Lightest Supersymmetric **Neutral Higgs** mass in the **Extra-Dimensional** Scenario

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Ref: Nuclear Physics B **793** (2008) 114-130

Plan

- Why do we need the Higgs boson in the Standard Model?
- Higgs bosons in SUSY: lightest neutral Higgs, h
- Radiative correction to m_h in SUSY
- extra dimensions
- Radiative correction to m_h in the extra dimensional scenario
- Conclusions

Standard Model Higgs

SM: $\underbrace{SU(3)}_{strong} \times \underbrace{SU(2) \times U(1)}_{electroweak}$

Higgs: $\Phi \equiv$ (0,2,1) $\Rightarrow \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \Leftarrow$ *complex scalar*

$$V = m^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

Symmetry breaking $\Rightarrow m^2 < 0 \Rightarrow \langle 0|\phi^0|0\rangle = v$

$$\boxed{m_H = \sqrt{-2m^2}, \quad v = \sqrt{\frac{-m^2}{\lambda}} = 246 \text{ GeV}}$$

Other components of $\Phi \Rightarrow$ *Goldstone bosons*

Higgs in SUSY

$$H_1 \equiv \text{(0,2,-1)} \Rightarrow \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \quad H_2 \equiv \text{(0,2,1)} \Rightarrow \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

- Tree level potential:

$$V = m_1^2|H_1|^2 + m_2^2|H_2|^2 + m_{12}^2(H_1H_2 + \text{h.c}) +$$
$$\frac{1}{8}g_2{}^2(H_2^\dagger\sigma^a H_2 + H_1^\dagger\sigma^a H_1)^2 + \frac{1}{8}g_1{}^2(|H_2|^2 - |H_1|^2)^2$$

$g_2 = SU(2)$ coupling constant
$g_1 = U(1)$ coupling constant

- Charged Higgs bosons $H^\pm$
- Neutral Higgs: H^0, h^0 (scalars), A^0 (pseudoscalar)
- $\langle 0|H_1^0|0\rangle = v_1, \quad \langle 0|H_2^0|0\rangle = v_2, \quad v_1^2 + v_2^2 = v^2, \quad \tan\beta = \frac{v_2}{v_1}$

Higgs in SUSY: tree level

Neutral sector potential:

$$\begin{aligned} V_0 &= m_1^2|H_1^0|^2 + m_2^2|H_2^0|^2 - m_{12}^2(H_1^0H_2^0 + \mathrm{h.c}) \\ &+ \frac{1}{8}(g_2^2 + g_1^2)(|H_1^0|^2 - |H_2^0|^2)^2 \end{aligned}$$

Eigenvalues: neutral higgs -

$$\begin{aligned} m_A^2 &= \frac{2m_{12}^2}{\sin 2\beta}\,, \\ m_{h,H}^2 &= \frac{1}{2}\left[m_A^2 + M_Z^2 \mp \sqrt{(m_A^2 + M_Z^2)^2 - 4m_A^2M_Z^2\cos^2 2\beta}\right] \\ m_h &\leq \min\,(m_A, M_Z)|\cos 2\beta| \leq \min\,(m_A, M_Z) \end{aligned}$$

Conclusion:- At the tree level (i) the lighter of the two CP-even Higgs (h) weighs less than $M_Z(= 91.2\mathrm{GeV})$, and (ii) the CP-odd Higgs (A) is heavier than h but lighter than H.

Radiative correction to m_h

- Points to note:-
  - Dominated by top quark and its superpartners $(\tilde{t}_1, \tilde{t}_2)$.
  - For large $\tan\beta$, the b-sector is also important.
  - Ignore the corrections due to gauge and first two generation fermions.
  - With exact supersymmetry , the entire correction vanishes. So correction to m_h will be controlled by M_S.

