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Progress in the NNPDF global analysis and the impact of the legacy HERA combination

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The H1 and ZEUS collaborations have recently presented their final results for the combination of inclusive cross-section measurements taken during Run I and Run II at the HERA collider. In this contribution, following an overview of recent progress in the NNPDF framework, we quantify the impact of the legacy HERA dataset on the NNPDF3.0 analysis, finding that it has a very moderate effect in the global fit. On the other hand, we also find that a HERA-only fit using the legacy dataset leads to a rather more accurate determination of PDFs as compared to a fit including only the HERA-I data. We also explore the sensitivity of the fit with respect to kinematical cuts in the small-x and small-Q^2 region, finding hints of a possible tension between data and theory.

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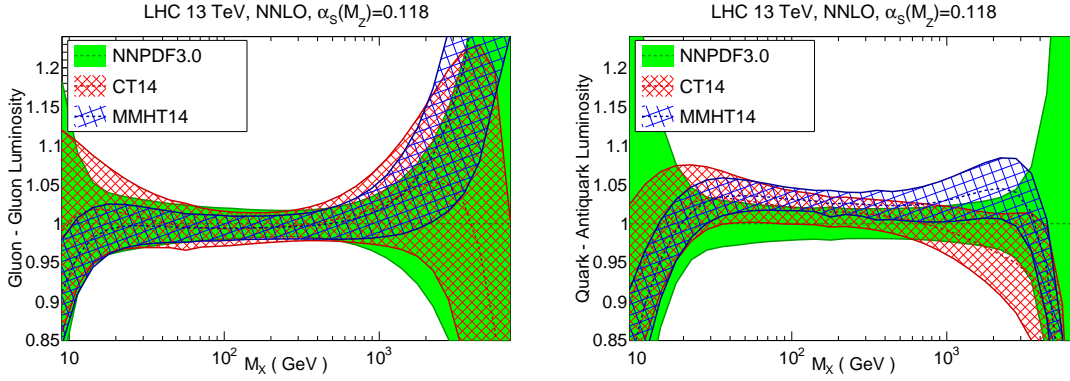
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Figure 1: Comparison of the gluon-gluon (left) and quark-antiquark (right) PDF luminosities from the NNLO NNPDF3.0, CT14 and MMHT14 global analyses at the LHC Run II.

PDFs for the LHC Run II. The accurate determination of Parton Distribution Functions (PDFs) is an essential component for a successful LHC program [1, 2, 3]. Recently, the three main PDF fitting collaborations have presented updates of their global analysis: NNPDF3.0 [4], CT14 [5] and MMHT14 [6]. As compared to previous releases, an improved agreement is now found for some key PDF combinations such as the gluon at medium-x, relevant for Higgs production in gluon fusion, though discrepancies remain in other flavors and regions of x, in particular at large-x. In Fig. 1 we compare the NNLO gluon-gluon and quark-quark PDF luminosities from NNPDF3.0, CT14 and MMHT14 at a center of mass energy of 13 TeV.

In addition to the delivery of the updates of global PDF fits, there has also been intensive activity in the development of new methods for the combination of PDF sets, motivated by ongoing updates of the PDF4LHC Working Group prescriptions [7]. The main idea of these methods is to achieve a statistically well-defined combination of individual PDF sets in terms of a reduced number of Hessian eigenvectors or Monte Carlo replicas, to be used to quantify the overall PDF uncertainty in LHC analysis such as Higgs coupling measurements and New Physics searches.

The starting point of these PDF combination strategies is the Monte Carlo (MC) method [8], by means of which Hessian PDF sets are represented in terms of a MC ensemble. Then, assuming equal likelihood for each PDF set enter in the combination, one needs to add together the same number of replicas from each set. The resulting combination is given in terms of a large number, $\mathcal{O}(1000)$, of replicas, a number that needs to be reduced in order to streamline its application to LHC analyses. This can be achieved either by compressing the original MC representation (CMC-PDFs [9]) or by constructing a suitable Hessian representation, either by projecting in a subspace of PDF functional forms (Meta-PDFs [10]) or by using the MC replicas themselves as basis of the linear expansion (MC2H [11]). Each of these methods is more suited for different applications, for instance, CMC-PDFs should be more reliable for analysis where the underlying probability distribution for the PDFs has sizable non-gaussian features, such as New Physics searches at high invariant masses.

