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Higgs Boson Production and Decay at the Tevatron*

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Abstract

The theoretical status of Higgs boson production and decay at the Tevatron within the Standard Model and its minimal supersymmetric extension is reviewed. The focus will be on the evaluation of higher-order corrections to the production cross sections and their phenomenological implications.

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1 Introduction

The search for Higgs bosons is of primary interest for present and future experiments. In the Standard Model [SM] the existence of a single Higgs particle is predicted as a consequence of electroweak symmetry breaking by means of the Higgs mechanism [1]. The direct search at the LEP experiments leads to a lower bound of ~ 90 GeV [2] on the value of the Higgs mass, while triviality and unitarity constraints require the Higgs mass to be smaller than $\mathcal{O}(1$ TeV). At the upgraded Tevatron experiment, a $p\bar{p}$ collider with a c.m. energy $\sqrt{s} = 2$ TeV, SM Higgs bosons will mainly be produced via gluon fusion $gg \to H$ and the Drell–Yan like production $q\bar{q} \to W^* \to WH$. Since an intermediate mass Higgs boson will dominantly decay into $b\bar{b}$ pairs, the QCD background of $b\bar{b}$ production will be too large to allow for a detection of the Higgs boson produced in the gluon fusion process. Recently it has been shown that a detection of the Higgs boson from W fusion $WW \to H$ seems to be impossible due to the overwhelming QCD background [3]. Thus, the primary possibility to find the SM Higgs boson at the Tevatron will be via the Drell–Yan like process. Careful studies have shown that a discovery of the SM Higgs boson at the upgraded Tevatron might be possible for Higgs masses up to about 120 GeV [4]. Apart from the dominant $b\bar{b}$ decay [4] it turned out that a discovery may also be feasible via the $H \to \tau^+\tau^-$ decay [5] in $H + W/Z$ production, while the gold-plated mode of the LHC, $gg \to H \to ZZ^* \to 4\ell^\pm$, is hopeless at the Tevatron [4]. Recently it has been found that there is also the possibility to detect the processes $gg \to H \to W^*W^* \to \ell\nu jj, \ell^+\ell^-\nu\bar{\nu}$ by using the strong angular correlations among the final state leptons [6].

The SM Higgs mass is unstable against quantum fluctuations in the context of grand unified theories, which force the Higgs mass to be of the order of the GUT scale $M_{GUT} \sim 10^{16}$ GeV. The most attractive solution to this hierarchy problem is provided by the introduction of supersymmetry. The minimal supersymmetric extension of the SM [MSSM] requires two Higgs doublets, leading to the existence of 5 elementary Higgs particle, two neutral $\mathcal{CP}$-even (h, H), one neutral $\mathcal{CP}$-odd (A) and two charged ones $(H^\pm)$. At tree-level the mass of the light scalar Higgs boson h is restricted to be smaller than the Z mass M_Z. However, radiative corrections to the MSSM Higgs sector are large, since they increase with the fourth power of the large top quark mass m_t. They enhance the upper bound on the light scalar Higgs mass to $M_h \lesssim 135$ GeV [7].

For the discovery at the Tevatron the light scalar Higgs boson h will mainly be produced via $q\bar{q} \to W/Z + h$ analogously to the SM case. However, for large tgβ the associated production meachanisms $q\bar{q}, gg \to b\bar{b} + h/A$ become competitive due to the enhanced Yukawa couplings to b quarks. Finally, similar to the LHC the light scalar Higgs may be detectable in SUSY particle production process via the decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$ in the final state cascade decays [8].

Charged Higgs bosons can also be searched for at the Tevatron [9]. They will be produced in top quark decays $t \to bH^+$, if their masses are light anough. At the Tevatron the process $p\bar{p} \to t\bar{t}$ with $t \to bH^+$ is sensitive to charged Higgs bosons for large tgβ. The Drell–Yan like charged Higgs pair production $p\bar{p} \to H^+H^-$ and gluon fusion $gg \to H^+H^-$ processes seem to be difficult to detect, while the analysis of the associated production

$p\bar{p} \to W^{\pm}H^{\mp}$ requires a more careful background study in order to investigate its relevance for charged Higgs searches at the Tevatron. Finally gluon-gluon fusion $gg \to t\bar{b}H^-$, gluon-bottom fusion $gb \to tH^-$ and quark-bottom fusion $qb \to q'bH^{\pm}$ provide additional possibilities to search for charged Higgs bosons at the Tevatron.

