nNNPDF3.0: Evidence for a modified partonic structure in heavy nuclei

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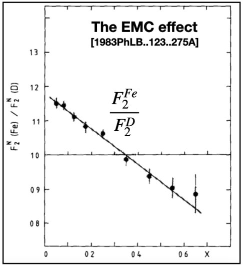
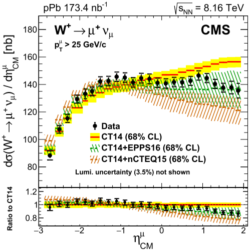
Why nuclear PDFs?

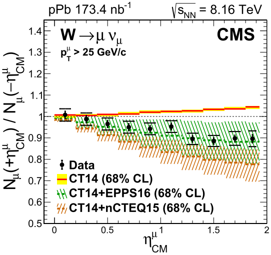
Nucleus is not an ensemble of Z free protons and A-Z free neutrons.

$$F_2\left(x, Q^2, A\right) = \sum_i C_i\left(x, Q^2\right) \otimes f_j^{(N/A)}\left(x, Q^2\right) + \ldots$$

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







- LHC experiments colliding nuclei
- signal and background events in neutrino-nucleus scattering (IceCube)
- investigating gluon saturation
- determine flavour, atomic mass A and x dependence nuclear modifications
- pion PDF (extracted from pion-A collisions)

nNNPDF3.0

1. new data
2. methodology and general strategy
3. results

New data in nNNPDF3.0

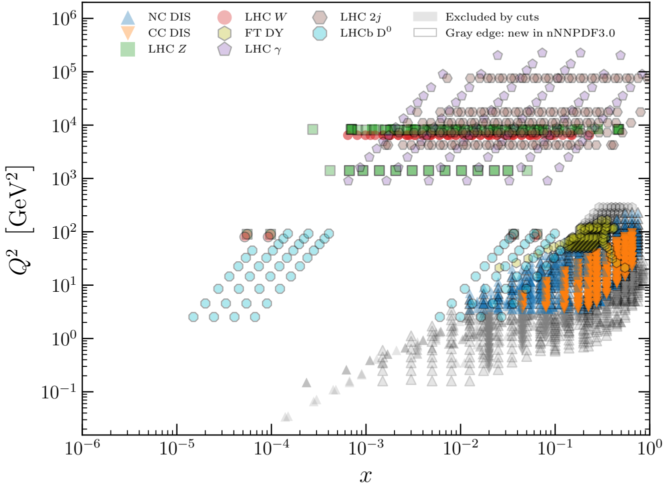
Data in nNNPDF2.0:

- NC and CC DIS structure functions for a range of nuclei
- inclusive gauge boson production in p-Pb collisions at LHC

Two group of new measurements in nNNPDF3.0:

1. DIS and fixed-target DY involving D and Cu targets
2. LHC data from p-Pb collision

Process	Dataset	$n_{\rm dat}$	Nucl. spec.	Theory
NC DIS	NMC 96	123/260	^{2}D/p	APFEL
	SLAC 91	38/211	^{2}D	APFEL
	BCDMS 89	250/254	^{2}D	APFEL
Fixed-target DY	FNAL E866	15/15	^{2}D/p	APFEL
	FNAL E605	85/119	^{64}Cu	APFEL
Collider DY	ALICE $W^\pm$, Z (5.02 TeV)	6/6	^{208}Pb	MCFM
	LHCb Z (5.02 TeV)	2/2	^{208}Pb	MCFM
	ALICE Z (8.16 TeV)	2/2	^{208}Pb	MCFM
	CMS Z (8.16 TeV)	36/36	^{208}Pb	MCFM
Dijet production	CMS p–Pb/pp (5.02 TeV)	84/84	^{208}Pb	NLOjet++
Prompt photon production	ATLAS p–Pb/pp (8.16 TeV)	43/43	^{208}Pb	MCFM
Prompt D^0 production	LHCb p–Pb/pp (5.02 TeV)	37/37	^{208}Pb	POWHEG