Note that as a byproduct of the development of the MC2H method, Hessian versions of NNPDF3.0 have also been publicly released, as illustrated in Fig. 2.

Progress in the NNPDF global analysis framework. Since the release of the NNPDF3.0 global
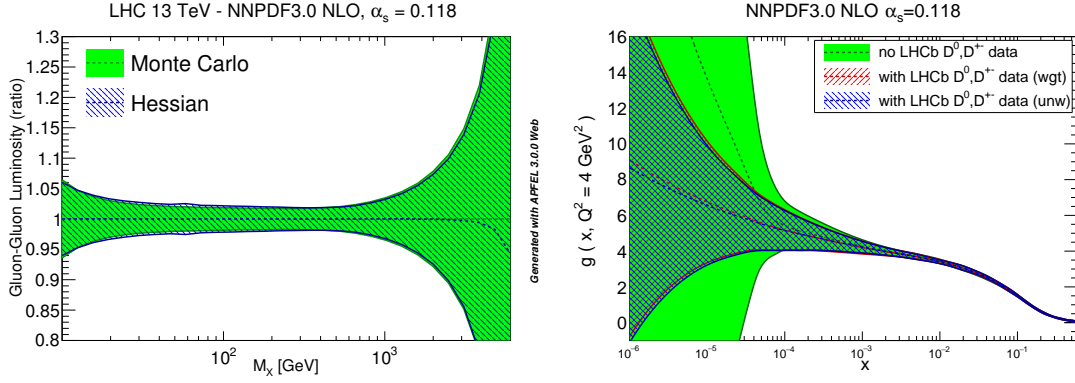
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Figure 2: Left plot: comparison of the native Monte Carlo and the new Hessian representations of NNPDF3.0 NLO. Right plot: constraints on the small-x gluon PDF from the inclusion in the NNPDF3.0NLO fit of the forward charm production data from LHCb.

fit, the main activity within the NNPDF collaboration has been the addition of new LHC datasets that have become available since then, as well as the addition of the legacy HERA inclusive combination [12], to be discussed in more detail below. New measurements that will be part of future NNPDF releases include the CMS 8 TeV double differential distributions [13], the ATLAS 2011 inclusive jets [14] and the LHCb forward electroweak measurements [15], among several others.

In addition to these measurements, the impact on NNPDF3.0 of the LHCb data on forward charm production was recently quantified in Ref. [16] by means of the Bayesian reweighting method [17, 18]. Following a suitable normalization of the differential cross-sections, good consistency between the LHCb data and NLO QCD theory was found, and a substantial reduction of the gluon PDF uncertainties at small-x (beyond the HERA coverage) was obtained, as can be seen in Fig. 2. These results, consistent with a similar `HERAfitter` study [19], are a crucial input to provide robust predictions for the charm-induced neutrino flux at neutrino telescopes like IceCube, which is the dominant background to astrophysical neutrinos.

Another important recent development in the NNPDF framework is the release, for the first time, of a global PDF fit which goes beyond fixed-order QCD perturbation theory and incorporates the effects of soft-gluon (threshold) resummation [20]. The motivation for these resummed PDFs was provided by the availability of state-of-the-art calculations where fixed order NLO or NNLO QCD was matched to NLL or NNLL threshold resummation, in processes like Higgs, top quark pair production or supersymmetric pair production: these calculations are theoretically inconsistent since up to know they had to rely on fixed-order (rather than resummed) PDFs.

