Lightest SUSY Higgs mass bound in Extra Dimension

Gautam Bhattacharyya

Saha Institute of Nuclear Physics, Kolkata

[with: S.K. Majee and A. Raychaudhuri (HRI), arXiv:0705.3103, Nucl Phys B (2008)]

- Brief review of standard (4d) MSSM radiative correction to the lightest Higgs
- Impact of Kaluza-Klein towers

The essential points!

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

Can it be relaxed?

$$m_h^2 \lesssim M_Z^2 \cos^2 2\beta + \frac{3 G_F m_t^4}{\sqrt{2}\pi^2} \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

- Extended Higgs models offer tree level quartic coupling. $W = \lambda X H_d H_u$. $\Rightarrow m_h <$ 200 GeV (Espinosa, Quiros)
- Embedding MSSM in ‘flat’ extra dimension(s):

$$\Delta m_h^2\ (5d, n) \sim \frac{3 G_F m_t^4}{\sqrt{2}\pi^2} \frac{(M_S R)^2}{n^2}$$

Conservative: $m_h(5d) \lesssim$ 200 GeV, $m_h(6d) \lesssim$ 330 GeV

4d MSSM limit (tree level)

$$\textbf{Complex scalars}: \qquad H_1 = \left({H_1}^0, {H_1}^-\right)^T, \quad H_2 = \left({H_2}^+ {H_2}^0\right)^T$$

$$\textbf{Neutral pot}: \; V_0 \;=\; m_1^2|H_1^0|^2 + m_2^2|H_2^0|^2 - m_{12}^2(H_1^0 H_2^0 + \text{h.c}) + \frac{1}{8}(g^2 + g'^2)(|H_1^0|^2 - |H_2^0|^2)^2$$

Neutral eigenvalues:

$$m_A^2 = \frac{2m_{12}^2}{\sin 2\beta}, \quad \text{where} \quad \tan\beta = \frac{v_2}{v_1}$$

$$m_{h,H}^2 = \frac{1}{2}\left[m_A^2 + M_Z^2 \mp \sqrt{(m_A^2 + M_Z^2)^2 - 4m_A^2 M_Z^2 \cos^2 2\beta}\right]$$

$$m_h \leq \text{min}\,(m_A, M_Z)|\cos 2\beta| \leq \text{min}\,(m_A, M_Z)$$

4d MSSM limit (One-loop)

- Radiative corrections dominated by large h_t and masses of $(\tilde{t}_1, \tilde{t}_2)$. For large $\tan\beta$, the b-sector is also important. Gauge and first two gen matter effects small.
- With exact supersymmetry, the entire correction vanishes. So correction to m_h will be controlled by M_S.
- 3 approaches: (i) effective potential technique, (ii) direct diagram calculations, and (iii) RG method, assuming $M_S \gg M_Z$ and fixing $\lambda \propto (g^2 + g'^2)$ at that scale and then evolving down to weak scale.

Ellis, Ridolfi, Zwirner; Okada, Yamaguchi, Yanagida; Haber, Hempfling; Brignole; Berger; Gunion, Turski (all early 90's).

4d MSSM limit (1-loop) Contd..

The one-loop corrected potential

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

Supertrace to be taken over all members of a multiplet

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

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

4d MSSM limit (1-loop) Contd...

Field-dependent quark masses

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

The fi eld-dependent stop and sbottom squark mass matrices

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

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

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

The Δ matrix

$$\Delta^t_{11} = \frac{m_t^4}{\sin^2\beta}\left(\frac{\mu(A_t+\mu\cot\beta)}{m^2_{\tilde{t}_1}-m^2_{\tilde{t}_2}}\right)^2 g(m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2})$$

$$\Delta^t_{12} = \frac{m_t^4}{\sin^2\beta}\frac{\mu(A_t+\mu\cot\beta)}{m^2_{\tilde{t}_1}-m^2_{\tilde{t}_2}}\left[\ln\frac{m^2_{\tilde{t}_1}}{m^2_{\tilde{t}_2}} + \frac{A_t(A_t+\mu\cot\beta)}{m^2_{\tilde{t}_1}-m^2_{\tilde{t}_2}} g(m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2})\right]$$

$$\Delta^t_{22} = \frac{m_t^4}{\sin^2\beta}\left[\ln\frac{\mathbf{m^2_{\tilde{t}_1} m^2_{\tilde{t}_2}}}{\mathbf{m^4_t}} + \frac{2A_t(A_t+\mu\cot\beta)}{m^2_{\tilde{t}_1}-m^2_{\tilde{t}_2}}\ln\frac{m^2_{\tilde{t}_1}}{m^2_{\tilde{t}_2}}\right] + \frac{A_t^2}{\mu^2}\Delta^t_{11}$$

