Phenomenology of Light Higgses in supersymmetric left-right models

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Outline:

- Motivation
- Supersymmetric left-right models
- The lightest neutral Higgs
- The lightest doubly charged Higgs

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MOTIVATION

- In any extended model the Higgs sector is more complicated than in the MSSM.
- In MSSM $m_h \lesssim 130$ GeV. What about the extended models? Decay modes? Possible other light degrees of freedom?
- Left-right model and its supersymmetric version are very well based extensions of the SM and MSSM:
  - See-saw mechanism for neutrino masses.
  - The gauge group contains $B-L$: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. Thus the Lagrangian automatically conserves the R-parity.

SUPERSYMMETRIC LEFT-RIGHT MODELS

Chacko, Dutta, Kuchimanchi, Mohapatra, Muller, Aulakh, Benakli, Melfo, Rasin, Senjanovic, Babu, Couture, Francis, Frank, Hamidian, Kalman, Konig, Pospelov, Saif, Gunion, Huitu, Maalampi, Pandita, Puolamäki, Raidal,...

The superfields:

$$\Phi_{i=1,2} = \begin{pmatrix} \Phi_1^{(i)0} & \Phi_1^{(i)+} \\ \Phi_2^{(i)-} & \Phi_2^{(i)0} \end{pmatrix} \sim (1,2,2,0),$$

$$\Delta_{R,L} = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta^-_{R,L} & \Delta^0_{R,L} \\ \Delta^{--}_{R,L} & -\frac{1}{\sqrt{2}}\Delta^-_{R,L} \end{pmatrix} \sim \begin{cases} (1,1,3,-2) \\ (1,3,1,-2) \end{cases}$$

$$\delta_{R,L} = \begin{pmatrix} \frac{1}{\sqrt{2}}\delta^+_{R,L} & \delta^{++}_{R,L} \\ \delta^0_{R,L} & -\frac{1}{\sqrt{2}}\delta^+_{R,L} \end{pmatrix} \sim \begin{cases} (1,1,3,2) \\ (1,3,1,2) \end{cases},$$

and

$Q(2,1,1/3)$; $Q^c(1,2,-1/3)$; $L(2,1,-1)$; $L^c(1,2,1)$.

The possible vacuum expectation values:

$$\langle \Phi_1^{(1)0} \rangle = \kappa_1,\ \langle \Phi_2^{(2)0} \rangle = \kappa_2,\ \langle \Phi_2^{(1)0} \rangle = \kappa_1',\ \langle \Phi_1^{(2)0} \rangle = \kappa_2',$$
$$\langle \Delta_R^0 \rangle = v_{\Delta_R},\ \langle \Delta_L^0 \rangle = v_{\Delta_L},\ \langle \delta_R^0 \rangle = v_{\delta_R},\ \langle \delta_L^0 \rangle = v_{\delta_L},$$
$$\langle \tilde{\nu}_R \rangle = \sigma_R,\ \langle \tilde{\nu}_L \rangle = \sigma_L.$$

These have constraints:

- In order to have $\rho = 0.9998 \pm 0.0008$, $\langle \Delta_L \rangle$ and $\langle \delta_L \rangle$ must be small.
- $\kappa'_{1,2}$ contribute to the mixing of the charged gauge bosons and to FCNC and are usually assumed to vanish.
- $\kappa_{1,2}$ and σ_L can be at most of the order of weak scale,

$$m_{W_L}^2 = \frac{1}{2} g_L^2 \left(\kappa_1^2 + \kappa_2^2 + \kappa_1'^2 + \kappa_2'^2 + \sigma_L^2 + 2v_{\Delta_L}^2 + 2v_{\delta_L}^2 \right) + \mathcal{O}\left(\frac{\kappa'^2 m_{W_L}^2}{m_{W_R}^2} \right).$$

With the minimal particle content two possibilities:

- The model is renormalizable.
  - The R-parity is spontaneously broken and $m_R \sim m_{SUSY}$.
  - At least one of the sneutrinos has VEV in the minimum of the potential.
- Non-renormalizable terms are added in the model.
  - The R-parity may be preserved and one can have $m_R \gg m_{SUSY}$.

An alternative is to take nonminimal particle content: with $\Omega_L(1,3,1,0)$ and $\Omega_R(1,1,3,0)$ an intermediate $SU(2)_L \times U(1)_R \times U(1)_{B-L}$ -symmetry.

- The R-parity remains unbroken and $m_R \gg m_{SUSY}$.

