Neutrinos, Inflation & Higgs Vacuum Stability

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Archil Kobakhidze & A.F.S-S [1301.2846] & [1305.7283]

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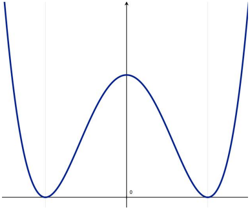
A 125 GeV Higgs Boson

- ATLAS & CMS announced the discovery of a new boson with mass $\approx 125 - 126$ GeV.
- Further measurements have shown that it's *a* Higgs boson, perhaps even *the* Higgs boson.
- Let's assume it's *the*!
- What are the implications for new physics?

Higgs Vacuum Stability Problem

- Classical SM Higgs potential in unitary gauge

$$V(h) = \frac{\lambda}{4}\left(h^2 - v_{EW}^2\right)^2 \tag{1}$$



- RG improved effective potential for h

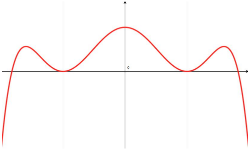
$$V_{eff}^{(1-loop)}(h) = \frac{\lambda(h)}{4}\left(h^2 - v_{EW}^2\right), \tag{2}$$

$$\lambda(h) = \lambda(\mu) + \beta_\lambda \ln\left[\frac{h}{\mu}\right], \tag{3}$$

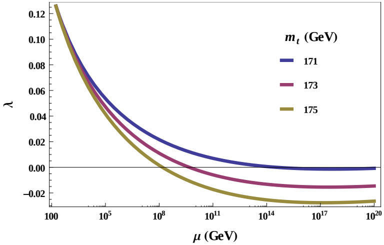
$$(4\pi)^2 \beta_\lambda \approx 24\lambda^2 - 6y_t^4 + \ldots, \tag{4}$$

$$y_t(m_t) \approx 1 \ \& \ \lambda(m_t) \approx 0.12 \tag{5}$$

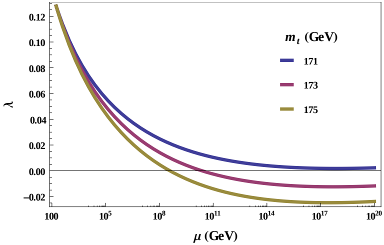
$$\Rightarrow \beta_\lambda(m_t) < 0. \tag{6}$$



Running of λ in the SM



(a) $m_h = 125$ GeV



(b) $m_h = 126$ GeV

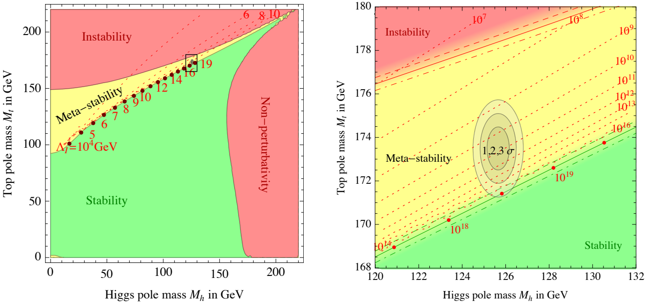
- $\lambda(\mu_I) = 0$ for $\mu_I \approx 10^{10}$ GeV.

- EW vacuum can decay to true vacuum.
- Using Coleman's prescription obtain decay probability using instanton/bounce solution to Euclidean EOM for h in $V(h)$,

$$p \approx e^{-B}, \tag{7}$$

$$B_{LW} = \frac{8\pi^2}{3|\lambda(\mu_m)|} \tag{8}$$

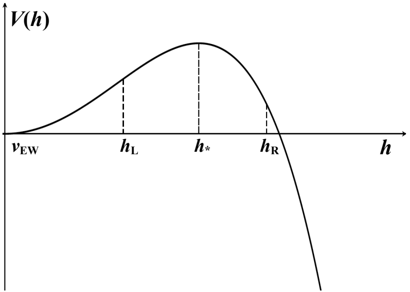
- SM EW vacuum in flat spacetime is *metastable*.



(Buttazzo et. al. [hep-ph:1307.3536])

- Taking into account cosmological history of the universe we must examine the decay rate of v_{EW} during inflation.

