1 Inclusive Collinear PDFs

1.1 Proton PDFs

This section expands on the information in the ATHENA proposal surrounding figure 3.20, which illustrates the potential impact of ATHENA data in constraining the collinear proton parton densities at large x.

The potential improvements are most readily visualised on a linear x scale, in contrast to the commonly adopted logarithmic presentation. Figure 1 shows the proton up-valence, down-valence, gluon and sea quark densities at the starting scale for DGLAP evolution, $Q^2 = 1.9 \text{ GeV}^2$, obtained from NLO fits in the HERAPDF2.0 framework [1] using the xFitter toolset [2].[1] Results are shown both for the published HERAPDF2.0 baseline and with the additional inclusion of simulated ATHENA data. The simulated ATHENA measurements are obtained using cross sections taken from the HERAPDF2.0 parameterisations, with smearing carried out according to the correlated and uncorrelated uncertainties described elsewhere in this work. The central values of the PDF sets with and without simulated ATHENA data thus coincide by construction and the uncertainties can be compared directly. Theory / modelling and parameterisation uncertainties are not considered.

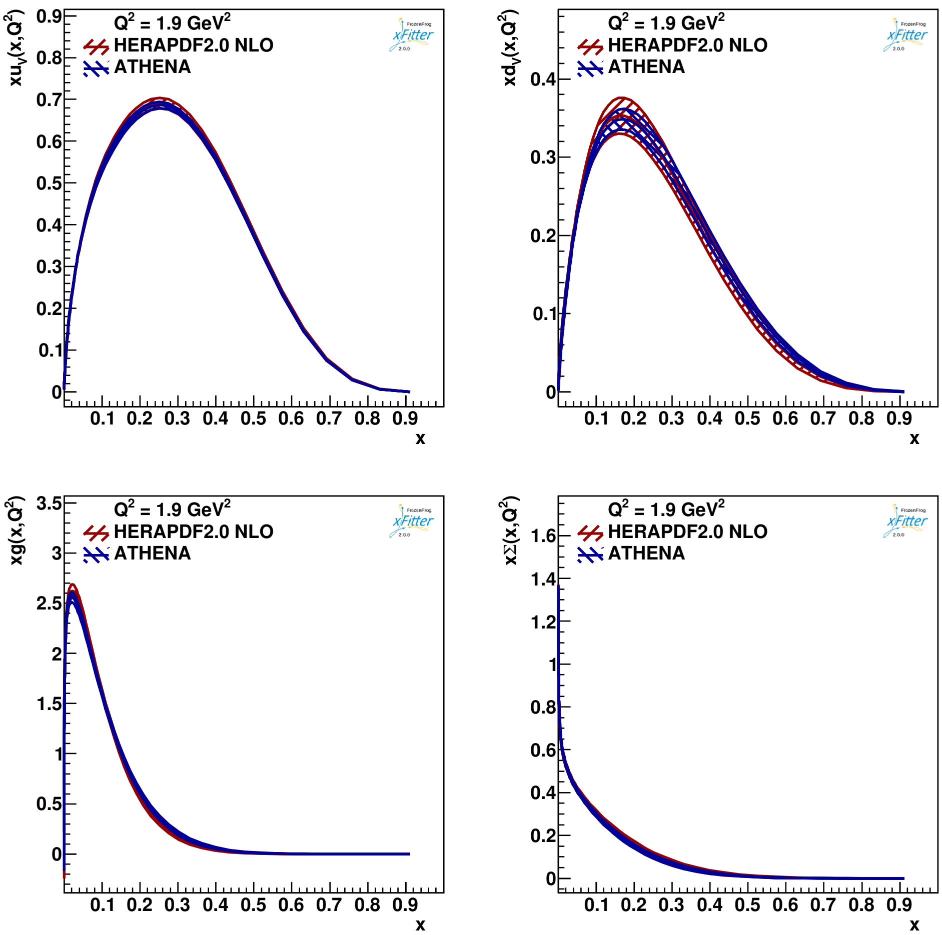

Figure 1: Collinear proton parton densities at large x for $Q^2 = 1.9 \text{ GeV}^2$, the starting scale for DGLAP evolution in the HERAPDF2.0 framework. The up-valence, down-valence, gluon and summed sea antiquark (Σ) distributions are shown for the original HERAPDF2.0 and for a modified HERAPDF2.0 in which simulated ATHENA data are also included.

