I present recent progress in the NNPDF global analyses of parton distributions (PDFs) focusing on developments contributing to its new upcoming release: NNPDF4.0. The NNPDF4.0 determination represents unprecedented progress in three main directions: i) the systematic inclusion of LHC Run II data at $\sqrt{s} = 13$ TeV and of new processes from dijets to single top distributions, ii) the deployment of state-of-the-art machine learning algorithms, from automated hyperparameter optimisation to stochastic gradient descent training; and iii) the complete statistical validation of PDF uncertainties, both in the data and extrapolation regions, by means of closure and future tests. Other methodological improvements in NNPDF4.0 include strict PDF positivity, integrability constraints at small-$x$, and deuteron and heavy nuclear corrections. I present representative results from NNPDF4.0 and assess its impact on open issues such as the light anti-quark asymmetry and the charm content of protons.

The road towards NNPDF4.0. Since the release of the NNPDF3.1 global analysis\cite{ref1} in 2017, a significant amount of work has been invested in laying the groundwork for the subsequent major update, dubbed NNPDF4.0 and now close to completion. Progress towards NNPDF4.0 has taken place along several complementary directions, such as addition of new datasets, many of them from Run II of the LHC, and altogether new types of processes, the implementation of powerful machine learning fitting tools, novel strategies for the statistical validation of PDF uncertainties, and the refined implementation of theoretical constraints that restrict the possible shapes that the PDFs are allowed to take.

New groups of processes added for the first time in NNPDF4.0 include dijet cross-sections, single top quark distributions, direct photon production, and $W$ boson production in association with jets, among several others. As an illustration of the impact of these new processes, the left panel Fig. 1 demonstrates\cite{ref2} that the constraints on the gluon PDF from Run I inclusive jet and dijet cross-sections is qualitatively consistent when added on top of a baseline NNPDF3.1-like fit that does not include any jet data. Furthermore, all available 7 and 8 TeV dijet cross-sections are successfully described by NNLO QCD theory once included in the fit, without the need to introduce tailored decorrelation models as is sometimes the case with inclusive jets.

Another data-related study on the road towards NNPDF4.0 was the reappraisal of the proton
strangeness content based on the combination of all relevant experimental inputs\(^3\), among them the NOMAD dimon neutrino-induced cross-sections which provide significant constraints. Interestingly, a satisfactory joint description of all datasets is found, with no evidence for tensions between groups of processes. As indicated by Fig. 1, which displays the ratio \(R_s(x, Q) = (s + \bar{s})/(\bar{u} + d)\) at \(x = 0.023\) and \(Q = 1.6\) GeV, a global analysis of all strangeness-sensitive measurements favors a moderately suppressed strangeness PDF, and disfavors scenarios with either a heavily suppressed \((R_s \lesssim 0.5)\) of a symmetric \((R_s \approx 1)\) strange sea.

Concerning the improved treatment of theoretical constraints, NNPDF4.0 accounts for the strict positivity of \(\overline{\text{MS}}\) PDFs\(^4\), the integrability of the non-singlet quark combinations \(T_3\) and \(T_8\) at small-\(x\), and the uncertainties associated to deuteron and heavy nuclear effects for data involving nuclear targets. The latter, relevant in particular for the description of the NuTeV and CHORUS neutrino structure functions, is implemented using the method from\(^5\) with the 

nNNPDF2.0 global nPDF fit\(^6\) as input. This choice is particularly suitable here, given that the fitting methodology\(^7\) of nNNPDF2.0 is consistent with that used in the NNPDF4.0 analysis.

From the point of view of machine learning tools, NNPDF4.0 benefits from a suite of state-of-the-art stochastic gradient descent methods for neural network training, combined with the automated optimisation of model hyperparameters such as the network architecture\(^8\). These improvements have resulted into a dramatic speed-up of the per-replica running time of up to a factor 10, as well as a reduction of the PDF uncertainties by removing minimisation inefficiencies present in genetic algorithms. The statistical interpretation of PDF uncertainties is then carefully validated by means of closure tests\(^9,10\), where PDFs are fitted to pseudo-data generated with a known underlying law, and future tests\(^11\), which verify the forecasting performance of the new methodology to predict novel datasets with different kinematic coverage.

