

Nuclear Parton Distribution Functions from NNPDF

Parton Distributions and Lattice Calculations – PDFLattice2019

Based on Eur.Phys.J. C79 (2019) 471 (NNPDF Collaboration)

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Foreword

Nuclei behave rather differently than a simple incoherent superposition of protons and neutrons

Quarks and gluons in bound nucleons exhibit highly non-trivial momentum distributions

We aim to understand such distributions (anti)shadowing, EMC effect, Fermi motion

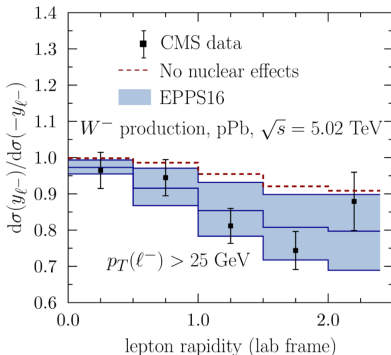
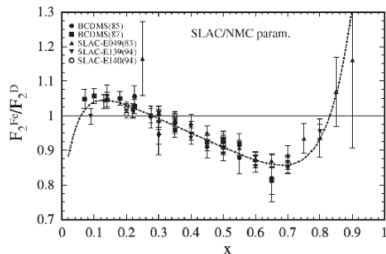
Combining data across different nuclear targets allows one to test different nuclear models

Neutrino-induced CC-DIS on nuclear targets helps disentangle the proton's q and \bar{q} PDFs

Pb, Xe PDF for the LHC heavy-ion program

Four equally possible scenarios

- 1 - the fundamental interactions are the same but PDFs are different
- 2 - the fundamental interactions are different in the medium but PDFs are the same
- 3 - both 1 and 2
- 4 - the factorisation picture is no longer valid



Overview of the available nPDF sets

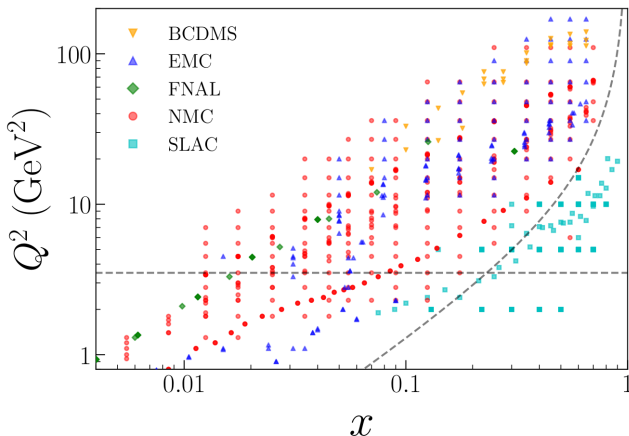
	EPS09	DSSZ12	Ka15	NCTEQ15	EPPS16	nNNPDF1.0
Order in α_s	LO & NLO	NLO	NNLO	NLO	NLO	NNLO
Neutral current DIS $\ell+A/\ell+d$	✓	✓	✓	✓	✓	✓
Drell-Yan dilepton $p+A/p+d$	✓	✓	✓	✓	✓	
RHIC pions $d+Au/p+p$	✓	✓		✓	✓	
Neutrino-nucleus DIS		✓			✓	
Drell-Yan dilepton $\pi+A$					✓	
LHC $p+Pb$ jet data					✓	
LHC $p+Pb$ W, Z data					✓	
Q cut in DIS	1.3 GeV	1 GeV	1 GeV	2 GeV	1.3 GeV	1.87 GeV
datapoints	929	1579	1479	708	1811	451
free parameters	15	25	16	17	20	183*
error analysis	Hessian	Hessian	Hessian	Hessian	Hessian	Monte
error tolerance $\Delta\chi^2$	50	30	not given	35	52	Carlo rep
Free proton baseline PDFs	CTEQ6.1	MSTW2008	JR09	CTEQ6M-like	CT14NLO	NNPDF3.1
Heavy-quark effects		✓		✓	✓	✓
Flavor separation				some	✓	
Reference	[JHEP 0904 065]	[PR D85 074028]	[PR D93, 014026]	[PR D93 085037]	[EPL C77 163]	[arXiv:1904.00018]

