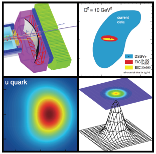
nCTEQ15 nuclear parton distributions with uncertainties

[arXiv:1509.00792]

A. Kusina

Laboratoire de Physique Subatomique et de Cosmologie (LPSC)
53 Rue des Martyrs Grenoble, France

in collaboration with:
K. Kovařík, T. Ježo, D. B. Clark,
C. Keppel, F. Lyonnet, J. Morfin,
F. I. Olness, J. Owens,
I. Schienbein, J. Y. Yu,



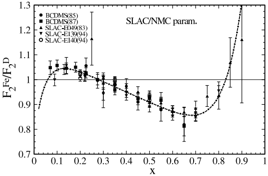
POETIC VI

6th International Conference
on Physics Opportunities at
an Electron-Ion Collider

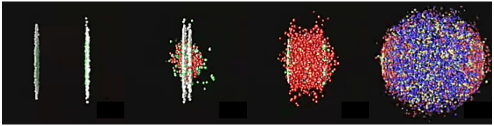
7-11 September 2015,
Palaiseau, France

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. $x \in (0,1)$ 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**

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

  - 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 [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 [arXiv:1509.00792]

- Functional form of the bound proton PDF same as for the free proton (∼CTEQ61 [hep-ph/0702159], x restricted to $0 < x < 1$)

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

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

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

- PDFs for nucleus (A, Z)

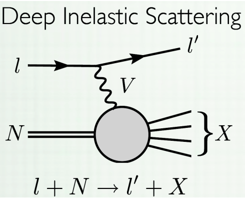
$$f_i^{(A,Z)}(x, Q) = \frac{Z}{A} f_i^{p/A}(x, Q) + \frac{A-Z}{A} f_i^{n/A}(x, Q)$$

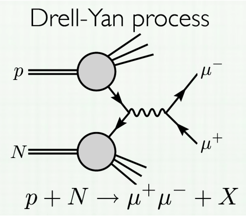
(bound neutron PDF $f_i^{n/A}$ by isospin symmetry)

Data sets

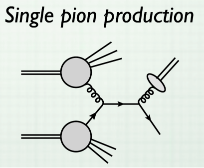
- NC DIS & DY

  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)





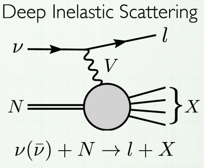
- Single pion production (new)



  RHIC - PHENIX & STAR

  N = Au

- Neutrino (to be included later)



  CHORUS CCFR & NuTeV

  N = Pb N = Fe

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 free parameters
  - 7 gluon
  - 7 valence
  - 2 sea
- $\chi^2 = 611$, giving $\chi^2/\text{dof} = 0.85$

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

Fit propert

- fit @N ... od
- $Q_0 =$ ... $a_i - a_i^0)(a_j - a_j^0)$
- using
- kinematic cuts:
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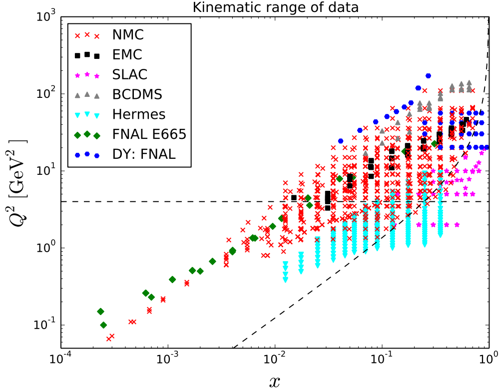

nCTEQ: 740 data points

EPS09: 929 data points

Fit details

Fit properties:

Hessian method

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

$p_T > 1.7$ GeV

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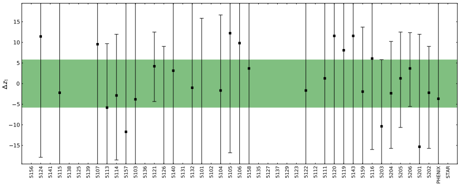

nuclear target within 90% C.L.)

