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Combination of aN^3LO PDFs and implications for Higgs production cross-sections at the LHC

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Abstract

We discuss how the two existing approximate N³LO (aN³LO) sets of parton distributions (PDFs) from the MSHT20 and NNPDF4.0 series can be combined for LHC phenomenology, both in the pure QCD case and for the QCD \otimes QED sets that include the photon PDF. Using the resulting combinations, we present predictions for the total inclusive cross-section for Higgs production in gluon fusion, vector boson fusion, and associated production at the LHC with $\sqrt{s} = 13.6$ TeV (Run 3). For the gluon fusion and vector boson fusion channels, the corrections that arise when using correctly matched aN³LO PDFs with N³LO cross section calculations, compared to using NNLO PDFs, are significant, in many cases larger than the PDF uncertainty, and generally larger than the differences between the two aN³LO PDF sets entering the combination. The combined aN³LO PDF sets, MSHT20xNNPDF40_an3lo and MSHT20xNNPDF40_an3lo_qed, are made publicly available in the LHAPDF format and can be readily used for LHC phenomenology.

Keywords: large hadron collider, parton distribution functions, higgs boson productions, N³LO QCD calculations

1. Introduction

The two global determinations of parton distribution functions (PDFs) from the MSHT [1] and NNPDF [2] collaborations have been recently extended to approximate next-to-next-to-next-to-leading order (aN³LO), in [3] and [4] respectively. Both the MSHT and NNPDF aN³LO PDF sets have been subsequently enlarged to also include a photon PDF and mixed QED \otimes QCD corrections to perturbative evolution [5, 6].

The inclusion of N³LO QCD corrections in the determination of these PDF sets is approximate in two different respects. First, N³LO perturbative evolution is only known approximately. Indeed, splitting functions are not known exactly, so an approximation to them must be constructed based on exact knowledge of the small- and large- x behavior at higher perturbative orders (e.g. from resummation) and a finite set of Mellin moments [7–17]. Knowledge of N³LO splitting functions has progressed rapidly, with more Mellin moments being gradually published over the years. In fact, now [18, 19] the full set of Mellin moments up to $N=20$ is available for all elements of the splitting function matrix. Heavy quark transition matrix elements at $\mathcal{O}(\alpha_s^3)$, which are needed for massless perturbative evolution in a variable-flavor number scheme, are now also fully known, albeit only recently in complete form [20–30]. Hence N³LO perturbative evolution is known exactly for all practical purposes, as we shall discuss in somewhat more detail below.

Second, however, N³LO partonic cross-sections are only known for a subset of the processes used for PDF determination, namely massless deep-inelastic scattering (DIS) [31, 32] and the total Drell–Yan cross-section and on-shell rapidity distribution [33–37]. In particular, whereas the computation of the high Q^2 limit of heavy quark structure functions was recently completed, permitting the determination of heavy quark transition matrix elements, the computation of corrections to DIS coefficient functions proportional to powers of $\frac{m_h^2}{Q^2}$ of the heavy quark mass is beyond the current state of the art, as is the computation of fiducial N³LO

corrections to hadronic processes, which are needed for a meaningful comparison to hadron collider data.

As a consequence, while approximate N^3 LO perturbative evolution is close to exact, knowledge of N^3 LO hard cross sections is limited. Moreover, massless DIS data do not fully determine the PDFs, and consequently a N^3 LO PDF determination must include a number of processes for which only NNLO matrix elements are available. It is in this respect that perturbative accuracy in a N^3 LO PDF determination is not fully N^3 LO.

The two available a N^3 LO PDF determinations include estimates of the uncertainty due to incomplete knowledge of N^3 LO terms, namely, both the incomplete knowledge of splitting functions, and the missing N^3 LO hard cross-sections, as well as that related to missing perturbative corrections at N^4 LO and beyond. In [3] (MSHT) the uncertainty estimation is done by means of nuisance parameters, while in [4] (NNPDF) it is done through a theory covariance matrix. As is well known, (see e.g. [38, 39]) the nuisance parameter and theory covariance matrix approaches are completely equivalent for Gaussian uncertainties, provided only the eigenvectors and eigenvalues of the covariance matrix coincide with the nuisance parameters and their uncertainties.

The approaches of [3, 4] consequently only differ in the way the covariance matrix, or the corresponding nuisance parameters, are estimated. In [3] this is done based on a judicious estimate of the form of missing terms, which also incorporates effects of varying the parametrization of the splitting functions. In [4], instead, the contributions to the covariance matrix due to incomplete knowledge of splitting functions are estimated differently from all those due to missing higher order terms (missing N^4 LO splitting functions, missing N^4 LO massless DIS coefficient function, and missing N^3 LO hard cross sections for all other processes). Namely, variation of the parametrization of splitting functions (as in [3]) is used for the estimate of their incomplete knowledge, while renormalization and factorization scale variation is used for missing higher order perturbative corrections.

Both [3, 4] included all the information that was available at the time of their publication, and consequently, because [3] was published earlier, it included less information on N^3 LO evolution, and specifically it did not yet include the more recent information on Mellin moments from [11, 14–16, 40], and the exact knowledge of the heavy quark transition matrix elements, both of which are instead included in [4] (with the only exception of the heavy quark terms of [30]) as they had become available meanwhile. Neither determination includes the higher moments of P_{gq} [17] and P_{gg} [18, 19]. Some uncertainties in [3] are accordingly larger, but with the information now available it is possible to check that uncertainties in [3, 4] were estimated accurately.

Specifically, the uncertainty on splitting functions with Mellin moments up to $N = 20$ for all matrix elements but P_{gg} was assessed in both [4, 16] with very similar results, and shown in [4] to be smaller than the uncertainty due to the missing N^4 LO corrections estimated by scale variation. This assessment was extended to P_{gg} recently in [19]. The only other uncertainty on perturbative evolution present in [4] are the contributions, computed in [30], to transition matrix elements, which however were found in [30] to agree perfectly within the uncertainty band with the previous approximation [20] adopted in [4]. Based on this, it can be safely concluded that, as mentioned, N^3 LO perturbative evolution is fully known for all practical purposes. Furthermore, the splitting functions of [3, 4] agree within uncertainties, with the exception of the P_{gq} splitting function, that differs at approximately the two-sigma level, see also the benchmarking comparison of [41, 42]. Note, however, that as far as PDF evolution is concerned P_{gg} is much more important than P_{gq} , and the effects at small- x are to a large extent anti-correlated. Updated knowledge of the splitting functions effectively removes this one source of moderate discrepancy.

A preliminary analysis of the effect of including these additional Mellin moments, and hence improved splitting functions, which have been determined since the original MSHT publication was presented in [43], and observed a small increase in the gluon near $x = 0.01$, though still within the original MSHT uncertainties. While this is significantly washed out in parton luminosities, it does further improve the agreement between the two PDF sets. Furthermore, updated PDF sets obtained using a parametrization of the N^3 LO splitting function constructed in [19] that includes the full information on Mellin moments (and most recently by MSHT, also the complete heavy quark transition matrix elements already used by NNPDF) now available have been presented in preliminary form both by MSHT [44, 45] and NNPDF [46]. These preliminary results allow for a comparison in which all the currently available information on perturbative evolution is consistently used by the two groups. Based on these results, it can be concluded that, whereas the use of a common parametrization of splitting functions and transition matrix elements reduces somewhat the differences between the MSHT and NNPDF aN^3 LO PDF sets, results change by a small amount. We shall come back to this point in section 4 below.

Estimates of the impact of the use of aN^3 LO PDFs in the computation of the Higgs total production cross-section in both [3, 4] suggest that using NNLO PDFs, instead of aN^3 LO PDFs, with the N^3 LO matrix element for Higgs production in gluon fusion and vector boson fusion leads to an error that is comparable to, or even larger than the PDF uncertainty on the N^3 LO result. Also, this error is found [4] to be rather larger than the estimate of its size based on the corresponding shift at one less perturbative order [47, 48]. This suggests that using NNLO PDFs in the N^3 LO computation spoils the accuracy of the N^3 LO result, in a way that, moreover, may not be reflected in a corresponding increase in uncertainty, if the latter is estimated in this way.

Given the availability of two different aN^3 LO PDF sets, accurate N^3 LO phenomenology requires therefore a comparison of the impact of the use of either of these PDF sets, and a prescription for their combination. It is the purpose of this brief note to provide a first assessment and suggest a possible prescription, having specifically in view Higgs production in gluon fusion, but presenting results also for other Higgs production modes. We will first compare the aN^3 LO PDFs of [3, 4], both without and with QED corrections, to each other, then assess for each of them the impact of aN^3 LO corrections on parton luminosities, and finally construct a combination of these PDFs based on the PDF4LHC combination methodology [49]. We will finally discuss results for the cross-section for Higgs production in gluon fusion and other channels based on individual and combined aN^3 LO PDF sets.

2. Comparison of aN^3 LO PDFs

We will compare NNPDF4.0 and MSHT PDF sets both with and without QED effects. The QED sets include a photon PDF that mixes with the quark and gluon PDFs upon combined QED \times QCD evolution, and mostly differ from the pure QCD set due to slight depletion of the gluon PDF due to the momentum fraction carried by the photon. They are consequently important when assessing the behavior of the gluon PDF.

When comparing MSHT and NNPDF PDF sets, care must be taken to compare sets that include the same uncertainties. Specifically, all NNPDF4.0 PDF sets are now delivered in two different versions, one in which the PDF uncertainty includes the uncertainty due to missing higher-order corrections on the theory predictions used for PDF determination (MHOU, henceforth), and the other in which it does not. Hence uncertainties due to missing N^4 LO corrections are only included by NNPDF in the aN^3 LO MHOU sets, though both NNPDF and

MSHT aN^3LO sets include uncertainties due to missing N^3LO corrections to hadronic processes and massive DIS. Note that the NLO and NNLO sets with MHOU were not included at the time of first release of NNPDF4.0 [2], and only released at a later stage [50]. On the other hand, in the MSHT approach all uncertainties, including all MHOUs, are included at N^3LO , while MHOUs are not included at NNLO (as they were not in the original NNLO NNPDF4.0 PDFs of [2]). The pertinent comparison of the MSHT20 sets is therefore at N^3LO with the NNPDF4.0 sets with MHOUs included, while at NNLO with the NNPDF4.0 sets without MHOUs. Note that in [4] the MSHT20 aN^3LO PDFs were instead compared to the NNPDF4.0 set without MHOUs. Henceforth we will here tacitly assume that for NNPDF4.0 NNLO refers to the non-MHOU sets while aN^3LO refers to the MHOU sets.

