

PDF4LHC recommendations for Run II

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The interpretation of LHC measurements requires a careful estimate of various sources of uncertainties that affect theoretical calculations. In this contribution, we present the PDF4LHC Working Group recommendation for the usage of sets of parton distribution functions (PDFs) at the LHC Run II. We review the construction and validation of the PDF4LHC15 combined sets, and study some of their phenomenological implications. We also address some recent criticism of these recommendations.

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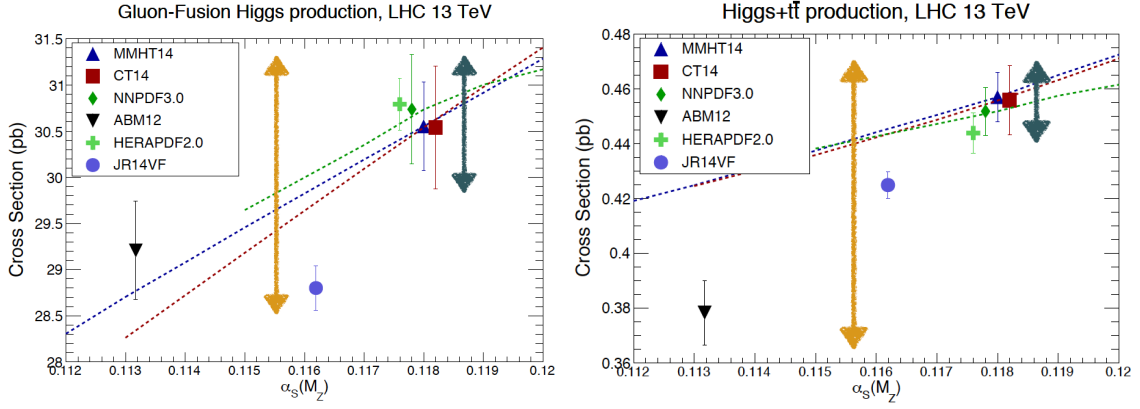


Figure 1: NLO inclusive cross-sections, evaluated with NNLO PDFs, for Higgs production at the LHC with $\sqrt{s} = 13$ TeV in the gluon-fusion (left) and the $t\bar{t}$ associated production (right) channels, for different PDFs, as a function of the native value of the strong coupling $\alpha_s(m_Z)$ value in each case. In each plot, two arrows indicate schematically two possible definitions of the *total PDF uncertainty* in these observables.

Why a recommendation? Given the ever-increasing precision of LHC measurements, careful assessment of theoretical uncertainties in LHC cross-sections is of utmost importance. One of the dominant sources arises from our imperfect knowledge of the structure of the proton, encoded by the parton distribution functions (PDFs) [1], as well as of related physical parameters such as the strong coupling α_s or the charm mass m_c . Quantifying the total PDF+ α_s uncertainties is of high importance in a number of LHC applications: a prime example is the extraction of the Higgs boson properties, such as couplings and branching fractions, which can only be achieved by a comparison of theoretical predictions with the corresponding LHC measurements. Other examples include the determination of exclusion ranges for specific BSM scenarios, when searches return null results, and determination of fundamental parameters, such as the mass of the W boson.

To illustrate the challenge, in Fig. 1 we show the NLO cross-sections (with NNLO PDFs) for Higgs production in gluon fusion and in $t\bar{t}$ associated production for different PDF sets, as a function of the native value of the strong coupling $\alpha_s(m_Z)$. These processes have been computed with MadGraph5_aMC@NLO [2, 3] using default scale settings. From Fig. 1 it is clear that results from different PDF sets are not always compatible within uncertainties. The issue is then how one can define a total PDF+ α_s uncertainty: this is required to extract the Higgs couplings from the measurements of the cross-sections shown in Fig. 1. Should one maybe take an envelope of the three global fits, CT14, MMHT14, and NNPDF3.0? Or maybe one should account for the complete spread of PDF variations? In addition, an important motivation for having an uniform treatment of PDF uncertainties in LHC calculations is allowing to establish a consistent framework for the evaluation of PDF uncertainties and their correlations in generic LHC processes.

Different points of view have been advocated to define a total PDF+ α_s uncertainty on LHC cross-sections. In this contribution, we review the recommendations of the PDF4LHC Working Group [4] for the usage of PDFs and their uncertainties for applications at the LHC Run II. We also briefly comment on an alternative recommendation presented by authors of the Ref. [5].

