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Higgs Production and Decay at Future Machines*

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Higgs boson production at future colliders within the Standard Model and its minimal supersymmetric extension is reviewed. The predictions for decay rates and production cross sections are presented including all relevant higher-order corrections.

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1805: Higgs Production and Decay at Future Machines

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Abstract. Higgs boson production at future colliders within the Standard Model and its minimal supersymmetric extension is reviewed. The predictions for decay rates and production cross sections are presented including all relevant higher-order corrections.

1 Introduction

Standard Model [SM]. The SM contains one isospin doublet of Higgs fields, which leads to the existence of one elementary neutral CP-even Higgs boson H [1]. Only its mass is unknown. The direct search for the Higgs boson at the LEP experiments excludes Higgs masses below ~ 77 GeV [2]. Unitarity of scattering amplitudes requires the introduction of a cut-off Λ [3], which imposes an upper bound on the Higgs mass. For the minimal value $\Lambda \sim 1$ TeV the upper bound on the Higgs mass is $M_H \lesssim 700$ GeV. For $\Lambda \sim M_{GUT} \sim 10^{15}$ GeV, the Higgs mass has to be smaller than ~ 200 GeV.

Minimal Supersymmetric Extension [MSSM]. Supersymmetry provides a solution to the hierarchy problem of the SM, which arises for small Higgs masses. The MSSM requires the introduction of two Higgs doublets, which leads to five elementary Higgs particles: two neutral CP-even (h, H), one neutral CP-odd (A) and two charged $(H^\pm)$ Higgs bosons. In the Higgs sector only two parameters have to be introduced, which are usually chosen as $\mathrm{tg}\beta = v_2/v_1$, the ratio of the two vacuum expectation values of the CP-even Higgs fields, and the pseudoscalar Higgs mass M_A. Radiative corrections to the MSSM Higgs sector are large, since the leading part grows as the fourth power of the top quark mass. They increase the upper limit on the light scalar Higgs mass to $M_h \lesssim 130$ GeV [4].

2 Standard Model

2.1 Decay Modes

$H \to f\bar{f}$. For $M_H \lesssim 140$ GeV the branching ratios of $H \to b\bar{b}\,(\tau^+\tau^-)$ reach values of $\sim 90\%$ ($\sim 10\%$). Above the $t\bar{t}$ threshold the branching ratio of $H \to t\bar{t}$ amounts to $\lesssim 20\%$. QCD corrections to the $b\bar{b}, c\bar{c}$ decays are large, owing to large logarithmic contributions, which can be absorbed in the running quark mass $\overline{m}_Q(M_H)$. Far above the $Q\bar{Q}$ threshold they are known up to three loops [5, 6]. The NLO corrections have been evaluated including the full quark mass dependence [5]. They are moderate in the threshold region $M_H \gtrsim 2m_Q$.

$H \to W^+W^-, ZZ$. The $H \to WW, ZZ$ decay modes dominate for $M_H \gtrsim 140$ GeV. Electroweak corrections are small in the intermediate Higgs mass range, while they enhance the partial widths by about 20% for $M_H \sim 1$ TeV due to the self-interaction of the Higgs particle [7]. For $M_H < 2M_{W,Z}$ off-shell decays $H \to W^*W^*, Z^*Z^*$ are important. They lead to WW (ZZ) branching ratios of about 1% for $M_H \sim 100$ (110) GeV.

$H \to \gamma\gamma$. The decay $H \to \gamma\gamma$ is mediated by fermion and W-boson loops, which interfere destructively. The W-boson contribution dominates [8]. The photonic branching ratio reaches a level of $\gtrsim 10^{-3}$ for Higgs masses $M_H \lesssim 150$ GeV. This decay mode plays a significant rôle for the Higgs search at the LHC for $M_H \lesssim 140$ GeV. QCD corrections are small in the intermediate mass range [9].

Branching ratios and decay width. The branching ratios of the Higgs boson are presented in Fig. 1. For $M_H \lesssim 140$ GeV, where the $b\bar{b}, \tau^+\tau^-, c\bar{c}$ and gg decay modes are dominant, the total decay width is very small, $\Gamma \lesssim 10$ MeV. Above this mass value the WW, ZZ decay modes become dominant. For $M_H \lesssim 2M_Z$ the decay width amounts to $\Gamma \lesssim 1$ GeV, while it reaches ~ 600 GeV for $M_H \sim 1$ TeV. Thus the intermediate Higgs boson is a narrow resonance.

