Higgs relaxation and leptogenesis

- The origin of matter-antimatter asymmetry, and the Sakharov's conditions for baryogenesis
- Scalar fields at the end of inflation
- Higgs relaxation: the epoch after inflation implied by the Higgs mass measurement at the LHC
- Higgs relaxation and leptogenesis

[Lauren Pearce, Louis Yang, AK, arXiv:1410.0722]

Baryogenesis

$$\eta \equiv \frac{n_B}{n_\gamma} = 10^{-10} (\text{observations, nucleosynthesis, etc.})$$

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However, these conditions are **not necessary** if CPT is broken

The seesaw mechanism

The seesaw model for neutrino masses introduces gauge-singlet states

$$\{\nu_e, \nu_\mu, \nu_\tau, \nu_{s,1}, \nu_{s,2}, \ldots, \nu_{s,N}\}$$

in the following Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\nu}_{s,a}\left(i\partial_\mu\gamma^\mu\right)\nu_{s,a} - y_{\alpha a} H\,\bar{L}_\alpha \nu_{s,a} - \frac{M_{ab}}{2}\,\bar{\nu}^c_{s,a}\nu_{s,b} + h.c.\,,$$

where H is the Higgs boson and L_α $(\alpha = e, \mu, \tau)$ are the lepton doublets. The mass matrix:

$$m_\nu \sim \frac{y^2 \langle H\rangle^2}{M_R}$$

One can understand the smallness of neutrino masses for the Yukawa couplings $y \sim 1$ **[Yanagida; Gell-Mann, Ramond, Slansky; Minkowski]**.

Leptogenesis

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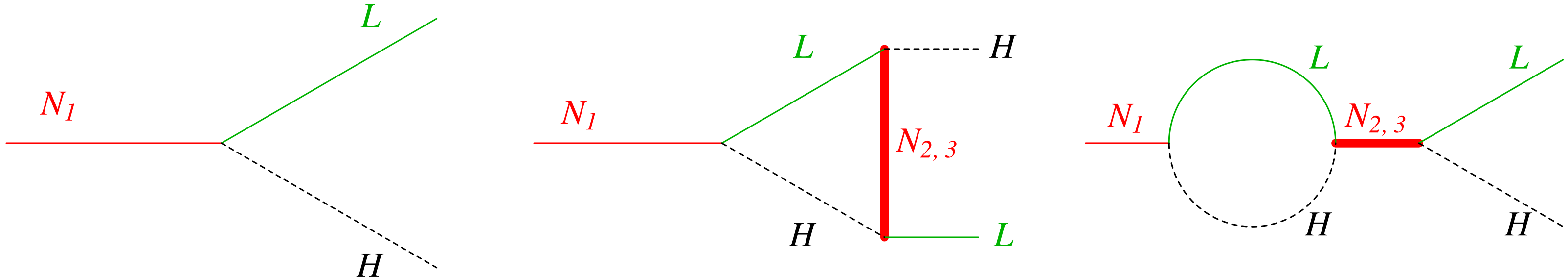
Consider again the seesaw Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N}_a \left(i\partial_\mu\gamma^\mu\right) N_a - y_{\alpha a} H \, \bar{L}_\alpha N_a - \frac{M_{aa}}{2} \, \bar{N}_a^c N_a + h.c. \, ,$$

Out-of-equilibrium decays with CP violation (from interference).



The asymmetry is proportional to the imaginary parts of the Yukawa couplings of the N's to the Higgs:

$$\epsilon = \frac{\Gamma(N_1 \to \ell H_2) - \Gamma(N_1 \to \bar{\ell}\bar{H}_2)}{\Gamma(N_1 \to \ell H_2) + \Gamma(N_1 \to \bar{\ell}\bar{H}_2)} \quad (1)$$

$$= \frac{1}{8\pi}\frac{1}{hh^\dagger}\sum_{i=2,3} \mathrm{Im}[(h_\nu h_\nu^\dagger)_{1i}]^2 f\left(\frac{M_i^2}{M_1^2}\right) \quad (2)$$

where f is a function that represents radiative corrections. For example, in the Standard Model $f = \sqrt{x}[(x-2)/(x-1) + (x+1)\ln(1+1/x)]$, while in the MSSM $f = \sqrt{x}[2/(x-1) + \ln(1+1/x)]$.

