Higgs Boson Mass Bounds in General SUSY Models

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From Strings to LHC
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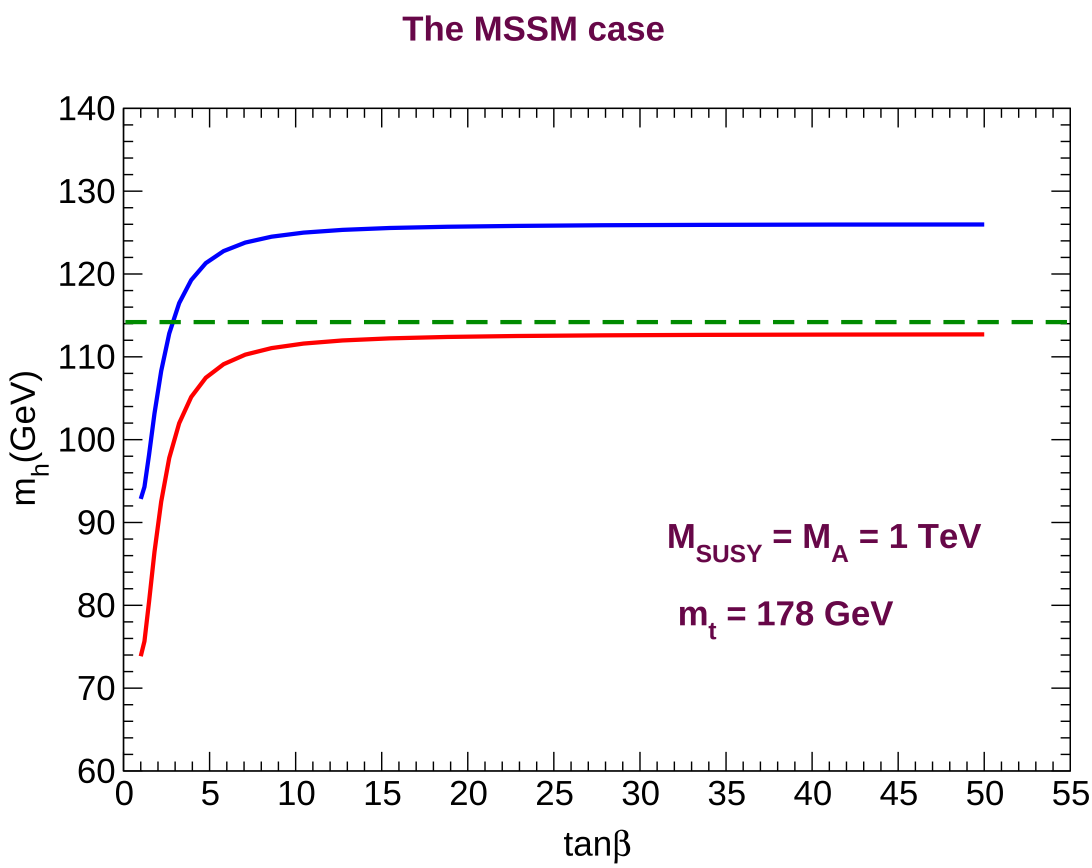
In the MSSM, the lightest CP−even Higgs boson mass is

$$
\begin{aligned}
m_h^2 &\simeq \frac{g^2+g'^2}{2} v^2 \cos^2 2\beta \left(1 - \frac{3}{8\pi^2}\frac{m_t^2}{v^2}\ t\right) \\
&+ \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[t + \frac{1}{2}X_t \right. \\
&+ \left. \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(X_t t + t^2\right)\right]
\end{aligned}
$$

where

$$
t = \log\frac{M_{SUSY}^2}{m_t^2}, \qquad \tilde{A}_t = A_t - \mu \cot\beta
$$

$$
X_t = \frac{2\tilde{A}_t^2}{M_{SUSY}^2}\left(1 - \frac{\tilde{A}_t^2}{12 M_{SUSY}^2}\right)
$$



