Standard Model and beyond after the Higgs discovery

Gino Isidori
[*INFN, Frascati & CERN*]

- Introduction
- The Higgs potential at high energies
- Stability and metastability bounds
- Vacuum stability at NNLO
- Speculations on Planck-scale dynamics
- Conclusions

Introduction

All known phenomena in particle physics (*leaving aside a few cosmological observations*) can be described with good accuracy by a remarkably simple (*effective*) theory:

$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\rm Symm.\ Break.}(\phi, A_a, \psi_i)$$

- *Natural*
- Experimentally tested with high accuracy
- Stable with respect to quantum corrections (UV insensitive)
- Highly symmetric

$$\mathscr{L}_{\rm gauge} = \Sigma_a - \frac{1}{4g_a^2}(F_{\mu\nu}^a)^2 + \Sigma_\psi \Sigma_i \bar{\psi}_i i\not{D}\psi_i$$

- $SU(3)_c \times SU(2)_L \times U(1)_Y$ *local symmetry*
- *Global flavor symmetry*

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- Stable with respect to quantum corrections (UV insensitive)
- Highly symmetric [*gauge + favor symmetries*]

- *Ad hoc*
- Necessary to describe data [*the electroweak symmetry forbid masses for all the elementary particles observed so far...*]
- Not stable with respect to quantum corrections (UV sensitive)
- Origin of the flavor structure of the model [*and of all the problems of the model...*]

Introduction

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- *Natural*
- Experimentally tested with high accuracy

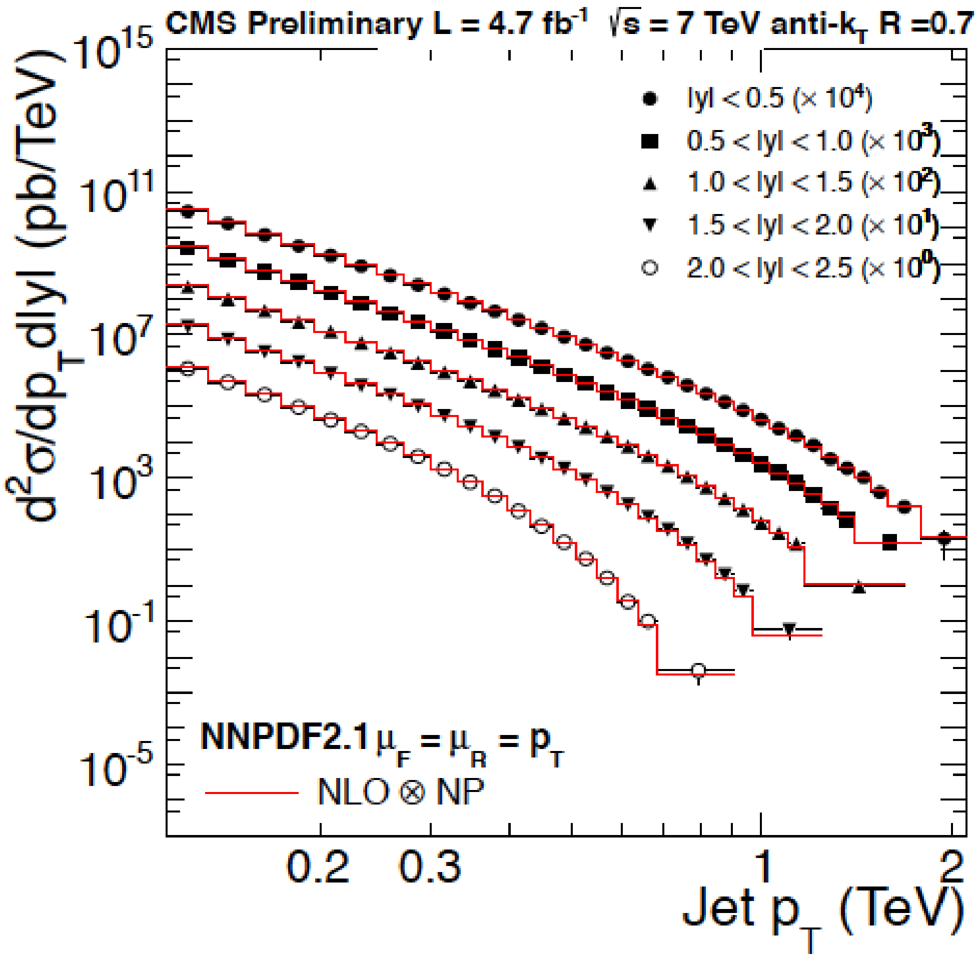
Elegant & stable, but also a bit boring...

- *Ad hoc*
- Necessary to describe data [*we couldn't live in a fully symmetric world...*]

Ugly & unstable, but is what makes nature interesting...!

Introduction

LHC experiments have confirmed once more that we understand very well gauge interactions...



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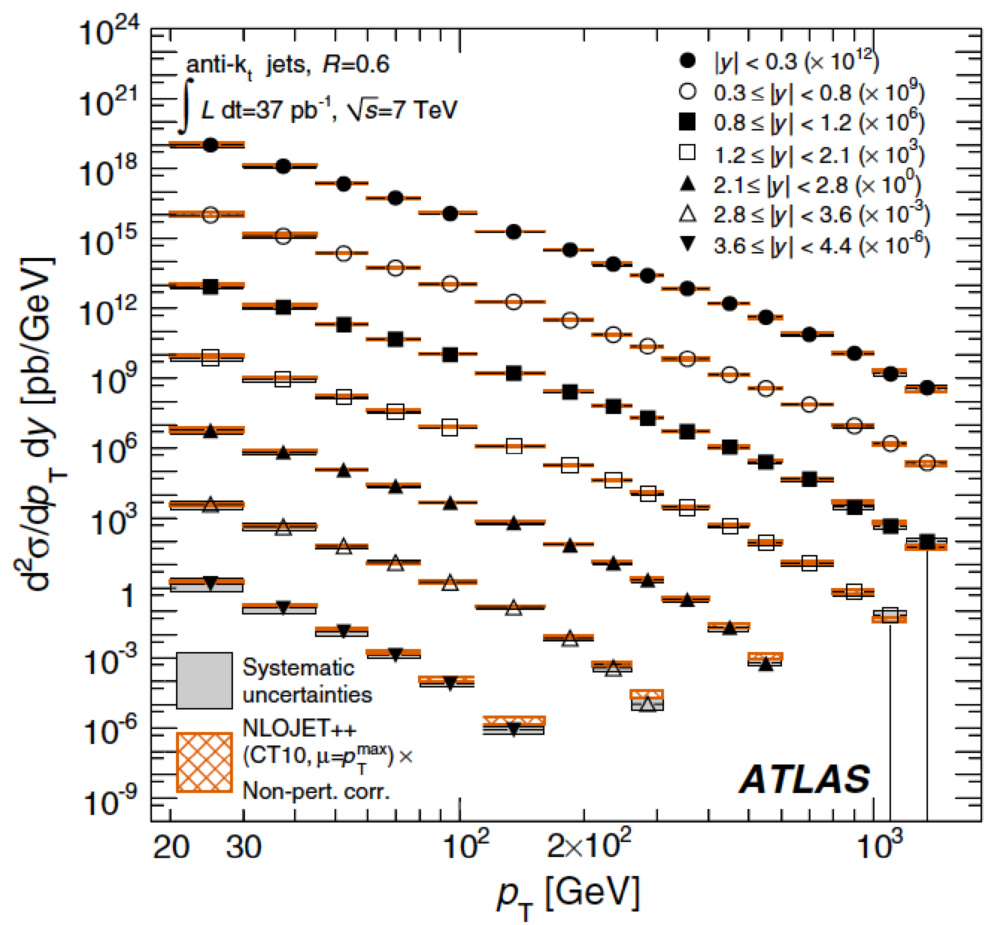
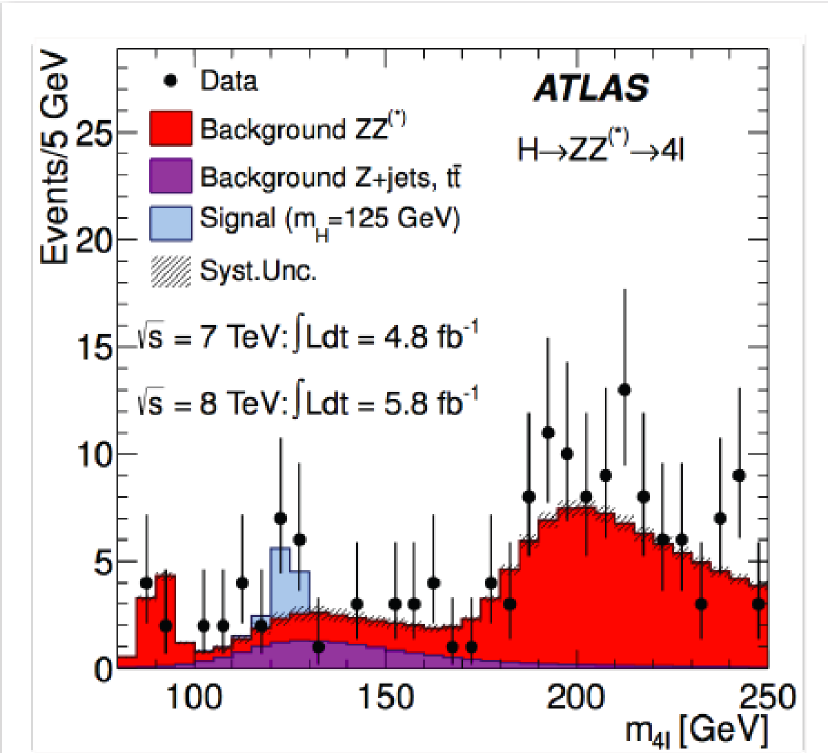
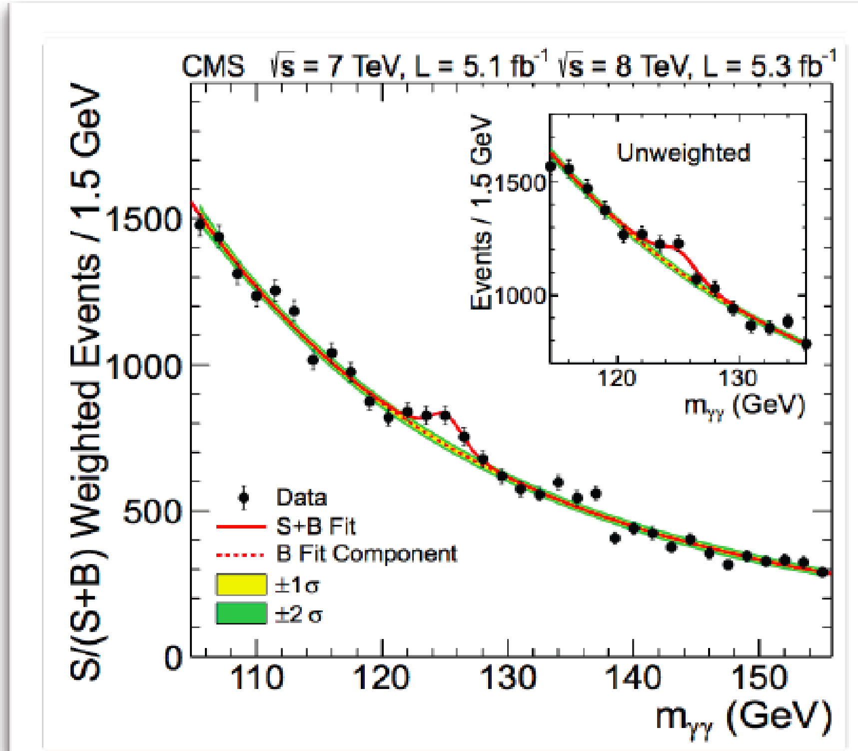


Introduction

LHC experiments have confirmed once more that we understand very well gauge interactions, but the "*breaking-news*" announced the 4th of July 2012 is about the symmetry breaking sector of the theory:



arXiv:1207.7214v1 [hep-ex]

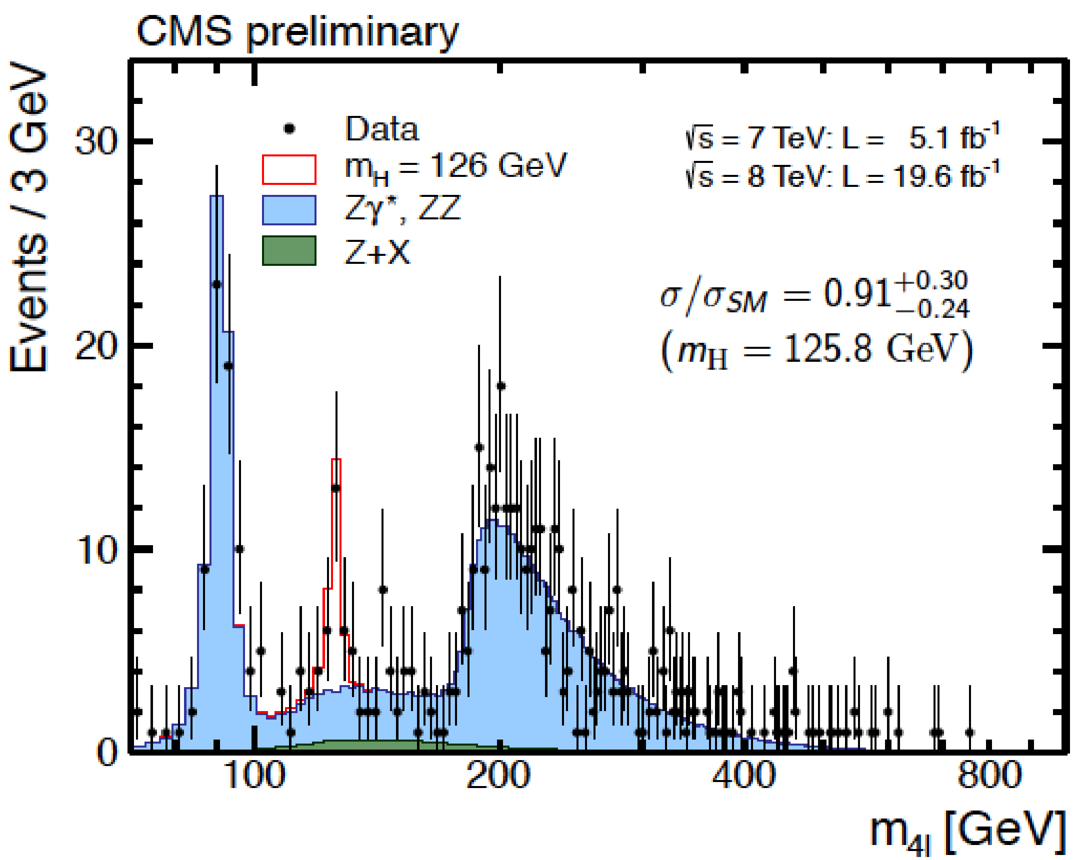


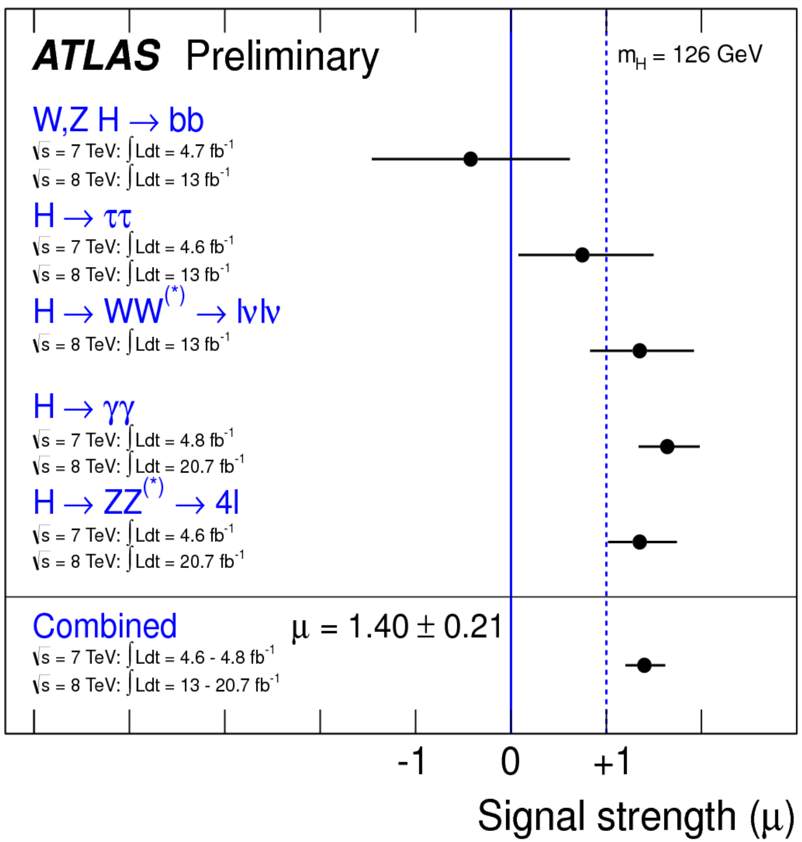
arXiv:1207.7235v1 [hep-ex]

Clear evidence of a new particle compatible with the properties of the Higgs boson

