Stability condition of the EW vacuum and Top Mass measurements

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Top Mass workshop, Frascati, May 6-8, 2015

Stability condition of the EW vacuum ... Time honored subject

List of some References ... far from being exhaustive ...

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... But let me please quote the most recent one ...

High Energy Physics - Phenomenology

Submissions received from Tue 5 May 15 to Wed 6 May 15,

announced Thu, 7 May 15

arXiv:1505.01279 Title: The Standard Model from the LHC to future colliders: a contribution to the Workshop "What Next" of INFN

Authors: S.Forte, A.Nisati, G.Passarino, R.Tenchini, C.M.Carloni Calame, M.Chiesa, M.Cobal, G.Corcella, G.Degrassi, G.Ferrera, L.Magnea, F.Maltoni, G.Montagna, P.Nason, O.Nicrosini, C.Oleari, F.Piccinini, F.Riva, A.Vicini

Subjects: High Energy Physics - Phenomenology (hep-ph)

This Report summarizes the results of the activities in 2014 Standard Model Working Group within the workshop "What Next" of INFN. ...

Section 5 of this Report : **G. Degrassi**

The Higgs potential and the Electroweak vacuum

Section 3 of this Report : **G. Corcella, M. Cobal**

Top quark physics

... both sections related to the topic that I am going to discuss ...

Probably worth to begin with a

DISCLAIMER

On precision measurements of M_t

Statement

The top mass is one of the fundamental parameters of the SM

- Top cross sections
- Size of the quantum corrections to different processes
- Value of the top Yukawa coupling

(just to mention few examples) all crucially depend on M_t

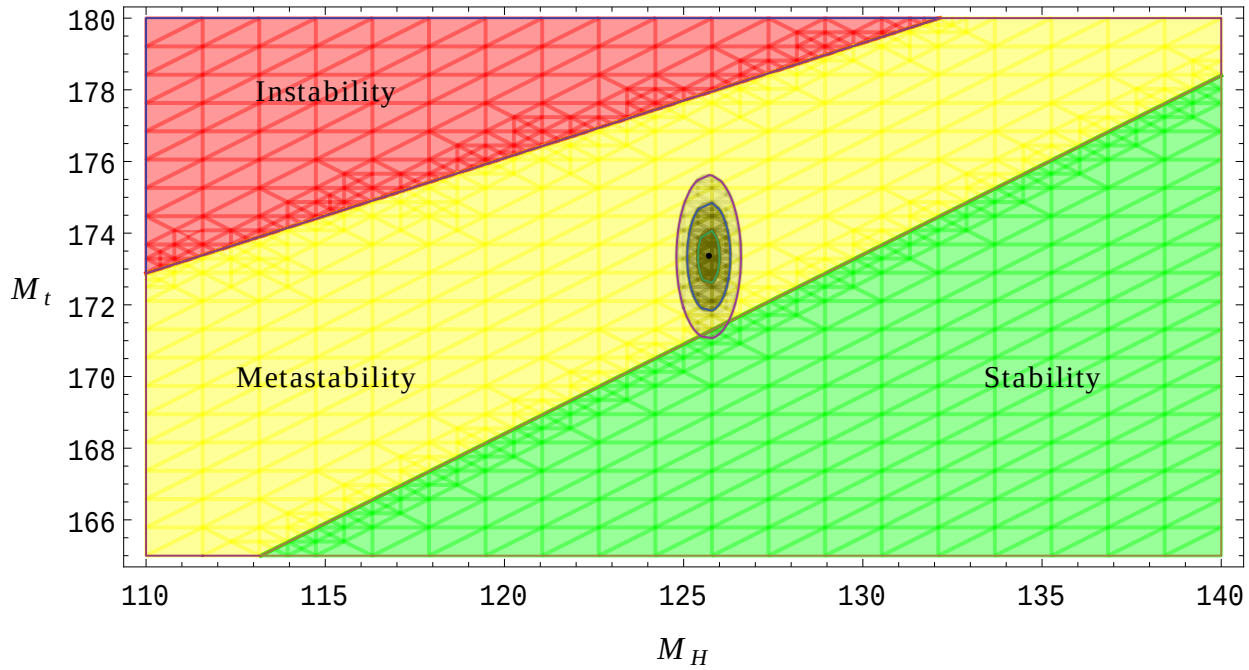
Precision measurements of M_t are of the greatest importance

What I do not claim...

I do not think and I have never thought or said that M_t should not be measured with the greatest possible precision ...

What I do claim ... concerning precision measurements of M_t ...

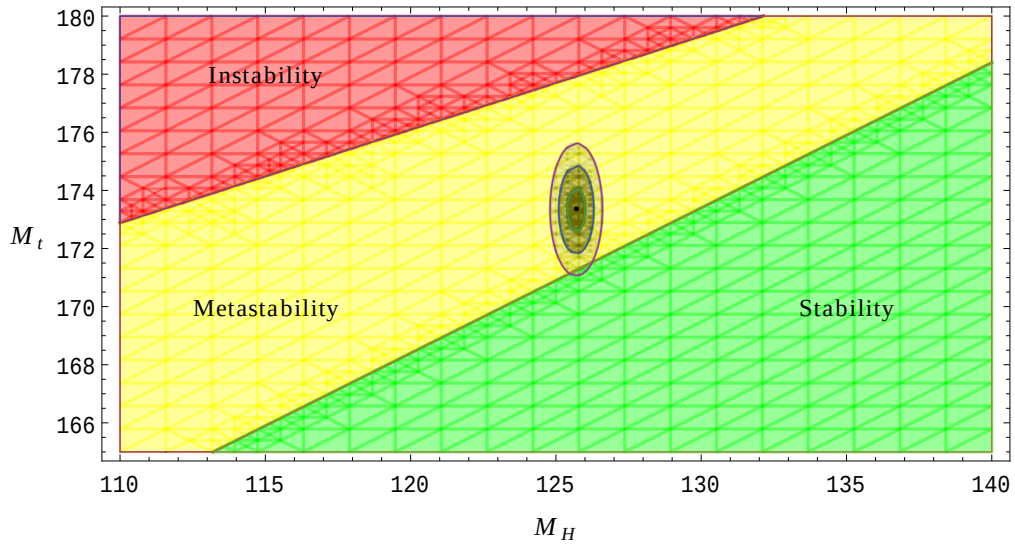
Based on the "Stability Diagram" below, it **is/was stated** that once we have a more precise measurement of M_t we'll be able to say something on the **fate of our Universe ... stable, metastable, critical ...**



I claim that this is not generically true
... I am going to explain why...

... More generally ... What I do claim ...

It **is/was stated** stated that **if there is no "New Physics" all the way up to the Planck scale**, **that means that "New Physics" shows up at the Planck scale**, **the "Stability Diagram" is given by the figure below** (... that is the reason why people conclude that precision measurements of M_t can teach us something on the fate of the Universe ...)

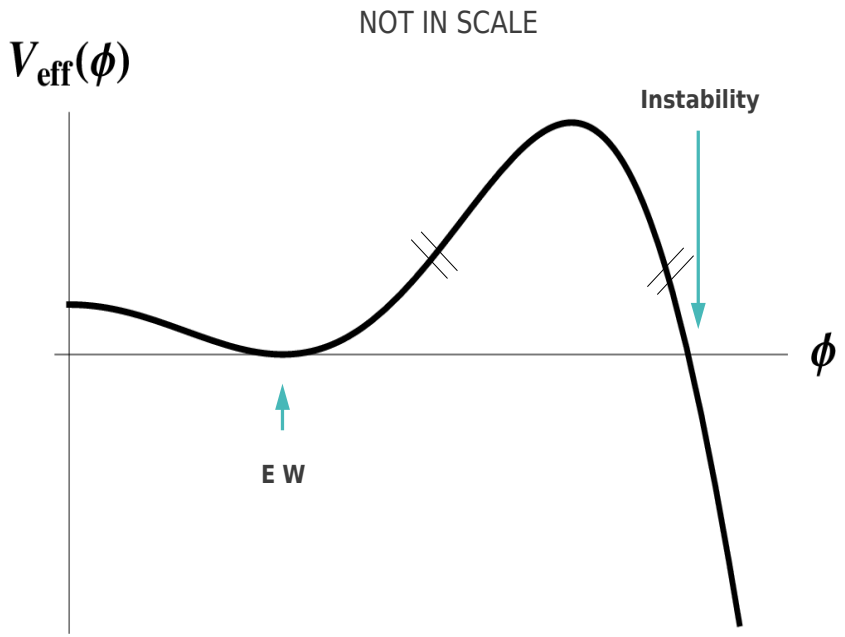


I claim that this is not generically true: the Stability Diagram depends on New Physics even if New Physics shows up only at very high ($\sim M_P$) energies. It is/was thought that New Physics at M_P does not affect the Stability Diagram ...

Stability analysis of the EW vacuum

Top loop-corrections to the Higgs Effective Potential

destabilize the electroweak vacuum...



Higgs boson : $M_H \sim 125$ GeV

Experimental data consistent with Standard Model predictions

No sign of new physics

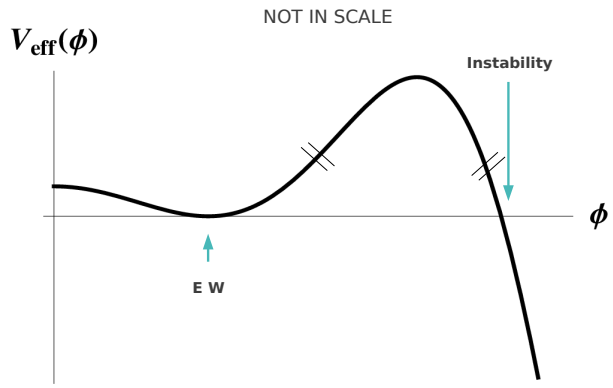
This has boosted new interest and work on an old idea

... the possibility that

New Phyiscs shows up only at very high energies

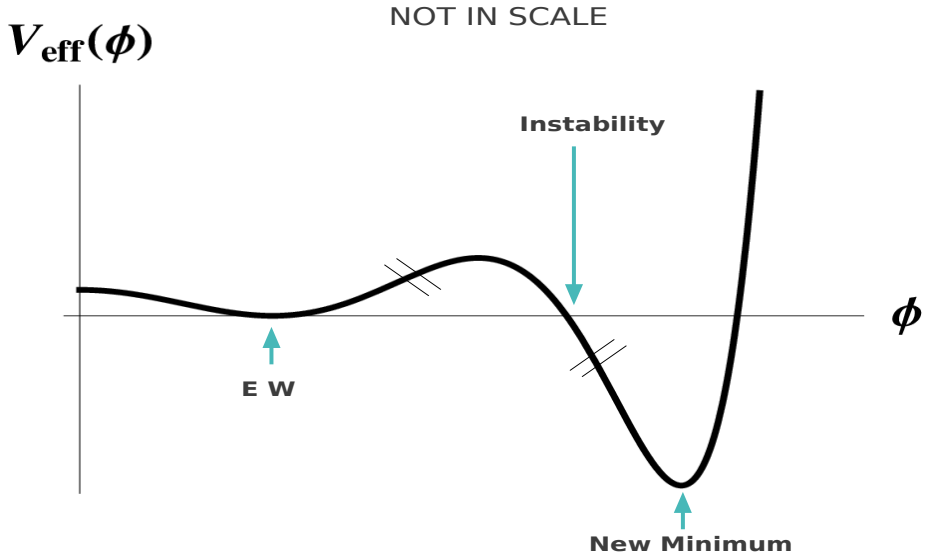
... up to Planck scale ...

