Right-Handed Neutrinos as the Origin of the Electroweak Scale

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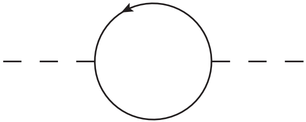
Motivation

- Higgs boson at ~ 125 GeV, appears mostly Standard Model like.
- Many additional new physics motivations not yet explained: baryon asymmetry of the universe, dark matter, neutrino masses.
- Theoretical issues with a boson, unstable against large quadratic quantum corrections.

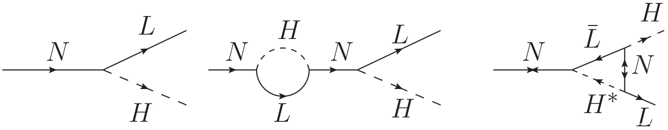


- To avoid fine-tuning, new heavy states should have masses, M, with couplings, λ, to the Higgs such that

$$\delta m_h^2 \sim \frac{\lambda^2 M^2}{8\pi^2} \lesssim v^2$$

- Some issues:
  - Grand unification.
  - Typical leptogenesis with a Type I seesaw does not satisfty this criteria.

Motivation



- In typical scenario, inject lepton number via a heavy neutrino decay $N \to LH$ with a CP-asymmetry:

$$\varepsilon = \frac{\Gamma(N \to LH) - \Gamma(N \to \overline{L}H^*)}{2\Gamma(N)} \sim \frac{y_N^2}{8\pi}$$

- Converted into baryon asymmetry:

$$\frac{n_B}{s} \sim \frac{\varepsilon}{g_*} \sim \frac{y_N^2}{8\pi g_*} \sim 10^{-10} \quad \Rightarrow \quad y_N \gtrsim 5 \times 10^{-4}$$

- Apply to typical seesaw mechanism with neutrino mass $m_\nu = 0.1$ eV.

$$m_\nu \sim \frac{y_N^2 v^2}{M_N} \quad \Rightarrow \quad M_N \gtrsim 10^8 \text{ GeV}$$

- The Higgs mass correction is then:

$$\delta m_H^2 \sim \frac{y_N^2}{4\pi^2} M_N^2 \gtrsim (8 \text{ TeV})^2 \gg v^2$$

The Model

- Major issue of the above setup is that the same set of couplings are responsible to leptogenesis, neutrino mass, and the Higgs mass correction.
- Consider and inert Higgs doublet model, in which we charge a second Higgs doublet H_2 and the heavy neutrinos under a Z_2 parity, while SM particle are even under the Z_2.

The Model

- Major issue of the above setup is that the same set of couplings are responsible to leptogenesis, neutrino mass, and the Higgs mass correction.
- Consider and inert Higgs doublet model, in which we charge a second Higgs doublet H_2 and the heavy neutrinos under a Z_2 parity, while SM particle are even under the Z_2.
- Then have neutrino mass and yukawa couplings:

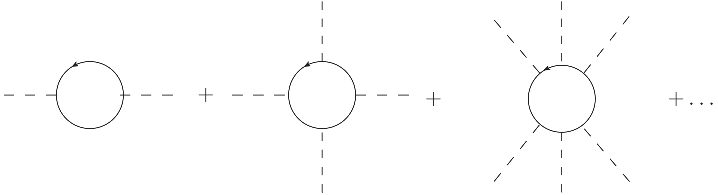
$$-\mathcal{L}_N = y^{ai} H_2^* \overline{L_i} N_a + \frac{1}{2} M_{N_a} \overline{N_a^c} N_a + \text{H.C.},$$

- Start with massless Higgs potential:

$$V_0 = \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + \text{h.c.}\right]$$

- Now the SM Higgs (H_1) is one removed from the heavy neutrinos, alleviating the above problems.
- Will not explain origin of M_N, however, the neutrino mass may come from a heavy scalar that obtains a mass via the Coleman-Weinberg mechanism.
- Will set $\lambda_4 = 0$ for simplicity.