When comparing the aN^3LO PDF sets, it should of course be borne in mind that the MSHT20 and NNPDF4.0 sets already differ at NNLO due to differences in dataset and methodology. On top of the difference in basic underlying methodology, namely generalized polynomial parametrization and Hessian uncertainties for MSHT, neural network parametrization and Monte Carlo uncertainties for NNPDF, several details of the theoretical approach also differ. Specifically, there are several differences in the treatment of heavy quarks: the values of heavy quark masses are somewhat different; the charm PDF is fitted to the data in NNPDF4.0, while in MSHT20 it is determined by perturbative matching conditions; and for DIS the massive and massless heavy quark schemes are matched using the Thorne-Roberts scheme by MSHT and the FONLL scheme by NNPDF. A detailed comparison of the NNLO MSHT20 and NNPDF4.0 PDF sets was performed in [2], see in particular figure 21 and figure 60 of that reference. Several of the differences seen in the comparison of [2] are also seen when comparing MSHT20 to the previous NNPDF3.1 PDF set, and indeed many of the methodological differences (in particular those related to the treatment of heavy quarks) are the same. This is relevant because MSHT20 and NNPDF3.1 were included in a detailed benchmarking presented in [51, 52], along with the CT18 PDF set. In this work, dedicated PDF sets from the three groups were produced by adopting common assumptions and settings (specifically for the treatment of heavy quarks), instead of the inconsistent settings used in the original fits, as well as a relatively similar global dataset. These PDF sets were called ‘reduced’ in [51] (though not based on a reduced dataset). These dedicated sets turned out to be in quite good agreement with each other within uncertainties, thereby showing that the differences between the original sets were partly due to these inconsistent settings.

These more consistent sets were then used to produce the PDF4LHC21 combination [51]. The combination that we will discuss here is instead based on the publicly available aN^3LO PDF sets, thereby leading to a more conservative uncertainty estimate that encompasses the differences between the PDF sets entering the combination, as we shall explain below. To understand the features of this combination we therefore start with a comparison of the published MSHT20 and NNPDF4.0 aN^3LO sets, along with the NNLO sets, to see how much of the differences seen at aN^3LO reflect those already present at NNLO, whose origin was largely understood in [51, 52].

The comparison of the aN^3LO sets is presented in figures 1–2 (left), together with the comparison of the corresponding NNLO sets (right). The aN^3LO sets including QED corrections are compared in figure 3. All PDFs are shown at $Q = 100$ GeV, normalized to the NNPDF4.0 central value. All error bands are one sigma uncertainties. The dominant differences between the aN^3LO PDF sets are essentially the same as at NNLO, with the largest difference observed for the charm PDF, which, as mentioned, is independently parametrized in NNPDF4.0, but not in MSHT20, where it is determined by perturbative matching conditions. Indeed, it is clear from figures 1–2 that most differences between MSHT and NNPDF

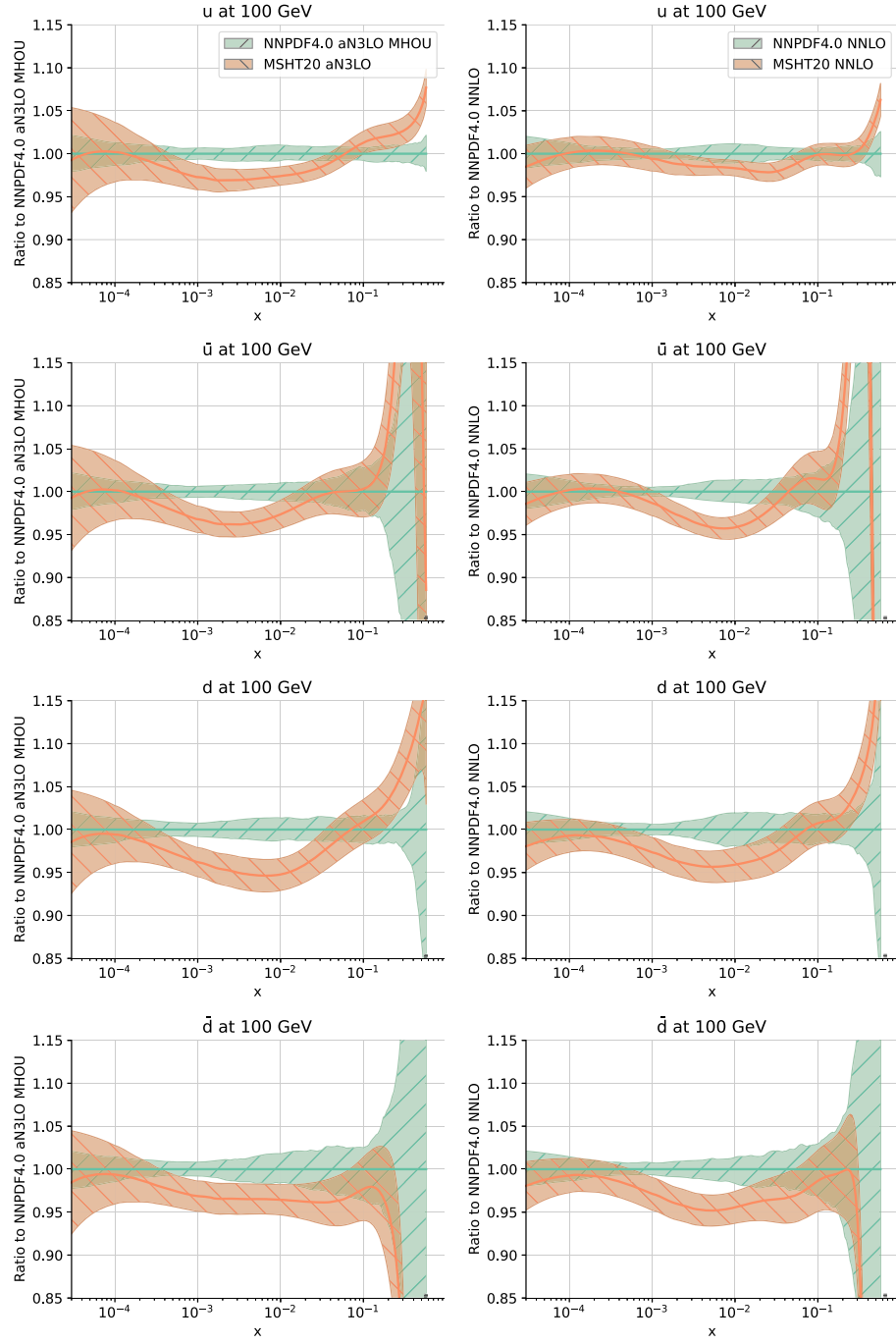


Figure 1. The NNPDF4.0 [4] and MSHT20 [3] aN^3LO (left) and NNLO (right) PDFs, for the u and d sector at $Q = 100$ GeV, shown as a ratio to NNPDF4.0. All uncertainties shown are one sigma.

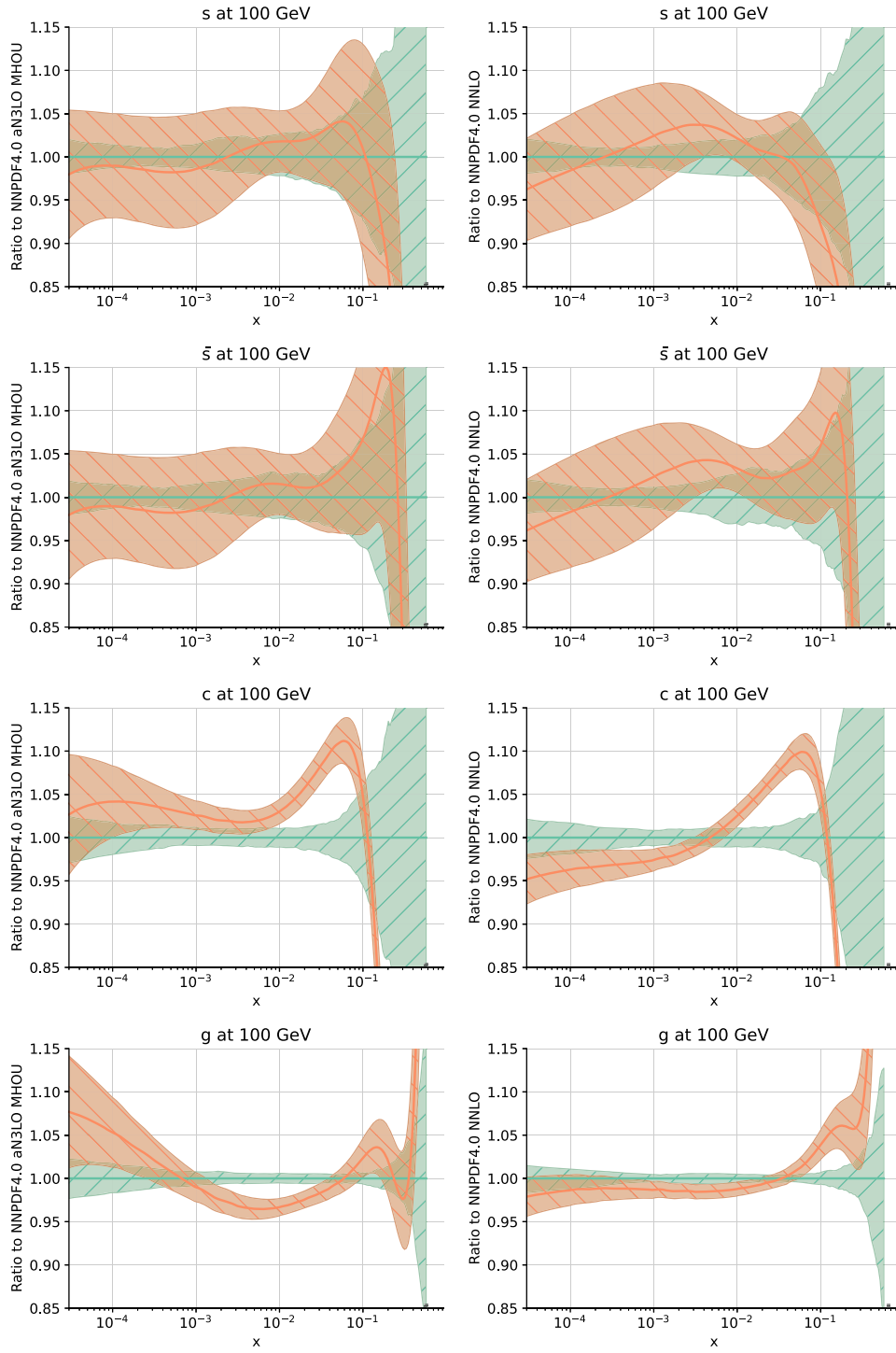


Figure 2. As in figure 1 but for the s , \bar{s} , c , g PDFs.

