Recent Results on Structure Functions

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Outline

• Introduction
• Unpolarized nucleon structure
• Longitudinal (transverse) spin structure
• 3-dimensional Structure of nucleon
  – Transverse momentum dependent parton distributions (TMDs)
  – Generalized parton distributions (GPDs)
• Summary and outlook
QCD: still unsolved in non-perturbative region

• 2004 Nobel prize for "asymptotic freedom"
• non-perturbative regime QCD ?????
• One of the top 10 challenges for physics!
• QCD: Important for discovering new physics beyond SM
• Nucleon structure is one of the most active areas
Lepton Scattering  ---- A powerful tool

\[ Q^2 = -q^2 = -(l - l')^2 \]
\[ \nu = E_l - E_{l'} \]
\[ x_{\text{Bjorken}} = \frac{Q^2}{2 m \nu} \]

4-momentum transfer squared: resolution.
Energy transfer.
Longitudinal momentum fraction of parton in the light cone frame.

QCD factorization
⇒ structure (non-perturbative) \( \otimes \) hard part (pQCD)
Universal Parton Distribution

Drell-Yan and DIS cross sections are well described by Next-to-Leading Order QCD
Incl. HERA I data and PDF fit

- complete HERA I combined incl. cross sections
- O(1%) precision for $10 < Q^2 < 100 \text{ GeV}^2$
- sole input for HERAPDF1.0

→ precise PDFs in the region relevant for LHC
Nucleon Spin Structure

• Understand Nucleon Spin in terms of quarks and gluons (QCD).
  – Nucleon spin is ½ at all energies.

\[
\frac{1}{2} = \frac{1}{2} \sum_j (q_f^+ - q_f^-) + L_q + J_g
\]

~30% from data “spin crisis”

– Small contribution from quarks and gluons’ intrinsic spin
– Orbital angular momentum of quarks and gluons is important
  • Understanding of spin-orbit correlations.
Longitudinal Spin Structure

Probability for quark polarized in the nucleon spin direction

\[ g_{1L} \]

\[ x = \frac{Q^2}{2M_\nu} \] Fraction of nucleon momentum carried by the struck quark

\[ Q^2 = 4\text{-momentum transfer of the virtual photon}, \quad \nu = \text{energy transfer}, \quad \theta = \text{scattering angle} \]

- All information about the nucleon vertex is contained in
  - \( F_2 \) and \( F_1 \) the unpolarized (spin averaged) structure functions,
  - \( g_1 \) and \( g_2 \) the spin dependent structure functions
Experiments \textit{\textcopyright}Lepton facilities

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Particle</th>
<th>Energy (GeV)</th>
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<tr>
<td>E80, E130</td>
<td>$\bar{e}\bar{p}$</td>
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<td>$\bar{\mu}\bar{p}$</td>
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<td>COMPASS</td>
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<tr>
<td>CLAS</td>
<td>$e^+\bar{p}, \bar{d}$</td>
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SLAC

CERN

DESY

JLab

Jlab - CLAS, Hall A

Horst Fischer DIS2010
Proton-Proton Scattering Experiments

RHIC @ BNL: Proton-Proton
$\sqrt{s}=200/500$ GeV
$\sim 50\%$ polarization
Lumi: L/T 48/18 pb$^{-1}$

Horst Fischer DIS2010

Talks by Surrow 636, Haggerty 1013
Global NLO QCD Analysis

SLAC and JLab $^3$He data not shown

See Talk 1193 by F. Kunne
Summary Gluon Polarization

Presently all Analysis in LO only

COMPASS Open Charm:

\[ \Delta G/G = -0.08 \pm 0.21(\text{stat}) \pm 0.11(\text{sys}) \]

(Systematic error still under investigations)

(Value supersedes previous publication)

C. Franco

See Talk 1193 by F. Kunne

Horst Fischer DIS2010
Gluon Polarization from RHIC

One example from PHENIX & STAR:

\[ p^+ p^+ \rightarrow \pi^0 X \]

- Confirmation of lepton scattering experiments
- Impact on extraction of \( \Delta g(x) \) in QCD-fits

STAR PV SSA results from W production (B. Surrow, Talk 636)

Horst Fischer DIS2010
Parton Distributions (CTEQ and DSSV)

Unpolarized PDFs

CT10.00 PDFs


Polarized PDFs

Stefano Forte Talk 509

DSSV, PRL101, 072001 (2008)
Parity-violating single-spin asymmetry $W^+/W^-$ $A_L$ results

$$A_L(W^+) = -0.33 \pm 0.10{\text{(stat.)}} \pm 0.04{\text{(syst.)}}$$

$$A_L(W^-) = 0.18 \pm 0.19{\text{(stat.)}} ^{+0.04}_{-0.03}{\text{(syst.)}}$$

- $A_L(W^+)$ negative with a significance of 3.3$\sigma$
- $A_L(W^-)$ central value positive
- Systematic errors of $A_L$ under control
- TPC charge separation works up to $p_T \sim 50$GeV
- Measured asymmetries are in agreement with theory evaluations using polarized pdf’s (DSSV) constrained by polarized DIS data

⇒ Universality of helicity distribution functions!
Longitudinal Spin structure function: $g_{1L}$
Its transverse spin counter part (Transversity): $h_{1T}$

- **Some characteristics of transversity**
  - $h_{1T} = g_{1L}$ for non-relativistic quarks
  - No gluon transversity in nucleon
  - Chiral-odd $\rightarrow$ difficult to access in inclusive DIS
  - Soffer’s bound
    - $|h_{1T}| \leq (f_1 + g_{1L})/2$
Q: how about quark transverse momentum? 3-D description in momentum space?

