Theory and Phenomenology of Higgs Bosons in Left-Right Supersymmetric Models

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Outline

- Why Left-Right Supersymmetry?
- Higgs Boson spectrum in Supersymmetric Left-Right models
  - Models with Higgs triplets + bidoublets
  - Models with Higgs doublets + bidoublets: Inverse seesaw models
  - Models with Higgs doublets: Universal seesaw models
  - E_6 motivated Left-Right models
- Emergence of a Light Doubly Charged Higgs boson and associated phenomenology
- Conclusions

Based on: K.S. Babu and Ayon Patra, 2014 (to appear);
K.S. Babu, Ayon Patra, Santsh Kumar Rai, Phys. Rev. D88, 055006 (2013).

Highlights

- Supersymmetric versions of some models written down and analyzed for the first time.
- Lightest neutral Higgs boson mass can easily be 125 GeV with low $\tan\beta \sim 1$, with light stops of mass below 1 TeV and negligible stop mixing. This results in reduced fine-tuning.
- Non-decoupling $SU(2)_R$ D-term makes this possible (within MSSM, $\tan\beta > 5$ and stop mass > 1 TeV is needed).
- A light doubly charged Higgs boson is predicted in models with Higgs triplets, which acquires its mass entirely from radiative corrections.

Why Left-Right Supersymmetry?

Addresses important open questions of the Standard Model:

- Understanding the origin of parity violation.
- Natural setting for small neutrino mass via seesaw mechanism.
- Provides a simple solution to the Strong CP Problem.
- SUSY stabilizes the Higgs boson mass.
- Natural dark matter candidate without assuming R-parity.
- Solves the SUSY CP problem.

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).

How Left-Right Symmetry solves the Strong CP Problem & SUSY CP Problem

Strong interaction sector admits a term that violates both CP and P:

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

Leads to the physical observable

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

Neutron electric dipole moment limits imply $\bar{\theta} < 10^{-10}$.

With left-right symmetry, θ = 0 due to Parity; M_q is Hermitian also due to Parity, and thus $\bar{\theta} = 0$ at tree level.

Induced $\bar{\theta}$ is small and consistent.

Parity symmetry also makes the new SUSY phases zero, thus solving the SUSY CP problem.

R.N. Mohaptra and A. Rasin, Phys. Rev. Lett. 76, 3490 (1996);
R. Kuchimanchi, Phys. Rev. Lett. 76, 3486 (1996);
K.S. Babu, B. Dutta, R.N. Mohapatra, Phys. Rev. D60, 095004 (1999);
K.S. Babu, B. Duta, R.N. Mohapatra, Phys. Rev. D65, 016005 (2002).

Left-Right Supersymmetric models

- ✓ Explain the origin of parity violation.
- ✓ Contain right-handed neutrinos which help induce small neutrino mass via the seesaw mechanism.
- ✓ Solve the Strong CP problem without an axion.
- ✓ Solve the hierarchy problem with SUSY.
- ✓ Solve the SUSY CP problem via Parity symmetry.
- ✓ *R* parity is part of *(B-L)* segment of gauge symmetry, leading to automatic dark matter candidate in LSP.

Higgs Boson masses in Supersymmetric Left-Right models

- Supersymmetric versions of left-right symmetry has the 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 to $U(1)_Y$ at a high scale.
- Here we consider several variations with different symmetry breaking sectors. Either Higgs triplets or Higgs doublets are used for the high scale symmetry breaking.
- Higgs boson spectrum is calculated in each case.

Fermion Content of Left-Right Models

- The common Quark and Lepton sectors of all models are:

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

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

  - The Right-handed quarks and leptons are doublets of $SU(2)_R$.
  - Presence of Right-handed neutrino required by gauge structure.

- Each model has to explain
  - Consistent symmetry breaking mechanism.
  - Quarks and Lepton masses and CKM mixing.
  - Small neutrino mass generation.

Models with Higgs triplets + bidoublets

Most straightforward way to break symmetry and generate large mass for right-handed neutrinos.

Under $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

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

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

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

R. Kuchimanchi, R. N. Mohapatra, Phys. Rev. D48, 4352 (1993) .
C.S. Aulakh, K. Benakli, G. Senjanovic, Phys. Rev. Lett. 79, 2188 (1997);
C.S. Aulakh, A. Melfo, G. Senjanovic, Phys. Rev. D57, 4174 (1998).

- 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 their parity partners.
- 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

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

where

$$v_R, \bar{v}_R >> v_u, v_d$$

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

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

The Superpotential in invariant under parity transformation.

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

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

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

$$
\begin{aligned}
M_{11} &= \frac{g_L^2(v_1^2-v_2^2)^2+g_R^2(v_1^2-v_2^2)^2+8v_1^2v_2^2\lambda'^2}{2(v_1^2+v_2^2)},\\
M_{12} &= \frac{v_1v_2(v_1^2-v_2^2)(g_L^2+g_R^2-2\lambda'^2)}{(v_1^2+v_2^2)},\\
M_{13} &= \frac{-g_R^2(v_1^2-v_2^2)(v_R^2-\overline{v}_R^2)-4\lambda\lambda' v_1v_2v_R\overline{v}_R}{\sqrt{(v_1^2+v_2^2)(v_R^2+\overline{v}_R^2)}},\\
M_{14} &= -\frac{2[g_R^2(v_1^2-v_2^2)v_R\overline{v}_R-\lambda\lambda' v_1v_2(v_R^2-\overline{v}_R^2)]}{\sqrt{(v_1^2+v_2^2)(v_R^2+\overline{v}_R^2)}},\\
M_{15} &= \frac{2\lambda'[-2A_{\lambda'}v_1v_2+(v_1^2+v_2^2)(v_S\lambda'+\mu)-\mu_S v_1v_2]}{\sqrt{v_1^2+v_2^2}},\\
M_{22} &= \Big[(2g_L^2+2g_R^2)v_1^2v_2^2+2m_5^2(v_1^2+v_2^2)+\lambda'^2(v_1^2-v_2^2)^2+2\lambda'^2v_S^2(v_1^2+v_2^2)\\
&+ 4\lambda'\mu v_S(v_1^2+v_2^2)+2\mu^2(v_1^2+v_2^2)\Big]/(v_1^2+v_2^2),\\
M_{23} &= \frac{2\left[g_R^2v_1v_2(-v_R^2+\overline{v}_R^2)+\lambda\lambda'(v_1^2-v_2^2)v_R\overline{v}_R\right]}{\sqrt{v_1^2+v_2^2}\sqrt{v_R^2+\overline{v}_R^2}},\\
M_{24} &= \frac{-4g_R^2v_1v_2v_R\overline{v}_R-\lambda\lambda'(v_1^2-v_2^2)(v_R^2-\overline{v}_R^2)}{\sqrt{v_1^2+v_2^2}\sqrt{v_R^2+\overline{v}_R^2}},\\
M_{25} &= \frac{\lambda'(v_1^2-v_2^2)(2A_{\lambda'}+\mu_S)}{\sqrt{v_1^2+v_2^2}},\\
M_{33} &= \frac{2\left[(g_R^2+g_V^2)(v_R^2-\overline{v}_R^2)^2+2\lambda^2v_R^2\overline{v}_R^2\right]}{v_R^2+\overline{v}_R^2},\\
M_{34} &= \frac{2v_R\overline{v}_R(v_R^2-\overline{v}_R^2)^2(2g_R^2+2g_V^2+\lambda^2)}{v_R^2+\overline{v}_R^2},
\end{aligned}
$$

