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SM and MSSM Higgs Boson Production Cross Sections at the Tevatron and the LHC *

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Abstract

We present results for the SM and MSSM Higgs-boson production cross sections at the Tevatron and the LHC. The SM cross sections are a compilation of the state-of-the-art theoretical predictions. The MSSM cross sections are obtained from the SM ones by means of an effective coupling approximation, as implemented in `FeynHiggs`. Numerical results have been obtained in four benchmark scenarios for two values of $\tan\beta$, $\tan\beta = 5, 40$.

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1 Introduction

Deciphering the mechanism of electroweak symmetry breaking (EWSB) is one of the main quests of the high energy physics community. Electroweak precision data in combination with the direct top-quark mass measurement at the Tevatron have strongly constrained the range of possible scenarios and hinted to the existence of a light scalar particle [1]. Both in the standard model (SM) and in its minimal supersymmetric extensions (MSSM), the W and Z bosons and fermions acquire masses by coupling to the vacuum expectation value(s) of scalar SU(2) doublet(s), via the so-called Higgs mechanism. The common prediction of such models is the existence of at least one scalar state, the Higgs boson. Within the SM, LEP has put a lower bound on the Higgs mass, $m_h > 114.4$ GeV [2], and has contributed to the indirect evidence that the Higgs boson should be relatively light with a 95% probability for its mass to be below 166 GeV [1]. In the MSSM the experimental lower bound for the mass of the lightest state is somewhat weaker, while the theory predicts an upper bound of about 135 GeV [3–5].

If the Higgs sector is realized as implemented in the SM or the MSSM, at least one Higgs boson should be discovered at the Tevatron and/or at the LHC. Depending on the mass, there are various channels available where Higgs searches can be performed. The power of each signature depends on the production cross section, σ, and the Higgs branching ratio into final state particles, such as leptons or b-jets, the total yield of events being proportional to $\sigma \cdot$ BR. In some golden channels, such as $gg \to h \to Z^{(*)}Z \to 4\mu$, a discovery will be straightforward and mostly independent from our ability to predict signal and/or backgrounds. On the other hand, for coupling measurements or for searches in more difficult channels, such as $t\bar{t}h \to t\bar{t}b\bar{b}$ associated production, precise predictions for both signal and backgrounds are mandatory. Within the MSSM such precise predictions for signal and backgrounds are necessary in order to relate the experimental results to the underlying SUSY parameters.

The aim of this note is to collect up-to-date predictions for the most relevant signal cross sections, for both the SM and the MSSM. In Section 2 we collect the results of state-of-the-art calculations for the SM cross sections as a function of the Higgs mass. In Section 3 we present the MSSM cross sections for the neutral Higgs-bosons in four benchmark scenarios. These results are obtained by rescaling the SM cross sections presented in the previous sections, using an effective coupling approximation.

2 SM Higgs production cross sections

In this section we collect the predictions for the most important SM Higgs production processes at the Tevatron and at the LHC. The relevant cross sections are presented in Figs. 1 and 2 as function of the Higgs mass. The results refer to fully inclusive cross sections. No acceptance cuts or branching ratios are applied[1]. We do not consider here diffractive Higgs production, $pp \to p \oplus H \oplus p$ [6]. For the discussion of this channel in the MSSM we refer to Ref. [7].

We do not aim here at a detailed discussion of the importance of each signature at the Tevatron or the LHC, but only at providing the most accurate and up-to-date theoretical

[1]More details and data files can be found at `maltoni.web.cern.ch/maltoni/TeV4LHC` .

