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

Highlights

- 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.
- Several variants supersymmetrized for the first time.
Why Left-Right Supersymmetry?

Addresses some 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);
How Left-Right Symmetry solves the Strong CP Problem & SUSY CP Problem

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

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

Leads to the physical observable

\[ \bar{\theta} = \theta + \text{Arg} (\text{Det} M_q) \]

\[ M_q \rightarrow \text{quark mass matrix} \]

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

With left-right symmetry, \( \theta = 0 \) 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. Mohapatra 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);
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:

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

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

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

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

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

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

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

$$\Phi_a (1,2,2,0) = \begin{bmatrix} \phi^+_1 \\ \phi^-_1 \\ \phi^+_2 \\ \phi^-_2 \end{bmatrix} (a = 1, 2)$$

C.S. Aulakh, K. Benakli, G. Senjanovic, Phys. Rev. Lett. 79, 2188 (1997);


S (1,1,1,0)
• The $SU(2)_R$ Higgs boson triplets ($\Delta^c$ and $\bar{\Delta}^c$) 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 ($\Delta$ and $\bar{\Delta}$) are their parity partners.

• The two bi-doublet Higgs fields $\Phi_a$ 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

\[
\langle \delta^c_0 \rangle = v_R, \quad \langle \bar{\delta}^c_0 \rangle = \bar{v}_R, \quad \langle \phi^0_{1_a} \rangle = v_{u_a}, \quad \langle \phi^0_{2_a} \rangle = v_{d_a}
\]

where

\[
v_R, \bar{v}_R \gg v_u, v_d
\]

Previous Higgs boson mass analysis: Zhang, An, Ji, Mohapatra (2008)
The Yukawa couplings terms in the superpotential are

\[
W = Y_u Q^T \tau_2 \phi_1 \tau_2 Q^c + Y_d Q^T \tau_2 \phi_2 \tau_2 Q^c + Y_v L^T \tau_2 \phi_1 \tau_2 L^c + Y_l L^T \tau_2 \phi_2 \tau_2 L^c
+ i(f^T \tau_2 \Delta L + fL^T \tau_2 \Delta^c L^c)
\]

- \( \nu^c_\epsilon \) is heavy and generates small neutrino mass.

The Higgs boson only superpotential is

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

The Superpotential in invariant under parity transformation.

- Yukawa coupling matrices are hermitian.
- \( \lambda'_{ab}, \mu, \mu_s \) 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 \[ V_{\text{Higgs}} = V_F + V_D + V_{\text{Soft}} \]

\[
V_F = \text{Tr} \left[ (\lambda \Delta \bar{\Delta}) + (\lambda^* \Delta^c \bar{\Delta}^c) + \frac{\lambda'}{2} (\Phi^T \tau_2 \Phi \tau_2) - M^2 + \mu_S S \right]^2 + \text{Tr} \left| \mu \Phi + \lambda' S \Phi \right|^2 \\
+ \text{Tr} \left[ |\mu_1 \Delta + \lambda S \Delta|^2 + |\mu_1 \bar{\Delta} + \lambda S \bar{\Delta}|^2 + |\mu_2 \Delta^c + \lambda^* S \Delta^c|^2 \right] \\
+ |\mu_2 \bar{\Delta}^c + \lambda^* S \bar{\Delta}^c|^2, \]

\[
V_D = \frac{g_L}{8} \sum_{a=1}^{3} \left| \text{Tr} (2 \Delta^\dagger \tau_a \Delta + 2 \bar{\Delta}^\dagger \tau_a \bar{\Delta} + \Phi^\dagger \tau_a \Phi) \right|^2 \\
+ \frac{g_R}{8} \sum_{a=1}^{3} \left| \text{Tr} (2 \Delta^c \tau_a \Delta^c + 2 \bar{\Delta}^c \tau_a \bar{\Delta}^c + \Phi \tau_a \Phi) \right|^2 \\
+ \frac{g_V}{2} \left| \text{Tr} \left( \Delta^\dagger \Delta - \bar{\Delta}^\dagger \bar{\Delta} - \Delta^c \bar{\Delta}^c + \bar{\Delta}^c \Delta^c \right) \right|^2, \]