- extended coverage at small-x (D meson data) and high Q (photon and dijets data)
- kinematic cuts: $Q^2 \geq 3.5\,\mathrm{GeV}^2$, $W^2 \geq 12.5\,\mathrm{GeV}^2$
- nNNPDF2.0: 1476 datapoints, nNNPDF3.0: 2188 datapoints

Treatment of D meson production data

We consider in a coherent manner the constraints of the LHCb D-meson data both on the proton and nuclear PDFs while keeping track of their correlation

- LHCb measurements of D^0 meson production in pPb collisions at $\sqrt{s} = 5.02$ TeV

$$R_{\mathrm{pPb}}(y^{D^0}, p_{\mathrm{T}}^{D^0}) = \left. \frac{d\sigma^{\mathrm{pPb}}(y^{D^0}, p_{\mathrm{T}}^{D^0})}{dy^{D^0} dp_{\mathrm{T}}^{D^0}} \right/ \frac{d\sigma^{\mathrm{pp}}(y^{D^0}, p_{\mathrm{T}}^{D^0})}{dy^{D^0} dp_{T}^{D^0}}$$

- D^0, D^+, D_s^+ meson production in pp collisions at 7 and 13 TeV into the proton PDF baseline

$$N_X^{pp}(y^D, p_{\mathrm{T}}^D) \equiv \left. \frac{d\sigma^{\mathrm{pp}}\,(X\ \mathrm{TeV})}{dy^D dp_{\mathrm{T}}^D} \right/ \frac{d\sigma^{\mathrm{pp}}\,(X\ \mathrm{TeV})}{dy_{\mathrm{ref}}^D dp_T^D}$$

No public interface for the computation of fast interpolation tables
$\rightarrow$ **multi-stage Bayesian reweighting procedure to include these data**

Methodology

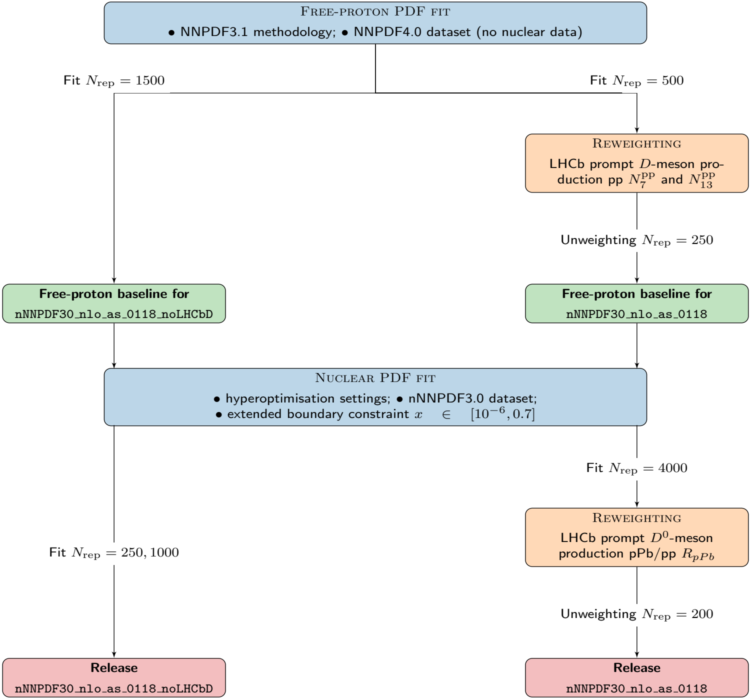
Six independent nPDF of a proton bound in a nucleus with atomic mass number A

