High-energy spin physics at fixed-target experiments

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Highlights on measurements of:
• Nucleon spin, Gluon and quark helicities: DIS
• Transverse spin: DIS and Drell-Yan
• Generalized parton distributions : DVCS, HEMP

SPIN21, Matsue, Japan, Oct. 18-22, 2021
HERMES at DESY

27 GeV e+ & e-
Longit. polarized ~ 54%
Gaseous intern. polar target
1995 to 2007

COMPASS at CERN

160-200 GeV
polarized muon beam DIS
pion beam: Drell-Yan
Long solid polarized targets

JLab

12 GeV
Polarized CW e- beam
Pol=85%,
High luminosity

Hall D: hybrid mesons

Hall C

Hall B: GPDs

Hall A: form factors + Moller & SOLID…
Kinematical ranges
Nucleon spin - longitudinal

How is the nucleon spin distributed among its constituents?

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

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

\[ \Delta q = \vec{q} - \vec{\bar{q}} \]

Parton spin parallel or anti parallel to nucleon spin

\( \Delta \Sigma \) Today:

Precise world data on polarized DIS: \( g_1 + \text{SU}_f(3) \)

\( a_0 = \Delta \Sigma \sim 0.3 \)

Quark spin contribution \( \sim 30\% \)

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

Large experimental effort on:

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

- 3D mapping of nucleon and constraining L
  - through DVCS and Hard Exclusive Meson Production

See talk of C. Alexandrou
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 in DIS not yet sufficient for precise $\Delta g$

Need to use constraint from pp data (as DSSV, NNPDF...)

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**NLO pQCD fit to $g_1$ DIS world data**

- Assume functional forms for $\Delta \Sigma$, $\Delta G$ and $\Delta q^{NS}$
- Use DGLAP equations, relating $\Delta \Sigma$, $\Delta G$ evolutions
- Fit $g_1^p$, $g_1^d$, $g_1^n$ DIS world data. ($SU_3$)

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

$\Delta G$ not well constrained using DIS only

Obtain solutions with $\Delta G > 0$ and $\Delta G < 0$

Solution with $\Delta G > 0$ agrees with result from DSSV++ which uses RHIC pp data

$\Delta \Sigma$ well constrained in valence region

$\Delta \Sigma = 0.31 (5)$ at $Q^2 = 3$ (GeV/c)$^2$

Still large uncertainty coming from the bad knowledge of functional form
Global fits to polarized PDFs (I)

Fits to world data, including collider data. Many fitters. Some examples:

Blue: DSSLV
from DSSV14 w. replicas and MC average

Green: NNPDFpol1.1

More realistic evaluation of uncertainties

Still some discrepancies in $\Delta s$ sign (and in $\Delta d$ position of minimum)

Large uncertainties in $\Delta G$, below $x \sim 0.1$
Global fits to polarized PDFs (II)

A₁ – helicity low x

Small-x evolution equations for g₁
Data from SLAC, CERN, DESY.

- Present projections toward low x
- Expected impact of EIC future data

\[ Q^2 = 10 \text{ GeV}^2 \]
Global fits to polarized PDFs (III)

ΔΣ and ΔG

Expected impact of EIC future data on integrals truncated to x ~ 10^{-4}

Huge reduction of uncertainties but need to use SU3
Gluon helicity $\Delta G/G$ direct measurement

Photon Gluon Fusion

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

$Q^2 > 1 \text{(GeV/c)}^2$

Extraction at LO:

$\Delta g/g \ (x=0.1) = 0.11 \pm 0.04 \pm 0.04$

Results are in agreement with fits from NNPDF and DSSV++ using RHIC $\vec{p}\vec{p}$ data, which give

$$\int_{0.05}^{0.2} \Delta g(x) \, dx \simeq 0.20$$
Quark helicities from semi-inclusive DIS

\[ l \to p \to l \, h^{+/−} \, X \]

Outgoing hadron tags quark flavor (via quark fragmentation functions)

Flavour separation of quark helicities:

\[ \mathbf{Q}^2 = 3 \, (\text{GeV/c})^2 \]

NB: The SIDIS extraction uses input of quark Fragmentation Functions, not that well determined yet, especially for the strange quark sector.