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

Fit details

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Hessian method

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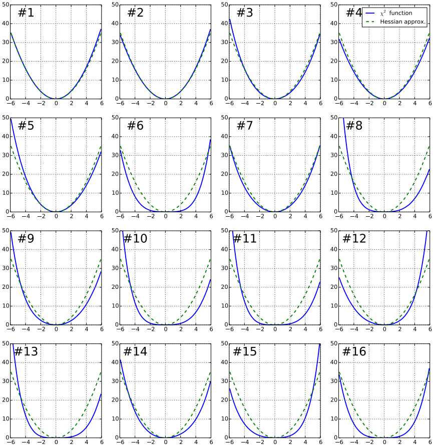

Fit details

Fit properties:

Fit quality

- $\chi^2/dof = 0.85$

- kinematic cuts:
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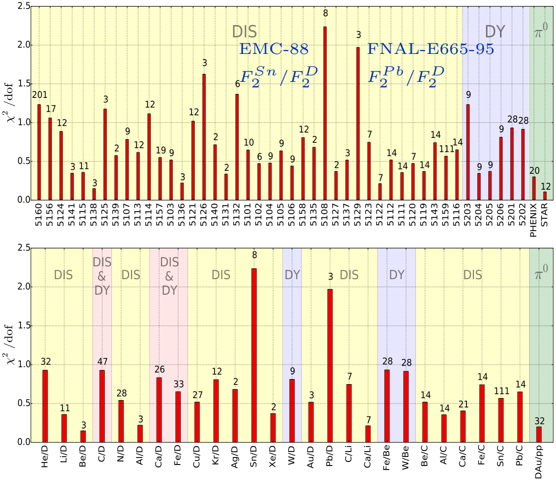


nCTEQ RESULTS

[arXiv:1509.00792]

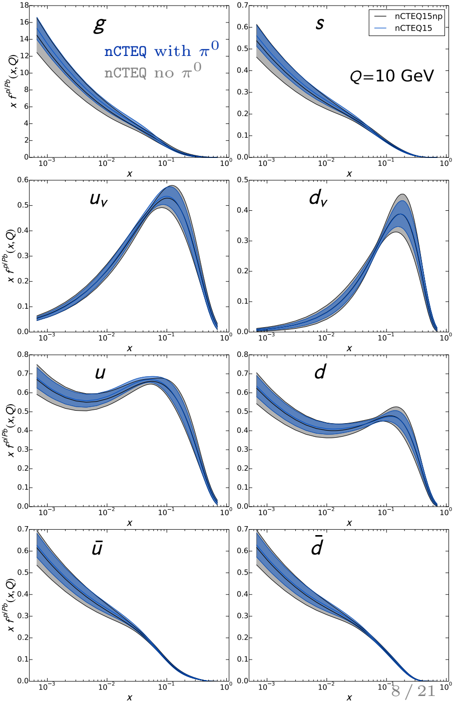
nCTEQ results

Bound proton PDFs
($Q = 10$ GeV)

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

Compare **nCTEQ** fits:

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



nCTEQ results

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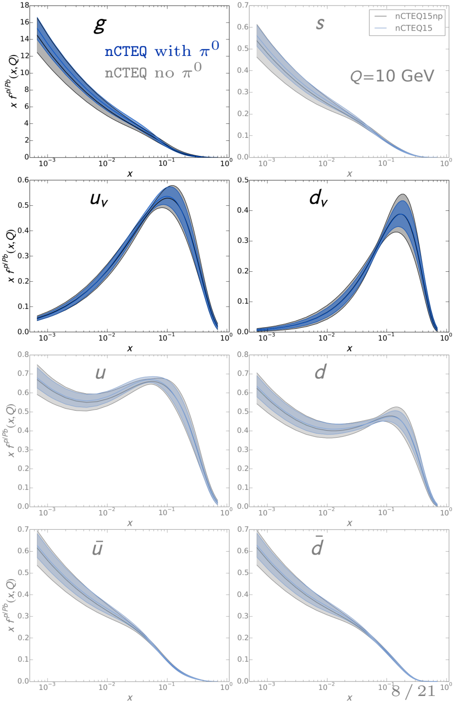

nCTEQ results

Nuclear correction factors
($Q = 10$ GeV)

