On decays of heavy higgs: case of extra generations

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Abstract

The prediction of higgs boson to be light is not stable under those extensions of Standard Model in which new particles do not decouple. In particular, with additional generations of fermions higgs boson is allowed to become heavy; accordingly the pattern of higgs decays changes as soon as new decay channels open.

The precision measurement of Z-boson parameters, W-boson mass, top quark mass and the value of running electromagnetic coupling constant at Z-boson mass allow to predict the mass of the higgs boson in the framework of Standard Model. Table 1 contains the LEPTOP fit of electroweak observables with experimental data updated to the spring 2004. Increase of t-quark mass according to D0 reanalysis push higgs mass up:

$$(M_H)^{2004}_{\text{Standard Model}} = (103 + 55 - 40) \text{ GeV} \ , \tag{1}$$

and quality of fit is good:

$$N_G = 0 : \qquad \chi^2/n_{\text{d.o.f.}} = 16.7/12 \ . \tag{2}$$

So, in the framework of Standard Model central value of m_H is still below direct search lower bound from LEP II, $M_H > 115$ GeV. Most probably higgs should be lighter than 200 GeV. The SM prediction of higgs boson mass originates from the dependence of electroweak radiative corrections on it which at first approximation looks like:

$$\delta V_i \approx (m_t/M_Z)^2 - 3/4s^2 \ln(\frac{M_H}{M_Z})^2 \ , \tag{3}$$

where $s \equiv \sin\theta$, θ is electroweak mixing angle, and definitions of functions V_i are given in [1]. It is evident that introducing heavy fermionic generations we add new contributions to the first term on right hand side of eq.(3) and in order for functions V_i to remain the same M_H should become larger. Indeed, it was noted in paper [2] that the 500 GeV higgs does not contradict electroweak precision data if accompanied by fourth generation. In paper [3] five dimensional parameter space of the model with fourth generation $(m_H, m_U, m_D, m_E, m_N)$ was investigated and the values of new quark and lepton masses which allow heavy higgs were found.

In the present paper we investigate how higgs decay branching ratios change when new generations are added to the Standard Model. Let us determine how many new generations can be added to Standard Model. New quarks contribution to the radiative corrections depends mainly on the difference of the masses of up and down quarks.

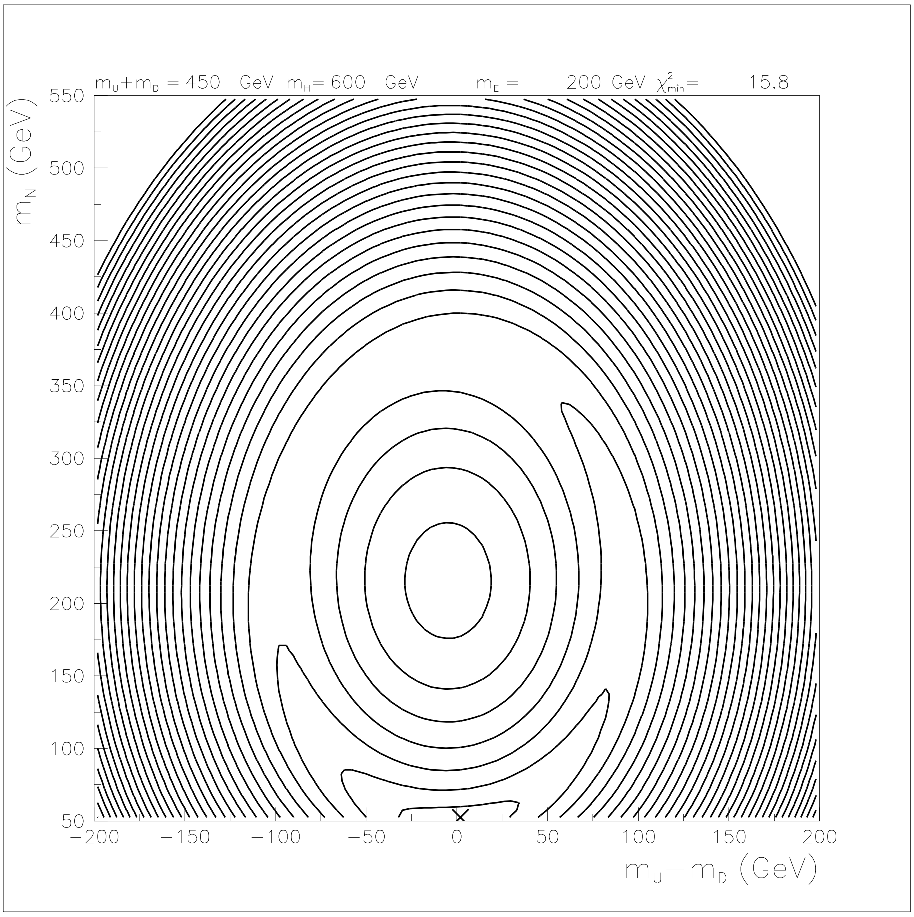

Figure 1:

Concerning leptons the difference of masses of neutral and charged isodublet members matter as well, however new aspect emerges. It is the fact that χ^2 rapidly diminishes when neutral lepton mass approach one half of a Z-boson mass, $m_N \approx 50$ GeV.