2 Higgs Boson Decays

$\underline{\phi \to f\bar{f}}$

In the intermediate Higgs mass range the SM Higgs decay $H \to b\bar{b}$ is dominating, while the decay $H \to \tau^+\tau^-$ reaches a branching ratio of $\mathcal{O}(10\%)$, see Fig. 1. In the past the QCD

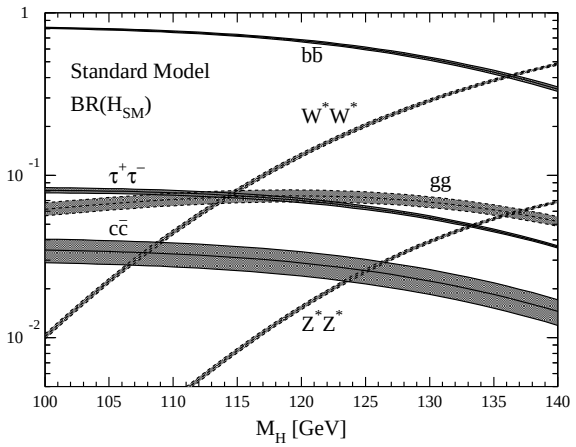

Figure 1: *Branching ratios of the dominant decay modes of the SM Higgs particle. All relevant higher order corrections are taken into account. The shaded bands represent the variations due to the uncertainties in the input parameters:* $\alpha_s(M_Z^2) = 0.120 \pm 0.003$, $\overline{m}_b(M_b) = (4.22 \pm 0.05)$ *GeV,* $\overline{m}_c(M_c) = (1.22 \pm 0.06)$ *GeV,* $M_t = (174 \pm 5)$ *GeV.*

corrections have been evaluated [10]. They turn out to be moderate for the decay mode $H \to t\bar{t}$ in the threshold region, while they are large for the $H \to b\bar{b}, c\bar{c}$ decays due to large logarithmic contributions. These can be absorbed in the running quark mass by replacing the scale by the Higgs mass. In order to gain a consistent prediction of the partial decay widths one has to use direct fits of the $\overline{\rm MS}$ masses $\overline{m}_Q(M_Q)$ to experimental data. The evolution of $\overline{m}_Q(M_Q)$ to $\overline{m}_Q(M_H)$ is controlled by the renormalization group equations for the running $\overline{\rm MS}$ masses. As a result the QCD corrections reduce the $H \to b\bar{b}$ decay width by $\sim 50\%$ and the $H \to c\bar{c}$ width by $\sim 75\%$ relative to the Born term expressed in terms of the quark pole masses M_Q.

In the MSSM the decay modes $h, H, A \to b\bar{b}, \tau^+\tau^-$ dominate the neutral Higgs decay modes for large tgβ, while for small tgβ they are important for $M_{h,H,A} \lesssim 150$ GeV as can be inferred from Figs. 2a–c. The dominant decay modes of the charged Higgs particles are $H^+ \to \tau^+\nu_\tau, t\bar{b}$ [see Fig. 2d]. Analogous to the SM case the QCD corrections reduce the partial decay widths into b, c quarks by about 50–75% as a result of the running quark masses, while they are moderate for decays into top quarks.

