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Higgs production in bottom quark annihilation and gluon fusion*

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Some aspects and recent developments of Higgs production in bottom-quark annihilation and gluon fusion are reviewed. Concering scale dependence, PDF uncertainties, and top quark mass effects, a number of as of yet unpublished studies is presented.

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1. Introduction

The recently discovered boson seems quite consistent with a Standard Model (SM) Higgs boson [1, 2]. On the other hand, the measured mass of roughly 126 GeV is below the upper mass bound of the Minimal Supersymmetric SM (MSSM) [3, 4]. Combined with the fact that both ATLAS and CMS observe a branching ratio of the new particle into $\gamma\gamma$ which is slightly higher than BR($H \to \gamma\gamma$), it is important to consider seriously the possibility that the observed particle is *not* the SM Higgs boson.

While many of the results obtained for the Higgs production in the SM are transferable to the MSSM my means of effective couplings, there can be quite significant modifications due to the additional particle spectrum and the altered couplings in the MSSM. One of the most drastic differences is the increased importance of associated Higgs production with bottom quarks due to a possibly enhanced bottom Yukawa coupling (see, e.g. Refs. [5, 6]). On the one hand, this additional process leads to interesting new phenomenology, of course. On the other hand, its theoretical desription has led to a number of insightful discussions in the literature which may be considered interesting for their own sake.

In this talk, I briefly review the different theoretical approaches to the $b\bar{b}h$ process, report on recent developments, and show some as of yet unpublished studies.

2. Bottom quark annihilation

2.1 4- vs. 5-flavor scheme

Two formally equivalent approaches have been persued for the theoretical descriptions of the associated bottom-Higgs production process (called $b\bar{b}h$ in what follows). In the 4-flavor scheme (4FS), the leading order (LO) partonic processes are $gg \to b\bar{b}h$ and $q\bar{q} \to b\bar{b}h$, $q \in \{u,d,c,s\}$. For consistency, DGLAP evolution of the parton distribution functions (PDFs) should be done with only four active flavors as well in this case. In the 5FS, the LO partonic process is $b\bar{b} \to h$, where the b-PDFs are generated perturbatively through DGLAP-evolution with five active quark flavors. The pros and cons of both approaches have been discussed extensively in the literature and are summarized in Ref. [7], for example.

The 4FS and 5FS are complementary in many respects, which is why a proper combination of the two has been of some concern. In particular, it turns out that – for Higgs masses ≥ 200 GeV – the theoretical uncertainty as estimated from scale variation is significantly larger in the 4FS than in the 5FS.

Let us recall that a theoretically consistent combination of the 5FS with the 4FS is actually achieved by a next-to-next-to-LO (NNLO) calculation in the 5FS approach [8]: all LO diagrams of the 4FS are included in the 5FS in this case, and any potential double counting is taken care of by collinear subtraction based on the usual splitting functions. However this NNLO result in the 5FS is formally of $\mathcal{O}(\alpha_s^2)$, while the 4FS result is known through $\mathcal{O}(\alpha_s^3)$ [9, 10]; it would therefore be desirable to include this prediction in the combination.

In Ref. [7], a very pragmatic combination has been suggested. It incorporates the following observations and requirements:

- Empirically, the 4FS and the 5FS give the same result (central value and uncertainty) at $M_\mathrm{h} = 100\,\mathrm{GeV}$. We consider them equally valid at this value of M_h; they should therefore enter with the same weight there.
- For large M_h, the 5FS is more appropriate due to logarithms of the form $\ln M_\mathrm{b}{}^2/M_\mathrm{h}^2$.
- The transition between the two approaches should depend logarithmically on M_h.

This leads to the formula [7]

$$\sigma^{\mathrm{matched}} = \frac{\sigma^{\mathrm{4FS}} + w\,\sigma^{\mathrm{5FS}}}{1+w}\,, \qquad w = \ln\frac{M_\mathrm{b}^2}{M_\mathrm{h}^2} - 2\,. \tag{2.1}$$

The uncertainties are combined analogously, separately for the upper and the lower bounds. It is clear, however, that an empirical formula such as Eq. (2.1) can only be a temporary solution to the problem. First steps towards a more systematic approach has been presented in Ref. [11].

