CJ PDFs and Impact of Nuclear Corrections on d/u

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“The coherence provided by QCD means that insights [into hadron structure] may arise from unexpected quarters.

It is more than ever advisable to take a broad view that integrates across hadronic physics, and to connect with the rest of subatomic physics.”

C. Quigg, 2011

“The Future of Hadrons: The Nexus of Subatomic Physics”
New physics

In-medium protons and neutrons

Global QCD fits

Nuclear data
HEP data
Nuclear, hadron theory
Overview

- **Why large \( x \)?**

- **The CTEQ-JLab fits**
  - TMCs, HTs, nuclear corrections, \( d \)-quark parametrization

- **Applications**
  - \( d/u \) ratio extrapolated to \( x=1 \)
  - Parton luminosities, \( W' \) and \( Z' \) production

- **Constraining nuclear corrections**
  - Jefferson Lab data
  - Tevatron, LHC data (!?)
  - ...and more...
Why large $x$?

- Large (experimental) uncertainties in Parton Distribution Functions (PDFs)

- Precise PDFs at large $x$ are needed, *e.g.*,
  - Non-perturbative nucleon structure:
    - $d/u$, $\Delta u/u$, $\Delta d/d$ at $x \to 1$
  - at LHC, Tevatron
    - New physics as excess on QCD large $p_T$ spectra $\Leftrightarrow$ large $x$ PDF
    - Forward physics
  - At RHIC:
    - Spin structure of the nucleon at small $x$
  - Neutrino oscillations, ...
Valence quarks at large $x$

- At large $x$, valence $u$ and $d$ extracted from $p$ and $n$ DIS structure functions

\[ F_2^p \approx \frac{4}{9} u_v + \frac{1}{9} d_v \]
\[ F_2^n \approx \frac{1}{9} u_v + \frac{4}{9} d_v \]

- $u$ quark distribution well determined from proton data
- $d$ quark distribution requires neutron structure function

\[ \frac{d}{u} \approx \frac{4 F_2^n/F_2^p - 1}{4 - F_2^n/F_2^p} \]
But... deuteron corrections!

- Absence of free neutron targets
  ⇒ use deuterons (weakly bound $p$ and $n$)

- Deuteron model dependence obscures free neutron at large $x$
  - We will see quantitatively how much

Arrington et al. arXiv:1110.3362

Different models of “deuteron corrections”

Non-perturbative proton models

SU(6) spin-flavor

hard gluon exchange

$S=0$ diquark dominance
Large $x$ at colliders - new physics searches

- Remember, $x = \frac{M}{\sqrt{s}} e^y$

- Examples:
  - $Z'$ production $M'_Z \gtrsim 1$ TeV
  - $W$ at forward rapidity: $y > 2$
    \[ x > 0.1 \text{ (LHC)} \]
    \[ x > 0.5 \text{ (Tevatron)} \]

- Precise large-$x$ PDFs needed to:
  - reduce QCD background
  - optimize searches involving large masses
  - precisely characterize new particle properties
The CTEQ-JLab fits
The CTEQ-JLab collaboration

- **Collaborators:**

- **Goals:**
  - Global QCD fits of unpolarized PDFs focused on large $x$
  - Improve the PDF experimental precision (“PDF errors”) by enlarging the fitted data set
  - Include all relevant large-$x$ / small-$Q^2$ theory corrections
  - **Quantitatively evaluate theoretical systematic errors**
  - **Use PDFs as tools for nuclear and particle physics**

- **Papers:**
  - New fit in preparation with latest data \textit{Available on request}
  - Public release planned
Global QCD fits of Parton Distribution Functions

Data:
- DIS: p, d
- p+p(pbar) → l⁺l⁻, W⁺
- p+p(pbar) → jets, γ+jet

Theory:
- pQCD at NLO
- Factorization & universality
- Large-x, low-Q², nuclear corr.

Fits:
- Parametrize PDF at Q₀, evolve to Q
- Minimize χ²

PDFs:

F²(n)
W, Z / W', Z', Higgs
(or any other “hard” observable)
Large-x, small-$Q^2$ corrections

- 1/$Q^{2n}$ suppressed:
  - Target mass corrections (TMC), higher-twists (HT)
  - Current jet mass, quark mass, large-x QCD evol.

- Non-suppressed
  - Nuclear corrections, threshold resum., parton recomb.

NPDF2.0 dataset

Green: BCDMS Black: NMC
Blue: SLAC Red: JLab

1/Q^{2n} suppressed:
- Target mass corrections (TMC), higher-twists (HT)
- Current jet mass, quark mass, large-x QCD evol.

Non-suppressed
- Nuclear corrections, threshold resum., parton recomb.
CJ10 fits: results in a nutshell


- **Standard cuts:**
  - PDF insensitive to TMC, HT
  - Nuclear corrections not negligible (but usually neglected...)

