Chapter 3

Higgs Boson Branching ratios

The measurements of the various Higgs decay channels will serve to discriminate between the Standard Model and other models with more complicated Higgs sectors which may have different decay chains and Yukawa couplings. It is therefore important that we have reliable predictions for the branching ratios in order to verify the correctness of the Yukawa couplings of the Standard Model.[?]

In this section, we review the Higgs boson branching ratios in the Standard Model.

3.0.6 *Decays to Fermion Pairs*

The dominant decays of a Higgs boson with a mass below the W^+W^- threshold are into fermion- antifermion pairs. In the Born approximation, the width into charged lepton pairs is

$$\Gamma(h \to l^+l^-) = \frac{G_F M_l^2}{4\sqrt{2}\pi} M_h \beta_l^3 \quad , \tag{3.1}$$

where $\beta_l \equiv \sqrt{1 - 4M_l^2/M_h^2}$ is the velocity of the final state leptons. The Higgs boson decay into quarks is enhanced by the color factor $N_c = 3$ and also receives significant QCD corrections,

$$\Gamma(h \to q\overline{q}) = \frac{3G_F M_q^2}{4\sqrt{2}\pi} M_h \beta_q^3 \left(1 + \frac{4}{3}\frac{\alpha_s}{\pi}\Delta_h^{QCD}\right) \quad , \tag{3.2}$$

where the QCD correction factor, Δ_h^{QCD}, can be found in Ref. 22. The final state quark mass is M_q and so the Higgs boson clearly decays predominantly into the heaviest fermion anti-fermion pair kinematically allowed.

A large portion of the QCD corrections can be absorbed by expressing the decay width in terms of a running quark mass, $M_q(\mu)$, evaluated at the scale $\mu = M_h$. The QCD corrected decay width can then be written as,[?]

$$\Gamma(h \to q\overline{q}) = \frac{3G_F}{4\sqrt{2}\pi} M_q^2(M_h^2) M_h \beta_q^3 \left(1 + 5.67 \frac{\alpha_s(M_h^2)}{\pi} + \cdots \right), \tag{3.3}$$

where $\alpha_s(M_h^2)$ is defined in the $\overline{MS}$ scheme with 5 flavors and $\Lambda_{\overline{MS}} = 150\, GeV$. The $\mathcal{O}(\alpha_s^2)$ corrections are also known in the limit $M_h >> M_q$.[?]

For 10 $GeV < M_h < 2M_W$, the most important fermion decay mode is $h \to b\overline{b}$. In leading log QCD, the running of the b quark mass is given by,

$$M_b(\mu^2) = M \left[\frac{\alpha_s(M^2)}{\alpha_s(\mu^2)} \right]^{(-12/23)} \left\{ 1 + \mathcal{O}(\alpha_s^2) \right\}, \tag{3.4}$$

where $M_b(M^2) \equiv M$ implies that the running mass at the position of the propagator pole is equal to the location of the pole. For $M_b(M_b^2) = 4.2\ GeV$, this yields an effective value $M_b((M_h = 100\ GeV)^2) = 3\ GeV$. Inserting the QCD corrected mass into the expression for the width thus leads to a significantly smaller rate than that found using $M_b = 4.2\ GeV$. For a Higgs boson in the 100 GeV range, the $\mathcal{O}(\alpha_s)$ corrections decrease the decay width for $h \to b\overline{b}$ by about a factor of two. The running of the b quark mass is shown in Fig.3.2.

The electroweak radiative corrections to $h \to q\overline{q}$ are not significant and amount to only a few percent correction.[?] These can be neglected in comparison with the much larger QCD corrections.

The branching ratios for the dominant decays to fermion- antifermion pairs are shown in Fig. 3.3.* The decrease in the $h \to f\overline{f}$ branching ratios at $M_h \sim 150\ GeV$ is due to the turn-on of the WW^* decay channel, where W^* denotes a virtual W. For most of the region below the W^+W^- threshold, the Higgs decays almost entirely to $b\overline{b}$ pairs, although it is possible that the decays to $\tau^+\tau^-$ will be useful in the experimental searches. The other fermionic Higgs boson decay channels are almost certainly too small to be separated from the backgrounds.

