Update on nCTEQ PDFs:
nuclear PDF uncertainties and LHC applications

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DIS 2014
Warsaw, 28 April - 2 May 2014
Motivations: Why do we need nuclear PDFs?

- What are PDFs of bound protons/neutrons?

- Heavy ion collisions in LHC and RHIC

- Differentiate flavors in free-proton PDFs (e.g. strange)

\[
F_2^{l \pm} \sim \left(\frac{1}{3}\right)^2 [d + s] + \left(\frac{2}{3}\right)^2 [u + c]
\]

\[
F_2^\nu \sim [d + s + \bar{u} + \bar{c}]
\]

\[
F_2^{\bar{\nu}} \sim [d + s + u + c]
\]

\[
F_3^\nu \sim 2[d + s - \bar{u} - \bar{c}]
\]

\[
F_3^{\bar{\nu}} \sim 2[u + c - \bar{d} - \bar{s}]
\]
Assumptions entering the nuclear PDF analysis

1. **Factorization** & DGLAP evolution
   - allow for definition of **universal** PDFs
   - make the formalism **predictive**
   - needed even if it is broken

2. Isospin symmetry
   \[
   \begin{align*}
   u^{n/A}(x) &= d^{p/A}(x) \\
   d^{n/A}(x) &= u^{p/A}(x)
   \end{align*}
   \]

3. \( x \in (0, 1) \) like in free-proton PDFs [instead of \((0, A)\)]

Then observables \( \mathcal{O}^A \) can be calculated as:

\[
\mathcal{O}^A = Z \mathcal{O}^{p/A} + (A - Z) \mathcal{O}^{n/A}
\]

With the above assumptions we can use the free proton framework to analyze nuclear data.
Available nuclear PDFs

- **Multiplicative nuclear correction factors**

\[ f_i^{p/A}(x_N, \mu_0) = R_i(x_N, \mu_0, A) \ f_i^{\text{free proton}}(x_N, \mu_0) \]

- Hirai, Kumano, Nagai [PRC 76, 065207 (2007), arXiv:0709.3038]
- Eskola, Paukkunen, Salgado [JHEP 04 (2009) 065, arXiv:0902.4154]
- de Florian, Sassot, Stratmann, Zurita [PRD 85, 074028 (2012), arXiv:1112.6324]

- **Native nuclear PDFs**

- nCTEQ [PRD 80, 094004 (2009), arXiv:0907.2357]

\[ f_i^{p/A}(x_N, \mu_0) = f_i(x_N, A, \mu_0) \]
\[ f_i(x_N, A = 1, \mu_0) \equiv f_i^{\text{free proton}}(x_N, \mu_0) \]
The functional form of the bound proton PDF is the same as for the free proton (\( \sim \text{CTEQ61} \) [hep-ph/0702159], \( x \) restricted to \( 0 < x < 1 \)):

\[
x f_i^{p/A}(x, Q_0) = c_0 x^{c_1} (1 - x)^{c_2} e^{c_3 x} (1 + e^{c_4 x})^{c_5}, \quad i = u, d, g, \ldots
\]

\[
\bar{d}(x, Q_0)/\bar{u}(x, Q_0) = c_0 x^{c_1} (1 - x)^{c_2} + (1 + c_3 x)(1 - x)^{c_4}
\]

A-dependent fit parameters (reduces to free proton for \( A = 1 \)):

\[
c_k \rightarrow c_k(A) \equiv c_{k,0} + c_{k,1} (1 - A^{-c_{k,2}}), \quad k = \{1, \ldots, 5\}
\]

PDFs for nucleus \((A, Z)\):

\[
f_i^{(A,Z)}(x, Q) = \frac{Z}{A} f_i^{p/A}(x, Q) + \frac{A - Z}{A} f_i^{n/A}(x, Q)
\]

(bound neutron PDF \( f_i^{n/A} \) by isospin symmetry)
Data sets

- **NC DIS & DY**
  - **CERN BCDMS & EMC & NMC**
    - \(N = (D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W)\)
  - **FNAL E-665**
    - \(N = (D, C, Ca, Pb, Xe)\)
  - **DESY Hermes**
    - \(N = (D, He, N, Kr)\)
  - **SLAC E-139 & E-049**
    - \(N = (D, Ag, Al, Au, Be,C, Ca, Fe, He)\)
  - **FNAL E-772 & E-886**
    - \(N = (D, C, Ca, Fe,W)\)

