Higgs Boson spectrum in Left-Right Supersymmetric Models

In collaboration with K. S. Babu (arxiv:1412.8714)

Ayon Patra
Seoul National University of Science & Technology

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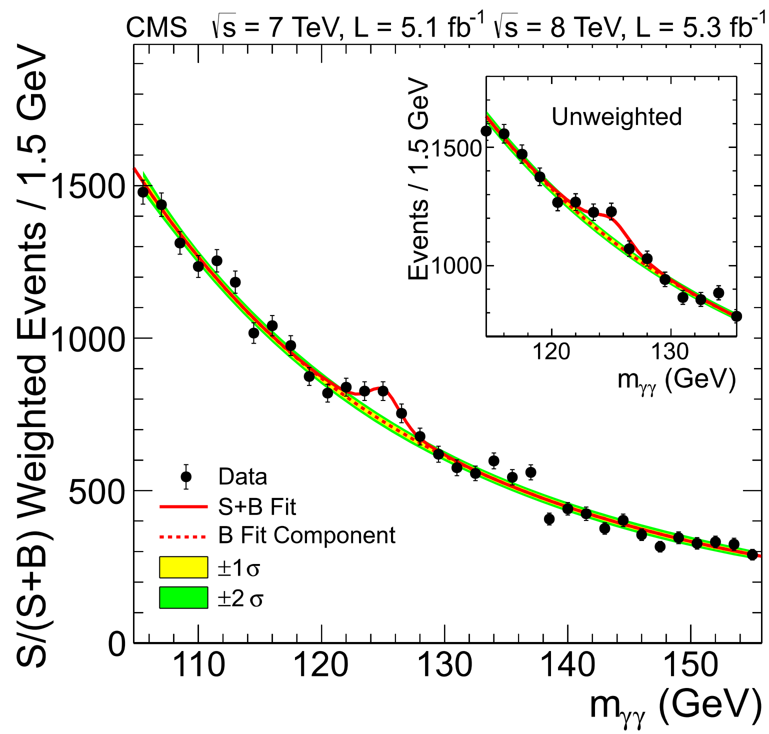
* For the Higgs spectrum of universal seesaw and E_6-inspired models please refer to our paper.

INTRODUCTION

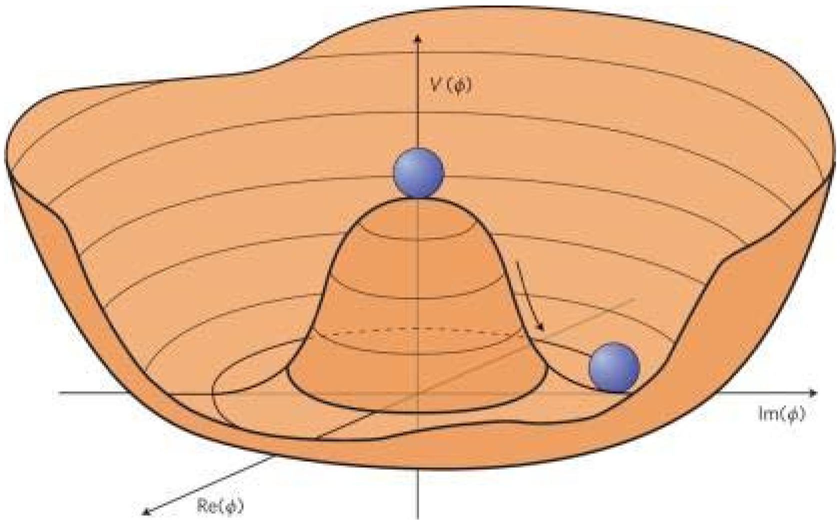
A Standard Model-like Higgs Boson was discovered at the Large Hadron Collider in 2012.

Found to have a mass of around 125.09±0.24 GeV.



CMS Higgs discovery channel

- Discovery of Standard Model-like Higgs Boson strongly supports the spontaneous symmetry breaking mechanism.
- An added impetus to look for models with varying symmetry breaking mechanism and study their Higgs sector.



- Left-right supersymmetric models with different symmetry breaking sectors.
- Many of these supersymmetric models are constructed and analyzed here for the first time.
- Can easily explain the observed Higgs boson mass without much fine tuning.

WHY LEFT-RIGHT SYMMETRY AND WHY SUPERSYMMETRY?

THE STANDARD MODEL HAS BEEN VERY SUCCESSFUL BUT THERE REMAINS SOME UNANSWERED QUESTIONS.

- ORIGIN OF PARITY VIOLATION.
- STRONG CP PROBLEM.
- ORIGIN OF NEUTRINO MASS.
- DARK MATTER.

J. C. Pati and A. Salam, Phys. Rev. D (1973) ; R. N. Mohapatra and J. C. Pati, Phys. Rev. D (1975) ; G. Senjanovic and R. N. Mohapatra, Phys. Rev. D (1975)

Origin of parity violation

- Gauge group of Standard Model is $SU(3)_c \times SU(2)_L \times U(1)_Y$.
- Parity is explicitly broken.
- It would be desirable to understand the origin of parity violation as spontaneous.

Strong CP Problem

- CP violation is seen in the weak forces sector (e.g. $K^0 - \overline{K}^0$ mixing) but not in strong forces.
- One can write CP and P violating term in the QCD Lagrangian

$$\mathscr{L}_{QCD} = \frac{\theta g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

- Actual physical observable is

$$\bar{\theta} = \theta + \text{Arg}(\text{Det}\, M_q) \,, \qquad M_q \rightarrow \text{quark mass matrix}$$

- Experimental limit from neutron electric dipole moment measurements constraints $\bar{\theta} < 10^{-10}$.
- This is the Strong CP problem.

Neutrino Oscillation

- Neutrinos of different flavor (ν_e, ν_μ, ν_τ) can oscillate into one another due to non-zero neutrino mass and mixing angles.
- Flavor eigenstates of neutrinos are linear combination of field of three (or more) neutrinos (ν_j) with non-zero mass.

$$\nu_{lL}(x) = \sum_j U_{lj}\nu_{jL}(x) \qquad l = e, \mu, \tau$$

- From current experimental results, defining $\Delta m_{ij}^2 = m_i^2 - m_j^2$

$$\Delta m_{21}^2 = 7.59^{+0.20}_{-0.18} \times 10^{-5}\ eV^2$$

$$\Delta m_{31}^2 = \begin{cases} (2.45 \pm 0.09) \times 10^{-3}\ eV^2, & \text{for } m_1 < m_2 < m_3 \\ -(2.34^{+0.10}_{-0.09}) \times 10^{-3}\ eV^2, & \text{for } m_3 < m_1 < m_2 \end{cases}$$

- Extension of Standard Model with a right-handed neutrino (N^C) which is a singlet under $SU(2)_L$ will have terms

$$\mathcal{L}_{\nu-mass} = m_D \nu_L N^C + \frac{1}{2} m_R N^C N^C , \qquad m_D = Y_\nu \mathrm{v}$$

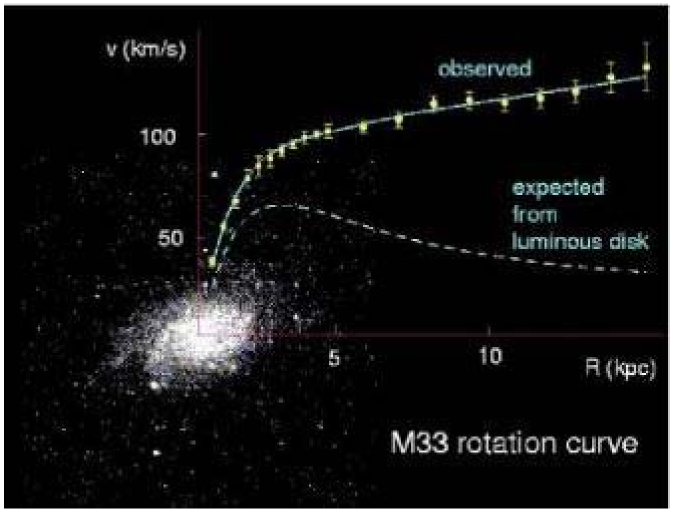
- Solving for the light neutrino mass gives

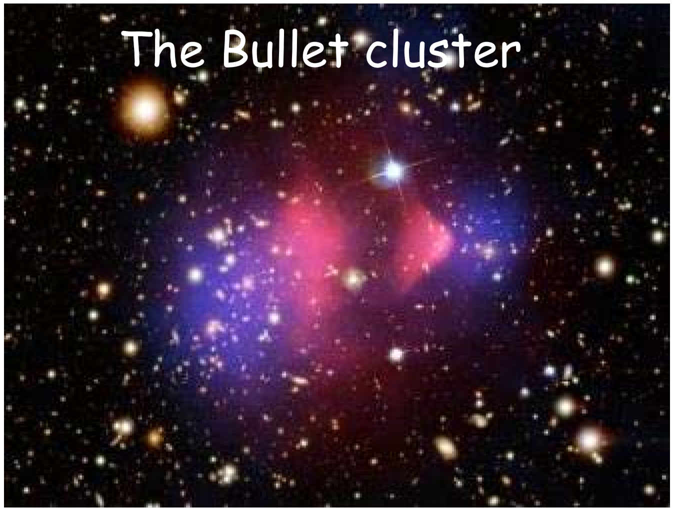
$$m_\nu \simeq \frac{m_D^2}{m_R}$$

We can get $m_\nu \sim 0.1$ eV with $m_R \sim 10^4$ GeV and $Y_\nu \sim 10^{-5}$.