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

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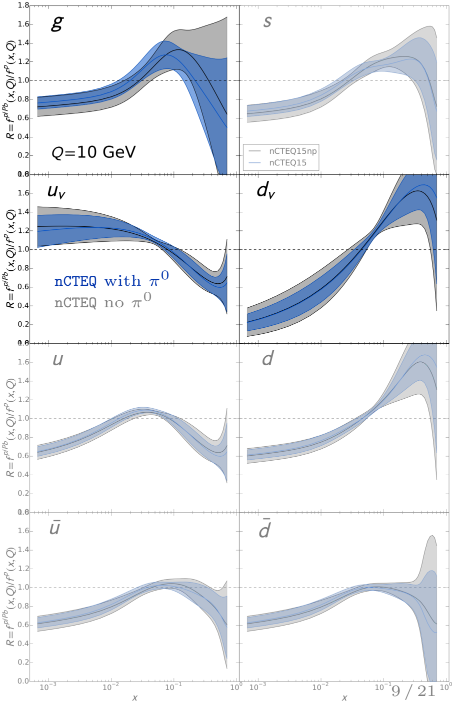
- nCTEQ15np without π^0 data

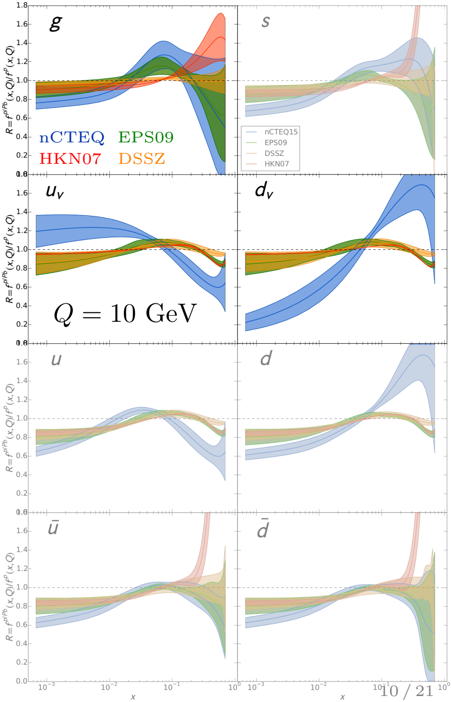


nCTEQ results

Nuclear correction factors
($Q = 10$ GeV)

