Stability of the Electroweak Vacuum and New Physics

Vincenzo Branchina

University of Catania and INFN, Italy

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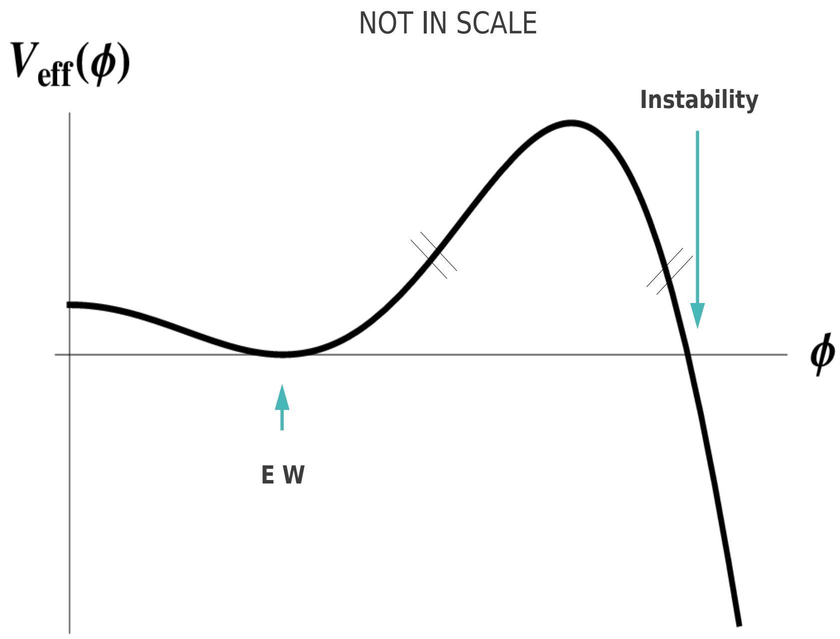
Heidelberg, November 24, 2014

Top loop-corrections to the Higgs Effective Potential

destabilize the electroweak vacuum...



Some References on Stability/Instability...far from being exhaustive

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J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori, A. Riotto, A. Strumia, Phys.Lett. **B709** (2012) 222-228

G. Degrassi, S. Di Vita, J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G.Isidori, A. Strumia, JHEP **1208** (2012) 098.

Discovery of the Higgs boson : $M_H = 125 - 126$ GeV

Experimental data consistent with Standard Model predictions

No sign of new physics

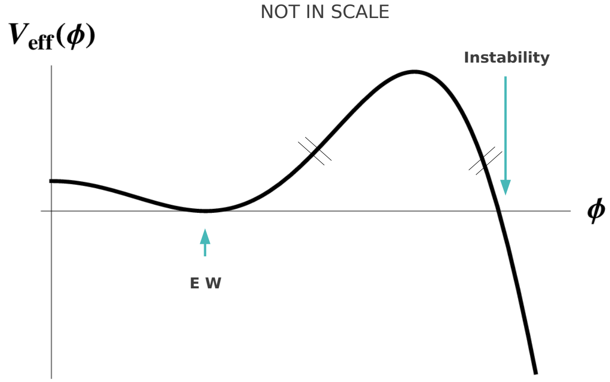
Boost new interest and work on these earlier speculations

Possibility for new phyiscs to show up only at very high energies

Possible scenario: new physics only appears at M_P

Where do these ideas come from?

Higgs One-Loop Effective Potential $V^{1l}(\phi)$

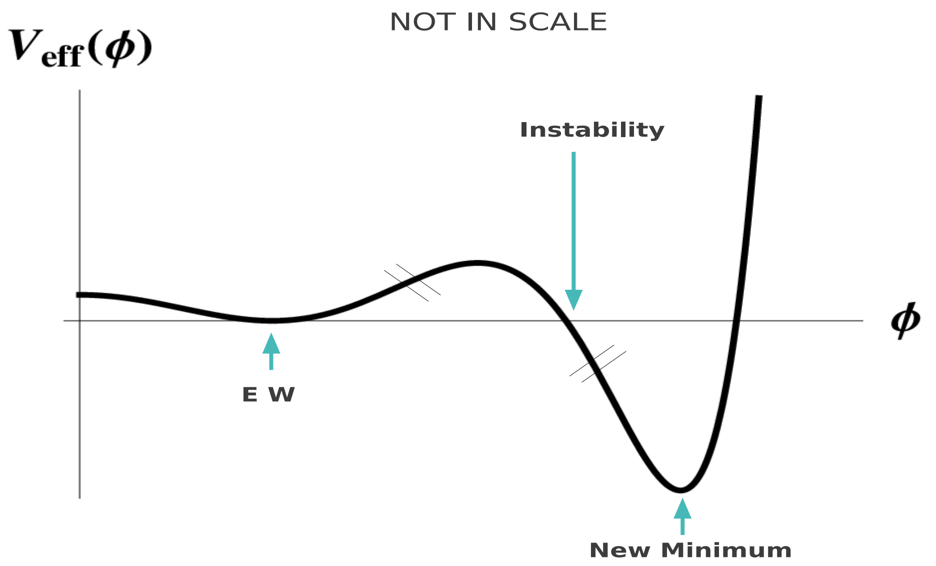


$$V^{1l}(\phi) = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{24}\phi^4 + \frac{1}{64\pi^2}\left[\left(m^2 + \frac{\lambda}{2}\phi^2\right)^2 \left(\ln\left(\frac{m^2 + \frac{\lambda}{2}\phi^2}{\mu^2}\right) - \frac{3}{2}\right)\right.$$

$$+3\left(m^2 + \frac{\lambda}{6}\phi^2\right)^2 \left(\ln\left(\frac{m^2 + \frac{\lambda}{6}\phi^2}{\mu^2}\right) - \frac{3}{2}\right) + 6\,\frac{{g_1}^4}{16}\phi^4 \left(\ln\left(\frac{\frac{1}{4}{g_1}^2\phi^2}{\mu^2}\right) - \frac{5}{6}\right)$$

$$\left. +3\,\frac{\left({g_1}^2 + {g_2}^2\right)^2}{16}\phi^4 \left(\ln\left(\frac{\frac{1}{4}\left({g_1}^2 + {g_2}^2\right)\phi^2}{\mu^2}\right) - \frac{5}{6}\right) - 12\,h_t^4\phi^4\left(\ln\frac{g^2\phi^2}{\mu^2} - \frac{3}{2}\right)\right]$$

RG Improved Effective Potential $V_{RGI}(\phi)$



Depending on M_H and M_t, the second minimum can be : (1) lower than the EW minimum (as in the figure) ; (2) at the same level of the EW minimum ; (3) higher than the EW minimum.

Note : $V_{RGI}(\phi)$ is obtained by considering SM interactions only

Note : the instability occurs for large values of the field

$\Rightarrow$ $V_{_{RGI}}(\phi)$ **well approximated by keeping only the quartic term :**

$$V_{_{RGI}}(\phi) \sim \frac{\lambda_{eff}(\phi)}{24}\phi^4$$

and $\lambda_{eff}(\phi)$ **depends on** ϕ **essentially as** $\lambda(\mu)$ **depends on** μ

$\Rightarrow$ **we can read the Effective Potential from the** $\lambda(\mu)$ **flow**

.... and explore the possibility that ....

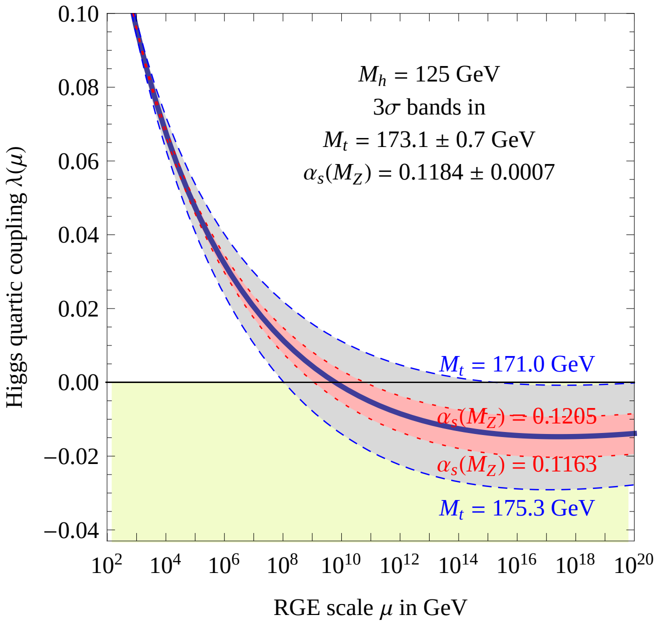
.... SM valid up to very high scales... Planck scale ???