- In a cosmological spacetime v_{EW} can also decay via
  - Thermal activation
  - Production of large amplitude Higgs perturbations during inflation (Espinosa et. al. [hep-ph:0710.2484])
  - Instantons (Hawking-Moss or Coleman-deLuccia) (Archil Kobakhidze & A.F.S-S [hep-ph:1301.2846])



- Instantons dominate, type is model dependent:
  - Negligible inflaton-Higgs interactions: HM instanton dominates

$$B_{HM} = \frac{8\pi^2}{3}\frac{\lambda(\mu_I e^{-1/4})\mu_I^4 e}{4H_{inf}^4} \tag{9}$$

  - Sizable inflaton-Higgs interactions (fine tuning needed): CdL instanton dominates. In this case the rate of decay is exponentially enhanced and inflation ceases globally.

$$B_{\mathrm{CdL}} = -\frac{2\pi^2}{\lambda} I \,, \tag{10}$$

where

$$I = \int_0^\infty x^3 dx \left[h^2(x) \left(1 - \frac{h^2(x)}{2h_*^2} \right) \right] < 0. \tag{11}$$

with

$$h(x) = \begin{cases} 8h_{\mathrm{R}} \left(8 + \left(\frac{h_{\mathrm{R}}}{h_*}\right)^2 x^2 \right)^{-1} , & 0 \leq x < x_* \\ \frac{x_* h_*}{x(J_1(ix_*)+iY_1(-ix_*))} \left(J_1(ix) + iY_1(-ix) \right) , & x_* < x < \infty \end{cases} , \tag{12}$$

$$x_* = \frac{2\sqrt{2}h_*}{h_{\mathrm{R}}} \left(\frac{h_{\mathrm{R}}}{h_*} - 1 \right)^{1/2} . \tag{13}$$

Constraints on Models of Inflation

- Requiring that decay processes do not prevent inflation from proceeding globally we obtain, for models with negligible inflaton-Higgs interactions, the bound
$$H_{inf} < 1.7 \times 10^{9} (1 \times 10^{12}) \mathrm{GeV} \tag{14}$$
for $m_h = 126$ GeV, $m_t = 174(172)$ GeV.

- Relating the bound to CMB observables we find:
  - $\eta < 0$: Only small field models are viable/large field models ruled out
  - $r \approx 10^{-11}(10^{-5})$: The ratio of tensor to scalar perturbations in the CMB must be tiny - if Planck sees tensor perturbations then all models of inflation are ruled out, unless there is new physics beyond the SM, responsible for stabilisation of the EW vacuum.

- Argument also applies to curvaton models.

New Physics and Higgs Vacuum Stability

- Stability of EW vacuum depends on whether λ runs negative or not $\Rightarrow$ New physics before $\mu_I \approx 10^{10}$ GeV.

- Typically one works in $\overline{\text{MS}}$ and any effect on couplings arises as
  - Modification of β-functions
  - Threshold corrections to effective couplings

  at heavy particle thresholds/symmetry breaking VEVs

- Three ways to implement an extension to the SM, affecting running of λ:
  - Affect λ directly (scalars)
  - Affect the largest Yukawa couplings (fermions)
  - Embed the EW gauge group into a larger group to affect the gauge couplings (gauge groups)

Neutrinos and Higgs Vacuum Stability

- Established evidence for physics beyond the SM: Neutrino masses, Dark Matter & Dark Energy

- What can vacuum stability tell us about Neutrino masses?

- Type-I & III seesaws, add fermions, stability condition: $\lambda > 0$

- Type-I seesaw mechanism, add ν_R to the SM

- 'Typical' seesaw with $M_R \approx 10^{15}$ GeV automatically ruled out

- Need $M_R < \mu_I$ (low scale seesaw)
  - For large σ new Yukawa couplings acts like top $\Rightarrow \lambda$ runs negative quicker! $\Rightarrow$ unstable EW vacuum (Rodejohann, Zhang [hep-ph:1203.3825])
  - For smaller σ find 3.3 TeV $< M_R <$ 4.5 TeV from LFV and $(0\nu\beta\beta)$ (Chakrabortty et. al. [hep-ph:1207.2027])

- Type-III seesaw mechanism (triplet fermions) argument is similar with relaxed bounds for case of smaller σ.