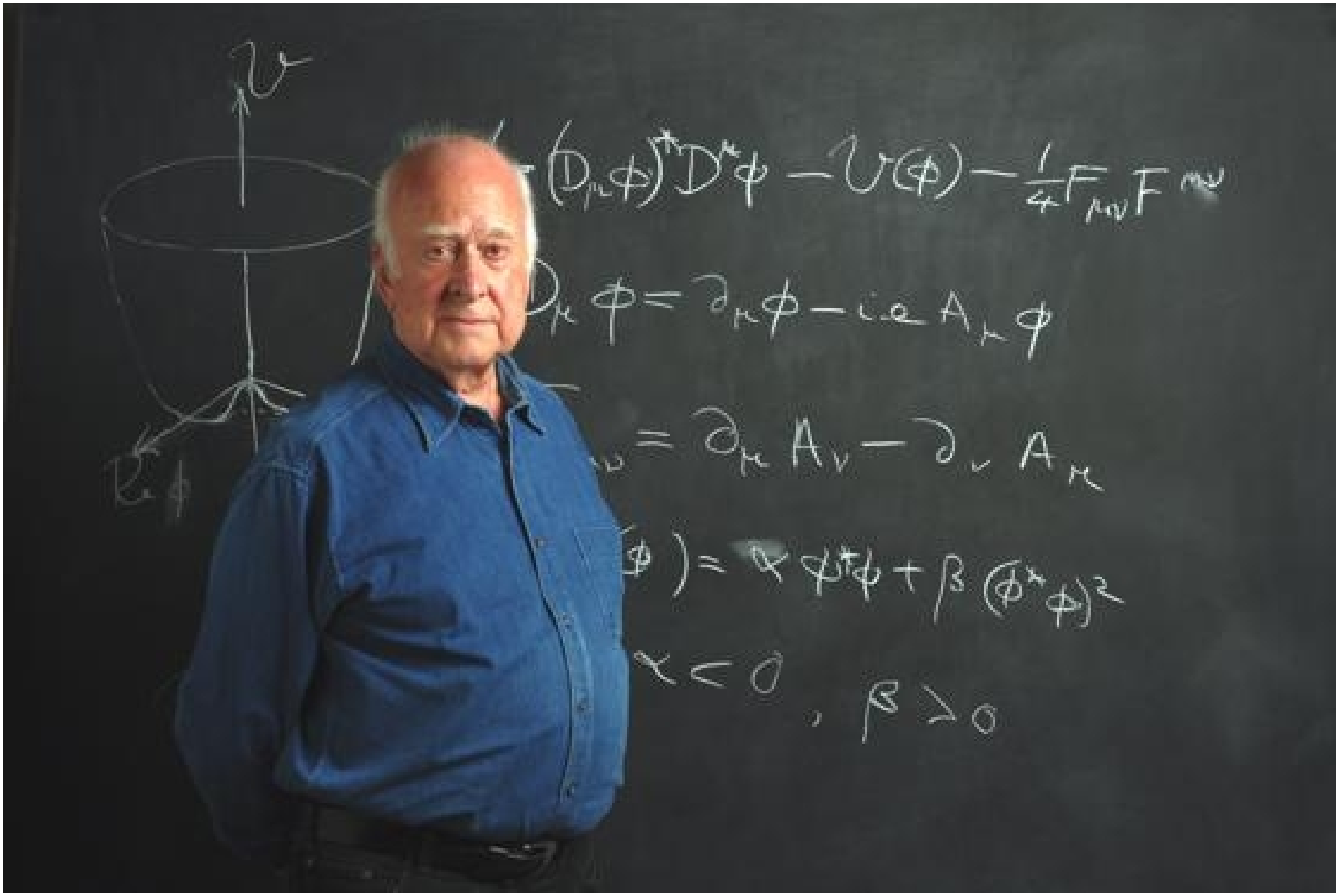
Introduction

The more we a look at it, the more this particle looks like the "standard" Higgs boson:



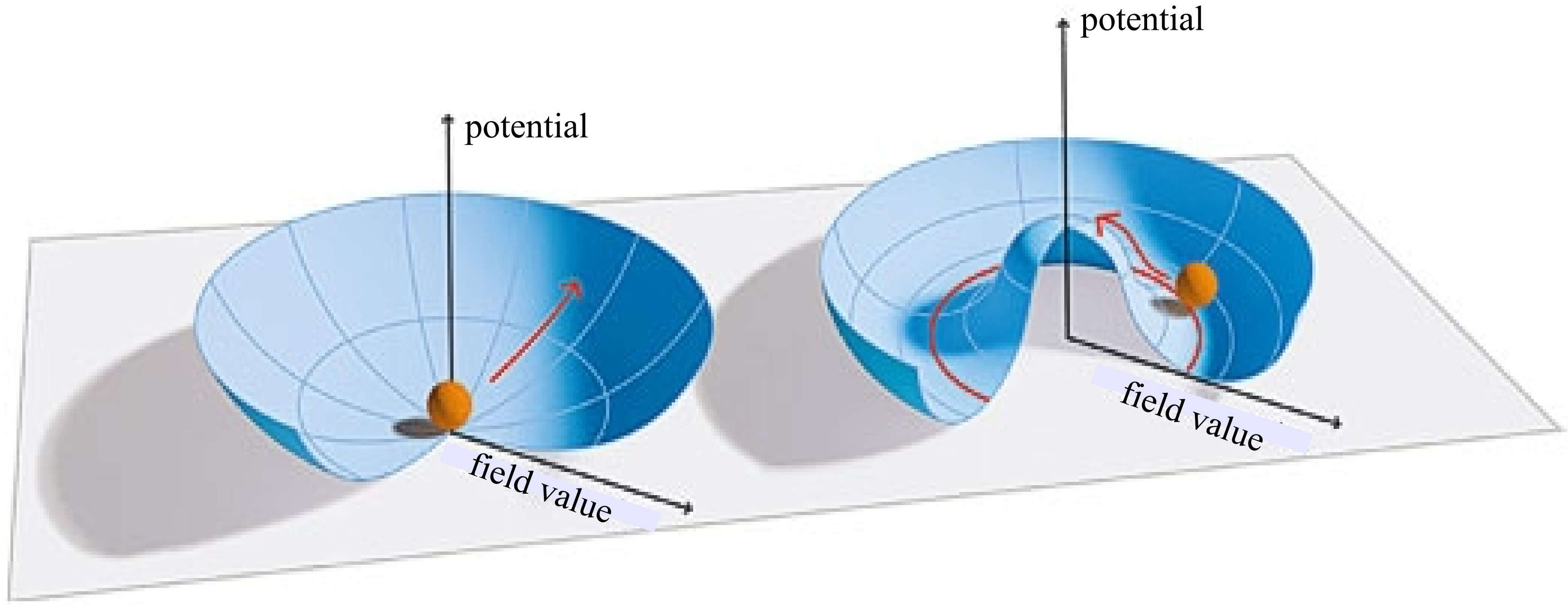


The SM Higgs sector



The SM Higgs sector

The Higgs mechanism, namely the introduction of an elementary $SU(2)_L$ scalar doublet, with ϕ^4 potential, is the most economical & simple choice to achieve the spontaneous symmetry breaking of both gauge [$SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$] and flavor symmetries that we observe in nature.



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$$\mathscr{L}_{\mathrm{higgs}}(\phi, A_a, \psi_i) = D\phi^+ D\phi - V(\phi)$$

$$V(\phi) = -\mu^2 \phi^+\phi + \lambda(\phi^+\phi)^2 + Y^{ij}\, \psi_L^{\,i}\, \psi_R^{\,j}\, \phi$$

Before the start of the LHC only the ground state determined by this potential (*and the corresponding Goldstone boson structure*) was tested with good accuracy:

$$v = \langle \phi^+\phi \rangle^{1/2} \sim 246\ \mathrm{GeV} \quad [\, m_W = \tfrac{1}{2}\, g\, v \,]$$

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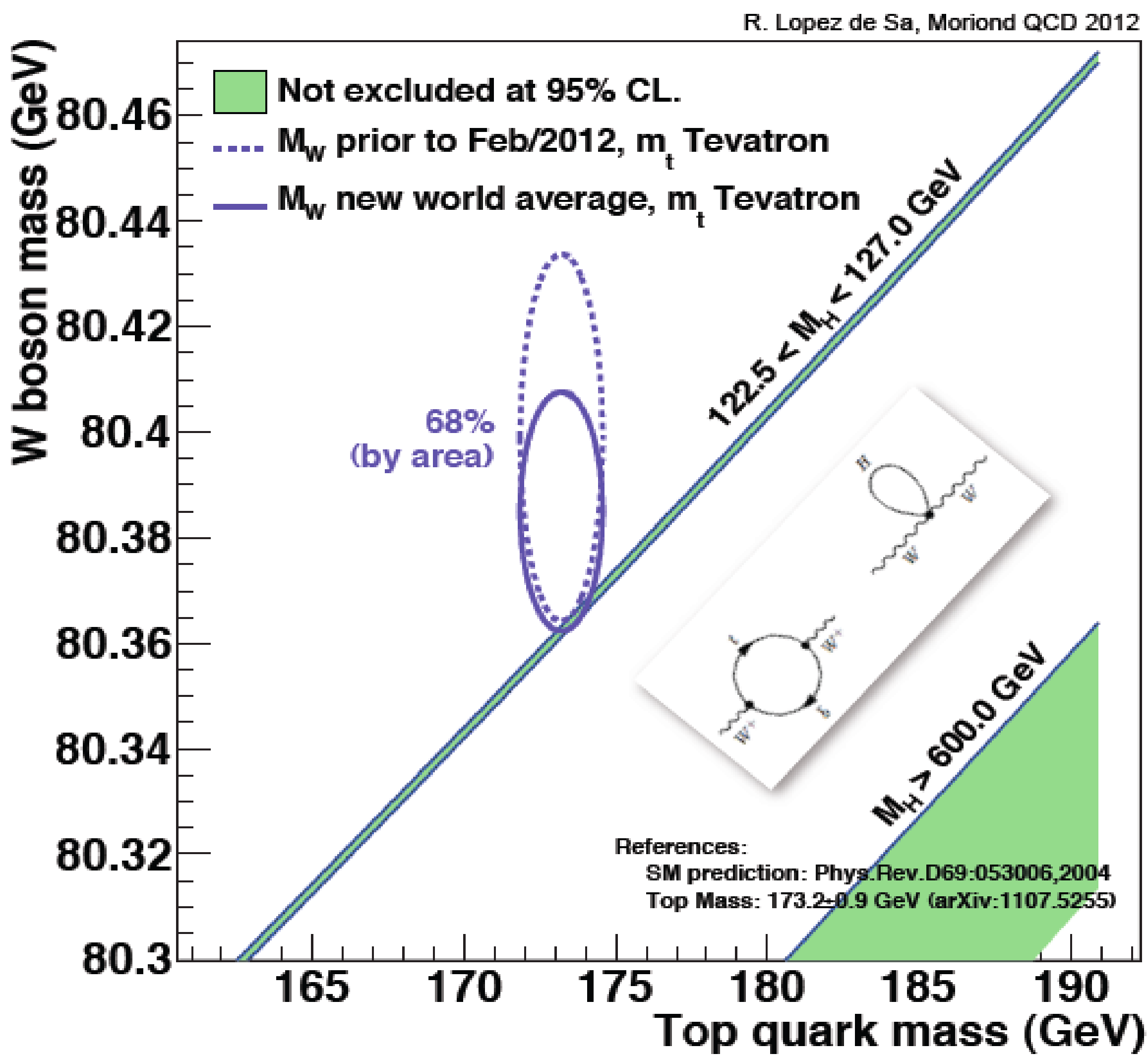
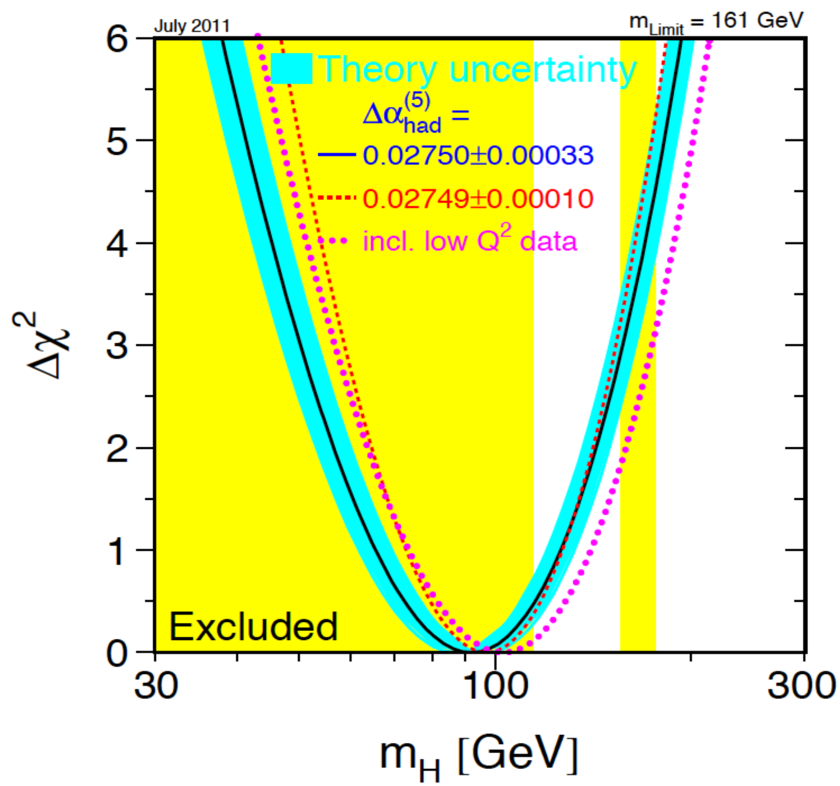
The situation has substantially changed a few months ago, with the observation of the 4^{th} degree of freedom of the Higgs field (or its *massive excitation*):

$$\lambda_{(\text{tree})} = \tfrac{1}{2}\, m_h^{\ 2} / v^2 \sim 0.13$$

▶ The SM Higgs sector

Actually some information about the Higgs mass was already present in the e.w. precision tests (*assuming the validity of the SM up to high scales*):





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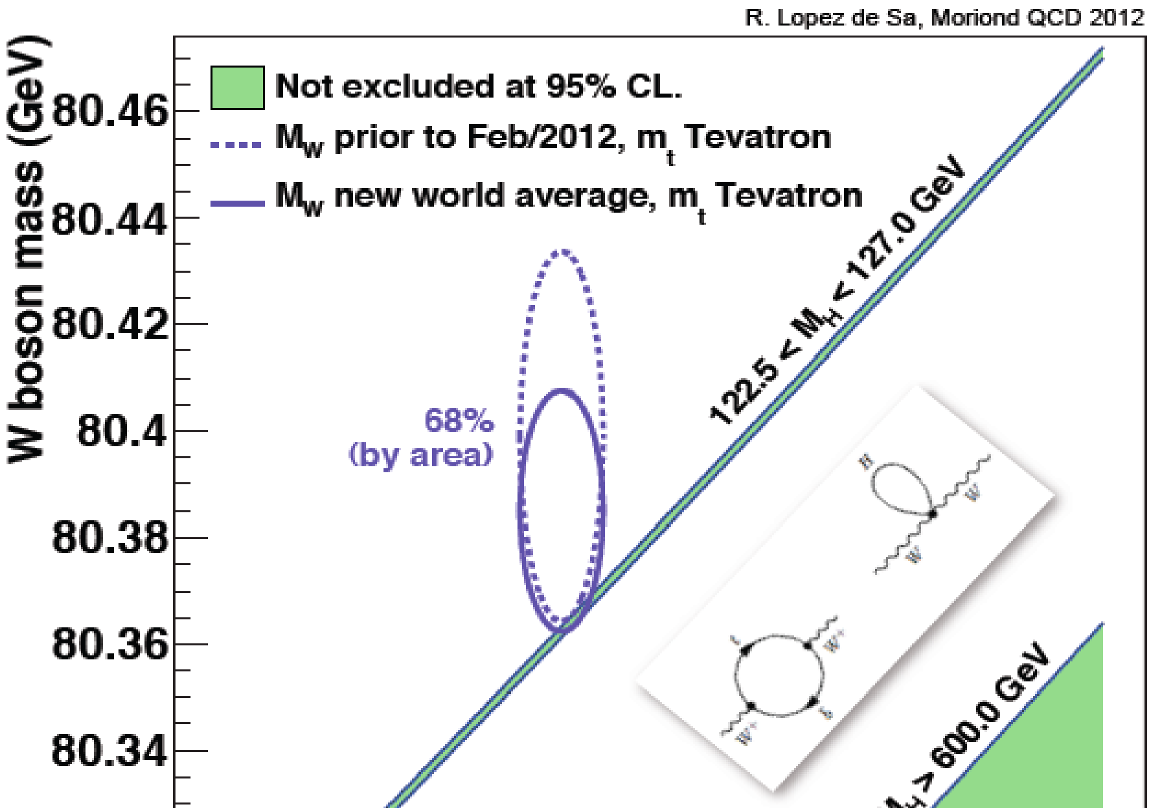

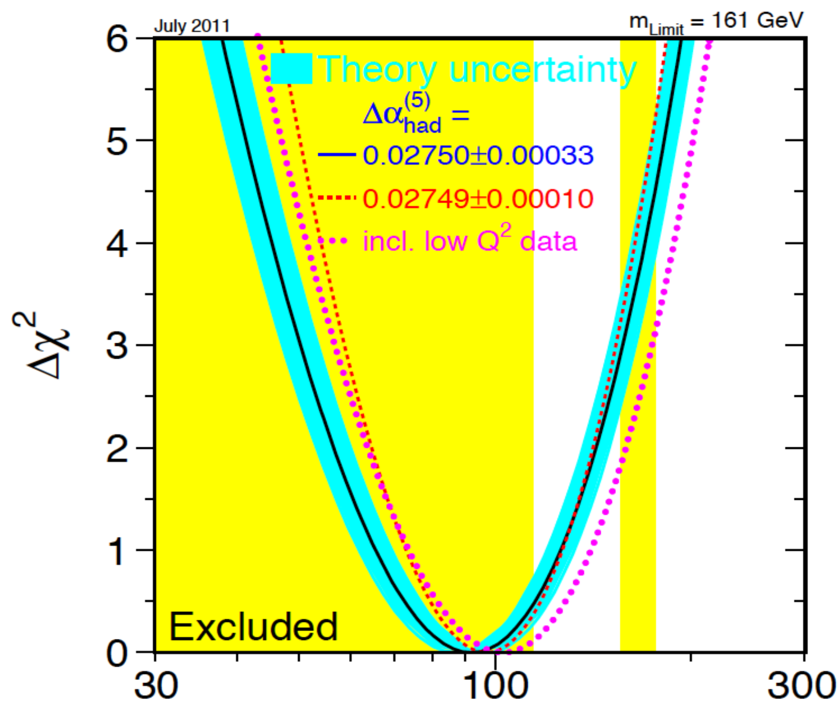

Message n.1: The observation of the physical Higgs boson with m_h well consistent with the (indirect) prediction of the e.w. precision tests is a *great success of the SM !*

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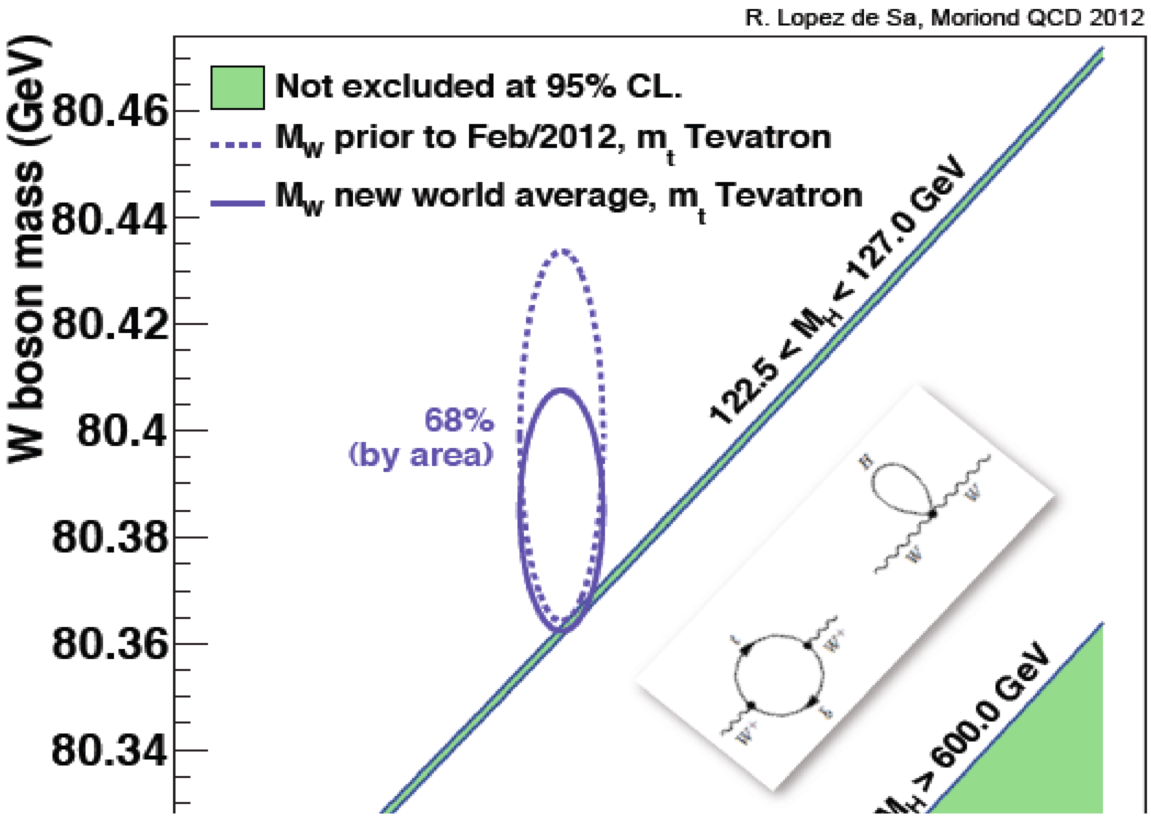