The main outcome of this study was precisely to emphasize the crucial importance of the consistent use of resummed PDFs with resummed partonic cross-sections. This point is illustrated in Fig. 3 with two examples of phenomenological relevance: slepton pair production at high invariant masses, and Higgs production, both SM and for a heavy Higgs. We find that, at TeV scales, the consistent use of resummed PDFs with resummed calculations brings the overall result closer to its fixed-order counterpart, while using resummed calculations with fixed-order PDFs overestimates the overall impact of the resummation. At moderate invariant masses, around the electroweak scale, resummed PDFs reduce to their fixed-order counterparts, and thus the overall effect of the
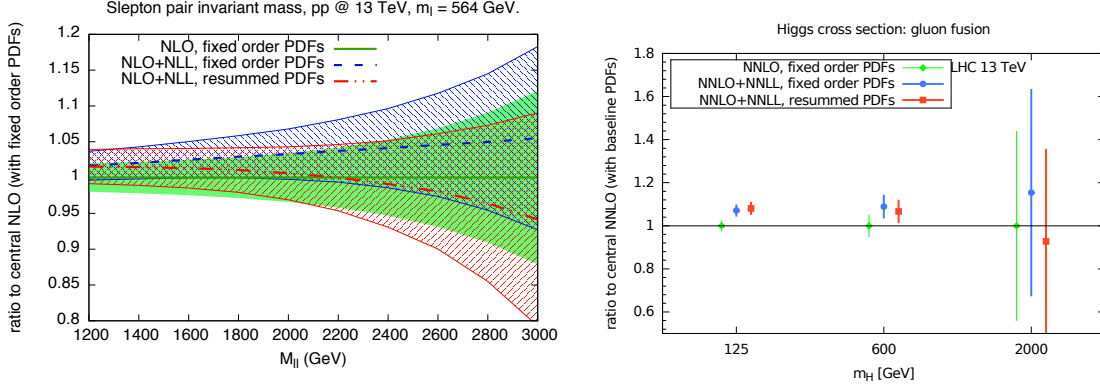
Figure 3: Comparison of fixed-order and resummed calculations using either fixed-order or resummed PDFs, for slepton pair production (left) and for light and heavy Higgs production (right) at the LHC 13 TeV.

resummation arises only from the partonic cross-sections.

Other ongoing developments in NNPDF include fits with a fitted charm PDF (for which a suitable modification of the FONLL general-mass VFN scheme [21] is required), updated QED fits [22] and NNPDF fits with theoretical uncertainties, both from scale variations and from heavy quark mass variations. From the technical point of view, we have completed the interfacing of the `APFEL` program [23] with the NNPDF fitting code, which allows to streamline the study of the impact, at the PDF level, of new theory settings.

PDF impact of the legacy HERA inclusive combination. The H1 and ZEUS collaborations have recently presented the legacy combination of all HERA inclusive structure function data from Runs I and II [12]. This combined dataset supersedes both the HERA-I combination [24] and the separate HERA-II measurements from H1 and ZEUS. In the NNPDF3.0 global fit, both the HERA-I data and the inclusive measurements from HERA-II were already included, so one expected that the replacement of these with the legacy combination would have a very moderate effect. To verify if this expectation is borne out, we have produced NLO and NNLO versions of NNPDF3.0 with the HERA legacy combination replacing the corresponding inclusive measurements. The comparison is shown in Fig. 4. Indeed we verify that the impact of the final HERA combination on the NNPDF3.0 fits is minimal, both for central values and for PDF uncertainties.

