Nuclear parton distributions from the nCTEQ group

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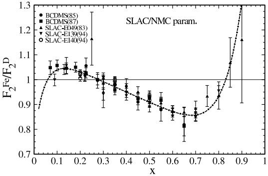
Outline:

- Motivations & Introduction
- Framework
- `nCTEQ15` results
- Impact of LHC data
- Summary

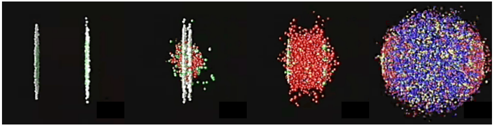
DIS16
DESY, HAMBURG 11-15 APRIL 2016

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)

charged lepton DIS

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

neutrino DIS

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

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

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

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

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 $\begin{cases} u^{n/A}(x) = d^{p/A}(x) \\ d^{n/A}(x) = u^{p/A}(x) \end{cases}$
3. The *bound proton* PDFs have the *same evolution equations* and sum rules as the free proton PDFs *provided we neglect any contributions from the region* $x > 1$ (which is expected to have negligible contribution [PRC 73, 045206 (2006), arXiv:hep-ph/0509241])

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**

$$f_i^{p/A}(x_N, \mu_0) = R_i(x_N, \mu_0, A)\; f_i^{free\ proton}(x_N, \mu_0)$$

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

- **Native nuclear PDFs**
  - `nCTEQ` [PRD 80, 094004 (2009), `arXiv:0907.2357`, `arXiv:1509.00792`]

$$f_i^{p/A}(x_N, \mu_0) = f_i(x_N, A, \mu_0)$$

$$f_i(x_N, A = 1, \mu_0) \equiv f_i^{free\ proton}(x_N, \mu_0)$$

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

- Functional form of the bound proton PDF same as for the free proton (CTEQ6M, x restricted to $0 < x < 1$)

$$x f_i^{p/A}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4} x)^{c_5}, \qquad i = u_v, d_v, g, \dots$$
$$\bar{d}(x, Q_0)/\bar{u}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} + (1 + c_3 x)(1-x)^{c_4}$$

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

$$c_k \to c_k(A) \equiv c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right), \quad k = \{1, \dots, 5\}$$

- PDFs for nucleus (A, Z)

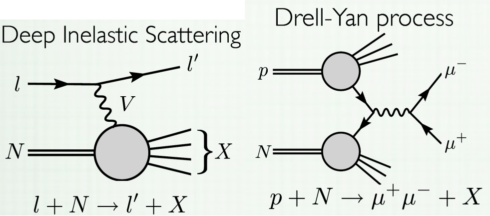
$$f_i^{(A,Z)}(x, Q) = \frac{Z}{A} f_i^{p/A}(x, Q) + \frac{A-Z}{A} f_i^{n/A}(x, Q)$$

(bound neutron PDF $f_i^{n/A}$ by isospin symmetry)

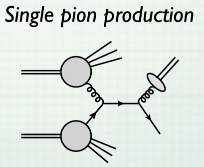
Data sets

- 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)



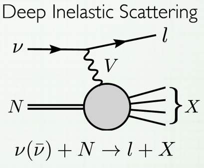
- Single pion production (new)



RHIC - PHENIX & STAR

N = Au

- Neutrino (to be included later)



CHORUS CCFR & NuTeV

N = Pb N = Fe

Fit details

Fit properties:

- fit @NLO
- $Q_0 = 1.3\text{GeV}$
- using ACOT heavy quark scheme
- kinematic cuts:
  $Q > 2\text{GeV}$, $W > 3.5\text{GeV}$
  $p_T > 1.7$ GeV
- 708 (DIS & DY) + 32 (single π^0)
  = 740 data points after cuts
- 16+2 free parameters
  - 7 gluon
  - 7 valence
  - 2 sea
  - 2 pion data normalizations
- $\chi^2 = 587$, giving $\chi^2/\text{dof} = 0.81$

Error analysis:

- use Hessian method

$$\chi^2 = \chi_0^2 + \frac{1}{2} H_{ij}(a_i - a_i^0)(a_j - a_j^0)$$

$$H_{ij} = \frac{\partial^2 \chi^2}{\partial a_i \partial a_j}$$

- 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

Fit details

Kinematic cuts

nCTEQ:

$$\begin{cases} Q > 2 \text{ GeV} \\ W > 3.5 \text{ GeV} \end{cases}$$

EPS: $Q > 1.3$ GeV

HKN: $Q > 1$ GeV

DSSZ: $Q > 1$ GeV

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d

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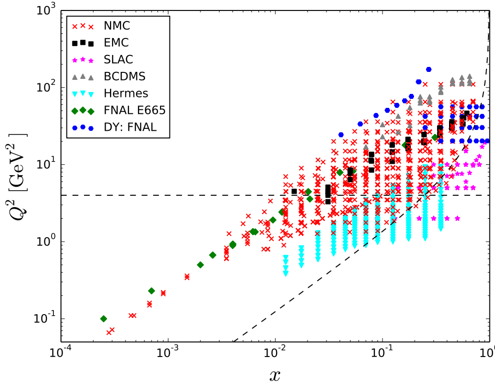

nCTEQ: 740 data points

EPS09: 929 data points

Fit details

Fit properties:

Hessian method

- choice of tolerance: $T = 35$
  [PRD65 (2001) 014012, `arXiv:hep-ph/0101051`]
- quadratic approximation

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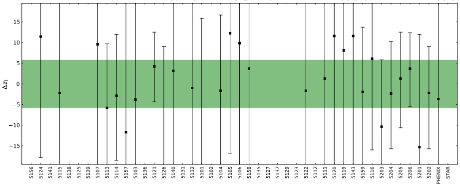

- eigenvalues span 10 orders of magnitude → require numerical precision
- use noise reducing derivatives

Fit details

Fit properties:

Hessian method

- choice of tolerance: $T = 35$
- quadratic approximation

$Q^2 > 2\mathrm{GeV}^2$, $W^2 > 3.5\mathrm{GeV}^2$
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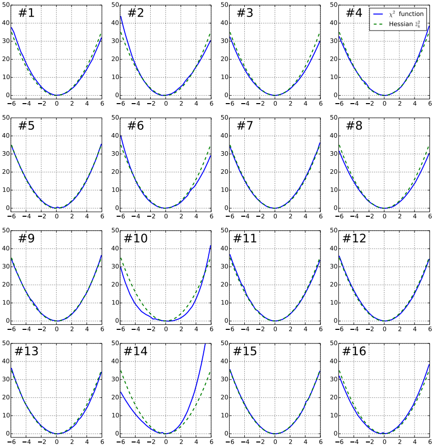

Fit details

Fit properties:

Fit quality

- $\chi^2/dof = 0.81$

sc

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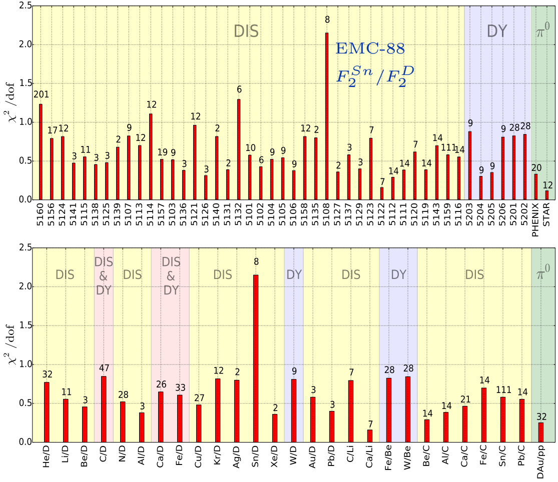


nCTEQ RESULTS

[arXiv:1509.00792]

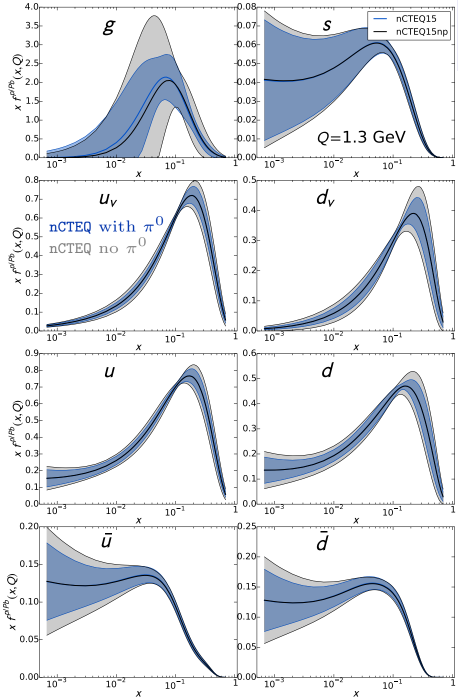
nCTEQ results

Bound proton PDFs
($Q = 1.3$ GeV)

$$x f_i^{p/Pb}(x, Q)$$

Compare nCTEQ fits:

- nCTEQ15 with π^0 data
- nCTEQ15np without π^0 data

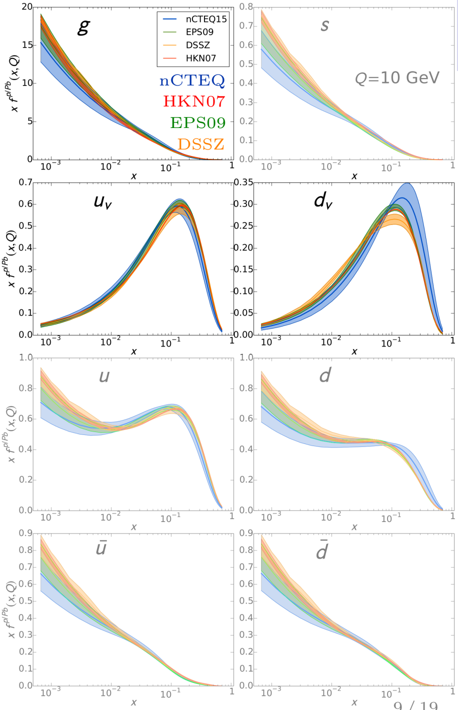


nCTEQ results

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

$$x\, f_i^{p/Pb}(x, Q)$$

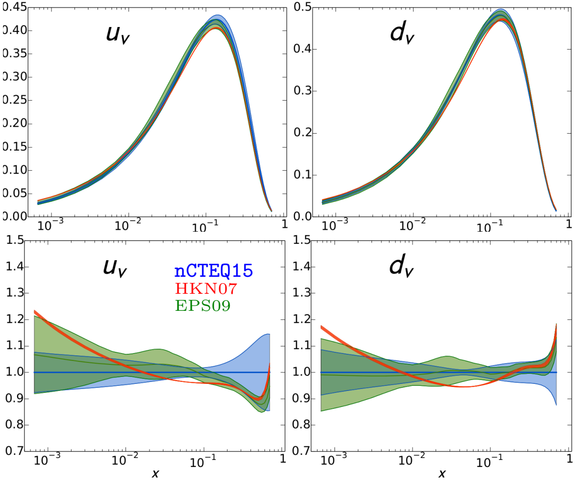
- nCTEQ features larger uncertainties than previous nPDFs
- better agreement between different groups (nPDFs don't depend on proton baseline)



Valence nuclear distributions

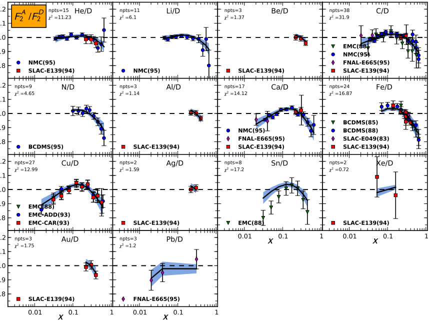
Full lead nucleus distribution:

$$f^{Pb} = \frac{82}{208} f^{p/Pb} + \frac{208-82}{208} f^{n/Pb}$$

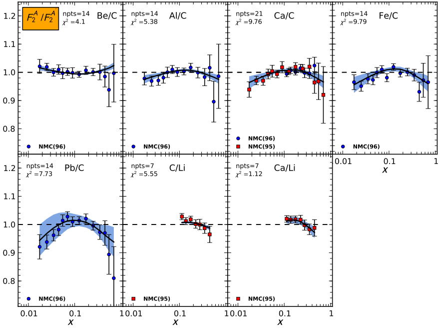


Description of fitted data: F_2 ratios

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

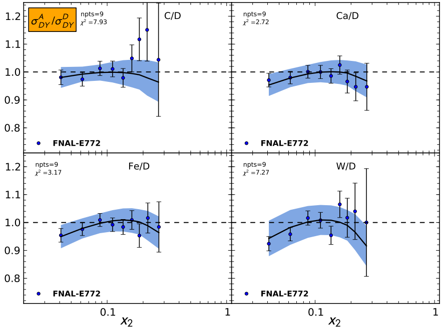


$$R = \frac{F_2^A(x,Q)}{F_2^{A'}(x,Q)}$$

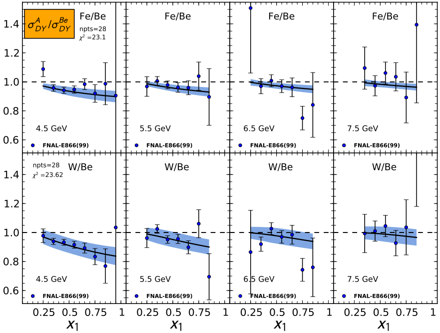


Description of fitted data: σ_{DY} ratios

$$R = \frac{\sigma^A_{DY}(x,Q)}{\sigma^D_{DY}(x,Q)}$$



$$R = \frac{\sigma^A_{DY}(x,Q)}{\sigma^{A'}_{DY}(x,Q)}$$



LHC data

Available pPb LHC data

- W/Z production
  - ATLAS [arXiv:1507.06232, ATLAS-CONF-2015-056]
  - CMS [arXiv:1512.06461, arXiv:1503.05825]
  - LHCb [arXiv:1406.2885]
  - ALICE [arXiv:1511.06398]
- Jets
  - ATLAS [arXiv:1412.4092]
  - CMS [arXiv:1401.4433, CMS-PAS-HIN-14-001]
- Charged particle production (FFs dependence)
  - CMS [CMS-PAS-HIN-12-017]
  - ALICE [arXiv:1405.2737, arXiv:1505.04717]
- Isolated photons (PbPb)
  - ATLAS [arXiv:1506.08552]
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Reweighting for Hessian PDFs [arXiv:1310.1089, arXiv:1402.6623]

1. Convert Hessian error PDFs into replicas

$$f_k = f_0 + \sum_i^N \frac{f_i^{(+)} - f_i^{(-)}}{2} R_{ki},$$

2. Calculate weights for each replica

$$w_k = \frac{e^{-\frac{1}{2}\chi_k^2/T}}{\frac{1}{N_{\rm rep}} \sum_i^{N_{\rm rep}} e^{-\frac{1}{2}\chi_k^2/T}}, \qquad \chi_k^2 = \sum_j^{N_{\rm data}} \frac{(D_j - T_j^k)^2}{\sigma_j^2}$$

3. Calculate observables with new (reweighted) PDFs

$$\langle \mathcal{O} \rangle_{\rm new} = \frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} w_k \mathcal{O}(f_k),$$

$$\delta \langle \mathcal{O} \rangle_{\rm new} = \sqrt{\frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} w_k \left(\mathcal{O}(f_k) - \langle \mathcal{O} \rangle \right)^2}.$$

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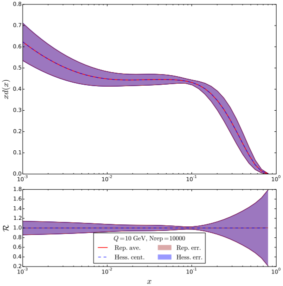

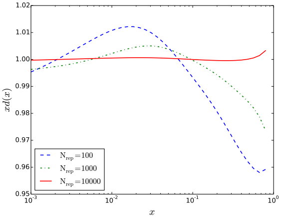

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   To speed up calculations in case of pPb data we can exploit

$$\sigma_k = f^{\rm p} \otimes \hat{\sigma} \otimes \left[f_0^{\rm Pb} + \sum_i^N \frac{f_i^{{\rm Pb}(+)} - f_i^{{\rm Pb}(-)}}{2} R_{ki} \right].$$

Reweighting with LHC

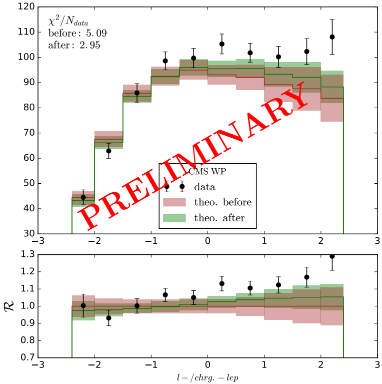
- We used only W/Z production data from pPb collisions
  - ATLAS [arXiv:1507.06232, ATLAS-CONF-2015-056]
  - CMS [arXiv:1512.06461, arXiv:1503.05825]
  - LHCb [arXiv:1406.2885]
  - ALICE [arXiv:1511.06398]
- The dominate role is played by the CMS W production data [arXiv:1503.05825]