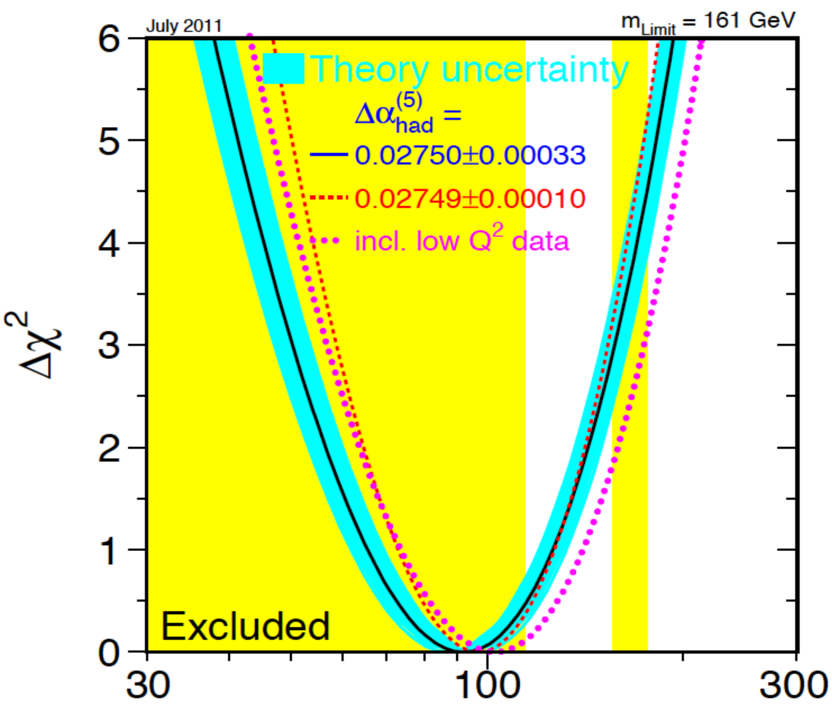

More generally, we have a strong indication that the symmetry breaking sector of the theory has a *minimal* and *weakly coupled* structure (at least around the TeV scale) as in the SM.

The SM Higgs sector

Still, the SM Higgs potential is “ugly” and hides the most serious *theoretical problems* of this highly successful theory:

$$V(\phi) = - \mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2 + Y^{ij} \psi_L^i \psi_R^j \phi$$

vacuum instability

possible internal inconsistency of the model ($\lambda < 0$) at large energies [*key dependence on* m_h]

Quadratic sensitivity to the cut-off

$$\Delta\mu^2 \sim \Delta m_h^2 \sim \Lambda^2$$

(indication of *new physics* close to the electroweak scale ?)

SM flavor problem

(unexplained span over several orders of magnitude and strongly hierarchical structure of the Yukawa coupl.)

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effective neutrino mass term

Cosmological constant prob.

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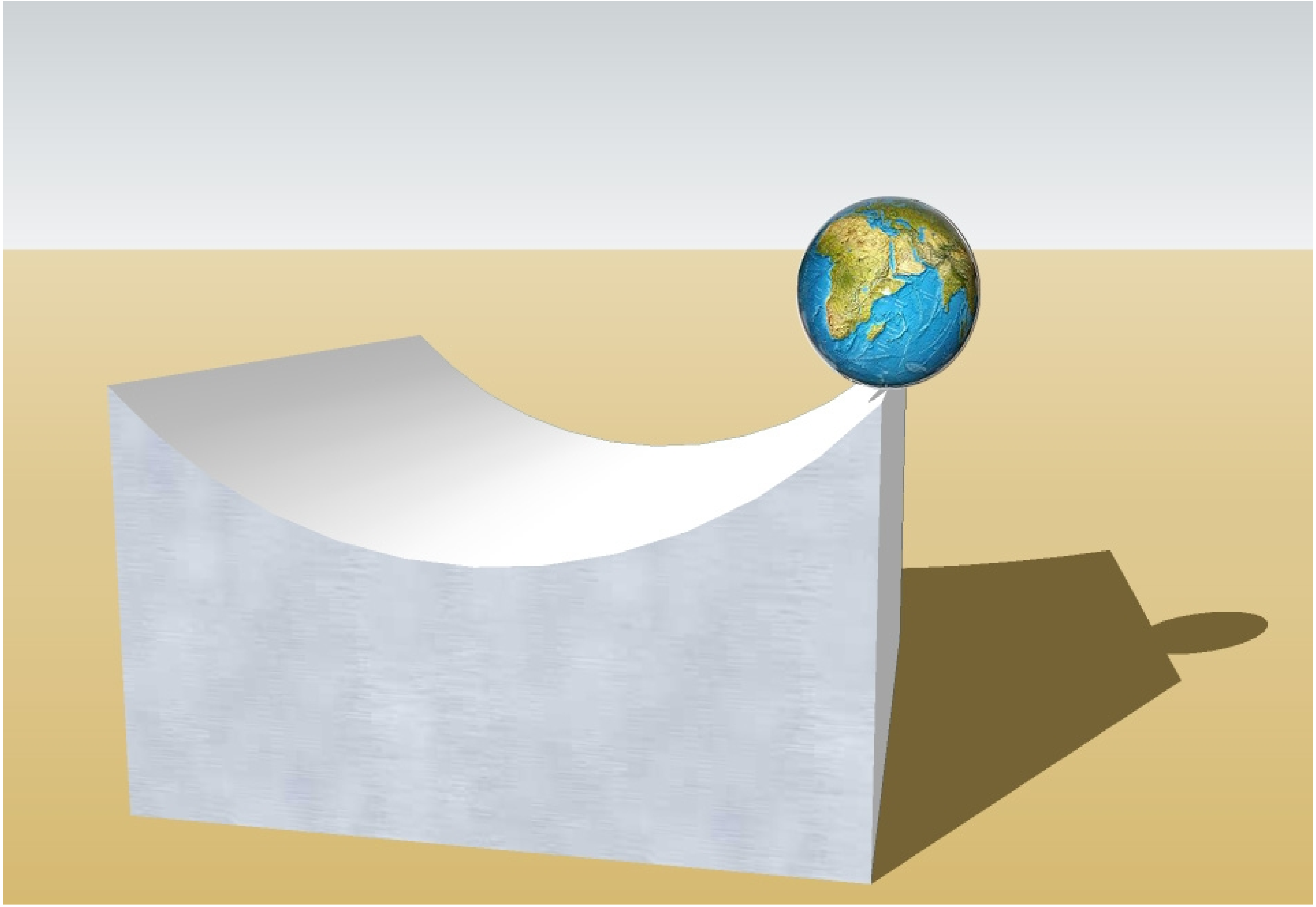
▶ *Stability and metastability bounds*

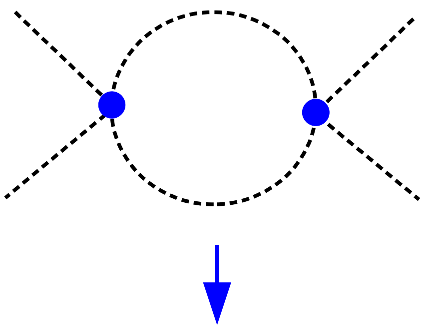


Stability and metastability bounds

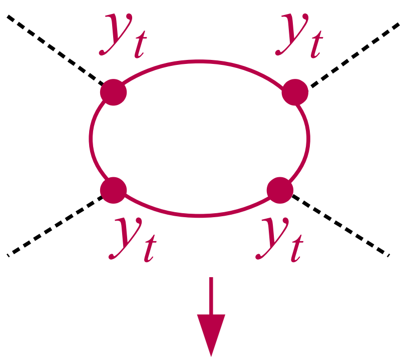
At large field values the shape of the Higgs potential is determined by the RGE evolution of the Higgs self coupling:

$$V_{eff}(\ |\phi| \gg v\ ) \approx \lambda(|\phi|) \times |\phi|^4 + O(v^2|\phi|^2)$$

The evolution of λ is determined by two main effects:



growing λ at large energies



decreasing λ

$$\lambda(v) \propto \frac{m_h^2}{v^2}$$

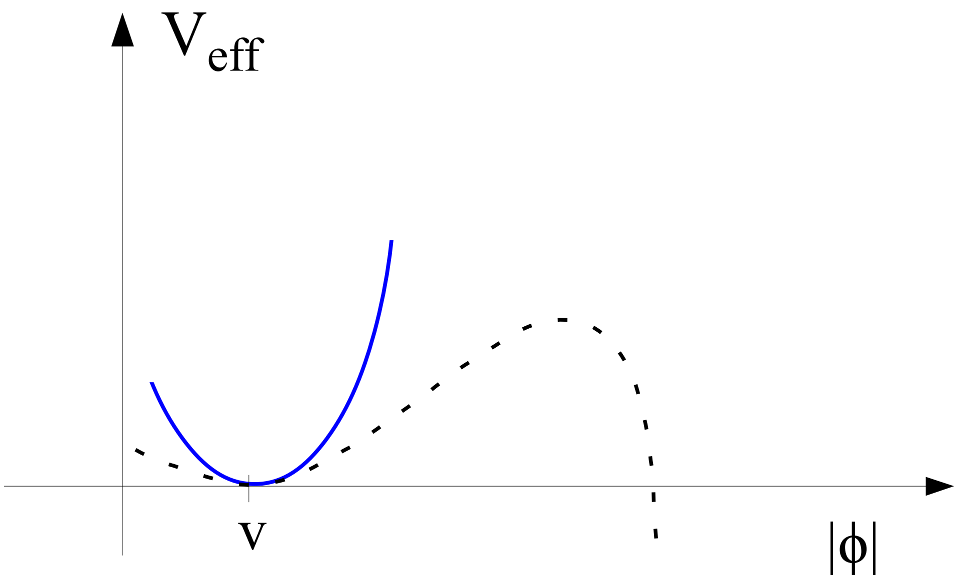
$$y_t(v) \propto \frac{m_t}{v}$$

Given the large value of y_t, the destabilization due to top-quark loops is quite relevant

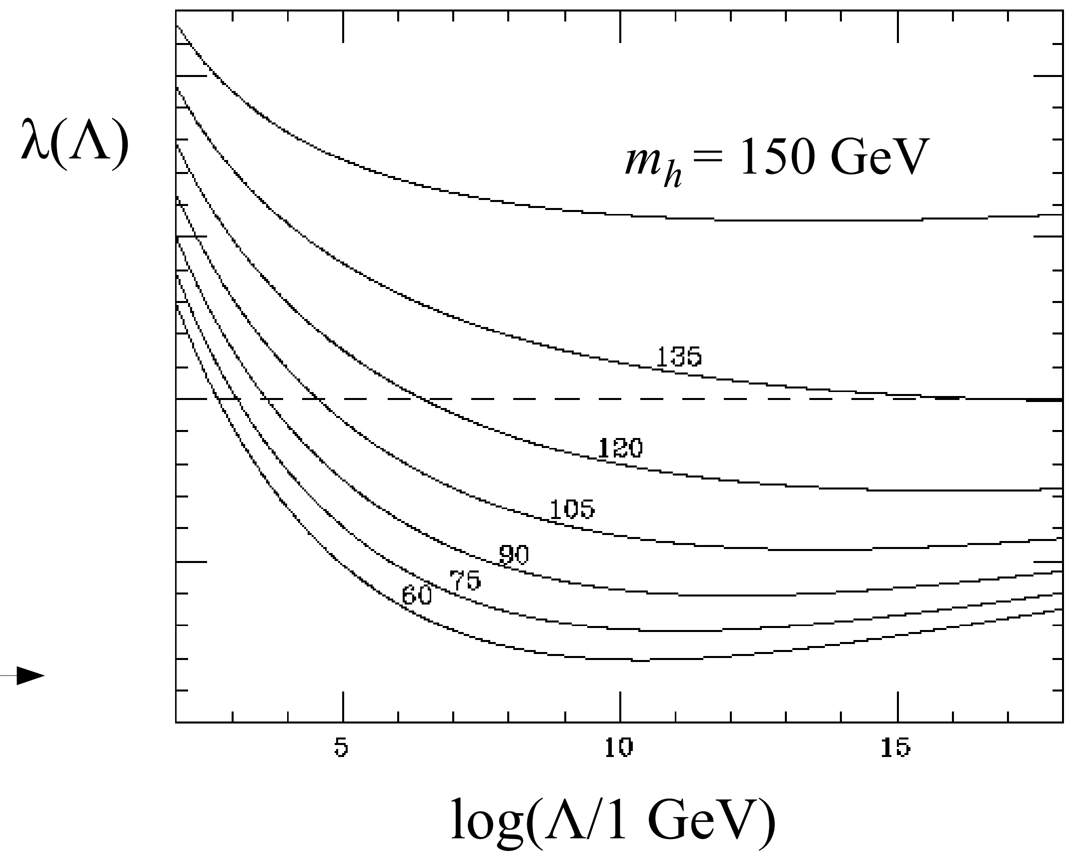
Stability and metastability bounds

At large field values:

$$V_{\rm eff}(|\phi|) \approx \lambda(|\phi|) \times |\phi|^4$$



Altarelli, G.I, '94



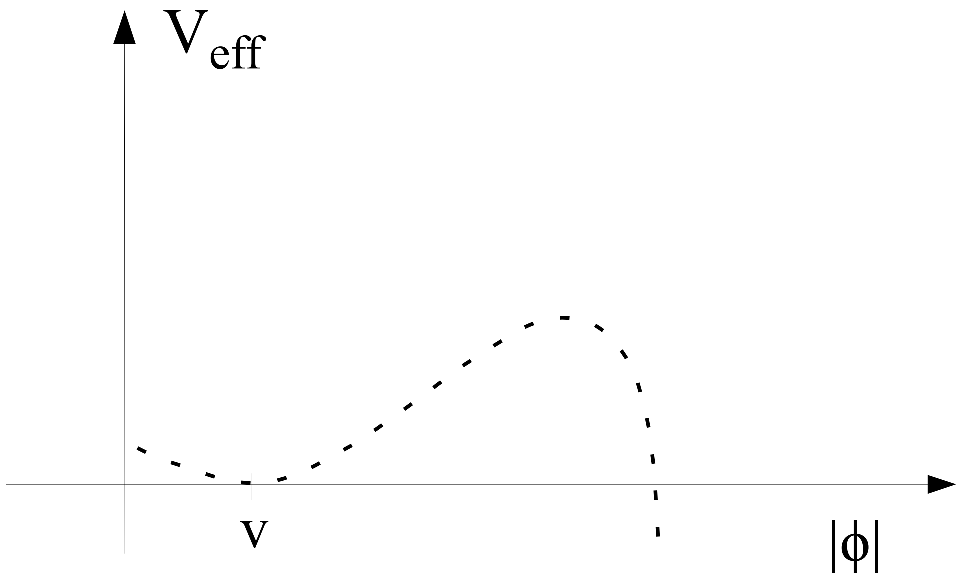
The problem was well-known since a long time, but now for the first time we can "quantify it", knowing the Higgs mass

Cabibbo, Maiani, Parisi, Petronzio, '79; Hung '79; Lindner 86; Sher '89; ....

✯ *The metastability condition:*

Can we rule out the model (and determine an upper bound on the new-physics scale Λ) if there is a second (deeper) minimum at large field values ?

Not really: The model could still be consistent if the lifetime of the (unstable) e.w. minimum is sufficiently long (i.e. longer than the age of the Universe)



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The e.w. minimum is destabilized by:

quantum fluctuations (at T=0)

computable in a model-independent way

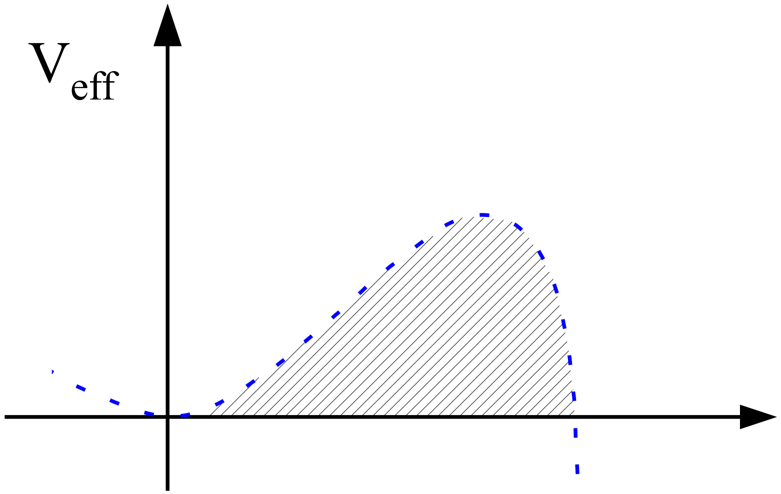
thermal fluctuations

the probability depends on the thermal history of the universe & competes with the quantum tunneling only for very high T

$\Downarrow$

The most conservative bound is obtained by considering the stability under quantum fluctuations at zero temperature

✭ The quantum-tunneling rate:



The quantum tunneling occurs via bubble formation in the homogeneous background of the false (e.w.) minimum

Coleman '79

At the semi-classical level, the tunneling probability can be written as:

$$\boxed{p \approx K\, e^{-S_0[h]}}$$

Volume factor

$K \propto T_U^4$ not exactly calculable within the semi-classical approx.