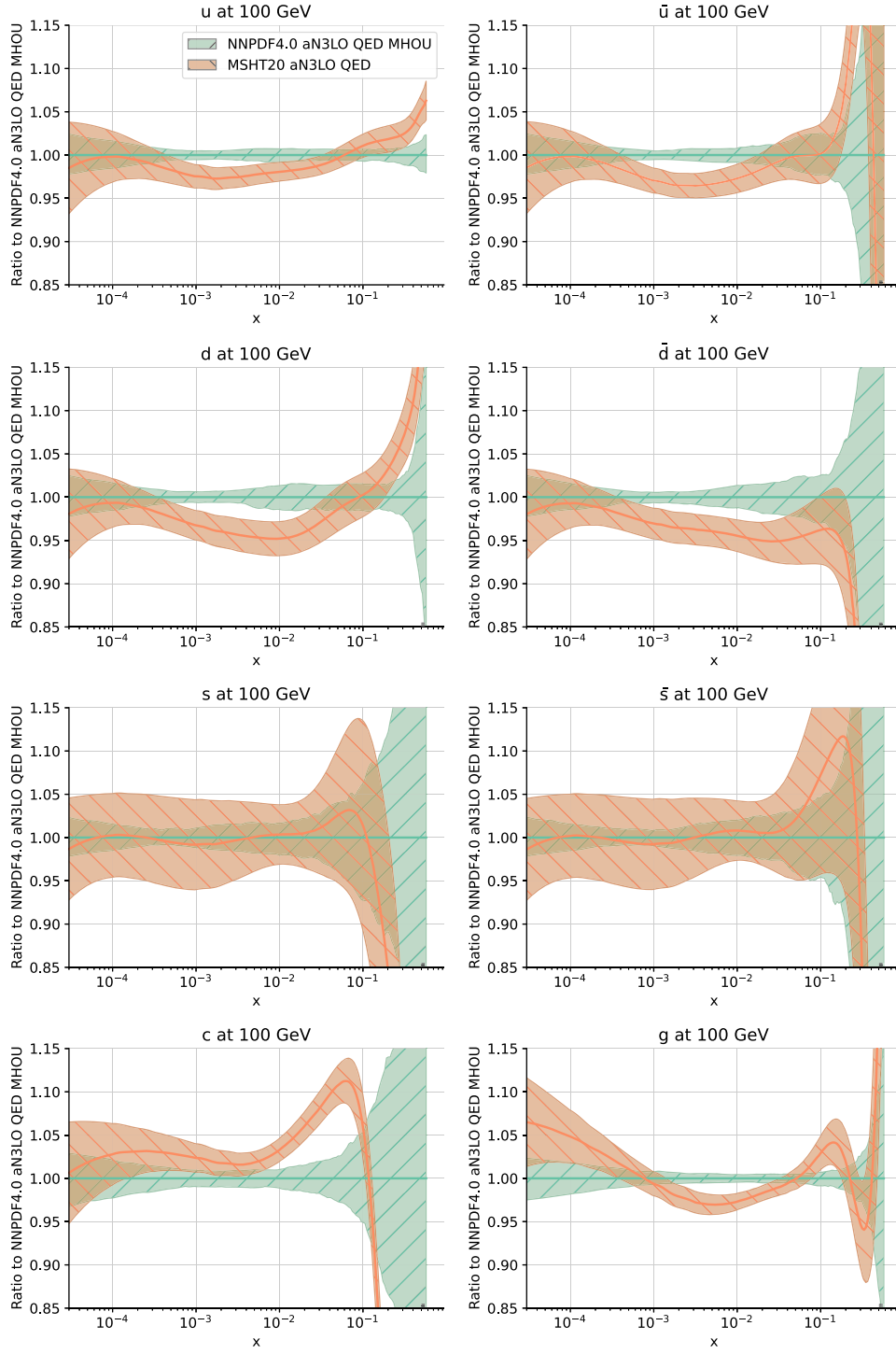


Figure 3. The NNPDF4.0 [6] and MSHT20 [5] aN³LO+QED PDFs at $Q = 100$ GeV, shown as a ratio to NNPDF4.0. All uncertainties shown are one sigma.

change very little when moving from NNLO to aN³LO. An exception is the gluon PDF, which differs more between NNPDF and MSHT at aN³LO. Specifically, while reasonably compatible for $x \lesssim 0.07$ at NNLO, the MSHT and NNPDF gluons disagree at aN³LO, with the MSHT20 result suppressed in comparison to NNPDF4.0 by 3-4% in the region $10^{-3} \lesssim x \lesssim 10^{-1}$, with a PDF uncertainty of 1-2%.

This suppression can, to some extent, be traced to the difference in the behavior of P_{gq} mentioned in the introduction. The P_{gq} splitting function contains more unknown small- x divergent terms than the other splitting functions, and hence has more potential uncertainty at small x , especially if a color-charge relationship that would relate these unknown terms to known contributions to P_{gg} is not assumed to be approximately true for subleading terms (and indeed it is assumed by NNPDF but not by MSHT). Hence, with the smaller moment information and weaker constraints used by MSHT [3], deviations are possible but have been largely eliminated with the improved information now available.

In practice, the differences between the two aN³LO PDF sets are at most at the two sigma level. Furthermore, a recent MSHT preliminary study shows that updating the splitting function with the additional moments now known [14–16] results in a $\sim 1.5\%$ increase in the gluon at $x \sim 0.01$ [43], though it does still remain within the uncertainty band of the original MSHT determination, thereby further reducing differences. Hence, updates in P_{gq} do improve the comparison, but do not remove the difference in the gluon. Recall however that, as mentioned in section 1, the very recent additional moments now known for P_{gq} [17] and P_{gg} [18, 19] are not included in either the MSHT or NNPDF sets discussed here. Finally, the inclusion of the photon PDF also has a moderate impact on the other PDFs, mostly limited to a suppression of the gluon PDF due to the 1% shift in momentum fraction from the gluon to the photon, as well as some reduction in the u, \bar{u} PDFs at high x , due to $q \rightarrow q\gamma$ splitting.

The MSHT and NNPDF aN³LO parton luminosities are compared in figures 4–5, respectively without and with QED effects, while, in order to appreciate better the impact of N³LO corrections, the aN³LO luminosities (without QED) are compared for each set to the respective NNLO luminosities in figure 6, normalized to the aN³LO result. The pattern of differences reproduces that seen at the level of PDFs, with a suppression of the MSHT gluon-gluon, quark-antiquark, and gluon-quark luminosities in comparison to NNPDF in the $M_X \sim 100$ GeV region, while the quark-quark luminosity in the two sets is very similar. The suppression can be traced to the behavior of the light quark and gluon PDFs seen in figures 1–2 (right). Interestingly, the difference in gluon-gluon luminosity is slightly reduced for the QED PDF sets compared to the pure QCD sets.

The qualitative impact of the aN³LO corrections on either set for $M_X \gtrsim 30$ GeV is similar (and almost identical for the quark-quark luminosity), but with a stronger aN³LO suppression of gluon luminosities for MSHT20. In particular the gluon-gluon luminosity is suppressed for $10^2 \lesssim m_X \lesssim 10^3$ GeV by about 3% in NNPDF4.0 and up to 6% in MSHT20 and the gluon-quark luminosity is suppressed in the same region by about 1% in NNPDF4.0 and 3% in MSHT20. Note that the impact on this comparison of the aforementioned update studied in [43] of the splitting functions in MSHT is very small due to the integration over rapidity washing out small differences in the gluon.

These comparisons show that the differences between NNLO and aN³LO for each set are generally larger than the differences between the two aN³LO sets, or indeed the two NNLO sets, especially in the case of MSHT. Furthermore, the differences between NNLO and aN³LO PDFs are often comparable and sometimes (specifically for the gluon-gluon luminosity) larger than the respective PDF uncertainties. These two observations taken together suggest that the use of aN³LO PDFs is mandatory for accurate N³LO phenomenology, because using NNLO PDFs with the aN³LO matrix element leads to an error that may be

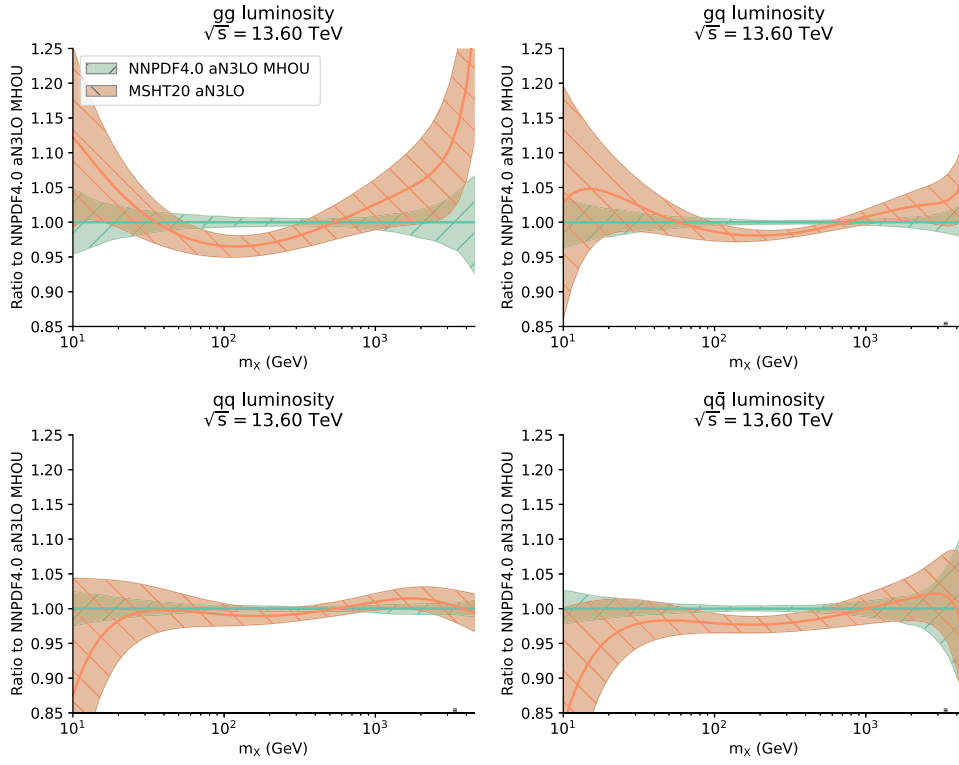


Figure 4. The same comparison as in figures 1-2 (right) but for the corresponding parton luminosities.

larger than the PDF uncertainty, especially in the Higgs gluon and vector boson fusion channels, that are respectively mostly sensitive to the gluon-gluon and quark-quark luminosities. Therefore, even though the MSHT and NNPDF aN³LO PDF sets do not always agree within uncertainties, their combination will lead to results that are more accurate than the use of NNLO PDFs. These considerations motivate the construction of a combined aN³LO PDF set.

