Higgs Troika for Baryon Asymmetry

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Based on: H.D., I Lewis, and M. Sullivan, arXiv:1909.02044 [hep-ph]

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Introduction

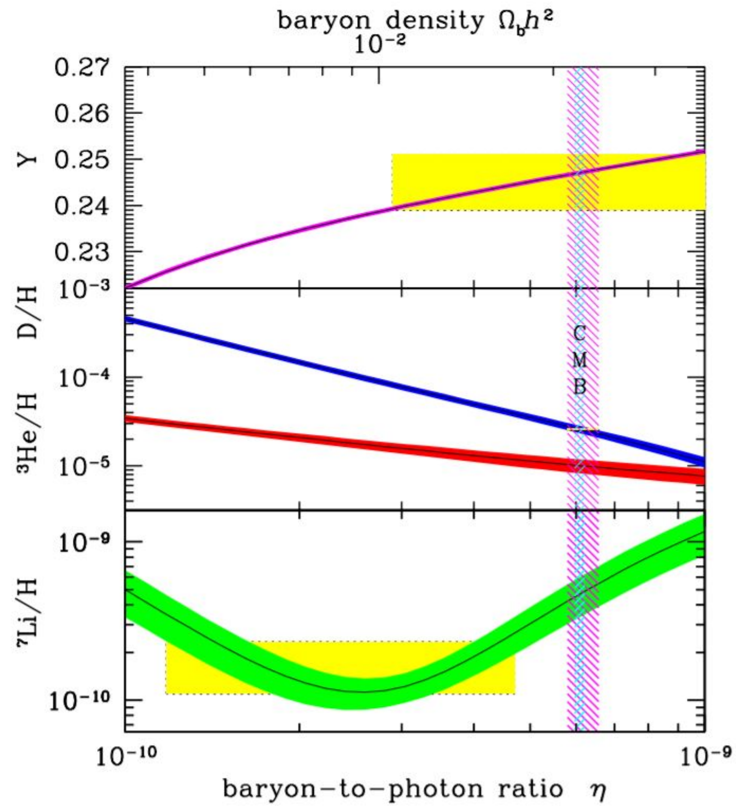
- Outstanding fundamental problems:

(1) Neutrino masses ($m_\nu \neq 0$)

(2) Dark matter (DM)

(3) Baryon asymmetry of the Universe (BAU)

- Strong evidence for physics beyond SM



(PDG, 2019)

- DM may be from a secluded "dark sector"

- BAU could plausibly be connected to "visible sector"

- Perhaps significantly coupled to SM

- BAU and m_ν could be connected through *leptogenesis*

- Decays of heavy ν_R ($m_R \gg$ TeV) yield $\Delta(B-L) \neq 0 \to \Delta B$ (*EW sphalerons*)

- Unlike "EW baryogenesis" largely inaccessible to direct tests

This talk:

- Extend SM Higgs sector by 2 new doublets $\rightarrow$ *Higgs Troika*
- Three ν_R states (associated with m_ν), $\sim 0.1 - 10$ TeV
- Consider generating $\Delta(B-L)$ from new heavy Higgs doublets

$$H_a \rightarrow \bar{L}\nu_R \quad ; \quad a = 1, 2, 3$$

- Higgs decays out-of-equilibrium, but above $T \gtrsim 100$ GeV

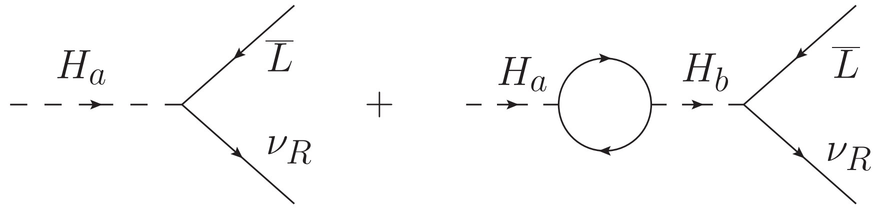
\- Need sphalerons to be active and generate $\Delta B \neq 0$

- No first order phase transition required
- H_1 is identified as the observed ("SM") Higgs with $m_1 \approx 125$ GeV
- New Higgs masses $\sim$ TeV or higher, potentially testable (LHC, precision, ...)