Scalar Masses



- Effect of the neutrinos on the Higgs potential at one loop are obtained via the Coleman-Weinberg potential from neutrino states
  - High mass state: $M^2_\alpha(H_2) = \frac{M^2_{N_\alpha}}{2}\left(1 + 2y^2_\alpha \frac{|H_2|^2}{M^2_{N_\alpha}} + \sqrt{1 + 4y^2_\alpha \frac{|H_2|^2}{M^2_{N_\alpha}}}\right)$
  - Low mass states: $m^2_\alpha(H_2) = \frac{M^2_{N_\alpha}}{2}\left(1 + 2y^2_\alpha \frac{|H_2|^2}{M^2_{N_\alpha}} - \sqrt{1 + 4y^2_\alpha \frac{|H_2|^2}{M^2_{N_\alpha}}}\right)$
- Obtain a mass squared term for H_2 (using dim. reg.):

$$V_1(H_2, \mu) = \sum_\alpha \frac{y^2_\alpha M^2_{N_\alpha}}{8\pi^2}\left[\kappa_N - \log\left(\frac{M^2_{N_\alpha}}{\mu^2}\right)\right]|H_2|^2 + \dots$$

- H_2 mass loop suppressed compared to M_N, so integrate out heavy neutrinos.

Scalar Masses

- At scale below M_N the effect of the neutrinos on the H_2 are parameterized by a mass term for H_2:

$$V_0 \to V_0 + \mu_2^2 |H_2|^2$$

- Matching onto the high energy theory at a scale $\mu = M_N$ obtain (μ without subscript is renormalization scale):

$$\mu_2^2 = \frac{M_N^2 y_N^2 \kappa_N}{4\pi^2}$$

A few comments are in order:

  - κ_N introduced to parameterize renormalization scheme dependence.
  - The $\overline{\text{MS}}$ scheme corresponds to $\kappa_N = 1$ and $\kappa_N > 0$ for MS scheme.
  - Hence, the finite contribution of neutrino loops gives a $\mu_2^2 > 0$ and the Z_2 symmetry is a good symmetry with a candidate DM candidate.

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  - Hence, the finite contribution of neutrino loops gives a $\mu_2^2 > 0$ and the Z_2 symmetry is a good symmetry with a candidate DM candidate.
- In this EFT, H_2 has a mass and couples to H_1.
- Hence, H_1 will obtain a loop induced mass.

Scalar Masses

- In the EFT the one-loop Coleman-Weinberg induces a mass for H_1:

$$V_1(H_2, H_1, \mu) \quad = \quad -\frac{\mu_2^2}{16\pi^2}\left(\kappa_2 - \log\frac{\mu_2^2}{\mu^2}\right)\left(2\lambda_3\,|H_1|^2 + 3\lambda_2\,|H_2|^2\right) + \ldots,$$

- Again, H_1 mass loop suppressed compared to μ_2, so work in EFT for scales $\mu < \mu_2$:

$$V_0 = -\mu_1^2|H_1|^2 + \frac{\lambda_1}{2}|H_1|^4,$$

- Matching at a scale $\mu = \mu_2$, obtain:

$$\mu_1^2 = \frac{\lambda_3\kappa_2}{8\pi^2}\mu_2^2$$

- For $\overline{\text{MS}}$ scheme ($\kappa_2 = 1$) and MS scheme ($\kappa_2 > 0$), have a negative mass squared for H_1 and obtain electroweak symmetry breaking.

Scalar Masses

- For simplicity set set renormalization equal $\kappa_2 = \kappa_N = \kappa_1 = \kappa$, final result for scalar masses:

$$\mu_1^2 \approx \frac{\lambda_3 y_N^2 \kappa^2}{32\pi^4} M_N^2$$
$$\mu_2^2 \approx \frac{y_N^2 \kappa}{4\pi^2} M_N^2$$

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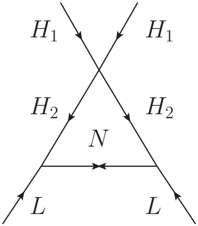
- μ_1^2 is two-loop suppressed compared to heavy neutrino mass, hopefully alleviate the fine-tuning problem in typical leptogenesis.
- For the $\overline{\text{MS}}$ scheme ($\kappa = 1$) and MS scheme ($\kappa = 1 - \gamma_E + \log(4\pi) > 0$):
  - Mass squared parameter of H_1 is negative (the negative sign was pulled out in the definition of μ_1).
  - Mass squared parameter of H_2 is positive.
  - Electroweak symmetry is broken and the Z_2 preserved, leaving a DM candidate.
  - The finite pieces of the loops obtain the desired symmetry breaking pattern.
- Now can this scenario be compatible with leptogenesis and neutrino masses?

