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Predictions for exclusive Higgs cross sections

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ABSTRACT

I give an overview of recent theoretical results for exclusive Higgs-production cross sections, focusing in particular on processes where precise predictions will be relevant in the near future.

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1 Introduction

Regardless of whether hints of new-Physics in direct searches will show up in current and future LHC Runs, precision measurements in Higgs studies will play a major role in the future. This is particularly true because the increase in luminosity and collision energy in Run II and beyond will allow for measurements of differential distributions. In order to fully exploit the latter, it's necessary that the theoretical accuracy for signal predictions matches the experimental one. In this manuscript, I review some of the recent developments relevant to this end. First I will focus on "parton level" predictions, whereas, in the second part, I will review status and recent news in the development of fully exclusive "MC generators".

I will mostly focus on higher-order results in "perturbative QCD", and only mention a few cases of recent progress in higher-order perturbative computations in the "EW" couplings. Moreover, I will not discuss recent results on the computation of higher-order corrections for the Higgs-boson decays. For further details and a fully comprehensive review, I advise the reader to refer to ref. [1].

2 Parton-level results

Higgs production at the LHC is usually categorized according to its four main production channels, namely "gluon-fusion production" (henceforth denoted as "$gg \to H$"), "vector-boson fusion production" (VBF), "associated production" (VH) and "top-associated production" ($t\bar{t}H$). The state of the art for cross sections for these processes is summarized in table 1, where I specify the perturbative order at which the fully inclusive result, as well as the order at which differential distributions for "Born-like" observables (σ_{tot} and $d\sigma$, respectively), are known.*

	QCD order	EW order	other corrections known
$gg \to H$	σ_{tot}: N3LO, $d\sigma$: NNLO	$\sigma_{tot}, d\sigma$: NLO	N3LL threshold resummation m_q dependence: NLO (approx. NNLO) mixed QCD/EW corrections
VBF	σ_{tot}: N3LO (NNLO), $d\sigma$: NNLO	$\sigma_{tot}, d\sigma$: NLO	
VH	$\sigma_{tot}, d\sigma$: NNLO	$\sigma_{tot}, d\sigma$: NLO	
$t\bar{t}H$	$\sigma_{tot}, d\sigma$: NLO	$\sigma_{tot}, d\sigma$: NLO	NNLL threshold resummation

Table 1: Total and differential cross sections for the four main Higgs production processes at hadron colliders. Notice that the VBF total cross-section is known at N3LO [2] but only in the structure-function approach, where it's not possible to apply the standard cuts on the two leading jets which define the VBF signal region. The NNLO result of ref. [3] is instead fully differential.

Together with the above results, the knowledge of more exclusive distributions will become more and more important in the years to come: the transverse-momentum spectrum of the Higgs-boson, or the cross section for producing the Higgs-boson in association with jets (1, 2, as well as 0), are such an example. In the rest of this section, I'll review some recent developments in this context, focusing primarily on the gluon-fusion and VBF production mechanisms.

2.1 The Higgs-boson transverse momentum

The Higgs transverse-momentum ($p_{T,H}$) spectrum in gluon fusion is now known at NNLO in QCD [4, 5, 6], although exact corrections beyond leading order have been computed only in the HEFT approach, *i.e.* in the limit $m_t \to \infty$. As shown in the left-hand plot in fig. 1, the NNLO/NLO K-factor is large and non flat: including NNLO corrections not only reduces the theoretical uncertainties, but also improves the data-theory agreement.

*These are the observables whose definition does not involve any requirement on initial or final state radiation, except on the one already present at leading order, as in VBF. For example, the Higgs rapidity in gluon-fusion, or the transverse momentum of a tagging-jet in VBF, belong to this category.