- Effective potential technique

Ref: Ellis, Ridolfi, Zwirner;

Ref: Okada, Yamaguchi, Yanagida; Haber, Hempfling; Brignole; Berger; Gunion, Turski

Effective potential in SUSY

The one-loop corrected potential

$$\begin{aligned} V_1(Q) &= V_0(Q) + \Delta V_1(Q) \\ \Delta V_1(Q) &= \frac{1}{64\pi^2} \mathrm{Str} M^4(H) \left\{ \ln \frac{M^2(H)}{Q^2} - \frac{3}{2} \right\} \end{aligned}$$

Higgs masses from the second derivative of V_1 w.r.t Higgs fields

Str $\equiv$ Supertrace, taken over all members of a supermultiplet

$$\mathrm{Str} f(m^2) = \sum_i (-1)^{2J_i} (2J_i + 1) f(m_i^2)$$

$$\Delta V_t = \frac{3}{32\pi^2} \left[m_{\tilde{t}_1}^4 \left(\ln \frac{m_{\tilde{t}_1}^2}{Q^2} - \frac{3}{2} \right) + m_{\tilde{t}_2}^4 \left(\ln \frac{m_{\tilde{t}_2}^2}{Q^2} - \frac{3}{2} \right) - 2 m_t^4 \left(\ln \frac{m_t^2}{Q^2} - \frac{3}{2} \right) \right]$$

Field-dependent masses

Quarks:

$$m_t^2(H) = h_t^2|H_2^0|^2 \ ; \ m_b^2(H) = h_b^2|H_1^0|^2$$

Stop and sbottom squarks:

$$M_{\tilde{t}}^2(H) = \begin{pmatrix} m_Q^2 + h_t^2|H_2^0|^2 & h_t(A_t H_2^0 + \mu H_1^{0*}) \\ h_t(A_t H_2^{0*} + \mu H_1^0) & m_U^2 + h_t^2|H_2^0|^2 \end{pmatrix}$$

$$M_{\tilde{b}}^2(H) = \begin{pmatrix} m_Q^2 + h_b^2|H_1^0|^2 & h_b(A_b H_1^0 + \mu H_2^{0*}) \\ h_b(A_b H_1^{0*} + \mu H_2^0) & m_D^2 + h_b^2|H_1^0|^2 \end{pmatrix}$$

Higgs masses with loop corrections

Scalars: m_h is the smaller eigenvalue of

$$\mathcal{M}^2_{(\mathrm{even})} = \begin{pmatrix} M_Z^2 c_\beta^2 + m_A^2 s_\beta^2 & -(m_A^2 + M_Z^2) s_\beta c_\beta \\ -(m_A^2 + M_Z^2) s_\beta c_\beta & M_Z^2 s_\beta^2 + m_A^2 c_\beta^2 \end{pmatrix} + \frac{3G_F}{2\sqrt{2}\pi^2} \begin{pmatrix} \Delta_{11} & \Delta_{12} \\ \Delta_{12} & \Delta_{22} \end{pmatrix}$$

- $m_A \equiv$ loop-corrected pseudoscalar mass
- Δ captures the loop contributions.

The Delta matrix

$$
\begin{aligned}
\Delta_{11}^t &= \frac{m_t^4}{\sin^2\beta}\left(\frac{\mu(A_t+\mu\cot\beta)}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2}\right)^2 g(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2) \\
\Delta_{12}^t &= \frac{m_t^4}{\sin^2\beta}\frac{\mu(A_t+\mu\cot\beta)}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2}\left[\ln\frac{m_{\tilde{t}_1}^2}{m_{\tilde{t}_2}^2} + \frac{A_t(A_t+\mu\cot\beta)}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} g(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2)\right] \\
\Delta_{22}^t &= \frac{m_t^4}{\sin^2\beta}\left[\ln\frac{\mathbf{m_{\tilde{t}_1}^2\, m_{\tilde{t}_2}^2}}{\mathbf{m_t^4}} + \frac{2A_t(A_t+\mu\cot\beta)}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2}\ln\frac{m_{\tilde{t}_1}^2}{m_{\tilde{t}_2}^2}\right] + \frac{A_t^2}{\mu^2}\Delta_{11}^t
\end{aligned}
$$

$$
g(m_1^2, m_2^2) = 2 - \frac{m_1^2+m_2^2}{m_1^2-m_2^2}\ln\frac{m_1^2}{m_2^2}
$$

$$
\boxed{\mathbf{m_h^2} \lesssim \mathbf{M_Z^2}\cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2}\left[\ln\left(\frac{\mathbf{m_{\tilde{t}}^2}}{\mathbf{m_t^2}}\right) + \frac{\mathbf{A_t^2}}{\mathbf{M_S^2}}\left(1 - \frac{1}{12}\frac{\mathbf{A_t^2}}{\mathbf{M_S^2}}\right)\right]}
$$

MSSM: $m_h \lesssim$ 135-150 GeV for $M_S = \mathcal{O}$ (1 TeV).

