On the fate of the Standard Model in view of 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
  - $SU(3)_c \times SU(2)_L \times U(1)_Y$ *local symmetry*
  - *Global flavor symmetry*

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

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:

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

- *Natural*
- Experimentally tested with high accuracy
- 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

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

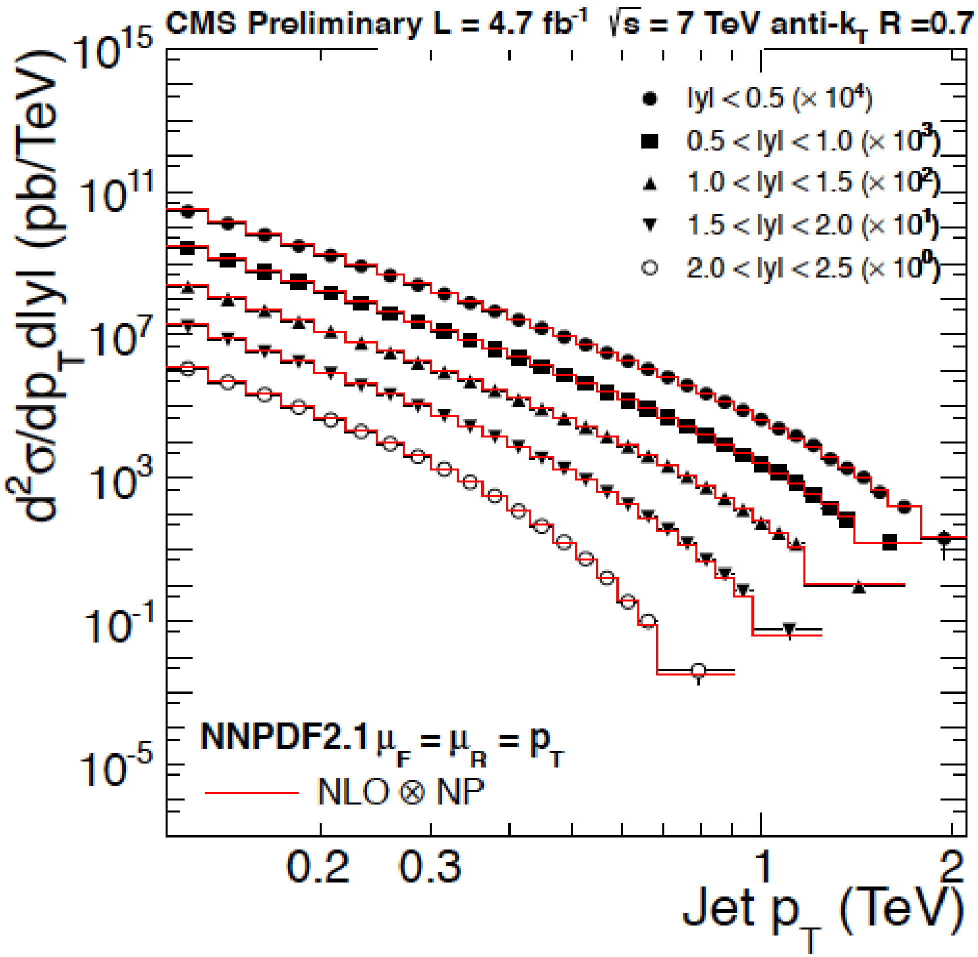
Elegant & stable, but also a bit boring...

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

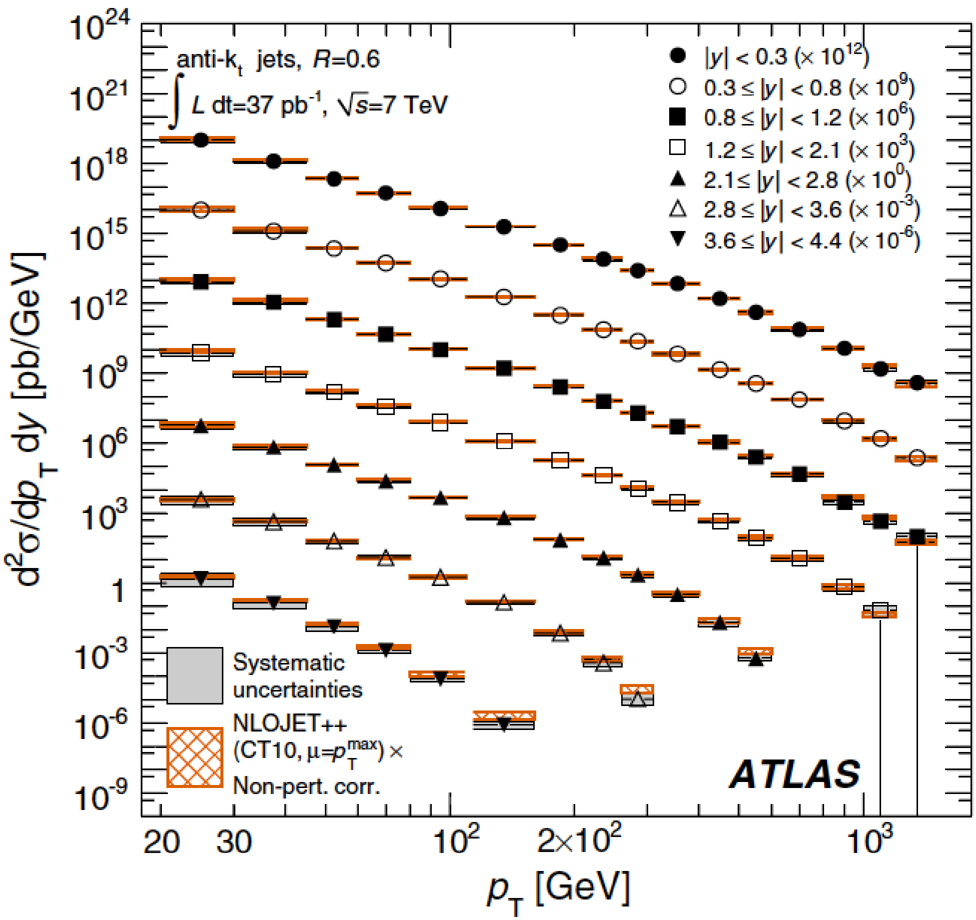
Ugly & unstable, but is what makes nature interesting...!

Introduction

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

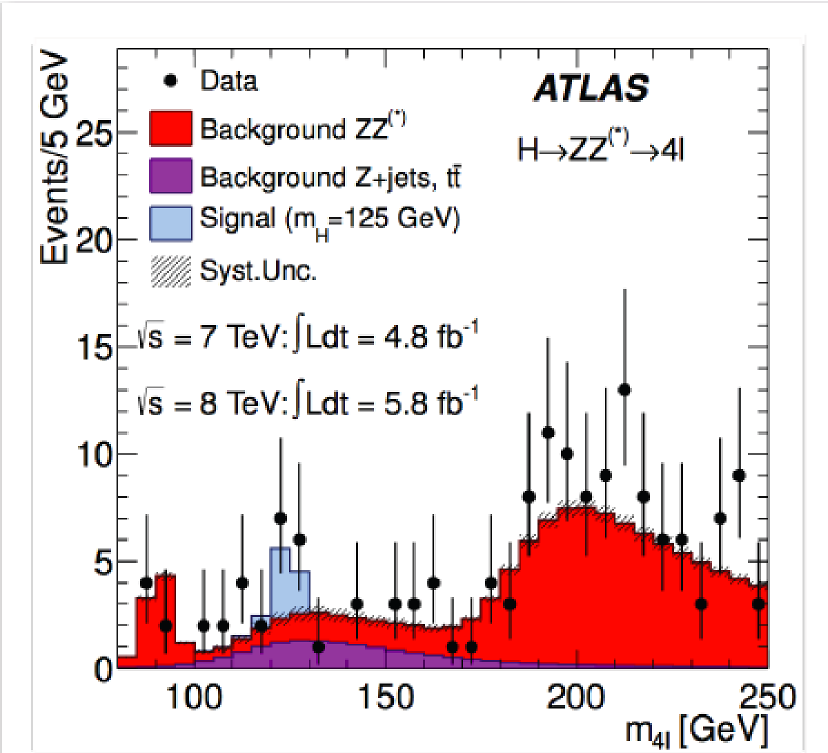


PHYSICAL REVIEW D **86**, 014022 (2012)

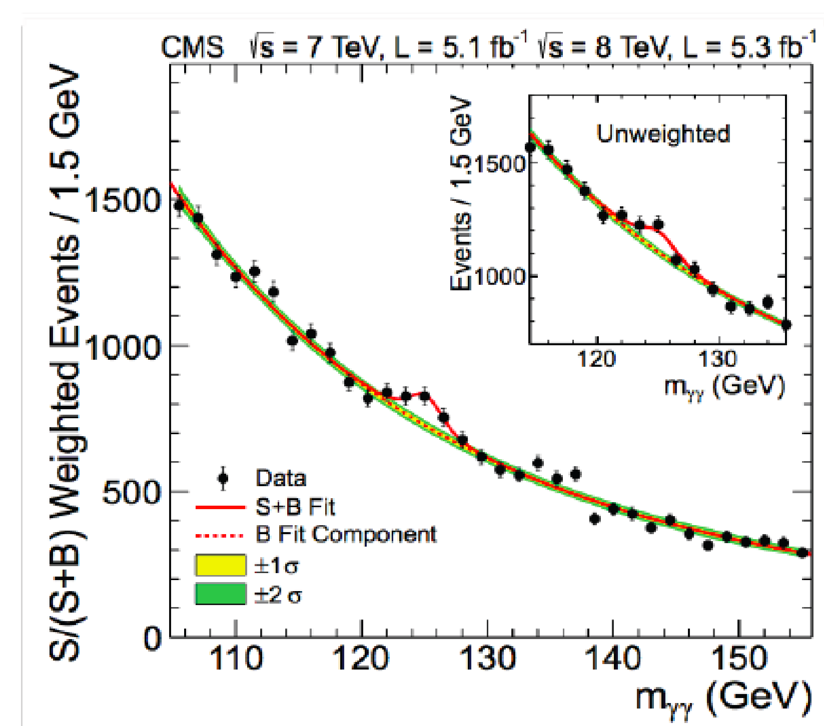


▶ Introduction

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



arXiv:1207.7214v1 [hep-ex]

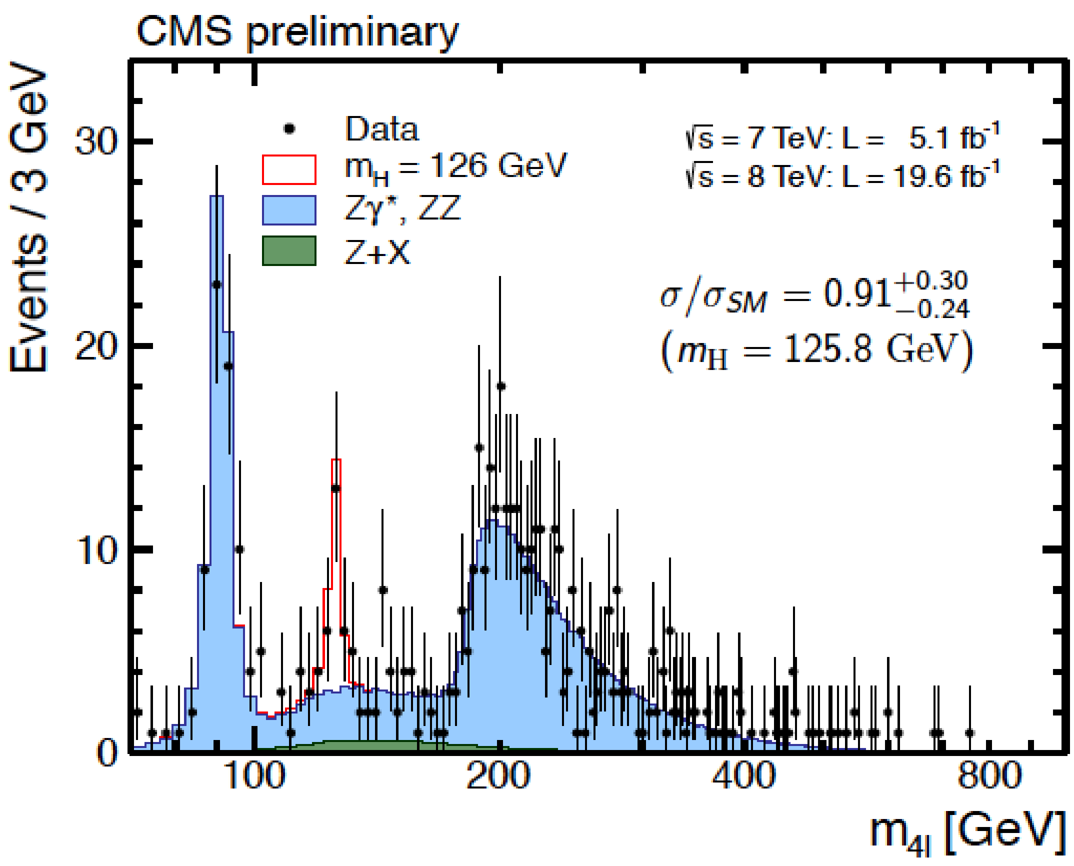


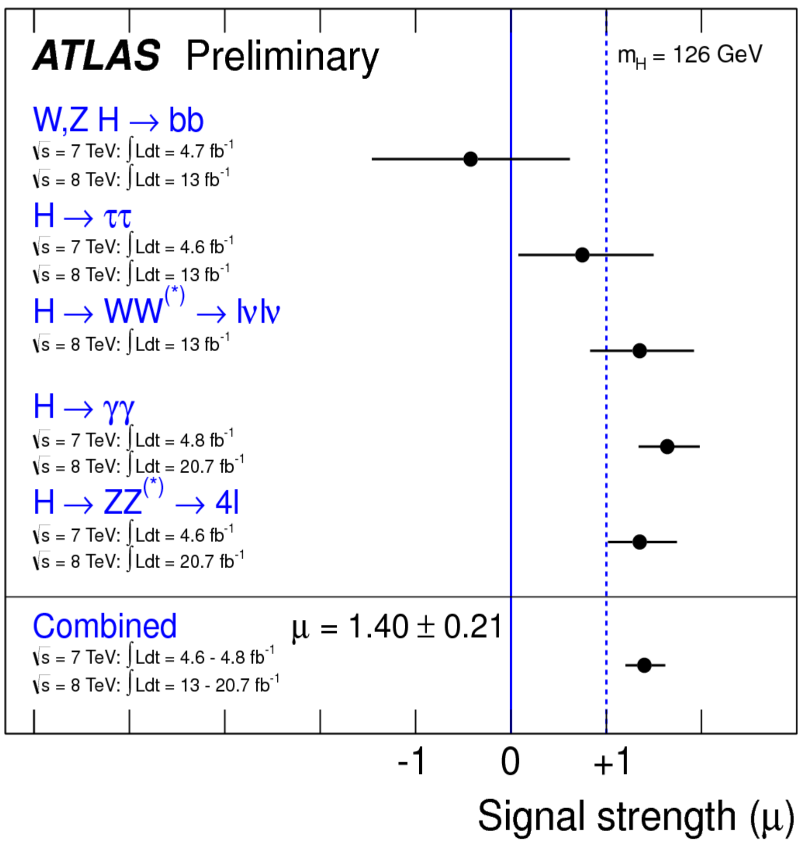
arXiv:1207.7235v1 [hep-ex]

