Higgs Troika for Baryon Asymmetry

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Baryogenesis and the Search for New Physics

- Sakharov conditions are three necessary conditions for a model to produce a baryon asymmetry
  - Baryon number violation
  - C and CP violation
  - Interactions out of thermal equilibrium
- Standard Model (SM) doesn't meet all the requirements
  - Electroweak (EW) sphalerons can give baryon number violation
  - C and CP violation present, but CP phase from quark sector not large enough
  - Potential source of out of equilibrium interaction would be a first order EW phase transition; phase transition in SM is not first order
- Experimental observation of baryon asymmetry motivates looking for physics Beyond the Standard Model (BSM)

Neutrinos and Neutrino Masses

- SM has massless neutrinos
- Mixing between different neutrino species implies neutrinos have different masses
  - The lightest neutrino species may or may not have zero mass
- Including right-handed neutrino singlets leads to more Yukawa interaction terms
- Majorana neutrinos and a seesaw mechanism are a straight-forward way to reproduce three light neutrino species

Extra Higgs Doublets

- SM has three generations of fermions but only one Higgs doublet - why?
- BSM models can have extended scalar sectors
- More Higgs doublets means more Yukawa couplings
    - More sources of CP violation
    - Have to worry about flavor constraints
- Heavy Higgs doublet decays before EW symmetry breaking
    - CP violating Yukawa couplings means a heavy Higgs doublet and its anti-particle can decay differently
- To avoid fine tuning, we will include three total Higgs doublets, hence our "Higgs Troika"

Benchmark Flavor Model, Yukawa Sector

- We work with three Higgs doublets Φ_1, Φ_2, Φ_3
- Impose that the Higgs doublets $\Phi_{2,3}$ and lepton doublets L are odd under a Z_2 symmetry
- We get the following Yukawa terms:

$$y_1^u \tilde{\Phi}_1^* \bar{Q} u + y_1^d \Phi_1^* \bar{Q} d + \sum_{b=2,3} y_b^\nu \tilde{\Phi}_b^* \bar{L} \nu_R + y_b^\ell \Phi_b^* \bar{L} \ell \qquad (1)$$

- We will use order 1 couplings for the largest quark and charged lepton Yukawa couplings
- To reproduce the top quark mass, we want $v_1 \sim v_{EW} = 246$ GeV
- Using Φ_2 to generate lepton masses, we get $v_2 \sim 2.5$ GeV to reproduce the tau mass

Benchmark Flavor Model, Scalar Sector

- We allow for soft-breaking of the Z_2 by mass terms
- Our potential looks like (leaving off uninteresting terms)

$$\begin{gathered} -\mu^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 + m_3^2\Phi_3^\dagger\Phi_3 \\ -\left(\mu_{12}^2\Phi_1^\dagger\Phi_2 + \mu_{13}^2\Phi_1^\dagger\Phi_3 + \mathrm{h.c}\right) + \lambda(\Phi_1^\dagger\Phi_1)^2 + \cdots \end{gathered} \tag{2}$$

- The masses m_2, m_3 are ~ 1 TeV
- After symmetry breaking, the soft-breaking mass terms lead to tadpole terms for Φ_2, Φ_3 that lead to small vevs:

$$v_2 \approx v_1 \frac{\mu_{12}^2}{m_2^2} \ll v_1 \text{ and } v_3 \approx v_1 \frac{\mu_{13}^2}{m_3^2} \ll v_1 \tag{3}$$

- $v_2 \sim 2.5$ GeV only requires $\mu_{12} \sim 100$ GeV

Rotating to the Higgs Basis

- To leading order, we can perform the following rotation to the doublet mass eigenbasis:

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} \approx \begin{pmatrix} 1 & \mu_{12}^2/m_2^2 & \mu_{13}^2/m_3^2 \\ -\mu_{12}^2/m_2^2 & 1 & 0 \\ -\mu_{13}^3/m_3^2 & 0 & 1 \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \\ \Phi_3 \end{pmatrix} \tag{4}$$