The PDF4LHC 2015 recommendations. One of the main limitations of the 2011 PDF4LHC

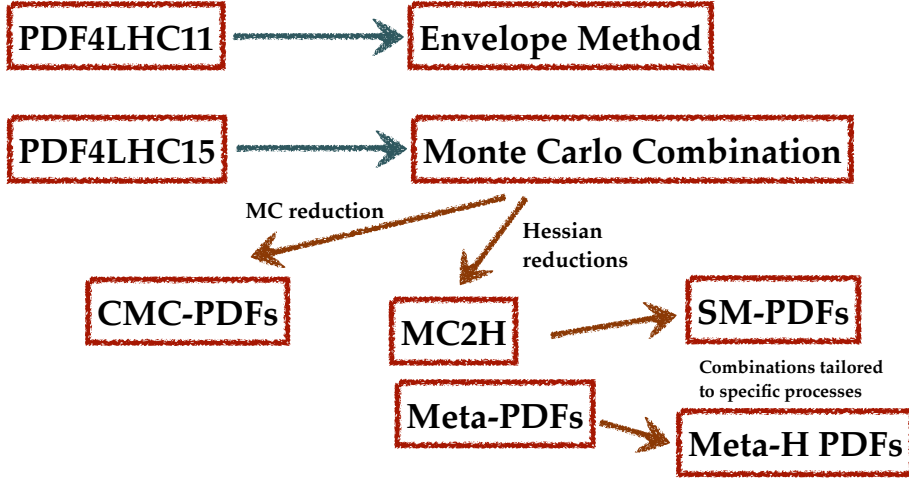


Figure 2: Schematic representation of the different algorithms leading to the PDF4LHC15 combined sets.

recommendations [6] was that it required a calculation of cross-sections for each individual PDF sets, and then combine them *a posteriori* by taking the envelope of the PDF+ α_s uncertainties from each set. Moreover, the statistical interpretation of such envelope was unclear, since it gave too much weight to outliers. To overcome these limitations, the PDF4LHC15 recommendations are now provided in terms of combined PDF sets. It is important to emphasize that switching from the envelope of the 2011 recommendation to the statistical combination of the 2015 one is at least in part motivated by the improved agreement between the three PDFs sets that enter the combination [7, 4], namely CT14 [8], MMHT14 [9] and NNPDF3.0 [10], as compared to the previous generation sets, CT10, MSTW08 and NNPDF2.1.

The PDF4LHC15 combined sets, available from LHAPDF6 [11], are constructed as follows. First of all, $N_{\text{rep}} = 300$ Monte Carlo (MC) replicas of NNPDF3.0 are combined with the same number from CT14 and MMHT14 using the Watt-Thorne method [12] for the representation of Hessian sets in terms of MC replicas. The resulting set of $N_{\text{rep}} = 900$ replicas is then reduced into more compact representations, two Hessian ones, and a MC one. In the latter case, the CMC-PDF algorithm is used [13], while in the former case the two Hessian reduced sets are constructed one with $N_{\text{eig}} = 30$ eigenvectors, using the META method [14], and the other with $N_{\text{eig}} = 100$ eigenvectors, using the MC2H algorithm [15]. This procedure is summarized in Fig. 2.¹

In general, good agreement is obtained between the prior combination and the three reduced sets in most of the relevant phase space. In Fig. 3 we compare the NNLO gluon-gluon luminosity for the PDF4LHC15 prior combination, compared with the Monte Carlo and the Hessian reduced sets. In Fig. 3 we also show a comparison of the predictions for differential distributions in Higgs production in gluon fusion at the LHC with $\sqrt{s} = 13$ TeV, in particular the rapidity and p_T distributions, obtained from the three PDF4LHC15 combined sets. A similar level of agreement is obtained at the level of correlations, both between PDFs and between different collider cross-sections.

A complete set of comparisons of the PDF4LHC15 combined sets at the level of PDFs, lumi-

¹ Although not part of the recommendation, it is possible to further compact the two Hessian reduced by specifying a preferred set of input cross-sections to be reproduced, using either the SM-PDF [16] or the META-H [17, 14] approaches.