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

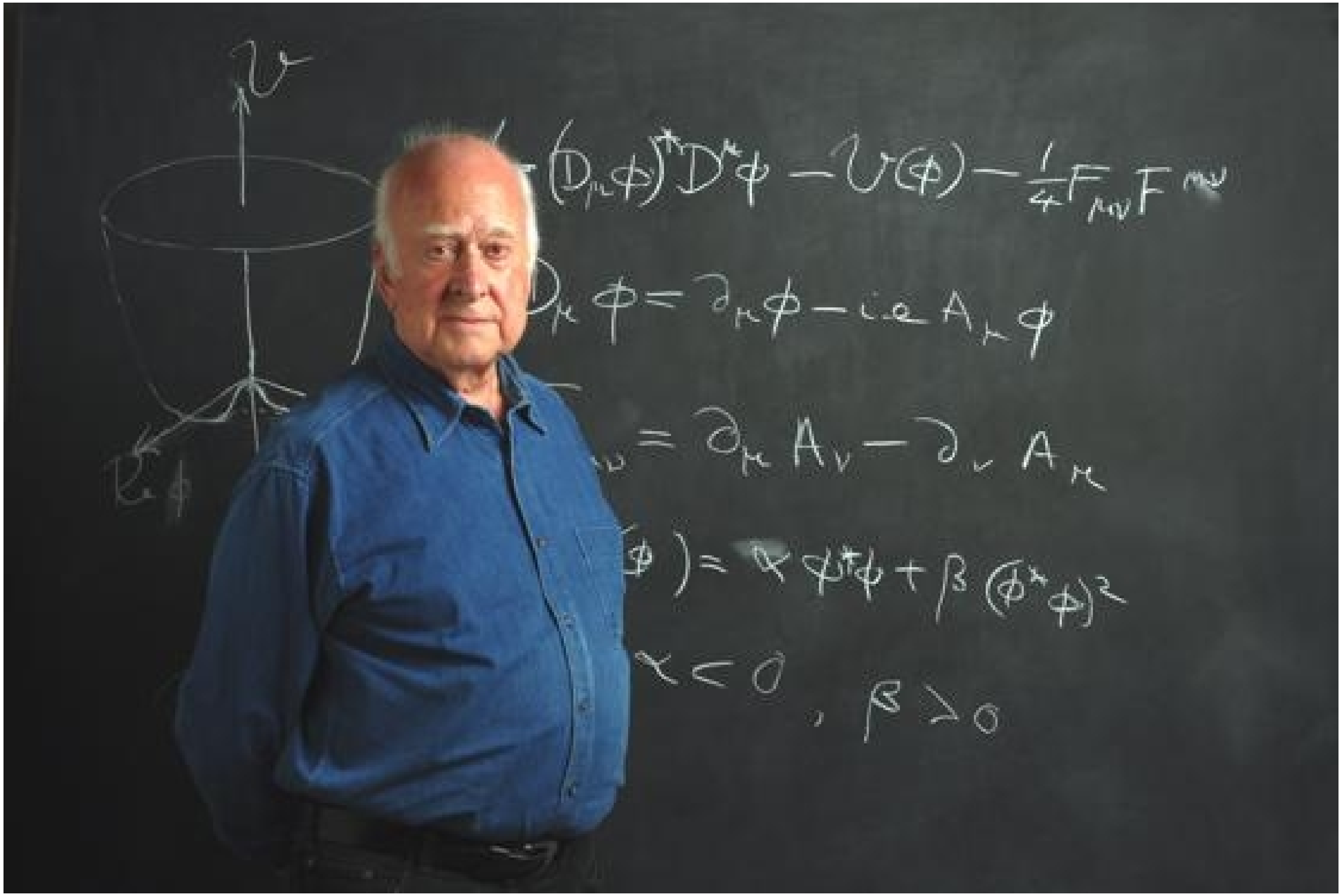
▶ Introduction

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



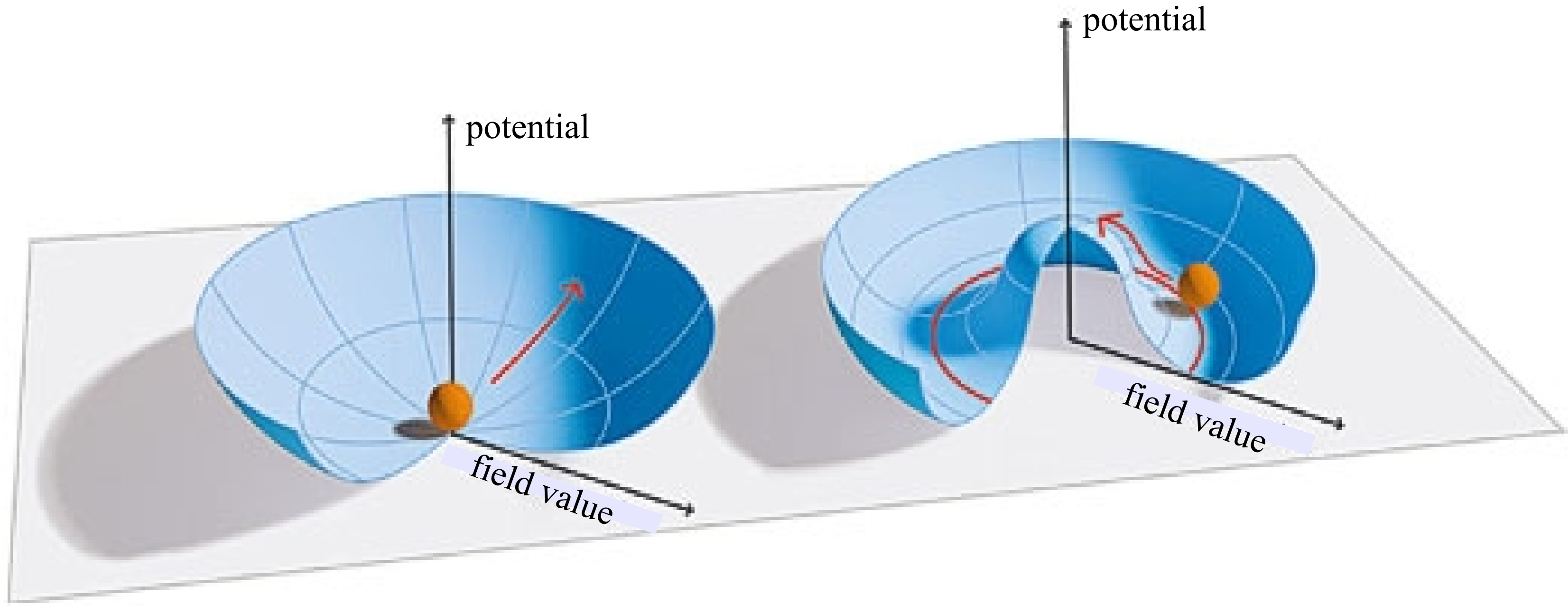


▶ *The SM Higgs sector*



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 [$SU(2)_L \times U(1)_Y \to U(1)_Q$] and flavor symmetries that we observe in nature.



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 [$SU(2)_L \times U(1)_Y \to U(1)_Q$] and flavor symmetries that we observe in nature.

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

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

Till very recently only the ground state determined by this potential (*and the corresponding Goldstone boson structure*) was tested with good accuracy:

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

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.

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

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

Till very recently only the ground state determined by this potential (*and the corresponding Goldstone boson structure*) was tested with good accuracy:

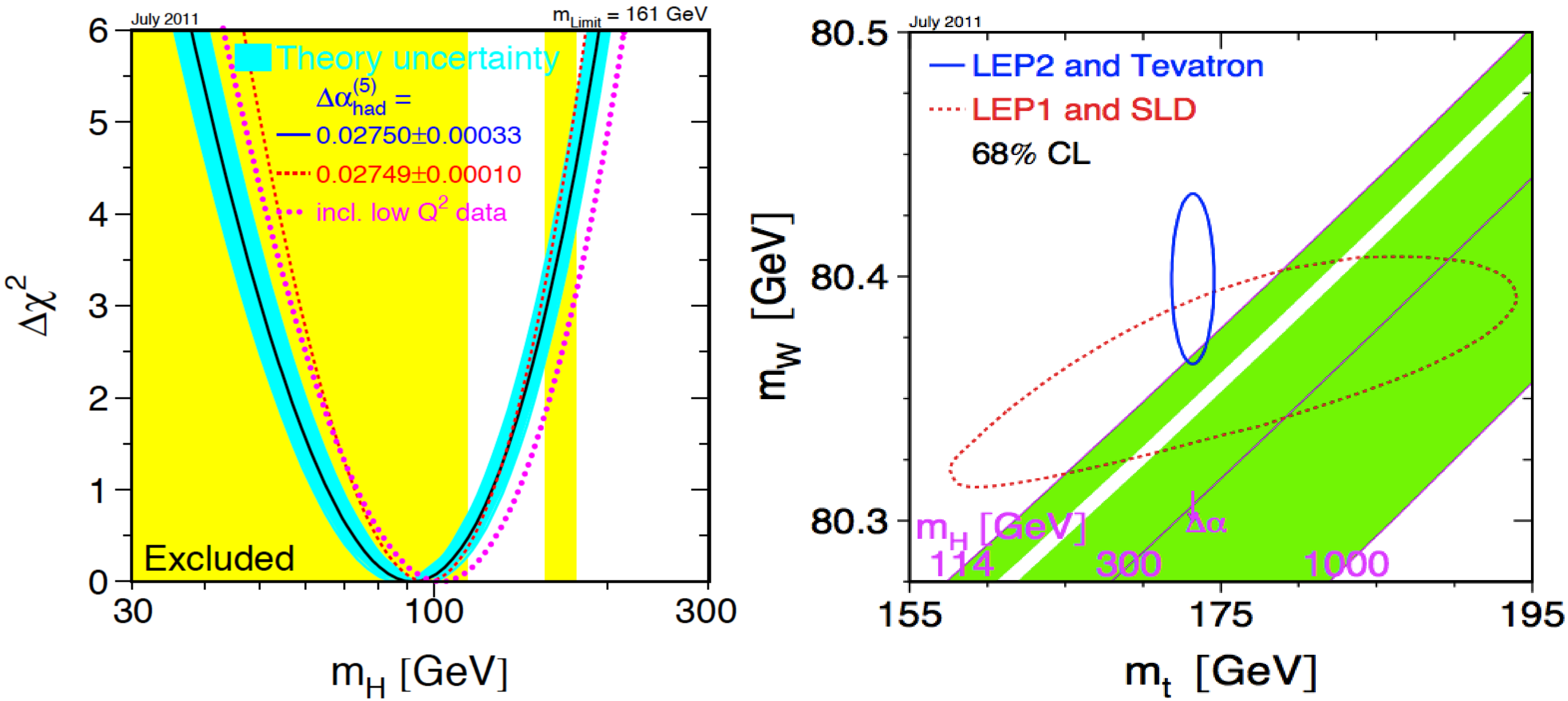
$$v = \langle \phi^+\phi \rangle^{1/2} \sim 246\ \mathrm{GeV} \quad [\ m_W = \tfrac{1}{2}\, g\, v\ ]$$

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

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

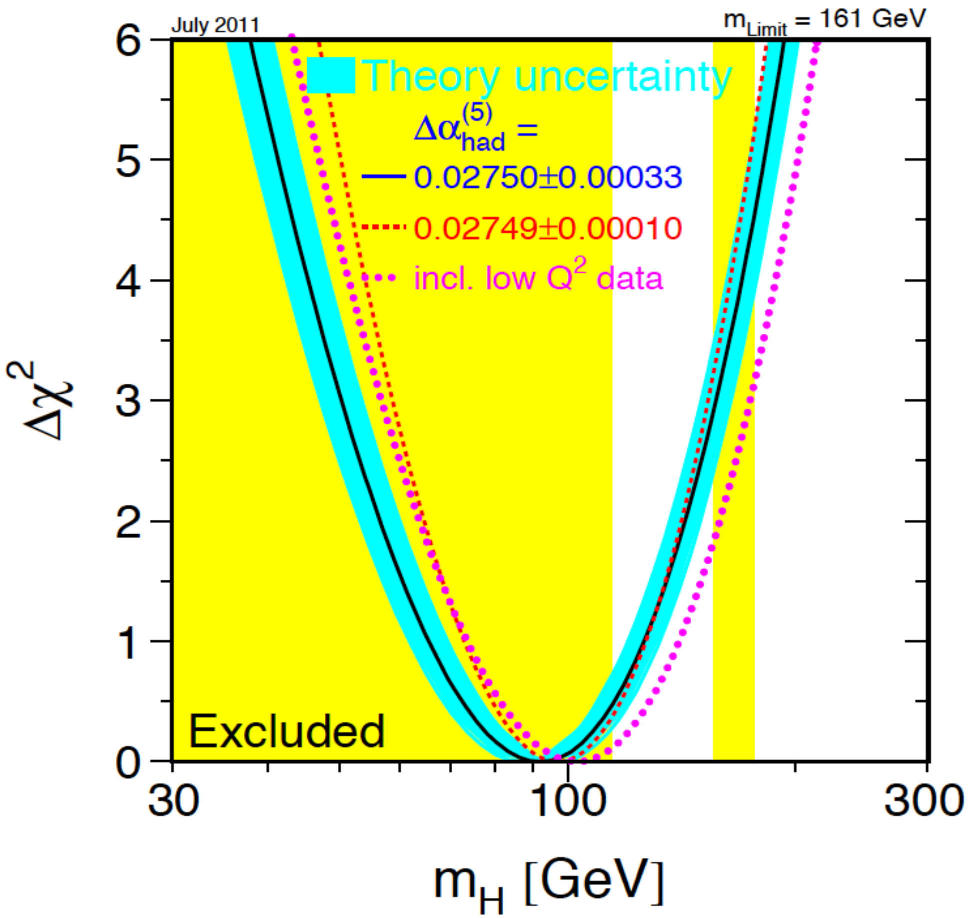
The SM Higgs sector

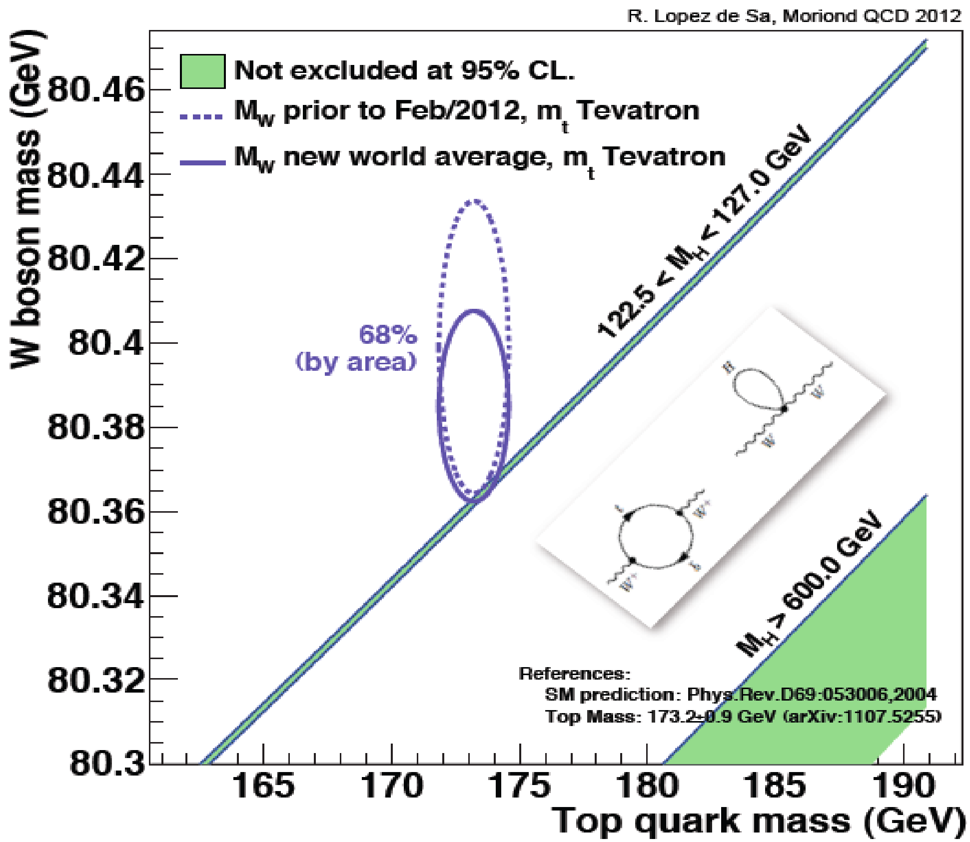
Actually some information about the Higgs mass was already present in the e.w. precision tests (*assuming the validity of the SM up to high scales*):



The SM Higgs sector

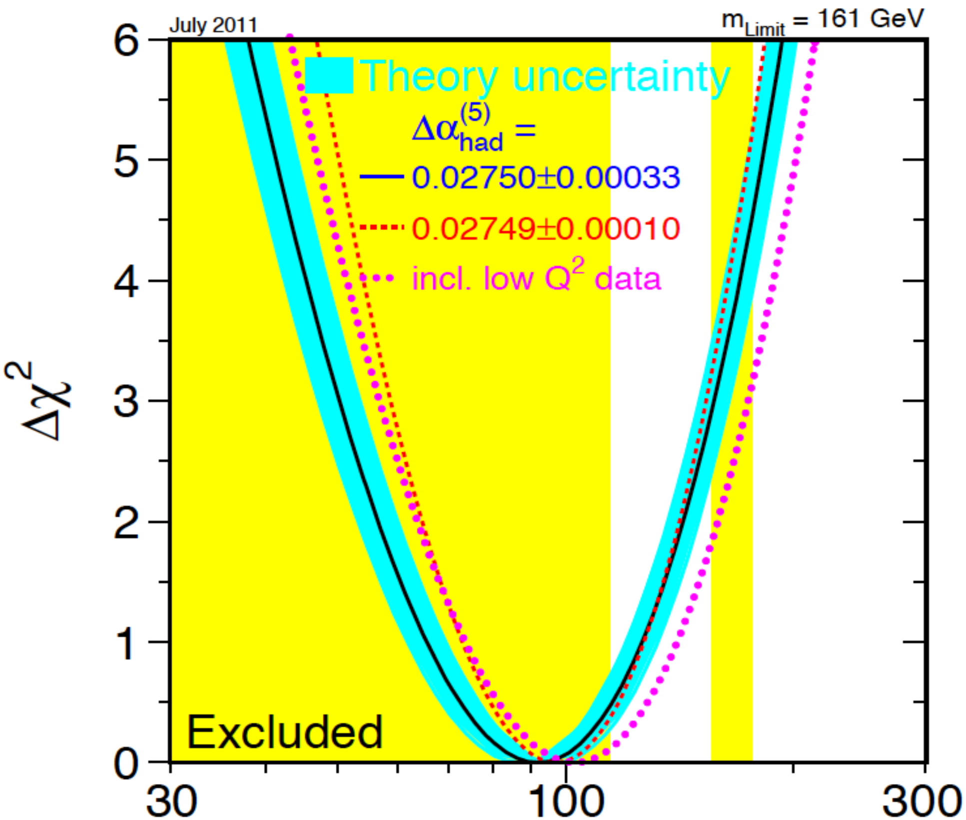
Actually some information about the Higgs mass was already present in the e.w. precision tests (*assuming the validity of the SM up to high scales*):

