Stabilization of the EW vacuum by a scalar threshold effect

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joint work with J.R. Espinosa,
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Rencontres de Moriond EW 2013

Work based on collaboration with:

- J.R. Espinosa, G.F. Giudice, H.M. Lee, A. Strumia **[hep-ph/1203.0237]**

For recent related work see:

- O. Lebedev **[hep-ph/1203.0156]**
- A. H. Chamseddine, A. Connes **[hep-ph/1208.1030]**
- M. Gonderinger, H. Lim, M. Ramsey-Musolf **[1202.1316]**
- ...

The scalar sector of the SM

It is the part of the theory from which we have less experimental information.

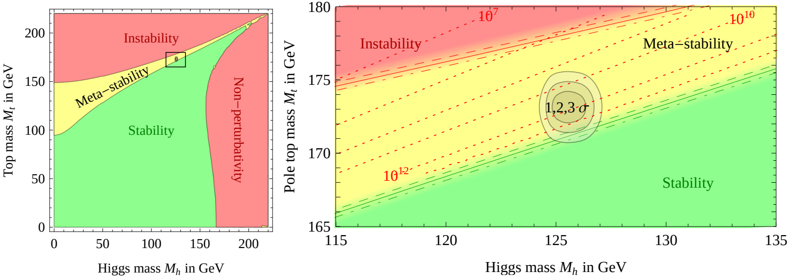
Interestingly, most of the theoretical problems of the SM arise from the scalar sector.

In the previous talk we saw that...

A Standard Model Scalar (SMS) (also called Higgs) mass of ~ 125 GeV is a very special value:

Assume the SM up to very high energies,
is it a consistent model?

Assume the SM up to very high energies, is it a consistent model? **Yes**



G.Degrassi, S. Di Vita, J.EM, J. Espinosa, G.F. Giudice, G. Isidori, A. Strumia. [hep-ph/1205.6497]

Instability of the SM effective potential is not necessarily a problem

- The SM is likely[1] to be embedded in a more fundamental theory not far from the $\sim TeV$ scale.
- And, is not "very unstable", i.e. it is sufficiently long lived. (Age universe)/(Lifetime universe) $\sim 10^{-90\pm10}$

[1] Although it is scary that, for the first time in particle physics, all the degrees of freedom found in collider searches are described by a dimension 4 Lagrangian which is consistently extrapolated up to very high energies.

However...

- It can be desirable to cure the Higgs instability at large field values
  1. to avoid cosmological constraints
  2. extreme high energy SUSY should be below the instability scale.
  3. avoid coinstraints from see-saw.
  4. Higgs inflation should be matched before the instability.
  5. ...
- We would like to understand how the EW vacuum could be stabilized in different extensions of the SM.

There are a lot of *ad-hoc* possibilities to modify the Higgs potential and increase the instability scale Λ_I.

Purpose of the talk:

- Review a simple and robust mechanism to stabilize the EW vacuum.
- Put the mechanism into context, examples of new physics scenarios where the mechanism could be naturally at work:
  1. see-saw neutrinos,
  2. invisible axion,
  3. unitarized Higgs inflation.

JEM, J.R. Espinosa, G.F. Giudice, H.M. Lee, A. Strumia. 1203.0237 [hep-ph]

The mechanism

Consider a simple extension of the SM with a singlet. The Higgs potential is[2]

$$V_0 = \lambda_H \left(H^\dagger H - v^2/2\right)^2 + \lambda_S \left(S^\dagger S - w^2/2\right)^2 + \\ +2\lambda_{HS} \left(H^\dagger H - v^2/2\right)\left(S^\dagger S - w^2/2\right) \quad . \tag{1}$$

[2] Most general potential with the field S charged under a $U(1)$. The analysis is easily extended to multi-Higgs doublets or real singlets.

For $\lambda_H, \lambda_S > 0$ and $\lambda_{HS}^2 < \lambda_H \lambda_S$, the minimum of V_0 is at

$$\langle H^\dagger H \rangle = v^2/2 \,, \quad \langle S^\dagger S \rangle = w^2/2 \,. \tag{2}$$

At the minimum, the mass matrix is:

$$\mathcal{M}^2 = 2 \begin{pmatrix} \lambda_H v^2 & \lambda_{HS} v w \\ \lambda_{HS} v w & \lambda_S w^2 \end{pmatrix} \; ; \tag{3}$$

its eigenvalues are:

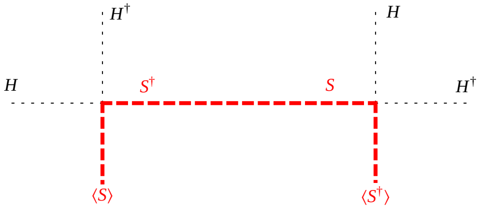
$$\begin{aligned} m_h^2 &= 2v^2 \left(\lambda_H - \frac{\lambda_{HS}^2}{\lambda_S} \right) + \mathcal{O}\left(\frac{v^4}{w^2} \right) , \\ M_s^2 &= 2\lambda_S w^2 + 2(\lambda_{HS}^2/\lambda_S) v^2 + \mathcal{O}\left(\frac{v^4}{w^2} \right) \; . \end{aligned} \tag{4}$$

Supose $w^2 >> v^2$, then...