5D Model

- We consider only ***one space-type extra dimension*** (y)
  So our co-ordinate system : $\{x(t,\vec{x}), y\}$

- Compactification : S^1/Z_2

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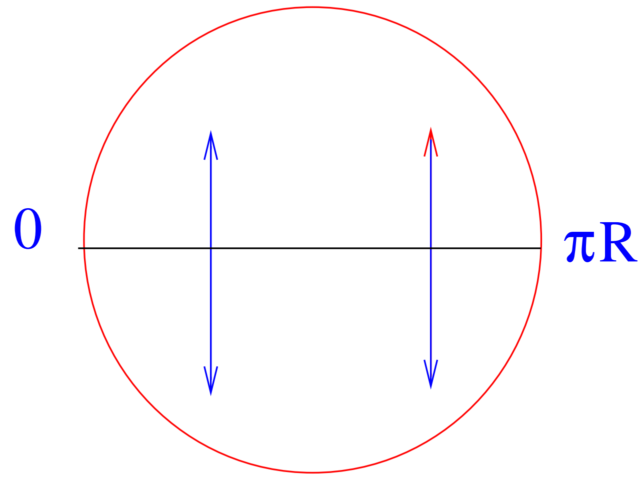


  - Translational symmetry breaks $\Rightarrow p_5$, hence KK number (n) is not conserved.
  - KK parity $\equiv (-1)^n$conserved.

$$\boxed{\mathbf{R^{-1}} \gtrsim \text{ 300 GeV}}$$

Gauge, Scalar, and Fermion

Scalar :

$$\phi(x,y) = \frac{\sqrt{2}}{\sqrt{2\pi R}}\phi^{(0)}(x) + \frac{2}{\sqrt{2\pi R}}\sum_{n=1}^{\infty}\phi^{(n)}(x)\cos\frac{ny}{R}.$$

Fermions :

$$\mathcal{Q}_i(x,y) = \frac{\sqrt{2}}{\sqrt{2\pi R}}\left[\begin{pmatrix} t_i \\ b_i \end{pmatrix}_L(x) + \sqrt{2}\sum_{n=1}^{\infty}\left[\mathcal{Q}_{iL}^{(n)}(x)\cos\frac{ny}{R} + \mathcal{Q}_{iR}^{(n)}(x)\sin\frac{ny}{R}\right]\right],$$

$$\mathcal{T}_i(x,y) = \frac{\sqrt{2}}{\sqrt{2\pi R}}\left[t_{iR}(x) + \sqrt{2}\sum_{n=1}^{\infty}\left[\mathcal{T}_{iR}^{(n)}(x)\cos\frac{ny}{R} + \mathcal{T}_{iL}^{(n)}(x)\sin\frac{ny}{R}\right]\right],$$

$$\mathcal{B}_i(x,y) = \frac{\sqrt{2}}{\sqrt{2\pi R}}\left[b_{iR}(x) + \sqrt{2}\sum_{n=1}^{\infty}\left[\mathcal{B}_{iR}^{(n)}(x)\cos\frac{ny}{R} + \mathcal{B}_{iL}^{(n)}(x)\sin\frac{ny}{R}\right]\right].$$

Gauge boson :

$$A_\mu(x,y) = \frac{\sqrt{2}}{\sqrt{2\pi R}}A_\mu^{(0)}(x) + \frac{2}{\sqrt{2\pi R}}\sum_{n=1}^{\infty}A_\mu^{(n)}(x)\cos\frac{ny}{R},$$

$$A_5(x,y) = \frac{2}{\sqrt{2\pi R}}\sum_{n=1}^{\infty}A_5^{(n)}(x)\sin\frac{ny}{R}.$$

5D Supersymmetry details

- $N = 1$ SUSY in 5d is equivalent to $N = 2$ SUSY in 4d, i.e. two different $N = 1$ SUSY in 4d.
- Now: In 4d one fermion is related by SUSY to two different scalars, and *vice versa*.
- Doubling of states: supermultiplet (ϕ, ψ) becomes hypermultiplet (ϕ_i, ψ_i) with $i = (1, 2)$.
- Yukawa : $-\frac{h_{t5}}{\Lambda^{3/2}} \int d^4x \; dy \; \delta(y) \int d^2\theta \; (\mathcal{H}_u \mathcal{Q} \mathcal{T} \; + \; \mathrm{h.c.})$
- Yukawa coupling only at the brane
- As in 4d SUSY, dominant radiative corrections come from 3^{rd} generation.