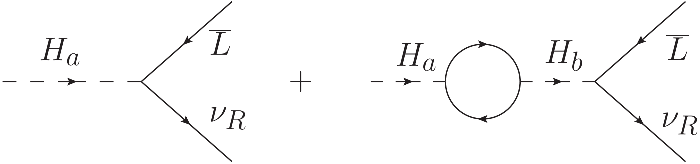
- This is also the Higgs basis: $\langle H_2 \rangle = \langle H_3 \rangle = 0$
- In the Higgs basis, with the vev hierarchy $v_1 \gg v_2 \gg v_3$, the Yukawa coupling are:

$$\begin{aligned} &\lambda_1^{u,d} \approx y_1^{u,d}, & &\lambda_{2,3}^{u,d} \approx y_1^{u,d} v_{2,3}/v_{EW}, \\ &\lambda_1^{\ell} \approx y_2^{\ell} v_2/v_{EW}, & &\lambda_{2,3}^{\ell} \approx y_{2,3}^{\ell}, \\ &\lambda_1^{\nu} \approx (y_2^{\nu} v_2 + y_3^{\nu} v_3)/v_{EW}, & &\lambda_{2,3}^{\nu} \approx y_{2,3}^{\nu} \end{aligned} \tag{5}$$

Benchmark Flavor Model, Neutrino Sector

- We have three right-handed neutrinos, ν_{R1}, ν_{R3}, ν_{R3}
- Choose $m_{R3} \sim 100$ GeV and $m_{R1,2} \sim 10$ TeV
- This means ν_{R3} is the only right-handed neutrino that the heavy doublets can decay into

Our Baryogenesis Mechanism



- Before EW symmetry breaking, a population of H_3 is created by the decay of a heavy modulus with mass m_Φ
- We use an asymmetry of decays of H_3 into a lepton doublet and right-handed neutrino:

$$\varepsilon \equiv \frac{\Gamma(H_a \to \bar{L}\nu_R) - \Gamma(H_a^* \to \bar{\nu}_R L)}{2\Gamma(H_a)} \tag{6}$$

- With our flavor and mass structure, this looks like:

$$\varepsilon = \frac{1}{8\pi} \frac{m_3^2}{m_2^2 - m_3^2} \frac{|\lambda_2^\ell \lambda_2^\nu \lambda_3^\ell \lambda_3^\nu| \sin\phi}{|\lambda_3^\ell|^2 + |\lambda_3^\nu|^2} \tag{7}$$

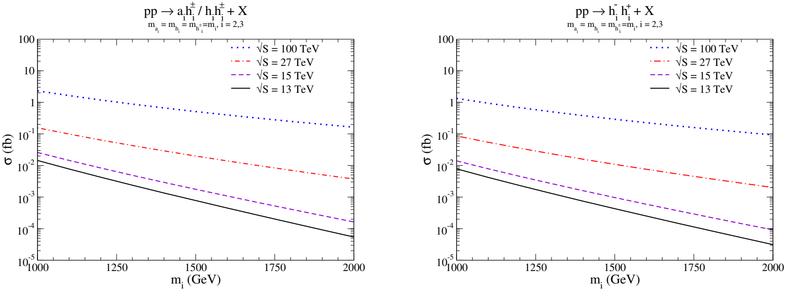
A Sample Parameter Point

- Lots of moving parts relate the decay asymmetry ε to the observed baryon asymmetry $\frac{n_B}{s} \approx 9 \times 10^{-11}$
- We present a parameter choice that can satisfy all of the (yet unspecified)moving parts:

$$\begin{array}{ll} m_\Phi = 100 \text{ TeV} & m_3 = 1.5 \text{ TeV} \\ \lambda_2^\ell \sim 1 & \lambda_2^\nu \sim 2 \times 10^{-6} \\ \lambda_3^\ell \sim 1.4 \times 10^{-3} & \lambda_3^\nu \sim 1.4 \times 10^{-3} \end{array} \tag{8}$$

- With an order 1 CP phase ϕ and around a 10% mass degeneracy for H_2 and H_3, this leads to $\varepsilon \sim 2 \times 10^{-7}$ which can generate a sufficient baryon asymmetry

Collider Production of Heavy Scalars



- These production rates are driven by gauge couplings
- The heavy scalar states will decay to various interesting final states, such as many leptons, missing energy, etc.
- LHC may probe around 1 TeV mass; future colliders might be needed for higher masses

