Higgsogenesis

Recall from Steve's talk the problem of baryogenesis and the proposed general mechanism:

Problem:

- There is an asymmetry of matter-to-antimatter in the universe as evidenced by:
  - We don't see spontaneous bursts of energy released from the cosmos at any scale or distance.
  - The CMB shows that at recombination there were about 1 billion photons for every proton;

$$\eta_{CMB} = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.23 \pm 0.17) \times 10^{-10}$$

Proposed conditions (Sakharov Conditions) that solutions to this problem must satisfy:

1. Baryon number violation

$$Y_{\Delta B} \equiv Y_B - Y_{\bar{B}} = \frac{n_B - n_{\bar{B}}}{s}$$

$Y_X \equiv \frac{n_X}{s}$ is the comoving number density

s is the entropy density of the universe

Experimentally: $Y_{\Delta B} = (8.79 \pm 0.44) \times 10^{-11}$

Assuming a spatially flat Universe (which is true!)

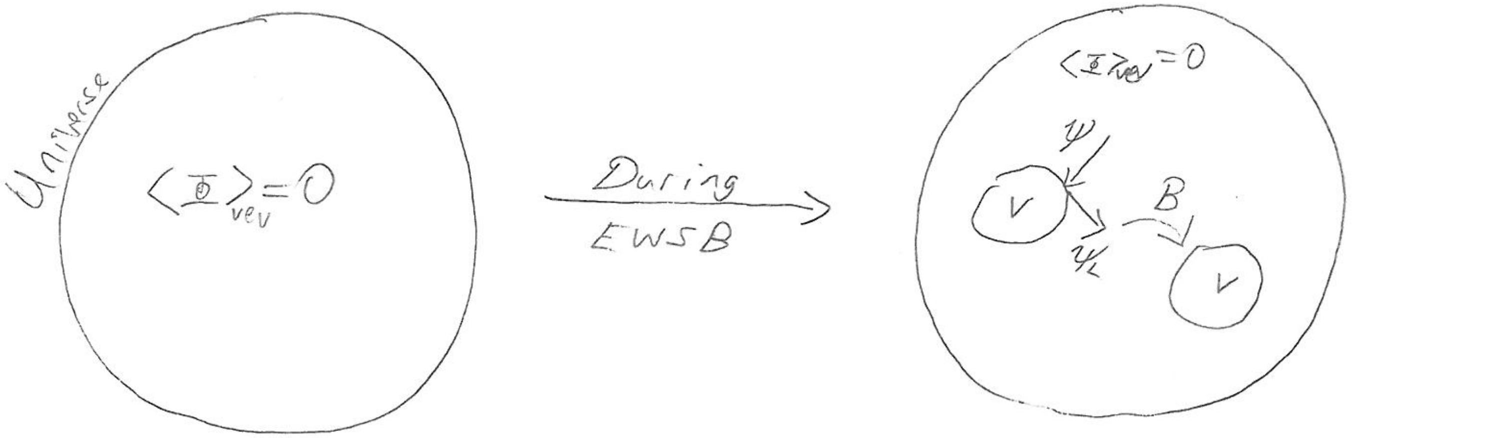
2. C and CP violation
   - to produce unequal numbers of L, R baryons vs. anti-baryons.

3. Interactions occur out of thermal equilibrium
   - The temperature when key decays take place must be smaller then the mass of the decaying particle:

$$T_{\text{at decay}} < M_X \quad \text{for decay } \Gamma(X \to 1 + 2 + \ldots)$$

General Mechanism Proposed (EWSB):

- before EWSB $\langle \Phi \rangle_{vev} = 0$ everywhere, then pockets of $\langle \Phi \rangle_{vev} = v$ begin to open up due to 1. the universe cooling (expansion) and 2. slight asymmetries in temperature:



- During EWSB, sphalerons transfer fermions produced asymmetrically through proposed CP violations in thermal equilibrium to baryons which then find their way into out-of-equilibrium areas.

