University of Zurich[UZH]

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

LHC Physics: Higgs and beyond

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LHC Physics: Higgs and beyond

(*a personal selection of topics in the wast domain of LHC physics*)

Gino Isidori
[*University of Zürich*]

- Lecture I: *What we learned from run-I*
  [The SM as an effective theory & the "ghost" of the anthropic principle]

- Lecture II: *What we can hope to learn from run-II (at high-pT)*
  [Future prospects in Higgs physics and direct NP searches]

- Lecture III: *Indirect searches for NP*
  [Flavor physics beyond the SM]

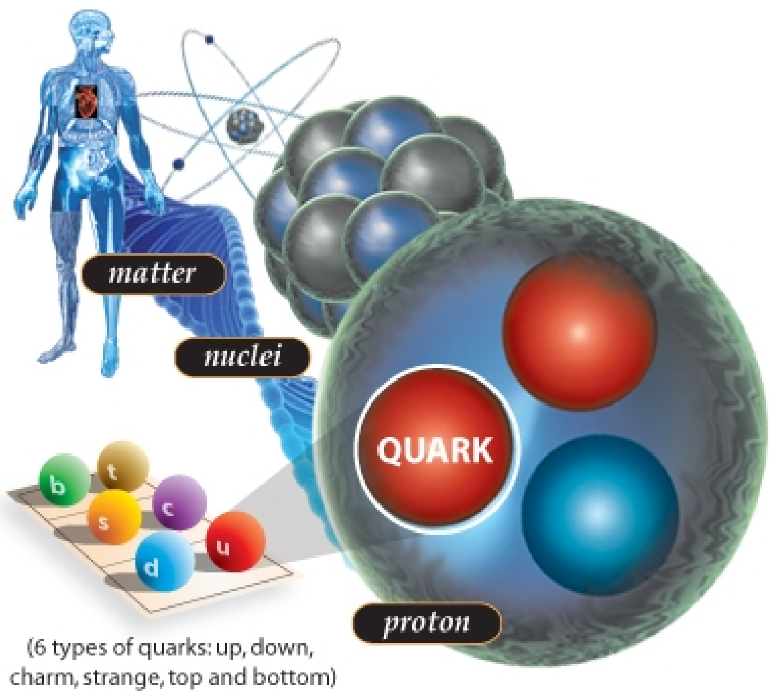
Lecture I: *What we learned from run-I*

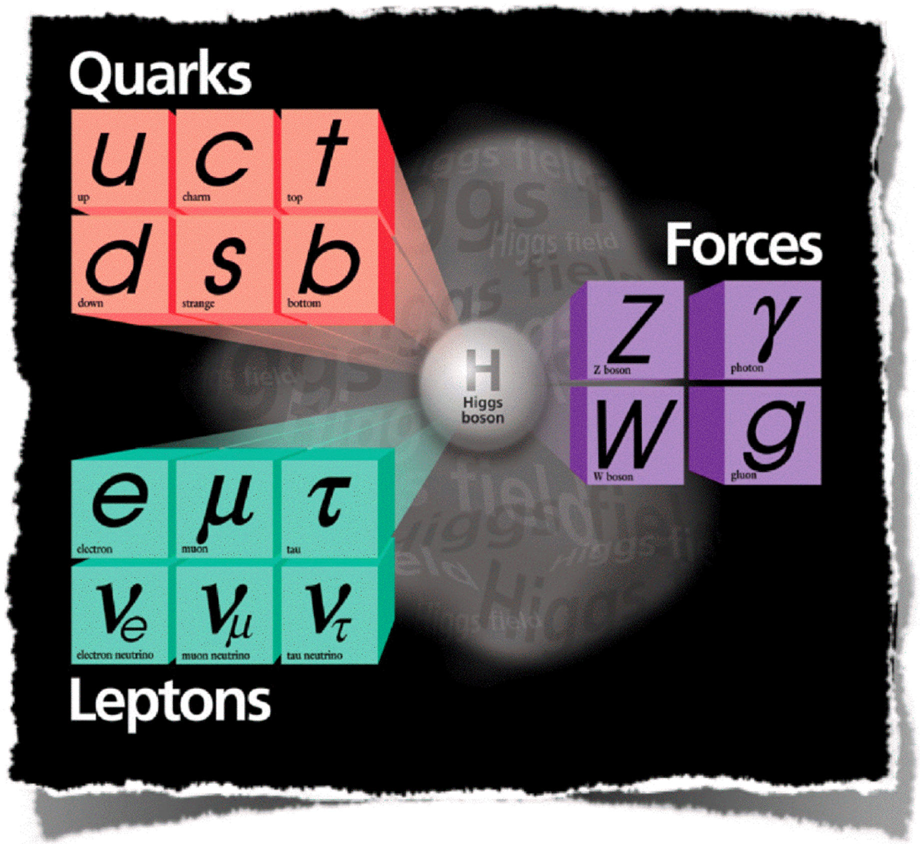
[The SM as an effective theory & the "ghost" of the anthropic principle]