Below $x \sim 0.2$, the PDFs are dominated by the gluon density, whereas at larger x values,

[1] With thanks to K. Wichmann (DESY Hamburg).

the valence quarks quickly become dominant. Constraining these large x PDFs as strongly as possible is of enormous importance to any experiment with an interest in physics near the $x \to 1$ kinematic limit. The most notable example is the energy frontier discovery programme at the CERN LHC, where new exotic states may be created for example through gluon-gluon or quark-antiquark interactions.

At low and intermediate x, our knowledge of proton collinear structure is dominated by data from HERA. However, the constraints from HERA become weaker in the key large x region, due to the kinematic correlation with large Q^2 and the modest integrated luminosity accumulated by the HERA collider experiments (~ 0.5 fb^{-1} each). ATHENA data are very well suited to improving the situation at large x in a pure DIS fit of the HERAPDF2.0 type. Orders of magnitude larger integrated luminosities will be available than was the case at HERA and the kinematic coverage will be optimised through variations in the beam energies. In addition, for fixed large x, the cross section is higher at EIC than at HERA due to the lower (but still comfortably perturbative) Q^2 region accessed.

The impact of the simulated ATHENA data on the experimental uncertainties in the HERAPDF2.0 fits is illustrated in figure 2. A significant reduction in uncertainties is observed for all parton species, an improvement that would have a major impact on the LHC search programme, among many other applications.