$$
\begin{aligned}
M_{35} &= \frac{2\lambda\left[A_\lambda v_R\overline{v}_R+v_R^2(\lambda v_S+\mu_2)+\overline{v}_R^2(\lambda v_S+\mu_2)+v_R\overline{v}_R\mu_S\right]}{\sqrt{v_R^2+\overline{v}_R^2}},\\
M_{44} &= \Big[8(g_R^2+g_V^2)v_R^2\overline{v}_R^2+(m_1^2+m_2^2)(v_R^2+\overline{v}_R^2)+\lambda^2(v_R^2-\overline{v}_R^2)^2\\
&+ 2(\lambda v_S+\mu_2)^2(v_R^2+\overline{v}_R^2)\Big]/(v_R^2+\overline{v}_R^2),\\
M_{45} &= -\frac{(v_R^2-\overline{v}_R^2)\lambda(A_\lambda+\mu_S)}{\sqrt{v_R^2+\overline{v}_R^2}},\\
M_{55} &= m_S^2+\lambda'^2(v_1^2+v_2^2)+\lambda^2(v_R^2+\overline{v}_R^2)+\mu_S^2+2\mu_S B_S.
\end{aligned}
$$

$$\left(\mathrm{Re}\rho_1,\ \mathrm{Re}\rho_2,\ \mathrm{Re}\rho_3,\ \mathrm{Re}\rho_4,\ \mathrm{Re}\,S\right)$$

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

Procedure adopted to derive light Higgs mass

- Choose λ', $A_{\lambda'}$ and A_λ such that M_{13}, M_{15} and M_{35} vanish. This would maximize the lightest Higgs boson mass.

- Lightest neutral scalar tree-level Higgs mass is found to be

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

- 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

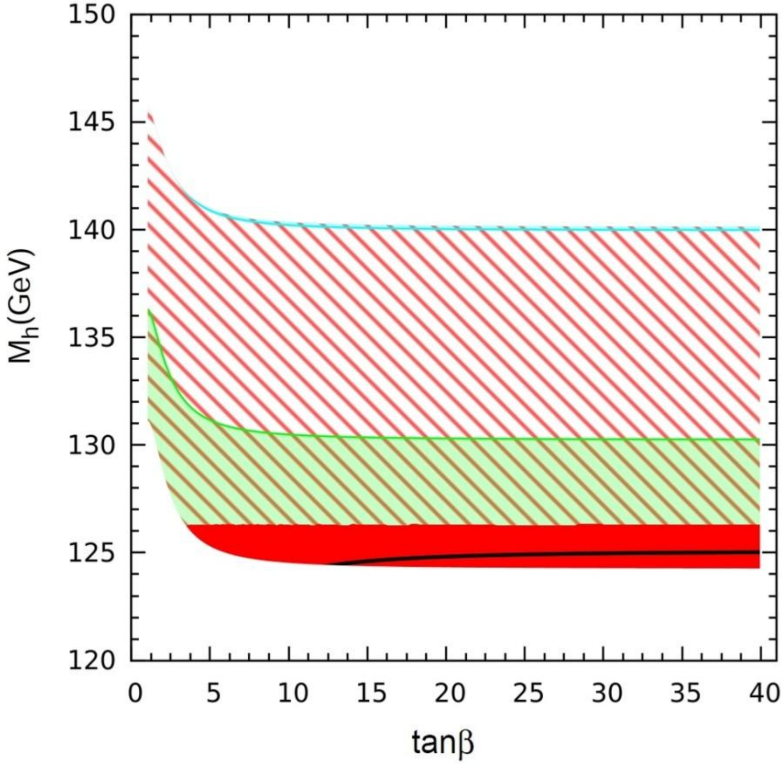
$$\Delta_2 \;=\; \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right],$$

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

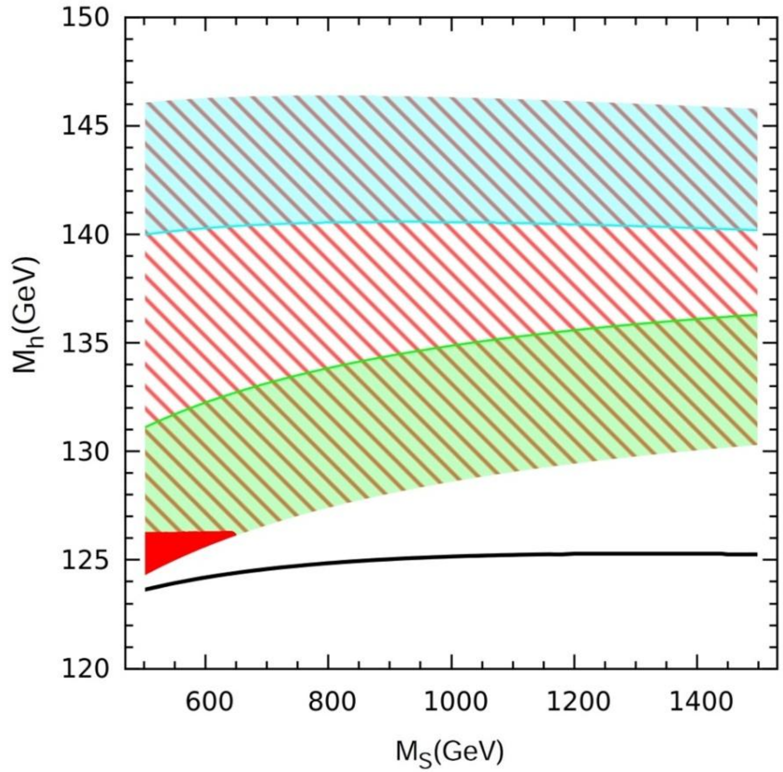
m_t is top running mass, $\tilde{X}_t$ is the stop mixing, M_S is squark mass geometric mean and $v = \sqrt{v_1^2 + v_2^2} \approx 174\ \mathrm{GeV}$.

Higgs triplets and a singlet

Maximum Higgs mass vs tan β



Maximum Higgs mass vs stop mass



- Green shaded region: $X_t = 0$, Blue shaded region: $X_t = 6$, Red shaded region: all possible values of parameters.
- Solid red region is for m_h between 124 GeV and 126 GeV.
- Solid black line: MSSM result with $X_t = 6$ and $M_S = 1.5$ TeV (or $\tan\beta = 40$).
- Plot on the right panel shows that even for a relatively low stop mass and for small stop mixing the correct Higgs mass is produced.