Even including the QCD corrections, the rates roughly scale with the

*A convenient FORTRAN code for computing the QCD radiative corrections to the Higgs boson decays is HDECAY, which is documented in Ref. 25.

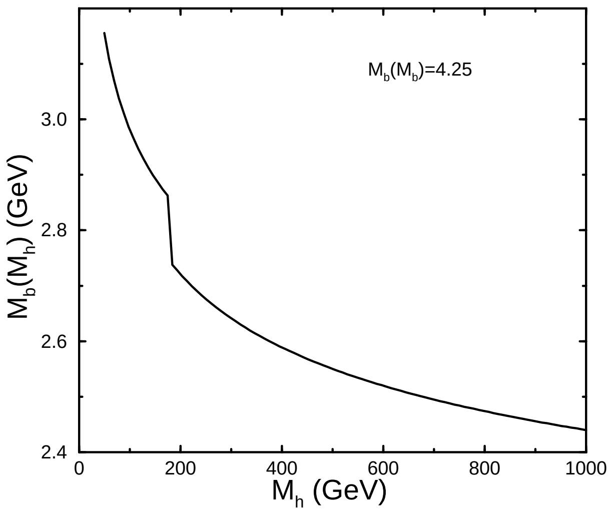

Fig. 3.1 Running of the b-quark mass.

fermion masses and the color factor, N_c,

$$\frac{\Gamma(h \to b\bar{b})}{\Gamma(h \to \tau^+\tau^-)} \sim \frac{3M_b^2(M_h^2)}{M_\tau^2}, \tag{3.5}$$

and so a measurement of the branching ratios could serve to verify the correctness of the Standard Model couplings. The largest uncertainty is in the value of α_s, which affects the running b quark mass, as in Eq. 3.8 .

3.0.7 *Decays to Gauge Boson Pairs*

The Higgs boson can also decay to gauge boson pairs. At tree level, the decays $h \to W^+W^-$ and $h \to ZZ$ are possible, while at one-loop the decays $h \to gg, \gamma\gamma,\ \gamma Z$ occur.

The decay widths of the Higgs boson to physical W^+W^- or ZZ pairs are given by,

$$\begin{aligned}\Gamma(h \to W^+W^-) =& \quad \tfrac{G_F M_h^3}{8\pi\sqrt{2}}\sqrt{1-r_W}(1-r_W+\tfrac{3}{4}r_W^2)\\ \Gamma(h \to ZZ) =& \quad \tfrac{G_F M_h^3}{16\pi\sqrt{2}}\sqrt{1-r_Z}(1-r_Z+\tfrac{3}{4}r_Z^2),\end{aligned} \tag{3.6}$$

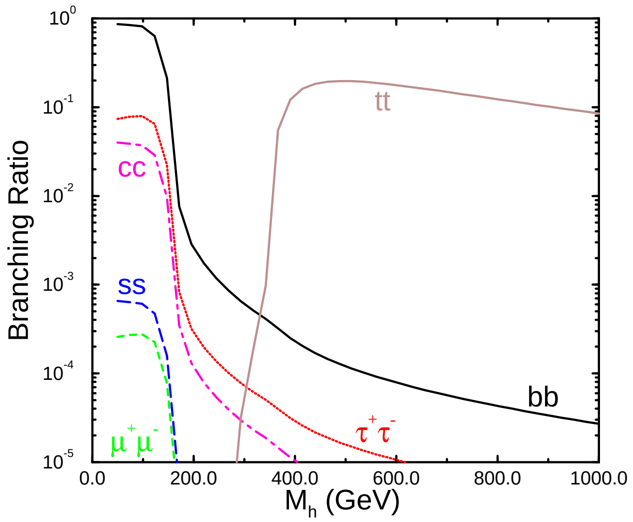

Fig. 3.2 Branching ratios of the Standard Model Higgs boson to fermion-antifermion pairs, including QCD radiative corrections. The radiative corrections were computed using the program HDECAY.[25]

where $r_V \equiv 4M_V^2/M_h^2$.