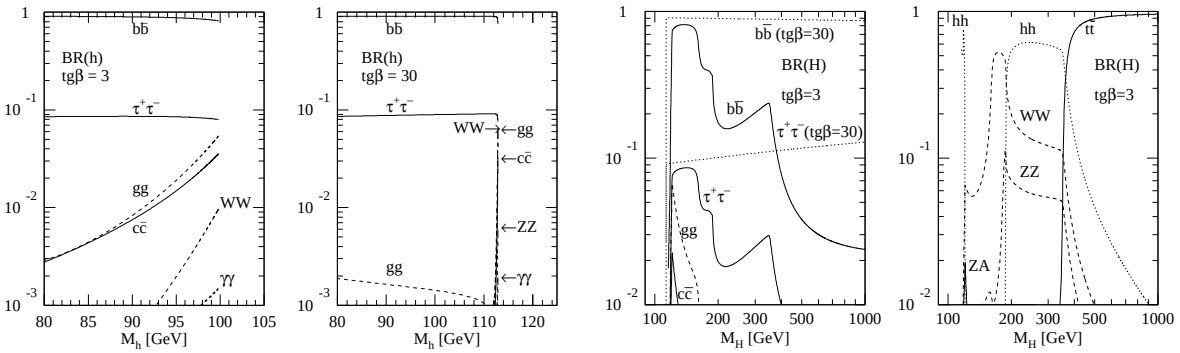

Fig. 2a **Fig. 2b**

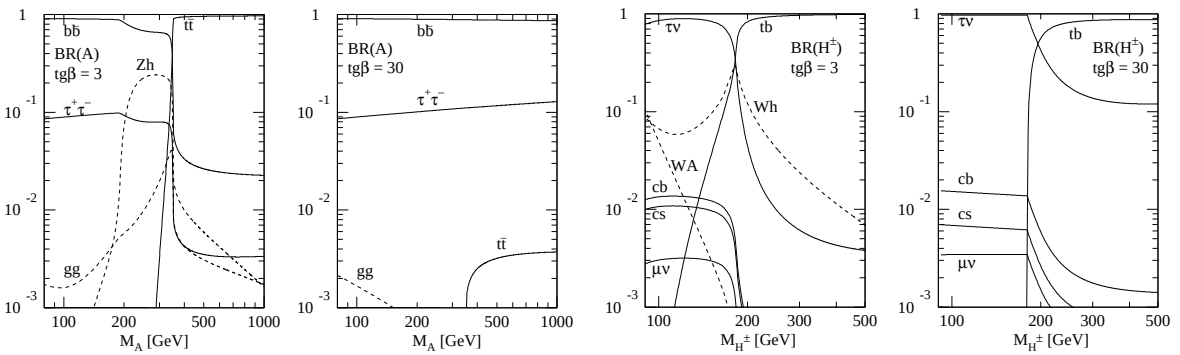

Fig. 2c **Fig. 2d**

Figure 2: *Branching ratios of the MSSM Higgs bosons $h(a), H(b), A(c), H^{\pm}(d)$ for non-SUSY decay modes as a function of their masses for two values of $tg\beta = 3, 30$ and vanishing mixing. The common squark mass has been chosen as $M_S = 1$ TeV.*

Below the corresponding thresholds the decays $A \to t^*t$ and $H^+ \to t^*\bar{b}$ into off-shell top quarks turn out to be important, since they reach branching ratios of $\mathcal{O}(1\%)$ already far below the thresholds for on-shell top quarks [11].

$\underline{H \to WW, ZZ}$

In the SM the decays $H \to WW, ZZ$ are dominant for $M_H \gtrsim 140$ GeV, since they increase with the third power of the Higgs mass for large Higgs masses, see Fig. 1. Decays into off-shell W, Z bosons $H \to W^*W^*, Z^*Z^*$ are sizeable already for Higgs masses $M_H \gtrsim 100$ GeV, i.e. significantly below the WW/ZZ thresholds [11, 12].

In the MSSM the decays $h, H \to WW, ZZ$ are suppressed by kinematics and, in general, by SUSY couplings and are thus less important than in the SM. Their branching ratios turn out to be sizeable only for small tgβ or in the decoupling regime, where the light scalar Higgs particle h reaches the upper bound of its mass.

The gluonic (photonic) decays of the Higgs bosons $h, H, A \to gg(\gamma\gamma)$ reach branching ratios of $\sim 10\%$ ($\sim 10^{-3}$) in the SM and MSSM and are unimportant at the Tevatron.