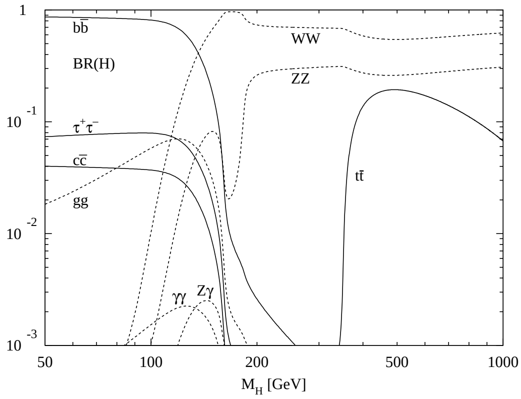

Fig. 1. Branching ratios of the SM Higgs boson as a function of its mass [10].

2.2 Higgs Boson Production.

<u>e^+e^- *colliders.*</u> At lower energies Higgs bosons

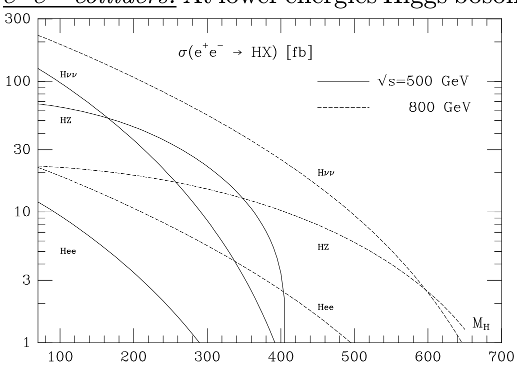

Fig. 2. Production cross sections of SM Higgs bosons at future e^+e^- linear colliders [11].

are dominantly produced via Higgs-strahlung off Z bosons, $e^+e^- \to ZH$, while at high energies the W fusion process $e^+e^- \to \nu_e\bar{\nu}_e H$ dominates [11]. Electroweak corrections to the Higgs-strahlung process are moderate [12]. The production cross sections at future e^+e^- colliders are shown in Fig. 2 for c.m. energies of 500 and 800 GeV. They range between 1 and 300 fb in the relevant mass range and provide clean signatures for the Higgs boson. The angular distribution of Higgs-strahlung is sensitive to the spin and parity of the Higgs particle [11].

<u>*LHC.*</u> Higgs boson production at the LHC

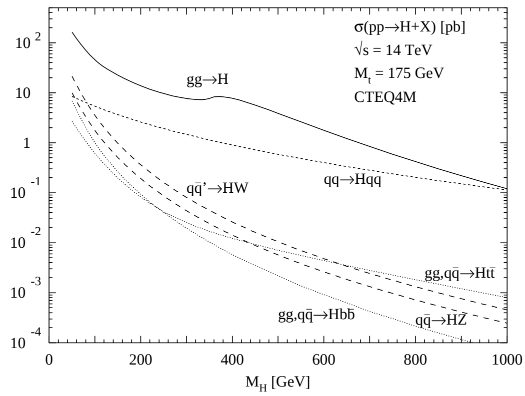

Fig. 3. Higgs production cross sections at the LHC for the various mechanisms as a function of the Higgs mass [10].

is dominated by the gluon fusion mechanism $gg \to H$, which is mediated by top and bottom triangle loops [9, 13]. This can be inferred from Fig. 3, which presents all relevant Higgs production cross sections as a function of the Higgs mass. The two-loop QCD corrections increase the production cross section by 60–90%, so that they can no longer be neglected [9]. [The QCD corrections to most of the background processes at the LHC are also known.] In spite of the large size of the QCD corrections the scale dependence is reduced significantly, thus rendering the NLO result reliable.

For large Higgs boson masses the vector boson fusion mechanism $WW, ZZ \to H$ becomes competitive, while for intermediate Higgs masses it is about an order of magnitude smaller than gluon fusion [14]. The QCD corrections are small and thus negligible [15].

Higgs-strahlung $W^*/Z^* \to HW^*/Z^*$ plays a rôle only for $M_H \lesssim 100$ GeV. The QCD corrections are moderate, so that this process is calculated with reliable accuracy [16].

Higgs bremsstrahlung off top quarks, $gg, q\bar{q} \to Ht\bar{t}$, is sizeable for $M_H \lesssim 100$ GeV [17]. The QCD corrections to this process are unknown, so that the cross section is uncertain within a factor of ~ 2.

3 MSSM

3.1 Decay Modes

Typical examples of the branching ratios and decay widths of the MSSM Higgs bosons can be found in Refs. [10, 11].