5D Supersymmetry details

- 3^{rd} generation is in the bulk. Localise the first two generations at a brane.
- A bulk field is equivalent to ‘zero-mode’ and KK excitations
- Here M_S and R are independent parameters of the same order.

$$\Delta V_t^n = \frac{3}{32\pi^2}\left[m^4_{\tilde{t}_1^n}\left(\ln\frac{m^2_{\tilde{t}_1^n}}{Q^2} - \frac{3}{2}\right) + m^4_{\tilde{t}_2^n}\left(\ln\frac{m^2_{\tilde{t}_2^n}}{Q^2} - \frac{3}{2}\right) - 2m^4_{t^n}\left(\ln\frac{m^2_{t^n}}{Q^2} - \frac{3}{2}\right)\right]$$

where $m_n^2 = m_0^2 + n^2/R^2$.

The Δ^n matrix

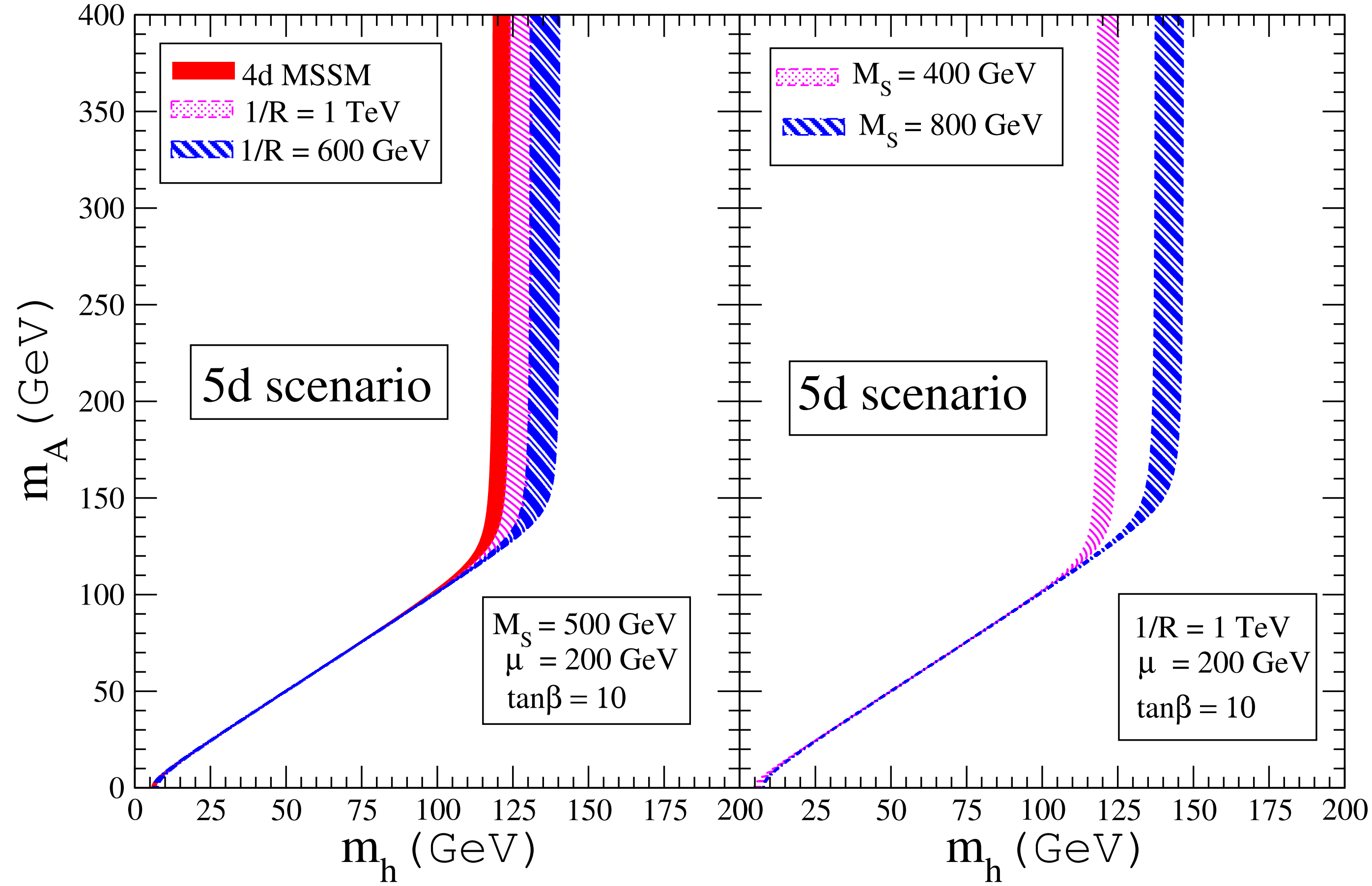
$$
\begin{aligned}
(\Delta^t_{11})^n &= \frac{m_t^4}{\sin^2\beta}\left(\frac{\mu(A_t+\mu\cot\beta)}{m^2_{\tilde{t}^n_1}-m^2_{\tilde{t}^n_2}}\right)^2 g(m^2_{\tilde{t}^n_1}, m^2_{\tilde{t}^n_2}) \\