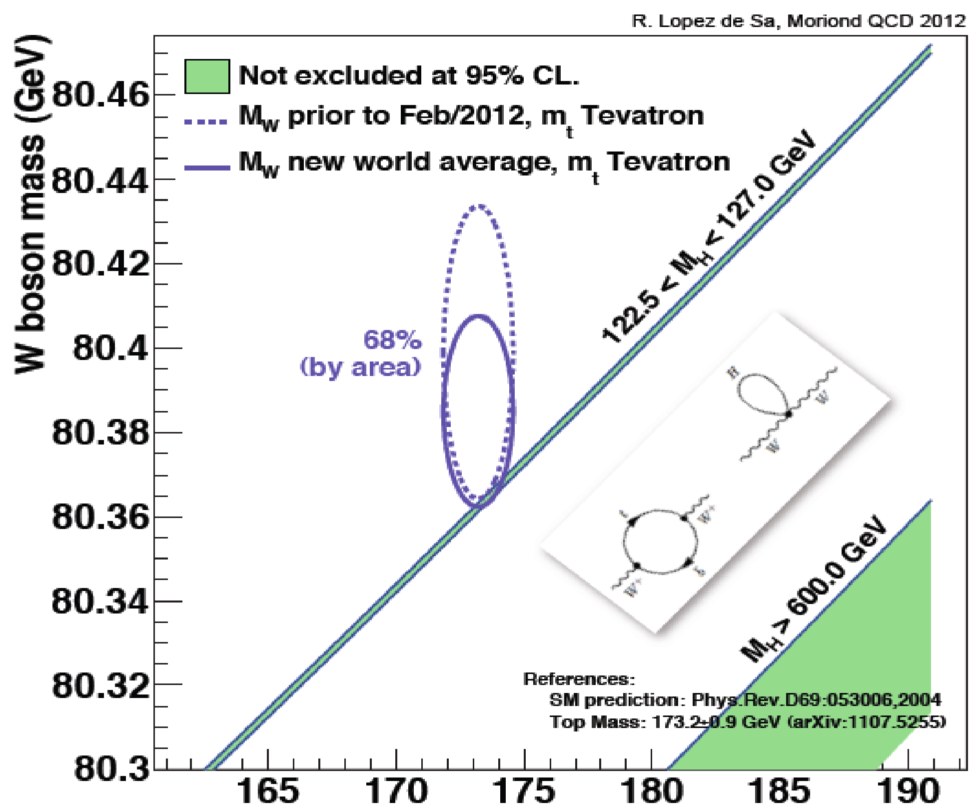




The SM Higgs sector

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*):

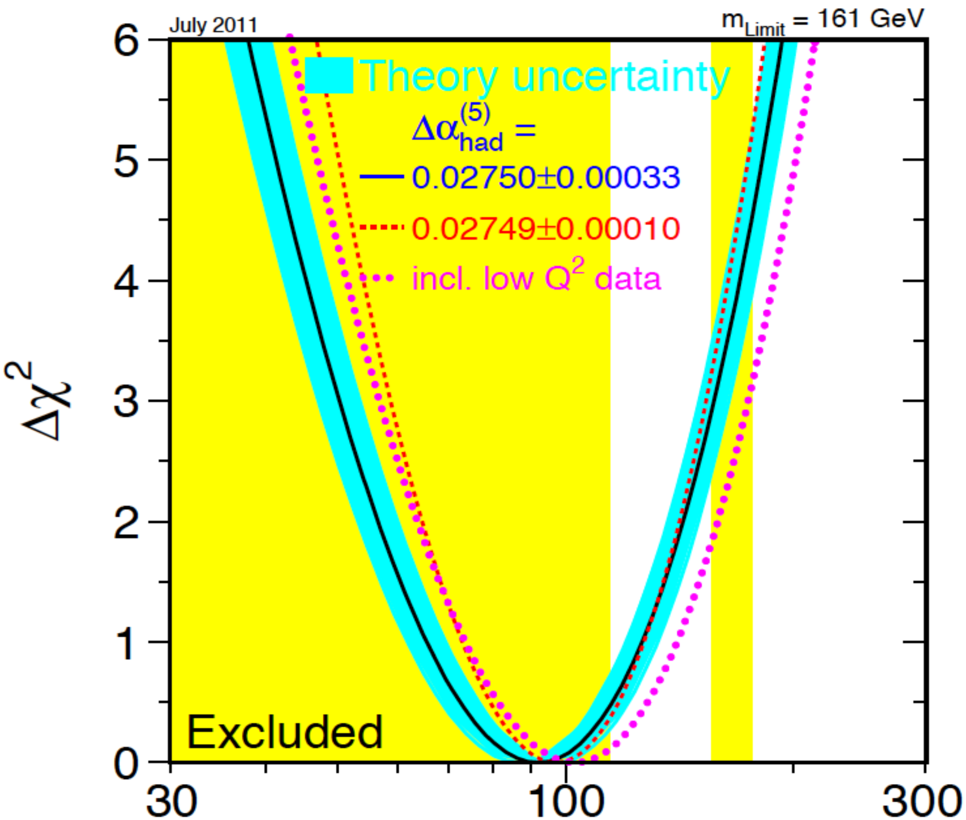


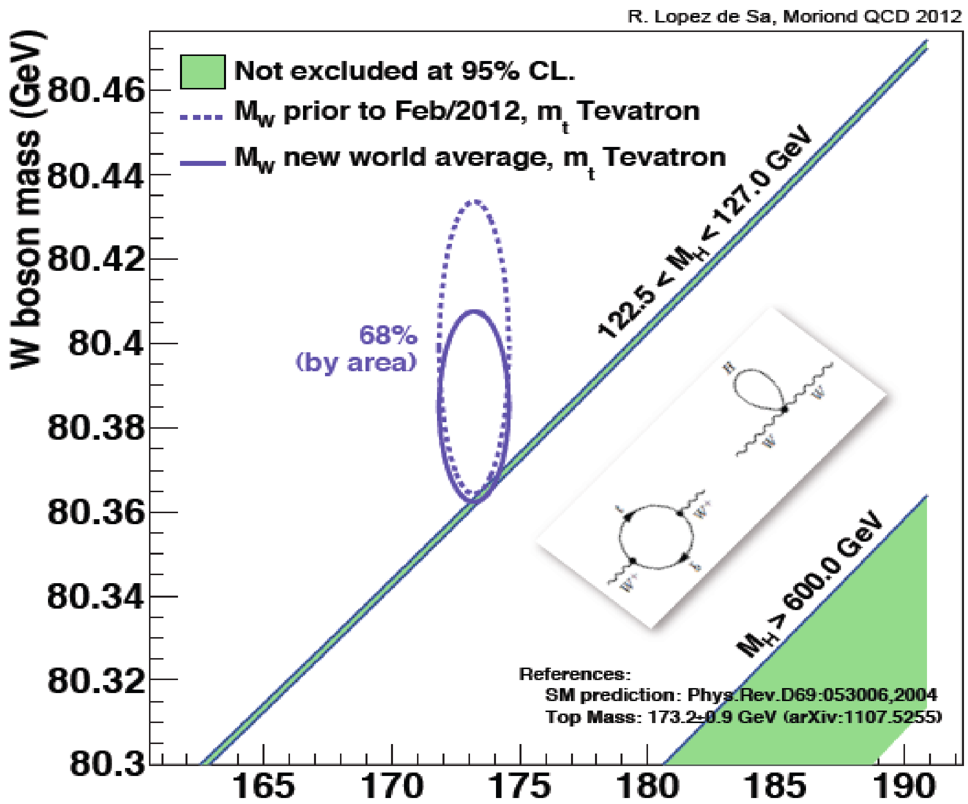


Message n.1: The observation of the physical Higgs boson with m_h well consistent with the (indirect) prediction of the e.w. precision tests is a *great success of the SM !*

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*):





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)

▶ *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.)

The SM Higgs sector

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

$$V(\phi) = \Lambda^4 - \mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2 + Y^{ij} \psi_L^{\,i} \psi_R^{\,j} \phi + \frac{g^{ij}}{\Lambda} \psi_L^{\,i}\psi_L^{\,Tj} \phi\, \phi^T$$

effective neutrino mass term

Cosmological constant prob.

vacuum instability
possible <u>internal inconsistency</u> 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.)

▶ *The SM Higgs sector*

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

$$V(\phi) = \Lambda^4 - \mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2 + Y^{ij} \psi_L^i \psi_R^j \phi + \frac{g^{ij}}{\Lambda} \psi_L^i \psi_L^{Tj} \phi \phi^T$$

effective neutrino mass term

Cosmological constant prob.

