Delineating the polarized and unpolarized parton structure of the nucleon

QCD Evolution Workshop,
Santa Fe, May 13, 2014

Pedro Jimenez-Delgado

Jefferson Lab
Overview

- Overview of unpolarized PDFs
- Updating the unpolarized distributions: JR14
- The role of the input scale and *procedural* bias

The *Jefferson Lab Angular Momentum* collaboration
- Improving the description of polarized DIS: JAM13
- Large-\(x\) constraints and impact of (future) data from JLab
- Moving forwards: Including RHIC data
Our determinations of unpolarized PDFs and the strong coupling: JR


Introduction: non-singlet sector

- $u$-valence rather well determined

- larger differences for $d$-valence, but also relatively stable

- much smaller but can be determined using Drell-Yan $\sigma^{pd}/\sigma^{pp}$ ratios

- far less relevant except for $\nu, \bar{\nu}$ differences in dimuon production
Introduction: singlet sector

sea distributions at small $x$ determined by the gluon via RGE evolution

$d/u$ ratio at large $x$ sensitive to nuclear corrections and parametrizations [CJ 2011]

strange-quark well determined from dimuon data (also HERMES, LHC)

largest and most relevant differences in the gluons and $\alpha_s$ values
Constraints on the gluon

Gluon only enters directly (at LO) in:
- $F_L$ (both small and large $x$)
- HQ electroproduction (small $x$)
- Jet production (medium to large $x$)

But constrained via scaling violations in the small-$x$ region

Momentum sum rule correlates small and large $x$

DIS data often excluded from fits:

$Q^2 \gtrsim 4$ GeV$^2$, $W^2 \gtrsim 10$ GeV$^2$

Moderate cuts lead to larger $\alpha_s$, thus softer small-$x$ gluons

Jet data also moderately increase $\alpha_s$; should not be used beyond NLO

\[\begin{align*}
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\end{align*}\]
Updating JR09: data selection

- Switched to HERA combined neutral-current DIS $\sigma_r, \sigma^c_r$
  and included charged-current

- $F_2$ replaced for cross-section for SLAC, BCDMS and NMC [ABM 2010]

- From 30 points on $p/n$ ratios to an equal-footing treatment of fixed-target data

- Dimuon data included in nominal fits

- JLab proton and deuteron data included (need lower $W$ cuts)

  \[ Q^2 \geq 2\text{GeV}^2, W^2 \geq 3.5\text{GeV}^2 \]

- Inclusion of Rosenbluth separated $(F_2, F_L)$ data from H1, and from BCDMS, SLAC and JLab

![Graph showing data points and curves](image-url)
Updating JR09: calculations

- Experimental correlations properly treated (also multiplicative errors)
- Switched to $\overline{\text{MS}}$ scheme for heavy quark masses [ABM 2010]
- Target mass corrections used also for $F_L$ (in addition to $F_2$)
- Nuclear corrections for deuteron data [CJ 2012]
- Determination of higher-twist contributions to structure functions

$$F_{2,L}^{p,n}(x, Q^2) + \frac{h_{2,L}^{p,n}(x)}{Q^2}$$
Status of gluon distributions

Reduced experimental uncertainties due to new constraints

Systematic *(procedural)* uncertainties become dominant
The role of the input scale in PDF analysis

Any dependence is due to shortcomings of the estimation: procedural bias (e.g. parametrization bias, backwards evolution to low scales, … rather general)

These variations can be used to estimate the procedural uncertainty (devise a measure: e.g. in JR half the difference between dynamical and standard)
Benchmark cross-sections and other predictions

PDFs, details of the fits (correlations, eigenvectors, etc.), predictions for structure functions, LHC cross-sections, etc., available:

http://users.hepforge.org/~pjimenezdelgado
...and polarized PDFs: JAM

Parallel effort to our unpolarized PDFs: CJ and JR

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The JAM Collaboration

www.jlab.org/jam

to start with, open to further contributions

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The JAM database

Public database with all data on polarized scattering experiments

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Current status of polarized PDFs