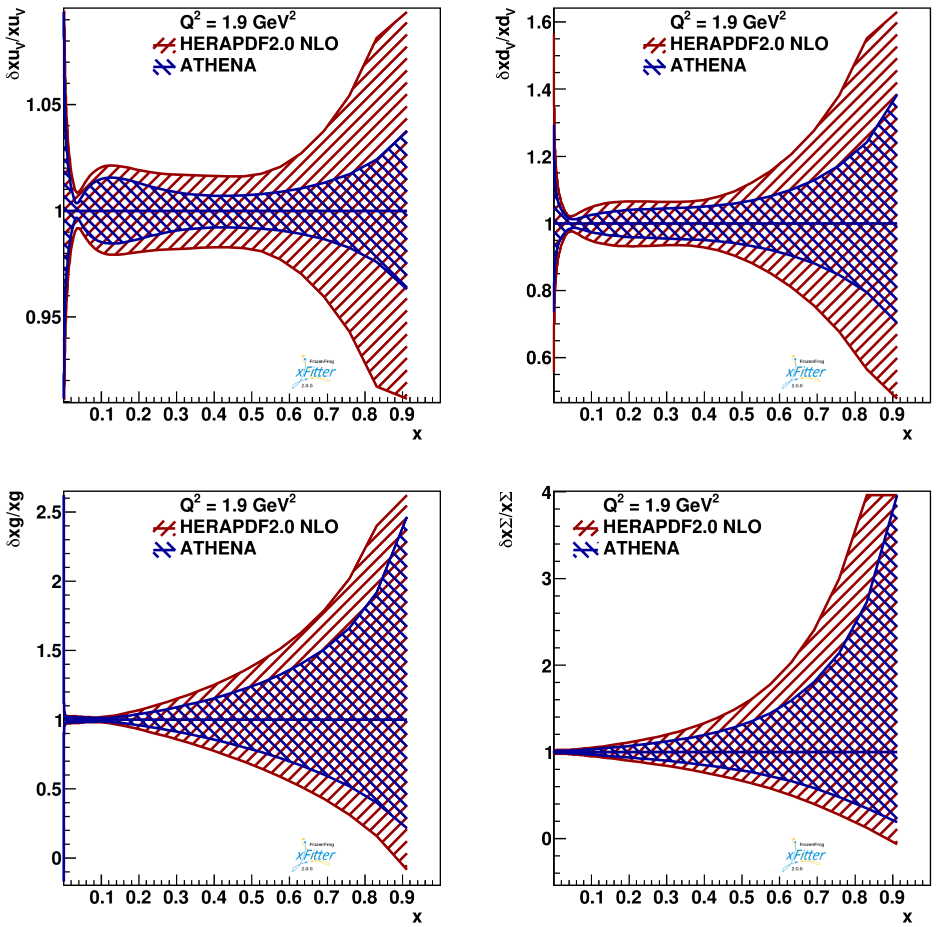

Figure 2: Impact of simulated ATHENA data on the collinear parton distributions of the proton. The bands show relative experimental uncertainties as a function of x for the up-valence, down-valence, gluon and summed sea antiquark distributions. The HERAPDF2.0 uncertainties (using HERA data alone) are compared with results in which simulated ATHENA data are also included in the HERAPDF2.0 fitting framework.

Several groups worldwide are engaged in ‘global’ fits that use a range of input data to constrain the proton PDFs. Whilst the results continue to be dominated by HERA data at low and intermediate x values, the large x region is additionally constrained with a mixture of fixed target DIS data (low Q^2, high x) and various PDF-sensitive observables from the LHC (high Q^2, high x). This dramatically improves the large x precision, and global fits are consequently used in most studies of LHC data. However, it also brings problems associated with the more complex theoretical description of pp data, non-perturbative corrections due for example to hadronisation and nuclear target corrections in the fixed target case. In places, there are also tensions between data sets, which are handled by increasing tolerances in the fitting procedures.

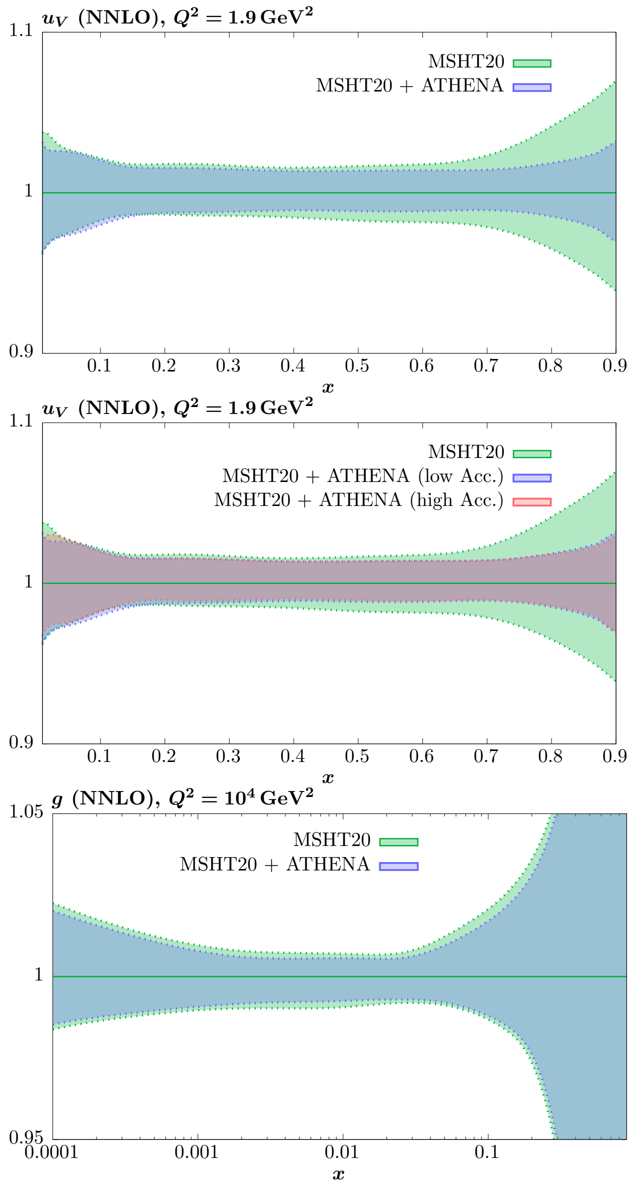

Figure 3: Impact of simulated ATHENA data on the collinear proton parton distributions relative to the MSHT20 global fits. The bands show relative uncertainties as a function of x, comparing the MSHT20 baseline with results when additionally including ATHENA data. Top: up valence density at $Q^2 = 1.9$ GeV^2. Middle: up valence density at $Q^2 = 1.9$ GeV^2, also comparing ATHENA scenarios with selections at $y > 10^{-2}$ data (low Acc.) and $y > 10^{-3}$ (high Acc.). Bottom: gluon density at $Q^2 = 10^4$ GeV^2.

