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Update on Higgs production in gluon fusion

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Abstract:

We provide a status report on the ongoing discussion within the working group on the benchmarking of the calculation of the total cross-section for Higgs production in gluon fusion beyond NNLO. This benchmarking is essential in view of upcoming updates of the current recommended prescription. Furthermore, we discuss plans for studies of the Higgs transverse momentum distribution and of exclusive cross-section in separate jet-bins.

1 Introduction

This document presents a status report of the ongoing work, benchmarking, and discussions within the gluon fusion subgroup. More specifically, we present results collected in view of the first subgroup meeting of November 18, 2014 [1], discussed at the meeting, and benchmarked after the meeting.

This work has focussed on recent advances on the computation of the total cross section beyond NNLO, that will be reviewed briefly in Sect. 2. This Section is primarily based on results (specifically, cross-section values) provided by the authors of the various approaches to be discussed below upon request of the working group convenors. However, in its currently status, it reflects the understanding of these numbers by the convenors, and it has not been revised or approved by individual authors. Future work on this topic is expected to include a more extensive discussion of the proper estimate of theoretical uncertainties on the cross section.

Work is also envisaged on jet multiplicity and Higgs p_T distributions in gluon-fusion production, which provide important theoretical inputs to Higgs measurements. The relevant issues, and plans for future work on this topic, is briefly reviewed in Sect. 3 of this document.

2 The total cross section

The computation of the total cross section for Higgs boson production in gluon fusion has recently been the subject of considerable theoretical activity. The focus of the discussion within the task force has thus far been the comparison and benchmarking of QCD corrections to this process beyond NNLO, in view of updating the current recommendation of ref. [2] (as currently given on the HXSWG Twiki) for the computation of this process, now or at some later stage. Here we briefly summarise the status of this benchmarking: first, we review the current recommendation and detail the settings adopted for the benchmarking exercise; then we discuss the current knowledge and present the benchmarking results for resummed and fixed-order results; finally, we collect the benchmarked results as well as the preferred results of the various groups.

2.1 Current recommendation and benchmark settings

The cross section for Higgs boson production in gluon fusion is known exactly for finite m_t at NLO in QCD [3–8]; it is known exactly in the limit of infinite top mass (the point-like limit) at NNLO in QCD [9–11], while subleading terms in the m_H/m_t series expansion have been computed in [12], confirming the accuracy of the point-like limit to the percent level or below. Using these results it is possible to construct resummed results up to NNLL. These results have been extended in various exact and approximate ways, as we shall discuss below.

Note that in the literature, there is a certain variety of definitions of logarithmic counting: here, as in Ref. [2], by N^{k}LL we mean that at order α_s^n the coefficients of logarithmically-enhanced terms in Mellin space ($\ln^l N$) are determined for $2(n-k) \leq l \leq 2n$, so in particular by NNLL we mean that at order α_s^n the coefficients of logarithmically-enhanced terms in Mellin space ($\ln^k N$) are known for $2n-4 \leq k \leq 2n$ (see Sec. 2.2 below and specifically Eq. (2.1) for a definition of the Mellin variable N). We will refer to this as the "standard" definition (meaning that it is the standard of the present document). According to a different definition, often used in the SCET literature, what is called N^{k}LL using the standard definition is instead called N^{k}LL', with N^{k}LL instead meaning that at order $\alpha_s^n \ln^l N$) the coefficients are determined for $2(n-k)+1 \leq l \leq 2(n-k+1)$. We will refer to this as SCET definition of logarithmic counting.

The current recommendation is the cross section computed at NNLO+NNLL in QCD, with a specified set of parameter settings. Because our main interest is in discussing QCD terms beyond NNLO, we have performed a benchmarking exercise in which we have suggested simplified choices for these settings. For many of these settings there has been no progress and therefore no need to test or update them. For future reference, here we summarize briefly the current recommended choices, possible updates, their typical impact, and the settings used in the benchmarking.

- **PDFs and α_s**: The choice of parton distributions and the value of α_s contribute in approximately equal parts to the uncertainty and have a sizeable combined impact on it: their combined contribution to the uncertainty is certainly above 5% and perhaps as large as 10%, depending on how conservatively it is estimated. The current HXSWG recommendation relies on the so-called PDF4LHC prescription [13]. A provisional simplified and updated version of this prescription is currently available, and a complete revision is anticipated soon [14]. For the benchmarking the MSTW08 NNLO central PDF is used, with its default value of $\alpha_s(M_z) = 0.1171$.

- **Heavy quarks**: The use of finite top- and bottom-quark mass corrections have an impact of $\approx +7\%$ (top-quark only) and $\approx -5\%$ (top-bottom quark interference), while the charm-quark mass effect has an impact at the 1% level or below. The current recommendation includes all these corrections to NLO and NLL, with the point-like approximation used at NNLO and NNLL, as its impact, as mentioned, is very small. For the benchmarking, finite m_t effects have been included to NLO, with $m_t = 172.5$ GeV, and at the NNLO level, they are simulated by the multiplication by $K = \frac{\sigma_{\text{LO,exact top}}}{\sigma_{\text{LO,EFT}}}$, which already at NLO works to better than 1% (indeed, one of the approximate N^{3}LO results which we will compare can only be constructed if m_t is kept finite).

- **Electroweak corrections**: Electroweak (EW) corrections have a non-negligible impact, at the 5% level. In the current recommendation, virtual EW corrections are included to NLO using complete factorization. Mixed QCD-EW corrections and real EW radiation terms are not included. Electroweak corrections are not included in the benchmark.

- **Higgs decay** For a low-mass Higgs boson, finite-width effects are below the 1% level. In the current recommendation they are included using an effective implementation of the complex-pole scheme (the so-called off-shell propagator, or OFFP scheme of Ref. [15]. They are not included in the benchmark.