3. Combination of aN³LO PDFs

Based on the PDF comparisons presented in section 2, phenomenological predictions for hadronic processes at N³LO could be obtained by simply using the two available aN³LO PDF sets and combining results as a weighted average. However, given that the two sets do not always agree within uncertainties, a more conservative way of estimating the uncertainty on the final result is advisable, such as the so-called PDG prescription and variations thereof [53], see also Section 12.5 of [54].

An effective way of arriving at a conservative uncertainty estimate in our case is to produce unweighted Monte Carlo combined PDF sets [49, 55]. This is done by first turning all the PDF sets to be combined into a set of Monte Carlo replicas, which for Hessian sets can be done using the methodology of [56], and then merging an equal number of replicas from each set into a single replica set. The merged set then corresponds to a probability distribution

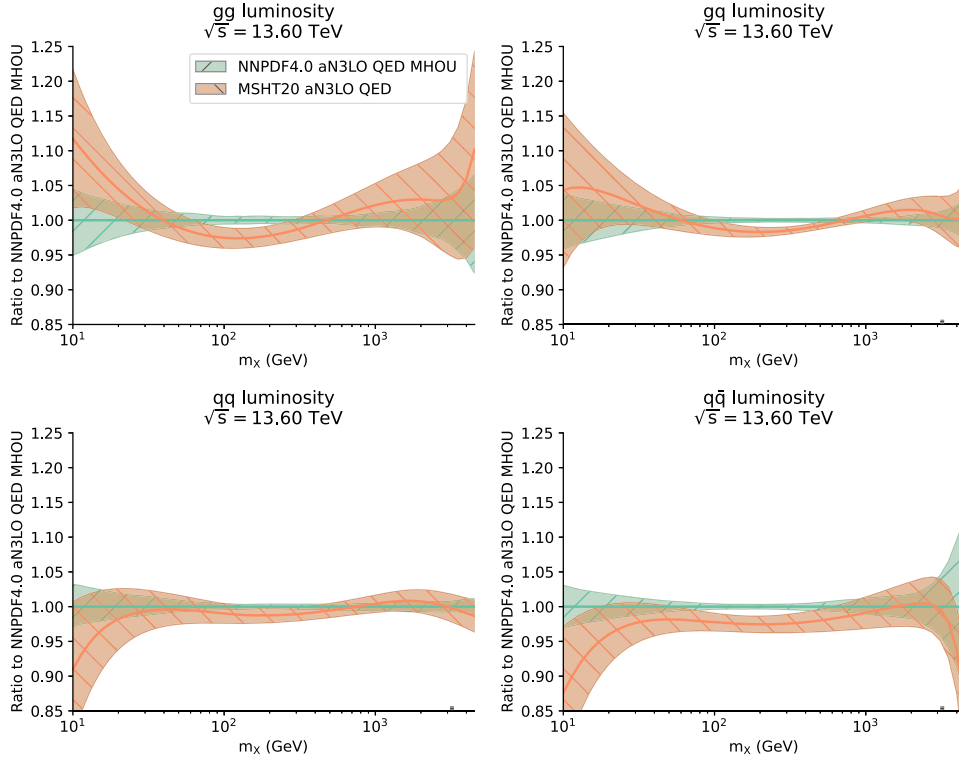


Figure 5. The same comparison as in figure 4 but including QED corrections.

that is the equally likely combination of the probability distribution of the input sets, and thus will lead to uncertainties that encompass those of the sets that are being combined. This way if combining uncertainties leads to results that are more conservative than those that would be obtained by performing a weighted average, or possibly including correlations from the underlying data; however, correlations cannot [57] be reliably taken into account, and differences due to different but equally plausible underlying methodological assumptions are thereby correctly accounted for.

We have produced this combination by merging 100 Monte Carlo replicas produced using the method of [56] from the default Hessian aN³LO set of [3] after symmetrization of the Hessian uncertainties, with 100 replicas from the MHOUs set of [50]. In order to improve numerical stability of results, for the NNPDF4.0 PDFs the (x, Q^2) interpolation LHAPDF grid has been recast to match the MSHT20 grid. We have then repeated the procedure for the QED variants presented in [5, 6]. We will henceforth denote these combined PDF sets as MSHT20xNNPDF40_aN3LO; the corresponding LHAPDF grid files are MSHT20xNNPDF40_an3lo and MSHT20xNNPDF40_an3lo_qed. We have also produced combined pure QCD and QCD \otimes QED NNLO sets obtained using the same procedure, but now starting from the NNPDF4.0 and MSHT NNLO PDF sets. The sole purpose of these sets is to provide a baseline to the corresponding aN³LO sets, in order to assess the effect of N³LO corrections with everything else unchanged. In particular, they should not be viewed as a substitute for the PDF4LHC21 NNLO combined sets. These sets are denoted as MSHT20xNNPDF40_NNLO, and the corresponding LHAPDF grid files

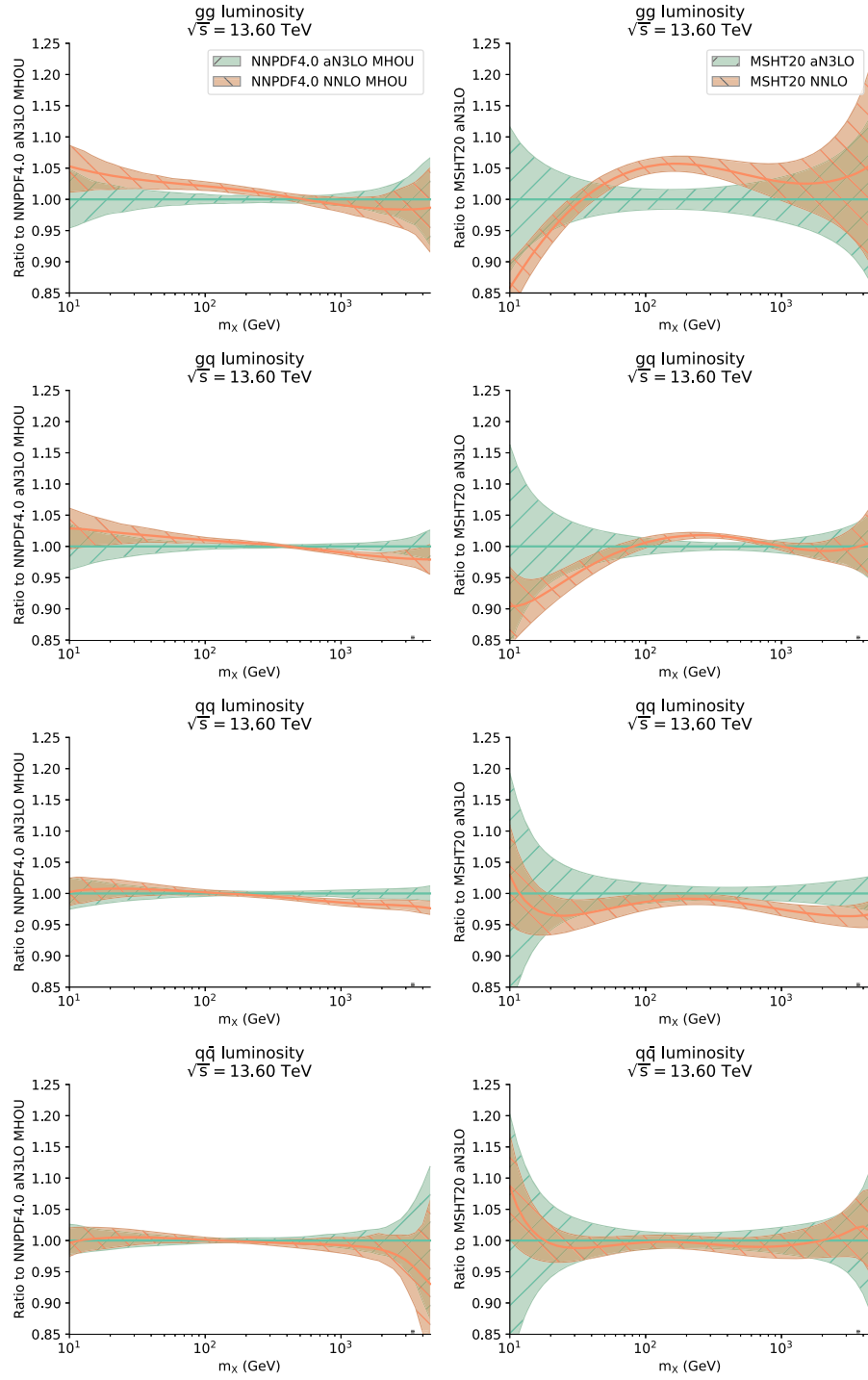


Figure 6. Comparison of NNLO and aN³LO parton luminosities for NNPDF4.0 [2, 4] (left) and MSHT20 [1, 3] (right), normalized to the aN³LO result.

MSHT20xNNPDF40_nnlo and MSHT20xNNPDF40_nnlo_qed. Note that, as discussed in section 2, the aN³LO sets do include while the NNLO sets do not include uncertainties due to MHO in the theory predictions used for PDF determination.