\[
V_{\text{Soft}} = m_1^2 \text{Tr} (\Delta^c \Delta^c) + m_2^2 \text{Tr} (\bar{\Delta}^c \bar{\Delta}^c) + m_3^2 \text{Tr} (\Delta^\dagger \Delta) + m_4^2 \text{Tr} (\bar{\Delta}^\dagger \bar{\Delta}) \\
+ m_5^2 |S|^2 + m_5^2 \text{Tr} (\Phi^\dagger \Phi) + [\lambda A_\lambda S \text{Tr} (\bar{\Delta} \Delta + \Delta^c \bar{\Delta}^c) + \text{h.c.}] \\
+ [\lambda' A_{\lambda'} S \text{Tr} (\Phi^T \tau_2 \Phi \tau_2) + \text{h.c.}] + (\lambda C_{\lambda} M^2 S + \text{h.c.}) + (\mu_S B_S S^2 + \text{h.c.}) \\
+ [\mu_1 B_1 \text{Tr} (\Delta \bar{\Delta}) + \mu_2 B_2 \text{Tr} (\Delta^c \bar{\Delta}^c) + \mu B \text{Tr} (\Phi^T \tau_2 \Phi \tau_2) + \text{h.c.}].
\[
\begin{align*}
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_1^2 - \bar{v}_R^2) - 4\lambda\lambda'v_1v_2v_R\bar{v}_R}{\sqrt{(v_1^2 + v_2^2)(v_1^2 + \bar{v}_R^2)}}, \\
M_{14} &= \frac{-2[g_R^2(v_1^2 - v_2^2)v_R\bar{v}_R - \lambda\lambda'v_1v_2(v_1^2 - \bar{v}_R^2)]}{\sqrt{(v_1^2 + v_2^2)(v_1^2 + \bar{v}_R^2)}}, \\
M_{15} &= \frac{2\lambda'[-2\lambda\lambda'v_1v_2 + (v_1^2 + v_2^2)(v_1^2 + \bar{v}_R^2)]}{\sqrt{v_1^2 + v_2^2}}, \\
M_{22} &= \left[ (2g_L^2 + 2g_R^2)v_1^2v_2^2 + 2m_s^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) \right] / (v_1^2 + v_2^2), \\
M_{23} &= \frac{-2 [g_R^2v_1v_2(-v_1^2 + \bar{v}_R^2) + \lambda\lambda'(v_1^2 - v_2^2)v_R\bar{v}_R]}{\sqrt{v_1^2 + v_2^2}\sqrt{v_1^2 + \bar{v}_R^2}}, \\
M_{24} &= \frac{-4g_R^2v_1v_2v_R\bar{v}_R - \lambda\lambda'(v_1^2 - v_2^2)(v_1^2 - \bar{v}_R^2)}{\sqrt{v_1^2 + v_2^2}\sqrt{v_1^2 + \bar{v}_R^2}}, \\
M_{25} &= \frac{\lambda'(v_1^2 - v_2^2)(2\lambda\lambda' + \mu S)}{\sqrt{v_1^2 + v_2^2}}, \\
M_{33} &= \frac{[g_R^2 + g_V^2](v_R^2 - \bar{v}_R^2)^2 + 2\lambda^2v_R^2\bar{v}_R]}{v_R^2 + \bar{v}_R^2}, \\
M_{34} &= \frac{2v_R\bar{v}_R(v_R^2 - \bar{v}_R^2)^2(2g_R^2 + 2g_V^2 + \lambda^2)}{v_R^2 + \bar{v}_R^2}, \\
M_{35} &= \frac{2\lambda [A_\lambda v_R\bar{v}_R + v_R^2(\lambda v_S + \mu_2) + \bar{v}_R^2(\lambda v_S + \mu_2) + v_R\bar{v}_R\mu_S]}{\sqrt{v_R^2 + \bar{v}_R^2}}, \\
M_{44} &= \left[ 8(g_R^2 + g_V^2)v_R^2\bar{v}_R^2 + (m_1^2 + m_2^2)(v_R^2 + \bar{v}_R^2) + \lambda^2(v_R^2 - \bar{v}_R^2)^2 \\
&+ 2(\lambda v_S + \mu_2)^2(v_R^2 + \bar{v}_R^2) \right] / (v_R^2 + \bar{v}_R^2), \\
M_{45} &= \frac{- (v_R^2 - \bar{v}_R^2)\lambda(A_\lambda + \mu S)}{\sqrt{v_R^2 + \bar{v}_R^2}}, \\
M_{55} &= \frac{m_s^2 + \lambda'^2(v_1^2 + v_2^2) + \lambda^2(v_R^2 + \bar{v}_R^2) + \mu_s^2 + 2\mu_s B_S}{\sqrt{v_R^2 + \bar{v}_R^2}}.
\end{align*}
\]

\[\text{Re}\rho_1, \text{Re}\rho_2, \text{Re}\rho_3, \text{Re}\rho_4, \text{Re} S\]
Procedure adopted to derive light Higgs mass