In the benchmark, cross sections have been compared using these settings for LHC $\sqrt{s} =$ 13 TeV, assuming $m_h = 125$ GeV. Results were requested both for the gluon partonic subchannel (i.e., results such as would be obtained if only the gluon PDF were different

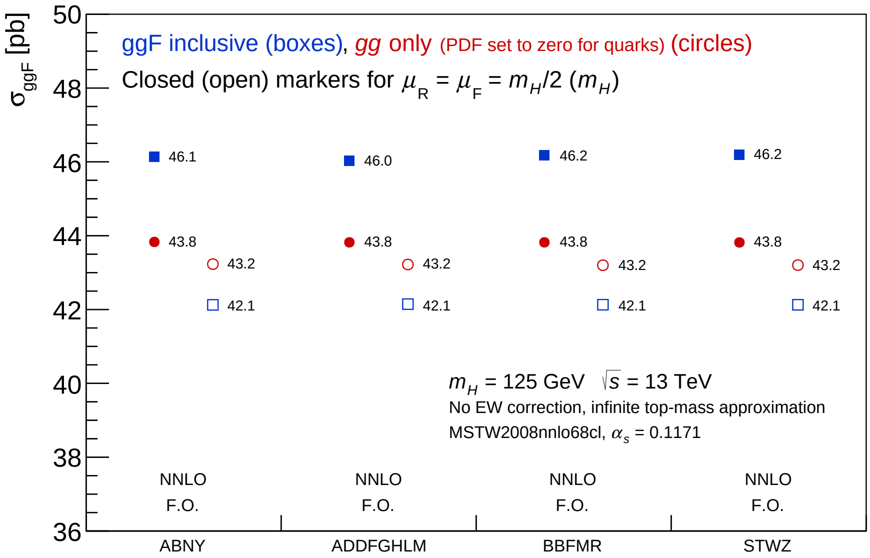

Figure 1. Demonstration of consistent NNLO results from the groups participating in the benchmarking.

from zero, and all quark PDFs vanished), and for the total. Also, results were requested with two different possible choices for the central factorization and renormalization scales, $\mu_r = \mu_f = m_H$ and $\mu_r = \mu_f = m_H/2$, with variation of all scales by a factor two about these central choices, but avoiding the two extreme cases $\mu_r/\mu_f = 4$, $\mu_r/\mu_f = 4$.

We will present results as K-factors relative to the fixed-order NNLO prediction obtained with the same settings. As shown in Fig. 1, we have verified that this prediction is reproduced by the various groups participating in the benchmarking. In this and in the following plots, ABNY denotes the authors of Ref. [16], ADDFGHLM the authors of Ref. [17, 18], BBFMR the authors of Ref. [19], STWZ the authors of Ref. [20], and dFMMV the authors of Ref. [21]. All of these groups were asked to provide numbers; when a group is not shown, the corresponding number from the group is not available. Results corresponding to the current recommendation Ref. [22] are denoted as dFG.

2.2 Resummation

The general structure of the resummed level is best discussed by considering the Mellin transform

$$\hat{\sigma}(N, m_H^2) \equiv \int_0^1 d\tau\, \tau^{N-2} \hat{\sigma}(\tau, m_H^2) \tag{2.1}$$

of the partonic cross section $\hat{\sigma}(z, m_H^2)$, with $z = m_h^2/\hat{s}$ and $\hat{s}$ the partonic center-of-mass energy.

At the resummed level, the partonic cross section can be written as

$$\sigma_{\rm res}(N, \alpha_S) \quad = \quad \sigma_0 g_0(\alpha_S) \exp\left[\frac{1}{\alpha_S} g_1 + g_2 + \alpha_S g_3 + \alpha_S^2 g_4 + \ldots\right], \tag{2.2}$$

$$g_0(\alpha_S) \;=\; 1 + \alpha_S g_{0,1} + \alpha_S^2 g_{0,2} + \alpha_S^3 g_{0,3} + \mathcal{O}(\alpha_S^4), \tag{2.3}$$

where $g_i \equiv g_i(\alpha_S \ln N)$ for $i > 0$: these g_i functions in the exponent contain terms enhanced by powers of $\ln N$, while g_0 contains N-independent terms (constants, henceforth). At the N^{n}LL level (with the standard definition) the g functions are included up to g_{n+1} in Eq. (2.2), and terms up to $g_{0,n}$ are included in Eq. (2.3). As mentioned above, using the SCET definition this is called N^{n}LL', and at the N^{n}LL level only terms up to $g_{0,n-1}$ are included in g_0. In the current recommendation, resummation is included up to NNLL (standard definition). The constant $g_{0,3}$ has been computed recently in the point-like limit, so N^{3}LL resummation is almost possible: it requires knowledge of the function g_4, which is determined except for the still unknown coefficient of $\ln N$ to order α_s^4, in the gluon-channel anomalous dimension $\gamma_{gg}(\alpha_s, N)$ (i.e. the Mellin transform of the gluon-gluon Altarelli-Parisi splitting function).

The logarithmic counting can be equivalently performed in z, for the partonic cross section $\hat{\sigma}(z, m_H^2)$. Indeed the inverse Mellin transform of $\ln^k N$ contains "plus" distributions of the form $\left(\frac{\ln^n(1-z)}{1-z}\right)_+$ (where $+$ denotes the addition of a Dirac delta term to the quantity to which it is applied, such that its first Mellin moment vanishes), with all $n \leq k-1$, up to terms of relative $\mathcal{O}(1-x)$. Of course, this means that if the logarithmic counting is performed in z space, and the N^{k}LL result is then Mellin-transformed, the result generally differs by both logarithmically subleading and power-suppressed terms relative to that which is obtained if the log counting is performed in N space.