- This is the **Seesaw** mechanism.

◆ DARK MATTER





- Roughly 27% of our universe is made up of invisible Dark matter which exerts gravitational force on other objects.
- Galactic rotation curves and recent observation of the Bullet cluster have given undeniable proof of the existence of dark matter.
- Standard Model has no such invisible particles with the required properties.

Left-Right Supersymmetric model

- ✓ Solve the hierarchy problem.
- ✓ Explain the origin of parity violation and solve the strong CP problem.
- ✓ Contain right-handed neutrinos which can help generate a small left-handed neutrino mass via the Seesaw mechanism.
- ✓ If R-parity is conserved, it can prevent the lightest supersymmetric particle (LSP) from decaying and can be a dark matter candidate with the required properties.

Higgs Boson spectrum in Supersymmetric Left-right models.

- Supersymmetric version of left-right symmetric model with gauge group extended to $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.
- Electric charge defined as $Q = I_{3L} + I_{3R} + \frac{B-L}{2}$.
- The $SU(2)_R \times U(1)_{B-L}$ symmetry is broken spontaneously at a high scale leading to observed parity asymmetry at low scale.
- Consider several variations with different symmetry breaking sector.
- Higgs boson mass spectrum is calculated in each case.

- The common Quark and Lepton sectors are given as

$$Q\,(3,2,1,1/3) = \begin{bmatrix} u \\ d \end{bmatrix} \quad ; \quad Q^c\,(3^*,1,2,-1/3) = \begin{bmatrix} d^c \\ -u^c \end{bmatrix}$$

$$L\,(1,2,1,-1) = \begin{bmatrix} \nu_e \\ e \end{bmatrix} \quad ; \quad L^c\,(1,1,2,1) = \begin{bmatrix} e^c \\ -\nu_e{}^c \end{bmatrix}$$

  - The Right-handed quarks and leptons are doublets of $SU(2)_R$.
  - Presence of Right-handed neutrino.
- Each model has to explain
  - Consistent symmetry breaking mechanism.
  - Quarks and Lepton masses and CKM mixing.
  - Small neutrino mass generation.

Models with triplet and bidoublet Higgs fields

The Higgs sector is given as

$$\Delta^c(1,1,3,-2) = \begin{bmatrix} \frac{\delta^{c-}}{\sqrt{2}} & \delta^{c0} \\ \delta^{c--} & -\frac{\delta^{c-}}{\sqrt{2}} \end{bmatrix} \qquad \bar{\Delta}^c(1,1,3,2) = \begin{bmatrix} \frac{\bar{\delta}^{c+}}{\sqrt{2}} & \bar{\delta}^{c++} \\ \bar{\delta}^{c0} & -\frac{\bar{\delta}^{c+}}{\sqrt{2}} \end{bmatrix}$$

$$\Delta(1,3,1,2) = \begin{bmatrix} \frac{\delta^{+}}{\sqrt{2}} & \delta^{++} \\ \delta^{0} & -\frac{\delta^{+}}{\sqrt{2}} \end{bmatrix} \qquad \bar{\Delta}(1,3,1,-2) = \begin{bmatrix} \frac{\bar{\delta}^{-}}{\sqrt{2}} & \bar{\delta}^{0} \\ \bar{\delta}^{--} & -\frac{\bar{\delta}^{-}}{\sqrt{2}} \end{bmatrix}$$

$$\Phi_a(1,2,2,0) = \begin{bmatrix} \phi_1^{+} & \phi_2^{0} \\ \phi_1^{0} & \phi_2^{-} \end{bmatrix}_a \left(a = 1,2\right) \qquad S\,(1,1,1,0)$$

- The $SU(2)_R$ Higgs boson triplets (Δ^c and $\overline{\Delta}^c$) are needed to break $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ without inducing R-Parity violating couplings.
- The $SU(2)_L$ Higgs boson triplets (Δ and $\overline{\Delta}$) are needed for parity invariance.
- The two bi-doublet Higgs fields Φ_a generate the quark and lepton masses and the CKM mixings.
- The optional singlet field S makes sure that the right-handed symmetry breaking may occurs in the supersymmetric limit.

The non-zero vacuum expectation values of the fields are

$$\left\langle \delta^{c^0} \right\rangle = v_R, \quad \left\langle \overline{\delta}^{c0} \right\rangle = \overline{v}_R, \quad \left\langle \phi^0_{1_a} \right\rangle = v_{u_a}, \quad \left\langle \phi^0_{2_a} \right\rangle = v_{d_a}$$

where $v_R, \overline{v}_R >> v_u, v_d$.

The Yukawa couplings terms in the superpotential are

$$W = Y_u Q^T \tau_2 \phi_1 \tau_2 Q^c + Y_d Q^T \tau_2 \phi_2 \tau_2 Q^c + Y_\nu L^T \tau_2 \phi_1 \tau_2 L^c + Y_l L^T \tau_2 \phi_2 \tau_2 L^c$$
$$+ i(f^* L^T \tau_2 \Delta L + f L^{cT} \tau_2 \Delta^c L^c)$$

- ν_e^c is heavy and generates small neutrino mass.

The Higgs boson only superpotential is

$$W_{Higgs} = S\left[\mathrm{Tr}(\lambda^* \Delta\overline{\Delta} + \lambda \Delta^c \overline{\Delta}^c) + \lambda'_{ab}\mathrm{Tr}(\phi_a^T \tau_2 \phi_b \tau_2) - M_R^2\right]$$
$$+ \mathrm{Tr}\left[\mu_1 \Delta\overline{\Delta} + \mu_2 \Delta^c \overline{\Delta}^c\right] + \frac{\mu}{2}\mathrm{Tr}(\phi_a^T \tau_2 \phi_b \tau_2) + \frac{\mu_S}{2} S^2 + \frac{\kappa}{3} S^3$$

The Superpotential in invariant under parity transformation.

- Yukawa coupling matrices are hermitian.
- λ'_{ab} ,μ_S, μ and M_R^2 are real and $\mu_1 = \mu_2^*$.
- If the vev of S and the bi-doublets are real, it will solve the Strong CP and SUSY CP problem.

A pair of triplets, a bidoublet and a singlet

- Only one bidoublet for simplicity.
- Write the Higgs potential as

$$V_{Higgs} = V_F + V_D + V_{Soft}$$

- Calculate the minimization conditions.

- Change our basis as

$$\rho_1 = \frac{v_1\phi_1^0 + v_2\phi_2^0}{\sqrt{v_1^2 + v_2^2}}, \; \rho_2 = \frac{v_2\phi_1^0 - v_1\phi_2^0}{\sqrt{v_1^2 + v_2^2}}, \; \rho_3 = \frac{v_R\delta^{c0} + \overline{v}_R\overline{\delta}^{c0}}{\sqrt{v_R^2 + \overline{v}_R^2}}, \; \rho_4 = \frac{\overline{v}_R\delta^{c0} - v_R\overline{\delta}^{c0}}{\sqrt{v_R^2 + \overline{v}_R^2}}.$$

- ρ_1 gets a non-zero electroweak vev.
- Calculate the scalar Higgs boson mass-squared matrix in the basis $(\mathrm{Re}\rho_1, \mathrm{Re}\rho_2, \mathrm{Re}\rho_3, \mathrm{Re}\rho_4, \mathrm{Re}\,S)$.