The superpotential for renormalizable model with minimal particle content is

$$
\begin{aligned}
W &= h_{\delta_L} L^T i\tau_2 \delta_L L + h_{\Delta_R} L^{cT} i\tau_2 \Delta_R L^c \\
&+ h_{\phi_1 L} L^T i\tau_2 \Phi^{(1)} L^c + h_{\phi_2 L} L^T i\tau_2 \Phi^{(2)} L^c \\
&+ h_{\phi_1 Q} Q^T i\tau_2 \Phi^{(1)} Q^c + h_{\phi_2 Q} Q^T i\tau_2 \Phi^{(2)} Q^c \\
&+ \mu_1 \mathrm{Tr}(i\tau_2 \Phi^{(1)T} i\tau_2 \Phi^{(2)}) + \mu_1' \mathrm{Tr}(i\tau_2 \Phi^{(1)T} i\tau_2 \Phi^{(1)}) \\
&+ \mu_1'' \mathrm{Tr}(i\tau_2 \Phi^{(2)T} i\tau_2 \Phi^{(2)}) \\
&+ \mathrm{Tr}(\mu_{2L} \Delta_L \delta_L + \mu_{2R} \Delta_R \delta_R).
\end{aligned}
$$

The relevant nonrenormalizable terms are

$$
\begin{aligned}
W_{NR} &= \frac{1}{M_{Pl}} \Big(\alpha_{ij} \mathrm{Tr}\, \tau_2 \Phi^{(i)T} \tau_2 \Phi^{(j)} \Delta_R \delta_R \\
&+ \beta_{ij} \mathrm{Tr}\, \tau_2 \Phi^{(i)T} \tau_2 \Phi^{(j)} \,\mathrm{Tr}\, \Delta_R \delta_R \\
&+ \lambda_{ijkl} \mathrm{Tr}\, \tau_2 \Phi^{(i)T} \tau_2 \Phi^{(j)} \,\mathrm{Tr}\, \tau_2 \Phi^{(k)T} \tau_2 \Phi^{(l)} \Big) .
\end{aligned}
$$

Limits on triplet Yukawa couplings

$$
\frac{h^{ee}_{\text{triplet}}}{m_{H^{--}}} \lesssim 10^{-3}, \quad \frac{h^{ee}_{\text{triplet}} h^{\mu\mu}_{\text{triplet}}}{m^2_{H^{--}}} \lesssim 10^{-7},
$$

no limit on $h^{\tau\tau}_{\text{triplet}}$.

THE LIGHTEST NEUTRAL HIGGS

The lightest neutral Higgs mass upper limit for

1. R-parity is broken ($\langle\tilde{\nu}\rangle \neq 0.$),
2. R-parity is conserved because of extra triplets
3. or nonrenormalizable terms.

1. R-parity is broken.

$$
\begin{aligned}
m_h^2 &\leq \frac{1}{2v^2}\left[g_L^2(\omega_\kappa^2+\sigma_L^2)^2+g_R^2\omega_\kappa^4+g_{B-L}^2\sigma_L^4\right. \\
&\quad \left. +8(h_{\phi^{(1)}L}\kappa_1'+h_{\phi^{(2)}L}\kappa_2)^2\sigma_L^2+8h_{\Delta_L}^2\sigma_L^4\right] \\
&\rightarrow \frac{1}{2}(g_L^2+g_R^2)(\kappa_1^2+\kappa_2^2)\cos^2 2\beta \\
&= \left(1+\frac{g_R^2}{g_L^2}\right)m_{W_L}^2\cos^2 2\beta \\
&\quad \text{for } \ \kappa_{1,2}', \sigma_L, v_{\Delta_L,\delta_L} \rightarrow 0,
\end{aligned}
$$

where

$$\omega_\kappa^2 = \kappa_1^2 - \kappa_2^2 - \kappa_1'^2 + \kappa_2'^2, \quad g_R \geq 0.55 g_L,$$

and $v^2 = \kappa_1^2 + \kappa_1'^2 + \kappa_2^2 + \kappa_2'^2 + \sigma_L^2$.

2. R-parity is conserved because of extra triplets.

The bound is found from previous by taking $\sigma_L \to 0$.

3. R-parity is conserved because of nonrenormalizable terms. The contribution of the nonrenormalizable terms to the Higgs mass bound is of the form

$$\mathcal{O}(v_R^2/M_{\rm Pl}^2)v^2 + \mathcal{O}(1/M_{\rm Pl}^2)v^4.$$

Numerically this contribution to m_h is negligible for $v_{\Delta_R,\delta_R} \sim v_R \sim 10^{10}$ GeV.