Transverse Momentum-dependent parton distributions (TMDs)

At leading twist 8 total, only 3 TMDs non vanishing upon integrating over transverse momentum of the quark

$f_1 = \uparrow$
$g_{1L} = \uparrow \rightarrow$
$h_{1T} = \rightarrow$

So how to study transversity and other TMDs experimentally?
### All Leading Twist TMDs

<table>
<thead>
<tr>
<th>Nucleon Polarization</th>
<th>Quark polarization</th>
<th>Longitudinally Polarized</th>
<th>Transversely Polarized</th>
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<tr>
<td>Un-Polarized</td>
<td>$f_1 = \bullet$</td>
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<td>$h_{1T} = \hfill$</td>
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<td>$g_1 = \hfill$</td>
<td>$h_{1L} = \hfill$</td>
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<td>$h_{1T} = \hfill$</td>
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<tr>
<td>T</td>
<td>$f_{1T} = \hfill$</td>
<td>$g_{1T} = \hfill$</td>
<td>$h_{1T} = \hfill$</td>
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<td></td>
<td>$\hfill$</td>
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<td>$h_{1T} = \hfill$</td>
</tr>
</tbody>
</table>

- Un-Polarized
- Longitudinally Polarized
- Transversely Polarized

- $f_1$, $g_1$, $h_{1T}$
- $h_{1L}$

**Annotations:**
- Sivers
- Boer-Mulder
- Helicity
- Transversity
- Pretzelosity
Access TMDs through Hard Processes

SIDIS

Drell-Yan

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

\[ h_1^+(\text{SIDIS}) = -h_1^+(\text{DY}) \]
Access Parton Distributions through Semi-Inclusive DIS

\[
\frac{d\sigma}{dxdydzd\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1 - \varepsilon)}.
\]

\[\{F_{UU,T} + \ldots \]
\[+ \varepsilon \cos(2\phi_h) \cdot F_{UU}^{\cos(2\phi_h)} + \ldots \]
\[+ S_L [\varepsilon \sin(2\phi_h) \cdot F_{UL}^{\sin(2\phi_h)} + \ldots] \]
\[+ S_T [\varepsilon \sin(\phi_h + \phi_S) \cdot F_{UT}^{\sin(\phi_h + \phi_S)} + \ldots] \]
\[+ \sin(\phi_h - \phi_S) \cdot (F_{UL}^{\sin(\phi_h - \phi_S)} + \ldots) \]
\[+ \varepsilon \sin(3\phi_h - \phi_S) \cdot F_{UT}^{\sin(3\phi_h - \phi_S)} + \ldots \]
\[+ S_L \lambda_e [\sqrt{1 - \varepsilon^2} \cdot F_{LL} + \ldots] \]
\[+ S_T \lambda_e [\sqrt{1 - \varepsilon^2} \cos(\phi_h - \phi_S) \cdot F_{LT}^{\cos(\phi_h - \phi_S)} + \ldots] \}\]

\(S_L, S_T: \) Target Polarization; \(\lambda_e: \) Beam Polarization
Separation of Collins, Sivers and pretzelosity effects through angular dependence

\[ A_{UT}(\phi_h, \phi_S) = \frac{1}{P} \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \]

\[ = A_{UT}^{\text{Collins}} \sin(\phi_h + \phi_S) + A_{UT}^{\text{Sivers}} \sin(\phi_h - \phi_S) \]

\[ + A_{UT}^{\text{Pretzelosity}} \sin(3\phi_h - \phi_S) \]

\[
A_{UT}^{\text{Collins}} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^\perp
\]

\[
A_{UT}^{\text{Sivers}} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^\perp \otimes D_1
\]

\[
A_{UT}^{\text{Pretzelosity}} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^\perp \otimes H_1^\perp
\]

SIDIS SSAs depend on 4-D variables \((x, Q^2, z \text{ and } P_T)\)
Large angular coverage and precision measurement of asymmetries in 4-D phase space is essential.
• Non-zero Collins asymmetry
• Assume $\delta q(x)$ from model, then $H_{1\text{ unfav}} \sim -H_{1\text{ fav}}$
• $H_1$ from Belle (arXiv:0805:2975)

• Sivers function nonzero ($\pi^+$) → orbital angular momentum of quarks
• Regular fragmentation functions

Klaus Rith, Talk 1194
Transversity Distributions

A global fit to the HERMES p, COMPASS d and BELLE e+e- data by the Torino group, Anselmino et al., arXiv:0812.4366