Worse known than the unpolarized

$$\Delta u^+ = \Delta u + \Delta \bar{u}$$ and

$$\Delta d^+ = \Delta d + \Delta \bar{d}$$ better known

Sea distributions $\Delta \bar{u}, \Delta \bar{d}$
do not enter in DIS asymmetries

$\Delta g$ less known, determined mainly from RHIC data (also COMPASS)
Data considered at this (first) stage

World data on polarized DIS (for $Q^2 \geq 1$ GeV$^2$, $W^2 \geq 3.5$ GeV$^2$)

Mainly on measured asymmetries:

$$A_{\parallel} = D(A_1 + \eta A_2)$$

$$A_{\perp} = d(A_2 - \xi A_1)$$

$D$, $d$ depend on

$$R = \frac{F_L}{(1 + \gamma^2)F_2 - F_L}$$

$$\gamma^2 = 4\frac{M^2}{Q^2}x^2$$

We consistently develop our own unpolarized analysis in parallel (JR NLO)

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Dedicated analyses of the impact of *individual* data sets from JLab

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Parametrization

Only two independent combinations of quark distributions contribute:

\[ x \Delta u^+(x, Q_0^2) = N_u x^{a_u} (1 - x)^{b_u} (1 + A_u \sqrt{x} + B_u x) \]
\[ x \Delta d^+(x, Q_0^2) = N_d x^{a_d} (1 - x)^{b_d} (1 + A_d \sqrt{x} + B_d x) \]
\[ \Delta q^+ \equiv \Delta q + \Delta \bar{q} \]
\[ Q_0^2 = 1 \text{ GeV}^2 \]

Constrains from hyperon decays relate \( N_u \) and \( N_d \), and fix \( N_s \):

\[
\int_0^1 (\Delta u^+ - \Delta d^+) dx = 1.269 \pm 0.003 \\
\int_0^1 (\Delta u^+ + \Delta d^+ - 2\Delta s^+) dx = 0.586 \pm 0.031
\]

The \( x \)-dependence of the sea has been fixed by counting rule and imposing:

\[
\lim_{x \to 0} \Delta \bar{q}(x, Q_0^2) = \frac{1}{2} \lim_{x \to 0} \Delta q^+(x, Q_0^2) \\
\frac{1}{2} \left( \left| \frac{\Delta q^{(2)}}{\Delta \bar{q}^{(2)}} \right| + \left| \frac{\Delta \bar{s}^{(2)}}{\Delta \bar{q}^{(2)}} \right| \right) = 1 \pm 0.25
\]

For the gluon we leave \( N_g \) and \( B_g \) as free parameters

Goal is to asses the impact of improvements in DIS description (corrections)

Nominally 13 (LT) + 14 (HT) = 27 parameters to be determined
Simple fit without further corrections: reference

Nuclear targets treated with the “effective polarization” approximation:

\[ g_1^d = (1 - \frac{3}{2} \omega_d)(g_1^p + g_1^n) \]

\[ g_1^{\text{He}^3} = P_n g_1^n + P_p g_1^p \]

More similar to DSSV, LSS than to others
Baseline for assessing the impact of additional corrections
Improved description of nuclear targets

Improved by using “smearing functions” derived from nuclear wave functions:

\[ g_i^A(x) = \sum_{j=1,2} \int \frac{dy}{y} f_j N(y, \gamma) g_j^N \left( \frac{x}{y} \right) \]

\[ \gamma^2 = 1 + 4 \frac{M^2}{Q^2} x^2 \]

[Kulagin, Petti 06]

Most relevant for $\Delta d$ in the medium- and large-$x$ region
Target-mass corrections

We use power corrections from finite target mass calculated in the OPE approach:

\[ g_1^{\text{TMC}}(n) = g_1(n) + \frac{M^2}{Q^2} \frac{n^2(n+1)}{(n+2)^2} g_1(n+2) + \frac{M^4}{Q^4} \ldots + \mathcal{O}\left(\frac{M^8}{Q^8}\right) \]

[Bluemlein, Tkabladze 99]

\[ \Delta q^+(\text{TMC}) / \Delta q^+(\text{no TMC}) \]