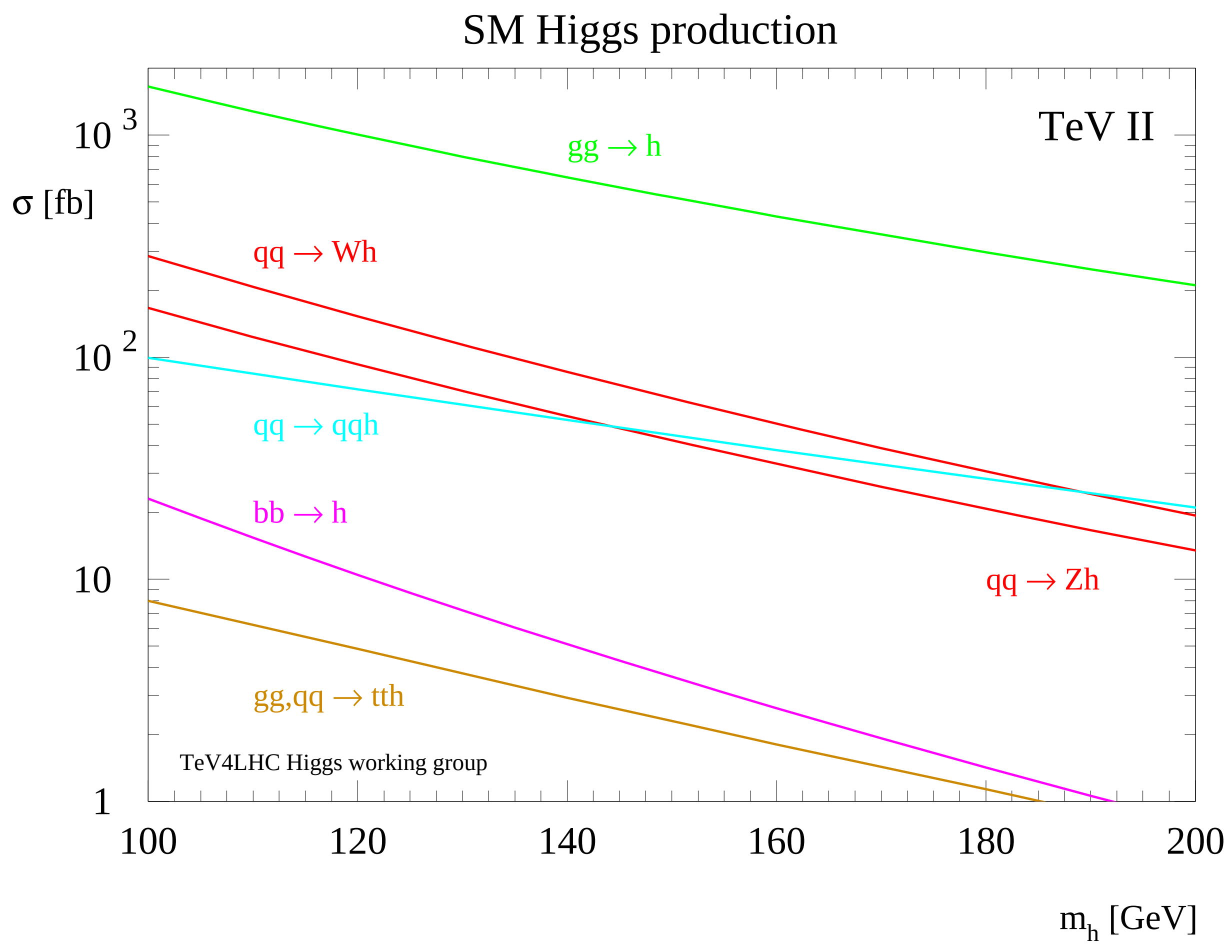

Figure 1: Higgs-boson production cross sections (fb) at the Tevatron ($\sqrt{s} = 1.96$ TeV) for the most relevant production mechanisms as a function of the Higgs-boson mass. Results for $gg \to h$, $q\bar{q} \to Vh$, $b\bar{b} \to h$ are at NNLO in the QCD expansion. Weak boson fusion ($qq \to qqh$) and $t\bar{t}$ associated production are at NLO accuracy.

predictions. To gauge the progress made in the last years, it is interesting to compare the accuracy of the results available in the year 2000, at the time of the Tevatron Higgs Workshop [8], with those shown here. All relevant cross sections are now known at least one order better in the strong-coupling expansion, and in some cases also electroweak corrections are available.

- $gg \to h + X$: gluon fusion

  This process is known at NNLO in QCD [9–11] (in the large top-mass limit) and at NLO in QCD for a quark of an arbitrary mass circulating in the loop [12]. Some N^{3}LO results have recently been obtained in Refs. [13, 14]. The NNLO results plotted here are from Ref. [15] and include soft-gluon resummation effects at NNLL. MRST2002 at NNLO has been used [16], with the renormalization and factorization scales set equal

