Strong EW phase transition from varying Yukawas

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Higgs Hunting - Paris, 1 September 2016
Electroweak baryogenesis — an possible link between the Higgs and cosmology.

Electroweak baryogenesis requires:
- A strong first order phase transition \( \frac{\phi_c}{T_c} \gtrsim 1 \)
- Sufficient CP violation

However in the SM:
- The Higgs mass is too large
- Quark masses are too small
Electroweak phase transition

Lattice calculations show the SM Higgs mass is too large.

\[ R_{HW} \equiv \frac{m_H}{m_W} \]

Endpoint at:
\[ m_H \approx 67 \text{ GeV} \]

The Higgs potential must be modified.

Baryogenesis from charge transport with SM CP violation

\[ R_{LR} = \text{Diagram 1} + \text{Diagram 2} + \ldots \]

\[ \epsilon_{\text{CP}} \sim \frac{1}{M_W^6 T_c^6} \prod_{i>j} (m_i^2 - m_j^2) \prod_{i>j} (m_i^2 - m_j^2) J_{\text{CP}} \]

- Gavela, Hernandez, Orloff, Pène, Quimbay [hep-ph/9406289],
- Huet, Sather [hep-ph/9404302].

SM quark masses are too small!
Solutions to the flavour puzzle

Yukawa interactions:

\[ y_{ij} f^i_L \Phi^{(c)} f^j_R \]

Possible solutions
- Froggatt-Nielsen
- Composite Higgs
- Randall-Sundrum Scenario

Froggatt-Nielsen Yukawas:

\[ y_{ij} \sim \left( \frac{\langle \chi \rangle}{\Lambda} \right)^{-q_i + q_j + q_H} \]

Some previous work: Baryogenesis from the Kobayashi-Maskawa phase
- Perez, Volansky - Phys. Rev. D 72 (2005) 103522
Varying Yukawas

Study the strength of the EWPT with varying Yukawas in a model independent way. - IB, Konstandin, Servant (1604.04526)

Ansatz

\[ y(\phi) = \begin{cases} 
  y_1 \left(1 - \left(\frac{\phi}{v}\right)^n\right) + y_0 & \text{for } \phi \leq v, \\
  y_0 & \text{for } \phi \geq v.
\end{cases} \]
Effective Potential

\[ V_{\text{eff}} \supset -\frac{g_* \pi^2}{90} T^4 \]

Thermal correction

\[ n = 0 \quad y_{n=0}^{n=0}(\phi) = 1 \quad y_{1\neq 0}^{n=0} = 1 \]
\[ y_{0\neq 0}^{n=0} = 0.02 \]
Second order phase transition $T_c = 163 \text{ GeV}$.

$$V_{\text{eff}} = V_{\text{tree}}(\phi) + V_1^0(\phi) + V_1^T(\phi, T) + V_{\text{Daisy}}(\phi, T)$$
Effective Potential - Varying Yukawas

Strong first order phase transition

\[ \phi_c = 230 \text{ GeV}, \quad T_c = 128 \text{ GeV}, \quad \phi_c / T_c = 1.8 \]
Effective Potential - $T = 0$ terms

$$V_{\text{eff}} = V_{\text{tree}}(\phi) + V_1^0(\phi) + V_1^T(\phi, T) + V_{\text{Daisy}}(\phi, T)$$

$$V_{\text{tree}}(\phi) = -\frac{\mu_\phi^2}{2} \phi^2 + \frac{\lambda_\phi}{4} \phi^4$$

$$V_1^0(\phi) = \sum_i \frac{g_i (-1)^F}{64\pi^2} \left\{ m_i^4(\phi) \left( \log \left[ \frac{m_i^2(\phi)}{m_i^2(\nu)} \right] - \frac{3}{2} \right) + 2m_i^2(\phi)m_i^2(\nu) \right\}$$

Gives a large negative contribution to the $\phi^4$ term.

- Can lead to a new minimum between $\phi = 0$ and $\phi = 246$ GeV.
- Not an issue for previous $y_1 = 1$, $n = 1$ example.
- Can make phase transition weaker.
Effective Potential - one-loop $T \neq 0$ correction

$$V_1^T(\phi, T) = \sum_i g_i(-1)^F \frac{T^4}{2\pi^2} \times \int_0^\infty y^2 \text{Log} \left(1 - (-1)^F e^{-\sqrt{y^2 + m_i^2(\phi)/T^2}}\right) dy$$

$$V_f^T(\phi, T) = -\frac{gT^4}{2\pi^2} J_f \left(\frac{m_f(\phi)^2}{T^2}\right)$$

$$J_f \left(\frac{m_f(\phi)^2}{T^2}\right) \approx \frac{7\pi^4}{360} - \frac{\pi^2}{24} \left(\frac{m}{T}\right)^2 - \frac{1}{32} \left(\frac{m}{T}\right)^4 \text{Log} \left[\frac{m^2}{13.9T^2}\right], \quad \text{for } \frac{m^2}{T^2} \ll 1,$$

$$\delta V \equiv V_f^T(\phi, T) - V_f^T(0, T) \approx gT^2 \phi^2[y(\phi)]^2$$
Effective Potential - daisy correction

\[ V_{\phi}^D (\phi, T) = \frac{T}{12\pi} \left\{ m_{\phi}^3 (\phi) - \left[ m_{\phi}^2 (\phi) + \Pi_{\phi} (\phi, T) \right]^{3/2} \right\} \]

\[ \Pi_{\phi} (\phi, T) = \left( \frac{3}{16} g_2^2 + \frac{1}{16} g_Y^2 + \frac{\lambda}{2} + \frac{y_{t}^2}{4} + \frac{g y(\phi)^2}{48} \right) T^2 \]
Including the flavon

Flavor Cosmology: Dynamical Yukawas in the Froggatt-Nielsen Mechanism
- IB, Konstandin, Servant (1608.03254)

- Have to take into account constraints from flavour physics.
- Flavon dof also affects $\phi_c/T_c$.
- Generic prediction: light flavon with mass below the EW scale.

