TeV Scale Seesaw Mechanism, Singlet Scalar Dark Matter and Electroweak Vacuum Stability

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Overview

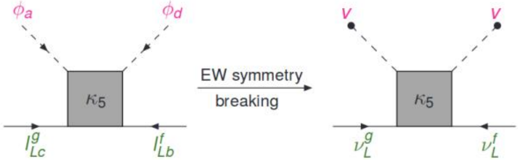
- Introduction
- TeV Scale Seesaw model : Inverse Seesaw
- Singlet Scalar DM
- SM + Inverse Seesaw + Singlet Scalar and EW vacuum stability
- Numerical Analysis and Results

Introduction

- The Standard Model (SM) of particle physics is a very successful theory
- Neutrino oscillation $\Longrightarrow$ neutrinos have Mass and Mixing
- The first indication towards the need for a theory beyond SM
- Another issue that the SM does not have an answer to : the existence of Dark Matter (DM)
- These issues could be addressed either by extending just the particle content or by extending the gauge group
- It is important to study the implications of the BSM models that can solve these issues

Neutrino mass : Seesaw Mechanism

- The most natural approach towards understanding the sub-eV neutrino mass scale
- Neutrinos are Majorana particles and the lepton number must be explicitly violated at a high-energy scale
- Tree level exchange of some heavy particle present at a higher energy $\Longrightarrow$ Effective dimension-5 operator * $\frac{\kappa_5 LL\Phi\Phi}{M}$ at low scale



- Introduce 3 heavy right handed Majorana neutrinos (N_R) into the Standard Model : Type-1 seesaw mechanism †

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*Weinberg (1979)

†Minkowski(1977), Mohapatra and Senjanovic (1980)

TeV Scale Seesaw Mechanism

- The minimal type 1 seesaw model is not testable
- Motivates us to look for testable TeV scale seesaw models
- To the type-1 seesaw picture , add 3 additional gauge-singlet neutrinos with opposite lepton number, $S_R^i\,(\,i\;=\;1,2,3)$

$$-L_\nu = \bar{l}_L Y_\nu\, H^c N_R \;+\; \bar{N}_R^c\, M_S\, S_R \;+\; \frac{1}{2}\,\bar{S}_R^c M_\mu S_R \;+\; \text{h.c.}$$

- Once the Higgs field H acquire a vev (v), $M_D = Y_\nu v/\sqrt{2}$,

$$-L_{mass} = \frac{1}{2}(\,\bar{\nu}_L\;\;\bar{N}_R^c\;\;\bar{S}_R^c\,)\begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M_S \\ 0 & M_S^T & M_\mu \end{pmatrix}\begin{pmatrix} \nu_L^c \\ N_R \\ S_R \end{pmatrix} \;+\; \text{h.c.}$$

- The mass scales of three sub-matrices of M may naturally have a hierarchy $M_S >> M_D >> M_\mu$
- $\implies\;\; M_\nu \;=\; M_D(M_S^T)^{-1}M_\mu M_S^{-1}M_D^T\,:$ Inverse Seesaw Mechanism

Inverse Seesaw : Key Features

- The smallness of M_ν is naturally attributed to both the smallness of M_μ and the smallness of $\frac{M_D}{M_S}$.
- $M_\nu \approx O(0.1)\, eV$ can easily be achieved from $\frac{M_D}{M_S} \approx 10^{-2}$ and $M_\mu \approx O(1keV)$
- Lepton number is softly broken by M_μ
- M_ν goes to 0 in the limit of M_μ going to 0
- Heavy neutrino masses : a few 100 GeV to a few TeV
- Can give large unitarity violation and lepton flavour violating radiative decays
- BR $(\mu \to e\gamma) \approx 10^{-14}$