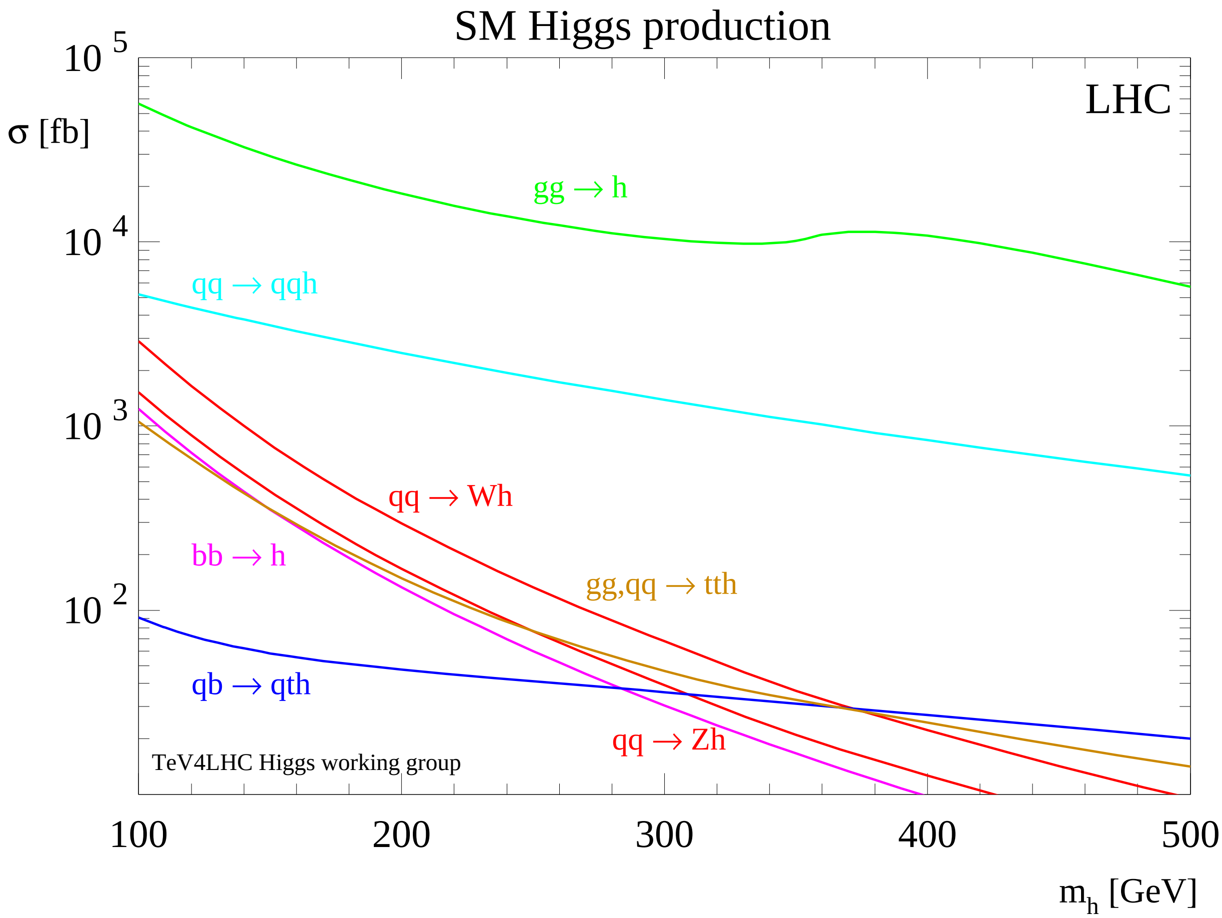

Figure 2: Higgs-boson production cross sections (fb) at the LHC ($\sqrt{s} = 14$ TeV) for the most relevant production mechanisms as a function of the Higgs-boson mass. Results for $gg \to h$, $q\bar{q} \to Vh$, $b\bar{b} \to h$ are at NNLO in the QCD expansion. Weak boson fusion ($qq \to qqh$) and $t\bar{t}$ associated production are at NLO accuracy. Single-top associated production ($qb \to qth$) is at LO.

to the Higgs-boson mass. The overall residual theoretical uncertainty is estimated to be around 10%. The uncertainties due to the large top mass limit approximation (beyond Higgs masses of $2 \times m_t$) are difficult to estimate but expected to be relatively small. Differential results at NNLO are also available [17]. NLO (two-loop) EW corrections are known for Higgs masses below $2m_W$, [18,19], and range between 5% and 8% of the lowest order term. These EW corrections, however, are not included in Figs. 1, 2, and they are also omitted in the MSSM evaluations below. The same holds for the recent corrections obtained in Refs. [13,14].

- $qq \to qqh + X$: weak boson fusion

This process is known at NLO in QCD [20–22]. Results plotted here have been obtained with MCFM [23]. Leading EW corrections are taken into account by using $\alpha(M_Z)$ as the (square of the) electromagnetic coupling. The PDF used is CTEQ6M [24] and the renormalization and factorization scales are set equal to the Higgs-boson mass. The theoretical uncertainty is rather small, less than 10%.

- $q\bar{q} \to Vh + X$: W, Z associated production

  These processes are known at NNLO in the QCD expansion [25] and at NLO in the electroweak expansion [26]. The results plotted here have been obtained by the LH2003 Higgs working group by combining NNLO QCD and NLO EW corrections [27]. The PDF used is MRST2001 and the renormalization and factorization scales are set equal to the Higgs-vector-boson invariant mass. The residual theoretical uncertainty is rather small, less than 5%.

- $b\bar{b} \to h + X$: bottom fusion

  This process is known at NNLO in QCD in the five-flavor scheme [28]. The cross section in the four-flavor scheme is known at NLO [29, 30]. Results obtained in the two schemes have been shown to be consistent [27,31,32]. The results plotted here are from Ref. [28]. MRST2002 at NNLO has been used, with the renormalization scale set equal to m_h and the factorization scale set equal to $m_h/4$. For results with one final-state b-quark at high-p_T we refer to Ref. [31, 33]. For results with two final-state b-quarks at high-p_T we refer to Ref. [29, 30].

- $q\bar{q}, gg \to t\bar{t}h + X$: $t\bar{t}$ associated production

  This process is known at NLO in QCD [34–36]. The results plotted here are from Ref. [36]. The PDF used is CTEQ6M and the renormalization and factorization scales are set equal to $m_t + m_h/2$.

- $qb \to qth$: single-top associated production

  This process is known at LO in QCD [37]. The results plotted here (t-channel production, LHC only) are from Ref. [38]. The PDF used is CTEQ5L and the renormalization and factorization scales are set equal to the Higgs-boson mass.

3 MSSM Higgs production cross sections

The MSSM requires two Higgs doublets, resulting in five physical Higgs boson degrees of freedom. These are the light and heavy $\mathcal{CP}$-even Higgs bosons, h and H, the $\mathcal{CP}$-odd Higgs boson, A, and the charged Higgs boson, $H^{\pm}$. The Higgs sector of the MSSM can be specified at lowest order in terms of M_Z, M_A, and $\tan\beta \equiv v_2/v_1$, the ratio of the two Higgs vacuum expectation values. The masses of the $\mathcal{CP}$-even neutral Higgs bosons and the charged Higgs boson can be calculated, including higher-order corrections, in terms of the other MSSM parameters.

After the termination of LEP in the year 2000 (the final LEP results can be found in Refs. [2, 39]), the Higgs boson search has shifted to the Tevatron and will later be continued at the LHC. For these analyses and investigations a precise prediction of the Higgs boson masses, branching ratios and production cross sections in the various channels is necessary.

Due to the large number of free parameters, a complete scan of the MSSM parameter space is too involved. Therefore the search results at LEP [39] and the Tevatron [40–42], as well as studies for the LHC [43] have been performed in several benchmark scenarios [44–46].

The code `FeynHiggs` [3, 4, 47, 48] provides a precise calculation of the Higgs boson mass spectrum, couplings and the decay widths[2]. This has now been supplemented by the evaluation of all relevant neutral Higgs boson production cross sections at the Tevatron and the LHC (and the corresponding three SM cross sections for both colliders with $M_H^{\rm SM} = m_h, m_H, m_A$). They are calculated by using the effective coupling approach, rescaling the SM result[3].

