

# 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 give 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)

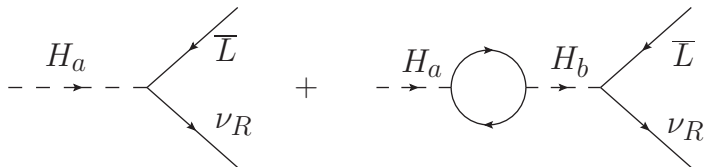
# Neutrinos and Neutrino Masses

- 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”

# Our Baryogenesis Mechanism



- We add three singlet neutrinos and two heavy Higgs doublets onto the SM at around the TeV scale
- There is an asymmetry of decays of  $H_a$  into a lepton doublet and right-handed neutrino:

$$\varepsilon \equiv \frac{\Gamma(H_a \rightarrow \bar{L}\nu_R) - \Gamma(H_a^* \rightarrow \bar{\nu}_R L)}{2\Gamma(H_a)}, \quad (1)$$

- We want the decays to happen before EW symmetry breaking

# Our Baryogenesis Mechanism, cont.

- Before EW symmetry breaking, sphalerons can change lepton asymmetries into baryon asymmetries
- The decays generate a non-zero  $\Delta(B - L)$  in the left-handed lepton sector
- Sphalerons don't act on the neutrino singlets
- The left-handed lepton asymmetry can thus convert into a baryon asymmetry

# Rough Sketch of the Asymmetry

- Assume  $H_a$  decays predominantly to fermion  $f'$ , so that  $\lambda_2^{f'}$  is the largest Yukawa coupling
- Assume diagrams with intermediate fermion  $f$  and intermediate scalar  $H_b$  are the dominant contributors to the asymmetry
- The asymmetry looks roughly like so:

$$\varepsilon \sim \frac{\lambda_b^\nu \lambda_b^f \lambda_a^\nu \lambda_a^f}{8\pi (\lambda_a^{f'})^2} \quad (2)$$

- We want  $\varepsilon \gtrsim 10^{-9}$  for baryogenesis

# Benchmark Flavor Model, Yukawa Sector

- We work with three Higgs doublets  $\Phi_1, \Phi_2, \Phi_3$
- 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:

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

- 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  $\Phi_2$  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)

$$-\mu^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 + m_3^2 \Phi_3^\dagger \Phi_3 - \left( \mu_{12}^2 \Phi_1^\dagger \Phi_2 + \mu_{13}^2 \Phi_1^\dagger \Phi_3 + \text{h.c.} \right) + \lambda (\Phi_1^\dagger \Phi_1)^2 + \dots \quad (4)$$

- The masses  $m_2, m_3$  are  $\sim 1$  TeV
- After symmetry breaking, the soft-breaking mass terms lead to tadpole terms for  $\Phi_2, \Phi_3$  that lead to small vevs:

$$v_2 \approx v_1 \frac{\mu_{12}^2}{m_2^2} \ll v_1 \text{ and } v_3 \approx v_1 \frac{\mu_{13}^2}{m_3^2} \ll v_1 \quad (5)$$

- $v_2 \sim 2.5$  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:

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} \approx \begin{pmatrix} 1 & \mu_{12}^2/m_2^2 & \mu_{13}^2/m_3^2 \\ -\mu_{12}^2/m_2^2 & 1 & 0 \\ -\mu_{13}^2/m_3^2 & 0 & 1 \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \\ \Phi_3 \end{pmatrix} \quad (6)$$

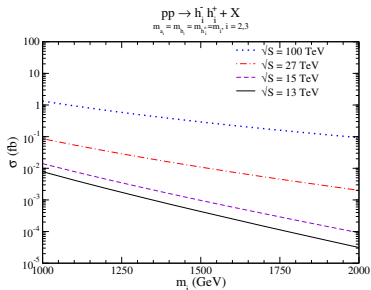
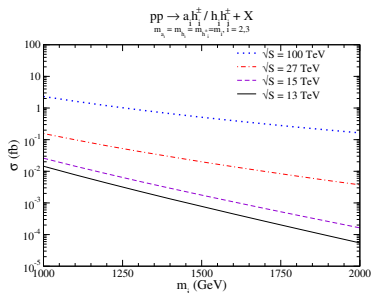
- This is also the Higgs basis:  $\langle H_2 \rangle = \langle H_3 \rangle = 0$
- In the Higgs basis, with the vev hierarchy  $v_1 \gg v_2 \gg v_3$ , the Yukawa coupling are:

$$\begin{aligned} \lambda_1^{u,d} &\approx y_1^{u,d}, & \lambda_{2,3}^{u,d} &\approx y_1^{u,d} v_{2,3}/v_{EW}, \\ \lambda_1^\ell &\approx y_2^\ell v_2/v_{EW}, & \lambda_{2,3}^\ell &\approx y_{2,3}^\ell, \\ \lambda_1^\nu &\approx (y_2^\nu v_2 + y_3^\nu v_3)/v_{EW}, & \lambda_{2,3}^\nu &\approx y_{2,3}^\nu \end{aligned} \quad (7)$$

# Benchmark Flavor Model, Neutrino Sector

- We have three right-handed neutrinos,  $\nu_{R1}$ ,  $\nu_{R2}$ ,  $\nu_{R3}$
- Choose  $m_{R3} \sim 100$  GeV and  $m_{R1,2} \sim 10$  TeV
- This means  $\nu_{R3}$  is the only right-handed neutrino that the heavy doublets can decay into

# 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

- 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  $\mu \rightarrow e\gamma$

# Higgs-mediated Washout

- We have to make sure that 2 to 2 processes of the form  $L\nu_R \rightarrow Ff$  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:

$$\Gamma \sim (\lambda_1^\nu \lambda_1^f)^2 T \quad (8)$$

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

$$\Gamma \sim (\lambda_a^f \lambda_a^\nu)^2 T^5 / m_a^4 \quad (9)$$

- 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:

$$\lambda_1^\nu \lambda_1^f \lesssim 10^{-8}, \lambda_{2,3}^\nu \lambda_{2,3}^f \lesssim 10^{-6} \quad (10)$$



# Why Three Doublets?

- Let's look at the asymmetry from decays of  $H_2$  with  $H_1$  as the intermediate scalar:

$$\varepsilon \sim \frac{\lambda_1^\nu \lambda_1^f \lambda_2^\nu \lambda_2^f}{8\pi (\lambda_2^{f'})^2} \quad (11)$$

- 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