• Choose $\lambda', A_{\lambda'}$ and $A_{\lambda}$ 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

$$M_{h_{\text{tree}}}^2 = 2M_W^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta, \quad (M_{h_{\text{MSSM}}}^2 = M_Z^2 \cos^2 2\beta)$$

• Using radiative corrections from top quark and stop squark

$$M_{h_t}^2 = (2M_W^2 \cos^2 2\beta + \lambda^2 \sin^2 2\beta)\Delta_1 + \Delta_2$$

where

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

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

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

13
Higgs triplets and a singlet

- 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.
Pseudoscalar Higgs boson mass spectrum

Removing the two Goldstone states, elements of the $3 \times 3$ matrix in a certain basis is

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

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

\[
\begin{bmatrix}
m_3^2 + \frac{g_2^2}{2}(v_1^2 - v_2^2) + g_V^2(-v_R^2 + \overline{v}_R^2) + (\lambda v_s + \mu_1)^2 & \lambda(M^2 - \lambda v_R \overline{v}_R + \lambda'v_1v_2 - \mu_s v_s) - \lambda A_\lambda v_s - \mu_1 B_1 \\
\lambda(M^2 - \lambda v_R \overline{v}_R + \lambda'v_1v_2 - \mu_s v_s) - \lambda A_\lambda v_s - \mu_1 B_1 & m_4^2 - \frac{g_2^2}{2}(v_1^2 - v_2^2) + g_V^2(v_R^2 - \overline{v}_R^2) + (\lambda v_s + \mu_1)^2
\end{bmatrix}
\]
Charged Higgs boson mass spectrum

Removing the two charged Goldstone states, elements of the $2 \times 2$ matrix is

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

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

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

16
Light doubly charged scalar

- Unlike the charged scalar, which is eaten up by $W_R^\pm$, one combination of doubly charged scalars from $\delta^{c--}$ 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.\(^4,5\)

\(^2\)C.S. Aulakh, K. Benakli, G. Senjanovic, Phys. Rev. Lett. 79, 2188 (1997);
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.

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

\[
V_{soft} = M_1^2 \text{Tr}(\Delta^c \Delta^{c\dagger}) + M_2^2 \text{Tr}(\overline{\Delta}^c \overline{\Delta}^{c\dagger}) + M_S^2 |S|^2
+ \left\{ A \lambda S \text{Tr}(\Delta^c \overline{\Delta}^c) - C \lambda M_R^2 S + h.c. \right\}
\]

\[
V_D = \frac{g_R^2}{8} \sum_a \left| \text{Tr}(2\Delta^{c\dagger} \tau_a \Delta^c + 2\overline{\Delta}^{c\dagger} \tau_a \overline{\Delta}^c + \Phi_a \tau_a \Phi_a^\dagger) \right|^2
+ \frac{g^2}{8} \sum_a \left| \text{Tr}(2\Delta^{c\dagger} \Delta^c + 2\overline{\Delta}^{c\dagger} \overline{\Delta}^c) \right|^2
\]
• The charge-conserving VEV structure for the right-handed triplet Higgs boson is

\[
\langle \Delta^c \rangle = \begin{bmatrix} 0 & v_R \\ 0 & 0 \end{bmatrix} \quad \langle \bar{\Delta}^c \rangle = \begin{bmatrix} 0 & 0 \\ \bar{v}_R & 0 \end{bmatrix}
\]

while we can consider a charge-breaking vacuum given by

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

• 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.

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

\[ M_{\delta^{++}}^2 = \begin{pmatrix} -2g_R^2(|v_R|^2 - |\bar{v}_R|^2) - \frac{v_R}{v_R} Y & Y^* \\ Y & 2g_R^2(|v_R|^2 - |\bar{v}_R|^2) - \frac{v_R}{v_R} Y \end{pmatrix} \]

where \[ Y = \lambda A_\lambda S + |\lambda|^2(v_R\bar{v}_R - \frac{M_R^2}{\lambda}) \]

Eigenvalues of the matrix

\[ M_{\delta^{\pm\pm}}^2 = -Y(|v_R|^2 + |\bar{v}_R|^2) \pm \sqrt{(|v_R|^2 - |\bar{v}_R|^2)^2 4g_R^2 v_R \bar{v}_R - Y^2 + 4|v_R|^2|\bar{v}_R|^2|Y|^2} \]

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

However, radiative corrections can make the squared mass positive.