The effective potential below the scale M_S:

$$V_{\text{eff}} = \lambda \left(H^\dagger H - \frac{v^2}{2} \right)^2 , \quad \lambda = \lambda_H - \frac{\lambda_{HS}^2}{\lambda_S} . \tag{5}$$

The matching condition at the scale $Q = M_S$ gives a tree-level shift, $\delta\lambda \equiv \lambda_{HS}^2/\lambda_S$.



Stability conditions below M_s

So, below the high scale M_S we recover the SM Higgs potential.

$$V_{\text{eff}} = \lambda \left(H^\dagger H - \frac{v^2}{2} \right)^2 . \tag{6}$$

Therefore, the stability condition below M_S is simply $\lambda > 0$.

Stability conditions above M_s

Recall that

$$V_0 = \lambda_H \left(H^\dagger H - v^2/2\right)^2 + \lambda_S \left(S^\dagger S - w^2/2\right)^2 + \\ +2\lambda_{HS} \left(H^\dagger H - v^2/2\right)\left(S^\dagger S - w^2/2\right) \; . \qquad (7)$$

Hence, the stability conditions are:

- First two obvious conditions $\lambda_H > 0$ and $\lambda_S > 0$.
- Then, we can distinguish two cases $\lambda_{HS} > 0$ and $\lambda_{HS} < 0$. Notice that $\beta_{\lambda_{HS}} \sim \lambda_{HS} \times (...)$.

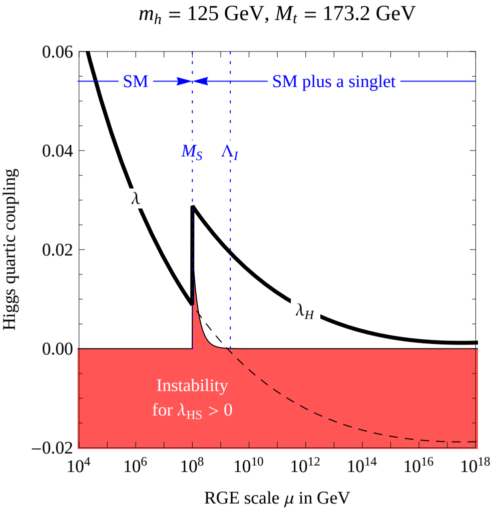
1.- $\boldsymbol{\lambda_{HS} > 0}$:

V_0 can become negative only for $|S| < w/\sqrt{2}$.
The stability condition is

$$\frac{\lambda_{HS}^2(\mu)}{\lambda_S(\mu)} < \lambda_H(\mu) \ . \tag{8}$$

recall that $m_h^2 = 2v^2 \left(\lambda_H - \frac{\lambda_{HS}^2}{\lambda_S}\right) + \mathcal{O}\left(\frac{v^4}{w^2}\right)$

$\lambda_{HS} > 0$



J.EM, J.R.Espinosa, G.F. Giudice, H.M.Lee, A. Strumia. [hep-ph/1203.0237]

2.- $\boldsymbol{\lambda_{HS} < 0}$:

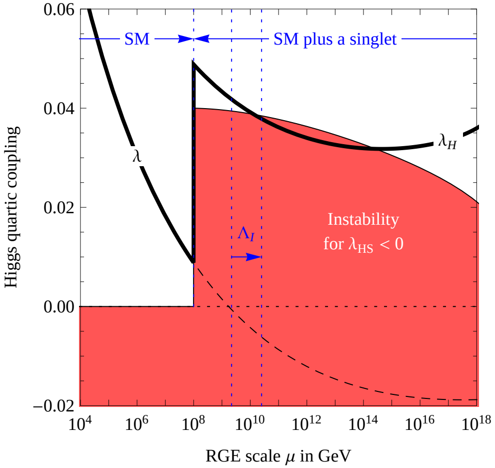
Now, V_0 can become negative only for $|S| > w/\sqrt{2}$.
The stability condition is:

$$-\lambda_{HS}(\mu) < \sqrt{\lambda_H(\mu)\lambda_S(\mu)}\ , \tag{9}$$

which have to be fullfilled for large field values.