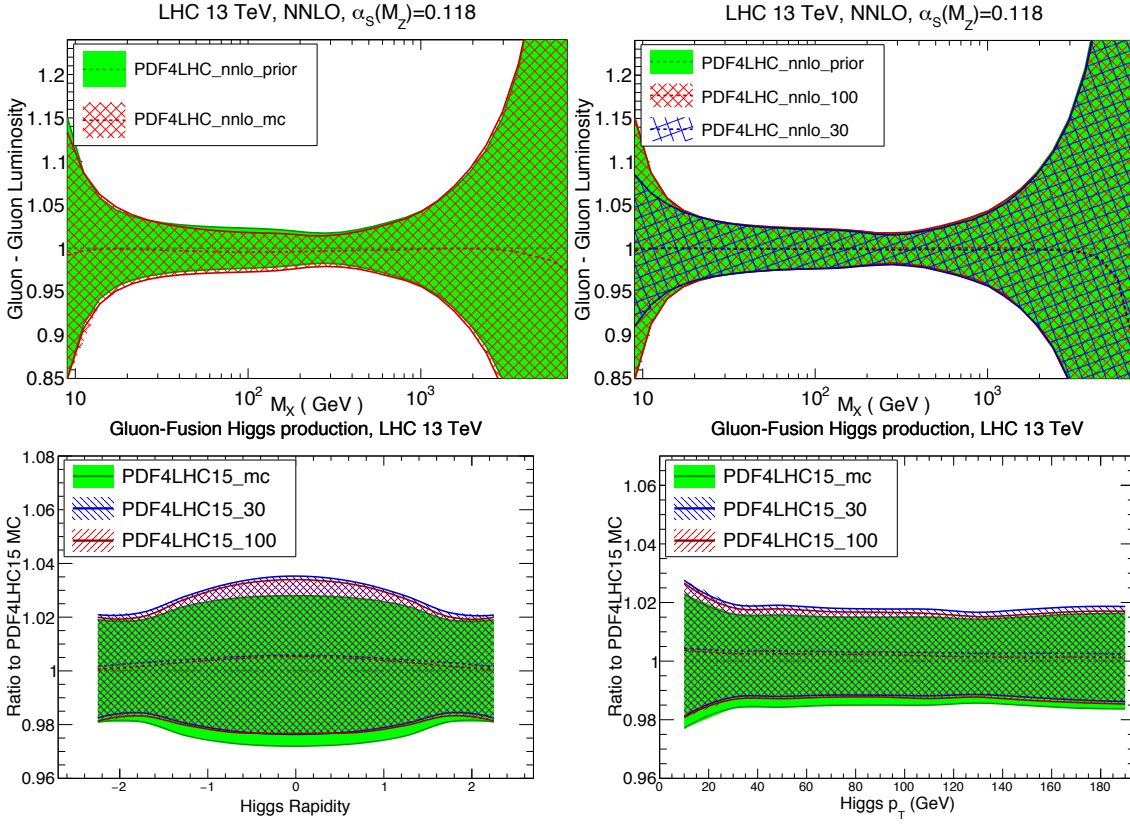


Figure 3: Upper plots: the NNLO gluon-gluon luminosity for the PDF4LHC15 prior combination, compared with the subsequent Monte Carlo (left) and Hessian (right plot) reduced sets. Lower plots: comparison of the predictions for differential distributions in Higgs production in gluon fusion obtained from the three PDF4LHC15 combined sets.

nosities and LHC cross-sections can be found at the following two websites:

<https://www.hep.ucl.ac.uk/pdf4lhc/mc2h-gallery/website/>
http://metapdf.hepforge.org/2016_pdf4lhc/

In addition to the benchmark exercise performed in the context of Ref. [4], subsequent studies in the framework of the Les Houches workshop [18] further explore both the validity and the phenomenological implications of the PDF4LHC15 recommendations, for instance addressing in more detail the issues that arise when the prior PDF combination exhibits non-Gaussian features.

An alternative recommendation. Recently, an alternative proposal for PDF usage at the LHC has been advocated by Accardi *et al* in Ref. [5]. There, a rather more conservative approach is advocated: for precision theory predictions, the recommendation would be to use the individual PDF sets from as many groups as possible, together with the respective uncertainties and the values of $\alpha_s(m_Z)$, m_c and m_b . In other words, the suggestion is to take the widest possible envelope of theoretical inputs that enter an LHC calculation. As illustrated by Fig. 1, adopting this recommendation would lead to much larger theoretical uncertainties in Higgs characterization studies

and New Physics searches, affecting the physics output of the LHC, and thus it is important to understand the reasoning that motivates this recommendation.

In this respect, there are a number of questionable assumptions in Ref. [5]:

- It does not seem justified to disregard the wealth of PDF-sensitive measurements available, including from the LHC [19], for precision physics, and treat on equal footing all PDF sets irrespectively of their level of agreement with existing data: an envelope of results based on fits to different-sized datasets degrades the accuracy to that of the fit obtained from the smallest dataset.
- In the same way as new and more precise higher-order calculations, or Monte Carlo simulations, replace older and less accurate ones, also from the PDF point of view, mixing state-of-the-art PDFs with rather older sets does not seem justified.
- The envelope procedure leads to uncertainties that are bigger than a statistical combination, but is justified only when there are large and poorly understood discrepancies. This was arguably the case at the time of the previous recommendation, but it does not seem to be the case now.
- We do not think it is justified to ignore the PDG average (and the associated uncertainty) for the strong coupling $\alpha_s(m_Z)$ [20], implicitly declaring that both the quoted central value and the uncertainty are off by a substantial amount.