We have implemented this idea in some non-standard Froggatt-Nielsen scenarios.
Experimental signatures - Model A-2

Couple a flavon to each mass eigenstate - Knapen, Robinson (1507.00009)

\[ \Lambda_s = 1 \text{ TeV}, \lambda_s = 10^{-5}, \lambda_{\phi_s} = 10^{-3.5}, m_\sigma = 0.75 \text{ GeV}, \epsilon_s \equiv \nu_s / (\sqrt{2}\Lambda_s) = 0.12 \]

\[ \mathcal{L} \supset \frac{y_b}{\sqrt{2}} \left( \frac{\sigma}{\sqrt{2}\Lambda_s} \right)^2 \phi \bar{b}b \quad \text{Br}(\phi \rightarrow \bar{b}b\sigma) = 1.1\% \left( \frac{0.1}{\epsilon_s} \right)^2 \left( \frac{1 \text{ TeV}}{\Lambda_s} \right)^2 \]
Model B-1: $Q_{FN}(X) = -1/2$ - phase transition strength

Here we assume a simple polynomial scalar potential up to dimension four + the Yukawa sector.

$\Lambda_\chi = 1 \text{ TeV}, \lambda_\chi = 10^{-4}, \lambda_{\phi \chi} = 10^{-2}, m_\chi = 14 \text{ GeV}$

\[
\Gamma(\chi \to \bar{c}c) \approx 10^{-12} \text{ GeV} \left( \frac{m_\chi}{10 \text{ GeV}} \right) \left( \frac{\nu_\chi^{\text{today}}}{1 \text{ GeV}} \right)^2 \left( \frac{1 \text{ TeV}}{\Lambda_\chi} \right)^4
\]
Conclusions

The Higgs may have links to cosmology with experimentally accessible signatures.

**Yukawa variation may allow us to address:**

- The lack of a strong first order phase transition in the SM
- The insufficient CP violation for EW baryogenesis
  - Bruggisser, Konstandin, Servant (in preparation)
- The related limits on EDMs (this approach leads to a lack of EDM signals)

This offers additional motivation to consider low scale flavour models and their cosmology.

Other models of flavour are worth looking at too (not just Froggatt-Nielsen). e.g. RS1 - von Harling, Servant (in preparation)

New experimental signatures should then be accessible as we further probe the Higgs potential!
$y(\phi) = y_1 \left(1 - \left[\frac{\phi}{\nu}\right]^n\right) + y_0$ for $\phi \leq \nu$
Model A-2: Disentangled hierarchy and mixing mechanism

Couple a flavon to each mass eigenstate - Knapen, Robinson (1507.00009)

Here we assume a simple polynomial scalar potential up to dimension four augmented with a $\sigma$ dependent Yukawa term.

$$\epsilon_s \equiv \frac{\langle \sigma \rangle}{\sqrt{2}\Lambda_s}$$

$$\mathcal{L} \supset \frac{y_b}{\sqrt{2}} \left( \frac{\sigma}{\sqrt{2}\Lambda_s} \right)^2 \phi^b \bar{b} b$$
Constraints on disentangled flavour and hierarchy mechanism

$$\text{Br}(\phi \to \bar{b}b\sigma) = 1.1\% \left( \frac{0.1}{\epsilon_s} \right)^2 \left( \frac{1 \text{ TeV}}{\Lambda_s} \right)^2$$
Two FN fields

\[ \mathcal{L} = \tilde{y}_{ij} \left( \frac{S}{\Lambda_s} \right)^{\tilde{n}_{ij}} \bar{Q}_i \tilde{\Phi} U_j + y_{ij} \left( \frac{S}{\Lambda_s} \right)^{n_{ij}} \bar{Q}_i \Phi D_j \\
+ \tilde{f}_{ij} \left( \frac{X}{\Lambda_\chi} \right)^{\tilde{m}_{ij}} \bar{Q}_i \tilde{\Phi} U_j + f_{ij} \left( \frac{X}{\Lambda_\chi} \right)^{m_{ij}} \bar{Q}_i \Phi D_j \]

We assume a small VEV for the second FN field today: \( \langle X \rangle \simeq 0 \). The VEV \( \langle S \rangle \) sets the Yukawas today while \( \langle X \rangle \) varies during the EWPT.

Model B-1: \( Q_{\text{FN}}(X) = -\frac{1}{2} \)

\[ \Lambda_\chi \gtrsim 700 \text{ GeV} \ (K - \bar{K}) \]
\[ \Lambda_\chi \gtrsim 250 \text{ GeV} \ (B_s - \bar{B}_s) \]

Model B-2: \( Q_{\text{FN}}(X) = -1 \)

\[ \Lambda_\chi \gtrsim 2.5 \text{ TeV} \ (K - \bar{K}) \]
\[ \sqrt{\Lambda_\chi m_\chi} \gtrsim 500 \text{ GeV} \ (D - \bar{D}) \]
Model B-1: $Q_{FN}(X) = -1/2$ - phase transition strength

Yukawas sector

$$\mathcal{L} \supset \tilde{f}_{ij} \left( \frac{X}{\Lambda_\chi} \right)^{\tilde{m}_{ij}} \overline{Q}_i \tilde{\Phi} U_j + f_{ij} \left( \frac{X}{\Lambda_\chi} \right)^{m_{ij}} \overline{Q}_i \Phi D_j + H.c.$$