Higgs Potential

$$
\begin{aligned}
V_F &= \mathrm{Tr}\left|(\lambda\Delta\overline{\Delta}) + (\lambda^*\Delta^c\overline{\Delta}^c) + \frac{\lambda'}{2}(\Phi^T\tau_2\Phi\tau_2) - M^2 + \mu_S S + \kappa S^2\right|^2 + \mathrm{Tr}\left|\mu\Phi + \lambda' S\Phi\right|^2 \\
&+ \mathrm{Tr}\left[|\mu_1\Delta + \lambda S\Delta|^2 + \left|\mu_1\overline{\Delta} + \lambda S\overline{\Delta}\right|^2 + |\mu_2\Delta^c + \lambda^* S\Delta^c|^2\right. \\
&+ \left.\left|\mu_2\overline{\Delta}^c + \lambda^* S\overline{\Delta}^c\right|^2\right], \\
V_D &= \frac{g_L^2}{8}\sum_{a=1}^{3}\left|\mathrm{Tr}(2\Delta^\dagger\tau_a\Delta + 2\overline{\Delta}^\dagger\tau_a\overline{\Delta} + \Phi^\dagger\tau_a\Phi)\right|^2 \\
&+ \frac{g_R^2}{8}\sum_{a=1}^{3}\left|\mathrm{Tr}(2\Delta^{c\dagger}\tau_a\Delta^c + 2\overline{\Delta^c}^\dagger\tau_a\overline{\Delta}^c + \Phi^*\tau_a\Phi^T)\right|^2 \\
&+ \frac{g_V^2}{2}\left|\mathrm{Tr}(\Delta^\dagger\Delta - \overline{\Delta}^\dagger\overline{\Delta} - \Delta^{c\dagger}\Delta^c + \overline{\Delta^c}^\dagger\overline{\Delta}^c)\right|^2, \\
V_{Soft} &= m_1^2\mathrm{Tr}(\Delta^{c\dagger}\Delta^c) + m_2^2\mathrm{Tr}(\overline{\Delta}^{c\dagger}\overline{\Delta}^c) + m_3^2\mathrm{Tr}(\Delta^\dagger\Delta) + m_4^2\mathrm{Tr}(\overline{\Delta}^\dagger\overline{\Delta}) \\
&+ m_S^2|S|^2 + m_5^2\mathrm{Tr}(\Phi^\dagger\Phi) + [\lambda A_\lambda S\mathrm{Tr}(\Delta\overline{\Delta} + \Delta^c\overline{\Delta}^c) + h.c.] \\
&+ [\lambda' A_{\lambda'} S\mathrm{Tr}(\Phi^T\tau_2\Phi\tau_2) + h.c.] + (\lambda C_\lambda M^2 S + h.c.) + \left(\mu_S B_S S^2 + h.c.\right) \\
&+ \left[\mu_1 B_1\mathrm{Tr}\left(\Delta\overline{\Delta}\right) + \mu_2 B_2\mathrm{Tr}\left(\Delta^c\overline{\Delta}^c\right) + \mu B\mathrm{Tr}\left(\Phi^T\tau_2\Phi\tau_2\right) + \kappa A_\kappa S^3 + h.c.\right].
\end{aligned}
$$

$$M_{11} = \frac{g_L^2(v_1^2-v_2^2)^2 + g_R^2(v_1^2-v_2^2)^2 + 8v_1^2v_2^2\lambda'^2}{2(v_1^2+v_2^2)},$$

$$M_{12} = \frac{v_1v_2(v_1^2-v_2^2)(g_L^2+g_R^2-2\lambda'^2)}{(v_1^2+v_2^2)},$$

$$M_{13} = \frac{g_R^2(v_1^2-v_2^2)(v_R^2-\overline{v}_R^2) - 4\lambda\lambda' v_1v_2v_R\overline{v}_R}{\sqrt{(v_1^2+v_2^2)(v_R^2+\overline{v}_R^2)}},$$

$$M_{14} = \frac{2[g_R^2(v_1^2-v_2^2)v_R\overline{v}_R - \lambda\lambda' v_1v_2(v_R^2-\overline{v}_R^2)]}{\sqrt{(v_1^2+v_2^2)(v_R^2+\overline{v}_R^2)}},$$

$$M_{15} = \frac{2\lambda'[-2A_{\lambda'}v_1v_2 + (v_1^2+v_2^2)(v_S\lambda'+\mu) - (\mu_S+2\kappa v_S)v_1v_2]}{\sqrt{v_1^2+v_2^2}},$$

$$\begin{aligned} M_{22} &= \Big[(2g_L^2+2g_R^2)v_1^2v_2^2 + 2m_5^2(v_1^2+v_2^2) + \lambda'^2(v_1^2-v_2^2)^2 + 2\lambda'^2v_S^2(v_1^2+v_2^2) \\ &+ 4\lambda'\mu v_S(v_1^2+v_2^2) + 2\mu^2(v_1^2+v_2^2)\Big]/(v_1^2+v_2^2), \end{aligned}$$

$$M_{23} = \frac{2\left[g_R^2v_1v_2(v_R^2-\overline{v}_R^2) + \lambda\lambda'(v_1^2-v_2^2)v_R\overline{v}_R\right]}{\sqrt{(v_1^2+v_2^2)(v_R^2+\overline{v}_R^2)}},$$

$$M_{24} = \frac{4g_R^2v_1v_2v_R\overline{v}_R - \lambda\lambda'(v_1^2-v_2^2)(v_R^2-\overline{v}_R^2)}{\sqrt{(v_1^2+v_2^2)(v_R^2+\overline{v}_R^2)}},$$

$$M_{25} = \frac{\lambda'(v_1^2-v_2^2)(2A_{\lambda'}+\mu_S+2\kappa v_S)}{\sqrt{v_1^2+v_2^2}},$$

$$M_{33} = \frac{2\left[\left(g_R^2+g_V^2\right)\left(v_R^2-\overline{v}_R^2\right)^2 + 2\lambda^2v_R^2\overline{v}_R^2\right]}{v_R^2+\overline{v}_R^2},$$

$$M_{34} = \frac{2v_R\overline{v}_R(v_R^2-\overline{v}_R^2)^2\left(2g_R^2+2g_V^2+\lambda^2\right)}{v_R^2+\overline{v}_R^2},$$

$$M_{35} = \frac{2\lambda\left[A_\lambda v_R\overline{v}_R + (\lambda v_S+\mu_2)(v_R^2+\overline{v}_R^2) + v_R\overline{v}_R(\mu_S+2\kappa v_S)\right]}{\sqrt{v_R^2+\overline{v}_R^2}},$$

$$\begin{aligned} M_{44} &= [8(g_R^2+g_V^2)v_R^2\overline{v}_R^2 + (m_1^2+m_2^2)(v_R^2+\overline{v}_R^2) + \lambda^2(v_R^2-\overline{v}_R^2)^2 \\ &+ 2(\lambda v_S+\mu_2)^2(v_R^2+\overline{v}_R^2)]\,/(v_R^2+\overline{v}_R^2), \end{aligned}$$

$$M_{45} = -\frac{\lambda(v_R^2-\overline{v}_R^2)(A_\lambda+\mu_S+2\kappa v_S)}{\sqrt{v_R^2+\overline{v}_R^2}},$$

$$\begin{aligned} M_{55} &= m_S^2 + \lambda'^2(v_1^2+v_2^2) + \lambda^2(v_R^2+\overline{v}_R^2) + \mu_S^2 + 2\mu_S B_S \\ &+ 2\kappa[-M^2 + \lambda v_R\overline{v}_R - \lambda' v_1v_2 + 3(A_\kappa+\mu_S+\kappa v_s)v_S. \end{aligned}$$

Procedure adopted to get lightest Higgs mass

- Choose λ', $A_{\lambda'}$ and A_λ such that M_{13}, M_{15} and M_{35} vanish.
- Assume soft mass term m_1 is bigger than right-handed scale.
- Lightest neutral scalar tree-level Higgs mass

$$M^2_{h_{tree}} = 2M_W^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta, \qquad (M^2_{h_{MSSM}} = M_Z^2 \cos^2 2\beta\ )$$