In this section we will briefly describe the benchmark scenarios with their respective features. The effective coupling approach, used to obtain the production cross sections within `FeynHiggs`, is discussed. Results for the neutral Higgs production cross sections at the Tevatron and the LHC are presented within the benchmark scenarios for two values of $\tan\beta$, $\tan\beta = 5, 40$.

3.1 The benchmark scenarios

We start by recalling the four benchmark scenarios [45] suitable for the MSSM Higgs boson search at hadron colliders[4]. In these scenarios the values of the parameters of the $\tilde{t}$ and $\tilde{b}$ sector as well as the gaugino masses are fixed, while $\tan\beta$ and M_A are the parameters that are varied. Here we fix $\tan\beta$ to a low and a high value, $\tan\beta = 5, 40$, but vary M_A. This also yields a variation of m_h and m_H.

In order to fix our notations, we list the conventions for the inputs from the scalar top and scalar bottom sector of the MSSM: the mass matrices in the basis of the current eigenstates $\tilde{t}_L, \tilde{t}_R$ and $\tilde{b}_L, \tilde{b}_R$ are given by

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + \cos 2\beta(\frac{1}{2} - \frac{2}{3}s^2_{\rm w})M_Z^2 & m_t X_t \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + \frac{2}{3}\cos 2\beta s^2_{\rm w} M_Z^2 \end{pmatrix}, \quad (1)$$

$$\mathcal{M}^2_{\tilde{b}} = \begin{pmatrix} M^2_{\tilde{b}_L} + m_b^2 + \cos 2\beta(-\frac{1}{2} + \frac{1}{3}s^2_{\rm w})M_Z^2 & m_b X_b \\ m_b X_b & M^2_{\tilde{b}_R} + m_b^2 - \frac{1}{3}\cos 2\beta s^2_{\rm w} M_Z^2 \end{pmatrix}, \quad (2)$$

where

$$m_t X_t = m_t (A_t - \mu\cot\beta\,), \quad m_b\, X_b = m_b\,(A_b - \mu\tan\beta). \quad (3)$$

Here A_t denotes the trilinear Higgs–stop coupling, A_b denotes the Higgs–sbottom coupling, and μ is the higgsino mass parameter. SU(2) gauge invariance leads to the relation

$$M_{\tilde{t}_L} = M_{\tilde{b}_L}. \quad (4)$$

[2]The code can be obtained from `www.feynhiggs.de` .

[3]The inclusion of the charged Higgs production cross sections is planned for the near future.

[4]In the course of this workshop they have been refined to cover wider parts of the MSSM parameter space relevant especially for heavy MSSM Higgs boson production [46].

For the numerical evaluation, a convenient choice is

$$M_{\tilde{t}_L} = M_{\tilde{b}_L} = M_{\tilde{t}_R} = M_{\tilde{b}_R} =: M_{\rm SUSY}. \tag{5}$$

The parameters in the $\tilde{t}/\tilde{b}$ sector are defined here as on-shell parameters, see Ref. [49] for a discussion and a translation to $\overline{\rm DR}$ parameters. The top-quark mass is taken to be $m_t = m_t^{\rm exp} = 172.7$ GeV [50].

- The $m_h^{\rm max}$ scenario:

  This scenario had been designed to obtain conservative $\tan\beta$ exclusion bounds [51]. The parameters are chosen such that the maximum possible Higgs-boson mass as a function of $\tan\beta$ is obtained (for fixed $M_{\rm SUSY}$ and m_t, and M_A set to its maximal value, $M_A = 1$ TeV). The parameters are[5]:

$$\begin{aligned} &M_{\rm SUSY} = 1 \text{ TeV},\ \mu = 200 \text{ GeV},\ M_2 = 200 \text{ GeV}, \\ &X_t = 2\, M_{\rm SUSY}\ A_b = A_t, m_{\tilde{g}} = 0.8\, M_{\rm SUSY}\ . \end{aligned} \tag{6}$$

- The no-mixing scenario:

  This benchmark scenario is associated with vanishing mixing in the $\tilde{t}$ sector and with a higher SUSY mass scale as compared to the $m_h^{\rm max}$ scenario to increase the parameter space that avoids the LEP Higgs bounds:

$$\begin{aligned} &M_{\rm SUSY} = 2 \text{ TeV},\ \mu = 200 \text{ GeV},\ M_2 = 200 \text{ GeV}, \\ &X_t = 2\, M_{\rm SUSY}\ A_b = A_t, m_{\tilde{g}} = 0.8\, M_{\rm SUSY}\ . \end{aligned} \tag{7}$$

- The gluophobic Higgs scenario:

  In this scenario the main production cross section for the light Higgs boson at the LHC, $gg \to h$, can be strongly suppressed for a wide range of the $M_A - \tan\beta$-plane. This happens due to a cancellation between the top quark and the stop quark loops in the production vertex (see Ref. [52]). This cancellation is more effective for small $\tilde{t}$ masses and for relatively large values of the $\tilde{t}$ mixing parameter, X_t. The partial width of the most relevant decay mode, $\Gamma(h \to \gamma\gamma)$, is affected much less, since it is dominated by the W boson loop. The parameters are:

$$\begin{aligned} &M_{\rm SUSY} = 350 \text{ GeV},\ \mu = 300 \text{ GeV},\ M_2 = 300 \text{ GeV}, \\ &X_t = -750 \text{ GeV}\ A_b = A_t, m_{\tilde{g}} = 500 \text{ GeV}\ . \end{aligned} \tag{8}$$