(\Delta^t_{12})^n &= \frac{m_t^4}{\sin^2\beta}\frac{\mu(A_t+\mu\cot\beta)}{m^2_{\tilde{t}^n_1}-m^2_{\tilde{t}^n_2}}\left[\ln\frac{m^2_{\tilde{t}^n_1}}{m^2_{\tilde{t}^n_2}}+\frac{A_t(A_t+\mu\cot\beta)}{m^2_{\tilde{t}^n_1}-m^2_{\tilde{t}^n_2}}g(m^2_{\tilde{t}^n_1}, m^2_{\tilde{t}^n_2})\right] \\
(\Delta^t_{22})^n &= \frac{m_t^4}{\sin^2\beta}\left[\ln\frac{m^2_{\tilde{t}^n_1}m^2_{\tilde{t}^n_2}}{m^4_{t^n}}+\frac{2A_t(A_t+\mu\cot\beta)}{m^2_{\tilde{t}^n_1}-m^2_{\tilde{t}^n_2}}\ln\frac{m^2_{\tilde{t}^n_1}}{m^2_{\tilde{t}^n_2}}\right]+\frac{A_t^2}{\mu^2}(\Delta^t_{11})^n
\end{aligned}
$$

$\boxed{\text{Assuming } M_S R \ll 1}$

$$
\begin{aligned}
(\Delta^t_{11})^n &\sim -\frac{1}{6}\left(\frac{R^4}{n^4}\right)\frac{m_t^4}{\sin^2\beta}\left[\mu(A_t+\mu\cot\beta)\right]^2 \\
(\Delta^t_{12})^n &\sim \left(\frac{R^2}{n^2}\right)\frac{m_t^4}{\sin^2\beta}\mu(A_t+\mu\cot\beta) \\
(\Delta^t_{22})^n &\sim \left(\frac{R^2}{n^2}\right)\frac{m_t^4}{\sin^2\beta}\left[(m^2_{\tilde{t}_1}+m^2_{\tilde{t}_2}-2m_t^2)+2A_t(A_t+\mu\cot\beta)\right]
\end{aligned}
$$