- **Looser kinematic cuts**
  - PDFs stable as cut is varied about the largest allowed
  - Substantial reduction in “experimental” PDF errors

- **Stability w.r.t. TMCs**
  - The fitted HT term compensates for differences in TMC models
    - Leading-twist PDFs have little systematic error (good!)
    - HT term has ≈ 50% uncert. (not so good, if you care for this...)
  - TMC theory uncertainty can be improved:
    
    *Brady, Accardi, Hobbs, Melnitchouk, PRD 84, 074008 (2011)*
CJ11 fits: results in a nutshell


- New $d$-quark parametrization

\[ d'(x) = d(x) + \alpha x^\beta u(x) \]

- Allows $d/u$ to be non-zero at $x = 1$
- Produces dramatic increase in $d$ PDF in $x \rightarrow 1$ limit

- Large sensitivity to nuclear model
  - The $d$-quark at $x > 0.5$ is almost fully correlated to nuclear correction model
  - Very large theoretical uncertainty
Nuclear corrections - theoretical uncertainty

\[ F_{2d}(x_B, Q^2) = \int_{x_B}^{A} dy \, S_A(y, \gamma) F_2^{TMC+HT}(x_B/y, Q^2) \left( 1 + \frac{\delta^{off} F_2(x)}{F_2(x)} \right) \]

“Smearing function”
Calculated from nuclear wave-function:
- CD-Bonn
- AV18
- WJC-2
- WJC-1

Off-shell correction
Models (little theory guidance):
- Melnitchouk & C. (MST)
- Kulagin-Petti (KP) fits of A/d ratios
- modified KP model

Low-energy factorization issues
- Renormalization of nuclear operators
- Lorentz vs. gauge invariance, FSI, ...
Nuclear corrections - theoretical uncertainty

\[ F_{2d}(x_B, Q^2) = \int_{x_B}^{A} dy \ S_A(y, \gamma) F_{2}^{TMC+HT}(x_B/y, Q^2) \left( 1 + \frac{\delta^{off} F_2(x)}{F_2(x)} \right) \]

Free nucleon str.fn.
CJ fits: effect of $d$-quark parametrization

Accardi et al. PRD 84, 014008 (2011)

- Dramatic increase in $d$ PDF as $x \to 1$ with more flexible parametrization

$$d'(x) = d(x) + \alpha x^\beta u(x)$$
CJ fits: nuclear model systematic error

Accardi et al. PRD 84, 014008 (2011)

- Large sensitivity to nuclear corrections model
  - \textit{d}-quarks: directly, due to corrections applied to $F_2(d)$
  - \textit{gluons}: due to correlation with d-quarks induced by jet data
Application:
The $d/u$ ratio at $x \to 1$
The CTEQ-JLab $d/u$

- **Large nuclear uncertainty:**
  - Covers all non-perturbative model results
  - Eats away improved statistics from low-$W^2$ data

\[ \Delta \chi = 1 \]

Accardi et al. PRD 84, 014008 (2011)
Application: Parton Luminosities W',Z' bosons
Parton luminosities

- Large-\(x\) PDF uncertainties affect total cross sections for objects of large mass

\[ \hat{s} = (p_1 + p_2)^2 = x_1 x_2 s \]

\[
L_{ij} = \frac{1}{s(1 + \delta_{ij})} \left[ \int_{\hat{s}/s}^{1} \frac{dx}{x} f_i(x, \hat{s}) f_j \left( \frac{\hat{s}}{xs}, \hat{s} \right) + (i \leftrightarrow j) \right]
\]
Parton luminosities

... or large rapidity:

\[
\frac{dL_{ij}}{dy} = \frac{1}{s(1 + \delta_{ij})} \left[ f_i(\tau e^y, \hat{s}) f_j(\tau e^{-y}, \hat{s}) + (i \leftrightarrow j) \right]
\]

\[
x_{1,2} = \tau e^{\pm y} \quad \tau = \sqrt{\hat{s}/s}
\]

(Note: ratios are largely independent of \(s\))
Heavy $W'$ and $Z'$ boson production

- Some extensions of Standard Model predict heavy versions of $W$, $Z$ bosons
  - current limits $M_{W'} > 2.1$ TeV, $M_{Z'} > 1.8$ TeV
  
  (assuming Standard Model couplings)

- Observation of new physics signal requires accurate determination of QCD backgrounds, which depend on PDFs!

- Example: total cross sections ($M_{W'}/M_{Z'}$ fixed)

  - uncertainties in large-$x$ PDFs could affect interpretation of experiments searching for new particles
Constraining nuclear corrections
Need data to constrain nuclear corrections!