$\lambda_{HS} < 0$

$m_h = 125$ GeV, $M_t = 173.2$ GeV



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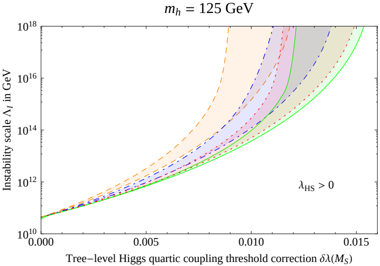
Shift of the instability scale

A numerical study exhibits the features of the detailed analysis performed above:

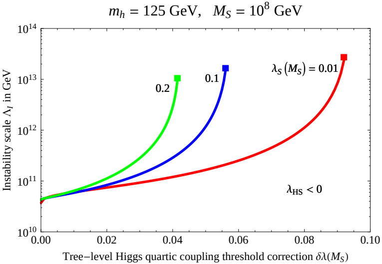
$(\delta\lambda = \frac{\lambda_{HS}^2}{\lambda_S})$

$\lambda_{HS} > 0$



Bands correspond to
$M_S = 10^4,\ 10^6,\ 10^8,\ 10^{10}$ GeV.

$\lambda_{HS} < 0$



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See-saw neutrino masses

Possible role of the singlet: gives mass to the right-handed neutrino ($RH\nu$) of the See-saw mechanism.

$$\mathcal{L}_N = i\bar{N}\gamma^\mu\partial_\mu N + y_\nu LNH + \frac{M_N}{2}N^2 + h.c. \;, \tag{10}$$

After EW symmetry breaking, nonzero neutrino masses are generated

$$m_\nu = \frac{y_\nu^2 v^2}{M_N} \;, \tag{11}$$

which are naturally small provided $M_N \gg v$.

The vev of S sets the scale of the Majorana mass $M_N = \kappa\langle S\rangle$.

$$\frac{\kappa}{2}\, S\, N^2 + \mathrm{h.c.} \tag{12}$$

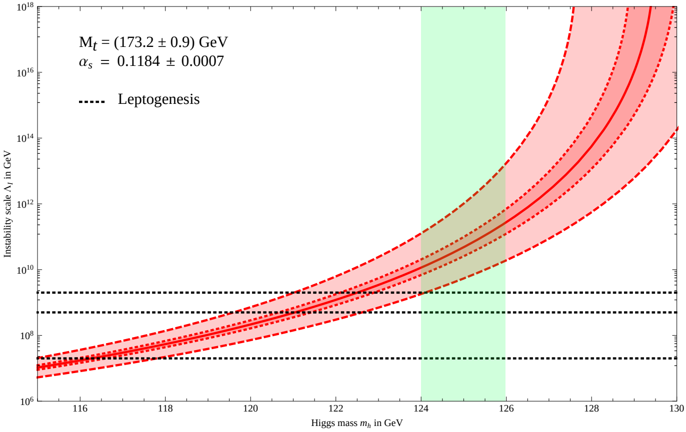
Assuming thermal leptogenesis (and non-degenerate RH neutrinos) the following bounds can be obtained:

- $M_1 > 2 \times 10^9$ GeV, $RH\nu$ initial density vanishes at high temperature.
- $M_1 > 5 \times 10^8$ GeV, $RH\nu$ initial density is thermal at high temperature.
- $M_1 > 2 \times 10^7$ GeV, $RH\nu$ initial density dominates the universe at high temperature.

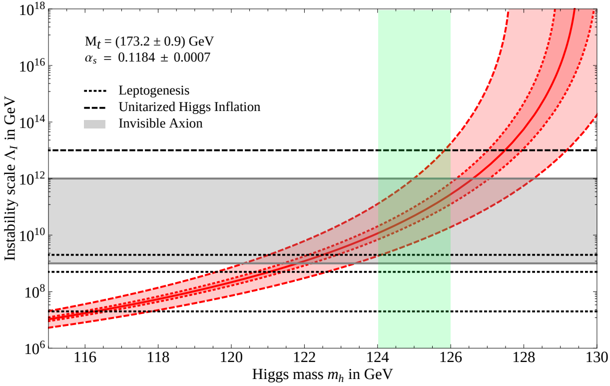
S. Davidson, A. Ibarra [hep-ph/0202239]

G.F. GIudice, A. Notari, M.Raidal, A.Strumia [hep-ph/0310123]

Mass scale of the singlet field S superimposed in an electroweak stability plot of the Standard Model.