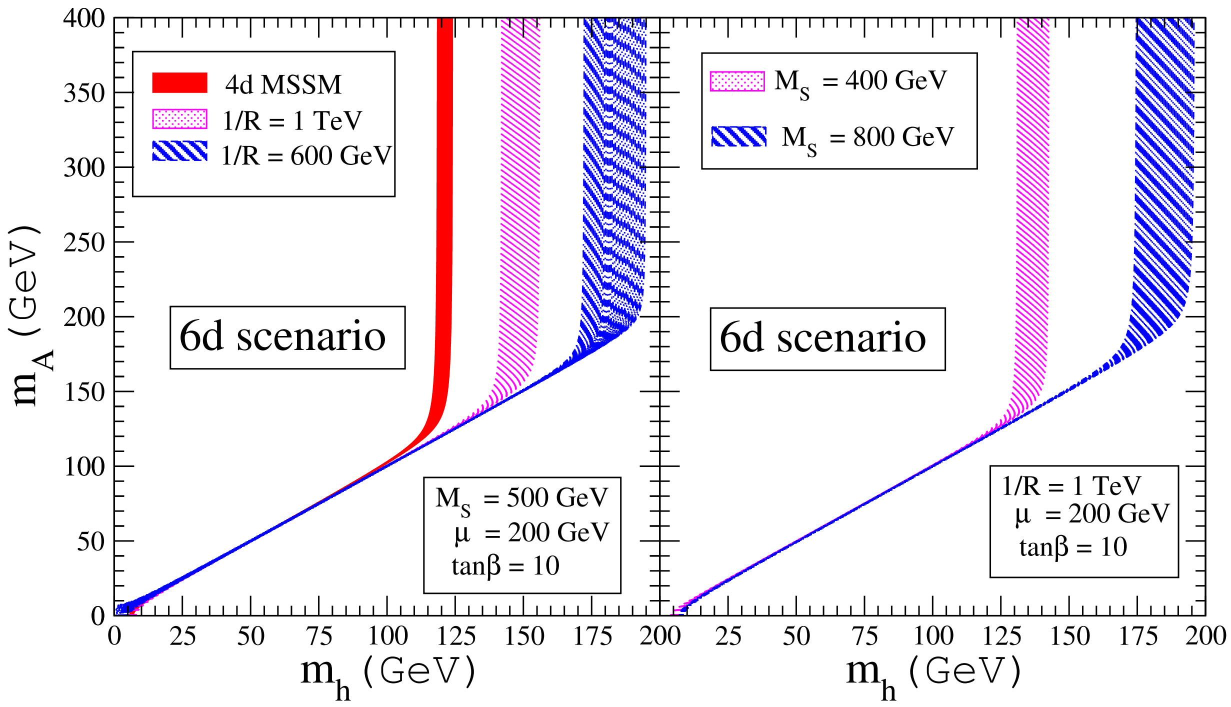
m_h vs m_A in 5d

$A_t = A_b = [0.8 - 1.2]\ M_S$



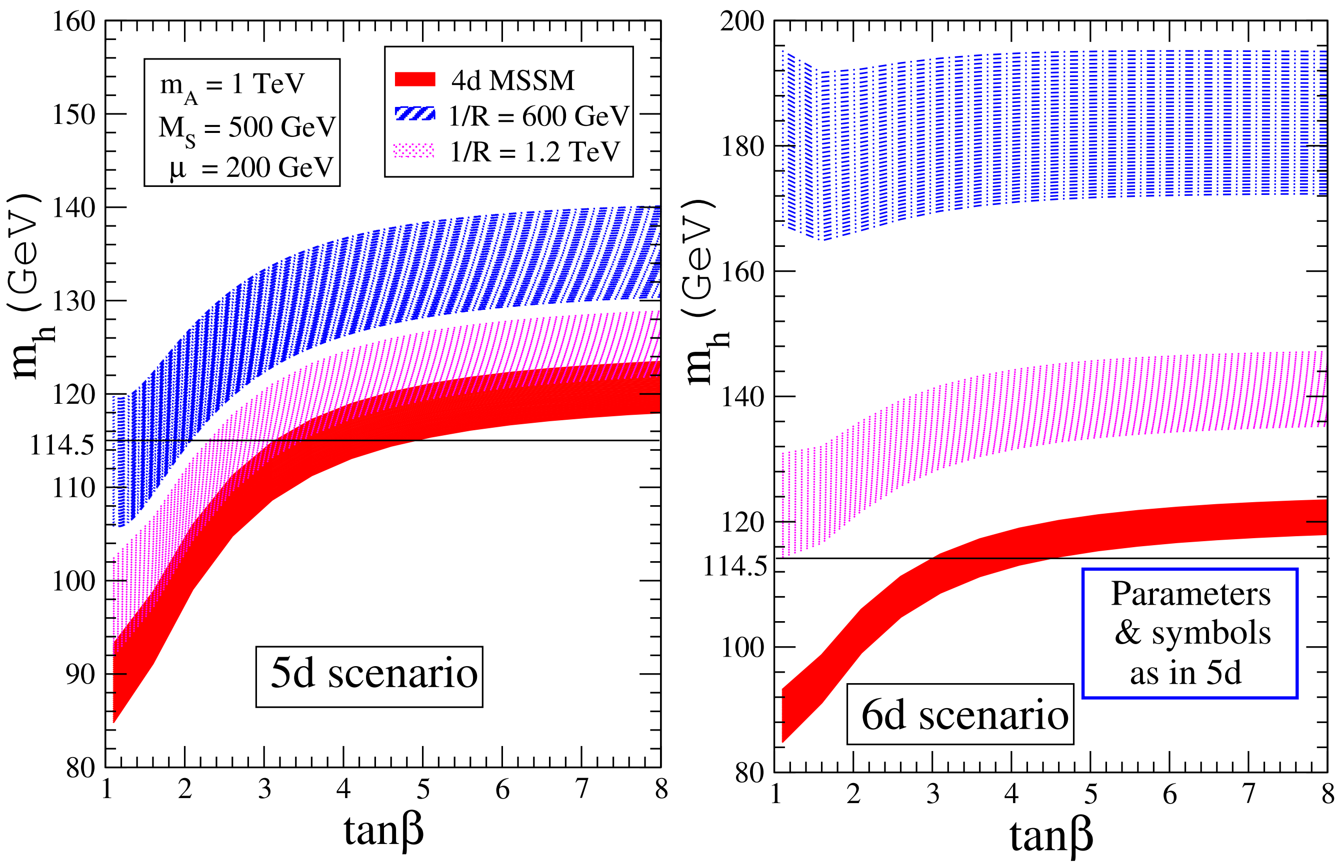
m_h vs m_A in 6d chiral square

- $(y,0) \equiv (0,y)$, $(y,L) \equiv (L,y)$, i.e. adjacent sides of the square identified (T^2/Z_4) (Dobrescu, Ponton, Burdman, Fabbrichesi, Serone,...)
- $n^2 = j^2 + k^2, \qquad A_t = A_b = [0.8 - 1.2]\ M_S$



m_h vs low $\tan\beta$

$$m_h^2 = M_Z^2 \left(\frac{1-\tan^2\beta}{1+\tan^2\beta}\right)^2 + \ldots\ldots$$



Conclusions

- In SUSY, the lightest higgs mass m_h is bounded by 135-150 GeV.
- For 5d and ignoring left-right squark mixing, m_h^2 can be enhanced by as much as $\sim (60\ \mathrm{GeV})^2 \times (M_S R)^2$.
- Low $\tan\beta$ region can be revived.