Another point raised by the authors of Ref. [5] is that, for the PDF fits that enter the PDF4LHC 2015 recommendations, the numerical value of the charm mass is effectively *tuned* to reach an artificial agreement for the Higgs cross-section in gluon fusion. A first reply to this objection is that, in the three global fits, the value of $\sigma(gg \rightarrow h)$ depends only mildly on the specific value of m_c used. To illustrate this point, in Fig. 4 we show the Higgs cross-section in gluon fusion computed with NLO PDFs for a range of values of the charm pole mass m_c , for NNPDF3 [21] and MMHT14 [22]. Even in this wide range, the cross-section varies no more than 1%. In Fig. 4 we show a similar stability study, this time in the CT10 framework [23], using NNLO PDFs. Secondly, the general-mass variable-flavour number (GM-VFN) schemes used by the three groups have been extensively benchmarked [24] up to NNLO, and are known to differ only by small, formally subleading, terms. Therefore, there is little room to modify the GM-VFN matching, which by construction is more accurate than a fixed-flavour number (FFN) calculation. Finally, it should be emphasized that while the conversion of the charm mass from the pole to the $\overline{\text{MS}}$ scheme is perturbatively unstable, the same conversion is better behaved for the bottom quark. Together with the fact that $m_b^{\text{pole}} - m_c^{\text{pole}}$ is free of renormalon ambiguities, this implies that a measurement of $m_b^{\overline{\text{MS}}}$ leads to a reasonably accurate prediction of $m_c^{\text{pole}} = 1.51 \pm 0.13$ [25], consistent with the values used in the global fits.

Outlook. The PDF4LHC 2015 recommendations are the result of a joint effort by theorists and experimentalists aiming to provide a robust estimate of the combined PDF+ α_s uncertainties for precision LHC calculations. The main forum of the PDF4LHC Working Group are its periodic meetings, which provide a unique opportunity for the cross-talk between theory and experiment, as well as between PDF fitters. Topics that will be explored in the coming months include the

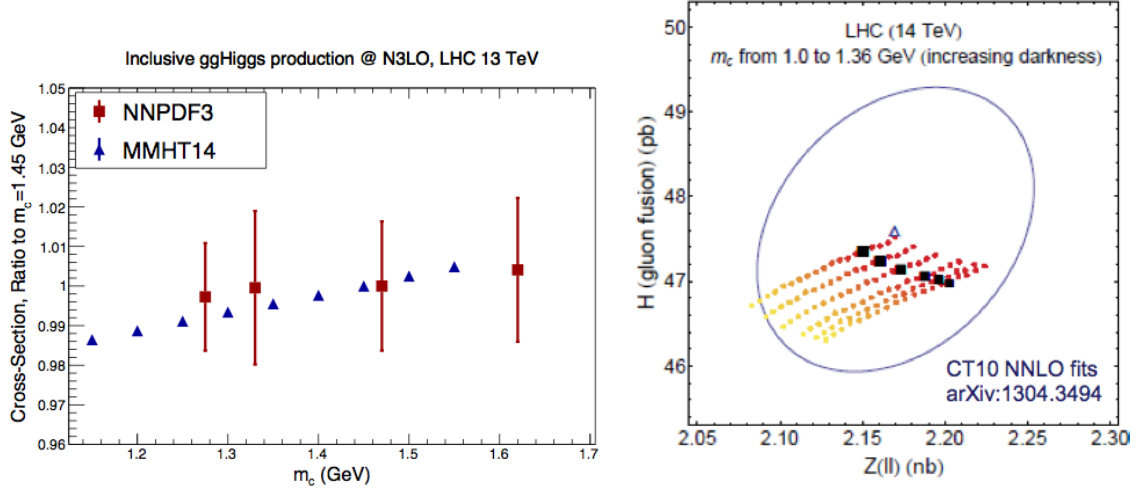


Figure 4: Left: the Higgs cross-section in gluon fusion computed with NLO PDFs for a range of values of the charm pole mass m_c , for NNP3 and MMHT14. Results are normalized to the respective values for $m_c = 1.45$ GeV. Right: the gluon-fusion Higgs cross-section as a function of $\sigma(Z)$ for a range of values of the charm mass, from the NNLO PDF fits of Ref. [23].

impact of LHC data from the 13 TeV runs, including new NNLO calculations in PDF fits and the role of electroweak corrections and the photon PDF. Eventually, PDF4LHC will present updated recommendations to take into account developments from the theory, data, and methodology points of view. For instance, future updates might include additional PDF sets. In any case, the general combination strategy developed in the context of present recommendation is flexible and robust enough to accommodate these and other foreseeable updates.

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