Future of nuclear and polarised PDFs: the NNPDF perspective

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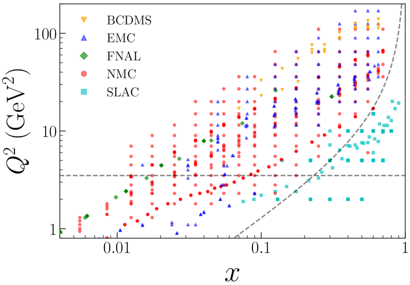
The nNNPDF family

nNNPDF1.0 [EPJ C79 (2019) 6]
Neutral Current DIS $\ell + A/\ell + A'$
SLAC, BCDMS, NMC, EMC, FNAL

2 PDF combinations: Σ, g
no positivity imposed
free proton boundary condition from NNPDF3.1
NLO and NNLO

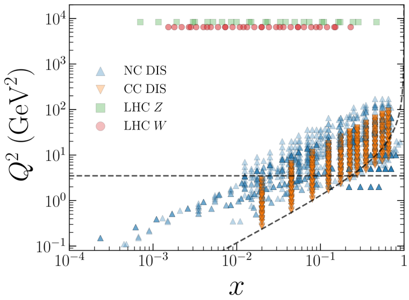
single feed-forward NN, A dependence as input



nNNPDF2.0 [JHEP 09 (2020) 183]
Charged Current DIS $\nu + A$
Chorus, NuTeV
LHC W, Z production $p + Pb$
CMS 5 & 8 TeV, ATLAS 5 TeV

6 PDF combinations: Σ, g, V, V_3, T_3, T_8
positivity imposed
free proton boundary condition from NNPDF3.1
NLO only

single feed-forward NN, A dependence as input



Beyond nNNPDF2.0

Data

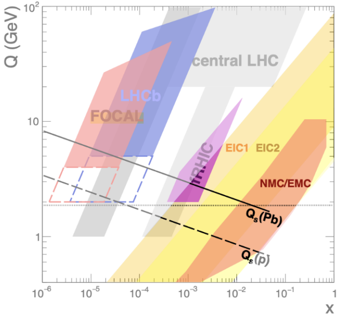
- Dijet production at the LHC
  Neutral pion production at RHIC
- Photon production at ALICE-FoCal
- DIS at the Electron Ion Collider
- Heavy-flavoured meson production at the LHC: D^0, J/Ψ
- Ultraperipheral collisions at the LHC

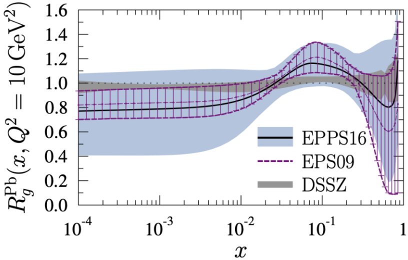
Theory

- Inclusion of NNLO corrections for gauge boson and dijet production at the LHC
- Reliability of nPDF factorisation in the nuclear environment

Methodology

- Allow for global, simultaneous fits
  efficient and scalable methodology





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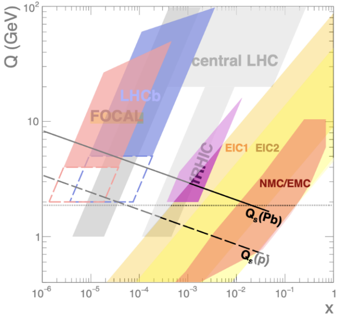

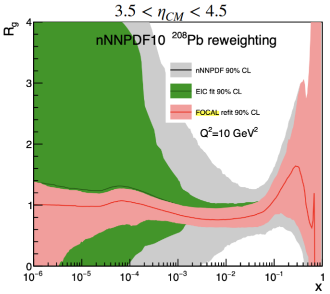

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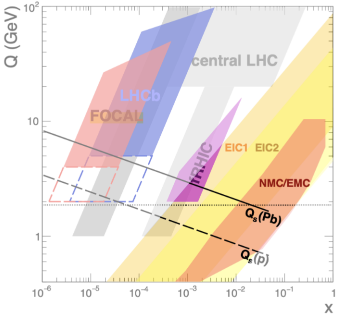
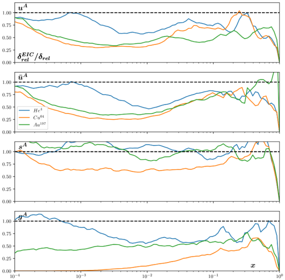




