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# THE HIGGS BOSON DECAY $H \to Zgg$

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## ABSTRACT

The decay mode $H \to Zgg$ is investigated using analytic results for the $HZgg$ vertex in the minimal standard model. It is compared to the major decay channels of the Higgs boson in the window $M_W < M_H < 2M_W$ and $B(H \to Zgg) < 2 \times 10^{-6}$ is found for the branching ratio.

The minimal standard model of electroweak interactions postulates the presence of a neutral scalar Higgs boson, $H$. This particle is a necessary remnant of the spontaneous symmetry breaking mechanism which generates the particle mass spectrum and its discovery would provide a crucial confirmation of this theory. The vacuum expectation value of the Higgs boson is predicted to be equal to $2^{-1/4}G_F^{-1/2} \approx 246\,\text{GeV}$ but its mass, $M_H$, is only feebly constrained. Recently, the experimental bound $M_H \geq 24\,\text{GeV}$ [1] has been obtained at the CERN Large Electron Positron Collider (LEP). On the other hand, if $M_H$ exceeds 1 TeV, the Higgs boson becomes strongly coupled to the $W^\pm$ and $Z$ bosons and no longer behaves as a particle [2].

Depending on the value of $M_H$, different search techniques are required. Low-mass Higgs bosons are most conveniently detected in $e^+e^-$ colliding beam experiments because of low backgrounds. At LEP I the mass range $M_H \lesssim 50\,\text{GeV}$ will be covered via the Bjorken process [3], $e^+e^- \to Z \to H f\bar{f}$, on $Z$ resonance. The cross section for the bremsstrahlung process $e^+e^- \to Z \to ZH$ [4, 5] peaks at an energy of $\sqrt{s} = M_Z + \sqrt{2}M_H$ so that at the future LEP II machine operating at $\sqrt{s} = 200\,\text{GeV}$, $M_H$ may be scanned up to values of approximately 80 GeV. At the other end of the scale, high-mass Higgs bosons ($M_H > 2M_W$) are preferably produced at future multi-TeV hadron colliders, such as the Large Hadron Collider (LHC) and the Superconducting Super Collider (SSC), through gluon fusion [6], $gg \to H$, which is mediated by quark triangle graphs, and $WW/ZZ$ fusion [7], $qq \to qq\,H$, where the intermediate vector bosons are emitted from the initial quarks and annihilate to create a Higgs boson. The dominant decay modes are then $H \to W^+W^-$, $H \to ZZ$, and $H \to t\bar{t}$ [8] and subsequent leptonic decays of the vector bosons may serve as signals to identify the Higgs boson.

The most appropriate tool to discover Higgs bosons in the window $M_W < M_H < 2M_W$ would be an $e^+e^-$ collider with $\sqrt{s} = 300$–$400\,\text{GeV}$, however, such a machine will not be available in the foreseeable future. Intermediate-mass Higgs bosons could be copiously produced at hadron colliders also, but there the signals are severely obscured by QCD background inevitably requiring some kind of electromagnetic or leptonic trigger. Possible candidates are the channels $H \to W^\pm X$ or $H \to ZX$ [8–10] followed by a leptonic decay of the $W^\pm$ or $Z$ bosons. After fragmentation, the parton level process $H \to Zgg$ leads to the same class of final states as $H \to Z\, q\bar{q}$: one leptonically or hadronically decaying $Z$ boson and two jets. In this letter we calculate the partial decay width $\Gamma(H \to Z\, gg)$, which has not been done elsewhere in the literature, using an analytic expression for the $HZgg$ vertex derived previously [11].

To lowest order the $HZgg$ coupling is generated by the set of quark triangle and box diagrams depicted in Fig. 1. It is of first order in $\alpha_s/\pi$ as compared to the tree level $HZq\bar{q}$ coupling. As a consequence of the Landau-Yang theorem [12], the pole of the $Z$ boson propagator in the triangle type diagram is cancelled and the resonance behaviour at the threshold $M_H = 2M_Z$ is absent in $\Gamma(H \to Z\, gg)$. Due to charge conjugation invariance, the $Z$ boson couples only axially to the internal quark so that the contribution from a mass-degenerate weak isodoublet of quarks vanishes; it is therefore justified to neglect the contribution from light quark pairs. Nevertheless, we include the $(c, s)$ doublet in our analysis.