The above conclusion is perhaps not completely surprising, since we already verified that, in the NNPDF3.0 global analysis, the impact of the individual HERA-II inclusive measurements from H1 and ZEUS was moderate to begin with [4], though providing some useful constraints on quarks at medium and large x. The situation is unchanged with the availability of the legacy HERA combination, as illustrated in Fig. 5, where we compare the global fit, including the final HERA dataset, with the same fit, but now including only the HERA-I data. We observe that the central values are essentially unchanged in the two fits, with a moderate reduction of the PDF uncertainties on the quark PDFs at intermediate values of x. Therefore, we conclude that the addition of the HERA-II inclusive data into a global PDF fit that already includes the HERA-I combination, while leaving unchanged the central values, helps in reducing the PDF uncertainties of quarks, and that the impact of the combination *per se* is negligible. Let us mention that more detailed studies of
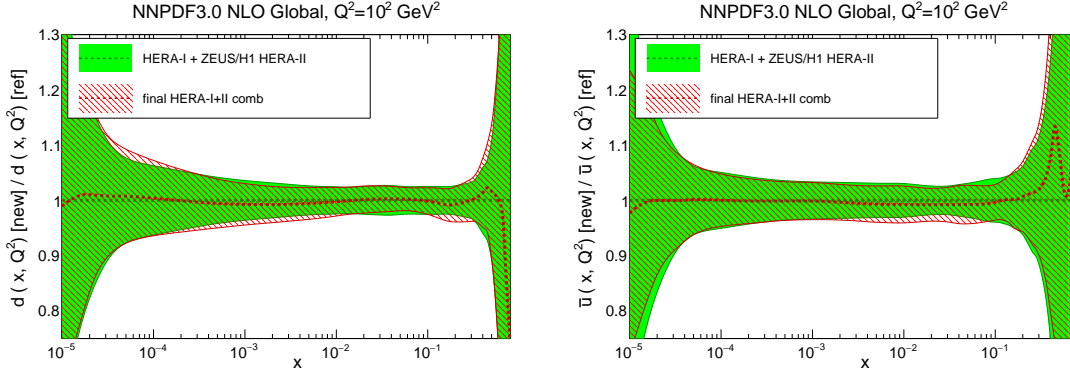
Figure 4: Comparison of the down quark $d(x, Q^2)$ (left plot) and the anti-up quark $\bar{u}$ PDFs (right plot) in the baseline NNPDF3.0 NLO fit and in the variant where all inclusive HERA data has been replaced by the legacy combination. The comparison is performed at $Q^2 = 100 \, \mathrm{GeV}^2$.
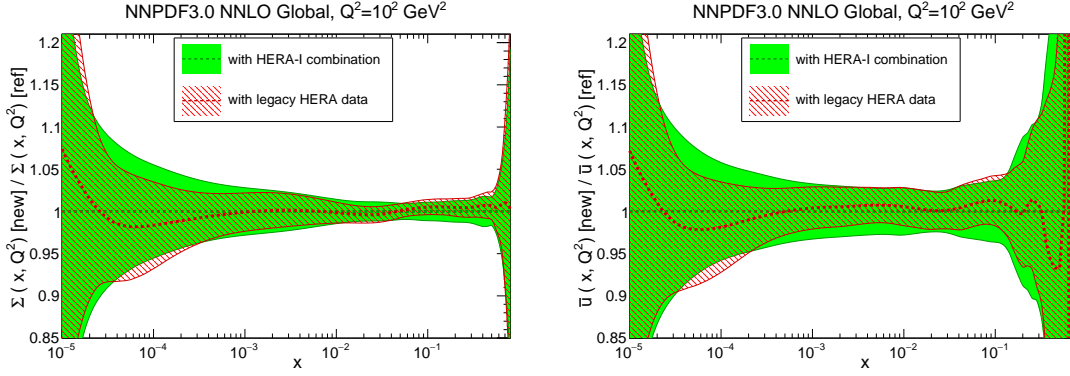

Figure 5: Same as Fig. 4 now comparing the total quark singlet $\Sigma(x, Q^2)$ and the anti-up quark $\bar{u}(x, Q^2)$ PDFs from the NNPDF3.0 NNLO global fit with the legacy HERA dataset, with a global fit without any HERA-II inclusive data.

the impact of the legacy HERA combination in the NNPDF global fit will be presented in a future publication. The impact of this dataset in the MMHT14 framework has recently been explored in Ref. [25].