... clearly ignoring the Naturalness Problem !!! ...

(... however: interesting connections with the Naturalness problem ...)

Running of $\lambda(\mu)$ in the SM

From: Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia, JHEP 1208 (2012) 098.



Blue thick line : $M_H = 125\,GeV$, $m_t = 173.1\,GeV$; $\lambda(\mu) = 0$ for $\mu \sim 10^{10}\,GeV$

Summary up to now

For large values of ϕ $\quad V_{RGI}^{Higgs}(\phi) \simeq \frac{\lambda_{eff}(\phi)}{24}\phi^4$

at the same time $\quad \lambda_{eff}(\phi) \sim \lambda(\mu)$

$\Rightarrow$ **We are interested in the running of $\lambda(\mu)$**

more precisely in the running of all of the SM couplings (coupled RG equations)

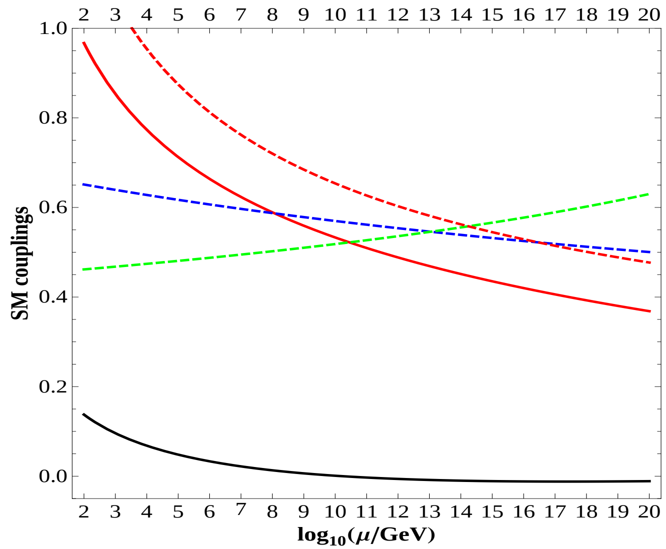
...and this is what people does...

...solving the RG equations for the SM couplings...

$$
\begin{aligned}
\mu \frac{d}{d\mu} \lambda(\mu) &= \beta_\lambda \left(\lambda, h_t, \{g_i\}\right) \\
\mu \frac{d}{d\mu} h_t(\mu) &= \beta_{h_t} \left(\lambda, h_t, \{g_i\}\right) \\
\mu \frac{d}{d\mu} g_i(\mu) &= \beta_{g_i} \left(\lambda, h_t, \{g_i\}\right)
\end{aligned}
$$

with $i = 1, 2, 3$ and $g_i = \{g', g, g_s\}$

Running of the SM couplings

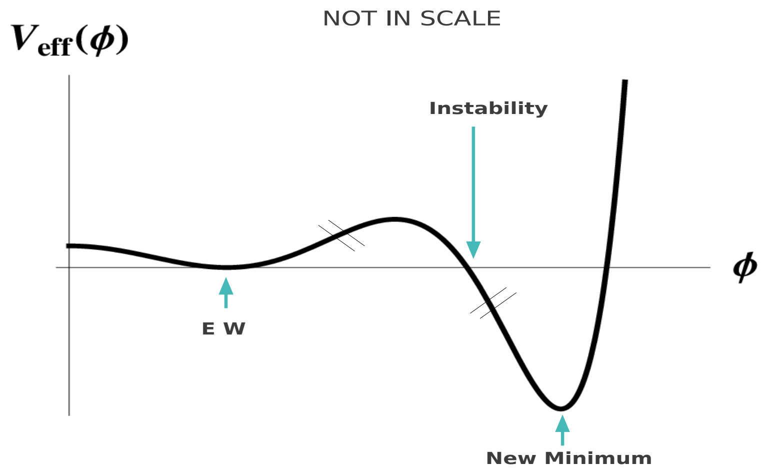


$M_t = 173.1\, GeV$, $M_H = 125\, GeV$, $M_Z = 91.45\, GeV$, $\lambda(M_t) = 4.53$,
$h_t(M_t) = 0.936$, $g'(M_Z) = 0.652$, $\sqrt{5/3}g(M_Z) = 0.46$, $g_s(M_Z) = 1.22$.

$\lambda(\mu)$ (black line), $h_t(\mu)$ (red, solid line), $g'(\mu)$ (blue line), $g(\mu)$ (greenline) $g_s(\mu)$ (red, dashed line).

Then we have all the ingredients

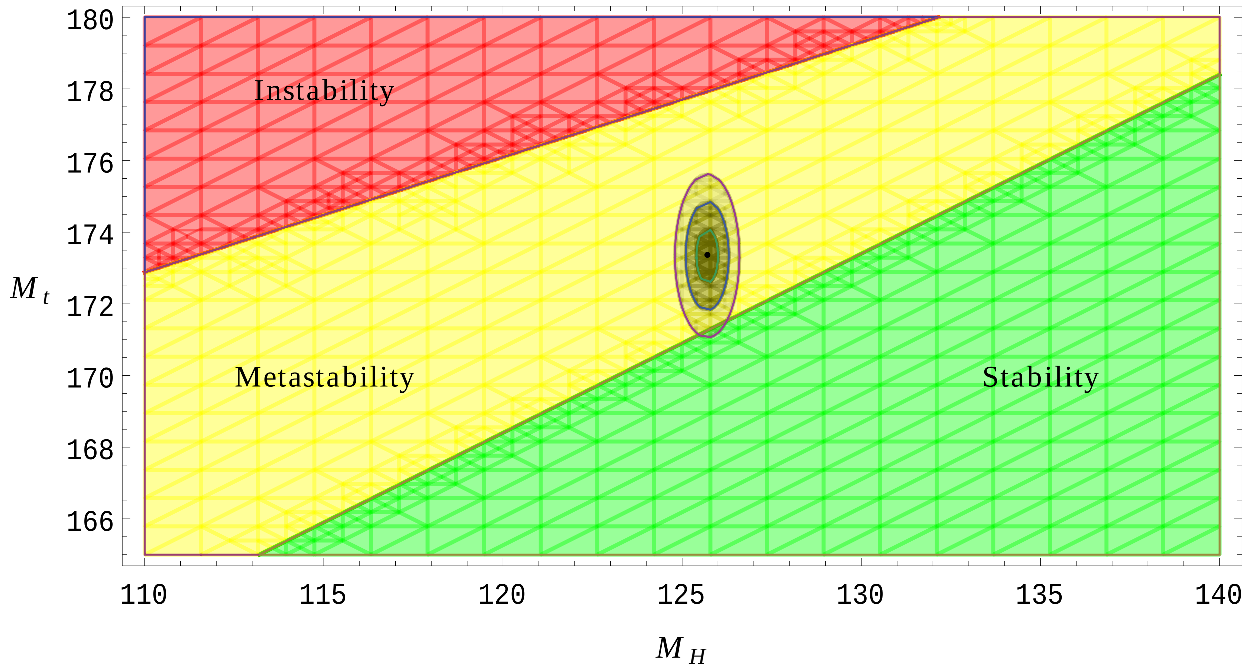
...to cook up the RGI Higgs effective potential $V_{RGI}(\phi)$...



As already pointed out, depending on M_H and M_t, the second minimum can be : (1) lower (as in figure), (2) at the same level, or (3) higher than the EW minimum. If the New Minimum is lower than the EW minimum, the latter is a false vacuum... and we have to consider its lifetime τ ...

... we can then draw the stability diagram $\Rightarrow$

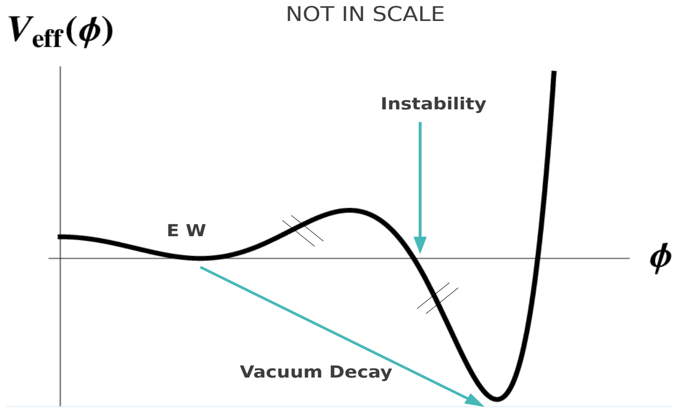
Stability Diagram in the $M_H - M_t$ plane



Stability region : $V_{eff}(v) < V_{eff}(\phi^{(2)}_{min})$. **Meta-stability** region : $\tau > T_U$. **Instability** region : $\tau < T_U$. Stability line : $V_{eff}(v) = V_{eff}(\phi^{(2)}_{min})$. Instability line : M_H and M_t such that $\tau = T_U$.