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

- 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

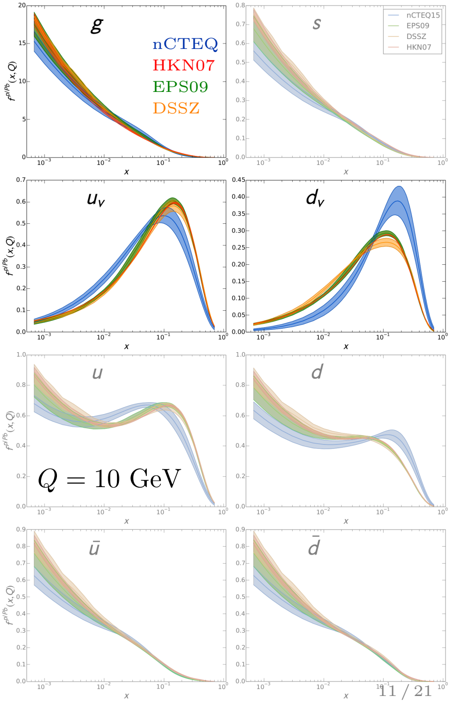


nCTEQ results

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 distributions

nCTEQ

$$xu_v^{p/A}(Q_0) = x^{c_1^u}(1-x)^{c_2^u} e^{c_3^u x}(1+e^{c_4^u}x)^{c_5^u}$$

$$xd_v^{p/A}(Q_0) = x^{c_1^d}(1-x)^{c_2^d} e^{c_3^d x}(1+e^{c_4^d}x)^{c_5^d}$$

$$c_k^{u_v} = c_{k,0}^{u_v} + c_{k,1}^{u_v}\left(1 - A^{-c_{k,2}^{u_v}}\right)$$

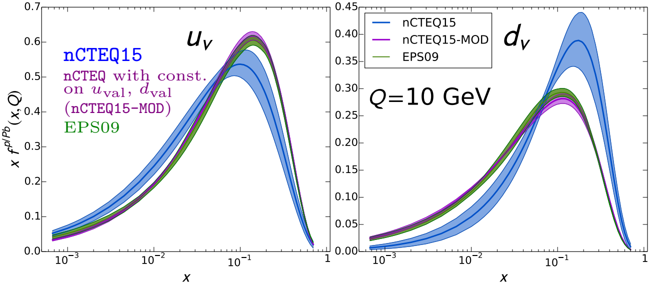
$$c_k^{d_v} = c_{k,0}^{d_v} + c_{k,1}^{d_v}\left(1 - A^{-c_{k,2}^{d_v}}\right)$$

EPS09

$$u_v^{p/A}(Q_0) = R_v(x, A, Z)\, u(x, Q_0)$$

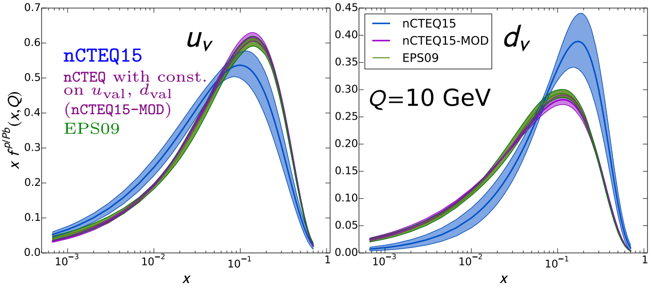
$$d_v^{p/A}(Q_0) = R_v(x, A, Z)\, d(x, Q_0)$$

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



we set: $c_{1,1}^{d_v} = c_{1,1}^{u_v},\ c_{1,2}^{d_v} = c_{1,2}^{u_v},\ c_{2,1}^{d_v} = c_{2,1}^{u_v},\ c_{2,2}^{d_v} = c_{2,2}^{u_v},$
$c_{3,1}^{d_v} = c_{3,1}^{u_v},\ c_{3,2}^{d_v} = c_{3,2}^{u_v},\ c_{5,1}^{d_v} = c_{5,1}^{u_v},\ c_{5,2}^{d_v} = c_{5,2}^{u_v}$

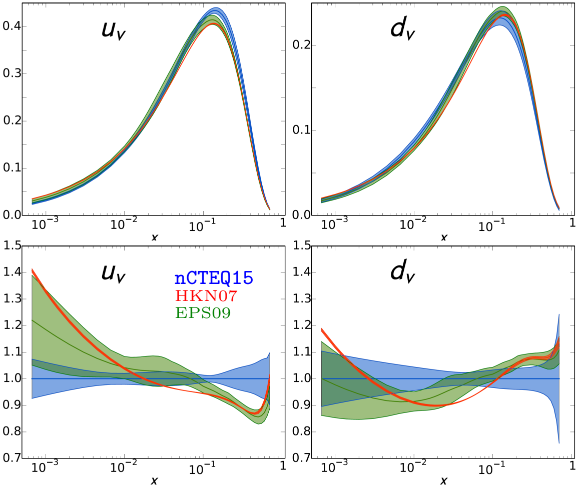
nCTEQ15 vs. nCTEQ15-MOD



- nCTEQ15: $\chi^2 = 611$
- nCTEQ15-MOD: $\chi^2 = 677$
- Tolerance used to defined error PDFs $\Delta\chi^2 = 35$
- Modified fit (with "universal" valence nuclear correction) do not lay within our error bands