Below the W^+W^- and ZZ thresholds, the Higgs boson can also decay to vector boson pairs VV^*, $(V = W^\pm, Z)$, with one of the gauge bosons off-shell. The widths, summed over all available channels for $V^* \to f\overline{f}$ are: [?]

$$\begin{aligned}\Gamma(h \to ZZ^*) &= \frac{g^4 M_h}{2048(1-s_W)^2\pi^3}\left(7 - \frac{40}{3}s_W + \frac{160}{9}s_W^2\right)F\left(\frac{M_Z}{M_h}\right)\\ \Gamma(h \to WW^*) &= \frac{3g^4 M_h}{512\pi^3}F\left(\frac{M_W}{M_h}\right) \quad ,\end{aligned} \tag{3.7}$$

where $s_W \equiv \sin^2\theta_W$ and

$$\begin{aligned}F(x) \equiv & -\mid 1-x^2 \mid \left(\frac{47}{2}x^2 - \frac{13}{2} + \frac{1}{x^2}\right) - 3\left(1 - 6x^2 + 4x^4\right)\mid \ln(x) \mid\\ & +3\frac{1-8x^2+20x^4}{\sqrt{4x^2-1}}\cos^{-1}\left(\frac{3x^2-1}{2x^3}\right) \quad .\end{aligned} \tag{3.8}$$

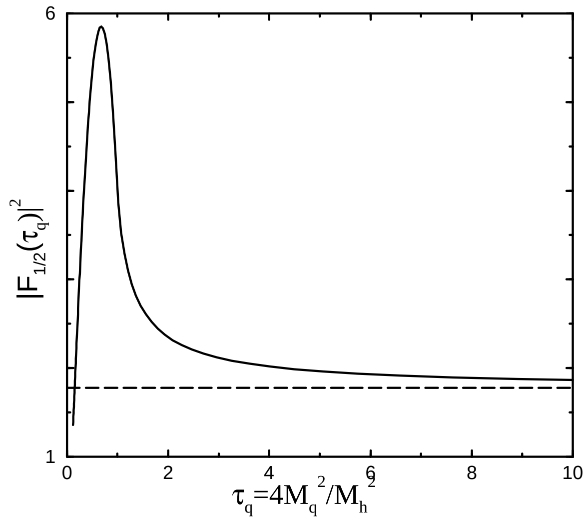

Fig. 3.3 Form factor for $gg \to h$. The dashed line is the $\tau_q \to \infty$ limit .

These widths can be significant when the Higgs boson mass approaches the real W^+W^- and ZZ thresholds, as can be seen in Fig. 3.5. The WW^* and ZZ^* branching ratios grow rapidly with increasing Higgs mass and above $2M_W$ the rate for $h \to W^+W^-$ is close to 1. The decay width to ZZ^* is roughly an order of magnitude smaller than the decay width to WW^* over most of the Higgs mass range due to the smallness of the neutral current couplings as compared to the charged current couplings.

The decay of the Higgs boson to gluons arises through fermion loops,[**?**]

$$\Gamma_0(h \to gg) = \frac{G_F \alpha_s^2 M_h^3}{64\sqrt{2}\pi^3} \mid \sum_q F_{1/2}(\tau_q) \mid^2 \tag{3.9}$$

where $\tau_q \equiv 4M_q^2/M_h^2$ and $F_{1/2}(\tau_q)$ is defined to be,

$$F_{1/2}(\tau_q) \equiv -2\tau_q \Big[1 + (1-\tau_q)f(\tau_q)\Big] \quad . \tag{3.10}$$

The function $f(\tau_q)$ is given by,

$$f(\tau_q) = \begin{cases} \left[\sin^{-1}\left(\sqrt{1/\tau_q}\right)\right]^2, & \text{if } \tau_q \geq 1 \\ -\frac{1}{4}\left[\log\left(\frac{x_+}{x_-}\right) - i\pi\right]^2, & \text{if } \tau_q < 1, \end{cases} \tag{3.11}$$

with

$$x_{\pm} = 1 \pm \sqrt{1-\tau_q}. \tag{3.12}$$

In the limit in which the quark mass is much less than the Higgs boson mass, (the relevant limit for the b quark),

$$F_{1/2} \rightarrow \frac{2M_q^2}{M_h^2}\log^2\left(\frac{M_q}{M_h}\right). \tag{3.13}$$