In Ref. 11 we have decomposed the polarization tensor, that is to say the tensorial kernel which is dressed by the polarization four-vectors of the gauge bosons to form the invariant matrix element, into basic Lorentz tensors multiplied by certain form factors using the reduction algorithm described in Ref. 13. In turn the form factors are expressed in terms of complex logarithms and Spence functions [14]. The final result includes 136 Spence functions of distinct arguments and is listed in the appendices of Ref. 11. In the limit that the top quark is infinitely heavy while the other quarks are massless, the three-particle phase space integration can be performed analytically and yields

$$\Gamma_0(H \to Z\, gg) = \left(\frac{\alpha_s}{\pi}\right)^2 \frac{G_F^2 M_H^5}{1024\pi^3} (1 - 8r + 8r^3 - r^4 - 12r^2 \ln r)\,, \quad r = \frac{M_Z^2}{M_H^2}\,, \qquad (1)$$

where $G_F$ denotes the Fermi constant and finite $Z$ width effects have been neglected.

In the numerical analysis throughout this letter we set $M_Z = 91.17\,\text{GeV}$, $\Gamma_Z = 2.54\,\text{GeV}$, $\sin^2\theta_W = 0.225$ [15], adopt the lepton masses from Ref. 16, the light quark masses from Ref. 17, and vary $m_t$ between 80 GeV [18] and 200 GeV [19]. For the strong coupling constant, $\alpha_s(\mu^2)$, we employ the representation in the modified minimal-



subtraction ($\overline{MS}$) scheme as in Eq. (6) of Ref. 20 with $\Lambda^{(5)}_{\overline{MS}} = 140\,\text{MeV}$ [21] and we choose $\mu = M_H/2$ as the renormalization scale.

Figure 2 displays $\Gamma(H \to Z\, gg)$ as a function of $M_H$ for $m_t = 80$, 140, and 200 GeV (dashed, dash-dotted, and solid line, respectively). As $M_H$ approaches $M_Z$ the decay is increasingly phase space suppressed. The striking inflection points are located at the toponium threshold, $M_H = 2m_t$, and arise from imaginary parts in the box amplitude which are switched on as the top quark may be pair-produced from Higgs boson decay. Equation (1) (dotted line) leads to an excellent approximation below threshold whereas above threshold it provides a satisfactory description to within the uncertainty introduced by the ambiguity in the choice of $\mu$ in $\alpha_s(\mu^2)$, $\delta\alpha_s^2/\alpha_s^2 \approx 50\%$.

Because of the dramatic variation of the total Higgs width, $\Gamma_H$, with $M_H$, it is perhaps more instructive to consider branching fractions, $B(H \to X) = \Gamma(H \to X)/\Gamma_H$. Figure 3 shows the branching ratios of the major leptonic and semi-leptonic decay modes in the interval $M_W < M_H < 2M_W$. The dotted lines represent the decays into massive lepton pairs in the Born approximation [22]. For $M_H \lesssim 120\,\text{GeV}$ tau pairs are the most likely leptonic decay products with an almost constant value of $B(H \to \tau^+\tau^-) \approx 4\%$. Heavier Higgs bosons prefer the semi-leptonic channel $H \to W^{+*}W^{-*} \to \ell^{\pm}\overset{(-)}{\nu}_{\ell} X$ (upmost dashed line). In the massless fermion approximation, the corresponding partial width is given by

$$\Gamma(H \to W^{+*}W^{-*} \to X) \times \left(1 - B(W^{\pm} \to \text{hadrons})^2\right)\,, \qquad (2)$$

where $B(W^{\pm} \to \text{hadrons}) = 2/3$ and

$$\Gamma(H \to W^{+*}W^{-*} \to X) \qquad (3)$$

$$= \int\limits_{\sqrt{s_+}+\sqrt{s_-}\le M_H} \frac{ds_+\, ds_-}{\pi^2} \frac{\mathcal{I}m\,\Pi_{WW}(s_+)}{(s_+ - M_W^2)^2 + M_W^2\Gamma_W^2} \frac{\mathcal{I}m\,\Pi_{WW}(s_-)}{(s_- - M_W^2)^2 + M_W^2\Gamma_W^2} \Gamma(M_H^2, s_+, s_-)\,.$$