- The process continues until the universe is completely out of equilibrium, leaving a net baryon asymmetry.

· Higgsogenesis is an exploration of extensions to the 2HDM that might be used as a source for CP violation. Such models have these potential characteristics:

- CP violating 2HDM extensions can generate asymmetries before the electroweak phase transition (EWPT),
- No additional B, L, or B−L - violating interactions, besides sphalerons, need to be postulated.

The general Higgsogenesis mechanism:

- Additional heavy scalars, S_i, that interact only with the Higgs sector in a CP-violating manner generate an asymmetry of Higgs doublets.

$T \gtrsim M_{S_i} > T_{EWSB}$ $\quad$ $M_{S_i} > T > T_{EWSB}$ (out of equilibrium) decays $\quad$ $T \sim T_{EWSB}$

- A population of S_i's are produced in equilibrium with Higgs Doublets,
- The heavy scalars then decay in a CP-violating manner asymmetrically into Higgs doublets out of equilibrium.
- The asymmetry in the Higgs doublets is then transfered to a baryon asymmetry via sphalerons.
- Note that this process might occur alongside the conventional EWSB baryogenesis.

To see this in action, we have to re-introduce the 2HDM:
- The most general gauge invariant scalar potential is:

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.) + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2$$
$$+ \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$$
$$+ \left[\frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + h.c.\right]$$

where Φ_1 and Φ_2 are $SU(2)_L$ doublet scalars,
$m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4$ are real, and
$m_{12}^2, \lambda_5, \lambda_6, \lambda_7$ are complex.

You've probably noticed that $m_{12}^2, \lambda_5, \lambda_6, \lambda_7$ appear to be new, but that is just because we haven't chosen a basis by applying a global $SU(2)$ transformation in (Φ_1, Φ_2) space yet.

- The Yukawa interactions, which are important for transfering Φ_i asymmetries into lepton asymmetries, are:

$$\mathcal{L}_Y = \bar{Q}_L(\Gamma_1\Phi_1 + \Gamma_2\Phi_2)d_R + \bar{Q}_L(\Gamma_3\tilde{\Phi}_1 + \Gamma_4\tilde{\Phi}_2)u_R + L_L(\Gamma_5\tilde{\Phi}_1 + \Gamma_6\tilde{\Phi}_2)\ell_R + h.c.$$

where $Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$, $L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}$, and Γ_i are generic 3×3 matrices in their respective sectors.

- There are (at least) four different ways to define how Φ_1 and Φ_2 couple to fermions:

Model Type	Φ_1	Φ_2
Type I	—	u, d, ℓ
Type II	d, ℓ	u
Type X	ℓ	u, d
Type Y	d	u, ℓ

Type II and Type Y formulations end up removing any Higgs asymmetries between Φ_1 and Φ_2 before sphalerons can transfer them to baryon asymmetries.

From here on we will only consider Type I WLOG.

- We will be using the <u>symmetry basis</u> where $m_{12}^2 = \lambda_6 = \lambda_7 = 0$ when considering 2HDM extensions and the <u>thermal mass basis</u> where $\lambda_i \to \Lambda_i$ when considering equilibrium constraints on the coupling constants.

- There are many possible Higgsogenesis models because it's easy enough to add more scalars and doublets to your theory. We'll consider three such models:

- <u>Higgsogenesis Model 1:</u>

- 2HDM plus one heavy real scalar S where the fields transform under parity as such:

$$\Phi_1 \to -\Phi_1 \quad , \quad \Phi_2 \to \Phi_2 \quad , \quad S \to -S$$

$$V = V_\Phi + V_S + V_{S\Phi}$$

$$V_\Phi = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 + \frac{1}{2}\lambda_1 |\Phi_1|^4 + \frac{1}{2}\lambda_2 |\Phi_2|^4$$
$$+ \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{1}{2}\lambda_5 \left[(\Phi_1^\dagger \Phi_2)^2 + h.c.\right]$$