**Solid red line**: transversity distribution, analysis at $Q^2=2.4$ (GeV/c)$^2$

**Solid blue line**: Soffer bound $|h_{1T}| \leq (f_1+g_{1L})/2$

GRV98LO + GRSV98LO

**Dashed line**: helicity distribution $g_{1L}$, GRSV98LO

$\Delta_T = h_{1T}$

A. Prokudin, Talk 1059
Sivers asymmetry - proton

comparison with theory

... most recent predictions from *M. Anselmino et al.*

based on the fit of HERMES proton and COMPASS deuteron data
Jefferson Lab Experimental Halls

6 GeV polarized CW electron beam
Pol=85%, 180\(\mu\text{A}\)

Will be upgraded to 12 GeV by ~2014 with a new Hall D

HallA: two HRS’

Hall B: CLAS

Hall C: HMS+SOS

\(^3\text{He}\) target

\(\text{NH}_3\) & \(\text{ND}_3\) targets
JLab E06-010 Experiment

- Polarized $^3$He Target, > 60% with beam, world record
- Polarized Electron Beam
  - ~80% Polarization
  - Fast Flipping at 30Hz
  - PPM Level Charge Asymmetry controlled by online feedback
- BigBite at 30º as Electron Arm
  - $P_e = 0.7 \sim 2.2$ GeV/c
- HRS$_L$ at 16º as Hadron Arm
  - $P_h = 2.35$ GeV/c
6 GeV Preliminary Results

$^3$He Target Single-Spin Asymmetry in SIDIS:
JLab E06-010

$^3$He$^\uparrow (e, e'h)$
$h = \pi^{+/−}, K^{+/−}$

\[ S \quad S' \quad D \]

~87%   ~8%   ~1.5%

To extract information on neutron, one would assume:

$^3$He$^\uparrow = 0.865 \cdot n^\uparrow - 2 \times 0.028 \cdot p^\uparrow$

$^3$He Collins SSA are not large (as expected).

$^3$He Sivers SSA are smaller than expected (Vogelsong and Yuan 2006), follow the trend of Anselmino et al. 2009.
JLab Upgrade to 12 GeV

- Add new hall
- Add 5 cryomodules
- 20 cryomodules
- Add arc
- Enhance equipment in existing halls
Solenoid detector for SIDIS at 11 GeV
Experiment E12-10-006
Power of SOLID
The size and structure of proton.
Nobel prize 1961 - R. Hofstadter

Internal constituents of the nucleon
Nobel prize 1990 - J. Friedman, H. Kendall, R. Taylor

Generalized Parton Distributions (GPDs)

Extended longitudinal quark momentum & helicity distributions to transverse momentum distributions - TMDs

Next talk by Dieter Mueller, Talk 228 (M, Guidal), Talk 1116 (V. Kubarovsky)
K. Rith, Talk 1194 on HERMES GPD program
Deeply Virtual Compton Scattering (DVCS) (clean probe, flavor blind)

GPDs depend on 3 variables, e.g. \( H(x, \xi, t) \). They describe the internal nucleon dynamics.

- **Hard exclusive meson productions** (quark flavor filter) access GPDs
Deeply Virtual Compton Scattering & GPDs

Unprecedented set of Deeply Virtual Compton Scattering data accumulated in Hall A and with CLAS in Hall B at JLab

Hall A

Unpolarized beam, polarized target:

\[ t = -0.17 \text{ GeV}^2 \]

\[ Q^2 = 2.3 \text{ GeV}^2, x_B = 0.36 \]

\[ t = -0.23 \text{ GeV}^2 \]

\[ t = -0.28 \text{ GeV}^2 \]

Unpolarized beam, unpolarized target:

\[ e^- + p \rightarrow e^- + p + \gamma \quad (E_e = 5.75 \text{ GeV}) \]

\[ A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta \sigma_{LU}}{2 \sigma} \]

Polarized beam, unpolarized target:

\[ \Delta \sigma_{LU} \sim \sin \phi \{ F_1 H + \xi (F_1 + F_2) \}_{T,E} \alpha \phi \]

Kinematically suppressed:

\[ \Delta \sigma_{LU} \]

Model independent extraction of GPDs Talk 228: M. Guidal

Talk 1194 (K. Rith) on HERMES DVCS
Virtual Exclusive Processes - Kinematics Coverage of the 12 GeV Upgrade

At 12 GeV, CEBAF will be ideal for GPD studies using CLAS12

Study of high \(x_B\) domain requires high luminosity

Talk 1116 by V. Kubarovsky

COMPASS II, Talk 1193 F. Kunne
Summary

• Major progress made in unpolarized and polarized structure functions
• Frontiers in nucleon structure go beyond colinear, 1-D picture
  – three-dimensional imaging of the nucleon through GPDs, revealing hidden aspects of its internal dynamics
  – TMDs
    • Direct link with orbital motion (orbital angular momentum)
    • Transverse motion: spin-orbit correlations, multi-parton correlations, dynamics of confinement and QCD
• JLab 12-GeV upgrade and COMPASS II will provide excellent opportunities to map out the 3-dimensional structure of the nucleon

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