Full lead nucleus distribution:

$$f^{Pb} = \frac{82}{207} f^{p/Pb} + \frac{207-82}{207} f^{n/Pb}$$

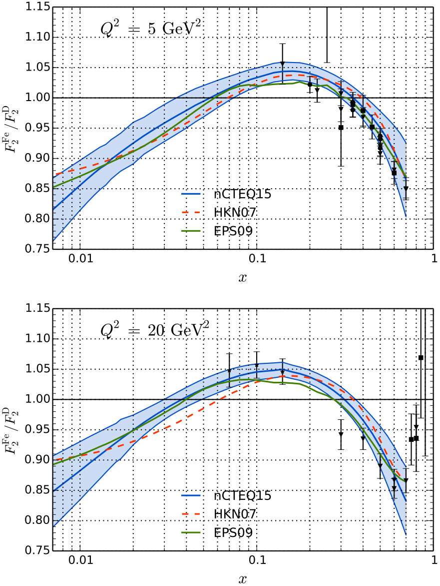


nCTEQ results: F_2 ratios

Structure function ratio

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

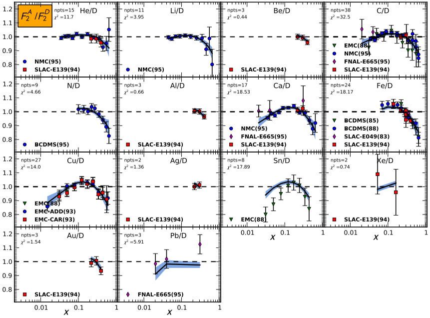
- good data description
- despite different u-valence & d-valence ratios are similar to EPS09

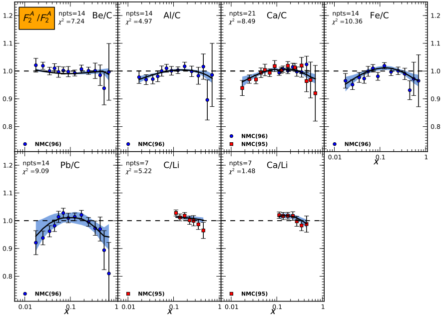


Description of fitted data: F_2 ratios

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

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

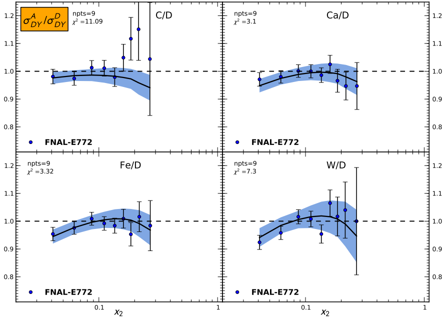


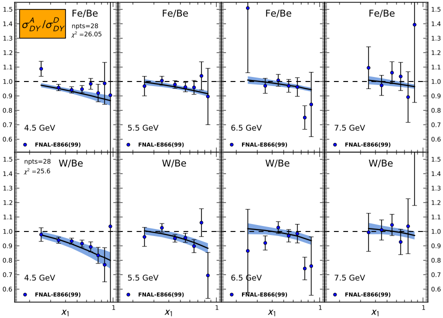


Description of fitted data: σ_{DY} ratios

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

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



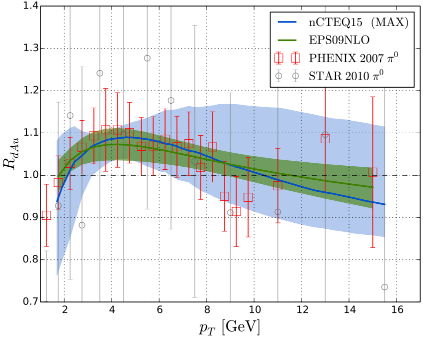


nCTEQ results: π^0 production

Pion production, ratio

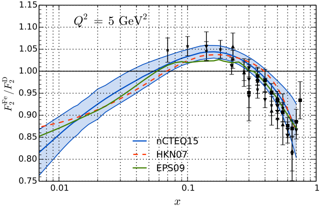
$$R^{\pi}_{\mathrm{dAu}} = \frac{\frac{1}{2A} d^2\sigma^{\mathrm{dAu}}_{\pi} / dp_T dy}{d^2\sigma^{\mathrm{pp}}_{\pi} / dp_T dy}$$

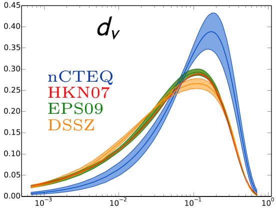
- good data description, however big experimental uncertainties do not allow for strong constraints on PDFs
- despite different u-valence & d-valence ratios are similar to EPS09



Summary

- We have released the nCTEQ15 error PDFs [arXiv:1509.00792].
- They are available on the nCTEQ website:
  http://ncteq.hepforge.org
- We see substantial differences in the valence distributions which highlights the impact of different assumptions entering nPDF analyses. → Uncertainties are strongly underestimated (assumptions replace uncertainties).
- Regardless of big differences in valence distributions we obtain very good description of the fitted data.