2.2 Theory uncertainties

Apart from the central values for the cross section, it is important to haven an estimate of its theoretical uncertainties. Two sources of uncertainty are common to all theory predictions for cross sections at hadron colliders: the parton densities and the truncation of the perturbative series.

2.2.1 Scale uncertainties

The effects of higher, uncalculated orders in perturbation theory are usually estimated from the residual dependence on the renormalization μ_R and factorization scale μ_F (collectively denoted as μ in what follows). The precise procedure is not uniquely defined though, because neither the position nor the width of the μ-interval is fixed, for example. Also, although μ_F and μ_R are in principle independent, they are often equated with each other, be it for convenience, or in order to be consistent with the PDFs which usually assume $\mu_\mathrm{F} = \mu_\mathrm{R}$.

If a physical process depends only on a single physical scale, the central value for μ is typically chosen to be that scale. At LO, and if physically motivated arguments are missing, this is a reasonable procedure. At higher orders, the dependence of the cross section on μ as well as the behaviour of successive perturbative orders may be used as additional information for the scale choice.

The total $b\bar{b}h$ cross section is a particularly instructive example. While the naive central scale choice is M_h (the only physical scale available), it has been argued, based on the behaviour of the bottom-PDFs, that a somewhat smaller value, say $M_\mathrm{h}/4$, appears more appropriate [12, 13, 14]. And in fact, the explicit NNLO calculation confirms these arguments [8], as can be seen in Fig. 1 (a): the first three terms of the perturbative series are rather well-behaved at $\mu_\mathrm{F} = M_\mathrm{h}/4$, and the dependence on μ_F is fairly weak.

Independent of that, another observation is remarkable (see also Ref. [15]): as shown in Fig. 1 (b), at $\mu_\mathrm{F} = M_\mathrm{h}/4$, the total inclusive cross section is almost completely saturated by the $b\bar{b}$ sub-process, while all other channels basically vanish there. For $M_\mathrm{h} = 125\,\mathrm{GeV}$, this statement is true at all values of $\mu_\mathrm{R}/M_\mathrm{h} \in [0.1, 10]$, and it depends only weakly on M_h.

2.2.2 PDF uncertainties

The PDFs induce an uncertainty due to (a) the experimental error of the input data, as well as the finite perturbative order of (b) the reference calculations and (c) the DGLAP evolution. Furthermore, as is obvious from a direct comparison among the various available PDF sets, the precise method on how the PDFs are obtained from the input data induces another – rather significant – uncertainty [16].

All modern sets of PDFs provide a means to estimate the uncertainty they induce into a hadronic cross section. This usually requires the evaluation of the cross section for a rather large number of "member PDFs" (41 for MSTW2008, 51 for CT10 etc.). Instead of this proper uncertainty evaluation, Fig. 2 shows the inclusive cross section for a random selection of member PDFs for various NNLO PDF sets. It is immediately apparent that the individual PDF uncertainties are much smaller than the spread between the different sets. Therefore, in the "official numbers" for the LHC Higgs searches [5, 6], a recipe to obtain an overall PDF uncertainty which basically relies on the envelope of several PDFs has been defined. In the near future, it will certainly be desirable to replace this procedure by a theoretically more sound method.

One of the issues that have been discussed quite extensively in this context is whether $\alpha_s(M_Z)$ should be used as a fit parameter, or whether it should be fixed to a pre-defined value. While leaving it as a free parameter certainly has advantages for the fit quality, there is also a number of arguments for a pre-defined fixed value:

- The world average for $\alpha_s(M_Z)$ is very precise [17, 18] and should be taken into account.
- Processes at hadron colliders have a rather different dependence on α_s. While gluon fusion is proportional to α_s^2, for example, the Drell-Yan process does not depend on α_s at all at LO. Ignoring the world average of $\alpha_s(M_Z)$ therefore introduces an unnecessary uncertainty.
- The cross section may depend strongly on other parametes which have to be derived perturbatively from the input. For example, the $b\bar{b}h$ cross section is proportional to the square of the bottom-quark mass. In order to absorb logarithmic terms $\sim \ln M_\mathrm{h}^2$, it should be renormalized in the $\overline{\mathrm{MS}}$ scheme at a scale $\mu_\mathrm{R} \sim M_\mathrm{h}$ which is usually evaluated by RG evolution from $M_\mathrm{b}(M_\mathrm{b})$. This evolution depends on $\alpha_s(M_Z)$ and so again, there is an uncertainty introduced when $\alpha_s(M_Z)$ is used from the PDFs.