Introduction

In last 40 years a highly successful Theory has emerged in the study of fundamental interactions: the so-called Standard Model.

The Standard Model describes with success both *nature* and *interactions* of matter constituents. It is a Theory valid over a huge range of energies: from the few eV of atomic bounding energies up to (at least) the few TeV energy reached in LHC collisions.

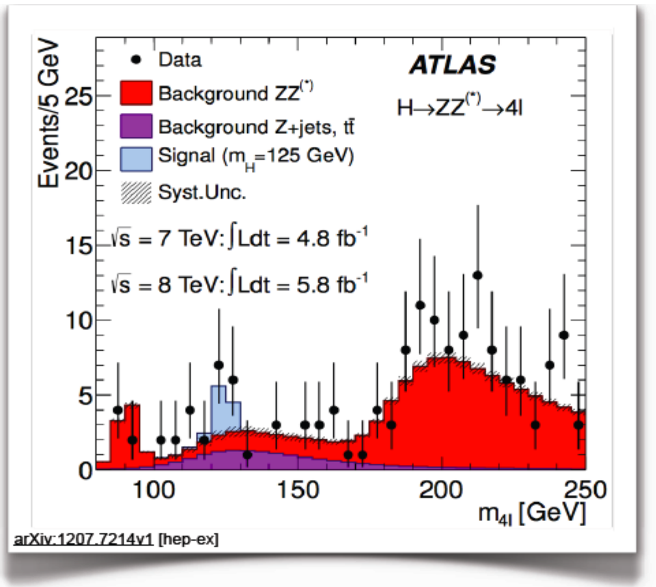


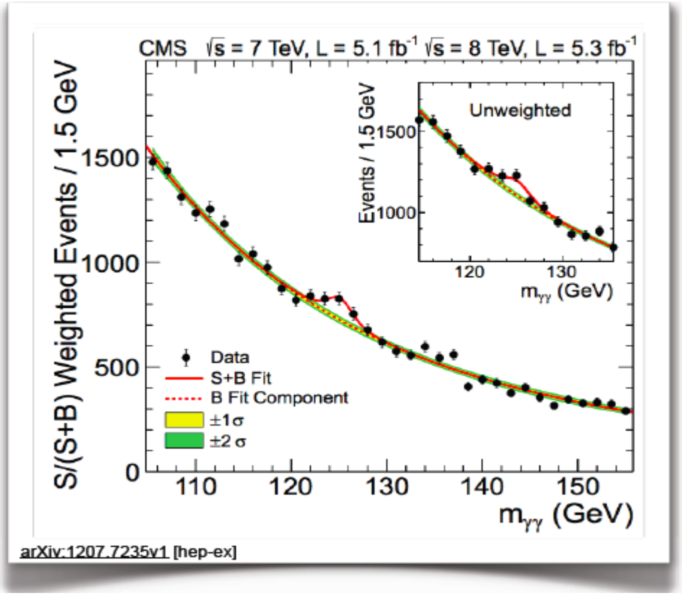


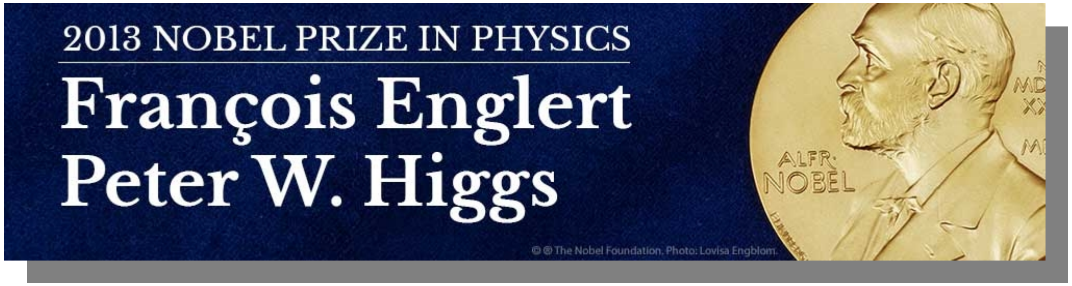
Introduction

It has been called "model" since, till recently, many of us were not convinced this was the right Theory of nature...

...but the situation has changed after the discovery of the Higgs particle at the LHC in 2012: this "model" is now the reference Theory describing strong, weak, and electromagnetic forces, consistently with the principles of quantum mechanics and special relativity.







