Multi-TeV Signals of Baryogenesis in Higgs Troika Model

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Baryogenesis

- Cosmological observations give a baryon asymmetry of $\frac{n_B}{s} \approx 9 \times 10^{-11}$
- Sakharov conditions are necessary for dynamical production of baryon asymmetry
  - Baryon number violation
  - C and CP violation
  - Interactions out of thermal equilibrium
Fulfilling the Sakharov Conditions

- Baryon number violation is already present in the SM
  - Non-perturbative sphalerons (electroweak vacuum transitions)
- CP violation in the SM is not big enough
  - CKM matrix (SM) and PMNS matrix (BSM, strictly speaking) have CP phases, but not enough for the observed asymmetry
- A few options for out of equilibrium dynamics:
  - Heavy particles decaying out of thermal equilibrium (e.g. leptogenesis)
  - First-order phase transition (e.g. electroweak baryogenesis)
Introducing the Troika: Three Higgs Doublets

- Standard Model (SM) has three generations of fermions but only one Higgs doublet
- We propose adding two more Higgs doublets (for three total), whose decays in the early universe give the out of equilibrium interaction necessary for baryogenesis
- More Higgs doublets means more Yukawa couplings
  - Flavor physics constraints (or observation opportunities)
  - More potential CP violation sources
- We also add three right handed neutrinos, accommodating (Dirac) neutrino masses
Before EW symmetry breaking, a population of heavy Higgs doublets $H_a$ is created by the decay of a heavy modulus.

We use an asymmetry of decays of $H_3$ into a lepton doublet and right-handed neutrino:

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

- $H_2$ is an intermediate state in the loop diagrams.
- Asymmetry is enhanced when $H_2$ and $H_3$ are close in mass.
- Washout constraints for light mediators, plus mass generation, make using $H_1$ difficult without fine-tuning.
- This is why we need two heavy doublets for our mechanism.
Yukawa Couplings

\[ \lambda_{u}^{2,3} = \xi \lambda_{u}^{1} \]
\[ \lambda_{d}^{2,3} = \text{diag}(\kappa_{d}, \kappa_{s}, \kappa_{b}) \]
\[ \lambda_{\ell}^{2,3} = \xi_{\ell} \lambda_{\ell}^{1} \]
\[ \lambda_{\nu}^{2,3} = \text{diag}(\kappa_{\nu_{1}}, \kappa_{\nu_{2}}, \kappa_{\nu_{3}}) \]

Based on Egana-Ugrinovic, Homiller, Meade’s Spontaneous Flavor Violating 2HDM framework (Phys. Rev. D 100, 115041)

- Added right-handed neutrinos and corresponding Yukawa couplings
- Add another new doublet with the same coupling structure
- Couplings are in the basis where the down-type quark and charged lepton Yukawa couplings of \( H_{1} \) are flavor-diagonal
- \( \lambda_{\ell}^{1}, \lambda_{u}^{1} \) are the couplings of \( H_{1} \) to charged leptons and up-type quarks, respectively
- Include the PMNS and CKM matrices
- \( H_{1} \) is the source of all mass (including Dirac neutrino masses)
- Put all new CP violating phases into the \( \kappa_{\nu_{i}} \)
Neutral meson mixing and flavor-changing decays provide constraints on the Yukawa couplings.

We show upper bounds from the different experimental constraints on Yukawa coupling $\kappa_d$ to down-quark for certain choices of $\kappa_s$, $\kappa_b$, $\xi$ as a function of the mass $m_a$ of the heavy Higgs bosons.

- Assuming all the heavy Higgses have the same mass
Flavor Constraints, cont.

- Same as before, for smaller $\xi$
- $D$ meson mixing gives the dominant constraint for heavy Higgses
  - Theoretical and experimental improvements for $D$ mixing could be a new discovery avenue
Flavor structure allows large couplings to light quarks
  - Allows large production cross sections from quark initial states
  - Decay will primarily be dijets or top pairs

We show discovery reach in $\kappa_d$ as a function of the mass $m_a$ of the heavy Higgs bosons, superimposed with flavor constrain bounds, current dijet bounds, and bounds for successful baryogenesis.
Same plots, for lower value of $\xi = 0.1$ (basically top coupling for current purposes)

Lower mass region opens up for successful baryogenesis
Same plots again, for even lower value of $\xi = 0.01$

Lower mass region opens up for successful baryogenesis
Conclusions

- Three Higgs doublets can generate the baryon asymmetry of the universe
- No first order phase transition is necessary, unlike electroweak baryogenesis
- High energy hadron colliders can see the heavy Higgses directly
- Precision flavor physics, particularly $D$ meson mixing, can provide orthogonal discovery avenues

Thank you!