A Higgs boson decaying to $b\overline{b}$ will therefore be extremely narrow. On the other hand, for a heavy quark, $\tau_q \rightarrow \infty$, and $F_{1/2}(\tau_q)$ approaches a constant,

$$F_{1/2} \rightarrow -\frac{4}{3}. \tag{3.14}$$

It is clear that the dominant contribution to the gluonic decay of the Higgs boson is from the top quark loop and from possible new generations of heavy fermions. A measurement of this rate would serve to count the number of heavy quarks since the effects of the heavy quarks do not decouple from the theory.

The QCD radiative corrections from $h \rightarrow ggg$ and $h \rightarrow gq\overline{q}$ to the hadronic decay of the Higgs boson are large and they typically increase the width by more than 50%. The radiatively corrected width can be approximated by

$$\Gamma(h \rightarrow ggX) = \Gamma_0(h \rightarrow gg)\left[1 + C\frac{\alpha_s(\mu)}{\pi}\right] \quad , \tag{3.15}$$

where $C = \frac{215}{12} - \frac{23}{6}\log(\mu^2/M_h^2)$, for $M_h < 2M_t$.[?] The radiatively corrected branching ratio for $h \rightarrow ggX$ is the solid curve in Fig. 3.5.

The decay $h \rightarrow Z\gamma$ is not useful phenomenologically, so we will not discuss it here although the complete expression for the branching ratio can be found in Ref. 28. On the other hand, the decay $h \rightarrow \gamma\gamma$ is an

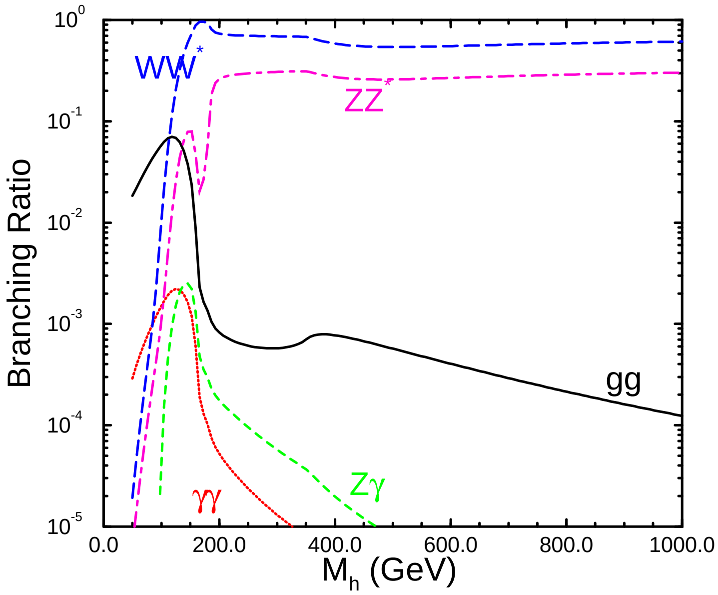

Fig. 3.4 Branching ratios of the Standard Model Higgs boson to gauge boson pairs, including QCD radiative corrections. The rates to WW^* and ZZ^* must be multiplied by the appropriate branching ratios for W^* and Z^* decays to $f\overline{f}$ pairs. The radiative corrections were computed using the program HDECAY.[25]

important mode for the Higgs search at the LHC. At lowest order, the branching ratio is, [?]