The MSSM case
140
130
120
110
100
90
80
70
60
0
5
10
15
20
25
30
35
40
45
50
55
m_h(GeV)
tanβ
M_SUSY = M_A = 1 TeV
m_t = 178 GeV

Some attempts to raise the Higgs mass

- **Extend the MSSM Higgs sector with singlets, $SU(2)_W$ triplets, ...**

  J. Espinosa, M. Quiros, Phys. Rev. Lett. (1998)

- **Theories with a low cutoff scale**

  K. Tobe, J.D. Wells, Phys. Rev. D66, 013010 (2002)

- **Extension of the MSSM gauge symmetry**

  P. Batra, A. Delgado, D. E. Kaplan, T.M.P. Tait, JHEP 0402: 043 (2004)

- **"Fat Higgs" model – Higgs boson as composite particle**

  R. Harnik, G.D. Kribs, D.T. Larson, H. Murayama, hep-ph/0311349

- **Introduce vector-like matter at TeV scale**

  K.S. Babu, I. Gogoladze, C. Kolda, hep-ph/0410085

Complete Vectorlike Multiplets

Restriction: maintain gauge coupling unification and perturbativity up to GUT or Planck scale.

New particles should be in SU(5) complete multiplets

- $(\mathbf{5}+\overline{\mathbf{5}})_\mathbf{i}$ and $\mathbf{i}=\mathbf{1},\mathbf{2},\mathbf{3},\mathbf{4}$
- $(\mathbf{10}+\overline{\mathbf{10}})$
- $(\mathbf{5}+\overline{\mathbf{5}})$ and $(\mathbf{10}+\overline{\mathbf{10}})$
- Any number of gauge singlets

$10 + \overline{10}$ of SU(5)

General superpotential for extra vector-like complete multiplets is

$$\mathbf{W = 10 \cdot 10 \cdot 5_H + \overline{10} \cdot 5 \cdot 5_H + 10 \cdot \overline{5} \cdot \overline{5}_H + \overline{10} \cdot \overline{10} \cdot \overline{5}_H}$$

relevant couplings for our calculation are

- $\mathbf{h_1 Q \cdot U^c \cdot H_u} \quad \Longleftarrow \quad \mathbf{10 \cdot 10 \cdot 5_H}$
- $\mathbf{h_2 \overline{Q} \cdot \overline{D^c} \cdot H_u} \quad \Longleftarrow \quad \mathbf{\overline{10} \cdot 5 \cdot 5_H}$