Available resummed results differ because of two main classes of reasons, explored by the benchmarking:

- **Treatment of constants**. The function $g_0(\alpha_s)$ in Eq. (2.2) may be exponentiated entirely or in part: if the partonic cross-section is computed to a given logarithmic accuracy (say NLL, in which case $g_{0,1}$ only would be kept), its exponentiation leads to a logarithmically subleading contribution (indeed exponentiation of the $g_{0,1}$ term leads to term of order of $g_{0,2}$ and beyond). Of course, the separation between what one calls constant and what one calls logarithmically enhanced is itself conventional and changes e.g. if one lets $N \to N+1$ in the argument of the log: we refer to the resummed result in Eq. (2.2) as a result with "non-exponentiated constants". This is the result used in the current recommendation [22]. The two groups which provide alternative resummed predictions, namely Refs. [16, 23], have a preferred treatment of constants, in which some part of the function g_0 is included in the exponent ("exponentiated constants"). We thus compare results from these groups with their preferred treatment of constants, to those which would be obtained with the constants treated as in the current recommendation, i.e. using Eq. (2.2). The difference between the K-factors computed with and without exponentiated constants can be viewed as the effect of their exponentiation (regardless of the way the logarithmic resummation is performed). We also provide a prediction from a third group, namely Ref. [20], which simply supplements the fixed-order result with an exponentiation of constants. This prediction thus provides a third determination of the effect of constant exponentiation.

  Figure 2 shows the impact of the exponentiation of constants; note that results differ not only because of the details of the choice of the constants to be exponentiated, but

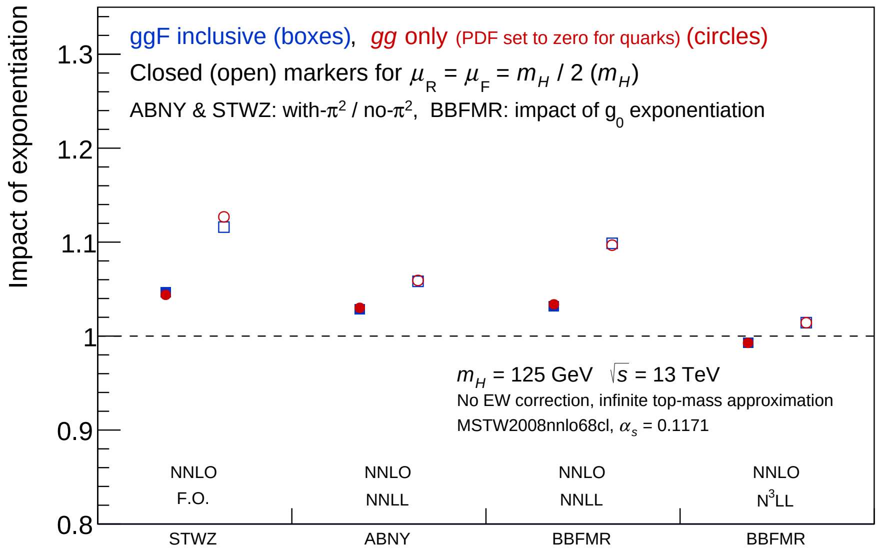

Figure 2. Impact of the exponentiation of constants.

also sometimes because the baseline results to which the exponentiation is applied differ. The effect of the exponentiation of constants is always larger with $\mu_r = m_H$, and more moderate if $\mu_R = m_H/2$. As one would expect, and perhaps reassuringly, the impact is largest for the group (STWZ) which applies it to unresummed (NNLO) results, intermediate when applied to resummed NNLO+NNLL results (ABNY and BBFMR) and smallest (and in fact negligible) when applied to resummed results at one more perturbative order, namely N^3LO+N^3LL (BBFMR).

- **Subleading and power-suppressed terms**. As mentioned, performing the resummation in z space or in N space naturally leads to results which differ by logarithmically subleading and power suppressed terms, which can be further adjusted in each approach. Resummed results of Ref. [16] have been obtained using a SCET approach, which is naturally formulated in z space, while the current recommendation is based on N-space resummation. Furthermore, in Ref. [23] resummation is also performed in N space, but a specific choice of subleading terms is advocated, based on analyticity arguments [24] (see also Sect. 2.3 below) which differs from the default choice in the current recommendation. In Ref. [23], resummed results at N^3LL are also presented, both with the choice of subleading terms of the current recommendation, and with their preferred choice based on analyticity; both cases include a guess of the unknown coefficient referred to above (which has a completely negligible impact, as it only enters at $\mathcal{O}(\alpha_s^4)$). Note that the resummed results of Ref. [16] are in fact obtained at N^3LL according to the SCET definition of logarithmic counting; they should therefore be compared to the NNLL result with the current definition of log counting, as it turns out that the N^kLL result with SCET counting is very close to the N^{k-1}LL result with standard counting.

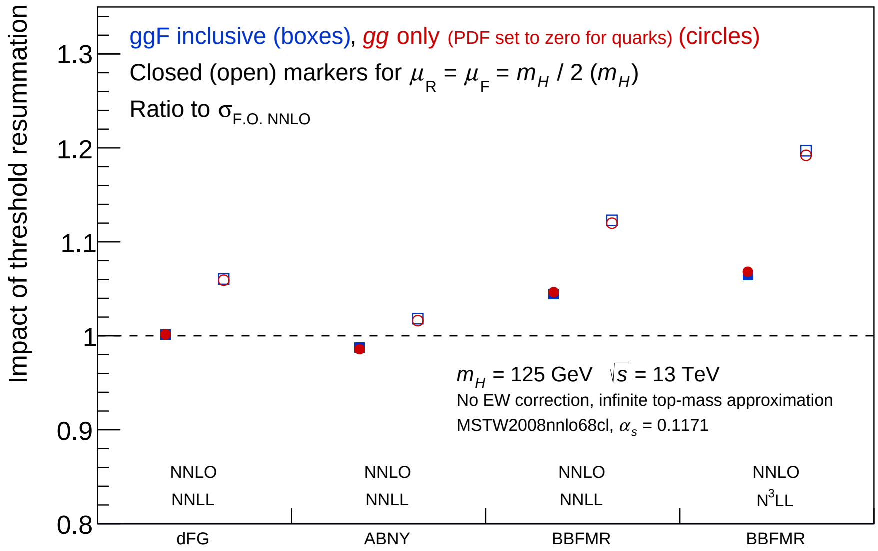

Figure 3. Impact of threshold resummation.