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The 1st run of the LHC has tested the validity of the SM in an un-explored range of energies, finding no significant deviations. The key results of the 1st LHC run of the LHC can indeed summarized as follows:

- The last missing ingredient of the SM, namely the excitation of the Higgs field, has been found

- The Higgs is "light", with a mass of ~ 125 GeV (it is not the heaviest particle of the SM)

- There is a "mass-gap" above the SM spectrum (i.e. no sign of New Physics up to ~ 1 TeV)

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Physical Theories at the end of 1900:

Electromagnetism (Maxwell's Theory)

Gravity (Newton's Theory)

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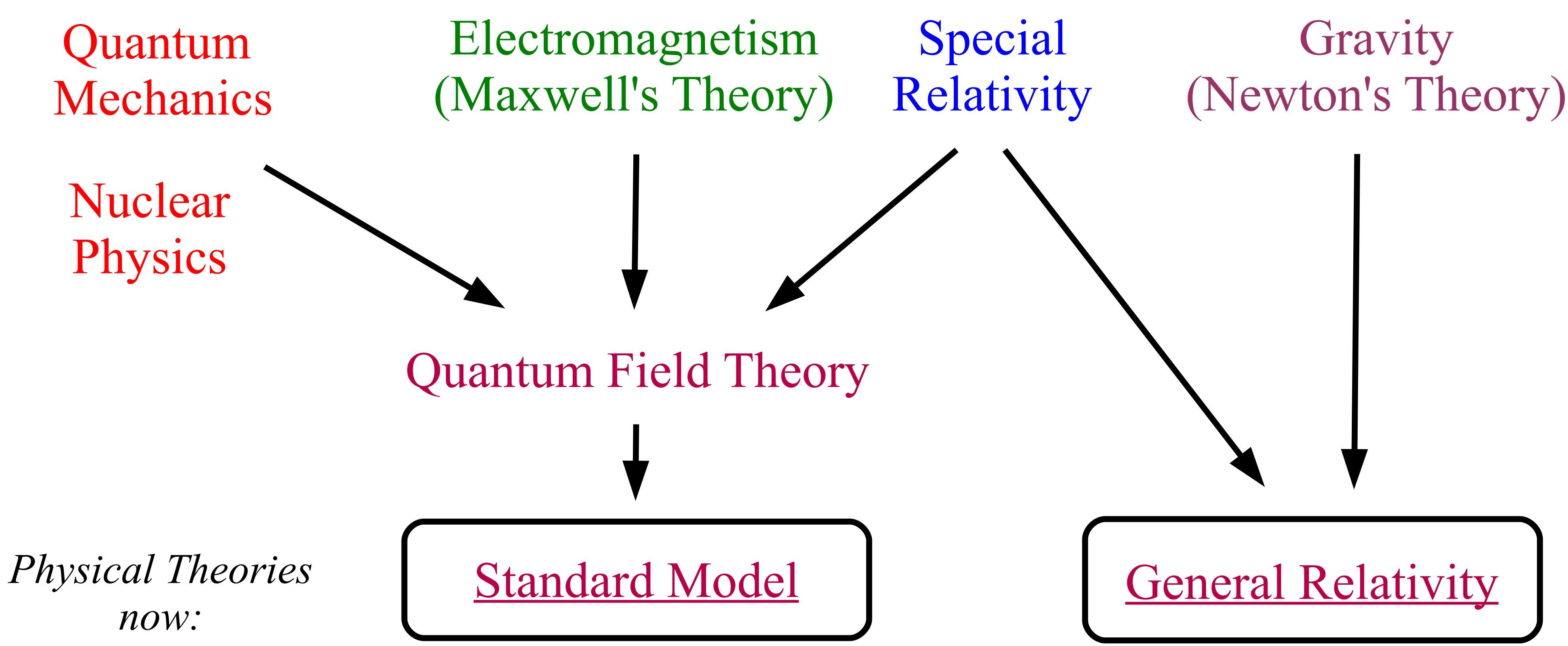