Pseudo-scalar Higgs boson mass spectrum

Removing the two Goldstone states, elements of the 3×3 matrix in a certain basis is

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

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

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

Charged Higgs boson mass spectrum

Removing the two charged Goldstone states, elements of the 2×2 matrix is

$$\begin{aligned}
M_{11} &= -\frac{g_R^2(v_R^2-\overline{v}_R^2)\left[v_1^4+2v_1^2(-v_2^2+v_R^2+\overline{v}_R^2)+v_2^4+2v_2^2(v_R^2+\overline{v}_R^2)\right]}{(v_1^2-v_2^2)(v_R^2+\overline{v}_R^2)}, \\
M_{12} &= \frac{2g_R^2 v_R\overline{v}_R\sqrt{v_1^4+2v_1^2(-v_2^2+v_R^2+\overline{v}_R^2)+v_2^2[v_2^2+2(v_R^2+\overline{v}_R^2)]}}{v_R^2+\overline{v}_R^2}, \\
M_{22} &= \left[g_R^2\left\{v_R^4(-v_1^2+v_2^2-2v_R^2-2\overline{v}_R^2)+\overline{v}_R^4(-v_1^2+v_2^2+2v_R^2+2\overline{v}_R^2)-6(v_1^2-v_2^2)v_R^2\overline{v}_R^2\right\}\right. \\
&+ \left.4g_V^2(v_R^2\overline{v}_R^4-v_R^6-v_R^4\overline{v}_R^2+\overline{v}_R^6)-2(m_1^2-m_2^2)(v_R^2+\overline{v}_R^2)^2\right]/(v_R^4-\overline{v}_R^4).
\end{aligned}$$

Left-handed charged triplet Higgs fields decouple and has a mass-squared matrix

$$\begin{pmatrix} g_V^2(\overline{v}_R^2-v_R^2)+m_3^2+\mu_1^2 & B_1\mu_1 \\ B_1\mu_1 & g_V^2(v_R^2-\overline{v}_R^2)+m_4^2+\mu_1^2 \end{pmatrix}$$

Light doubly charged scalar

- Unlike the charged scalar, which is eaten up by $W_R^{\pm}$, one combination of doubly charged scalars from δ^{c--} and $\bar{\delta}^{c++}$ remains massless at tree level .
- This is due to the extra global symmetry of the model.
- The charge breaking vacuum turns out to be lower than the desired charge conserving vacuum.[1]
- Possible solutions with unbroken *R* Parity:
  - Planck scale corrections – Would require the right-handed symmetry breaking scale to be of order 10^{11} GeV.[2]
  - Add new particles, eg: (1,1,3,0).[3]
  - Stay minimal, but rely on radiative corrections to the Higgs mass.[4,5]

[1]R. Kuchimanchi, R. N. Mohapatra, Phys. Rev. D48, 4352 (1993) .
[2,3]C.S. Aulakh, K. Benakli, G. Senjanovic, Phys. Rev. Lett. 79, 2188 (1997);
C.S. Aulakh, A. Melfo, G. Senjanovic, Phys. Rev. D57, 4174 (1998).
[3] Z. Chacko, R. N. Mohapatra, Phys. Rev. D58, 015003 (1998).
[4] K.S. Babu, R. N. Mohapatra, Phys. Lett. B668, 404 (2008).
[5] K.S. Babu, A. Patra, to appear (2014).

Doubly charged Higgs mass from radiative corrections

We have computed the full Majorana Yukawa contribution to the doubly charged Higgs mass.

The Higgs potential studied is a simplified version where electroweak VEVs are ignored.

$$V_F = \left|\lambda \mathrm{Tr}(\Delta^c \overline{\Delta}^c) + \lambda'_{ab} \mathrm{Tr}(\Phi_a^T \tau_2 \phi_b \tau_2) - M_R^2\right|^2 + |\lambda|^2 |S|^2 \left|\mathrm{Tr}(\Delta^c \Delta^{c\dagger}) + \mathrm{Tr}(\overline{\Delta}^c \overline{\Delta}^{c\dagger})\right|$$

$$V_{soft} = M_1^2 \mathrm{Tr}(\Delta^c \Delta^{c\dagger}) + M_2^2 \mathrm{Tr}(\overline{\Delta}^c \overline{\Delta}^{c\dagger}) + M_S^2 |S|^2 + \left\{A_\lambda \lambda S \mathrm{Tr}(\Delta^c \overline{\Delta}^c) - C_\lambda M_R^2 S + h.c.\right\}$$

$$V_D = \frac{g_R^2}{8} \sum_a \left|\mathrm{Tr}(2\Delta^{c\dagger} \tau_a \Delta^c + 2\overline{\Delta^c}^\dagger \tau_a \overline{\Delta}^c + \Phi_a \tau_a^T \Phi_a^\dagger)\right|^2 + \frac{g^2}{8} \sum_a \left|\mathrm{Tr}(2\Delta^{c\dagger} \Delta^c + 2\overline{\Delta^c}^\dagger \overline{\Delta}^c)\right|^2$$

- The charge-conserving VEV structure for the right-handed triplet Higgs boson is

$$\langle \Delta^c \rangle = \begin{bmatrix} 0 & v_R \\ 0 & 0 \end{bmatrix} \qquad \langle \bar{\Delta}^c \rangle = \begin{bmatrix} 0 & 0 \\ \bar{v}_R & 0 \end{bmatrix}$$

while we can consider a charge-breaking vacuum given by

$$\langle \Delta^c \rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & v_R \\ v_R & 0 \end{bmatrix} \qquad \langle \bar{\Delta}^c \rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & \bar{v}_R \\ \bar{v}_R & 0 \end{bmatrix}$$

- The $SU(2)_R$ D-term vanishes for the charge-breaking vacuum.
- Charge-conserving vacuum has a positive D-term.
- The charge-breaking vacuum has a lower minima than the charge-conserving.
- The charge conserving vacuum leads to a massless (or negative squared mass) doubly charged scalar boson.

R. Kuchimanchi and R. N. Mohapatra, Phys. Rev. D (1993)

Right-handed doubly-charged Higgs boson mass-squared matrix (tree-level) is

$$M^2_{\delta^{++}} = \begin{pmatrix} -2g_R^2(|v_R|^2 - |\overline{v_R}|^2) - \frac{\overline{v_R}}{v_R} Y & Y^* \\ Y & 2g_R^2(|v_R|^2 - |\overline{v_R}|^2) - \frac{v_R}{\overline{v_R}} Y \end{pmatrix}$$

where $\quad Y = \lambda A_\lambda S + |\lambda|^2 (v_R \overline{v}_R - \frac{M_R^2}{\lambda})$

Eigenvalues of the matrix

$$M^2_{\delta^{\pm\pm}} = \frac{-Y(|v_R|^2 + |\overline{v_R}|^2) \pm \sqrt{(|v_R|^2 - |\overline{v_R}|^2)^2 |4g_R^2 v_R \overline{v_R} - Y|^2 + 4|v_R|^2 |\overline{v_R}|^2 |Y|^2}}{2|v_R||\overline{v_R}|}$$

One of the eigenvalues is negative. Becomes zero if gauge couplings vanish.

However, radiative corrections can make the squared mass positive.

K. S. Babu and R. N. Mohapatra, Phys. Lett. B (2008)

The problem solves itself through the one-loop Majorana Yukawa corrections, which break the accidental global symmetry of the tree-level Higgs potential.