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 G_F}{128\sqrt{2}\pi^3} M_h^3 \mid \sum_i N_{ci} Q_i^2 F_i(\tau_i) \mid^2 \tag{3.16}$$

where the sum is over fermions and $W^\pm$ bosons with $F_{1/2}(\tau_q)$ given in Eq. 23, and

$$F_W(\tau_W) = 2 + 3\tau_W [1 + (2 - \tau_W) f(\tau_W)] \quad . \tag{3.17}$$

$\tau_W = 4M_W^2/M_h^2$, $N_{Ci} = 3$ for quarks and 1 otherwise, and Q_i is the electric charge in units of e. The function $f(\tau_q)$ is given in Eq. 3.15. The $h \to \gamma\gamma$ decay channel clearly probes the possible existence of heavy charged particles. (Charged scalars, such as those existing in supersymmetric models,

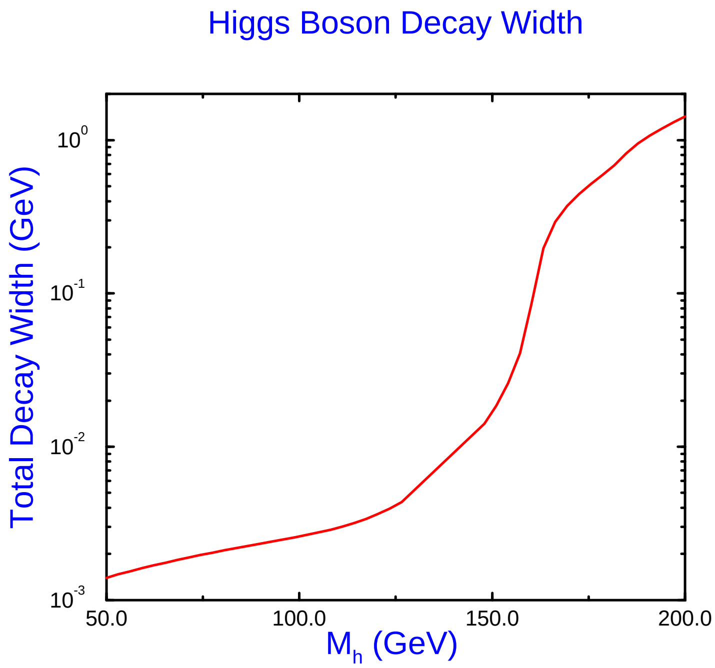

Fig. 3.5 Total Higgs boson decay width in the Standard Model, including QCD radiative corrections. The turn-on of the W^+W^- threshold at $M_h \sim 160\ GeV$ is obvious.

would also contribute to the rate.)[**?**]

In the limit where the particle in the loop is much heavier than the Higgs boson, $\tau \to \infty$,

$$\begin{aligned} F_{1/2} &\rightarrow -\frac{4}{3} \\ F_W &\rightarrow 7 \quad . \end{aligned} \tag{3.18}$$

The top quark contribution ($F_{1/2}$) is therefore much smaller than that of the W loops (F_W) and so we expect the QCD corrections to be less important than is the case for the $h \to gg$ decay. In fact the QCD corrections to the total width for $h \to \gamma\gamma$ are quite small.[**?**] The $h \to \gamma\gamma$ branching ratio is the dotted line in Fig. 3.5. For small Higgs masses it rises with increasing M_h and peaks at around 2×10^{-3} for $M_h \sim 125\ GeV$. Above this mass, the WW^* and ZZ^* decay modes are increasing rapidly with increasing Higgs mass and the $\gamma\gamma$ mode becomes further suppressed.

The total Higgs boson width for a Higgs boson with mass less than $M_h \sim 200\ GeV$ is shown in Fig. 3.6. As the Higgs boson becomes heavier twice the W boson mass, its width becomes extremely large (see Eq. 122). Below around $M_h \sim 150\ GeV$, the Higgs boson is quite narrow with $\Gamma_h < 10\ MeV$. As the WW^* and ZZ^* channels become accessible, the width increases rapidly with $\Gamma_h \sim 1\ GeV$ at $M_h \sim 200\ GeV$. Below the W^+W^- threshold, the Higgs boson width is too narrow to be resolved experimentally. The total width for the lightest neutral Higgs boson in the minimal supersymmetric model is typically much smaller than the Standard Model width for the same Higgs boson mass and so a measurement of the total width could serve to discriminate between the two models.