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Standard Model

- *Forces*: Strong, Weak, Electrom.
- *Matter constituents*:
  quarks & leptons
- *Fundamental couplings*:
  c (relativity)
  ħ (quantum mechanics)
  dimensionless coupl. (forces)
  Higgs mass (energy scale)
- "*Vacuum structure*": Higgs field

General Relativity

- *Forces*: Gravity
- *Matter constituents*:
  not specified
- *Fundamental couplings*:
  c (relativity)
  G_N (gravity ↔ energy scale)
- "*Vacuum structure*":
  Cosmological constant

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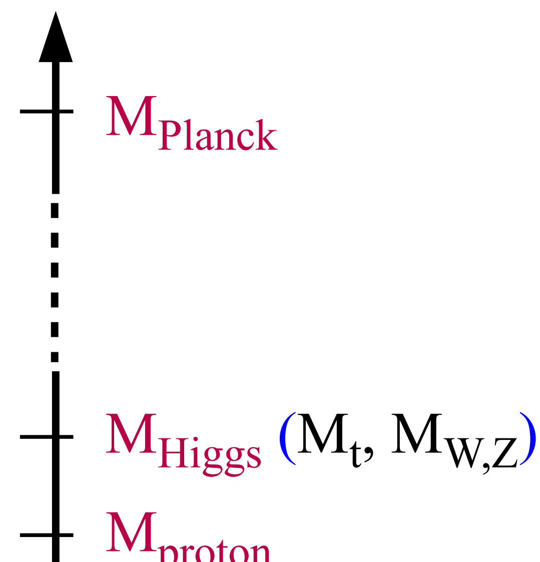
Introduction

The discovery of the Higgs boson is certainly a great triumph for the Standard Model. But there are a few important questions that are still open:

The Higgs boson mass (non predicted within the model) turns out to be $M_{Higgs} \sim 125$ GeV. This is the only fundamental scale of energy within the Standard Model.