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



$$V^{1l}(\phi) = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{24}\phi^4 + \frac{1}{64\pi^2}\left[\left(m^2+\frac{\lambda}{2}\phi^2\right)^2\left(\ln\left(\frac{m^2+\frac{\lambda}{2}\phi^2}{\mu^2}\right)-\frac{3}{2}\right)\right.$$
$$+3\left(m^2+\frac{\lambda}{6}\phi^2\right)^2\left(\ln\left(\frac{m^2+\frac{\lambda}{6}\phi^2}{\mu^2}\right)-\frac{3}{2}\right)+6\,\frac{{g_1}^4}{16}\phi^4\left(\ln\left(\frac{\frac{1}{4}{g_1}^2\phi^2}{\mu^2}\right)-\frac{5}{6}\right)$$
$$\left.+3\,\frac{\left({g_1}^2+{g_2}^2\right)^2}{16}\phi^4\left(\ln\left(\frac{\frac{1}{4}\left({g_1}^2+{g_2}^2\right)\phi^2}{\mu^2}\right)-\frac{5}{6}\right)-12\,h_t^4\phi^4\left(\ln\frac{g^2\phi^2}{\mu^2}-\frac{3}{2}\right)\right]$$

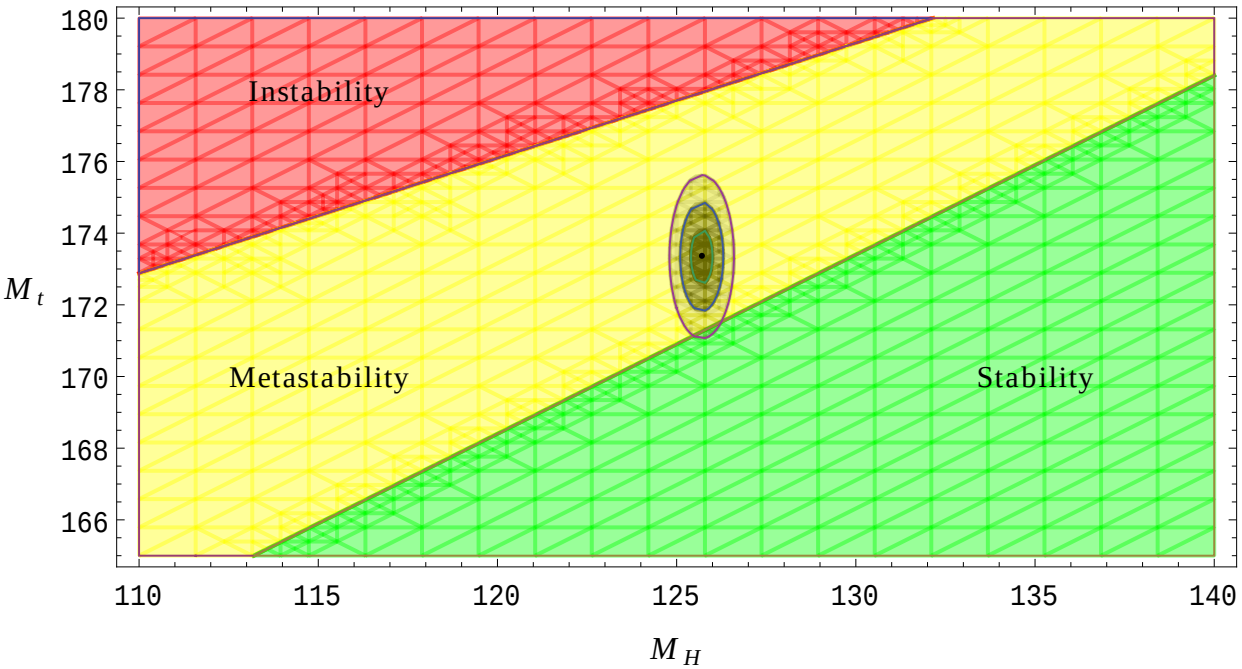
RG Improved Effective Potential $V_{RGI}(\phi)$



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.

When the potential at the New Minimum is lower than the potential at the EW Minimum, compute the Tunnelling Time and draw the ...

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 $\tau = T_U$.

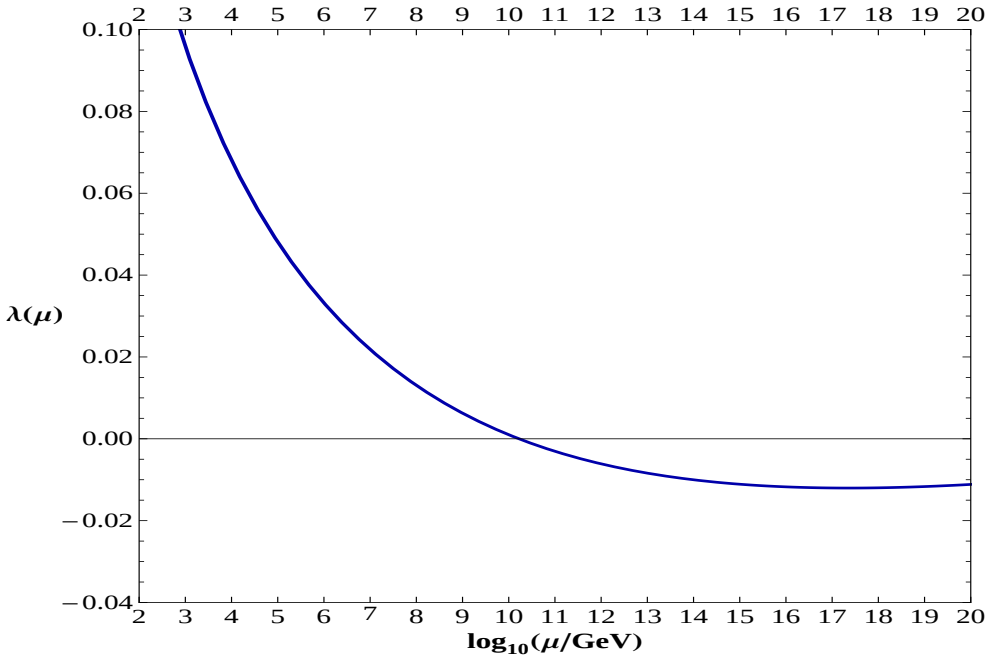
Note : the instability occurs for large values of ϕ

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

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

Moreover : $\lambda_{eff}(\phi)$ depends on ϕ essentially as the running quartic coupling $\lambda(\mu)$ depends on the running scale μ

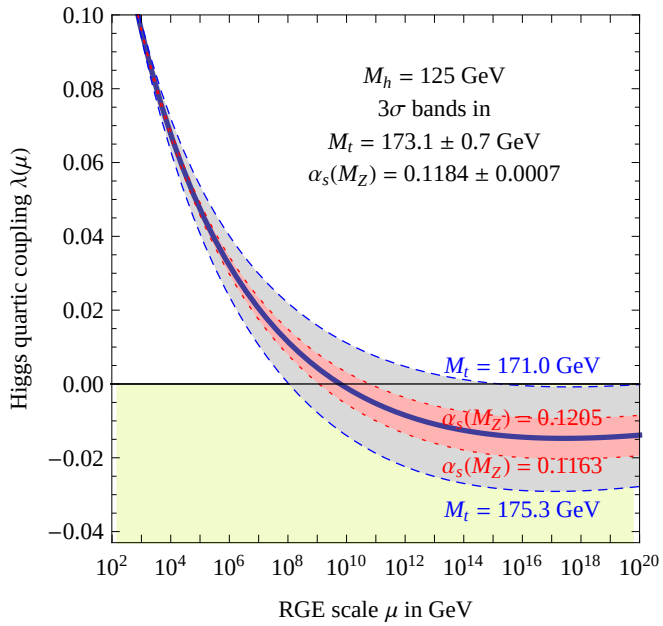
$\Rightarrow$ **we can read the Effective Potential from the $\lambda(\mu)$ flow**



Running of the quartic coupling $\lambda(\mu)$

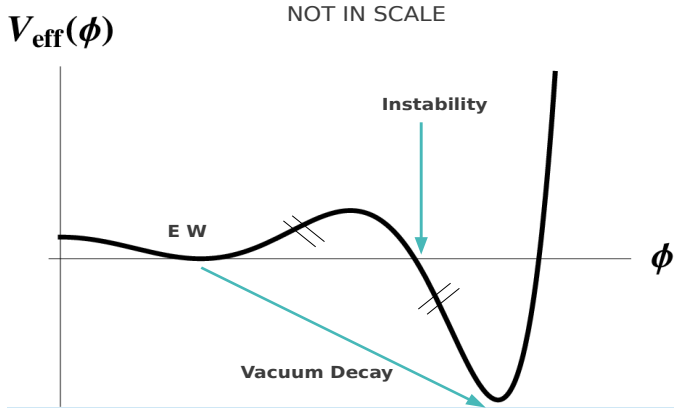
Running of $\lambda(\mu)$ in the SM

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



Metastability Scenario

When the second minimum is 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 ?