Metastability Scenario

If second minimum lower than EW



Tunnelling between the Metastable EW Vacuum and the True Vacuum.

As long as EW vacuum lifetime larger than the age of the Universe ...

.... we may well live in the Meta-Stable (EW) Vacuum ....

How do we compute the tunneling time ?

How do we compute the tunneling time ?

EW vacuum lifetime (= Tunneling Time τ)

$$\Gamma = \frac{1}{\tau} = T_U^3 \frac{S[\phi_b]^2}{4\pi^2} \left| \frac{\det' \left[-\partial^2 + V''(\phi_b)\right]}{\det\left[-\partial^2 + V''(v)\right]} \right|^{-1/2} e^{-S[\phi_b]}$$

$\phi_b(r)$ **:** **Bounce Solution**

Solution to the Euclidean Equation of Motion with appropriate boundary conditions

S. Coleman, Phys. Rev. D 15 (1977) 2929

C.G.Callan, S.Coleman, Phys. Rev. D 16 (1977) 1762

Tunneling and bounces

Bounce : solution to Euclidean equations of motion

$$-\partial_\mu\partial_\mu\phi + \frac{d\,V(\phi)}{d\,\phi} = -\frac{d^2\phi}{dr^2} - \frac{3}{r}\frac{d\phi}{dr} + \frac{d\,V(\phi)}{d\,\phi} = 0 \ ,$$

Boundary conditions : $\phi'(0) = 0 \ , \qquad \phi(\infty) = v \to 0 \ .$

Potential : $V(\phi) = \frac{\lambda}{4}\phi^4$

with negative λ

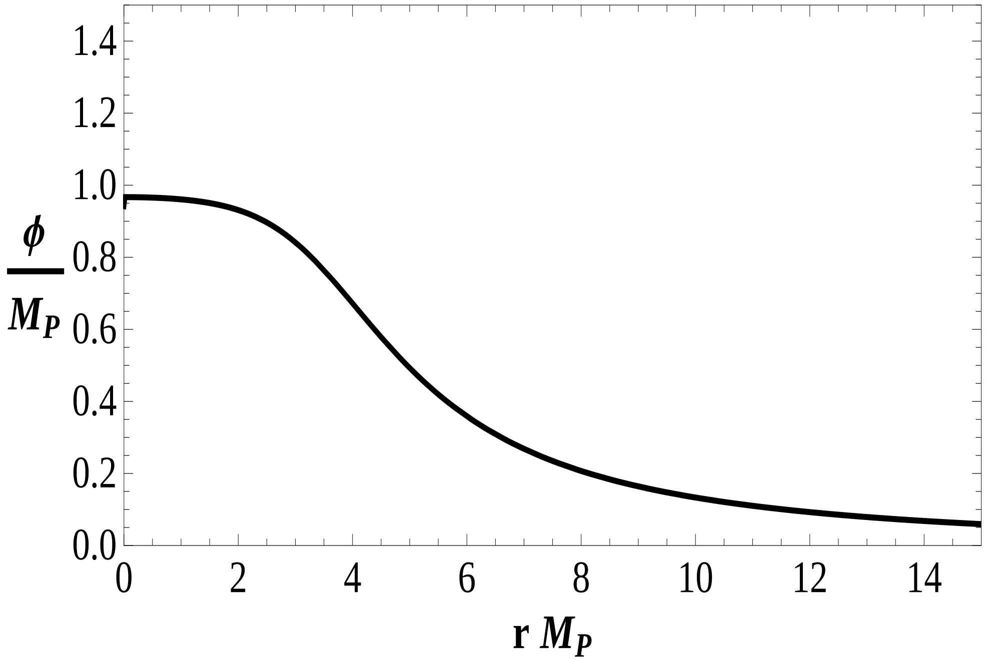
Bounce solutions :

$$\phi_b(r) = \sqrt{\frac{2}{|\lambda|}}\frac{2R}{r^2 + R^2}$$

R **is the size of the bounce**

Bounces : $$\phi_b(r) = \sqrt{\frac{2}{|\lambda|}}\frac{2R}{r^2+R^2}$$

$R =$ **bounce size** – **Classical degeneracy :** $\quad S[\phi_b] = \frac{8\pi^2}{3|\lambda|}$

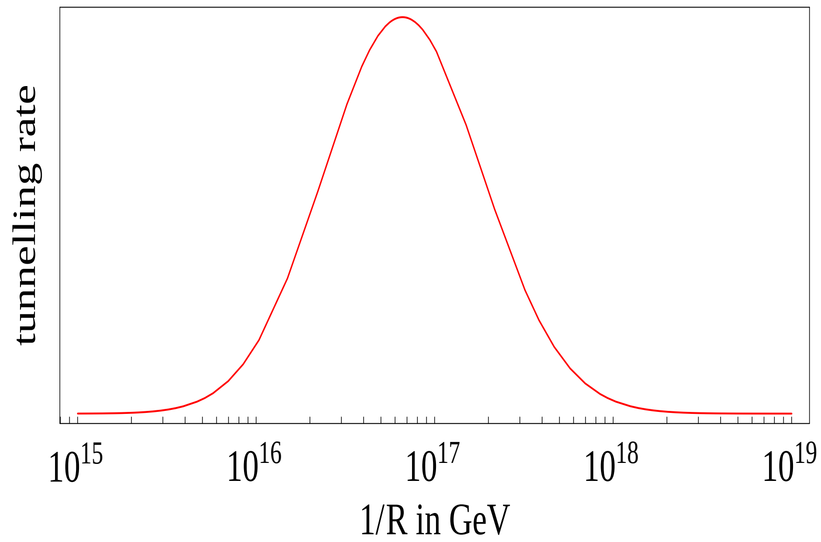


Degeneracy removed at the Quantum Level

Degeneracy removed at the Quantum Level

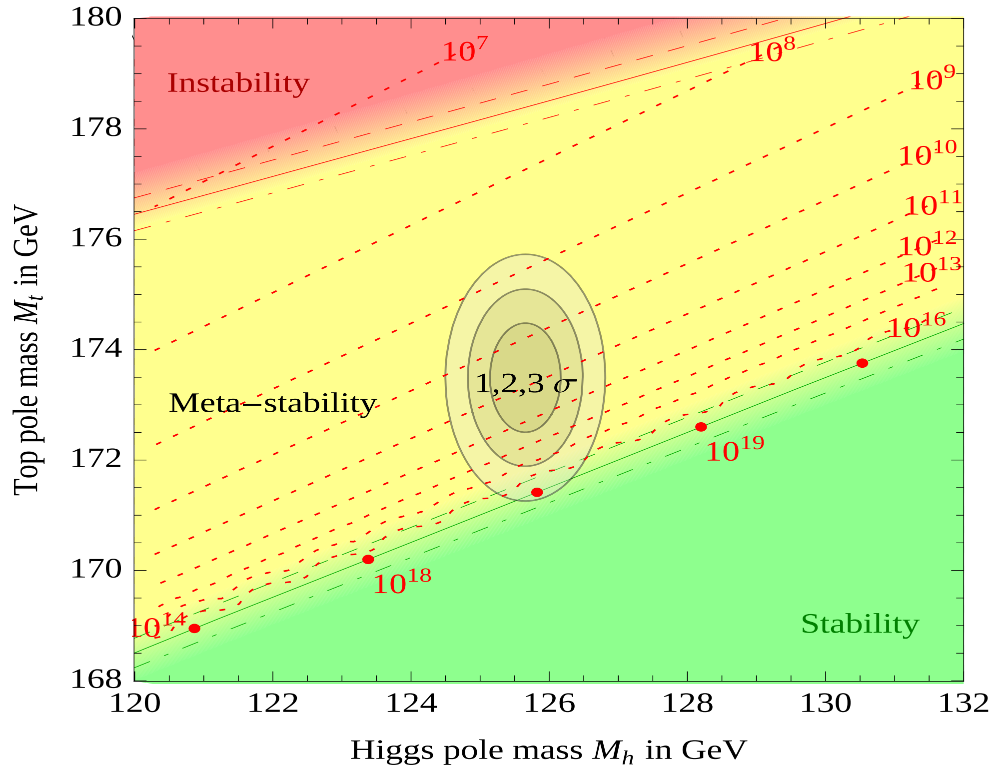
Transition rate as a function of R : ($\mu \sim \frac{1}{R}$)

$$p = \max_R \frac{V_U}{R^4} \exp\left[-\frac{8\pi^2}{3\,|\lambda(\mu)|} - \Delta S\right]$$



from : G. Isidori, G. Ridolfi, A. Strumia, Nucl.Phys.B 609 (2001) 387

With this Heavy Artilery ⇒ Stability Diagram



Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia, JHEP 1312 (2013) 089.