- The small $\alpha_{\rm eff}$ scenario:

  Besides the channel $gg \to h \to \gamma\gamma$ at the LHC, the other channels for light Higgs searches at the Tevatron and at the LHC mostly rely on the decays $h \to b\bar{b}$ and $h \to \tau^+\tau^-$. Including Higgs-propagator corrections the couplings of the lightest Higgs

[5] As mentioned above, no external constraints are taken into account. In the minimal flavor violation scenario, better agreement with BR($b \to s\gamma$) constraints would be obtained for the other sign of X_t (called the "constrained $m_h^{\rm max}$" scenario [45]).

boson to down-type fermions are $\sim \sin\alpha_{\rm eff}$, where $\alpha_{\rm eff}$ is the loop corrected mixing angle in the neutral $\mathcal{CP}$-even Higgs sector. Thus, if $\alpha_{\rm eff}$ is small, the two main decay channels can be heavily suppressed in the MSSM compared to the SM case. Such a suppression occurs for large $\tan\beta$ and not too large M_A. The parameters of this scenario are:

$$
\begin{aligned}
&M_{\rm SUSY} = 800 \text{ GeV},\ \mu = 2.5\, M_{\rm SUSY},\ M_2 = 500 \text{ GeV},\\
&X_t = -1100 \text{ GeV},\ A_b = A_t, m_{\tilde g} = 500 \text{ GeV}\ . \qquad (9)
\end{aligned}
$$

3.2 The effective coupling approximation

We consider the following neutral Higgs production cross sections at the Tevatron and the LHC (ϕ denotes all neutral MSSM Higgs bosons, $\phi = h, H, A$):

$$
\begin{aligned}
gg &\to \phi + X\ , &(10)\\
qq &\to qq\phi + X\ , &(11)\\
q\bar q &\to W/Z\phi + X\ , &(12)\\
b\bar b &\to \phi + X\ , &(13)\\
gg, qq &\to t\bar t\phi\ . &(14)
\end{aligned}
$$

The MSSM cross sections have been obtained by rescaling the corresponding SM cross sections of Section 2 either with the ratio of the corresponding MSSM decay with (of the inverse process) over the SM decay width, or with the square of the ratio of the corresponding couplings. More precisely, we apply the following factors:

- $gg \to \phi + X$:
$$\frac{\Gamma(\phi \to gg)_{\rm MSSM}}{\Gamma(\phi \to gg)_{\rm SM}} \qquad (15)$$
We include the full one-loop result with SM QCD corrections. MSSM two-loop corrections [53] have been neglected.

- $qq \to qq\phi + X$:
$$\frac{|g_{\phi VV,{\rm MSSM}}|^2}{|g_{\phi VV,{\rm SM}}|^2},\ V = W, Z\ . \qquad (16)$$
We include the full set of Higgs propagator corrections in the effective couplings.

- $qq \to W/Z\phi + X$:
$$\frac{|g_{\phi VV,{\rm MSSM}}|^2}{|g_{\phi VV,{\rm SM}}|^2},\ V = W, Z\ . \qquad (17)$$
We include the full set of Higgs propagator corrections in the effective couplings.

- $b\bar b \to \phi + X$:
$$\frac{\Gamma(\phi \to b\bar b)_{\rm MSSM}}{\Gamma(\phi \to b\bar b)_{\rm SM}}\ . \qquad (18)$$
We include here one-loop SM QCD and SUSY QCD corrections, as well as the resummation of all terms of $\mathcal{O}((\alpha_s \tan\beta)^n)$.

- $gg, qq \to t\bar{t}\phi$:

$$\frac{|g_{\phi t\bar{t},\mathrm{MSSM}}|^2}{|g_{\phi t\bar{t},\mathrm{SM}}|^2}\ , \tag{19}$$

  where $g_{\phi t\bar{t},\mathrm{MSSM}}$ and $g_{\phi t\bar{t},\mathrm{SM}}$ are composed of a left- and a right-handed part. We include the full set of Higgs propagator corrections in the effective couplings.

In the effective couplings introduced in eqs. (15)–(19) we have used the proper normalization of the external (on-shell) Higgs bosons as discussed in Ref. [54].

It should be noted that the effective coupling approximation as described above does not take into account the MSSM-specific dynamics of the production processes. The theoretical uncertainty in the predictions for the cross sections will therefore in general be somewhat larger than for the decay widths.

3.3 Results

Results for the neutral Higgs production cross sections at the Tevatron and the LHC are presented within the four benchmark scenarios for two values of $\tan\beta$, $\tan\beta = 5, 40$, giving a total of eight plots for each collider.

Figs. 3 and 4 show the results for the Tevatron, while Figs. 5 and 6 show the LHC results. In Fig. 3 (5) the Higgs production cross sections for the neutral MSSM Higgs bosons at the Tevatron (LHC) in the $m_h^{\max}$ scenario (upper row) and the no-mixing scenario (lower row) can be found. Fig. 4 (6) depicts the same for the gluophobic Higgs scenario (upper row) and the small α_{eff} scenario (lower row).

For low M_A values the production cross section of the h and the A are similar, while for large M_A the cross sections of H and A are very close. This effect is even more pronounced for large $\tan\beta$.

The results presented in this paper have been obtained for the MSSM with real parameters, i.e. the $\mathcal{CP}$-conserving case. They can can easily be extended via the effective coupling approximation to the case of non-vanishing complex phases (as implemented in `FeynHiggs`).

