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HIGGS THEORY OVERVIEW*

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This contribution reviews the most recent theoretical developments concerning Higgs production at the Large Hadron Collider. Emphasis is put on the inclusive and exclusive cross sections for gluon fusion, both in the Standard Model and in the MSSM, as well as on the associated production with bottom quarks.

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1. Introduction

The most important observables and input quantities to experimental analyses for Higgs physics at the Large Hadron Collider (LHC) are meanwhile known with rather high precision. In particular, the dominant Higgs production cross sections are under good theoretical control: the next-to-leading order (NLO) predictions for associated $t\bar{t}H$ production [1–3] and weak boson fusion [4], as well as the next-to-next-to-leading order (NNLO) cross sections for gluon fusion [5–7] and Higgs Strahlung [8, 9] all exhibit nicely converging perturbative series and only a moderate dependence on the renormalization and factorization scale.

Quite a number of theoretical methods have been developed out of the need for reliable predictions of Higgs production at the LHC. This brief overview reports on the most recent of these developments LHC (see also Ref. [10]). For more comprehensive surveys, we refer the reader to some recent reviews (see, *e.g.*, Refs. [11, 12]).

2. Gluon fusion

Higher order corrections to the gluon fusion process have been of great interest for many years now. The main reason is, of course, that it is one of the most important discovery channels for Higgs bosons at the LHC, and that, therefore, a precise prediction for its cross section should be available.

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However, the NLO radiative corrections turned out to be very large [13–15], amounting to an increase of up to 100% with respect to the leading-order (LO) value. In addition, the NLO corrections did not lead to a decrease of the renormalization and factorization scale dependence (when measured in absolute rather than relative values of the cross section). Due to these issues in the theoretical prediction, the K-factor was often discarded in experimental analyses, in order not to overestimate the Higgs cross section.

A lesson learned from the NLO corrections was that the gluon–Higgs interaction seems to be approximated very well [16, 17] by an effective Lagrangian

$$\mathcal{L}_{ggH} = -\frac{H}{4v}\, C(\alpha_{\rm s})\, G^a_{\mu\nu} G_a^{\mu\nu}\,, \tag{1}$$

if the LO top mass dependence of the cross section is factored out. In Eq. (1), $v = 246\,\text{GeV}$ and $C(\alpha_{\rm s})$ is the Wilson coefficient which is meanwhile known through $\alpha_{\rm s}^5$ [18,19]. This observation allowed to tackle the NNLO calculation on the basis of Eq. (1) [20–22]. The full NNLO corrections [5–7] exhibited the features of a well-behaved perturbative series: they are significantly smaller than the NLO corrections, and also the scale dependence reduces to an acceptable level.

Progress concerning higher order corrections to the gluon fusion process has been made in various respects. On the one hand, the validity of the perturbative prediction for the total cross section has been confirmed by the evaluation of effects that go beyond NNLO. On the other hand, various resummations for kinematical distributions of the Higgs boson have been carried out. And finally, a fully differential partonic Monte Carlo program, valid through NNLO, has been developed. Let us discuss these topics in more detail in what follows.

2.1. Inclusive Higgs production

With the higher order QCD effects for gluon fusion being quite sizable, one may wonder about the reliability of the fixed order NNLO prediction. To answer this question, one may try to identify and resum the dominant terms to the inclusive cross section. In fact, it had been realized long ago that soft gluon radiation contributes significantly to the total rate [16, 21, 22]. However, how well the cross section is approximated by this contribution alone depends strongly on the way the "soft limit" is defined. To see what we mean by this, consider the general expression for the hadronic cross section $\sigma(s)$ in terms of parton densities ϕ_i ($i = q, \bar{q}, g$) and the partonic cross section $\hat{\sigma}(\hat{s})$:

$$\sigma(s) = \int_0^1 dx_1 \int_0^1 dx_2 \phi_i(x_1)\phi_j(x_2)\hat{\sigma}_{ij}(x_1 x_2 s)\,. \tag{2}$$

One way to define the soft limit is to expand $\hat{\sigma}$ in the limit $x \equiv M_H^2/\hat{s} \to 1$:

$$\hat{\sigma}_{ij}(\hat{s}) = \sigma_0 \left(a\,\delta(1-x) + \sum_{k\geq 0} b_k \mathcal{D}_k(x) + \ldots \right), \tag{3}$$

where

$$\mathcal{D}_k(x) \equiv \left[\frac{\ln^k(1-x)}{1-x} \right]_+ \tag{4}$$

and the dots denote formally subleading terms which are dropped. However, one may equally well trade a factor of x between the partonic cross section and the parton density functions, and rather expand $\hat{\sigma}(\hat{s})/x$ around $x = 1$. This will lead to significantly different numerical results for the hadronic cross section σ [21, 22].