Here $\Pi_{WW}(s)$ denotes the transverse $W$ self energy and, in the Born approximation,

$$\Gamma(M_H^2, s_+, s_-) = \frac{3g_{HWW}^2}{16\pi} \frac{\sqrt{\lambda(M_H^2, s_+, s_-)}}{M_H^3} \left(1 + \frac{\lambda(M_H^2, s_+, s_-)}{12 s_+ s_-}\right)\,, \qquad (4)$$

$$\mathcal{I}m\,\Pi_{WW}(s) = \frac{s}{12\pi}\sum_f N_c(v_{Wf}^2 + a_{Wf}^2)\,, \tag{5}$$

where $\lambda(x,y,z) = x^2 + y^2 + z^2 - 2(xy + yz + zx)$, $g_{HWW}^2 = 4\sqrt{2}G_F M_W^4$, $v_{Wf}^2 = a_{Wf}^2 = G_F M_W^2/\sqrt{2}$, and $N_c = 1$ (3) for lepton (quark) flavours, $f$. On mass-shell, the following identities hold:

$$\Gamma(M_H^2, M_W^2, M_W^2) = \Gamma(H \to W^+W^-)\,, \tag{6}$$

$$\mathcal{I}m\,\Pi_{WW}(M_W^2) = M_W\Gamma_W\,. \tag{7}$$

In the narrow-width approximation,

$$\lim_{\Gamma_W\to 0}\frac{1}{\pi}\frac{\mathcal{I}m\,\Pi_{WW}(s)}{(s-M_W^2)^2 + M_W^2\Gamma_W^2} = \delta(s - M_W^2)\,, \tag{8}$$

Eq. (3) reproduces Eq. (6) for $M_H > 2M_W$, while for $M_W < M_H < 2M_W$ the expression for $\Gamma(H \to W^\pm X) = \Gamma(H \to W^+X) + \Gamma(H \to W^-X)$ as of Eq. (9) in Ref. 9 is recovered. Note, however, that the latter expression vanishes for $M_H < M_W$ and essentially leads to double counting for $M_H > 2M_W$, whereas our Eq. (3) is correct for arbitrary values of $M_H$. The above relations may be translated to the case $H \to Z^*Z^* \to \ell^+\ell^-X$ by substituting $1 - B(Z \to \text{hadrons})^2 \approx 52\%$, $g_{HZZ}^2 = 4\sqrt{2}G_F M_Z^4$, $v_{Zf}^2 = \sqrt{2}G_F M_Z^2(I_f - 2\sin^2\theta_W Q_f)^2$, $a_{Zf}^2 = G_F M_Z^2/(2\sqrt{2})$, and by multiplying the right-hand side of Eq. (4) by an extra factor of 1/2, which accounts for the identical-particle symmetrization. However, one should keep in mind that such a procedure disregards final state interference effects in the case of the creation of two fermion pairs of the same flavour (and colour), that is the contribution from the terms in the squared matrix element which correspond to one closed fermion line instead of two. This may be justified by observing that, since $\Gamma_Z \ll M_Z$, the $Z$ bosons are quasi-real so that prior to their decay they gain a spatial separation which is sufficient to regard the individual decay systems as independent of each other. Upon phase space integration, these terms are suppressed by a factor of $\Gamma_Z^2/M_Z^2$.

The decays into $\gamma\gamma$ and $Z\gamma$ proceed to lowest order via $W$ boson and massive fermion loops. $\Gamma(H \to \gamma\gamma)$ was originally calculated in Ref. 4 in the approximation $M_H \ll M_W$;



the general result may be found in Refs. 23, 24. In the context of the crossed process, $Z \to H\gamma$, the $HZ\gamma$ coupling was derived in Ref. 25 in terms of parametric integrals; the final analytic representation of $\Gamma(H \to Z\gamma)$ is presented in Refs. 10, 24, 26.# Here the $Z$ boson is taken on-shell and the decay is phase space suppressed for $M_H \gtrsim M_Z$.

The same argument applies to our treatment of $H \to Z\,gg$, too (solid line). At $M_H \approx 150\,\text{GeV}$, $B(H \to Z\,gg)$ assumes its maximum value of about $2 \times 10^{-6}$, which is further reduced to $5 \times 10^{-7}$ if the $Z$ boson is tagged by its subsequent decay into pairs of electrons, muons, or neutrinos ($B \approx 27\%$). For comparison, $B(H \to gg)$ is also shown (dash-dotted line), to which the radiation of a supplementary $Z$ boson may be considered as a bremsstrahlung correction.