- Extend scalar sector with EW triplet of scalars

$$V(\phi,\Delta) = -m_\phi^2 \phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 + m_\Delta^2 \mathrm{tr}(\Delta^\dagger\Delta) + \frac{\lambda_1}{2}(\mathrm{tr}(\Delta^\dagger\Delta))^2 + \frac{\lambda_2}{2}\left[(\mathrm{tr}(\Delta^\dagger\Delta))^2 - \mathrm{tr}(\Delta^\dagger\Delta)^2\right] + \lambda_4(\phi^\dagger\phi)\mathrm{tr}(\Delta^\dagger\Delta) + \lambda_5\phi^\dagger[\Delta^\dagger,\Delta]\phi + \left[\frac{\lambda_6}{\sqrt{2}}\phi^T i\sigma_2\Delta^\dagger\phi + \mathrm{h.c.}\right]. \quad (15)$$

- All except λ, m_ϕ are arbitrary, just need to make sure we can avoid instability and triviality from choice of boundary conditions at m_Δ
- Many stability conditions (Ahrib et. al. [hep-ph:1105.1925]):

$$\lambda > 0, \quad (16)$$

$$\lambda_1 > 0, \quad (17)$$

$$\lambda_1 + \frac{\lambda_2}{2} > 0, \quad (18)$$

$$\lambda_4 \pm \lambda_5 + 2\sqrt{\lambda\lambda_1} > 0, \quad (19)$$

$$\lambda_4 \pm \lambda_5 + 2\sqrt{\lambda\left(\lambda_1 + \frac{\lambda_2}{2}\right)} > 0. \quad (20)$$

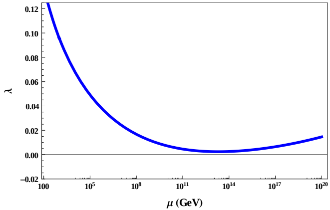
- Threshold correction:

$$\lambda_h = \lambda - \frac{\lambda_6^2}{2m_\Delta^2}. \tag{21}$$

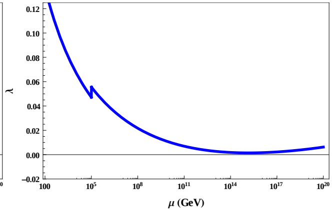
- Modification of β_λ

$$\beta_{\lambda_h}^{(1)} = \lambda_h \left(-9g_2^2 - 3g_1^2 + 12y_t^2\right) + 24\lambda_h^2 + \frac{3}{4}g_2^4 + \frac{3}{8}\left(g_1^2 + g_2^2\right)^2 - 6y_t^4 \tag{22}$$

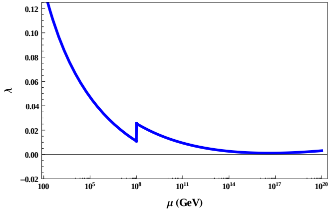
$$\rightarrow \beta_{\lambda}^{(1)} = \lambda \left(-9g_2^2 - 3g_1^2 + 12y_t^2\right) + 24\lambda^2 + \frac{3}{4}g_2^4 + \frac{3}{8}\left(g_1^2 + g_2^2\right)^2 - 6y_t^4 + 3\lambda_4^2 + 2\lambda_5^2 \tag{23}$$



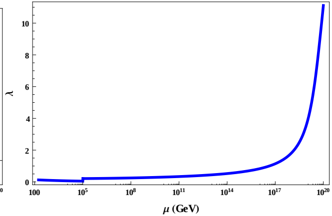
(c) $m_\Delta = 1$ TeV.



(d) $m_\Delta = 100$ TeV.



(e) $m_\Delta = 10^8$GeV.



(f) $m_\Delta = 100$ TeV.