Summary up to now

The scenario that we are considering is the following:

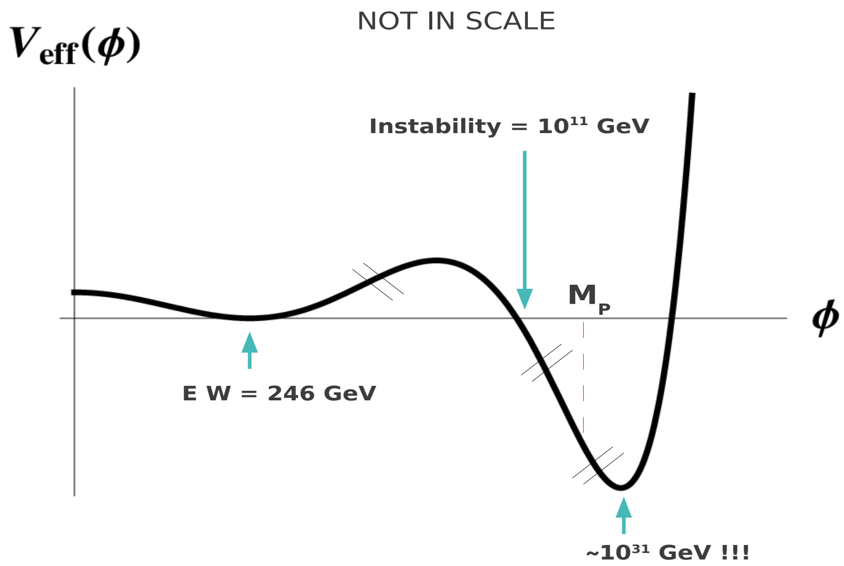
New Physics shows up only at the Planck scale

Within this scenario we study the stability of the EW vacuum

... Perfectly legitimate scenario to explore ...

..... However .....

Probably worth to know : $M_H \sim 126$ **GeV and** $M_t \sim 173$ **GeV**



New minimum at $\phi^{(2)}_{min} \sim 10^{30}$ **GeV !!!!**

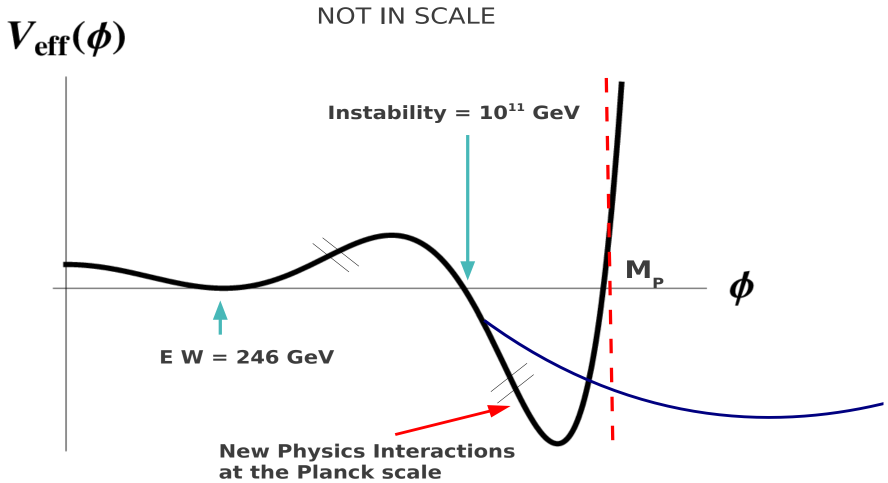
SM Effective Potential extrapolated well above M_P **!!!**

(you normally hear : assume SM valid up to M_P**)**

Does it make any sense ??? Is this a problem or not ???

To make sense out of this potential, people have some arguments ...

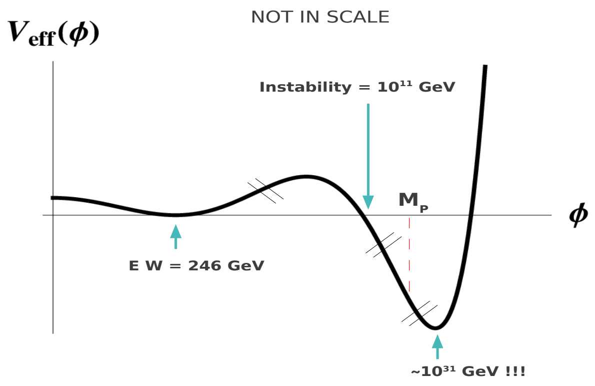
1. New Physics Interactions that appear at the Planck scale M_P eventually stabilize the potential around M_P



2. These New Physics Interactions present at the Planck scale do not affect the EW vacuum lifetime τ (can be neglected when computing τ)

(a) - Instability scale much lower than Planck scale $\Rightarrow$ suppression $(\frac{\Lambda_{inst}}{M_P})^n$

(b) - For tunnelling, only height of the barrier and turning points matter



Example of point 1 : "The SM potential is eventually stabilized by unknown new physics around M_P"

from : G. Isidori, G. Ridolfi, A. Strumia, "On the metastability of the standard model vacuum", Nucl.Phys. B609 (2001) 387.

Example of point 2 (Instability scale much lower than Planck scale $\Rightarrow$ suppression $(\frac{\Lambda_{inst}}{M_P})^n$) : "the instability scale is sufficiently smaller than the Planck mass, justifying the hypothesis of neglecting effects from unknown Planckian physics."

from: J.R. Espinosa, G.F. Giudice, A. Riotto, JCAP 0805 (2008) 002

Let us consider New Physics at M_P

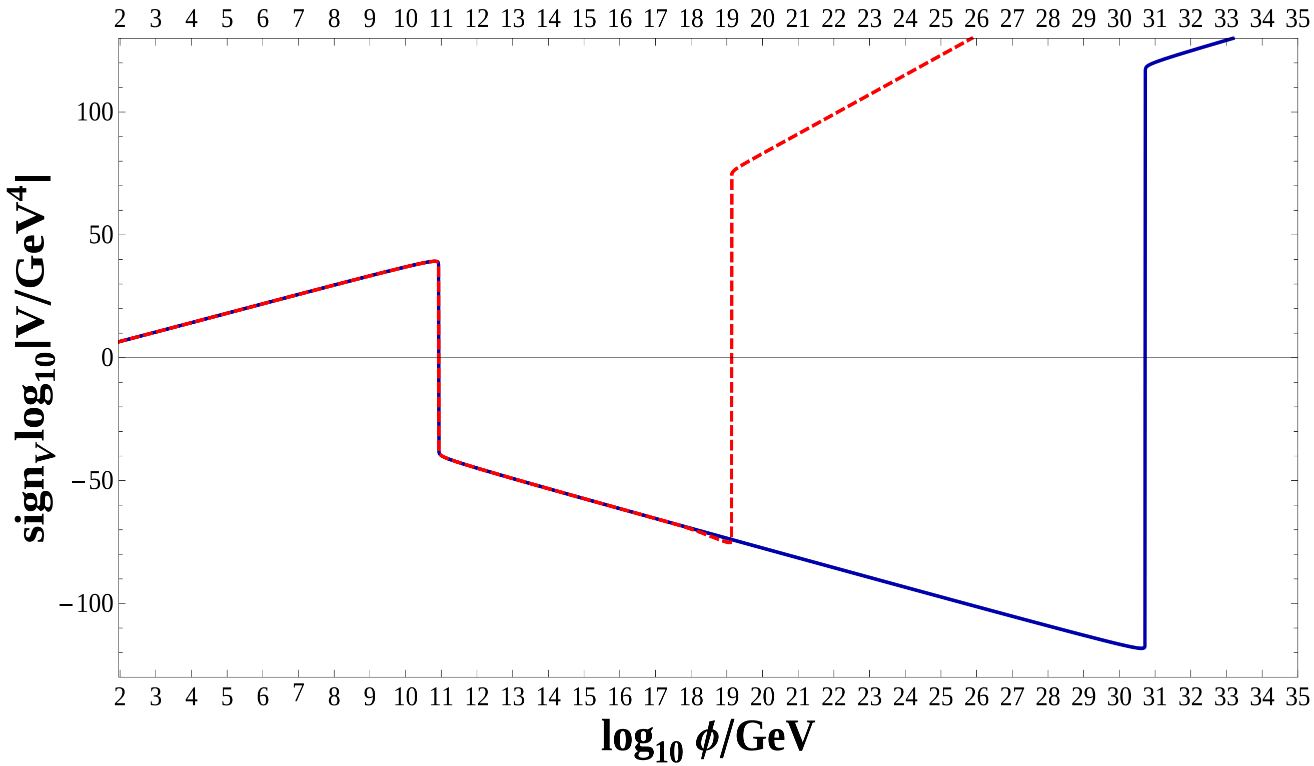
Add, for instance, ϕ^6 and ϕ^8 to the SM Higgs potential:

$$V(\phi) \;=\; \frac{\lambda}{4}\phi^4 + \frac{\lambda_6}{6}\frac{\phi^6}{M_P^2} + \frac{\lambda_8}{8}\frac{\phi^8}{M_P^4}$$