- **Single pion production (new)**
  - **RHIC - PHENIX & STAR**
    - \(N = Au\)

- **Neutrino (to be included later)**
  - **CHORUS CCFR & NuTeV**
    - \(N = Pb N = Fe\)
Data sets: Single pion production

**RHIC - PHENIX & STAR**

$\text{PHENIX Collaboration:}$

[Phys.Rev.Lett. 98 (2007) 172302, nucl-ex/0610036]

$\text{STAR Collaboration:}$

[Phys.Rev. C81 (2010) 064904, arXiv:0912.3838]

**Theory calculation:**

P. Aurenche, M. Fontannaz, J.-Ph. Guillet, B. A. Kniehl, M. Werlen

[Eur. Phys. J. C13, 347-355, (2000), arXiv:hep-ph/9910252]

**Fragmentation functions:**

J. Binnewies, Bernd A. Kniehl, G. Kramer

[Z. Phys. C65 (1995) 471-480, arXiv:hep-ph/9407347]
Fit details

Fit properties:
- fit @NLO
- $Q_0 = 1.3\text{GeV}$
- using ACOT heavy quark scheme
- kinematical cuts: $Q > 2\text{GeV}$, $W > 3.5\text{GeV}$
- 708 (DIS & DY) + 32 (single $\pi^0$) = 740 data points after cuts
- 16 free parameters
  - 7 gluon
  - 7 valence
  - 2 sea
- $\chi^2 = 618$, giving $\chi^2/\text{dof} = 0.85$

Error analysis:
- use Hessian method
  \[ \chi^2 = \chi^2_0 + \frac{1}{2}H_{ij}(a_i - a_i^0)(a_j - a_j^0) \]
  \[ H_{ij} = \frac{\partial^2 \chi^2}{\partial a_i \partial a_j} \]
- tolerance $\Delta \chi^2 = 35$ (every nuclear target within 90% C.L.)
- eigenvalues span 10 orders of magnitude → require numerical precision
- use noise reducing derivatives
nCTEQ RESULTS

(preliminary)
nCTEQ results

Nuclear PDFs \((Q = 10\text{GeV})\)

\[ x f_i^{Pb}(x, Q) \]

Compare nCTEQ fits:
- with \(\pi^0\) data (violet)
- without \(\pi^0\) data (gray)

PRELIMINARY
nCTEQ results

Nuclear correction factors
($Q = 10\text{GeV}$)

$$R_i(Pb) = \frac{f_i^{Pb}(x, Q)}{f_i^p(x, Q)}$$

Compare nCTEQ fits:
- with $\pi^0$ data (violet)
- without $\pi^0$ data (gray)
nCTEQ results

Nuclear correction factors 
\((Q = 10\text{GeV})\)

\[ R_i(Pb) = \frac{f_i^{Pb}(x, Q)}{f_i^{p}(x, Q)} \]

- different solution for 
  \(d\)-valence & \(u\)-valence
  compared to EPS09 & DSSZ
- sea quark nuclear correction factors similar to EPS09
- nuclear correction factors depend largely on underlying proton baseline
nCTEQ results

Nuclear PDFs ($Q = 10\text{GeV}$)

\[ x f_i^{Pb}(x, Q) \]

- nCTEQ $d$-valence & $u$-valence solution between HKN07 & EPS09
- nCTEQ features larger uncertainties than previous nPDFs
- better agreement between different groups (nPDFs don’t depend on proton baseline)
nCTEQ vs. EPS09

**nCTEQ**

\[
\begin{align*}
    x u_v^p/A(Q_0) &= x^u_1 (1-x) e^u_2 e^u_3 x (1 + e^u_4 x) e^u_5 \\
    x d_v^p/A(Q_0) &= x^d_1 (1-x) e^d_2 e^d_3 x (1 + e^d_4 x) e^d_5
\end{align*}
\]

\[
\begin{align*}
    c^u_k &= c^u_{k,0} + c^u_{k,1} (1 - A^{-c^u_{k,2}}) \\
    c^d_k &= c^d_{k,0} + c^d_{k,1} (1 - A^{-c^d_{k,2}})
\end{align*}
\]