It should always be kept in mind that, as already mentioned, unlike the PDF4LHC21 combined PDFs [51], these aN³LO and NNLO MSHT20xNNPDF40 PDFs are an unmodified combination of the two input sets, which are based on somewhat different theoretical and methodological assumptions. They should be viewed as a means to obtain accurate but conservative N³LO predictions for LHC processes, not as an optimized PDF combined set. For example, due to the aforementioned different treatment of heavy quarks, the combined PDFs are only reliable for scales well above the heavy quark thresholds, and should not be used in regions where heavy quark mass effects are relevant, such as Higgs production via bottom quark fusion. However, we will show below that for scales $M_X \gtrsim 50$ GeV the effects of these different treatments of quark masses are in general smaller than the differences between NNLO versus aN³LO PDFs.

The combined aN³LO PDFs are displayed at $Q = 100$ GeV in figures 7–8, respectively without and with QED effects, together with the two sets that are being merged, shown as a ratio to the central value of the combined set. The central value of the combined set is, by construction, the unweighted average of the two starting sets, and the uncertainty is seen to encompass that of the two sets that enter the combination.

In order to assess the impact of the N³LO corrections, in figure 9 we compare luminosities for the LHC $\sqrt{s} = 13.6$ TeV at NNLO and aN³LO, in the latter case both without and then with QED corrections, shown as a ratio to the NNLO result, computed using the PDF4LHC21 combined NNLO PDF set [51]. For reference, the NNLO sets are compared to each other in figure 10, where we show the two different combinations, PDF4LHC21 and MSHT20xNNPDF40_NNLO, the latter both without and with QED corrections. It is clear that for the gluon-gluon and quark-quark luminosities at all scales $M_X \gtrsim 100$ GeV the impact of the aN³LO corrections is quite significant and in the gluon-gluon channel well outside the NNLO uncertainty band. On the other hand, the difference between the two NNLO combinations is significantly smaller, with each of them well within the uncertainty band of the other, thereby showing that the significance of the aN³LO does not depend on the NNLO baseline that one compares it to. For the gluon-gluon luminosity the impact of QED corrections is also significant, both at NNLO and aN³LO.

It is interesting to observe that for the gluon-gluon luminosity in the range $30 \lesssim M_X \lesssim 300$ GeV the difference between aN³LO and NNLO is significantly larger than the difference between NNLO and NLO, with the effect peaking around $M_X \sim 100$ GeV (see figure 24 of [4]), though somewhat reduced upon the inclusion of MHOU. This can be understood as the consequence of the fact that at N³LO there is a leading small x logarithmic contribution to P_{gg} and P_{gq} , which instead accidentally vanishes both at NLO and NNLO. This results in N³LO corrections leading to sizable contribution to gluon evolution even at intermediate x : indeed, both splitting functions at N³LO are qualitatively similar to the form that one obtains when including into the splitting function full small- x resummation [4]. Furthermore, the effect of N³LO corrections on splitting functions, heavy flavour contributions, and light quark coefficient functions all conspire to push the gluon in the same direction for all $x \lesssim 0.1$ (see figure 44 of [3]).

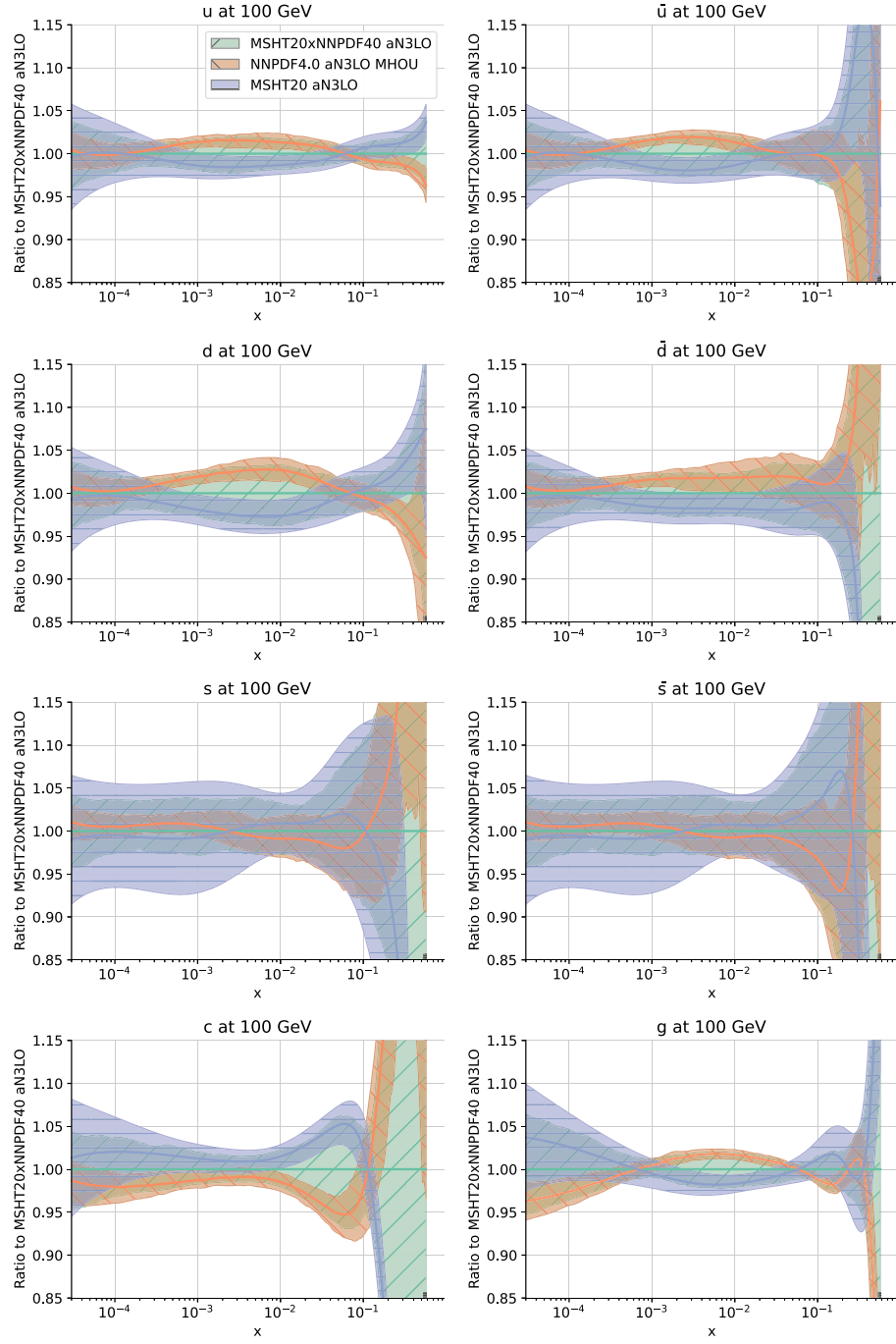


Figure 7. The combined MSHT20xNNPDF40_aN3LO PDFs, compared to the NNPDF and MSHT aN³LO PDFs that enter the combination [3, 4], shown as a ratio to MSHT20xNNPDF40_aN3LO.

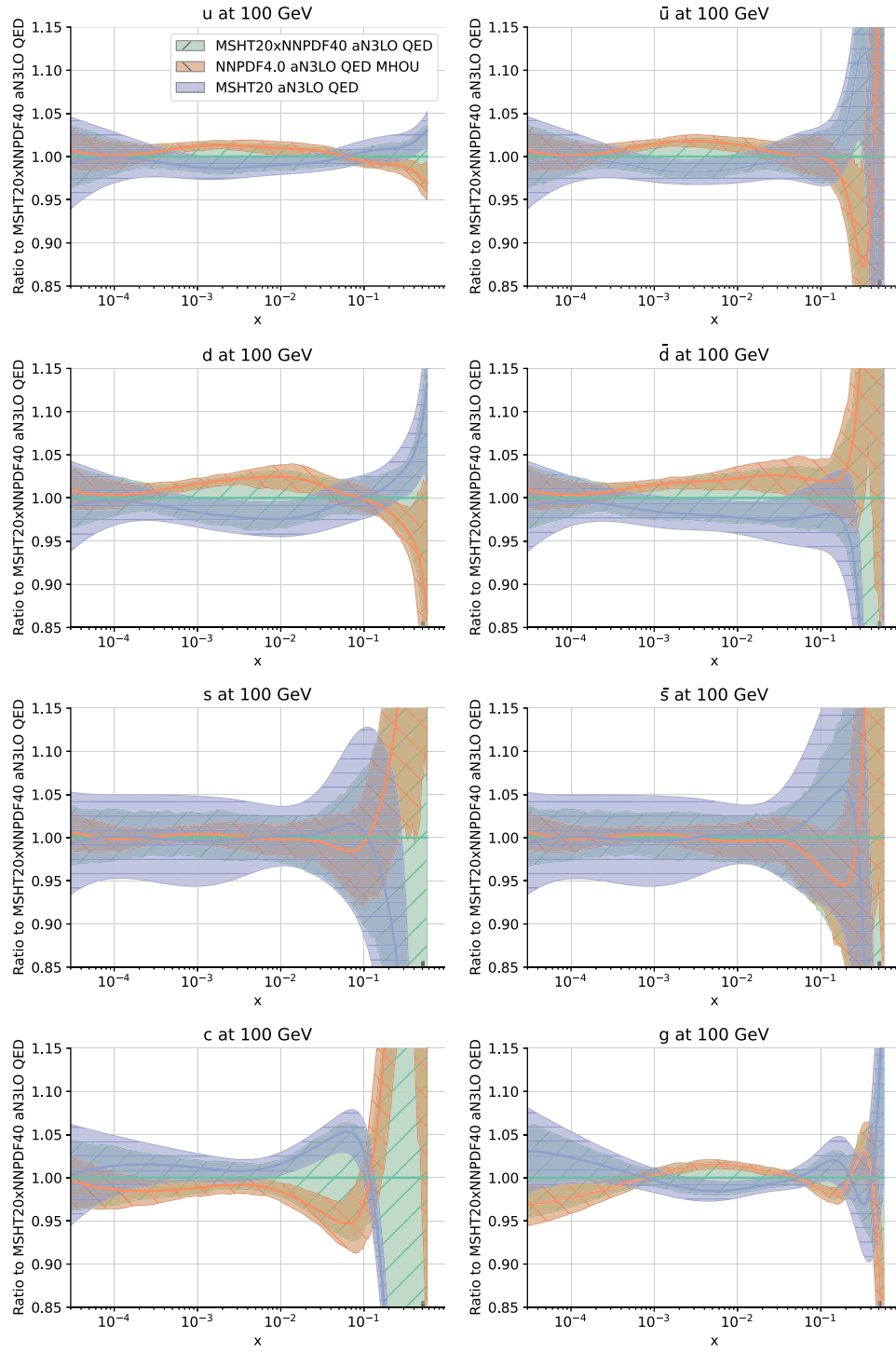


Figure 8. Same as figure 7, but for the QED PDF sets.