See also: Dick, Lindner, Ratz, Wright, 1999; Murayama, Pierce, 2002; Gu, He, 2006; H.D., Lewis, 2011

Why a Higgs Troika?

- $\Delta(B-L) \neq 0$ via tree and 1-loop interference, requires at least H_2



- Asymmetry: $\varepsilon \sim \dfrac{\lambda_1^\nu \lambda_1^f \lambda_2^\nu \lambda_2^f}{8\pi\,(\lambda_2^{f'})^2}$ $\quad$ H_a Yukawa coupling to fermion f, λ_a^f

\- Assuming f' sets the width, has dominant Yukawa

- $n_B/s \approx 9 \times 10^{-11}$ requires $\varepsilon \gtrsim 10^{-9}$, assuming $\mathcal{O}(1)$ phase

- Avoiding washout $2 \to 2$ processes via H_1 down to $T_* \sim 100$ GeV

$\Gamma_* \sim (\lambda_1^\nu \lambda_1^f)^2 T_* \lesssim H(T_*)$, where $H(T) \approx g_*^{1/2} T^2/M_P$ $\quad$ $g_* \sim 100$, $M_P \approx 1.2 \times 10^{19}$ GeV

$$\lambda_1^\nu \lambda_1^f \lesssim 10^{-8} \Rightarrow \varepsilon < 4 \times 10^{-10}$$

- Light Higgs couplings too constrained for baryogenesis

- $\therefore$ **Typically need H_3 together with H_2 to generate $\Delta(B-L)$**

Reheat Temperature and Washout

- Reheat $T_{rh} \gtrsim 100$ GeV, say through a modulus Φ decay
- Φ decay non-thermally produces H_3 and H_3^* population
- T_{rh} not too high to avoid washout via H_a, $a = 2, 3$

$$(\lambda_a^f \lambda_a^\nu)^2 \lesssim \frac{g_*^{1/2} m_a^4}{M_P T_{rh}^3}$$

- For $m_a \sim 1$ TeV, $T_{rh} \sim 100$ GeV, we get $\lambda_a^f \lambda_a^\nu \lesssim 10^{-6}$

- Less stringent constraint can allow large enough ε

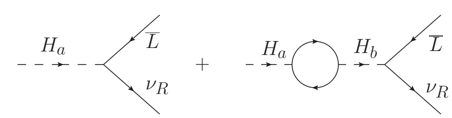
General Model

$$\lambda_a^u \tilde{H}_a^* \bar{Q}\, u + \lambda_a^d H_a^* \bar{Q}\, d + \lambda_a^\nu \tilde{H}_a^* \bar{L}\, \nu_R + \lambda_a^\ell H_a^* \bar{L}\, \ell$$

$\ell = e, \mu, \tau$

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

- Consider the $m_2 \approx m_3$ limit, dominated by self-energy 1-loop process



\- Sufficient to show order of magnitude

\- Also, both H_2 and H_3 potentially accessible: a more "testable" case

$$\varepsilon = \frac{1}{8\pi} \sum_{b \neq a} \frac{m_a^2}{m_b^2 - m_a^2} \frac{\sum_{f=e,u,d} N_{c,f}\, \mathrm{Im}\left(\mathrm{Tr}_{ba}^\nu \mathrm{Tr}_{ba}^{f*}\right)}{\sum_{f=e,u,d,\nu} N_{c,f}\, \mathrm{Tr}_{aa}^f}$$

$$\begin{aligned} \mathrm{Tr}_{ba}^f &= \mathrm{Tr}\left[\lambda_b^{f\dagger} \lambda_a^f\right], \\ \mathrm{Tr}_{ba}^\nu &= \mathrm{Tr}\left[\lambda_b^{\nu\dagger} \lambda_a^\nu (1 - m_R^2/m_a^2)^2\right] \end{aligned}$$

Diagonal m_R mass matrix assumed; $m_f = 0$ before EWSB

- For $m_{2,3} \gg T_{rh}$ and decoupled ν_R, basically have SM plasma: $\Delta B = \frac{28}{79}\Delta(B-L)$

Harvey, Turner, 1990

- Energy density in H_3 doublet less than radiation: $r \equiv m_3 n_3/\rho_R \Rightarrow r < 1$