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

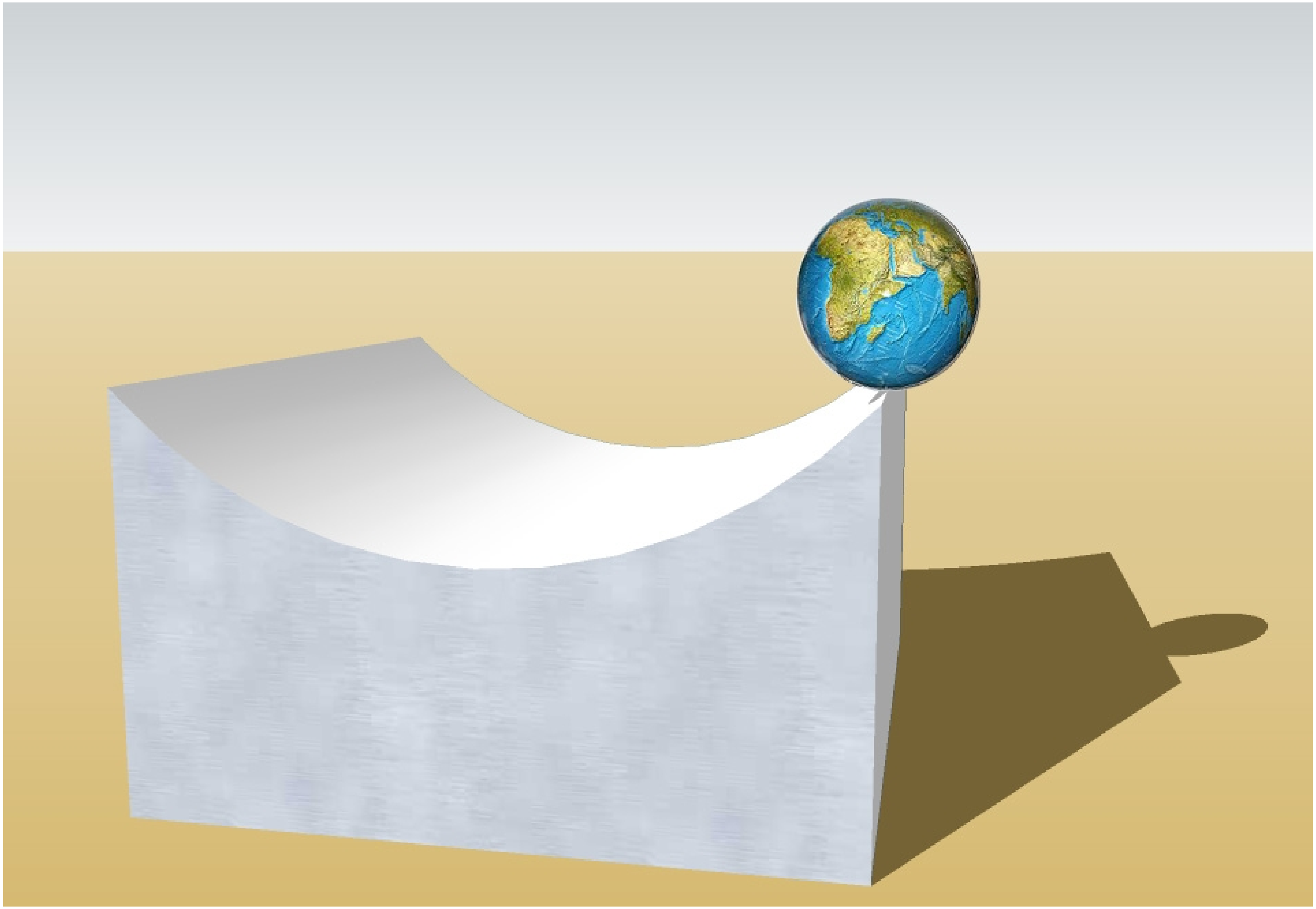
Quadratic sensitivity to the cut-off

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

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

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

▶ Stability and metastability bounds

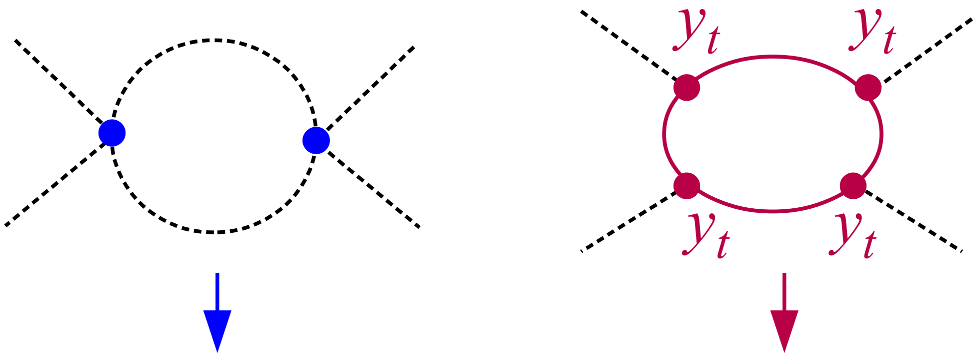


Stability and metastability bounds

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

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

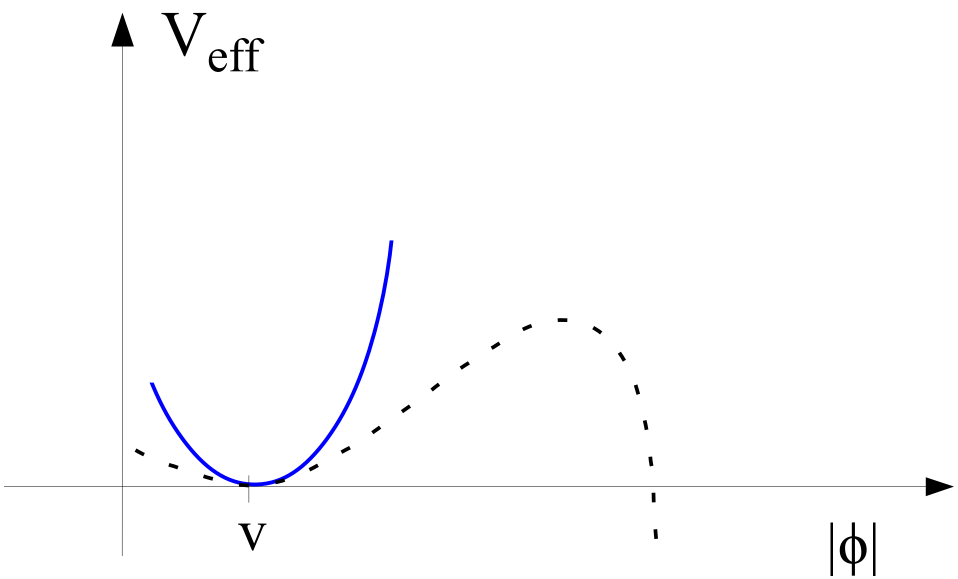
$$y_t(v) \propto \frac{m_t}{v}$$

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

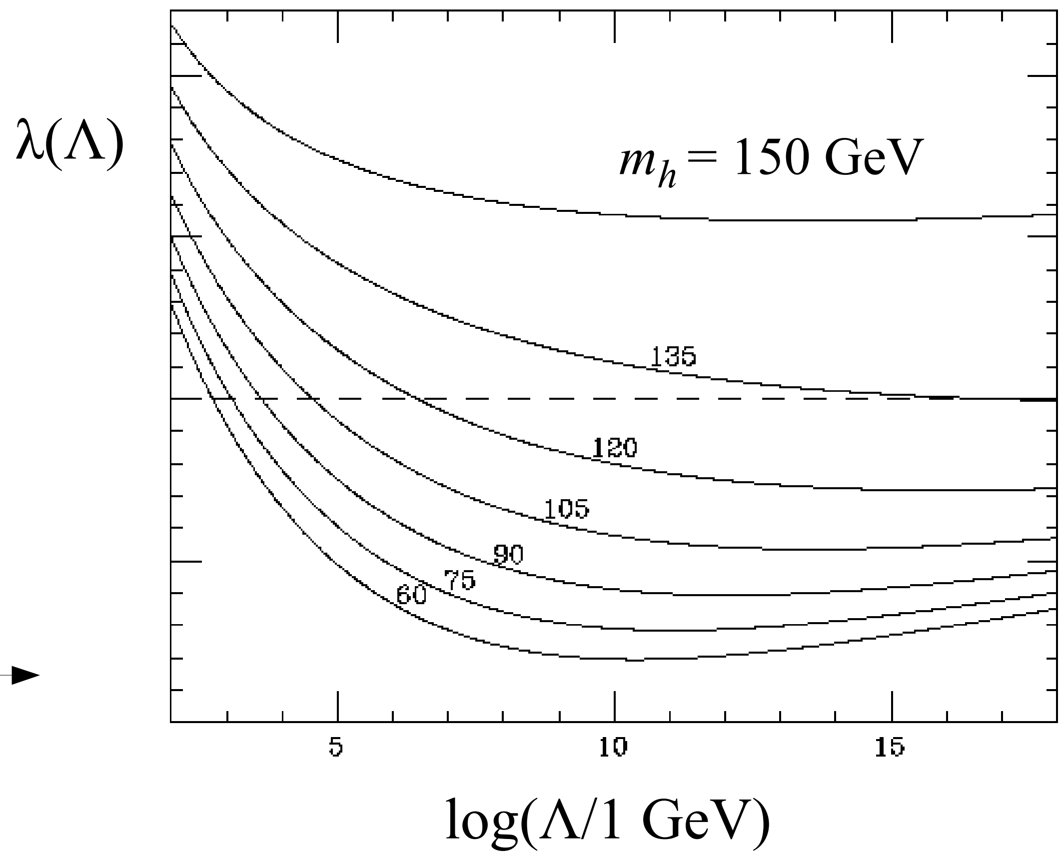
Stability and metastability bounds

At large field values:

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



Altarelli, G.I, '94

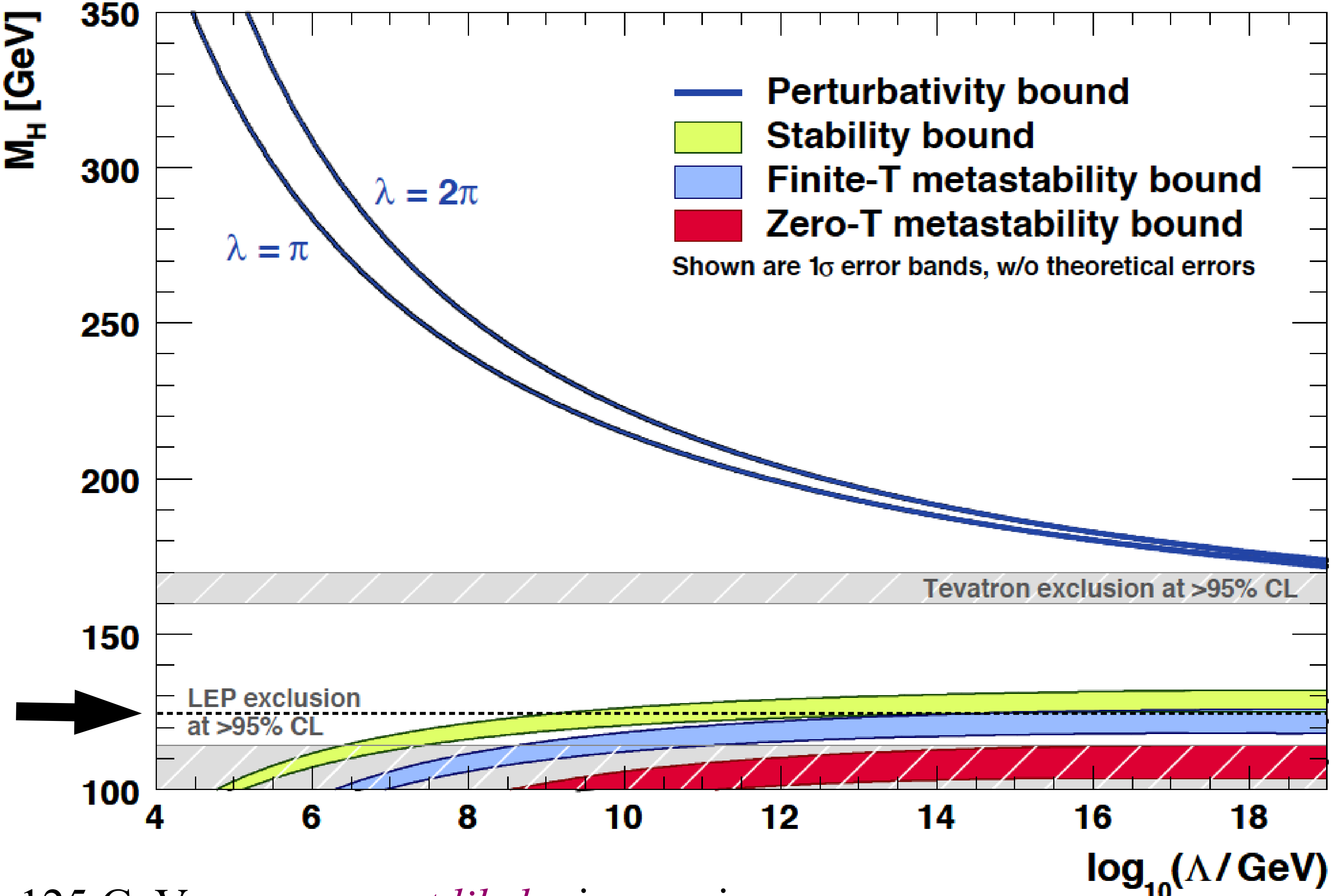


The problem was well-known since a long time, but now for the first time we can "quantify it", knowing the Higgs mass

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

▶ Stability and metastability bounds

Ellis et al. '09



For $m_h \sim 125$ GeV we are -*most likely*- in a region where the Higgs potential is not absolutely stable

✯ *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)

✭ *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)

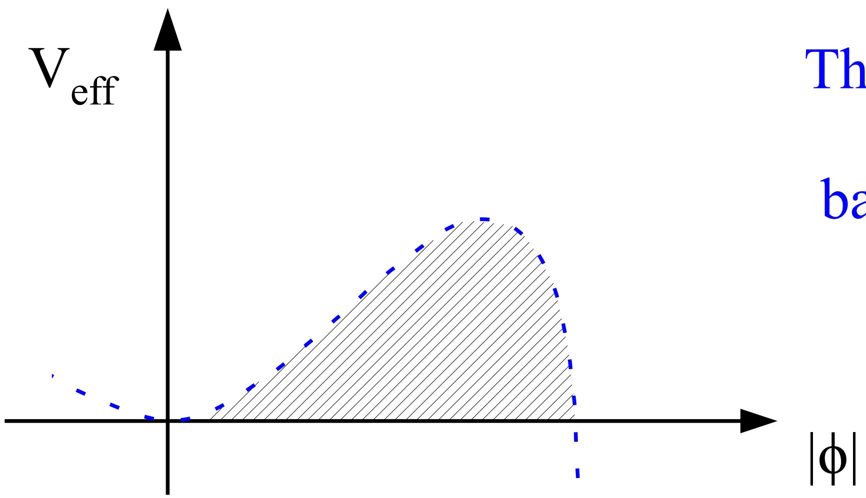
The e.w. minimum is destabilized by:

quantum fluctuations (at T=0)	thermal fluctuations
computable in a model-independent way	strongly dependent on the thermal history of the universe & competing with quant. fluctuations only for very high T

⬇

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:

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

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

↓

$$S_0[h] = \frac{8\pi^2}{3|\lambda|}$$

→

$$p_{semicl.} \approx (T_U / R)^4 \, e^{-8\pi^2/3|\lambda|}$$

If |λ| 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 tunneling is dominated by bounces of size R, such that λ(1/R) reaches its minimum value:

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

μ independent

$\Delta S \approx 0$ if we set $\mu = 1/R$

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 tunneling is dominated by bounces of size R, such that $\lambda(1/R)$ reaches its minimum value
- The critical R determine the reference scale of the volume pre-factor:

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

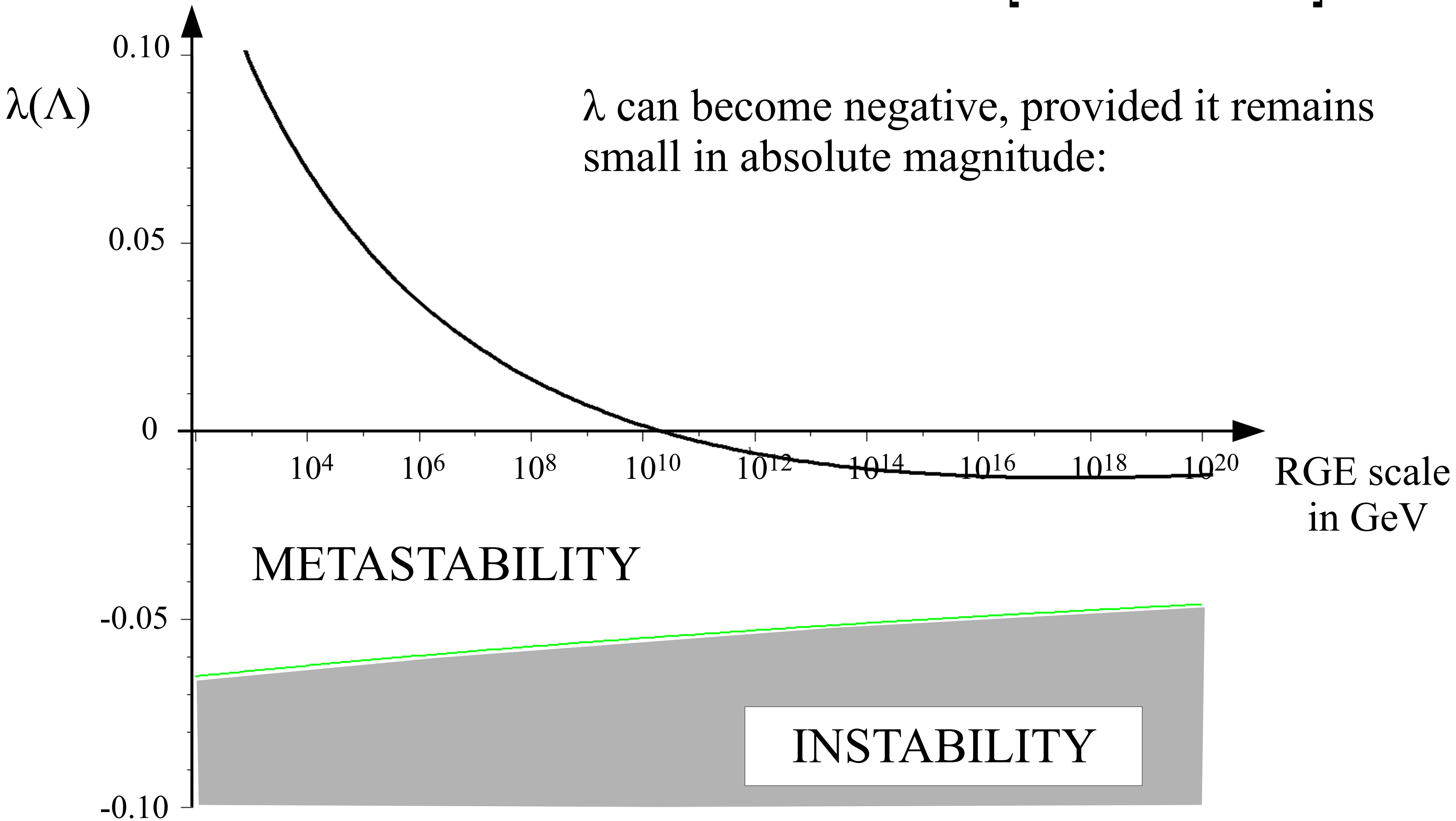
The leading gravitational effects are also calculable when 1/R is not far from (but below) M_{pl}

G.I., Rychkov, Strumia, Tetradis '08

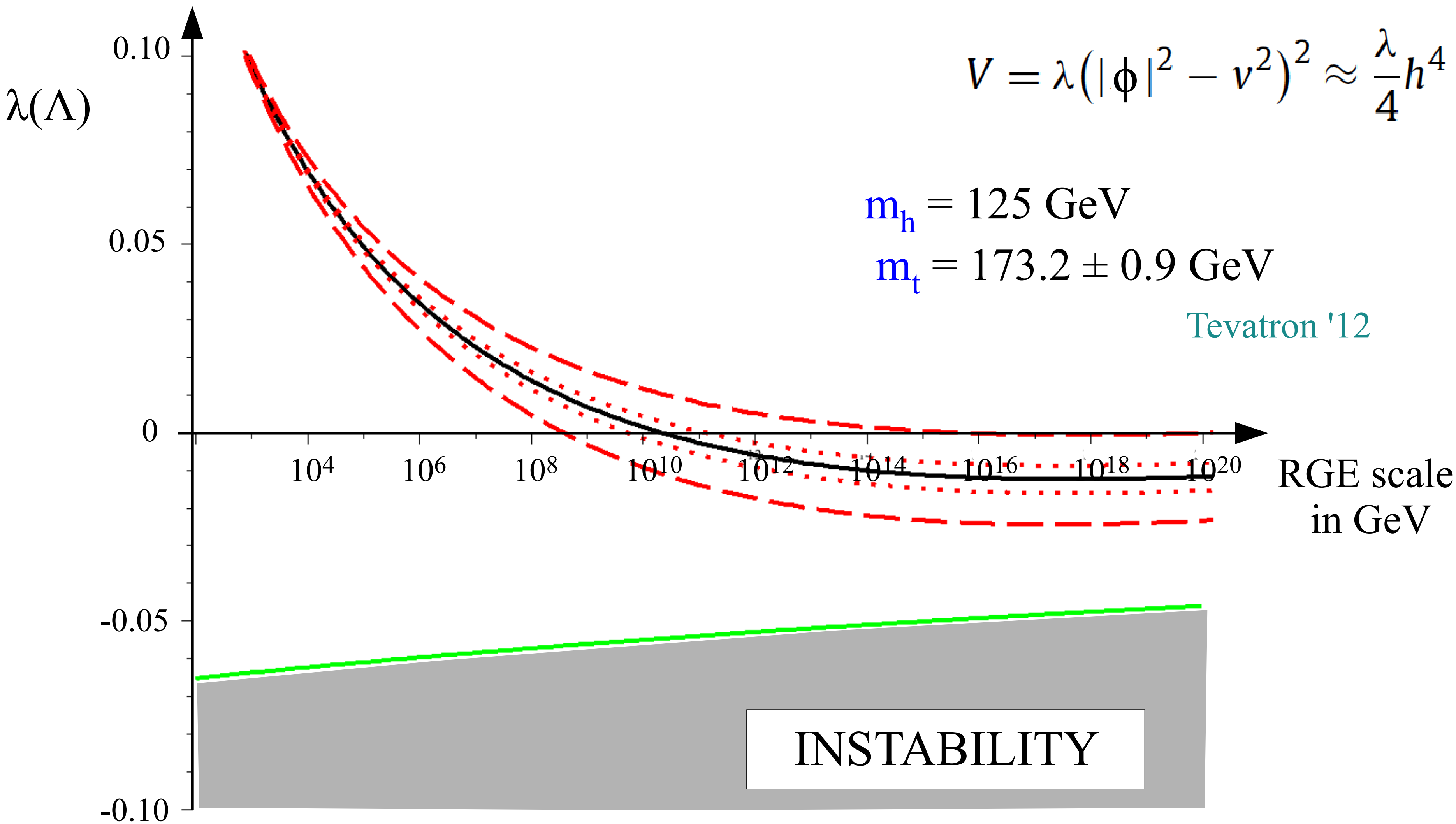
✯ The metastability condition:

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

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



Message n.2: For m_h =125 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)

For m_h =125 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

How "precise" is this statement?