At small values of $p_{T,H}$ (below ~ 30 GeV) large logarithms of the type $\log(m_H/p_{T,H})$ arise at all orders, due to (multiple) soft/collinear radiation, and in order to obtain a meaningful and well-behaved prediction, an all-order resummation is needed. Until recently the more accurate results were those obtained in refs. [8, 9],

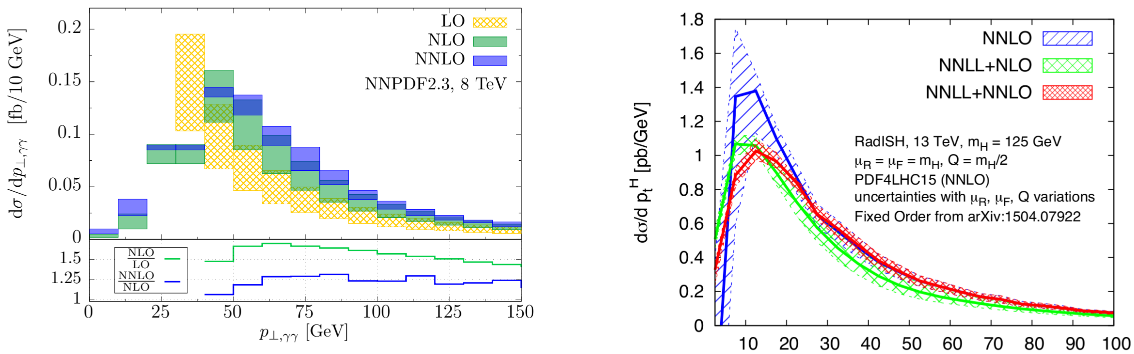

Figure 1: Left: $p_{T,H}$ distribution at LO, NLO and NNLO, in presence of fiducial cuts on the photons from the Higgs decay, as well as with a cut on the hardest jet (plot taken from ref. [7]). Right: resummed predictions up to NNLL+NNLO for $p_{T,H}$ as obtained with the `Radish` code, developed in refs. [10, 11].

where the resummation was carried out at the NNLL+NLO order, *i.e.* the NNLL resummed result was matched to the NLO computation of the differential cross section $d\sigma/dp_{T,H}$, yielding also NNLO accuracy for the integrated spectrum. In two recent papers [10, 11], a new method was formulated to resum small $p_{T,H}$ logarithms directly in momentum space, avoiding at the same time the spurious singularities in the spectrum usually arising when resumming in direct space. The method was used to obtain NNLL+NNLO accurate results, and, more recently, to achieve N3LL+NNLO accuracy [11].[†] An example of the numerical relevance of some of these effects is shown in the right-hand side panel of fig. 1, which has been obtained using the `Radish` code. Although numerical results have not been published yet, a different approach to perform this resummation in direct space was also formulated in ref. [14].

Hints of new-Physics can be found by looking at the Higgs transverse momentum spectrum. For instance, it is known that in the large $p_{T,H}$ limit of gluon-fusion production (boosted Higgs regime), effects due to the presence of new heavy states circulating in the loop can be exposed, since a boosted Higgs boson probes the heavy degrees of freedom in virtual corrections. Although this idea is very powerful, it is clear that a very precise knowledge of the SM result in the boosted regime is needed in order to fully exploit it. Of chief importance are the top-mass effects beyond leading order: it is indeed known that the heavy-top approximation significantly overestimates the exact LO result, as first observed in refs. [15, 16]. Currently these corrections are not known, because some 2-loop integrals have not been fully computed yet [17]. On the other hand, one loop amplitudes with full top-mass dependence are known for $H+2$ [18] and $H+3$ [19, 20] jets. By using them, different strategies to estimate the complete result have been put forward: for instance, improving upon previous results [21], the authors of ref. [22] used the exact 1-loop results for $H+1$ and $H+2$ partons matrix elements together with an expansion up to $\mathcal{O}(m_t^{-4})$ to estimate the (unknown) finite parts of the massive virtual (2-loop) corrections. A reweighting procedure was used by the authors of ref. [6] to include the unknown mass effects in their NNLO computation. The authors of ref. [23] have instead proposed a method to perform a systematic approach in powers of $m_t/p_{T,H}$. In ref. [24] the high-energy behavior of the Higgs plus jet have also been used to estimate mass effects in this regime. Other results important for current phenomenology have been obtained in the context of NLO+PS merging, as discussed in sec. 3.