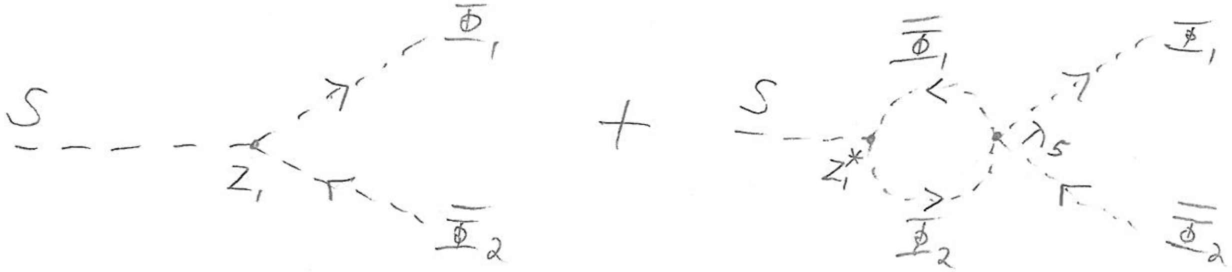
$$V_S = m_S^2 S^2 + \lambda_S S^4$$

$$V_{S\Phi} = z_1 m_S (\Phi_1^\dagger \Phi_2) S + z_1^* m_S (\Phi_2^\dagger \Phi_1) S + \beta_1 |\Phi_1|^2 S^2 + \beta_2 |\Phi_2|^2 S^2$$

All parameters are real except for z_1, which allows for potential CP violation.

- So can a population of S's generate an asymmetry of Φ_1 and Φ_2's through their CP-violating decays?

- Consider $S \to \Phi_1 + \Phi_2$ at the tree and one-loop level:



- Recall that z_1, z_1^* are CP-violating couplings while λ_5 is not. The second diagram thus allows for CP violation in decays.

- We can calculate the asymmetry from the interference of these two diagrams:

$$\epsilon = \frac{\Gamma(S \to \bar{\Phi}_1 \bar{\Phi}_2) - \Gamma(S \to \Phi_1 \Phi_2)}{\Gamma(S \to \bar{\Phi}_1 \bar{\Phi}_2) + \Gamma(S \to \Phi_1 \Phi_2)}$$

let A_0 and A_1 be the amplitudes of the first and second diagrams, respectively, and let $c_0 = -z_1$, $c_1 = 3\lambda_5 z_1^*$, $A_0 = 1$. Then:

$$\epsilon \simeq \frac{(|c_0 A_0 + c_1 A_1|^2)^* - (|c_0^* A_0 + c_1^* A_1|^2)^*}{(|c_0 A_0 + c_1 A_1|^2)^* + (|c_0^* A_0 + c_1^* A_1|^2)^*}$$

$$\epsilon \simeq -4 \frac{Im(c_0^* c_1) Im[(A_0^* A_1)^*]}{2|c_0|^2(|A_0|^2)^*}$$

$$\epsilon \simeq -\frac{3}{8\pi} \frac{Im[z_1^* \lambda_5 z_1^*]}{2|z_1|^2} = \frac{3}{16\pi} \lambda_5 \sin[2\arg(z_1)]$$

$$|\epsilon| \lesssim 6 \times 10^{-2} \lambda_5$$

- This says that a Higgs asymmetry generated by a heavy scalar's Higgs decay process depends on the coupling constant λ_5 (quartic) and the phase of the coupling z_1.