$\underline{H \to hh, AA}$

The decay mode $H \to hh$ is dominant in the MSSM for small tgβ in a wide range of heavy scalar Higgs masses M_H below the $t\bar{t}$ threshold, see Fig. 2b. The dominant radiative corrections to this decay arise from the corrections to the self-interaction λ_{Hhh} in the MSSM and are large [7]. The decay mode $H \to AA$ is only important at the lower end of the heavy scalar Higgs mass range.

$\underline{\phi \to \phi' + W/Z}$

The decay modes $H \to AZ$ and $A \to hZ$ are important for small tgβ below the $t\bar{t}$ threshold, see Figs. 2b,c. Similarly the decays $H^+ \to W^* A, W^{(*)} h$ are sizeable for small tgβ and $M_{H^+} < m_t + m_b$, see Fig. 2d. The dominant higher-order corrections can be absorbed into the couplings and masses of the Higgs sector. Below the corresponding thresholds decays into off-shell Higgs and gauge bosons turn out to be important especially for small tgβ [11], see Figs. 2b–d.

Decays into SUSY particles

Higgs decays into charginos, neutralinos and third-generation sfermions can become important, once they are kinematically allowed [13] as can be inferred from Fig. 3, which shows the branching ratios of the heavy Higgs bosons into gauginos and squarks as functions of their masses for a special SUSY scenario. Thus they could complicate the Higgs search at the Tevatron, since the decay into the LSP will be invisible.

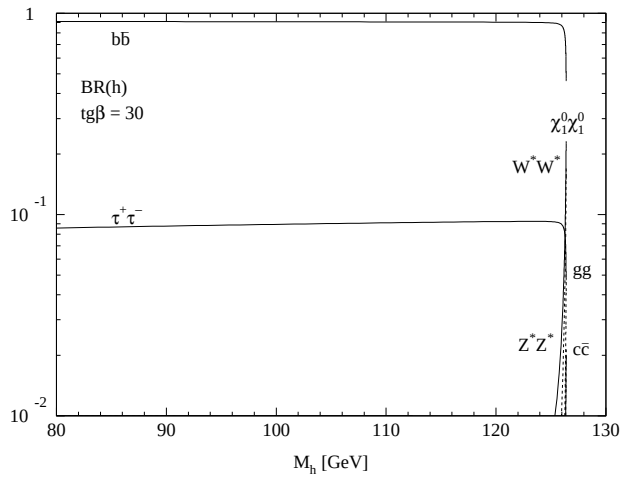

Figure 3: *Branching ratios of the light scalar MSSM Higgs boson h decays into charginos/neutralinos as a function of its mass for tgβ = 30. The mixing parameters have been chosen as $\mu = 150$ GeV, $A_t = 2.45$ TeV, $A_b = 0$ and the squark masses of the first two generations as $M_{\tilde{Q}} = 1000$ GeV. The gaugino mass parameter has been set to $M_2 = 136$ GeV. The masses of the lightest gauginos are $m_{\tilde{\chi}_1^0} = 56.5$ GeV and $m_{\tilde{\chi}_1^\pm} = 94.1$ GeV.*

3 Higgs Boson Production

$\underline{q\bar{q} \to V^* \to VH \; [V = W, Z]}$

The most relevant SM Higgs production mechanism at the Tevatron is Higgs-strahlung off W, Z bosons $q\bar{q} \to W^*/Z^* \to W/Z + H$. The cross section reaches values of 10^{-1}–1 pb in the relevant Higgs mass range $M_H \lesssim 120$ GeV, where this production process may be visible at the Tevatron [4], see Fig. 4. The QCD corrections coincide with those of the Drell-Yan process and increase the cross sections by about 30% [14, 15]. The theoretical uncertainty can be estimated as $\sim 15\%$ from the remaining scale dependence. The dependence on different sets of parton densities is rather weak and leads to a variation of the production cross sections by about 15%.