$$
\begin{aligned}
x\Sigma^{(p/A)}(x, Q_0) &= x^{\alpha_\Sigma}(1-x)^{\beta_\Sigma}\,\mathrm{NN}_\Sigma(x, A)\,, \\
xT_3^{(p/A)}(x, Q_0) &= x^{\alpha_{T_3}}(1-x)^{\beta_{T_3}}\,\mathrm{NN}_{T_3}(x, A)\,, \\
xT_8^{(p/A)}(x, Q_0) &= x^{\alpha_{T_8}}(1-x)^{\beta_{T_8}}\,\mathrm{NN}_{T_8}(x, A) \\
xV^{(p/A)}(x, Q_0) &= B_V(A)x^{\alpha_V}(1-x)^{\beta_V}\,\mathrm{NN}_V(x, A)\,, \\
xV_3^{(p/A)}(x, Q_0) &= B_{V_3}(A)x^{\alpha_{V_3}}(1-x)^{\beta_{V_3}}\,\mathrm{NN}_{V_3}(x, A)\,, \\
xg^{(p/A)}(x, Q_0) &= B_g(A)x^{\alpha_g}(1-x)^{\beta_g}\,\mathrm{NN}_g(x, A)\,,
\end{aligned}
$$

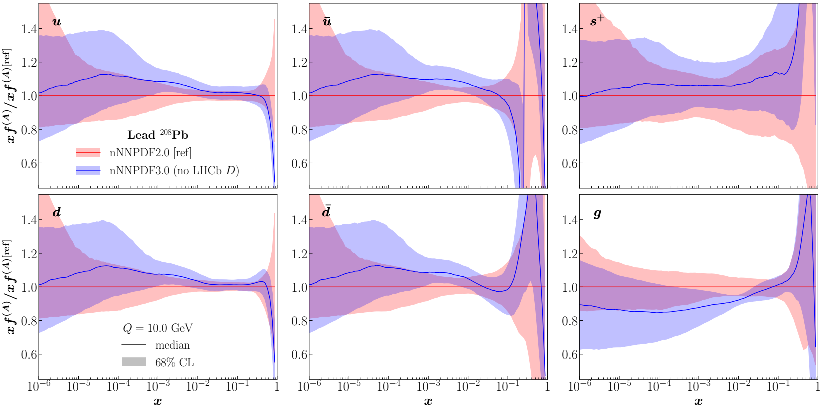
- parameterization valid from $A = 1$ (free proton) to $A = 208$ (lead)
- Hyperparameters (NN architecture, optimizer, learning rate ...) determined through automated hyperoptimization (backup slides)
- distributions for bound neutrons obtained assuming isospin symmetry

average bound nucleon N within nucleus A defined as

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

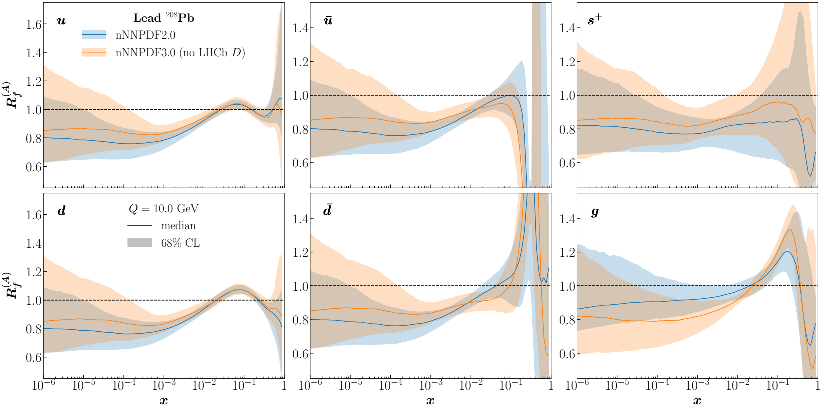

Free-proton PDF fit
• NNPDF3.1 methodology; • NNPDF4.0 dataset (no nuclear data)
Fit $N_{\rm rep} = 1500$
Fit $N_{\rm rep} = 500$
Reweighting
LHCb prompt D-meson production pp $N_7^{\rm pp}$ and $N_{13}^{\rm pp}$
Unweighting $N_{\rm rep} = 250$
Free-proton baseline for
nNNPDF30_nlo_as_0118_noLHCbD
Free-proton baseline for
nNNPDF30_nlo_as_0118
Nuclear PDF fit
• hyperoptimisation settings; • nNNPDF3.0 dataset;
• extended boundary constraint $x \in [10^{-6}, 0.7]$
Fit $N_{\rm rep} = 4000$
Reweighting
LHCb prompt D^0-meson production pPb/pp R_{pPb}
Fit $N_{\rm rep} = 250, 1000$
Unweighting $N_{\rm rep} = 200$
Release
nNNPDF30_nlo_as_0118_noLHCbD
Release
nNNPDF30_nlo_as_0118