They mostly differ in three aspects:

the input data set, the details of the QCD analysis and the fitting methodology

nNNPDF1.0: kinematics

^2D , ^4He , ^6Li , ^9Be , ^{12}C , ^{14}N , ^{27}Al , ^{40}Ca , ^{56}Fe , ^{64}Cu , ^{108}Ag , ^{119}Sn , ^{131}Xe , ^{197}Au , ^{208}Pb



	nNNPDF1.0	nCTEQ15	EPPS16		nNNPDF1.0	nCTEQ15	EPPS16
W_{\min}^2 [GeV 2]	12.5	12.25	n/a	Q_{\min}^2 [GeV 2]	3.5	4.0	1.69

Kinematic cuts consistent with the boundary proton PDF set (NNPDF3.1)

nNNPDF1.0: parametrisation

Observables

isoscalar F_2^A in DIS

isoscalar \rightarrow insensitive to T_3

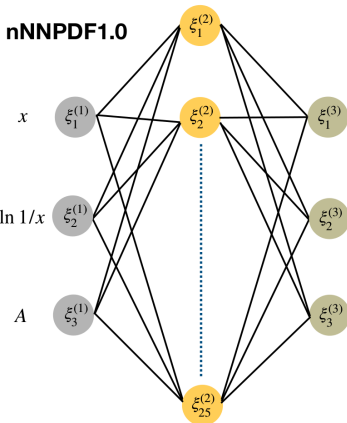
DIS: \rightarrow insensitive to valence

Momentum sum rule

$$B_g(A) = \frac{1 - \int_0^1 dx x \Sigma(x, Q_0, A)}{\int_0^1 dx x g(x, Q_0, A)}$$

Independent nPDFs

singlet $\Sigma = \sum_i q_i^+, q^+ = q + \bar{q}$
 octet $T_8 = u^+ + d^+ - 2s^+$
 gluon g



$$g(x, Q_0, A) = B_g x^{-\alpha_g} (1-x)^{\beta_g} \xi_1^{(3)}$$

$$\Sigma(x, Q_0, A) = x^{-\alpha_\Sigma} (1-x)^{\beta_\Sigma} \xi_2^{(3)}$$

$$T_8(x, Q_0, A) = x^{-\alpha_{T_8}} (1-x)^{\beta_{T_8}} \xi_3^{(3)}$$

Single feed-forward Neural Network with only one hidden layer (25 nodes)

A total of $N_{\text{par}} = 178$ NN parameters + $N_{\text{prep}} = 6$ preprocessing exponents are fitted

$$\text{Boundary condition } f(x, Q, A = 1) = \frac{1}{2} [f_p(x, Q^2) + f_n(x, Q^2)] \quad f = \Sigma, T_8, g$$

nNNPDF1.0: minimisation

Cost function

$$\chi^2 = \sum_{i,j}^{N_{\text{dat}}} [D_i - T_i(\{f_m\})] (\text{cov}_{t_0})_{t_j}^{-1} [D_j - T_j(\{f_m\})] + \lambda P \quad \lambda = 100$$

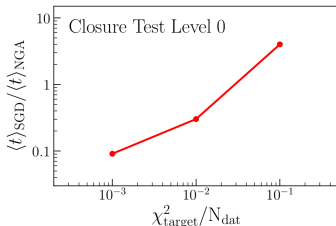
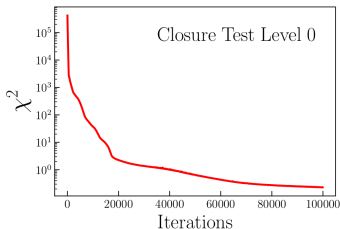
$$P = \lambda \sum_{m=g,\Sigma,T_8} \sum_{l=1}^{N_x} \left[f_m(x_l, Q_0, A=1) - f_m^{(p+n)/2}(x_l, Q_0) \right]^2 \quad N_x \in [10^{-3}, 0.7]$$