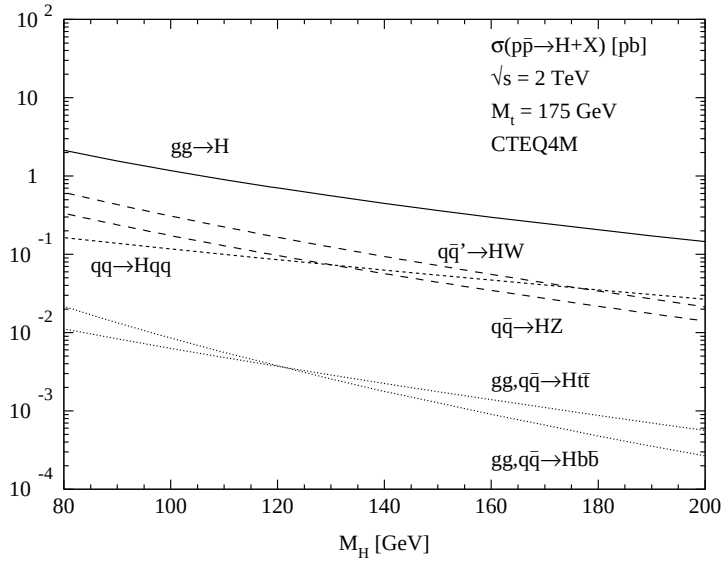

Figure 4: *Higgs production cross sections at the Tevatron [$\sqrt{s} = 2$ TeV] for the various production mechanisms as a function of the Higgs mass. The full QCD-corrected results for the gluon fusion $gg \to H$, vector boson fusion $qq \to VVqq \to Hqq$, Higgs-strahlung $q\bar{q} \to V^* \to HV$ and associated production $gg, q\bar{q} \to Ht\bar{t}, Hb\bar{b}$ are shown. The QCD corrections to the last process are unknown and thus not included.*

In the MSSM the Higgs-strahlung processes are in general suppressed by the SUSY couplings. However, the process $q\bar{q} \to W^*/Z^* \to W/Z + h$ can be important in the decoupling regime, where the light scalar Higgs particle h exhibits SM Higgs properties, see Fig. 5a,b.

$\underline{q\bar{q}, gg \to \phi t\bar{t}, \phi b\bar{b}}$

In the SM both processes of Higgs radiation off top and bottom quarks are unimportant due to the small event rates, see Fig. 4. However, in the MSSM Higgs radiation off bottom quarks becomes important for large tgβ with cross sections exceeding 10 pb for the light scalar (h) and the pseudoscalar (A) Higgs particles, see Fig. 5. Thus, the theoretical prediction is crucial for the large tgβ regime in the MSSM.