Relevant for both \( \Delta u \) and \( \Delta d \) in the large-\( x \) region

Both TMC and nuclear corrections should be included in global fits

\[ Q^2 = 1 \text{ GeV}^2 \]
Higher twist contributions

We consider also corrections from higher twist contributions:

\[ g_1 = g_1^{\tau=2} + g_1^{\tau=3} + g_1^{\tau=4} \]

\[ g_2 = g_2^{\tau=2} + g_2^{\tau=3} \]

The Bluemlein-Tkabladze relation:

\[ g_1^{\tau=3}(x, Q^2) = 4x^2 \frac{M^2}{Q^2} \left( g_2^{\tau=3}(x, Q^2) - 2 \int_x^1 \frac{dy}{y} g_2^{\tau=3}(y, Q^2) \right) \]

With a phenomenological parametrization:

\[ g_2^{\tau=3} = A[\ln x + (1 - x) + \frac{1}{2}(1 - x)^2] + (1 - x)^3[B + C(1 - x) + D(1 - x)^2 + E(1 - x)^3] \]

And a splines approximation for:

\[ g_1^{\tau=4} = \frac{h(x)}{Q^2} \]

Possible scale dependence in \( h \) and \( g_2^{\tau=3} \) have been neglected.
Higher twist contributions

Considerable improvement of $\chi^2$ for some sets (globally $1.07 \rightarrow 0.98$, $3\sigma$)

$Q^2 = 1 \text{ GeV}^2$

Very large changes in $\Delta d$
Higher twist contributions

It is possible to determine *simultaneously* higher-twist contributions for $g_1$ and $g_2$

Qualitative agreement with previous (separated) determinations
Including all these corrections

This corrections are *manifestly important* for PDF extractions.
Constraints at large $x$

Current data can be accommodated by a range of large-$x$ behaviors

Systematic uncertainties should be considered, and more data needed...
Impact of JLab data

(a) $\Delta u^+ / \Delta u^+(JAM)$

(b) error($\Delta u^+$) / $\Delta u^+(JAM)$

(c) $\Delta d^+ / \Delta d^+(JAM)$

(d) error($\Delta d^+$) / $\Delta d^+(JAM)$
Impact of JLab 12 data

70% reduction of experimental uncertainty for \( 0.6 \leq x \leq 0.8 \)
Moving forwards: including RHIC data

High $p_T$ pion production at RHIC: $pp \rightarrow \pi^0 X$

We use scaled LO (K-factors):

$$A_{LL}^{\pi} = \frac{d\Delta \sigma}{d\sigma} = \frac{d\sigma^{++} - d\sigma^{-+}}{d\sigma^{++} + d\sigma^{-+}}$$

We use scaled LO (K-factors):

$$d\Delta \sigma^{NLO} = 1 \times d\Delta \sigma^{LO}$$

$$d\sigma^{NLO} = 1.5 \times d\sigma^{LO}$$

One should use the full calculation, however experimental errors are large

[B. Jäger et al., PRD67 (2003) 054005]
Moving forwards: including RHIC data

Already “well described” by JAM because of relatively large errors

Data do not affect quark distributions or DIS asymmetries, but do constrain $\Delta g$ at small $x$

Preliminary!!
Effect on the polarized gluon distribution

Quite comparable with DSSV++, except for small-\(x\) error band

\[
\int_{0.05}^{0.2} dx \, \Delta g(x, Q^2 = 10 GeV^2) = 0.15 \pm 0.09 \rightarrow 0.07 \pm 0.03
\]

JAM13                JAM14

Preliminary!!
Summary and outlook

Last update JR14 of our unpolarized distributions has recently been presented.

Results not very different from JR09 although with several improvements.

A procedural bias which is usually disregarded in PDF analysis can be estimated from input-scale variations and is not always small.

Next natural step: inclusion of LHC data.

First JAM results on the determination of polarized parton distributions:
- More accurate nuclear corrections relevant
- Target mass corrections should be used
- Complete inclusion of higher-twist possible and manifestly important

Dedicated studies of large-x region and impact of JLab data

Other developments in progress or planned: RHIC, SIDIS, EIC, combined fit …