- Radiative corrections:
  In the approximation where the b-quark contribution can be neglected and

$$|m^2_{\tilde{t}_1} - m^2_{\tilde{t}_2}| \ll |m^2_{\tilde{t}_1} + m^2_{\tilde{t}_2}|,$$

  the upper bound reduces to

$$\begin{aligned} m_h^2 \quad \leq \quad & \frac{1}{2}\left[(g_L^2 + g_R^2)\left(\kappa_1^2 + \kappa_2^2\right)\cos^2 2\beta \right. \\ & + \frac{3g_L^2 m_t^4}{8\pi^2 m^2_{W_L}}\left(\ln(\frac{m^2_{\tilde{t}_1} m^2_{\tilde{t}_2}}{m_t^4}) \right. \\ & \left.\left. + 2\frac{\tilde{A}_t^2}{M_s^2}(1 - \frac{\tilde{A}_t^2}{12M_s^2}) - 8\frac{\mu_1''^4}{3M_s^4}\right)\right] \end{aligned}$$

  where $\tilde{A}_t^2 = A_t - \mu_1 \cot\beta$, and $2M_s^2 = m^2_{\tilde{t}_1} + m^2_{\tilde{t}_2}$. The upper bound is maximised by

$$|\tilde{A}_t| = (\sqrt{6})M_s$$

  for a given value of μ_1''.

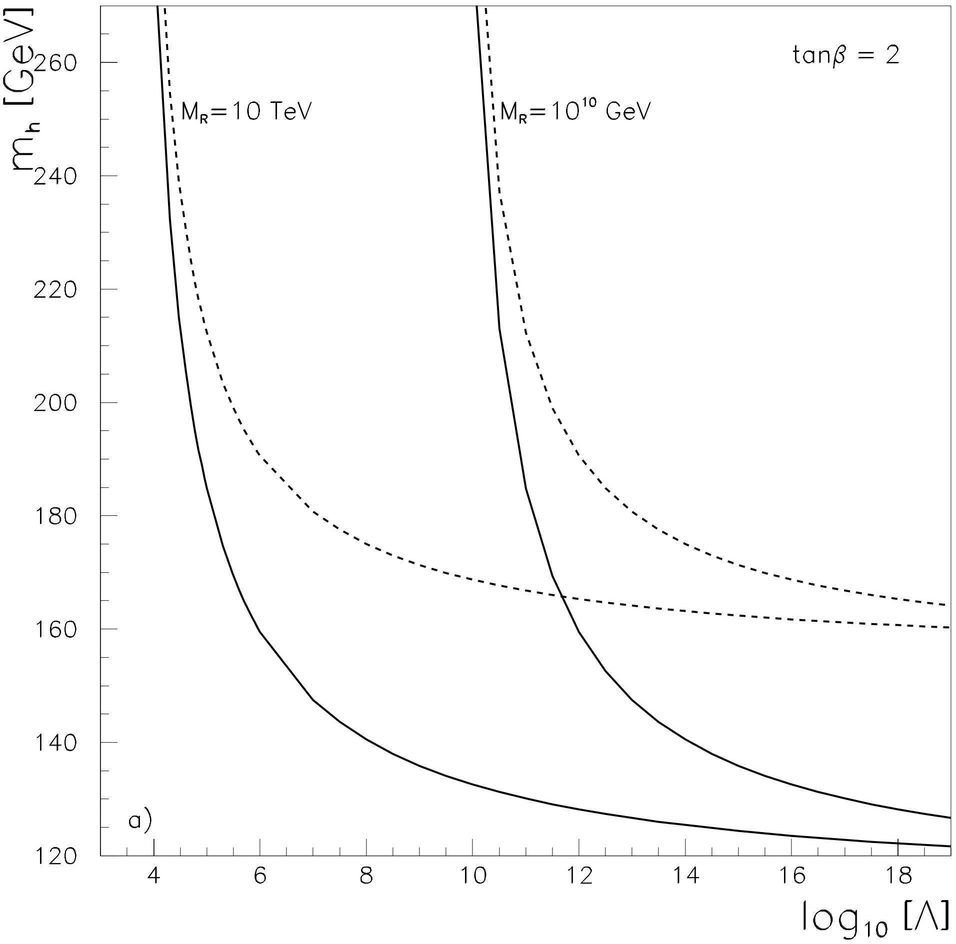
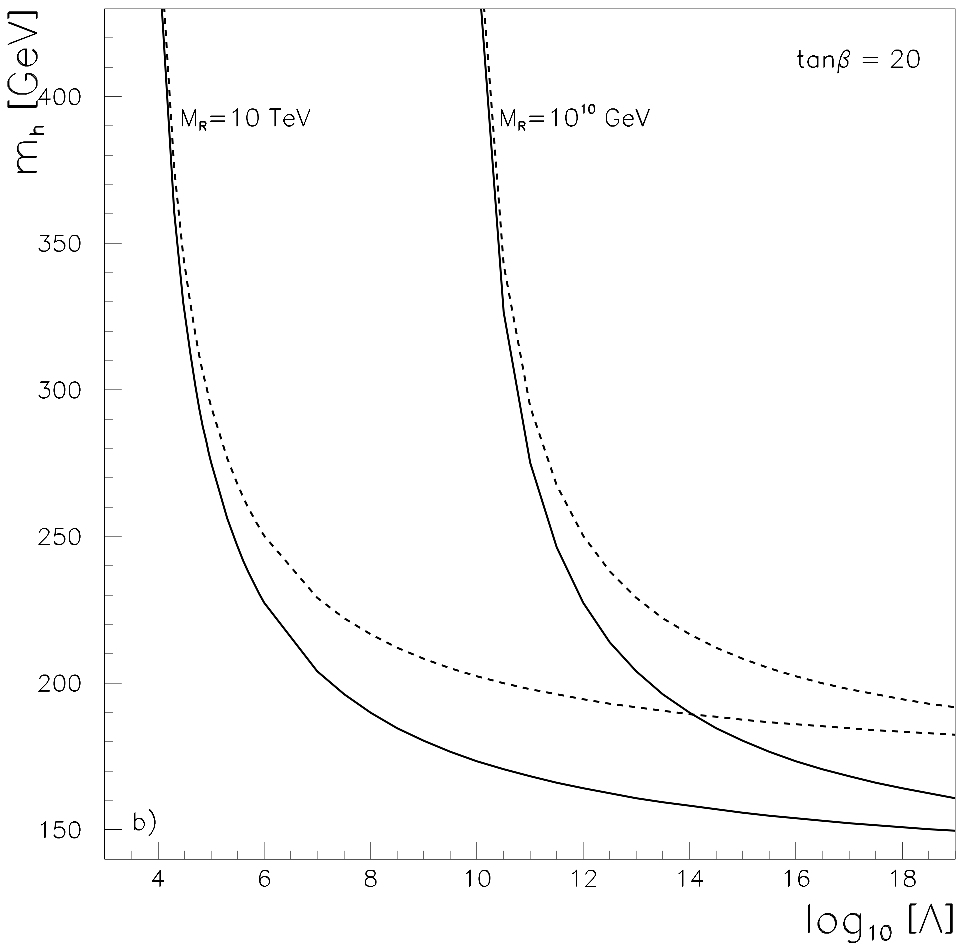