The most recent achievement concerning the fixed-order calculation is the evaluation of the soft terms through N^{3}LO or, in terms of Eq. (3), the coefficients b_k, $k = 0, \ldots, 5$, through α_s^3 [23]. The $\delta(1-x)$ piece in Eq. (3) receives contributions from the virtual terms which are still unknown, but one may deduce from the lower order results that they are numerically small. Note also that the terms for $k = 1, \ldots, 5$ could be derived from the NNLL resummation formula [24], thus providing a useful check. The effect of these N^{3}LO terms is again a mild increase of the cross section (for $\mu_{\rm F} = \mu_{\rm R} \approx M_H$), and a reduction of the scale uncertainty. On the other hand, these terms allow to push the resummation of the soft terms to higher orders [23, 25, 26], with again rather small numerical impact (see Fig. 1).

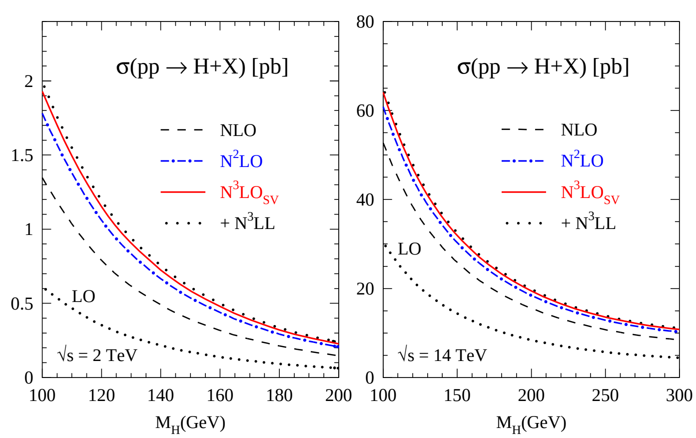

Fig. 1. Inclusive Higgs production cross section through gluon fusion, including the soft N^{3}LO and corresponding resummation effects. From Ref. [23].

It remains to be said that apart from the phenomenological significance of such higher order results, they appear to reveal interesting structures of the perturbative series that are worth studying for their own sake [27, 28].

Clearly, if so much effort is put into minimizing the theoretical uncertainty due to QCD effects, one needs to start thinking about electro-weak corrections as well. In fact, terms of order $G_{\rm F} m_{\rm t}^2$ have been known for quite a while now, resulting in effects below 1% of the LO rate [29]. The full set of Feynman diagrams can be divided into those that contain a top quark, and those that contain only light quarks. The latter set has been evaluated in Ref. [30], while the full result for the former was obtained in Ref. [31]. The numerical impact of the electro-weak corrections ranges between 5 and 8% of the LO term.

2.2. Transverse momentum and rapidity distributions

A large K-factor for the total cross section leaves open the question on how the radiative corrections affect different regions of phase space. Better insight into this issue is provided by differential quantities such as $d\sigma/dp_{\rm T}\,dy$, where $p_{\rm T}$ and y are the transverse momentum and the rapidity of the Higgs boson, respectively.

At the partonic level, the Higgs boson can only be produced at finite transverse momentum $p_{\rm T}$ if the latter is balanced by the real radiation of a quark or a gluon. Thus, distributions at non-zero $p_{\rm T}$ are related to the process H+jet whose LO prediction is of order $\alpha_{\rm s}^3$. The corresponding NLO effects were studied both analytically [32, 33], and in the form of a partonic Monte Carlo program [34], yielding a rather flat dependence of the K-factor on $p_{\rm T}$ and y at intermediate values of these variables. At small $p_{\rm T}$, the fixed-order perturbative approach breaks down, but this can be accounted for by resummation of logarithms (see, *e.g.*, Ref. [35] and references therein). At large $p_{\rm T}$, on the other hand, one again encounters similar logarithms as for the inclusive rate, arising from soft gluon radiation. Their resummation is known through NLL [36].

2.3. NNLO Monte Carlo

Currently the most general higher order prediction for the gluon fusion process is available in the form of the partonic NNLO Monte Carlo program `FEHiP` [37]. It allows to study arbitrary kinematical distributions of the Higgs boson with NNLO accuracy, as well as the application of phase space cuts. This provides detailed information on how the radiative corrections affect the various regions of phase space.

