Next generation proton PDFs

with deuteron and nuclear uncertainties

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NNPDF

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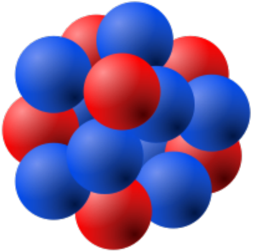
Overview

Introduction

Why do we need nuclear uncertainties?



- Wide range of data in proton PDFs
- Includes data with **nuclear targets**
- Nuclear environment alters proton's interaction
- Impacts PDFs in a way that is **hard to quantify precisely**

How do we deal with them?

Two main approaches:

1. Model correction to central values
2. Estimate nuclear uncertainties (and shifts) empirically using nuclear PDFs

We will use the second one.

Previously **models** have been used to estimate corrections. [Owens et al.: arXiv:1212.1702, Ball et al.: arXiv:1303.1189, Harland-Lang et al.: arXiv:1412.3989 & Accardi et al.: arXiv:1602.03154]

... Unreliable - can lead to bias

In the past NNPDF has chosen to ignore them (they are “small”)

... But not when we want 1% accuracy

Taking an empirical approach

Use nuclear PDFs to tell us about nuclear structure.

What we **are** doing

$T_i^N[f_p]$

What we **should be** doing

$T_i^N[f_N]$

Theory covariance matrix

[Ball, Nocera, RP: arXiv:1812.09074 & 2011.00009]

$$S_{ij} = \frac{1}{N_{rep}} \sum_{k}^{N_{rep}} \Delta_i^{(k)} \Delta_j^{(k)} \tag{1}$$

$$\Delta_i^{(k)} = T_i^N[f_N^{(k)}] - T_i^N[f_p] \tag{2}$$

Nuclear data

Nuclear data		
Dataset	Observable	Target
DYE605	DY dimuon cross sections	${}^{64}_{32}$Cu
NuTeV	DIS dimuon cross sections	${}^{56}_{26}$Fe
CHORUS	CC DIS cross sections	${}^{208}_{82}$Pb
SLAC	DIS structure functions F_2^d	${}^{4}_{2}D$
BCDMS	DIS structure functions F_2^d	${}^{4}_{2}D$
NMC	DIS structure function ratios F_2^d/F_2^p	${}^{4}_{2}D$
DYE866/NuSea	DY cross section ratios $\sigma_{pd}^{\mathrm{DY}}/\sigma_{pp}^{\mathrm{DY}}$	${}^{4}_{2}D$

Consider deuteron and heavy nuclear data separately.

Heavy nuclear uncertainties

Heavy nuclear covariance matrix

Use nuclear PDFs at NLO from nNNPDF2.0 [Abdul-Khalek et al.: arXiv:2006.14629] to empirically determine uncertainty.

"Deweighted" approach

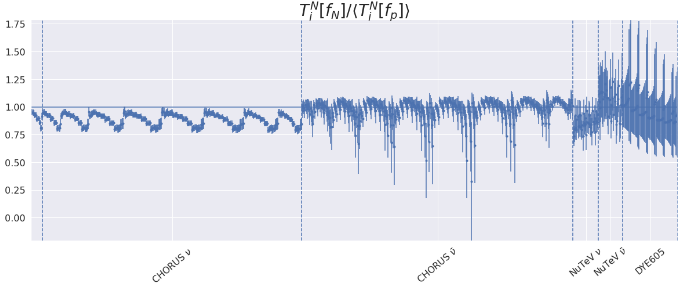
$$\Delta_i^{(k)} = T_i^N[f_N^{(k)}] - T_i^N[f_p] \tag{3}$$

"Shifted" approach

$$\delta T_i^N = T_i^N[f_N] - T_i^N[f_p] \tag{4}$$

$$\Delta_i^{(k)} = T_i^N[f_N^{(k)}] - T_i^N[f_N] \tag{5}$$

Change to heavy nuclear observables



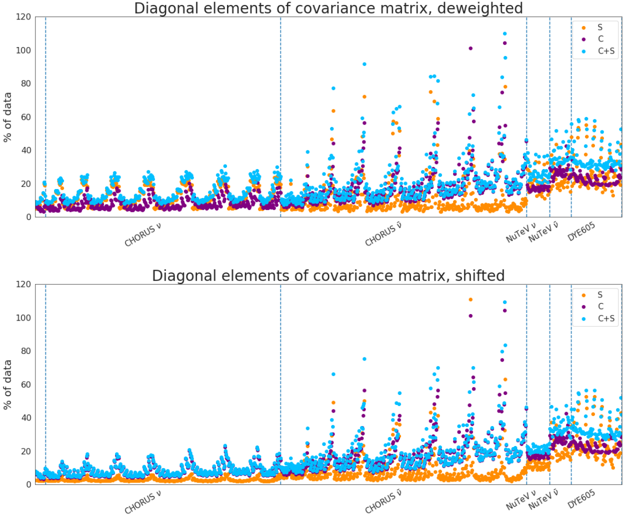
- Data are arranged in Q^2 bins with increasing x in each bin
- Kinematic dependence mirrors f_N/f_p - nuclear shadowing at high x
- Systematic shift (CHORUS ν)