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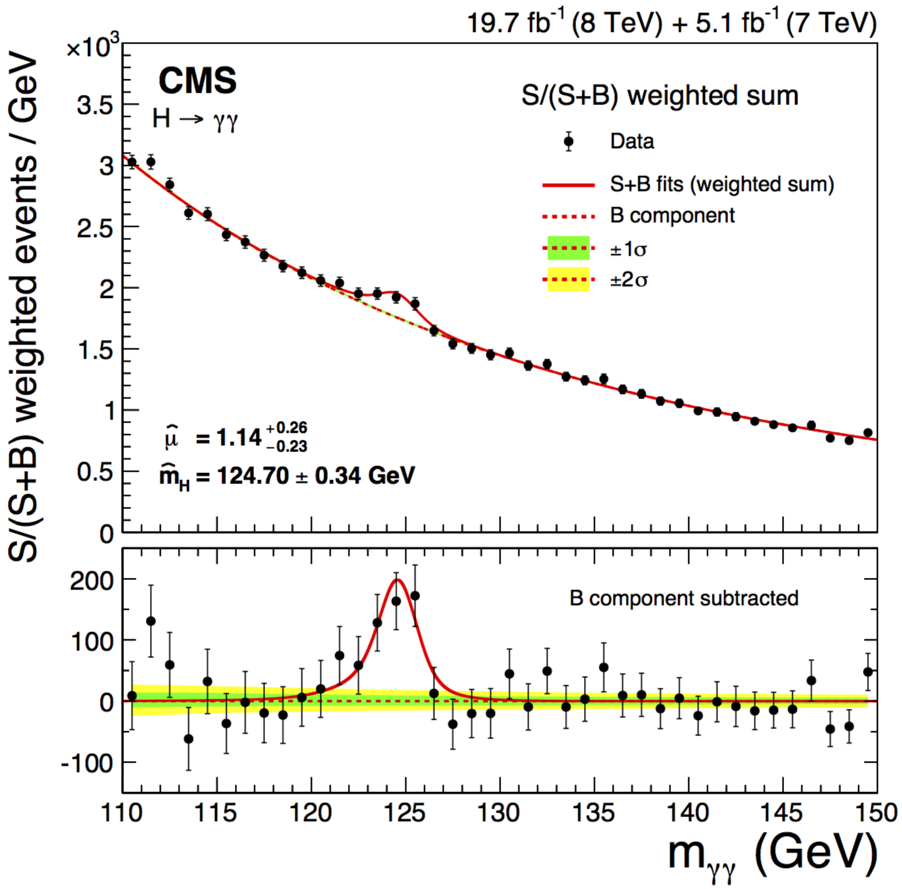
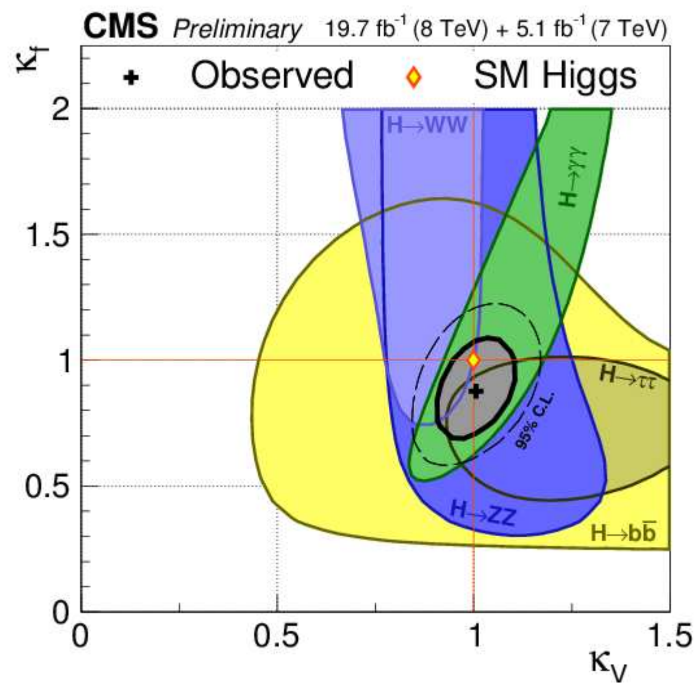
A viable and appealing way to explain the matter-antimatter asymmetry