You can find other examples of BSM physics where the singlet nicely fits in [hep-ph/1203.0237]



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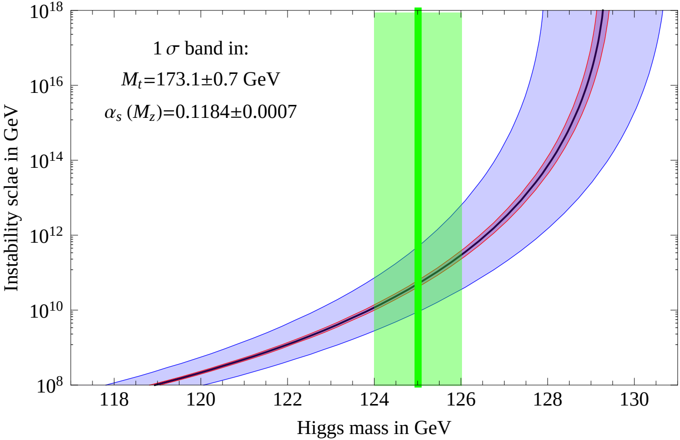
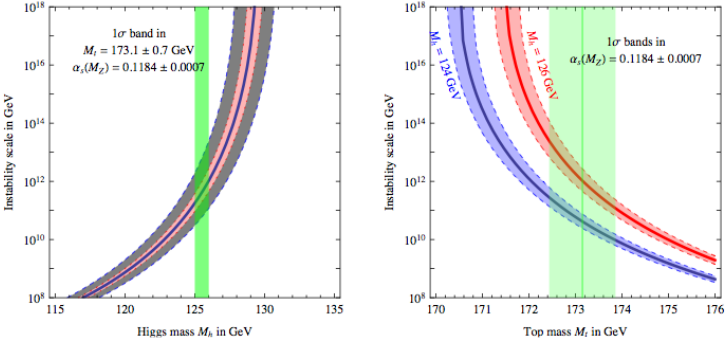
Conclusions

- The EW minimum of the SM is unstable, but very long lived. (within the current preferred experimental values of M_H, M_t and α_s)
- We have proposed a **simple**, **robust** and **efficient** mechanism that cures its potential instability problems:
  1. **simple**, it is based on an economical (possibly single field) extension of the SM scalar sector.
  2. **robust** and **efficient**, it is based on a tree-level threshold effect. The effect does not decouple, it is independent of the scalar singlet mass. And it can be easily large.
- We have seen that the presented mechanism could be naturally operative in extensions of the SM, which have motivations different than the instability of the EW vacuum.

Thanks for your attention!

$$
\begin{aligned}
(4\pi)^2 \frac{d\lambda_H}{d\ln\mu} &= \left(12y_t^2 - 3g'^2 - 9g^2\right)\lambda_H - 6y_t^4 \\
&\quad + \frac{3}{8}\left[2g^4 + (g'^2 + g^2)^2\right] + 24\lambda_H^2 + 4\lambda_{HS}^2 \ , \\
(4\pi)^2 \frac{d\lambda_{HS}}{d\ln\mu} &= \lambda_{HS}[\frac{1}{2}\left(12y_t^2 - 3g'^2 - 9g^2\right) \\
&\quad + 4\left(3\lambda_H + 2\lambda_S\right) + 8\lambda_{HS}] \ , \\
(4\pi)^2 \frac{d\lambda_S}{d\ln\mu} &= 8\lambda_{HS}^2 + 20\lambda_S^2 \ .
\end{aligned}
\tag{13}
$$


1 σ band in:
M_t=173.1±0.7 GeV
α_s (M_z)=0.1184±0.0007
Instability sclae in GeV
10^{18}
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
118
120
122
124
126
128
130
Higgs mass in GeV



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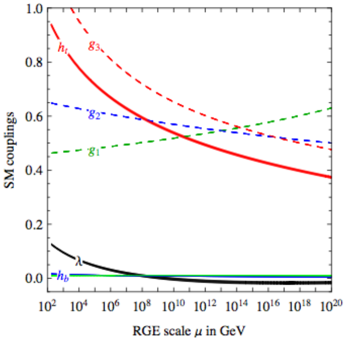

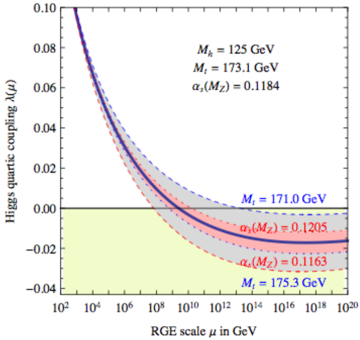

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