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*)

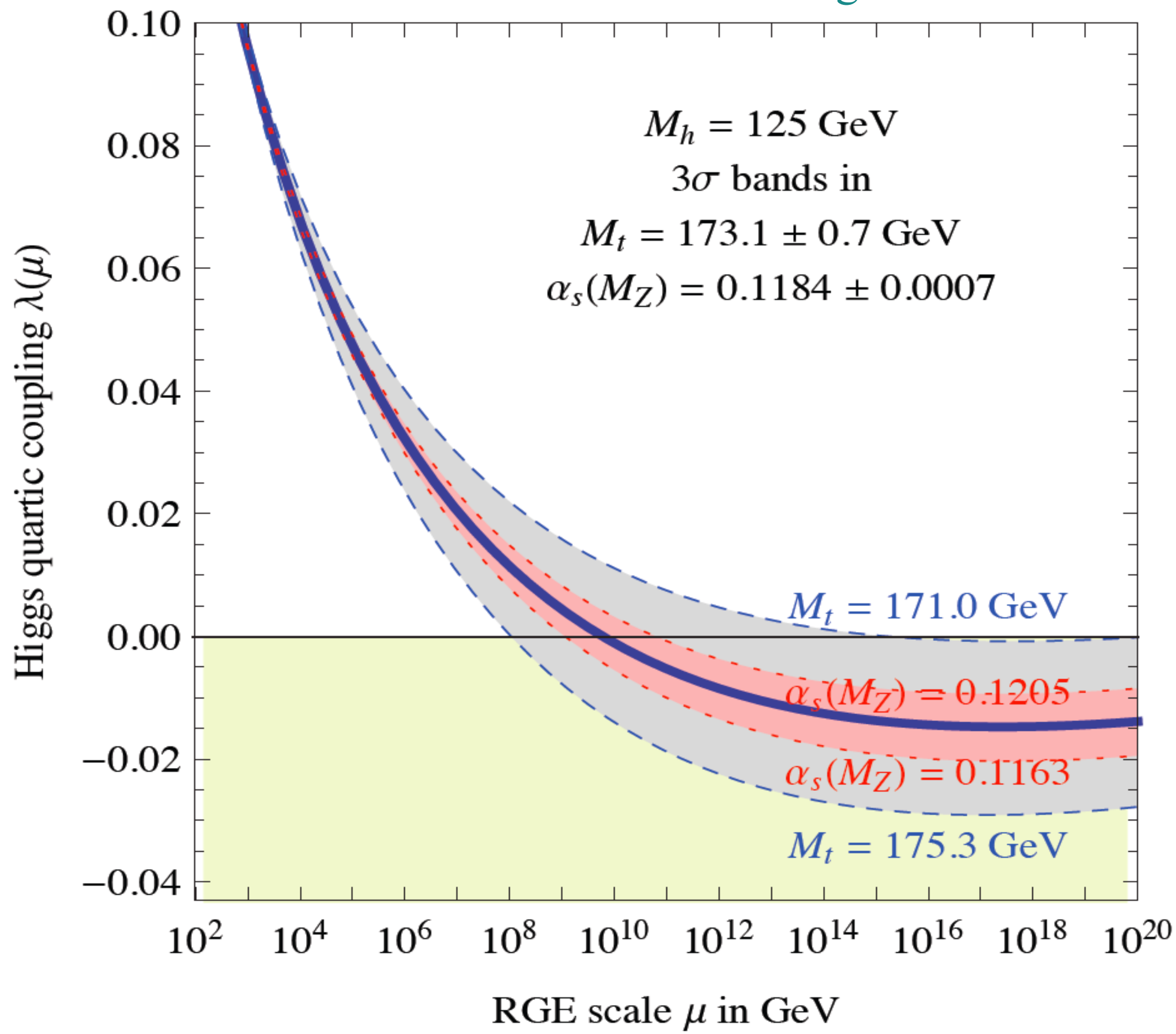
Yukawa×QCD — Bezrukov, Kalmykov, Kniehl, Shaposhnikov, 1205. 2893

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).

Degrassi *et al.* '12

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).



With the NNLO calculation we are able to derive a <u>very precise</u> 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

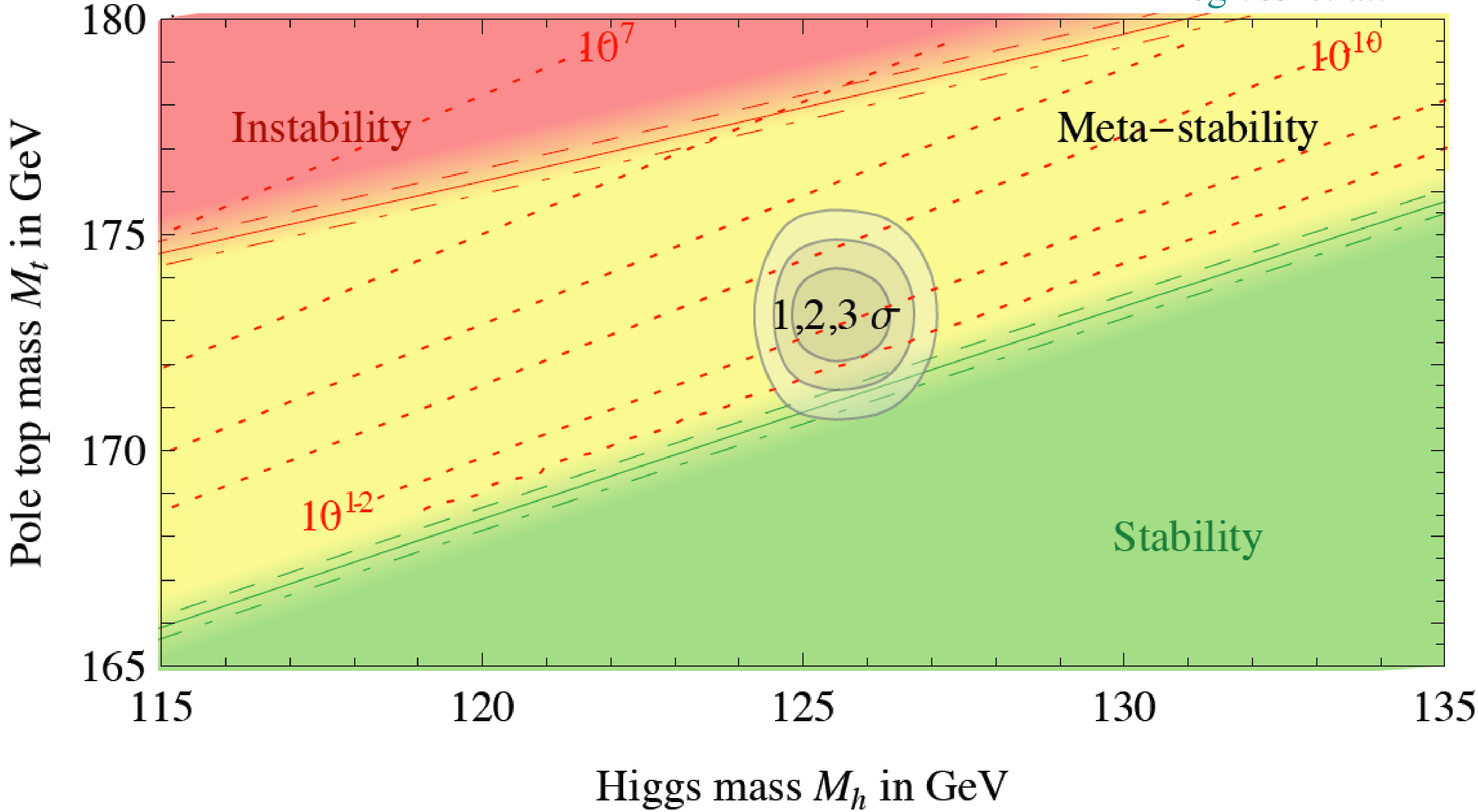
$+\,0.2\,\mathrm{GeV}$ due to the Yukawa threshold corrections to λ

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

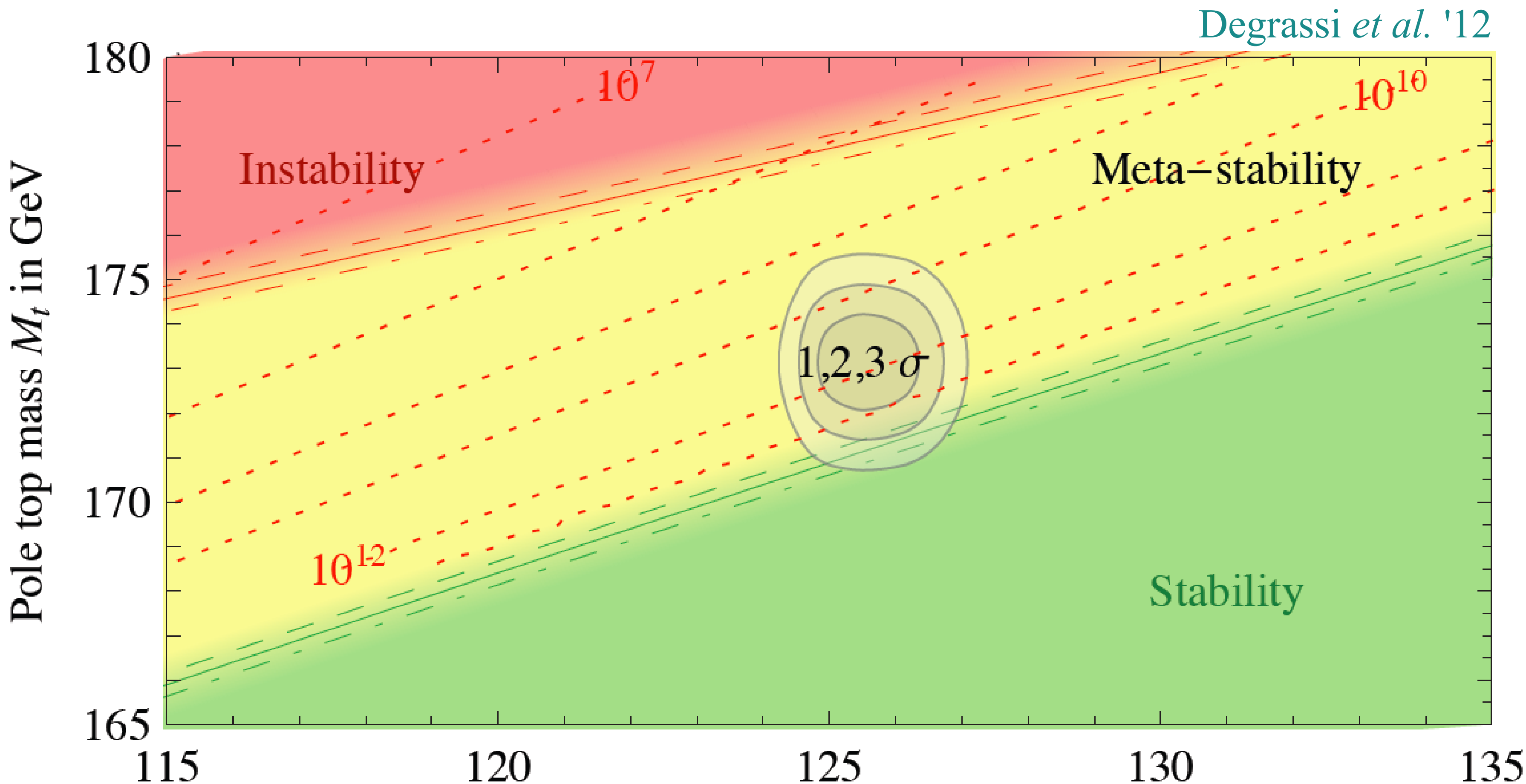
$-\,0.1\,\mathrm{GeV}$ from the effective potential at 2 loops.

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

Degrassi *et al.* '12



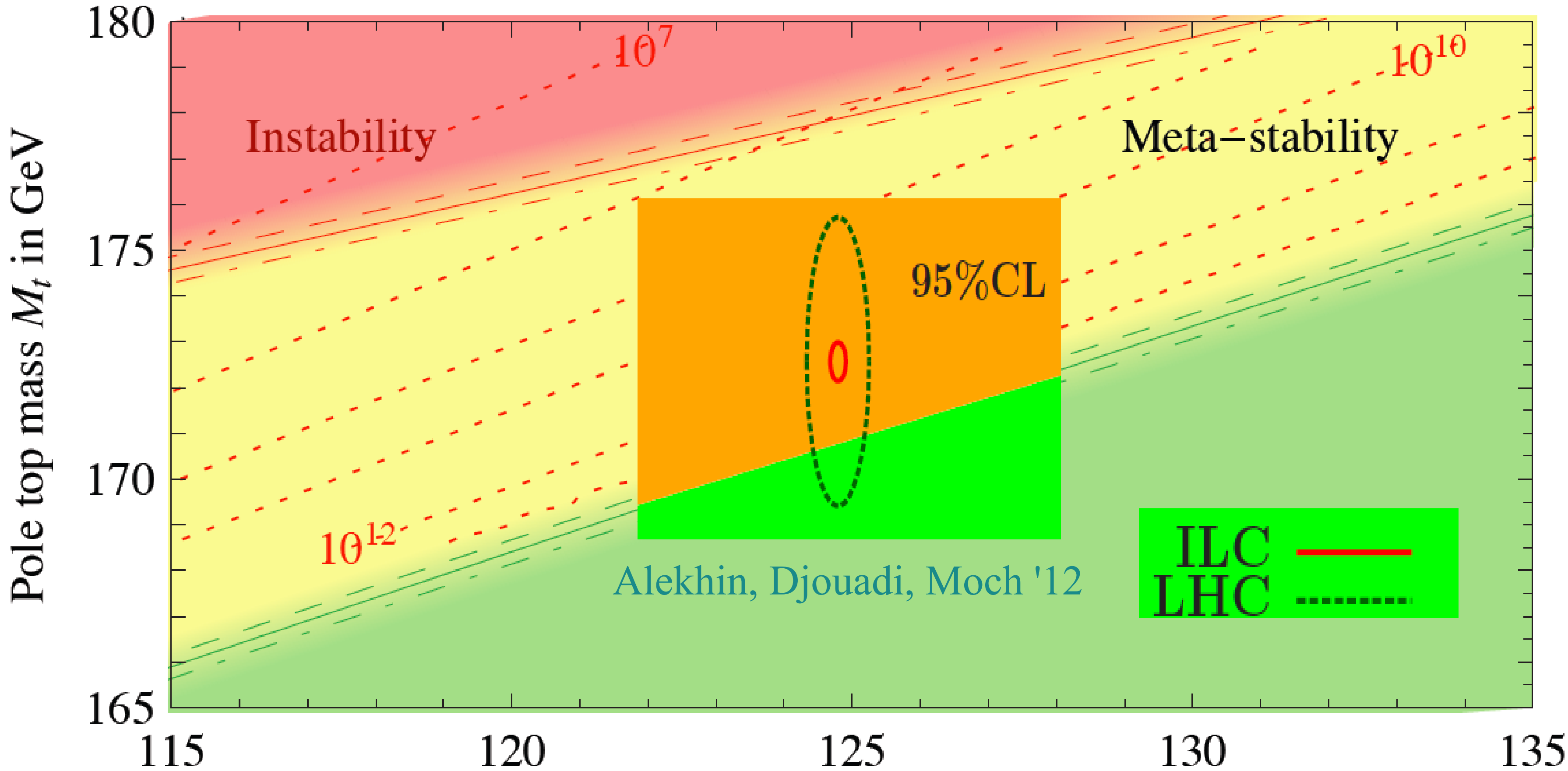
With the NNLO calculation we are able to derive a very precise relation between Higgs and top masses from vacuum stability:



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)

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



A linear collider would be the ideal machine to bring down this uncertainty, determining more precisely the fate of the SM vacuum (*if in the meanwhile we have not found anything else...!*)

Two additional remarks about the instability of the SM potential:

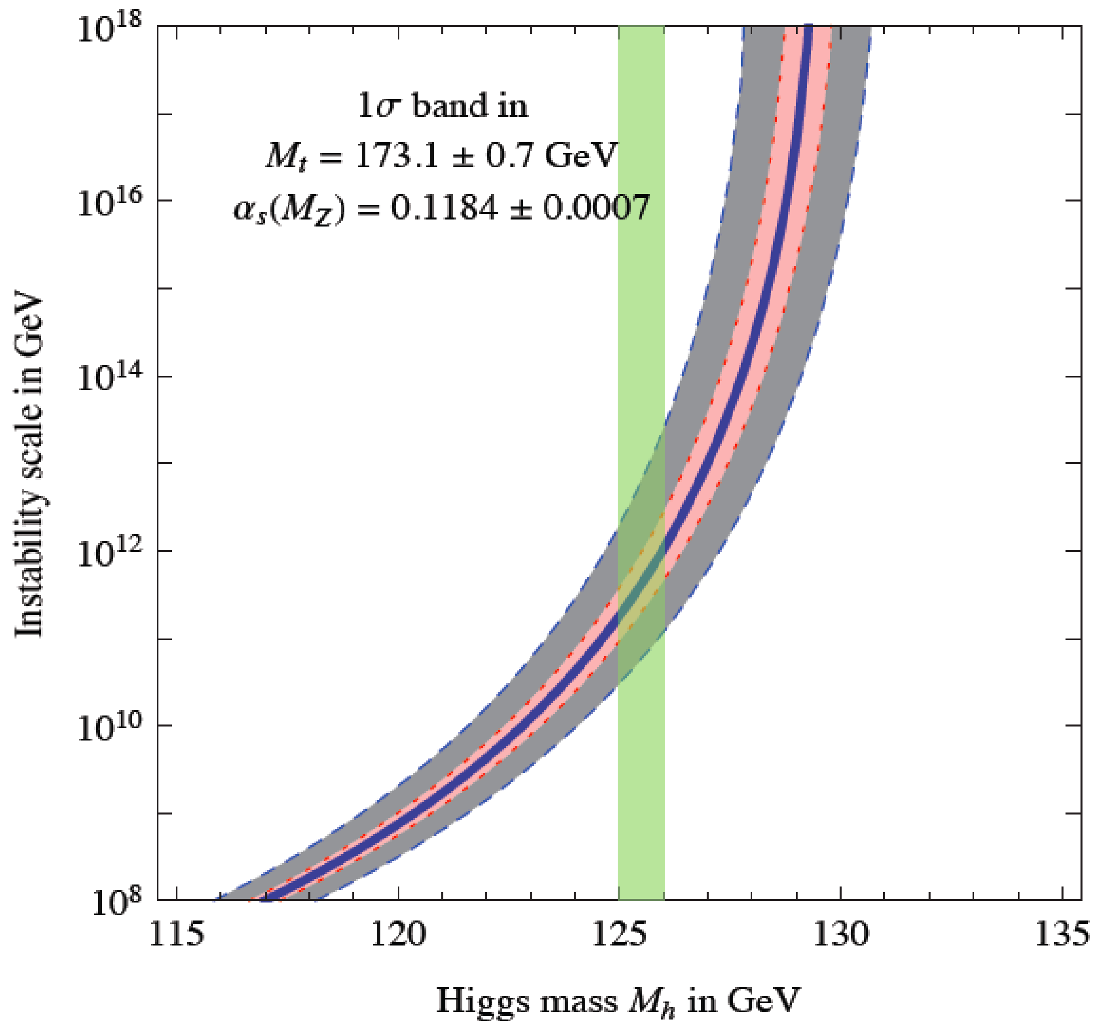
I. What about the instability because of thermal fluctuations?

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

Two additional remarks about the instability of the SM potential:

I. What about the instability because of thermal fluctuations?

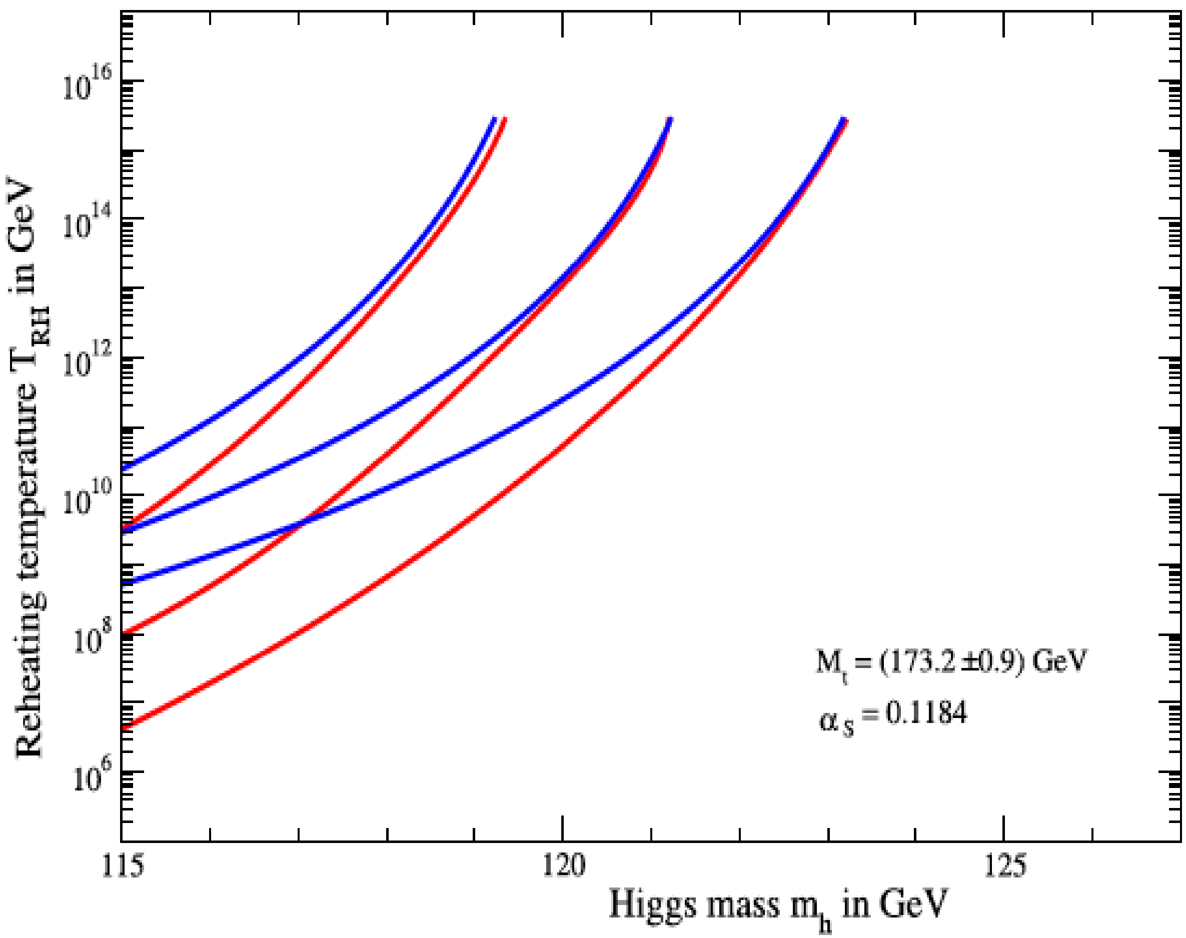
Since the instability occurs at very high energies, thermal corrections do not play a significant role in destabilizing the potential.



Two additional remarks about the instability of the SM potential:

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.



Two additional remarks about the instability of the SM potential:

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?

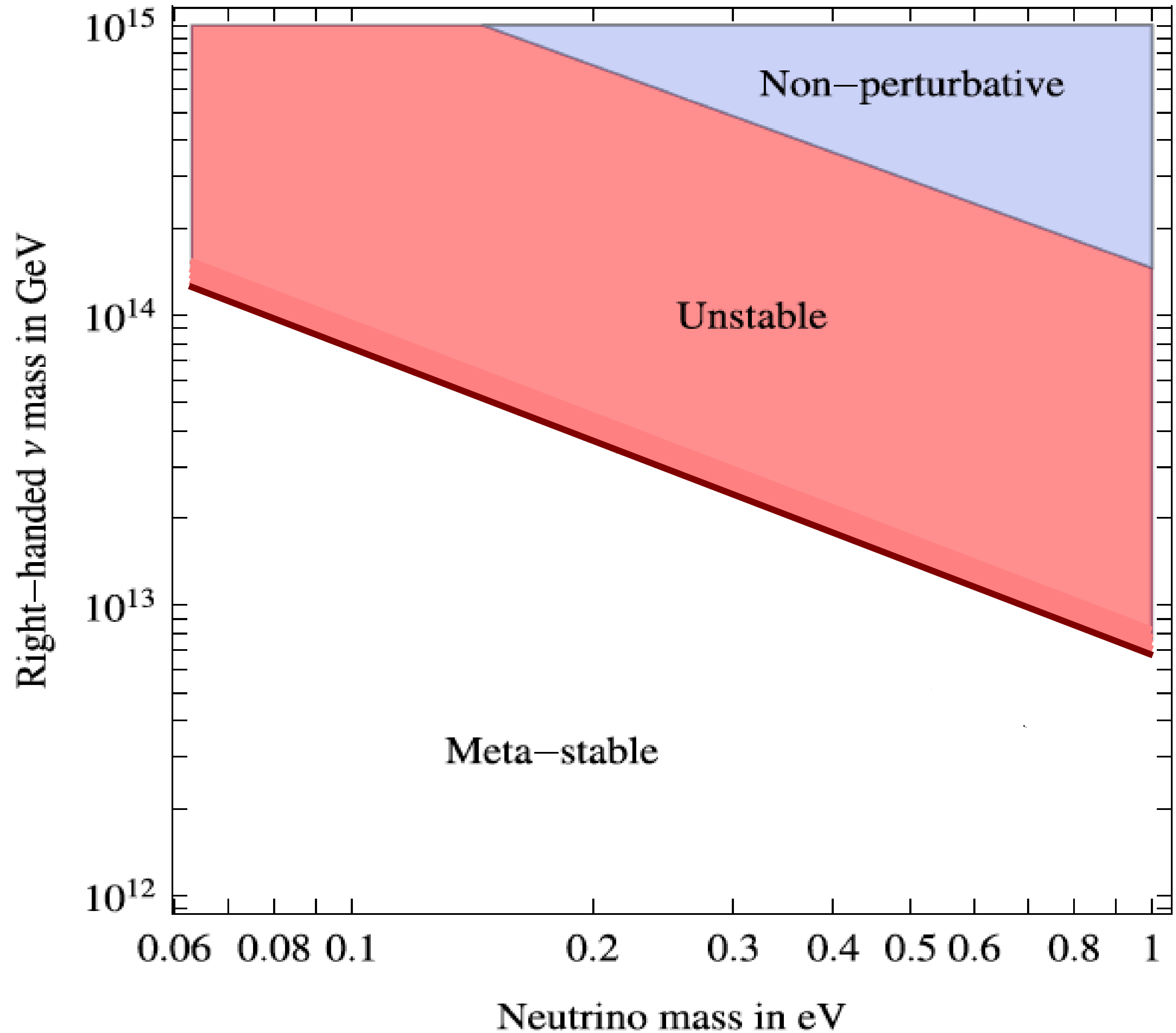
On general ground, adding new fermions may induce a further destabilization of the potential. However, the effect depend on the size of the new Yukawa couplings:

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

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

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

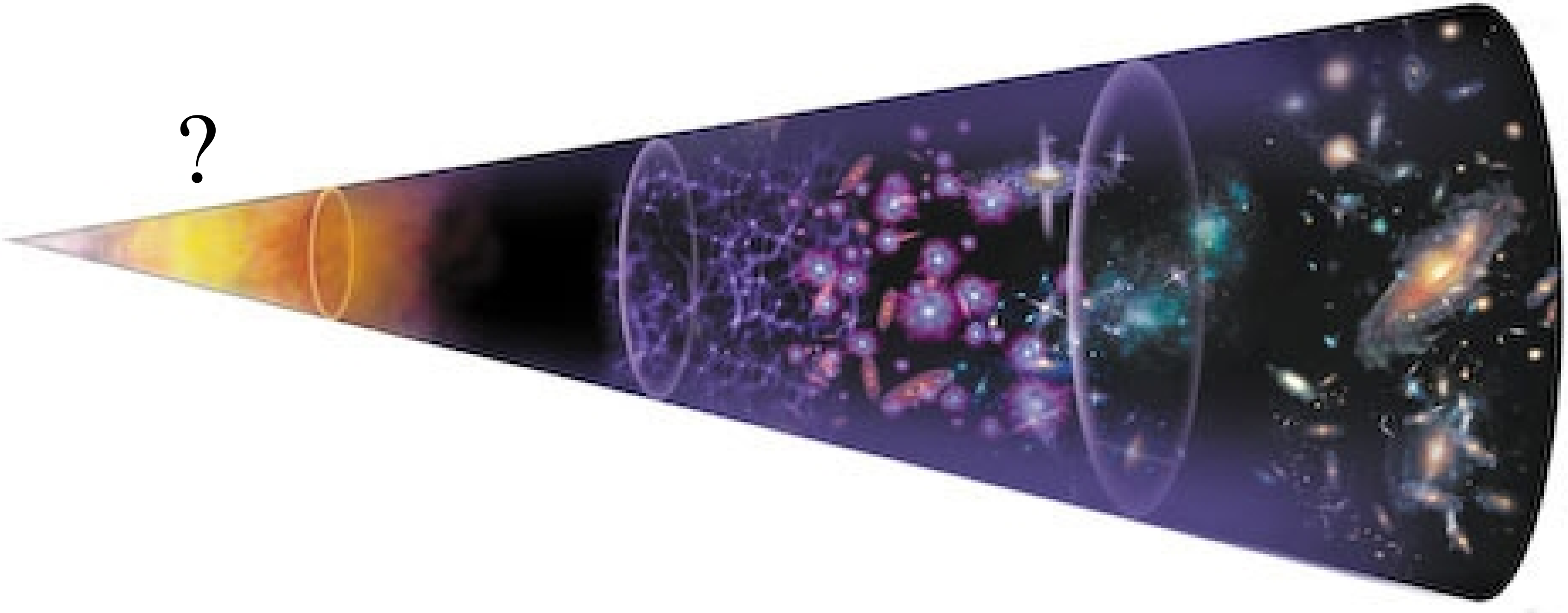
Elias-Miro *et al.* '11



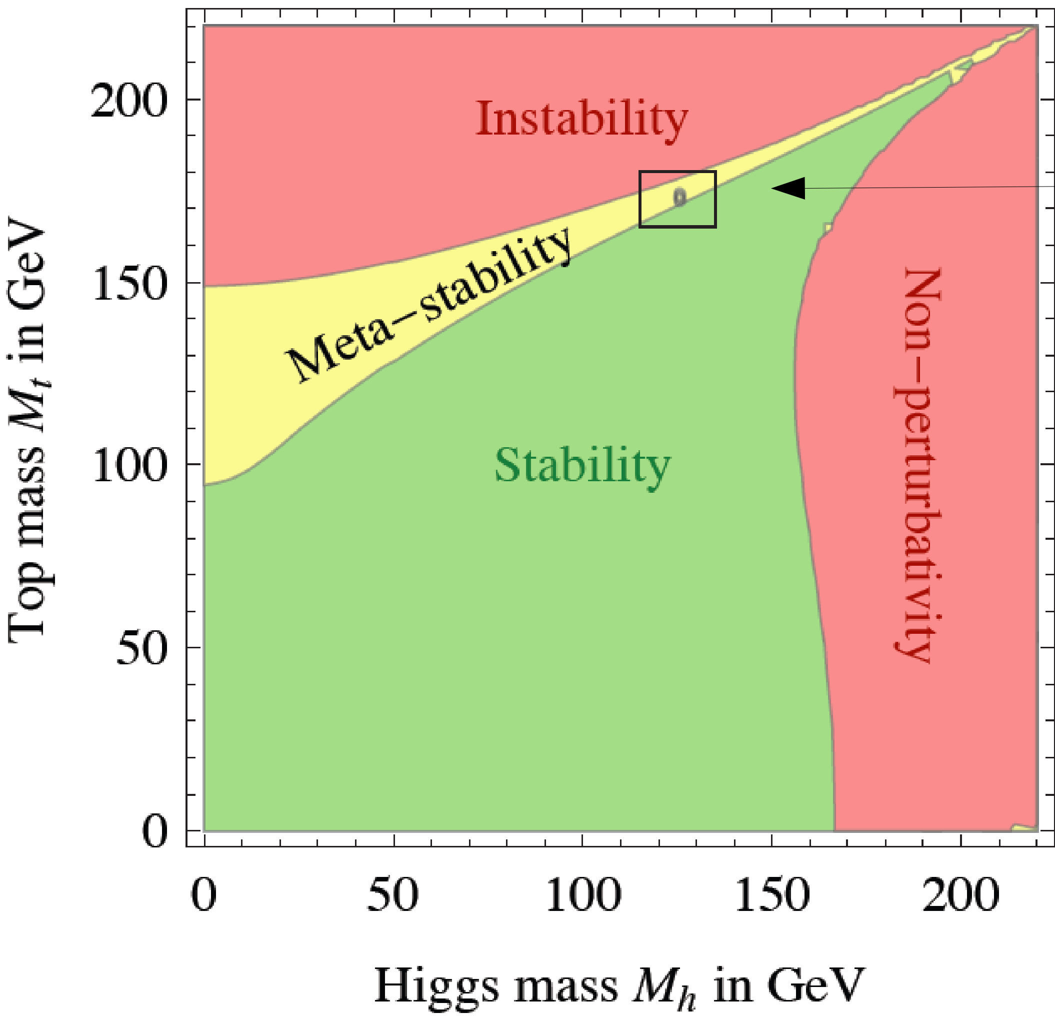
Still enough room for leptogenesis to take place.

