COLLINEAR PDF: STATUS AND OUTLOOK

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Overview

• Collinear Structure of the Nucleon -
• Polarized and Unpolarized PDFs
• Recent Results
  • Spin-Averaged PDFs
  • Spin-Dependent PDFs
• Outlook
  • Future Experiments
  • EIC

OPE, twist >2

Duality

\[ \Delta \Sigma \]

\[ \Delta G \]

\[ d/u, \Delta q/q \]

\[ x \to 1 \]
Collinear Parton Distribution Functions - (still) highly relevant!

- The 1D world of nucleon collinear structure:
  - Take a nucleon
  - Move it real fast along z
    ⇒ light cone momentum
    \[ P_+ = P_0 + P_z \ (>>M) \]
  - Select a “parton” (quark, gluon) inside
  - Measure its l.c. momentum
    \[ p_+ = p_0 + p_z \ (m\approx0) \]
  - ⇒ Momentum Fraction \( x = p_+ / P_+ \)
  - In DIS **): \( p_+ / P_+ \approx \xi = (q_z - \nu) / M \)
    \[ \approx x_{Bj} = Q^2 / 2 M \nu \]
  - Probability: \( f_i^1(x), i = u, d, s, \ldots, G \)

In the following, will often write “\( q_i(x) \)” for \( f_i^1(x) \)

*) Advantage: Boost-independent along z

**) DIS = “Deep Inelastic (Lepton) Scattering; here assuming target rest frame
**I n c l u s i v e l e p t o n s c a t t e r i n g**

- **Callan-Gross**
  
- **Wandzura-Wilczek**

**Parton model:** DIS can access

\[
F_1(x) = \frac{1}{2} \sum_i e_i^2 q_i(x) \quad \text{(and } F_2(x) \approx 2xF_1(x))
\]

\[
g_1(x) = \frac{1}{2} \sum_i e_i^2 \Delta q_i(x) \quad \text{(and } g_2(x) \approx -g_1(x) + \int_x^1 \frac{g_1(y)}{y} dy)
\]

At finite \( Q^2 \): pQCD evolution \( q(x,Q^2), \Delta q(x,Q^2) \Rightarrow \) DGLAP equations, and gluon radiation

\[
g_i(x,Q^2)_{\text{pQCD}} = \frac{1}{2} \sum_q e_q^2 [(\Delta q + \Delta q^-) \otimes (1 + \frac{\alpha_s(Q^2)}{2\pi} \Delta C_q) + \frac{\alpha_s(Q^2)}{2\pi} \Delta G \otimes \Delta C_G]
\]

\[\Rightarrow \text{access to gluons. } \Delta C_q, \Delta C_G - \text{Wilson coefficient functions}\]

**SIDIS:** Tag the flavor of the struck quark with the leading FS hadron \( \Rightarrow \) separate \( q_i(x,Q^2), \Delta q_i(x,Q^2) \)

**Fixed target kinematics:** \( Q^2 \approx M^2 \Rightarrow \) target mass effects, higher twist contributions and resonance excitations

- Non-zero \( R = \frac{F_2}{2xF_1} \left( \frac{4M^2x^2}{Q^2} + 1 \right) - 1, \quad g_2^{HT}(x) = g_2(x) - g_2^{WW}(x) \)
- Further \( Q^2 \)-dependence (power series in \( \frac{1}{Q^2} \))
- Ultra-low \( Q^2 \): \( \chi \)PT, EFT, …
Moments of Structure Functions

Importance of \(high\) \(x\)!

Related to matrix elements of local operators (OPE) - in principle accessible to lattice QCD calculations

Sum rules relate moments to the total spin carried by quarks in the nucleon (and \(\beta\)-decay matrix elements), sea quark asymmetries etc.

At low \(Q^2\): Higher Twist, Parton-Hadron Duality, Chiral Perturbation Theory, GDH Sum Rule all make predictions for moments

Gottfried Sum Rule:
\[
\int_0^1 \left[ F_2^p(x,Q^2) - F_2^n(x,Q^2) \right] dx = \frac{1}{3} \left( 1 - \frac{2}{3} \int_0^1 [\bar{d}(x,Q^2) - \bar{u}(x,Q^2)] dx \right) \Gamma_1
\]

Bjorken Sum Rule: \(\Gamma_1^p - \Gamma_1^n = \frac{g_A}{6} + \text{QCD corr.}\)

GDH Sum Rule: \(\Gamma_1(Q^2 \rightarrow 0) \rightarrow -\frac{Q^2}{2M^2} \frac{\kappa^2}{4}\)

...and \(\gamma_0, \delta_{LT}\)
Unpolarized PDFs

World Data Coded by Physics Process

Kinematic coverage

NPNDF4.0

PDFs: each point corresponds to the value of $x f(x, Q^2)$ for a given $Q^2$.