nNNPDF3.0, no D-meson data



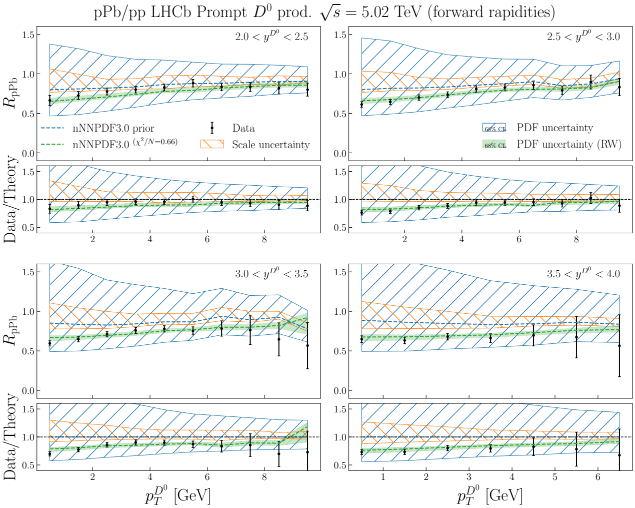
- differences due to i) new data involving D, Cu and Pb targets ii) different boundary condition iii) automated optimization of model parameters
- bigger small-x uncertainties (due to new boundary condition)
- impact of W and Z LHC data visible in $\bar{u}$ and $\bar{d}$, impact of D and Cu data in s^+

$$R_f^{(A)}(x,Q) \equiv \frac{f^{(N/A)}(x,Q)}{\frac{Z}{A} f^{(p)}(x,Q) + \frac{(A-Z)}{A} f^{(n)}(x,Q)}$$

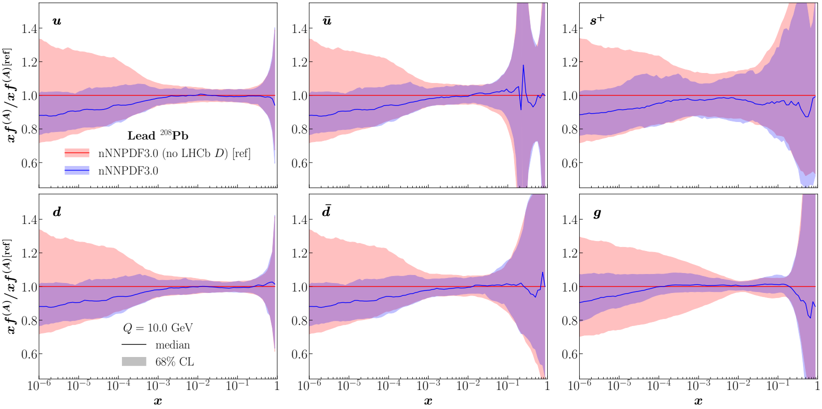


- reduced (increased) small-x shadowing in the quark (gluon) nPDFs
- increased gluon anti-shadowing peaking at $x \sim 0.2$ (dijets cross-sections in pPb)