**EPS09**

\[
\begin{align*}
    u_v^p/A(Q_0) &= R_v(x, A, Z) u(x, Q_0) \\
    d_v^p/A(Q_0) &= R_v(x, A, Z) d(x, Q_0)
\end{align*}
\]

\[
R_v = \begin{cases} 
    a_0 + (a_1 + a_2 x)(e^{-x} - e^{-x a}) & x \leq x_a \\
    b_0 + b_1 x + b_2 x^2 + b_3 x^3 & x_a \leq x \leq x_e \\
    c_0 + (c_1 - c_2 x)(1 - x)^{-\beta} & x_e \leq x \leq 1
\end{cases}
\]

we set:

\[
\begin{align*}
    c^d_1 &= c^u_1 \\
    c^d_2 &= c^u_2
\end{align*}
\]
nCTEQ results: $F_2$ ratios

Structure function ratio

$$R = \frac{F_2^{Fe}(x, Q)}{F_2^{D}(x, Q)}$$

- good data description
- despite different $u$-valence & $d$-valence ratios are similar to EPS09
nCTEQ results: $\pi^0$ production

Pion production, ratio

$$R_{dAu}^\pi = \frac{\frac{1}{2A}d^2\sigma_{dAu}^{\pi}}{d^2\sigma_{pp}^{\pi}} / dp_T dy$$

- good data description, however big experimental uncertainties do not allow for strong constraints on PDFs
- despite different $u$-valence & $d$-valence ratios are similar to EPS09
What can we give/gain from LHC data?

Recent ATLAS results for $W/Z$ production in lead collisions are analyzed using proton PDFs

$N_{\ell\ell\rightarrow ZdN}=0.15\text{ nb}^{\text{int}}$ Data 2011 L

Centrality 0-80%

$ll \rightarrow Z$ Model

$Z\gamma^{*}$ at 2.76 TeV

- No shape change for on-shell $Z$ (and $W^{-}$) rapidity when using free-proton or lead PDFs.
- The shapes of the lepton distributions for these bosons are also indistinguishable.

[Refs: PRL 110, 022301 (2013), arXiv:1210.6486]
What can we give/gain from LHC data?

- There is a observable shape change in for on-shell $W^+$ production. The difference is up to 20% in some regions of parameter space.
- These differences should be seen with higher statistics.
Summary

- We have updated the nCTEQ error PDFs (still preliminary).
- nCTEQ PDFs features larger uncertainties but they are still underestimated.

To have reliable estimate of nuclear corrections we need more data (LHC lead run can help).

Nuclear component important not only for heavy ion collisions, but also for the free-proton analysis.
nCTEQ

nuclear parton distribution functions

nCTEQ project is an extension of the CTEQ collaborative effort to determine parton distribution functions inside of a free proton. It generalizes the free-proton PDF framework to determine densities of partons in bound protons (hence nCTEQ which stands for nuclear CTEQ). More details on the framework and the first results can be found in arXiv:09072357 [hep-ph].

The effects of the nuclear environment on the parton densities can be shown as modified parton densities

where all black curves stand for free proton PDF and red, green, blue, cyan, pink, yellow, magenta and brown curves show PDF in protons bound in nuclei - from deuterium (red) to lead (brown).

An alternative way how effects of nuclear environment can be displayed is in ratios of Deep Inelastic Scattering (DIS) structure functions e.g. ratios of of the structure function $F_2$ for a neutral current DIS as in the figure below on the left or ratios of of the same structure function $F_2$ but for a charged current DIS.
BACKUP SLIDES
Variables: DIS of nuclear target $eA \to e'X$

- DIS variables in case on nucleons in nucleus:
  \[
  \begin{align*}
  Q^2 &\equiv -q^2 \\
  x_A &\equiv \frac{Q^2}{2p_A \cdot q}
  \end{align*}
  \]
  - $p^A$ – nucleus momentum
  - $x_A \in (0, 1)$ – analog of Bjorken variable (fraction of the nucleus momentum carried by a nucleon)

- Analogue variables for partons:
  - $p_N = \frac{p^A}{A}$ – average nucleon momentum
  - $x_N \equiv \frac{Q^2}{2p_N \cdot q} = A \cdot x_A$ – parton momentum fraction with respect to the average nucleon momentum $p_N$
  - $x_N \in (0, A)$ – parton can carry more than the average nucleon momentum $p_N$. 