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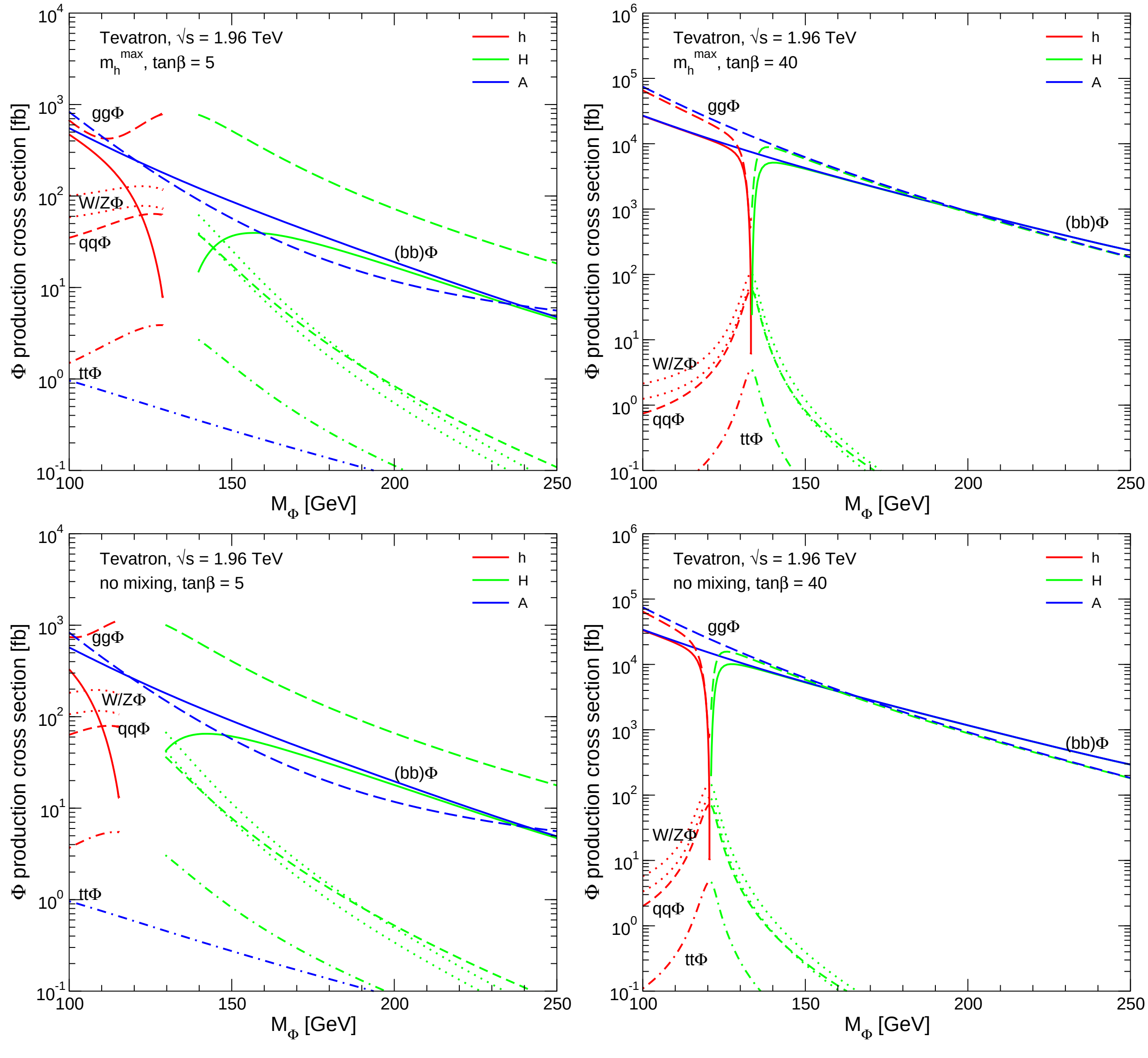

Figure 3: Neutral Higgses production cross sections (fb) at the Tevatron ($\sqrt{s} = 1.96$ TeV) for the most relevant production mechanisms as a function of the Higgs-boson mass. Results are based on the SM cross sections and evaluated through an effective coupling approximation in the $m_h^{\rm max}$ and no-mixing scenarios, for $\tan\beta = 5, 40$ and $\Phi = h, H, A$.