Impact of D-meson data

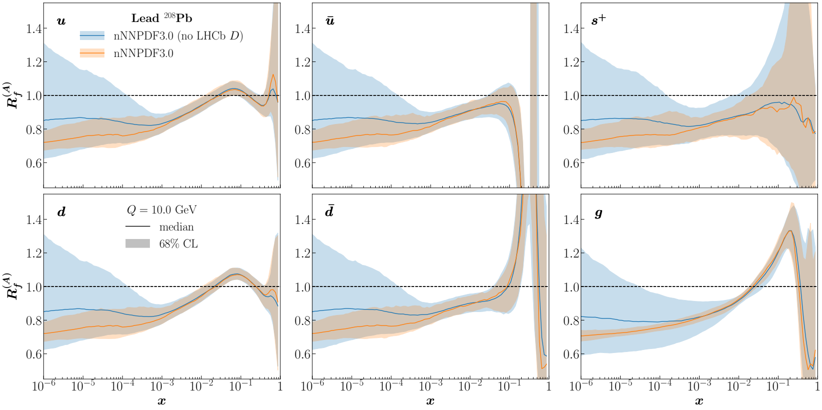


- experimental data well described within the big nPDF uncertainty
- nPDF error dominates over missing high orders uncertainty

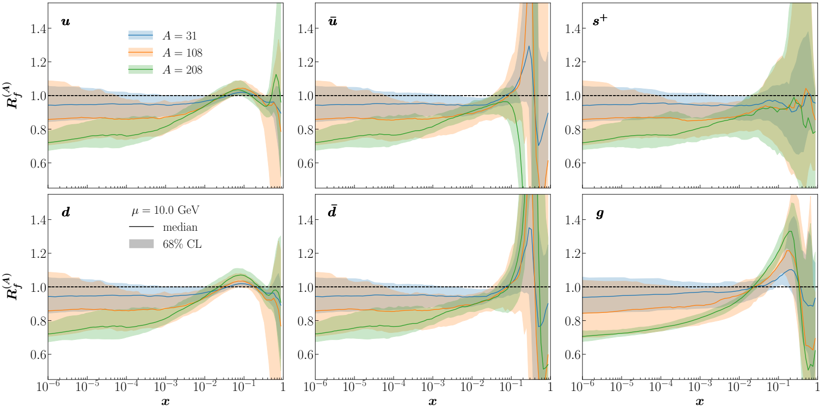


u
$\bar{u}$
s^+
d
$\bar{d}$
g
Lead ^{208}Pb
nNNPDF3.0 (no LHCb D) [ref]
nNNPDF3.0
$Q = 10.0$ GeV
median
68% CL
$xf^{(A)}/xf^{(A)[\mathrm{ref}]}$
x

D-meson data both on the proton and nuclear PDFs while keeping track of their correlation → the impact on the ratio $R_f^{(A)}$ is expected to be more marked as compared to that restricted to the lead PDFs.

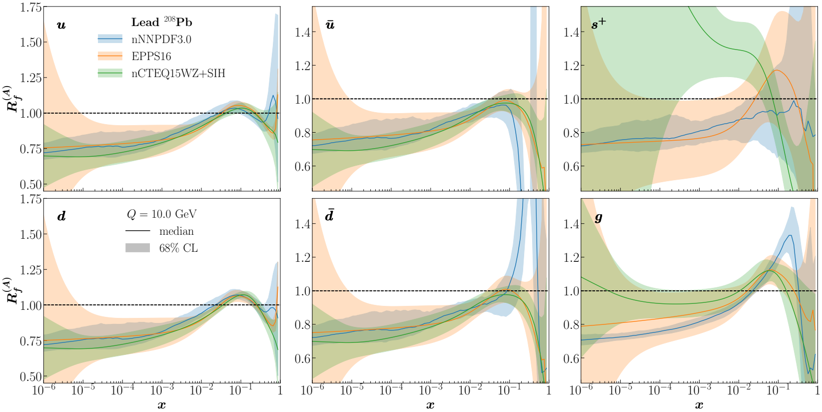


A-dependence of nuclear modifications



- nuclear modification well constrained for lead (LHC data)
- few point available for silver, no points for $A = 31$ (average atomic mass number of Earth matter)
- largest uncertainties for $A = 108$, being far from both $A = 1$ (proton boundary condition) and $A = 208$ (pPb data from LHC)

Comparison with other results



Good agreement between different groups, with few exceptions:

- strength of gluon small-x shadowing and large-x anti-shadowing
- strangeness nuclear modification
- large-x behaviour of nuclear antiquarks