In the same publication that presented the HERA legacy combination [12], the HERAPDF2.0 analysis was also introduced, and a substantial reduction of PDF uncertainties as compared to the previous HERAPDF1.5 was reported. To explore the impact that the legacy HERA combination has as compared to a HERA-I only fit in the NNPDF framework, we have produced variants of NNPDF3.0 based only on either HERA-I data or on the legacy HERA combination. In Fig. 6 we show the comparison of the up quark (left plot) and total quark singlet (right plot) in a HERA-I only fit and in a PDF fit including only the final HERA-I+II combination. We now observe that the impact of the new HERA data is larger than in the global fit, in particular in what concerns quark flavor separation at medium and large-x. This is consistent with the results of the HERAPDF2.0 paper.

The HERAPDF2.0 analysis also reported [12] a sizable dependence of the fit results and the data χ^2 values with respect to the choice for the minimum value of Q^2, denoted by Q^2_{min}, included
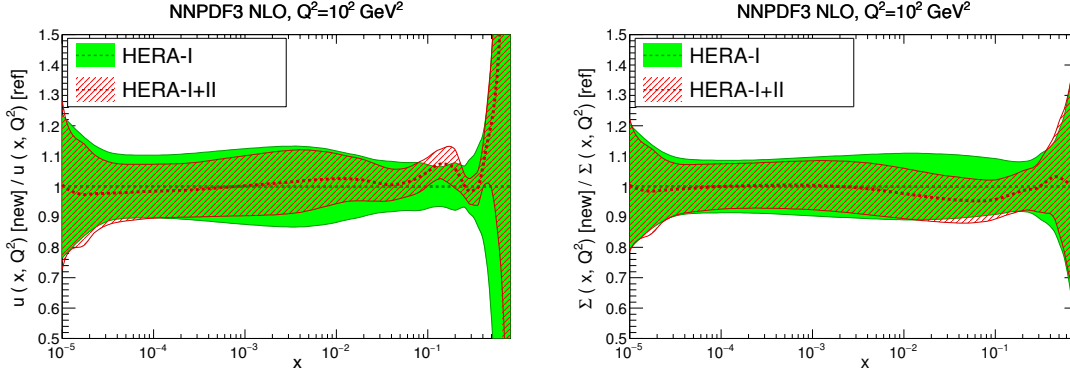
Figure 6: Comparison of the up quark (left plot) and total quark singlet (right plot) in a HERA-I only fit and in a PDF fit based on the final HERA-I+II combination.
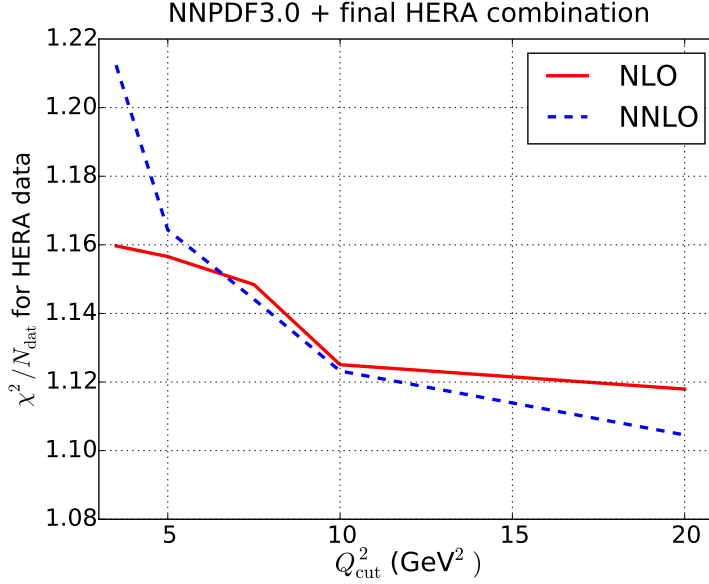

Figure 7: The value of χ^2/N_{dat} for the legacy HERA combination in the variants of the NNPDF3.0 fits with different values of Q^2_{cut}, for the NLO and NNLO fits.

in the analysis. Such instability, if confirmed by other groups, could have different origins, like an inadequacy of the theory used for the fit, for example if small-x (BFKL) resummation [26] is needed to describe the precise inclusive HERA data at low-x and low-Q^2. To verify this observation, we have produced variants of the NNPDF3.0 global fit, including the HERA legacy combination, for different values of Q^2_{min}. The results of this study are summarized in Fig. 7, where we show for the NLO and NNLO fits the value of χ^2/N_{dat} as a function of Q^2_{cut}.