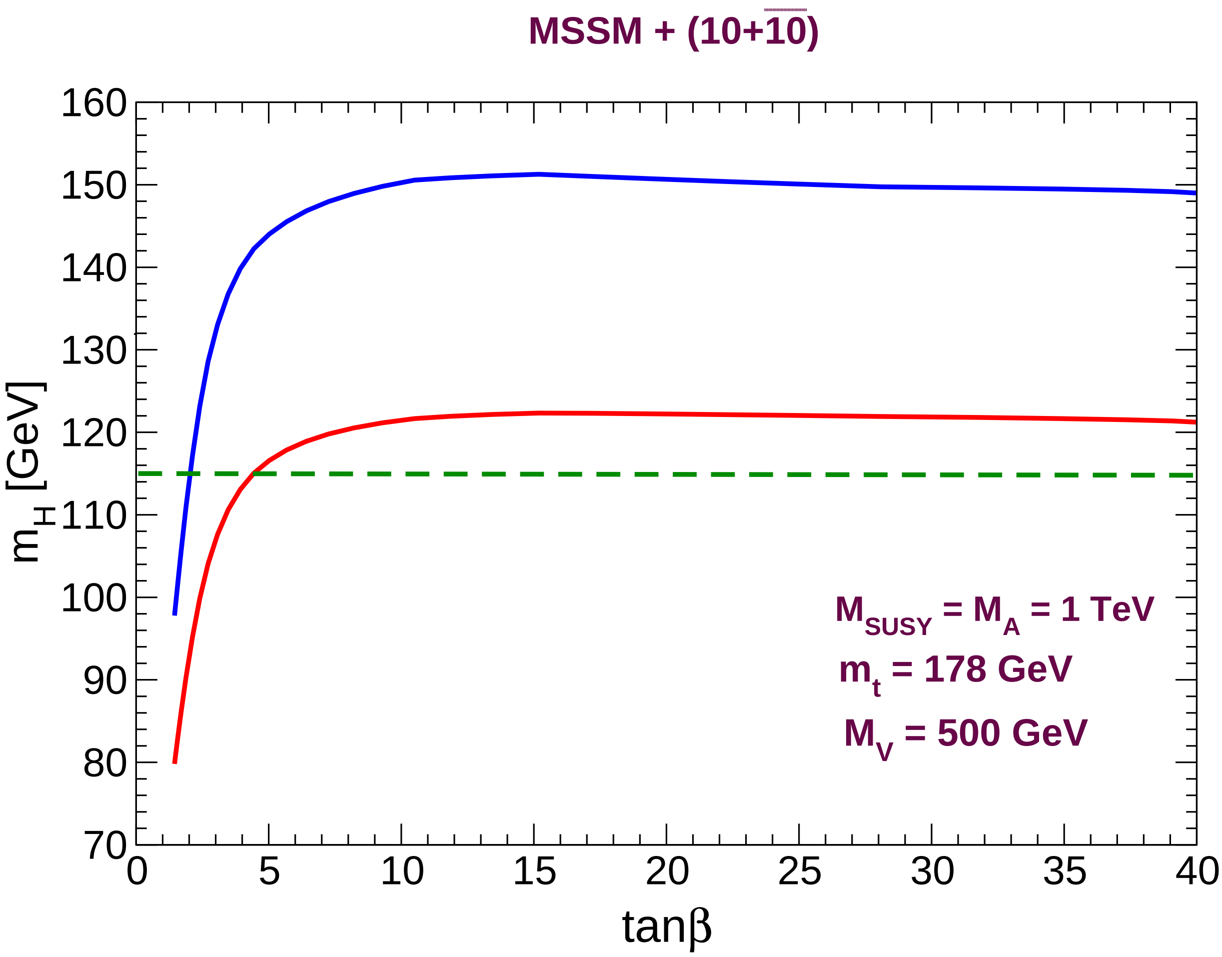
Radiative correction from the vector-like particle

$$\begin{aligned}
\Delta m_h^2 &= -\frac{3}{8\pi^2} M_Z^2 \cos^2 2\beta \sin^2\beta\, h^2\, t_1 \\
&+ \frac{3}{4\pi^2} h^4 v^2 \sin^4\beta \left[t_1 + \frac{1}{2} X_h \right. \\
&+ \left. \frac{1}{16\pi^2}\left(\frac{3}{2} h^2 \sin^2\beta - 32\pi\alpha_3\right)\left(X_h t_1 + t_1^2\right)\right]
\end{aligned}$$

where

$$t_1 = \log\frac{M_{SUSY}^2}{M^2}, \qquad \tilde{A}_h = A_h - \mu\cot\beta$$

$$X_h = \frac{2\tilde{A}_h^2}{M_{SUSY}^2}\left(1 - \frac{\tilde{A}_h^2}{12 M_{SUSY}^2}\right)$$



MSSM + (10+$\overline{10}$)
M_{SUSY} = M_A = 1 TeV
m_t = 178 GeV
M_V = 500 GeV
m_H [GeV]
tanβ
160
150
140
130
120
110
100
90
80
70
0
5
10
15
20
25
30
35
40