- Using radiative corrections from top quark and stop squark

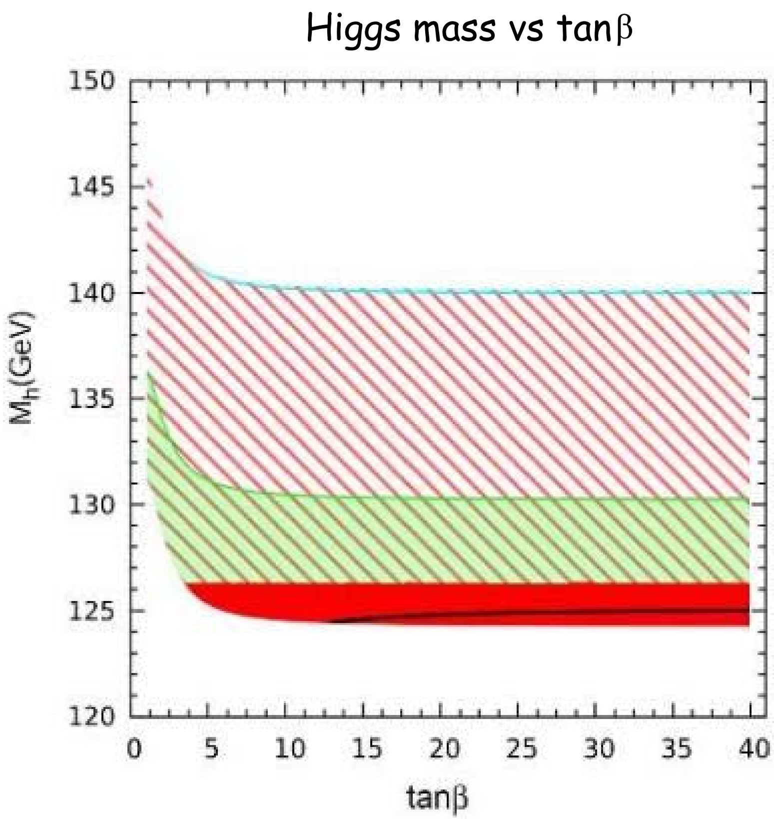
$$M_h^2 = (2M_W^2 \cos^2 2\beta + \lambda^2 \sin^2 2\beta)\Delta_1 + \Delta_2$$

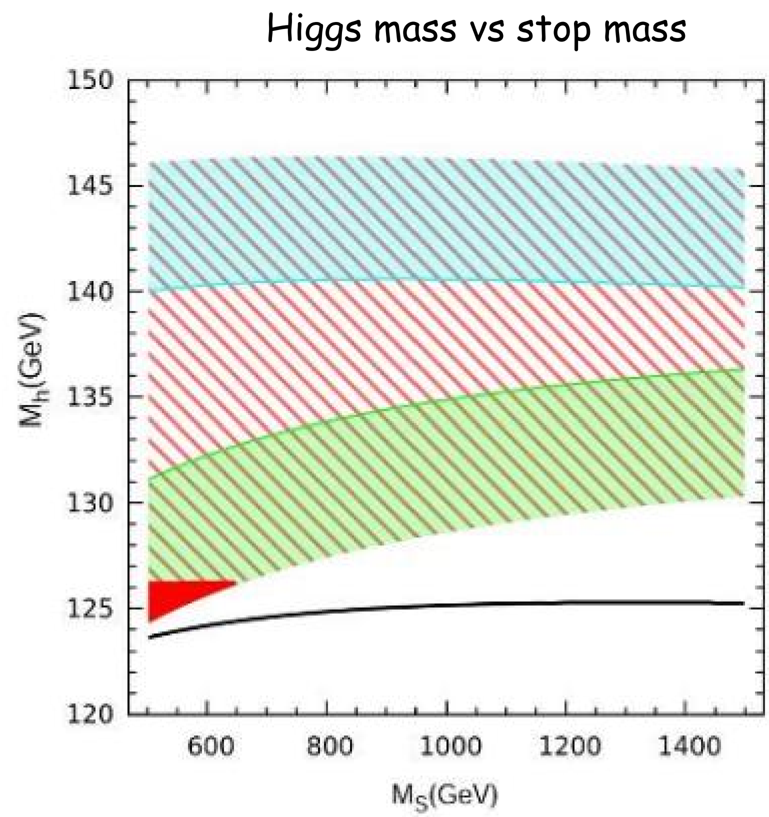
where

$$\Delta_2 = \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]$$

$$\Delta_1 = \left(1 - \frac{3}{8\pi^2}\frac{m_t^2}{v^2}t\right), \quad t = \log\frac{M_S^2}{M_t^2}$$

m_t is top running mass, $\tilde{X}_t$ is the stop mixing, M_S is squark mass geometric mean and $v = \sqrt{v_1^2 + v_2^2} \approx 174\ \mathrm{GeV}$.





- Red region is for m_h between 124 GeV and 126 GeV.
- Solid black line is the MSSM Higgs mass.
- Second plot shows even for a relatively low stop mass and low stop mixing we can easily get a correct Higgs mass.

Pseudo-scalar Higgs boson mass spectrum

Left-handed triplet Higgs fields decouple and give mass-squared matrix

$$\begin{bmatrix} m_3^2 + \frac{g_L^2}{2}(v_1^2 - v_2^2) + 2g_V^2(-v_R^2 + \overline{v}_R^2) + (\lambda v_S + \mu_1)^2 & -\lambda(M^2 - \lambda v_R \overline{v}_R + \lambda' v_1 v_2 - \mu_S v_S - \kappa v_S^2) + \lambda A_\lambda v_S + \mu_1 B_1 \\ -\lambda(M^2 - \lambda v_R \overline{v}_R + \lambda' v_1 v_2 - \mu_S v_S - \kappa v_S^2) + \lambda A_\lambda v_S + \mu_1 B_1 & m_4^2 - \frac{g_L^2}{2}(v_1^2 - v_2^2) + 2g_V^2(v_R^2 - \overline{v}_R^2) + (\lambda v_S + \mu_1)^2 \end{bmatrix}$$

Integrating out two Goldstone states, elements of the 3×3 matrix is

$$\begin{aligned}
M_{11} &= m_1^2 + m_2^2 + \lambda^2(v_R^2 + \overline{v}_R^2 + 2v_S^2) + 2\mu_2(2\lambda v_s + \mu_2), \\
M_{12} &= -\lambda\lambda'\sqrt{(v_1^2 + v_2^2)(v_R^2 + \overline{v}_R^2)}, \\
M_{13} &= \lambda(\mu_S + 2\kappa v_S - A_\lambda)\sqrt{v_R^2 + \overline{v}_R^2}, \\
M_{22} &= 2m_5^2 + \lambda'^2(v_1^2 + v_2^2 + 2v_S^2) + 2\mu(2\lambda' v_S + \mu), \\
M_{23} &= \lambda'(2A_{\lambda'} - \mu_S - 2\kappa v_S)\sqrt{v_1^2 + v_2^2}, \\
M_{33} &= m_S^2 + \lambda^2(v_R^2 + \overline{v}_R^2) + \lambda'^2(v_1^2 + v_2^2) - \mu_S(2B_S - \mu_S) \\
&+ 2\kappa(M^2 - \lambda v_R \overline{v}_R + \lambda' v_1 v_2 + \mu_S v_S + \kappa v_S^2 - 3A_\kappa v_S).
\end{aligned}$$

Charged Higgs boson mass spectrum

Left-handed triplet Higgs fields decouple and give mass-squared matrix

$$\begin{pmatrix} g_V^2(\overline{v}_R^2 - v_R^2) + m_3^2 + (\mu_1 + \lambda v_S)^2 & -\lambda(M^2 - \lambda v_R \overline{v}_R + \lambda' v_1 v_2 - \mu_S v_S - \kappa v_S^2 - A_\lambda v_S) + \mu_1 B_1 \\ -\lambda(M^2 - \lambda v_R \overline{v}_R + \lambda' v_1 v_2 - \mu_S v_S - \kappa v_S^2 - A_\lambda v_S) + \mu_1 B_1 & g_V^2(v_R^2 - \overline{v}_R^2) + m_4^2 + (\mu_1 + \lambda v_S)^2 \end{pmatrix}$$

Integrating out two Goldstone states, elements of the 2×2 matrix is

$$\begin{aligned} M_{11} &= \frac{g_R^2\left\{(v_1^2 - v_2^2)(v_R^2 - \overline{v}_R^2) + 2(v_R^2 + \overline{v}_R^2)^2\right\}}{(v_R^2 + \overline{v}_R^2)} \\ &- \frac{2(v_R^2 + \overline{v}_R^2)\left\{\lambda(-M^2 + A_\lambda v_S + \lambda v_R \overline{v}_R - \lambda' v_1 v_2 + \mu_S v_S + \kappa v_S^2) + B_2 \mu_2\right\}}{v_R \overline{v}_R}, \\ M_{12} &= \frac{2 g_R^2 v_R \overline{v}_R \sqrt{v_1^4 + 2v_1^2(-v_2^2 + v_R^2 + \overline{v}_R^2) + v_2^2[v_2^2 + 2(v_R^2 + \overline{v}_R^2)]}}{v_R^2 + \overline{v}_R^2}, \\ M_{22} &= -\frac{g_R^2(v_R^2 - \overline{v}_R^2)\left[v_1^4 + 2v_1^2(-v_2^2 + v_R^2 + \overline{v}_R^2) + v_2^4 + 2v_2^2(v_R^2 + \overline{v}_R^2)\right]}{(v_1^2 - v_2^2)(v_R^2 + \overline{v}_R^2)}. \end{aligned}$$

