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Are supersymmetric models with minimal particle content under tension for testing at LHC?

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ABSTRACT

In supersymmetric models with minimal particle content and without large left-right squarks mixing, the conventional knowledge is that the Higgs Boson mass around 125 GeV leads to top squark masses $\mathcal{O}(10)$ TeV, far beyond the reach of colliders. Here, we pointed out that this conclusion is subject to several theoretical uncertainties. We find that electroweak symmetry breaking and evaluation of Higgs mass at a scale far away from the true electroweak symmetry breaking scale introduce a large uncertainty in Higgs mass calculation. We show that the electroweak symmetry breaking at the scale near the true vacuum expectation value of Higgs field can increase the Higgs Boson mass about 4–5 GeV and can lower the bounds on squarks and slepton masses to 1 TeV. Here we pointed out that the Higgs mass even with inclusion of radiative corrections can vary with electroweak symmetry breaking scale. We calculate it at two loop level and show that it varies substantially. We argue that Higgs mass like other coupling parameters can vary with energy scale and the Higgs potential with all orders loop corrections is scale invariant. This uncertainty to the Higgs mass calculation due to electroweak symmetry breaking around the supersymmetry breaking scale, normally taken as $\sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$, to minimize the 1-loop radiative corrections can be removed if one considers all significant radiative contributions to make Higgs potential renormalization group evolution scale invariant and evaluates electroweak symmetry breaking at the scale near the electroweak symmetry breaking scale. A large parameter space becomes allowed when one considers electroweak symmetry breaking at its true scale not only for producing correct values of the Higgs masses, but also for providing successful breaking of this symmetry in more parameter spaces.

1. Introduction

The discovery of Higgs Boson at ATLAS [1] and CMS [2] leads to Higgs mass (m_h) calculation an important subject of impressive precision studies. In supersymmetric models with minimal particle content the tree level Higgs mass can not be larger than $m_Z \simeq 91$ GeV. The large radiative corrections which are function of masses and couplings of supersymmetric theories have direct implications on the discovery prospects of supersymmetry at colliders. But, there are many theoretical uncertainties in m_h calculation and it needs to improve them for definite conclusion for the discovery prospect of supersymmetry at LHC. In this paper, we first pointed out that electroweak symmetry breaking (EWSB) and calculation of m_h at the renormalization group evolution (RGE) scale far away from the EWSB scale (which might be close to the vacuum expectation value (VEV) of Higgs field (v_{weak})) introduce a large uncertainty in m_h calculation.

We show significant increase in the mass of the CP-even neutral Higgs Boson m_h if one evaluates EWSB and calculates m_h at $Q_{\mathrm{EW}} \sim v_{\mathrm{weak}}$ instead of $Q_{\mathrm{EW}} = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$. This leads to a dramatic change in the allowed parameter space in supersymmetric models.

The EWSB is considered at $Q_{\mathrm{EW}} = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$ in all spectrum generator packages available in literature [4–8] and also in finding post-LHC constraints [3]. This technique to evaluate EWSB at RGE scale other than the true EWSB scale is used to make radiative corrections negligible compared to the tree level Higgs potential. In these studies, m_h is also calculated at $Q_{\mathrm{EW}} = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$. It has been shown in [9] that the RGE scale dependence of the Higgs potential becomes negligible if one adds the dominant two loop corrections $\mathcal{O}(\alpha_t\alpha_s + \alpha_t^2)$ to the Higgs potential and it enables one to calculate EWSB and Higgs masses at any scale other than the scale where the 1-loop corrections to the Higgs potential is negligible.

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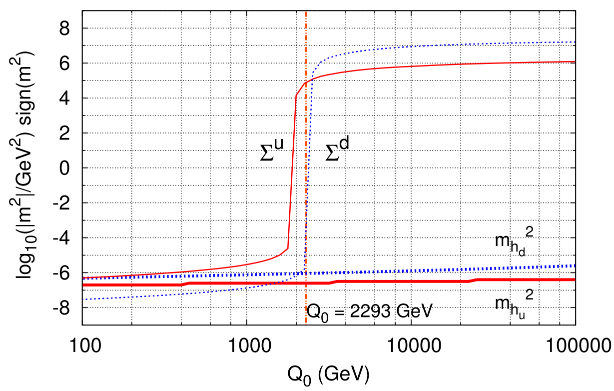

Fig. 1. The variations of $m^2_{h_{u,d}}$ and $\Sigma^{u,d}$ with electroweak symmetry breaking scale $Q_{\rm EW}$ for a typical set of mSUGRA input parameters $m_0 = 600, m_{1/2} = 1500, A_0 = -1700, \tan\beta = 40, sign(\mu) = +1$.