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

$$\boxed{\mathbf{m^2_h} \lesssim \mathbf{M^2_Z}\cos^2 2\beta + \frac{\mathbf{3G_F m_t^4}}{\sqrt{2}\pi^2}\left[\ln\left(\frac{\mathbf{m^2_{\tilde{t}}}}{\mathbf{m^2_t}}\right) + \frac{\mathbf{A^2_t}}{\mathbf{M^2_S}}\left(1 - \frac{1}{12}\frac{\mathbf{A^2_t}}{\mathbf{M^2_S}}\right)\right]}$$

Extra compactified dimension

- One extra coordinate (y) compactifi ed on S^1/Z_2. Orbifolding: zero mode chirality (UED: Appelquist, Cheng, Dobrescu).
- p_y quantised as n/R, KK parity $(-)^n$ is conserved, n conserved at all tree vertices.
-
  - $(g-2)_\mu$ (Nath, Yamaguchi)
  - FCNC (Buras, Spranger, Poschenrieder, Weiler)
  - $Z \to b\bar{b}$ (Oliver, Papavassiliou, Santamaria)
  - $\Delta\rho$ (Appelquist, Cheng, Dobrescu, Yee)
  - All EW precision observables (Gogoladze, Mascesanu)
  - Direct search at Colliders

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

Fourier expansion

Each 5d field either even or odd under Z_2.

$$
\begin{aligned}
A_\mu(x,y) &= \frac{\sqrt{2}}{\sqrt{2\pi R}} A_\mu^{(0)}(x) + \frac{2}{\sqrt{2\pi R}} \sum_{n=1}^{\infty} A_\mu^{(n)}(x) \cos\frac{ny}{R} \\
A_5(x,y) &= \frac{2}{\sqrt{2\pi R}} \sum_{n=1}^{\infty} A_5^{(n)}(x) \sin\frac{ny}{R} \\
\phi(x,y) &= \frac{\sqrt{2}}{\sqrt{2\pi R}} \phi^{(0)}(x) + \frac{2}{\sqrt{2\pi R}} \sum_{n=1}^{\infty} \phi^{(n)}(x) \cos\frac{ny}{R} \\
\mathcal{Q}(x,y) &= \frac{\sqrt{2}}{\sqrt{2\pi R}} \left[\begin{pmatrix} t \\ b \end{pmatrix}_L (x) + \sqrt{2} \sum_{n=1}^{\infty} \left\{ \mathcal{Q}_L^{(n)}(x) \cos\frac{ny}{R} + \mathcal{Q}_R^{(n)}(x) \sin\frac{ny}{R} \right\} \right] \\
\mathcal{T}(x,y) &= \frac{\sqrt{2}}{\sqrt{2\pi R}} \left[t_R(x) + \sqrt{2} \sum_{n=1}^{\infty} \left\{ \mathcal{T}_R^{(n)}(x) \cos\frac{ny}{R} + \mathcal{T}_L^{(n)}(x) \sin\frac{ny}{R} \right\} \right] \\
\mathcal{B}(x,y) &= \frac{\sqrt{2}}{\sqrt{2\pi R}} \left[b_R(x) + \sqrt{2} \sum_{n=1}^{\infty} \left\{ \mathcal{B}_R^{(n)}(x) \cos\frac{ny}{R} + \mathcal{B}_L^{(n)}(x) \sin\frac{ny}{R} \right\} \right]
\end{aligned}
$$