Singlet Scalar with a Z_2

- Nearly 95 percent of the Universes matter density is dark ; $\sim$ 26 percent DM
- Among the various models of DM that are proposed, the most minimal extension of the SM : Higgs portal models
- Here, we add a real scalar singlet, A, to the SM with a discrete Z_2 symmetry and 0 vev
- The new scalar potential becomes,

$$V = V_{SM} + \frac{1}{2} m_A^2 A^2 + \frac{\kappa}{2} H^\dagger H A^2 + \frac{\lambda_A}{4} A^4$$

$$V_{SM} = m^2 \, H^\dagger H + \lambda \, (H^\dagger H)^2$$

- In a model with SM extended by a TeV seesaw + real singlet scalar, could there be a connection between the two seemingly disconnected sectors ? YES

Renormalization Group Equations

- Quantum loop corrections will make the mass parameter and coupling dependent on the energy scale Λ
- The λ for the quartic term is running with Λ as : $\Lambda \frac{d}{d\Lambda} = \beta_\lambda$
- At one-loop order,

$$\beta_{\lambda SM} = \frac{1}{(4\pi)^2} [\, 24\lambda^2 - 6y_t^4 + \frac{3}{8}(2g^4 + (g^2 + g'^2)^2) + (-9g^2 - 3g'^2 + 12y_t^2)\,\lambda \,]$$

- The relative sign between bosonic and fermionic contributions would dramatically affect the UV behaviour of the theory

Vacuum Stability in the Standard Model

- Due to the heavy quarks contribution
- λ runs as $-y_t^4$: The large top yukawa coupling will pull λ down to negative values at higher energies
- Then the potential might develop a new minimum at a higher energy scale $\implies$ The EW vacuum may be unstable due to quantum tunnelling
- In SM, λ becomes negative at an energy scale of $10^9 - 10^{10}$ GeV depending on the values of α_S and y_t used
- This is not a threat to the theory as long the decay time is greater than the age of the universe $\implies$ SM vacuum is metastable
- This gives a bound on λ :

$$\lambda(\Lambda_B) > \lambda_{\min}(\Lambda_B) = \frac{-0.06488}{1 - 0.00986\ ln(v/\Lambda_B)}$$

Effective Higgs Potential and λ_{eff}

- The tree level Higgs potential in the SM is given by,

$$V(h) = \frac{m^2}{2} h^2 + \frac{\lambda}{4} h^4$$

- This will get corrections from higher order loop diagrams

$$V_1^{SM+A+\nu}(h) = V_1^{SM}(h) + V_1^{A}(h) + V_1^{\nu}(h)$$

- For $h >> v$, the effective potential could be approximated as, (vacuum instability appears at a scale $>>$ ew vacuum)

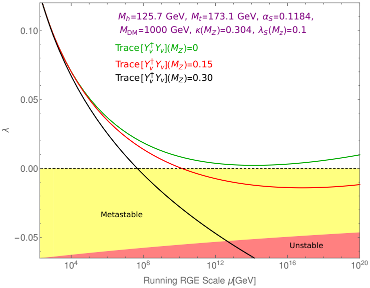
$$V_{eff}^{SM+A+\nu} = \lambda_{eff}(h,t) \frac{h^4}{4}$$

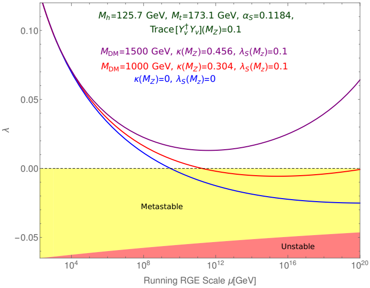
$$\lambda_{eff}(h) = \lambda_{eff}^{SM}(h) + \lambda_{eff}^{A}(h) + \lambda_{eff}^{\nu}(h)$$

- Modified RGE for λ : $\beta_\lambda = \beta_{\lambda SM} + \frac{1}{(4\pi)^2}[+ 4\kappa^2 - 2\mathrm{Tr}(Y_\nu^\dagger Y_\nu)^2]$