- $\rho_R = (\pi^2/30)g_* T^4$ and $s = (2\pi^2/45)g_* T^3$

$$\Rightarrow \frac{n_B}{s} = \frac{21}{79}\left(\frac{r\,T_{rh}\,\varepsilon}{m_3}\right)$$

- For $T_{rh}/m_3 \lesssim 0.1$ and $r \leq 1$, require $\varepsilon \gtrsim 10^{-9}$ with $\mathcal{O}(1)$ phases

- Many variations possible to achieve the requisite value of ε

- A viable "benchmark" model will be examined for illustrative purposes

A Benchmark Model of Flavor

- Three scalar (Higgs) doublets: Φ_a $(a = 1, 2, 3)$

- $\Phi_{2,3}$ and SM lepton doublets L odd under a $\mathbb{Z}_2$

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

u and d: up- and down-type quarks; $\ell = e, \mu, \tau$

- Adopted flavor principle: heaviest quark and lepton from $\mathcal{O}(1)$ Yukawa

- To get the top mass, need $v_1 \approx v_{EW} = 246$ GeV

- For $\lambda_a^\tau \sim 1$ we need $v_2 \sim 2.5$ GeV

- Neutrinos unlike charged fermions: unrestricted Yukawas for νs

- We could, in principle, assume $v_3 \to 0$, but not necessary

- Hierarchy among vevs v_a from softly broken $\mathbb{Z}_2$

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

- $v_2 \approx v_1\frac{\mu_{12}^2}{m_2^2} \ll v_1$ and $v_3 \approx v_1\frac{\mu_{13}^2}{m_3^2} \ll v_1$
- Baryogenesis: $m_2, m_3 \sim 1$ TeV $\Rightarrow v_2 \sim 2.5$ GeV from $\mu_{12} \sim 100$ GeV
- To $\mathcal{O}(\mu^2/m^2)$:

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

- Higgs basis: $\langle H_1 \rangle = v_{EW}/\sqrt{2}$ and $\langle H_{2,3} \rangle = 0$, $v_{EW}^2 = v_1^2 + v_2^2 + v_3^2 \approx v_1^2$

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

Assuming $v_2 \gg v_3$

Benchmark Asymmetry

- Avoid washout via $H_{2,3}$ into $L\,\nu_{R3}$ final state: $|\lambda^\ell_{2,3}\,\lambda^\nu_{2,3}| \lesssim 10^{-6}$

- Assumed $m_{R3} \sim 100$ GeV, comparable to T_{rh}

- For $\lambda^\tau_2 \sim 1$ requires $\lambda^{\nu_{R3}}_2 \lesssim 10^{-6}$ and hence $\lambda^{\nu_{R3}}_1 \lesssim 10^{-8} \Rightarrow \exists\, m_\nu \ll 0.1$ eV; allowed

- $\Gamma(\nu_{R3} \to L\,H_1) \sim (32\pi)^{-1}\,|\lambda^{\nu_{R3}}_1|^2 m_{R3} \lesssim 10^{-16}$ GeV $\Rightarrow \nu_{R3}$ decays *after* EWSB

- $m_{R1,2} \sim 10^2\,T_{rh} \sim 10$ TeV: $\nu_{R1,2}$ final states severely Boltzmann suppressed

- We get

$$\varepsilon \sim \frac{1}{8\pi}\left|\frac{\lambda^\nu_3\,\lambda^\ell_a\,\lambda^\nu_a}{\lambda^\ell_3}\,\mathrm{sin}\,\phi\right| \lesssim 4 \times 10^{-8}\,|\mathrm{sin}\,\phi|$$

- Assumption $\lambda^\nu_3 \sim \lambda^\ell_3$

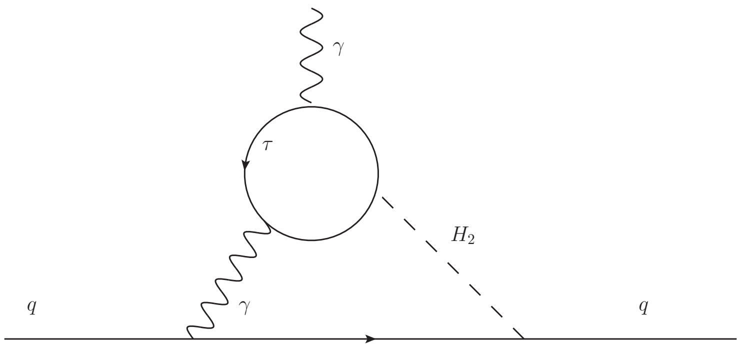
- For a generic relative phase $\phi \gtrsim 0.1$ one could obtain $\varepsilon \sim 10^{-9}$.