5d Supersymmetry

- $N = 1$ SUSY in 5d is equivalent to $N = 2$ SUSY in 4d, i.e. two different $N = 1$ SUSY in 4d.
- Doubling of states: supermultiplet (ϕ, ψ) becomes hypermultiplet (ϕ_i, ψ_i) with $i = (1, 2)$.
- Yukawa : $-\frac{h_{t5}}{\Lambda^{3/2}} \int d^4x \; dy \; \delta(y) \int d^2\theta \; (\mathcal{H}_u \mathcal{Q} \mathcal{T} \; + \; \mathrm{h.c.})$
- Dominant radiative corrections come from 3^{rd} generation bulk fi elds. Localise the fi rst two generations at brane.
- M_S may originate from Scherk-Schwarz mechanism. We treat M_S and R as independent parameters, but of the same order.

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

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

The Δ^n matrix

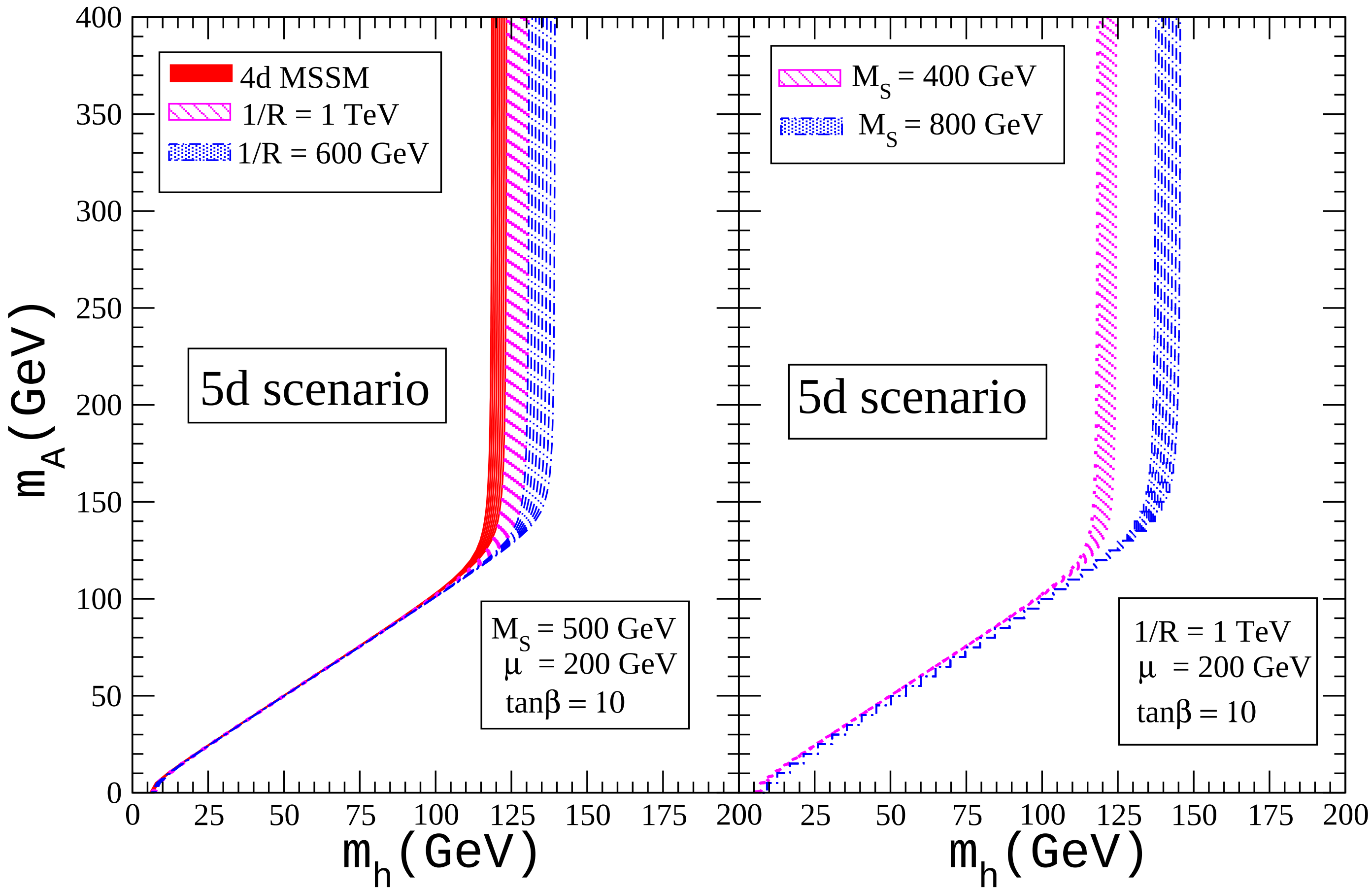
$$
\begin{aligned}
(\Delta^t_{11})^n &= \frac{m_t^4}{\sin^2\beta}\left(\frac{\mu(A_t+\mu\cot\beta)}{m^2_{\tilde{t}^n_1}-m^2_{\tilde{t}^n_2}}\right)^2 g(m^2_{\tilde{t}^n_1}, m^2_{\tilde{t}^n_2}) \\
(\Delta^t_{12})^n &= \frac{m_t^4}{\sin^2\beta}\frac{\mu(A_t+\mu\cot\beta)}{m^2_{\tilde{t}^n_1}-m^2_{\tilde{t}^n_2}}\left[\ln\frac{m^2_{\tilde{t}^n_1}}{m^2_{\tilde{t}^n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