- To determine the amount of baryogenesis possible given a Higgsogenesis model, we need to consider chemical equilibrium relations:
  - Yukawa interactions require:

$$-\mu_q + \mu_{\Phi_2} + \mu_{d_R} = 0$$

$$-\mu_q + \mu_{\Phi_2} + \mu_{u_R} = 0$$

$$-\mu_\ell + \mu_{\phi_e} + \mu_{e_R} = 0 \quad \text{where } \phi_e \text{: charged leptons}$$

  - Electroweak and QCD interactions require:

$$3\mu_q + \mu_\ell = 0 \quad (EW)$$

$$2\mu_q - \mu_{u_R} - \mu_{d_R} = 0 \quad (QCD)$$

  - Hypercharge conservation requires:

3 generations $\rightarrow$ $3(-\mu_{e_R} - \mu_\ell + \mu_q + 2\mu_R - \mu_{d_R}) + 2(\mu_{\Phi_1} + \mu_{\Phi_2}) = 0$

$$3(8\mu_q + \mu_{\phi_e} + 3\mu_{\Phi_2}) + 2(\mu_{\Phi_1} + \mu_{\Phi_2}) = 0$$

- The comoving asymmetries are given by:

$$Y_{\Delta i} = \frac{n_i - n_{\bar{i}}}{s} = \frac{g_i T^2}{6s} \mu_i \times \begin{cases} 2 & \text{for bosons} \\ 1 & \text{for fermions} \end{cases}$$

$$\Rightarrow Y_{\Delta B} = \overset{\#\text{ of generations}}{3}(2\mu_q + \mu_{u_R} + \mu_{d_R})\frac{T^2}{3s} = 4\mu_q \frac{T^2}{s}$$

$$Y_{\Delta L} = 3(2\mu_\ell + \mu_{e_R})\frac{T^2}{3s} = -(9\mu_q + \mu_{\phi_e})\frac{T^2}{s}$$

$$Y_{\Delta B} - Y_{\Delta L} = (13\mu_q + \mu_{\phi_e})\frac{T^2}{s}$$

Substituting in the hypercharge relation gives:

$$Y_{\Delta B} = \frac{8}{23}(Y_{\Delta B} - Y_{\Delta L}) + \frac{3}{46}(Y_{\Delta\Phi_1} - Y_{\Delta\Phi_2})$$

Here we see that even if B-L is conserved, we can still generate a baryon asymmetry from a Higgs asymmetry. Lets assume that $Y_{\Delta B} - Y_{\Delta L} = 0$.

- Getting back to the 2HDM + heavy singlet model, we can approximate the baryon asymmetry as:

$$Y_{\Delta B} \simeq Y_S^{eq} \cdot C \cdot \epsilon \cdot \eta$$

where Y_S^{eq}: comoving number density of S in equilibrium,

C: $\frac{3}{46}$, from above,

η: Efficiency factor of S's asymmetry generating ability; $(0 \leq \eta \leq 1)$

$$Y_{\Delta B} \simeq 2 \times 10^{-4} \epsilon \eta$$

$$Y_{\Delta B} \lesssim 1.2 \times 10^{-5} \lambda_5$$

Recall the measured $Y_{\Delta B} = (8.79 \pm 0.44) \times 10^{-11}$

$$\Rightarrow |\lambda_5| \lesssim 10^{-7}$$

So a 2HDM plus heavy singlet model can't provide enough baryon asymmetry to account for that which is observed.

Higgsogenesis Model 2

- 2HDM plus one heavy real singlet and an additional doublet that transform under parity like:

$$\Phi_1 \to -\Phi_1 \,, \quad \Phi_3 \to -\Phi_3 \,, \quad \Phi_2 \to \Phi_2 \,, \quad S \to -S$$