Changes to Yukawa Coupling of 125 GeV Scalar

- The doublet H_1 had SM-like quark and charged lepton Yukawa couplings
- But the 125 GeV scalar is a mixture of the H_1, H_2, and H_3 neutral, CP-even components h_1, h_2, h_3 (predominantly h_1)
- Mixing of h_1 and h_2 is expected to be $\sim v_1\, v_2/m_2^2$
- While the mixing is small, the charged lepton Yukawa coupling coming from H_2 is large
- The branching ratios of the 125 GeV scalar to charged leptons can be changed by $\sim 20\%$
    - Observable at HL-LHC

Low Energy Physics

- Neutron electric dipole moment (EDM) isn't very constraining
- $(g_\mu - 2)$ effects are too small to explain the observed anomaly
- Electron EDM and $\mu \rightarrow e\gamma$ give relevant constraints
- One person's constraint is another person's opportunity
  - Future electron EDM and $\mu \rightarrow e\gamma$ experiments may be able to see signatures of our model

Summary of the Higgs Troika

- Three Higgs doublets can generate the baryon asymmetry of the universe
- Interesting collider signatures for the heavy scalar production
- Predicts an order 20% change to charged lepton branching ratios for the 125 GeV scalar
- Low energy avenues via electron EDM and $\mu \to e\gamma$

Our Baryogenesis Mechanism, Detailed

- Pre-EWSB, sphalerons can change (left-handed) lepton asymmetries into baryon asymmetries, but don't touch the right-handed singlet neutrinos
- The end baryon asymmetry is then given by:

$$\frac{n_B}{s} = \frac{21}{79}\left(\frac{r\,T_{rh}\,\varepsilon}{E_3}\right). \tag{9}$$

- $r \leq 1$ the ratio of SM energy density to H_3 energy density
- E_3, the typical energies of the H_3 population, is set by the mass of the modulus m_Φ
- The reheat temperature T_{rh} should be $\gtrsim 100$ GeV so that sphalerons are active

Considering Some of the Moving Parts...

- We need to make sure decays to happen before any appreciable annihilation of H_3 population
  - Larger E_3 suppresses annihilation rates relative to decay rates, but also lowers asymmetry
- We need to make sure that H_1, H_2, and H_3 can't efficiently mediate 2 to 2 washout processes
  - This puts constraints on the Yukawa couplings
  - This also requires H_2 and H_3 to be heavy compared to T_{rh}
- We need to make sure the heavy neutrinos decay after EWSB

Higgs-mediated Washout

- We have to make sure that 2 to 2 processes of the form $L\nu_R \to Ff$ won't wash out the asymmetry up until EW symmetry breaking at $T_* \sim 100$ GeV
- Processes mediated by the SM doublet, H_1, lead to a washout rate:

$$\Gamma \sim (\lambda_1^\nu \lambda_1^f)^2 T \tag{10}$$

- Heavy doublets, H_2 and H_3, lead to a different, mass-suppressed washout rate:

$$\Gamma \sim (\lambda_a^f \lambda_a^\nu)^2 T^5 / m_a^4 \tag{11}$$

- Avoiding washout requires $\Gamma(T_*) \lesssim H(T_*)$, with the Hubble rate $H(T) \approx g_*^{1/2} T^2 / M_P$
- With TeV scale heavy doublets, this leads to a constraint on the Yukawa couplings:

$$\lambda_1^\nu \lambda_1^f \lesssim 10^{-8}, \lambda_{2,3}^\nu \lambda_{2,3}^f \lesssim 10^{-6} \tag{12}$$

Why Three Doublets?

- Let's look at the asymmetry from decays of H_2 with H_1 as the intermediate scalar:
$$\varepsilon \sim \frac{\lambda_1^\nu \lambda_1^f \lambda_2^\nu \lambda_2^f}{8\pi \, (\lambda_2^{f'})^2} \tag{13}$$
- The requirement that $\varepsilon \gtrsim 10^{-9}$ is in tension with the washout constraint $\lambda_1^\nu \lambda_1^f \lesssim 10^{-8}$
- The washout constraint $\lambda_{2,3}^\nu \lambda_{2,3}^f \lesssim 10^{-6}$ for the heavy doublets would give more room
- If we want to avoid a large degree of fine tuning while using this mechanism, we need two heavy doublets