- Corrections to pseudo-goldstone bosons must remain finite, which is a nontrivial check of the calculation.
- We neglect gauge couplings and calculate correction from Yukawa sector.
- This pseudo-Goldstone state is identified as

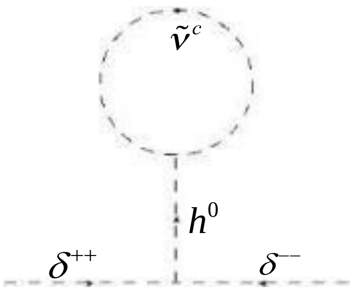
$$G^{++} = \frac{v_R^* \delta^{c^{--*}} + \overline{v}_R \overline{\delta}^{c^{++}}}{\sqrt{v_R^2 + \overline{v}_R^2}}$$

- The neutral Higgs boson couplings are written as

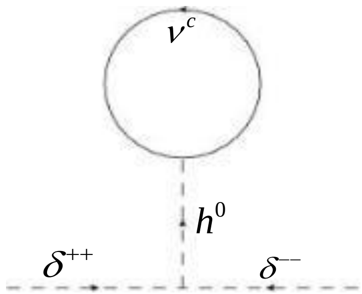
$$-\mathcal{L}_{\hat{X}} = P_i V_{ij} \hat{X}_j G^{++} G^{--} + Q_i V_{ij} \hat{X}_j n_1^2 + R_i V_{ij} \hat{X}_j n_2^2 + T_i V_{ij} \hat{X}_j \nu^c \nu^c$$

where $\hat{X} \rightarrow$ Mass eigenstate, $V \rightarrow$ Unitary diagonalizing matrix

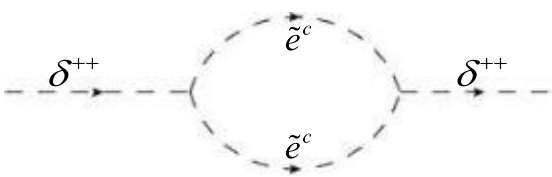
Feynman diagrams and corresponding contributions



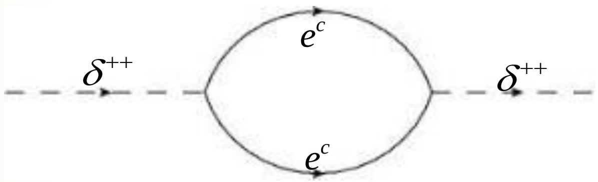
$$M_1 = -\frac{i}{2}\left[P^T M_h^{-2} Q \int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2 - m_{n_1}^2} + P^T M_h^{-2} R \int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2 - m_{n_2}^2}\right]$$



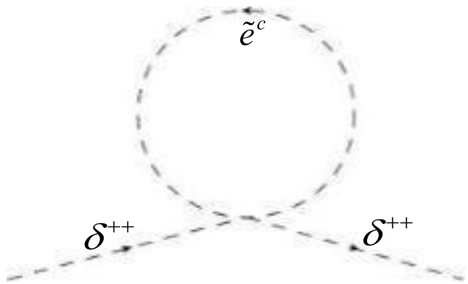
$$M_2 = 2iM_{\nu^c} P^T M_h^{-2} T \int \frac{d^4k}{(2\pi)^4}\mathrm{Tr}\left(\frac{\not{k} + M_{\nu^c}}{k^2 - M_{\nu^c}^2}\right)$$



$$M_3 = -\frac{i}{2}\frac{(fA_f v_R + f\lambda \overline{v}_R v_S)^2}{v_R^2 + \overline{v}_R^2}\int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2 - m_{\tilde{e}^c}^2}$$



$$M_4 = -\frac{i f^2 v_R^2}{v_R^2 + \overline{v}_R^2} \int \frac{d^4 k}{(2\pi)^4} \frac{1}{k^2}$$



$$M_5 = \frac{i f^2 v_R^2}{v_R^2 + \overline{v}_R^2} \int \frac{d^4 k}{(2\pi)^4} \frac{1}{k^2 - m_{\tilde{e}^c}^2}$$

Adding all these contributions

- Quadratic divergences cancelled.
- Log divergences cancelled.

Final expression for one-loop correction to the mass of the right-handed doubly-charged Higgs boson:

$$M^2_{\delta^{\pm\pm}} = \frac{1}{16\pi^2}\frac{1}{v_R^2+\bar{v}_R^2}\Bigg[f^2 v_R^2 m^2_{e^c} \ln\left(\frac{m^2_{\tilde{e}^c}}{M^2_{\nu^c}}\right) + \frac{f^2\left(\lambda\bar{v}_R v_S + A_f v_R\right)^2}{2\left(v_R^2+\bar{v}_R^2\right)}\left\{\ln\left(\frac{m^2_{\tilde{e}^c}}{M^2_{\nu^c}}\right)+1\right\}$$

$$-\frac{f}{4}\left(\lambda\bar{v}_R v_S + 2f\ v_R^2 + A_f v_R\right) m^2_{\tilde{\nu}_1^c} \ln\left(\frac{m^2_{\tilde{\nu}_1^c}}{M^2_{\nu^c}}\right)$$

$$-\frac{f}{4}\left(-\lambda\bar{v}_R v_S + 2f\ v_R^2 - A_f v_R\right) m^2_{\tilde{\nu}_2^c} \ln\left(\frac{m^2_{\tilde{\nu}_2^c}}{M^2_{\nu^c}}\right)\Bigg]$$

All the one-loop terms in the mass-square eigenvalues are of order $M^2_{SUSY}/16\pi^2$.

If right-handed gauge symmetry breaks at a high scale, the squared mass is negative. However, for v_R of order SUSY breaking scale, the mass squared is positive.

If SUSY is broken at the TeV scale, the doubly-charged Higgs boson mass has to be of electroweak symmetry breaking order (~ 100 GeV).

Special Cases: Back to Light Neutral Higgs

1. Case without a Singlet Higgs S

- Higgs superpotential is:

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

- Higgs mass is $M_h = \left(M_Z^2 \cos^2 2\beta\right)\Delta_1 + \Delta_2.$
- Same as in MSSM.

2. Case with the Singlet Higgs S integrated out

- The Higgs superpotential is

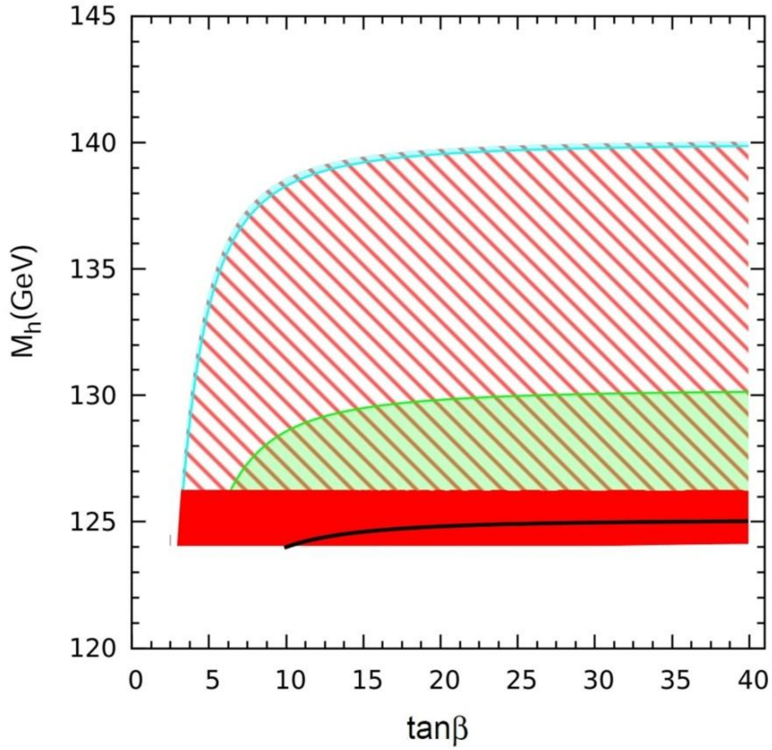
$$W_{Higgs} = \mu_1 \mathrm{Tr}\left(\Delta\bar{\Delta}\right) + \mu_2 \mathrm{Tr}\left(\Delta^c\bar{\Delta}^c\right) + \frac{\mu}{2}\mathrm{Tr}(\phi^T\tau_2\phi\tau_2) + \varepsilon \mathrm{Tr}\left(\Delta^c\bar{\Delta}^c\right)^2$$