Semiclassical calculation - WKB - instantons

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

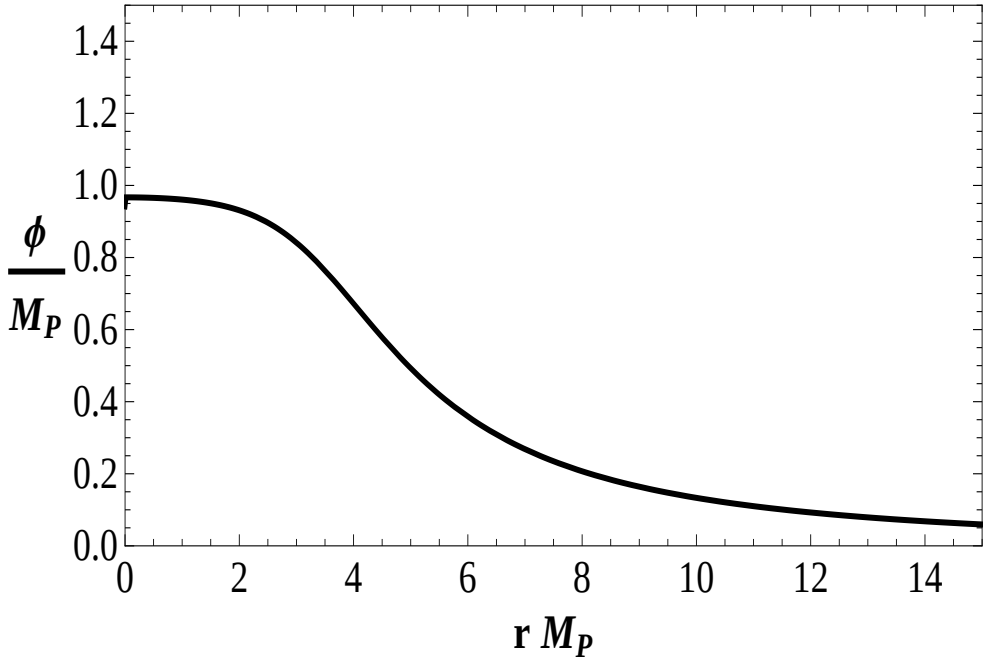
Bounce solutions :

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

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 :** $S[\phi_b] = \frac{8\pi^2}{3|\lambda|}$

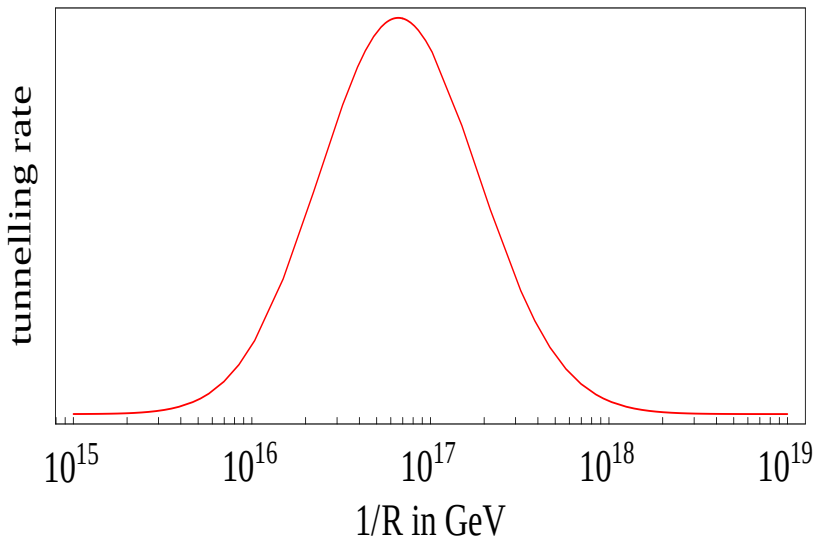


Degeneracy removed at the Quantum Level

Degeneracy removed at the Quantum Level

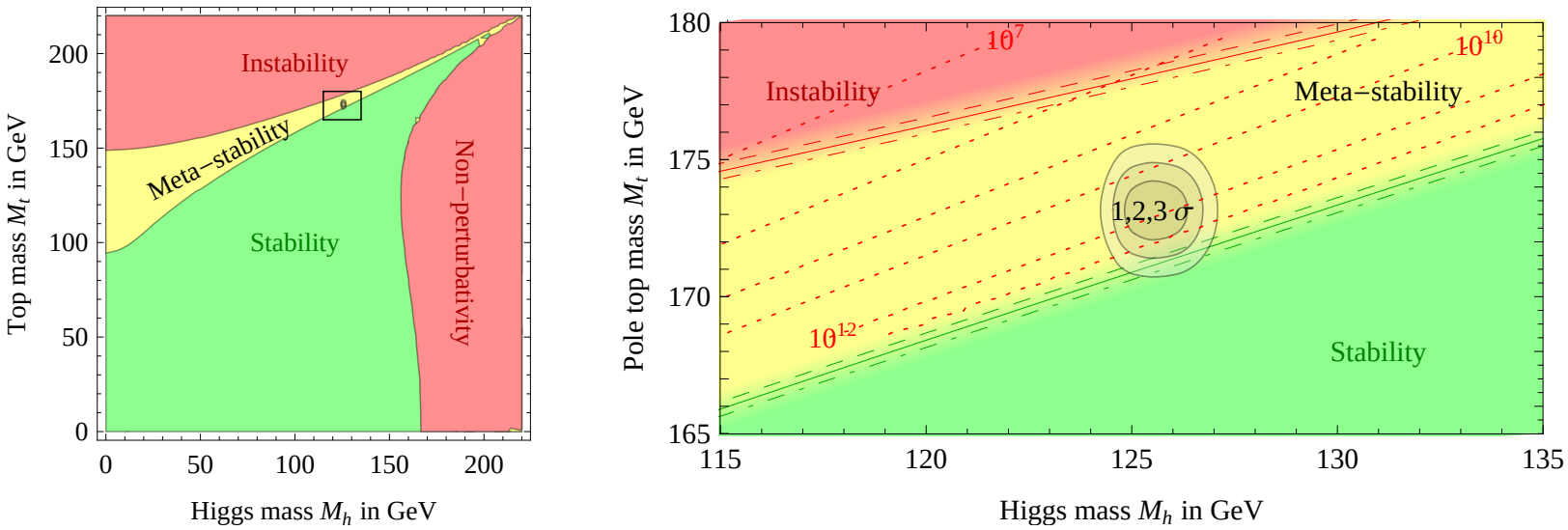
Transition rate as a function of R : ($\mu \sim \frac{1}{R}$)

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



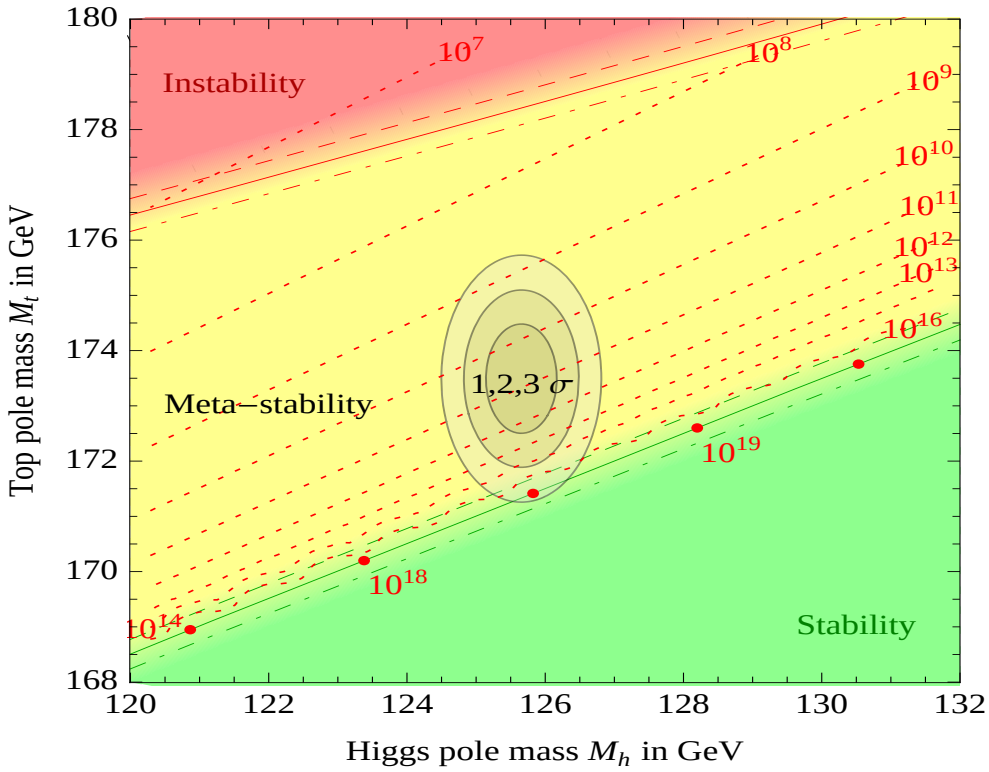
from : G. Isidori, G. Ridolfi, A. Strumia, Nucl.Phys.B 609 (2001) 387

... So ... Stability Diagram ...



Degrassi, Di Vita, J. Elias-Miró, Espinosa, Giudice, Isidori, Strumia, JHEP 1208 (2012) 098

... So ... Stability Diagram ...



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

... However ...

... Some warnings ...