Lateral Gauge Symmetry

New particles should be in **SU(5)** complete multiplets

Add N copies of $5+\overline{5}$ and singlets $S+\overline{S}$

$\mathbf{SU(3)_c \times SU(2)_W \times SU(N)_{\ell at} \times U(1)_Y}$

$$\begin{array}{cc} \overline{d}'\,(\bar{\mathbf{3}},\mathbf{1},\mathbf{N})_{\mathbf{1/3}}, & \mathbf{d}'\,(\mathbf{3},\mathbf{1},\bar{\mathbf{N}})_{\mathbf{-1/3}}, \\ \mathbf{L}'\,(\mathbf{1},\mathbf{2},\mathbf{N})_{\mathbf{-1/2}}, & \bar{\mathbf{L}}'\,(\mathbf{1},\mathbf{2},\bar{\mathbf{N}})_{\mathbf{1/2}}, \\ \mathbf{S}\,(\mathbf{1},\mathbf{1},\mathbf{N})_{\mathbf{0}}, & \bar{\mathbf{S}}\,(\mathbf{1},\mathbf{1},\bar{\mathbf{N}})_{\mathbf{0}}. \end{array}$$

General superpotential for extra vector-like complete multiplets are

$$\mathbf{W} = \kappa \mathbf{L}'\bar{\mathbf{S}}\mathbf{H_u} + \rho \bar{\mathbf{L}}'\mathbf{S}\mathbf{H_d} + \mathbf{M_V}(\bar{\mathbf{S}}\mathbf{S} + \bar{\mathbf{L}}'\mathbf{L}' + \bar{\mathbf{d}}'\mathbf{d}')$$

We assumed $\kappa \gg \rho$

One loop RGE for κ for general $\mathbf{SU(N)_{\ell at}}$

$$\frac{\mathbf{d}}{\mathbf{dQ}}\kappa = \frac{\kappa}{\mathbf{16}\pi^{\mathbf{2}}}[(3+N)\kappa^2 + 3y_t^2 - \left(\frac{\mathbf{3}}{\mathbf{5}}\mathbf{g_1^2} + \mathbf{3g_2^2} + \mathbf{4C_2\ g_{\ell at}^2}\right)]$$

where $\mathbf{C_2 = (N^2 - 1)/2N}$, $Q = \log(\Lambda/M_Z)$.

The RGE for the new gauge coupling $\alpha_{\ell at}$

$$\frac{d}{dQ}\alpha_{\ell at} = \frac{\mathbf{1}}{\mathbf{2}\pi}\beta_{\ell at}\,\alpha_{\ell at}^{\mathbf{2}}$$

Minimal case one loop gauge beta function

$$\mathbf{SU(2)_{\ell at}} \longrightarrow \beta_{\ell at} = \mathbf{0}$$
$$\mathbf{SU(3)_{\ell at}} \longrightarrow \beta_{\ell at} = \mathbf{-3}$$
$$\mathbf{SU(4)_{\ell at}} \longrightarrow \beta_{\ell at} = \mathbf{-6}$$

Radiative correction to $\mathbf{m_h^2}$ coming from the new matter:

$$\begin{aligned}\mathbf{m_h^2} &= \left[\mathbf{m_h^2}\right]_{\mathbf{MSSM}} + \mathbf{m_Z^2}\cos^2\mathbf{2}\beta\left(-\frac{\mathbf{N}}{\mathbf{8}\pi^{\mathbf{2}}}\kappa^{\mathbf{2}}\ \mathbf{t_1}\right)\\ &+ \mathrm{N}\kappa^4\frac{v^2\sin^4\beta}{4\pi^2}[\mathbf{t_1} + \frac{1}{2}\mathbf{X}_\kappa\\ &+ \frac{1}{16\pi^2}\left(\frac{\mathbf{N}}{\mathbf{2}}\kappa^{\mathbf{2}} - \mathbf{6C_2g^2_{\ell at}}\right)\left(\mathbf{X}_\kappa\mathbf{t_1} + \mathbf{t_1^2}\right)].\end{aligned}$$

where

$$\mathbf{t_1} = \log\left(\frac{\mathbf{M^2_{SUSY}} + \mathbf{M^2_V}}{\mathbf{M^2_V}}\right)$$

assuming the $\mathbf{M_V} \gg \mathbf{M_D}$ and $\mathbf{X}_\kappa$ is the new particle mixing parameter

$$\mathbf{X}_\kappa = \frac{\mathbf{2\tilde{A}^2_\kappa}}{\mathbf{M^2_{SUSY}} + \mathbf{M^2_V}}\left(\mathbf{1} - \frac{\mathbf{1}}{\mathbf{12}}\frac{\mathbf{\tilde{A}^2_\kappa}}{\mathbf{M^2_{SUSY}} + \mathbf{M^2_V}}\right)$$

where $\mathbf{\tilde{A}_\kappa} = \mathbf{A}_\kappa - \mu\cot\beta$ is a left-right mixing parameter.