- The lightest Higgs boson mass is

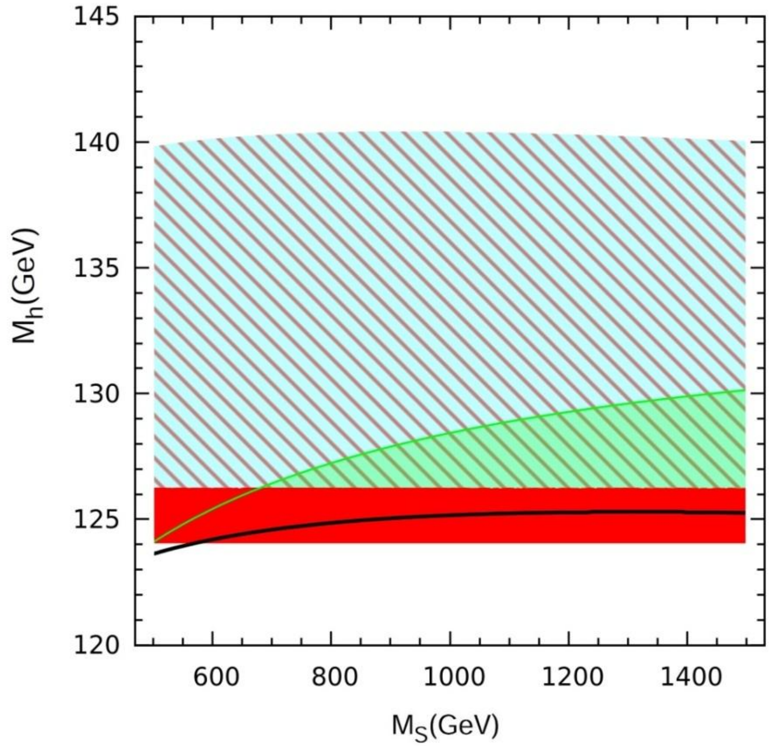
$$M_h = \left(2M_W^2 \cos^2 2\beta\right)\Delta_1 + \Delta_2.$$

Higgs triplets and a heavy singlet

Maximum Higgs mass vs tan β



Maximum Higgs mass vs stop mass



- Green shaded region: X_t = 0, Blue shaded region: X_t = 6, Red shaded region: all possible values of parameters.
- Solid red region is for m_h between 124 GeV and 126 GeV.
- Solid black line: MSSM result with X_t = 6 and M_S = 1.5 TeV (or tanβ = 40).
- Plot on the right panel shows that even for a relatively low stop mass and for small stop mixing the correct Higgs mass is produced.

Symmetry breaking with Higgs doublets: Inverse Seesaw Models

Higgs sector is simple with doublets, and no triplets.

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

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

- 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.

R. N. Mohapatra, J.W.F. Valle, Phys. Rev. D34, 1642 (1986).

- 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

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

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

- Neutrino mass matrix – Inverse seesaw:

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

S.M. Barr, Phys. Rev. Lett. 92, 101601 (2004).

- 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

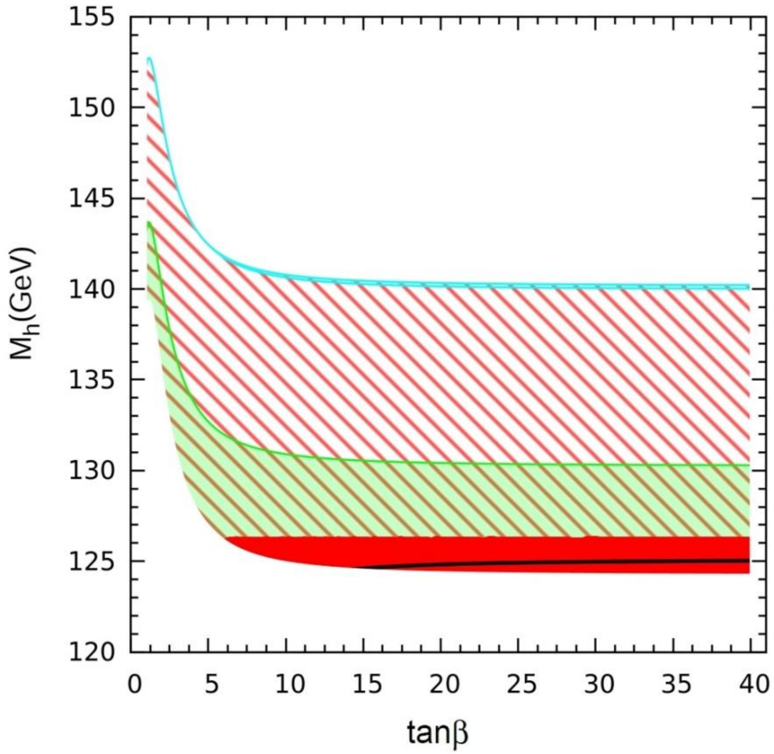
$$W_{Higgs} = i\mu_1 H_L^T \tau_2 \bar{H}_L + i\mu_1 H_R^T \tau_2 \bar{H}_R + \lambda \bar{H}_L^T \tau_2 \Phi \tau_2 \bar{H}_R$$
$$+\lambda H_L^T \tau_2 \Phi \tau_2 H_R + \mu \mathrm{Tr}\left[\Phi \tau_2 \Phi^T \tau_2\right]$$

- 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

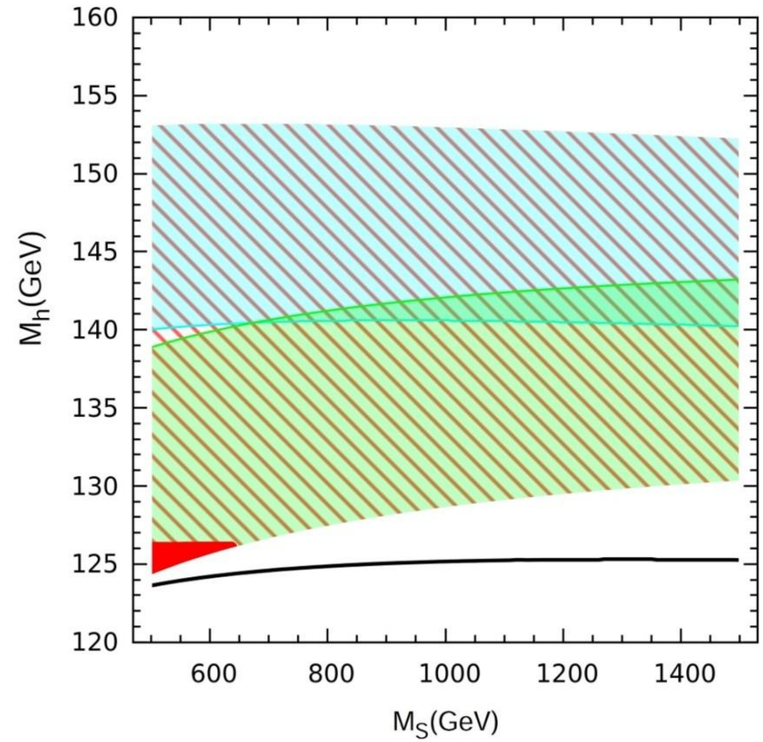
$$M_h = \left(2M_W^2 \sin^4\beta + \frac{M_W^4}{2M_W^2 - M_Z^2}\cos^4\beta - \frac{M_W^2}{2}\sin^2 2\beta + \lambda^2 v^2 \sin^2 2\beta \right)\Delta_1 + \Delta_2$$