The effect of a variation in $\alpha_s(M_Z)$ is illustrated in Fig. 3 for both the $b\bar{b}h$ and the gluon fusion process. It is produced with the MSTW2008 set [19] at NNLO which uses fixed values for $\alpha_s(M_Z)$ in the range $\alpha_s(M_Z) \in [0.107, 0.127]$. It shows that the cross section varies stronger than linearly with $\alpha_s(M_Z)$.

As a final topic, let us recall the standard lore that LO PDFs should be evaluated (and applied) with LO DGLAP evolution and running of α_s, NLO PDFs with NLO evolution and running, etc. However, similar to the discussion above, in many cases a particular calculation requires the transformation of parameters from one renormalization scheme/scale to another at the highest available order (e.g. transformation of SM to SUSY parameters). In order to be able to work with a consistent set of parameters, it would be helpful to have "NLO PDFs" (i.e. fitted to NLO cross sections) which, however, use the highest available order in the DGLAP evolution and the running of α_s.[1]

[1] Independently of that, it would be interesting to see whether the corresponding fits are of different quality than the

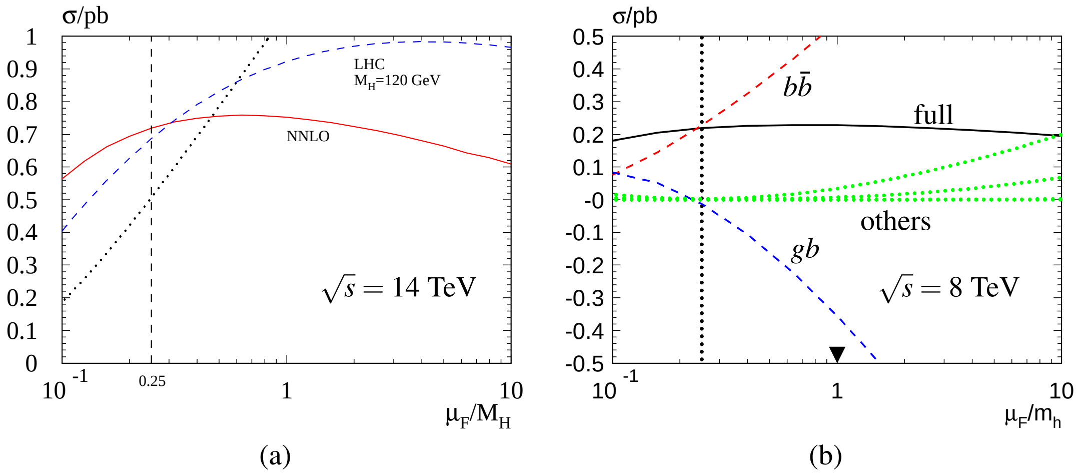


Figure 1: The total inclusive cross section for $b\bar{b}h$ in the 5FS at NNLO (solid); (a) behavior of the perturbative series, and (b) split into the individual subchannels contributing to it. Note that the center-of-mass energy is different in the two plots. Produced with `bbh@nnlo` [20].