The resulting asymmetry depends on CP violation in the neutrino mass matrix

Higgs boson discovery





Higgs potential

$$V(\Phi) = m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

where Φ is an SU(2) doublet. $\Phi = (1/\sqrt{2})\{e^{i\theta}\phi, 0\}$, where $\phi(x)$ is real.

LHC Higgs mass measurement $\Rightarrow$ λ is smaller than was previously expected. The value of the running coupling

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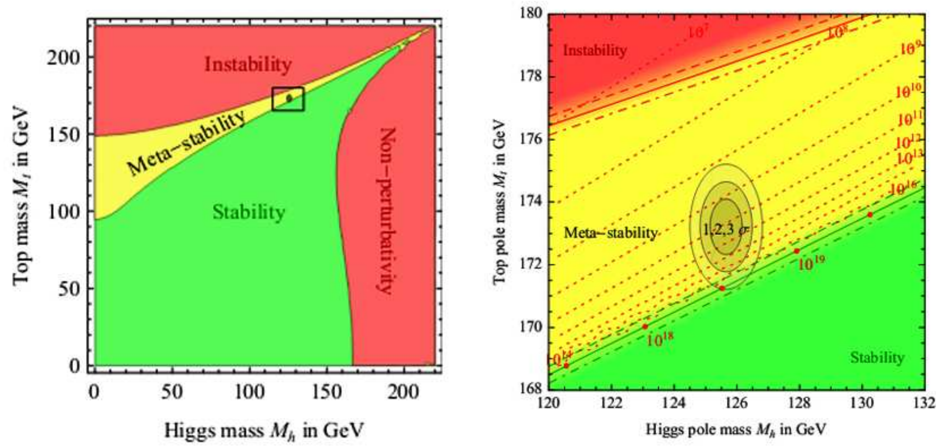
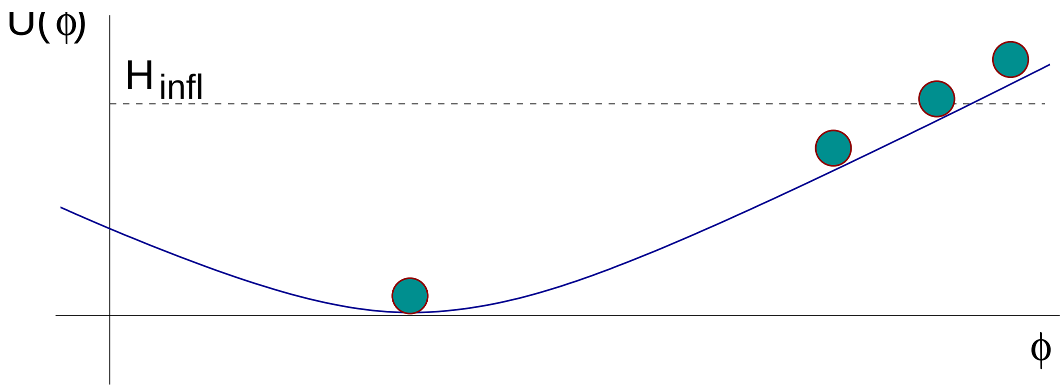


Degrassi et al.