Optimisation algorithm

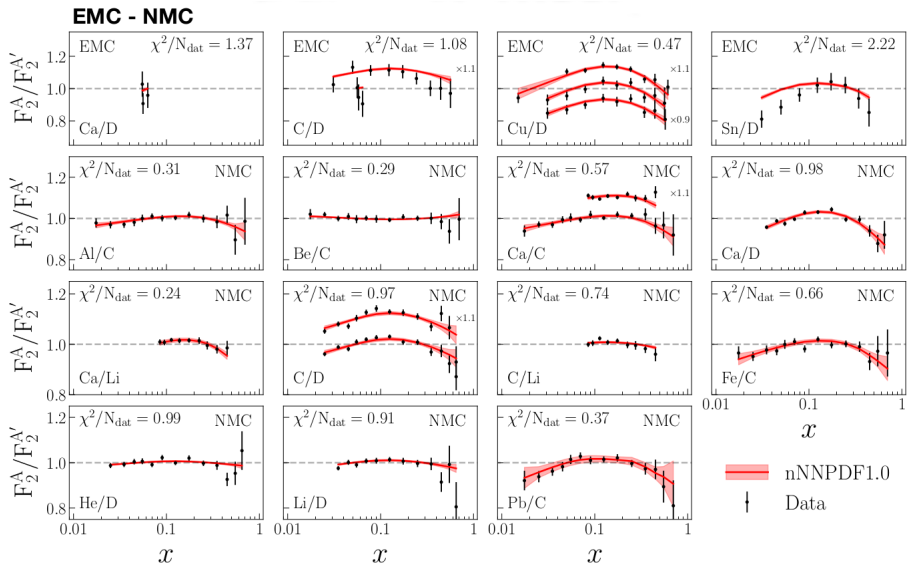
With TensorFlow



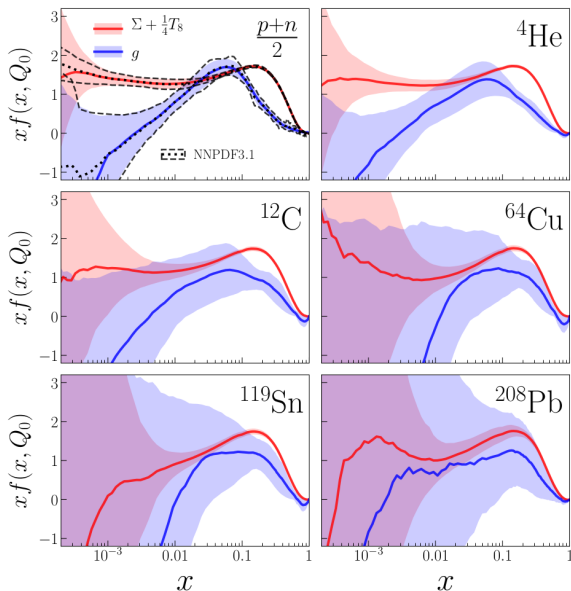
- Training and validation splitting
- Architecture: [3, 25, 3]
- Linear solver: Reverse Automatic Differentiation
- Minimisation: Backpropagation + gradient descent [ADAM]



nNNPDF1.0: fit quality



nNNPDF1.0: parton distributions

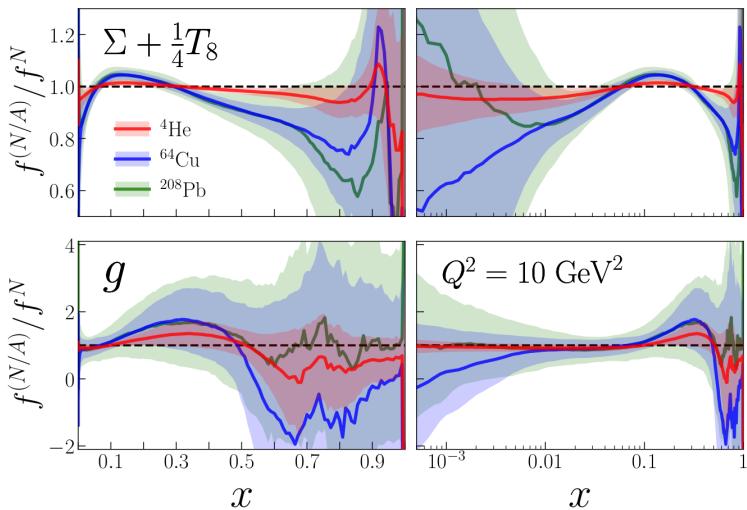


Uncertainty bands
correspond to 90% CL
(1k replicas)

NNPDF3.1 reproduced
(central value and
uncertainties)