The T parameter

$M_V \gg M_D$, the contribution from a single, large Yukawa coupling is

$$\mathbf{T} = \frac{\mathbf{N}(\mathbf{Yv})^2}{10\pi \sin^2\theta_\mathbf{W} \mathbf{m}_\mathbf{W}^2}\left[\left(\frac{\mathbf{Yv}}{\mathbf{M_V}}\right)^2 + \mathbf{O}\left(\frac{\mathbf{Yv}}{\mathbf{M_V}}\right)^4\right]$$

where $\mathbf{Y}$ is the new Yukawa coupling, $\mathbf{v}$ is VEV of corresponding Higgs field, and $\mathbf{N}$ counts an additional degrees of freedom possessed by the new field.

Precision electroweak data constrains $\mathrm{T} = -0.17 \pm 0.12$ for $\mathbf{m_h} = 117$ **GeV** or -0.08 ± 0.12 for $\mathbf{m_h} = 300$ **GeV**

The A term

In the MSSM the requirement that there be no charge- or color-breaking minima in the scalar potential lower than the desired minimum gives us

$$\mathbf{A_t^2 \leq 3(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + m_{H_U}^2)}$$

Since $M_{H_U}^2 < 0$ usualy, $|A_t| < \sqrt{6} M_{SUSY}$, assuming $m_{\tilde{t}_L} = m_{\tilde{t}_R} = M_{SUSY}$

Here

$$\mathbf{A_\kappa^2 \leq 6(M_V^2 + M_{SUSY}^2)}$$

Upper bound (in GeV) on the lightest CP-even Higgs boson mass ($M_{SUSY} = M_A =$ 1TeV and $\alpha_{lateral} = 0.3$

	univ. A-term	non-univ. A-term
	$SU(2)_{lateral}$	
$\beta_{lateral} = 0$	176	180
	$SU(3)_{lateral}$	
$\beta_{lateral} = 0$	212	230
$\beta_{lateral} = -3$	175	186
	$SU(4)_{lateral}$	
$\beta_{lateral} = 0$	240	275
$\beta_{lateral} = -6$	180	200

MSSM —– 125 GeV

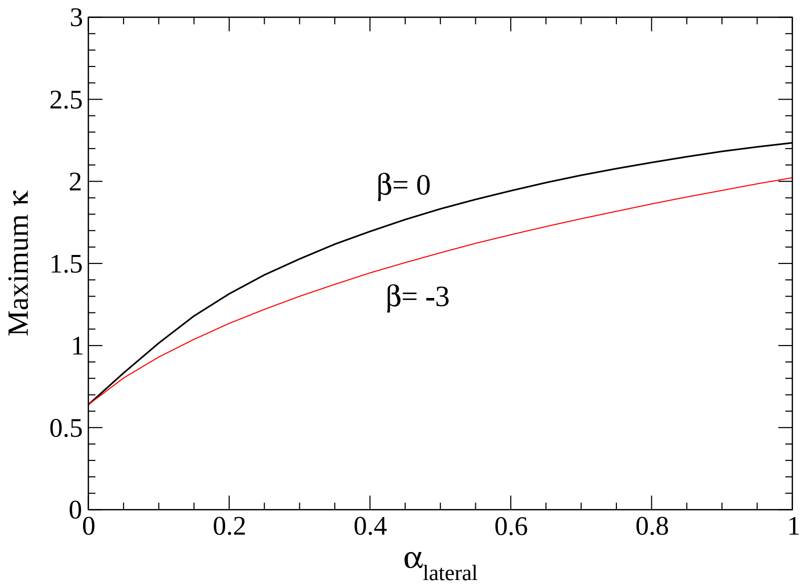


Figure 1: Plot of maximum allowed κ as a function of $\alpha_{\ell at}$ for the $N = 3$ case with $\beta_{\ell at} = 0$ and -3.