Higgs Effective Potential modified :

$$V_{eff}^{new}(\phi) = V_{eff}(\phi) + \frac{\lambda_6(\phi)}{6M_P^2}\xi(\phi)^6\phi^6 + \frac{\lambda_8(\phi)}{8M_P^4}\xi(\phi)^8\phi^8$$

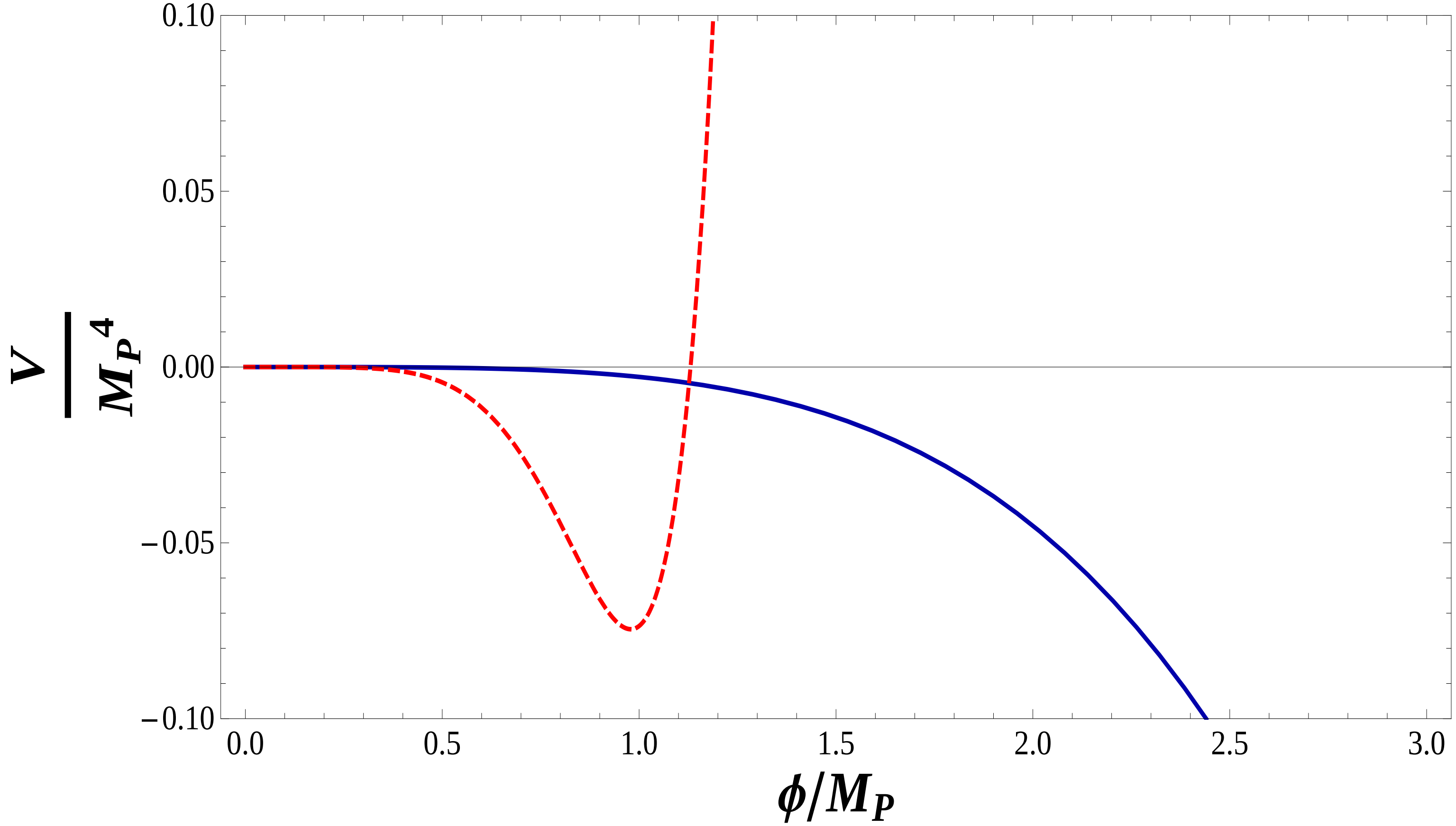
Effective Potential $M_H \sim 126$ $M_t \sim 173$ Log-Log Plot



Blue line : $V_{eff}(\phi)$ **no higher order terms**

Red line : $V_{eff}^{new}(\phi)$ **with** $\lambda_6(M_P) = -2$ $\lambda_8(M_P) = 2.1$

Zoom around the Planck scale



Blue line : $V_{eff}(\phi)$ **no higher order terms**

Red line : $V_{eff}^{new}(\phi)$ **with** $\lambda_6(M_P) = -2$ $\lambda_8(M_P) = 2.1$

We have a New Potential $\Rightarrow$ we have to consider new bounce configurations for the computation of the tunnelling time

$$V(\phi) = \frac{\lambda}{4}\phi^4 + \frac{\lambda_6}{6}\frac{\phi^6}{M_P^2} + \frac{\lambda_8}{8}\frac{\phi^8}{M_P^4}$$

In the computation of the EW vacuum lifetime :

Competition between

Old Bounce $\phi_b^{(Old)}(r)$ **and the New Bounce** $\phi_b^{(New)}(r)$

New Physics not included : Only $\phi_b^{(old)}$ **(Literature case)**

$$\Gamma = \frac{1}{\tau} = \frac{1}{T_U}\left[\frac{S[\phi_b^{(old)}]^2}{4\pi^2}\,\frac{T_U^4}{R_M^4}\,e^{-S[\phi_b^{(old)}]}\right] \times \left[e^{-\Delta S_1}\right]$$

New Physics included : $\phi_b^{(new)}$ and $\phi_b^{(old)}$ **(Our case)**

$$\Gamma = \Gamma_1 + \Gamma_2 = \frac{1}{\tau_1} + \frac{1}{\tau_2} \;=\; \frac{1}{T_U}\left[\frac{S[\phi_b^{(old)}]^2}{4\pi^2}\,\frac{T_U^4}{R_M^4}\,e^{-S[\phi_b^{(old)}]}\right] \times \left[e^{-\Delta S_1}\right]$$

$$+\;\frac{1}{T_U}\left[\frac{S[\phi_b^{(new)}]^2}{4\pi^2}\,\frac{T_U^4}{\overline{R}^4}\,e^{-S[\phi_b^{(new)}]}\right] \times \left[e^{-\Delta S_2}\right]$$

Neglecting for a moment the ΔS (quantum) contributions

Literature : $S[\phi_b^{(old)}] \sim 1833 \Rightarrow \quad \tau \sim 10^{555}\, T_U$

Our case : $S[\phi_b^{(new)}] \sim 82 \quad \Rightarrow \quad \tau \sim 10^{-208}\, T_U$

Contribution from $\phi_b^{(old)}$ exponentially suppressed !

New Physics Interactions at the Planck scale do matter !!!

Quantum fluctuations do not change significantly these "classical" results

	Literature : Loop contributions to τ
$e^{\Delta S_H}$	2.87185
$e^{\Delta S_t}$	1.20708×10^{-18}
$e^{\Delta S_{gg}}$	1.26746×10^{50}

$$\Rightarrow \qquad \tau_{cl} \sim 10^{555}\, T_U \quad \longrightarrow \quad \tau \sim 10^{588}\, T_U$$

	Our case : Loop contributions to τ
$e^{\Delta S_H}$	2.82295×10^{10}
$e^{\Delta S_t}$	8.62404×10^{-5}
$e^{\Delta S_{gg}}$	4.97869×10^{9}

$$\Rightarrow \qquad \tau_{cl} \sim 10^{-208}\, T_U \quad \longrightarrow \quad \tau \sim 10^{-189}\, T_U$$

How comes that new physics can have such an impact on τ ?