Neutrino Mass



- Since the neutrinos do not couple directly to H_1, typical Type I seesaw is does not work.
- However, there is a loop induced process E. Ma, hep-ph/0601225:

$$m_\nu \approx -\frac{\lambda_5 y_N^2 v^2}{8\pi^2 M_N}\left[\log\left(\frac{4\pi^2}{y_N^2 \kappa}\right) - 1\right].$$

- Setting $m_\nu = 0.1$ eV, using the previous constraints on $y_N \gtrsim 5\times 10^{-4}$ from leptogenesis, and the mass relations with $\mu_1 = 89$ GeV:

$$|\lambda_5| \lesssim \frac{0.3}{\sqrt{\lambda_3 \kappa}} \approx \frac{\mu_2}{\sqrt{\kappa}\, 2.7\ \text{TeV}}$$

- Hence, for reasonable parameter values, can bring everything into agreement.

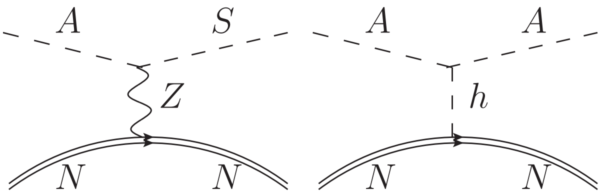
Dark Matter

- So far:
  - Have electroweak symmetry breaking.
  - Generate small neutrino masses.
  - Have viable leptogenesis.
  - Preserved a Z_2 so a candidate Dark Matter.
- The mass spectrum is (with simplifying assumption $\lambda_4 = 0$):

$$
\begin{aligned}
m_h^2 &= \lambda_1 v^2 \\
m_S^2 &= \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_5)\, v^2 \\
m_A^2 &= \mu_2^2 + \frac{1}{2}(\lambda_3 - \lambda_5)\, v^2 \\
m_{H^\pm}^2 &= \mu_2^2 + \frac{\lambda_3}{2} v^2 ,
\end{aligned}
$$

- For positive quartic couplings, the DM candidate is the pseudoscalar of the inert doublet.
- To be viable:
  - Avoid current direct detection limits.
  - Reproduce correct relic abundance.

Direct Detection



- Z exchange suppressed if initial energy of DM particle is insufficient to upscatter into S:

$$\text{KE} = \frac{1}{2}mv^2 \sim M_S - M_A$$

- For a DM velocity of ~ 200 km/s, the kinetic energy of a 1 TeV DM is a few 100 keV. As long as mass difference larger than this, Z exchange is neglible.

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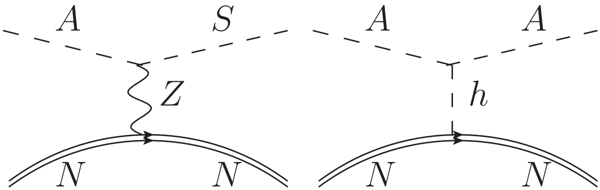

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- For a DM velocity of ~ 200 km/s, the kinetic energy of a 1 TeV DM is a few 100 keV. As long as mass difference larger than this, Z exchange is neglible.
- For Higgs exchange the cross section per nucleon is Hambye, Ling, Lopez Honorez, Rocher, 0903.4010

$$\sigma_n \simeq \frac{f_n^2\,(\lambda_3 - \lambda_5)^2}{4\pi}\,\frac{m_n^4}{\mu_2^2\, m_H^4},$$

- For $\mu_2 \sim 1$ TeV and $\lambda_5 \sim 0.01 - 1$: $\sigma_n \sim 1 - 5 \times 10^{-45}$ cm^2
- Near current limits, possibly detectable and near future direct detection experiments.

Relic Density

- Annihilation proceeds through gauge interactions and coannhilations with other components of inert doublet.
- For $M_A \gtrsim 550$ GeV, gauge interactions insufficient to deplete DM and will overclose universe Hambye, Ling, Lopez Honorez, Rocher, 0903.4010.
- Need coannihilation, and so have minimum values of scalar quartic interactions.