Higgs doublets: Inverse seesaw models

Maximum Higgs mass vs tan β



Maximum Higgs mass vs stop mass



- Green shaded region: X_t = 0, Blue shaded region: X_t = 6, Red shaded region: all possible values of parameters.
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- Solid black line: MSSM result with X_t = 6 and M_S = 1.5 TeV (or tanβ = 40).
- Plot on the right panel shows that even for a relatively low stop mass and for small stop mixing the correct Higgs mass is produced.

Universal Seesaw Models

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

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

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

A. Davidson, KC. Wali, Phys. Rev. Lett. 59, 393 (1987);
K.S. Babu and R.N. Mohapatra, Phys. Rev. Lett. 62, 1079 (1989).

- An optional heavy singlet neutrino N.

- Yukawa coupling terms in the superpotential

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

- 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.

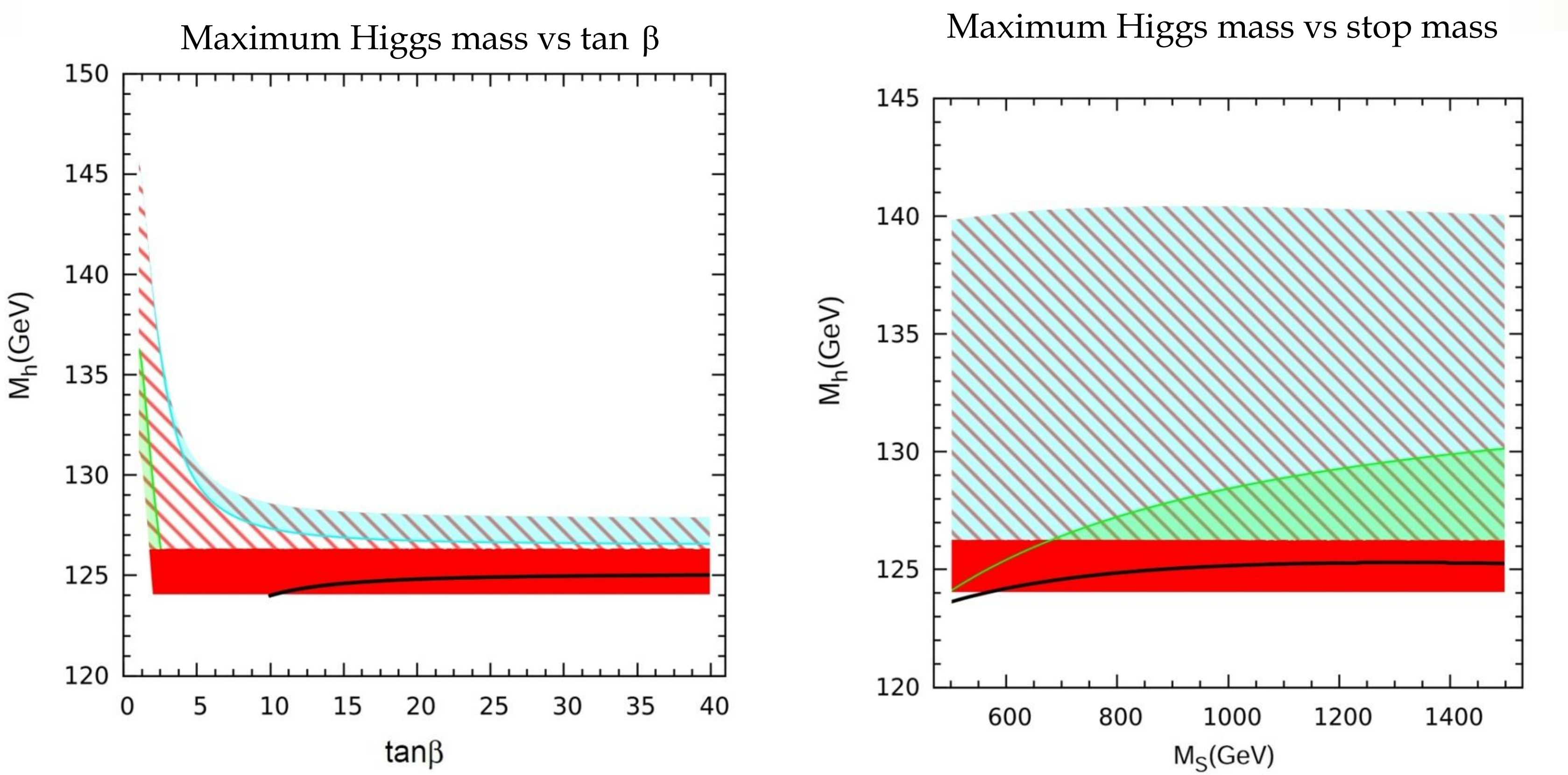
- The Higgs only superpotential is

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

- Mass of the lightest neutral scalar Higgs boson

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

Higgs doublets: Universal seesaw



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- Solid red region is for m_h between 124 GeV and 126 GeV.
- Solid black line: MSSM result with X_t = 6 and M_S = 1.5 TeV (or tanβ = 40).
- Plot on the right panel shows that even for a relatively low stop mass and for small stop mixing the correct Higgs mass is produced.