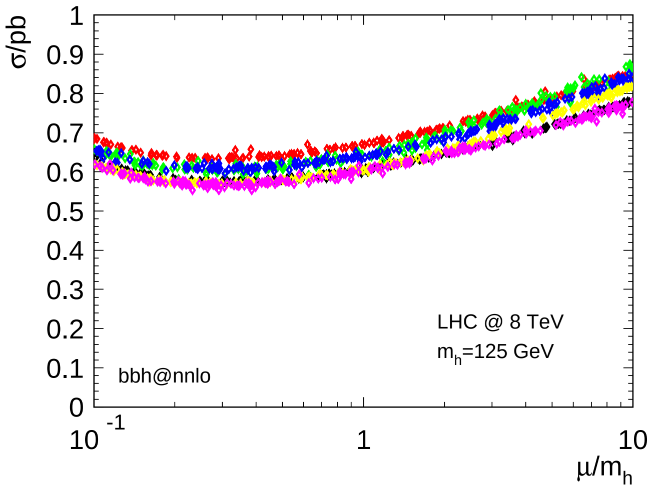
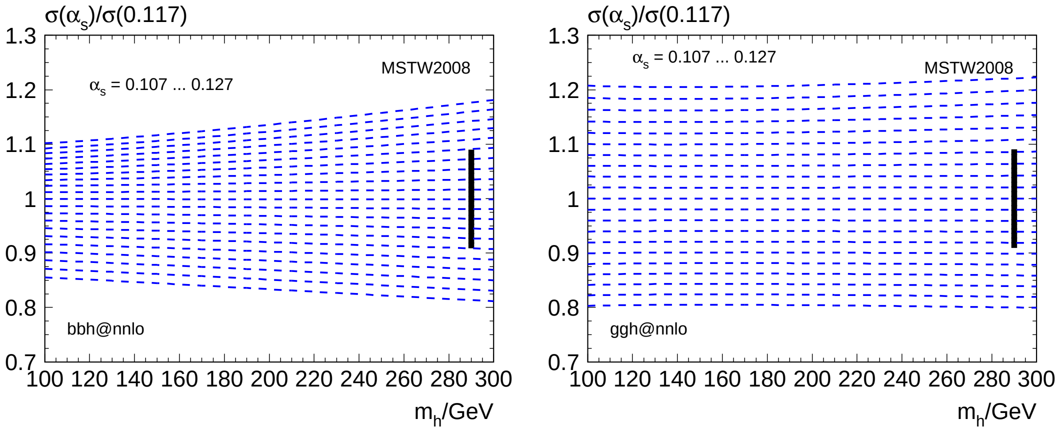


Figure 2: Total inclusive cross section for $b\bar{b} \to h$ as a function of $\mu = \mu_\mathrm{F} = \mu_\mathrm{R}$. The individual points correspond to a random selection of PDF members from various PDF sets (MSTW2008 [21] (black), CT10 [22] (pink), JR09 [23] (blue), ABM11 [24] (red), HERA [25] (yellow), NNPDF ($\alpha_s(M_Z) = 0.119$) [26] (green)). All sets as implemented in LHAPDF [27].



(a) (b)

Figure 3: (a) The total inclusive cross section for $b\bar{b}h$ in the 5FS at NNLO, obtained using the sets from MSTW2008 with pre-determined values of $\alpha_s(M_Z) \in [0.107, 0.127]$ (lower to upper curve), normalized to the cross section obtained with the set for $\alpha_s(M_Z) = 0.117$. The black vertical bar on the right simply shows the interval $[0.107, 0.127]/0.117$; (b) the analogous plot for gluon fusion.

2.3 Distributions

It seems obvious that the 5FS is a valid approach for the total inclusive Higgs production cross section. However, it has been used for less inclusive quantities as well, for example $H + b$-production, where one of the outgoing bottom jets is produced at large transverse momenta [28, 29, 28]. This process is particularly useful for identifying the Higgs boson as part of an extended theory, for example the MSSM.

If indeed associated Higgs-bottom production plays a significant role for the total cross section, it will be important to control kinematical distributions of the Higgs boson in this process, similar to what has been studied in gluon fusion. Therefore, in Refs. [30, 31, 32] differential quantities such as Higgs-p_T distributions through NLO, as well as p_T- and (b- or non-b-)jet vetos through NNLO were evaluated. A fully differential calculation through NNLO was presented in Ref. [33].

3. Gluon fusion

Being the dominant production mechanism for Higgs bosons at the LHC and the Tevatron, gluon fusion has received a lot of attention in the theory community, both for the total cross section and for distributions (for reviews, see Refs. [5, 6]).

In addition to the usual uncertainties from perturbation theory and PDFs, there is another potential source of uncertainties for the gluon fusion process which arises from the so-called heavy-top limit that is usually applied when higher orders are considered in this process. For the total inclusive cross section, this issue has been solved at NLO by a calculation that keeps the full top- and bottom-mass dependence [34]. At NNLO, the calculation of higher orders in the $1/M_t$ expansion

"conventional" ones.