Why the arguments on the suppression of new physics do not apply ?

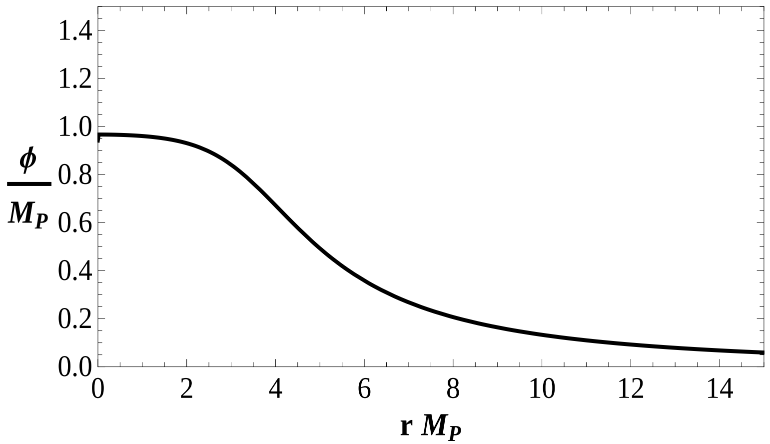
1. New physics appears in terms of higher dimension operators, and people expected their contribution to be suppressed as $(\frac{\Lambda_{inst}}{M_P})^n$

But: Tunnelling is a non-perturbative phenomenon. We first select the saddle point, i.e. compute the bounce (tree level), and then compute the quantum fluctuations (loop corrections) on the top of it.

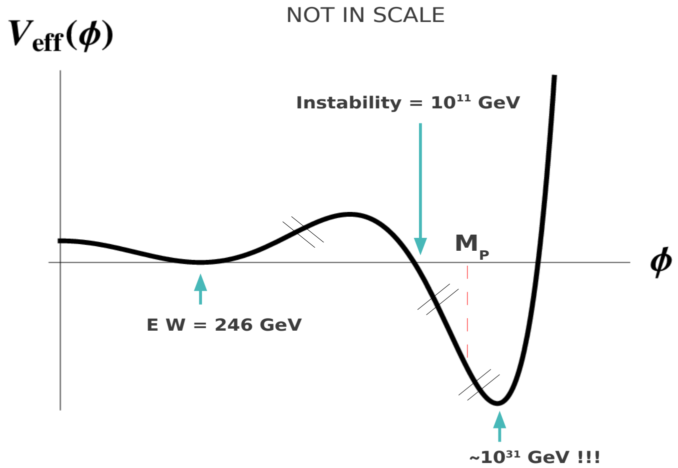
Suppression in terms of inverse powers of M_P (power counting theorem) concerns the loop corrections, not the saddle point (tree level).

Remember : $$\tau \sim e^{S[\phi_b]}$$

New bounce $\phi_b^{(2)}(r)$, New action $S[\phi_b^{(2)}]$, New τ



2. Height of the barrier and turning points...



This is QFT with "very many" dof, not 1 dof QM $\Rightarrow$ the potential is not $V(\phi)$ in figure with 1 dof, but...

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}(\vec{\nabla}\phi)^2 - V(\phi) = \frac{1}{2}\dot{\phi}(\vec{x},t)^2 - U(\phi(\vec{x},t))$$

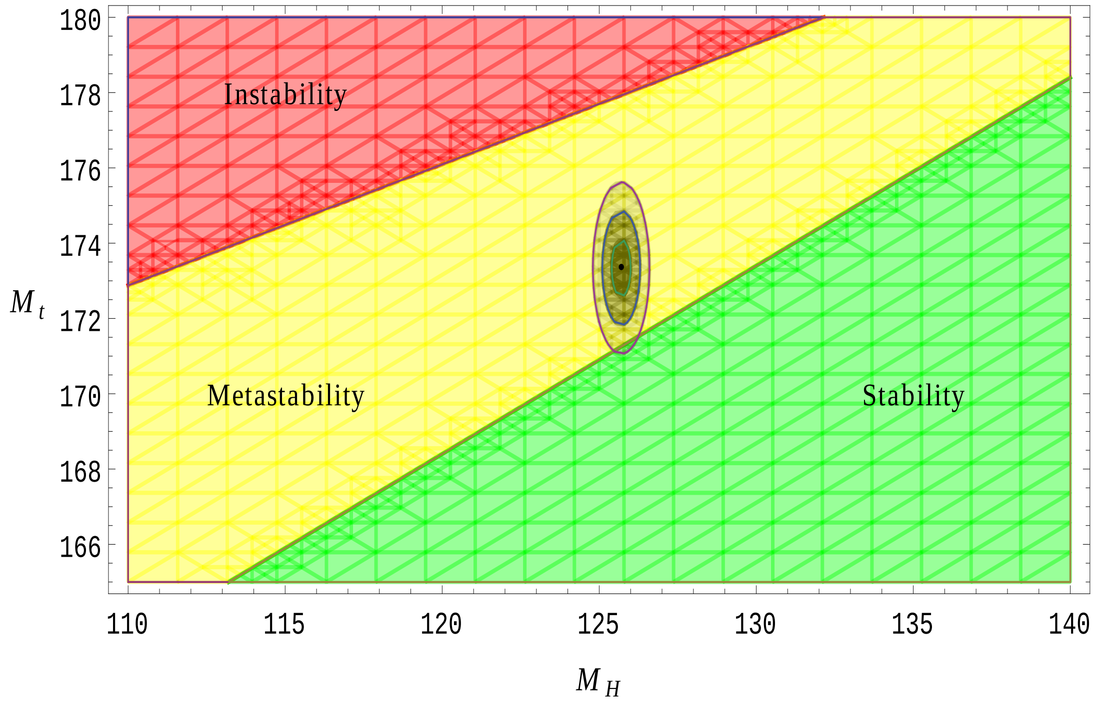
where $U(\phi(\vec{x},t))$ **is :** $\quad U(\phi(\vec{x},t)) = V(\phi(\vec{x},t)) - \frac{1}{2}(\vec{\nabla}\phi(\vec{x},t))^2$

Very many dof, not 1 dof... The Potential is : $\sum_{\vec{x}} U(\phi(\vec{x},t))$

The bounce is not a constant configuration ... Gradients do matter a lot!

Let us move now to Phase Diagrams...

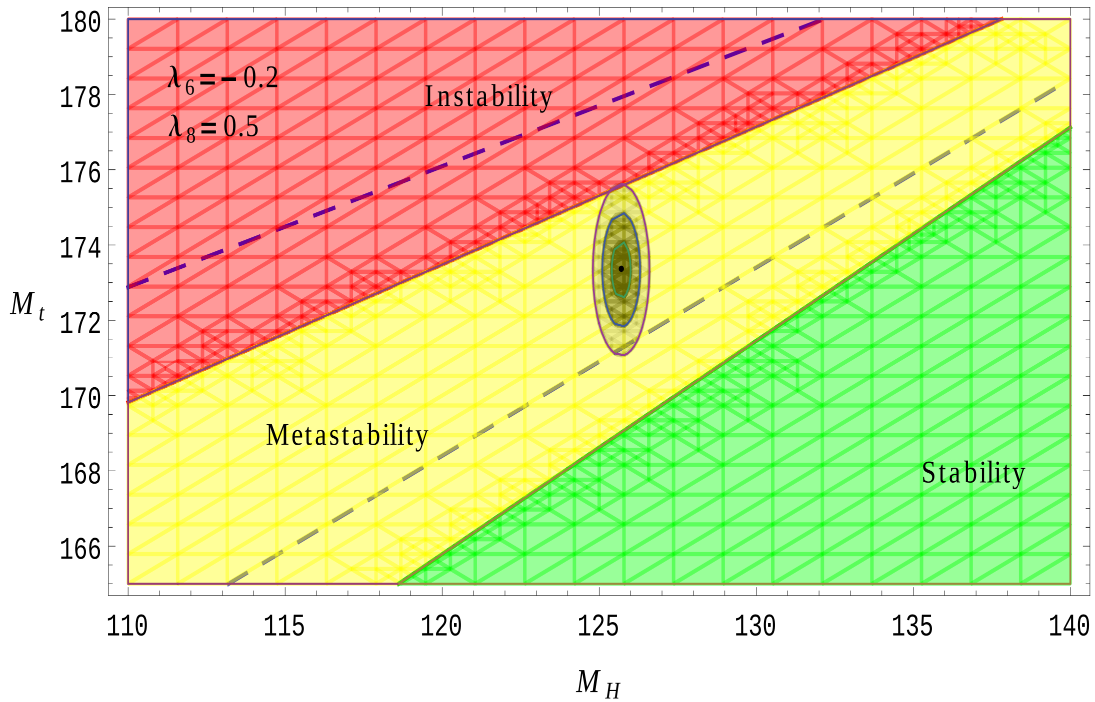
Phase diagram with $\lambda_6 = 0$ and $\lambda_8 = 0$ - Literature case



This is the well known Phase Diagram... Accordingly : (1) For $M_H \sim 125 - 126$ GeV and $M_t \sim 173$ we live in a metastable state ; (2) $3\,\sigma$ close to the stability line (Criticality) ; (3) Precision measurements of the top mass should allow to discriminate between stable, metastable, or critical EW vacuum ...