Chargino and neutralino mass

Chargino mass matrix is given as

$$-\frac{1}{2}\begin{pmatrix}\widetilde{\delta}^{c^-} & \widetilde{\overline{\delta}}^{-} & \widetilde{\phi}_2^- & \lambda_R^- & \lambda_L^-\end{pmatrix}\begin{pmatrix}\mu_2+\lambda^* v_S & 0 & 0 & -\sqrt{2}g_R v_R & 0\\ 0 & \mu_1+\lambda v_S & 0 & 0 & 0\\ 0 & 0 & \mu+\lambda' v_S & g_R v_2 & g_L v_2\\ \sqrt{2}g_R\overline{v}_R & 0 & g_R v_1 & M_R & 0\\ 0 & 0 & g_L v_1 & 0 & M_L\end{pmatrix}\begin{pmatrix}\widetilde{\overline{\delta}}^{c^+}\\ \widetilde{\delta}^+\\ \widetilde{\phi}_1^+\\ \lambda_R^+\\ \lambda_L^+\end{pmatrix}.$$

Neutralino mass matrix in the basis $\begin{pmatrix}\widetilde{\delta}^{c^0} & \widetilde{\overline{\delta}}^{c^0} & \widetilde{\phi}_1^0 & \widetilde{\phi}_2^0 & \lambda_0 & \lambda_{R_3} & \lambda_{L_3} & \widetilde{S}\end{pmatrix}$

$$\begin{pmatrix}0 & \mu_2+\lambda^* v_S & 0 & 0 & -\sqrt{2}g_V v_R & \sqrt{2}g_R v_R & 0 & \lambda^*\overline{v}_R\\ \mu_2+\lambda^* v_S & 0 & 0 & 0 & \sqrt{2}g_V\overline{v}_R & -\sqrt{2}g_R\overline{v}_R & 0 & \lambda^* v_R\\ 0 & 0 & 0 & -\mu-\lambda' v_S & 0 & -\frac{g_R v_1}{\sqrt{2}} & -\frac{g_L v_1}{\sqrt{2}} & -\lambda' v_2\\ 0 & 0 & -\mu-\lambda' v_S & 0 & 0 & \frac{g_R v_2}{\sqrt{2}} & \frac{g_L v_2}{\sqrt{2}} & -\lambda' v_1\\ -\sqrt{2}g_V v_R & \sqrt{2}g_V\overline{v}_R & 0 & 0 & M_1 & 0 & 0 & 0\\ \sqrt{2}g_R v_R & -\sqrt{2}g_R\overline{v}_R & -\frac{g_R v_1}{\sqrt{2}} & \frac{g_R v_2}{\sqrt{2}} & 0 & M_R & 0 & 0\\ 0 & 0 & -\frac{g_L v_1}{\sqrt{2}} & \frac{g_L v_2}{\sqrt{2}} & 0 & 0 & M_L & 0\\ \lambda^*\overline{v}_R & \lambda^* v_R & -\lambda' v_2 & -\lambda' v_1 & 0 & 0 & 0 & \mu_S\end{pmatrix}$$

Higgs Spectrum

Scalar Higgs boson masses	Pseudo-scalar Higgs boson masses	Single charged Higgs boson masses	Chargino masses	Neutralino masses
M_{H_1}=6.26 TeV, M_{H_2}=2.59 TeV, M_{H_3}=1.21 TeV, M_{H_4}=468 GeV, $M_{H_1^\Delta}$=4.51 TeV, $M_{H_2^\Delta}$=1.92 TeV	M_{A_1}=4.53 TeV, M_{A_2}=3.34 TeV, M_{A_3}=514 GeV, $M_{A_1^\Delta}$=4.51 TeV, $M_{A_2^\Delta}$=1.92 TeV	$M_{H_1^+}$=4.77 TeV, $M_{H_2^+}$=513 GeV, $M_{\Delta_1^+}$=4.51 TeV, $M_{\Delta_2^+}$=1.92 TeV	$M_{\tilde{\Delta}_1^+}$= 2.65 TeV, $M_{\tilde{\chi}_1^+}$= 4.23 TeV, $M_{\tilde{\chi}_2^+}$= 2.38 TeV, $M_{\tilde{\chi}_3^+}$= 809 GeV, $M_{\tilde{\chi}_4^+}$= 348 GeV	$M_{\tilde{\Delta}^0_{1,2}}$ = 2.65 TeV, $M_{\tilde{\chi}_1^0}$= 5.98 TeV, $M_{\tilde{\chi}_2^0}$= 4.85 TeV, $M_{\tilde{\chi}_3^0}$= 3.09 TeV, $M_{\tilde{\chi}_4^0}$= 2.00 TeV, $M_{\tilde{\chi}_5^0}$= 1.15 TeV, $M_{\tilde{\chi}_6^0}$= 885 GeV, $M_{\tilde{\chi}_7^0}$= 352 GeV, $M_{\tilde{\chi}_8^0}$= 346 GeV

Table 1: Higgs boson, chargino and neutralino masses for a sample point for case with triplets using the parameters given as: λ'=0.7, λ=-0.3, v_1=173.14 GeV, v_2=17.3 GeV, v_R=3 TeV, $\overline{v}_R$=3.1 TeV, μ_1=3.1 TeV, μ_2=3.1 TeV, μ=-1.4 TeV, μ_S=-700 GeV, m_S^2=9 TeV^2, v_S=1.5 TeV, B_S=2 TeV, $m_1^2 = m_3^2$=1 TeV^2, κ=0.1, A_κ=1 TeV, m_4^2=9 TeV^2, A_λ=-4 TeV, $A_{\lambda'}$=-1 TeV, M_R=800 GeV, M_L=800 GeV, M_1=400 GeV and B_1 is chosen to be equal to B_2 which was fixed using the minimization conditions.

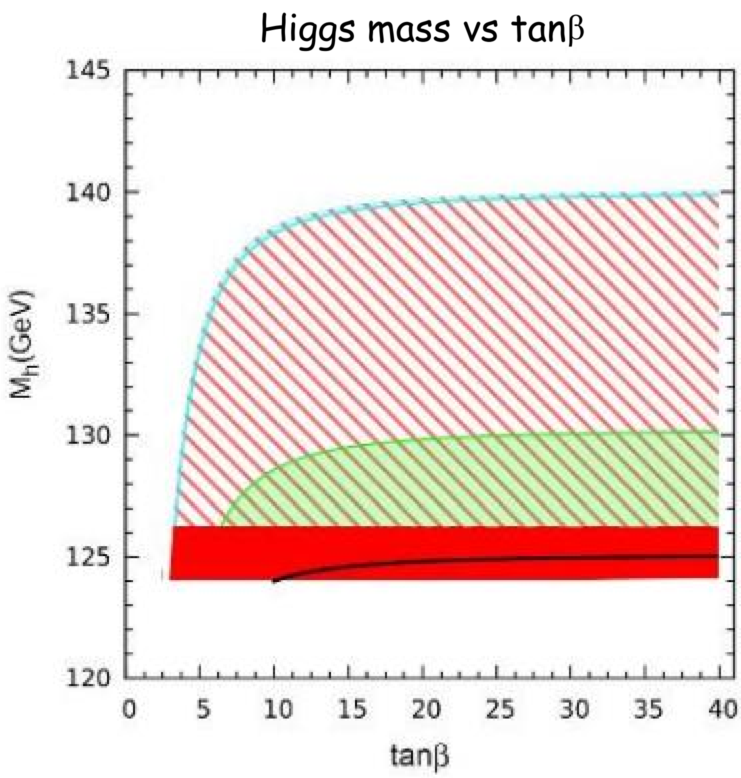
A pair of triplets, a bidoublet and a heavy singlet