Universal seesaw model without singlet

- Higgs superpotential terms are

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

- 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

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

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

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

- Discrete R-parity symmetry under which

$$\left(u,d,e,\nu_e\right) \in \mathrm{Even}, \quad (h,E,n,N_E^c,\nu_E) \in \mathrm{Odd}$$

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

$$W=\lambda_1 Qd^cE+\lambda_2 QX^cF+\lambda_3 hX^cL^c+\lambda_4 FL^cE+\lambda_5 FN^cF+\lambda_6 hd^cN^c$$

- 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

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

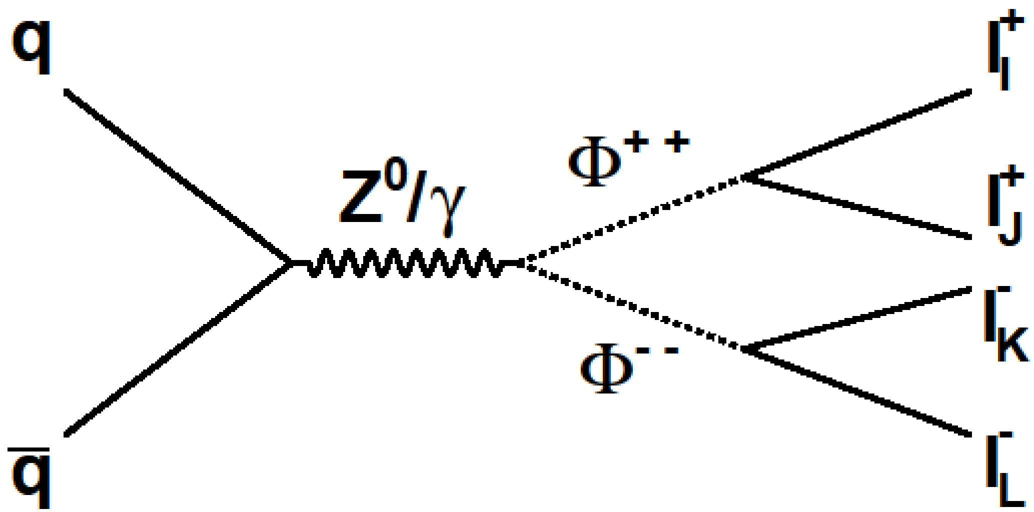
- The non-zero vacuum expectation values are given as

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

- 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

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

Experimental search for doubly-charged Higgs boson at LHC



Direct pair-production of doubly-charged Higgs Boson

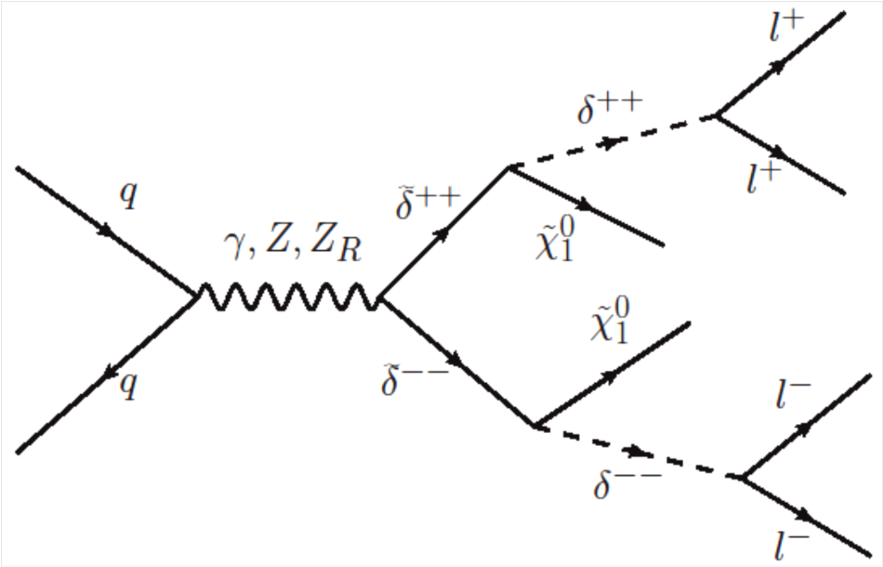
S. Chatrchyan et al. [CMS Collaboration], Eur. Phys. J. C 72, 2189 (2012);
G. Aad et al. [ATLAS Collaboration], Eur.Phys. J. C 72, 2244 (2012).

The mass limit on the right-handed doubly-charged Higgs boson from ATLAS experiment.

$\mathrm{BR}(H_R^{\pm\pm} \to \ell^\pm \ell'^\pm)$	95% CL lower limit on $m(H_R^{\pm\pm})$ [GeV]					
	$e^\pm e^\pm$		$\mu^\pm \mu^\pm$		$e^\pm \mu^\pm$	
	exp.	obs.	exp.	obs.	exp.	obs.
100%	329	322	335	306	303	310
33%	241	214	247	222	220	195
22%	203	199	223	212	194	187
11%	160	151	184	176	153	151

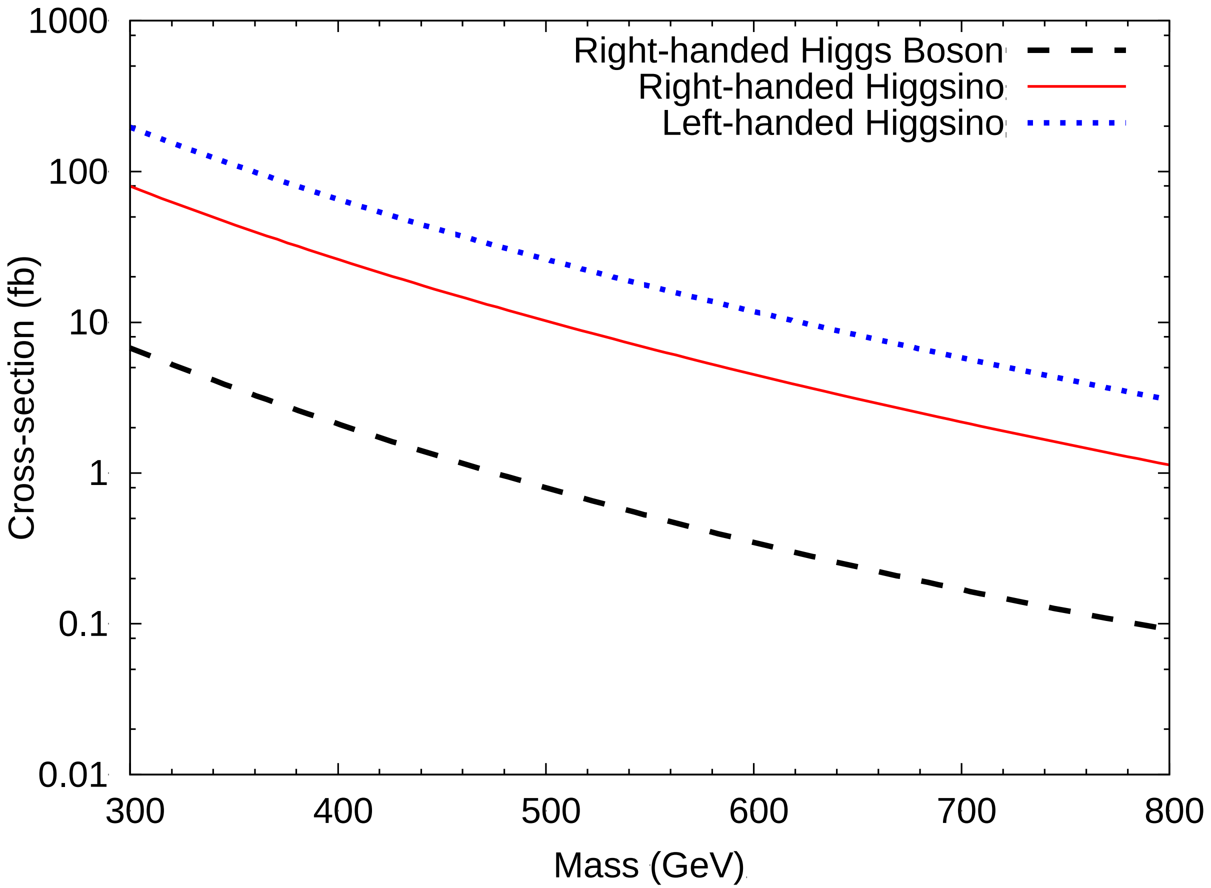
New signals of doubly-charged particles at the LHC

Production and decay of the doubly-charged Higgsino.