Phase diagram with $\lambda_6 = -0.2$ and $\lambda_8 = 0.5$

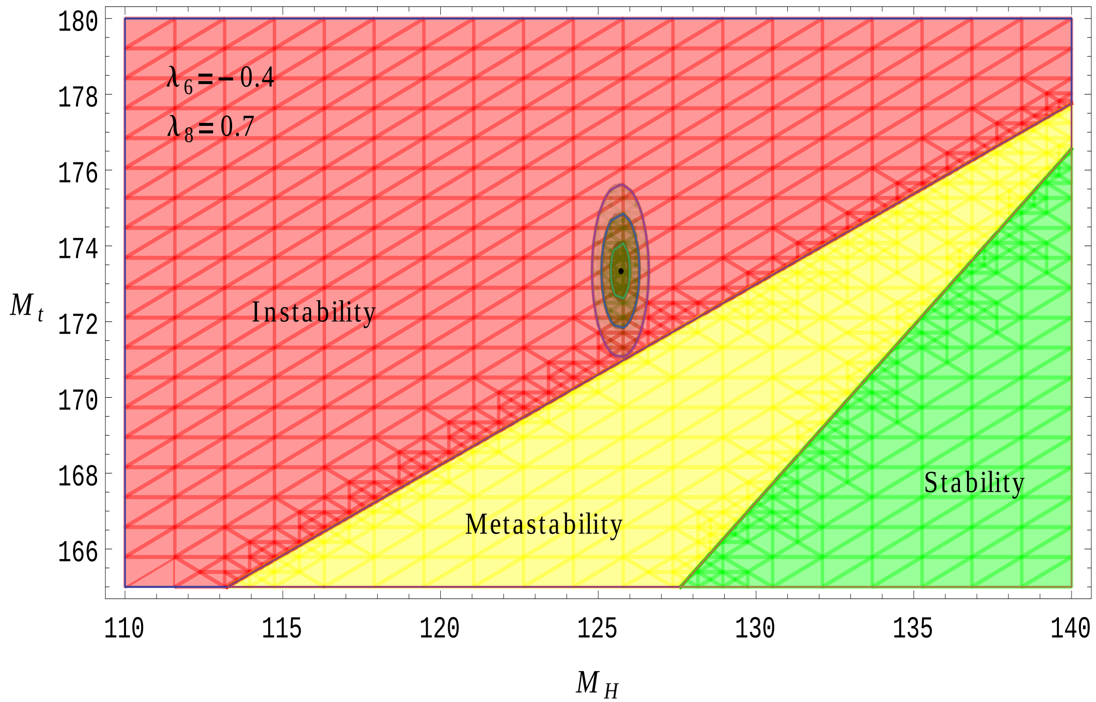
(Please note : Natural values for the coupling constants)



The strips move downwards ... The Exerimental Point no longer at $3\,\sigma$ from the stability line !!! ...

Phase diagram with $\lambda_6 = -0.4$ and $\lambda_8 = 0.7$

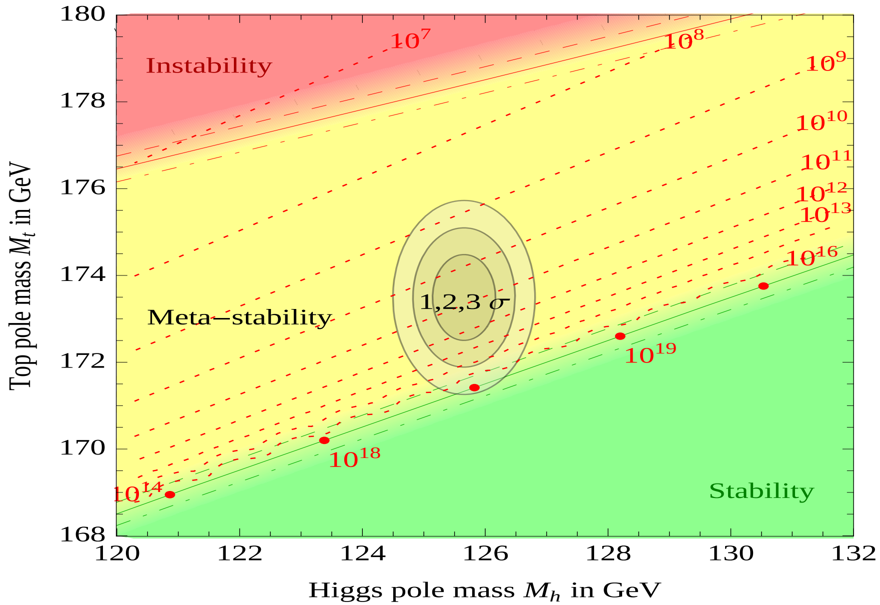
(Please note : Natural values for the coupling constants)



Even worse !

Lessons

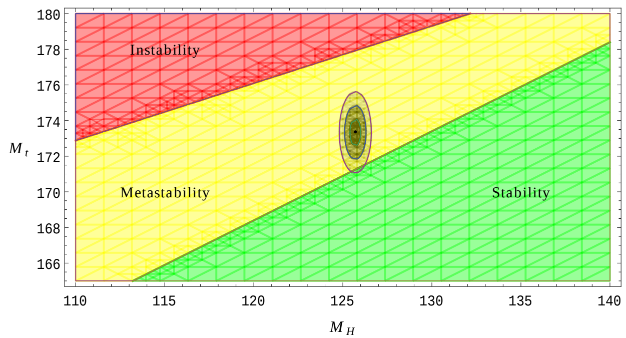
The Phase Diagram

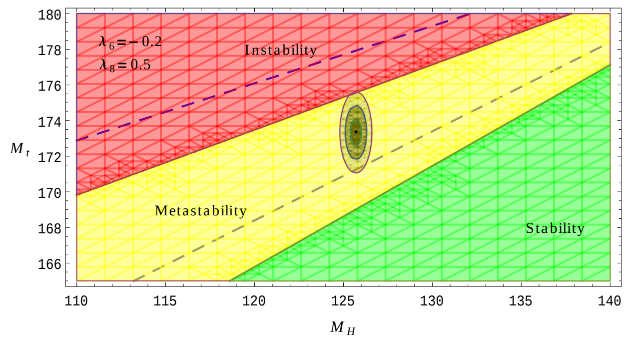


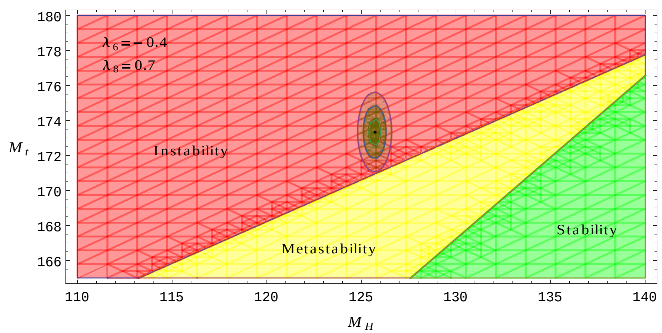
in not Universal !

It is one out of many different possibilities ....