2. Radiative corrections to EWSB

The tree level scalar potential keeping only the dependence on the neutral Higgs fields:

$$V_0 = \left(m^2_{H_u} + \mu^2\right) | H^0_u |^2 + \left(m^2_{H_d} + \mu^2\right) | H^0_d |^2 + m_3{}^2(H^0_u H^0_d + h.c.) + \frac{g^2 + g'^2}{8}(| H^0_u |^2 - | H^0_d |^2)^2. \quad (1)$$

Here, both the tree level potential V_0 and its parameters are strongly RGE scale dependent. However, in principle, if we include loop corrections at all orders, the effective potential $V_{\rm eff} = V_0 + \Delta V$ should be RGE scale independent. From the minimization criteria one can find

$$\mu^2 = -\frac{m_Z^2}{2} + \frac{m^2_{H_d} + \Sigma_d - (m^2_{H_u} + \Sigma_u)\tan^2\beta}{\tan^2\beta - 1}, \quad (2)$$

$$m_3^2 = -\frac{1}{2}\sin 2\beta \left(m^2_{H_d} + m^2_{H_u} + 2\mu^2 + \Sigma_d + \Sigma_u\right) \quad (3)$$

where,

$$\Sigma_a = \frac{1}{2v_a}\frac{\partial \Delta V}{\partial v_a}. \quad (4)$$

For simplicity, ΔV is not calculated separately, but one directly evaluates Σ_a. The checking of convergence of the $V_{\rm eff}$ is not done through evaluation of ΔV, but through the invariance of the value of μ with respect to EWSB scale $Q_{\rm EW}$. It ensures that perturbation series for $V_{\rm eff}$ converges at all RGE scales. The one loop corrections ΔV_1 in Landau gauge is given by [10]:

$$\Delta V_1 = \frac{1}{64\pi^2} STrM^4\left[\ln(M^2/Q^2) - 3/2\right] \quad (5)$$

The dominant contribution that comes from stop quarks is given by:

$$\Sigma_u(\tilde{t}_i) \sim \frac{3y_t^2}{16\pi^2} m^2_{\tilde{t}_i} ln(m^2_{\tilde{t}_i}/Q^2) \quad (6)$$

The loop corrections are very significant, without which the evaluation of parameters from minimization of the tree level potential may give even wrong results [11]. These radiative corrections depend strongly on the RGE scale Q and the 1-loop contributions normally become negligible at $Q = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$.

The minima of effective Higgs potential $V_{\rm eff}$ is strongly RGE scale dependent even with complete 1-loop corrections [12]. But, the addition of 2-loop corrections shows RGE scale invariance of the minima of the potential $V_{\rm eff}$ and the parameters obtained from this minimization criteria (μ and m_3^2) are RGE scale invariant [12]. The RGE scale dependence of $V_{\rm eff}$ is shown in terms of μ (obtained from the minimization of $V_{\rm eff}$) in Fig. 2 at tree level, 1-loop level and 2-loop level. It is seen that the scale dependence is almost completely negligible at 2-loop level.

Here, it should be noted that Σ_a can be large at any scale and may be even comparable with $m^2_{H_{u,d}}$ as it is the derivative of ΔV with respect to v_a. The large values of derivative of ΔV do not mean the violation of convergence of $V_{\rm eff}$. The Higgs mass squared parameters $m^2_{H_u}$ and $m^2_{H_d}$ are also not physically observable. The interaction of the Higgs field with other fields is such that these parameters $m^2_{H_{u,d}}$, $\Sigma_{u,d}$ can change rapidly with RGE scale by a few orders of magnitude from high positive to high negative value from GUT scale to weak scale (e.g., $+10^8$ GeV to -10^8 GeV for a typical set of input parameters). This is shown in Fig. 1.

3. EWSB scale and evaluation of Higgs mass

The Standard Model [13] identifies weak scale $Q_{\rm EW} = (\sqrt{2\sqrt{2}G_F})^{-1} = 175$ GeV with the VEV of a fundamental, isodoublet, "Higgs" scalar field. The minimization of the Higgs potential gives VEVs of the neutral part of the Higgs fields. In MSSM, EWSB fixes μ^2 and m_3^2 as the VEV $v_{weak} = \sqrt{\langle H^0_u\rangle^2 + \langle H^0_d\rangle^2}$ is already fixed from Standard Model predictions.

