New CTEQ–Jefferson Lab (CJ15) analysis of parton distribution functions

Wally Melnitchouk

CTEQ-JLab (CJ) collaboration: http://www.jlab.org/CJ
Alberto Accardi, Jeff Owens, Nobuo Sato (theory)
Eric Christy, Thia Keppel, Simona Malace, Peter Monaghan (experiment)
Outline

- **CJ PDFs – motivations and goals**

- **New developments since CJ12**
  - more complete treatment of nuclear corrections
  - impact of new lepton & W asymmetry data on $d/u$
  - inclusion of JLab data
  - analysis of $\bar{d} - \bar{u}$ at large $x$

- **Future plans**
  - inclusion of new (LHC & JLab) data
  - Monte Carlo based analysis
Next-to-leading order (NLO) analysis of expanded set of proton and deuterium data (no heavy nuclei)

→ include high-\(x\) region \((x > 0.4)\)

High-\(x\) region requires use of data at lower \(W^2\) & \(Q^2\)

\[
W^2 = M^2 + Q^2 \frac{(1 - x)}{x}
\]

strong cut:
\[
Q^2 > 4 \text{ GeV}^2, \quad W^2 > 12.25 \text{ GeV}^2
\]

weak cut:
\[
Q^2 > m_c^2, \quad W^2 > 3 \text{ GeV}^2
\]

→ factor 2 increase in # of DIS data points when relax strong cut (excludes most SLAC, all JLab data) → weak cut
Next-to-leading order (NLO) analysis of expanded set of proton and deuterium data (no heavy nuclei)

- include high-$x$ region ($x > 0.4$)

High-$x$ region requires use of data at lower $W$ & $Q^2$

- significant error reduction at high $x$
Next-to-leading order (NLO) analysis of expanded set of proton and deuterium data (no heavy nuclei)

→ include high-\(x\) region \((x > 0.4)\)

High-\(x\) region requires use of data at lower \(W\) & \(Q^2\)

Analysis of high-\(x\) data requires careful treatment of subleading \(1/Q^2\) corrections

→ target mass corrections, dynamical higher twists

Correct for nuclear effects in deuteron (binding + off-shell)

→ binding + Fermi motion (well known), nucleon off-shell (less well known)

→ impact on \(d/u\) ratio in large-\(x\) region
### CJ15 data sets and $\chi^2$ values

<table>
<thead>
<tr>
<th>experiment</th>
<th># points</th>
<th>$\chi^2$</th>
<th>NLO</th>
<th>LO</th>
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<td>$\chi^2$/dof</td>
<td></td>
<td>0.98</td>
<td>1.22</td>
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</table>
**CJ15 PDFs**

\[ x f(x, Q^2) = a_0 x^{a_1} (1 - x)^{a_2} \]
\[ \times (1 + a_3 \sqrt{x} + a_4 x) \]

at \( Q^2 = Q_0^2 \)

*except for \( d \) and \( \bar{d}/\bar{u} \)*

\[ f(u) = \varepsilon_0 \]
\[ f(d) = \bar{u} \]
\[ f(\bar{d} + \bar{u}) = \varepsilon_0 \]
\[ f(\bar{d} - \bar{u}) = \bar{d}/\bar{u} \]
\[ f(\bar{d} + \bar{u}) = \varepsilon_0 \]
\[ f(g/10) = \varepsilon_0 \]

\( Q^2 = 10 \text{ GeV}^2 \)

\( x \)

\( 10^{-4} \)
\( 10^{-3} \)
\( 10^{-2} \)
\( 0.1 \)
\( 0.2 \)
\( 0.3 \)
\( 0.4 \)
\( 0.5 \)
\( 0.6 \)
\( 0.7 \)
\( 0.8 \)
\( 0.9 \)

\[ Q^2 = 10 \text{ GeV}^2 \]

\[ x_f = x f(x, Q^2) \]

\[ (\bar{d} + \bar{u}) \]

**for strange assume** \( s = \bar{s} \propto (\bar{d} + \bar{u}) \) (no neutrino data)

**charm computed perturbatively** (S-ACOT scheme);

**no compelling reason for intrinsic charm**

*Jimenez-Delgado et al., PRL 114, 082002 (2015)*
CJ15 vs. other PDFs

currently use $\Delta \chi^2 = 1$ but assume tolerance $T=10$ for some app’s

HERAPDF15 errors comparable to $T=1$, others generally between $T=1$ & 10

larger uncertainty for $d$ PDF at high $x$ than for $u$
Nuclear corrections

- Nuclear structure function at $x \gg 0$ dominated by incoherent scattering from individual nucleons

$$q^d(x, Q^2) = \int \frac{dz}{z} dp^2 f_{N/d}(z, p^2) \tilde{q}^N(x/z, p^2, Q^2)$$