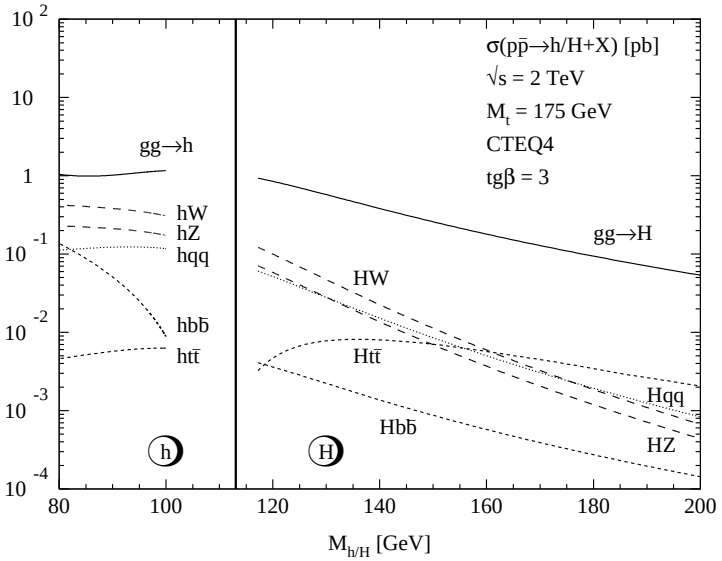

Fig. 5a

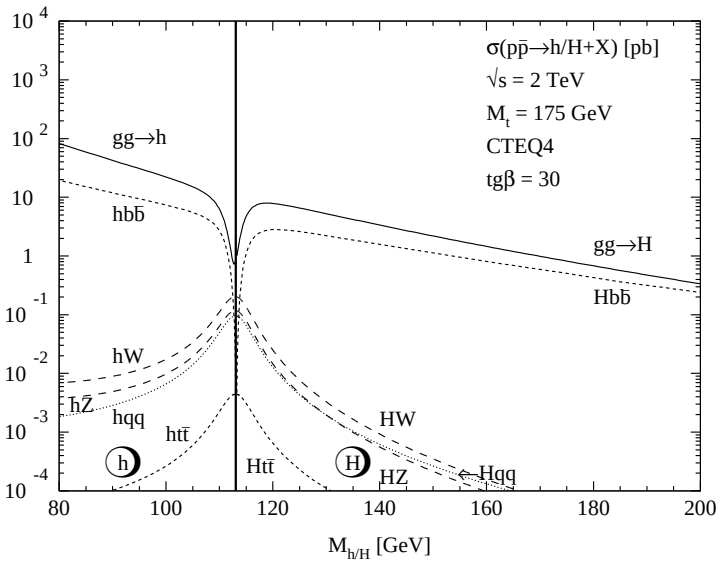

Fig. 5b

Figure 5: *Neutral MSSM Higgs production cross sections at the Tevatron* $[\sqrt{s} = 2\ TeV]$ *for gluon fusion* $gg \to \Phi$, *vector-boson fusion* $qq \to qqVV \to qqh/qqH$, *vector-boson bremsstrahlung* $q\bar{q} \to V^* \to hV/HV$ *and the associated production* $gg, q\bar{q} \to \Phi b\bar{b}/\Phi t\bar{t}$ *including all known QCD corrections. (a)* h, H *production for* $tg\beta = 3$, *(b)* h, H *production for* $tg\beta = 30$, *(c)* A *production for* $tg\beta = 3$, *(d)* A *production for* $tg\beta = 30$.