Nuclear uncertainties in proton PDF fits [EPJ C79 (2019) 282]

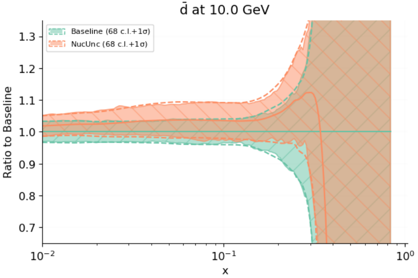
$$\text{cov} \longrightarrow \text{cov}_{\text{exp}} + \text{cov}_{\text{th}}$$

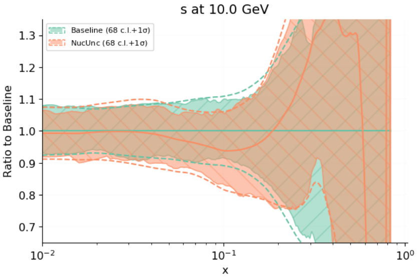
$$(\text{cov}_{\text{th}})_{ij} = \frac{1}{N}\sum_{k}^{N} \Delta_i^{(k)}\Delta_j^{(k)}$$

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

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
FT DIS	973	1.23	1.20
HERA DIS	1211	1.16	1.16
ATLAS	360	1.08	1.04
CMS	409	1.07	1.07
LHCb	85	1.46	1.32
	4285	1.18	1.07





Nuclear uncertainties in proton PDF fits [arXiv:2011.00009]

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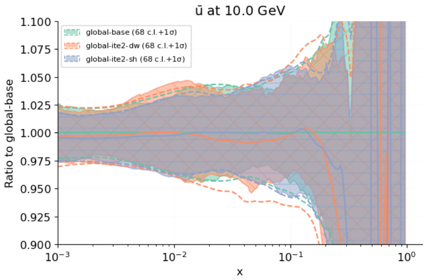
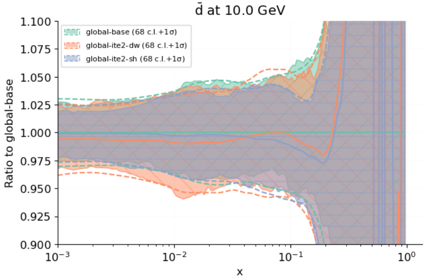
nuclear uncertainties determined from the data subset that involves deuterium targets by means of a self-consistent iterative procedure

Experiment	N_{dat}	χ^2/N_{dat} (bas.)	χ^2/N_{dat} (nucl.)
SLAC (F_2^d)	34	0.72	0.50
BCDMS (F_2^d)	248	1.10	0.91
NMC (F_2^d/F_2^p)	121	1.00	0.78
E866 (pd/pp)	15	0.47	0.71
FT DIS	1478	1.21	1.20
HERA DIS	1211	1.16	1.16
ATLAS	211	1.13	1.12
CMS	327	1.15	1.14
LHCb	85	1.62	1.67
	3978	1.18	1.16





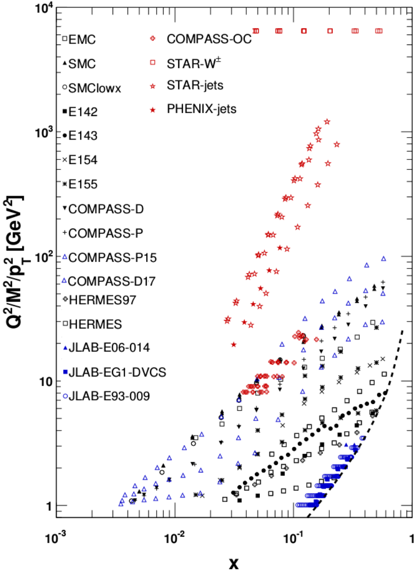
The NNPDFpol family

NNPDFpol1.0 [NPB 874 (2013) 36]
Neutral Current DIS
4 PDF combinations: Σ, T_3, T_8, g
LO positivity imposed via unpolarised PDFs
NLO