To perform fit we take $m_H = 600$ GeV, $m_U + m_D = 450$ GeV and $m_E = 200$ GeV and allow $m_U - m_D$ and m_N to vary. For $N_g = 1$ exclusion plot is shown in Fig. 1. The minimum of χ^2 is at $m_N = 52.5$ GeV and almost degenerate U- and D-quarks, $m_U - m_D = 2$ GeV, and it is equal to:

$$N_G = 1 : \qquad \chi^2/n_{\text{d.o.f.}} = 15.8/11 \quad , \tag{4}$$

so the quality of fit is the same as that of Standard Model, eq. (2).

In Fig. 2 exclusion plot for $N_G = 2$ is presented. In case of 2 extra generations we take masses of new fermions to be degenerate: $m_{U_4} = m_{U_5} = m_U$, $m_{D_4} = m_{D_5} = m_D$, $m_{E_4} = m_{E_5} = m_E$, $m_{N_4} = m_{N_5} = m_N$ in order to avoid multiplication of the number of fitted parameters. We believe that qualitatively results will not change if we allow fourth and fifth generation masses vary independently. At χ^2 minimum up and down quarks are still degenerate, like in case of one extra generation. Neutral leptons become a little bit heavier, $m_N \approx 60$ GeV. Quality of fit considerably worsens:

$$N_{G=2} : \qquad \chi^2/n_{\text{d.o.f.}} = 21.7/11 \tag{5}$$

We analyze the case with 3 extra generations in the same manner as that of 2 extra generations, taking new quarks and leptons with the same isospin projection degenerate

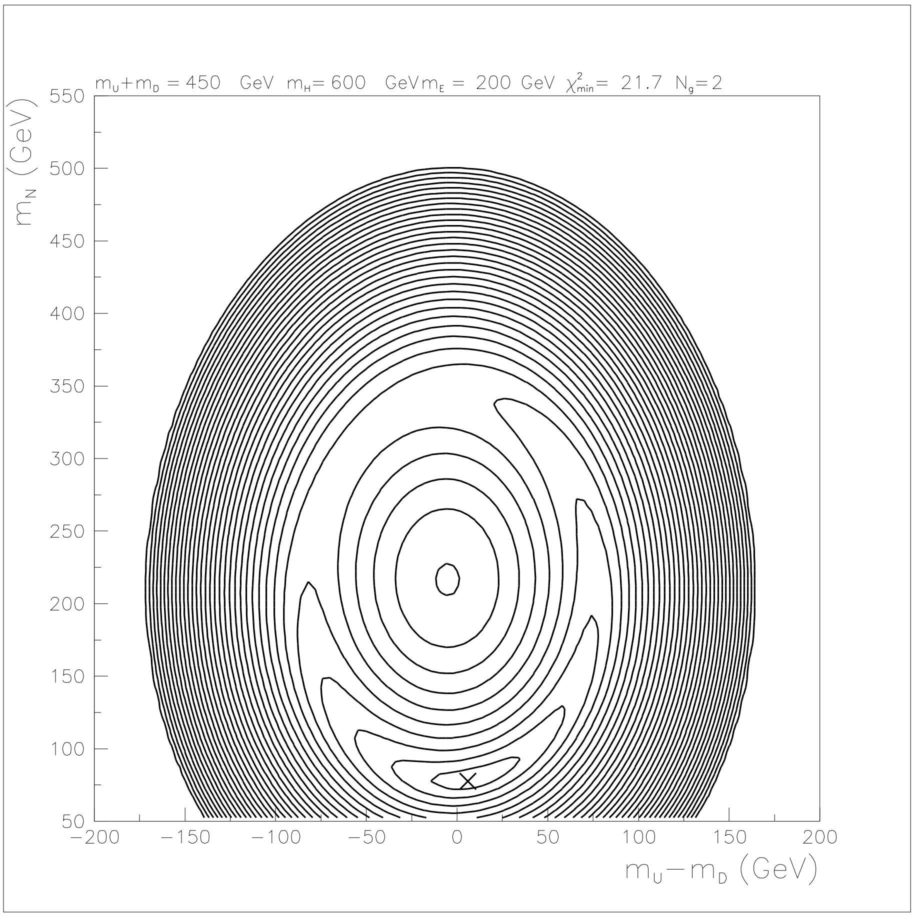

Figure 2:

and allow m_N and $m_U - m_D$ to vary. We get:

$$N_G = 3 : \qquad \chi^2/n_{\mathrm{d.o.f.}} = 30.4/11 \ , \tag{6}$$

and comparing with eq.(4) we conclude that 3 extra generations are excluded at the level of 4 standard deviations.