Summary

- we have presented a new set of nPDF based on an extensive dataset
- new hyperoptimized methodology and updated boundary condition
- coverage on small-x and high Q^2 regions from D-meson and dijets data
- D-meson data included consistently in both proton baseline and nuclear fit
- we deliver two variants with and without D-meson data

TO DOs:

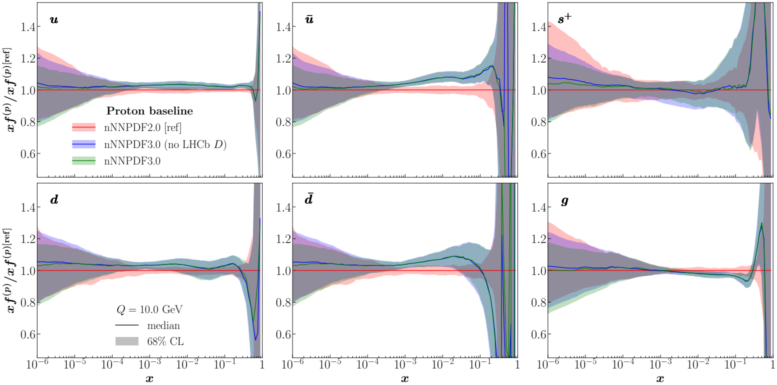
- move to NNLO QCD
- simultaneous fit of proton and nuclear PDFs

Fit quality

			nNNPDF3.0 (no LHCb D)	nNNPDF3.0
Dataset	A	$n_{\rm dat}$	$\chi^2/n_{\rm dat}$	$\chi^2/n_{\rm dat}$
FNAL Drell-Yan E605 **(*)**	^{64}Cu	85	0.82	0.85
FNAL Drell-Yan E886 **(*)**	^{2}d/^{1}p	15	1.04	1.16
ATLAS Z $\sqrt{s} = 5.02$ TeV	^{208}Pb	14	0.91	0.93
CMS Z $\sqrt{s} = 5.02$ TeV	^{208}Pb	12	0.6	0.6
CMS W$^-$ $\sqrt{s} = 5.02$ TeV	^{208}Pb	10	1.02	1.07
CMS W$^+$ $\sqrt{s} = 5.02$ TeV	^{208}Pb	10	1.11	1.08
CMS W$^-$ $\sqrt{s} = 8.16$ TeV	^{208}Pb	24	0.72	0.73
CMS W$^+$ $\sqrt{s} = 8.16$ TeV	^{208}Pb	24	0.77	0.8
ALICE Z $\sqrt{s} = 5.02$ TeV **(*)**	^{208}Pb	2	0.14	0.14
ALICE W$^-$ $\sqrt{s} = 5.02$ TeV **(*)**	^{208}Pb	2	0.18	0.18
ALICE W$^+$ $\sqrt{s} = 5.02$ TeV **(*)**	^{208}Pb	2	2.55	2.54
LHCb Z $\sqrt{s} = 5.02$ TeV **(*)**	^{208}Pb	2	0.9	0.9
CMS Z $\sqrt{s} = 8.16$ TeV **(*)**	^{208}Pb	36	2.49	2.49
ALICE Z $\sqrt{s} = 8.16$ TeV **(*)**	^{208}Pb	2	0.02	0.03
Total Drell-Yan		240	1.08	1.11
CMS dijet pPb $\sqrt{s} = 5.02$ TeV	^{208}Pb	85	[13.6]	[13.96]
CMS dijet pPb/pp $\sqrt{s} = 5.02$ TeV**(*)**	^{208}Pb	84	1.81	1.75
ATLAS photon pPb $\sqrt{s} = 8.16$ TeV	^{208}Pb	46	[3.33]	[3.21]
ATLAS photon pPb/pp $\sqrt{s} = 8.16$ TeV**(*)**	^{208}Pb	43	1.03	1.03
Total dataset		**2151**	**1.11**	**1.09**