NNPDFpol1.1 [NPB 887 (2014) 276]
Gauge boson and jet production at RHIC
Open charm production at COMPASS
6 PDFs: u, $\bar{u}$, d, $\bar{d}$, s, g
NLO

NNPDFpolEIC [PLB 728 (2014) 524]
Projected pseudodata at an EIC

NNPDFpol1.2 [arXiv:1510.04248; arXiv:1702.05077]
JLab DIS; RHIC dijets and π^0



Beyond NNPDFpol1.2

Data

- SIDIS and Fragmentation Functions
  [EPJ C77 (2017) 8; EPJ C78 (2018) 8; in preparation]
- DIS at the Electron Ion Collider
  [PLB 728 (2014) 524; EIC YR]

Theory

- Interplay with Fragmentation Functions
- Inclusion of higher orders
  [NPB 417 (1994) 61; NPB 682 (2004) 421;
  PRD 95 (2017) 034027; PRL 125 (2020) 8]
- Onset of small-x behaviour
  [Kovchegov et al.]
- Input from lattice
  [PPNP 100 (2018) 107; arXiv:2006.08636;
  JHEP 10 (2019) 137]

Methodology

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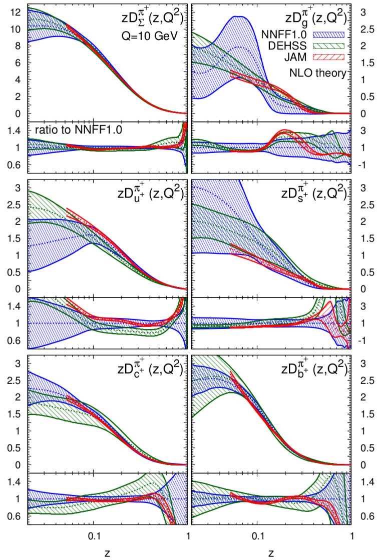
  efficient and scalable methodology



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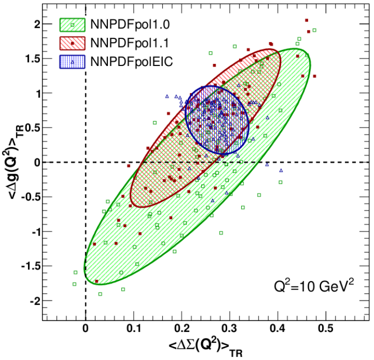
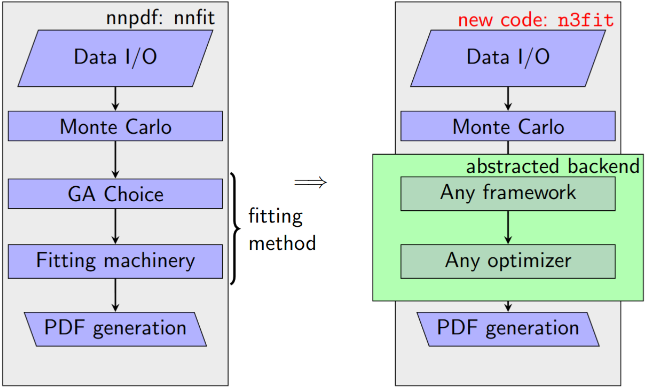


$Q^2 = 10$ GeV^2	$\int_{10^{-3}}^{1} dx\,\Delta\Sigma$	$\int_{10^{-3}}^{1} dx\,\Delta g$
NNPDFpol1.0	$+0.23 \pm 0.15$	-0.06 ± 1.12
NNPDFpol1.2	$+0.25 \pm 0.10$	$+0.49 \pm 0.75$
NNPDFpolEIC	$+0.24 \pm 0.04$	$+0.49 \pm 0.25$