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

\[ G^{++} = \frac{v_R^* \delta^{c--} + \bar{v}_R \delta^{c++}}{\sqrt{v_R^2 + \bar{v}_R^2}} \]

• The neutral Higgs boson couplings are written as

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

where \( \hat{X} \rightarrow \) Mass eigenstate, \( V \rightarrow \) Unitary diagonalizing matrix
Feynman diagrams and corresponding contributions

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

\[ M_2 = 2i M_{\nu c} P^T M_h^{-2} T \int \frac{d^4k}{(2\pi)^4} \text{Tr} \left( \frac{k + M_{\nu c}}{k^2 - M_{\nu c}^2} \right) \]

\[ M_3 = -\frac{i}{2} \left( f A f v_R + f \lambda \bar{v}_R v_S \right)^2 \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m_{\bar{e}e}^2} \]

S. Weinberg (1973)
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:

\[
M_{S^{\pm \pm}}^2 = \frac{1}{16\pi^2} \frac{1}{v_R^2 + \bar{v}_R^2} \left[ f^2 v_R^2 m_{e^c}^2 \ln \left( \frac{m_{e^c}^2}{M_{\nu^c}^2} \right) + \frac{f^2 \left( \lambda \bar{v}_R v_S + A_f v_R \right)^2}{2 \left( v_R^2 + \bar{v}_R^2 \right)} \left\{ \ln \left( \frac{m_{e^c}^2}{M_{\nu^c}^2} \right) + 1 \right\} \right. \\
\left. - \frac{f}{4} \left( \lambda \bar{v}_R v_S + 2 f v_R^2 + A_f v_R \right) m_{\nu_1^c}^2 \ln \left( \frac{m_{\nu_1^c}^2}{M_{\nu^c}^2} \right) \right. \\
\left. - \frac{f}{4} \left( -\lambda \bar{v}_R v_S + 2 f v_R^2 - A_f v_R \right) m_{\nu_2^c}^2 \ln \left( \frac{m_{\nu_2^c}^2}{M_{\nu^c}^2} \right) \right]
\]

All the one-loop terms in the mass-square eigenvalues are of order \( M_{SUSY}^2 / 16\pi^2 \).

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 (\( \sim 100 \text{ GeV} \)).
Back to Light Neutral Higgs: Special Cases

1. Case without a Singlet Higgs $S$

- Higgs superpotential is:
  \[ W_{\text{Higgs}} = \mu_1 \text{Tr}(\Delta \bar{\Delta}) + \mu_2 \text{Tr}(\Delta^c \bar{\Delta}^c) + \frac{\mu}{2} \text{Tr}(\phi^T \tau_2 \phi \tau_2) \]

- Higgs mass is
  \[ M_h = (M_Z^2 \cos^2 2\beta)\Delta_1 + \Delta_2. \]

- Same as in MSSM.

2. Case with the Singlet Higgs $S$ integrated out

- The Higgs superpotential is
  \[ W_{\text{Higgs}} = \mu_1 \text{Tr}(\Delta \bar{\Delta}) + \mu_2 \text{Tr}(\Delta^c \bar{\Delta}^c) + \frac{\mu}{2} \text{Tr}(\phi^T \tau_2 \phi \tau_2) + \varepsilon \text{Tr}(\Delta^c \bar{\Delta}^c)^2 \]

- The lightest Higgs boson mass is
  \[ M_h = (2M_W^2 \cos^2 2\beta)\Delta_1 + \Delta_2. \]
Higgs triplets and a heavy singlet

- 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.
Symmetry breaking with Higgs doublets: Inverse Seesaw Models

Higgs sector is simple with doublets, and no triplets.

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

\[
\bar{H}_R (1, 1, 2, -1) = \begin{pmatrix} \bar{H}^0_R \\ \bar{H}^-_R \end{pmatrix}, \quad \Phi_a (1, 2, 2, 0) = \begin{pmatrix} \phi^+_1 & \phi^0_2 \\ \phi^0_1 & \phi^-_2 \end{pmatrix}_a, \quad (a = 1, 2)
\]