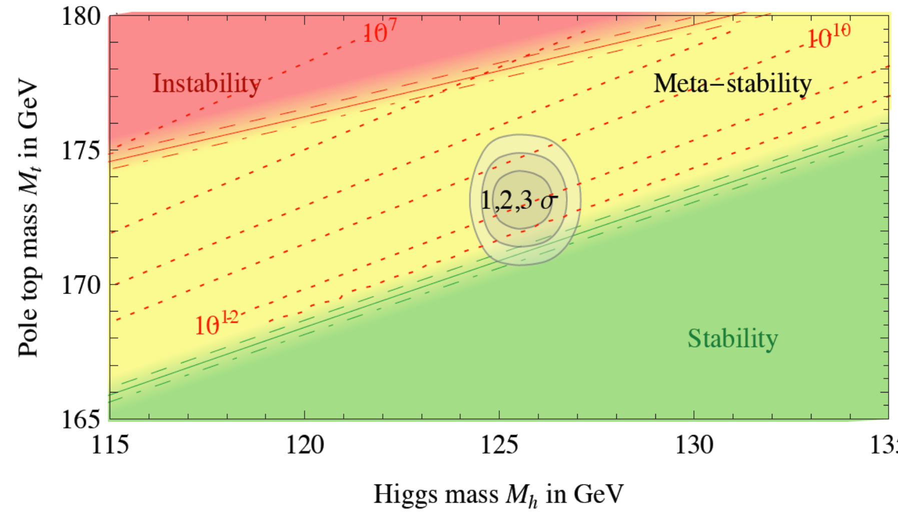
Speculations on Planck-scale dynamics

?



▶ 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...

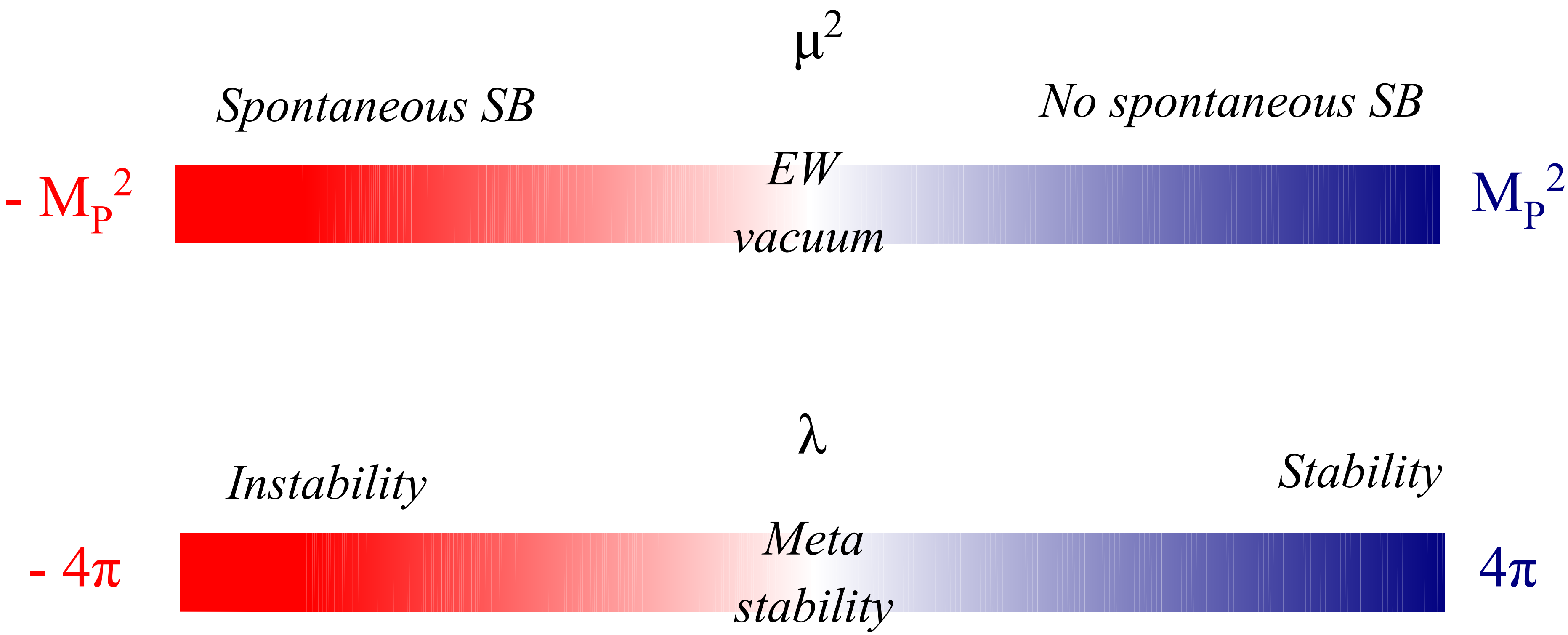
Moving m_t down by ~ 2 GeV, we reach the even more peculiar configuration where $\lambda(M_{pl})=0$

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

Speculations on Planck-scale dynamics

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

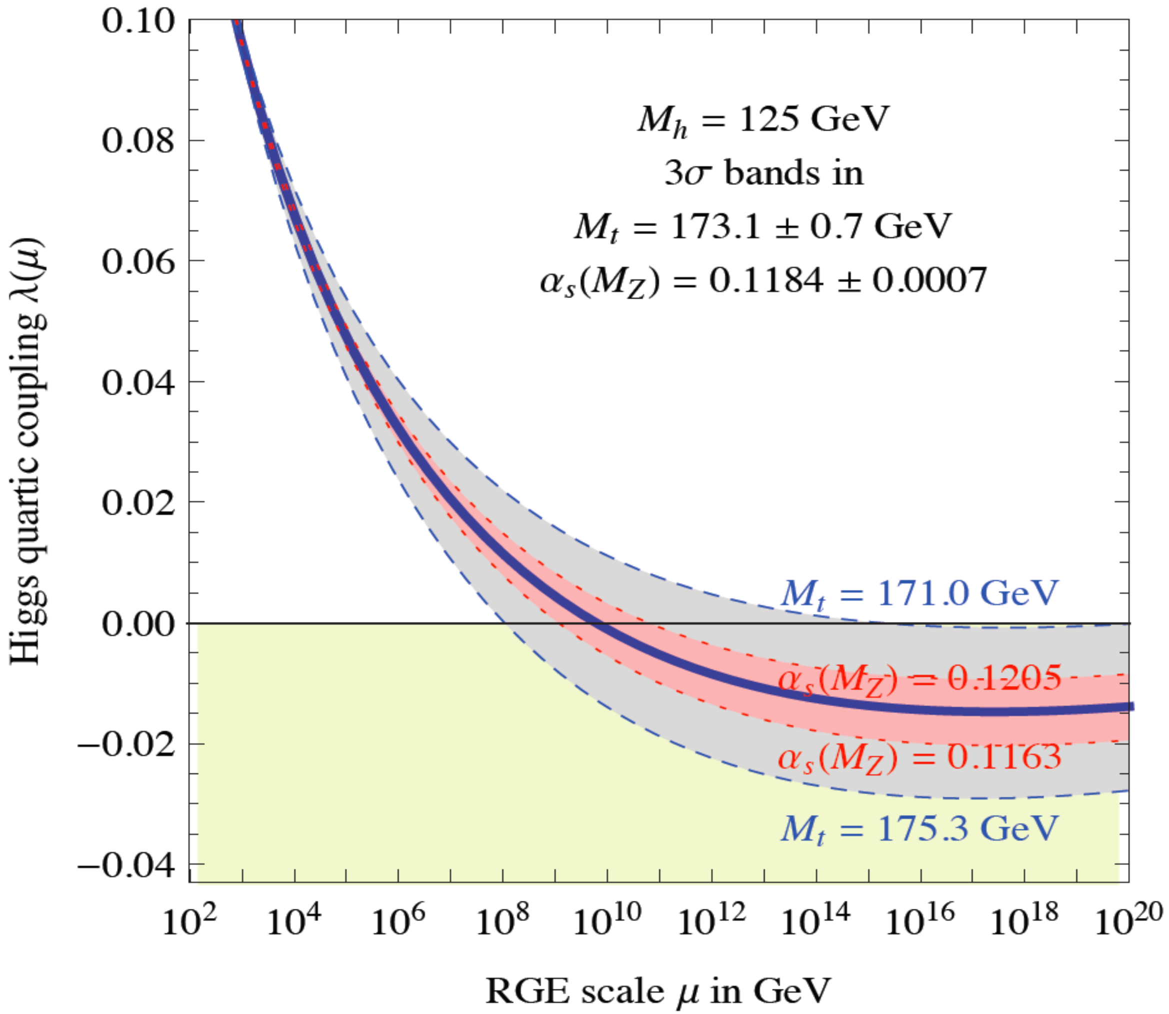
$$V(\phi) = -\mu^2 \phi^{+}\phi + \lambda\,(\phi^{+}\phi)^2$$



Speculations on Planck-scale dynamics

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

Despite also the beta function vanishes, is not a true fixed point (other coupl. ≠ 0)



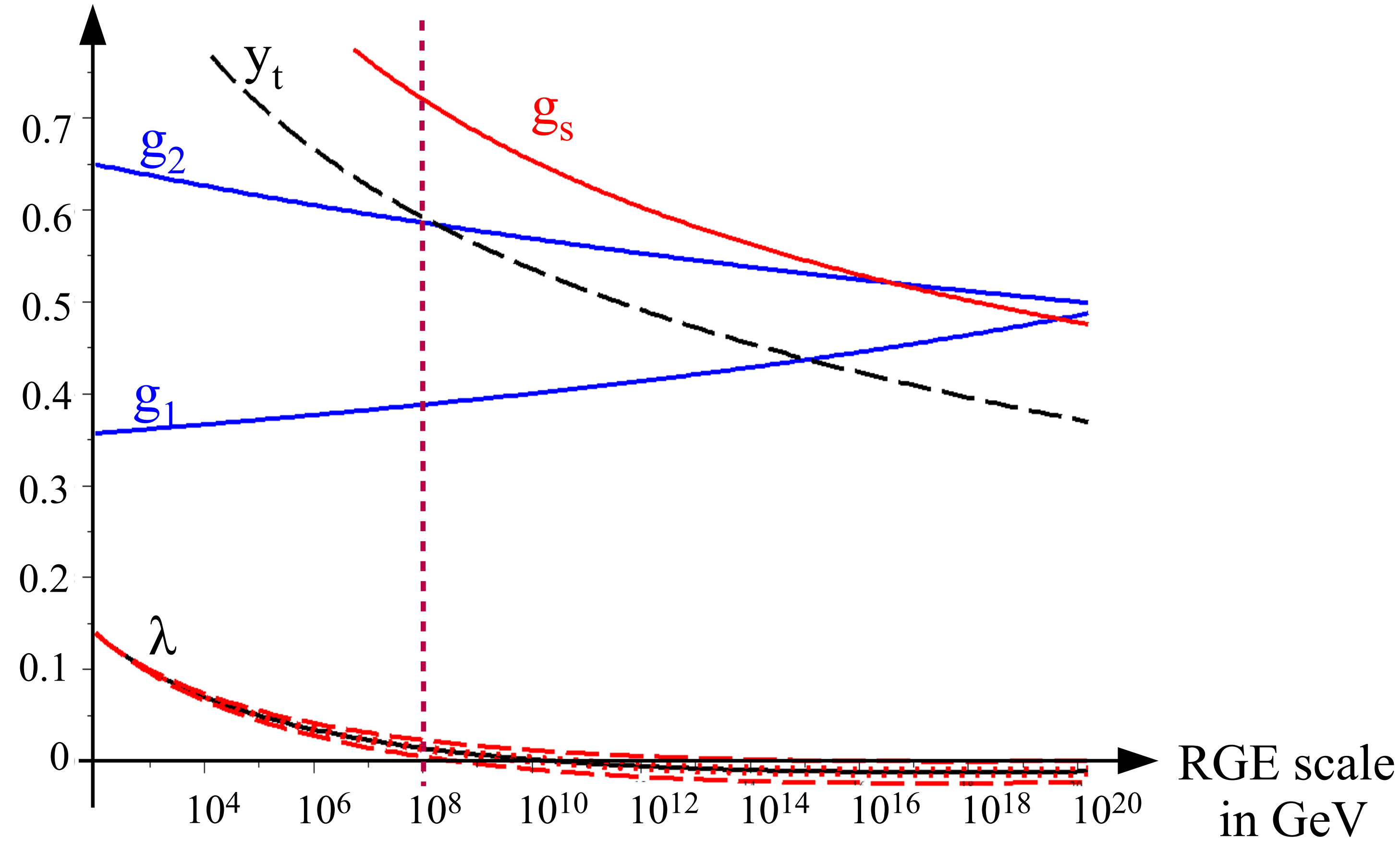
Speculations on Planck-scale dynamics

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

Despite also the beta function vanishes, is not a true fixed point (other coupl. ≠ 0).

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*?



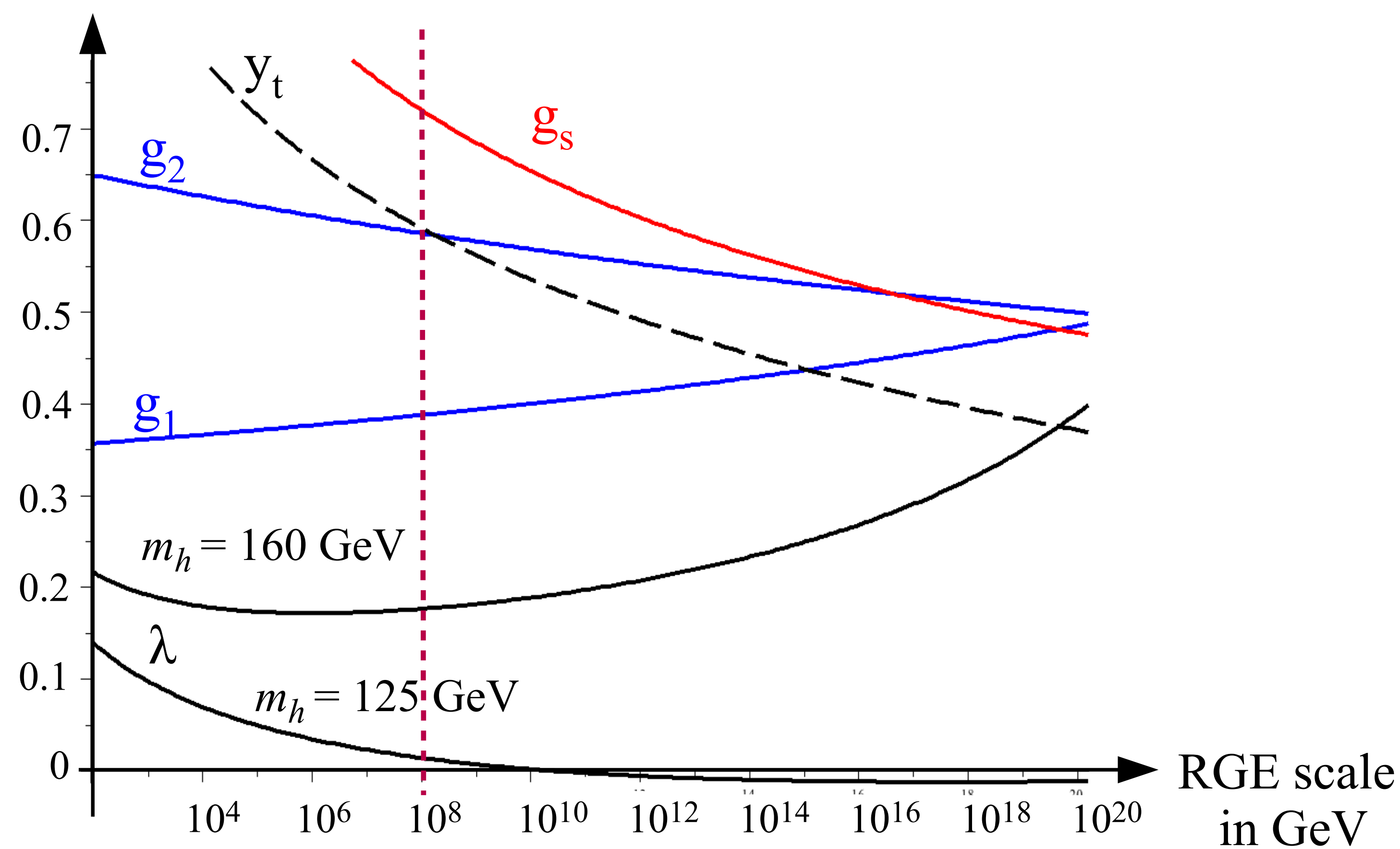
Speculations on Planck-scale dynamics

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

Despite also the beta function vanishes, is not a true fixed point (other coupl. $\neq 0$).