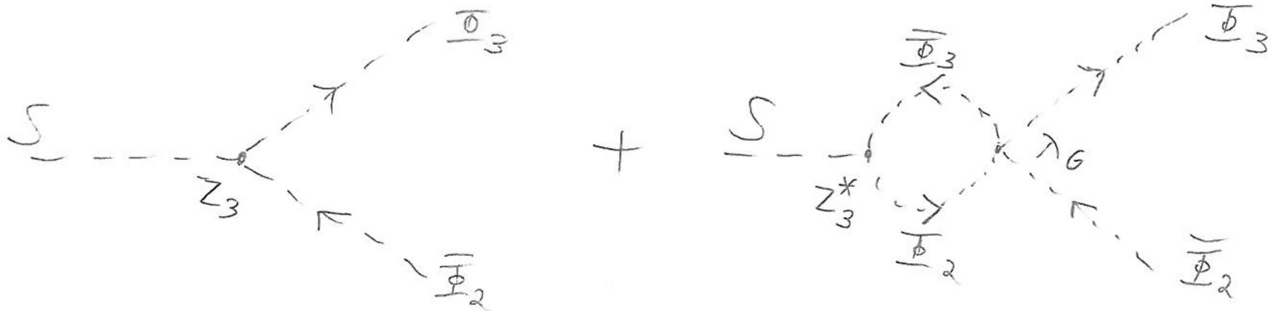
$$V_3 = V + \Delta V_\Phi + \Delta V_{S\Phi}$$

$$\begin{aligned}\Delta V_\Phi = {} & m_{33}^2 |\Phi_3|^2 + \tfrac{1}{2}\lambda_A |\Phi_3|^4 + \lambda_B |\Phi_1|^2 |\Phi_3|^2 + \lambda_C |\Phi_2|^2 |\Phi_3|^2 \\ & + \lambda_D (\Phi_1^\dagger \Phi_3)(\Phi_3^\dagger \Phi_1) + \lambda_E (\Phi_2^\dagger \Phi_3)(\Phi_3^\dagger \Phi_2) \\ & + \Big[\tfrac{1}{2}\lambda_F (\Phi_1^\dagger \Phi_3)^2 + \tfrac{1}{2}\lambda_G (\Phi_3^\dagger \Phi_2)^2 + \lambda_H (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_3) \\ & + \lambda_I (\Phi_1^\dagger \Phi_2)(\Phi_3^\dagger \Phi_2) + \lambda_J (\Phi_1^\dagger \Phi_3)(\Phi_1^\dagger \Phi_1) + \lambda_K (\Phi_1^\dagger \Phi_3)(\Phi_3^\dagger \Phi_3) + h.c.\Big]\end{aligned}$$

$$\begin{aligned}\Delta V_{S\Phi} = {} & z_3 m_S (\Phi_3^\dagger \Phi_2) S + z_3^* m_S (\Phi_2^\dagger \Phi_3) S + \beta_3 |\Phi_3|^2 S^2 \\ & + \left[\beta_{13} (\Phi_1^\dagger \Phi_3) S^2 + h.c.\right]\end{aligned}$$

where $m_S > m_{33}$

- Assuming that $S \to \Phi_3 \Phi_2^*$ to be much more prominent than $S \to \Phi_1 \Phi_2^*$, we will ignore the latter.
- Again we have tree and one-loop interfering diagrams:



- We've assumed that $m_{\Phi_3} \gg m_{\Phi_1}$, and so an asymmetry between Φ_3 and Φ_2 will turn into an asymmetry between Φ_1 and Φ_2 because Φ_3 will decay to Φ_1 due to parity.

$$\epsilon = \frac{\Gamma(S \to \Phi_3 \bar{\Phi}_2) - \Gamma(S \to \bar{\Phi}_3 \Phi_2)}{\Gamma(S \to \text{all})} \simeq \frac{3}{16\pi} \lambda_G \sin[2\arg(Z_3)]$$

- If you work out the thermally averaged scattering rate of these interactions (reference [1]), one can determine that:

$$|Z_3| \lesssim 10^{-7} \sqrt{\frac{M_{33}}{\text{TeV}}} \quad \text{and} \quad |\lambda_G| \lesssim 10^{-7} \sqrt{\frac{M_{33}}{\text{TeV}}}$$

- In order for this model to contribute to baryogenesis, it requires $M_{33} \gtrsim 10^8\,\text{GeV}$.