Euclidean action

$$\int \frac{1}{2}(\partial_\mu h)^2 + V(h)$$

Bounce

solution of the e.o.m. that interpolates between the false and the true vacuum

N.B.: within a QFT (system with infinite d.o.f.) the tunneling is suppressed even in absence of a potential barrier (kinematic barrier due to the boundary conditions)

✯ The quantum-tunneling rate:

If we neglect the mass term, the tree-level Higgs potential is scale invariant & its bounces have a rather simple form:

$$h(r) = \left(\frac{2}{|\lambda|}\right)^{1/2} \frac{2R}{r^2+R^2}$$

$r = x_\mu x_\mu$ $O(4)$ invariant bounces minimize the action

$R =$ arbitrary scale parameter

$$\Downarrow$$

$$S_0[h] = \frac{8\pi^2}{3|\lambda|} \quad \Rightarrow \quad p_{semicl.} \propto e^{-8\pi^2/3|\lambda|}$$

If $|\lambda|$ remains sufficiently small, the tunneling rate can be very suppressed

N.B.: the tunneling rate is a pure non-perturbative phenomenon - cannot be computed to any finite order in "ordinary" perturbation theory [*wrong choice of the vacuum*]

✭ The quantum-tunneling rate:

To go beyond the semi-classical level we need to take into account the quantum fluctuations around the (non-constant) bounce solution

Callan, Coleman '79

Non-trivial problem which has been solved (semi-analytically) in the SM case:

G.I., Ridolfi, Strumia '01

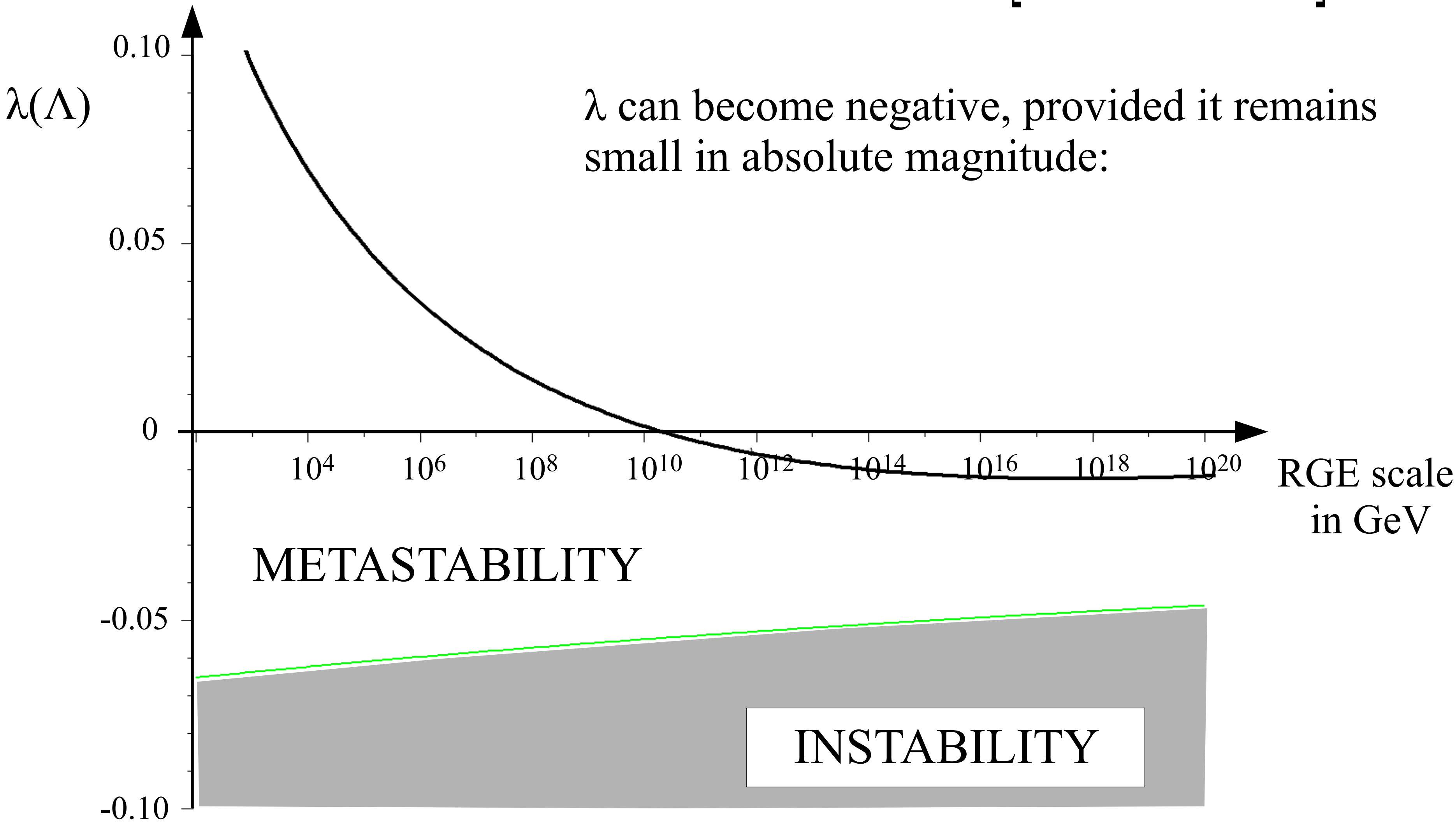
- Quantum corrections break scale invariance + the functional integral provides an unambiguous estimate of the volume factor.
- The tunneling is dominated by bounces of size R, such that λ(1/R) reaches its minimum value:

$$p = \max_R \frac{V_U}{R^4} \exp\left[-\frac{8\pi^2}{3|\lambda(1/R)|} + \begin{array}{c}\text{tiny}\\ \text{higher-order}\\ \text{terms}\end{array} \right]$$

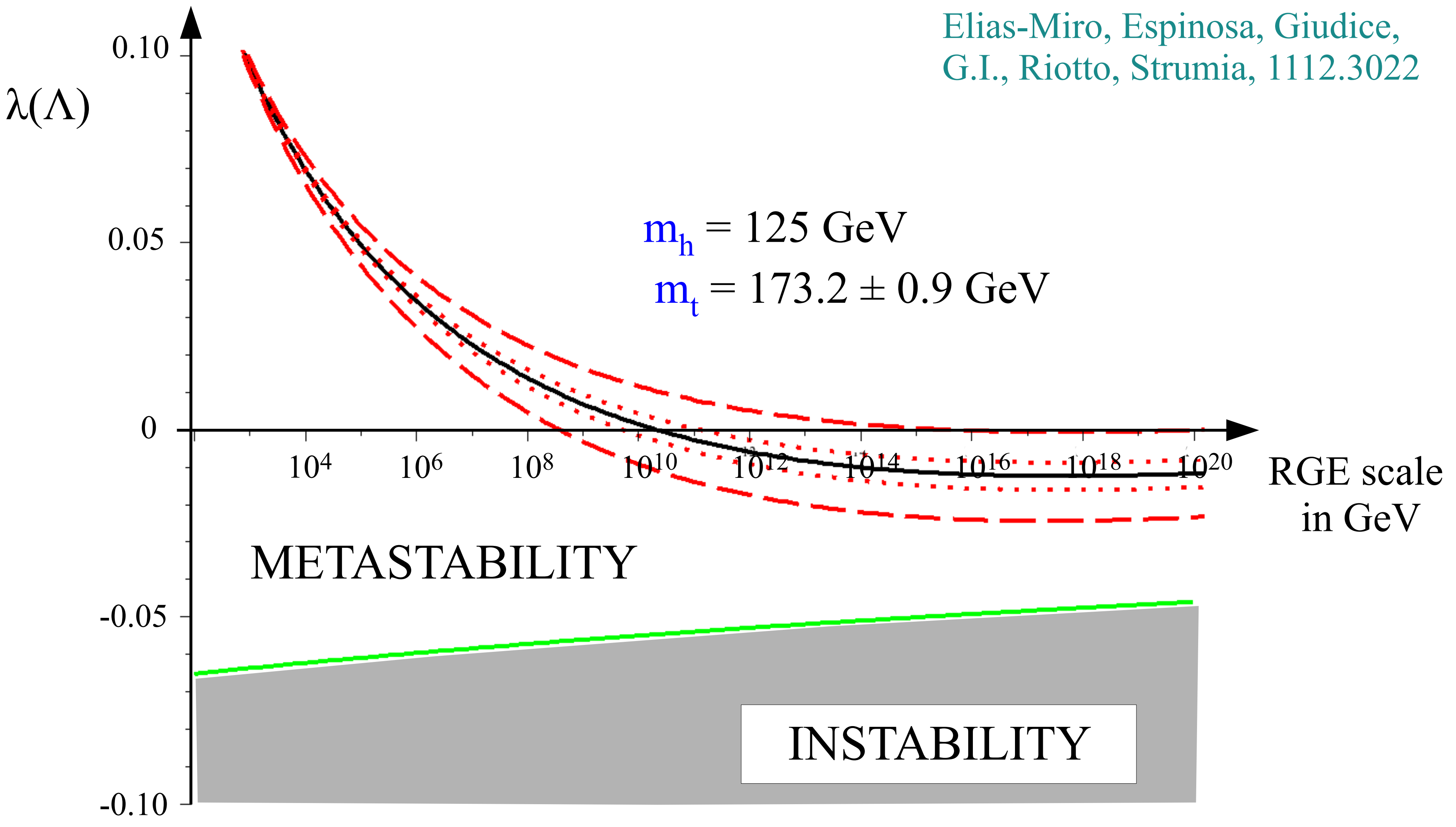
The metastability condition:

$$p \approx \max_R \frac{V_U}{R^4} \exp\left[-\frac{8\pi^2}{3\left|\lambda(1/R)\right|} \right]$$

λ can become negative, provided it remains small in absolute magnitude:



Message n.2: For $m_h \approx$ 125-126 GeV and the present central value of m_{top}, the SM vacuum is unstable but sufficiently long-lived, compared to the age of the Universe



▶ *Vacuum stability at NNLO* (for m_h ~125 GeV)

How "precise" is our estimate of the evolution of λ
(and the corresponding conclusion that the SM potential is unstable)?

A full NNLO analysis has recently become possible:

- Two-loop potential — Ford, Jack, Jones '92, '01
- Three-loop beta functions — Mihaila, Salomon, Steinhauser 1201.5868; Chetyrkin, Zoller, 1205.2892
- Two-loop threshold corrections in relating $\lambda(v)$ to the Higgs mass:

$$\lambda(\mu) = \frac{G_F\, m_h^{\,2}}{\sqrt{2}} + \Delta\lambda(\mu)$$

(*dominant uncertainty*)

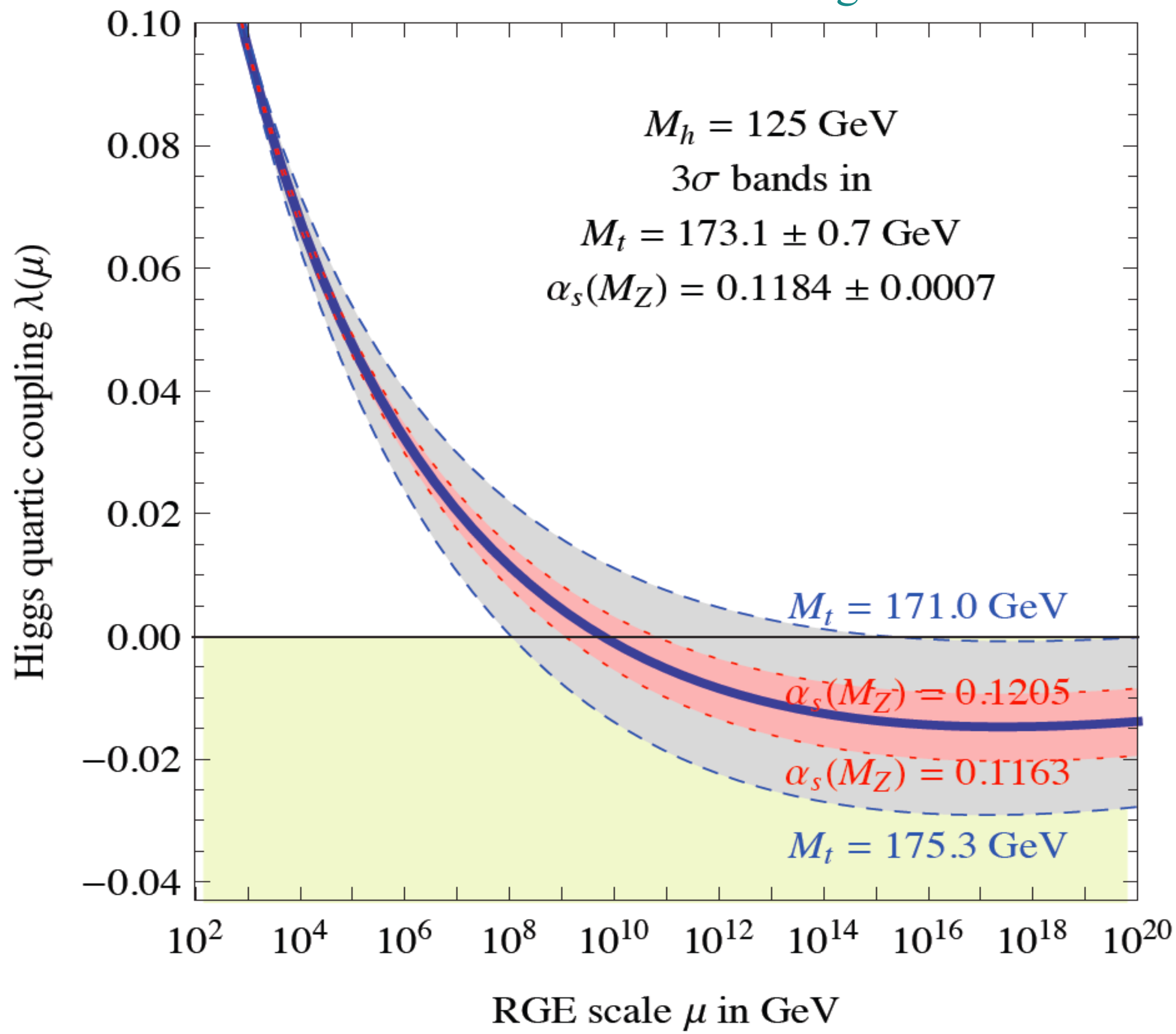
Yukawa×QCD — Bezrukov, Kalmykov, Kniehl, Shaposhnikov, 1205. 2893

Yukawa×QCD
Yuk.×Yuk. — Degrassi, Di Vita, Elias-Miro', Espinosa, Giudice, G.I., Strumia 1205.6497

Given the fast running of λ close to the e.w. scale, the dominant uncertainty comes from threshold (non-log enhanced) corrections at the electroweak scale (or in the precise evaluation of the initial condition).

While the smallness of λ (and the other couplings) at high energies imply that the 3-loop terms in the beta functions play a very minor role (useful to control the error).

Degrassi *et al.* '12



With the NNLO calculation we are able to derive a very precise relation between Higgs and top masses from vacuum stability:

Absolute stability:

$$M_h\ [\mathrm{GeV}] > 129.4 + 2.0\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{1.0}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}$$

Conservative th. error given the size of the shifts from NLO to NNLO:

$+\,0.6\,\mathrm{GeV}$ due to the QCD threshold corrections to λ

$+\,0.2\,\mathrm{GeV}$ due to the Yukawa threshold corrections to λ

$-\,0.2\,\mathrm{GeV}$ from RG equation at 3 loops

$-\,0.1\,\mathrm{GeV}$ from the effective potential at 2 loops.

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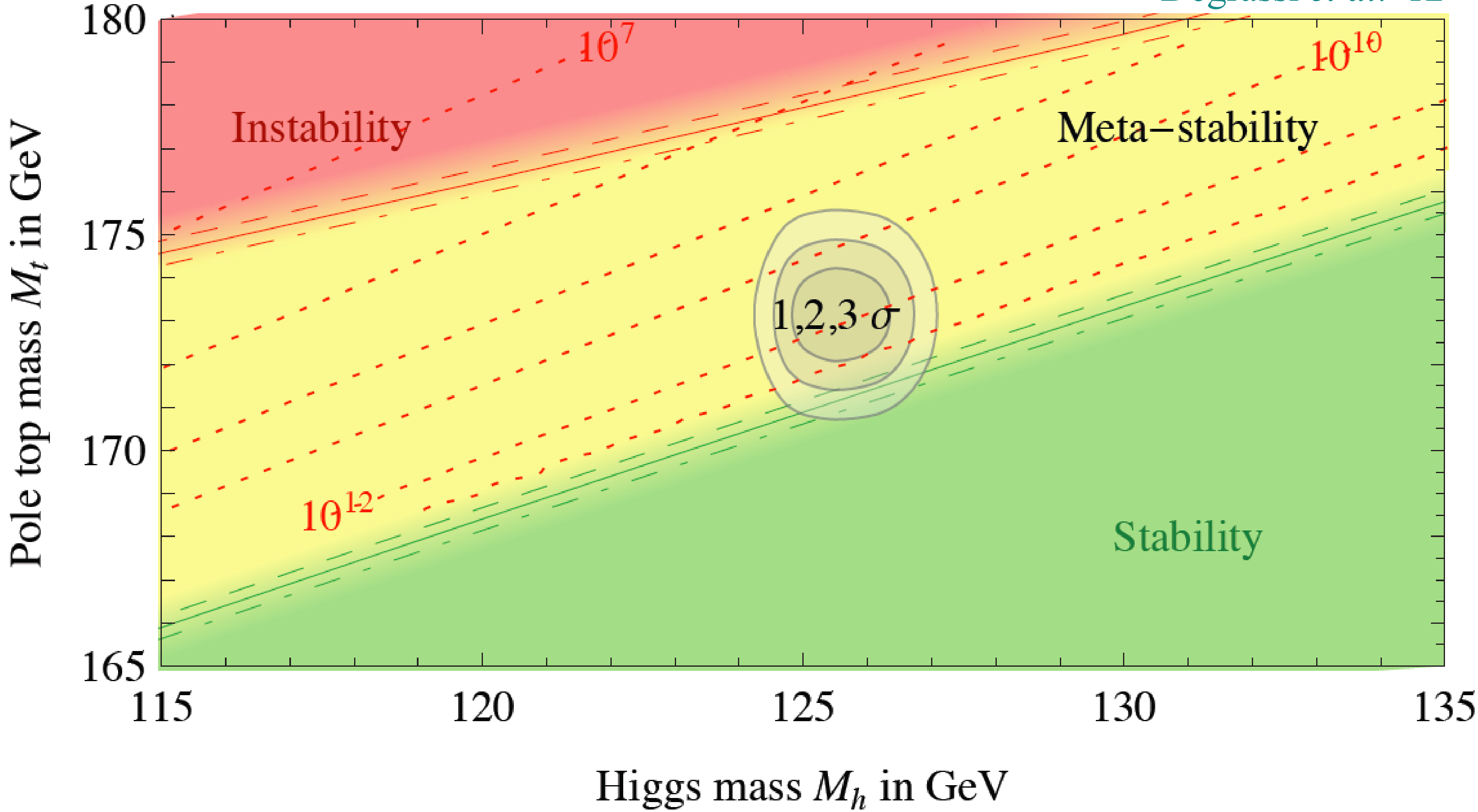