Per-point uncertainties

C: experimental

S: nuclear

C+S: total



Deuteron uncertainties

Deuteron PDFs

Traditionally we improve on proton PDFs by using the **isoscalar PDF**:

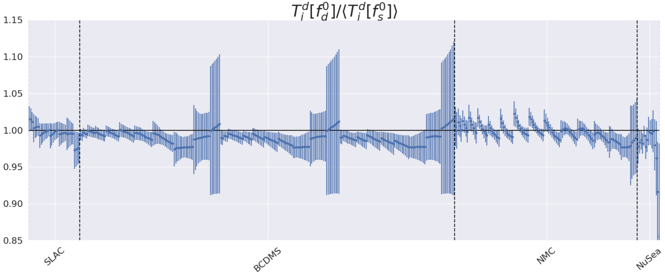
$f_s = \frac{1}{2}(f_p + f_n)$

Two types of deuteron data:

1. SLAC/BCDMS $F_2^d -> T_i^d[f_s]$
2. NMC/NuSea ratio data $-> T_i^d[f_s, f_p]$

Use an **iterative procedure** to determine the deuteron PDFs alongside proton PDFs with deuteron uncertainties. [Ball, Nocera, RP: arXiv:2011.00009]

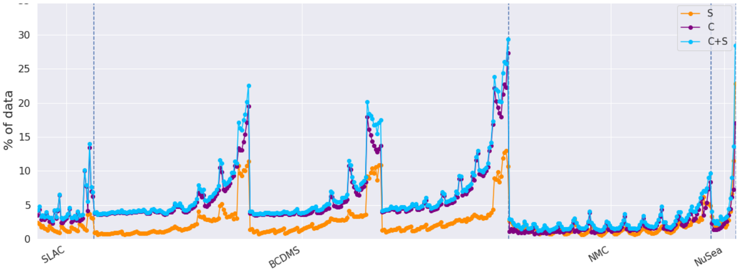
Change to deuteron observables



- (x, Q^2) bins as for heavy nuclear
- Consistent with 1 in most regions
- Difference is much smaller than for heavy nuclei - a few % rather than 10-20%.

Per-point uncertainties

C: experimental
S: nuclear
C+S: total



- Plot shows the deweighted case but the shifted case is qualitatively similar
- Similar pattern to heavy nuclear case
- Correction comparable to experiment for ratio data but les significant for the rest

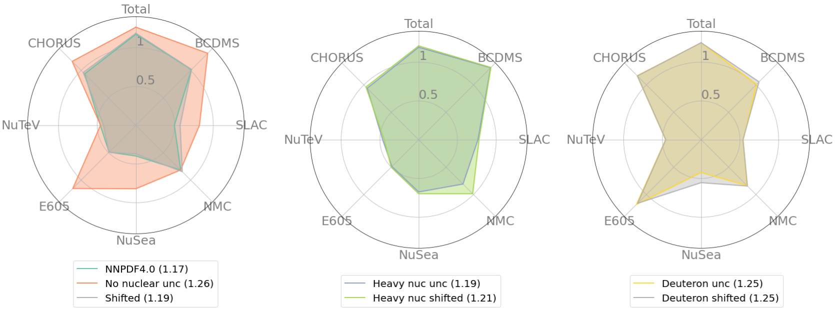
PDFs with nuclear uncertainties

Fits with nuclear uncertainties

Fit label	**Description**
NNPDF4.0	Baseline fit from NNPDF4.0 - **includes all nuclear uncertainties**
No nuclear unc.	Without nuclear uncertainties
Heavy nuclear unc.	Heavy nuclear uncertainties only
Heavy nuclear shifted	Heavy nuclear uncertainties with shifted central value
Deuteron unc.	Deuteron uncertainties only
Deuteron shifted	Deuteron uncertainties with shifted central value
Shifted	(All) nuclear uncertainties with shifted central value

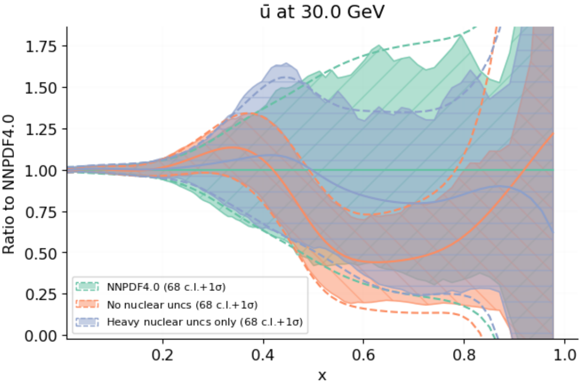
Table: A summary of the fits with nuclear uncertainties.

