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Supersymmetric Higgs production at the Large Hadron Collider

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Abstract. We review the status of theoretical predictions for the production of neutral Higgs bosons at the LHC. Special emphasis is put on the role of bottom quarks in the gluon fusion process and in the associated production of Higgs bosons with $b\bar{b}$ pairs.

PACS. 14.80.Cp Non-standard-model Higgs bosons – 12.38.Bx Perturbative calculations

1 Introduction

There has been significant progress in controlling the theoretical predictions for Standard Model Higgs production cross sections at the LHC over the past few years. The Higgs sector may play a crucial role for the discrimination among the Standard Model and various extended theories at the LHC. In the following, we discuss the status of theoretical predictions for supersymmetric Higgs production, focussing on the CP-even neutral Higgs bosons, generically denoted by H.

2 Gluon fusion

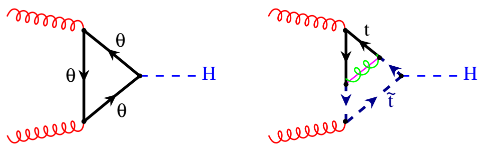
For the SM and most of its extensions, gluon fusion is the dominant production mode for a neutral Higgs boson at hadron colliders. A generic LO diagram is shown in Fig. 1 (a). The coupling of the gluons to the Higgs boson is a pure quantum effect: In the SM, it is mediated predominantly by top quarks, while the contribution of other fermions f is suppressed by m_f/m_t.

In the MSSM, the contribution from virtual bottom quarks can be significantly enhanced through large values of $\tan\beta$. Furthermore, top squarks can give a sizable contribution if their masses are of the order of m_t. We thus write the total cross section from gluon fusion as

$$\sigma = \sigma_t + \Delta\sigma_b + \Delta\sigma_{\tilde{t}} + \Delta\sigma_{b\tilde{t}}\,, \qquad (1)$$

where σ_t denotes the pure top quark contribution, and $\Delta\sigma_b$ ($\Delta\sigma_{\tilde{t}}$) the additional effects due to the presence of bottom quarks (top squarks). The term $\Delta\sigma_{b\tilde{t}}$ which arises from the interference of bottom quarks and top squarks, will not be considered any further in this paper. Note that we also neglect effects from bottom squarks which are suppressed by $(m_b/m_{\tilde{b}})^2$, modulo a possible enhancement due to large values of $\tan\beta$. Furthermore, we define

$$\sigma_{ti} \equiv \sigma_t + \Delta\sigma_i\,, \qquad i \in \{b, \tilde{t}\}\,. \qquad (2)$$



(a) (b)

Fig. 1. Feynman diagrams contributing to gluon fusion: (a) $\theta = t, b, \tilde{t}, \ldots$ — (b) two-loop contribution in the MSSM.

Top quark loops, Effective theory approach. Apart from an overall factor $f(\beta)$, the pure top quark contributions σ_t to the Higgs production cross section in the MSSM and the SM are identical to all orders in QCD. Higher orders are described extremely well by the "heavy-top limit" [1] which, for this particular case, is defined as follows:

$$\sigma_\theta^\infty = \kappa_\theta \cdot \sigma_\theta^{(0)}\,, \qquad \kappa_\theta = \frac{\sigma_\theta(m_\theta \to \infty)}{\sigma_\theta^{(0)}(m_\theta \to \infty)}\,, \qquad (3)$$

where $\theta = t$. Here, $\sigma_\theta^{(0)}$ denotes that part of σ_θ where all higher order corrections to the *partonic* process are dropped (they are kept in the parton densities and the running of α_s). Fig. 2 shows that the difference between σ_t^∞ and the exact result σ_t is less than 2% for $M_H < 2m_t$ at next-to-leading order. This should be compared to the NLO uncertainty of ±15% [1] as estimated from varying the renormalization and factorization scales μ_R and μ_F. It was therefore well justified to apply the heavy-top limit at NNLO [2,3][1] in order to obtain a theoretical prediction for the total cross section that is competitive with the expected experimental uncertainty.

Bottom quark loops. As was mentioned above, the gluon-Higgs coupling gets significant contributions from bottom quark loops for large values of $\tan\beta$. Since the "heavy-top

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[1] For resummation effects, see Ref. [4].