The impact of ATHENA data on the high x PDFs has been studied relative to a recent example global fit, MSHT20 [3].[2] The NNLO version is chosen. As expected, the ATHENA improvement

[2]With thanks to L. Harland-Lang (Oxford) and R. Thorne (UCL London).

is significantly reduced compared with the impact over HERAPDF2.0. However, there are still significant effects, as illustrated in figure 3. Due to the charge-squared coupling of the virtual photon in DIS, up quarks are more strongly impacted than down quarks, such that the biggest impact in on the up-valence distribution. The additional impact of including the region $10^{-3} < y < 10^{-2}$ (see performance studies elsewhere in this work) is relatively small, due to the overlapping phase space of the different beam configurations in the simulation. There is also a small, but nonetheless valuable, improvement in the precision on all of the other parton species, which is visible at all x and Q^2 values. The gluon density at the electroweak scale is chosen for illustration here.

1.2 Nuclear PDFs

This section expands on the information in the ATHENA proposal surrounding figure 3.21, which illustrates the potential impact of ATHENA data in constraining the collinear parton densities of nuclei.

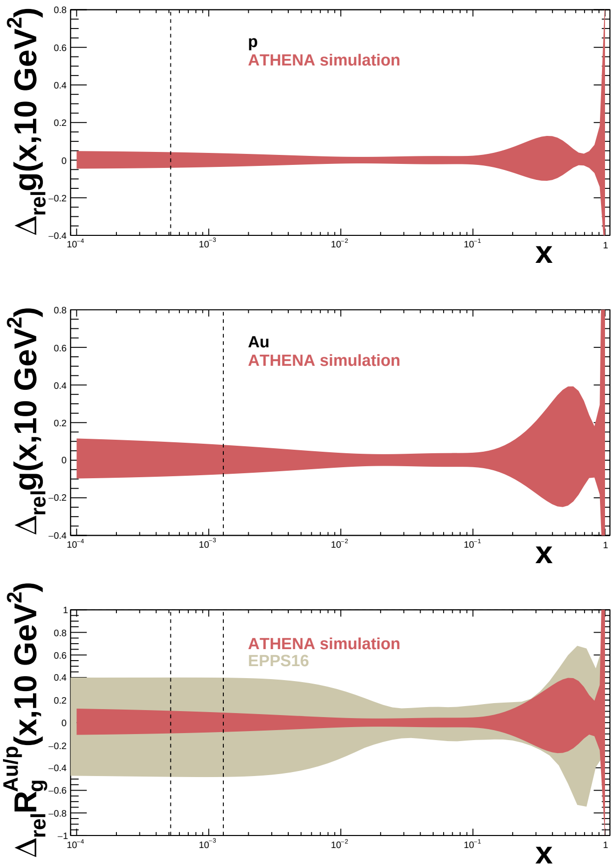

Figure 4: Impact of ATHENA data on the understanding of nuclear effects in the collinear gluon distribution, as obtained from DGLAP-based QCD fits. Top: projected relative uncertainty on the gluon density of the proton as a function of x for $Q^2 = 10\ \mathrm{GeV}^2$, using only ATHENA input data. Middle: projected relative uncertainty on the gluon density of a proton in the gold nucleus as a function of x for $Q^2 = 10\ \mathrm{GeV}^2$, using only ATHENA input data. Bottom: Nuclear modification factors formed from the ratio of projected gluon densities in gold and in the proton. The results obtained using only ATHENA data are compared with those from a global fit (EPPS16).

