Higgs-Boson Production in Association with Heavy Quarks

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Abstract. Associated production of a Higgs boson with a heavy, i.e. top or bottom, quark–anti-quark pair provide observation channels for Higgs bosons at the LHC which can be used to measure the respective Yukawa couplings. For the light supersymmetric Higgs boson we present SUSY-QCD corrections at the one-loop level, which constitute a significant contribution to the cross section.

INTRODUCTION

Higgs-boson Yukawa couplings to fermions are proportional to the fermion masses and hence are very small for the light quarks, \( u, d, s \) and \( c \). In contrast, the top-quark mass is of the same order as the Higgs vacuum expectation value, leading to a top-quark Yukawa coupling close to 1. The bottom-quark mass also leads to a rather weak Yukawa coupling in the Standard Model. In the Minimal Supersymmetric Standard Model (MSSM), the coupling to the lighter CP-even neutral Higgs boson \( h^0 \) can be enhanced for large values of \( \tan(\beta) \), the ratio of the two vacuum expectation values. Such large Yukawa couplings make Higgs-boson production in association with heavy quarks \[1\] a phenomenologically interesting process. At \( \mathcal{O}(\alpha_s^2\alpha) \), the Higgs boson is emitted off one of the heavy-quark lines; the cross section is thus sensitive to the Yukawa coupling and can be used to measure the respective Yukawa coupling. A precise determination requires to include at least the next-order QCD corrections. Here we present for the case of MSSM Higgs bosons the results from a calculation of the SUSY-QCD corrections, supplementing the standard QCD corrections by the loop contributions with virtual gluinos and squarks.

BOTTOM QUARKS

The production of a Higgs boson in association with a bottom quark–anti-quark pair was intensively studied in the literature \[2, 3\]. The analysis was soon extended \[4, 5\] to include the lightest MSSM-Higgs boson \( h^0 \). The diagram types are exactly the same as in the Standard Model case; only the bottom-quark–Higgs coupling is changed to its supersymmetric counterpart. The standard QCD corrections \[6\] to this process are already known and reduce the dependence of the cross section on the factorization and renormalization scales. The final-state bottom quarks are required to be explicitly observed in the detector via \( b \)-tagging, in contrast to inclusive processes \[7\] without
Therefore, a transverse-momentum cut on the bottom-quark jets, typically $p_T \geq 20$ GeV, is applied. The additional cuts reduce the cross section by one or two orders of magnitude, but also greatly reduce the background and ensure that the Higgs boson was emitted from a bottom quark and is therefore proportional to the square of the $b$-quark Yukawa coupling.

Here we concentrate on the SUSY-QCD corrections with squarks and gluinos in the loops. Part of these corrections were already calculated in ref. [8]. There an effective $bbh^0$-coupling was used which includes the one-loop vertex corrections, but no box-type or pentagon diagrams were added in their analysis. We have performed a full one-loop calculation of the SUSY-QCD corrections.

In certain regions of the MSSM parameter space a large contribution to the SUSY-QCD corrections originates from the effective coupling of the bottom quark to the second Higgs doublet. This changes the relation between bottom-quark mass and Yukawa coupling and the additional contribution is commonly referred to as $\Delta_b$ in the literature [9]. It is proportional to $\tan(\beta)$ and represents for large values of $\tan(\beta)$ the dominant supersymmetric correction. If the $\Delta_b$-contribution is compared with full one-loop results it is necessary to include it only to one-loop order as well and not use any resummed version, resulting in the replacement

$$m_b \to m_b (1 - \Delta_b) \quad ,$$

which has been used when calculating $\Delta_b$-corrected tree-level cross sections.

In order to assess the relative differences between cross sections the following quantities have been defined. The relative one-loop correction is given as

$$\Delta_1 = \frac{\sigma_1 - \sigma_0}{\sigma_0} \quad ,$$

where $\sigma_0$ denotes the tree-level cross section and $\sigma_1$ the one-loop one including SUSY-QCD corrections. Additionally, a $\Delta_b$-corrected tree-level cross section $\sigma_\Delta$ was calculated by using the replacement of eq. (1) and treating the $\Delta_b$ term as a one-loop contribution. Additionally, the contribution to the vertex from the term proportional to the second mixing angle in the MSSM-Higgs sector, $\alpha$, was included in $\sigma_\Delta$ according to ref. [4, 9, 10]. The relative correction using only these contributions is defined as

$$\Delta_0 = \frac{\sigma_\Delta - \sigma_0}{\sigma_0} \quad .$$

The Feynman diagrams were generated using FeynArts [11], the matrix elements calculated by FormCalc [12] and the loop integrals numerically evaluated by LoopTools [13]. The convolution with the parton distribution functions was performed with HadCalc [14] using the PDF set of ref. [15].