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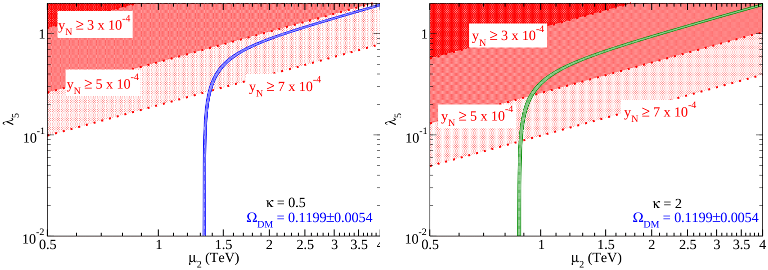
- Need coannihilation, and so have minimum values of scalar quartic interactions.
- With $\lambda_4 = 0$, the thermally averaged annihilation cross section depends on two quartic coupling, λ_3 and λ_5, and the DM mass scale μ_2.
- However, have a relationship between λ_3 and μ_2:

$$\mu_1^2 = \frac{\lambda_3 \kappa}{8\pi^2}\mu_2^2 \quad \Rightarrow \quad \lambda_3 \approx \frac{(790\ \text{GeV})^2}{\kappa \mu_2^2}$$

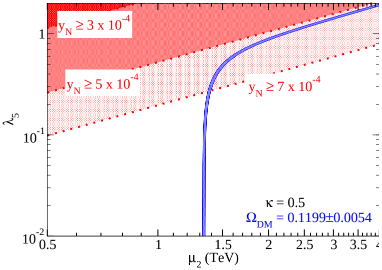
- Only two free parameters.

Relic Density



- Shaded bands are regions of λ_5 and μ_2 that correctly produce correct relic abundance.
    - For negligible λ_5, have only one parameter and unique solution for μ_2.

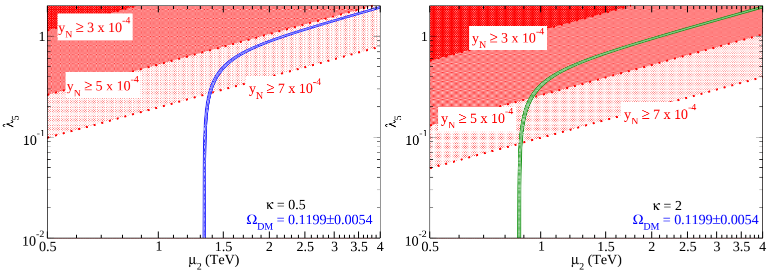
Relic Density



- Shaded bands are regions of λ_5 and μ_2 that correctly produce correct relic abundance.
  - For negligible λ_5, have only one parameter and unique solution for μ_2.
  - For $\mu_2 \gg 1$ TeV, $\lambda_3 \propto \mu_2^{-2}$ becomes negligible and obtain relation:

$$\lambda_5 \approx \frac{\mu_2}{2\ \text{TeV}}$$

Relic Density



- Red dashed lines correspond to constraints from neutrino mass, leptogenesis, higgs mass, and electroweak symmetry breaking vev. Region above is excluded.
- Light neutrino mass has cubic dependence on Yukawa coupling y_N, so bound is very sensitive to precise leptogenesis bound.
- In addition to canonical value of $y_N \gtrsim 5 \times 10^{-4}$, show consequence of $O(1)$ variations in this bound.
- A region in parameter space always exists that satisfies all of our requirements.

Conclusions

- To avoid fine-tuning, new heavy states should have masses, M, with couplings, λ, to the Higgs such that
$$\delta m_h^2 \sim \frac{\lambda^2 M^2}{8\pi^2} \lesssim v^2$$
- But have problem with typical leptogensis and Type I seesaw scenario.