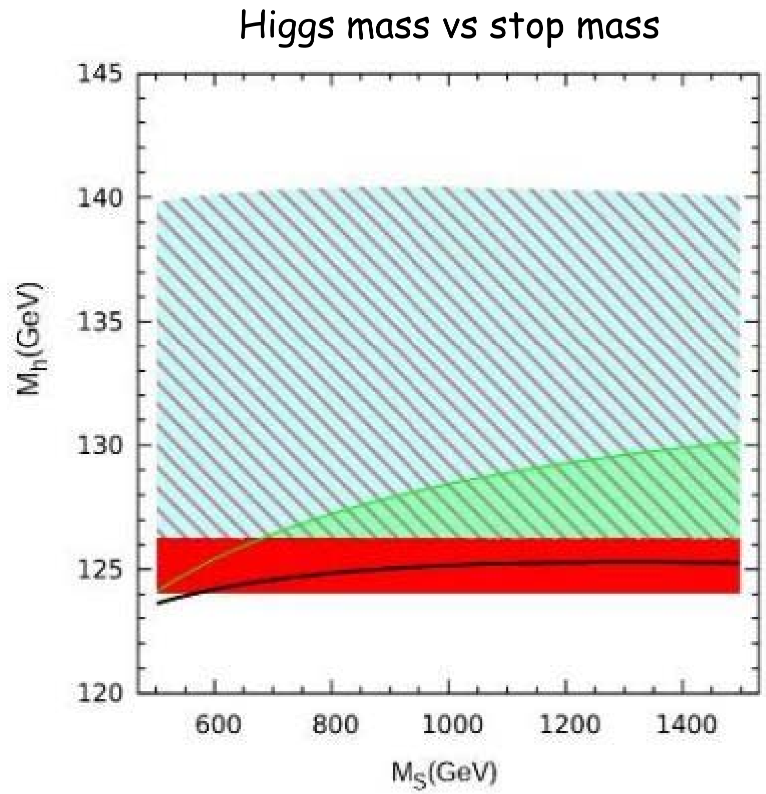
- Same as previous case but the singlet is heavy and can be integrated out.
- The Higgs only superpotential is given as

$$W_{Higgs} = \mu_1 \mathrm{Tr}\left(\Delta\overline{\Delta}\right) + \mu_2 \mathrm{Tr}\left(\Delta^c\overline{\Delta}^c\right) + \frac{\mu}{2}\mathrm{Tr}(\phi^T\tau_2\phi\tau_2) + \varepsilon \mathrm{Tr}\left(\Delta^c\overline{\Delta}^c\right)^2$$

- Calculate the Higgs potential
- Compute the neutral scalar Higgs boson mass-squared matrix and get the mass of the lightest Higgs boson.

$$M_h = \left(2M_W^2\cos^2 2\beta\right)\Delta_1 + \Delta_2.$$





- Red region is for m_h between 124 GeV and 126 GeV.
- Solid black line is the MSSM Higgs mass.
- Parameter space is a little less than the other cases.
- Low stop mass and stop mixing can easily give a correct Higgs mass.

A pair of triplets and a bidoublet

- Special case without a singlet.
- Right-handed symmetry breaking is at the same scale as supersymmetry breaking.
- The Higgs only superpotential is given as

$$W_{Higgs} = \mu_1 \mathrm{Tr}\left(\Delta\bar{\Delta}\right) + \mu_2 \mathrm{Tr}\left(\Delta^c \bar{\Delta}^c\right) + \frac{\mu}{2}\mathrm{Tr}(\phi^T \tau_2 \phi \tau_2)$$

- Calculate the Higgs potential.
- Compute the neutral scalar Higgs boson mass-squared matrix and get the mass of the lightest Higgs boson.

$$M_h = \left(M_Z^2 \cos^2 2\beta\right)\Delta_1 + \Delta_2.$$

- Same as the MSSM result.

A pair of triplets and two bidoublets

- Two bidoublet case but without singlet.
- The Higgs only superpotential is given as

$$W_{Higgs} = \mu_1 \mathrm{Tr}\left(\Delta\overline{\Delta}\right) + \mu_2 \mathrm{Tr}\left(\Delta^c \overline{\Delta}^c\right) + \frac{\mu}{2}\mathrm{Tr}(\phi_a^T \tau_2 \phi_b \tau_2)$$

- Compute the neutral scalar Higgs boson mass-squared matrix and get the mass of the lightest Higgs boson.

$$M_h = \left(M_Z^2 \cos^2 2\beta\right)\Delta_1 + \Delta_2.$$

- Same as with one bidoublet.

Inverse Seesaw Model

Higgs sector of the model is

$$H_L(1,2,1,-1)=\begin{pmatrix} H_L^0 \\ H_L^- \end{pmatrix},\quad \bar{H}_L(1,2,1,1)=\begin{pmatrix} \bar{H}_L^+ \\ \bar{H}_L^0 \end{pmatrix},\quad H_R(1,1,2,1)=\begin{pmatrix} H_R^+ \\ H_R^0 \end{pmatrix},$$

$$\bar{H}_R(1,1,2,-1)=\begin{pmatrix} \bar{H}_R^0 \\ \bar{H}_R^- \end{pmatrix},\quad \Phi_a(1,2,2,0)=\begin{bmatrix} \phi_1^+ & \phi_2^0 \\ \phi_1^0 & \phi_2^- \end{bmatrix}_a,\ (a=1,2)$$

- H_R and $\bar{H}_R$ breaks the right-handed symmetry.
- Allows right-handed symmetry breaking scale naturally of order TeV.
- Φ_a generates the quark and lepton masses and CKM mixing.
- Need extra singlet heavy neutrino N to generate small neutrino mass.

- The non-zero vacuum expectation values of Higgs fields

$$\langle H_R^0 \rangle = v_R, \quad \langle \bar{H}_R^0 \rangle = \bar{v}_R, \quad \langle H_L^0 \rangle = v_L, \quad \langle \bar{H}_L^0 \rangle = \bar{v}_L, \quad \langle \phi_{1_a}^0 \rangle = v_{1_a}, \quad \langle \phi_{2_a}^0 \rangle = v_{2_a}$$

- Yukawa terms in the superpotential are

$$W_Y = \sum_{j=1}^{2} Y_q^j Q^T \tau_2 \Phi_j \tau_2 Q^c + Y_l^j L^T \tau_2 \Phi_j \tau_2 L^c + ifL^T \tau_2 \bar{H}_L N$$

$$+ if^c L^{c^T} \tau_2 \bar{H}_L N + \frac{\mu_N}{2} NN.$$

- Neutrino mass matrix

$$\begin{pmatrix} 0 & Y_l v_1 & f\bar{v}_L \\ Y_l v_1 & 0 & f^c \bar{v}_R \\ f\bar{v}_L & f^c \bar{v}_R & \mu_N \end{pmatrix}$$

- If $\bar{v}_L \to 0$ and $\mu_N \to 0$, one of the eigenvalues of this matrix is zero.

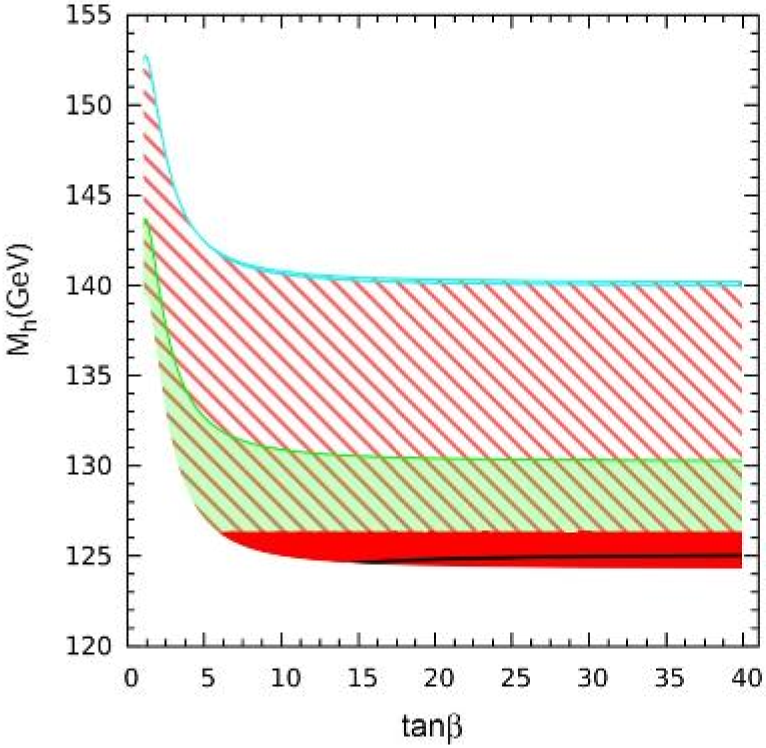
- Consider the case with one bidoublet for simplicity.
- The Higgs only superpotential is

$$W_{Higgs} = i\mu_1 H_L^T \tau_2 \bar{H}_L + i\mu_1 H_R^T \tau_2 \bar{H}_R + \lambda \bar{H}_L^T \tau_2 \Phi \tau_2 \bar{H}_R$$
$$+\lambda H_L^T \tau_2 \Phi \tau_2 H_R + \mu \mathrm{Tr}\left[\Phi \tau_2 \Phi^T \tau_2 \right]$$