In Figure 3 we show the ratio of resummed to unresummed results from these groups, also including the current recommendation (dFG). The constant exponentiation is not included, either at the resummed or the unresummed level, so that only the effect of the resummation in the form of Eq. (2.2) is compared here. This means (a) that differences between various results in this plot are only due to the treatment of subleading and power-suppressed terms, and (b) that the overall effect of resummation for the ABNY and BBFMR groups is found by multiplying the K-factors shown in Fig. 2 by those of Fig. 3 (recall that dFG, instead, does not exponentiate any constant).

The impact of resummation is found to be smaller with $\mu_R = m_H/2$ than it is with $\mu_r = m_H$, as it was already observed in Ref. [2] and elsewhere. For this choice of scale, also the ambiguity is smallest, with the SCET-based result of ABNY leading, at NNLL, to almost no enhancement for $\mu_r = m_H$, dFG to an enhancement of order of 7%, and BBFMR of order 12% in comparison to the fixed-order NNLO prediction (this hierarchy was already understood and discussed in Refs. [16, 24, 25]). At N^{3}LO BBFMR find a yet larger enhancement, of order of 20% in comparison to the unresummed NNLO.

2.3 N^{3}LO cross section

We first summarize the current partial knowledge of the N^{3}LO partonic cross section, and then discuss various approximations which have been suggested. Truncation of the resummed result up to $O(\alpha_s^3)$ clearly provides an approximate expression for the N^{3}LO cross section.

Based on this observation, a soft expansion for the N^{3}LO term can be considered, with the following form:

$$\hat{\sigma}^{(3)}(N) = c_{06} \ln^6 N + c_{05} \ln^5 N + \cdots + c_{02} \ln^2 N + c_{01} \ln N + c_{00} \tag{2.4}$$

$$+\frac{1}{N}\left(c_{15}\ln^5 N + c_{14}\ln^4 N + \cdots + c_{10}\right) \quad (2.5)$$

$$+\frac{1}{N^2}\left(c_{25}\ln^5 N + \cdots + c_{20}\right) + \ldots . \quad (2.6)$$

The terms in the first row provide the soft approximation to the N^{3}LL; the terms in the second row provide the next-to-soft (NS) approximation, and so on. The soft terms are only present in the gg partonic subchannel, while the quark-gluon channel starts at the NS level and the quark-antiquark at the NNS level. Note that the leading log is purely soft, because it corresponds to the pure eikonal approximation.

While the resummation calculations are traditionally described in Mellin space, fixed-order computations are usually done in z-space, where one defines the total cross section as the convolution

$$\sigma = \tau \sum_{ij} f_i \otimes f_j \otimes \frac{\hat{\sigma}_{ij}(z)}{z}\,, \quad (2.7)$$

where

$$\frac{\hat{\sigma}_{ij}}{z} = \frac{\pi}{64} C(\mu^2, a_s)^2 \sum_k \left(\frac{a_s}{\pi}\right)^k n_{ij}^{(k)}(z)\,, \quad (2.8)$$

and the N^{3}LO that we are interested in corresponds to $n_{ij}^{(3)}(z)$. These can be written as

$$n_{ij}^{(3)}(z) = n_{ij}^{(3),sing}(z) + n_{ij}^{(3),reg}(z)\,, \quad (2.9)$$

where with $n_{ij}^{(3),sing}(z)$ we denote terms which, in $z = 1$ diverge at least as $\frac{1}{1-z}$, or are distributions. These terms, as mentioned above, are those which, upon Mellin transformation, are either singular or constant as $N \to \infty$. The contribution $n_{ij}^{(3),reg}(z)$ diverges at most logarithmically in $z = 1$, and, upon Mellin transformation leads to terms which vanish as $N \to \infty$. The latter terms have the structure

$$\begin{aligned} n_{ij}^{(3),reg}(z) &= c_5(z)\log^5(1-z) + c_4(z)\log^4(1-z) + c_3(z)\log^3(1-z) \\ &\quad + c_2(z)\log^2(1-z) + c_1(z)\log^1(1-z) + c_0(z), \end{aligned} \quad (2.10)$$

where on the right-hand side the coefficients $c_i(z)$ should also carry partonic subchannel labels ij which we have suppressed for simplicity.

Finally, the coefficients $c_i(z)$ can be expanded in power series about $z = 1$:

$$c_i(z) = \sum_{k=0} (1-z)^k c_{ik}^{(z)}\,, \quad (2.11)$$

which then leads to a soft expansion, but now in z space. We can then define a z space soft approximation, which consists of including only $n_{ij}^{(3),sing}(z)$; a z-space next-to-soft approximation (NS) in which $n_{ij}^{(3),reg}(z)$ are also included, but with all coefficients $c_i(z)$ computed to 0-th order in Eq. ((2.11)) (i.e., the constants), a NNS approximation in which $c_i(z)$ are computed to first order, and so on.