Higgsogenesis Model 3

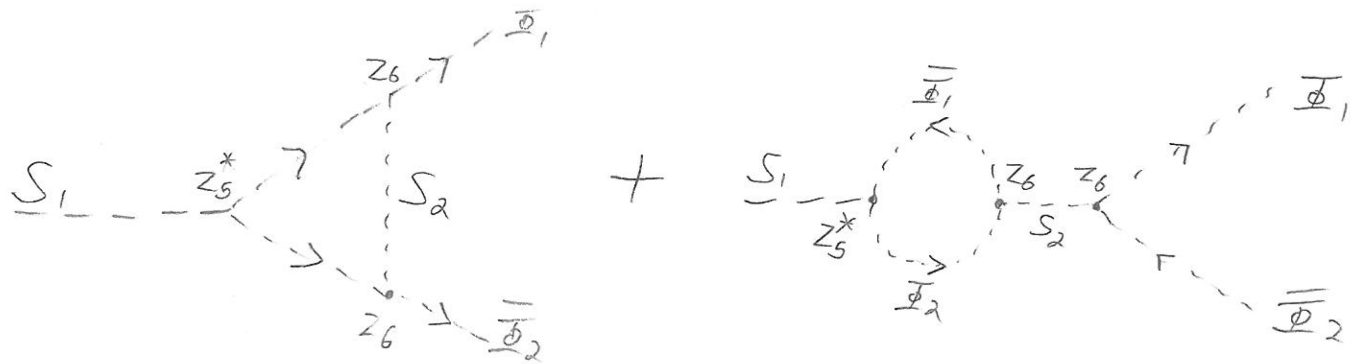
- 2HDM plus two heavy scalars, S_1 and S_2 where $m_{S_1} \ll m_{S_2}$. These both transform under parity like $S_{1,2} \to -S_{1,2}$.

$$V_{22} = V + \Delta V_S + \Delta V_{S\Phi}$$

$$\Delta V_S \sim \text{(quartic)}$$

$$\Delta V_{S\Phi} = z_5 m_{S_1} (\Phi_1^\dagger \Phi_2) S_1 + z_5^* m_{S_1} (\Phi_2^\dagger \Phi_1) S_1$$
$$+ z_6 m_{S_2} (\Phi_1^\dagger \Phi_2) S_2 + z_6^* m_{S_2} (\Phi_2^\dagger \Phi_1) S_2$$

- Due to the large mass difference, we assume that the thermal production of S_2 is negligable to that of S_1.



- If λ_5 vanishes, causing the 2HDM + one singlet model to not generate CP violating S decays, the 2HDM + two singlets still can!

$$\epsilon_1 \simeq \frac{-1}{4\pi} \frac{\mathrm{Im}[(z_5^* z_6)^2]}{|z_5|^2} \left[\frac{1}{2} f(x_2) + g(x_2)\right]$$

where $x_2 \equiv \frac{m_{S_2}^2}{m_{S_1}^2}$ and $f(x) = x \ln\left(\frac{x}{1+x}\right)$

$$g(x) = \frac{x}{1-x}$$

for $x_2 >> 1$, $f(x_2) \simeq -1$, $g(x_2) \simeq -1$

$$\Rightarrow \epsilon_1 \simeq \frac{3}{8\pi} \frac{\mathrm{Im}[(z_5^* z_6)^2]}{|z_5|^2} = \frac{3}{8\pi} |z_6|^2 \sin[2\arg(z_5^* z_6)]$$

$$\Rightarrow |z_6|^2 \gtrsim 10^{-6}$$

- As we've just seen, in considering whether 2HDM extensions can contribute to the observed baryon asymmetry in the universe, we can see that given certain coupling and mass constraints it is possible!

References:

[1] Davidson et. al., arXiv:1307.6218.
[2] J.F. Gunion, The Higgs Hunter's Guide.