The left-hand side of Table 1 contains the individual contributions from the various partonic processes to the hadronic process $pp \to bbh^0$ and their sum, for the MSSM reference point SPS1a' [16]. The gluon-fusion process clearly dominates the total hadronic cross section. This is because for the quark–anti-quark annihilation diagrams only an s-channel topology exists, which is propagator-suppressed. For the gluon-fusion diagrams
TABLE 1. Hadronic cross sections for $b\bar{b}h^0$ and $t\bar{t}h^0$ production at the parameter point SPS1a$'$.  

| Process            | $\sigma_0$ [fb] | $\sigma_1$ [fb] | $\Delta_1$ [%] | $\Delta_0$ [%] |
|--------------------|-----------------|-----------------|----------------|---------------|
| $dd \rightarrow b\bar{b}h^0$ | 0.107           | 0.104           | -2.48          | -1.95         |
| $u\bar{u} \rightarrow b\bar{b}h^0$ | 0.168           | 0.164           | -2.56          | -1.95         |
| $s\bar{s} \rightarrow b\bar{b}h^0$ | 0.028           | 0.028           | -2.26          | -1.95         |
| $c\bar{c} \rightarrow b\bar{b}h^0$ | 0.013           | 0.012           | -2.20          | -1.95         |
| $gg \rightarrow b\bar{b}h^0$ | 35.647          | 33.734          | -5.37          | -1.95         |
| $pp \rightarrow b\bar{b}h^0$ | 35.963          | 34.042          | -5.34          | -1.95         |
| $dd \rightarrow t\bar{t}h^0$ | 42.7            | 37.6            | -11.77         |               |
| $u\bar{u} \rightarrow t\bar{t}h^0$ | 71.9            | 63.4            | -11.81         |               |
| $s\bar{s} \rightarrow t\bar{t}h^0$ | 7.5             | 6.6             | -11.58         |               |
| $c\bar{c} \rightarrow t\bar{t}h^0$ | 2.8             | 2.5             | -11.53         |               |
| $gg \rightarrow t\bar{t}h^0$ | 273.7           | 264.7           | -3.30          |               |
| $pp \rightarrow t\bar{t}h^0$ | 399.0           | 374.8           | -5.96          |               |

there is an additional $t$-channel diagram which does not suffer from such a suppression. Additionally one can see that the $\Delta_b$-corrected tree-level cross section accounts only for less than half of the total SUSY-QCD corrections for this parameter point, and therefore a full calculation is necessary to determine the size of the additional contribution. The details of this additional contribution will be discussed in a future publication [17].

**TOP QUARKS**

The production of a Higgs boson in association with a top quark–anti-quark pair [18] proceeds in the same way as the one with a bottom quark–anti-quark pair and the same Feynman diagrams appear, where the bottom-quark line is replaced by a top-quark line. The standard QCD corrections to this process are also available in the literature [19]. A calculation of the SUSY-QCD corrections was performed recently in ref. [20]. As the figures of this article include both standard and SUSY-QCD contributions a direct comparison of the numerical results is difficult. The principal behavior when varying MSSM parameters agrees. Our calculation was performed using the same tools as mentioned beforehand in the bottom-quark case. No cuts were applied to the final state.

On the right-hand side of Table the results for the MSSM parameter point SPS1a$'$ are presented. In this case the gluon-fusion contribution is still the dominant one, but also the quark–anti-quark–annihilation subprocesses reach a significant size and cannot be neglected any more. This is because to produce the final state a higher center-of-mass energy than for bottom quarks is needed. The rapid decrease of the gluon density in the proton with growing momentum fraction $x$ partly cancels the effect of the s-channel propagator suppression in quark–anti-quark annihilation. We find that the total size of the SUSY-QCD corrections is of the order of several percent.

**SUMMARY**

Higgs-boson production in association with heavy, i.e. bottom or top, quarks is an important way to measure the respective Yukawa couplings. In the MSSM besides the standard QCD corrections also SUSY-QCD corrections appear. They modify the total cross section significantly and should be taken into account to extract the Yukawa coupling precisely from future experimental data.
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