Multi-TeV Signals of Baryogenesis in Higgs Troika Model

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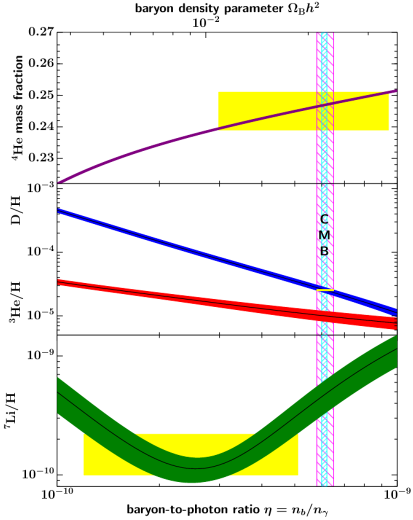
Reasons to go Beyond the Standard Model

- Standard Model (SM) doesn't explain some things:
  - Baryon asymmetry of the universe (more matter than antimatter)
  - Dark matter
  - Small but non-zero neutrino masses
- Beyond the Standard Model (BSM) physics can address these issues
- This talk will primarily address the baryon asymmetry of the universe (BAU) and tangentially neutrino masses

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



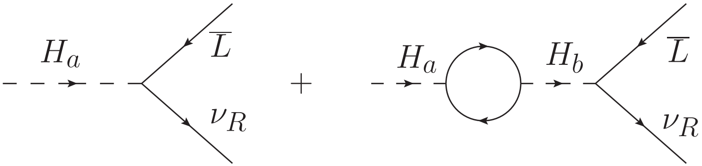
Fulfilling the Sakharov Conditions

- 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
- Our general Troika framework is covered in Phys. Rev. D 101, 055010 (arxiv:1909.02044)

The Higgs Troika Baryogenesis Mechanism



- 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:

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

- 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

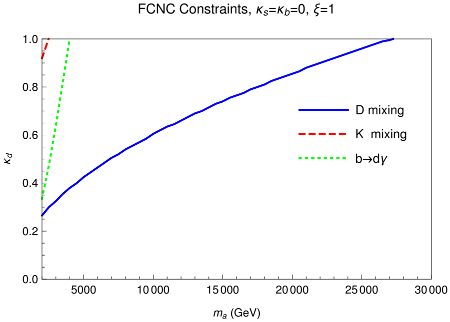
Yukawa Couplings

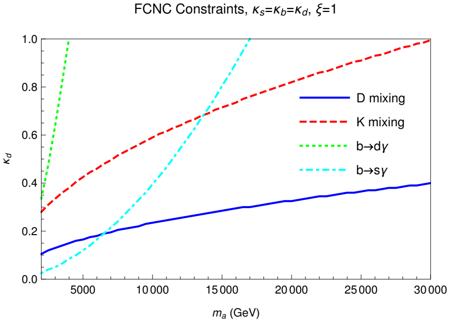
$$\lambda_u^{2,3} = \xi \lambda_u^1$$
$$\lambda_d^{2,3} = \mathrm{diag}(\kappa_d,\, \kappa_s,\, \kappa_b)$$
$$\lambda_\ell^{2,3} = \xi^\ell \lambda_\ell^1$$
$$\lambda_\nu^{2,3} = \mathrm{diag}(\kappa_{\nu_1},\, \kappa_{\nu_2},\, \kappa_{\nu_3})$$

- 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
- λ_ℓ^1, λ_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 κ_{ν_i}

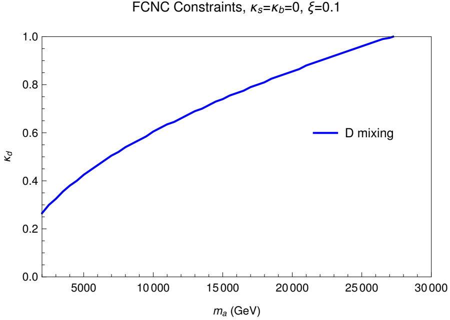
Flavor Constraints

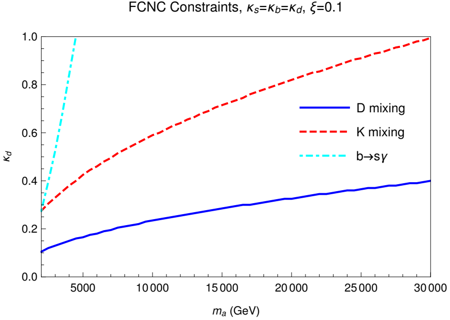




- Neutral meson mixing and flavor-changing decays provide constraints on the Yukawa couplings
- We show upper bounds from the different experimental constraints on Yukawa coupling κ_d to down-quark for certain choices of κ_s, κ_b, ξ as a function of the mass m_a of the heavy Higgs bosons
  - Assuming all the heavy Higgses have the same mass