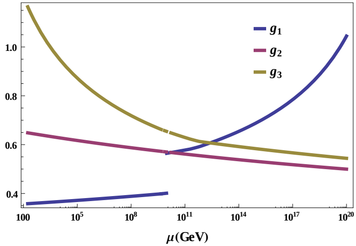
Figure: One loop running of λ in the type-II seesaw model, with $m_h = 125$ GeV and $m_t = 173$ GeV. (Archil Kobakhidze & A.F.S-S [hep-ph:1305.7283])

Left-Right Symmetric Model

- What about gauge, Yukawa *and* scalar sector effects?
- LR Symmetric model: $\mathrm{SU}(3) \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$
- Minimal scalar content: $\phi_L \in (\mathbf{1}, \mathbf{1}, \mathbf{2}, 1/2)$, $\phi_R \in (\mathbf{1}, \mathbf{2}, \mathbf{1}, 1/2)$, need vectorlike fermion F_i for each SM fermion (ALRSM (Davidson & Wali, PRL '87)).
- Scalar potential

$$V(\phi_L, \phi_R) = -m^2 \left(\phi_L^\dagger \phi_L + \phi_R^\dagger \phi_R\right) + \frac{\lambda}{2} \left(\phi_L^\dagger \phi_L + \phi_R^\dagger \phi_R\right)^2 + \sigma \phi_L^\dagger \phi_L \phi_R^\dagger \phi_R. \quad (24)$$

- Bounded from below for $\lambda > 0$ and $\sigma > -2\lambda$
- Two vacua, parity breaking for $\sigma > 0$ with $|v_R|^2 = \frac{m^2}{\lambda}$ and $v_L = 0$
- Hierarchy of scalar masses for $\sigma \ll \lambda$.
- Note: $v_L \neq 0$ radiatively and theory can be consistently matched to the SM EFT at one loop (Archil Kobakhidze & A.F.S-S [hep-ph:1305.7283])

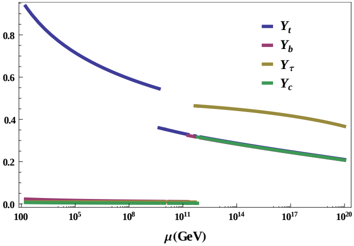


(a) Running gauge couplings with $M_T = 4.7 \times 10^9$ GeV and $m = 1 \times 10^{10}$ GeV.

- g_1 matched at v_R as

$$g_1 = \frac{g_R \; g_{B-L}}{\sqrt{g_R^2 + g_{B-L}^2}} = \frac{g_2 \; g_{B-L}}{\sqrt{g_2^2 + g_{B-L}^2}}, \tag{25}$$

- Vector-like fermions in a hierarchy to prevent a Landau pole for g_1.

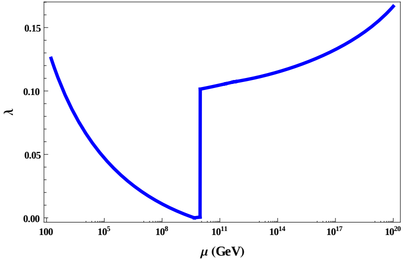


(b) Running Yukawa couplings.

- y_{F_i} matched at M_{F_i} with

$$y_{f_i} = y_{F_i}^2 \frac{v_R}{M_{F_i}}. \tag{26}$$

- Yukawas all become $\mathcal{O}(y_T)$ (universal seesaw).



(c) Running Higgs quartic coupling

Figure: Running couplings in the ALRSM with $M_T = 4.7 \times 10^9$ GeV and $m = 1 \times 10^{10}$ GeV.

- λ matched at m_R with

$$\frac{\lambda_{eff}}{8} = \frac{3y^4}{16\pi^2}\left(\frac{1}{4} - \frac{5}{8}\ln\left[\frac{M_T^2 + \frac{m^2 y_T^2}{\lambda}}{m_R^2}\right]\right) - \frac{9\lambda^2}{256\pi^2}, \qquad (27)$$

- $\lambda > 0$ can be satisfied, for $m_R \approx \mu_I$.

Conclusion

- Flat space-time analysis of Higgs vacuum stability shows EW vacuum is *metastable*
- Curved space-time analysis shows the EW vacuum is *unstable* unless the rate of inflation is low enough
- Possible Planck observation of tensor perturbations would provide a very strong hint of physics BSM
- Wide range of parameter space for (pure) type-I & type-III seesaw mechanisms excluded by consideration of EW vacuum stability
- Large range of parameter space possible for type-II seesaw
- ALRSM consistent with EW vacuum stability, demonstrates effects coming from gauge, Yukawa and scalar sectors
- Outside main line of talk, but ALRSM also exhibits some nice features:
    - Coleman-Weinberg mechanism generates VEV for Higgs radiatively
    - Universal seesaw mechanism generates Yukawa hierarchy