As already mentioned in Sect 2.2, Mellin transformation maps distributions and powers of logs of $(1 - z)$ into powers of $\ln N$. So knowledge of the full set of $n_{ij}^{(3),sing}(z)$ coefficients in Eq. (2.9) fully determines the soft terms in Eq. (2.4), and conversely: the soft approximations in z space and in N space are determined from each other, with the N^{k}LL in N space being determined by the N^{k}LL in z space. Likewise, knowledge of the NS approximation in z space determines the NS approximation in N space and conversely, and so on.

However, as also already mentioned, in each case the corresponding z- and N space approximations differ by logarithmically subleading and power-suppressed terms. This remains true order by order in the soft expansion: Eq. (2.11) in powers of $1-z$, which corresponds to the expansion Eq. (2.4) in powers of $\frac{1}{N}$. So the full set of NS terms in Eq. 2.4 fully determines all coefficients $c_i(z)$ up to order $(1-z)^k$, and so on. So for instance the N space NS approximation will contain all z space NS terms, but it will also contain N^{k}NS z space terms, and conversely, and thus the N space and z space approximation to given logarithmic or power will in general be numerically different.

We now come to the knowledge of various coefficients. The soft coefficients of Eq. (2.4) from c_{06} down to c_{02} are determined by NNLL resummation (generally for finite m_t). The coefficient c_{01} was computed long ago in Refs. [26, 27]. The coefficient of the $\delta(1-z)$ distribution term in z space has been recently computed in Ref. [28] (in the pointlike approximation), thus determining the last missing c_{00} coefficient, and thus also fully determining the soft approximation, or, equivalently the full z space singular terms.

Coming now to terms beyond the soft approximation, or nonsingular terms, the coefficients c_{15}, c_{25}, ... are all determined (to all orders in $1/N$) from leading-log resummation, thanks to an argument of Ref. [29]. This thus determines fully $c_5(z)$ Eq. (2.10). The NS coefficient c_{14} in the gg channel has been also recently computed in Ref. [21] based on a conjecture on the log structure of the hadronic cross section. The same authors have also presented an educated guess for the remaining NS in Eq. (2.5), and thus for the full NS contribution (in the point-like approximation) in the gg channel (approximate NS, henceforth). Recently in Ref. [18] the coefficients $c_0(z)$, i.e. the leading terms in the expansion of $n_{ij}^{(3),reg}(z)$ Eq. (2.11) have been fully determined in all channels. The full NS approximation is thus fully determined by this result, thus in particular confirming the conjecture of Ref. [21] for c_{14}. Finally, in Ref. [18] the coefficients $c_5(z)$, $c_4(z)$ and $c_3(z)$ with full z dependence have also been determined computed for all channels, thus confirming the known values of the c_{15}, c_{25}, ... coefficients Eqs. (2.5-2.6) and also determining fully the set of N space c_{i4} and c_{i3} N space coefficients. Hence, only the formally sub-leading terms in the expansion of $c_{2,1,0}(z)$ around $(1-z)$ are still unknown.

Several approximate N^{3}LO expressions have been suggested recently:

- Moch et al. [21] have suggested an approximation including the soft and next-to-soft terms in N space [Eqs. (2.4-2.5)], using their approximate NS. Of course, now that the exact NS is known it is in principle possible to construct this approximation using the exact NS expression.

- Bonvini et al. [24] have suggested an approximation based on combining all available information on the singularities of the Mellin-space partonic cross section, which include all the logarithmic singularities at $N \to \infty$ determined by resummation and discussed in Sect. 2.2, supplemented by the recently provided information on the soft approximation, as well as simple poles on the real N axis, whose coefficient is determined by the so-called high-energy or BFKL resummation. In the approach of Bonvini et al. the soft terms are thus included, but not written as powers of $\ln N$, but

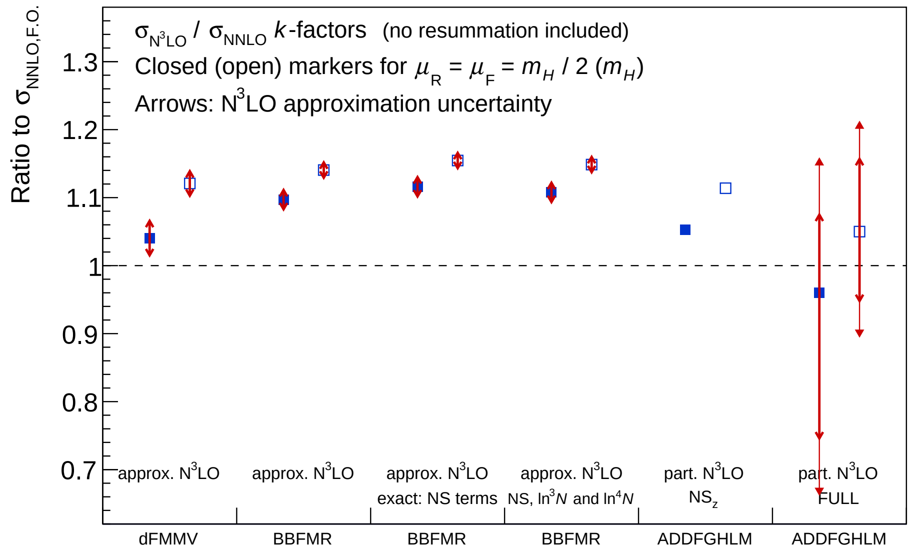

Figure 4. Impact of the approximate N^{3}LO corrections. Since the ADDFGHLM approximation uncertainty estimate is based on deviations from the NS$_z$ result, it doesn't apply to the NS$_z$ result itself, so the NS$_z$ ADDFGHLM point has no uncertainty arrows attached to it.

rather, as combinations of suitable functions which behave as powers of $\ln N$ as $N \to \infty$ but have simple poles (rather than cuts) in the N plane, specifically for $N = 0$. They correspond to the truncation of the preferred resummation by the same group referred to in Sect. 2.2 above. As a consequence, in this approximation subleading terms in the soft expansion are determined approximately. Again, now that some of these terms are known exactly it is possible to improve the approximation by replacing approximate coefficients with their exact form. This includes the full NS, and the coefficients of $\ln^4 N$ and $\ln^3 N$, as the exact coeffficients of $\ln^5 N$ which were already known from Ref. [29] are already included in the original approximation.