- \(H_R\) and \(\bar{H}_R\) breaks the right-handed symmetry.
- Allows right-handed symmetry breaking scale naturally of order TeV.
- \(\Phi_a\) 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

\[ \langle H_R^0 \rangle = v_R, \quad \langle \overline{H}_R^0 \rangle = \overline{v}_R, \quad \langle H_L^0 \rangle = v_L, \quad \langle \overline{H}_L^0 \rangle = \overline{v}_L, \quad \langle \phi_{1a}^0 \rangle = v_{1a}, \quad \langle \phi_{2a}^0 \rangle = v_{2a} \]

Yukawa terms in the superpotential are

\[ W_Y = \sum_{j=1}^{2} Y_{q_j}^j Q^T \tau_2 \Phi_j \tau_2 Q^c + Y_{l_j}^j L^T \tau_2 \Phi_j \tau_2 L^c + i f L^T \tau_2 \overline{H}_L^0 N \]

\[ + i f^c L^T \tau_2 \overline{H}_L^0 N + \frac{\mu_N}{2} N N. \]

Neutrino mass matrix – Inverse seesaw:

\[
\begin{pmatrix}
0 & Y_{l_1} v_1 & f \overline{v}_L \\
Y_{l_1} v_1 & 0 & f^c \overline{v}_R \\
f \overline{v}_L & f^c \overline{v}_R & \mu_N
\end{pmatrix}
\]


If \( \overline{v}_L \to 0 \) 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

\[
W_{\text{Higgs}} = i \mu_1 H_L^T \tau_2 \bar{H}_L + i \mu_1 H_R^T \tau_2 \bar{H}_R + \lambda \bar{H}_L^T \tau_2 \Phi \tau_2 \bar{H}_R
\]

\[
+ \lambda H_L^T \tau_2 \Phi \tau_2 H_R + \mu \text{Tr} \left[ \Phi \tau_2 \Phi^T \tau_2 \right]
\]

• 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

\[
M_h = \left( 2 M_W^2 \sin^4 \beta + \frac{M_W^4}{2 M_W^2 - M_Z^2} \cos^4 \beta - \frac{M_W^2}{2} \sin^2 2\beta + \lambda^2 v^2 \sin^2 2\beta \right) \Delta_1 + \Delta_2
\]
Higgs doublets: Inverse seesaw models

- 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.
Universal Seesaw Models

Higgs sector of the model is

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

\[ \bar{H}_R (1, 1, 2, -1) = \begin{pmatrix} \bar{H}_R^0 \\ H_R^- \end{pmatrix}, \quad S (1, 1, 1, 0) \]

- \( H_R \) 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

\[ P (3, 1, 1, -\frac{4}{3}), \quad R (3, 1, 1, \frac{2}{3}), \quad E (1, 1, 1, 2) \]

\[ P^c (3, 1, 1, \frac{4}{3}), \quad R^c (3, 1, 1, -\frac{2}{3}), \quad E^c (1, 1, 1, -2) \]

A. Davidson, KC. Wali, Phys. Rev. Lett. 59, 393 (1987);
• An optional heavy singlet neutrino \( N \).

• Yukawa coupling terms in the superpotential

\[
W_Y = Y_u Q \bar{H}_L P - Y_d Q H_L R - Y_l L H_L E + Y_v L \bar{H}_L N
\]

\[
+ Y_u^c Q^c \bar{H}_R P^c - Y_d^c Q^c H_R R^c - Y_l^c L^c H_R E^c + Y_v^c L^c \bar{H}_R N
\]

\[
+ m_u^cPP^c + m_d^cRR^c + m_l^cEE^c + m_v^cNN
\]

• Mass of fermions are generated via the seesaw mechanism.

\[
M_u = \begin{pmatrix}
0 & \bar{Y}_u V_L \\
Y_u^c \bar{V}_R & m_u
\end{pmatrix}
\]

• 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

\[ M_h = \left( \frac{M_W^4}{2M_W^2 - M_Z^2} \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta \right) \Delta_1 + \Delta_2 \]
- 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.
Universal seesaw model without singlet

- Higgs superpotential terms are

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

- Calculate the Higgs potential and the minimization conditions.

- Calculate the Higgs boson mass-squared matrix.