In conclusion, we expect less than one identifiable $H \to Z\,gg$ event per year of running at SSC ($\sqrt{s} = 40\,\text{TeV}$) assuming an integrated luminosity of $10^4\,\text{pb}^{-1}$ [27] and single Higgs production from gluon fusion, $\sigma(gg \to H) \approx 100\,\text{pb}$ for $100\,\text{GeV} < M_H < 160\,\text{GeV}$ and $90\,\text{GeV} < m_t < 200\,\text{GeV}$ [10].

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# The typographical errors in Eqs. (A.1), (A.2) in the appendix of Ref. 10 are corrected in Ref. 26.

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## FIGURE CAPTIONS

1) Feynman diagrams pertinent to the decay $H \to Z\,gg$.

2) Partial decay rate $\Gamma(H \to Z\,gg)$ as a function of $M_H$ for selected values of $m_t$. The dotted line represents the approximation by Eq. (1).

3) Branching fractions of the major leptonic and semi-leptonic Higgs decay modes in the window $M_W < M_H < 2M_W$ as a function of $M_H$.

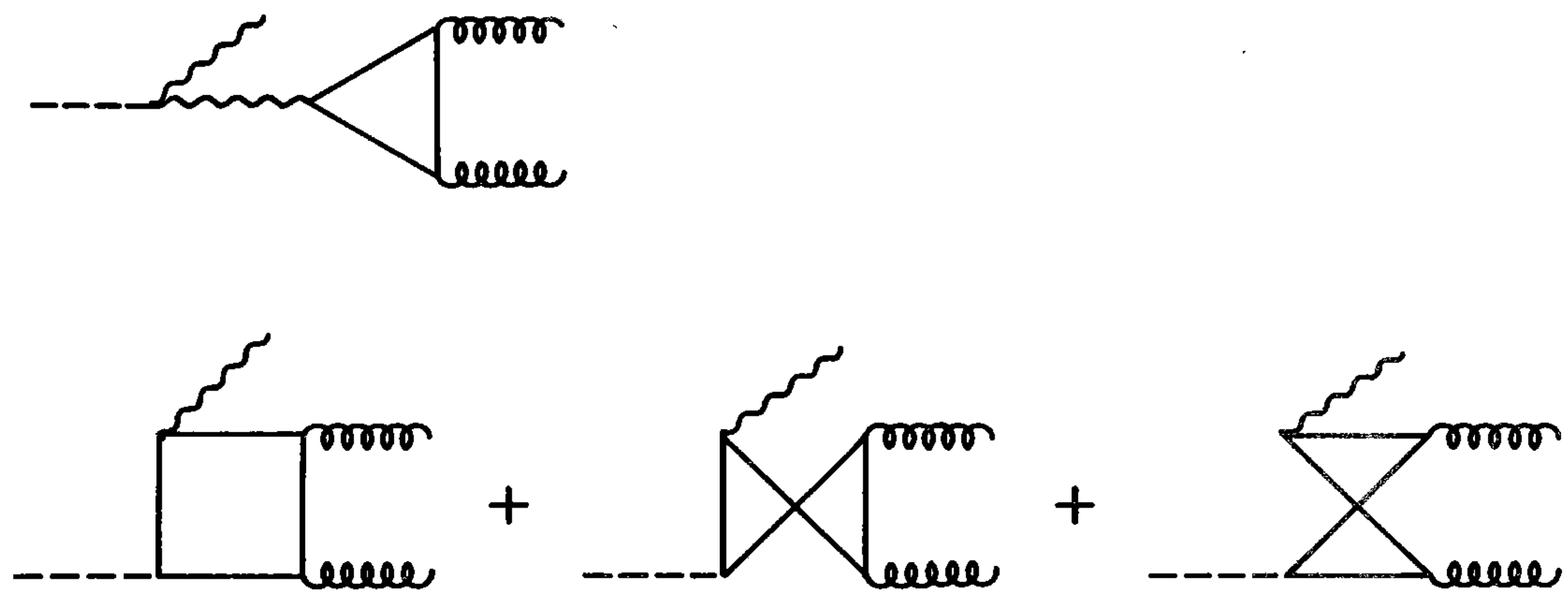


Fig. 1