Starting with :

VB, E. Messina, Phys.Rev.Lett.111, 241801 (2013) (arXiv:1307.5193)

and then

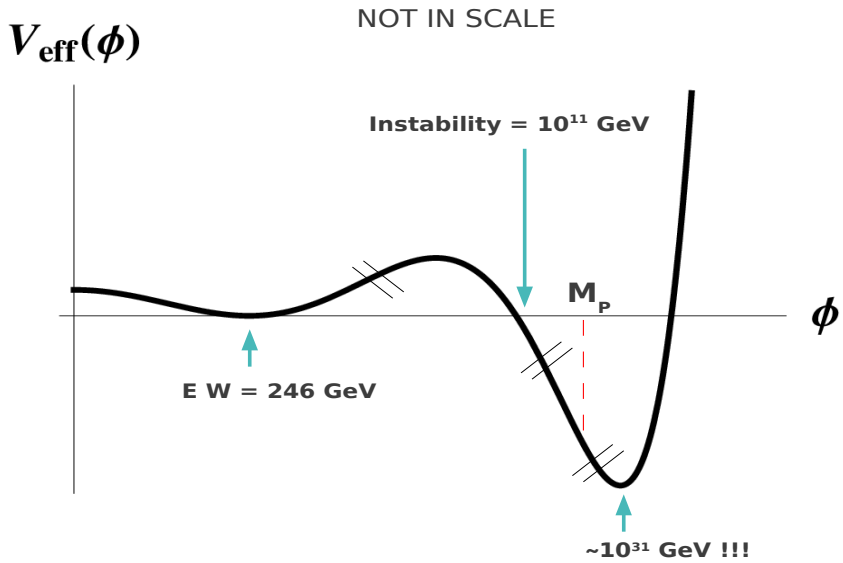
VB, arXiv:1405.7864, Moriond 2014

VB, E. Messina, A. Platania JHEP 1409 (2014) 182 (arXiv:1407.4112)

VB, E. Messina, M. Sher, Phys.Rev.D91 (2015) 1, 013003 (arXiv:1408.5302)

VB, E. Messina, in preparation

Probably worth to know that for $M_H \sim 125$ **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 **!!!**

Remember : you normally hear... "assume SM valid up to M_P**"**

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

Let me please quote from Degrassi et al. arxiv ....

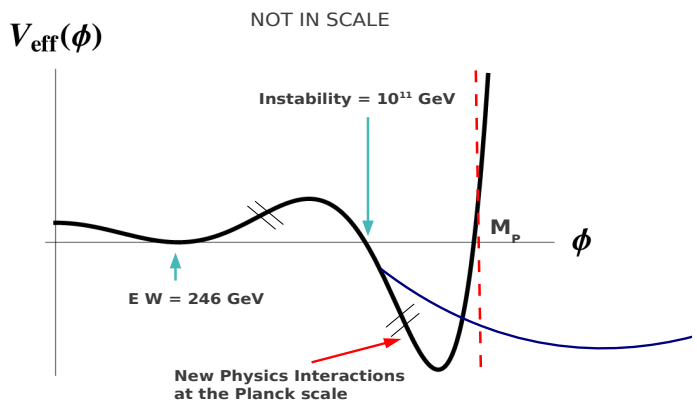
"... A more refined analysis [31] shows that $\Lambda_{inst} \sim 10^{11}$ GeV implying that our EW minimum is not the true minimum of the Higgs potential and there is a tunnelling probability between the EW false vacuum and the true vacuum at high field values. In this situation, we can be sure that New Physics must appear below Λ_{inst} to cure the instability of the SM potential only if the lifetime of EW vacuum is shorter than the life of the universe."

"The appearance in $V_{eff}(\phi)$ **below** M_{Pl} of a second minimum deeper than the EW minimum, or the fact that $V_{eff}(\phi)$ at high scale is not bounded from below, are signals of the need (with some caveat to be discussed below) of New Physics to rescue the stability of the EW vacuum."

Issue of the True Vacuum (?) : Should we even mention the True Vacuum if it shows up at $\phi_{min} \sim 10^{30}$ GeV ???

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

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



... meaning that if you take into account the presence of these new physics interactions at M_P, given in terms of higher order operators as

$$\frac{\phi^6}{M_P^2} \quad , \quad \frac{\phi^8}{M_P^4} \quad , \ldots .$$

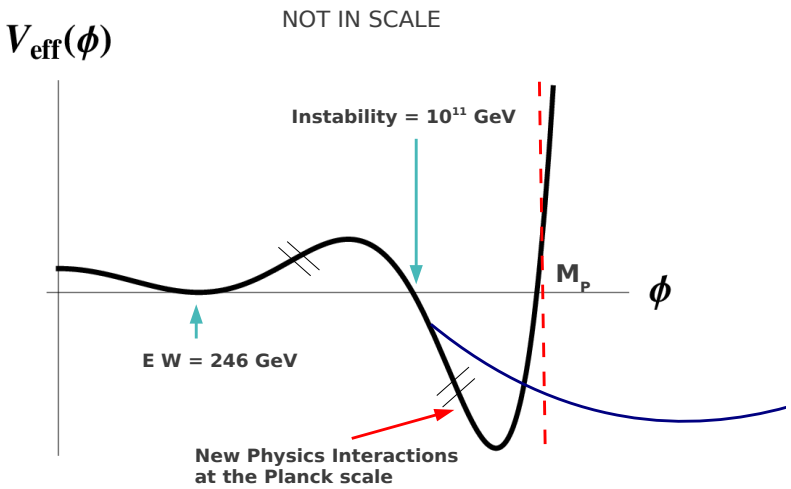
these terms stabilize the Higgs potential around M_P...

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 $\Rightarrow$

$$\Rightarrow \quad \text{suppression} \left(\frac{\Lambda_{inst}}{M_P}\right)^n$$

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



... These arguments turn out to be incorrect ... we'll see why ...

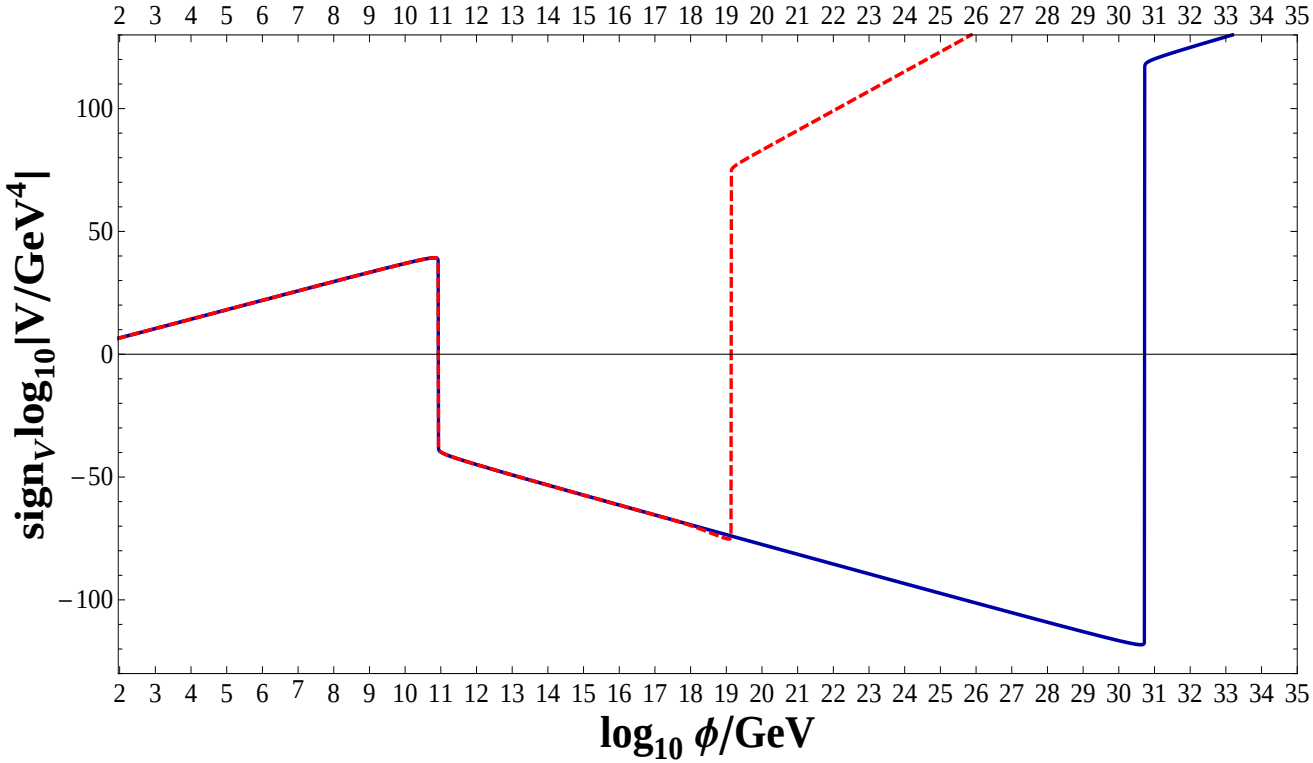
Let us consider New Physics at M_P

Add ϕ^6 and ϕ^8 in such a way to implement the stabilization of the SM Higgs potential at M_P :

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

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

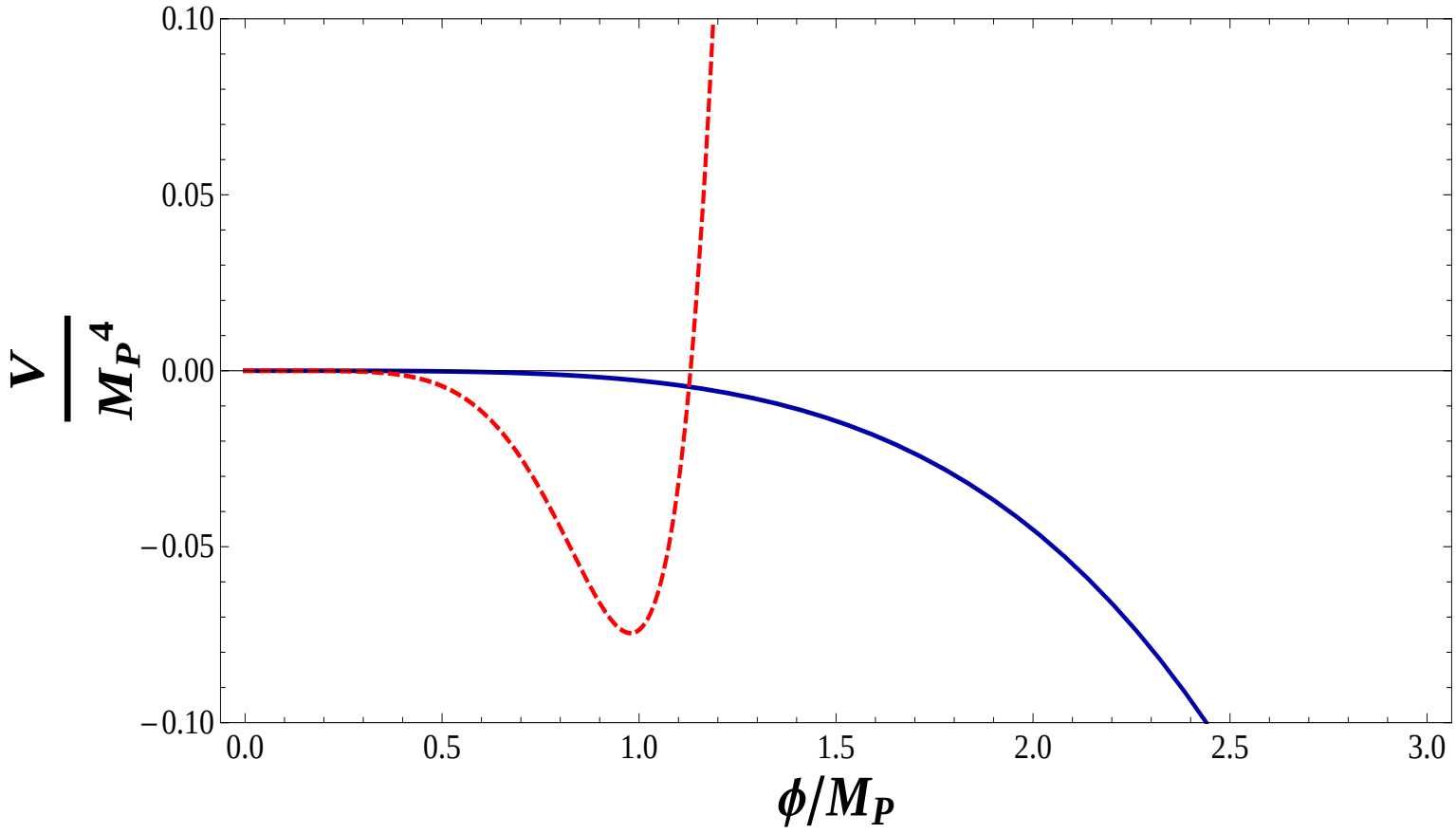
Effective Potential $M_H \sim 125$ $M_t \sim 173$ Log-Log Plot