0 HERMES
PRD71(2005)012003

• COMPASS
PLB693(2010)227, using DSS-07 FFs

___ DSSV at NLO

• Full flavour separation \( \rightarrow \, x \sim 0.004 \)
• Sea quark distributions \( \sim \) zero
• Good agreement with global fits
Kaons- Quark fragmentation functions from NLO fits

Extensive sets of SIDIS kaon data change significantly flavor decomposition of FFs (& PDFs)

Ex1: DEHSS-17 fit to quark FF, includes recent kaon SIDIS data.

Ex:2: JAM18 w/wo SIDIS
Combined fit of PDFs and FFs (prelim)

Also simultaneous/ iterative fits of PDFs & FFs:

‘SIA + SIDIS data : strong preference for smaller strange to nonstrange PDF ratio, and enhanced DsK’

-> revisit Δs(x) extraction from SIDIS data

See plenary talk on FFs by F. Ringer
Transverse Momentum Dependent distr. : TMDs

Importance of $p_T$:
$P_T$ dependence results from:
- intrinsic $k_\perp$ of the quarks
- $p_\perp$ generated in the quark fragmentation

Global analyses of SIDIS, Drell-Yan and Z production data with TMD $Q^2$ evolution

SIDIS multiplicity (example)

Drell-Yan cross section

Transverse momentum distribution

A. Bacchetta et al., JHEP06 (2017) 081
See also A. Martin talk
Transverse spin- Collins and Sivers functions (DIS)

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

- Measure simultaneously several azimuthal asymmetries, out of which:
  \[
  \begin{align*}
  \text{Collins:} & \quad \text{Outgoing hadron direction} \& \text{quark transverse spin} \\
  \text{Sivers:} & \quad \text{Nucleon spin} \& \text{quark transverse momentum} k_T
  \end{align*}
  \]

\[ A_{\text{Coll}} = \frac{\sum_q e_q^2 \cdot x \cdot h_{Tq}^q \otimes H_{1q}^⊥}{\sum_q e_q^2 \cdot x \cdot q \otimes D_{1q}^h} \]

Collins TMD fragmentation function, depends on spin, and hadron p_T

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

Unpolarized quark TMD fragmentation function

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Collins asymmetry $\rightarrow$ Transversity $h_1$

- 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

$h_1^u > 0$ and $h_1^d < 0$
Smaller than helicity

NB: asymmetries also measured for $\pi$ and K

HERMES PLB 693(2010)  
COMPASS PLB 744 (2015)  
Anselmino et al., PRD87(2013) 094019
Sivers asymmetry $\rightarrow$ Sivers function

Correlation between Nucleon spin & quark transverse momentum $k_T$

Large signal with proton target.
Was measured compatible with zero on deuteron

Compared to COMPASS, HERMES (smaller $Q^2$) has larger signal

HERMES PRL 103 (2009)
COMPASS PLB 744 (2015)

Anselmino et al., JHEP04 (2017)046
Collins & Sivers. Recent global fits

Many global analyses of SIDIS, Drell-Yan, pp and e+e-.
Great progress: theoretical developments, large data sets, uncertainty studies
JAM20, Etchevaria et al., Anselmino et al., Radici, Bacchetta, Kang et al., D’Alesio et al., Boglione et., Bury et al. ...
e.g.:

JAM20, PRD102, 054002 (2020)
Transversity $h_1$ / tensor charge

More data on deuteron needed
COMPASS projection for 2022 data, pol. 6LiD:

**Present**
- $P$ all, $D$ 2002-2004

**Projected**
- $P$ all, $D$ 2021/22 only

<table>
<thead>
<tr>
<th>$\delta_u = \int_{x_0}^1 dx h_1^{u}(x)$</th>
<th>$\delta_d = \int_{x_0}^1 dx h_1^{d}(x)$</th>
<th>$g_T = \delta_u - \delta_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present</td>
<td>0.201 ± 0.032</td>
<td>-0.189 ± 0.108</td>
</tr>
<tr>
<td>Projected</td>
<td>0.201 ± 0.019</td>
<td>-0.189 ± 0.040</td>
</tr>
</tbody>
</table>

Expected improvement on uncertainties by factors of : ~2 (u), ~3 (d)
SIDIS transverse spin
TMDs, new approach: weighted asymmetries

\[ A_{S_{iv}}^{(p_T/zM)}(x, z) = \frac{2}{\sum_q e_q^2 f_{1T}^{q}(x) \cdot D_1^q(z)} \sum_q e_q^2 f_{1T}^{q}(x) \cdot D_1^q(z) \]

\[ f_{1T}^{(1)}(x, Q^2) = \int \frac{d^2 k_T}{2M^2} \frac{k_T^2}{2M^2} f_{1T}^{(1)}(x, k_T, Q^2). \]

\[ \rightarrow \text{extract first moment of Sivers without assumption on } k_T \text{ dependence} \]

Sivers asymmetry, with weight \( p_T/zM \)
No more convolution of TMDs and FFs but a product of integrals.

Point by point extraction using \( h^+ \) and \( h^- \) asym (NH3 target)

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More on TMDs

**HERMES**: extensive 3D analysis update

First Collins & Sivers for p & pbar

- Collins: vanishing
- Sivers: simil. magnitude as $\pi^+$

Pretzelosity for $\pi$ and K

- (quadrupole deformation): no sign

$\rho^0$ COMPASS first Collins and Sivers measurement

- $\rho^0$ Collins asym: positive, opposite to $\pi^+$, as expected from models large at small $p_T$
- $\rho^0$ Sivers asym: positive, similarly to $\pi^+$, as expected

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TMDs in polarized Drell-Yan

COMPASS, \( \pi \) induced Drell-Yan on \( \text{pol. NH}_3 \): 

\[ \text{Sivers function:} \]
non-vanishing orbital angular momentum,
Process dependence expected:
sign change between SIDIS and Drell-Yan
Both measured in COMPASS
at similar hard scale

See also Global analysis SIDIS+Star W, Z data:
only slight preference for Sivers sign-change
(new STAR data not yet included).

\[ \text{COMPASS, PRL} 119 \ (2017) \ 112002 \]
GPDs generalized Parton Distributions

Physics goal: 3D mapping of nucleon and access to Orbital Angular Momentum

See theory talk by B. Pasquini

Determine 4 GPDs: $H, E, \tilde{H}, \tilde{E}$ (Re and Im parts)
via ‘exclusive’ processes: DVCS ($\gamma$) and DVMP ($\rho, \omega, \phi$)

Measurements at Jlab, Compass, Hermes and pioneering work at H1 and Zeus

DVCS interferes with Bethe-Heitler process
→ Can use interference terms (e.g. at Jlab) or pure DVCS production
with appropriate combinations of beam sign and polarization (COMPASS).

Way to it:
• Collect very large sample of data, various observables and several kinematic variables
• Global analyses to extract 4x2 Compton Form Factors CFFs
• Deconvolutions to finally access GPDs.
DVCS – Jlab CLAS proton target, e H → e’p γ

\[ d^4\sigma(x, Q^2, t, \phi) \text{ and } \Delta(d^4\sigma) \text{ beam spin difference, sensitive to } Im[H] \sim e^{-b(x) t} \]

\( b \) related to proton transverse size

Assuming one GPD, fit to CFF at 3 x values:

- \( Q^2=1.11 \text{ GeV}^2 \)
  - \( x_B=0.126 \)
  - \( A = 5.30\pm0.95 \)
  - \( b = 4.25\pm0.98 \)