Scalars in de Sitter space during inflation

A scalar with a small mass develops a VEV (for low-k modes, averaged over superhorizon scales). [Bunch, Davies; Linde; Starobinsky; Vilenkin, Gibbons, Hawking; Lee, Weinberg; Starobinsky, Yokoyama]



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- For a massive field with $V(\phi) = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4}\phi^4$, the VEV is evolution is given by

$$H\partial_t\langle\phi^2\rangle = \frac{H^4}{4\pi^2} - \frac{2m^2}{3}\langle\phi^2\rangle - 2\lambda\langle\phi^2\rangle^2$$

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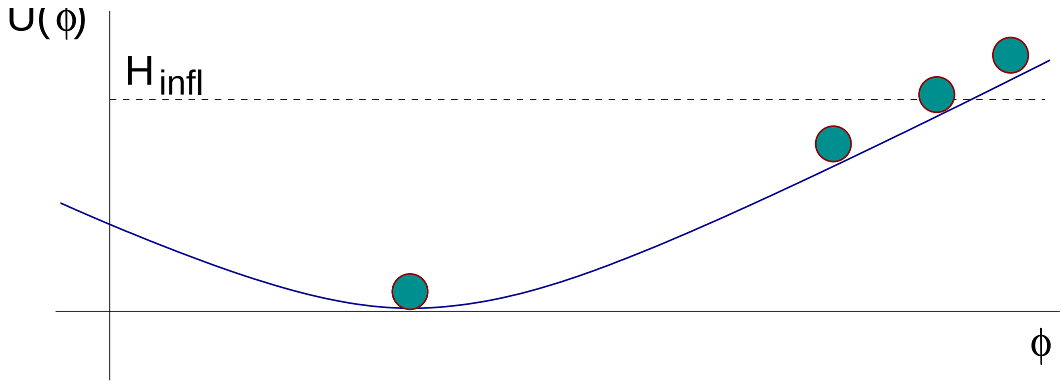
- on average, each degree of freedom carries energy $\sim H^4$ in the de Sitter universe

$$\langle V(\phi)\rangle \sim H^4$$



At the end of inflation, the field is not at the minimum of the effective potential.

For the Standard Model Higgs,

$$\sqrt{\langle\phi^2\rangle} = \phi_0 \sim 0.36\, H_I/\lambda^{1/4},$$

where $H_I = \sqrt{8\pi/3}\Lambda_I^2/M_{\rm P}$ is the Hubble parameter during inflation.

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$\Longrightarrow$ Higgs relaxation epoch

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For example, the following operator is unsuppressed for large VEVs:

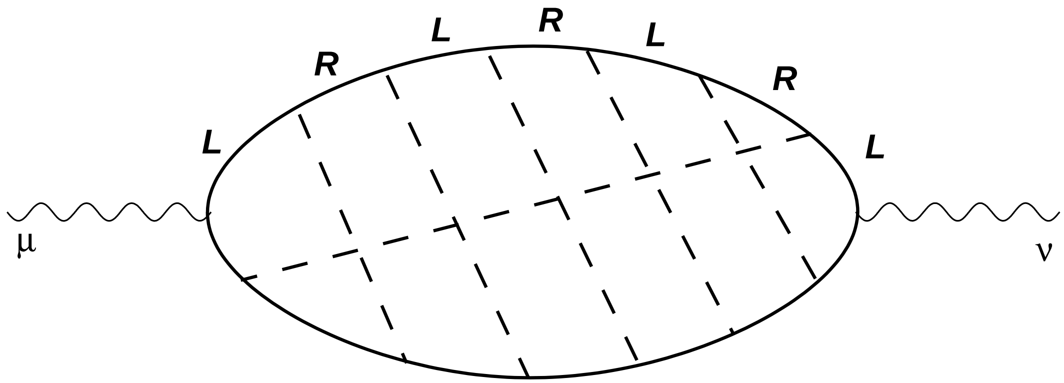
$$\mathcal{O}_6 = \frac{1}{M_n^2}\partial_\mu(\Phi^\dagger\Phi)\, j^\mu, \quad \text{where} \quad j^\mu = \bar{\psi}\gamma^\mu\psi$$

This operator can arise from CP violating diagrams with new physics at a scale M_n that yields $\frac{1}{M_n^2}(\Phi^\dagger\Phi)F_{\mu\nu}\tilde{F}^{\mu\nu}$, which is equivalent to the above after replacing $F_{\mu\nu}\tilde{F}^{\mu\nu}$ with j^μ via anomaly:

$$\partial_\mu j^\mu = \frac{1}{32\pi^2}\text{Tr}(F_{\mu\nu}\tilde{F}^{\mu\nu})$$

and then integrating by parts.