As the world's first eA collider, the EIC will explore partonic nuclear structure at an unprecedented level of detail. In particular, it opens up a new region at low x that has not been constrained previously. The topic is commonly discussed in terms of nuclear PDFs (nPDFs), or nuclear modification ratios, which encode the deviations of nPDFs from simple scaling of free nucleon PDFs with

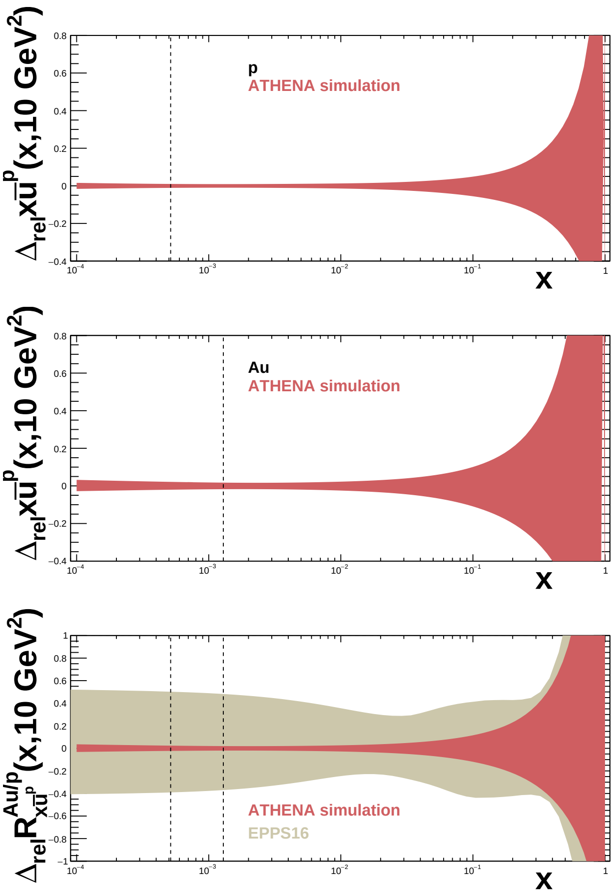

Figure 5: As for figure 4, but for the sea up quark density.

atomic mass A after appropriately accounting for varying proton-to-neutron ratios using isospin symmetry. The deviations from scaling with A may be due to binding effects or, at low x, to new parton dynamics ('saturation' phenomena) associated with the denser systems of gluons found in heavy nuclei than in nucleons. This topic therefore lies at the heart of the EIC physics programme.

Previous DIS data feeding into nPDFs are limited to fixed target measurements at large x and relatively low Q^2. Data from fixed target and colliding mode hadron-hadron experiments can be used to extend the sensitivity, but with similar associated theoretical difficulties to those discussed in the proton context in section 1.1 and, even for LHC observables, with limited range in x. The sensitivity of ATHENA to new low x dynamics is therefore closely related to the precision and kinematic range in which the nuclear modification ratios can be measured. Since the nuclear modification factors are expected to be large at low x, ATHENA will have an impact already with relatively modest amounts of eA data.

The potential impact on nuclear PDFs of the simulated ATHENA data described in the performance section of this work has been studied[3] through a reweighting procedure in the xFitter framework [2]. Data from ATHENA only are used as input to fits in which the PDFs evolve according to the next-to-leading order (NLO) DGLAP equations, with a minimum Q^2 of $3.5\ \mathrm{GeV}^2$ and using a parameterisation at the starting scale taken from the HERAPDF2.0 studies. Figures 4, 5 and 6 show the results for the gluon density, the sea up quark density and the sea valence quark density, respectively. The relative precision is shown separately for the proton and for gold nuclei, as well as for their ratio. The ATHENA-only projections for the nuclear modification ratios are compared with the precision of a representative current global fit, EPPS16 [4], which includes data from fixed target DIS and Drell-Yan experiments, hard processes in pA collisions at the LHC and π^0 data from PHENIX.

[3] With thanks to N. Armesto (Santiago de Compostela) and K. Wichmann (DESY).