Figure 1: The bi- and trilinear soft supersymmetry breaking parameters are 1 TeV (solid line) and 10 TeV (dashed line). Supersymmetric Higgs mixing parameters are assumed to vanish, and $m_{top} = 175$ GeV.



m_h [GeV]
400
350
300
250
200
150
M_R=10 TeV
$M_R=10^{10}$ GeV
tanβ = 20
b)
4
6
8
10
12
14
16
18
$\log_{10}$ [Λ]

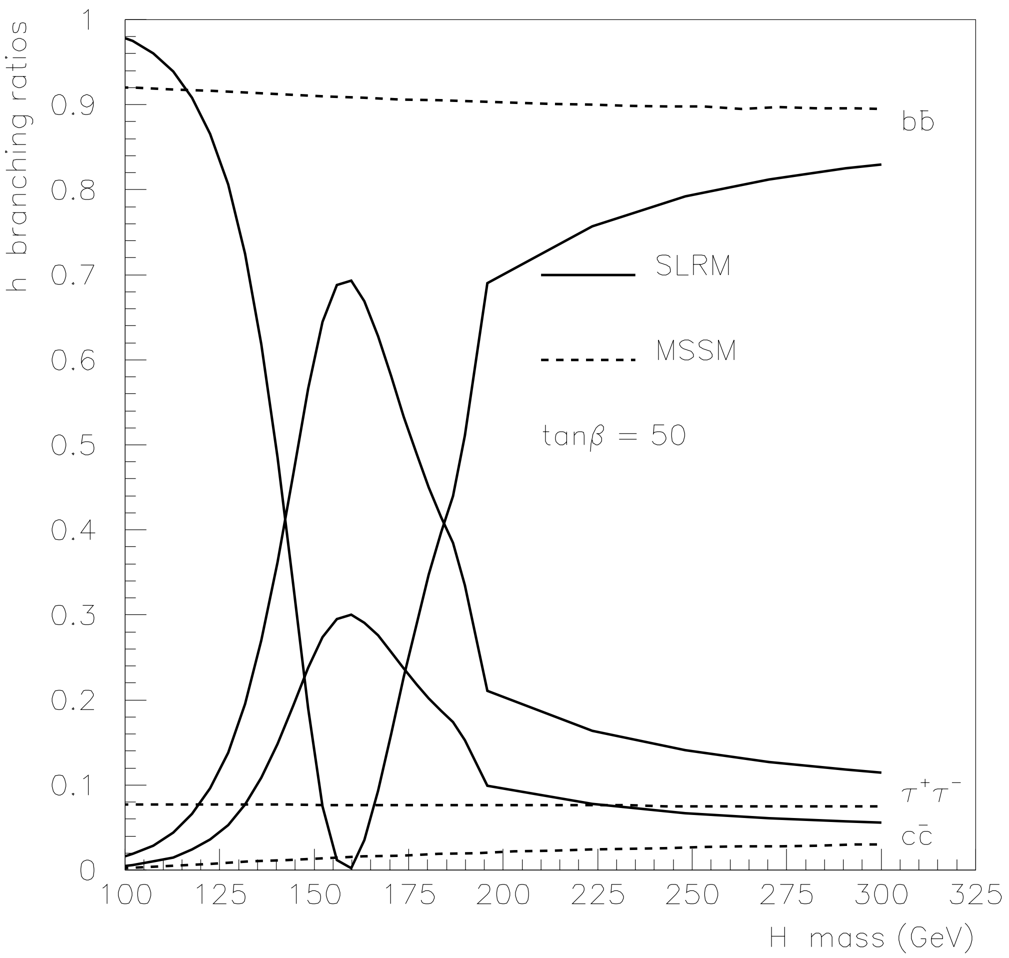


Figure 2: The branching ratio of the lightest neutral CP even Higgs boson h to fermion pairs in SLRM (solid curves) as a function of the second lightest Higgs H mass. The tree level mass of the lightest Higgs is $\sim$78 GeV and $\tan\beta = 50$. The dotted curves correspond to MSSM.

Decoupling:

- When the lepton sector is mixed with the Higgs sector due to the breaking of R-parity, one might expect that the couplings of the lightest neutral Higgs with leptons differ from the Standard Model.
- Because of the FCNC problem in the LR models, the masses of the FCNC Higgses have to be $\gtrsim 1$ TeV.
- One can show that in the physically relevant decoupling limit, the couplings responsible for Higgs decays to the charged leptons or quarks are the same as in the Standard Model.
- If kinematically possible, the lightest Higgs could decay to a τ + heavier chargino.

THE LIGHTEST DOUBLY CHARGED HIGGS

Rizzo, Lusignoli, Petrarca, Swartz, Gunion, Grifols, Mendez, Schuler, Lepore, Thorndyke, Nadeau, London, Accomando, Barenboim, Huitu, Maalampi, Pietilä, Puolamäki, Raidal, Cuypers,...

- The neutral Higgs sector contains one relatively light Higgs boson, which may be heavier than in the MSSM and which has SM like couplings with the fermions of the model.
- SUSY LR models contain doubly charged scalars. One of these may be light in the models with minimal particle content.
- Strong constraints on the parameters follow from the requirement that all the mass^2 of scalars remain nonnegative.

1. Constraints in the model with broken R-parity.

$$-\frac{1}{2}g_L^2(\kappa_2^2-\kappa_1^2)-\frac{1}{2}g_R^2D-(h_{\chi L}^2\kappa_2^2-h_{\phi L}^2\kappa_1^2)\sigma_R^2\geq 0,$$

where $D=2v_{\Delta_R}^2-2v_{\delta_R}^2-\sigma_R^2+\kappa_2^2-\kappa_1^2$.
If the terms with bidoublet lepton Yukawa couplings are ignored, and $\tan\beta>1$,
$D<0$ and thus $2v_{\delta_R}^2+\sigma_R^2>2v_{\Delta_R}^2$.

Other constraints:

$$(A_\Delta v_{\Delta_R}-4h_{\Delta_R}^2v_{\Delta_R}^2+h_{\Delta_R}\mu_{2r}v_{\delta_R})\sigma_R^2$$
$$+g_R^2D(v_{\delta_R}^2-v_{\Delta_R}^2)\geq 0,$$
$$A_\Delta v_{\Delta_R}+h_{\Delta_R}\mu_{2r}v_{\delta_R}\geq 0.$$