For example, Table I compares the ratio $K^{(2)}$ of the NNLO to the NLO cross section as obtained by the fully inclusive calculation (subscript "inc") to the one where "standard cuts" are applied (subscript "cut"; see Ref. [37] for details). The numbers show that the radiative corrections are only slightly affected by the cuts, and that the cross section including cuts is approximated to better than 5% by the quantity $K^{(2)}_{\rm inc} \times \sigma^{\rm cut}_{\rm NLO}$.

TABLE I

Comparisons between the cut and inclusive cross sections for different Higgs masses. The second column contains the ratio of the NNLO cross section with the standard cuts over the inclusive cross section, while the third column contains the ratio of cut and inclusive results for the K-factor $K^{(2)} = \sigma_{\rm NNLO}/\sigma_{\rm NLO}$. It is $\mu_{\rm R} = \mu_{\rm F} = M_H/2$. From Ref. [37].

M_H GeV	$\sigma^{\rm cut}_{\rm NNLO}/\sigma^{\rm inc}_{\rm NNLO}$	$K^{(2)}_{\rm cut}/K^{(2)}_{\rm inc}$
110	0.590	0.981
115	0.597	0.968
120	0.603	0.953
125	0.627	0.970
130	0.656	1.00
135	0.652	0.98

These results are all obtained at the partonic level. At the level of a hadronic event generator, a NLO prediction can be obtained from the program `MC@NLO` [38, 39]. A detailed comparison of these hadronic NLO results to the partonic NNLO results from `FEHiP` can be found in Ref. [40].

But the observation of a rather uniform distribution of the radiative corrections in phase space as indicated above motivates yet another step towards more realistic higher order event simulations: In order to transfer the purely partonic NNLO result of Ref. [37] to truly hadronic final states, the `Pythia` [41] and `MC@NLO`event generators have been supplemented by a re-weighting grid in the $p_{\rm T}$-y plane [42], evaluated from the ratio of the partonic `FEHiP` and the hadronic results, integrated over two-dimensional intervals. This procedure is based on the fact that sufficiently inclusive quantities should be described equally well in a partonic and a hadronic approach. A similar strategy was followed in Ref. [43], where the re-weighting was based only on the NLO $p_{\rm T}$-spectrum of the Higgs boson, however.

2.4. Background calculations

An important issue for Higgs searches and studies at the LHC is the theoretical control of background processes. The number of higher order results available in this context is way too large to even attempt giving proper credit to each one of them. An extensive list of programs to evaluate higher order cross sections can be found at Ref. [44].

Quite often, side band subtractions rather than NLO simulations will be the most efficient way in order to separate the signal from the background, once enough data are available. But in certain cases, such a procedure will not be possible, for instance if missing energy in the Higgs decay does not allow the reconstruction of a Higgs mass peak. An example for such a case is the WW decay mode of the Higgs boson. In fact, in order to use this channel as a discovery mode, one needs to keep track of the angular correlations among the Higgs decay products [45]. Also here, the NLO corrections have been known for a while. However, recently it was found that the gg initiated component, although being formally of NNLO, can amount to 30% of the NLO rate, once the relevant cuts for Higgs searches are applied [46, 47].

3. Weak boson fusion

The weak boson fusion (WBF) process itself is under very good theoretical control: the NLO corrections have a comparatively simple structure, since single gluon exchange between the incoming quarks is not allowed by color conservation, meaning that 5-point functions are absent in the calculation. The NLO corrections are available [4, 48] and have been implemented in `MCFM` [49], allowing for application of cuts as it is particularly important for this process in order to separate it from the background.

The biggest challenge concerning radiative corrections is in fact related to background processes. The dominant source is purely hadronic Higgs production in association with two jets. The LO prediction for this process is of order α_s^4, meaning that the renormalization scale dependence is rather large. The full top mass dependence of the cross section at LO has been evaluated in Ref. [50]. The NLO calculation involves massive two-loop five-point functions and is certainly out of reach at the moment. However, the LO calculation revealed that for jet transverse momenta $p_{\mathrm{T}j} \lesssim m_{\mathrm{t}}$, one may integrate out the top quark, thus arriving at one-loop five-point functions, calculated in Ref. [51]. The amplitude for the corresponding real radiation has been evaluated in Ref. [52–54]. Real and virtual terms were recently combined in Ref. [55] to give the NLO prediction of this background process.

Other important background processes to WBF are Vjj and $VVjj$ production, and also here NLO corrections are available [56, 57].

