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Mass and decays of Brout-Englert-Higgs scalar with extra generations

J.-M. Frére
Physique Théorique, ULB, Brussels
A.N. Rozanov
ITEP, Moscow, Russia
and
CPPM-IN2P3-CNRS-Universite Mediterrane, Marseille, France
M.I. Vysotsky
ITEP, Moscow, Russia

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Abstract

The higher bound on the mass of the Brout-Englert-Higgs scalar boson (BEH boson for brevity) arising from radiative corrections is not stable when the Standard Model is extended to include non-decoupling particles. In particular additional generations of fermions allow for a heavier scalar. We investigate how the decay branchings of scalar boson are affected by the opening of new channels.

The precision measurement of Z-boson parameters, W-boson mass, top quark mass and the value of the running electromagnetic coupling constant at the Z-boson mass allow to predict the mass of the Brout-Englert-Higgs (BEH) boson in the framework of the Standard Model.

Table 1 contains the LEPTOP fit of electroweak observables to the experimental data updated in spring 2004. The increase of the t-quark mass according to the D0 reanalysis pushes the scalar boson mass up:

$$(M_{BEH})^{2004}_{\text{Standard Model}} = (103 + 54 - 39)\ \text{GeV} \ \ , \tag{1}$$

and the quality-of-fit is good:

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

So, in the framework of the 3-generations Standard Model, the central value of M_{BEH} is close to the direct-search lower bound from LEP II, $M_{BEH} > 115$ GeV. Most probably it

Table 1: LEPTOP fit of the precision observables.

Observ.	Exper. data	LEPTOP fit	Pull
Γ_Z [GeV]	2.4952(23)	2.4969(15)	-0.7
σ_h [nb]	41.540(37)	41.481(14)	1.6
R_l	20.767(25)	20.736(18)	1.2
A^l_{FB}	0.0171(10)	0.0164(2)	0.7
A_τ	0.1465(33)	0.1480(11)	-0.5
R_b	0.2164(7)	0.2156(1)	1.2
R_c	0.172(3)	0.1723(1)	-0.1
A^b_{FB}	0.0997(16)	0.1038(8)	-2.6
A^c_{FB}	0.0706(35)	0.0742(6)	-1.0
s^2_l (Q_{FB})	0.2324(12)	0.2314(1)	0.8
s^2_l (A_{LR})	*0.2310(3)*	*0.2314(1)*	-1.6
A_b	0.925(20)	0.9348(1)	-0.5
A_c	0.670(26)	0.6683(5)	0.1
m_W [GeV]	80.426(34)	80.391(20)	1.0
m_t [GeV]	178.0(4.3)	177.5(3.9)	0.1
M_{BEH} [GeV]		103^{+54}_{-39}	
$\hat{\alpha}_s$		0.1183(27)	
$\bar{\alpha}^{-1}$	128.936(49)	128.924(48)	0.2
χ^2/n_{dof}		16.7/12	

should be lighter than 200 GeV. This prediction originates from the electroweak radiative corrections, which in first approximation look like:

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

where $s \equiv \sin\theta$, θ is the electroweak mixing angle, while the definitions of functions V_i are given in [1]. It is evident that introducing heavy fermionic generations will 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_{BEH} should become larger. Indeed, it was noted in paper [2] that a 500 GeV scalar does not contradict electroweak precision data if accompanied by a fourth generation. In paper [3], the five-dimensional parameter space of the model with a fourth generation $(M_{BEH}, m_U, m_D, m_E, m_N)$ was investigated and the values of new quark and lepton masses which allow for a heavy scalar were obtained.

In the present paper we investigate how the BEH-scalar decay branching ratios change when new generations are added to the Standard Model. Let us first determine how many new generations can be added. New quarks contributions to the radiative corrections depend mainly on the difference of the masses of up and down quarks. Concerning leptons the difference of masses of neutral and charged isodoublet members matters as well, however anew aspect emerges: the χ^2 diminishes rapidly when the new neutral lepton mass approaches one half of the Z-boson mass, $m_N \approx 50$ GeV.