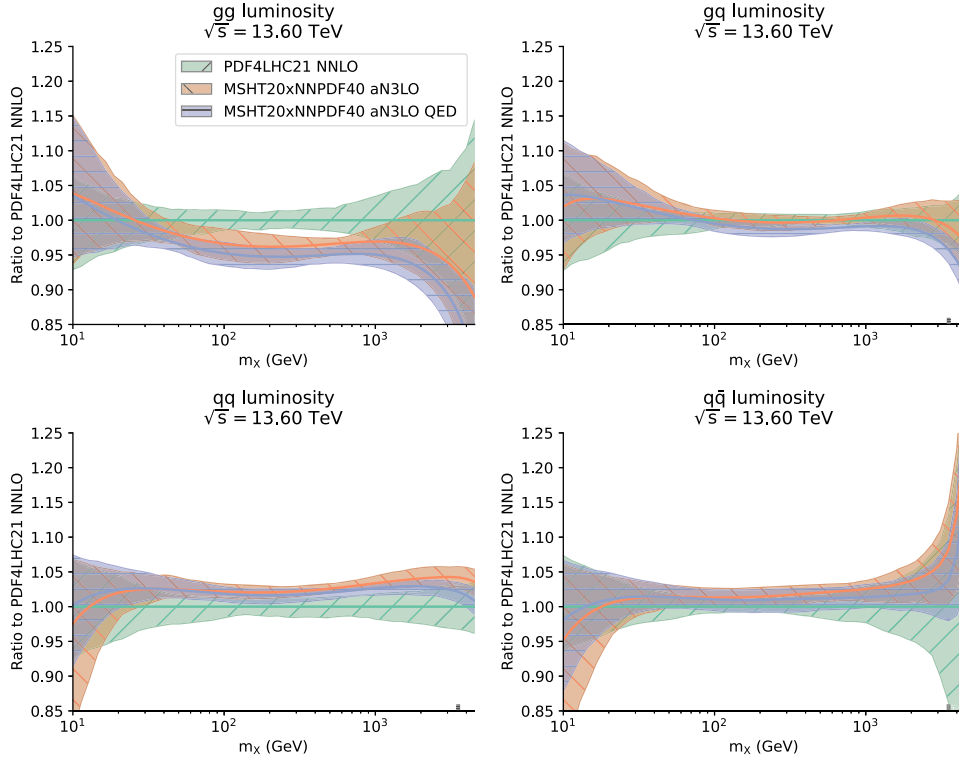


Figure 9. Parton luminosities for the LHC $\sqrt{s} = 13.6$ TeV computed from the MSHT20xNNPDF40_aN3LO pure QCD and QCD + QED sets, compared to the NNLO PDF4LHC21 result [51], and shown a ratio to the latter.

4. Implications for higgs production

We now present predictions for Higgs production at the LHC in gluon fusion, in vector boson fusion (VBF), and in association with a weak gauge boson (hV). Results are collected in tables 1–2 and displayed in figure 11. All results shown are computed for the LHC with $\sqrt{s} = 13.6$ TeV using N³LO matrix elements, and only differ in the input PDF set. No QED or electroweak corrections are included in the matrix element, and in particular photon-initiated processes are not included. The impact of these on the processes considered here is assessed e.g. in [58], it is negligible for gluon fusion, of order of a percent for VBF and a few percent for associate production, and it is similar for all PDF sets considered here as the photon PDF in the NNPDF4.0 and MSHT20 sets is quite similar, so it does not affect the comparisons presented here.

The cross-sections are computed using the `ggHiggs` code [59, 60] for gluon fusion, `n3lox`s [47] for associated production, and `proVBFH` [61, 62] for VBF. The central factorization and renormalization scales are set to $\mu_F = \mu_R = m_H/2$ for Higgs production in gluon fusion, $\mu_F = \mu_R = Q_V$ (the vector boson virtuality) for VBF, and $\mu_F = \mu_R = m_{hV}$, the event-by-event invariant mass of the hV system, in associated production. In figure 11 we do not display the hW^- cross-sections since they have the same qualitative behavior as the hW^+ cross-sections, as can also be observed from table 1.

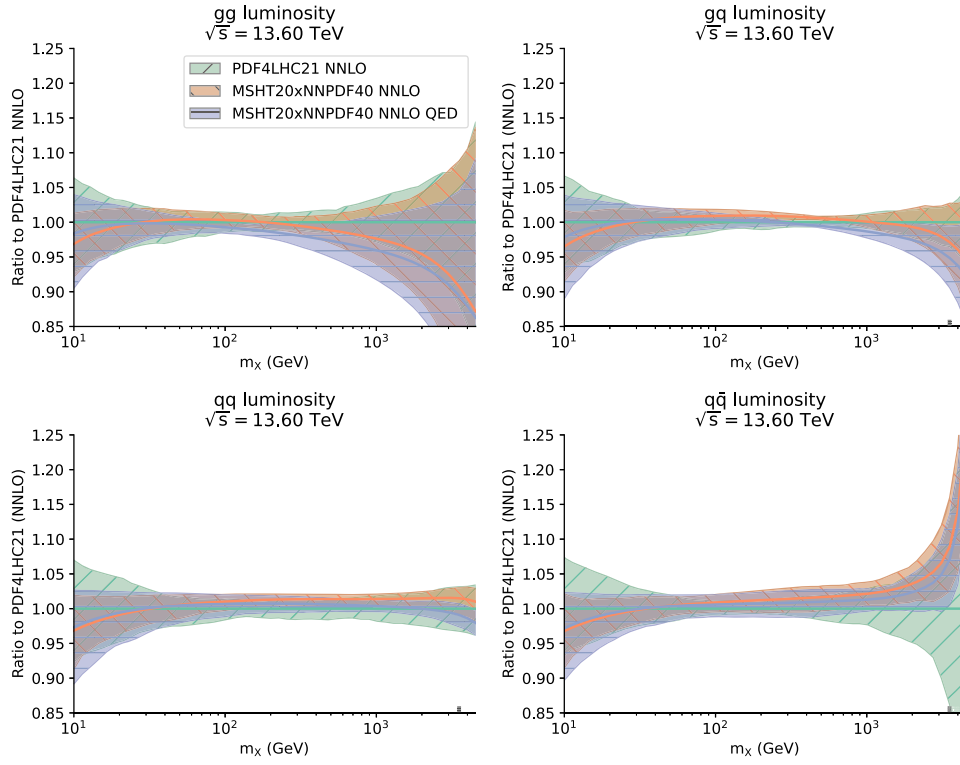


Figure 10. Comparison of NNLO parton luminosities for the LHC with $\sqrt{s} = 13.6$ TeV: the MSHT20xNNPDF40_nnlo pure QCD and QCD + QED results are compared to the PDF4LHC21 combination [51].

The uncertainties shown in tables 1–2 and in figure 11 are the pure PDF uncertainty (first uncertainty in the table and inner error bar in the figure) as well as the sum in quadrature of the PDF uncertainty and MHO uncertainties on the matrix element, the latter evaluated with the 7 point scale variation prescription (second uncertainty in the table and outer error bar in the figure). For the VBF and hV production channels the two uncertainties essentially coincide, because scale variations are negligible and the PDF uncertainty dominates, while in the gluon-fusion cross-sections scale errors represent the largest theoretical uncertainty.

Results are shown for the MSHT20 and NNPDF4.0 aN^3LO sets both with and without QED corrections, and the combined MSHT20xNNPDF40 aN^3LO sets constructed here, also with and without QED corrections. Results obtained by using perturbatively mismatched NNLO PDFs together with the N^3LO matrix element are also shown, both for the PDF4LHC21 and MSHT20xNNPDF40 NNLO combined sets. In order to visually assess the error involved in this procedure, in figure 11 we also show results as a ratio of the result to that found using mismatched NNLO PDFs, specifically from the MSHT20xNNPDF40_NNLO combined baseline set.

Table 1. The total inclusive cross-section (in pb) for higgs production in the gluon-fusion and VBF channels at the LHC run 3 with $\sqrt{s} = 13.6$ TeV. In all cases, the partonic matrix element is evaluated at N³LO accuracy not including QED or electroweak corrections. The central scales are set to be $\mu_{F,R} = m_H/2$ (gluon fusion) and $\mu_{F,R} = Q_V$ (VBF). The first uncertainty shown is the pure PDF uncertainty, and the second is the sum in quadrature of the PDF uncertainty and the MHOU on the hard cross-section evaluated with the 7-point prescription. The PDF4LHC21_mc [51] and MSHT20xNNPDF40_nnlo PDF sets are at NNLO, while all the other PDF sets [3, 4] are determined at aN³LO accuracy. The error $\Delta_{\text{NNLO}}^{\text{exact}}$, equation (1), that is made when using NNLO PDFs with the aN³LO matrix element, and its approximate estimate $\Delta_{\text{NNLO}}^{\text{app}}$, equation (2), are also provided both separately for NNPDF4.0, MSHT20, and for their combination in the case of the pure QCD fits.