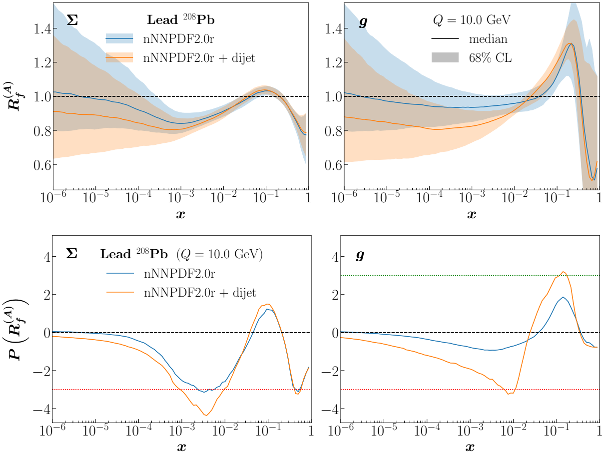
Free proton boundary condition

PDFs at $A = 1$ are fixed such that central values and uncertainties reproduce those of a given free-proton baseline PDF.



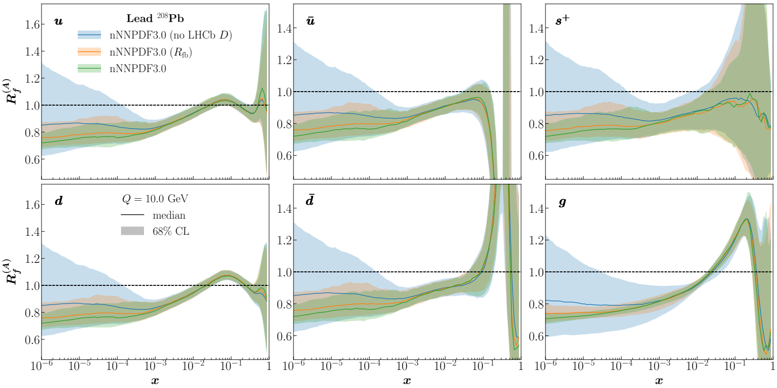
- all datasets included in NNPDF4.0 NLO except those involving nuclear targets
- extended up to $x = 10^{-6}$
- two variant with and without LHCb D-meson production data in pp collisions at 7 and 13 TeV are produced

Impact of CMS dijets production at $\sqrt{s} = 5.02$ TeV

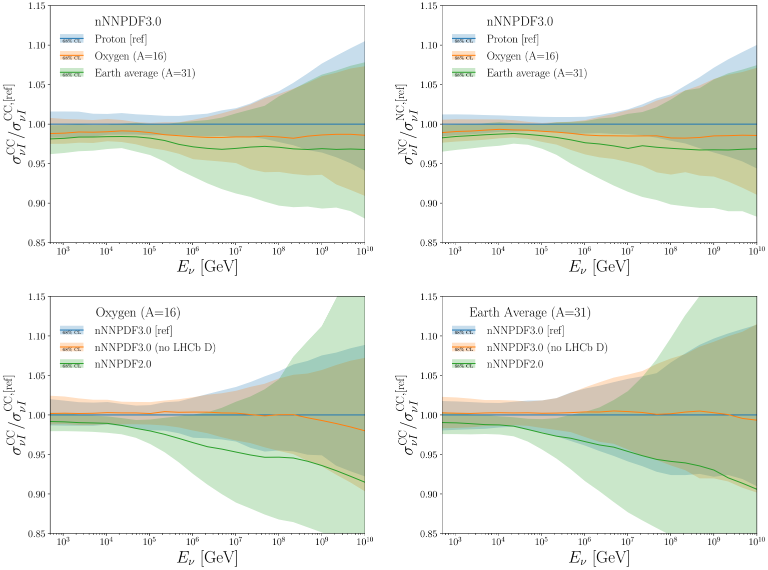


- for the quark singlet nPDF stronger small-x shadowing is favored
- for the gluon nPDF stronger enhancement of small-x shadowing and of large-x anti-shadowing