In the Standard Model, there are diagrams that have a non-vanishing part antisymmetrized in $[\mu\nu]$:



These diagrams are suppressed by some high power of the Yukawa couplings, which is a statement regarding the smallness of CP violation in the Standard Model for baryogenesis.

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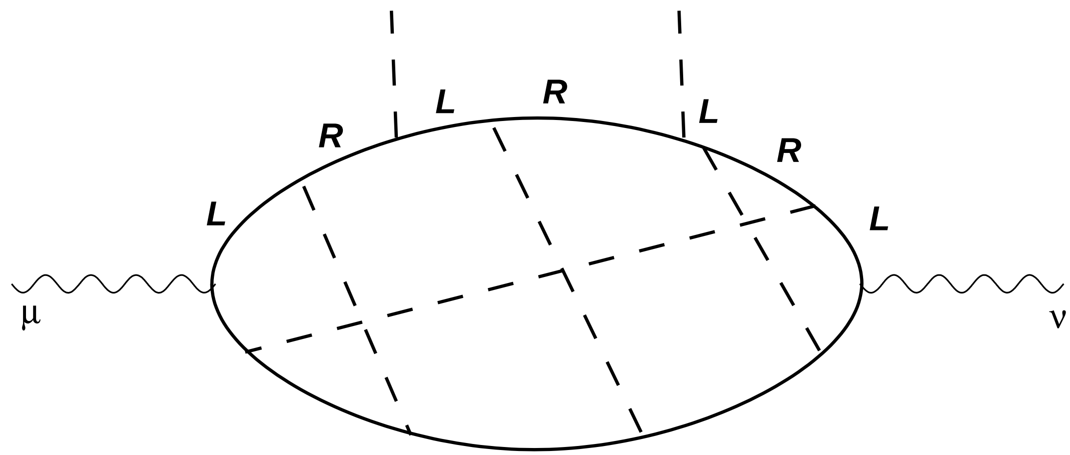
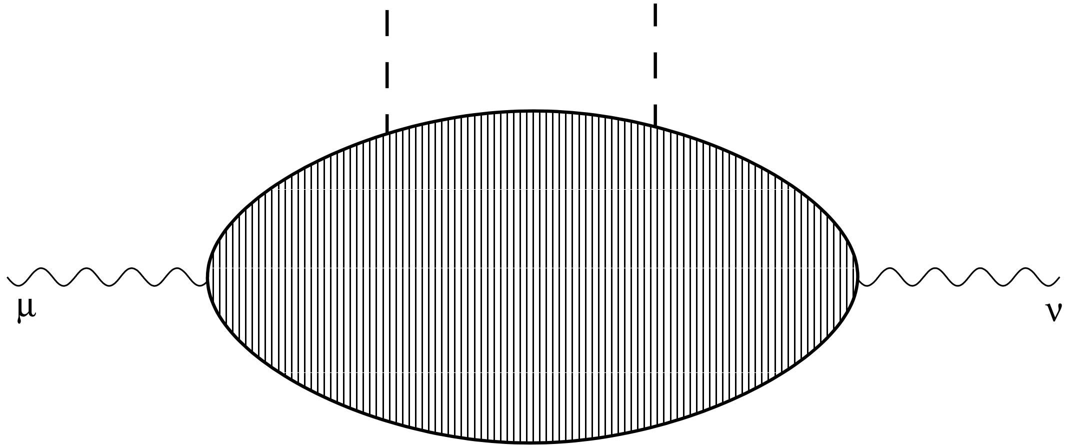