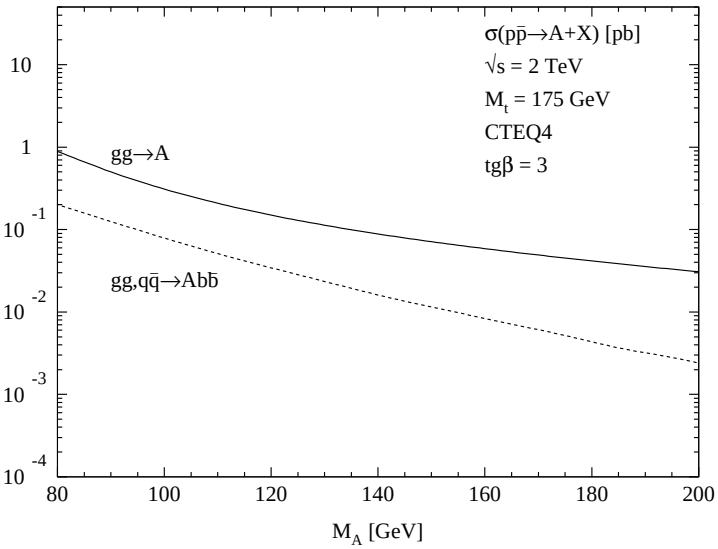

Fig. 5c

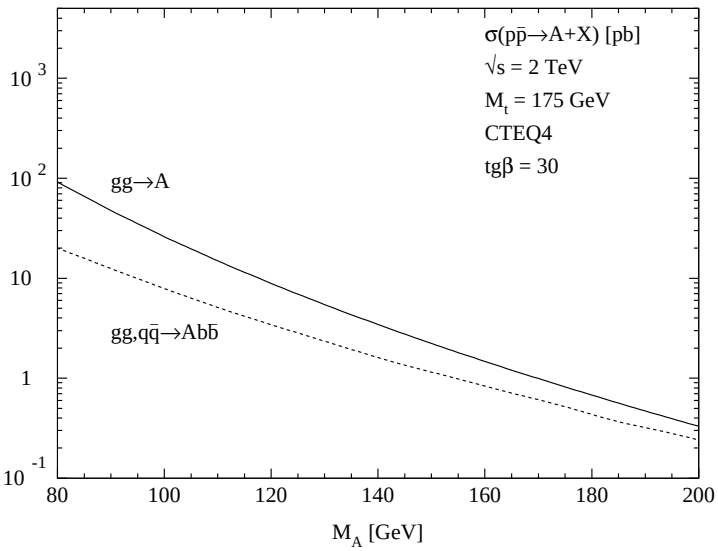

Fig. 5d

Figure 5: *Continued.*

Until now the full QCD corrections are unknown so that the cross sections are only known within about a factor of 2. However, the QCD corrections are known in the limit of light Higgs particles compared with the heavy quark mass, which is applicable for $t\bar{t}+h$ production [16]. In this limit the cross section factorizes into the production of a $t\bar{t}$ pair, which is convoluted with a splitting function for Higgs radiation $t \to t+h$. This reults in an increase of the cross section by about 20–60%. However, since this equivalent Higgs approxiamtion is only valid within a factor of 2 the result may not be sufficiently reliable. Moreover, it is not valid for bottom quarks, which are more relevant for the Tevatron.

In the opposite limit of large Higgs masses $M_H \gg M_Q$ large logarithms $\log M_H^2/M_Q^2$ arise due to quasi-on-shell t-channel quark exchanges, which can be resummed by absorbing them into the heavy quark parton densities. After adding the processes $q\bar{q}, gg \to b\bar{b}+\phi$, $gb \to b+\phi$ and $b\bar{b} \to \phi$, after the logarithms have been subtracted accordingly, the final result turns out to be about a factor of 2 larger than the pure $q\bar{q}, gg \to b\bar{b}+\phi$ processes [17]. However, there are additional sources of large logarithms, e.g. Sudakov logarithms from soft gluon radiation and large logarithms related to the Yukawa coupling, which will appear in the NLO cross section. Thus, a full NLO calculation is needed in order to gain a satisfactory theoretical prediction of these production processes. In this analysis the scales of the parton densities have been identified with the invariant mass of the final state $Q\bar{Q}\phi$ triplet and the bottom Yukawa coupling in terms of the bottom pole mass $M_b = 5$ GeV.

$\underline{gg \to \phi}$

The gluon fusion processes are mediated by heavy top and bottom quark triangle loops and in the MSSM by squark loops in addition [18–20]. Gluon fusion is the dominant neutral Higgs production mechanism at the Tevatron, even for large tgβ, with cross sections of $1\text{–}10^3 pb$, see Figs. 4, 5. However, the dominant $b\bar{b}$ final states are overwhelmed by the huge QCD background of $b\bar{b}$ production and thus hopeless for a detection of the Higgs bosons via gluon fusion. Only the $\tau^+\tau^-$ decay modes may be promising for large tgβ, especially if the Higgs bosons are produced in association with a jet [21]. Moreover, similar to the LHC it may be possible to detect the $H \to W^*W^*$ decay mode in a significant Higgs mass range due to the strong angular correlations of the final state leptons [6].

The two-loop QCD corrections enhance the gluon fusion cross sections by about 60–100% and are thus large [19]. They are dominated by soft and collinear gluon radiation in the SM and for small tgβ in the MSSM [22]. The remaining scale dependence yields an estimate of $\sim 15\%$ for the theoretical uncertainty. The dependence of the gluon fusion cross section on different parton densities amounts to about 15%. The K factor remains nearly the same after including squark loops, since the dominant soft and collinear gluon effects are universal, thus suppressing the (s)quark mass dependence [20].

Recently the analytical QCD corrections to Higgs + jet production have been evaluated in the limit of heavy top quarks, but there is no numerical analysis so far [23].