Important properties of the Higgs boson can also be inferred by looking at the medium-small $p_{T,H}$ region. For instance, a method to set competitive constraints on the bottom and charm Yukawa couplings $y_Q = \kappa_Q\, y_{Q,SM}$ $(Q = b, c)$ was proposed in ref. [25].[‡] The main idea is based on the following observation: among the Higgs production mechanisms, two of them depend on the charm (and bottom) Yukawa coupling, and

[†]The NNLO $p_{T,H}$ spectrum and the total N3LO cross sections used in refs. [10, 11] were taken from refs. [4] and [12, 13], respectively.

[‡]Similar ideas were also suggested in ref. [26].

are, at the same time, mostly relevant at medium-small $p_{T,H}$, *i.e.* gluon fusion ($gg \to Hg$) and heavy-quark-initiated ($gQ \to HQ$, $Q\overline{Q} \to Hg$) production. The cross section for the latter case depends upon y_Q^2, whereas, for gluon-fusion, the leading dependence is linear in y_Q, as it originates from the interference among $2 \to 2$ diagrams with a top loop and those with a bottom/charm loop, schematically $d\sigma_{tQ}^{LO} \sim \Re\{A_t^{1\text{-}loop} A_Q^{*,1\text{-}loop}\}$. Moreover, in the gluon fusion case, and in the regime $m_Q \ll p_{T,H} \ll m_H$, such interference features also (non-Sudakov) double logarithms of the form $\kappa_Q (m_Q/m_H)^2 \log^2(m_Q^2/p_{T,H}^2)$. As a consequence, the final differential cross-section $d\sigma/dp_{T,H}$ (as well as the leading-jet distribution) is quite sensitive to variations of the bottom and charm Yukawa modifiers κ_Q, particularly so at medium $p_{T,H}$, as shown for instance in the left panel of fig. 2. Thanks to this dependence, by using Run I data, and uncertainties thereof, together with the currently available theory predictions (where the total uncertainty amounts to 10% at most), the constraint $\kappa_c \in [-16, 18]$ at 95% CL was obtained in ref. [25]. If one assumes a total experimental uncertainty (dominated by systematic) of 3%, and a total theory uncertainty of 5%, it was shown in [25] that, with 300 fb^{-1}, the projection for the constraint on y_c reads $\kappa_c \in [-1.4, 3.8]$ at 95% CL, which is at least as good as what can be obtained with all the other available methods [28, 29, 30, 31, 32, 33] taken individually.

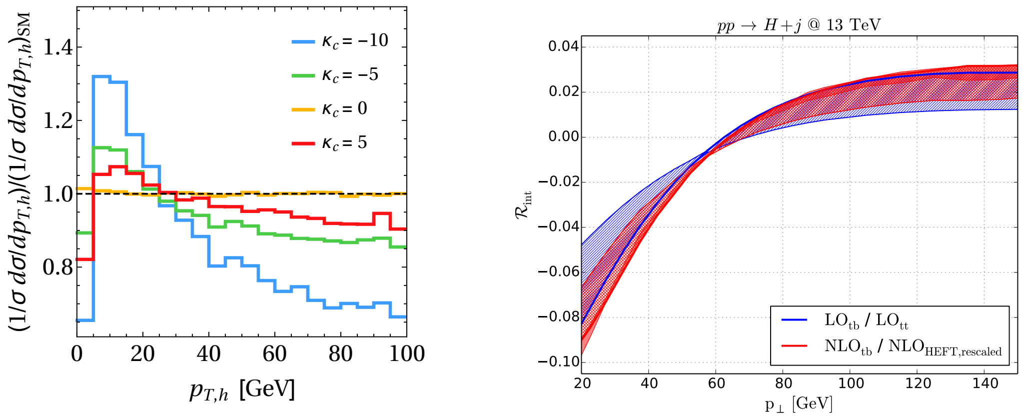

Figure 2: Left: normalised $p_{T,H}$ spectrum of inclusive Higgs production divided by the SM prediction for different values of κ_c (plot taken from ref. [25]). Right: relative top-bottom interference contribution to the transverse momentum distribution of the Higgs boson at LO and NLO (plot taken from ref. [27]).