From Fig. 7 we see that also in NNPDF3.0 we observe that the χ^2/N_{dat} of the HERA data decreases quite rapidly as Q^2_{cut} is increased, more at NNLO than at NLO. This effect disappears for $Q^2_{\text{min}} \geq 10$ GeV^2, for which the χ^2 profiles essentially flatten out. Interestingly, for $Q^2_{\text{min}} \geq 5$ GeV^2 we see that the quality of the NNLO fit is essentially the same or better than for the NLO fit. These results are consistent with the possibility of large unresummed small-x logarithms, though
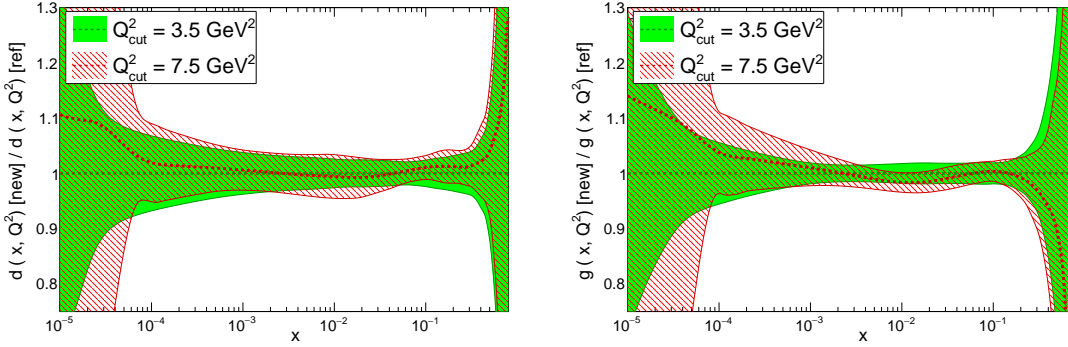
Figure 8: Comparison of variants of the NNPDF3.0 NLO global fit with two different values of Q^2_{cut}, namely 3.5 GeV^2 (the default) and 7.5 GeV^2, for the down quark (left plot) and the gluon PDF (right plot).

there are also alternative explanations, such as an possible internal tension between the HERA data at small-Q^2 and the rest of the dataset.

Whatever the origin of this dependence with Q^2_{min} is, it is reassuring that its impact on mainstream LHC physics, which typically probe PDFs at medium and large-x and at large Q^2, is moderate. In Fig. 8 we compare the NNPDF3.0 fits (with the legacy combination) for two values of Q^2_{min}, namely 3.5 GeV^2 (which is the default in NNPDF3.0) and 7.5 GeV^2. As we can see, while of course the PDF uncertainties at low-x increase strongly, for $x \gtrsim 10^{-3}$ the impact of removing low Q^2 data is small. The same holds true for other PDF combinations.

However, it is also important to note that in order to probe the possible effect of BFKL-like unresummed logs, it is more efficient [27] to use a kinematical cut of the form

$$Q^2 \geq A_{cut} x^{-\lambda}, \tag{1}$$

with $\lambda \sim 0.3$ and A_{cut} a parameter that is varied, analogously to Q^2_{cut}. This cut removes only small-x, small-Q^2 data but not small-Q^2 and large-x data that is certainly unaffected by small-x resummation (and where other effects, like TMCs and higher twists, might play a role). In any case, only a complete global analysis where NLO and NNLO fixed-order calculations are supplemented with small-x resummation should be able to definitely elucidate the origin of these effect. Such fit in the NNPDF framework is underway.

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