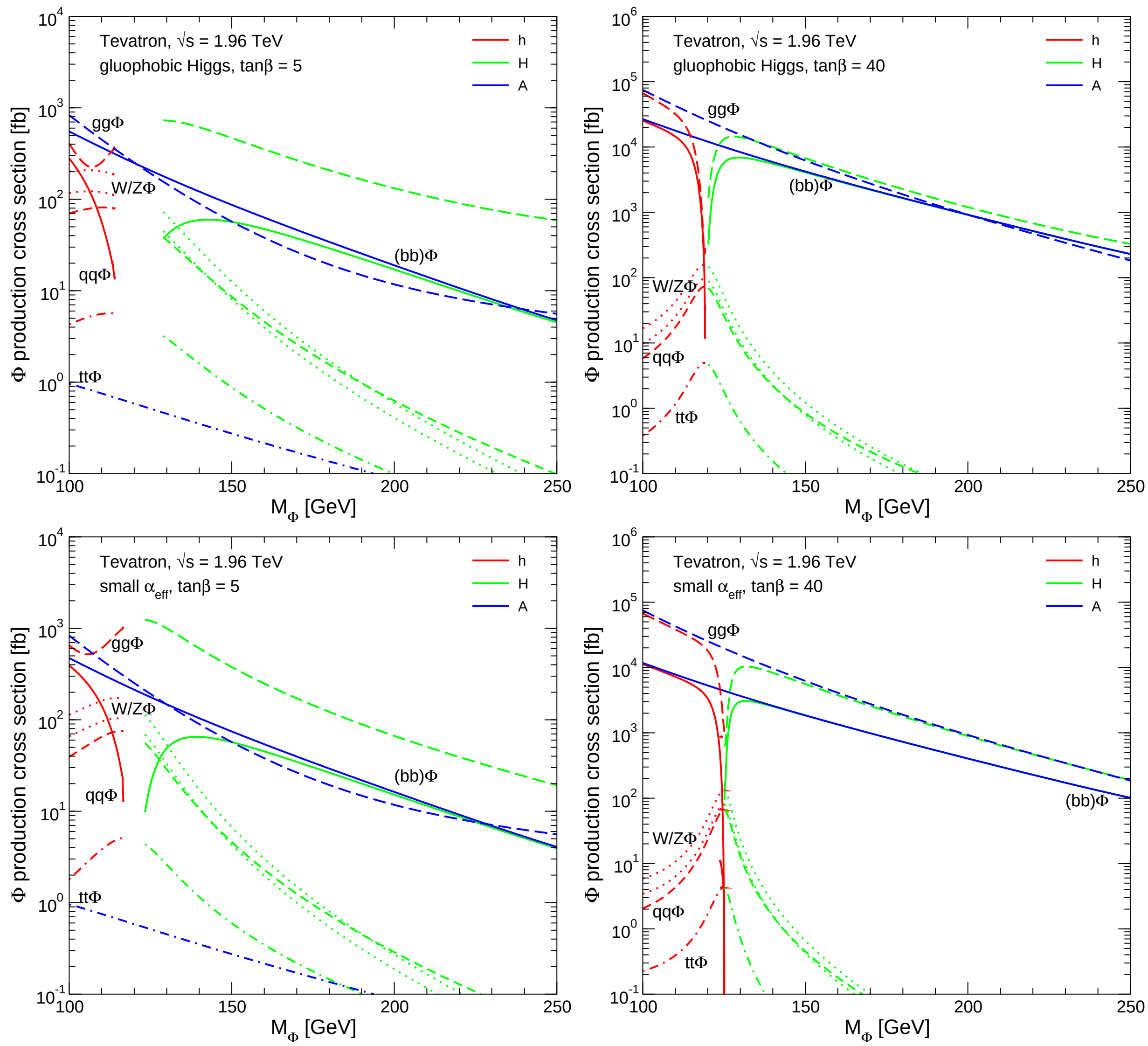

Figure 4: Same as Fig. 3, for the gluophobic Higgs and small $\alpha_{\rm eff}$ scenarios.