Assuming $M_S R \ll 1$

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

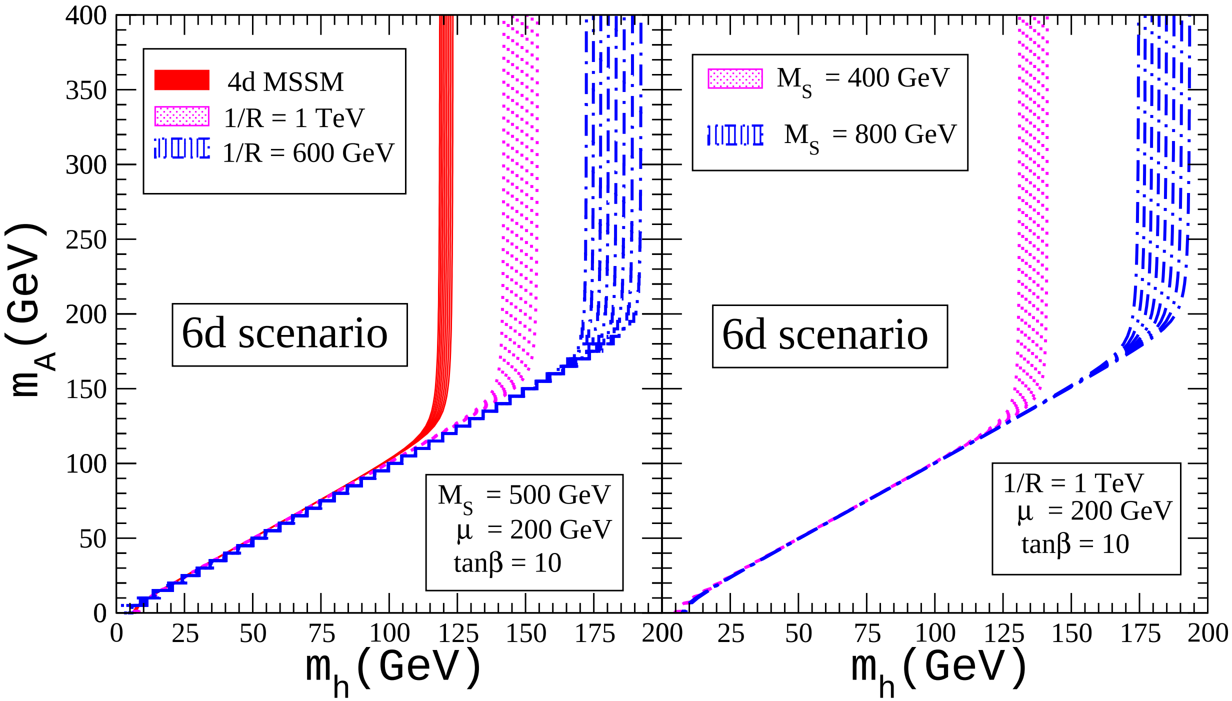
m_h vs m_A in 5d

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



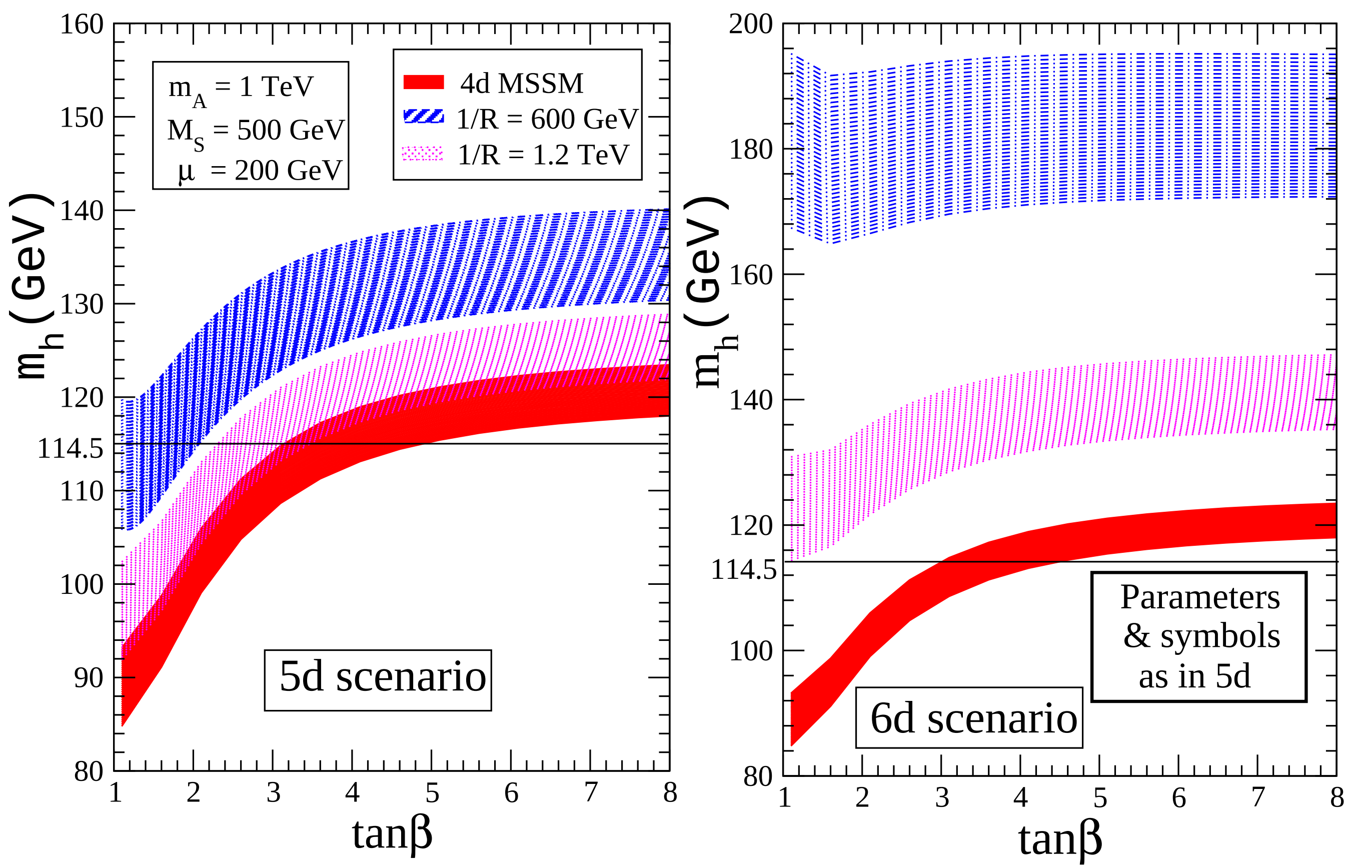
m_h vs m_A in 6d chiral square