- \( Q^2=1.63 \text{ GeV}^2 \)
  - \( x_B=0.185 \)
  - \( A = 4.98\pm0.56 \)
  - \( b = 3.03\pm0.55 \)

- \( Q^2=2.10 \text{ GeV}^2 \)
  - \( x_B=0.304 \)
  - \( A = 1.81\pm1.72 \)
  - \( b = 1.18\pm2.26 \)

\( b \) decreases as \( x_B \) increases

→ proton shrinking with \( x_B \)
DVCS- t-slope of Cross-section (COMPASS)

\[ \mu^+/- p \rightarrow \mu^- p \gamma \]

Combining data from $\mu^+$ and $\mu^-$ beams (beam spin & charge sum), measure t-slope of DVCS cross section $\rightarrow x$ dependence of transverse size of the nucleon

\[ \sigma^{DVCS}/dt \sim \exp^{-B|t|} \]

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

**Measurement of proton transverse size vs $x_B$**

**New prelim. COMPASS result:**

( J. Giarra talk)

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**COMPASS preliminary**

\[ e^{B|t|} \]

\[ B = 0.6 \pm 0.6_{stat} \pm 0.3_{sys} \text{ [GeV/c]^2} \]

2016 data : prelim. result

3 x more stat. expected from 2017 data

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\[ \sigma^{DVCS}/dt \sim \exp^{-B|t|} \]

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

Curves:

--- GK model at $Q^2=1.8$ & 10 GeV^2

--- KM15 at $Q^2=1.8$ & 10 GeV^2

--- COMPASS: $<Q^2>$ = 1.8 (GeV/c)^2

--- COMPASS: $<Q^2>$ = 1.8 (GeV/c)^2

--- ZEUS: $<Q^2>$ = 3.2 (GeV/c)^2

--- H1: $<Q^2>$ = 4.0 (GeV/c)^2

--- H1: $<Q^2>$ = 8.0 (GeV/c)^2

--- H1: $<Q^2>$ = 10. (GeV/c)^2

--- This analysis, preliminary


--- JHEP 0905 (2009) 108


--- 10 GeV < v < 32 GeV

--- $1 < Q^2 < 5$ (GeV/c)^2

--- $Q^2=1.8$ (GeV/c)^2

--- $Q^2=10$ GeV^2

--- $Q^2=1.8$ & 10 GeV^2

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--- $Q^2=1.8$ & 10 GeV^2

--- $Q^2=1.8$ & 10 GeV^2
Flavour separation of CFFs

JLab Hall-A neutron and proton DVCS

Benali, Desnault, Mazouz et al., Nature Physics 16 (2020) 191-198
CFFs from globat fits of DVCS data

Example: ‘PARTON’ fit at LO/LT DVCS proton, Including Jlab, HERMES and COMPASS data 2600 / 3970 points with constraints on GPDs (PDFs, elastic Form Factors, limits at $x \to 1$...)

CFFs:

$\Re H$

$\Im H$

Position of up quarks in a proton:

$\mathbf{b}_\perp$
Summary – Spin at fixed target experiments

Gluon and quark contribution to nucleon spin

Gluon \( \Delta G/G=0.1 \) at \( x=0.1 \) (photon gluon fusion process) agrees with RHIC \( \int \Delta G \sim 0.2 \)

Unknown contribution at low \( x \)

Quarks : \( \frac{1}{2} \Delta \Sigma \sim 0.15 \) from global QCD fit of \( g_1 \) world data

Largest uncertainty comes from functional shape (of \( \Delta G \) also)

Agreement with Lattice QCD

Flavor decomposition from SIDIS, down to \( x \sim 0.004 \).

Transverse Momentum Dependent parton distributions

Extensive and precise results on all azimuthal asymmetries

Global analyses

GPDs via DVCS: Many data coming and promising framework for global analyses.

Bright future See talks on EIC, SPD at NICA, pol. tagets at LHC…