PDF set	pert. order (PDF)	$\sigma(gg \rightarrow h)$	$\sigma(h\text{VBF})$
PDF4LHC21_mc	NNLO _{QCD}	46.56 ^{+1.5%} _{-1.5%} ^{+4.4%} _{-3.3%}	4.27 ^{+2.0%} _{-2.0%} ^{+2.0%} _{-2.0%}
MSHT20xNNPDF40_nnlo	NNLO _{QCD}	46.49 ^{+0.9%} _{-0.9%} ^{+4.2%} _{-3.3%}	4.35 ^{+1.3%} _{-1.3%} ^{+1.3%} _{-1.3%}
MSHT20xNNPDF40_nnlo_qed	NNLO _{QCD} \otimes NLO _{QED}	45.97 ^{+0.9%} _{-0.9%} ^{+4.3%} _{-5.4%}	4.34 ^{+1.6%} _{-1.6%} ^{+1.6%} _{-1.6%}
MSHT20xNNPDF40_an3lo	aN ³ LO _{QCD}	44.86 ^{+2.0%} _{-2.0%} ^{+4.4%} _{-5.6%}	4.45 ^{+1.2%} _{-1.2%} ^{+1.2%} _{-1.2%}
MSHT20xNNPDF40_an3lo_qed	aN ³ LO _{QCD} \otimes NLO _{QED}	44.20 ^{+1.7%} _{-1.7%} ^{+4.3%} _{-5.4%}	4.44 ^{+1.2%} _{-1.2%} ^{+1.2%} _{-1.2%}
NNPDF40_an3lo_as_01180_mhou	aN ³ LO _{QCD}	45.49 ^{+0.6%} _{-0.6%} ^{+4.1%} _{-5.2%}	4.44 ^{+0.6%} _{-0.6%} ^{+0.7%} _{-0.6%}
NNPDF40_an3lo_as_01180_qed_mhou	aN ³ LO _{QCD} \otimes NLO _{QED}	44.62 ^{+0.6%} _{-0.6%} ^{+4.1%} _{-5.2%}	4.45 ^{+0.6%} _{-0.6%} ^{+0.6%} _{-0.6%}
MSHT20an3lo_as118	aN ³ LO _{QCD}	44.08 ^{+1.8%} _{-1.6%} ^{+4.4%} _{-5.6%}	4.44 ^{+1.6%} _{-1.8%} ^{+1.7%} _{-1.8%}
MSHT20qed_an3lo	aN ³ LO _{QCD} \otimes NLO _{QED}	43.63 ^{+1.6%} _{-1.3%} ^{+4.3%} _{-5.3%}	4.43 ^{+1.5%} _{-1.8%} ^{+1.5%} _{-1.8%}
$\Delta_{\text{NNLO}}^{\text{exact}}$ (NNPDF4.0)		2.2%	1.3%
$\Delta_{\text{NNLO}}^{\text{exact}}$ (MSHT20)		5.3%	2.3%
$\Delta_{\text{NNLO}}^{\text{exact}}$ (combination)		3.3%	2.3%
$\Delta_{\text{NNLO}}^{\text{app}}$ (NNPDF4.0)		0.2%	0.2%
$\Delta_{\text{NNLO}}^{\text{app}}$ (MSHT20)		1.4%	1.3%
$\Delta_{\text{NNLO}}^{\text{app}}$ (combination)		0.9%	0.5%

Table 2. same as table 1 for higgs production in association with vector bosons.

PDF set	pert. order (PDF)	$\sigma(hW^+)$	$\sigma(hW^-)$	$\sigma(hZ)$
PDF4LHC21_mc	NNLO _{QCD}	$0.944^{+1.6\%}_{-1.4\%}^{+1.6\%}_{-1.5\%}$	$0.593^{+1.5\%}_{-1.2\%}^{+1.5\%}_{-1.3\%}$	$0.842^{+1.5\%}_{-1.0\%}^{+1.5\%}_{-1.1\%}$
MSHT20xNNPDF40_nnlo	NNLO _{QCD}	$0.957^{+1.9\%}_{-2.3\%}^{+1.9\%}_{-2.4\%}$	$0.601^{+1.5\%}_{-2.2\%}^{+1.6\%}_{-2.2\%}$	$0.855^{+1.6\%}_{-2.0\%}^{+1.6\%}_{-2.0\%}$
MSHT20xNNPDF40_nnlo_qed	NNLO _{QCD} \otimes NLO _{QED}	$0.952^{+2.1\%}_{-2.5\%}^{+2.1\%}_{-2.5\%}$	$0.598^{+1.8\%}_{-2.5\%}^{+1.8\%}_{-2.5\%}$	$0.851^{+2.0\%}_{-2.4\%}^{+2.1\%}_{-2.4\%}$
MSHT20xNNPDF40_an3lo	aN ³ LO _{QCD}	$0.961^{+1.4\%}_{-1.6\%}^{+1.4\%}_{-1.6\%}$	$0.604^{+1.2\%}_{-1.6\%}^{+1.2\%}_{-1.6\%}$	$0.859^{+1.4\%}_{-1.6\%}^{+1.4\%}_{-1.6\%}$
MSHT20xNNPDF40_an3lo_qed	aN ³ LO _{QCD} \otimes NLO _{QED}	$0.955^{+1.7\%}_{-2.1\%}^{+1.7\%}_{-2.1\%}$	$0.601^{+1.4\%}_{-2.0\%}^{+1.4\%}_{-2.0\%}$	$0.855^{+1.6\%}_{-2.0\%}^{+1.6\%}_{-2.0\%}$
NNPDF40_an3lo_as_01180_mhou	aN ³ LO _{QCD}	$0.972^{+0.6\%}_{-0.6\%}^{+0.7\%}_{-0.7\%}$	$0.610^{+0.6\%}_{-0.6\%}^{+0.6\%}_{-0.7\%}$	$0.869^{+0.5\%}_{-0.5\%}^{+0.6\%}_{-0.5\%}$
NNPDF40_an3lo_as_01180_qed_mhou	aN ³ LO _{QCD} \otimes NLO _{QED}	$0.969^{+0.6\%}_{-0.6\%}^{+0.6\%}_{-0.7\%}$	$0.608^{+0.5\%}_{-0.6\%}^{+0.6\%}_{-0.7\%}$	$0.867^{+0.4\%}_{-0.4\%}^{+0.4\%}_{-0.5\%}$
MSHT20an3lo_as118	aN ³ LO _{QCD}	$0.950^{+1.4\%}_{-1.4\%}^{+1.5\%}_{-1.5\%}$	$0.599^{+1.5\%}_{-1.5\%}^{+1.5\%}_{-1.5\%}$	$0.849^{+1.4\%}_{-1.4\%}^{+1.4\%}_{-1.4\%}$
MSHT20qed_an3lo	aN ³ LO _{QCD} \otimes NLO _{QED}	$0.941^{+1.5\%}_{-1.5\%}^{+1.5\%}_{-1.5\%}$	$0.595^{+1.6\%}_{-1.6\%}^{+1.6\%}_{-1.6\%}$	$0.844^{+1.4\%}_{-1.4\%}^{+1.5\%}_{-1.5\%}$
$\Delta_{\text{NNLO}}^{\text{exact}}$ (NNPDF4.0)		0.5%	0.3%	0.3%
$\Delta_{\text{NNLO}}^{\text{exact}}$ (MSHT20)		0.9%	1.0%	0.8%
$\Delta_{\text{NNLO}}^{\text{exact}}$ (combination)		0.6%	0.5%	0.5%
$\Delta_{\text{NNLO}}^{\text{app}}$ (NNPDF4.0)		0.2%	0.2%	0.1%
$\Delta_{\text{NNLO}}^{\text{app}}$ (MSHT20)		0.8%	0.9%	1.1%
$\Delta_{\text{NNLO}}^{\text{app}}$ (combination)		0.1%	0.2%	0.3%

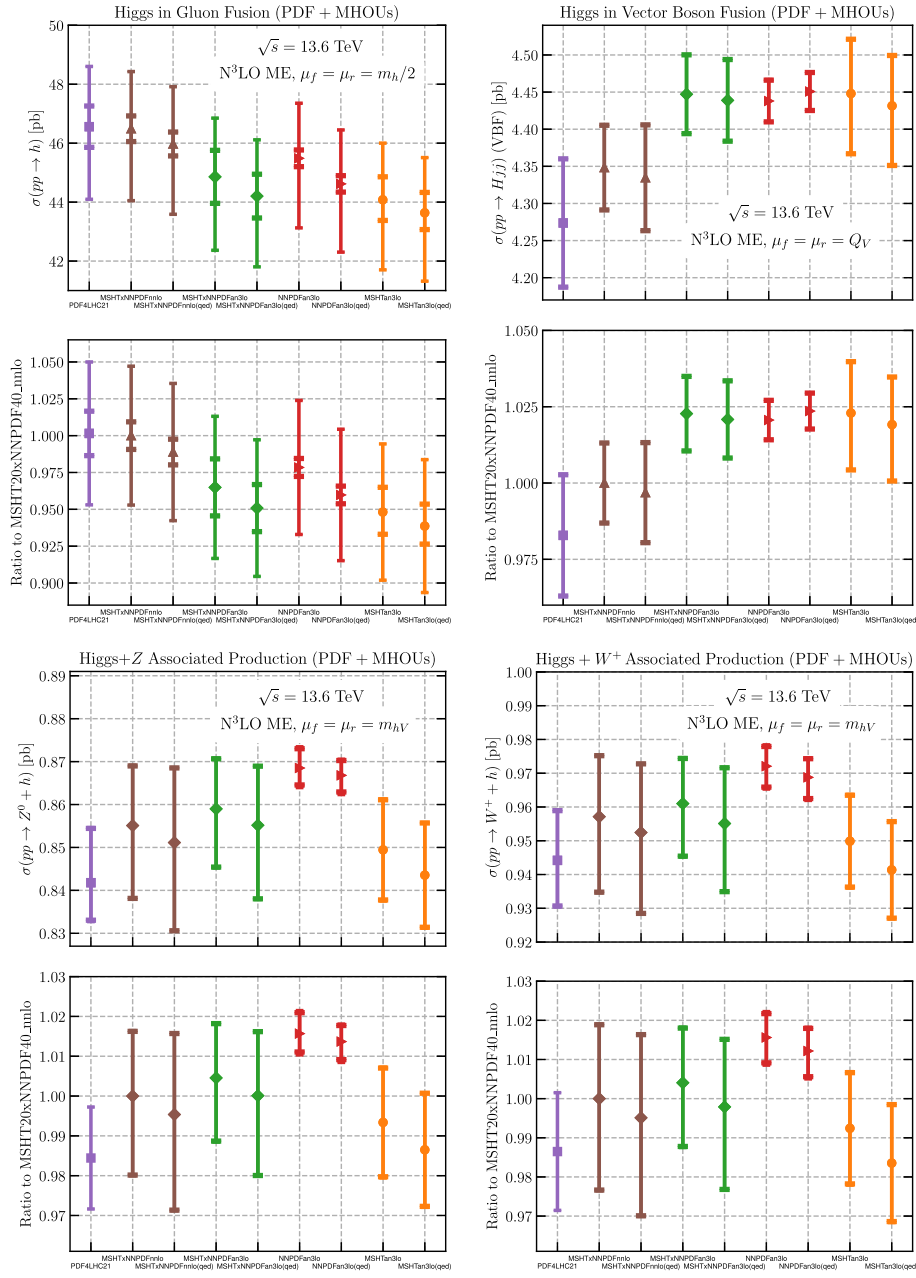


Figure 11. The cross-sections of tables 1–2, shown both in absolute scale (top) or as ratios to the result found using the MSHT20xNNPDF40_nlo baseline combination. In all cases, N³LO matrix elements are used. The results for hW^- are qualitatively similar as those for hW^+ and not shown. The inner interval is the pure PDF uncertainty (first uncertainty in tables 1–2) while the outer interval is the sum in quadrature of the PDF uncertainty and the MHOUs uncertainty on the hard cross section (second uncertainty in tables 1–2).