To perform our fit we take initially a "typical value" $M_{BEH} = 600$ GeV, $m_U + m_D = 450$ GeV and $m_E = 200$ GeV and allow $m_U - m_D$ and m_N to vary. If N_g is the number of extra

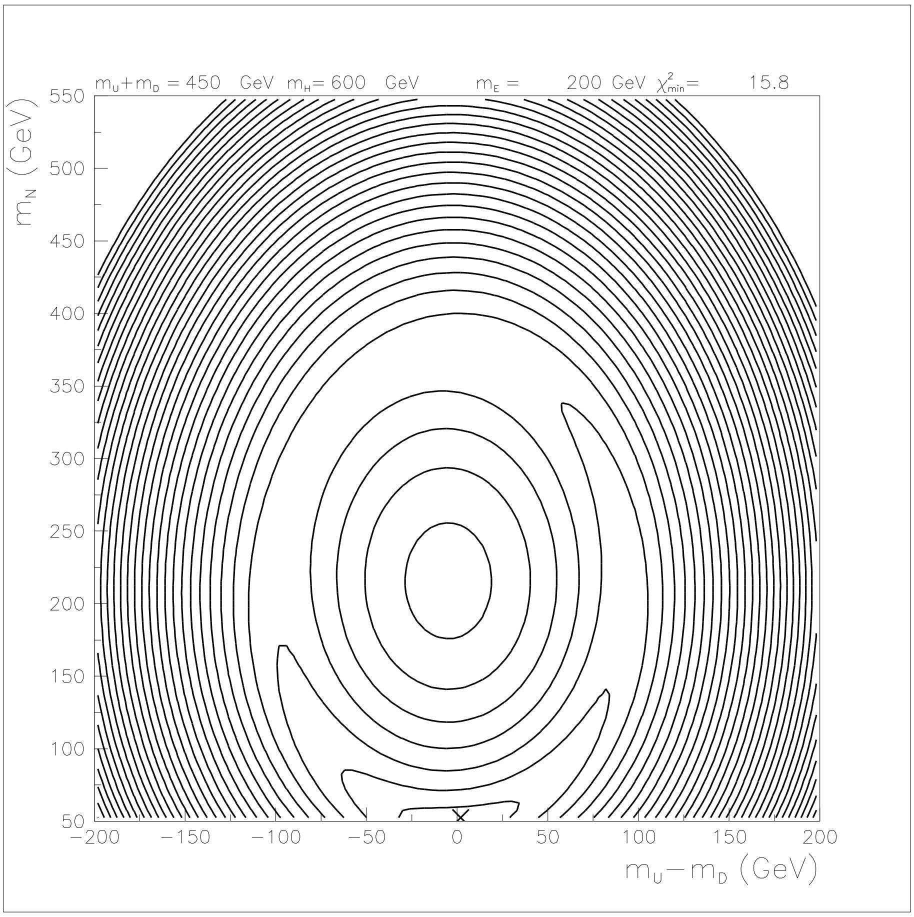

Figure 1: Exclusion plot for one extra generation.

generations, for $N_g = 1$, we obtain the exclusion plot 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:

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

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

In Fig. 2 the exclusion plot is given for $N_g = 2$. 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 a multiplication of the number of fitted parameters. While we have not exhausted the full parameter space, some other attempts did not give more encouraging results. 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., but the quality of fit worsens considerably:

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

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

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

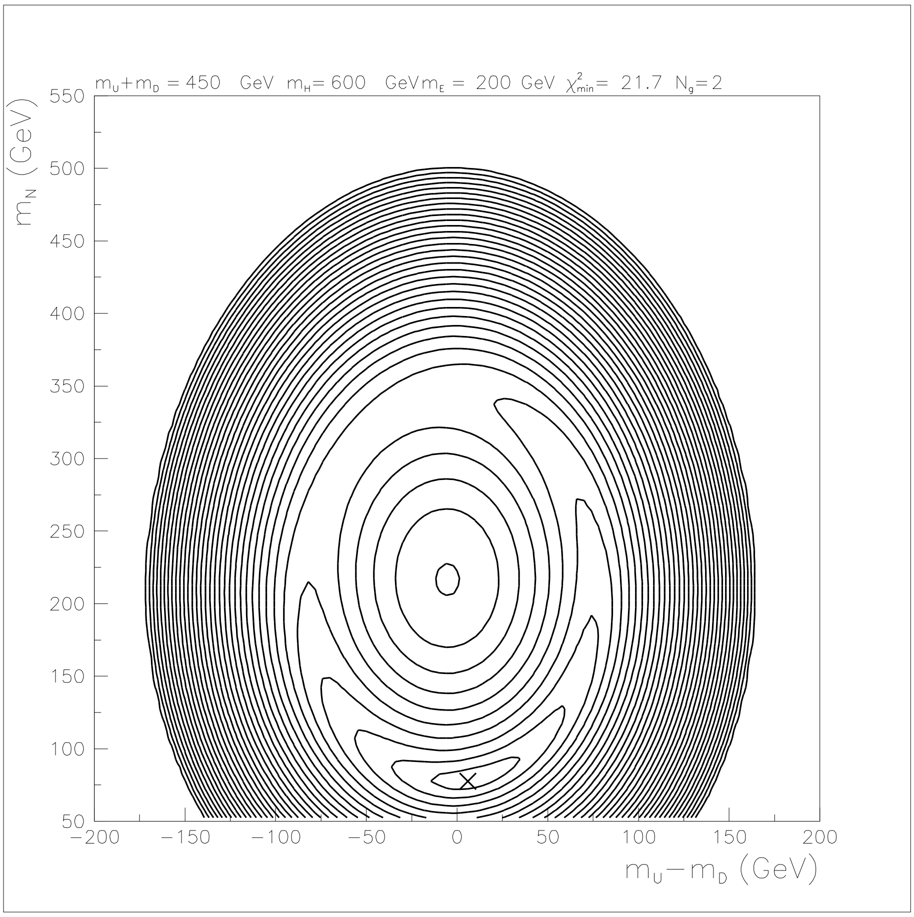

Figure 2: Exclusion plot for two extra generations.

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

So, not more than two extra fermionic generations (at least with the mass pattern considered) are allowed by current precision data.

The BEH scalar boson widths to pairs of intermediate vector bosons are given by the following formulas:

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

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

and they rapidly increase when the scalar particle becomes heavier.

The decay widths to fermion pairs read:

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

where $N_c = 1$ for lepton, $N_c = 3$ for quarks and η is the scalar boson expectation value. In case of BEH decay to quark-antiquark pair QCD running of quark mass takes into