Alternative observable for D^0 data



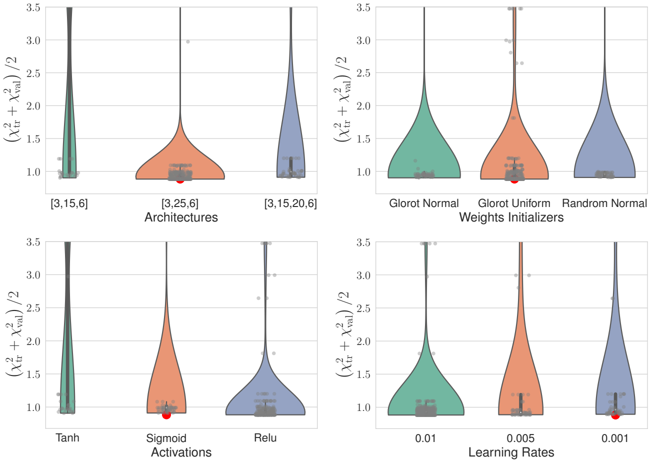
Ultra-High-energy neutrino-nucleus interactions



Hyperparameter optimization

Find the best combination of hyperparameters through an iterative search of the Hyperparameter space following some specific optimization algorithm.

$$L_{\text{hyperopt}} = \frac{1}{2}\left(\chi^2_{\text{tr}} + \chi^2_{\text{val}}\right)$$



	nNNPDF3.0	nNNPDF2.0
Architecture	$[3, 25, 6]$	$[3, 25, 6]$
Weight initialisation	`Glorot Normal`	`Glorot Uniform`
Bias initialisation	`Zeros`	`Zeros`
Activation function	ReLU	Sigmoid
Learning rate	10^{-2}	10^{-3}
Optimiser	Adam	Adam

A-dependence of nuclear modifications: pulls

$$P\left[R_f^{(A)}\right](x,Q) \equiv \frac{\left(R_f^{(A)}(x,Q)-1\right)}{\delta R_f^{(A)}(x,Q)}$$

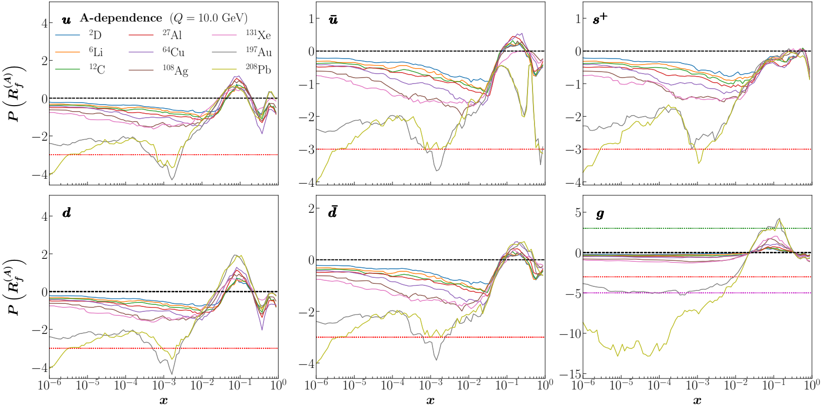


Figure of merit

$$\chi^2_{\rm fit} = \chi^2_{\rm t_0} + \kappa^2_{\rm pos} + \kappa^2_{\rm BC}$$

with

$$\chi^2_{t_0} = \sum_{ij}^{n_{\rm dat}} (T_i - D_i)\ (\mathsf{cov}_{t_0})^{-1}_{ij}\ (T_j - D_j)\,,$$

$$\kappa^2_{\rm pos} = \lambda_{\rm pos} \sum_{l=1}^{n_{\rm pos}} \sum_{j=1}^{n_A} \sum_{i_l=1}^{n^{(l)}_{\rm dat}} \max\left(0, -\mathcal{F}^{(l)}_{i_l}(A_j)\right)$$

$$\kappa^2_{\rm BC} = \lambda_{\rm BC} \sum_f \sum_{j=1}^{n_x} \left(f^{(p/A)}(x_j, Q_0, A=1) - f^{(p)}(x_j, Q_0)\right)^2$$