It is clear that, in the the long term, the bottleneck to fully exploit this idea will be the quality of the theory prediction. The most notable missing ingredient is the knowledge of the NLO corrections for $d\sigma/p_{T,H}$ with exact mass effects. For the case at hand, this reduces to the knownledge of $d\sigma_{tQ}^{virt} \sim \Re\{A_t^{1\text{-}loop} A_Q^{*,2\text{-}loop} + A_t^{2\text{-}loop} A_Q^{*,1\text{-}loop}\}$, *i.e.* the virtual correction to $d\sigma_{tQ}^{LO}$. In this respect, the results in refs. [27] are extremely relevant: for the bottom-quark case, the authors of refs. [34, 35] computed $A_b^{*,2loop}$ by consistently neglecting all the terms that are power-suppressed in the $m_b \to 0$ limit, whilst keeping all the non-analytic $\mathcal{O}(\log(m_b))$ terms. This is exactly the approximation needed to study the m_b effects on the $p_{T,H}$ spectrum in the intermediate range. By combining this result with the exact real-emission matrix elements, as well as using $A_t^{2\text{-}loop}$ in the $m_t \to \infty$ limit (which is perfectly adequate for $p_{T,H} \ll m_t$), a complete NLO result for $d\sigma_{tb}$ was published in ref. [27]: these corrections were found to be important($\mathcal{O}(40\%)$) and similar to the NLO corrections for $d\sigma_{tt}$, both in size and shape. Moreover, renormalization scheme ambiguities on the treatment of m_b were shown to reduce at NLO, at least for $p_{T,H} < 60$ GeV (see for instance the right panel in fig. 2). It will be extremely interesting to combine these results with the state-of-the-art computations of $p_{T,H}$ mentioned in the first part of this section. Moreover, the results of ref. [27] will allow to quantify more precisely the ultimate reach of the idea presented in ref. [25] to set bounds on the light-quark Yukawa couplings.

2.2 Cross section in jet bins

In several analyses relevant for precision Higgs measurements, events are categorized according to the number of jets accompanying the Higgs-boson decay products. An example is the 0-jet cross section (often called "jet-vetoed" cross section), where a jet-veto $p_{T,veto} \approx 30$ GeV is required for the hardest jet, in order to suppress the $t\bar{t}$ backgrounds when looking for $H \to WW$ and $H \to \tau\tau$ in gluon-fusion dominated searches. Another obvious example is the 2-jet cross section, which will become more and more important for VBF studies. In the rest of this section, I'll summarize recent progress made for the signal prediction in these two cases.

When a jet-veto is applied to the $gg \to H$ process, logarithms of the type $\log(m_H/p_{T,veto})$ are generated. Although a fixed order computation is known to yield a very accurate result for the central value of the jet-vetoed cross section, an all-order resummation is necessary if a perturbative uncertainty of few percent on the signal rate is sought for.[§] The more advanced results for this quantity were published in ref. [36], where the NNLL resummed results obtained by the authors of [37] were matched to the fully-inclusive N3LO cross section [12, 13] and the H+1 jet NNLO spectrum [4]. Mass effects were also taken into account following the scheme discussed in [38] and a leading-log resummation of jet-radii logarithms was also included [39]. The final perturbative uncertainty for $p_{T,veto} \sim 30$ GeV amounts to about 4%: about half of that is due to the N3LO result, and the residual part comes from the resummation accuracy.

In Run II and beyond, the measurements of VBF production will be particularly important. For instance, VBF Higgs production is the largest production mode involving only tree-level interactions, and, since $p_{T,H}$ is already non-vanishing at the leading order, it facilitates searches of Higgs invisible decay modes. One of the major background components for the extraction of the VBF signal is the gluon-fusion production of Higgs accompanied by two (or more) jets. In order to ennhance the signal over the background, the kinematics of the final state objects is heavily used. Although NNLO corrections to the total cross-section within VBF cuts are extremely small ($\mathcal{O}$(1-2%)), in ref. [3] it was found that they are not flat across the fiducial phase space, as they can reach up to $\mathcal{O}(10\%)$. Not only these results are extremely important on their own, but they also allow to expose current limitations of NLO+PS tools: in fact, although at times higher-order effects are (approximately) captured by these tools, in ref. [3] it was also found that, for VBF, this is not necessarily the case for all observables. As currently one of the largest theory uncertainties for VBF searches comes from NLO+PS generators [40], an interesting avenue for future developments will be to find an optimal way to use the NNLO results to improve MC tools. Eventually, it will be desirable to match these NNLO results to parton-showers, as it has been already done for $gg \to H$ and VH production (see sec. 3).