Numerical Analysis

- The vacuum stability/metastability analysis is done considering following constraints on both sectors.
- Bounds on the scalar sector:
  - Perturbative unitarity bound.
  - Dark matter relic abundance.
  - Bounds on dark matter mass and Higgs portal coupling from Higgs invisible decay width, direct (LUX-2016) and indirect detection (Fermi-LAT).
- The low energy constraints on the lepton sector:
  - Oscillation data : Mixing angles and Mass squared differences.
  - Constraints on the non-unitarity of PMNS matrix.
  - Bounds on heavy neutrino masses and light-heavy mixing from LEP experiments.
  - BR $(\mu \to e\gamma) \; < \; 4.2 \times 10^{-13}$.


M_h=125.7 GeV, M_t=173.1 GeV, α_S=0.1184,
M_{DM}=1000 GeV, $\kappa(M_Z)$=0.304, $\lambda_S(M_Z)$=0.1
Trace$[Y_\nu^\dagger Y_\nu](M_Z)$=0
Trace$[Y_\nu^\dagger Y_\nu](M_Z)$=0.15
Trace$[Y_\nu^\dagger Y_\nu](M_Z)$=0.30
Metastable
Unstable
λ
Running RGE Scale μ[GeV]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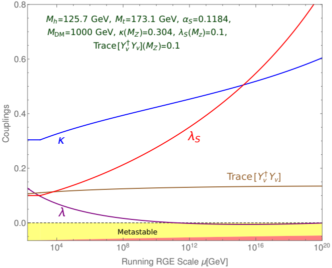
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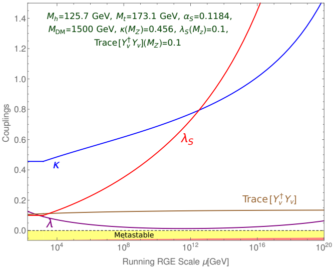
κ
λ_S
Trace$[Y_\nu^\dagger Y_\nu]$
λ
Metastable
Couplings
Running RGE Scale μ[GeV]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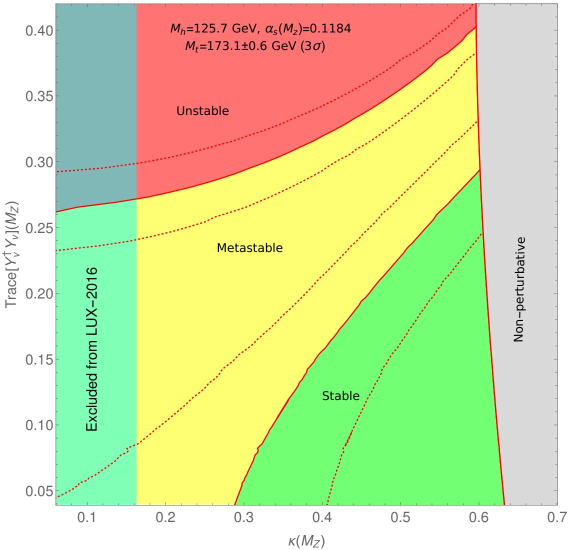
Phase Diagram in the $\mathrm{Tr}[Y_\nu^\dagger Y_\nu] - \kappa$ Plane



Summary

- The lack of experimental testability of canonical type - 1 seesaw mechanism motivates us to consider TeV scale seesaw mechanisms
- One of the most studied TeV scale seesaw models is the inverse seesaw model where the smallness of m_ν is naturally attributed to the smallness of a LNV parameter M_μ
- As a result of low mass thresholds, large values of Y_ν get constraints from vacuum stability considerations
- Adding the extra scalar allows us to have even larger values of Y_ν, giving rise to larger values of *LFV* decay rates and non-unitarity, and also having a stable DM candidate at the same time
- Two seemingly disjoint sectors connected by vacuum stability constraints

THANK YOU