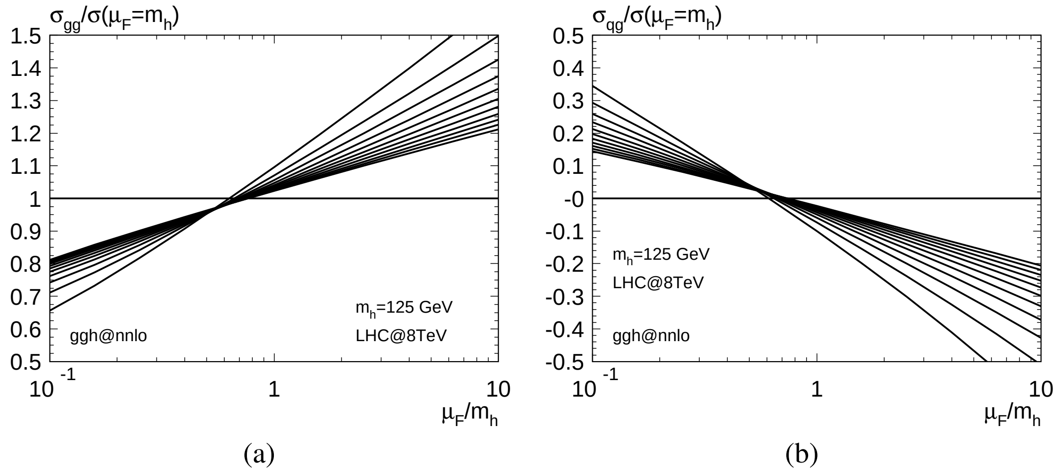


Figure 4: (a) The gg and (b) the qg sub-process of Higgs production in gluon fusion at NNLO as functions of the factorization scale, normalized to the total cross section at $\mu_F = M_h$. The various curves correspond to different values of the renormalization scale $\mu_R \in [0.1, 10]$.

has shown that the heavy-top limit works to better than 1% up to Higgs masses of the order of 300 GeV [35, 36, 37, 38] (see also Ref. [39]).

More recently, the quark mass effects have been investigated also for kinematical distributions: the exact top- and bottom-quark mass effects were studied for $H + n$ jet production at LO (i.e. $\mathcal{O}(\alpha_s^{n+2})$) matched to parton showers in Ref. [40], and for the inclusive p_T-distribution at NLO (i.e. $\mathcal{O}(\alpha_s^3)$) in Ref. [41, 42] (note that at $p_T > 0$, the latter is formally of LO). Similar to the NLO inclusive calculation, these studies were done again by including the full top- and bottom-quark mass in the calculation.

Even more recently, Ref. [43] considered the p_T-distribution of the Higgs at $\mathcal{O}(\alpha_s^4)$ for $p_T > 0$. Keeping the full top- and bottom-mass dependence is beyond current technology, which is why, similar to Refs. [35, 37], an expansion in $1/M_t$ was performed. It was found that even for this distribution, the heavy-top limit works at the percent-level as long as $p_T < 150$ GeV.

An interesting observation of this calculation is that the QCD corrections to the partonic gg-channel are almost completely insensitive to the top mass effects, while their influence on the qg-channel is much stronger. Since the qg-channel is sub-dominant, however, the mass effects for the sum over all channels are still rather small. Such a statement depends on the factorization scheme, of course. This suggests that one may use a factorization scheme where all partonic channels are zero, and the hadronic cross section is determined by the gg-channel alone. In fact, for the total inclusive cross section, this can be approximately achieved in the $\overline{\text{MS}}$ factorization scheme by a simple choice of scale. Fig. 4 (a) and (b) show the (numerically dominant) gg- and qg-induced sub-processes for Higgs production in gluon fusion at NNLO QCD. One observes that in the region $\mu_F/M_h \in [0.5, 1]$, the gg sub-channel almost completely saturates the total inclusive cross section, independent of μ_R. Note the similarity of this behaviour with the discussion around Fig. 1 for the $b\bar{b}h$ process.

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