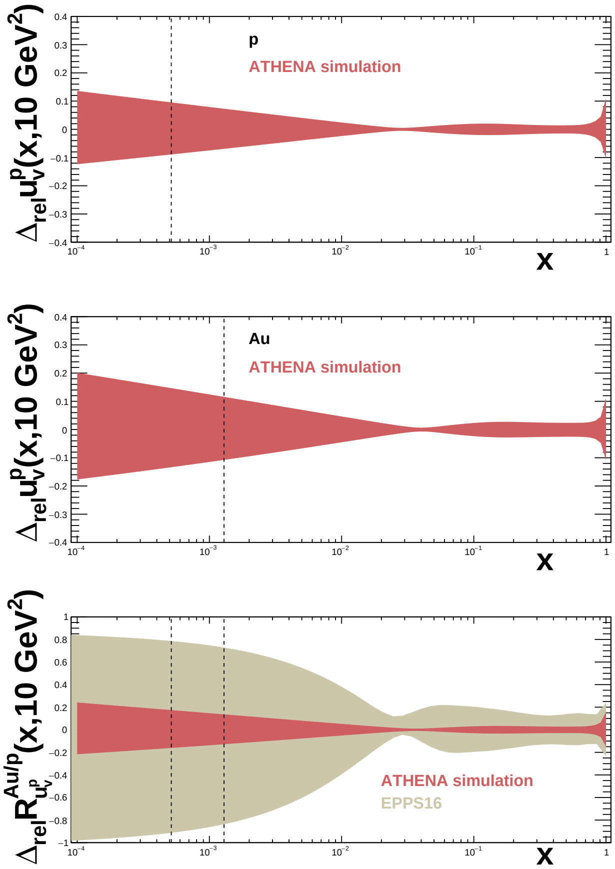

Figure 6: As for figure 4, but for the valence up quark density.

The behaviour of gluons at high densities is a cornerstone of the EIC physics programme. Since it is most clearly addressed through nuclear dynamics at low x, the case of the gluon density (figure 4) is pivotal. The precision obtainable using ATHENA data only is typically at the 5% level for the proton and at the 10% level for gold. Very large improvements over the EPPS16 baseline are observed for all x values. The precision in the region $x \sim 0.1$, where there are plentiful input data in the EPPS16 case, is improved by around a factor of 2 when using ATHENA data. This is partly due to the use of a $\Delta\chi^2 = 1$ condition in defining the uncertainty bands in the ATHENA case, as would be standard when fitting data from a single experiment, compared with $\Delta\chi^2 = 52$ as applied in the EPPS16 case to account for tensions between the different input data sets.

The largest improvements in the gluon nuclear modification ratio appear in the previously unconstrained region below $x \sim 10^{-2}$. The minimum x of data points included in the EPPS16 fit is 0.008, whereas in the ATHENA fits it is approximately 0.001, thus opening up an order of magnitude of previously completely unexplored low x physics in which novel dynamics may be observed, the gluon nuclear modification ratio being constrained with a precision of approximately 10%. As illustrated in figures 5 and 6, similarly profound improvements are expected for all other parton species.

References

[1] H. Abramowicz *et al.* [H1 and ZEUS], Eur. Phys. J. C **75**, no.12, 580 (2015) doi:10.1140/epjc/s10052-015-3710-4 [arXiv:1506.06042 [hep-ex]].

[2] S. Alekhin, O. Behnke, P. Belov, S. Borroni, M. Botje, D. Britzger, S. Camarda, A. M. Cooper-Sarkar, K. Daum and C. Diaconu, *et al.* Eur. Phys. J. C **75**, no.7, 304 (2015) doi:10.1140/epjc/s10052-015-3480-z [arXiv:1410.4412 [hep-ph]].

[3] T. Cridge, L. A. Harland-Lang, A. D. Martin and R. S. Thorne, [arXiv:2111.05357 [hep-ph]].

[4] K. J. Eskola, P. Paakkinen, H. Paukkunen and C. A. Salgado, Eur. Phys. J. C **77** (2017) no.3, 163 doi:10.1140/epjc/s10052-017-4725-9 [arXiv:1612.05741 [hep-ph]].