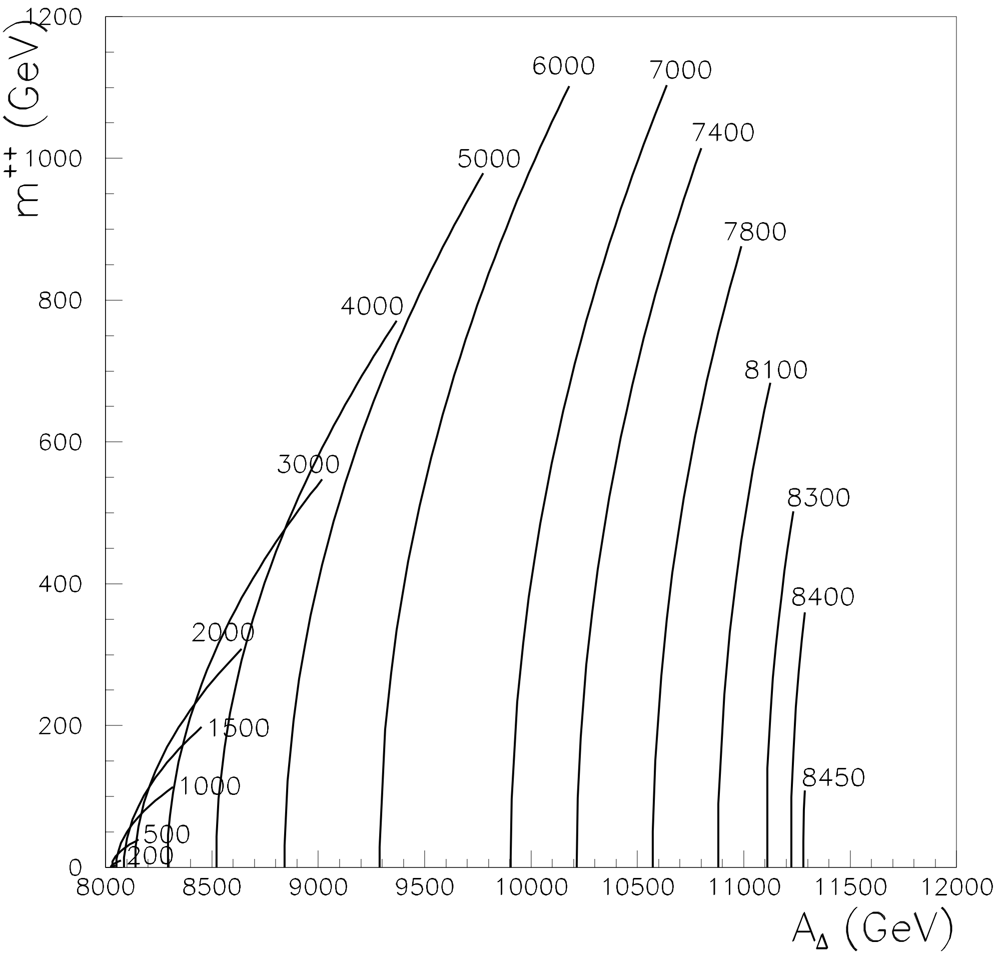


Figure 3: The mass m^{++} of the lightest doubly charged Higgs boson as a function of the soft trilinear coupling A_Δ for different values of the right-handed sneutrino VEVs σ_R. σ_R is varied in its allowed range of 100 GeV to 8.45 TeV as indicated in the figure.

2. Nonrenormalizable model with conserved R-parity.

$$0 < \frac{1}{2} g_R^2 (v_{\delta_R}^2 - v_{\Delta_R}^2)(\kappa_2^2 - \kappa_1^2).$$

This gives a condition $v_{\delta_R}/v_{\Delta_R} > 1$.

$$0 < \frac{1}{2}[-g_L^2(\kappa_2^2 - \kappa_1^2) - g_R^2(2v_{\Delta_R}^2 - 2v_{\delta_R}^2 - \kappa_2^2 + \kappa_1^2)]$$

Thus $D = 2v_{\Delta_R}^2 - 2v_{\delta_R}^2 + \kappa_2^2 - \kappa_1^2 < 0$.

$$\begin{aligned} 0 &< m^2_{H_1^{++}} \\ &< [-g_R^2(v_{\Delta_R}^2 - v_{\delta_R}^2)D]/(v_{\Delta_R}^2 + v_{\delta_R}^2) \\ &\quad + \frac{1}{M} 8 b_R v_{\Delta_R} v_{\delta_R} \mu_{2R} + \frac{1}{M^2} 4 b_R (2a_R + b_R) v_{\Delta_R}^2 \end{aligned}$$

Thus $b_R \neq 0$.