- **Data minimally sensitive to nuclear corrections**
  - DIS with slow spectator proton (BONUS, BONUS12)
    - Quasi-free neutrons
  - DIS with fast spectator (DeepX)
    - Off-shell neutrons – but large, poorly controlled FSI
  - $^3$He/$^3$H ratios (MARATHON)

- **Data on free (anti)protons, sensitive to $d$ or $g$**
  - $e+p$: $F_L$, parity-violating DIS  JLab, HERA ($e^+p$ vs. $e^-p$)
  - $\nu+p$, $\bar{\nu}+p$  Minerva ??
  - $p+p$, $p+p$ at large positive rapidity
    - $W$ charge asymmetry, $Z$ rapidity distribution

- **Cross-check data**
  - $p+d$ at large negative rapidity – dileptons; $W$, $Z$
    - Sensitive to nuclear corrections, cross-checks $e+d$
Quasi-free neutrons from BONUS

N. Baillie et al., PRL 108 (2012) 199902

- DIS data (black disks) too uncertain at $x > 0.5$
  - Need to wait for BONUS12 / MARATHON
Quasi-free neutrons from MARATHON

- Nuclear corrections largely cancel in the ratio of $^3\text{He}/^3\text{H}$ cross sections.
**W, Z production**

![Diagram of W, Z production](image)

- **Example:** W and decay lepton charge asymmetry at large rapidity

\[
A_W(y) = \frac{\sigma(W^+) - \sigma(W^-)}{\sigma(W^+) + \sigma(W^-)} \approx \frac{d/u(x_2) - d/u(x_1)}{d/u(x_2) + d/u(x_1)} \quad [x_1 \gg x_2]
\]

\[
A_l(y) = A_W \otimes B_{W \rightarrow l}(y)
\]
W charge asymmetry at Tevatron

Brady, Accardi, Melnitchouk, Owens, JHEP 1206 (2012) 019

Directly reconstructed W:
- highest sensitivity to large $x$

From decay lepton $W \rightarrow l+\nu$:
- smearing in $x$

Too little large-$x$ sensitivity in lepton asymmetry:
- need reconstructed $W$ (but: correlation to PDF used in exp. analysis...)

Can constrain Nuclear models!
**W charge asymmetry at LHC**

*Brady, Accardi, Melnitchouk, Owens, JHEP 1206 (2012) 019*

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**Directly reconstructed W:**
- highest sensitivity to large \( x \)

---

**From decay lepton** \( W \to l+\nu \):
- smearing in \( x \)

---

- **Would be nice to reconstruct** \( W \) at LHCb
  - Definitely needs more statistics
  - Is it at all possible?? (too many holes in detector?)
  - Systematics in \( W \) reconstruction?
  - **What about RHIC, AFTER@LHC?**
Z rapidity distribution

Brady, Accardi, Melnitchouk, Owens, JHEP 1206 (2012) 019

- Direct Z reconstruction is unambiguous in principle, but:
  - Needs better than 5-10% precision at large rapidity
  - Experimentally achievable?
    - At LHCb? RHIC? AFTER@LHC?
    - Was full data set used at Tevatron?
Summary

- Ongoing CTEQ-JLab global fits attacking large-x PDFs:
  - integrate across hadronic physics
  - connect with rest of subatomic physics
Plans

- **In preparation / near future**
  - Fits with latest data (HERA combined, LHC @ 7 TeV)
  - Correlated errors where available; tensions between data sets
  - Public release of PDF + error sets (and accompanying software)
  - LHC / RHIC / E906 phenomenology
  - Will be ready to fully exploit JLab 12 GeV upgrade, next generation exp's

- **Longer term**
  - \( F_L / \sigma \) data on deuterium (large-x gluons); heavy quarks
  - large-x resummation, jet mass corrections, quark-hadron duality
  - better off-shell corrections, extend to gluons
  - Integration to MCFM generator
  - Monte Carlo PDF errors
Backup slides
Small $x$ gluons at colliders: hadronic structure

- Gluon spin at small $x$ at RHIC requires particle production at large $y$

$$\sigma(p\bar{p} \to \pi^0 X) \propto \Delta q(x_1) \Delta g(x_2) \hat{\sigma}^{qg \to qg} D_{\pi^0}^{q}(z)$$

- Precise large-$x$ PDFs needed:
  - to measure smallest-$x$ gluon helicity

- $x_1 \approx 0.06$
- $x_1 \approx 0.01$
- $x_1 \approx 0.3$
- $\sqrt{s} = 500$ GeV
- $p_T \geq 2.5$ GeV
- $x_1 \approx 0$
- $x_2 \approx 1$
- $x_2 \approx y$
- $x_1 \sim \frac{p_T}{\sqrt{s}} e^y$
- $x_2 \sim \frac{p_T}{\sqrt{s}} e^{-y}$