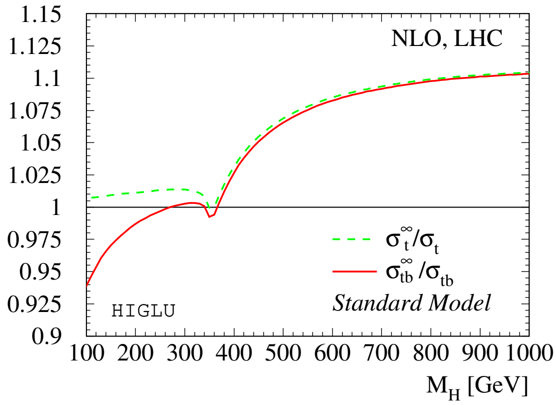

Fig. 2. The total cross section at NLO as evaluated in the effective theory (Eq. (3)), compared to the exact NLO result [5, 6]. Dashed line: only top quarks — solid line: including bottom quarks ($m_t^{\rm OS} = 175\,$GeV, $m_b^{\rm OS} = 5\,$GeV).

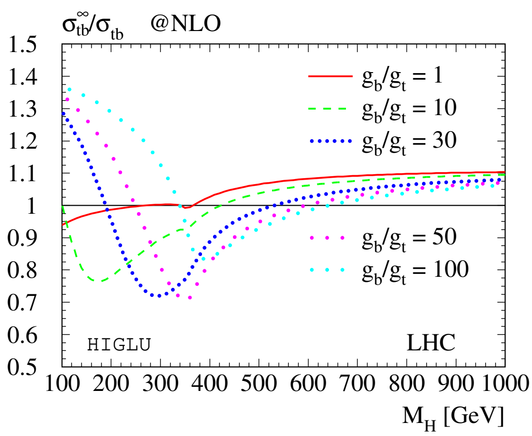

Fig. 3. Relevance of the exact bottom quark contribution for various values of the bottom Yukawa coupling [6]. $g_b/g_t = 1$ corresponds to the Standard Model (see also [7]).

limit" works at the 10% level even for very large Higgs boson masses (see Fig. 2), it is tempting to apply a formal "heavy-bottom approach", defined by Eq. (3) with $\theta = tb$ and $m_{tb} \equiv \{m_t, m_b\}$. At NLO, it is $\kappa_{tb} = \kappa_t$. Fig. 3 shows the deviation of σ_{tb}^∞ from the exact result at NLO [5,6] for various values of the ratio g_b/g_t, where $g_{b,t}$ are the Yukawa couplings of the bottom and top quark *relative to their SM values*. Note that the solid/red curves (Standard Model) of Figs. 3 and 2 are identical.

The curves in Fig. 3 show that the effect of the exact NLO bottom contribution stays below 40% even for very large bottom Yukawa couplings. For large Higgs boson masses, the curves approach the Standard Model value (solid/red curve).

SUSY loops. The contribution of squarks to the total Higgs production cross section goes like $(m_q/m_{\tilde q})^2$. Thus, as shown in Fig. 4, only top squarks with $m_{\tilde t} \lesssim 400\,$GeV give a sizable effect.

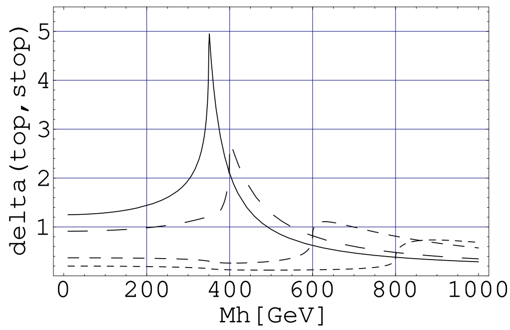

Fig. 4. Relative size of the top quark/squark contributions: `delta(top,stop)`$=\Delta\sigma_{\tilde t}/\sigma_t$, see Eq. (1). Furthermore, $m_t = 175\,$GeV, and $m_{\tilde t R} = m_{\tilde t L} \equiv m_{\tilde t}$. Solid line: $m_{\tilde t} = 175\,$GeV — long/middle/short dashes: $m_{\tilde t} = 200/300/400\,$GeV.

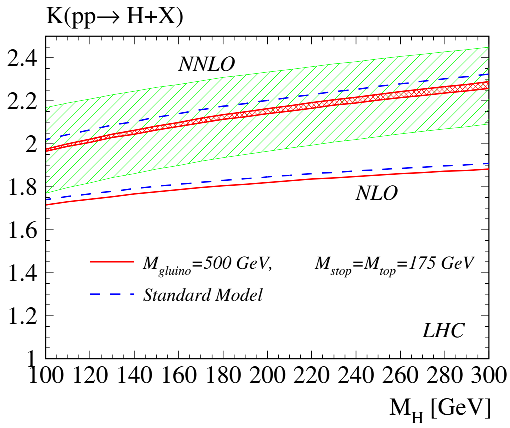

Fig. 5. K-factors for the gluon-fusion process. Dashed: Standard Model — Solid: MSSM (no stop mixing). The narrow (red) band shows the uncertainty due to the missing NNLO contribution in the effective vertex, the wide (green) band is the scale uncertainty (from Ref. [11]).