3 Monte Carlo event generators

Nowadays NLO+PS Monte Carlo event generators are well established and automated, and I will not attempt to reference all the available tools and implementations: table 2, though, summarizes schematically the current state of the art.

	matching	NLO+PS multi-jet merging
$gg \to H$	NNLO+PS	$d\sigma_{H+0j} + d\sigma_{H+1j} + d\sigma_{H+2j}$
VBF	NLO+PS ($d\sigma_{Hjj}$, $d\sigma_{Hjjj}$)	-
VH	NNLO+PS	$d\sigma_{VH+0j} + d\sigma_{VH+1j}$
$t\bar{t}H$	NLO+PS	-
$pp \to HH$	NLO+PS (exact m_t dependence)	-

Table 2: Summary of available fully-exclusive Monte-Carlo generators for the simulation of Higgs signal cross sections.

[§] A thourough discussion of the theoretical predictions for the backgrounds is equally important, but it goes beyond the scope of this manuscript.

As far as relatively recent NLO+PS results are concerned, in ref. [41] $gg \to H$ production was matched to parton showers using the so-called `KrKNLO` method [42], which is an approach different with respect to the commonly used `MC@NLO` and `POWHEG` methods. Another important development is that not only has the differential cross section for di-Higgs production been computed at NLO, including the exact dependence upon m_t [43, 44], but also that this computation, which is numerically very heavy due to the presence of massive 2-loop amplitudes, has been matched to parton shower [45] using the `POWHEG` method.

Aside from the aforementioned recent NLO+PS results, most of the more recent activity has focussed on the concept of NLO+PS multijet merging, which collectively denotes all the techniques aiming at describing with NLO+PS accuracy several jet multiplicities (possibly accompanied by a massive system) in a single event sample. To achieve this goal, several ideas have been put forward: `MEPS@NLO` [46, 47], "`FxFx`" merging [48], `UNLOPS` [49, 50, 51], `MiNLO` [52, 53], `Geneva` [54, 55], `Vincia` [56, 57]. The former four have been already used for processes relevant for Higgs Physics.

As explained in section 2, including exact top-mass effects is important to model precisely the large-$p_{T,H}$ spectrum in gluon-fusion production. This issue has also been addressed in the context of NLO+PS multijet merging, where results have been obtained using the `MEPS@NLO` [58] and `FxFx` [59] methods. In both cases, different approximations were made to simulate the unknown mass effects in the (2-loop) virtual corrections; notably, in [59], also b-quark mass effects have been considered. The left panel of fig. 3 allows to appreciate the size of heavy-quark effects as well as how important is it to merge (at NLO) the inclusive NLO+PS prediction to higher jet multiplicities (in this case, up to 2 jets at NLO).