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 new physics terms (SM alone)**

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 find the new bounce configurations and consider them for the computation of the tunnelling time

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

It turns out that 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 : $S[\phi_b^{(old)}] \sim 1800 \Rightarrow \quad \tau \sim 10^{600}\, T_U$

Our case : $S[\phi_b^{(new)}] \sim 80 \quad \Rightarrow \quad \tau \sim 10^{-200}\, T_U$

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

New Physics Interactions at High Scales (Planck) 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}

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}

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

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

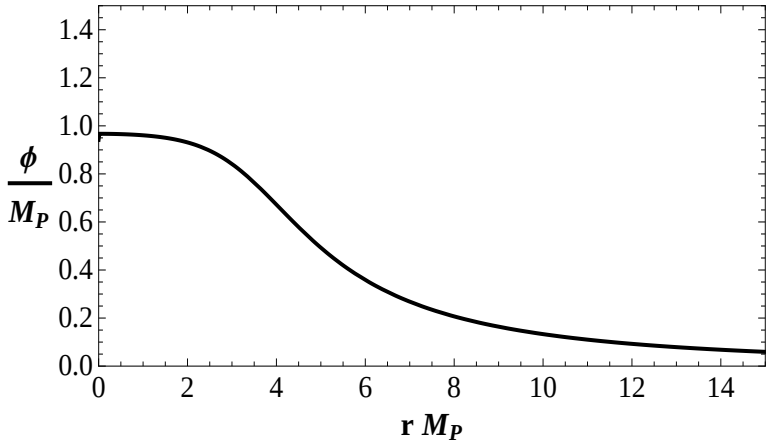
1. New physics appears in terms of higher dimension operators, and people expected their contribution to be suppressed as $(\frac{\Lambda_{inst}}{M_P})^n$

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.

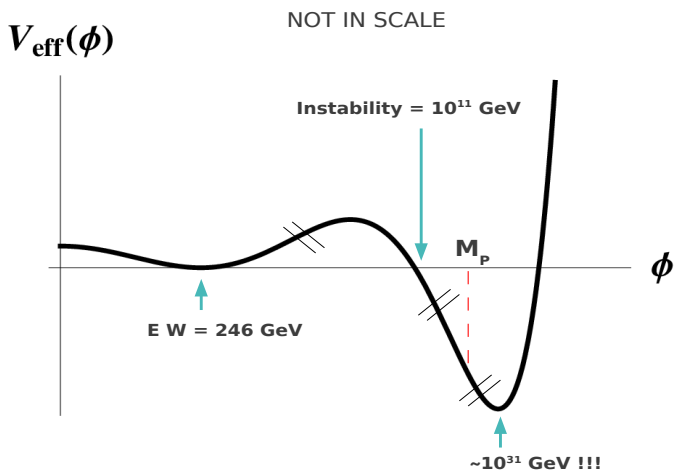
Suppression in terms of inverse powers of M_P (power counting theorem) concerns the loop corrections, not the selection of the saddle point (tree level).

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...

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

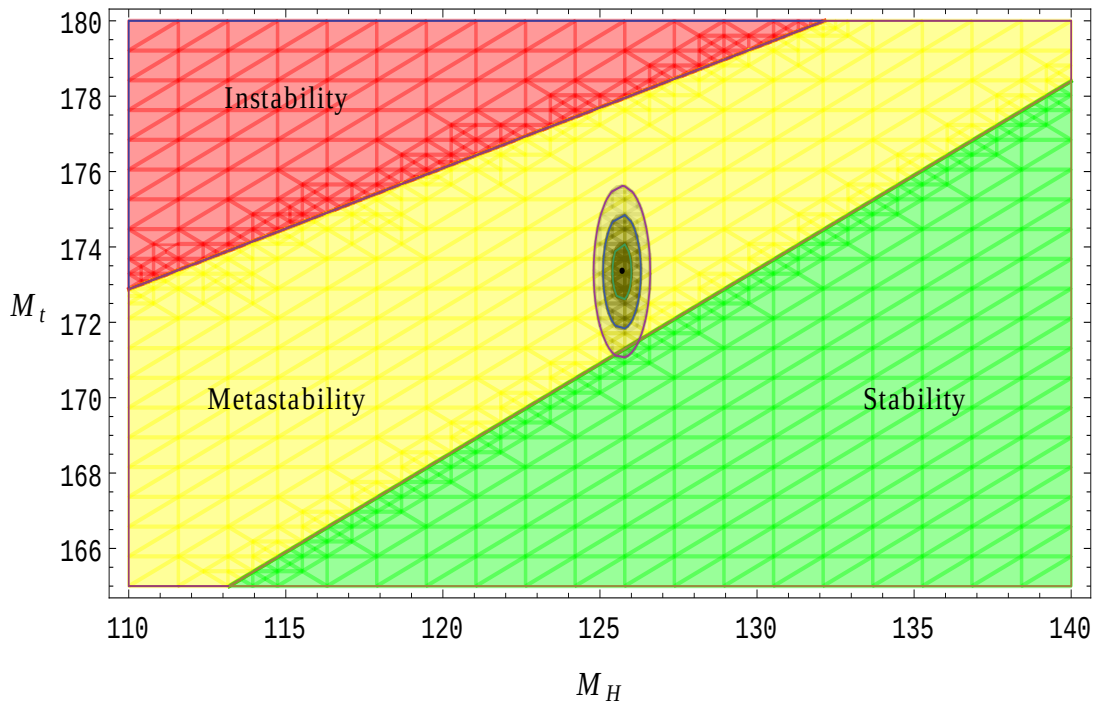
where $U(\phi(\vec{x},t))$ is : $\quad U(\phi(\vec{x},t)) = V(\phi(\vec{x},t)) + \frac{1}{2}(\vec{\nabla}\phi(\vec{x},t))^2$

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 Stability Diagram ... According to it :

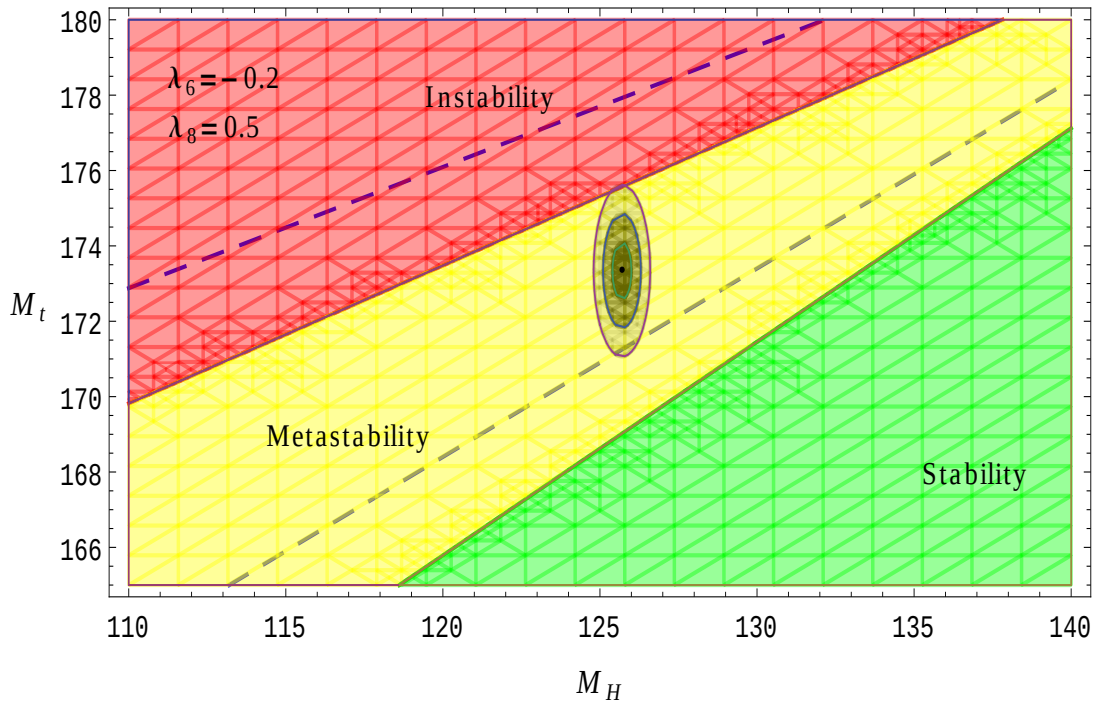
(1) For $M_H \sim 125$ GeV and $M_t \sim 173$ GeV we live in a metastable state ;

(2) $3\,\sigma$ close to the stability line (Criticality) ;

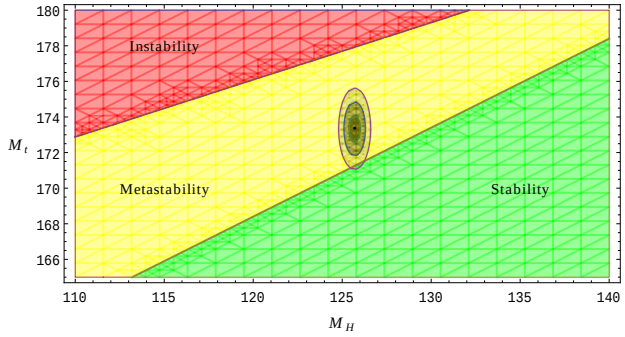
(3) Precision measurements of the top mass should allow to discriminate between stable, metastable, or critical EW vacuum ...