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

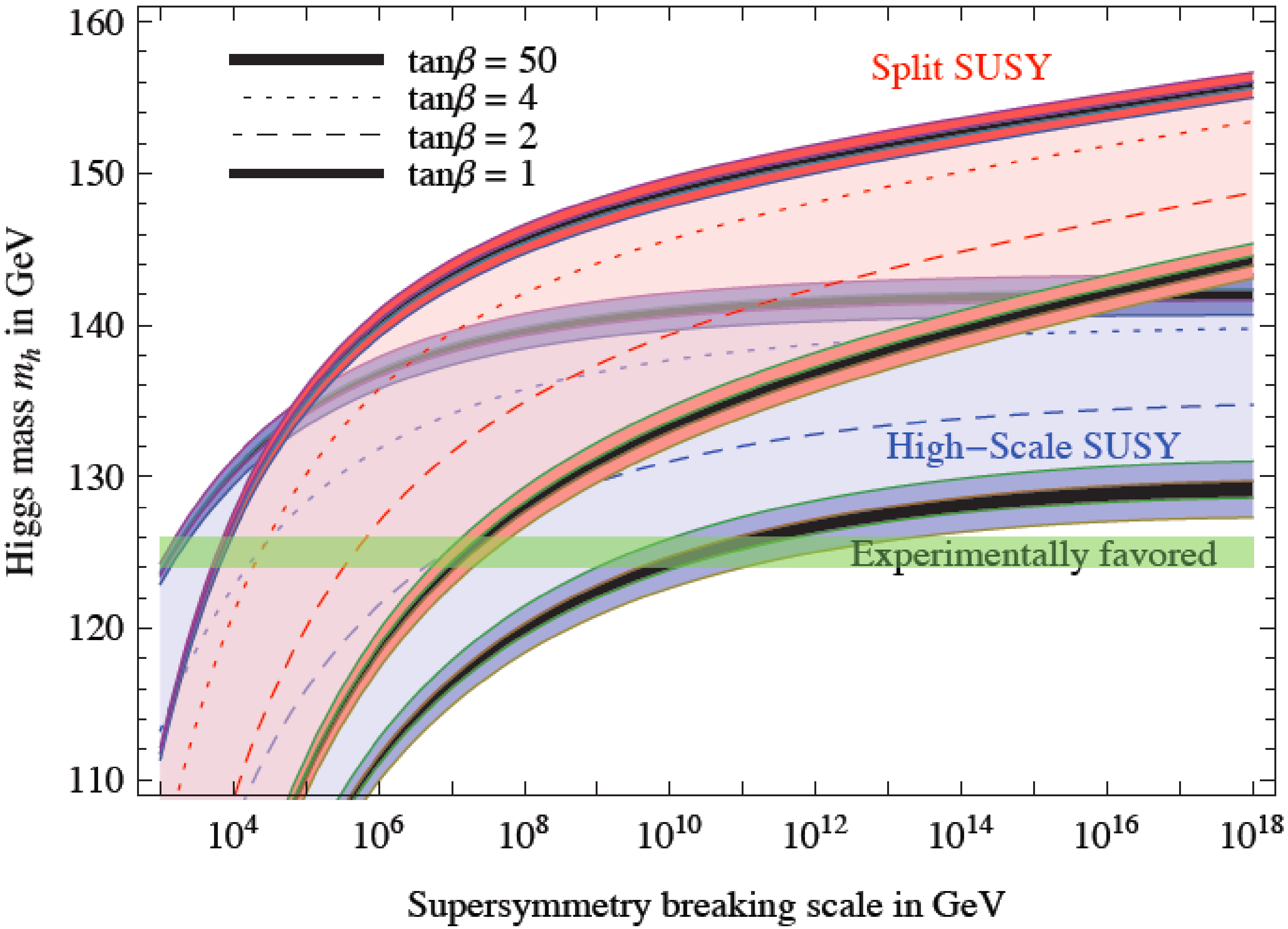
At a scale $\Lambda \gtrsim 10^8$ GeV λ becomes of the same order of its typical e.w. quantum corrections: *hints of a radiatively generated coupling*?



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

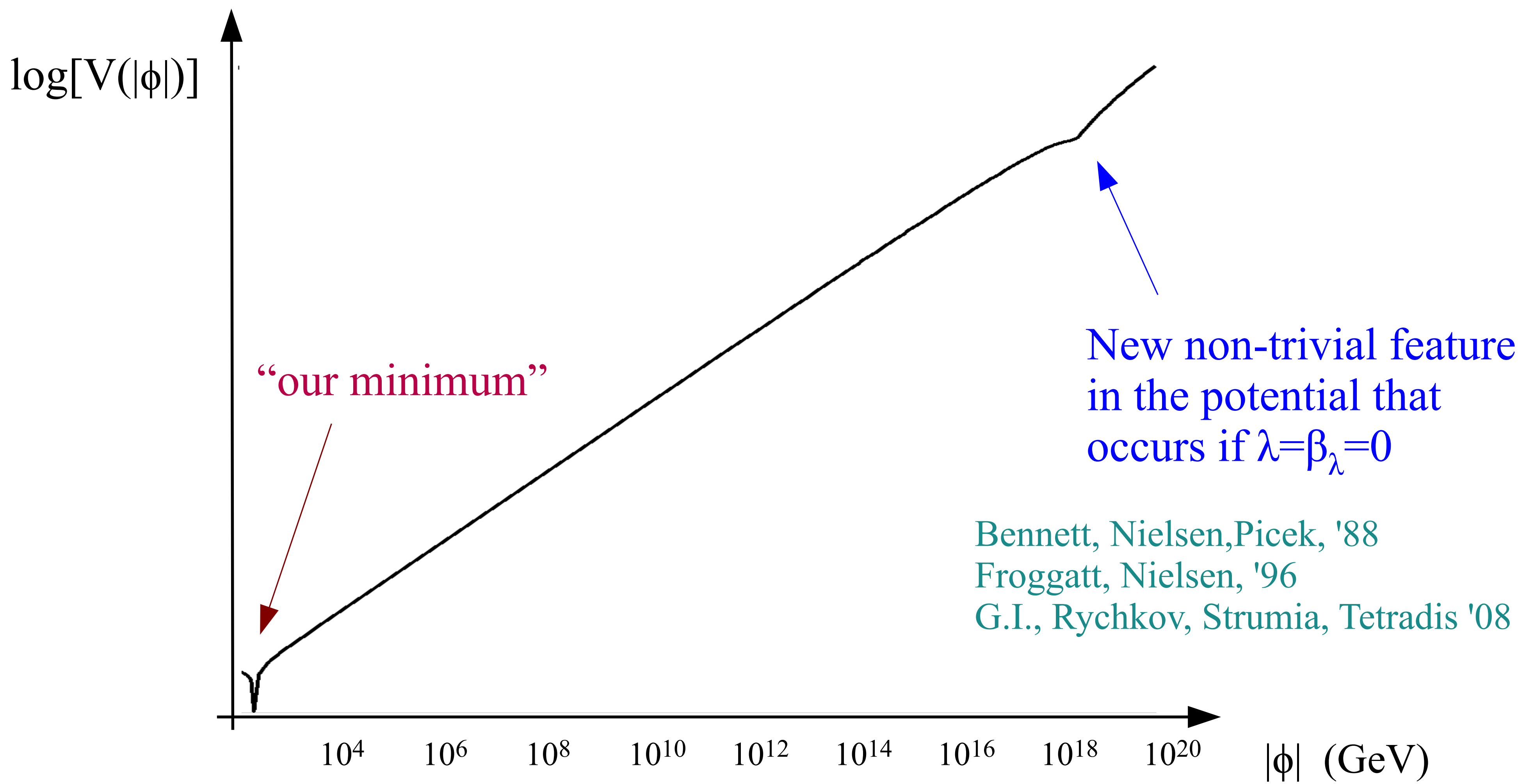
Giudice & Strumia '11-'12



Speculations on Planck-scale dynamics

Probably the most 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

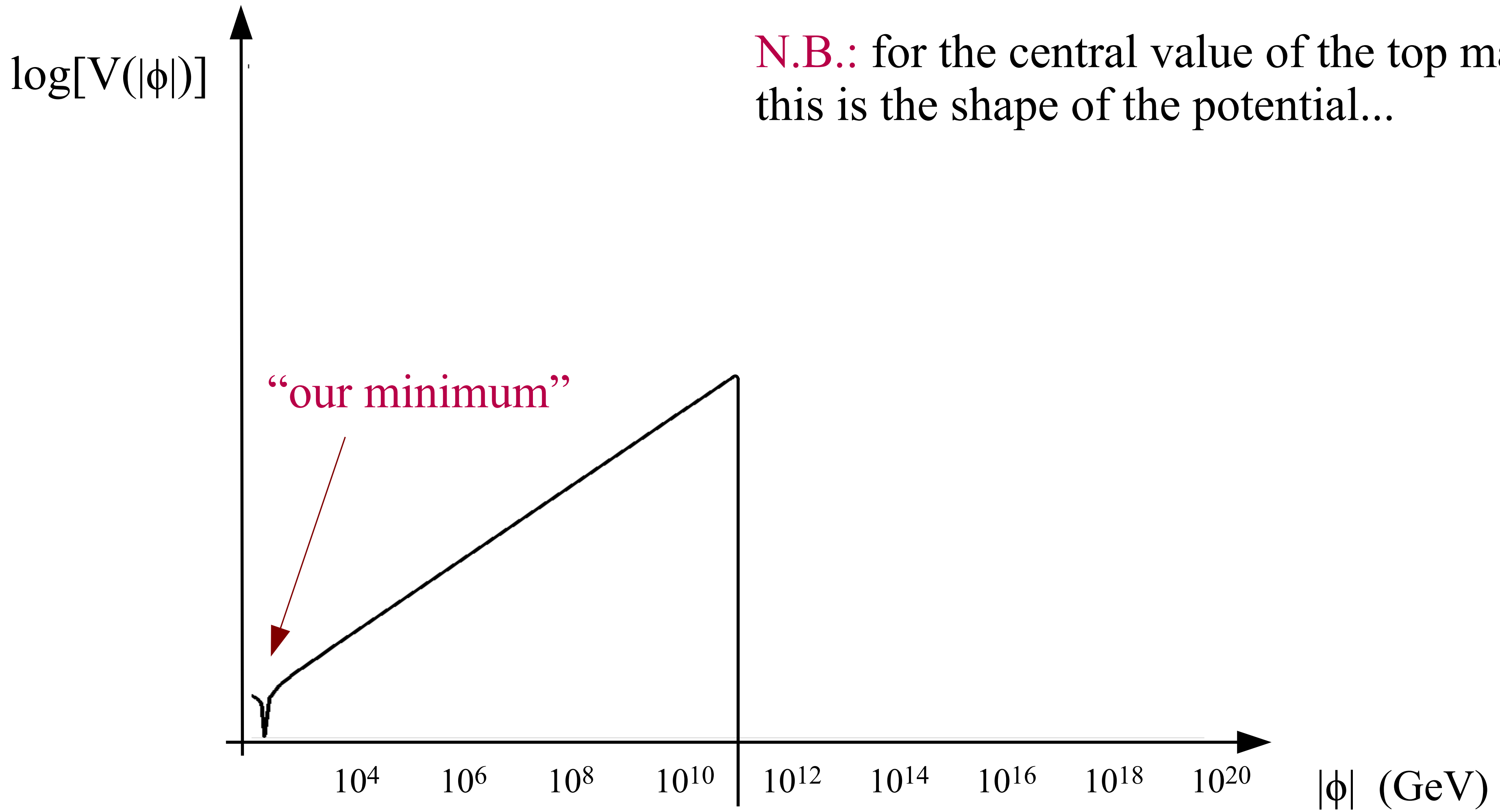


Bennett, Nielsen,Picek, '88
Froggatt, Nielsen, '96
G.I., Rychkov, Strumia, Tetradis '08

Speculations on Planck-scale dynamics

Probably the most 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.

N.B.: for the central value of the top mass this is the shape of the potential...



Speculations on Planck-scale dynamics

Probably the most 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.

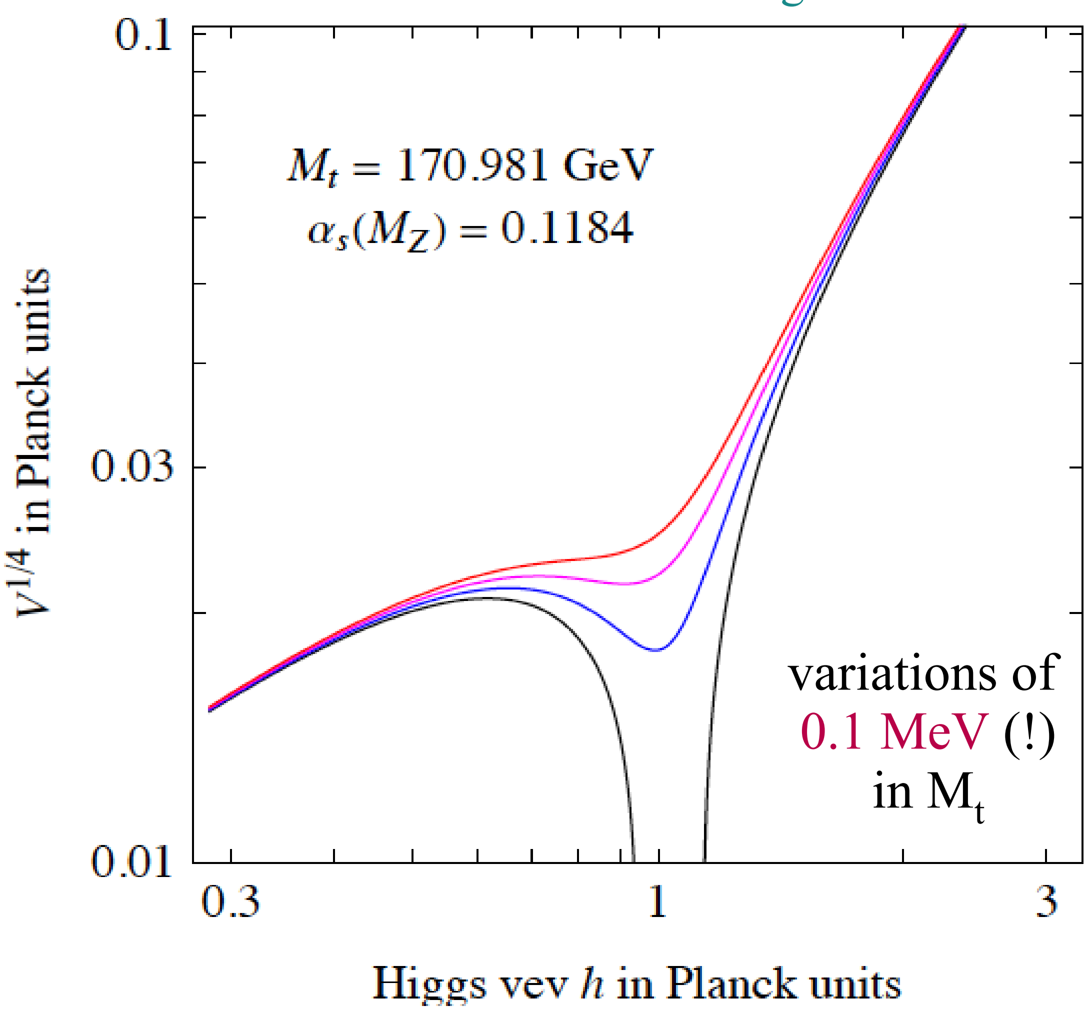
The minimal set-up (SM only) does not work (*field trapped into the new minimum or too large fluctuations*)

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

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

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

Degrassi *et al.* '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, or even vanishing, Higgs self-coupling 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*]
    - may have a vanishing intrinsic self-coupling (trivial $\lambda\phi^4$, with gauge & Yukawa), if the matching occurs above $\sim 10^8$ GeV

- More precise determinations of both m_h & m_t would be very useful, especially in absence of other NP signals, to better investigate the structure of the Higgs potential at high energies