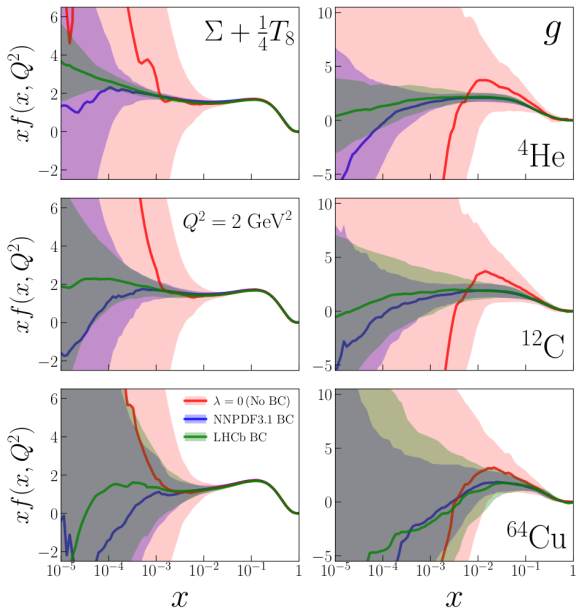
The boundary condition
constrains
the PDFs for low- A nuclei

nNNPDF1.0: A dependence



Nuclear effects more pronounced for larger A in the $\Sigma + 1/4T_8$ combination
Gluon uncertainties within unity

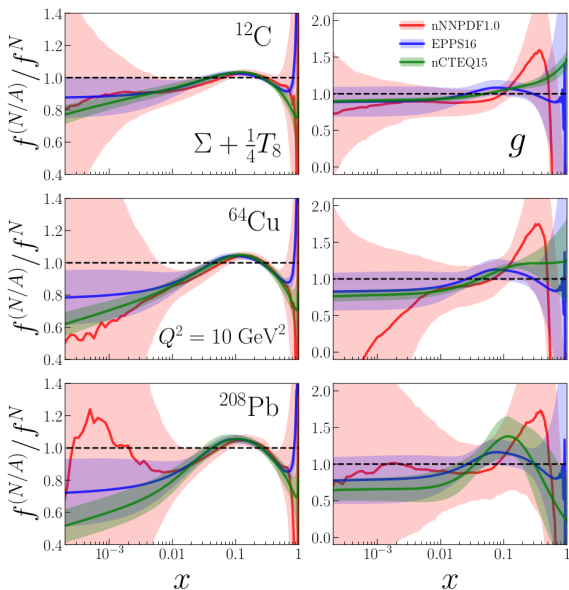
nNNPDF1.0: boundary condition



Important constraints on nPDF central values and uncertainties across A

Pronounced reduction of uncertainty due to the accurate determination of the proton's quark sea at small x in NNPDF3.1 + LHCb

nNNPDF1.0: comparison with other nPDF sets



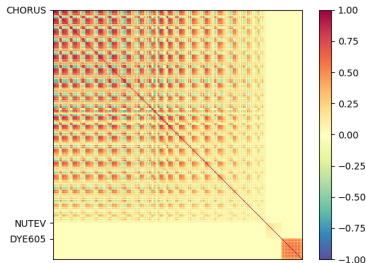
all nPDFs are normalised to the nNNPDF1.0(A=1) central value

90% CL for all nPDFs
Hessian
for nCTEQ15 and EPPS16
Monte Carlo
for nNNPDF1.0

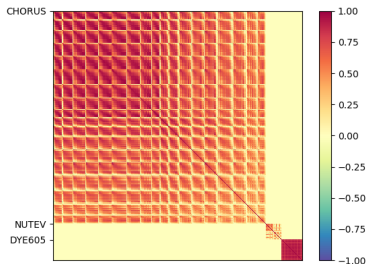
Significant differences in uncertainty in the extrapolation region

Nuclear uncertainties in proton PDF fits [EPJ C79 (2019) 282]

Experimental correlation matrix



Experimental+Nuclear correlation matrix



$$\text{COV} \longrightarrow \text{COV}_{\text{exp}} + \text{COV}_{\text{th}}$$

$$(\text{COV}_{\text{th}})_{ij} = \frac{1}{N} \sum_k \Delta_i^{(k)} \Delta_j^{(k)}$$

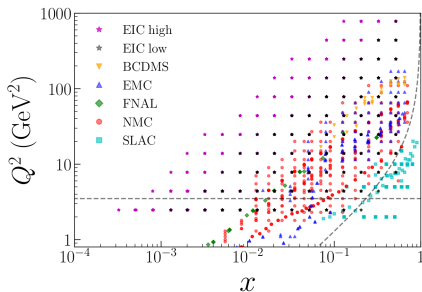
$$\Delta_i^{(k)} = T_i^N[f_N^{(k)}] - T_i^N[f_p^{(k)}]$$

nuclear uncertainties determined by averaging over Monte Carlo replicas from three nuclear PDF sets: DSSZ12, nCTEQ15 and EPPS16