The part that is antisymmetric in $[\mu\nu]$ contributes to

$$\mathcal{O}_6 = \frac{1}{M^2}(\Phi^\dagger\Phi)\ F_{\mu\nu}\tilde{F}^{\mu\nu} = \frac{1}{M^2}(\Phi^\dagger\Phi)\partial_\mu(\bar{\psi}\gamma^\mu\psi) = -\frac{1}{M^2}\partial_\mu(\Phi^\dagger\Phi)\ \bar{\psi}\gamma^\mu\psi$$

Large VEV brings is sensitive to new physics at a scale M_n:

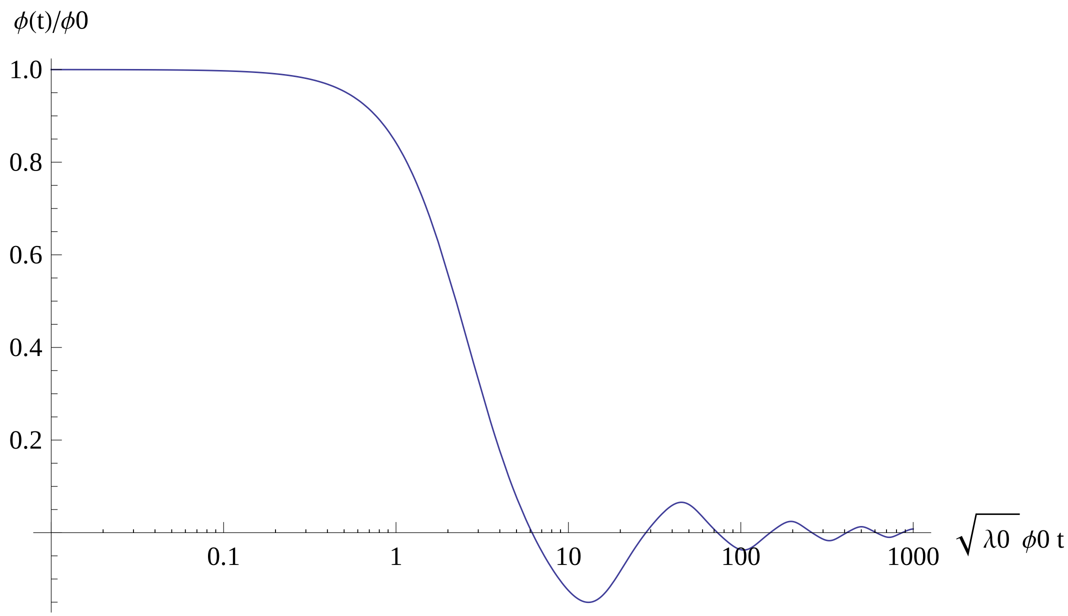


In particular, the following operator can play an important role:

$$\mathcal{O}_6 = \frac{1}{M_n^2} \partial_\mu (\Phi^\dagger \Phi) \; \bar{\psi} \gamma^\mu \psi$$

While the Higgs field is in motion, $\partial_t(\Phi^\dagger \Phi) = \partial_t |\phi^2|$ is not necessarily small in comparison with M_n. New *high-scale* physics can affect the conditions in plasma during the Higgs relaxation epoch.

Higgs field evolution at the end of inflation



Effective chemical potential

Fermion number density and the lepton number density:

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This operator and its effect as a chemical potential have been used extensively in models for electroweak baryogenesis [Dine et al.; Cohen, Kaplan, Nelson].

In the case of electroweak baryogenesis, $\phi(t)$ was the profile of the wall of the bubble in a first-order phase transition.