- Suppose $M_S = C/R$,Take$1/R \sim$ 1 TeV. Varying $C = [0.5 - 2.0]$ yields $m_h \simeq [150 - 230]$ GeV.
- If Higgs is found, R will be constrained, depending on M_S.

Thank You !

CP-odd Higgs masses with loop corrections

Non-zero eigenvalue of the matrix

$$\mathcal{M}^2_{(\rm odd)} \quad = \quad \begin{pmatrix} tan\beta & 1 \\ 1 & cot\beta \end{pmatrix} (m^2_{12} + \Delta)$$

- Δ captures the radiative corrections :
  $\Delta = \Delta^{\rm t} + \Delta^{\rm b}$, which is given by

$$\Delta^{\rm t(b)} = -\frac{3}{32\pi^2} \frac{h^2_{t(b)} \mu A_{t(b)}}{\left[m^2_{\tilde{t}_1(\tilde{b}_1)} - m^2_{\tilde{t}_2(\tilde{b}_2)}\right]} \left[f\left(m^2_{\tilde{t}_1(\tilde{b}_1)}\right) - f\left(m^2_{\tilde{t}_2(\tilde{b}_2)}\right)\right]$$

where

$$f(m^2) = 2m^2 \left(\ln \frac{m^2}{Q^2} - 1\right).$$

Maximum m_h vs $1/R$