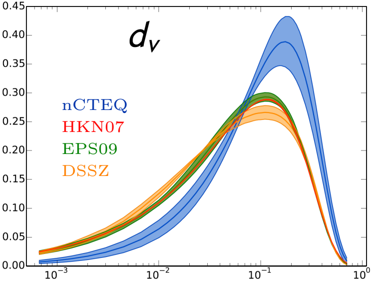




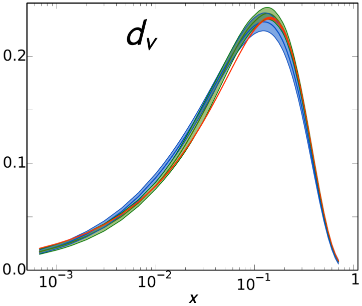
Summary

General remark on comparing nuclear PDFs

$d_v^{p/Pb}$

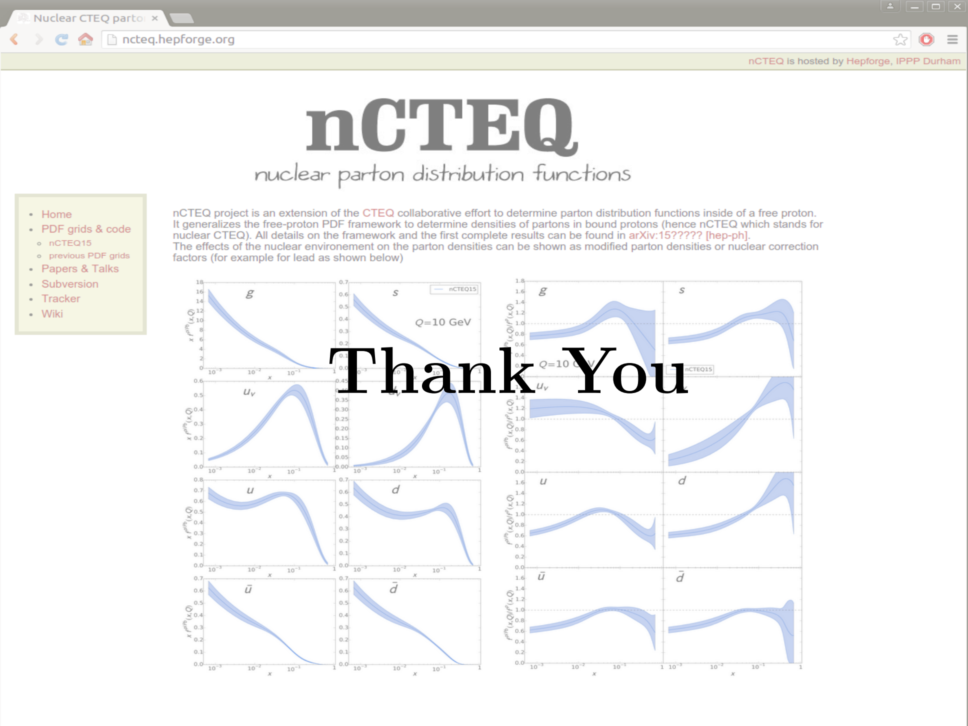


$$d_v^{Pb} = \frac{82}{207} d_v^{p/Pb} + \frac{207-82}{207} d_v^{n/Pb}$$



- Bound proton PDFs are effective quantities and should not be treated too literally.
- What enters cross section calculation (PDF fitting procedure) are PDFs of full nuclei: $f^{(A,Z)}$

Thank You


Nuclear CTEQ parto
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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)
Q=10 GeV
nCTEQ15