**A first look at NNPDF4.0.** A highly non-trivial self-consistency test of the new fitting methodology is that one is able to carry out PDF fits either in the evolution basis (where the NNs parametrise \(\Sigma, T_3, T_8, V\), and so on) or in the flavour basis (where instead they parametrise \(u, \bar{u}, d, \bar{d}\), and so on) finding fully consistent results. This feature is highlighted in Fig. 2, which compares the output of the nonsinglet quark triplet, \(T_3 = u + \bar{u} - d - \bar{d}\), at the initial scale \(Q = 1.65\) GeV obtained in the two parametrisation bases: excellent agreement is obtained, illustrating the robust basis independence of the NNPDF4.0 global analysis.

The right panel of Fig. 2 quantifies the impact of the new data added in NNPDF4.0 on the gluon-gluon partonic luminosity at \(\sqrt{s} = 14\) TeV as a function of invariant mass \(m_X\). In general, one finds agreement at the one-sigma level, with the new data (driven by dijet cross-sections) modifying the overall shape of \(\mathcal{L}_{gg}\) with a slight suppression for \(m_X \approx 100\) GeV, an enhancement
starting at 1 TeV, and then again a suppression from masses of 4 TeV onwards. The new data also leads to a reduction of the PDF errors in $L_{gg}$ in the region with $m_X \gtrsim 500$ GeV.

The novel NNPDF4.0 analysis also makes possible a high-precision assessment of many important open questions related to the non-perturbative QCD nature of proton structure. To illustrate this potential, Fig. 3 displays the NNPDF3.1 and NNPDF4.0 predictions for the light anti-quark PDF ratio, $\bar{d}(x, Q)/\bar{u}(x, Q)$ at $Q = 10$ GeV. This partonic ratio has also been recently evaluated by the SeaQuest experiment\textsuperscript{12}, following a model-dependent deconvolution from their cross-section measurements. We observe that both the NNPDF3.1 and NNPDF4.0 predictions are in good agreement with the SeaQuest determinations of the light quark sea asymmetry.

Then the right panel of Fig. 3 displays the charm PDF at $Q = 1.65$ GeV in the NNPDF4.0 fits. We provide results obtained both with perturbative charm and with fitted charm\textsuperscript{13}, in the latter case with and without the EMC charm structure functions included in the fit. This comparison highlights how current data favours a valence-like structure for the charm PDF at low-scales, which in turn is consistent with the hypothesis of an intrinsic charm component in the proton wave function. We note that the addition or not of the EMC data does not modify in a significant manner the resulting charm PDF, highlighting how the dominant constraints on $c(x, Q_0)$ arise from other datasets such as forward $W, Z$ production by LHCb.

**The road ahead.** The global NNPDF4.0 determination achieves an unprecedented accuracy in a broad kinematic range, thanks to its extensive dataset combined with deep-learning optimisation models. Its faithfulness in representing PDF uncertainties is validated in detail by closure tests, future tests, and parametrisation basis independence studies. Given the current level of PDF uncertainties obtained with NNPDF4.0, it becomes of paramount importance to continue the efforts towards the inclusion in the fit of various types of theoretical uncertainties, such as those arising from missing higher orders\textsuperscript{14} and from the SM parameters such as $\alpha_s(m_Z)$\textsuperscript{15}, and well as to account for higher order terms in the QCD (eventually up to N3LO) and EW perturbative expansions, in the latter case using recently developed tools such as PineAPPL\textsuperscript{16}.

**An open-source machine learning fitting framework.** The NNPDF machine learning fitting framework will be publicly released, fully open source, together with an extensive documentation and user-friendly examples. We believe that its availability will provide a useful resource for the community in cases where one aims to apply cutting-edge machine learning tools to the model-independent parametrisation of non-perturbative QCD quantities, as well as to related applications both within and beyond\textsuperscript{17} high-energy physics.
Figure 3 – Left: comparison of the NNPDF3.1 and NNPDF4.0 predictions for the light anti-quark PDF ratio $\bar{d}/\bar{u}$ at $Q = 10$ GeV with the SeaQuest results. Right: the charm PDF at $Q = 1.65$ GeV in the NNPDF4.0 fits with perturbative charm and with fitted charm (with and without EMC charm data).

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