- $\pi$ rapidity: $|\eta| \leq 0.35$
  - $\eta = 1.0 - 3.0$
  - $\eta = 3.1 - 3.9$
Valence quarks at large $x$

- $d/u$ quark ratio particularly sensitive to quark dynamics in nucleon

- SU(6) spin-flavor symmetry
  - proton wave function

$$p^\uparrow = -\frac{1}{3}d^\uparrow (uu)_1 - \frac{\sqrt{2}}{3}d^\downarrow (uu)_1$$

$$+ \frac{\sqrt{2}}{6}u^\uparrow (ud)_1 - \frac{1}{3}u^\downarrow (ud)_1 + \frac{1}{\sqrt{2}}u^\uparrow (ud)_0$$

- interacting quark
- diquark spin
- spectator diquark
Valence quarks at large $x$

- $d/u$ quark ratio particularly sensitive to quark dynamics in nucleon

- **SU(6) spin-flavor symmetry**
  - proton wave function

\[
\begin{align*}
  p^\uparrow &= -\frac{1}{3}d^\uparrow(uu)_1 - \frac{\sqrt{2}}{3}d^\downarrow(uu)_1 \\
  &\quad + \frac{\sqrt{2}}{6}u^\uparrow(ud)_1 - \frac{1}{3}u^\downarrow(ud)_1 + \frac{1}{\sqrt{2}}u^\uparrow(ud)_0
\end{align*}
\]

- $50\% (qq)_1, \ 50\% (qq)_0, \ u = 2d \ \text{at all} \ x$

\[
\frac{d}{u} = \frac{1}{2} \quad \Rightarrow \quad \frac{F_2^n}{F_2^p} = \frac{2}{3}
\]
Valence quarks at large $x$

- **Broken SU(6) : scalar diquark dominance**
  - $M_\Delta > M_N \Rightarrow (qq)_1$ has larger energy than $(qq)_0$
  - But only $u$ quark couples to scalar diquark:

  \[
  \frac{d}{u} \to 0 \implies \frac{F_2^n}{F_2^p} \to \frac{1}{4}
  \]

  *Feynman 1972, Close 1973, Close/Thomas 1988*

- **Broken SU(6) : hard gluon exchange**
  - Helicity of struck quark = helicity of struck hadron

\[
\frac{d}{u} \to \frac{1}{5} \implies \frac{F_2^n}{F_2^p} \to \frac{3}{7}
\]

*Farrar, Jackson, 1975*
The mKP off-shell nucleon model

- Nucleon at large $x = \text{valence quark} + \text{spectator diquark}$

\[
q_v(x, p^2) = \int ds \int_{-\infty}^{k_{\text{max}}^2} dk^2 D_{q/N}(s, k^2, x, p^2)
\]

- Quark spectral function, with spectator diquark

\[
D_{q/N} \approx \delta(s - s_0) \Phi(k^2, \Lambda(p^2)) \\
[s_0 = 2.1 \text{ GeV}^2 \text{ from fits}]
\]

- Physical interpretation: nucleon size changes with $p^2$: $R_N \sim 1/\Lambda$
The mKP off-shell nucleon model

Expand $F_2(N)$ to first order in virtuality:

$$F_2^N(x, Q^2, p^2) = F_2^N(x, Q^2) \left( 1 + \delta f_2(x, Q^2) \frac{p^2 - M^2}{M^2} \right)$$

In the mKP model

$$\delta f_2 = c + \frac{\partial \log q_v}{\partial x} x(1 - x) \frac{(1 - \lambda)(1 - x)M^2 + \lambda s_0}{(1 - x)^2 M^2 - s_0}$$

- Only 1 free parameter

$$\lambda = \frac{\partial \log \Lambda^2}{\partial \log p^2} \bigg|_{p^2=M^2} = -2(\delta R_N/R_N)(\delta p^2/M^2)$$

Physical interpretation: nucleon size changes with $p^2$: $R_N \sim 1/\Lambda$
Nuclear corrections

\[ F_{2d}(x_B, Q^2) = \int_{x_B}^{A} dy \, S_A(y, \gamma) F_2^{TMCPHT}(x_B/y, Q^2) \left( 1 + \frac{\delta^{off} F_2(x)}{F_2(x)} \right) \]

- Using off-shell model, obtains larger neutron (larger \( d \)) than light-cone model
- But smaller neutron (larger \( d \)) than no nuclear effects or density model
The CTEQ-JLab $F_2(n) / F_2(p)$

- Well behaved extrapolation for each nuclear model
  - however, beware of remaining PDF “parametrization bias”

- Needs some realistic nuclear corrections, or obtains non-sense results