- Nucleon momentum distribution in $d$ ("smearing function")
- PDF in bound (off-shell) nucleon

$$z = \frac{p \cdot q}{p_d \cdot q} \approx 1 + \frac{p_0 + \gamma p_z}{M} \left[ p_0 = M + \varepsilon, \quad \varepsilon = \varepsilon_d - \frac{p^2}{2M} \right]$$

- Momentum fraction of $d$ carried by $N$

- At finite $Q^2$, smearing function depends on $\gamma = \sqrt{1 + 4M^2x^2/Q^2}$
Nuclear corrections

- Expand off-shell nucleon PDF about on-shell \((p^2 = M^2)\) limit

\[
\tilde{q}^N(x, p^2) = q^N(x) \left[ 1 + \frac{(p^2 - M^2)}{M^2} \delta q^N(x) \right]
\]

\[
\delta q^N = \left. \frac{\partial \log q^N}{\partial \log p^2} \right|_{p^2 = M^2}
\]

- Deuteron PDF sum of on- and off-shell contributions

\[
q^d = q^{d(on)} + q^{d(off)}, \text{ where}
\]

\[
q^{d(on)}(x, Q^2) = \int \frac{dz}{z} f^{(on)}(z) q^N(x/z, Q^2)
\]

\[
q^{d(off)}(x, Q^2) = \int \frac{dz}{z} f^{(off)}(z) \delta q^N(x/z, Q^2) q^N(x/z, Q^2)
\]

on-shell & off-shell smearing functions

\[
f^{(on)}(z) = \int dp^2 f_{N/d}(z, p^2)
\]

\[
f^{(off)}(z) = \int dp^2 \frac{p^2 - M^2}{M^2} f_{N/d}(z, p^2)
\]

Ehlers et al., PRD 90, 014010 (2014)
Smearing function in the deuteron computed in “weak binding approximation” – expand in powers of $\tilde{p}^2/M^2$

$$f_{N/d}(z, p^2) = \frac{1}{(2\pi)^3} \frac{1}{\gamma^2} \left[ 1 + \frac{\gamma^2 - 1}{z^2} \left( 1 + \frac{2\varepsilon}{M} + \frac{\tilde{p}^2}{2M^2} (1 - 3\hat{p}_z^2) \right) \right] |\psi_d(p)|^2$$

→ effectively more smearing for larger $x$ and lower $Q^2$

→ greater wave function dependence at large $z$ ($\rightarrow$ large $x$)
Nuclear corrections

- Nucleon off-shell correction to quark PDF

  → off-shell covariant quark “spectator” (OCS) model

\[
\tilde{q}^N(x, p^2) = \int d\hat{p}^2 \Phi_{q/N}(\hat{p}^2, \Lambda(p^2))
\]

  momentum distribution of quarks with virtuality \( \hat{p}^2 \) in bound nucleon

  → scale parameter \( \Lambda(p^2) \) suppresses large-\( p^2 \) contributions

  → off-shell “rescaling” parameter \( \lambda = \frac{\partial \log \Lambda^2}{\partial p^2} \) fitted

  → applied to valence, antiquark & gluon PDFs

Owens et al., PRD 87, 094012 (2013)
Ehlers et al., PRD 90, 014010 (2014)
Nuclear corrections

- Nucleon off-shell correction to quark PDF

- larger off-shell effects for larger $\lambda$, and for KP model

- enhancement ("antishadowing") at $x \sim 0.2$ in KP model

Kulagin, Petti
NPA 765, 126 (2006)
Nuclear corrections

- Nucleon off-shell correction to quark PDF

  → alternatively, parametrize $\delta q^N$ phenomenologically

  \[ \delta q^N = C_N (x - x_0) (x - x_1) (1 + x - x_0) \]

  Kulagin, Petti, NPA 765, 126 (2006)

  → fit 2 of \{C, x_0, x_1\} for given deuteron wave function; fix third parameter from normalization condition

  \[ \int_0^1 dx \, \delta q^N (x) \left( q^N (x) - \bar{q}^N (x) \right) = 0 \]

  → similar to Kulagin-Petti, but fitted only to deuteron data
  (avoid uncontrolled extrapolations from large-A data)
Nuclear corrections

- Nucleon off-shell correction to quark PDF

---

Deuterons wave functions from NN scattering

(fitted off-shell corrections weakly dependent on wave function, except for WJC-1

(long-distance part of wfn. is model independent, from chiral symmetry)
Nuclear corrections

- **Nuclear EMC ratio in deuteron**

  ![Graph showing the ratio of nuclear corrections in deuteron](image)

  - observables sensitive only to combined smearing and off-shell corrections
  - no evidence for antishadowing at $x \sim 0.1$
Nuclear corrections