The final state signal is 4 leptons and missing energy (a new channel for doubly-charged Higgs boson search at the LHC).

K. S. Babu, A. Patra, S. Rai, Phys.Rev. D88 (2013) 055006



Direct production of the light doubly-charged Higgsinos and Higgs boson at LHC at 14 TeV.

Three cases we must consider

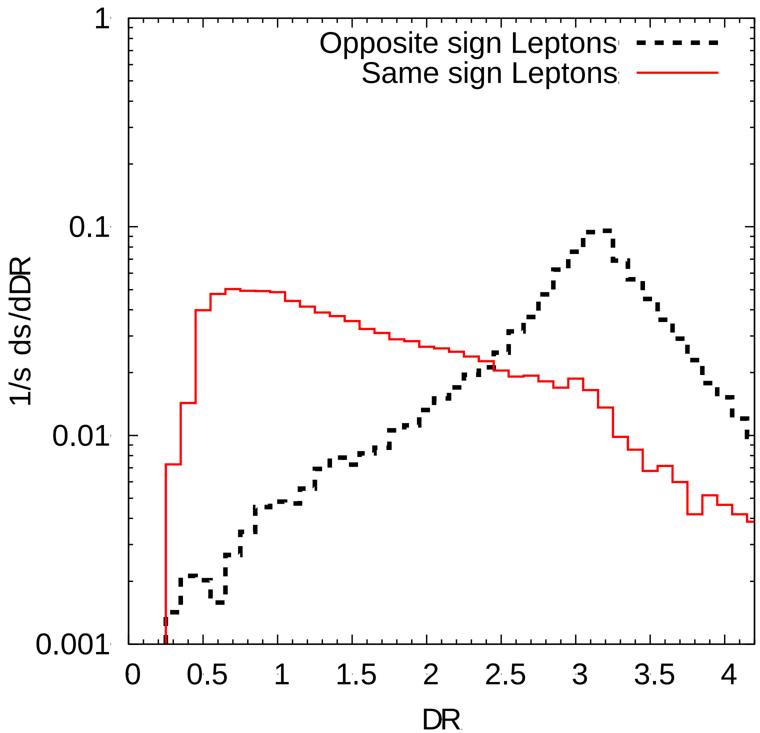
1. $p\, p \rightarrow \delta_R^{++} \delta_R^{--} \rightarrow l^+ l^+ l^- l^-$

2. $p\, p \rightarrow \widetilde{\delta}_R^{++} \widetilde{\delta}_R^{--} \rightarrow \delta_R^{++} \delta_R^{--} \widetilde{\chi}_1^0 \widetilde{\chi}_1^0 \rightarrow l^+ l^+ l^- l^- \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$

3. $p\, p \rightarrow \widetilde{\delta}_L^{++} \widetilde{\delta}_L^{--} \rightarrow \widetilde{l}^+ l^+ \widetilde{l}^- l^- \rightarrow l^+ l^+ l^- l^- \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$

We take two parameter space

- BP1 for which $M_{\delta_R^{\pm\pm}} = 300$ GeV, $M_{\tilde{\delta}_R^{\pm\pm}} = 500$ GeV and $M_{\chi_1^0} = 80$ GeV .
- BP2 for which $M_{\delta_R^{\pm\pm}} = 300$ GeV, $M_{\tilde{\delta}_R^{\pm\pm}} = 400$ GeV and $M_{\chi_1^0} = 80$ GeV .

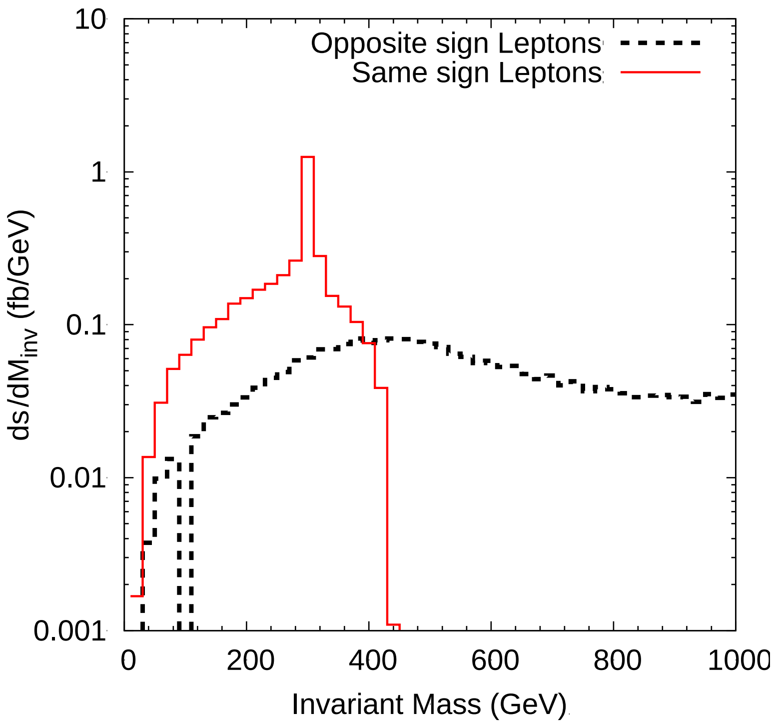


ΔR plot for the same-sign and opposite-sign final state leptons.

The same-sign lepton plot peaks at a low value of ΔR while the opposite-sign leptons peak at a much higher value.

Expected as the same-sign leptons come from the decay of one particle while the opposite sign leptons come from much further apart.

Measurement at the LHC for a four lepton final state can give definite indication of existence of doubly-charged particles if distribution is similar to our analysis.



Invariant Mass plot for the same- sign and opposite-sign final state leptons.

No events between 80 GeV and 100 GeV in the same-sign lepton plot because of the Z peak cut applied.

A clear peak in the same sign invariant mass while no such peak in the opposite sign plot at a mass of 300 GeV.

The Peak came due to the decay of the right-handed doubly-charged Higgs bosons into two same-sign leptons.

Difficult to see in experiments without a priori knowledge of the Higgs boson mass.

If seen, will be a definite signature of a doubly-charged particle.

Conclusions

- The Left-Right Supersymmetric models solve many of the problems in the Standard Model.
- Examineed various models with different symmetry breaking sectors.
- 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 and mixing.
- Models with triplets admit zero mass states of doubly-charged Higgs bosons which remains light after radiative corrections.

THANK YOU

The kinematic cuts applied

- The final state lepton must have a rapidity cut $-2.5 < \eta_l < 2.5$.
- $\Delta R_{ll} > 0.2$ between the final state leptons
  where $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ and ϕ is the azimuthal angle.
- Each lepton must have a transverse momentum $p_T > 15$ GeV.
- Invariant mass cut between the opposite sign same flavor leptons such that $M_{inv}^{OS} > 10$ GeV.
- A further invariant mass cut of $80 \text{ GeV} > M_{inv}^{OS} > 100 \text{ GeV}$ to get rid of the Z-boson peak.

We study the MET, ΔR and the invariant mass of the final state leptons.