The scale of supersymmetry breaking $Q_{\rm SB} \sim m_{\tilde{S}}$ (the masses of sparticles) and the scale of EWSB minima $Q_{\rm EW}$ originate from breaking of two completely separate symmetries and the physics at these two scales are completely different.

If $m_{\tilde{S}} \sim$ a few hundred GeV, then the running of parameters up to $Q = v_{weak}$ is negligible and one can use $Q_{\rm SB}$ as the weak scale. But, if $m_{\tilde{S}} \sim$ TeV, one cannot neglect the running of the parameters (particularly, $m^2_{H_u}$ and $m^2_{H_d}$) and the approximation of using $Q_{\rm SB}$ as $Q_{\rm EW}$ does not work. The value of m_h is increased significantly when one evaluates EWSB at $Q_{\rm EW} \approx v_{weak}$ (see Fig. 2). On the other-hand, if one considers EWSB scale $Q_{\rm EW} \sim$ TeV, EWSB also may not occur for some region of parameter space due to less running of $m^2_{H_d}$ and $m^2_{H_u}$ (EWSB requires μ^2 positive).

In our calculation, we consider program SuSeFLAV-1.2 [5]. It considers full one loop corrections together with two loop leading contributions $\mathcal{O}(\alpha_t\alpha_s + \alpha_t^2)$ to the Higgs mass squared parameters following ref. [9]. We have compared SuSeFLAV-1.2 with softsusy3.4.0 [6] for different sets of input parameters and find no significant change; similar changes in the spectra are observed with the changes in input parameters. For typical sets of mSUGRA [14] input parameters we show in Fig. 2 (left) that the variation

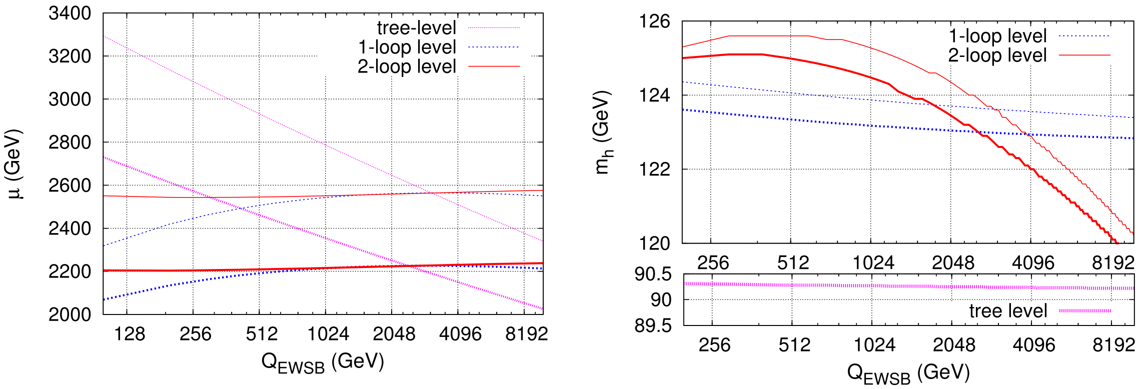

Fig. 2. The variation of μ (left) and m_h (right) with the electroweak symmetry breaking scale $Q_{\rm EW}$ for typical sets of mSUGRA input parameters $(m_0\ ({\rm GeV}), m_{1/2}\ ({\rm GeV}), A_0\ ({\rm GeV}), \tan\beta, sign(\mu)) = (390, 2490, 0, 14.5, 1)$ (thinner lines), and $(390, 1895, -1125, 14.5, 1)$ (thicker lines), respectively. The value of $\sqrt{m_{\tilde t_L} m_{\tilde t_R}}$ are 3817 GeV and 2900 GeV, respectively.

Table 1
The typical values of m_h calculated at $Q_{\rm EW} = \sqrt{m_{\tilde t_L} m_{\tilde t_R}}$ and $Q_{\rm EW} \approx v_{\rm weak} = \sqrt{\langle H_u\rangle^2 + \langle H_d\rangle^2}$ obtained from different program packages for different sets of inputs. The less differences in m_h values between two scales appear for FeynHiggs since the RG running of Yukawa and other couplings are not considered here and they are same at these two scales. The input MSSM parameters are only different at two scales.