- **Nuclear EMC ratio in deuteron**

\[
\frac{F_2^d}{F_2^N} \quad (Q^2 = 2 \text{ GeV}^2)
\]

\[
\frac{F_2^d}{F_2^N} \quad (Q^2 = 5 \text{ GeV}^2)
\]

\[
\frac{F_2^d}{F_2^N} \quad (Q^2 = 10 \text{ GeV}^2)
\]

\[
\frac{F_2^d}{F_2^N} \quad (Q^2 = 100 \text{ GeV}^2)
\]

**TMC effect!**

→ **ratio has significant** \(Q^2\) **dependence at low** \(Q^2\) **from target mass effects**
Nuclear corrections & CJ15 PDFs

→ results for PDFs using all_wfns.
other than WJC-1 are within $1\sigma$

→ WJC-1 outside $1\sigma$
error for $d$ at high $x$
& $u$ at low & high $x$
Nuclear corrections & CJ15 PDFs

→ results for PDFs using all wfns. other than WJC-1 are within $1\sigma$

→ WJC-1 outside $1\sigma$ error for $d$ at high $x$ & $u$ at low & high $x$

→ off-shell model dep. (cf. OCS) generally weak except for $d$ PDF
d/u ratio at high x of interest for nonperturbative models of nucleon

more flexible parametrization

d \rightarrow d + b x^c u

allows finite, nonzero x = 1 limit

(standard PDF form gives 0 or \infty unless \alpha_2^d = \alpha_2^u)

\begin{itemize}
  \item MMHT14: fitted deuteron correction, "standard" d parametrization
  \item CT14: flexible d parametrization, no nuclear corrections
  \item JR14: similar deuteron correction, no lepton/W asymmetry data
\end{itemize}
$d/u$ ratio at high $x$ of interest for nonperturbative models of nucleon

more flexible parametrization $d \rightarrow d + b x^c u$

allows finite, nonzero $x = 1$ limit

(standard PDF form gives $0$ or $\infty$ unless $a_2^d = a_2^u$)

ABMP15: includes new lepton asymmetries, K–P nuclear corrections
Effect of data sets of $d/u$

→ new JLab (BONuS) data reduces error at $x \sim 0.6$

BONuS: spectator proton tagging in semi-inclusive $ed$ DIS

Baillie et al.
PRL 108, 142001 (2012)
→ new JLab (BONuS) data reduces error at $x \sim 0.6$

→ significant reduction from new lepton asymmetry data
  (little effect from $Z$ rap. data)
Effect of data sets of $d/u$

- new JLab (BONuS) data reduces error at $x \sim 0.6$

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$W$ asymmetry at large $W$ rapidity more sensitive to $d/u$ at high $x$

early CDF data preferred smaller ("CJ12min") nuclear corrections
new JLab (BONuS) data reduces error at $x \sim 0.6$

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Effect of data sets of $d/u$

→ new JLab (BONuS) data reduces error at $x \sim 0.6$

→ significant reduction from new lepton asymmetry data
  (little effect from $Z$ rap. data)

→ $W$ asymmetry at large $W$ rapidity more sensitive to $d/u$ at high $x$

→ new D0 data reduce uncertainties at $x \sim 0.6 - 0.7$, strongly favor models with small (but nonzero) nuclear corrections
Light antiquark sea

- Flavor asymmetry $\bar{d} - \bar{u}$ in proton sea constrained mostly by FNAL E866 $\sigma^{pd}/\sigma^{pp}$ Drell-Yan data

- Recently nuclear corrections to $pd$ data have been computed in same framework (smearing + off-shell) as in DIS
  
  → requires nuclear modifications in antiquark and gluon PDFs

$Ehlers et al., PRD 90, 014010 (2014)$
Modest effect at E866 kinematics, given large errors at high $x$.

More important effects expected at E906/SeaQuest kinematics at $x > 0.2$ relevant for possible sign change of $\bar{d} - \bar{u}$ at high $x$?
New CJ15 PDFs will be released soon (~ autumn 2015)

- constraints on large-$x$ PDFs from new data on lepton & $W$-asymmetries; first JLab $F_2^n$ data
- reduced nuclear uncertainties on $d$ quark cf. CJ12, with smaller $d/u$ ratio for $x \rightarrow 1$ (smaller nuclear corrections)
- treatment of nuclear corrections in deuteron extended to sea quarks and gluons (important for $pd$ Drell-Yan cross sections for $\bar{q}$, and for $F_L$)

Future direction: minimize input parameter bias through Monte Carlo analysis

- explore parameter space through MC sampling
- no ambiguity in “tolerance criteria” (or assumptions about Gaussian errors)
- cross validation (random data partition) & bootstrap (data resampling)
JAM (JLab Angular Momentum) polarized PDF analysis: Nobuo Sato et al. (2015)

- ~ 10,000 fits,
- ~ 3,000 data points
  (~ 40 parameters)

- fast implementation in Mellin space
- easily extendable to unpolarized sector
Thank you