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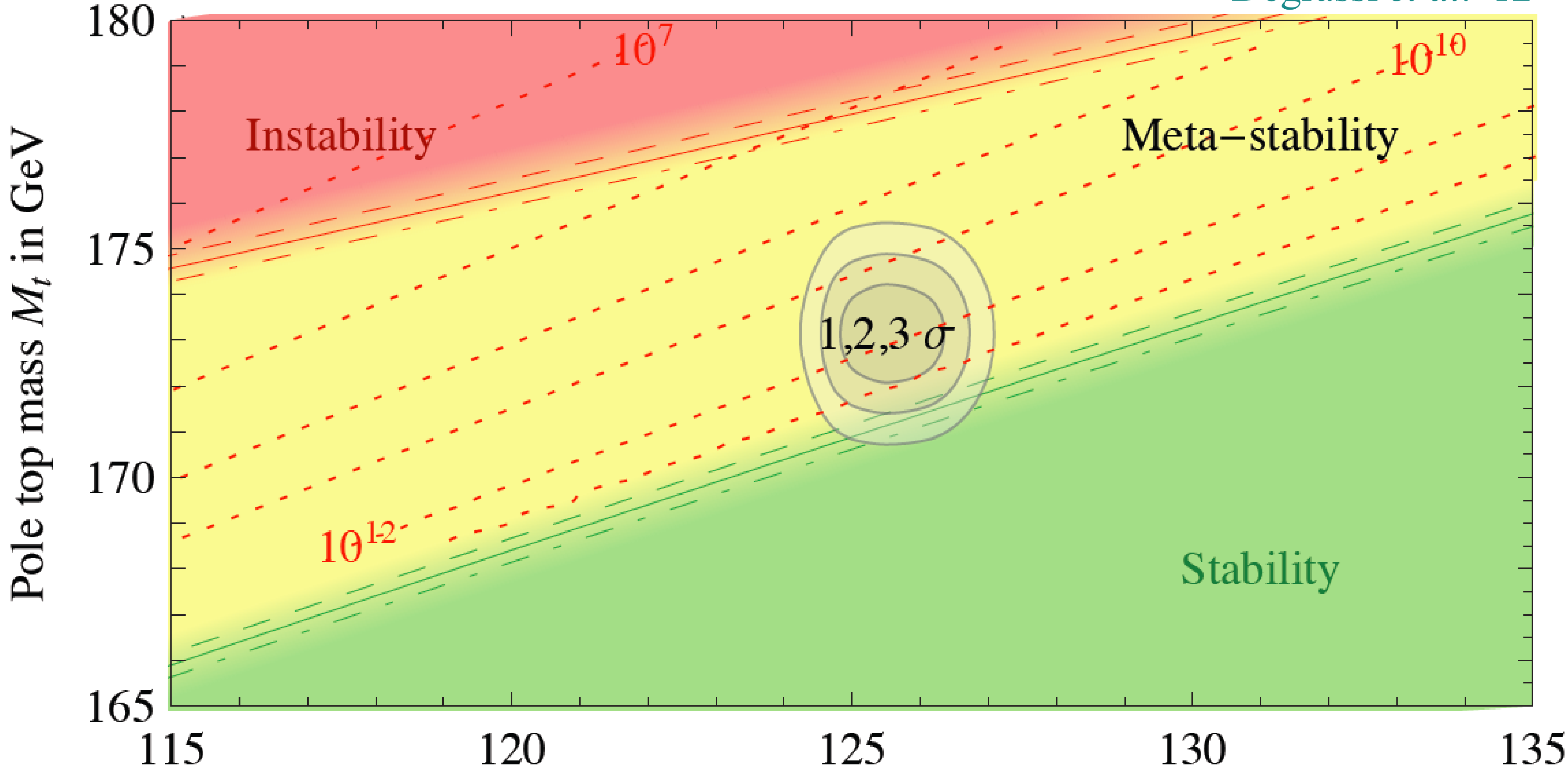

Assuming a precise determination of m_h by ATLAS & CMS in a short time, the main uncertainty will remain the top mass.

Note also that the m_t measured by Tevatron is not really the pole mass (*possible larger error...* Alekhin, Djouadi, Moch '12, Hoang & Stewart, '07-'08)

Two additional remarks about the instability of the SM potential:

I. What about the instability because of thermal fluctuations?

II. What about adding to the model heavy right-handed neutrinos?

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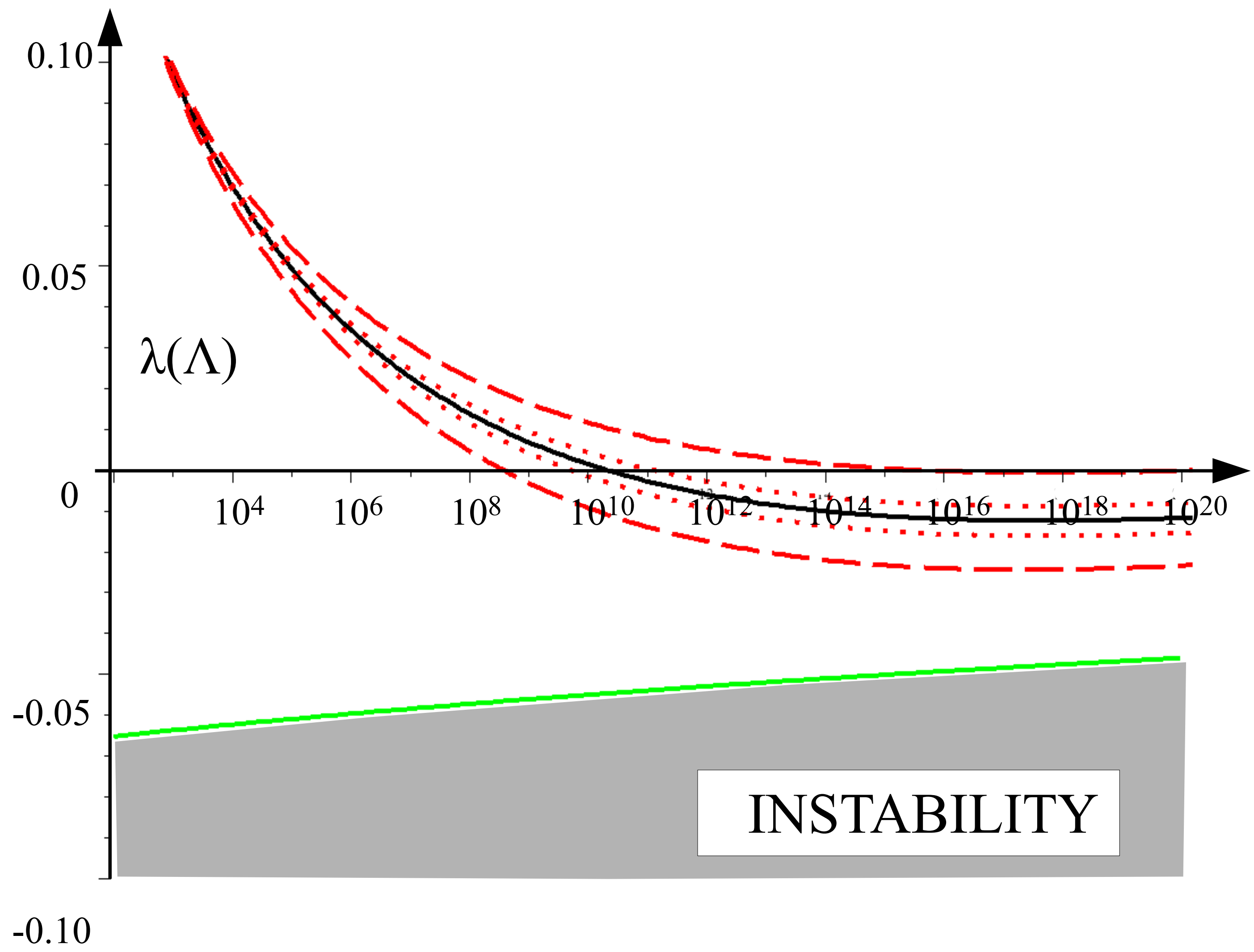
- The instability occurs at very high energies

+

- The Higgs mass is quite close to the stability border

↓

Thermal corrections do not destabilize further the potential.



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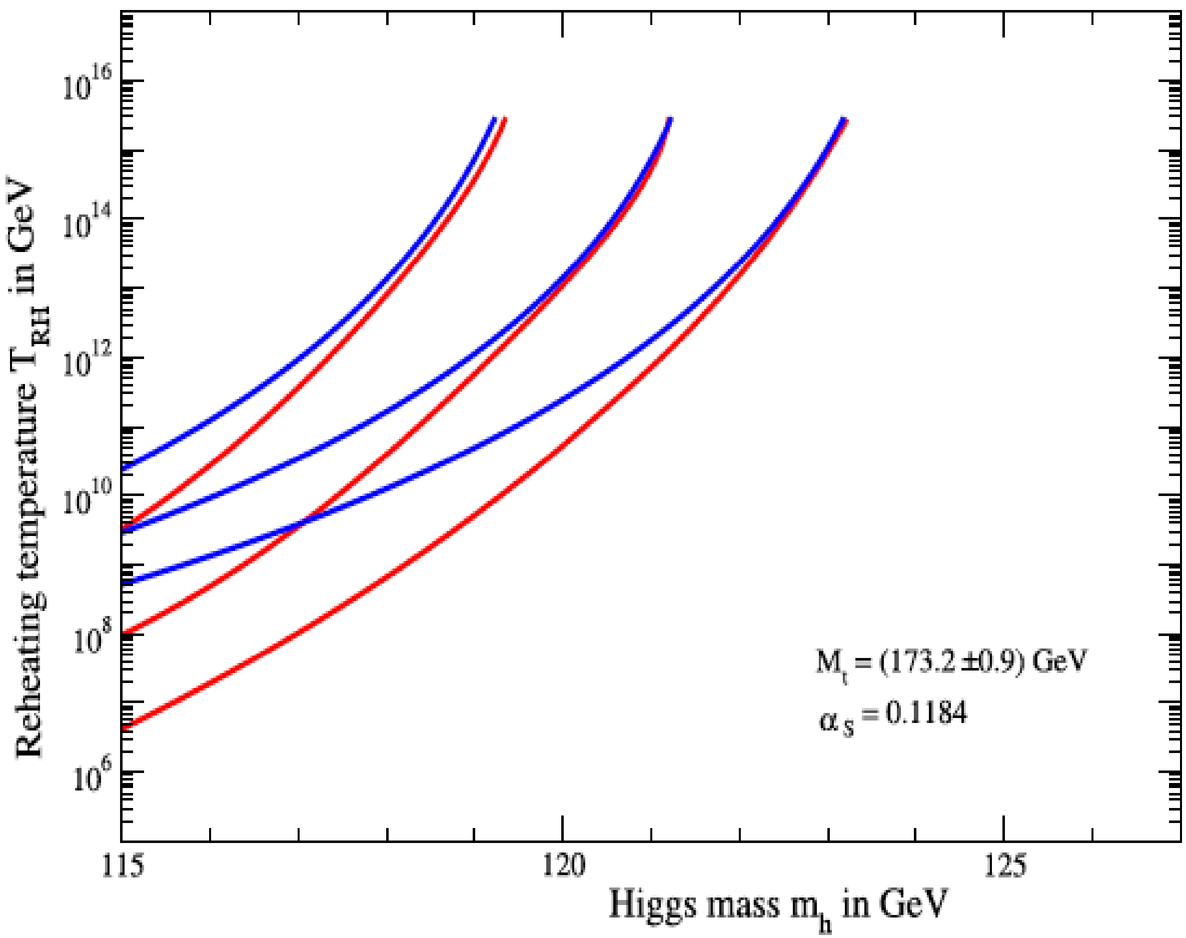
Elias-Miro *et al.* '11



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I. What about the instability because of thermal fluctuations?

Since the instability occurs at very high energies, thermal corrections do not play a significant role in destabilizing the potential.

II. What about adding to the model heavy right-handed neutrinos?

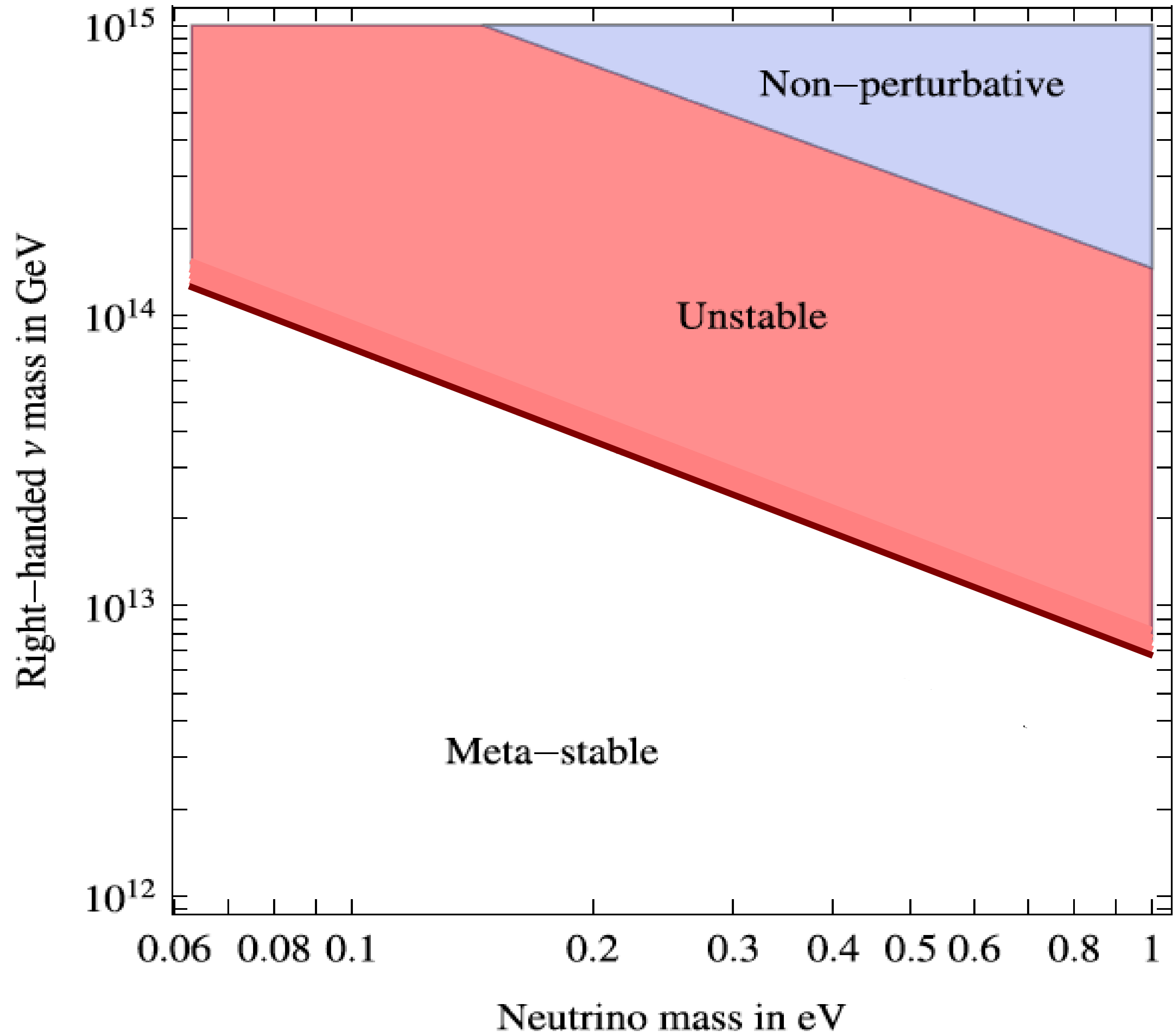
On general ground, adding new fermions may induce a further destabilization of the potential. However, the effect depend on the size of the new Yukawa couplings:

$$m_\nu \sim Y_n^T \frac{v^2}{M_R} Y_n \longrightarrow$$

Requiring a sufficiently stable Higgs potential allow us to derive an upper bound on M_R

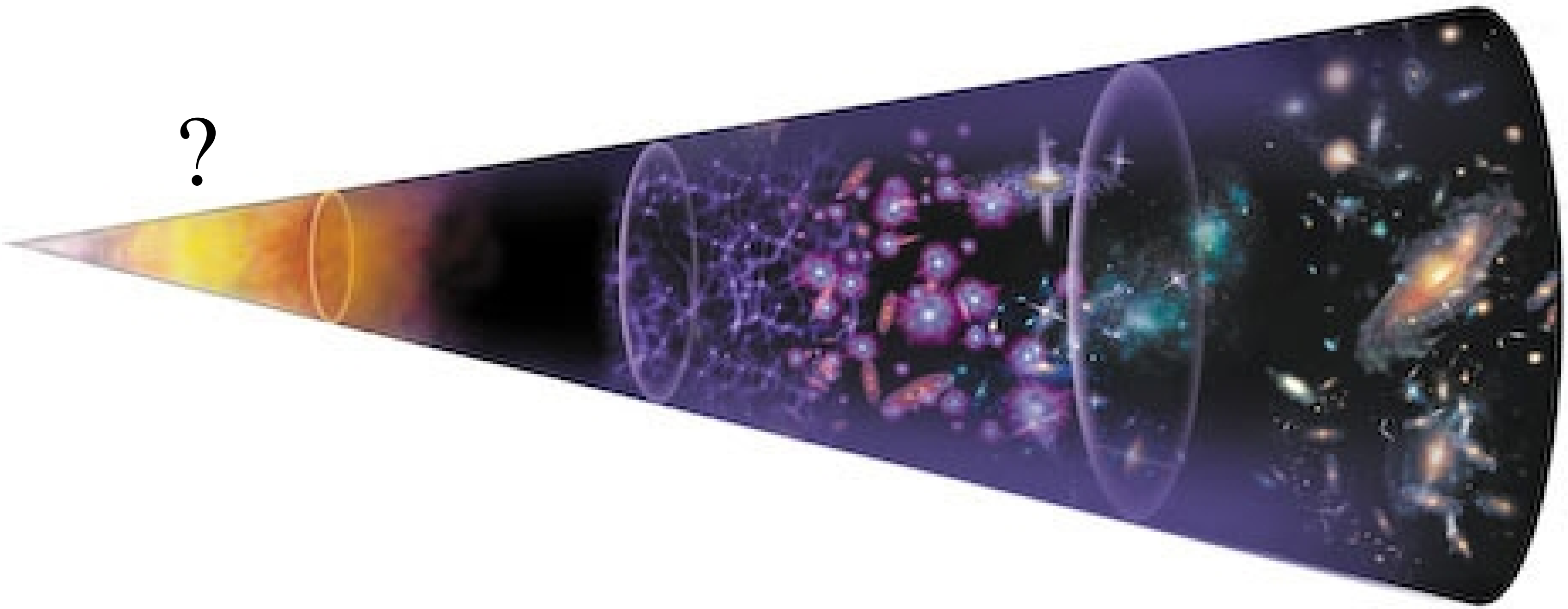
$$m_\nu \sim Y_n^{\,T} \frac{v^2}{M_R} Y_n$$