NPDF3.1

PDF determination, and its validation,

insato@jlab.org
wmelnitc@jlab.org
Unpolarized PDFs

Drell-Yan in pp-collisions at FermiLab

SeaQuest compared with global fits


Courtesy Paul Reimer, ANL
Unpolarized PDFs— high x

### Nucleon Model

<table>
<thead>
<tr>
<th>Model</th>
<th>( \frac{F_2^n}{F_2^p} ) \text{ at } x \to 1</th>
<th>( \frac{d}{u} ) \text{ at } x \to 1</th>
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<tr>
<td>SU(6) Symmetry</td>
<td>( \frac{2}{3} )</td>
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<td>Scalar diquark dominance</td>
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<tr>
<td>DSE contact interaction</td>
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<td>0.18</td>
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<tr>
<td>DSE realistic interaction</td>
<td>0.49</td>
<td>0.28</td>
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<tr>
<td>PQCD (helicity conservation)</td>
<td>( \frac{3}{7} )</td>
<td>0.2</td>
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</table>

**NPDF3.1**

**arXiv:2011.00009**

\( \frac{d}{u} \) from...

- \( \frac{F_2^n}{F_2^p} \), but
  - Free neutron targets don’t exist
  - Extraction from D data complicated by Binding, Fermi Motion, FSI
- 3H/3He, but
  - Still only smeared SF ratios
  - Requires assumptions about isospin-dependence of EMC effect
- PVDIS, but limited by statistics

**Figure 8.** Comparison between the global-base, global-ite2-dw and global-ite2-sh global fits of proton PDFs. The up, antiup, down and antidown PDFs, normalised to the global-base fit (left) and the corresponding relative uncertainties (right) are shown at \( Q = 10 \) GeV. Dashed lines denote one sigma uncertainties, while plain bands 68% confidence level intervals. The ReportEngine software \([36]\) was used to generate this figure.

**Phys. Rev. D 93, 114017 (2016)**
Spectator Tagging – BONuS12

SLOW, backward spectator – minimize FSI, Offshell effects, target fragmentation

\[ p_n = (M_D - E_S, -\vec{p}_S); \quad \alpha_n = 2 - \alpha_S \]
\[ M^*^2 = p_n^\mu p_{n\mu} \]

\[ x^* = \frac{Q^2}{2p_n^\mu q_\mu} \approx \frac{Q^2}{2M\nu(2 - \alpha_S)} \]
\[ W^*^2 = (p_n + q)^2 = M^*^2 + 2((M_D - E_S)\nu - \vec{p}_n \cdot \vec{q}) - Q^2 \]
\[ \approx M^*^2 + 2M\nu(2 - \alpha_S) - Q^2 \]
BONuS12

- CLAS12 Forward Detector:
  → Superconducting Torus magnet.
  → 6 independent sectors:
    → HTCC
    → 3 regions of DCs
    → LTCC / RICH
    → FTOF Counters
    → PCAL and ECs

- Central Detector:
  → Solenoid (3.5 - 4 T)
  → Target: D gas @ 6 atm, 293 K
  → BONuS12 RTPC
  → FMT
  → CTOF, and CND

<table>
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<th>Beam Energy</th>
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<th>Summer 2020</th>
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<td>Total</td>
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<table>
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BONuS12 - 2.1 GeV Data

BONuS12 – 10.4 GeV Data
Projected JLab@12 GeV d/u Results

2015 LRP

- CJ12 - PDF + nucl uncert.
- Hall A $^3$H/$^3$He DIS
- CLAS12 BoNuS
- CLAS12 BoNuS, relaxed cuts
- SoLID PVDIS

BoNuS sys. uncert.

Broken SU(6)

SU(6)

DSE

pQCD
Polarized Structure Functions

Kinematic coverage – World DIS data on $g_{1p}$

“EG1 fit” of the World Data
Polarized Structure Functions - Duality

Compare 4-6 GeV $g_{1p}$ data (eg1b) to JAM DGLAP fits in the DIS region ($W>2$).
Low $Q^2$ – testing $\chi$PT

**Figure 1:** (Color online.) The Bjorken Sum Rule

- **EG4p** Nature Physics
- **EG4d** Phys. Rev. Lett. 120, 062501 (2018)

![Graph showing low $Q^2$ testing $\chi$PT](image)

- **This work (full integral)**
- **This work (measured range only)**
- **Fersch et al. (full integral)**
- **Bernard et al.**
- **Alarcón et al.**
- GDH slope
- Burkert et al.
- Softer et al.
- Parameterization

![Graph showing $\Gamma_{\gamma^*p}$ vs. $Q^2$](image)

- **Data-only**
- **Data + Model**
- **Model**
- **Lensky et al.**
- **Bernard et al.**
- MAID–2007

![Graph showing $\Gamma_{\gamma^*p}$ vs. $Q^2$](image)

- **Parameterization**
- **Bernard et al.**
- **Alarcón et al.**
- **This work (full integral)**
- **This work (measured range only)**
- **Fersch et al. (full integral)**
- **Ahrens et al. (real photon)**

![Graph showing $\Gamma_{\gamma^*p}$ vs. $Q^2$](image)

- **Bernard et al. ($\chi$EFT)**
- **Lensky et al. ($\chi$EFT)**
- **Ji et al**
- **MAID 2007**