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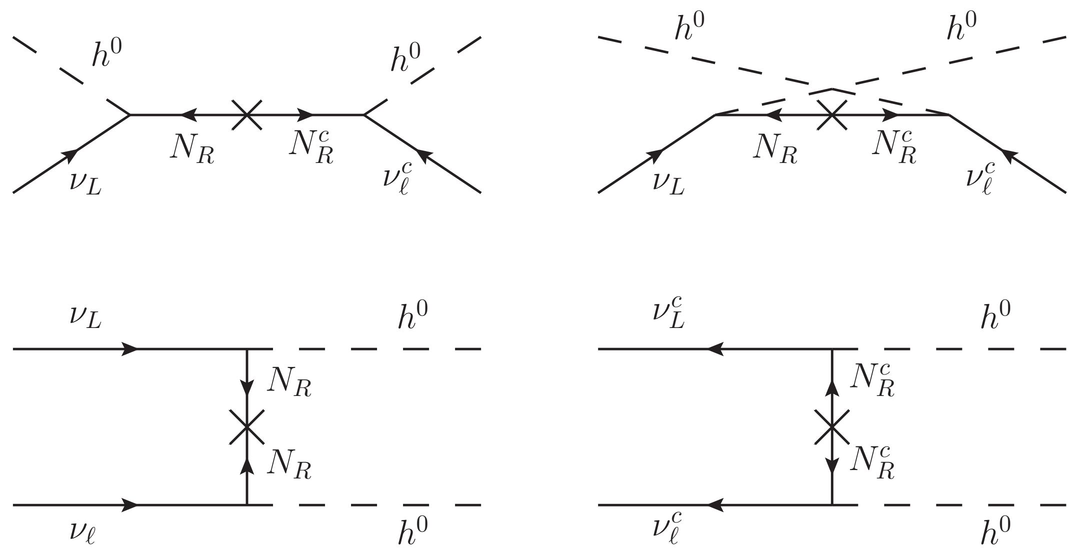
Our case: the "wall" moves in the timelike direction.

Lepton number violation

The term $\boldsymbol{\mu}_{\rm eff}(\boldsymbol{t})\ j^0$ violates CPT and splits the energy levels of leptons and antileptons. No additional source of CP violation is required. In particular, the baryon asymmetry does not depend on the phases in the neutrino mass matrix. If B,L were conserved, this would have no consequence. However, L (and, therefore, $(B+L)$ and $(B-L)$ are violated by the processes involving heavy neutrino lines ($M_R \gg T$):



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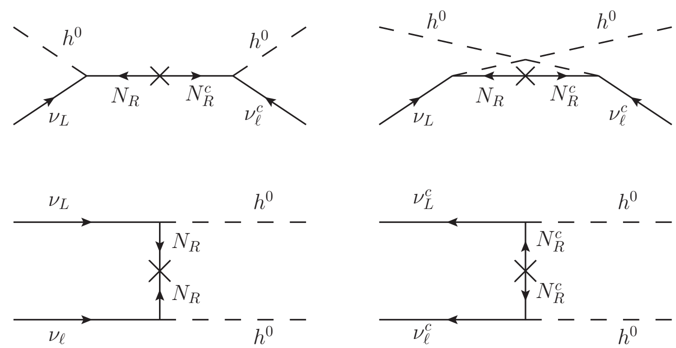


$$\boldsymbol{\sigma_R \simeq \frac{|(Y^\dagger Y)_{jj}|^2}{16\pi M_{R,j}^2} \simeq \frac{\sum_j m_{\nu,j}^2}{16\pi v_{EM}^4} \sim 10^{-31}\,\mathrm{GeV}^{-2}},$$

where Yukawa couplings are assumed to be ~ 1 in the spirit of the seesaw mechanism.

Lepton number generation in the presence of a time-dependent chemical potential

We define an *approximate* lepton number, which becomes exact in the limit $M_R \to 0$.

$$n_L = n_\nu - n_{\bar{\nu}}$$

In equilibrium, n_L would evolve to its equilibrium value $n_L^{\rm eq} \sim \mu_{\rm eff} T^2$. However, the time dependence complicates matter. The time scale for approaching equilibrium is controlled by σ_R. One can use an approximate Boltzmann equation (derived from detailed balance):

$$\frac{d}{dt} n_L + 3 H n_L \cong -\frac{2}{\pi^2} T^3 \sigma_R \left(n_L - \mu_{\rm eff} T^2 \right) .$$