Elias-Miro *et al.* '11

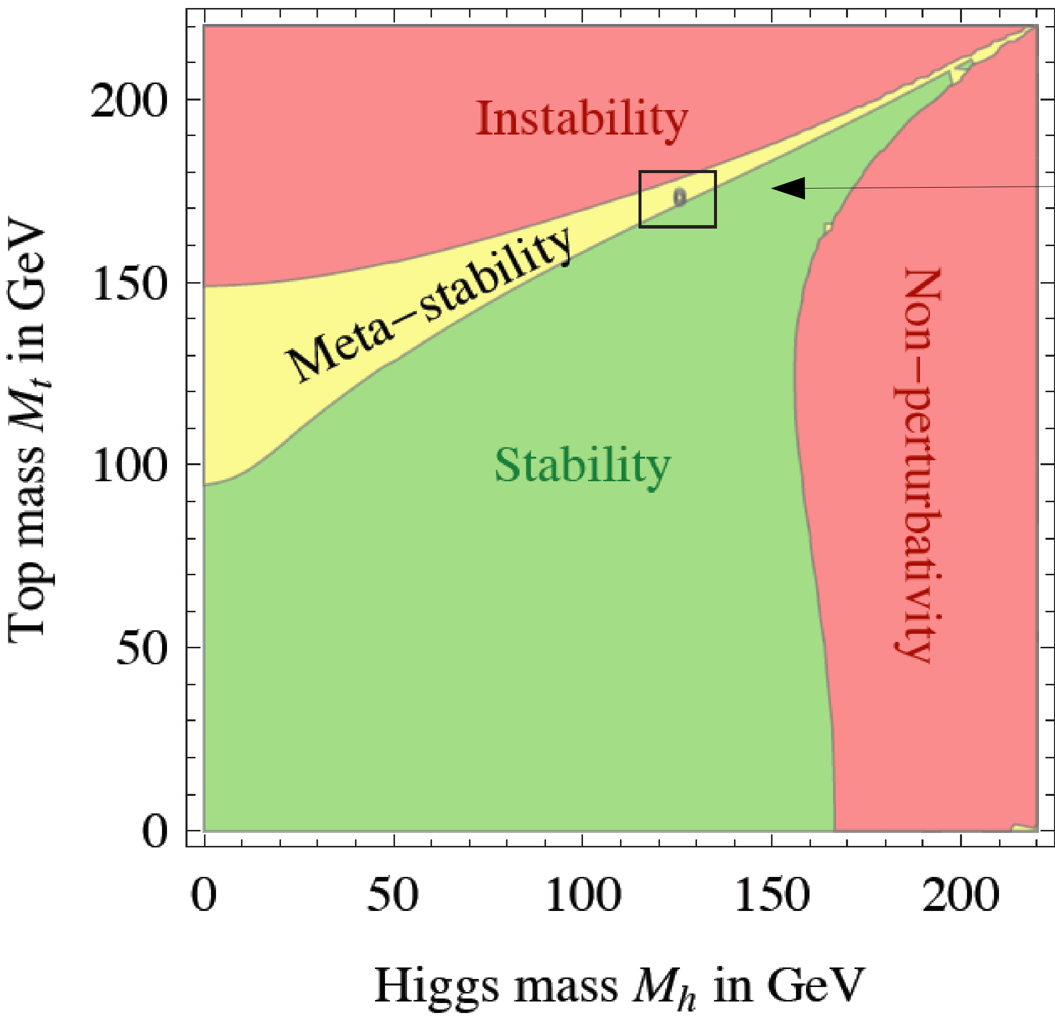


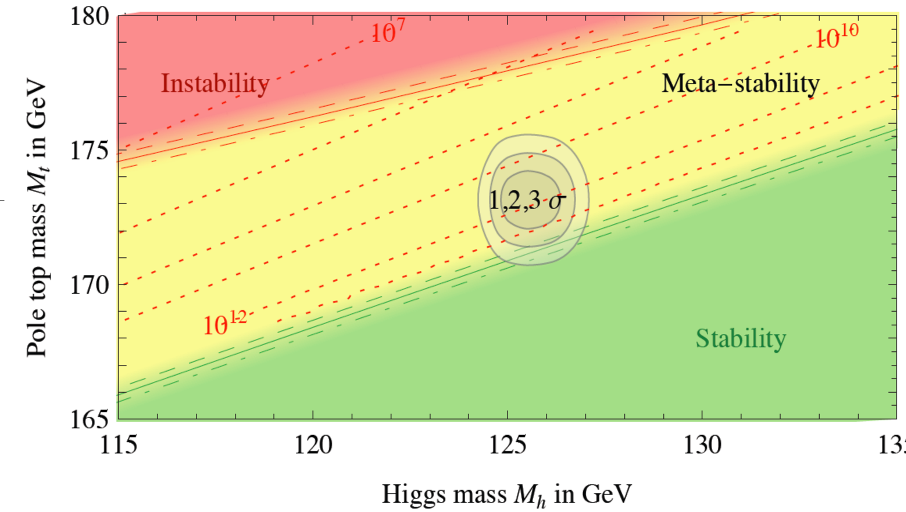
Still enough room for leptogenesis to take place.

Speculations on Planck-scale dynamics



Speculations on Planck-scale dynamics





Looking at the plane from a more distant perspective, it appears more clearly that "we live" in a quite "peculiar" region...

Moving m_t down by ~ 2 GeV, we reach the even more peculiar configuration where $\lambda(M_{pl})=0$

Froggatt, Nielsen, Takanishi, '01
Arkani-Hamed *et al.*, '08
Shaposhnikov, Wetterich, '10
...

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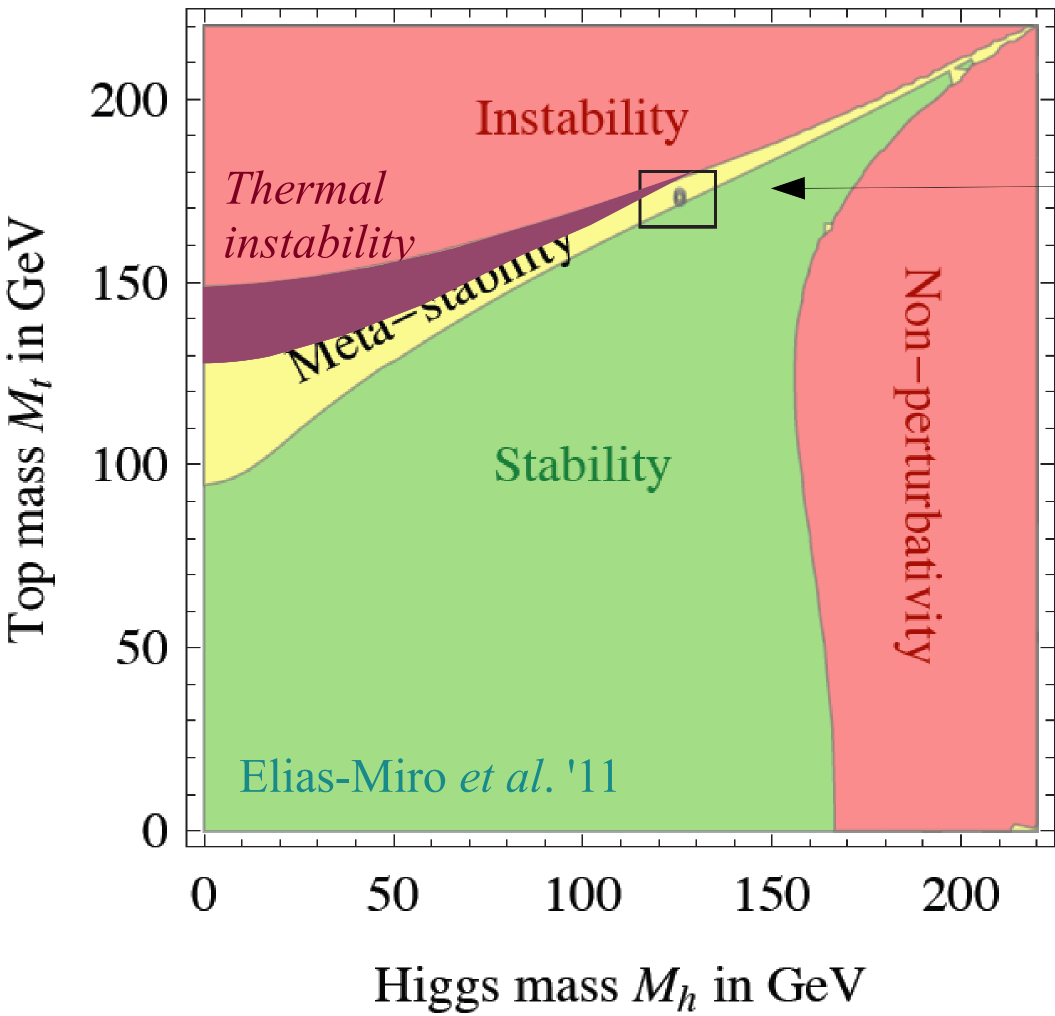

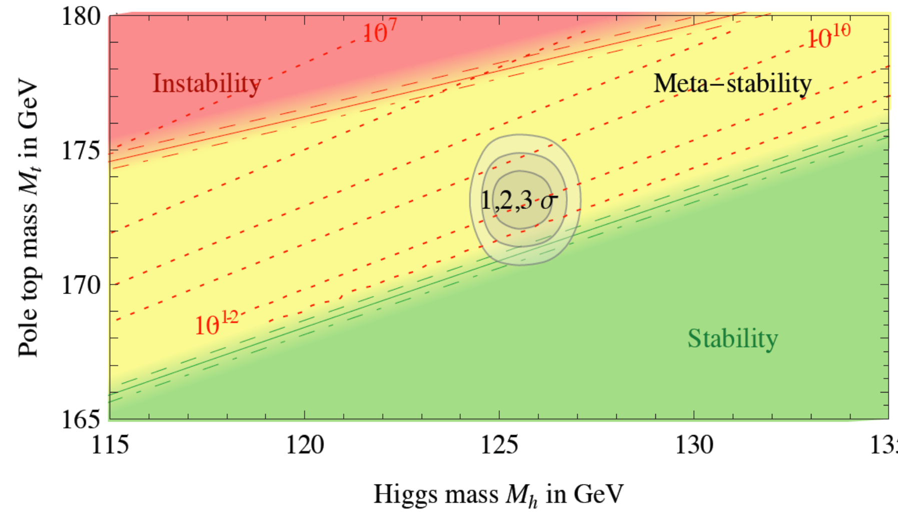

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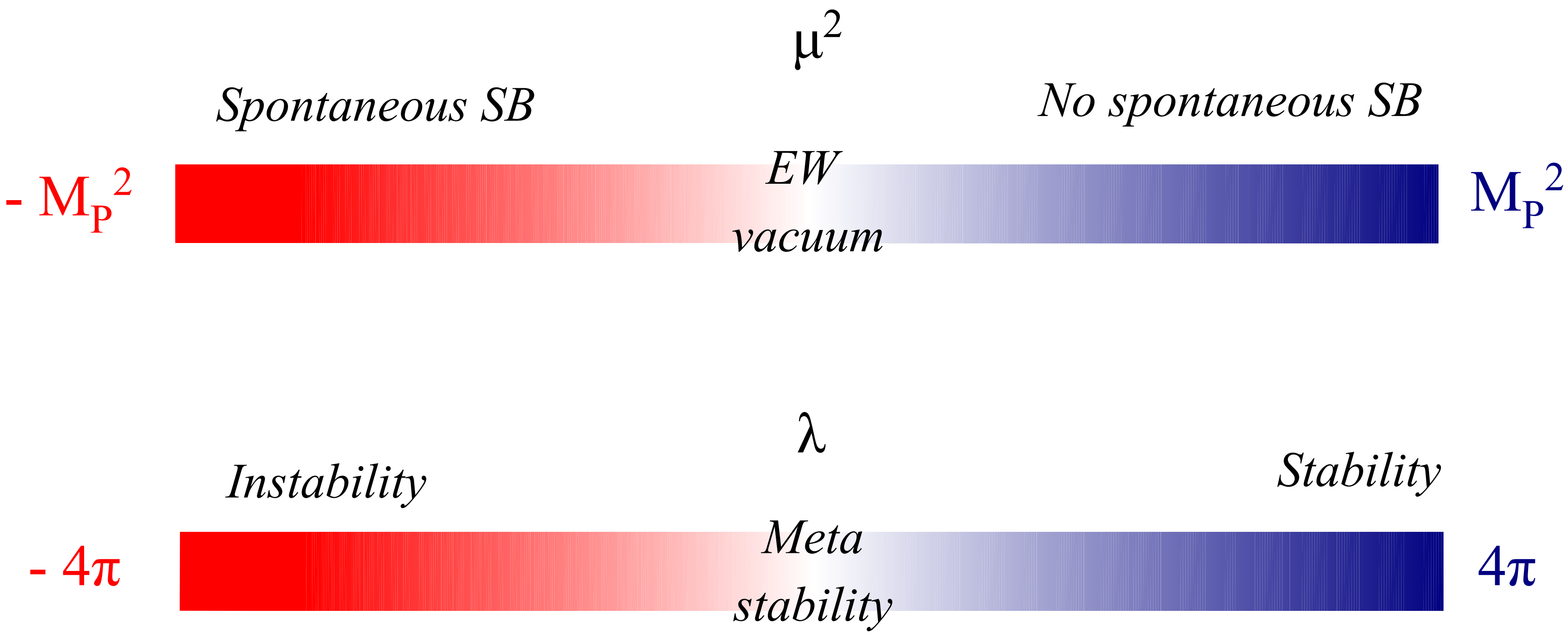
Speculations on Planck-scale dynamics

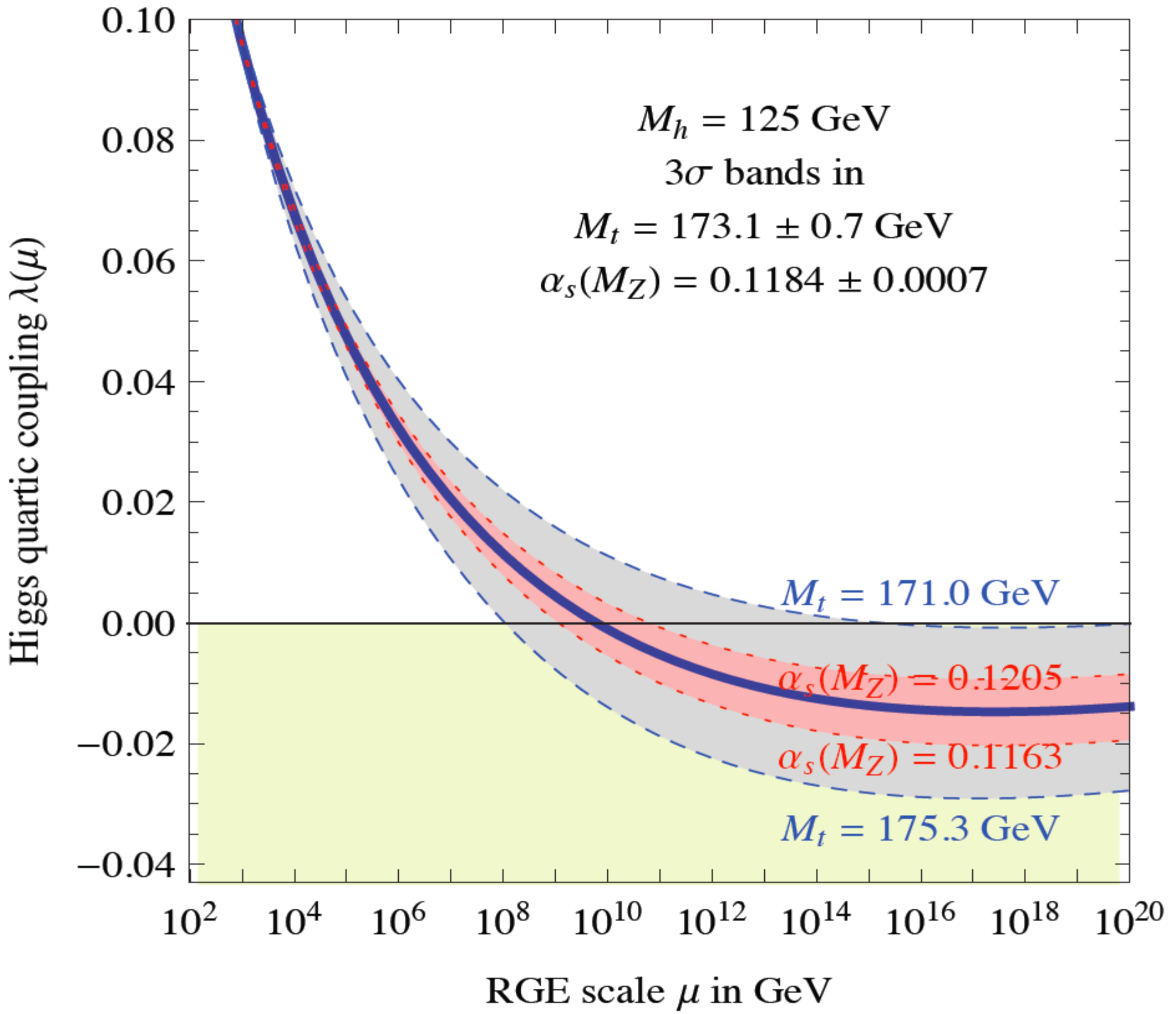
It seems that the Higgs potential is "doubly tuned" around two "critical values":

$$V(\phi) = -\mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2$$



Speculations on Planck-scale dynamics

What's special about $\lambda(M_{\rm pl})=0$?
Despite also the beta function vanishes, is not a true fixed point (other coupl. $\neq 0$)



Speculations on Planck-scale dynamics

What's special about $\lambda(M_{pl})=0$?