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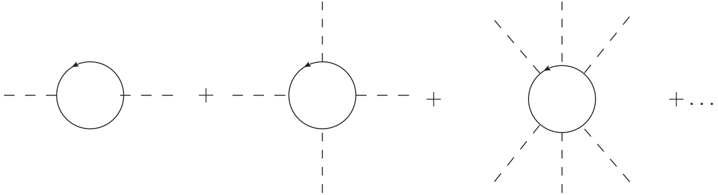
$$\delta m_h^2 \sim \frac{\lambda^2 M^2}{8\pi^2} \lesssim v^2$$
- But have problem with typical leptogensis and Type I seesaw scenario.
- We showed that in an inert Higgs doublet model with heavy right-handed neutrinos in which the heavy neutrinos do not couple to the SM Higgs at tree level:
  - Finite pieces of the mass corrections correctly break the electroweak symmetry and leave a Z_2 of the inert doublet intact.
  - Can make the electroweak scale, light neutrino mass, and leptogenesis compatible.
  - Showed that the pseudoscalar of the inert doublet is a viable DM candidate with a mass $\mu_2 \sim 1$ TeV.
  - Not shown here, but also possible to have perturbative quartic couplings up to the Planck scale.
- This scenario should be detectable at near future direct detection experiments.

BACKUP SLIDES

Scalar Masses

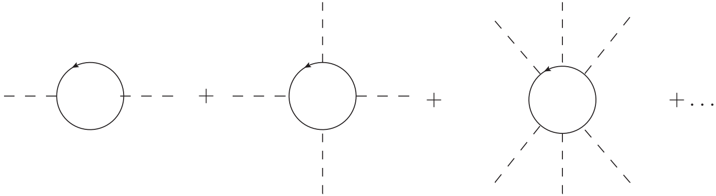


- Effect of the neutrinos on the Higgs potential at one loop are obtained via the Coleman-Weinberg potential:

$$V_1(H_2,\mu) = -\frac{1}{32\pi^2}\sum_{\alpha=1}^{2}\left\{M_\alpha^4(H_2)\left[\log\left(\frac{M_\alpha^2(H_2)}{\mu^2}\right)-\kappa_N-\frac{1}{2}\right] + m_\alpha^4(H_2)\left[\log\left(\frac{m_\alpha^2(H_2)}{\mu^2}\right)-\kappa_N-\frac{1}{2}\right]\right\}$$

- High mass states: $$M_\alpha^2(H_2)=\frac{M_{N_\alpha}^2}{2}\left(1+2y_\alpha^2\frac{|H_2|^2}{M_{N_\alpha}^2}+\sqrt{1+4y_\alpha^2\frac{|H_2|^2}{M_{N_\alpha}^2}}\right)$$
- Low mass states: $$m_\alpha^2(H_2)=\frac{M_{N_\alpha}^2}{2}\left(1+2y_\alpha^2\frac{|H_2|^2}{M_{N_\alpha}^2}-\sqrt{1+4y_\alpha^2\frac{|H_2|^2}{M_{N_\alpha}^2}}\right)$$

Scalar Masses

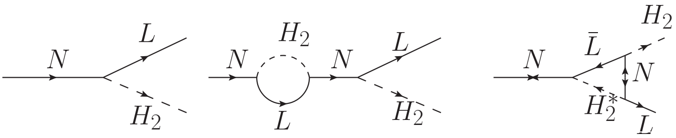


- Expand about $|H_2|$:

$$V_1(H_2,\mu) = \sum_{\alpha} \frac{y_\alpha^2 M_{N_\alpha}^2}{8\pi^2}\left[\kappa_N - \log\left(\frac{M_{N_\alpha}^2}{\mu^2}\right)\right]|H_2|^2 + \ldots,$$

- κ_N has been introduce to parameterize scheme dependence.
- $\kappa_N = 1$ is the $\overline{\text{MS}}$ scheme.
- H_2 mass loop suppressed compared to M_N. Appropriate to work in EFT with neutrinos integrated out.

Leptogenesis



- Heavy neutrinos only couple to the indert doublet H_2 and leptogenesis proceeds through

$$N \to LH_2$$

- The bound is still $y_N \gtrsim 5\times 10^{-4}$, where y_N is the coupling to the H_2
- Putting into our solution need with $\mu_1 = 89$ GeV.

$$\mu_1^2 \approx \frac{\lambda_3 y_N^2}{32\pi^4} M_N^2 \kappa^2 \quad \Rightarrow \quad M_N \lesssim \frac{5\times 10^4 \text{ TeV}}{\sqrt{\lambda_3}\,\kappa\,(y_N/10^{-3})} \lesssim \frac{10^5 \text{ TeV}}{\sqrt{\lambda_3}\,\kappa}.$$

Running Coupling