Reweighting with LHC

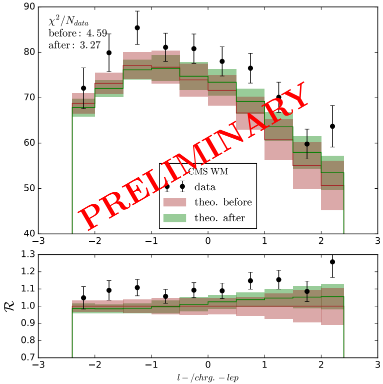
- CMS $W^{\pm}$ data [arXiv:1503.05825]

before reweighting
after reweighting

W^{+}

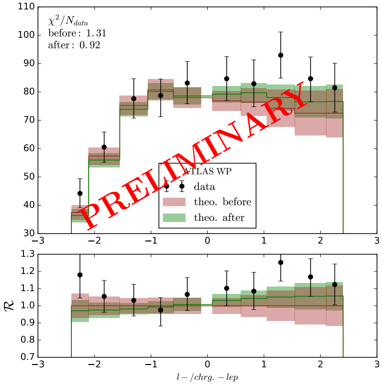


W^{-}

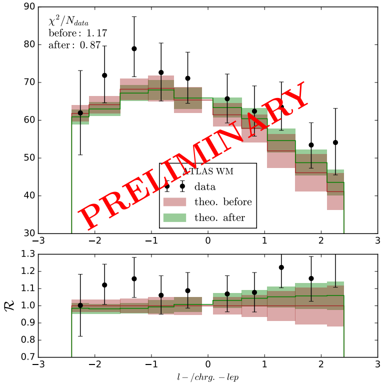


- ATLAS $W^{\pm}$ data [ATLAS-CONF-2015-056]
  - before reweighting
  - after reweighting

W^{+}

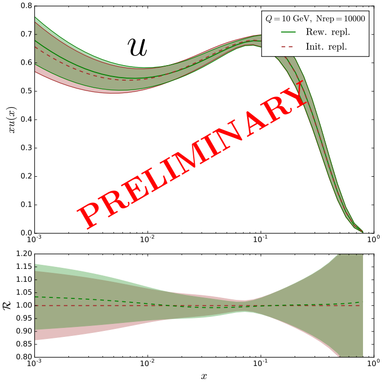


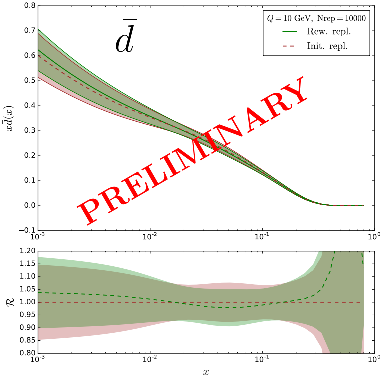
W^{-}



- Example reweighted PDFs

  before reweighting
  after reweighting





Summary

- We have released the `nCTEQ15` error PDFs [arXiv:1509.00792]
  - They are available on the `nCTEQ` website: `http://ncteq.hepforge.org` (and LHAPDF)
  - We provide two fits with and without Pion production data
- We see substantial differences in bound proton PDFs which vanish in full nuclear PDFs
  - bound proton PDFs are only **effective** means of parametrization of full nPDFs
- Uncertainties are still underestimated especially at low-x (no data below $x \lesssim 0.01$)
- LHC data will help but at the moment the errors are still to large

Thank You

Nuclear CTEQ parto ×

ncteq.hepforge.org

nCTEQ is hosted by Hepforge, IPPP Durham

nCTEQ

nuclear parton distribution functions

- Home
- PDF grids & code
  - nCTEQ15
  - previous PDF grids
- Papers & Talks
- Subversion
- Tracker
- Wiki

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). All details on the framework and the first complete results can be found in arXiv:15????? [hep-ph].
The effects of the nuclear environement on the parton densities can be shown as modified parton densities or nuclear correction factors (for example for lead as shown below)