PITHA 94/39

October 1994

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Supersymmetric Weinberg-Salam Model
Broken At High Scale.**

N.V. Krasnikov

G. Kreyerhoff

R. Rodenberg

III. Physikalisches Institut der Technischen Hochschule
Aachen

D-52056 Aachen, Germany

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PHYSIKALISCHE INSTITUTE
RWTH AACHEN
Sommerfeldstr.
52056 AACHEN, GERMANY

The Higgs boson mass in supersymmetric Weinberg-Salam model
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N.V.Krasnikov,

Institute for Nuclear Research Russian Academy of Sciences,
Moscow 117312

G.Kreyerhoff and R.Rodenberg

RWTH Aachen, III.Physikalisches Institut, Technische Hochschules
Aachen, Abteilung fur Theoretische Elementarteilchenphysik
D-5100 Aachen, Germany

Abstract

We study the dependence of the Higgs boson mass on
the scale of supersymmetry breaking in the minimal supersymmetric
extension of the standard Weinberg-Salam model.

At present one of the most urgent problems in high energy physics is the search for the top quark and the Higgs boson. Recently the CDF collaboration presented evidence for the top quark production in $\bar{p}p$ collisions [1]. The authors of ref.[1] estimated the top quark mass to be

$m_t = 174 \pm 10^{+13}_{-12}$ Gev. An analysis of radiative corrections at LEP1 leads to the similar mass for the top quark mass [2]

$m_t = 164^{+13}_{-14} + \frac{18}{19}(m_h)$ Gev. At present the lower LEP1 bound for the Higgs boson mass is $m_h > 63.8$ Gev [2]. In standard Weinberg-Salam model there are several theoretical bounds on the Higgs boson mass:

1. Tree level unitarity requirement leads to $m_h \leq 1$ Tev [3].
2. The requirement of the absence of the Landau pole singularity for the effective Higgs selfcoupling constant up to 10^{14} Gev gives $m_h \leq 200$ Gev for $m_t \leq 200$ Gev [4].
3. The vacuum stability requirement leads to the lower bound on the Higgs boson mass which depends on the top quark mass [5].

The minimal supersymmetric extension of the standard model [6] predicts at tree level that the lightest Higgs has to be lighter than the Z-boson [6]. Recent analysis of the radiative corrections [7] shows that it is possible to increase the value of the Higgs boson mass up to 130 Gev for $m_t = 180$ Gev and for the scale of supersymmetry breaking $M_s = 1$ Tev.

In this paper we study the dependence of the Higgs boson mass on the scale of supersymmetry breaking M_s in the minimal

supersymmetric extension of the standard Weinberg-Salam model. The allowed Higgs boson mass region depends on the value of the top quark mass and on the value of the scale of the supersymmetry breaking M_s . It appears that the dependence of the allowed Higgs boson mass interval on the scale of supersymmetry breaking M_s is rather weak. For instance, for $M_s \gg 10^4$ Tev and for $m_t(m_t) = 150$ Gev we find that $100 \text{ Gev} \leq m_h \leq 120 \text{ Gev}$.

So our main assumption is that the standard Weinberg-Salam model originates from its minimal supersymmetric extension which is explicitly broken due to soft supersymmetry breaking terms at scale M_s . The tree level Higgs potential in the minimal supersymmetric Weinberg-Salam model with general soft supersymmetry breaking terms is given by [6]

$$V(H_1, H_2) = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + m_3^2 (H_1^\dagger i\tau_2 H_2 + \text{h.c.}) + (g_1^2 + g_2^2) (H_1^\dagger H_1 - H_2^\dagger H_2)^2/8 + g_2^2 |H_1^\dagger H_2|^2/2 \quad (1)$$

Here g_1 and g_2 are the U(1) and SU(2) gauge coupling constants and the Higgs doublets H_1 and H_2 couples with $q = 1/3$ and $q = 2/3$ quarks respectively. We assume that one of the combinations of the H_1 and H_2

$$H_{\text{light}} = H_2 \cos(\varphi) + i\tau_2 H_1^\dagger \sin(\varphi) \quad (2)$$

is relatively light, $m_{\text{light}} \approx O(m_Z)$, whereas the other orthogonal combination

$$H_{\text{heavy}} = -H_2 \sin(\varphi) + i\tau_2 H_1^\dagger \cos(\varphi) \quad (3)$$

acquires a mass $m_{\text{heavy}} \approx O(M_s)$. We also assume that the masses of the superpartners of ordinary particles are of the order of

$O(M_S)$. It is clear that in our scenario for $M_S > O(1)$ TeV it is necessary to have fine tuning among the soft supersymmetry breaking terms however at present we don't have any idea how to realize fine tuning in a natural way.