4. Supersymmetry

Gluon fusion remains one of the most important production modes also in supersymmetric models. In fact, since the pseudo-scalar Higgs boson in the MSSM has no tree-level coupling to vector bosons, it cannot be produced through WBF, for example. Therefore, gluon fusion and associated $b\bar{b}A$ production are the dominant production modes in this case (see, *e.g.*, Ref. [58]).

Many of the higher order results that are available for SM Higgs production can be taken over to the case of the neutral, CP-even Higgs bosons within the MSSM. For example, if the squarks are heavy, they do not contribute significantly to the gluon–Higgs coupling, which is then again mediated predominantly by top and, for not too small values of $\tan\beta$, bottom loops. The cross section for h, H-production including QCD corrections can then be derived easily from the SM expression.

Pseudo-scalar Higgs production, on the other hand, requires a modification of the top-Higgs and thus the effective gluon–Higgs coupling with respect to Eq. (1). But also here, many higher order corrections are known, for example the inclusive NNLO cross section [7, 59, 60], and various NLO distributions [61–63].

Larger values of $\tan\beta$ increase the importance of bottom loops to the gluon–Higgs coupling (see, *e.g.*, Refs. [17, 64]). An effective theory for the gluon–Higgs interaction along the lines of Eq. (1) is not known in this case, so that higher order calculations are much more difficult. In fact, only the NLO result is available at the moment, in the form of a one-dimensional integral representation [65]. Let us remark, however, that the virtual corrections have meanwhile been expressed in terms of analytic functions [66].

If their masses are not too large, top squarks may influence the gluon–Higgs coupling as well. In this case, the NLO gets more involved as compared to the SM, mostly because several mass scales enter the problem. However, one may again employ an effective theory approach analogous to Eq. (1), where top quarks and squarks are considered as heavy [67, 68]. The particle spectrum of the effective theory is then the same as in the SM case, and the only unknown quantity is the Wilson coefficient $C(\alpha_s)$. The latter is obtained from massive tadpole integrals which can be evaluated analytically through two loops using the proper reduction formulas [69].

This allows one to evaluate the NLO corrections to SUSY Higgs production for small values of $\tan\beta$ (for large $\tan\beta$, the bottom and sbottom loop effects may be taken into account approximately using the leading order expression and resummation of $\tan\beta$ terms [70]). The results for both the production of a CP-even [68] and a CP-odd [71] Higgs boson have been evaluated through NLO in this way. For the CP-even Higgs, even an estimate at NNLO has been obtained [72] (denoted NNLO' in Fig. 2 below).

A particularly dramatic scenario is given by the so-called "gluophobic Higgs" [73, 74], where the quark and squark loops interfere destructively, such that the Higgs coupling to gluons becomes very small. Fig. 2 shows the effects of higher orders in α_s in this region of SUSY parameter space. One observes that the radiative corrections do not change the general behavior of the cross section. Rather, the LO rate is multiplied by an almost constant K-factor close to the one of the SM calculation [68].

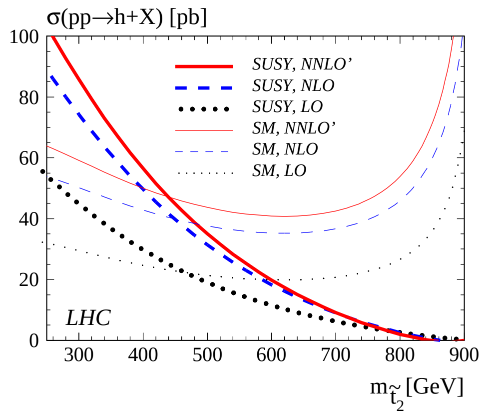

Fig. 2. Thick lines: gluon fusion cross section in the MSSM (for details, see Ref. [68]). The thin lines show the result when the squark effects are neglected.

Concerning differential distributions, the LO diagrams to Higgs plus jet production due to squark loops have been evaluated in Refs. [63, 75]. For higher order effects, one currently needs to rely on the effective Lagrangian approach due to the complexity of the calculation. Then, however, the SUSY effects factorize into the Wilson coefficient, just like for the inclusive rate.

5. Bottom quark annihilation

In SUSY, Higgs production in association with bottom quarks can give a significant contribution to the total Higgs production cross section at the LHC. In fact, it can even exceed the gluon fusion component. The proper theoretical description has been a subject of discussion for quite some time now. The difficulties arise from the fact that a potentially large mass difference between the Higgs boson and the bottom quark can lead to large logarithms that originate from integration over the collinear region of one or both of the produced bottom quarks. It has been suggested to use bottom quark parton densities as a way to resum these logarithms. However, this so-called 5-flavor scheme (5-FS) and the 4-flavor scheme (4-FS), where these logarithms are not resummed, lead to considerably different numerical results for the total cross section.

