & quark transverse momentum $k_T$

Large signal with proton target and $h^+$
Was measured compatible with zero on deuteron

When compared to HERMES, smaller strength at larger $Q^2$

$\Rightarrow$ Opposite sign for $u$ and $d$ quark Sivers function

Nh: Asymmetry also measured for $\pi$ and K

PLB 744 (2015) 250
Transversity from dihadrons – Extraction of $h_1$

using:
• COMPASS proton and deuteron data on dihadron azimuthal asymmetries (different analysis from Collins)
• dihadron FF + $Q^2$ evolution from Bacchetta et al. *JHEP03 (2013) 119*

Comparison with Anselmino et al. (global fits of single hadron Collins asymmetries+FFs):
Very good agreement for $u$ quark, and fair agreement for $d$ quark transversity.
Transversity from di-hadrons. Interplay with Collins

Fragmentation of a transversely polarized quark

Azimuthal asymmetries from production of:
- di-hadron (oppositely charged pair)
- single hadron (+ and -, mirror symmetric Collins asymmetries)

\[
\langle A_{\perp} \rangle
\]

\[
\langle \sin \Phi_C \rangle
\]

\(x\) range: \(10^{-2}\) to 1

\(A_{\perp}\) vs. \(x\)

\(\sin \Phi_C\) vs. \(x\)

→ Observe similar behaviour …

and establish correlation between the three

• First experimental indication for a common physical origin to the two processes, di-hadron and Collins, as originally suggested by different models.

• Results for ‘transversity’ from the two measurements are NOT independent
Six Transverse Target spin asymmetries

beyond Collins & Sivers, access TMDs

$k_T$ effects $\rightarrow$ modulations in SIDIS cross-section

- Major progress in TMD measurement
- Powerful tool to understand correlations

$A_{LT}^{\cos(\varphi_h - \varphi_s)}$ shown as example

In agreement with HERMES prelim., and with theoretical predictions
COMPASS ongoing program 2015 - 2018:

• **GPDs** (Generalized Parton Distributions) via **Deep Virtual Compton Scattering** $\mu p \rightarrow \mu p' \gamma$

• **TMDs** (Transverse Momentum Dependent distributions) via **spin dependent Drell-Yan** $\pi p \uparrow \rightarrow \mu^+ \mu^-$
Generalized parton distributions

Study correlation between parton longitudinal momentum & parton transverse position in the nucleon ‘3D’

- Nucleon ‘3D’ structure
- Link to orbital momentum $L_z$

Process:
Deep virtual Compton scattering (DVCS):
‘exclusive’ $\gamma$ production $\mu \ p \rightarrow \mu \ p' \ \gamma$
or Meson Production $\rho^0, \omega, \phi...$

$\rightarrow$ Proton transverse size

$\rightarrow$ Compton Form Factors in yet unexplored regions (160 GeV $\mu$ beam)
DVCS- t-slope of Cross-section

\[ \mu p \rightarrow \mu p \gamma \]

x dependence of transverse size of the nucleon

\[ \sigma_{\text{DVCS}} \sim \exp^{-B|t|} \]

\[ B(x_B) = \frac{1}{2} \langle r_{\perp}^2(x_B) \rangle \]

Also accessed via meson production \( \rho, \omega, \phi \)

Deep Virtual Compton Scattering (\( \gamma \))

Deep Virtual Meson Prod. (\( \rho \))

COMPASS result from 2012 pilot run

COMPASS projection 2 years

projection 2 years
COMPASS- Spin dependent Drell-Yan (2015 and 2018)

Pion beam on transversely polarized nucleon

Objectives for Drell-Yan measurements:

• Polarised: Sivers TMD PDF (correlation $k_T$ vs nucleon transverse spin) sign change DY vs SIDIS $\rightarrow$ test of factorization in QCD
• Unpolarized: Other TMD PDFs (Boer-Mulders…) ($k_T$ vs $s_q$)

COMPASS assets

• SIDIS and DY experiments: large acceptance, same spectrometer
• Unique hadron beam ($\pi$, K, p) with valence antiquarks
• Polarized target

Projection 2 years (2015+2018 data)
Summary

Gluon and quark contribution to nucleon spin
Gluon $\Delta G/G = 0.1$ at $x = 0.1$ from measurement in PGF 2 hadrons

Quarks: Sum $0.26 < \Delta \Sigma < 0.34$ from global QCD fit of $g_1$ world data
Largest uncertainty comes from functional shape (of $\Delta G$ also)
Extraction for all flavours from SIDIS measurements, down to $x \sim 0.004$.
Towards agreement with Lattice QCD calculation

Pion and kaon multiplicities in semi-inclusive DIS:
Large discrepancies between COMPASS and HERMES data

Transversity and Transverse Momentum Dependent parton distributions
Precise results on Collins and Sivers asymmetries
Interplay Collins effect / di-hadron
Much progress on all azimuthal asymmetries for TMDs

Future
TMDs via polarized Drell-Yan $\pi \, p \uparrow \rightarrow \gamma \, \gamma$
GPDs via Deep Virtual Compton Scattering $\mu \, p \rightarrow \mu \, p \, \gamma$
First result on proton transverse size
COMPASS Plans

2015  Polarized Drell-Yan  $\pi p^\uparrow$

2016  DVCS $\mu p$

2017  

2018  Polarized Drell-Yan  $\pi p^\uparrow$

2019  CERN Long Shutdown-2

2020  

2021  Ideas for future:

2022  - Kaon & p-bar beams  (for Drell-Yan and Meson Spectroscopy)

2023  - DVCS on Polarized Target  $\mu p^\uparrow$

(sensitive to nucleon orbital angular momentum)