$\phi \to f\bar{f}$. For large tgβ the decay modes $h, H, A \to b\bar{b}, \tau^+\tau^-$ dominate the neutral Higgs decay modes, while for small tgβ they are important for $M_{h,H,A} \lesssim 150$ GeV. The dominant decay modes of charged Higgs particles are $H^+ \to \tau^+\nu_\tau, t\bar{b}$. The QCD corrections reduce the partial decay widths into b, c quarks by 50%–75% as a result of the running quark masses, while they are moderate for decays into top quarks [5, 6].

Decays into Higgs and gauge bosons. The decay modes $H \to hh, AA, ZA$ and $A \to Zh$ are important for small tgβ below the $t\bar{t}$ threshold. Similarly the decays $H^+ \to WA, Wh$ are sizeable for small tgβ and $M_{H^+} < m_t + m_b$. 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 [18]. The decays $h, H \to WW, ZZ$ are suppressed by kinematics and, in general, by the SUSY couplings and are thus less important in the MSSM. The decay $h \to \gamma\gamma$ is only relevant for the LHC in the decoupling limit, where the light scalar Higgs boson h has similar properties to those of the SM Higgs particle.

Decays into SUSY particles. Higgs decays into charginos, neutralinos and third-generation sfermions can become important, once they are kinematically allowed [19]. Thus they could complicate the Higgs search at the LHC, since the decay into the LSP will be invisible.

3.2 Higgs Boson Production

e^+e^- colliders. Neutral MSSM Higgs bosons

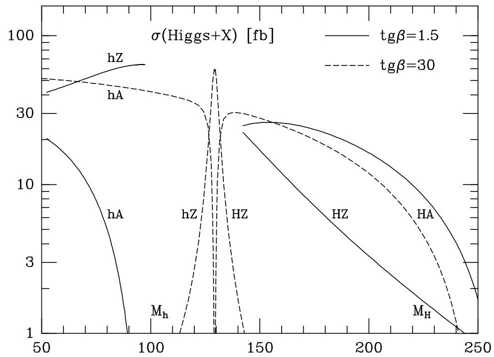

Fig. 4. Production cross sections of MSSM Higgs bosons at future e^+e^- linear colliders [11].

will be produced dominantly via $e^+e^- \to Z + h/H, A + h/H$ and W boson fusion $e^+e^- \to \nu_e\bar{\nu}_e + h/H$ at future e^+e^- colliders. The size of the individual cross sections depends strongly on tgβ, but the sum is always of the order of the SM cross section. Typical examples are presented in Fig. 4 for $\sqrt{s} = 500$ GeV, ranging between 1 and 100 fb [11].

Charged Higgs bosons can be produced via pair production $e^+e^- \to H^+H^-$ or through top quark decays $e^+e^- \to t\bar{t} \to H^+b\bar{t}$. They are in general detectable, with masses up to half the energy of the e^+e^- collider [11].

LHC. As can be inferred from Fig. 5, neutral MSSM Higgs bosons are dominantly produced via gluon fusion, $gg \to h, H, A$, which is mediated by top and bottom quark loops [9, 13]. Only for squark masses below ~ 400 GeV can the squark loop contributions become significant [20]. The two-loop QCD corrections increase the production cross sections by 10%–100% and thus cannot be neglected [9].

For large tgβ Higgs bremsstrahlung off b quarks, $gg, q\bar{q} \to b\bar{b} + h/H/A$, dominates in a large part of the relevant Higgs mass ranges [17, 21]. The QCD corrections are unknown.

Vector boson fusion $WW/ZZ \to h/H$ and Higgs-strahlung, $W^*/Z^* \to W/Z + h/H$, are suppressed in most of the parameter space by

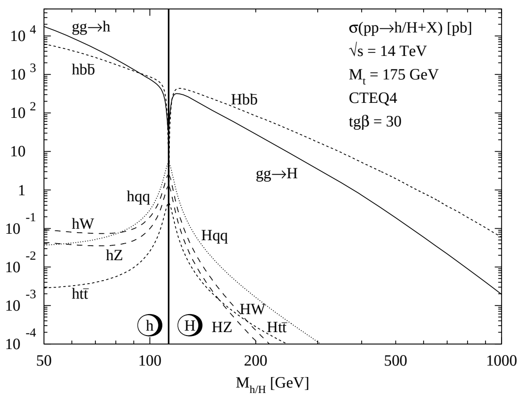

Fig. 5. Scalar Higgs production cross sections at the LHC for the various mechanisms as a function of the Higgs mass for $\mathrm{tg}\beta = 30$ [10].

SUSY couplings compared with the SM and thus less important.

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