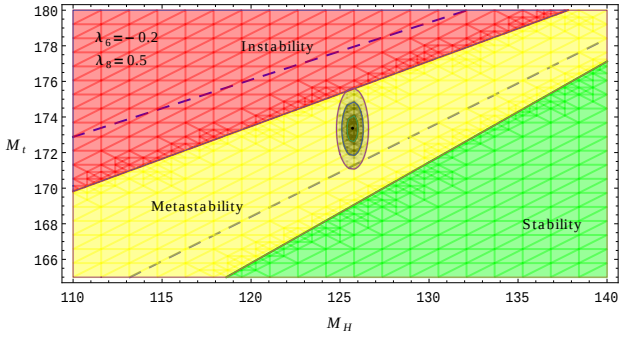
Phase diagram with $\lambda_6 = -0.2$ and $\lambda_8 = 0.5$

(Please note : Natural values for the coupling constants)



The strips move downwards ... The Experimental Point no longer at $3\,\sigma$ from the stability line !!! ... Stability Diagram depends on new physics !





Why should I be more interested in the diagram on the left panel than in the diagram on the right panel ... or in one of the billions of other diagrams that I can have ???

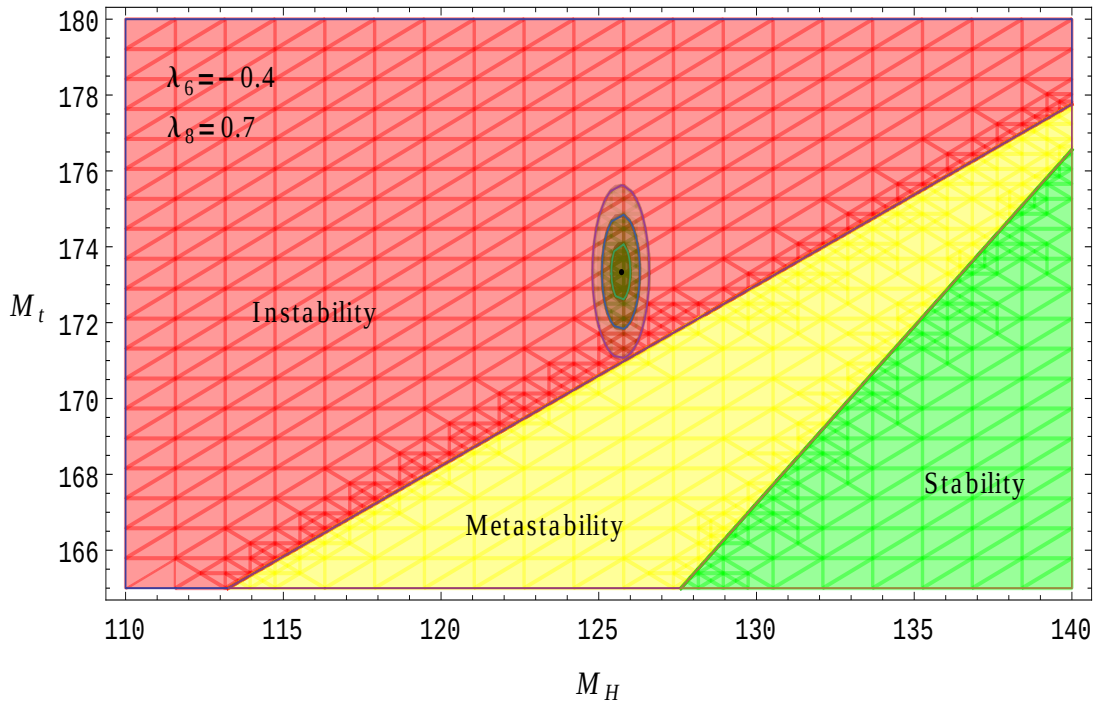
We have just seen that even if we want to explore the extreme case that there is no New Physics all the way up to the Planck scale, still the Stability Diagram depends on the specific form of New Physics at M_P ...

So, again... Why should I be more interested in the diagram on the left panel than in any other possible diagram ???

... For the reason that we like to explore what happens in the case that we ASSUME that New Physics at the Planck scale does not modify this picture ???

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

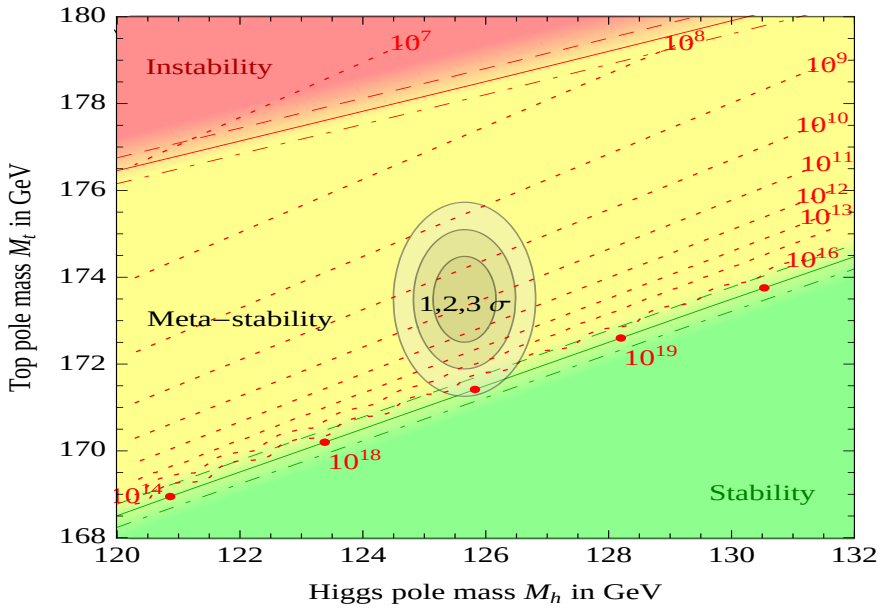
(Please note : Natural values for the coupling constants)



Even worse !

Lessons

The Phase Diagram

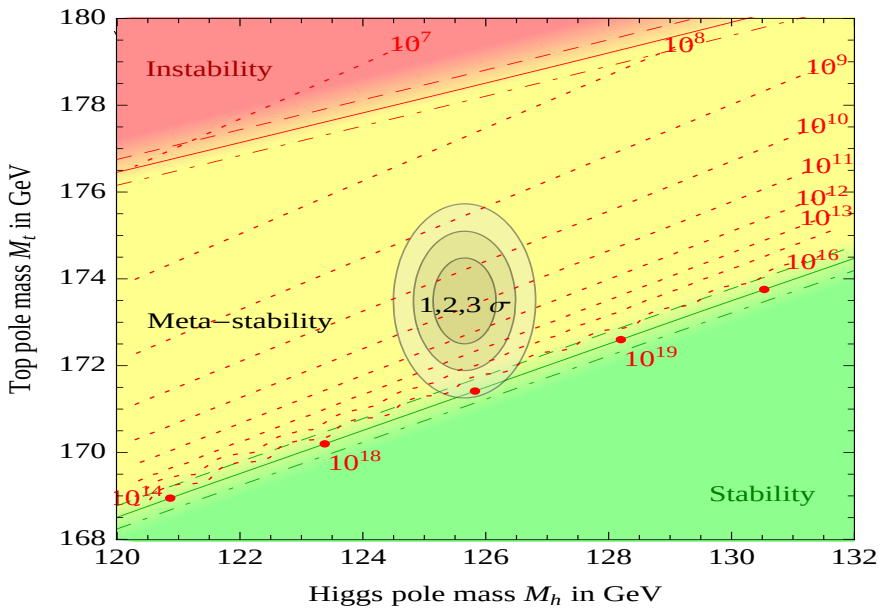


in not Universal !

... one out of different possibilities ....

...Before the statement was :

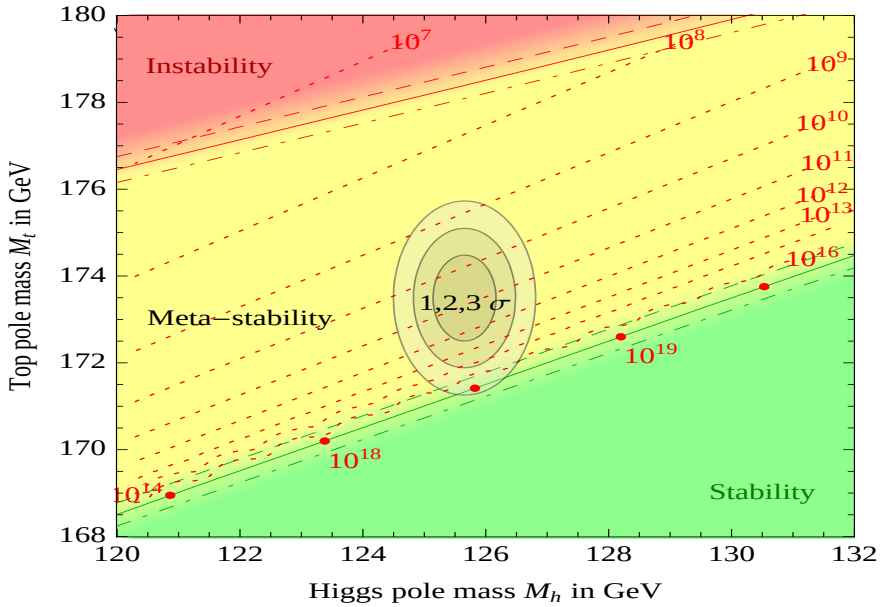
If we assume that there is no New Physics all the way up to the Planck scale M_P, then the Stability Diagram is :



... Now the statement is :