$\therefore$ TeV scale Higgs Troika Baryogesnesis can be a successful mechanism

Low Energy Constraints

- Assume $m_{2,3} \sim$ TeV
- Neutron EDM
- For $v_3 \to 0$ H_3 decoupled from quarks
- H_2 coupling to light quarks suppressed by v_2/v_{EW}; 2-loop Barr-Zee dominant
- H_2 coupling to $\gamma\gamma$ dominated by τ (similar sized contribution from top):

$$d_q \sim \frac{e^3\,\lambda_2^\tau\,\lambda_2^q\,m_\tau\,\sin\omega}{(16\pi^2)^2\,m_a^2} \qquad (\omega \text{ typical phase})$$



- $\lambda_2^q \sim 10^{-7} \Rightarrow d_q \sim 10^{-32}\sin\omega\ e$ cm, small
- Current 90% C.L. bound on neutron EDM $d_n < 3.0 \times 10^{-26}\ e$ cm
- For electron EDM, we need constraints on LFV couplings of H_a

- LFV decays:

$$\Gamma(\ell \to 3\, f) \approx \frac{\lambda_a^{f\,2} \lambda_a^{f\ell\,2}}{1536\pi^3} \frac{m_\ell^5}{m_a^4}\,,$$

$\ell = \mu, \tau$ and f is a light charged lepton

- For $\lambda_a^e \sim 3 \times 10^{-4}$, $\lambda_a^\mu \sim 6 \times 10^{-2}$

$$\Gamma(\mu \to 3\, e) \sim 10^{-28} |\lambda_a^{e\mu}|^2\, m_\mu$$

$$\Gamma(\tau \to 3\, \mu) \sim 10^{-18} |\lambda_a^{\mu\tau}|^2\, m_\tau$$

Current 90% C.L. bounds: (PDG)

BR$(\mu \to 3\, e) < 1.0 \times 10^{-12}$, BR$(\tau \to 3\, \mu) < 2.1 \times 10^{-8}$, and BR$(\tau \to e\mu\mu) < 2.7 \times 10^{-8}$

$$\Rightarrow |\lambda_a^{e\mu}| \lesssim 0.2,\ |\lambda_a^{\mu\tau}| \lesssim 0.2,\ \text{and } |\lambda_a^{e\tau}| \lesssim 0.2$$

- Electron EDM, dominantly from 1-loop LFV couplings of H_a

$$d_e \sim \frac{e\, \lambda_a^{e\ell\,2}\, m_\ell \sin\omega}{16\pi^2\, m_a^2} \sim \begin{cases} 10^{-23}\, |\lambda_a^{e\mu}|^2 \sin\omega\, e \text{ cm} & \text{for } \ell = \mu \\ 10^{-22}\, |\lambda_a^{e\tau}|^2 \sin\omega\, e \text{ cm} & \text{for } \ell = \tau \end{cases}$$

- At 90% C.L.: $d_e < 1.1 \times 10^{-28}\ e$ cm Andreev, et al. ACME Collaboration, 2018

$$\Rightarrow \quad \begin{aligned} |\lambda_a^{e\mu}| \sqrt{\sin\omega} &\lesssim 3 \times 10^{-3} \\ |\lambda_a^{e\tau}| \sqrt{\sin\omega} &\lesssim 1 \times 10^{-3} \end{aligned}$$

- $\mu \to e\gamma$ via the effective operator:

$$O \sim \frac{e\, m_\ell \lambda_a^{\mu\ell}\, \lambda_a^{e\ell}}{16\pi^2\, m_a^2}\, \bar{\mu}\, \sigma_{\mu\nu} e F^{\mu\nu}$$

$$\Rightarrow \mathrm{Br}(\mu \to e\gamma) \sim 3 \times 10^{-4} |\lambda_a^{e\ell}\, \lambda_a^{\mu\ell}|^2 \left(\frac{m_\ell}{\mathrm{GeV}}\right)^2$$