- Anastasiou et al. [18], having observed that the corrections to the full z-space NS approximation from the full inclusion of the formally leading $\ln^5(1-z)$, $\ln^4(1-z)$ and $\ln^4(1-z)$ logarithms are large and negative, have suggested to retain all the known contributions in z-space as an approximation of the cross section with current knowledge, but to allow for a very generous uncertainty due to the still unknown missing contributions of $\log^{0,1,2}(1-z)$. They claim that the deviation from the z-space NS approximation due to these logarithms can be as large as the one observed for $\log^{3,4,5}$, thus cancelling the suppression relative to the NS result, or leading to an overall enhancement.

In Fig. 4 we show the ratio between the N^{3}LO and NNLO predictions from the dFMMV, BBFMR and ADDFGHLM groups. For dFMMV only their original approximation is shown, though it is based on an approximate form of the NS N-space approximation, and it should thus be replaced with the exact NS approximation which is now known; the effect of the change is however expected to be small. For BBFMR, we show their original approximation as published in Ref. [19], as well as the version of this approximation in which all the NS terms are replaced by their exact values (denoted as exact NS terms), and that in which the coefficients of $\ln^4 N$ and $\ln^3 N$ terms are also replaced by their exact values (denoted as NS, $\ln^3 N$, $\ln^4 N$), thereby showing the effect on these approximation due to the exact knowledge acquired in Ref. [18]. For ADDFGHLM we show both their preferred result, including all known z space terms (denoted as FULL), as well as the pure z-space NS approximation (denoted as exact NS_z terms). The ADFFGHLM NS_z result should be compared to the BBFMR-"exact NS terms", and the ADFFGHLM FULL result to the BBFMR-"NS, $\ln^3 N$, $\ln^4 N$". The differences are due to the treatment to subleading terms, and also to the inclusion of known N-space poles by BBFMR. For all these approximations, an estimate of the approximation has also been provided by the respective authors: these estimates are shown as arrows. dFMMV estimate the total uncertainty band as that spanning from the N- space soft and NS approximations. BBFMR estimate the uncertainty by an estimate of the size of missing unknown subleading singularities, based on the known lower orders (up to NNLO). ADDFGHLM provide a pair of estimates, a more conservative and a less conservative one, computed by taking the envelope of all scale variation curves that correspond to corrections at $\mu = m_H$ due to the missing, beyond the next-to-soft $\log^{0,1,2}$ coefficients. These corrections are assumed, conservatively (and less conservatively) to be of size equal to 1.5 (1) times the shift induced on the NS_z by the computed beyond the next-to-soft terms for the $\log^{3,4,5}$ coefficients. Since the estimate is based on deviations from the NS_z result, it doesn't apply to the NS_z result itself, so the NS_z ADDFGHLM point in Fig. 4 has no uncertainty arrows attached to it.

The vastly different size of these uncertainty estimates is the object of ongoing debate.

2.4 Overall comparison and preferred choices

In Figures 5 and 6 we show the preferred predictions of the Higgs gluon fusion cross sections from various groups. For BBFMR, whose preferred prediction is the approximate N^{3}LO combined with N^{3}LL resummation, we also show the fixed-order approximate N^{3}LO. The uncertainty band is obtained from a six-point scale variation in which μ_R and μ_F are each varied by a factor of 2, avoiding the variation where they deviate by a factor of 4. In Fig. 5 the uncertainty is symmetrized, by taking the absolute value of the largest deviation from the nominal cross section, while in Fig. 6 the asymmetric uncertainty is shown. For the approximations shown in Fig. 4, the uncertainty on the approximation are also shown as arrows; for BBFMR the factorization scale uncertainty is added in quadrature to it and included in the arrow, as it includes the uncertainty due to the fact that their approximation is only constructed in the pure gluon channel.

This figure is produced using benchmark settings as discussed above. The unimproved NNLO result and current recommended NNLO+NLL results are also shown. For all other groups, their recommended best predictions (but with benchmark settings) is shown, which is NNLO+NNLL for ABNY, NNLO with a constant resummation for STWZ, an approximate N^{3}LO based on soft and approximate NS terms (now known exactly) from dFMMV, both approximate N^{3}LO, and approximate N^{3}LO supplemented by N^{3}LL resummation for BBFMR, with the approximation being based on an analyticity argument and includ-