1. If we assume that there is no New Physics all the way up to M_P

2. and we also assume that New Physics that lives at the Planck scale M_P does not modify the Diagram below

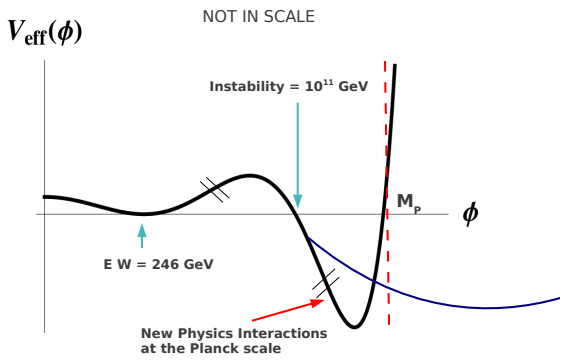


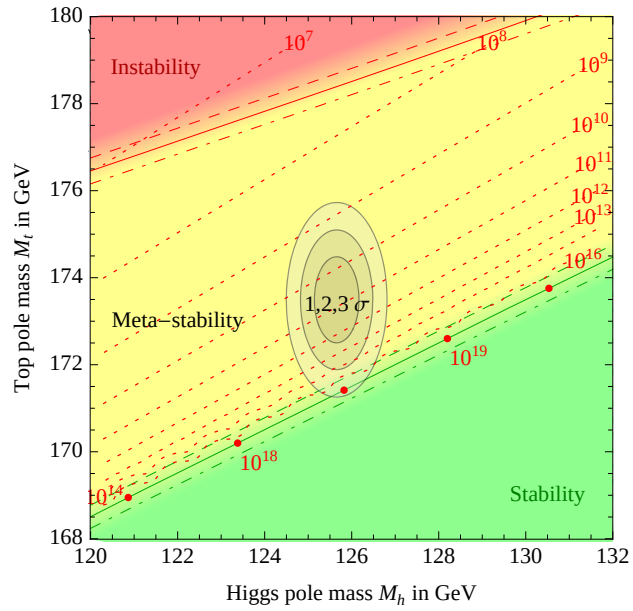
Then this Diagram is the Stability Diagram of the SM.

Certainly a much weaker statement... maybe too weak ...

The two statements :

(1) - There should be new physics at the Planck scale that stabilizes the potential

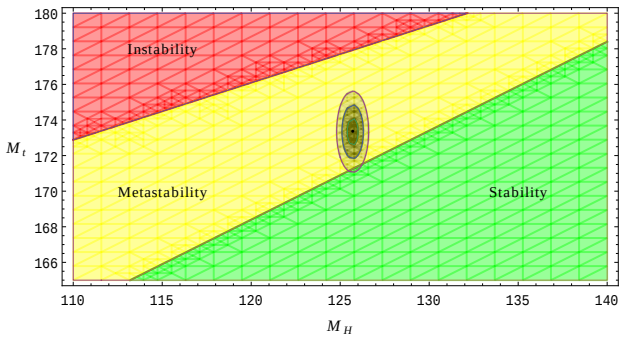


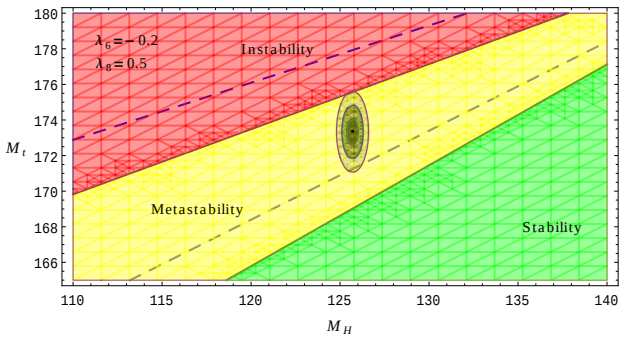


(2) - The stability phase diagram in independent on this new physics

Cannot be true at the same time

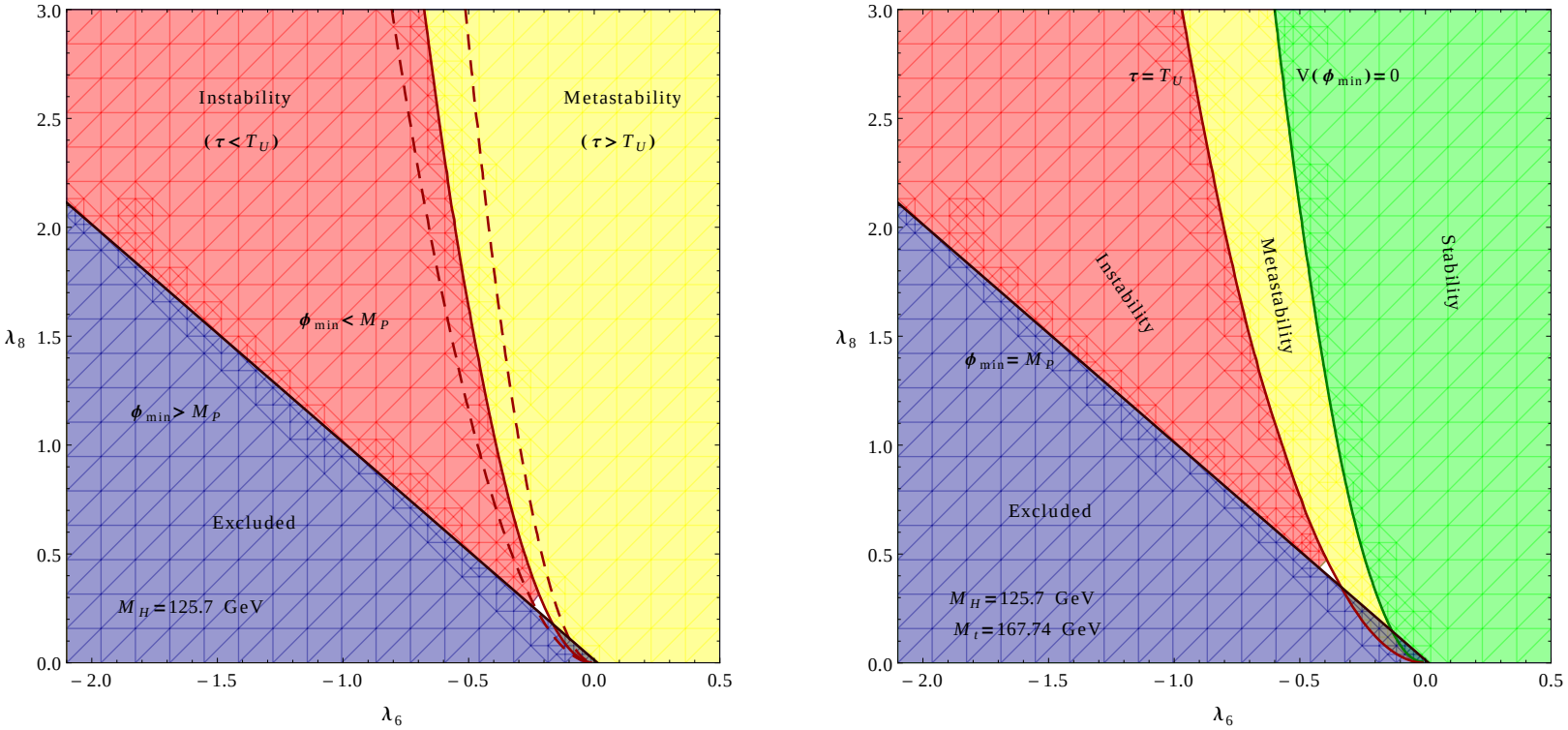
"Precision Measurements of M_t"





Precision measurements of M_t (and 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 ...

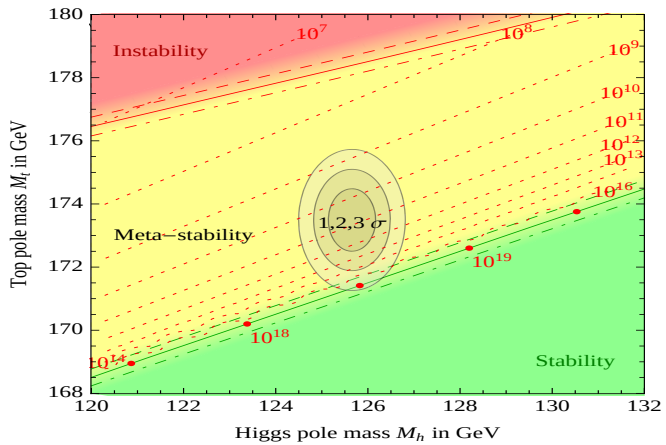
"Precision Measurements of M_t"



Constraints in the parameter space of New Physics Theories

BSM "Stability Test"

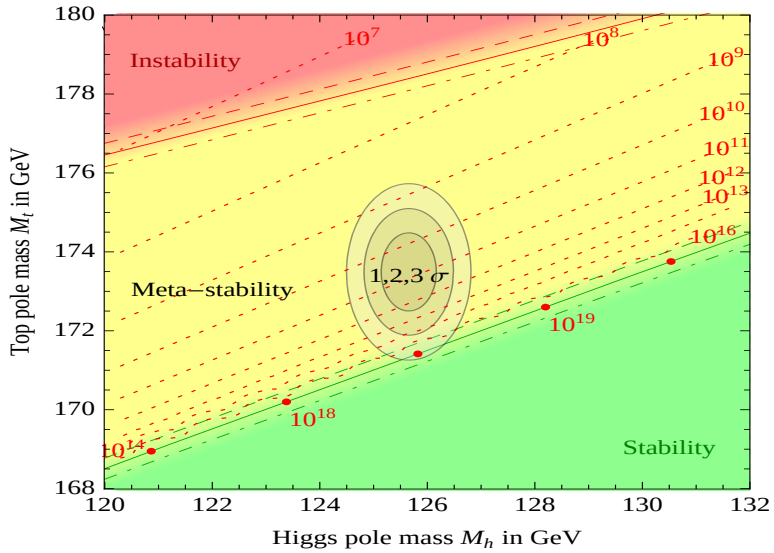
"Near-Criticality"



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



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

Dulcis in Fundo ...

... Although this morning ...

... Dulcis at the beginning ...