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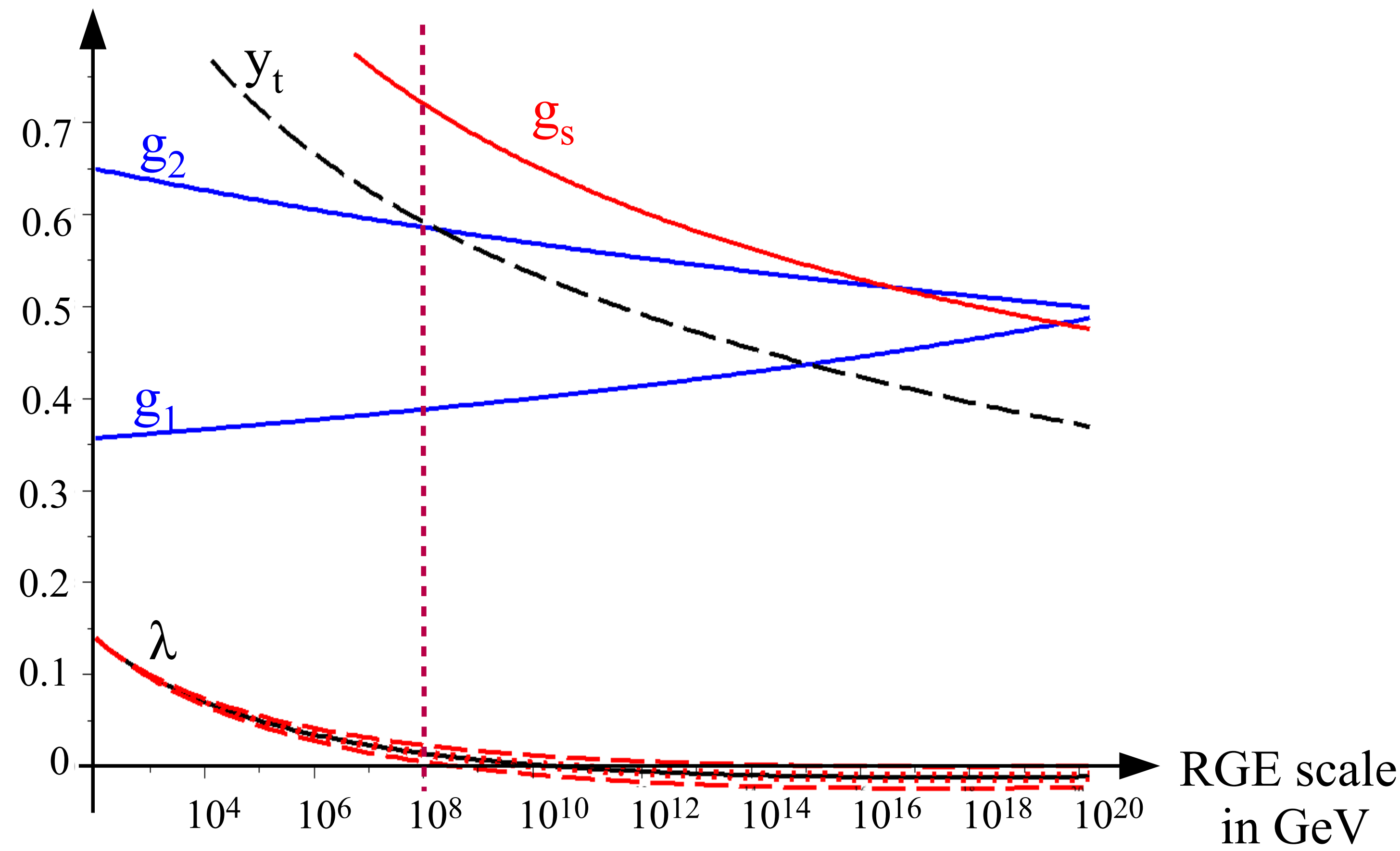
Maybe more interesting the overall smallness of λ compared to the other couplings.

At a scale $\Lambda \gtrsim 10^8$ GeV λ becomes of the same order of its typical e.w. quantum corrections: *hints of a radiatively generated coupling*?



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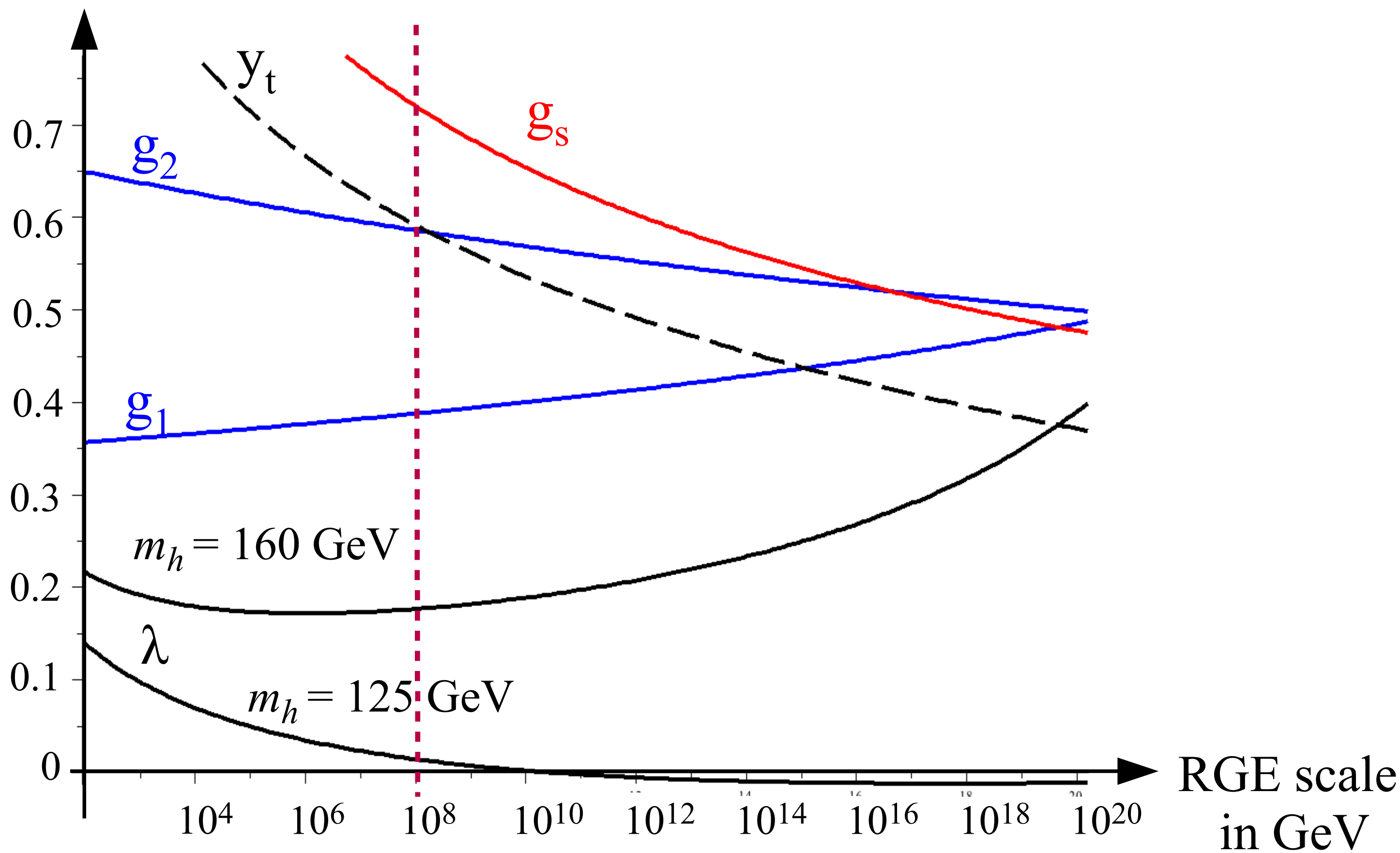
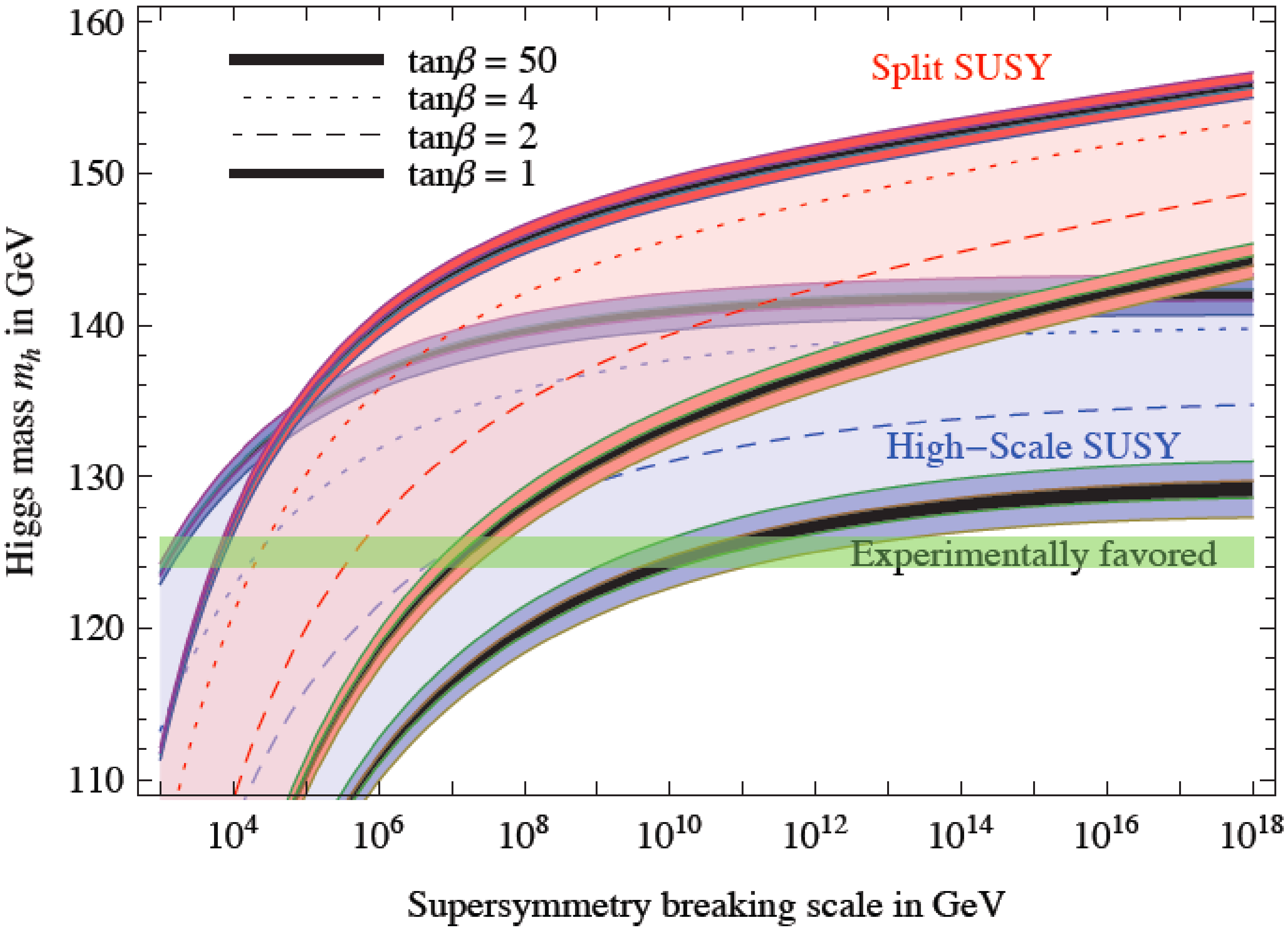


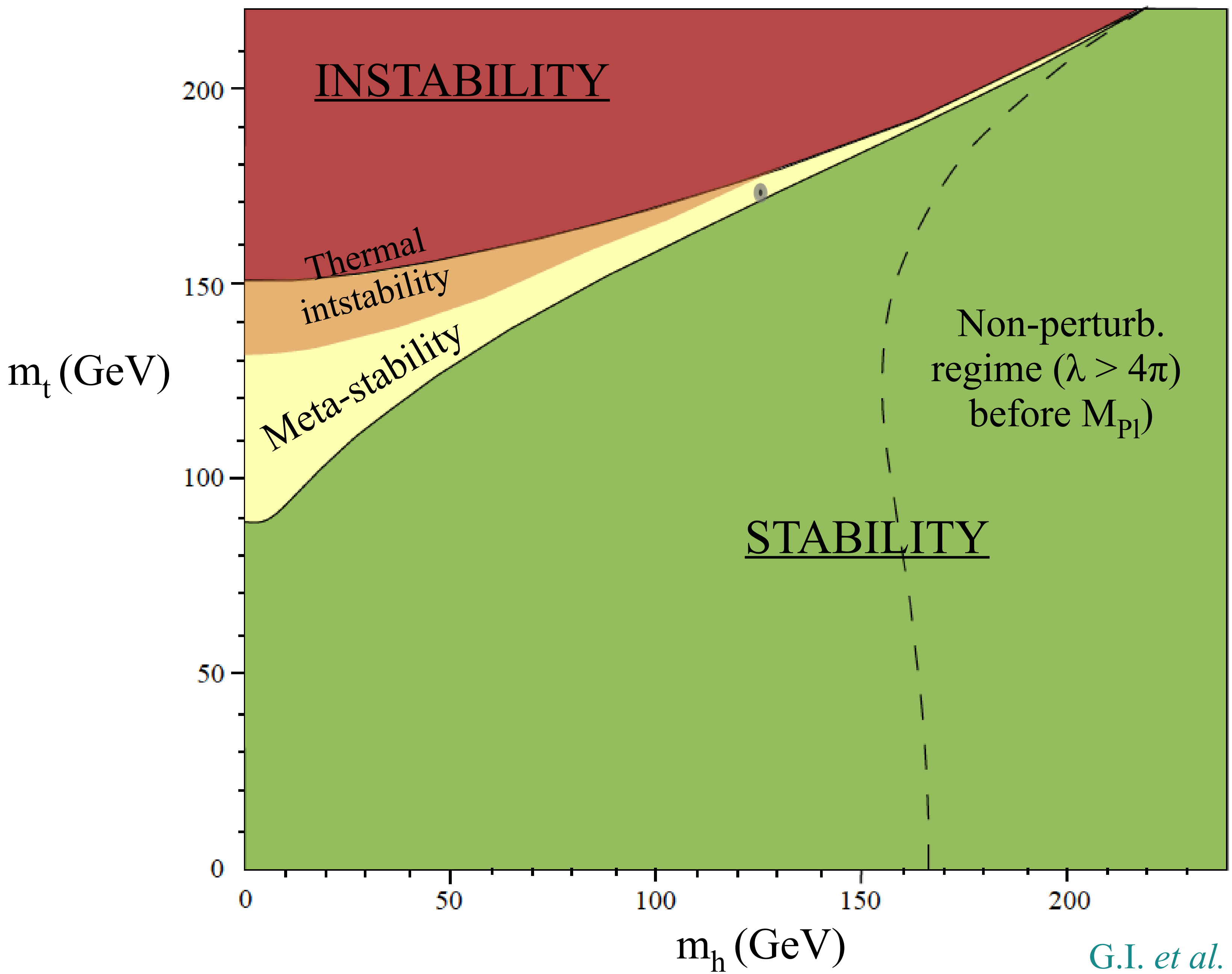
Speculations on Planck-scale dynamics

The smallness of λ certainly fits well with the possibility of a high-scale matching with a weakly coupled theory

Giudice & Strumia '11-'12

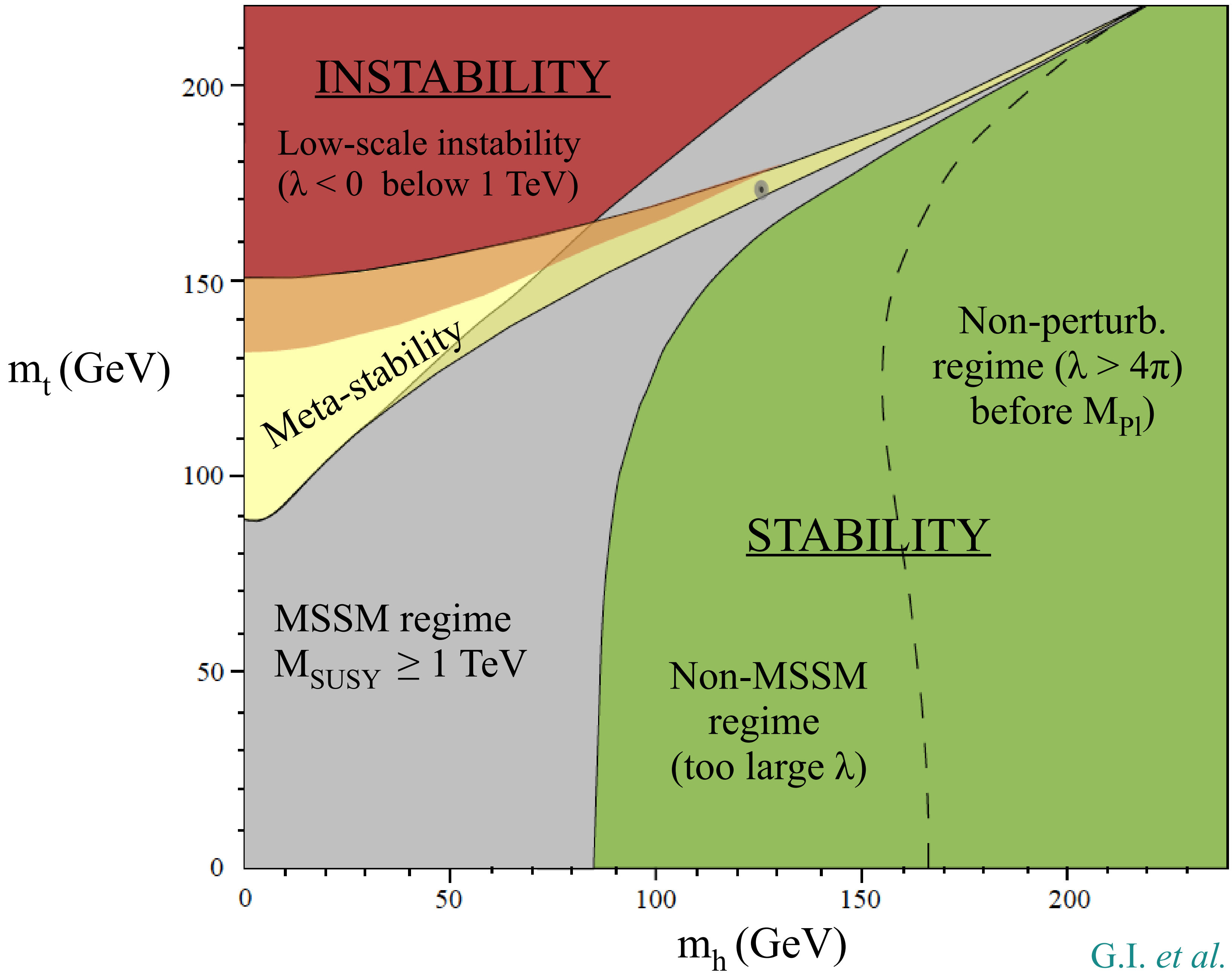


Speculations on Planck-scale dynamics



G.I. *et al.* - work in prog.