quarks and antiquarks $\sim 20\% - 30\%$
gluons $\sim 70\%$
OAM $\sim 0\%$

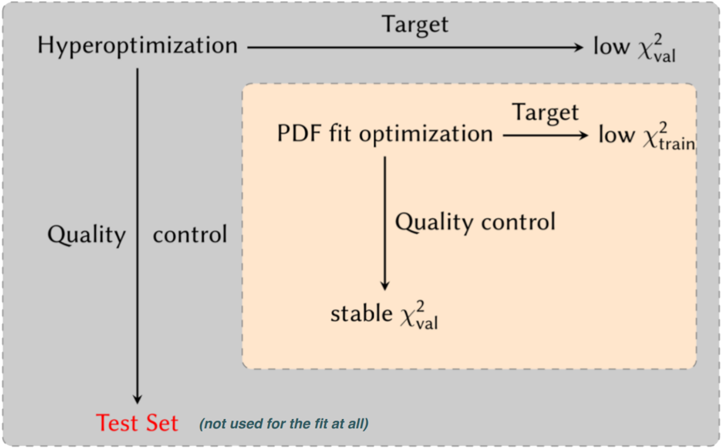
Methodology: from nnfit to n3fit



[EPJ C79 (2019) 8]

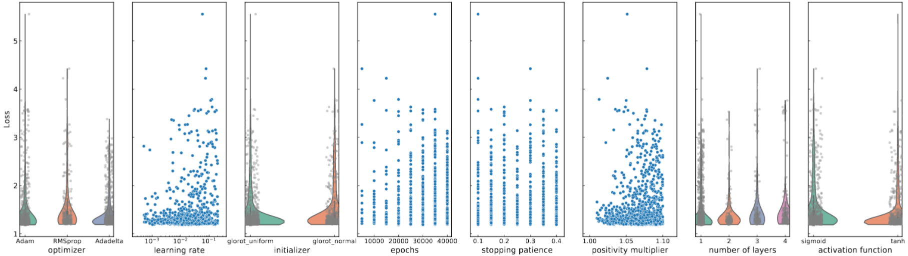
Complete restructuring of the NNPDF fitting framework
enhanced modularity to improve flexibility and exploitation of external ML libraries
Keras, TensorFlow, ...
Per replica training time reduced by a factor of $\mathcal{O}(30)$ thanks to SGD minimisers

Methodology: fitting the methodology



Compare to a Test Set (new set of data previously not used at all)
Who picks the Test Set? Automatic generalisation based on K foldings
Divide the data into n representative sets, fit $n-1$ sets and use n-th set as test set
Hyperoptimise on mean and standard deviation of $\chi^2_{\text{test},i}$, $i = 1 \ldots n$

Methodology: hyperoptimisation



SCAN parameter space; **OPTIMISE** $\chi^2_{\rm val}$; **BAYESIAN UPDATING**

Hyperoptimisation requires to define a reward (or loss) function to grade each model

This is different from the cost function (optimised separately for each model)

cost function: $C = E_{\rm tr}$ reward function: $R = \frac{1}{2}(E_{\rm val} + E_{\rm test})$

In a hyperparameter scan one compares the performance of hundreds parameter combinations

Some parameters are discrete (type of minimiser), other are continuous (learning rate)

One should visualise which parameters are relevant and which parameters are immaterial

The *violin* plots are the KDE-reconstructed probability distributions for the hyperparameters

Hyperoptimisation successfully validated in closure tests and in future tests

Summary

1. Continuous effort in improving the determination of nuclear/helicity PDFs
   - Data: *global fits*

     $\longrightarrow$ inclusion of a variety of obervables, consistency of the QCD framework

     $\longrightarrow$ increasing experimental precision, extended kinematic range
   - Theory: *improved fits*

     $\longrightarrow$ refinement of the QCD details in the PDF analyses
   - Methodology: *simultaneous fits*

     $\longrightarrow$ non-trivial interplay between PDFs and FFs

     $\longrightarrow$ accompanied by an increased sophistication of the fitting techniques
2. Possible fruitful interplay between (helicity) QCD fits and lattice QCD calculations
   - An extensive benchmark for helicity PDFs is now available

     $\longrightarrow$ competitive lattice QCD moments

     $\longrightarrow$ promising methods to determine the PDF x dependence
3. Combination of all the above will perfectly fit into the EIC program

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Thank you