- Lightest neutral scalar Higgs boson mass

\[ M_h = (M_Z^2 \cos^2 2\beta) \Delta_1 + \Delta_2. \]

- 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

\[
X^c (3,1,2,-\frac{1}{6}) = \left( h^c \quad u^c \right)_L, \quad Q(3,2,1,\frac{1}{6}) = \left( u \quad d \right)_L, \quad h(3,1,1,-\frac{1}{3}) = h_L,
\]

\[
L^c (1,1,2,\frac{1}{2}) = \left( e^c \quad n \right)_L, \quad E(1,2,1,-\frac{1}{2}) = \left( \nu_E \quad E \right)_L, \quad d^c (\overline{3},1,1,\frac{1}{3}) = d^c_L,
\]

\[
F(1,2,2,0) = \begin{pmatrix}
\nu^c_e & E^c_E \\
e & N^c_E \\
\end{pmatrix}_L, \quad N^c (1,1,1,0) = N^c_L.
\]

- Discrete R-parity symmetry under which

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

• The Higgs fields are identified as
\[
H_L(1,2,1,-1) = \begin{pmatrix} H^0_L \\ H^-_L \end{pmatrix} = \begin{pmatrix} \tilde{\nu}_E \\ \tilde{E} \end{pmatrix}, \quad H_R(1,1,2,1) = \begin{pmatrix} H^+_R \\ H^0_R \end{pmatrix} = \begin{pmatrix} \tilde{e}^c \\ \tilde{n} \end{pmatrix},
\]

\[ \Phi(1,2,2,0) = \begin{pmatrix} \phi^+_1 & \phi^0_2 \\ \phi^0_1 & \phi^-_2 \end{pmatrix} = \begin{pmatrix} \tilde{E}^c & \tilde{N}_E^c \\ \tilde{\nu}_e & \tilde{e} \end{pmatrix}. \]

• 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 $3\times3$ matrix in basis $(\nu_E, N_E^c, n)$ 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
\[ W_{\text{Higgs}} = \lambda H_L^T \tau_2 \Phi \tau_2 H_R + \mu \text{Tr} \left[ \Phi^T \tau_2 \Phi \tau_2 \right]. \]

• The non-zero vacuum expectation values are given as
\[ \langle H_R^0 \rangle = v_R, \quad \langle H_L^0 \rangle = v_L, \quad \langle \phi^0_1 \rangle = v_1, \quad \langle \phi^0_2 \rangle = v_2 \]

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

<table>
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<tr>
<th>BR($H_R^{\pm\pm} \rightarrow \ell^\pm \ell'^\pm$)</th>
<th>95% CL lower limit on $m(H_R^{\pm\pm})$ [GeV]</th>
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<td>$e^\pm e^\pm$ obs.</td>
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<td>22%</td>
<td>203</td>
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<td>160</td>
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</tbody>
</table>

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).

Three cases we must consider

1. \( p \ p \rightarrow \delta_{R}^{++} \delta_{R}^{--} \rightarrow l^{+} l^{+} l^{-} l^{-} \)

2. \( p \ p \rightarrow \tilde{\delta}_{R}^{++} \tilde{\delta}_{R}^{--} \rightarrow \delta_{R}^{++} \delta_{R}^{--} \tilde{\chi}_{1}^{0} \tilde{\chi}_{1}^{0} \rightarrow l^{+} l^{+} l^{-} l^{-} \tilde{\chi}_{1}^{0} \tilde{\chi}_{1}^{0} \)

3. \( p \ p \rightarrow \tilde{\delta}_{L}^{++} \tilde{\delta}_{L}^{--} \rightarrow \tilde{l}^{+} \tilde{l}^{+} \tilde{l}^{-} \tilde{l}^{-} \rightarrow l^{+} l^{+} l^{-} l^{-} \tilde{\chi}_{1}^{0} \tilde{\chi}_{1}^{0} \)

We take two parameter space

- BP1 for which \( M_{\delta_{R}^{\pm \pm}} = 300 \text{ GeV}, M_{\tilde{\chi}_{1}^{0}} = 500 \text{ GeV} \) and \( M_{\tilde{\chi}_{1}^{0}} = 80 \text{ GeV} \).

- BP2 for which \( M_{\delta_{R}^{\pm \pm}} = 300 \text{ GeV}, M_{\tilde{\chi}_{1}^{0}} = 400 \text{ GeV} \) and \( M_{\tilde{\chi}_{1}^{0}} = 80 \text{ GeV} \).
Direct production of the light doubly-charged Higgsinos and Higgs boson at LHC at 14 TeV.
The same-sign lepton plot peaks at a low value of $\Delta R$ 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.
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.
- Examined 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 $\phi$ 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 $M_{inv}^{\text{OS}} > 10$ GeV.
- A further invariant mass cut of $80$ GeV $> M_{inv}^{\text{OS}} > 100$ GeV to get rid of the Z-boson peak.

We study the MET, $\Delta R$ and the invariant mass of the final state leptons.