![Graph showing $f_T$ vs. $Q^2$](image)

- **E94-010 data**
- **E94-010 data + extr.**
- **E97-110 data**
- **E97-110 data + extr.**

![Graph showing $\delta^0_{\gamma^*}$ vs. $Q^2$](image)

- **MAID 2007**
- **Alarcón et al. $\chi$EFT**
- **Hall A E94-010**
- **Kao et al. Q(\rho) HB$g_{\rho}$PT**
- **Hall A E97-110**
- **Bernard et al. $\chi$EFT**
- **Bernard et al. RB$g_{\rho}$PT**
Polarized PDFs – pp collisions

FIG. 4. $A_{LL}$ versus $M_{inv}/\sqrt{s}$ for dijets with the $\text{sign}(\eta_1) = \text{sign}(\eta_2)$ (top) and $\text{sign}(\eta_1) \neq \text{sign}(\eta_2)$ (bottom) event topologies. The square markers show the present data, whereas the triangle markers show the data of Ref. [46]. The results are compared to theoretical predictions for dijets from DSSV14 [18] and NNPDFpol1.1 [20] with its uncertainty.
Future PDFs: What’s left to do for Jefferson Lab?

Figure 5: Large-scale evaluative evolution is a challenging aspect, particularly when data are available. Furthermore, as the endpoint largely remains uncertain at a specific value, the expectations are compatible, within uncertainties, with the model predictions at certain scales.

The original analysis in Ref. [42] has been recently revised [59], allowing for a nonzero gluon polarization at the initial input scale. The neutron (left) and proton (right) spin-dependent virtual photoabsorption asymmetry, $A_1^p(x,Q^2=4\text{ GeV}^2)$, and $A_1^n(x,Q^2=4\text{ GeV}^2)$, are shown along with various models, including NNPDF, RCQM, and NJL.

The ratio of polarized to unpolarized total cross-sections, $\frac{d\sigma^p}{d\sigma^u}$, and $\frac{d\sigma^n}{d\sigma^u}$, as a function of $x$, $Q^2=4\text{ GeV}^2$, is also displayed, with experimental data from HERMES and JLab A E99117.

Hall C projected online results (stat error only)

The expected results from Hall C, with projected online data (statistical error only), are shown in the right panel, comparing various models and experimental data. The comparison includes models like NNPDF, NJL, and SU(6)-breaking, along with statistical errors.
Future Spin PDFs: Hall B

Better determination of Higher Twist vs. $x$

Improved coverage to evaluate moments

Greater $x$-coverage for $\Gamma_1$
**SEAQUEST E1039 STATUS**

"Remodeling" plans for SeaQuest target cave

**Other Future Experiments**

SpinQuest at FNAL

**sPHENIX**

**Other Future Experiments**

**COMPASS++/AMBER**

**STAR**

**Other Future Experiments**

**Panda/Fair**
8.3 will likely enhance the EIC’s ability to disentangle a possible nonperturbative
charm-tagging abilities discussed briefly below and in greater detail in Sec.
4 four-gluon correlator functions. Measurements of nonperturbative charm may
be interpreted as involving twist-
intermediate model calculation [84] for two scenarios: highly suppressed
in typical model calculations is high
The kinematic region over which nonperturbative charm is expected to be visible
but have been challenging to accommodate in a global fit.
A recent analysis carried out by the
is used to constrain the twist-2 gluon PDF. A recent analysis carried out by the

Figure 7.8: Expected impact on the unpolarized (sea) quark PDFs when adding SIDIS information from pions and kaons in ep collisions. The baseline NNPDFs were take from Ref. [79].

Figure 7.16: Simulated EIC measurements of the longitudinal double-spin asymmetry $A_L$ in polarized deuteron DIS with proton tagging $e + d \rightarrow e' + X + p$. The asymmetry is shown as a function of the neutron virtuality $t = \tilde{M}_{NN}^2$, which is kinematically fixed by the tagged proton momentum (light-cone momenta $\alpha_P$ and $p_{T}$). In the limit $t = \tilde{M}_{NN}^2 \rightarrow 0$ (on-shell extrapolation) the tagged spin asymmetry coincides with the free neutron spin asymmetry $A_{L0}$ [108, 109]. The uncertainties shown are statistical ($L_{\text{int}} = 20 \text{ fb}^{-1}$, $P_P = 0.1$).
SUMMARY: COMPLETING THE PICTURE

Enormous Progress on understanding Collinear PDFs fueled by large new data sets and sophisticated phenomenology. Still, some questions remain:

- d/u, Δu/u and Δd/d at high x?
- Nuclear effects on nucleon structure
- Understanding the sea – Δs, ̅μ - ̅d, ̅Δμ - ̅Δd? JLab, FNAL, RHIC, AMBER, LHC
- Axial and Tensor charges of the nucleon COMPASS, JLab
- Gluon helicity distribution at large x AND at small x?
  - What is the integral ΔG?
  - Total contribution of parton helicity to proton spin?
- What happens at really small x << 0.01?