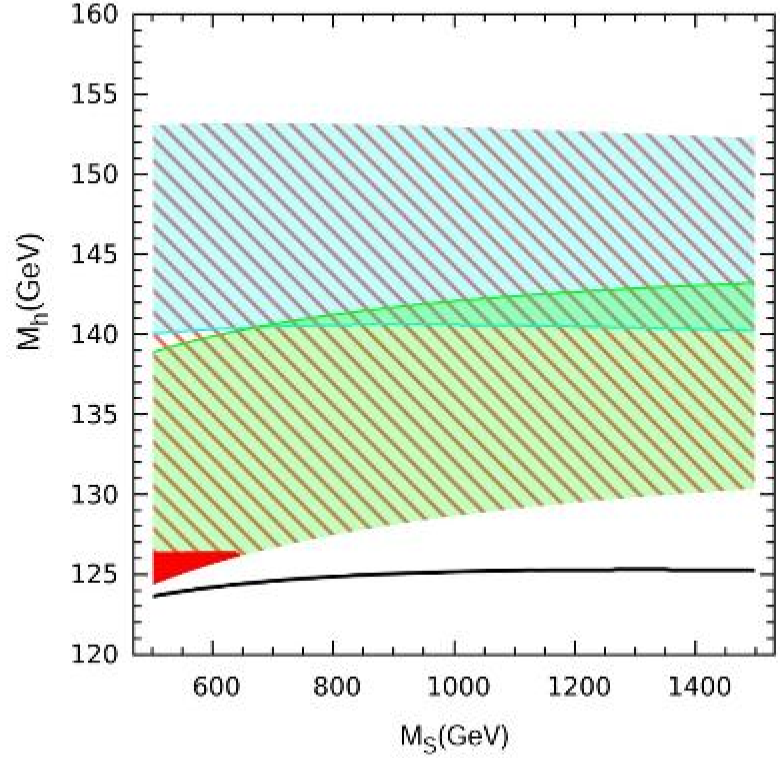
- Calculate the Higgs potential and the minimization conditions.
- Change the basis so that only one field gets EW vev.
- Compute the neutral scalar Higgs boson mass-squared matrix.
- Mass of the lightest neutral Higgs boson

$$M_h = \left(2M_W^2 \sin^4\beta + \frac{M_W^4}{2M_W^2 - M_Z^2}\cos^4\beta - \frac{M_W^2}{2}\sin^2 2\beta + \lambda^2 v^2 \sin^2 2\beta \right)\Delta_1 + \Delta_2$$

Higgs mass vs tanβ



Higgs mass vs stop mass



Red region is for m_h between 124 GeV and 126 GeV.

Solid black line is the MSSM Higgs mass.

Maximum freedom as Higgs mass can be highest in this case.

Low stop mass and stop mixing can easily get a correct Higgs mass.

Higgs Spectrum for Inverse seesaw model

Scalar Higgs boson masses	Pseudo-scalar Higgs boson masses	Single charged Higgs boson masses	Chargino masses	Neutralino masses
M_{H_1}=5.80 TeV, M_{H_2}=5.43 TeV, M_{H_3}=3.08 TeV, M_{H_4}=694 GeV, M_{H_5}=436 GeV	M_{A_1}=29.6 TeV, M_{A_2}=4.67 TeV, M_{A_3}=2.80 TeV, M_{A_4}=478 GeV	$M_{H_1^+}$=5.80 TeV, $M_{H_2^+}$=5.21 TeV, $M_{H_3^+}$=3.08 TeV, $M_{H_4^+}$=454 GeV	$M_{\tilde{\chi}_1^+}$=5.80 TeV, $M_{\tilde{\chi}_2^+}$=3.87 TeV, $M_{\tilde{\chi}_3^+}$=2.86 TeV, $M_{\tilde{\chi}_4^+}$=1.88 TeV, $M_{\tilde{\chi}_5^+}$=800 GeV	$M_{\tilde{\chi}_{1,2}^0}$=5.80 TeV, $M_{\tilde{\chi}_3^0}$=4.31 TeV, $M_{\tilde{\chi}_4^0}$=2.90 TeV, $M_{\tilde{\chi}_{5,6}^0}$=2.86 TeV, $M_{\tilde{\chi}_7^0}$=2.09 TeV, $M_{\tilde{\chi}_8^0}$=800 GeV, $M_{\tilde{\chi}_9^0}$=526 GeV

Table 2: Higgs boson, chargino and neutralino masses for inverse seesaw model with a sample point given as: λ=0.36, v_1=165.8 GeV, v_2=8 GeV, v_L=10 GeV, $\overline{v}_L$=51 GeV, v_R=3 TeV, $\overline{v}_R$=4 TeV, μ_1=-2.68 TeV, μ=-2.8 TeV, $m_4^2=-700^2$ GeV^2, A_λ=700 GeV, M_R=800 GeV, M_L=800 GeV, M_1=400 GeV.

CONCLUSIONS

- THE LEFT-RIGHT SUPERSYMMETRIC MODELS SOLVE MANY OF THE PROBLEMS IN THE STANDARD MODEL.
- THE TREE-LEVEL NEUTRAL HIGGS BOSON MASS CAN BE SIGNIFICANTLY INCREASED.
- EXPERIMENTALLY OBSERVED HIGGS BOSON MASS OF 125 GEV CAN BE EASILY ACHIEVED WITH LOW STOP MASS WITH NEGLIGIBLE MIXING.

THANK YOU

Universal Seesaw Model

Higgs sector of the model is

$$H_L(1,2,1,-1)=\begin{pmatrix} H_L^0 \\ H_L^- \end{pmatrix},\ \ \bar{H}_L(1,2,1,1)=\begin{pmatrix} \bar{H}_L^+ \\ \bar{H}_L^0 \end{pmatrix},\ \ H_R(1,1,2,1)=\begin{pmatrix} H_R^+ \\ H_R^0 \end{pmatrix},$$

$$\bar{H}_R(1,1,2,-1)=\begin{pmatrix} \bar{H}_R^0 \\ \bar{H}_R^- \end{pmatrix},\qquad S(1,1,1,0).$$

- H_R and $\bar{H}_R$ breaks the right-handed symmetry.
- No bidoublet to generate the quarks and lepton masses and mixings.
- Need extra heavy quarks and leptons

$$P(3,1,1,-\tfrac{4}{3}),\quad R(3,1,1,\tfrac{2}{3}),\quad E(1,1,1,2)$$

$$P^c(3,1,1,\tfrac{4}{3}),\quad R^c(3,1,1,-\tfrac{2}{3}),\quad E^c(1,1,1,-2)$$

- An optional heavy singlet neutrino N .

- Yukawa coupling terms in the superpotential

$$W_Y = Y_u Q\bar{H}_L P - Y_d Q H_L R - Y_l L H_L E + Y_\nu L\bar{H}_L N$$
$$+ Y_u^c Q^c \bar{H}_R P^c - Y_d^c Q^c H_R R^c - Y_l^c L^c H_R E^c + Y_\nu^c L^c \bar{H}_R N$$
$$+ m_u P P^c + m_d R R^c + m_l E E^c + m_\nu N N$$

- Mass of fermions are generated via the seesaw mechanism.

$$M_u = \begin{pmatrix} 0 & Y_u \bar{v}_L \\ Y_u^c \bar{v}_R & m_u \end{pmatrix}$$