At scales lower than the supersymmetry breaking scale M_S we have the standard Weinberg-Salam model with the single light Higgs isodoublet $H \equiv H_{\text{light}}$. The crucial point is that from the explicit formula for the effective potential (1) we find that the selfinteraction effective coupling constant λ for the light Higgs doublet H at scale M_S is

$$0 < \bar{\lambda}(M_S) = (\bar{g}_1^2(M_S) + \bar{g}_2^2(M_S)) (\cos(2\varphi))^2/4 < (\bar{g}_1^2(M_S) + \bar{g}_2^2(M_S))/4 \quad (4)$$

So the assumption that standard Weinberg-Salam model originates from its supersymmetric extension with the supersymmetry broken at scale M_S allows us to obtain nontrivial information about the low energy effective Higgs selfcoupling constant in the effective potential $V = m^2 H^\dagger H + \lambda (H^\dagger H)^2/2$ and hence to obtain nontrivial information about the Higgs boson mass. To relate the high energy value (4) of $\bar{\lambda}(M_S)$ with the low energy value of $\bar{\lambda}(m_Z)$ we use the renormalization group equations which at one loop read

$$\begin{aligned} d\bar{g}_3/dt &= -7\bar{g}_3^3, \\ d\bar{g}_2/dt &= -(19/6)\bar{g}_2^3, \\ d\bar{g}_1/dt &= (41/6)\bar{g}_1^3, \\ d\bar{h}_t/dt &= (9\bar{h}_t^2/2 - 8\bar{g}_3^2 - 9\bar{g}_2^2/4 - 17\bar{g}_1^2/12)\bar{h}_t, \\ d\bar{\lambda}/dt &= 12(\bar{\lambda}^2 + (\bar{h}_t^2 - \bar{g}_1^2/4 - 3\bar{g}_2^2/4)\bar{\lambda} - \bar{h}_t^4 + \bar{g}_1^4/16 + \bar{g}_1^2\bar{g}_2^2/8 + \end{aligned}$$

$$3\bar{g}_2^4/16) ,$$

$$t = (1/16\pi^2)\ln(\mu/m_Z)$$

Here $\bar{g}_3$, $\bar{g}_2$ and $\bar{g}_1$ are the SU(3), SU(2) and U(1) gauge coupling constants, respectively, and $\bar{h}_t$ is the top quark Yukawa coupling constant. In our analysis we neglected all Yukawa coupling constants except top quark coupling constant. We use the following values for the gauge coupling constants at electroweak scale [8]

$$\bar{\alpha}_3(m_Z) = 0.120 \pm 0.01$$

$$\bar{\alpha}_{em}(m_Z) = 127.9 \pm 0.2$$

$$\sin^2\theta_W(m_Z) = 0.2327 \pm 0.0008$$

These value correspond to electroweak gauge couplings of

$$\bar{\alpha}_1^{-1}(m_Z) = 58.89 \pm 0.11$$

$$\bar{\alpha}_2^{-1}(m_Z) = 29.75 \pm 0.11$$

In our numerical analysis we took the central values for $\bar{\alpha}_1(m_Z)$ and $\bar{\alpha}_2(m_Z)$ since the uncertainty in the determination of $\bar{\alpha}_1(m_Z)$ and $\bar{\alpha}_2(m_Z)$ practically does not change the allowed regions for the Higgs boson mass. The results of our numerical analysis for different values of top quark mass are summarized in figs.1- 9. The curve 1 corresponds to the initial value $\bar{\lambda}(M_s) = +\infty$ and it is the upper bound on the Higgs boson mass which comes from the requirement of the absence of the Landau pole singularity for the Higgs selfcoupling constant $\bar{\lambda}$ up to scale M_s . The curve 2 corresponds to the boundary condition $\bar{\lambda}(M_s) = (\bar{g}_1^2(M_s) + \bar{g}_2^2(M_s))/4$ and it is the upper bound on the Higgs boson mass provided the standard Weinberg-Salam model originates from the

minimal supersymmetric Weinberg-Salam model. The curve 3 corresponds to the boundary condition $\bar{\lambda}(M_s) = 0$ and it is lower bound on the Higgs boson mass. So the allowable values of the Higgs boson mass lie between the curves 2 and 3. Note that solid curves 2 and 3 correspond to the initial value $\bar{\alpha}_3(m_Z) = 0.120$ and the curves 2a(b), 3a(b) to the initial values $\bar{\alpha}_3(M_s) = 0.110(0.130)$. The curve 3 coincides with the vacuum stability bound which comes from the requirement that $\lambda(\mu) > 0$ for $\mu \leq M_s$. For $M_s \approx 10^4$ Tev the allowed values for the Higgs boson mass practically don't depend on the value of supersymmetry breaking scale M_s . We used the current top quark mass definition $m_t(m_t) = \bar{h}_t(m_t)\langle H \rangle$ ($\langle H \rangle = 174$ Gev). The relation between the pole top quark mass and the current top quark mass is [9]

