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 (SUSY)?
  - Appealing solution for the hierarchy problem
- Why Electroweak (EW) Scale?
  - We can test it at the LHC
- Why Seesaw?
  - Explanation for the smallness of neutrino masses

➡ A SUSY EW scale seesaw model

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Field content

[J. Chang, K. Cheung, H. Ishida, C.-T. Lu, MS, Y.-L. S. Tsai, 2017]

- 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

[J. Chang, K. Cheung, H. Ishida, C.-T. Lu, MS, Y.-L. S. Tsai, 2017]

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

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

- Lepton number broken by last term

Symmetries and Superpotential

[J. Chang, K. Cheung, H. Ishida, C.-T. Lu, MS, Y.-L. S. Tsai, 2017]

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_3 charge	1	1	1	0	0	1	2	2	1	1
Z_2 charge	1	1	1	1	1	0	0	1	1	0

- Z_6 broken to Z_2 by vev of X of $O(M_{\mathrm{SUSY}})$
- Z_2 acts like matter parity in MSSM
- Unbroken Z_2 stabilizes DM candidates:
  - ➡ Gravitino, Sneutrino, Neutralino
- Electroweak symmetry broken as in the MSSM

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

[J. Chang, K. Cheung, H. Ishida, C.-T. Lu, MS, Y.-L. S. Tsai, 2017]

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

$$M_D = Y_\nu v_u$$
$$M_S = \lambda v_X$$

- 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

[J. Chang, K. Cheung, H. Ishida, C.-T. Lu, MS, Y.-L. S. Tsai, 2017]

- 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

[J. Chang, K. Cheung, H. Ishida, C.-T. Lu, MS, Y.-L. S. Tsai, 2017]

- 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

[J. Chang, K. Cheung, H. Ishida, C.-T. Lu, MS, Y.-L. S. Tsai, 2017]

- New neutrino states almost Dirac
- Contributions to m_{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_{eff} is O(1) meV for NH and O(10) meV for IH

Non-Unitarity of the PMNS Matrix

[J. Chang, K. Cheung, H. Ishida, C.-T. Lu, MS, Y.-L. S. Tsai, 2017]

- 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

[J. Chang, K. Cheung, H. Ishida, C.-T. Lu, MS, Y.-L. S. Tsai, 2017]

- 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

[J. Chang, K. Cheung, H. Ishida, C.-T. Lu, MS, Y.-L. S. Tsai, 2017]

- 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

[J. Chang, K. Cheung, H. Ishida, C.-T. Lu, MS, Y.-L. S. Tsai, 2017]

- 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

[J. Chang, K. Cheung, H. Ishida, C.-T. Lu, MS, Y.-L. S. Tsai, 2017]

- 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, rather 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!