Speculations on Planck-scale dynamics



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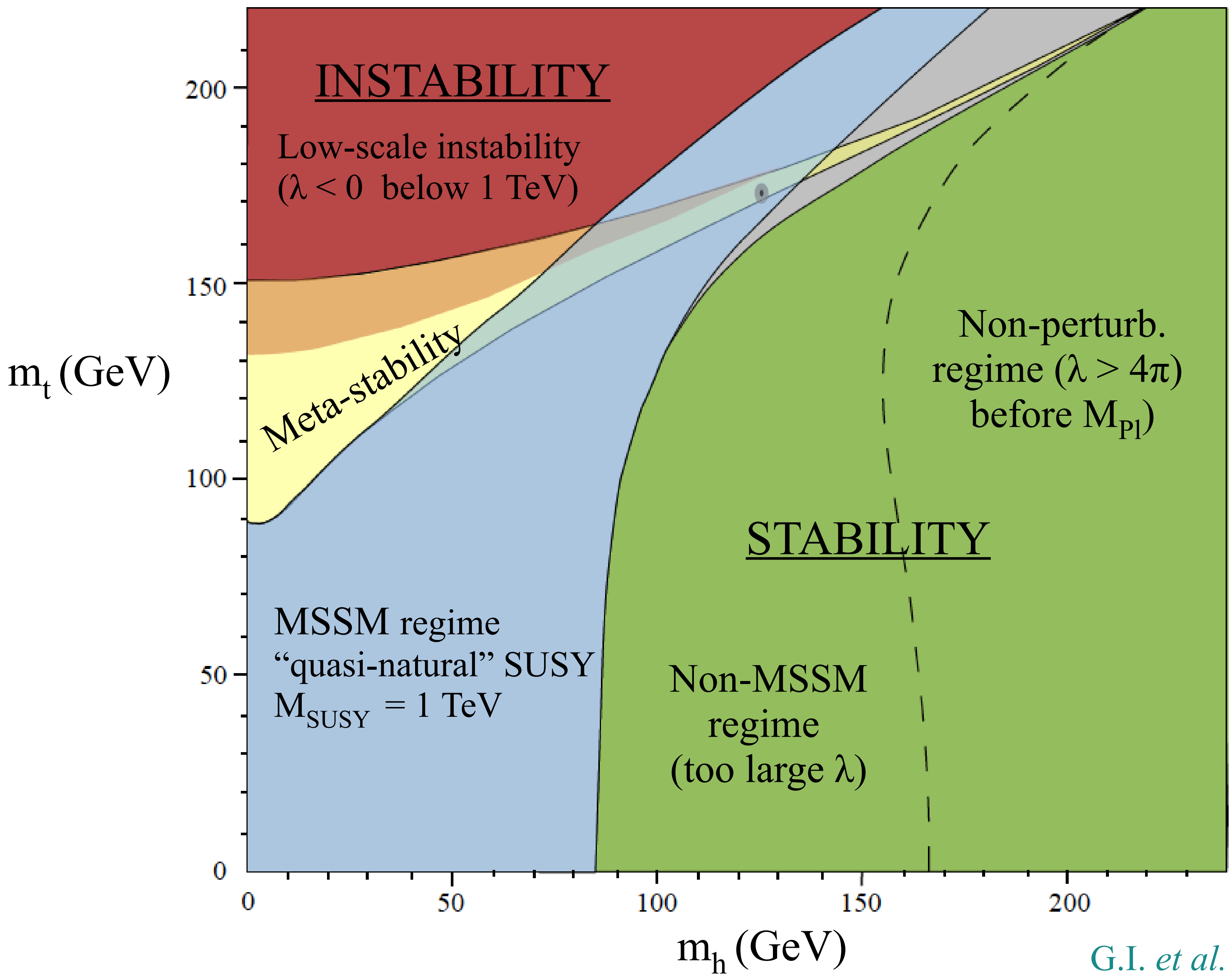
▶ Speculations on Planck-scale dynamics



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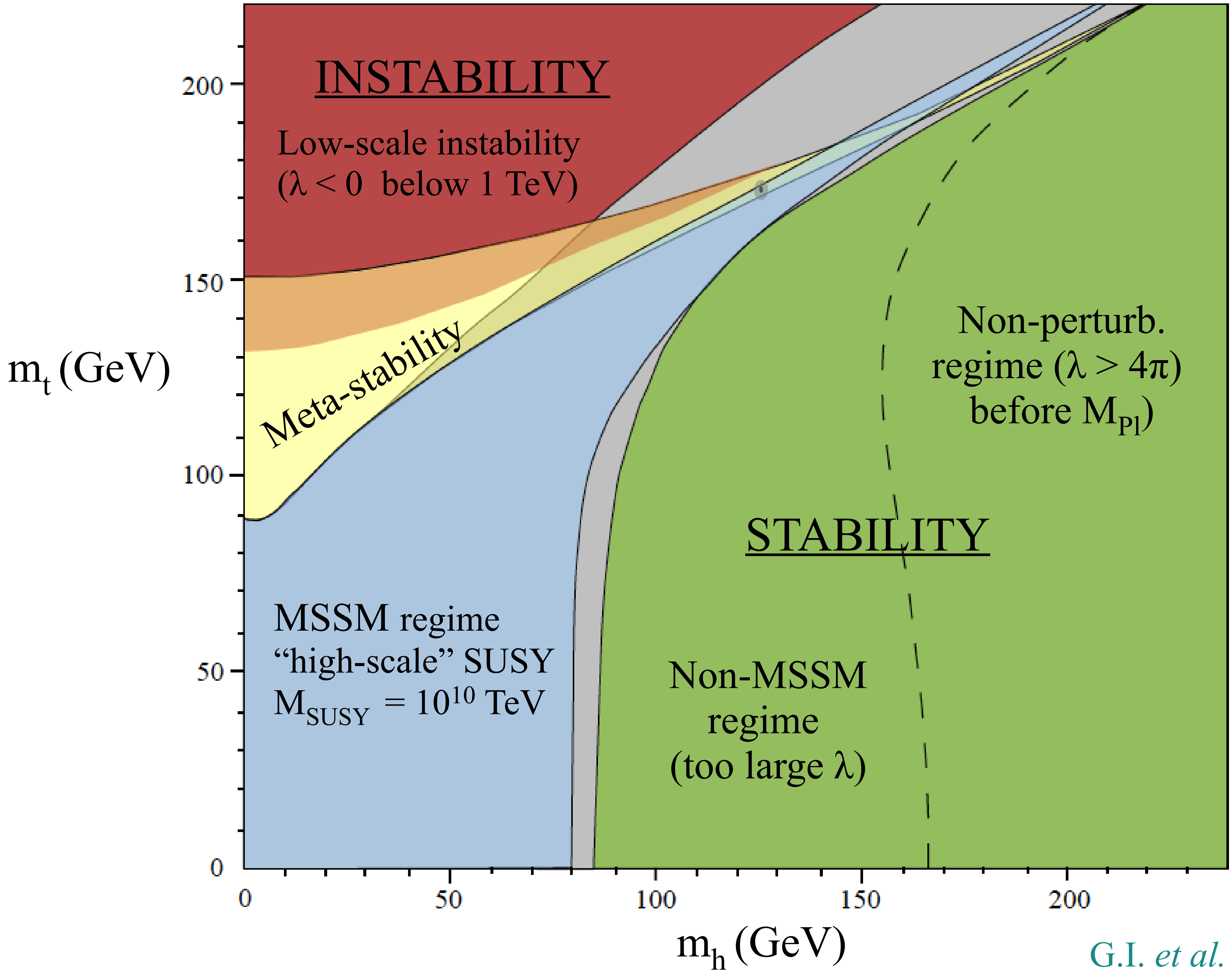

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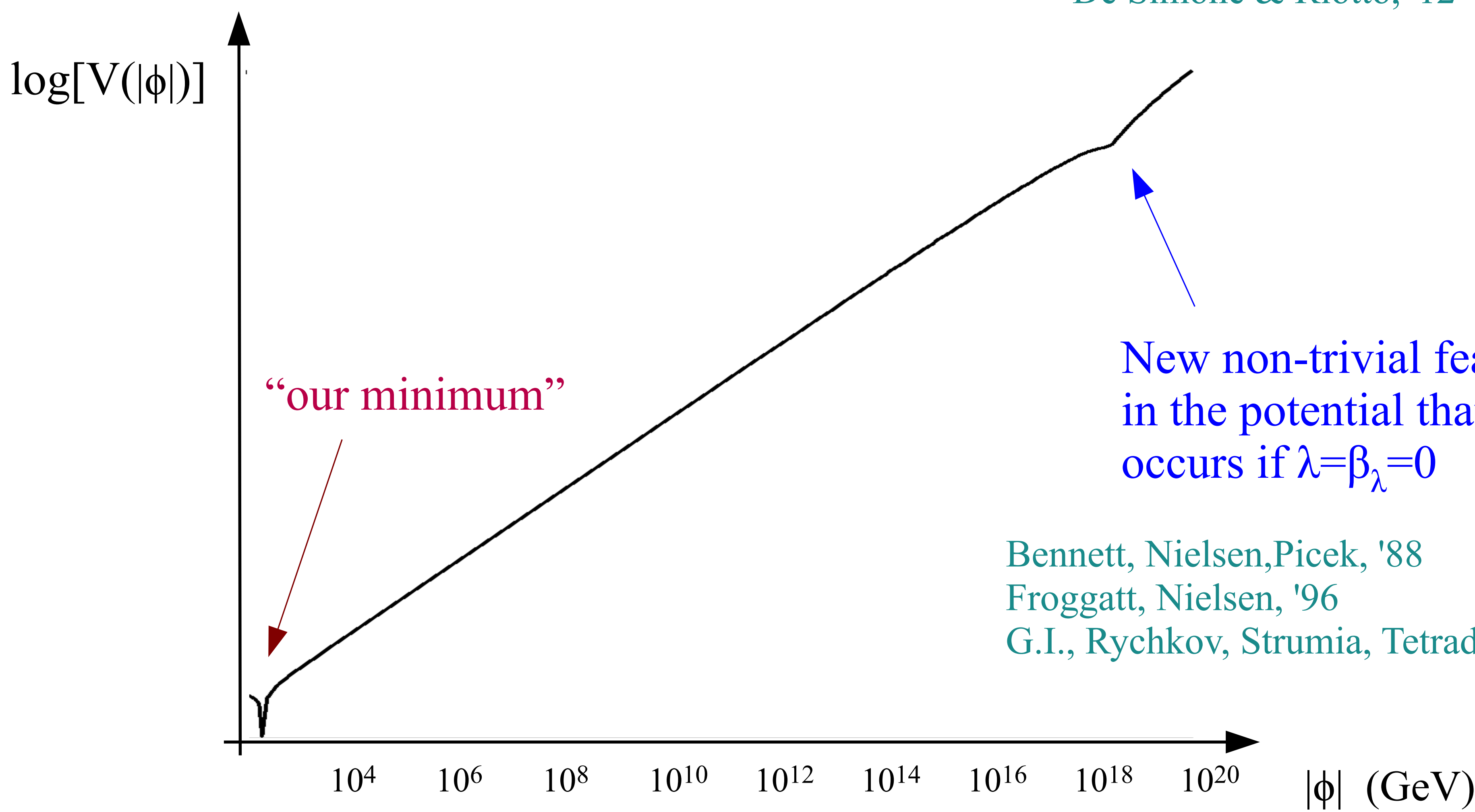
Speculations on Planck-scale dynamics

An attractive feature of having $\lambda=0$ close to M_{pl} (*assuming no new physics below such scale*) is the possibility that the Higgs field has played some role in the early Universe, during inflation.

Bezrukov & Shaposhnikov, '08
Notari & Masina '11-'12
De Simone & Riotto, '12



Bennett, Nielsen,Picek, '88
Froggatt, Nielsen, '96
G.I., Rychkov, Strumia, Tetradis '08

Speculations on Planck-scale dynamics

An attractive feature of having λ=0 close to M_{pl} (*assuming no new physics below such scale*) is the possibility that the Higgs field has played some role in the early Universe, during inflation.

The minimal set-up (SM only) does not work (*field trapped into the new minimum or too large fluctuations*) G.I. *et al.* '08

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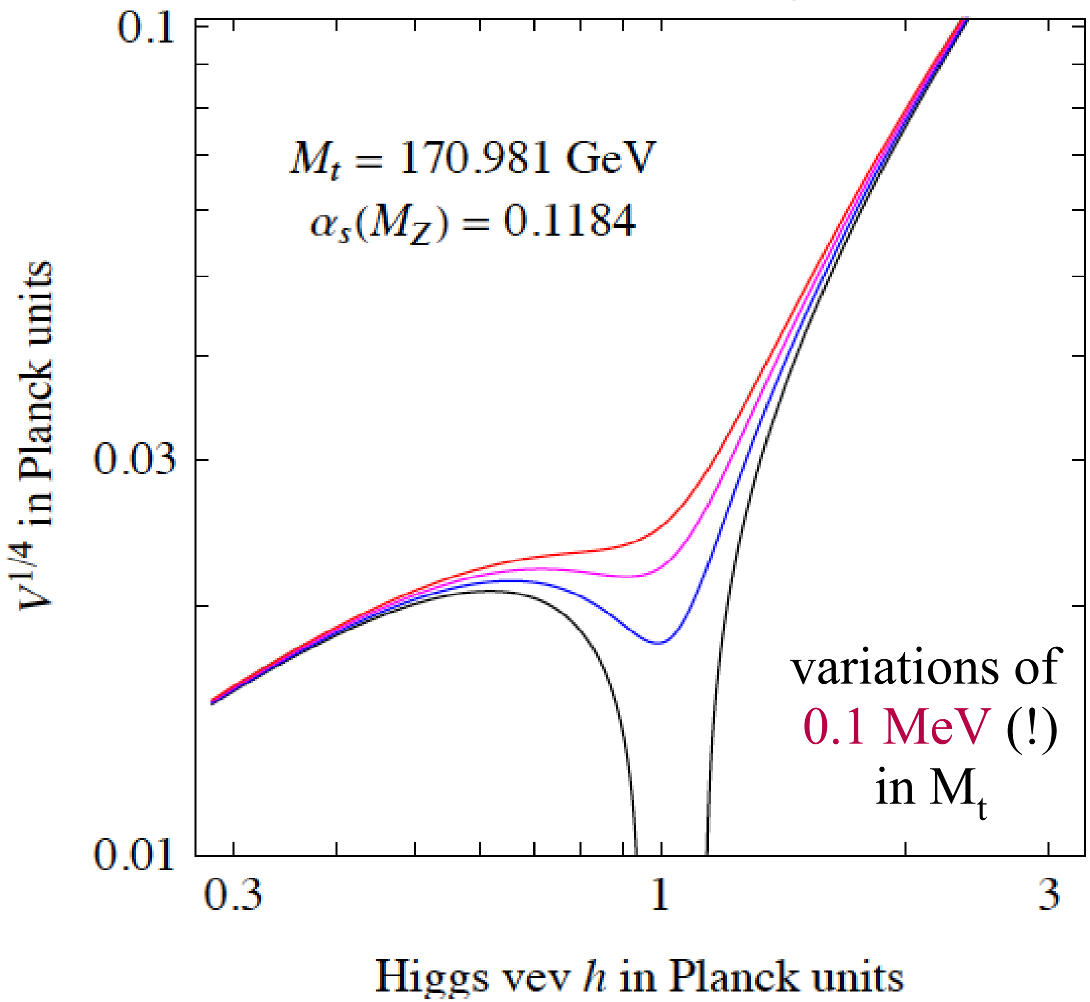

variations of 0.1 MeV (!) in M_t

Speculations on Planck-scale dynamics

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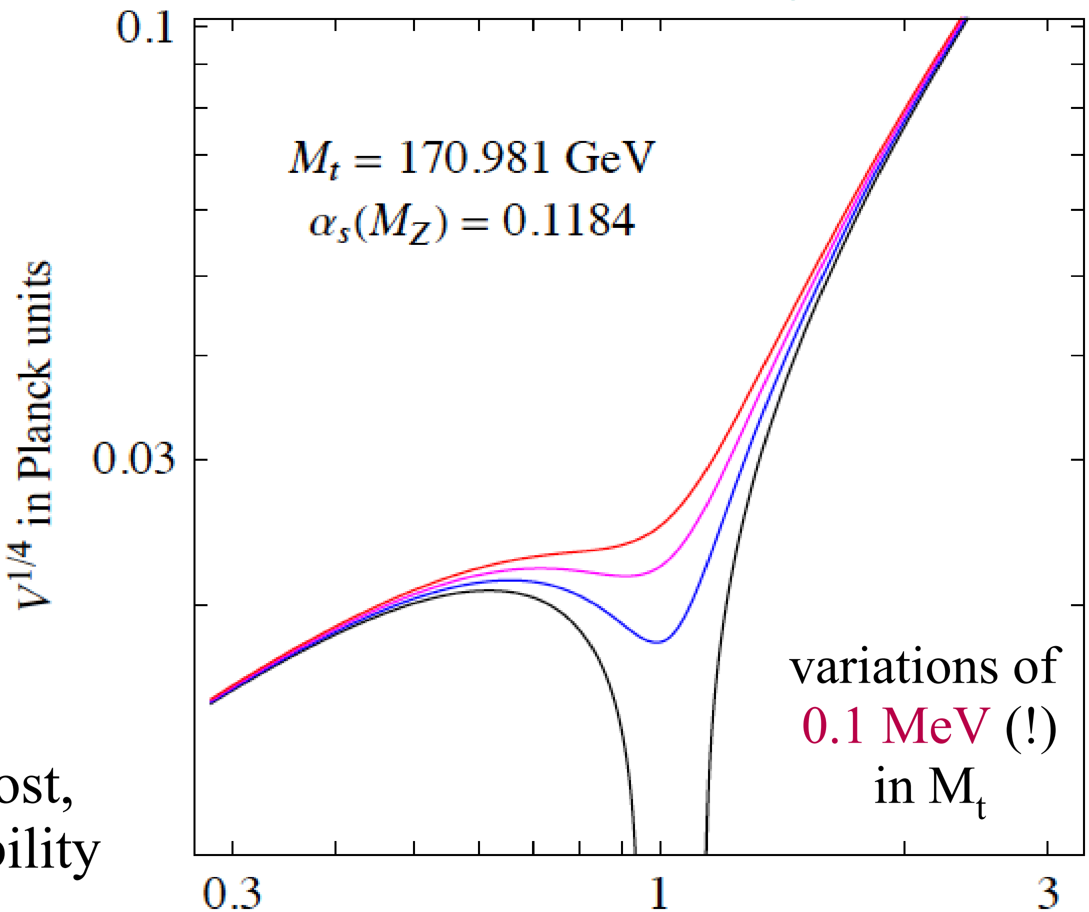

The problem can be solved with non-minimal couplings of the Higgs field to gravity and/or introducing other fields

Bezrukov & Shaposhnikov, '08
Notari & Masina '11-'12

The minimality of the scheme is lost, but it remains an intriguing possibility

Maybe even with some observable (cosmological) consequences De Simone & Riotto, '12

Conclusions

- A SM-like Higgs with $m_h \sim 125$ GeV does not allow us to derive model-independent conclusions about the scale of New Physics: the Higgs potential is most likely unstable, but the e.w. vacuum is certainly sufficiently long-lived.

Conclusions

- A SM-like Higgs with $m_h \sim 125$ GeV does not allow us to derive model-independent conclusions about the scale of New Physics: the Higgs potential is most likely unstable, but the e.w. vacuum is certainly sufficiently long-lived.

- Clear indication of a small λ at high energies: if the SM is only an effective theory, we have to match it into a model where the Higgs
  - is a weakly interacting particle - if the matching occurs close to the e.w. scale [*as indicated by naturalness*]
  - has a vanishing intrinsic self-coupling - if the matching occurs above $\sim 10^8$ GeV

- The peculiar "doubly-critical" structure of the Higgs potential may be an indication some (*non-understood yet*) phenomenon at high scales

- In absence of direct NP signals, more precise determinations of both m_h & m_t would be very useful to better investigate this problem.