- At 90% C.L. $\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ Baldini et al., MEG Collaboration, 2016

$$|\lambda_a^{e\mu}| \lesssim 8 \times 10^{-3}$$

$$|\lambda_a^{e\tau} \lambda_a^{\mu\tau}| \lesssim 2 \times 10^{-5}$$

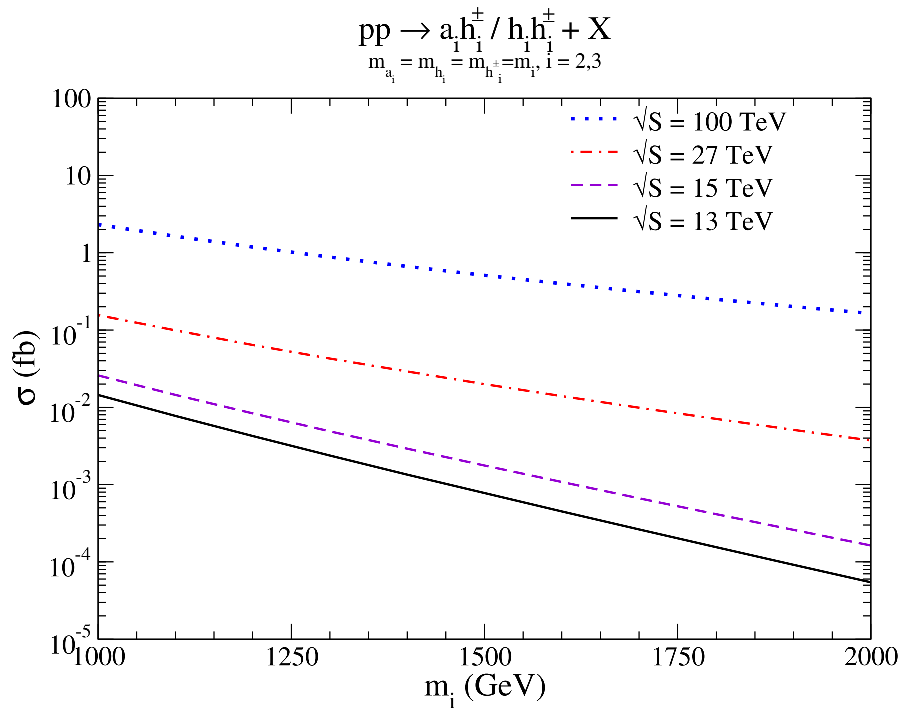
- Yukawa flavor structure $\lambda^{ij} \sim \mathrm{min}(m_i, m_j)/v_{EW}$ agrees well with data
Babu, Jana, 2018

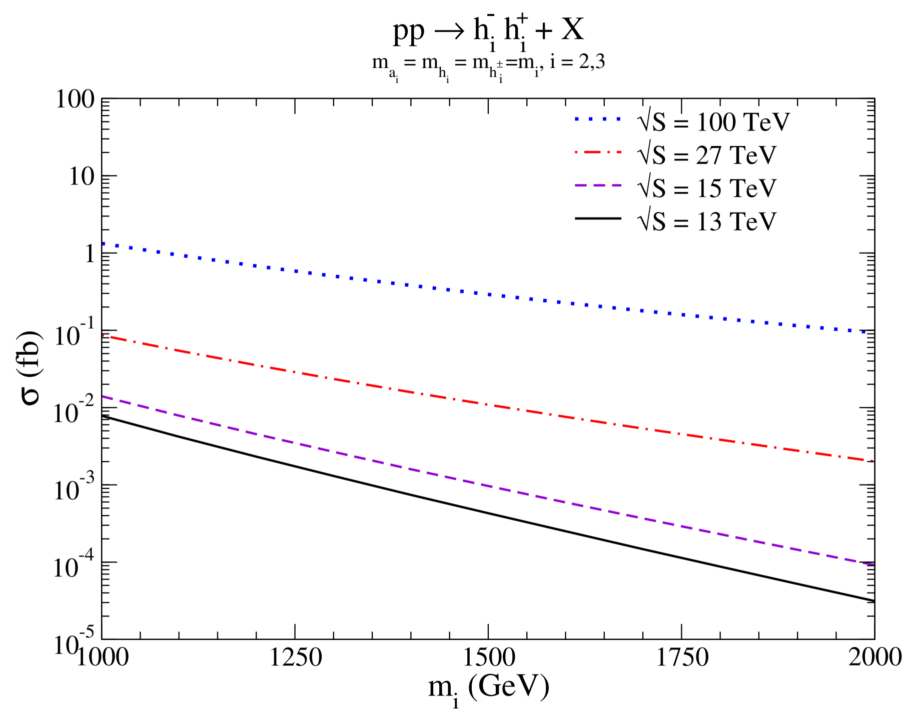
- We modify the ansatz to $\lambda_2^{ij} \sim \mathrm{min}(m_i, m_j)/m_\tau$