It was then realized that the discrepancies between the two approaches are much smaller once the factorization scale $\mu_{\rm F}$ for the bottom densities is chosen significantly lower than the supposedly "natural" choice $\mu_{\rm F} = M_H$. In fact, based on the argument that factorization works only in the collinear limit, it was suggested that a reasonable choice was $\mu_{\rm F} = M_H/4$ in this case [76–78]. This is because for $p_{\rm T} \gtrsim M_H/4$, the $p_{\rm T}$-distribution of the bottom quarks in the final state begins to deviate significantly from the collinear form $d\sigma/dp_{\rm T} \sim 1/p_{\rm T}$ [79].

This choice for the factorization scale later has found support from the NNLO result for that process, evaluated in the 5-FS [80]. This is shown in Fig. 3 (a) for the LHC. Clearly, convergence of the perturbative series appears to be much better for scales below M_H rather than above.

Yet another intriguing feature of this NNLO result indicates that indeed the scale $\mu_{\rm F} = M_H/4$ is markedly different from any other. To see this, Fig. 3 (b) shows separately the contributions from the $b\bar{b}$, $bg + \bar{b}g$, gg, and other, much smaller partonic sub-processes in the $\overline{\rm MS}$ scheme. Also shown is the sum of all these curves (solid line), corresponding to the NNLO result. It so happens that right at $\mu_{\rm F} = M_H/4$, all contributions except for the $b\bar{b}$ term practically vanish simultaneously [81].

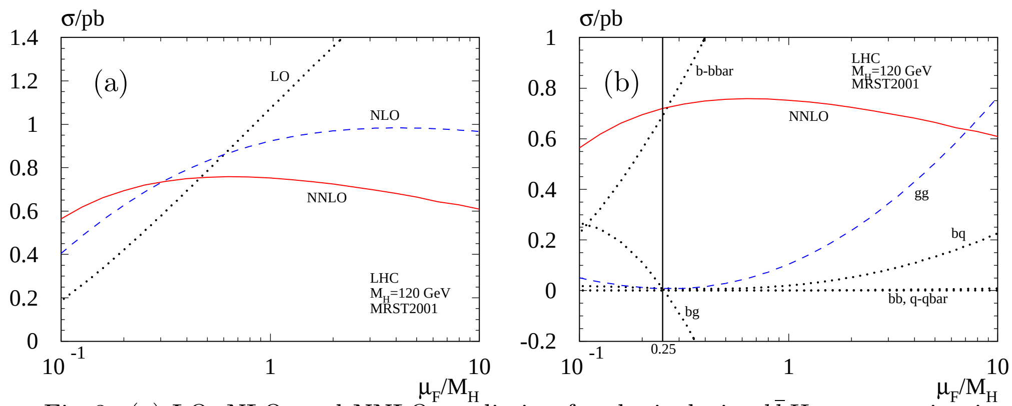

Fig. 3. (a) LO, NLO, and NNLO prediction for the inclusive $b\bar{b}H$ cross section in the 5-FS [80]. (b) Individual components to the NNLO prediction arising from various subprocesses in the $\overline{\rm MS}$ scheme. See also Ref. [81].

One may wonder whether the bottom quarks can be taken massless for the gg component of the NNLO contribution, which does not have an initial state bottom quark. These effects, however, are expected to be of order m_b^2/M_H^2 and thus negligible. This is indeed observed when comparing the massive [77] to the massless [80] result of this component [81].

Clearly, the pure 5-FS cannot be applied directly to *exclusive* $b\bar{b}H$ production, *i.e.*, if one or both of the bottom jets are required to be produced at large transverse momenta. In the fully exclusive case, the NLO corrections are available [82, 83]. If only one bottom quark is required at large $p_{\rm T}$, one may apply the 5-FS for the one that is integrated over. Also in this case, the NLO corrections are known [84, 85].

Concluding this section, the $b\bar{b}H$ process has been a very inspiring subject over the past few years, and there would still be several aspects to be discussed. However, in this short write-up, we have to refer the interested reader to the recent literature (see, *e.g.*, Refs. [81, 86, 87] and references therein).

6. Conclusions

Higgs physics has been a very fruitful field of research and, with the LHC data to come, will be even more so in the future. Progress has been fast-paced, and many of the results and techniques are general enough to find applications also in very different contexts. I have tried to summarize the most significant developments of the past few years related to Higgs production at the LHC, and to direct the reader to the relevant literature whenever more detailed information is required.

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