χ^2s



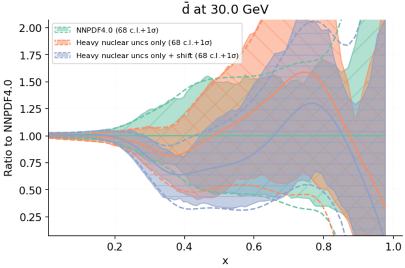
- Global χ^2: $1.26 \rightarrow 1.17$
- Little difference deweighted versus shifted

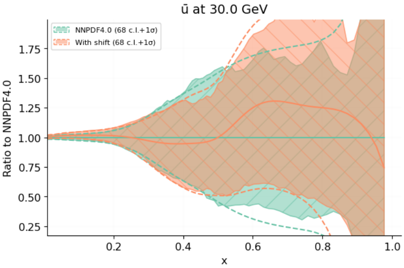
Impact on PDFs

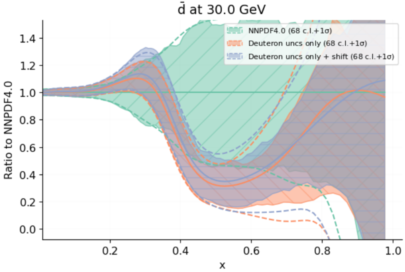


- No nuclear uncs - PDFs pulled down at large x (nuclear shadowing)
- Adding nuclear uncs increases PDF unc
- Heavy nuclear effects dominate over deuterium

Shifting versus deweighting







- More difference for heavy nuc
- Agree within errors
- Deweighted is more conservative and better χ^2
- We use deweighted approach in NNPDF4.0

Summary

Summary

Motivation

- Need nuclear data to determine proton PDFs
- At 1% accuracy nuclear effects matter

What we did

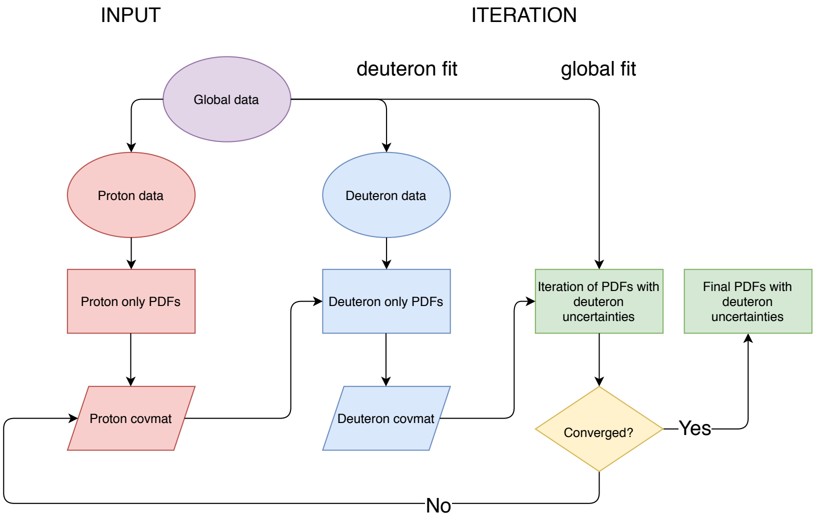
- Constructed nuclear covariance matrix using nPDFs
- Analysed deuteron and heavy nuclear separately
- Included nuclear uncertainties in NNPDF4.0

What we found

- Nuclear uncertainties are a crucial ingredient in NNPDF4.0
- Global χ^2: 1.26 → 1.17
- Uncertainties for heavy nuclei are more significant than for deuteron

Extra

Iterative approach



INPUT

ITERATION

deuteron fit

global fit

Global data

Proton data

Deuteron data

Proton only PDFs

Deuteron only PDFs

Iteration of PDFs with deuteron uncertainties

Final PDFs with deuteron uncertainties

Proton covmat

Deuteron covmat

Converged?

Yes

No

Deuteron covariance matrix

"Deweighted" approach

$$\Delta_i^{d,\,(k)} = \begin{cases} T_i^d[f_d^{(k)}] - T_i^d[f_s^{(0)}] & i \in \text{pure} \\ T_i^d[f_d^{(k)}, f_p^{(0)}] - T_i^d[f_s^{(0)}, f_p^{(0)}] & i \in \text{mixed}, \end{cases} \tag{6}$$

"Shifted" approach

$$\delta T_i^d = \begin{cases} T_i^d[f_d^{(0)}] - T_i^d[f_s^{(0)}] & i \in \text{pure} \\ T_i^d[f_d^{(0)}, f_p^{(0)}] - T_i^d[f_s^{(0)}, f_p^{(0)}] & i \in \text{mixed}. \end{cases} \tag{7}$$

$$\Delta_i^{d,\,(k)} = \begin{cases} T_i^d[f_d^{(k)}] - T_i^d[f_d^{(0)}] & i \in \text{pure} \\ T_i^d[f_d^{(k)}, f_p^{(0)}] - T_i^d[f_d^{(0)}, f_p^{(0)}] & i \in \text{mixed}, \end{cases} \tag{8}$$