- Various derived constraints seem consistent with this ansatz, for $\sin\omega \sim 0.1$

- Benchmark model does not seem to account for the muon $g-2$ anomaly

Collider Signals





MadGraph5_aMC@NLO; FeynRules

- Drell-Yan and VBF production mechanisms included for all processes, assuming degenerate masses

- These production modes governed almost entirely by gauge couplings, minimal dependence on the model parameters; h_ih_i and a_ia_i modes depend on trilinear scalar couplings, not discussed

- $\sqrt{S} = 100$ TeV (30 ab^{-1}), $\sqrt{S} = 27$ TeV (15 ab^{-1}), $\sqrt{S} = 15$ TeV (3 ab^{-1}), and $\sqrt{S} = 13$ TeV (3 ab^{-1}) $\Rightarrow$ For $m_i \sim 1 - 2$ TeV, (2800-50000, 30-2300, 1-80, 0-40) events, respectively.

Decays in Benchmark Scenario

- H_a BR into quarks, gauge bosons, di-Higgs suppressed by small mixing

- H_2 scalars decay dominantly to τ modes; H_3 couplings not necessarily hierarchic; decay branching ratios into $\nu_{R3}\nu, \ell\ell, \nu_{R3}\ell$ could be similar

- Decays of $\nu_R 3$ could be displaced on $\mathcal{O}$(m) scale:

$$\Gamma(\nu_{R3} \sim W^{\pm}\ell^{\mp}) \;\; \sim \;\; 4\Gamma(\nu_{R3} \to \nu_L\, Z) \sim \frac{\theta^2}{8\pi}\frac{m_{R3}^3}{v^2} \lesssim 10^{-16} \text{ GeV}$$

$$\Gamma(\nu_{R3} \to \nu_L\, h_1) \sim \frac{1}{32\pi}|\lambda_1^{\nu_{R3}}|^2 m_{R3} \lesssim 10^{-16} \text{ GeV} \;\; [\gg \Gamma(\nu_{R3} \to \nu_L\, \ell\, \ell)]$$

- For $\mathcal{O}(1)$ quartic couplings, expect $\xi \sim v_1\, v_2/m_2^2 \sim 0.1\%$ for $h_1 - h_2$ mixing

- Key decay rates ($b\bar{b}$, WW, ZZ, $\gamma\gamma$) of h_1 not significantly modified for $\xi \ll 1$

- Muon Yukawa for h_1 is $m_\mu/v_{EW} \sim 4 \times 10^{-4}$, while for h_2 is $m_\mu/\sqrt{2}m_\tau \sim 0.04$

- For $\xi \sim 0.1\%$, the shift in h_1 ("SM Higgs") coupling to muons $\sim 10\%$

- BR($h_1 \to \mu^+\mu^-$) shifted by $\sim 20\%$ (compared to SM); similarly for $h_1 \to \tau^+\tau^-$

- Observable at HE-LHC with 3 ab^{-1} or the HE-LHC with 15 ab^{-1} of data

M. Cepeda et al., HL/HE WG2 group Collaboration, 2019

Concluding Remarks

- The Higgs Troika model can provide a viable mechanism for Baryogenesis

- The main new ingredients are two additional Higgs doublets and right-handed neutrinos (associated with neutrino masses)

- The new states could be around the TeV scale: collider signals and precision effects could be within reach

- Heavy scalar pair signatures can include many leptons, missing energy, and possibly displaced vertices (ν_R decays)

- Can expect $\sim 20\%$ shift in "SM Higgs" branching fractions into $\mu^+\mu^-$ and $\tau^+\tau^-$; potentially measurable at HL-LHC, HE-LHC.

- The model could be testable (like "electroweak baryogenesis")