So, not more than two extra fermionic generations are allowed by precision data.

Higgs boson widths to the pair of intermediate vector bosons are given by the following formulas:

$$\Gamma_{H\to WW} = \frac{\alpha M_H^3}{16 s^2 M_W^2}\left[1 - (\frac{2M_W}{M_H})^2 + 12(\frac{M_W}{M_H})^4\right]\left[1 - \frac{4M_W^2}{M_H^2}\right]^{1/2} \quad , \tag{7}$$

$$\Gamma_{H\to ZZ} = \frac{\alpha M_H^3}{32 s^2 c^2 M_Z^2}\left[1 - (\frac{2M_Z}{M_H})^2 + 12(\frac{M_Z}{M_H})^4\right]\left[1 - \frac{4M_Z^2}{M_H^2}\right]^{1/2} \quad , \tag{8}$$

and they rapidly increases when higgs becomes heavier.

Higgs width to the pair of fermions is:

$$\Gamma_{H\to f\bar f} = N_c \frac{M_H}{8\pi}(\frac{m_f}{\eta})^2\left[1 - \frac{4m_f^2}{M_H^2}\right]^{3/2} \quad , \tag{9}$$

where $N_c = 1$ for lepton, $N_c = 3$ for quarks and η is higgs boson expectation value.

Extra factor $1 - \frac{4m_f^2}{M_H^2} = v_f^2$ (v_f is fermion velocity) is due to the fact that Dirac fermions are produced in P-wave when scalar particle decays. In order to compare the width to the fermions and that to the vector bosons it is convenient to present eq.(9) in the following way:

$$\Gamma_{H \to f\bar{f}} = N_c \frac{\alpha M_H}{8s^2} (\frac{m_f}{M_W})^2 \left[1 - \frac{4m_f^2}{M_H^2}\right]^{3/2} \quad . \tag{10}$$

As far as higgs boson decays to the pair of vector bosons is kinematically forbidden ($m_H < 160$ GeV) decays to fermions dominate. In the case of Standard Model it is decay to $b\bar{b}$ pair, see [4]. If extra generations are present and if decay to the pair of neutral leptons is kinematically allowed, then it dominates [5].

In the opposite case of very heavy higgs boson, $M_H = 600$ GeV, in Standard Model decays to vector bosons dominate. Let us investigate if decays to new fermions can considerably diminish branching of higgs to vector bosons. Let us adjust mass of fermion in such a way that higgs width to it becomes maximal. According to eq.(10) it happens for $m_f^2 = M_H^2/10$:

$$(\Gamma_{H \to f\bar{f}})_{\max} \approx 0.09 N_c \frac{\alpha M_H^3}{16 s^2 M_W^2} \quad , \tag{11}$$

and for two degenerate fermion generations the sum over all fermionic modes gives[1]:

$$\Gamma_{H \to \text{new degenerate fermions}} = 0.09 \cdot 16 \frac{\alpha M_H^3}{16 s^2 M_W^2} \quad . \tag{12}$$

Finally, higgs decay to the pair $t\bar{t}$ should be taken into account:

$$\Gamma_{H \to t\bar{t}} = \frac{3\alpha M_H}{8s^2} (\frac{m_t}{M_W})^2 \left[1 - \frac{4m_t^2}{M_H^2}\right]^{3/2} \quad , \tag{13}$$

and for the case $M_H = 600$ GeV we obtain:

$\Gamma_{\text{new degenerate fermions}}$	Γ_{WW}	Γ_{ZZ}	Γ_{tt}	Γ_H
96	60	29	18	203

All widths are in GeV. Doubling of higgs width would lead to four times less events of higgs decay to "golden mode" $H \to ZZ$ around cross-section maximum:

$$\sigma_{pp \to H \to ZZ} \sim \frac{\Gamma_{H \to ZZ} \Gamma_{H \to gg}}{(E - M_H)^2 + \Gamma_H^2/4} \quad . \tag{14}$$

However since $gg \to H$ fusion proceed through quark triangle new quarks enhance it [6]. In Standard Model triangle with top quark dominates; as far as masses of new quarks are close to that of top production amplitude in case of two extra generations is enhanced by factor 5 (contribution of U_4, U_5, D_4, D_5 should be taken into account), crossection is about 25 times that of Standard Model. Thus we demonstrate how noncoherent effect of heavy higgs ($M_H \sim 500 - 600$ GeV) decay to new quarks diminishes a bit coherent enhancement of higgs production in gluon fusion. Decays of comparatively light ($M_H < 200$ GeV) higgs boson to pair of neutral leptons dominate, making such a higgs invisible.

[1] It follows from the first part of the paper that in order to allow heavy higgs masses in fermion isodoublets should be splitted. We take degenerate doublets in order to diminish parameter space; it is clear that pattern of heavy higgs decays will not alter significally if splitting will be taken into account.

References

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