Input	$\sqrt{m_{\tilde t_L} m_{\tilde t_R}}$ (GeV)	SuSeFLAV-1.2 m_h (GeV) at		SuSpect 2 m_h (GeV) at		FeynHiggs-2.12.0 m_h (GeV) at	
m_0 (GeV), $m_{1/2}$ (GeV), A_0 (GeV), $\tan\beta$, sign(μ)		$\sqrt{m_{\tilde t_L} m_{\tilde t_R}}$	$v_{\rm weak}$	$\sqrt{m_{\tilde t_L} m_{\tilde t_R}}$	$v_{\rm weak}$	$\sqrt{m_{\tilde t_L} m_{\tilde t_R}}$	$v_{\rm weak}$
390, 2490, 0, 14.5, 1	3817	123.0	125.3	123.8	126.9	124.7	125.2
390, 1895, −1125, 14.5, 1	2900	122.8	125.0	123.5	126.3	125.1	125.4
513, 2321, −1281, 6.2, −1	3507	120.1	124.9	120.9	123.9	121.6	122.4
1956, 592, −4128, 14.3, −1	992	123.0	125.0	123.7	125.4	122.7	123.7

of μ (evaluated at Q_{EW}) with Q_{EW} at tree level, one loop level and two loop level. We find that μ is scale independent at two loop level. In Fig. 2 (right) we show the variation of m_h (evaluated at Q_{EW}) with Q_{EW} at one loop level and two loop level. We find that m_h remains scale dependent.

Here we pointed out that the Higgs mass (not potential) even with inclusion of radiative corrections can vary with electroweak symmetry breaking scale. We calculate it at two loop level and show that it varies substantially. We argue that Higgs mass like other coupling parameters can vary with energy scale.

In Table 1 we compare the values of m_h calculated at the two scales $Q_{\rm EW} = \sqrt{m_{\tilde t_L} m_{\tilde t_R}}$ and $Q_{\rm EW} \approx v_{\rm weak} = \sqrt{\langle H_u\rangle^2 + \langle H_d\rangle^2}$ obtained from SuSeFLAV-1.2 [5], SuSpect 2 [15] and FeynHiggs-2.12.0 [16]. The less differences in m_h values between two scales appear for FeynHiggs since the running of Yukawa and other couplings are not considered here and they are same at these two scales. The MSSM parameters are the input and they are considered to be different at these two scales. The EWSB at $Q_{\rm EW} = v_{\rm weak}$ is not only required for correct masses in the Higgs sector, but also for successful breaking of EW symmetry. The parameter $m^2_{H_u}$ goes to larger negative value as one decreases the RGE scale. This provides successful breaking of electroweak (EW) symmetry by yielding μ^2 positive. As a consequence a large parameter space becomes allowed.

In brief, one can conclude that $V_{\rm eff}$ with complete radiative corrections is RGE scale invariant and the accurate spectra through EWSB can be found by generating them at the true EWSB scale $Q_{\rm EW} \approx \sqrt{\langle H_u\rangle^2 + \langle H_d\rangle^2}$. In generation of spectra through EWSB (masses of the Higgs particles), we run all MSSM parameters up to $Q_{\rm EW}$, and in generation of the masses of sparticles, all MSSM parameters are stored at $Q_{\rm SB}$.

4. The mSUGRA parameter space

We have generated the allowed mSUGRA parameter space for two cases of evaluation of EWSB minima: i) at $Q_{\rm EW} = \sqrt{m_{\tilde t_L} m_{\tilde t_R}}$ (scale considered for finding post-LHC constraint in literature) and ii) $Q_{\rm EW} \approx v_{weak} \approx \sqrt{\langle H_u\rangle^2 + \langle H_d\rangle^2}$ (the true EWSB scale). Here, we consider the only parameter space where one can generate $m_h = 125.5 \pm 0.5$ GeV. No other constraints are considered (neutralino may not be the lightest supersymmetric particle (LSP)). We generate the spectra for the range of $m_0 = 100$–3100 GeV, $m_{1/2} = 100$–3100 GeV, $A_0 = -3m_0$ to $+3m_0$, $\tan\beta = 3$–63 and $sign(\mu) = \pm 1$.

In Fig. 3, it is seen that a dramatically large parameter space in mSUGRA model with almost no absolute bounds on $m_0, m_{1/2}$ and A_0 is allowed when EWSB minima is evaluated at $Q_{\rm EW} \approx v_{weak}$ in contrary with the one when EWSB minima is evaluated at $Q_{\rm EW} = \sqrt{m_{\tilde t_L} m_{\tilde t_R}}$.