The SUSY relation between the top and stop Yukawa coupling requires to include also gluino effects at higher orders in α_s to arrive at finite results. A sample diagram with top quark, top squark, and gluino is displayed in Fig. 1 (*b*).

The NLO corrections (evaluated through Eq. (3) with $\theta = t\tilde t$ and $m_{t\tilde t} \equiv \{m_t, m_{\tilde t}, m_{\tilde g}\}$) were found to be very similar to the Standard Model case [8] (see also Ref. [9], so that the tree-level ratios shown in Fig. 4 hardly change at NLO. In this first study, squark mixing effects had been neglected, but more detailed investigations are under way.

The dominant corrections to the Higgs production cross section originate from real gluon emission [10]. Thus, it is possible to derive a rather precise estimate of the NNLO terms based on the NNLO result in the SM [3] and the NLO effective Higgs-gluon coupling [8]. In this way, the reduced scale uncertainty of the NNLO in the SM directly carries forward to the supersymmetric case. The result is shown in Fig. 5, details can be found in Ref. [11].

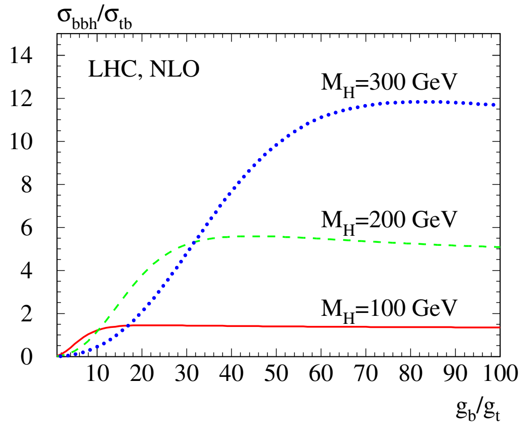

Fig. 6. Relative contribution of the process $b\bar{b} \to H$ to the total NLO cross section, compared to gluon fusion, as a function of the bottom Yukawa coupling. Note that for $\sigma_{b\bar{b}h}$ we use the running bottom Yukawa coupling with $m_b(m_b) = 4.3$ GeV, while for σ_{tb} we use the on-shell expression with $m_b^{\rm OS} = 5$ GeV.

3 Associated production with bottom quarks

A large value of $\tan\beta$ (i.e., $\tan\beta \gtrsim m_t/m_b \approx 35$) not only leads to a significant contribution of virtual bottom quarks to the gluon-Higgs coupling; it also brings in a new Higgs production mechanism, namely $pp \to b\bar{b}H$. The relative importance of both processes is shown in Fig. 6 as a function of the bottom Yukawa coupling.

The LO partonic Feynman diagram would be $gg \to b\bar{b}H$, Fig. 7 (b). However, integration over small transverse momenta $p_{T,b}$ of the bottom jets leads to collinear logarithms $\sim \ln(m_b/M_H)$. Resummation of these logarithms can be achieved by introducing bottom quark densities for the initial state hadrons, and using $b\bar{b} \to H$ as the LO partonic process (the two final state bottom jets remain unobserved). The LO contribution in this approach neglects contributions from *large* $p_{T,b}$; but they are re-introduced through higher order QCD corrections. In fact, a NNLO calculation [12] consistently combines the all-order resummation of the low-$p_{T,b}$ region with the LO contributions from large $p_{T,b}$. This is plausible because the diagrams for $gg \to b\bar{b}H$ are naturally part of the NNLO contribution to the process $b\bar{b} \to H$ (see Fig. 7).

The NNLO result depends only very weakly on the renormalization and factorization scales, thus providing a very precise prediction of the inclusive rate. In addition, it supports the analyses of Ref. [13] which suggest that the "central" choice of the factorization scale for this process should be $\mu_F = M_H/4$.

Recently, the NLO corrections for the *exclusive* process became available [14]. In this case, the LO partonic process is indeed $gg \to b\bar{b}H$. When integrated over *all* bottom quark transverse momenta, the cross section is in good agreement with the result from the bottom density approach [12], be it with much larger error bars.

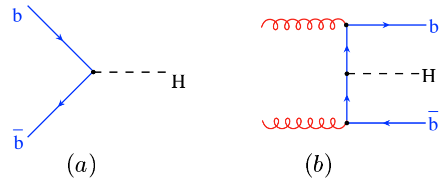

Fig. 7. Sample Feynman diagrams contributing to bottom annihilation (a) at leading order — (b) at NNLO.

Conclusions. The recent NNLO results for Higgs production at hadron colliders have brought confidence into the theoretical predictions[2]. The reduced uncertainties now have to be achieved also in extended models. First steps have been done, but there are still many problems to be solved that ask for technical progress and new ideas.

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[2] Unfortunately, we could not include recent NNLO results on pseudo-scalar Higgs production [15] and Higgs-Strahlung [16].