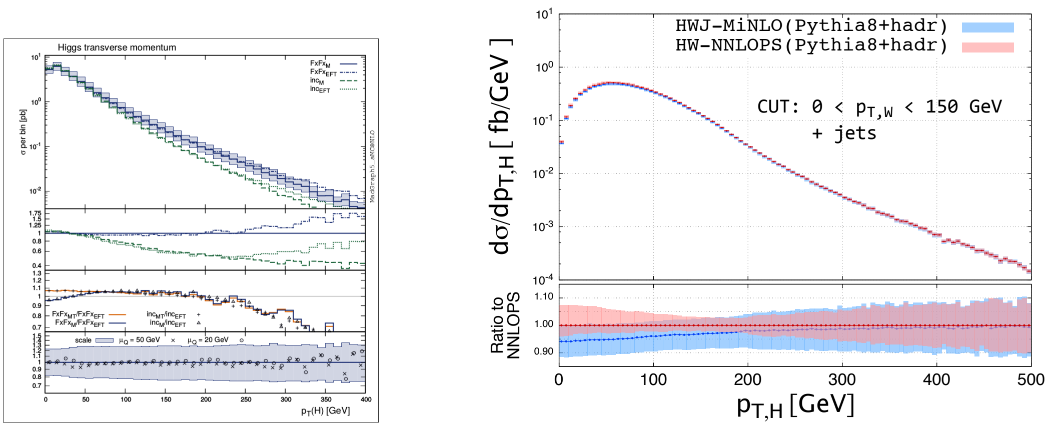

Figure 3: Left: inclusive $p_{T,H}$ distribution (plot taken from ref. [59]). Effects due to heavy-quark mass effects and NLO+PS (FxFx) merging are visible. Right: the Higgs $p_{T,H}$ distribution as obtained with the NNLO+PS generator for $pp \to WH$ developed in ref. [60]. Details on cuts applied can be found in section I.5.5 of ref. [1].

Top-quark mass effects are also important in other contexts: for instance, although it enters only at NNLO in the $pp \to ZH$ cross section, the loop-induced $gg \to ZH$ matrix element is numerically important, and gives sizeable effect in some phase-space corners. In the context of multijet-merging, these effects were included by merging (at LO) the $2 \to 2$ ($gg \to ZH$) and $2 \to 3$ ($gg \to ZH + 1$ jet) loop-induced processes [61, 62].

Multi-jet merging is at the core of all the three methods currently available to match NNLO computations with parton showers (NNLO+PS). So far, this has been achieved only for color-singlet production, and for relatively simple processes, *i.e.* for Drell-Yan [63, 64, 65], $gg \to H$ and $pp \to VH$ production. In particular, the "improved `MiNLO`" [53] and `UNLOPS` [49] techniques are at the core of the NNLO+PS accurate results obtained for gluon-fusion production [66, 67]. Including mass effects is obviously relevant also for NNLO+PS tools, and indeed, in ref. [68], a scheme to include top and bottom mass effects in the `MiNLO+POWHEG` result was proposed. It is foreseable that results using the `Geneva` approach will also appear in the future.

The simulation of VH production has recently witnessed several results. On the one hand, `MiNLO`-merged results for WH and $WH+1$ jet [69] were upgraded to NNLOPS accuracy [60] too, using the results from [70]:

a representative plot showing the difference between a NLO+PS merged result and the upgrade at NNLO for a standard observable as $p_{T,H}$ is shown in the right-hand side panel of fig 3. The inclusion of higher-order effects in the simulation of the $H \to b\bar{b}$ decay will be very useful for some searches aiming at measuring the bottom-quark Yukawa. Work is in progress to include NLO corrections to this decay channel in NNLO+PS-accurate event generator [71], using the techniques first developed to deal with NLO corrections to top-quark decays [72, 73].

The combination of EW and QCD NLO corrections is a topic which is receiving more and more attention. Although so far most of the studies have focused on processes involving weak bosons in the final state, a first result relevant for the modeling of Higgs signal was obtained by the authors of ref. [74]: fixed-order NLO QCD+EW calculations were combined with a QCD+QED parton shower for the process $pp \to VH$ in association with 0 and 1 jet, by means of a combination of `MiNLO` and the resonant-aware method [73] in the `POWHEG` framework.

To conclude this section, I'd like to mention a few publications which might give an idea of where future developments could be expected in the years to come. The authors of ref. [75] have proposed a method to lift one of the limitations of the `MiNLO` method, namely the fact that its NLO accuracy was proven only for the two lowest jet multiplicities, *i.e.* the "+0" and "+1" jet regions: it was indeed shown how to merge $H + 2j$ at NLO together with $H + j$ at NLO, as well as inclusive Higgs production at NNLO. So far this is the most accurate result obtained with `MiNLO` for the $gg \to H$ process, and a possible future development could be to include NNLO corrections for the $H + 1$ jet region.

It is also clear that the limited logarithmic accuracy of parton showers will soon become a bottleneck. Not surprisingly, in the last couple of years many studies addressing this point were performed, spanning from comprehensive estimates of uncertainties related to the parton-showering stage of the Monte Carlo simulation [76, 77, 78] to first attempts to improve accuracy of parton shower algorithms in general [79], and their logarithmic accuracy in particular [56, 80, 81].

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