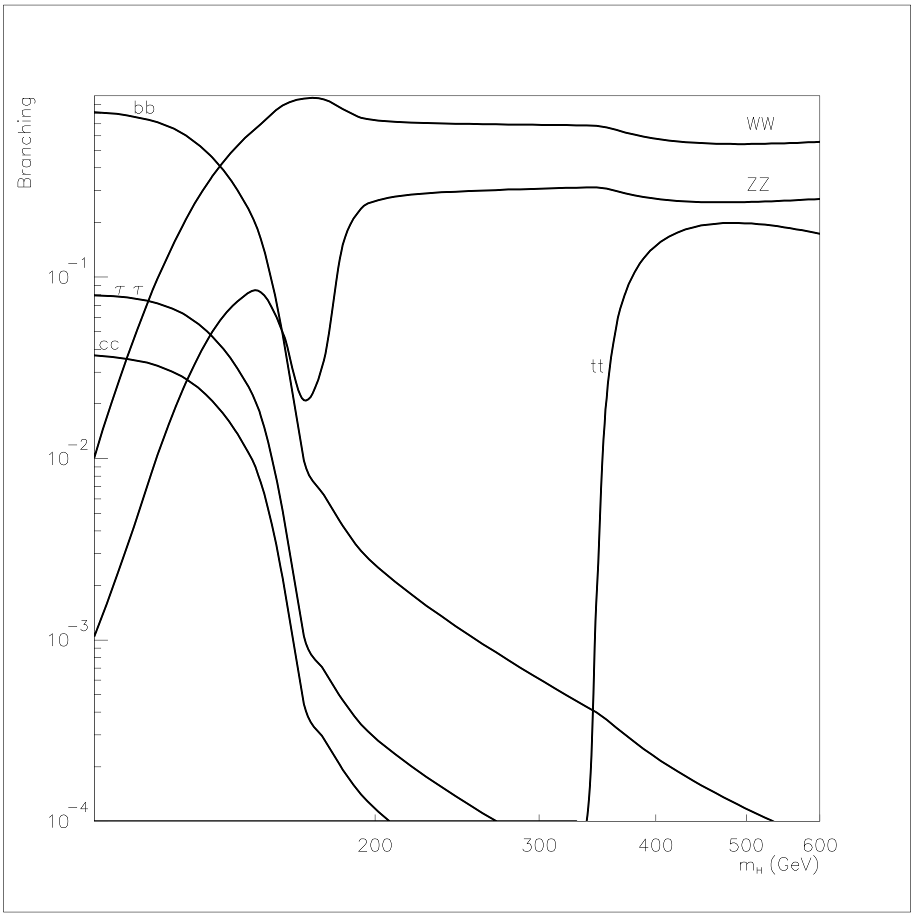

Figure 3: Branching ratios for scalar boson decays in Standard Model.

account leading gluonic corrections to $BEH - q\bar{q}$ vertex. An extra factor $1 - \frac{4m_f^2}{M_{BEH}^2} = v_f^2$ (v_f is the fermion velocity) is due to the fact that Dirac fermions are produced in P-wave when a scalar particle decays. In order to compare the width of fermionic decays to the width of the vector bosons channel, it is convenient to present eq.(9) in the following way:

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

As long as the BEH boson decays to the pair of vector bosons is kinematically forbidden ($M_{BEH} < 160$ GeV), fermionic decays dominate. In the case of the 3-generations Standard Model it is the decay to $b\bar{b}$ pair, see [4]. The BEH branchings in the Standard Model, calculated using HDECAY program [5] are shown on Fig.3. If extra generations are present and if the decay to the pair of heavy neutral leptons is kinematically allowed, then it dominates [6]. It can be seen on the Fig.4 for the case $m_N = 53$ GeV, $m_E = 200$ GeV, $m_U = m_D = 225$ GeV (calculated with modified version of HDECAY). The possibility of observing such an "invisible" BEH boson decay at the LHC was discussed in a recent paper [7].

In the opposite case of very heavy BEH boson, $M_{BEH} = 600$ GeV, the vector boson decay channel dominates in the strict Standard Model. Let us investigate if decays to new fermions can considerably diminish this branching ratio. Let us adjust the mass of