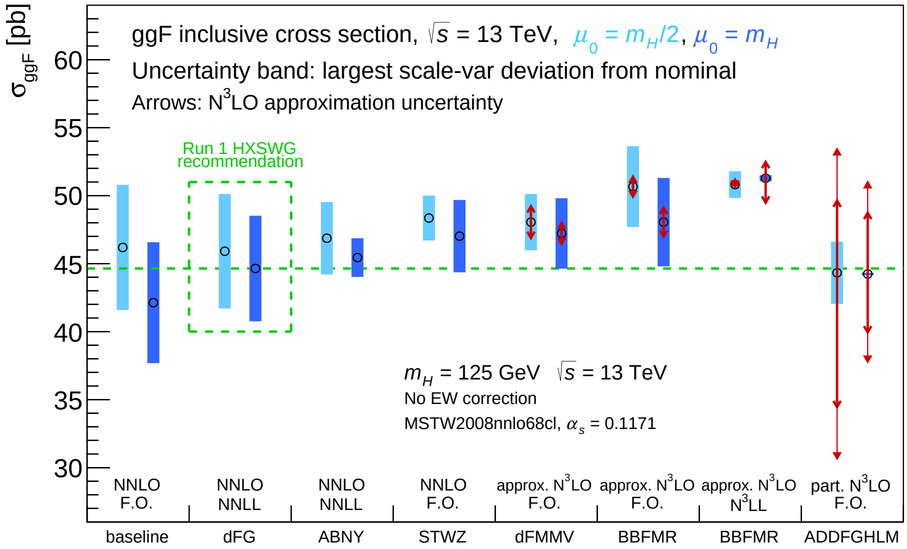

Figure 5. Predicted Higgs gluon fusion production cross sections for the two scale choices $\mu_R = \mu_F = m_H/2$ (left, brighter coloured band) and $\mu_R = \mu_F = m_H$ (right, darker couloured band), with symmetric scale uncertainty estimates.

ing soft and high-energy terms, and finally the best approximation from ADDFGHLM based on current knowledge of the z-space expansion of the N^{3}LO. When comparing these figures with Figs. **??**-**??**, which showed K-factors, it should be born in mind that there predictions at the two central values of μ_r where shown normalized to the NNLO a the respective scales, which differ from each other, as shown in Fig. 1.

3 Jets and p_T distributions

Aside from the total cross section, important theoretical inputs to Higgs measurements are the jet multiplicity and Higgs p_T distributions in gluon-fusion production. The jet multiplicity prediction is required in particular for the $H \to WW$ measurement, for which the experimental analysis is performed separately in jet bins. The Higgs p_T is sensitive to finite-mass effects at low p_T (b-quark), high p_T (t-quark), and potentially very high p_T (possible new-particle loops).

3.1 Jet multiplicity distribution

Inclusive rate and cross section measurements of Higgs boson decays to W-boson pairs separate events by jet multiplicity to increase measurement precision. An uncertainty arises on the signal strength that is about half that due to the total cross section [30]. In a given jet bin, the veto of higher jet multiplicities incurs an additional theoretical uncertainty beyond that of the corresponding inclusive calculation. This uncertainty is correlated between jet bins, i.e. it describes both the overall normalization and migrations

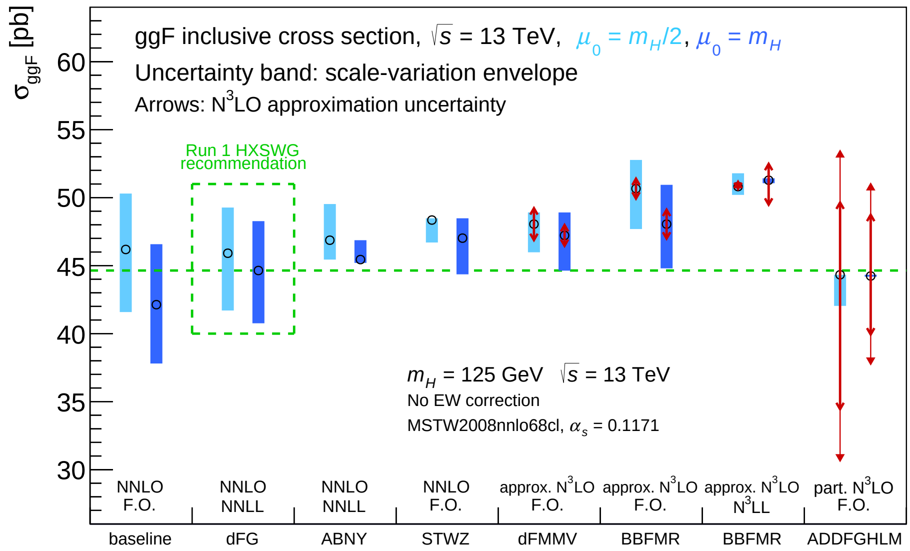

Figure 6. Same as Fig. 5, but with asymmetric scale uncertainty estimates.

between jet bins. There are currently three methods proposed to handle an experimental analysis with jet bins of 0, 1, and ≥ 2 jets (those used in the ATLAS analysis [30]). The most widely used method is the Stewart-Tackmann (or *combined inclusive*) method [31], which treats each inclusive jet-bin calculation as uncorrelated. A second method is the *jet-veto efficiency* method [32] used recently by ATLAS, where the efficiencies of the first and second jet vetos are factorized from the total cross section and treated as uncorrelated. A more recent proposed third method [33] defines a generalized covariance matrix with entries given by the best available calculations and split resummation techniques. A group review of these methods and their application to experimental analyses is foreseen in the future.

In general, measurements of vector-boson fusion production include a sizeable background from gluon fusion. This and other backgrounds are suppressed by vetoing on jets within the rapidity spanned by the two highest p_T jets. The uncertainty on this "central jet veto" has historically been evaluated using the Stewart-Tackmann method, and treated as uncorrelated with the gluon fusion analysis. With improved (NLO) calculations of Higgs+3 jets production now available, it may be possible to improve the theoretical accuracy of the central jet veto.

3.2 Higgs boson p_T distribution

The Higgs p_T distribution used in ATLAS Run 1 analyses was that of HRes 2.2, an NNLO+NNLL dynamic-scale calculation that includes top and b mass effects to NLO. The scale used for the central value was $\mu_R = \mu_F = m_H \oplus p_{T,H}$, where $\oplus$ denotes addition in quadrature. ATLAS obtains uncertainties based on all combinations of factor-of-2 scale variations of μ_R, μ_F and the two renormalization scales available in HRes. Variations where μ_R and μ_F differ by a factor of 4 were excluded. This yields a relative uncertainty of ∼25% for the region $p_{T,H} > 100$ GeV. Migration effects between high and low regions (e.g. above and below 100 GeV) were treated using the Stewart-Tackmann method.