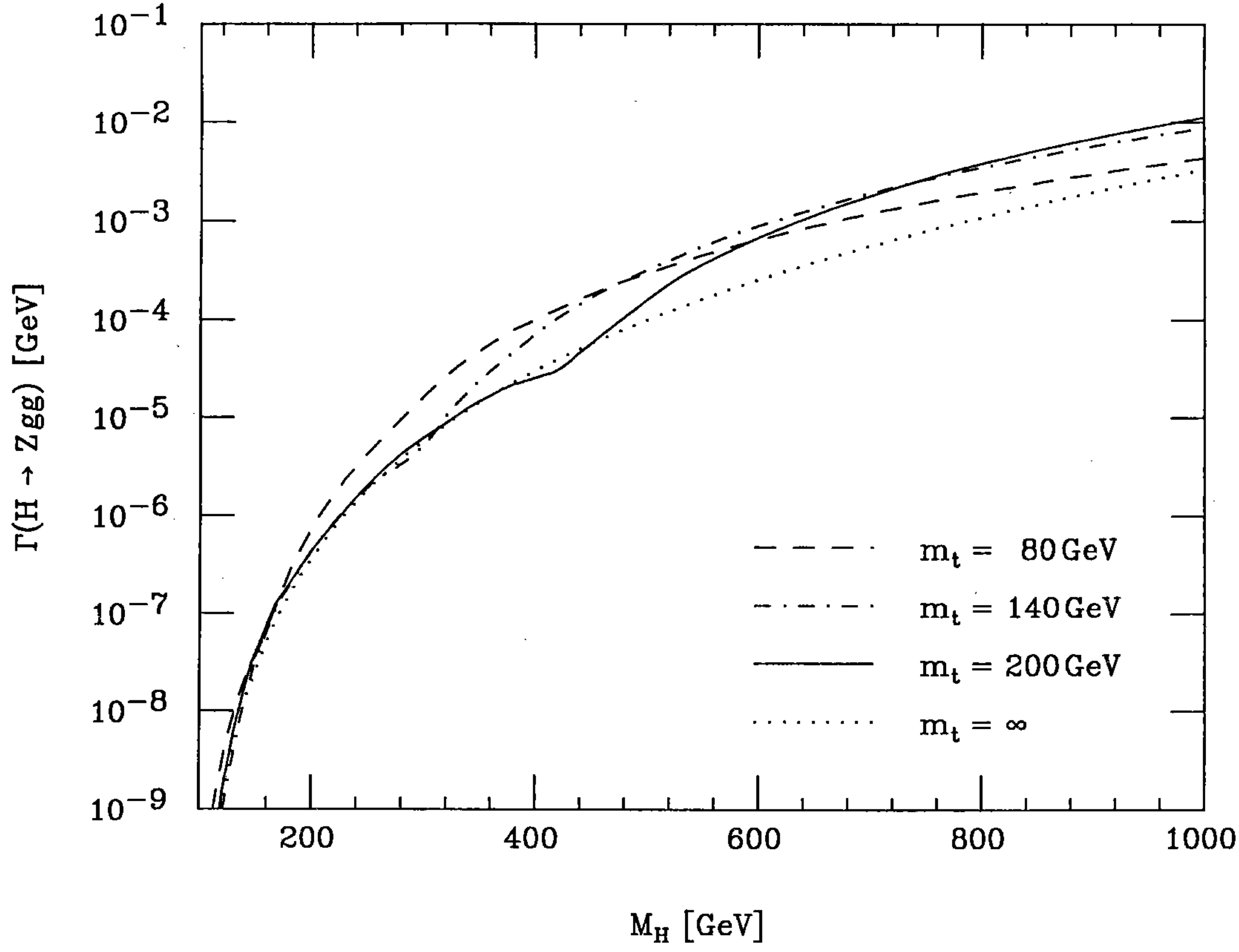
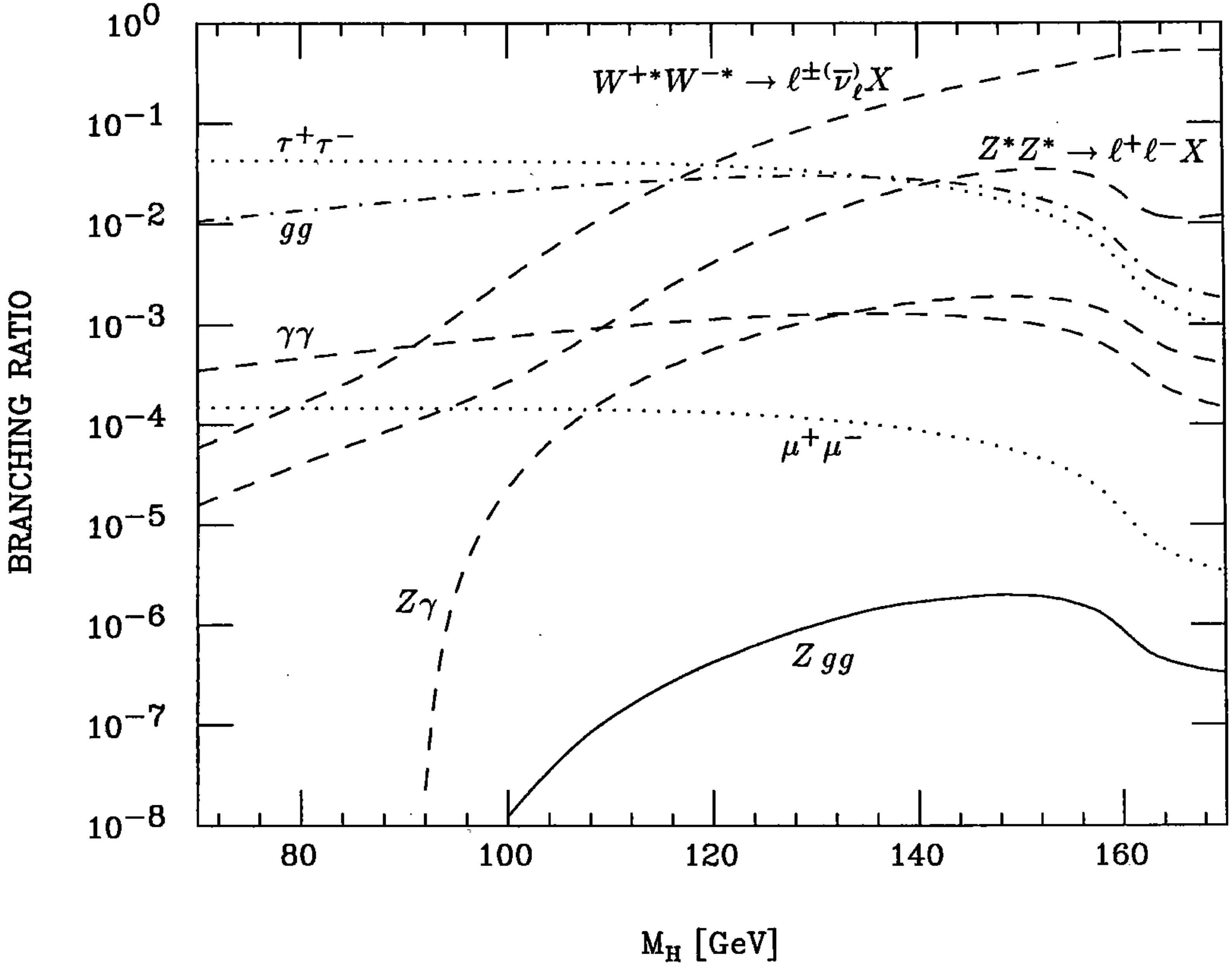

10^−1
10^−2
10^−3
10^−4
10^−5
10^−6
10^−7
10^−8
10^−9
Γ(H → Zgg) [GeV]
200
400
600
800
1000
M_H [GeV]
m_t = 80 GeV
m_t = 140 GeV
m_t = 200 GeV
m_t = ∞

**Fig. 2**



$W^{+*}W^{-*} \to \ell^{\pm}\overset{(-)}{\nu}_{\ell}X$
$Z^*Z^* \to \ell^+\ell^- X$
$\tau^+\tau^-$
$gg$
$\gamma\gamma$
$\mu^+\mu^-$
$Z\gamma$
$Z\,gg$
BRANCHING RATIO
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
80
100
120
140
160
$M_H$ [GeV]


**Fig. 3**