$WW/ZZ \to H$

Vector boson fusion $WW/ZZ \to H$ in the SM leads to a sizeable cross section at the Tevatron, see Fig. 4. Since there are two forward jets in the full process $qq \to WW/ZZ + qq \to H + qq$, one may hope to be able to suppress the QCD backgrounds by appropriate cuts. Unfortunatly it turned out that this is not possible [3].

The QCD corrections can easily be obtained in the structure function approach from deep inelastic scattering. They are small enhancing the cross section by about 10% [15, 24]. In the MSSM vector boson fusion is additionally suppressed by SUSY couplings and thus unimportant at the Tevatron.

Higgs pairs

Light scalar Higgs pair production $gg \to hh$ yields a sizeable cross section at the Tevatron with $\sigma \gtrsim 10 fb$ [25, 26]. The cross section for $q\bar{q}, gg \to hA$ is of similar size in some regions of the MSSM paramater space [see Fig. 6]. Since the process $gg \to H \to hh$ is sensitive to the trilinear coupling λ_{Hhh} it is important for a partial reconstruction of the Higgs potential. One may hope that the dominant $b\bar{b}b\bar{b}, b\bar{b}\tau^+\tau^-$ final states can be extracted from the QCD backgrounds due to the different event topologies. The two-loop QCD corrections have recently been calculated [for gg initial states in the limit of heavy top quarks, thus leading to a reliable result for small tgβ]. They enhance the $gg \to hh, hA$ production cross sections by about 70–90% and the Drell–Yan-like $q\bar{q} \to hA$ cross section by about 30% [26].

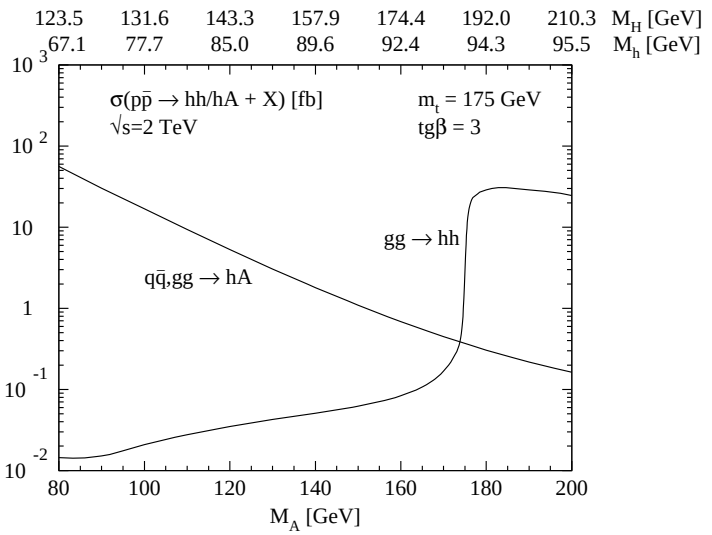

Figure 6: *QCD corrected production cross sections of hh, hA pairs at the Tevatron [$\sqrt{s} = 2$ TeV] as a function of the pseudoscalar Higgs mass for tg$\beta = 3$. The secondary axis exhibits the corresponding values of the light and heavy scalar Higgs masses M_h, M_H. The bump in the $gg \to hh$ cross section originates from resonance $gg \to H \to hh$ production.*

4 Conclusions

All relevant NLO QCD corrections to Higgs boson decays within the SM and MSSM are known so that the theoretical uncertainties are sufficiently small. At the Tevatron the decay modes $\phi^0 \to b\bar{b}, \tau^+\tau^-, W^*W^*$ are relevant for the Higgs boson search in Run II. All corrections beyond LO are contained in the program HDECAY[1] [15, 27], which calculates the branching ratios of SM and MSSM Higgs bosons.

For neutral Higgs boson production most QCD corrections are known leading to a nearly complete theoretical status. The only processes, which are known at LO, are Higgs radiation off top and bottom quarks, the latter being important for large tgβ in the MSSM. The known corrections to the important processes are moderate and thus well under control. The remaining theoretical uncertainties are less than $\sim 15\%$[2].

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