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

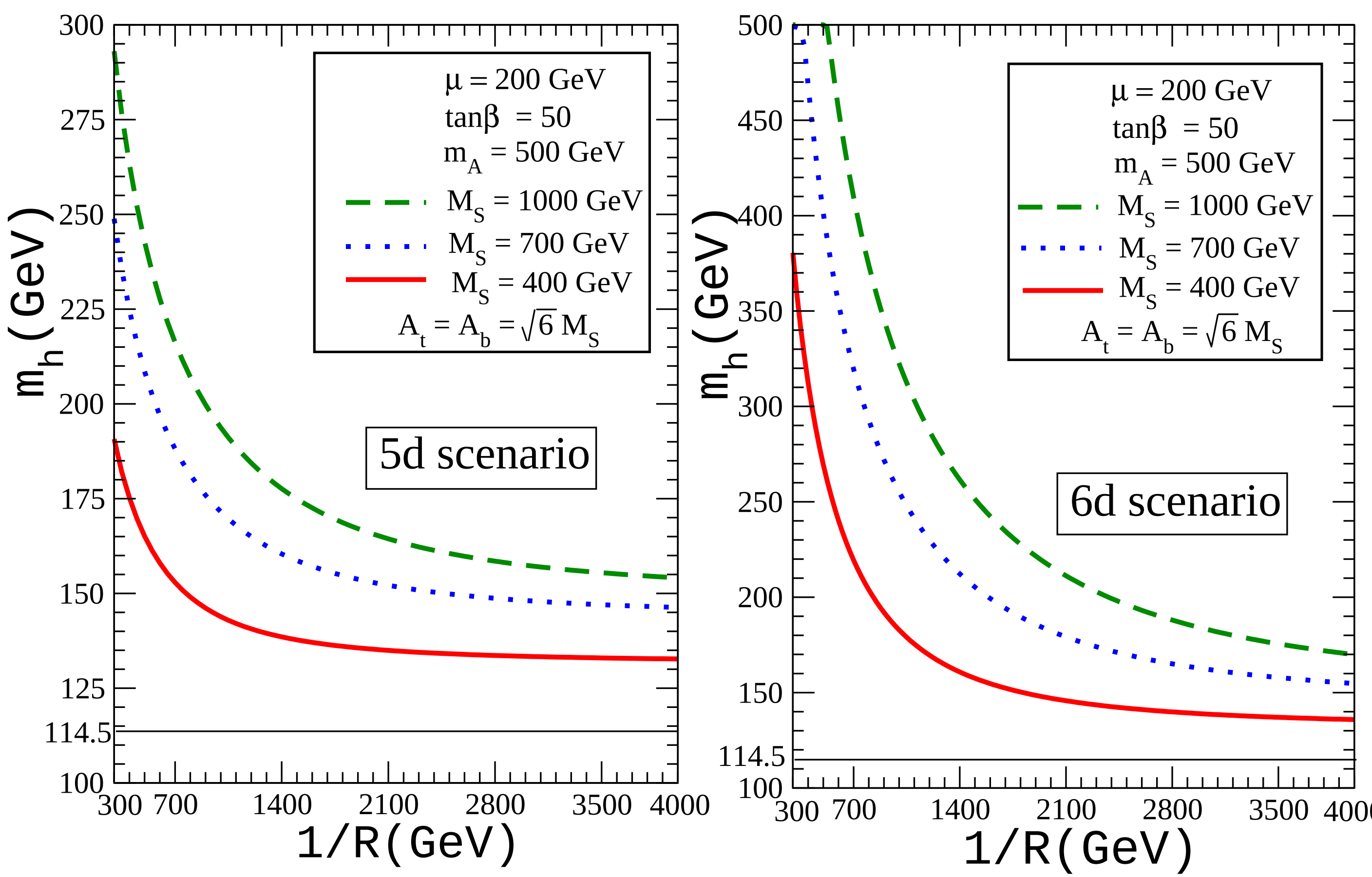


m_h vs low $\tan\beta$

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



Maximum m_h vs $1/R$



Conclusions and Outlook

- $\Delta m_h^2(\mathrm{KK}) \sim (60 \text{ GeV})^2 \times (M_S R)^2$. This is a 5d result, ignoring LR scalar mixing.
- Low $\tan\beta$ values can be revived, since tree contribution need not be that large, as there is a new loop contribution.
- Suppose $M_S = C/R$ (SS mechanism). 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.