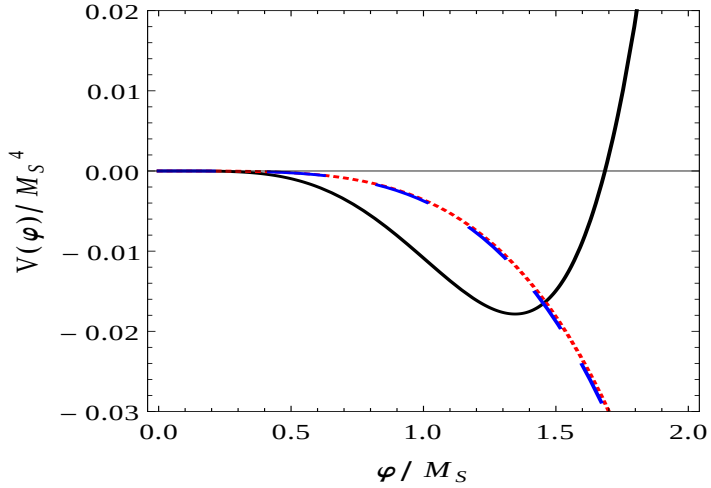
A Renormalizable (Toy) Model for New Physics

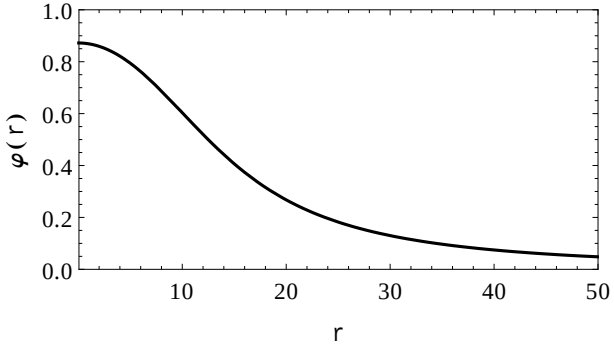
Consider the following UV completion for the SM :

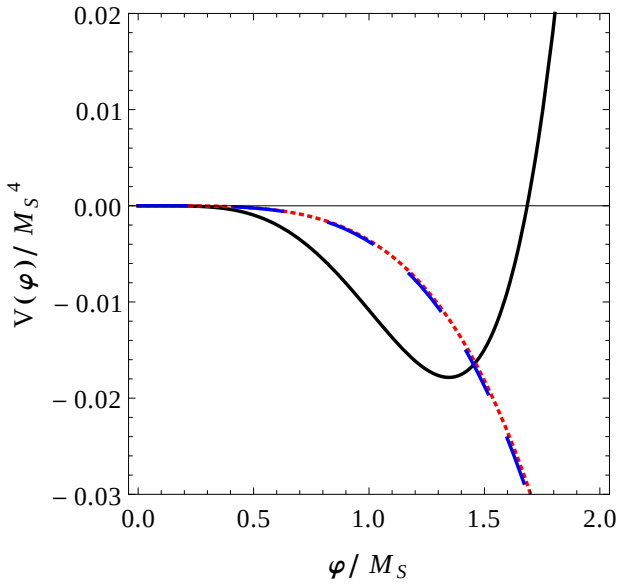
$$\Delta V(\phi, S, \psi) = \frac{M_S^2}{2} S^2 + \frac{\lambda_S}{4} S^4 + \frac{g_S}{4} \phi^2 S^2 + M_f \bar{\psi}\psi + \frac{g_f}{\sqrt{2}} \phi \bar{\psi}\psi$$

with $M_f \sim 10^{17}$ GeV and $M_S \sim 10^{18}$ GeV.

After imposing "treshold conditions" at M_f, so that the potential for $\phi \leq M_f$ has the SM form, we get the Modified Higgs Potential :







With this New Potential we compute again the "bounce solution" and then the tunnelling time ...

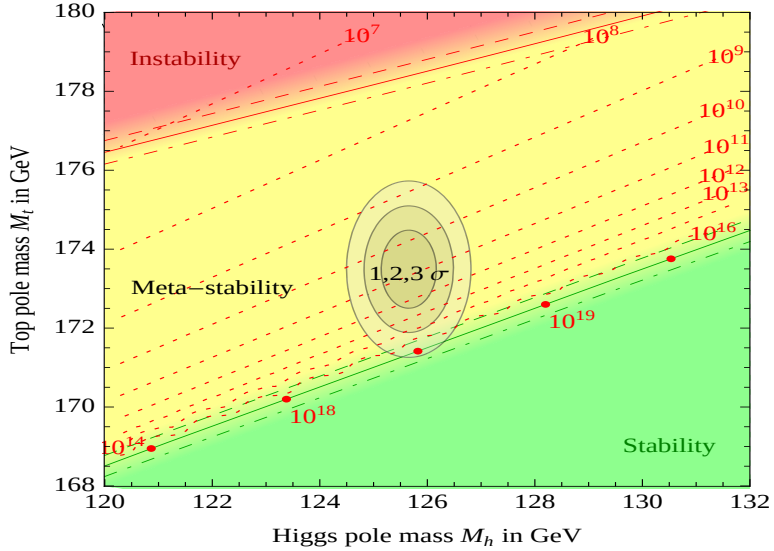
$$\tau \sim 10^{-30} T_U \quad ; \quad \tau \sim 10^{15} T_U \quad ; \quad \ldots$$

To be compared with : $\tau \sim 10^{600} T_U$ **(without new physics)**

... Remember ...

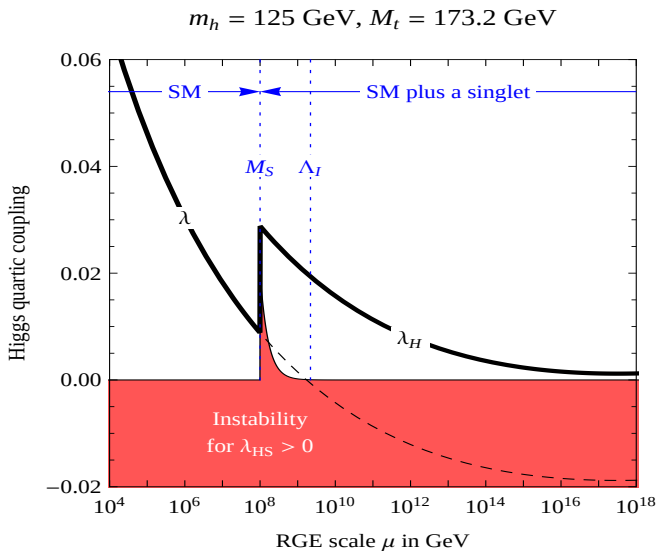
$$\tau \sim 10^{600} T_U$$

is the value associated with the experimental point in this stability diagram, where it is assumed that the UV completion of the SM at energies much higher than the instability scale has no impact on the stability diagram



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

... Before going to the Conclusions ... Note that ...



Elias-Miró, Espinosa, Giudice, Lee, Strumia, *Stabilization of the Electroweak Vacuum by a Scalar Threshold Effect*, **JHEP 1206 (2012) 031**

This is a different effect, known and accepted by everybody: New Physics below the instability scale Λ_I has an impact on the stability condition of the EW vacuum. What is new in the analysis that I have presented is that even if New Physics shows up only at very high energies (Planck scale), it can have a huge effect on the stability condition of the EW vacuum...This was unexpected for the reason that I explained...

Summary and Conclusions

- **The Stability Phase Diagram of the EW vacuum strongly depends on New Physics even if it shows up at very high energies ($\sim M_P$)**
- **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 ?? ... Any small seed of new physics screws up the conditions**

$$\lambda(M_P) \sim 0 \quad \text{and} \quad \beta(\lambda(M_P)) = \left(\mu \frac{d\,\lambda(\mu)}{d\,\mu}\right)_{\mu=M_P} \sim 0$$

- **The results that I presented 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 $\tau << T_U$!!).**
- **This analysis can be repeated even if the new physics scale lies below the Planck scale (for instance, GUT scale), or above ... transplanckian physics ...**

BACK UP SLIDES

... Quotations concerning the "Old View" ...

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

"For most of the relevant values of the top and Higgs masses, the instability scale Λ is sufficiently smaller than the Planck mass, **justifying the hypothesis of neglecting effects from unknown Planckian physics**."

From: **Isidori, Ridolfi, Strumia, Nucl.Phys. B609 (2001) 387**

"The SM potential is eventually stabilized by unknown new physics around Λ_{Pl} : because of this uncertainty, we cannot really predict what will happen after tunnelling has taken place. **Nevertheless, a computation of the tunnelling rate can still be performed, this result does not depend on the unknown new physics at the Planck scale.**"

"It is important to notice that, for the experimentally interesting values of m_H and m_t , the tunnelling rate is dominated by bubbles with $1/R$ about two orders of magnitude below Λ_{Pl}, as can be seen in Fig. 1 or, more clearly, in Fig. 3. **Therefore the metastability bound on m_H does not depend on the unknown physics around Λ_{Pl}**."

... "New" ...

- Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia, *Investigating the near-criticality of the Higgs boson*, JHEP 1312 (2013) 089 , arXiv:1307.3536v2

"Even if Λ_I is much smaller than M_P, new physics at the Planck scale can affect the stability condition [52]. [...] unknown Planckian dynamics can affect the tunnelling rate [52]"

- F. Bezrukov, M. Shaposhnikov, *Higgs inflation at the critical point*, arXiv: 1403.6078v2

"Adding operators suppressed by the Planck scale would change the inflationary physics, cf. [45] for importance of such terms for the stability of electroweak vacuum."

- T. Gehrmann, "QCD and High Energy Interactions: Moriond 2014 Theory Summary" , arXiv:1406.5379

"it has recently been demonstrated [37] that new physics at the Planck scale could lead to much smaller tunnelling times, thus invalidating the metastability condition. These new insights may provide very valuable input to model building for Planck scale physics."

- Degrassi et al., "What Next" May 2015 ...

"The fact that in Eq.(14) the probability for the vacuum to decay is connected to the scale Λ_B close to M_P and not to Λ_I is a signal that Planckian physics could affect the tunneling rate [183]. It is conceivable that at scales close to M_P the effective potential could be sensitive to Planckian physics which possibly could

dramatically modify the tunneling rate. An explicit toy example of this possibility has been constructed [183]. However, we do not know anything about Planckian physics and therefore no conclusion can be drawn whether the tunneling rate is modified by Planckian effects or not."

V. Branchina, E. Messina, Phys.Rev.Lett.111, 241801 (2013)