Experiment	N_{dat}	χ^2/N_{dat} (bas.)	χ^2/N_{dat} (nucl.)
CHORUS (ν)	416	1.29	0.97
CHORUS ($\bar{\nu}$)	416	1.20	0.78
NUTEV (ν)	37	0.41	0.31
NUTEV ($\bar{\nu}$)	39	0.90	0.62
DYE605	85	1.18	0.85
ATLAS	360	1.08	1.04
LHCb	85	1.46	1.32
	4285	1.18	1.07

The impact of an EIC

Scenario	A	E_e	E_A/A	Q^2_{\max}	x_{\min}	N_{dat}
eRHIC_5x50C	12	5 GeV	50 GeV	440 GeV ²	0.003	50
eRHIC_5x75C	12	5 GeV	75 GeV	440 GeV ²	0.002	57
eRHIC_5x100C	12	5 GeV	100 GeV	780 GeV ²	0.001	64
eRHIC_5x50Au	197	5 GeV	50 GeV	440 GeV ²	0.003	50
eRHIC_5x75Au	197	5 GeV	75 GeV	440 GeV ²	0.002	57
eRHIC_5x100Au	197	5 GeV	100 GeV	780 GeV ²	0.001	64
eRHIC_20x50C	12	20 GeV	50 GeV	780 GeV ²	0.0008	75
eRHIC_20x75C	12	20 GeV	75 GeV	780 GeV ²	0.0005	79
eRHIC_20x100C	12	20 GeV	100 GeV	780 GeV ²	0.0003	82
eRHIC_20x50Au	197	20 GeV	50 GeV	780 GeV ²	0.0008	75
eRHIC_20x75Au	197	20 GeV	75 GeV	780 GeV ²	0.0005	79
eRHIC_20x100Au	197	20 GeV	100 GeV	780 GeV ²	0.0003	82



Two scenarios considered

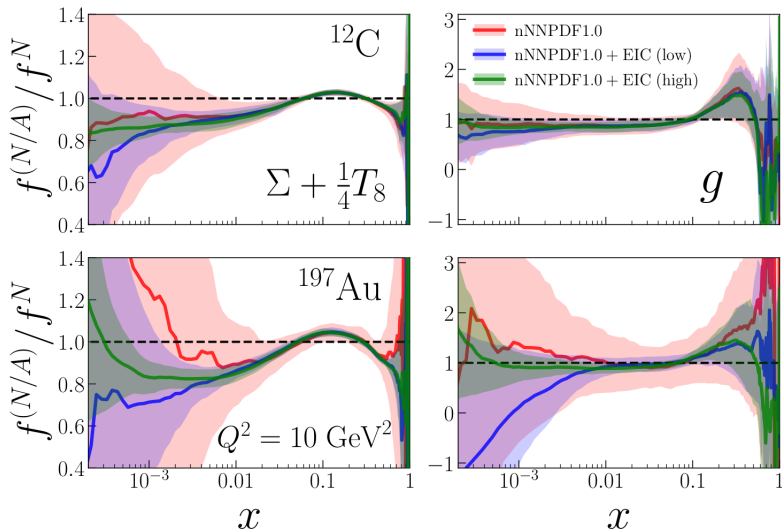
Low energy (5 GeV)

High energy (20 GeV)

Pseudo-data constructed with nNNPDF1.0 (¹²C, ¹⁹⁷Au)

Exercise similar to the one carried out in the EPPS16 framework [PRD 96 (2017) 114005]

The impact of an EIC



Signification reduction of nPDF uncertainties at low x for large A

Particularly for the higher energy scenario

Summary

The first determination of nPDF using the NNPDF methodology has been achieved

Excellent agreement (NLO and NNLO) with all available NC DIS data ($A=2$ to $A=208$)

Quark distributions are reasonably constrained for $x \gtrsim 10^{-2}$

Significant methodological improvements (TensorFlow and stochastic gradient descent)

Relevance of the boundary condition ($A = 1$ limit) to reproduce the NNPDF3.1 input

LHAPDF sets available on the NNPDF website

<http://nnpdf.mi.infn.it/for-users/nuclear-pdf-sets/>

A quantification of the future impact of an EIC $e + A$ measurements has been performed

Potential, significant constraints on the quark and gluon nPDFs down to $x \sim 5 \cdot 10^{-4}$

Future steps: including CC DIS data, LHC data in a global fit

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Thank you