During reheating,

$$\rho_R = \frac{g_* \pi^2}{30} T_{\rm eff}^4 \simeq \frac{M_{\rm P}^2 \Gamma_I}{10\pi} \frac{1}{t} \left[1 - \left(\frac{t_i}{t} \right)^{5/3} \right].$$

Higgs relaxation occurs on the time scale of H_ϕ^{-1}, and

$$\mu_{\rm eff} = \frac{\partial_t |\phi^2|}{M_n^2} \sim \frac{H_\phi \phi_0^2}{M_n^2} \sim \frac{\sqrt{\lambda}\phi_0^3}{M_n^2}.$$

As the Higgs field oscillates, the equilibrium value of n_L is

$$n_{L,\rm max} \sim \mu_{\rm eff} T^2 \sim \frac{\sqrt{\lambda}\phi_0^3 T_{\rm max}^2}{M_n^2}.$$

However, the relevant reactions may not be fast enough to equilibrate to this value before the Higgs VEV approaches zero at $t_{\rm rlx} \approx 6/\sqrt{\lambda}\phi_0$. In this case, the maximum asymmetry reached by the end of Higgs relaxation at time $t_{\rm rlx}$ is

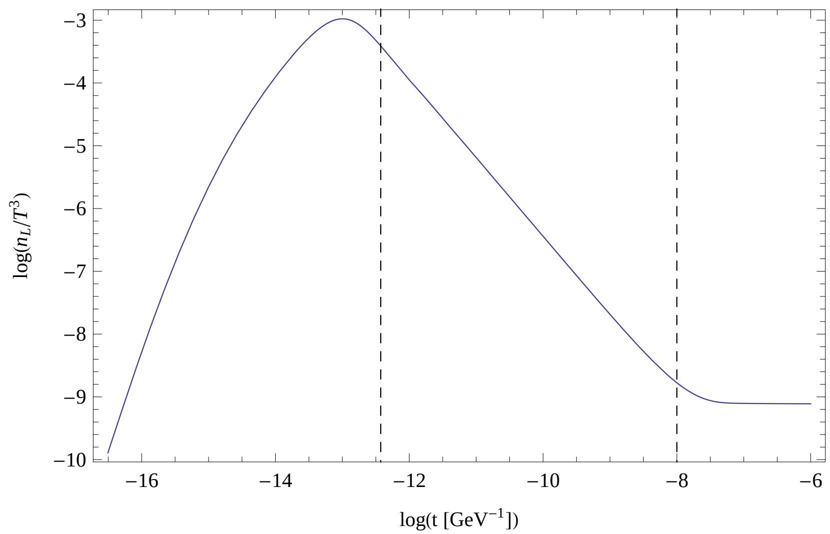
$$n_{\rm rlx} \sim n_{L,\rm max} T^3_{\rm rlx} \sigma_R \, t_{\rm rlx},$$

After that, there is partial washout:

$$\frac{d(n_L a^3)}{dt} \simeq -\frac{2}{\pi^2} T^3 \sigma_R a^3 n_L,$$

The equations can be solved numerically.

Numerical solution



The desired asymmetry $\eta \sim 10^{-9}$ (before dilution) can be achieved for parameters The parameters that we choose are $\Lambda_I = 3 \times 10^{16}$ GeV, $\Gamma_I = 10^8$ GeV, $M_n = 10^{14}$ GeV, and $M_R = 9 \times 10^{14}$ GeV. The maximum temperature during reheating is $T_{\max} = 2 \times 10^{14}$ GeV. The first dashed line corresponds to the time when ϕ first crosses zero. The second dashed line corresponds to the beginning of radiation-dominated era.

Conclusion

- LHC measurement of the Higgs boson mass implies that the Higgs field had a large VEV at the end of inflation
- Higgs relaxation should have taken place in the early stages of reheating
- Lepton number asymmetry could be generated during Higgs relaxation epoch; the lepton asymmetry is converted to baryon asymmetry by electroweak processes
- The matter-antimatter asymmetry can be explained by Higgs relaxation leptogenesis
- The parameter space is different from that of thermal leptogenesis
- The baryon asymmetry does not depend on CP violating phases in the neutrino mass matrix.