The percentage error made when using mismatched NNLO PDFs is

$$\Delta_{\text{NNLO}}^{\text{exact}} \equiv \left| \frac{\sigma_{\text{aN}^3\text{LO-PDF}}^{\text{N}^3\text{LO}} - \sigma_{\text{NNLO-PDF}}^{\text{N}^3\text{LO}}}{\sigma_{\text{aN}^3\text{LO-PDF}}^{\text{N}^3\text{LO}}} \right|. \quad (1)$$

An approximate way of estimating this error before knowledge of aN³LO PDFs, based on the behavior seen at one less perturbative order, was suggested in [47, 48] and it is given by

$$\Delta_{\text{NNLO}}^{\text{app}} \equiv \frac{1}{2} \left| \frac{\sigma_{\text{NNLO-PDF}}^{\text{NNLO}} - \sigma_{\text{NLO-PDF}}^{\text{NNLO}}}{\sigma_{\text{NNLO-PDF}}^{\text{NNLO}}} \right|. \quad (2)$$

The values of $\Delta_{\text{NNLO}}^{\text{exact}}$ and $\Delta_{\text{NNLO}}^{\text{app}}$ obtained for each process are also included in tables 1–2, both for NNPDF4.0, MSHT20, and the combined PDF sets constructed here, using in each case PDFs at the required perturbative orders from the same set. For the computation of $\Delta_{\text{NNLO}}^{\text{app}}$ for the combined set we use as a value for $\sigma_{\text{NLO-PDF}}^{\text{NNLO}}$ the average of the cross-sections computed using NNPDF4.0 and MSHT20 NLO PDFs.

It is clear that, as already noticed from the comparison of parton luminosities of figures 9–10, the effect of using aN³LO PDFs is most substantial for gluon fusion and vector boson fusion, which depend on the gluon-gluon and quark-quark luminosity respectively, and is small for associated hV production, which depends on the quark-antiquark luminosity. It follows that for gluon fusion and VBF using mismatched NNLO PDFs leads to a large error $\Delta_{\text{NNLO}}^{\text{exact}}$. Furthermore, the approximate estimate of this error $\Delta_{\text{NNLO}}^{\text{app}}$ is very unreliable, and specifically for gluon fusion and VBF it underestimates the true $\Delta_{\text{NNLO}}^{\text{exact}}$ significantly. The fact that for gluon fusion $\Delta_{\text{NNLO}}^{\text{app}}$ is rather smaller than $\Delta_{\text{NNLO}}^{\text{exact}}$ means that the difference between using N³LO and NNLO PDFs is significantly larger than one may expect comparing the change at the previous order, thus belying expectations [48, 63] that the impact of N³LO PDFs would be very small based on the behavior of the previous orders. This is a consequence of the behavior of the gluon luminosity discussed at the end of section 3.

Indeed, for gluon fusion there is a compensation between the hard cross-section and the gluon PDF when both are used at N³LO, with the former leading to a significant increase which is then largely eliminated by the reduced gluon distribution in the correctly matched PDFs. For VBF, instead, the use of aN³LO PDFs leads to a clear increase of 2.5% compared to using NNLO PDFs in all cases, much larger than the fixed-order uncertainty.

The choice of a specific PDF (either of the individual sets or any of the combinations) entering the calculation has a relatively small effect on VBF, either at NNLO or aN³LO. For gluon fusion this choice has a negligible effect at NNLO, while at aN³LO, as repeatedly observed, a stronger suppression is found using MSHT20 than NNPDF4.0 PDFs, with the combination providing a value in between and an uncertainty encompassing the different degrees of suppression. Hence in both cases, the error made using NNLO PDFs is larger than the PDF uncertainties, and also larger than the spread of aN³LO results. The picture is somewhat different for associate Higgs production. For this process, the impact of using aN³LO versus NNLO PDFs is negligible, so the dominant difference comes from the choice of PDF set, though results found using any of the PDF sets or combinations considered here all agree within uncertainties.

Also, we observe that for Higgs production in gluon fusion the effect of QED corrections, again as already seen in luminosities, is also not negligible, though smaller than that of using properly matched PDFs.

It is also interesting to compare results obtained using the MC combination of aN³LO PDF sets to those that would be found by performing the textbook weighted average and

uncertainty. For gluon fusion the weighted combination (with weights $1/\delta_{\text{pdf}}^2$) gives

$$\sigma_{\text{ggF}}^{\text{comb}} = 45.30 \pm 0.28_{\text{pdf}} \text{ pb} \quad (\text{pureQCD}) \quad (3)$$

$$\sigma_{\text{ggF}}^{\text{comb}} = 44.43 \pm 0.26_{\text{pdf}} \text{ pb} \quad (\text{QCD} + \text{QED}). \quad (4)$$

This is to be compared with the result found using the MSHT20xNNPDF40 aN³LO sets (both pure QCD and QCD \otimes QED) from table 1, namely

$$\sigma_{\text{ggF}}^{\text{MSHTxNNPDF}} = 44.86 \pm 0.90_{\text{pdf}} \text{ pb} \quad (\text{pureQCD}) \quad (5)$$

$$\sigma_{\text{ggF}}^{\text{MSHTxNNPDF-qed}} = 44.20 \pm 0.75_{\text{pdf}} \text{ pb} \quad (\text{QCD} + \text{QED}). \quad (6)$$

where in both cases we consider only the PDF uncertainty. It is clear that the latter result is significantly more conservative, in that it treats the two existing sets on the same footing and leads to a correspondingly rather larger uncertainty. Equations (5)–(6) should be considered our best result for Higgs production in gluon fusion, although we emphasize that the difference between this and the weighted average remains lower than the difference between the predictions based on NNLO and aN³LO PDFs.

Finally, as mentioned in the introduction, we have assessed the effect of using the preliminary variants of the aN³LO PDF sets presented here, and recently constructed by MSHT [44, 45] and NNPDF [46] using the parametrization of aN³LO splitting functions of [19], that includes all the perturbative information that is currently available, and also using for both sets the same N³LO heavy quark transition matrix element as used by NNPDF4.0. These preliminary variants have been also used in order to produce a variant combined set. Very moderate differences are found: specifically, for NNPDF, the central value of the gluon-fusion cross-section in the aN³LO baseline fit of 45.49 pb (see table 1) becomes 45.25 pb, namely a shift of -0.5% , while for MSHT the aN³LO baseline result of 44.08 pb becomes 44.26 pb, a shift of $+0.4\%$ (when only updated the splitting functions the respective value is 44.38 pb, i.e. a shift of 0.7%). In the case of the VBF cross-sections, we have verified that the impact of the updated splitting functions is negligible, i.e. of order 0.1% . Therefore, the difference between the central predictions of the aN³LO fits of NNPDF and MSHT is reduced by around 1% when the same parametrization of splitting functions from [19] is used. However, the average value obtained from a combined set of PDFs is almost unchanged. Moreover, because the updated PDFs get closer, the uncertainty found with this updated combination is reduced, consistent with the reduction in theoretical uncertainty due to better knowledge of N³LO splitting functions and transition matrix elements. In summary, the updated combination leads to an almost identical central prediction and a somewhat reduced uncertainty.

Hence, we conclude that the results using the combination presented here, based on published PDF sets, can currently be relied upon to produce a reliable set of predictions and a conservative uncertainty estimate. Similarly, the individual published aN³LO PDF sets can be taken to be reliable, as updated information results in very similar predictions well within the uncertainty, which again can be taken as conservative as improved N³LO knowledge would reduce theoretical uncertainty. On the other hand, we conclude that adopting a common set of N³LO splitting function does improve the overall consistency between the MSHT20 and NNPDF4.0 aN³LO sets, especially for the gluon-gluon luminosity. As more information on N³LO terms becomes available, it will be incorporated in future PDF sets, and PDFs based on common settings could be considered for future combinations. For the time being the existing sets may be reliably used, until they will be replaced by some newer version including updates based on improvements in N³LO knowledge but also potentially on increased data and other methodological changes.

5. Conclusion

In this note we have shown that the use of aN^3LO PDFs is mandatory for accurate N^3LO phenomenology at the LHC, focusing on the case of Higgs production cross-sections. For Higgs production in gluon fusion and in vector boson fusion the impact of switching from NNLO to aN^3LO PDFs is rather larger than the PDF uncertainty, and also larger (for VBF much larger) than the difference between different PDF sets. Indeed, we have shown that differences between existing aN^3LO PDF sets are moderate, and generally smaller than the difference between NNLO and aN^3LO . We have verified that updates due to improved knowledge of N^3LO splitting functions and transition matrix elements does not alter this conclusion.

Our results illustrate the limitations of N^3LO phenomenology at the LHC using NNLO PDFs. In order to deal with these limitations, we have constructed combined aN^3LO PDF sets, both pure QCD and QCD+QED, which allow for the computation of phenomenological predictions with a more conservative estimate of the uncertainty, as is appropriate when combining predictions that are not fully compatible. Clearly, a full N^3LO PDF determination will only be possible once all processes currently used for PDF determination are known at this order, which is likely to take some time. In particular, the calculation of the massive corrections to the DIS coefficient functions and the full set of N^3LO corrections to hadronic processes will almost certainly take many years to compute. In the meantime, our results clearly demonstrate that the available aN^3LO PDFs represent the most accurate option for the deployment of N^3LO calculations for LHC physics.

The MSHT20xNNPDF40_an3lo and MSHT20xNNPDF40_an3lo_qed PDF sets presented in this note have been submitted to the LHAPDF repository [64]. They are also made available (alongside the corresponding NNLO baseline sets) at the link:

<https://zenodo.org/records/13843626>.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <https://zenodo.org/records/13843626>.

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