$$m_t^{\text{pole}} = (1 + 4\alpha_3(m_t)/3\pi)m_t(m_t) \approx 1.05 m_t(m_t)$$

It should be noted that in nonminimal supersymmetric electroweak models, say in the model with additional gauge singlet supermultiplet σ we have due to the $k\sigma H_1 i\tau_2 H_2$ term in the superpotential an additional term $k^2 |H_1 i\tau_2 H_2|^2$ in the potential and as a consequence our boundary condition for the Higgs selfcoupling constant $\bar{\lambda}$ has to be modified, namely

$$\bar{\lambda}(M_s) = (1/4)(\bar{g}_1^2(M_s) + \bar{g}_2^2(M_s))\cos^2(2\varphi) + \bar{k}^2(M_s)\sin^2(2\varphi)/2 > 0 \quad (5)$$

The boundary condition (5) depends on unknown coupling constant $\bar{k}^2(M_s)$, so in general the allowed Higgs boson mass interval is between curves 1 and 3. It is very important to stress that

for all nonminimal supersymmetric models broken to standard Weinberg-Salam model at scale M_s the effective Higgs selfcoupling constant $\bar{\lambda}(M_s)$ is nonnegative that is direct consequence of the nonnegativity of the effective potential in supersymmetric models. So the curve 3 describes the lower bound on the Higgs boson mass in general case. The single condition is that the supersymmetry is broken at scale M_s and at lower scales we have standard Weinberg-Salam model with the single Higgs isodoublet.

To conclude, we have found the allowed regions for the Higgs boson mass in standard Weinberg-Salam model in the assumption that it originates from the minimal supersymmetric model with the supersymmetry broken at some scale M_s . The allowed Higgs boson mass region is between curves 2 and 3. In arbitrary case when standard Weinberg-Salam model originates from arbitrary supersymmetric model with the supersymmetry broken at scale M_s the allowed Higgs boson mass region is between curves 1 and 3.

One of us (N.V.K.) is indebted to the collaborators of the Physikalisches Institut of Aachen for the warm hospitality during his stay at Aachen where this work has been started. His work was partially supported by the Russian Scientific Foundation, Grant 94-02-04474-a. Last not least we thank the German Research Foundation (DFG) for financial support which made our collaboration possible.

Figures Caption

Figures 1-9: Allowed regions for the Higgs boson mass for different values of the current top quark mass $m_t(m_t) = h_t(m_t)\langle H \rangle$. Solid curve 1 describes the upper bound obtained from the requirement of the absence of Landau pole singularity for $\bar{\lambda}(\mu)$ up to scale M_s . Solid curve 2 describes the upper bound on the Higgs boson mass which corresponds to the boundary condition $\bar{\lambda}(M_s) = (\bar{g}_1^2(M_s) + \bar{g}_2^2(M_s))/4$ and $\alpha_3(m_Z) = 0.120$. Solid curve 3 describes the lower bound on the Higgs boson mass and it corresponds to the boundary condition $\bar{\lambda}(M_s) = 0$ and $\alpha_3(M_s) = 0.120$. Curves 2a, 3a and 2b, 3b correspond to $\alpha_3(M_s) = 0.130$ and $\alpha_3(M_s) = 0.110$.

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Fig. 1

$$X = \log \left(\frac{M_s}{1 \text{ TeV}} \right)$$

Fig. 2

$$X = \log \left(\frac{M_s}{1 \text{ TeV}} \right)$$

Fig. 3

topmass = 150 GeV

$$X = \log \left(\frac{M_s}{1 \text{ TeV}} \right)$$

Fig. 4

$$X = \log \left(\frac{M_s}{1 \text{ TeV}} \right)$$

Fig. 5

topmass=170 GeV

$$X = \log \left(\frac{M_s}{1 \text{ TeV}} \right)$$

Fig. 6

$$X = \log \left(\frac{M_s}{1 \text{ TeV}} \right)$$

Fig. 7

$$X = \log \left(\frac{M_s}{1 \text{ TeV}} \right)$$

Fig. 8

$$X = \log \left(\frac{M_s}{1 \text{ TeV}} \right)$$

Fig. 9

topmass=220 GeV

$$X = \log \left(\frac{M_s}{1 \text{ TeV}} \right)$$