The parameter $m^2_{H_u}$ goes to larger negative value as one decreases the RGE scale. This also provides successful breaking of EW symmetry in more parameter spaces producing μ^2 positive and yielding correct masses for Higgs particles. A large parameter space becomes allowed when one considers EWSB at its true scale.

5. Conclusion

In conclusion, we pointed out that electroweak symmetry breaking and calculation of m_h at the scale other than the true vacuum expectation value of Higgs field introduces an uncertainty in Higgs mass calculation. One can remove this uncertainty if one considers all significant radiative contributions to make Higgs potential renormalization group evolution scale invariant and evaluates electroweak symmetry breaking at the true vacuum expec-

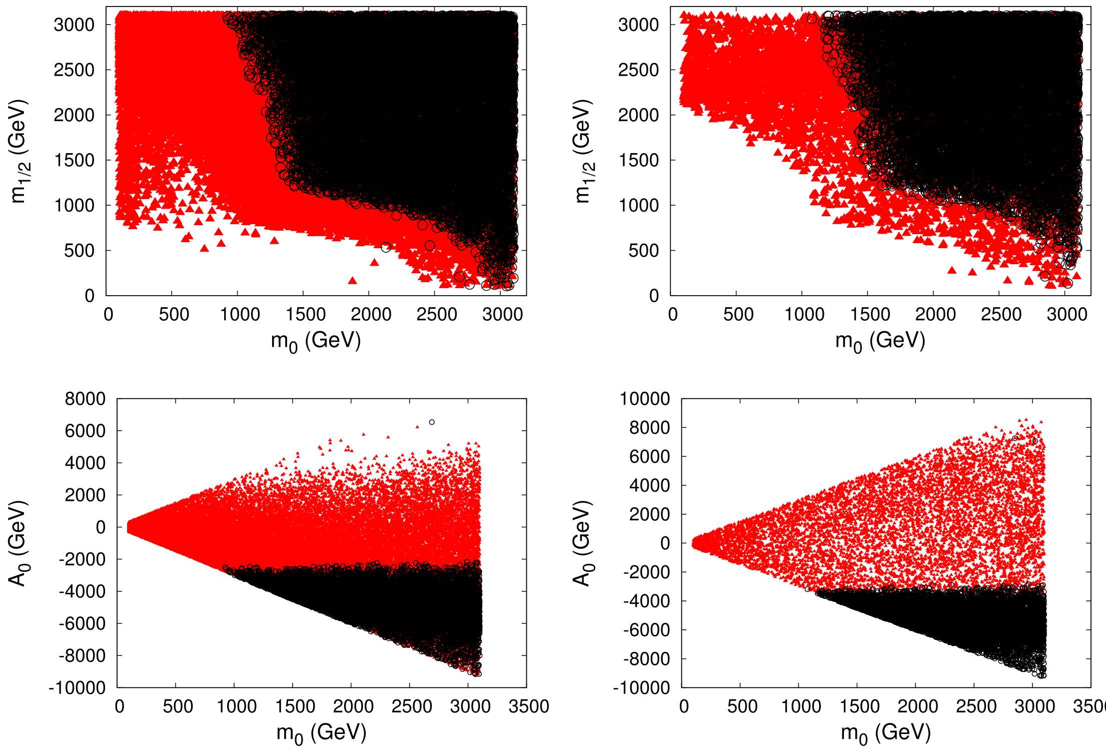

Fig. 3. The allowed parameter space for 125 GeV $< m_h <$ 126 GeV in $m_0 - m_{1/2}$, $m_0 - A_0$ planes for sign(μ) positive (left) and negative (right), respectively. The point represented by triangle (circle) denotes EWSB at $Q_{\rm EW} = v_{\rm weak}$ ($Q_{\rm EW} = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$).

tation value of Higgs field. Then, there will be no strong *absolute* bounds on m_0, $m_{1/2}$ and A_0 in mSUGRA model to produce m_h around 125 GeV. We pointed out that the Higgs mass (not Higgs potential) even with inclusion of radiative corrections can vary with electroweak symmetry breaking scale. We calculate it at two loop level and show that it varies substantially. Finally, we argue that Higgs mass like other coupling parameters can vary with energy scale. A large parameter space becomes allowed when one considers EWSB at its true scale not only for producing correct value of the Higgs mass, but also for providing successful breaking of EW symmetry in more parameter spaces.

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