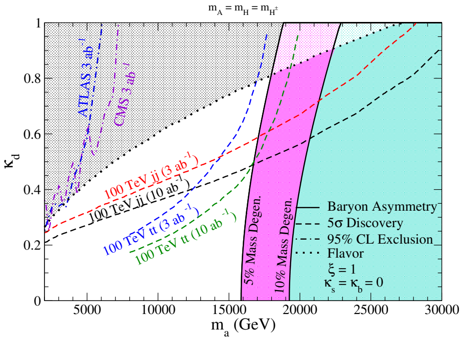
Flavor Constraints, cont.

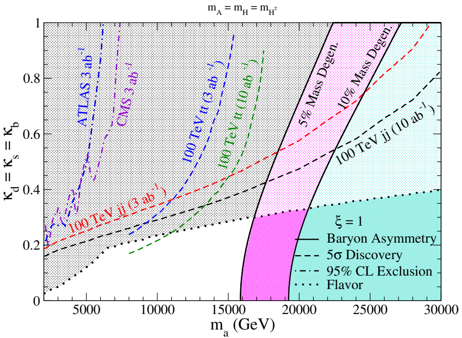




- Same as before, for smaller ξ
- D meson mixing gives the dominant constraint for heavy Higgses
  - Theoretical and experimental improvements for D mixing could be a new discovery avenue

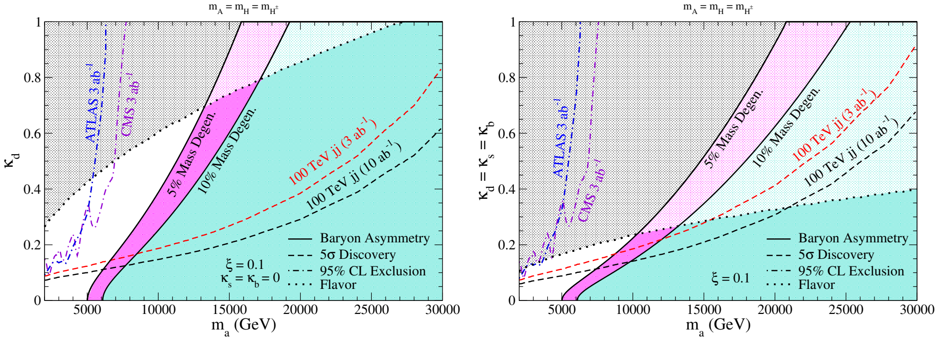
Heavy Higgs Discovery Reach at 100 TeV





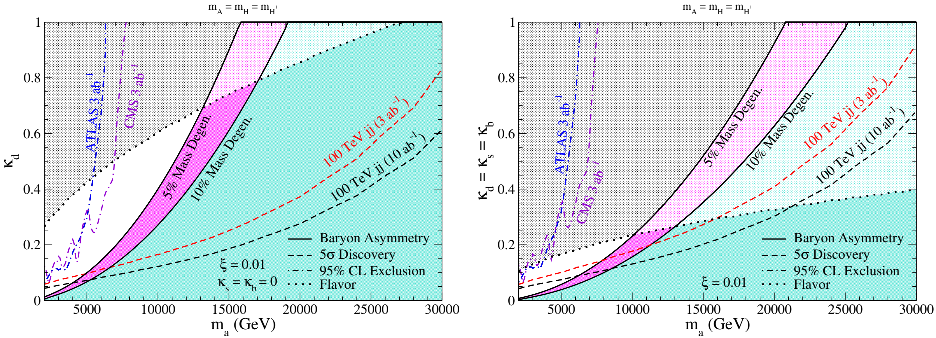
- Flavor structure allows large couplings to light quarks
  - Allows large production cross sections from quark initial states
  - Decay will primarily be dijets or top pairs
- We show discovery reach in κ_d as a function of the mass m_a of the heavy Higgs bosons, superimposed with flavor constrain bounds, current dijet bounds, and bounds for successful baryogenesis

Heavy Higgs Discovery Reach at 100 TeV, cont.



- Same plots, for lower value of $\xi = 0.1$ (basically top coupling for current purposes)
- Lower mass region opens up for successful baryogenesis

Heavy Higgs Discovery Reach at 100 TeV, cont. 2



- 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!