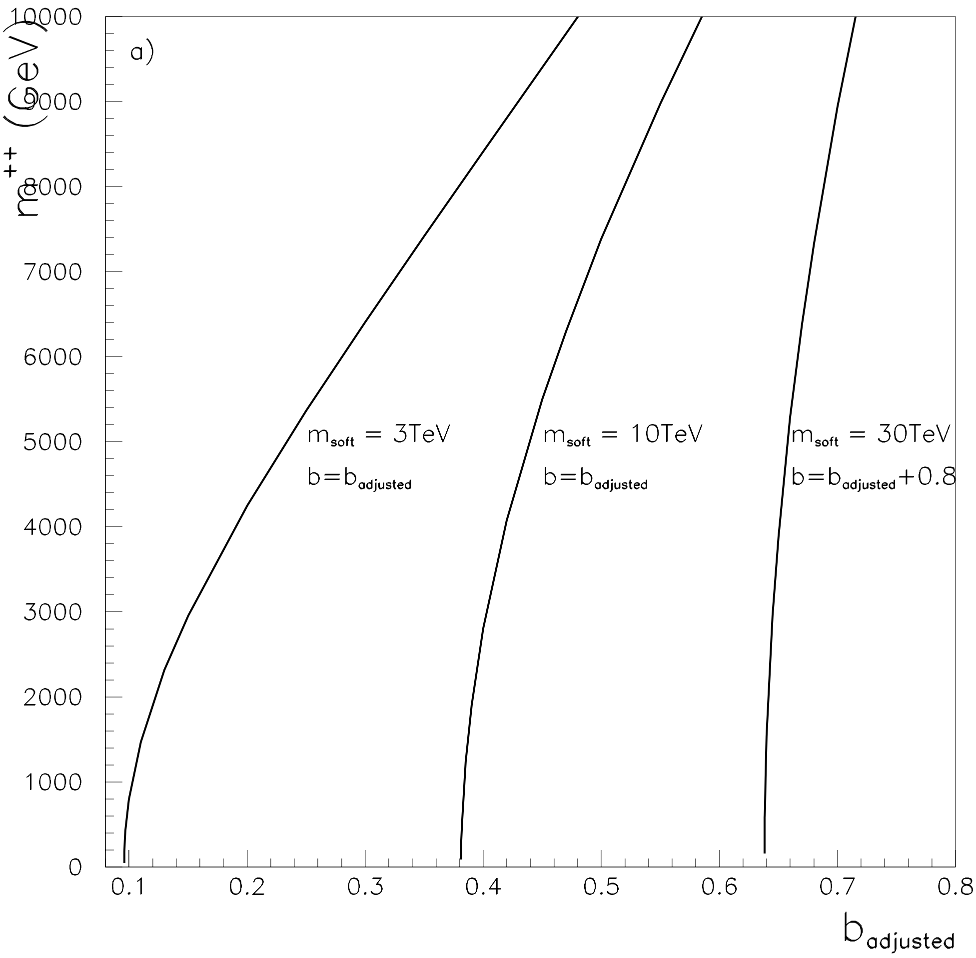


Figure 4: Mass of the doubly charged Higgs as a function of the nonrenormalizable b_R-parameter. $v_R^2/M = 10^4$ GeV, $M_R = 10^7$ GeV and $D = m_{soft}^2$. $\tan\beta = 50$, $M = 10^{10}$ GeV, $\mu_{2R} = 1$ TeV and $\mu_1 = \mu_1' = \mu_1'' = 500$ GeV.

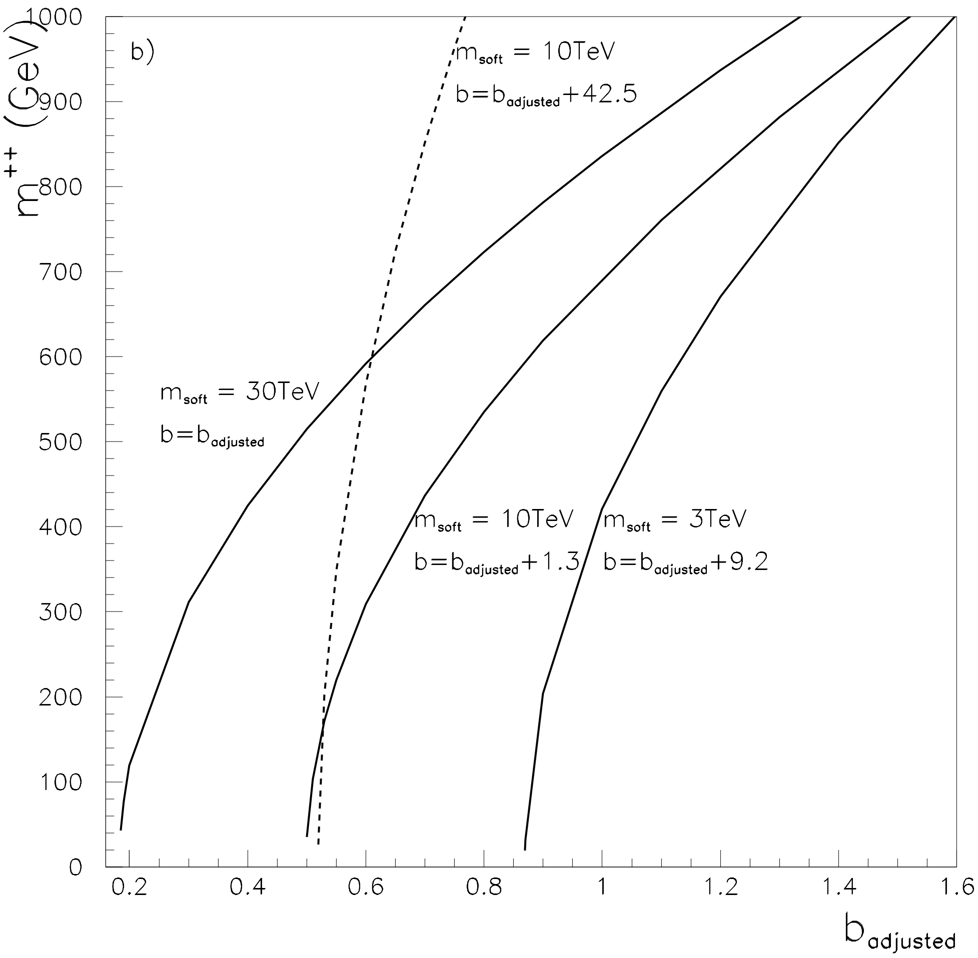


Figure 5: $v_R^2/M = 10^2$ GeV, $M_R = 10^6$ GeV and $D = (3 \text{ TeV})^2$ (solid line), except for $m_{soft} = 10$ TeV also $D = (10$ TeV^2 is shown (dashed line). $\tan\beta = 50$, $M = 10^{10}$ GeV, $\mu_{2R} = 1$ TeV and $\mu_1 = \mu_1' = \mu_1'' = 500$ GeV.