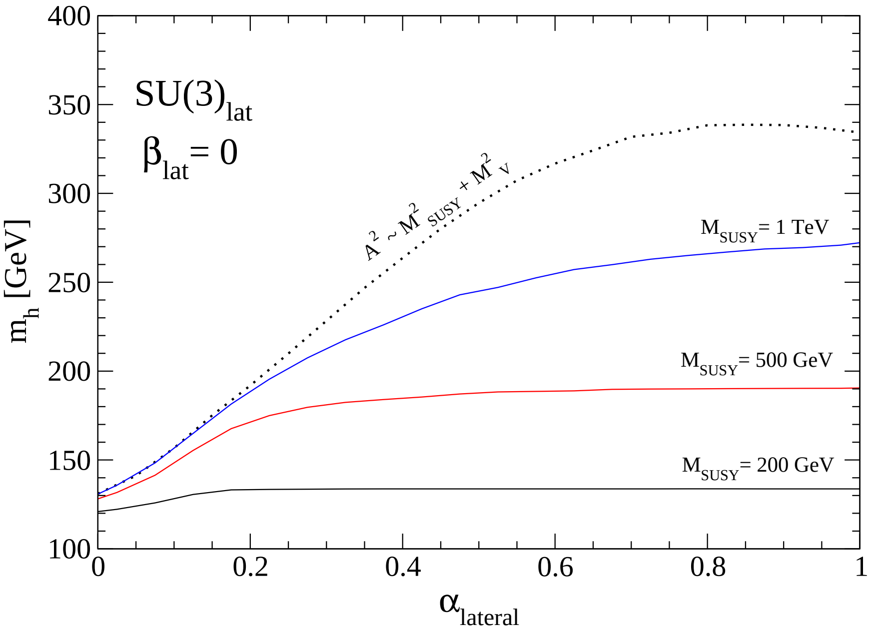


Figure 1: Plot of maximum allowed Higgs mass, m_h, as a function of $\alpha_{\ell at}$ for $SU(3)_{\ell at}$ with $\beta = 0$. The three lower lines assume $A^2 \sim M_{\rm SUSY}^2$ and $M_{\rm SUSY} = 200$, 500, and 1000 GeV respectively. The topmost dotted line represents the limit if $A^2 \sim M_{\rm SUSY}^2 + M_V^2$ (and is roughly independent of $M_{\rm SUSY}$ itself).