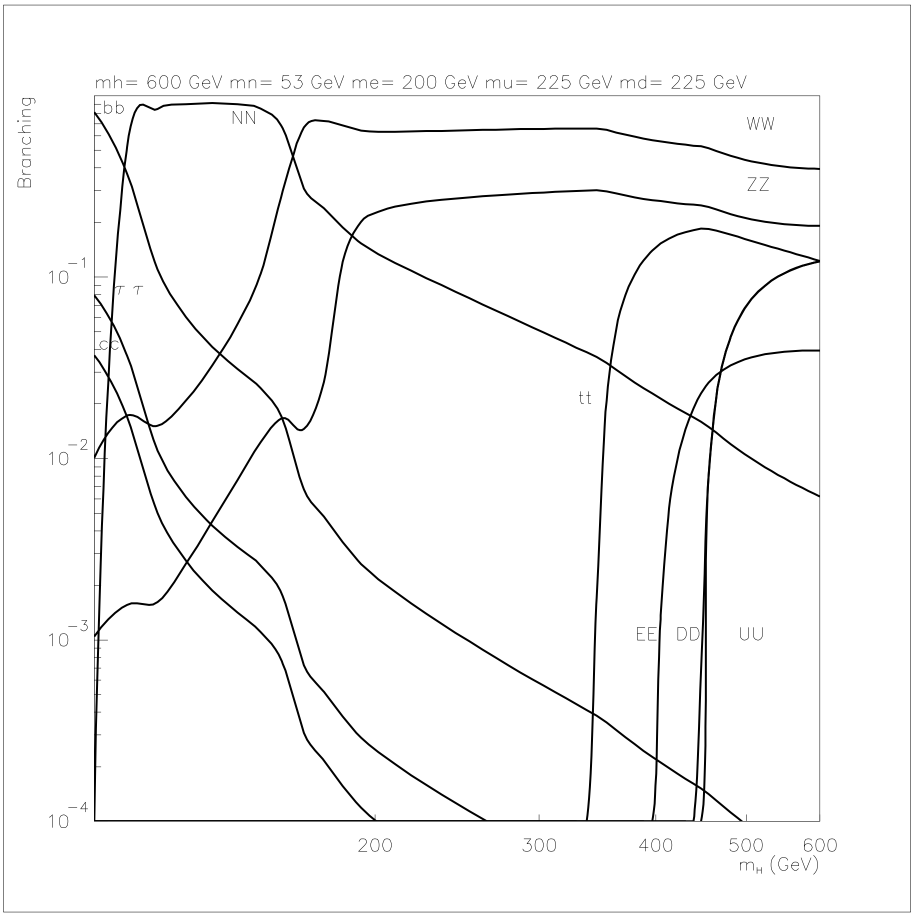

Figure 4: Branching ratios for scalar boson decays in case of one extra generation.

fermions in such a way that the BEH boson width to this channel becomes maximal. According to eq.(10) this happens for $m_f^2 = M_{BEH}^2/10$:

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

and for one extra degenerate fermion generation the sum over all// fermionic modes gives[1]:

$$\Gamma_{BEH \to \text{new degenerate fermions}} = 0.09 \cdot 8 \frac{\alpha M_{BEH}^3}{16 s^2 M_W^2} \quad . \tag{12}$$

Finally, the BEH boson decay to the pair $t\bar{t}$ should also be included :

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

In order to calculate BEH boson width eq.(7 - 9) were used, $\alpha/(s^2 M_W^2) = \alpha/((sc)^2 M_Z^2) = (\pi\eta^2)^{-1}$ were substituted in eq.(7 - 8), $m_f = 190$ GeV were taken in eq.(9) and numerical value $\eta = 246$ GeV was substituted.

[1]It follows from the first part of the paper that in order to allow a heavy BEH boson, masses in fermion isodoublets should be split. We take however degenerate doublets here for a quick estimation in order to diminish the parameter space; it is clear that the pattern of heavy BEH boson decays will not alter drastically if the splitting is taken into account.

For the case $M_{BEH} = 600$ GeV we obtain:

$\Gamma_{\text{new degenerate fermions}}$	Γ_{WW}	Γ_{ZZ}	Γ_{tt}	Γ_{BEH}
57	64	32	21	175

All widths are in GeV. In case of decays to quark pairs one and two loop QCD corrections which enhance width by approximately 20% are taken into account [8].

The doubling of the BEH boson width which occur in case of 2 extra generations would lead to four times less events of BEH boson decay to "golden mode" $BEH \to ZZ$ around the cross-section maximum:

$$\sigma_{pp\to BEH\to ZZ} \sim \frac{\Gamma_{BEH\to ZZ}\Gamma_{BEH\to gg}}{(E - M_{BEH})^2 + \Gamma^2_{BEH}/4} \quad . \tag{14}$$

However since the $gg \to BEH$ fusion proceeds through quark triangles, new quarks enhance it [9]. In the Standard Model the triangle with top quark dominates; as far as masses of new quarks are close to that of top, the 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), hence , the production cross section is about 25 times that of the Standard Model.

We have thus seen that the noncoherent effect of heavy BEH boson($M_{BEH} \sim 500-600$ GeV) decay to new quarks diminishes slightly the effect of coherent enhancement of BEH bosons production in gluon fusion. However, relatively light scalars ($M_{BEH} < 200$ GeV) would be much more severely affected by the now-predominant decay channel into a pair of neutral leptons, possibly making such a BEH invisible. Consequences of the additional fermion families on the BEH boson production at Tevatron and LHC was discussed in some details in [10].

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