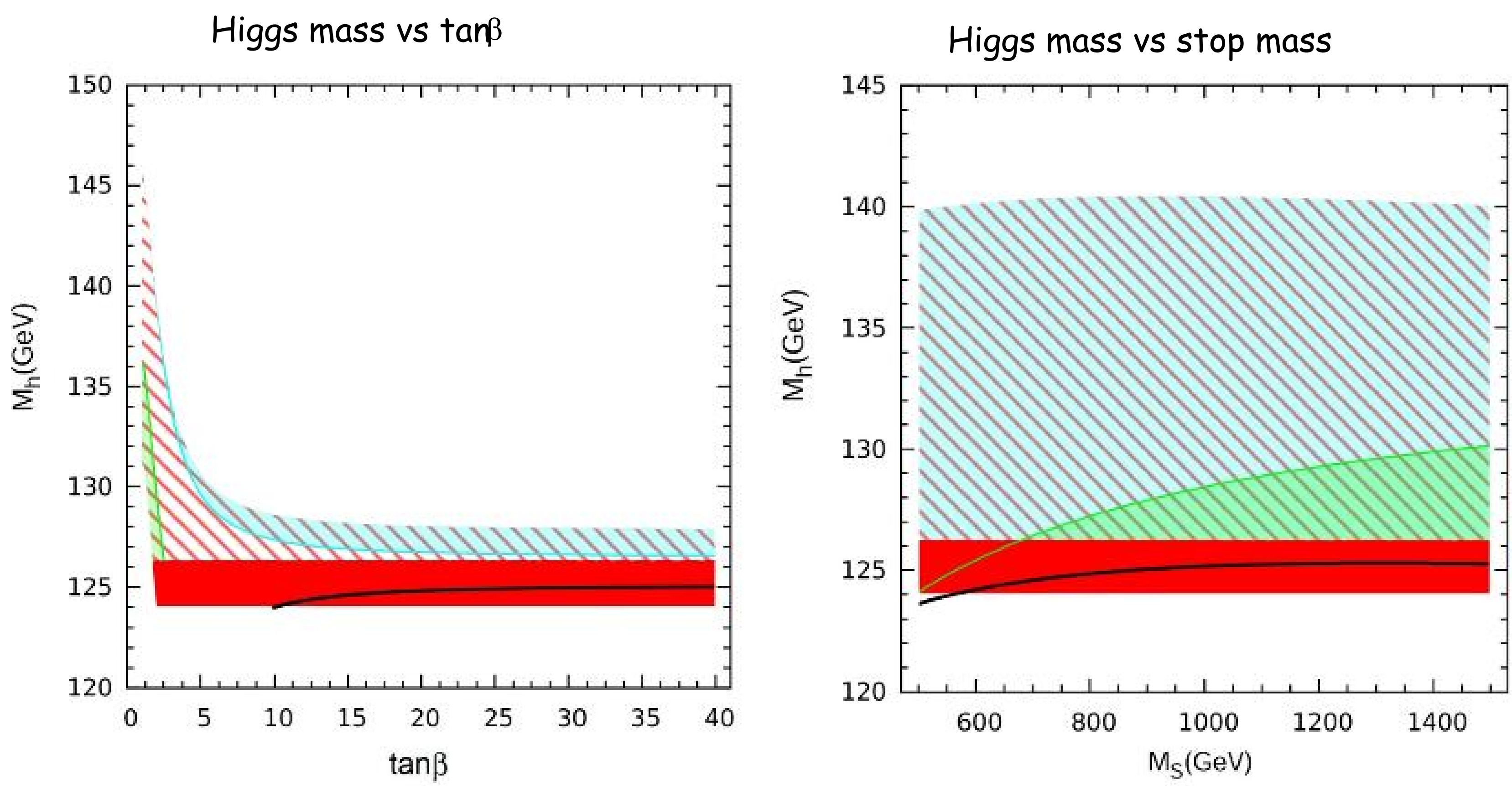
- Neutrino mass can also be generated at the two-loop level from W_L and W_R exchange.

- The Higgs only superpotential is

$$W_{Higgs} = S\left(i\lambda H_L^T \tau_2 \bar{H}_L + i\lambda H_R^T \tau_2 \bar{H}_R - M^2\right).$$

- Calculate the Higgs potential and the minimization conditions.
- Change basis so that only one field gets EW vev.
- Compute the Higgs boson mass-squared matrix.
- Mass of the lightest neutral scalar Higgs boson

$$M_h = \left(\frac{M_W^4}{2M_W^2 - M_Z^2}\cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta\right)\Delta_1 + \Delta_2$$



Red region is for m_h between 124 GeV and 126 GeV.

Solid black line is the MSSM Higgs mass.

Low stop mass and stop mixing can easily get a correct Higgs mass.

Universal seesaw model without singlet

- Higgs superpotential terms are

$$W_{Higgs} = i\mu_1 H_L^T \tau_2 \overline{H}_L + i\mu_1 H_R^T \tau_2 \overline{H}_R.$$

- Calculate the Higgs potential and the minimization conditions.
- Calculate the Higgs boson mass-squared matrix.
- Lightest neutral scalar Higgs boson mass

$$M_h = \left(M_Z^2 \cos^2 2\beta\right)\Delta_1 + \Delta_2.$$

- Same result as in MSSM.

E_6 motivated left-right SUSY model

- Low energy manifestation of superstring theory.
- Matter multiplets belong to 27 of E_6 group.
- Previously discussed by others but some parameters were zero, here we keep everything.
- Particle spectrum given as

$$X^c(\overline{3},1,2,-\tfrac{1}{6}) = \begin{pmatrix} h^c & u^c \end{pmatrix}_L, \quad Q(3,2,1,\tfrac{1}{6}) = \begin{pmatrix} u & d \end{pmatrix}_L, \quad h(3,1,1,-\tfrac{1}{3}) = h_L,$$

$$L^c(1,1,2,\tfrac{1}{2}) = \begin{pmatrix} e^c & n \end{pmatrix}_L, \quad E(1,2,1,-\tfrac{1}{2}) = \begin{pmatrix} \nu_E & E \end{pmatrix}_L, \quad d^c(\overline{3},1,1,\tfrac{1}{3}) = d^c_L,$$

$$F(1,2,2,0) = \begin{pmatrix} \nu_e & E^c \\ e & N^c_E \end{pmatrix}_L, \qquad N^c(1,1,1,0) = N^c_L.$$

- Discrete R-parity symmetry under which

$$\left(u,d,e,\nu_e\right) \in \text{Even}, \quad (h,E,n,N^c_E,\nu_E) \in \text{Odd}$$

K. S. Babu, X. G. He and E. Ma, Phys. Rev. D **36**, 878 (1987).

- The Higgs fields are identified as

$$H_L(1,2,1,-1)=\begin{pmatrix} H_L^0 \\ H_L^- \end{pmatrix}=\begin{pmatrix} \tilde{\nu}_E \\ \tilde{E} \end{pmatrix}, \quad H_R(1,1,2,1)=\begin{pmatrix} H_R^+ \\ H_R^0 \end{pmatrix}=\begin{pmatrix} \tilde{e}^c \\ \tilde{n} \end{pmatrix},$$

$$\Phi(1,2,2,0)=\begin{pmatrix} \phi_1^+ & \phi_2^0 \\ \phi_1^0 & \phi_2^- \end{pmatrix}=\begin{pmatrix} \tilde{E}^c & \tilde{N}_E^c \\ \tilde{\nu}_e & \tilde{e} \end{pmatrix}.$$

- The superpotential is

$$W=\lambda_1 Qd^c E+\lambda_2 QX^c F+\lambda_3 hX^c L^c+\lambda_4 FL^c E+\lambda_5 FN^c F+\lambda_6 hd^c N^c$$

- The quark and lepton masses are generated from this superpotential.
- The neutrino mass matrix is a 3×3 matrix in basis (ν_E, N_E^c, n) given as

$$\begin{pmatrix} 0 & \lambda_4\langle\tilde{n}\rangle & \lambda_4\langle\tilde{N}_E^c\rangle \\ \lambda_4\langle\tilde{n}\rangle & 0 & \lambda_4\langle\tilde{\nu}_E\rangle \\ \lambda_4\langle\tilde{N}_E^c\rangle & \lambda_4\langle\tilde{\nu}_E\rangle & 0 \end{pmatrix}$$

- The Higgs only superpotential is

$$W_{Higgs} = \lambda H_L^T \tau_2 \Phi \tau_2 H_R + \mu \mathrm{Tr}\left[\Phi^T \tau_2 \Phi \tau_2\right].$$

- The non-zero vacuum expectation values are given as

$$\left\langle H_R^0 \right\rangle = v_R, \quad \left\langle H_L^0 \right\rangle = v_L, \quad \left\langle \phi_1^0 \right\rangle = v_1, \quad \left\langle \phi_2^0 \right\rangle = v_2$$

- Calculate the Higgs potential and the minimization conditions.
- Change basis so that only one field gets EW vev.
- Compute the Higgs boson mass-squared matrix.
- Mass of the lightest neutral Higgs boson

$$M_h = \left(2M_W^2 \cos^2 2\beta\right)\Delta_1 + \Delta_2$$