# A Supersymmetric Electroweak Scale Seesaw Model

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# Outline

- Introduction
- The Model
- Phenomenology
- Summary and Outlook

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# Introduction

- Why Supersymmetry?
  - Appealing solution for the hierarchy problem
- Why Electroweak Scale?
  - We can test it now at the LHC
- Why Seesaw?
  - Explanation for the smallness of neutrino masses

➡ A SUSY EW scale seesaw model

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# Field content

- MSSM fields
- Right-handed neutrinos $N$ (at least 2)
- Lepton-like gauge singlet fields $S$ (at least 2)
- Higgs-like gauge singlet field $X$ (at least 1)

# Symmetries and Superpotential

| Superfield | $\hat{Q}_i$ | $\hat{U}_i^c$ | $\hat{E}_i^c$ | $\hat{L}_i$ | $\hat{D}_i^c$ | $\hat{H}_u$ | $\hat{H}_d$ | $\hat{N}_\alpha^c$ | $\hat{S}_\alpha$ | $\hat{X}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $Z_6$ charge | 5 | 5 | 5 | 3 | 3 | 2 | 4 | 1 | 5 | 2 |

- SM gauge symmetries + $Z_6$ (SU(5) compatible)
- Superpotential (R-parity conserved by $Z_6$)

$$\mathcal{W} = \mathcal{W}_{\text{MSSM}} + Y_\nu \, \hat{L}\hat{H}_u\hat{N}^c + \mu_{NS} \, \hat{N}^c\hat{S} + \frac{\lambda}{2} \, \hat{X} \, \hat{S}^2 + \frac{\kappa}{3} \, \hat{X}^3$$

# Broken Symmetries

- Lepton number explicitly broken
- Electroweak symmetry broken as in the MSSM
- $Z_6$ broken to $Z_2$ by vev of $X$

$$v_X = -\frac{A_\kappa}{4\,\kappa^2} \pm \frac{\sqrt{A_\kappa^2 - 8\,\kappa^2 M_X^2}}{4\,\kappa^2}$$

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  - **Neutrino Masses and Mixing**
  - Neutrinoless Double Beta Decay
  - Charged Lepton Flavor Violation
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# ISS Types

$$M_\nu = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & \mu_{NS} \\ 0 & \mu_{NS}^T & M_S \end{pmatrix}$$

- 3 kinds of Inverse SeeSaw (ISS) mechanism:
  - ISS Type I: $M_S \ll M_D \ll \mu_{NS}$ (conventional ISS)
  - ISS Type II: $M_S \sim M_D \ll \mu_{NS}$
  - ISS Type III: $M_D \ll M_S \ll \mu_{NS}$
- $M_D$ and $M_S$ proportional to EW scale vevs

# Neutrino Masses & Yukawa Couplings

- Common leading order light neutrino masses

$$m_\nu = M_D \, \mu_{NS}^{-1} \, M_S \, \mu_{NS}^{-1} \, M_D^T \sim Y_\nu \, \lambda \, Y_\nu^T \, \mathcal{O}(\mathrm{TeV})$$

- Tiny masses due to small Yukawa couplings
- Casas-Ibarra formula in our case

$$Y_\nu = \frac{\mathrm{i}}{v_u} U_{\mathrm{PMNS}} \sqrt{m_i} \, \Omega \, \left( \sqrt{M_S^d} \right)^{-1} V_S$$

# Neutrino Masses & Yukawa Couplings

- In minimal case one neutrino massless
- Sizes of the Yukawa couplings
  - ISS Type I: $Y_\nu \sim 10^{-4}$ and $\lambda \sim 10^{-8}$ and $\epsilon_I \sim 10^{-4}$
  - ISS Type II: $Y_\nu \sim 10^{-5}$ and $\lambda \sim 10^{-5}$ and $\epsilon_{II} \sim 10^{-5}$
  - ISS Type III: $Y_\nu \sim 10^{-6}$ and $\lambda \sim 10^{-3}$ and $\epsilon_{III} \sim 10^{-3}$

# Neutrinoless Double Beta Decay

- New neutrino states almost Dirac
- Contributions to $m_{\text{eff}}$ small, e.g. ISS Type I:

$$m_{\text{eff}}^{\text{new}} \simeq \sum_{i=4}^{7} (U_{ei})^2 \frac{\langle p^2 \rangle}{\mu_{NS}^2} M_S \approx 8 \times 10^{-9} \ \text{meV} \cdot \left( \frac{\text{TeV}}{\mu_{NS}} \right)$$

- In minimal version $m_{\text{eff}}$ is O(1) meV for NH and O(10) meV for IH

# Non-Unitarity of the PMNS Matrix

- The 3x3 PMNS matrix is not unitary anymore
- In this model

$$U_{\mathrm{PMNS}} U^\dagger_{\mathrm{PMNS}} = 1 + \mathcal{O}(\epsilon^2)$$

- Current constraints $\epsilon < O(10^{-3} - 10^{-1})$

**[Fernandez-Martinez, Hernandez-Garica, Lopez-Pavon 2016]**

# Charged Lepton Flavor Violation

- Smoking gun for new physics
- In our model two kind of contributions
  - Non-SUSY contributions from new neutrinos
  - SUSY contributions involving charged sleptons and sneutrinos

# Charged Lepton Flavor Violation

- The non-SUSY part can be written as

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U_{ie} U^*_{i\mu} \, F(m_i^2/M_W^2) \right|^2$$

- Dominant contribution from non-unitarity of the mixing matrix

$$\mathrm{BR}(\mu \to e\gamma) = \begin{cases} \mathcal{O}(10^{-20}) & \text{for ISS type I,} \\ \mathcal{O}(10^{-24}) & \text{for ISS type II,} \\ \mathcal{O}(10^{-28}) & \text{for ISS type III,} \end{cases}$$

- Experiment: BR($\mu \to e\gamma$) < $4.2 \cdot 10^{-13}$ @90%CL

**[Final MEG result 2016]**

# Charged Lepton Flavor Violation

- SUSY part very similar to MSSM apart from sneutrinos
- Sneutrinos combination of left-, right-handed sneutrinos and scalar component of extra singlets
- The vev of $X$ induces (small) mass splitting of the real and imaginary part of the sneutrinos
- Minimally 14 (real) sneutrinos

# Charged Lepton Flavor Violation

- Neglecting contributions proportional to small Yukawa couplings

$$m^2_{\tilde{\nu}^R} \approx m^2_{\tilde{\nu}^I} \approx \begin{pmatrix} \Re(M^2_{\tilde{L}}) + \frac{1}{2} M_Z^2 \cos(2\beta) & 0 & 0 \\ 0 & \Re(M^2_{\tilde{N}^c} + \mu_{NS}\mu^\dagger_{NS}) & \Re(b_{NS}) \\ 0 & \Re(b^T_{NS}) & \Re(M^2_{\tilde{S}} + \mu^\dagger_{NS}\mu_{NS}) \end{pmatrix}$$

- Real and imaginary part have same mass
- Small mixing of left-handed sneutrinos with other sneutrinos

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# Summary and Outlook

- Attractive minimal supersymmetric low-scale seesaw model
- No ad-hoc assumptions on which symmetry is broken at which scale
- Many predictions
- Many features yet to be explored (DM, Leptogenesis, …)

Thanks a lot for your attention!