# Integrated Determination of Proton And Nuclear PDFs (WIP)

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- 1. State-of-the-art in Proton, Deuteron, and nuclear fits [(n)NNPDF]
- 2. Toward a Simultaneous determination
- 3. Preliminary Results



### Outline





### **Introduction & Motivations**

### So far:

- O Proton PDF fits include theoretical uncertainties due to Nuclear Effects: requires nuclear PDFs as input
- O Nuclear PDF fits **depend** on Proton PDF: requires a fixed Proton baseline PDF

### However:

- O Various Nuclear datasets constrains Proton PDFs: from lepton-nucleon, lepton-nucleus, and protonnucleus measurements
- O A **combined** (potentially with <u>polarised</u> & fragmentation fits) QCD analysis is crucial to **fully interpret** the **EIC** data





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# State-of-the-Art in Free-Proton and Nuclear PDF fits - (n)NNPDF

## **NNPDF Free-Proton PDF Fit: Methodology**



- **Integrability** of Non-Singlet Distributions (**Gottfried** Sum Rules) 0











# **NNPDF Free-Proton PDF Fit: Experimental & Theory Inputs**





### **NNPDF Free-Proton PDF Fit: Precision Determination**



Achieves ~ONE percent accuracy across a Wide range of kinematics





### **nNNPDF** nuclear PDF Fit: Methodology

 $f_i^{p/A} \equiv f_i(x, A)$ : Object

In the nNNPDF[3.0] determination, only 6 independent nuclear PDF (nPDF) combination are parametrised:

$$\Sigma(x, Q_0), g(x, Q_0), T_3(x, Q_0))$$

$$\chi^{2} = \sum_{i,j} \left( D_{i} - T_{i} \right) \left( \operatorname{cov}_{t_{0}} \right)_{ij}^{-1} \left( D_{j} - T_{j} \right) + \lambda_{bc} \sum_{m}^{n_{f}} \sum_{l=1}^{N_{x}} \left( f_{m}^{(p/A)} \left( x_{l}, Q_{0}, A = 1 \right) - f_{m}^{(p)} \left( x_{l}, Q_{0} \right) \right)^{2}$$

The nucleus is not just an ensemble of Z free-protons and (A - Z) free neutrons. Nuclear PDFs are defined at scale Q as:

 $T_{8}(x, Q_{0}), T_{8}(x, Q_{0}), V(x, Q_{0}), V_{3}(x, Q_{0})$ 

A = 1 is **not fitted** alongside but rather defined as a **Boundary Condition** via a **Lagrange Multiplier** (at the  $\chi^2$  level):





oment Sum Rules	Positivity of Observables
ositivity of $\overline{MS}$ PDFs	X Integrability of $T_{3,8}$ Distribution







# Simultaneous determination of Proton, Deuteron and Nuclear PDFs

# **Integrated Proton & Nuclear Fit: Methodology**



$$\chi_{\rm tot}^2 = \sum_A \chi_{t_0}^2(A)$$





# Integrated Proton & Nuclear Fit: Experimental & Theory Inputs

Kinematic coverage



# Integrated Proton & Nuclear Fit: Stability of the Training



Dataset	NNPDF4.0	Integrated		
NMC	1.63	1.62		
HERACOMB	1.18	1.16		
CDF	1.29	1.24		
ATLAS	1.57	1.38		
CMS	1.44	1.53		
LHCb	1.54	1.46		



# Integrated Proton & Nuclear Fit: Stability of the Training



Dataset	nNNPDF3.0	Integrated
NMC	0.88	1.61
SLAC	1.09	1.38
EMC	0.78	1.80
FNAL	1.01	0.50
BCDMS	0.82	1.35
LHC	1.09	1.15



### **Integrated Proton & Nuclear Fit:** A = 1 **Limit**

d at 1.651 GeV



### ū at 1.651 GeV

- O <u>Comparisons</u>: Free-Proton + Nuclear Uncertainties vs Integrated Fit
- Qualitative Shapes of both determinations are comparable within  $1\sigma$  error bands
- Enhanced effects in the large-xanti-shadowing regions of the  $\bar{u}$ and  $\bar{d}$  quarks: genuine effects or fit artifacts?





### Integrated Proton & Nuclear Fit: Heavy Nuclei



g at 1.65 GeV

- **Comparisons**: Nuclear PDFs from 0 nNNPDF3.0 determination vs Nuclear PDFs from Integrated Fit
- Results from **Both determinations** are 0 compatible within  $1\sigma$  error bands
- Better agreement for Lead while some 0 discrepancy can be seen for Iron





# Towards an Integrated NNLO Proton and Nuclear Global Fits

## NNLO Global Fit: Status & Aims

	DSSZ12	KA15	nCTEQ15	EPPS16	TUJU19	TUJU21	nNNPDF1.0	nNNPDF2.0	nNNPDF3.0	Integrated
Order	NLO	NNLO	NLO	NLO	NNLO	NNLO	NNLO	NLO	NLO	NNLO
NC DIS										
DY (p+N)					X		×	×		
RHIC		×			X	×	×	×	×	-
CC DIS		×	×				×			
DY (Pion+A)	×	×	×		X	X	×	×	X	_
LHC Di-Jet	×	×	×		X		×	×		Z
LHC W,Z	×	×	×		X		×			Z
LHC D0	×	×	×	×	X	X	×	×		
Fitting Scale	1.00	1.41	1.30	1.30	1.30	1.30	1.00	1.00	1.00	1.00
Q Cut	1.00	1.41	2.00	1.00	1.30	1.30	1.87	1.87	1.87	1.87
Datapoints	1579	1479	708	1811	2336	2336	451	1467	2151	2151 <b>+4426</b>
Error Analys.	Hessian	Hessian	Hessian	Hessian	Hessian	Hessian	Monte Carlo	Monte Carlo	Monte Carlo	Monte Carl
Proton Bas.	MSTW08	JR09	CTEQ6.1	CT14nlo	HERA2.0		NNPDF3.1	NNPDF3.1	NNPDF3.1	N/A
HQ Effects		×								
Flavour Sep.		×	Partly		×	×	×			
Parametriz.	Ratio in Mell.	Ratio	PDF(A)	Ratio	PDF(A)	PDF(A)	NN(A)	NN(A)	NN(A)	NN(A)
Reference	PR D.100.096015	PR D.93.014026	PR D.93.085037	EPJ C77 163	PR D.100.096015	PR D.105.094031	EPJ C79 471	JHEP 09 (2020) 183	JHEP 82 (2022) 507	-





# **NNLO Global Fit: Benefitting from a New Pipeline**



arXiv:2302.12124



### netherlands NNLO Global Fit: Exploiting Hardware Acceleration Science center

- parallelisation
- level of the **PDF distribution**













# Summary & Outlook

- O An integrated analysis of proton, deuteron, and nuclear PDFs is under way and benefits from the features of the NNPDF codebase
- O Further works are required in order to fully understand the stability of the combined fits
- O Extend the framework to a global fit @ NNLO potentially with Missing Higher Order Uncertainties estimation
- O Computing DIS theory @ NNLO is nowadays more convenient and easier thanks to the new Pipeline
- O Remain to compute NNLO K-factors for the hadronic processes thanks to the modified MCFM codes provided by the TUJU group