“Precision Measurements of M_t”

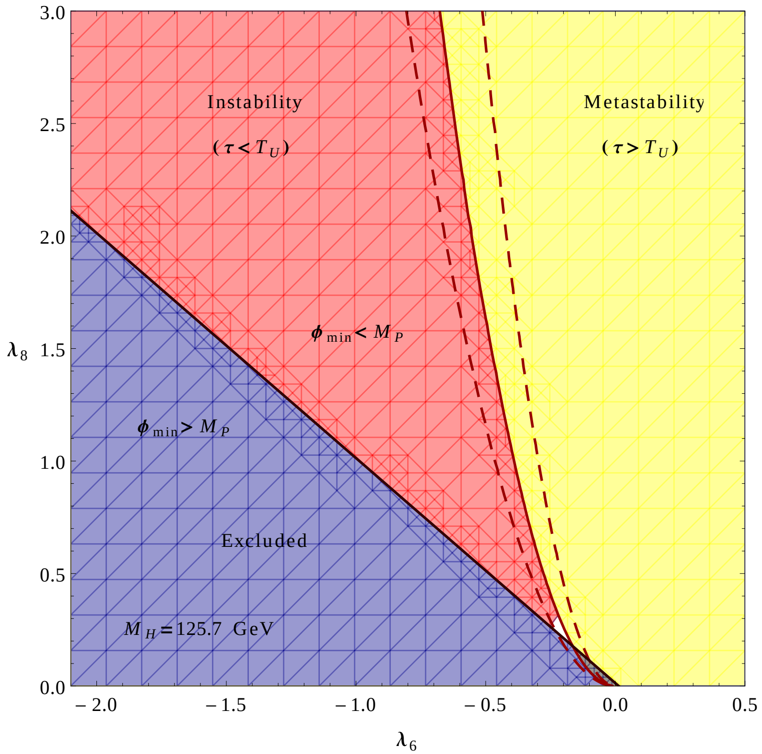


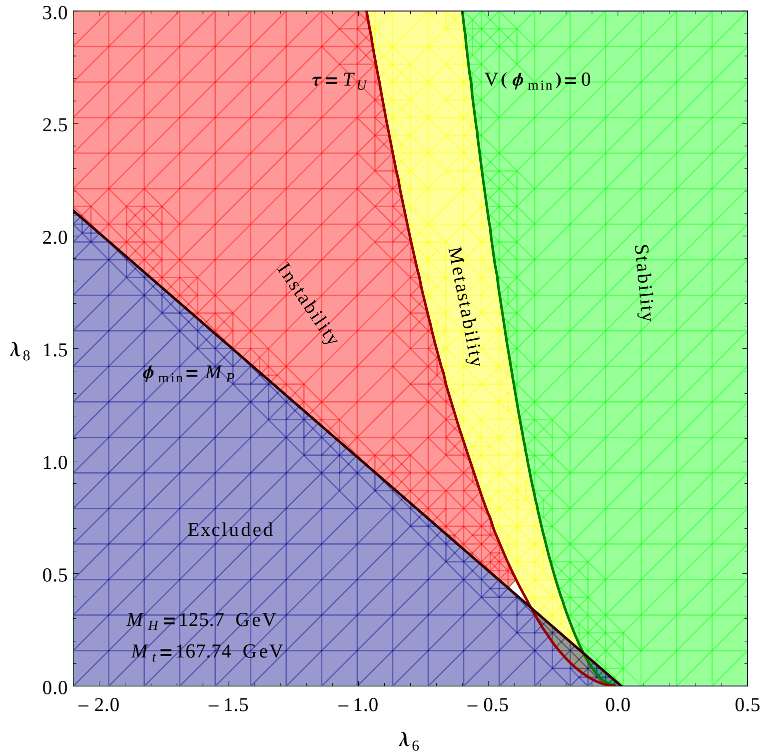




Precision measurements of M_t (and/or M_H) cannot discriminate between stability, metastability or criticality ! The knowledge of M_t and M_H alone is not sufficient to decide of the EW vacuum stability condition. We need informations on NEW PHYSICS in order to asses this question !

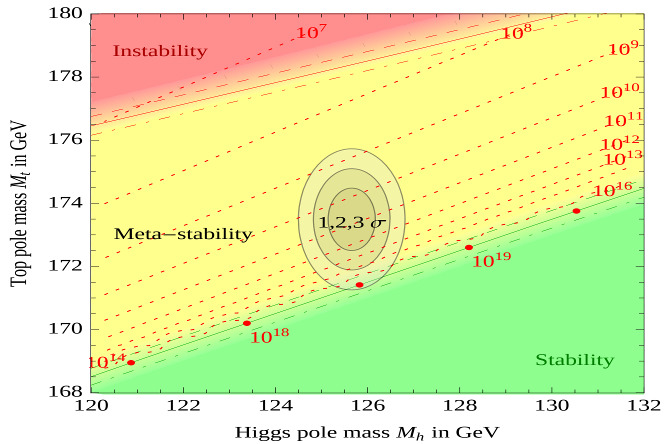
“Precision Measurements of M_t”





Constraining allowed region in theory space - BSM “Stability Test”

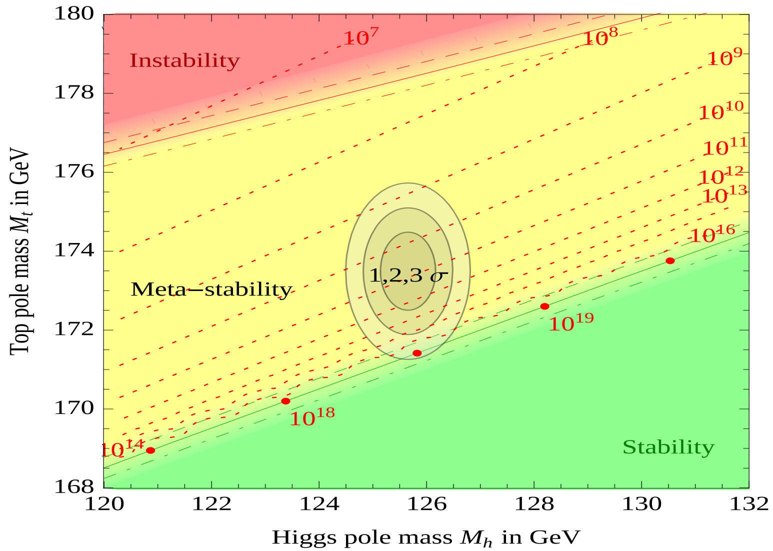
“Near-Criticality”



Somebody considers this near-criticality of the SM vacuum as the most important message so far from experimental data on the Higgs boson

But : This “near-criticality” picture (technically $\lambda(M_P) \sim 0$ and $\beta(\lambda(M_P)) \sim 0$) can be easily screwed up by even small seeds of new physics ! Strong sensitivity to new physics, No Universality.

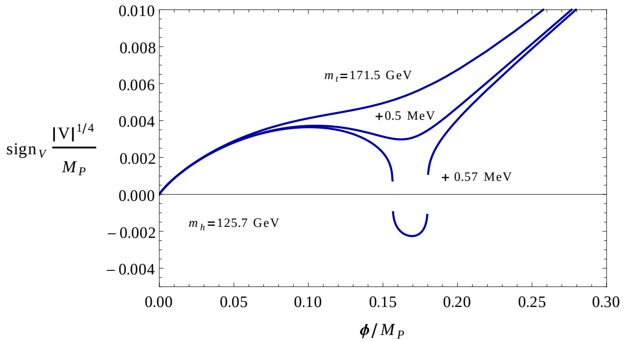
Higgs Inflation "1"

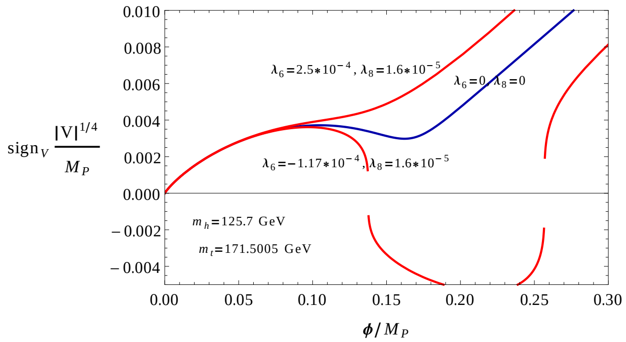


The Higgs inflation scenario of Shaposhnikov - Bezrukov strongly relies on the realization of the criticality picture ($\lambda(M_P) \sim 0$ and $\beta(\lambda(M_P)) \sim 0$). As we have just said, even a little seed of new physics can easily screw up this picture

Higgs Inflation “2” (Masina - Notari)

For a narrow band of values of the top quark and Higgs boson masses, the Standard Model Higgs potential develops a shallow local minimum higer than the EW minimum, where primordial inflation could have started





Again : Strong sensitivity to new physics !

Summary and Conclusions

- The Stability Phase Diagram of the EW vacuum strongly depends on New Physics
- Precision Measurements of the Top Mass will not allow to discriminate between stability, metastability or criticality of the EW vacuum. Phase Diagram too sensitive to New Physics
- Higgs Inflation in trouble. Any small seed of new physics screws up the picture
- Our results provide a "BSM stability test". A BSM is acceptable if it provides either a stable EW vacuum or a metastable one, with lifetime larger than the age of the universe (No $\tau << T_U$!!). In the past, it was thought that the stability of the EW vacuum could be studied with no reference to the UV completion of the SM
- This analysis can be repeated even if the new physics scale lies below the Planck scale, say, for instance, GUT scale, or ...