- Kinematically, production of a single doubly charged scalar would be favoured.
  - The cross section in e^+e^- collisions depends on the coupling between electrons and triplet Higgses.
  - In l^-l^- colliders the doubly charged Higgs can be produced as an s-channel resonance for nonzero triplet couplings.
- The advantage of pair production of the doubly charged scalars is the model independence.
  - It can occur even if W_R is very heavy, as in the nonrenormalizable case, or the triplet Yukawa couplings are very small.
  - If kinematically allowed, the doubly charged Higgses can be produced in $e^+e^- \to \gamma, Z_L \to H^{++}H^{--}$. The detection is possible close to the kinematical limit.

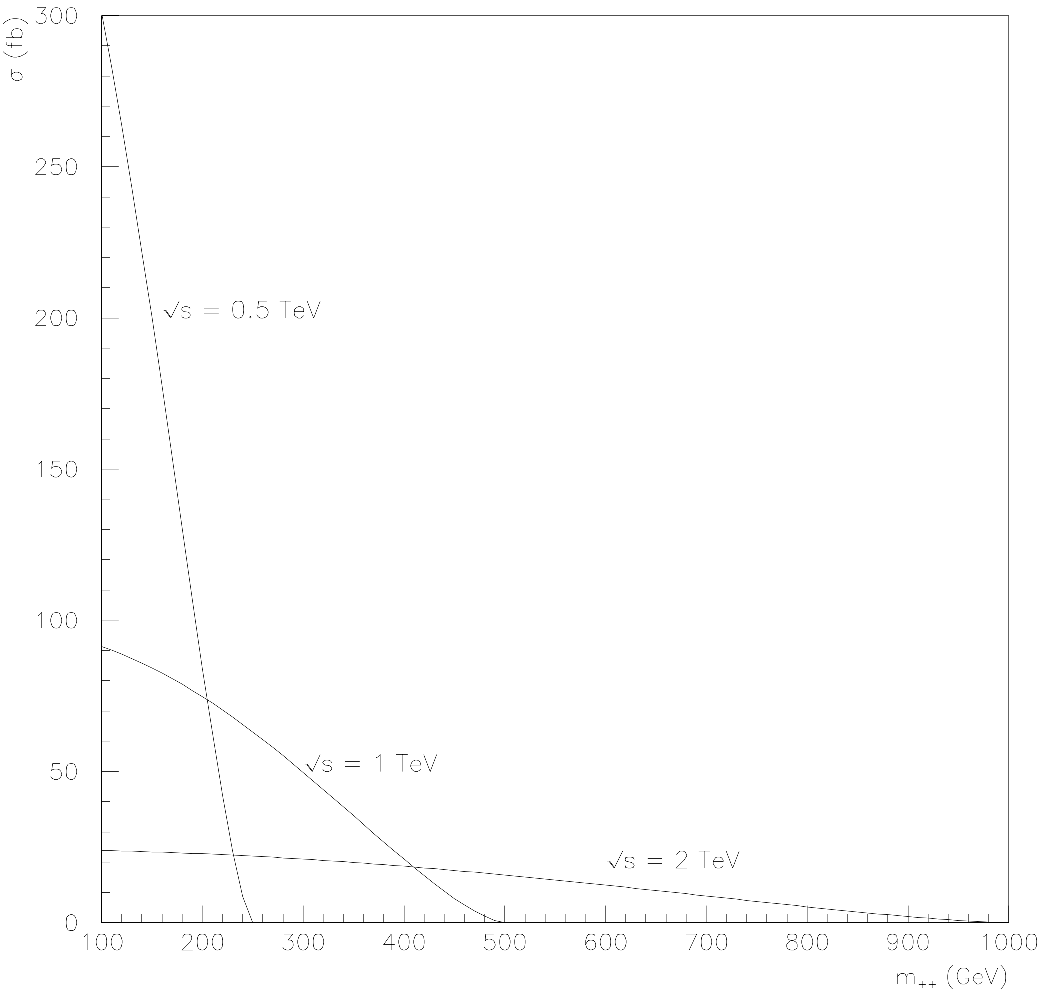


Figure 6: Cross section for $e^+e^- \rightarrow H^{++}H^{--}$.

CONCLUSIONS

- If Higgs boson, which is heavier than the MSSM Higgs boson is found, one should consider extended models.
- The SLRM with minimal particle content typically contains a light doubly charged Higgs boson.