Recent theoretical discussion has focused on the effect of the b-quark mass at low p_T, and the appropriate uncertainty. Future theoretical progress is expected with an inclusive Higgs + jet NNLO calculation in the limit of infinite top-quark mass. In the further future, the inclusion of top-quark mass effects in the inclusive NNLO calculation will improve the p_T predictions at values of order m_t and above. A group discussion of these issues is expected in the near future.

References

[1] https://indico.cern.ch/event/346485/

[2] S. Dittmaier *et al.* [LHC Higgs Cross Section Working Group Collaboration], arXiv:1101.0593 [hep-ph].

[3] D. Graudenz, M. Spira, and P. Zerwas, Phys.Rev.Lett. **70** (1993) 1372

[4] M. Spira, A. Djouadi, D. Graudenz, and P. Zerwas, Nucl.Phys. **B453** (1995) 17, [[hep-ph/9504378]].

[5] R. Harlander and P. Kant, JHEP **0512** (2005) 015, [[hep-ph/0509189]].

[6] C. Anastasiou, S. Beerli, S. Bucherer, A. Daleo, and Z. Kunszt, amplitudes and master integrals for the production of a Higgs boson via a JHEP **0701** (2007) 082, [[hep-ph/0611236]].

[7] U. Aglietti, R. Bonciani, G. Degrassi, and A. Vicini, *JHEP* **0701** (2007) 021, [[hep-ph/0611266]].

[8] R. Bonciani, G. Degrassi, and A. Vicini, JHEP **0711** (2007) 095, [[arXiv:0709.4227]].

[9] R. V. Harlander and W. B. Kilgore, Phys. Rev. Lett. **88** (2002) 201801 [hep-ph/0201206].

[10] C. Anastasiou and K. Melnikov, Nucl. Phys. B **646** (2002) 220 [hep-ph/0207004].

[11] V. Ravindran, J. Smith and W. L. van Neerven, Nucl. Phys. B **665** (2003) 325 [hep-ph/0302135].

[12] R. V. Harlander, H. Mantler, S. Marzani and K. J. Ozeren, Eur. Phys. J. C **66** (2010) 359 [arXiv:0912.2104 [hep-ph]].

[13] M. Botje, J. Butterworth, A. Cooper-Sarkar, A. de Roeck, J. Feltesse, S. Forte, A. Glazov and J. Huston *et al.*, arXiv:1101.0538 [hep-ph].

[14] `http://www.hep.ucl.ac.uk/pdf4lhc/`

[15] S. Dittmaier, S. Dittmaier, C. Mariotti, G. Passarino, R. Tanaka, S. Alekhin, J. Alwall and E. A. Bagnaschi *et al.*, arXiv:1201.3084 [hep-ph].

[16] V. Ahrens, T. Becher, M. Neubert and L. L. Yang, Phys. Lett. B **698**, 271 (2011) [arXiv:1008.3162 [hep-ph]].

[17] C. Anastasiou, S. Buehler, F. Herzog and A. Lazopoulos, JHEP **1204** (2012) 004 [arXiv:1202.3638 [hep-ph]].

[18] C. Anastasiou, C. Duhr, F. Dulat, E. Furlan, T. Gehrmann, F. Herzog and B. Mistlberger, arXiv:1411.3584 [hep-ph].

[19] M. Bonvini, R. D. Ball, S. Forte, S. Marzani and G. Ridolfi, J. Phys. G **41** (2014) 095002 [arXiv:1404.3204 [hep-ph]].

[20] I. W. Stewart, F. J. Tackmann, J. R. Walsh and S. Zuberi, Phys. Rev. D **89** (2014) 5, 054001 [arXiv:1307.1808].

[21] D. de Florian, J. Mazzitelli, S. Moch and A. Vogt, JHEP **1410** (2014) 176 [arXiv:1408.6277 [hep-ph]].

[22] D. de Florian and M. Grazzini, Phys. Lett. B **718** (2012) 117 [arXiv:1206.4133 [hep-ph]].

[23] M. Bonvini and S. Marzani, JHEP **1409** (2014) 007 [arXiv:1405.3654 [hep-ph]].

[24] R. D. Ball, M. Bonvini, S. Forte, S. Marzani and G. Ridolfi, Nucl. Phys. B **874** (2013) 746 [arXiv:1303.3590 [hep-ph]].

[25] M. Bonvini, S. Forte, G. Ridolfi and L. Rottoli, arXiv:1409.0864 [hep-ph].

[26] S. Moch and A. Vogt, Phys. Lett. B **631** (2005) 48 [hep-ph/0508265].

[27] E. Laenen and L. Magnea, Phys. Lett. B **632** (2006) 270 [hep-ph/0508284].

[28] C. Anastasiou, C. Duhr, F. Dulat, E. Furlan, T. Gehrmann, F. Herzog and B. Mistlberger, Phys. Lett. B **737** (2014) 325 [arXiv:1403.4616 [hep-ph]].

[29] S. Catani, D. de Florian and M. Grazzini, JHEP **0105** (2001) 025 [hep-ph/0102227].

[30] ATLAS Collaboration, arXiv:1412.2641v1 (2014).

[31] I. W. Stewart and F. J. Tackmann, Phys. Rev. D **85** (2012) 034011 [arXiv:1107.2117 [hep-ph]].

[32] A. Banfi, G. P. Salam and G. Zanderighi, JHEP **1206** (2012) 159 [arXiv:1203.5773 [hep-ph]].

[33] R. Boughezal, X. Liu, F. Petriello, F. J. Tackmann and J. R. Walsh, Phys. Rev. D **89** (2014) 7, 074044 [arXiv:1312.4535 [hep-ph]].