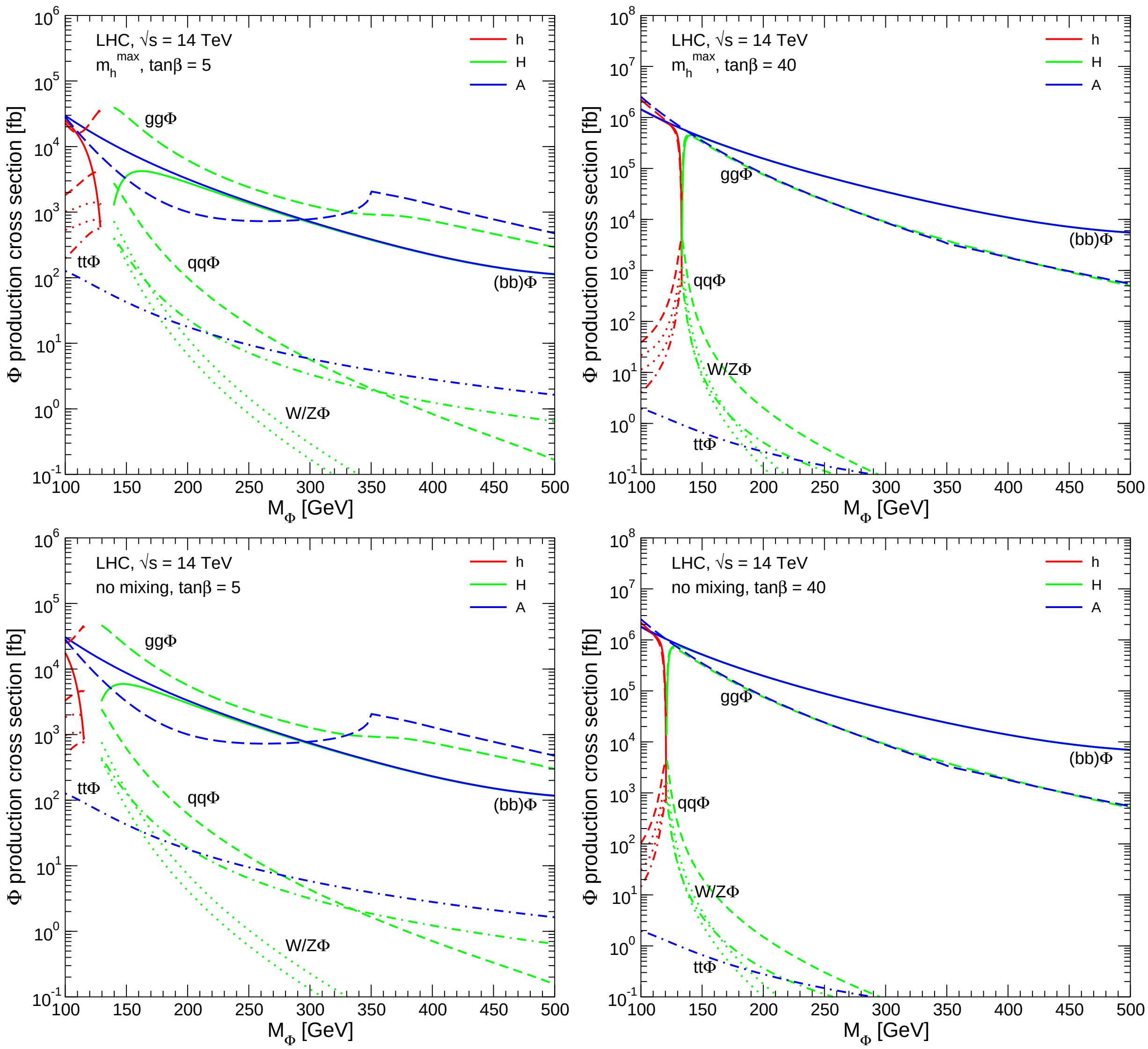

Figure 5: Neutral Higgses production cross sections (fb) at the LHC ($\sqrt{s} = 14$ TeV) for the most relevant production mechanisms as a function of the Higgs-boson mass. Results are based on the SM cross sections and evaluated through an effective coupling approximation in the $m_h^{\max}$ and no-mixing scenarios, for $\tan\beta = 5, 40$ and $\Phi = h, H, A$.

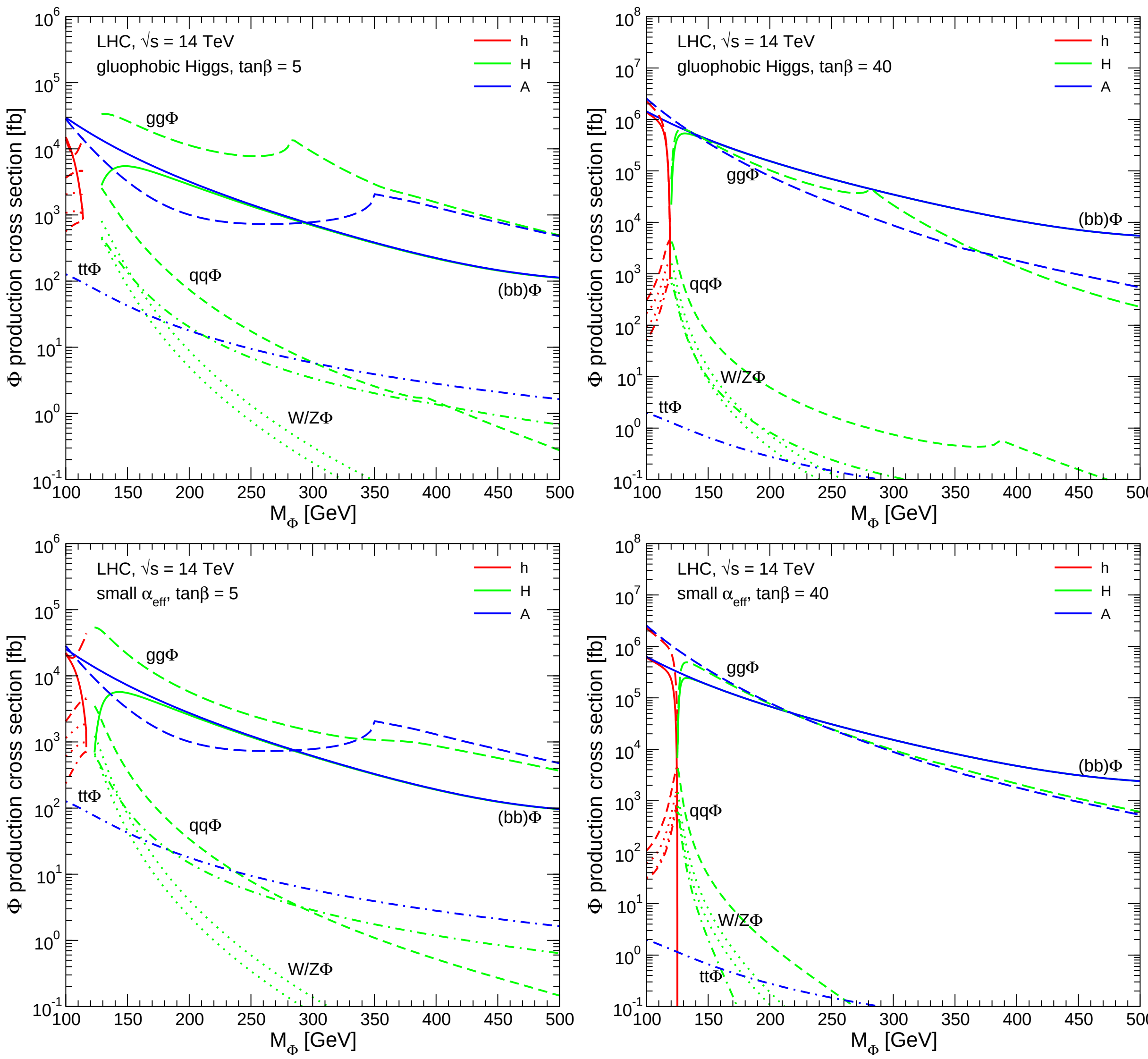

Figure 6: Same as Fig. 5, for the gluophobic Higgs and small $\alpha_{\rm eff}$ scenarios.

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