TeV Scale Seesaw Mechanism, Singlet Scalar Dark Matter and Electroweak Vacuum Stability
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Vishnudath K.N.
Physical Research Laboratory, Ahmedabad, India
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1I.Garg, S.Goswami, VKN, N. Khan
Overview

- Introduction
- TeV Scale Seesaw model: Inverse Seesaw
- Singlet Scalar DM
- SM + Inverse Seesaw + Singlet Scalar and EW vacuum stability
- Numerical Analysis and Results
The Standard Model (SM) of particle physics is a very successful theory

Neutrino oscillation $\Rightarrow$ 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 \( \Rightarrow \) Effective dimension-5 operator \( \kappa_5 \frac{L^L \Phi \Phi}{M} \) at low scale

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

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*Weinberg (1979)
\(\dagger\)Minkowski(1977), Mohapatra and Senjanovic (1980)
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, $S^i_R$ ($i = 1, 2, 3$)

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

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

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

The mass scales of three sub-matrices of $M$ may naturally have a hierarchy $M_S >> M_D >> M_\mu$

$$\implies M_\nu = M_D (M_S^T)^{-1} M_\mu M_S^{-1} M_D^T : \text{Inverse Seesaw Mechanism}$$
Inverse Seesaw: Key Features

- The smallness of $M_{\nu}$ is naturally attributed to both the smallness of $M_{\mu}$ 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 $M_{\mu} \approx O(1\ keV)$

- Lepton number is softly broken by $M_{\mu}$

- $M_{\nu}$ goes to 0 in the limit of $M_{\mu}$ 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

- $BR (\mu \rightarrow e\gamma) \approx 10^{-14}$
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 $\Lambda$
- The $\lambda$ for the quartic term is running with $\Lambda$ as: $\Lambda \frac{d}{d\Lambda} = \beta_\lambda$
- At one-loop order,
  \[
  \beta_{\lambda_{SM}} = \frac{1}{(4\pi)^2} \left[ 24\lambda^2 - 6y_t^4 + \frac{3}{8} (2g^4 + (g^2 + g'^2)^2) \right] \\
  + (-9g^2 - 3g'^2 + 12y_t^2) \lambda
  \]
- 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
- $\lambda$ runs as $-y_t^4$: The large top yukawa coupling will pull $\lambda$ down to negative values at higher energies
- Then the potential might develop a new minimum at a higher energy scale $\Rightarrow$ The EW vacuum may be unstable due to quantum tunnelling
- In SM, $\lambda$ becomes negative at an energy scale of $10^9 - 10^{10}$ GeV depending on the values of $\alpha_S$ 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 $\Rightarrow$ SM vacuum is metastable
- This gives a bound on $\lambda$:

$$\lambda(\Lambda_B) > \lambda_{\text{min}}(\Lambda_B) = \frac{-0.06488}{1 - 0.00986 \ln(v/\Lambda_B)}$$
Effective Higgs Potential and $\lambda_{\text{eff}}$

- 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 $h \gg \nu$, the effective potential could be approximated as, (vacuum instability appears at a scale $\gg$ ew vacuum)

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

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

- Modified RGE for $\lambda$:

$$\beta_{\lambda} = \beta_{\lambda}^{SM} + \frac{1}{(4\pi)^2} \left[ + 4\kappa^2 - 2 \text{Tr}(Y_{\nu}^\dagger Y_{\nu})^2 \right]$$
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.
  - $\text{BR} (\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$. 

$\text{BR} (\mu \rightarrow e\gamma)$
$M_h = 125.7$ GeV, $M_t = 173.1$ GeV, $\alpha_s = 0.1184$,
$M_{\text{DM}} = 1000$ GeV, $\kappa(M_Z) = 0.456, \lambda_s(M_Z) = 0.1$

$\text{Trace}[Y^\dagger_{\nu} Y_{\nu}](M_Z) = 0.1$

$M_h = 125.7$ GeV, $M_t = 173.1$ GeV, $\alpha_s = 0.1184$,
$M_{\text{DM}} = 1000$ GeV, $\kappa(M_Z) = 0.304, \lambda_s(M_Z) = 0.1$

$\text{Trace}[Y^\dagger_{\nu} Y_{\nu}](M_Z) = 0.1$

$M_h = 125.7$ GeV, $M_t = 173.1$ GeV, $\alpha_s = 0.1184$,
$M_{\text{DM}} = 1500$ GeV, $\kappa(M_Z) = 0.304, \lambda_s(M_Z) = 0.1$

$\text{Trace}[Y^\dagger_{\nu} Y_{\nu}](M_Z) = 0.1$
Phase Diagram in the $\text{Tr}[Y^\dagger Y] - \kappa$ Plane

$M_h = 125.7$ GeV, $\alpha_s(M_Z) = 0.1184$

$M_{\tau} = 173.1 \pm 0.6$ GeV (3σ)

Excluded from LUX-2016

Unstable

Metastable

Stable

Non-perturbative

Trace $[Y^\dagger Y](M_Z)$

$\kappa(M_Z)$
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 $m_\nu$ is naturally attributed to the smallness of a LNV parameter $M_\mu$.

As a result of low mass thresholds, large values of $Y_\nu$ get constraints from vacuum stability considerations.

Adding the extra scalar allows us to have even larger values of $Y_\nu$, 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