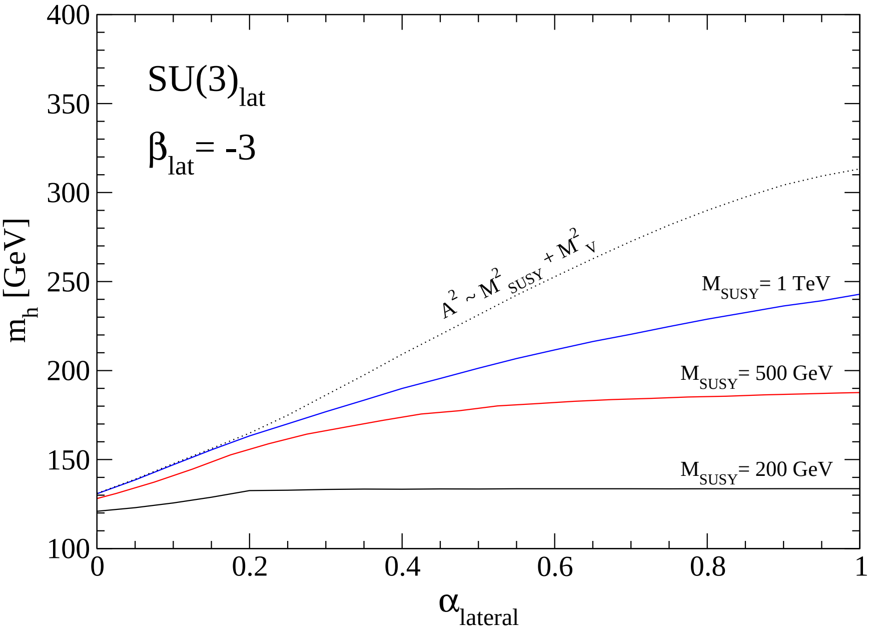
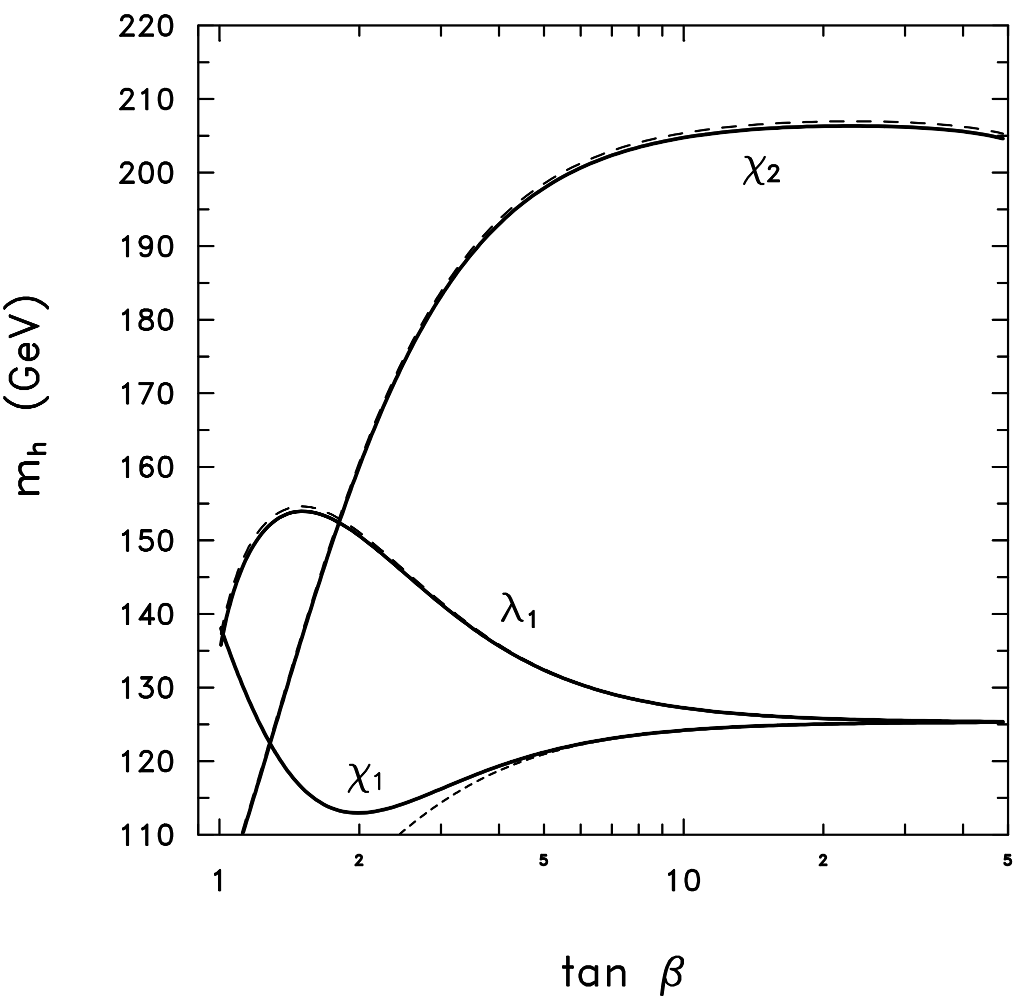
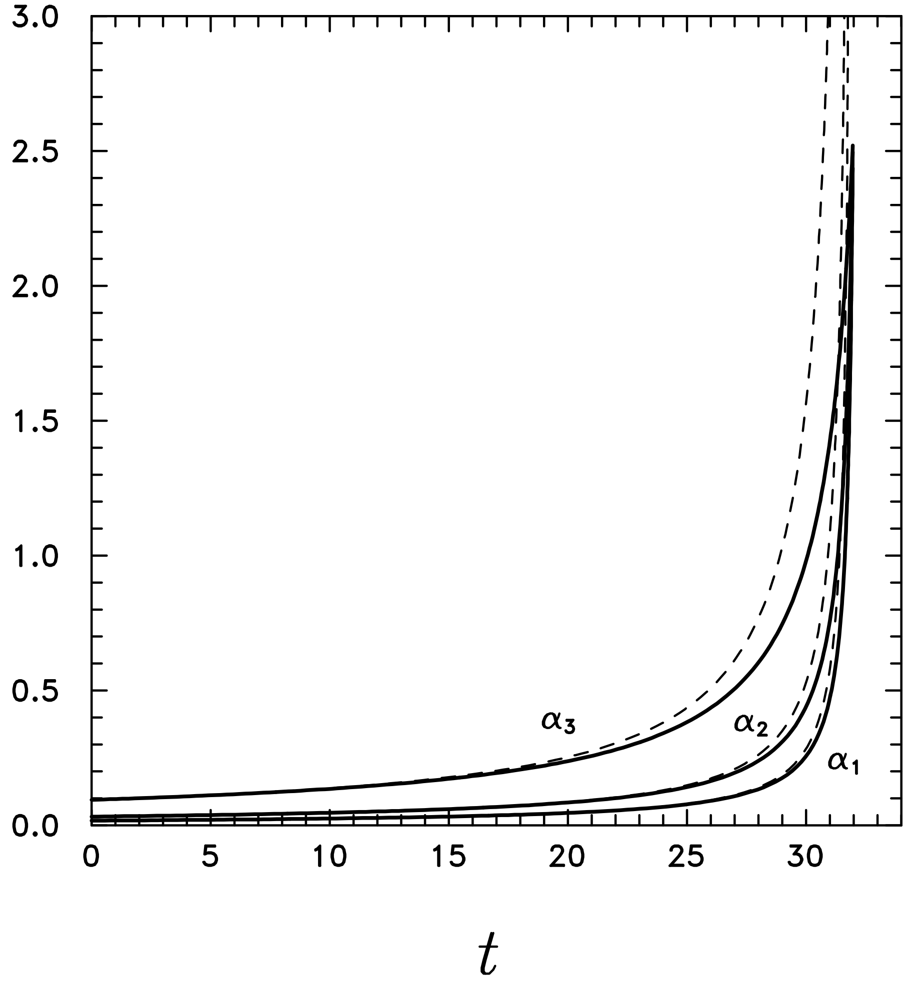


Figure 1: Plot of maximum allowed Higgs mass, m_h, as a function of $\alpha_{\ell at}$ for $SU(3)_{\ell at}$ with $\beta = -3$. The lines follow those in Fig. **??**.



220
210
200
190
180
170
160
150
140
130
120
110
m_h (GeV)
1
2
5
10
2
5
tan β
χ_2
λ_1
χ_1



3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
25
30
α3
α2
α1
t

Conclusions

MSSM can be extended to include complete GUT multiplets and gauge symmetries acting on them - $\mathrm{SU(N)}_{\mathrm{lateral}}$

- With vectorlike matter alone, lightest CP even Higgs mass is raised to about 160 GeV

- With a lateral gauge symmetry Higgs boson mass can exceed 300 GeV

- There is possible stringy unification of the SM gauge couplings with lateral gauge coupling. In this case the light CP even Higgs boson mass bound is 200 GeV