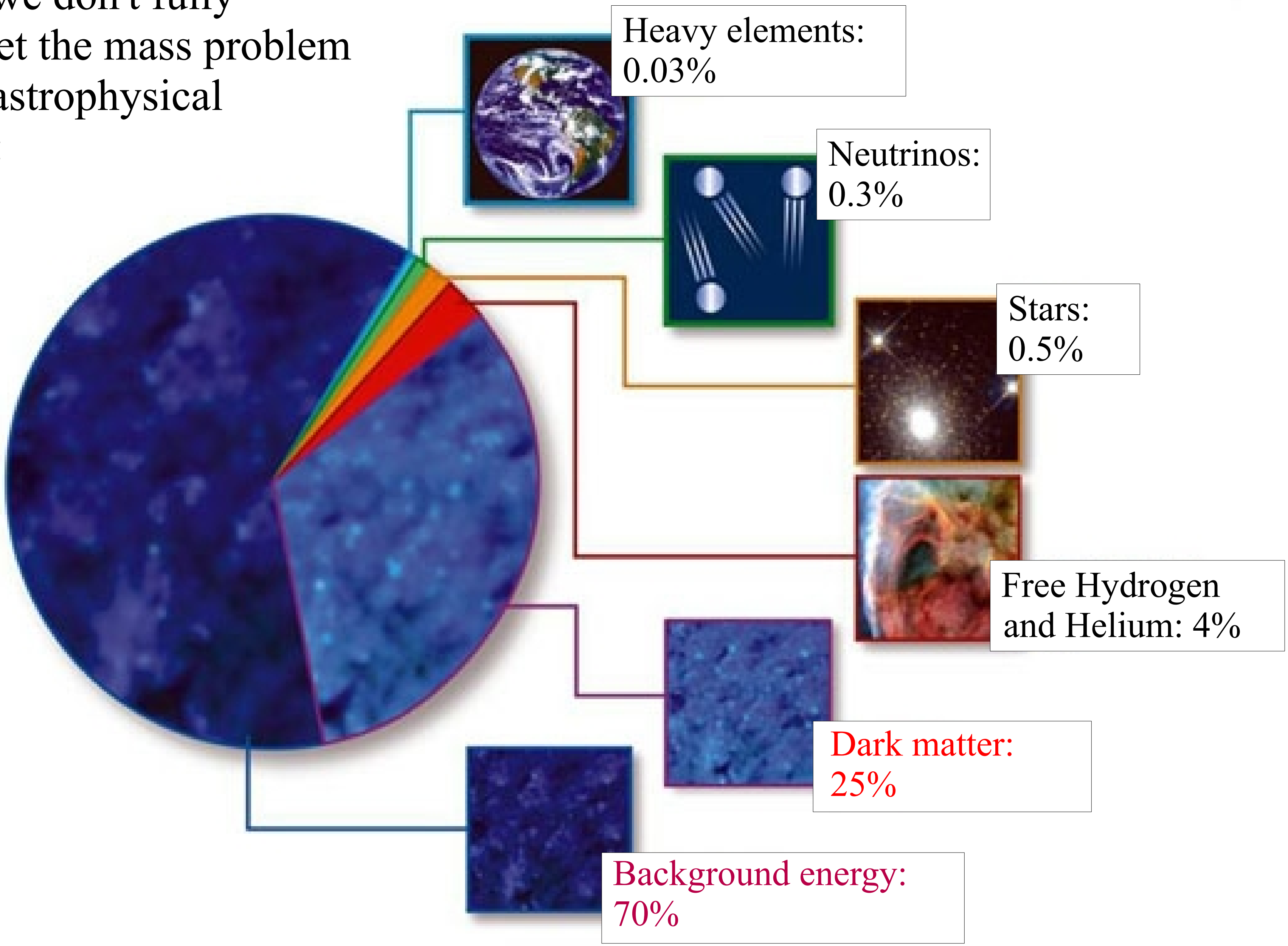
This energy scale is much higher compared to the proton mass, but is still well below $M_{Planck} = (\hbar c/G_N)^{-1/2} \sim 10^{19}$ GeV (*universal energy scale associated to gravity*)

- Why $M_{Higgs} \ll M_{Planck}$?
- Can we extend the validity of the model up to energies $\sim M_{Planck}$?
- What determines the coupling of the Higgs boson to the various particles?
- ...



Introduction

A clear clue we don't fully understand yet the mass problem comes from astrophysical observations:



Introduction

We are certainly in a special time in particle physics, where "near-by" discoveries are not anymore guaranteed: the SM is a very successful theory with no intrinsic energy limitation.

Physical Theories now:

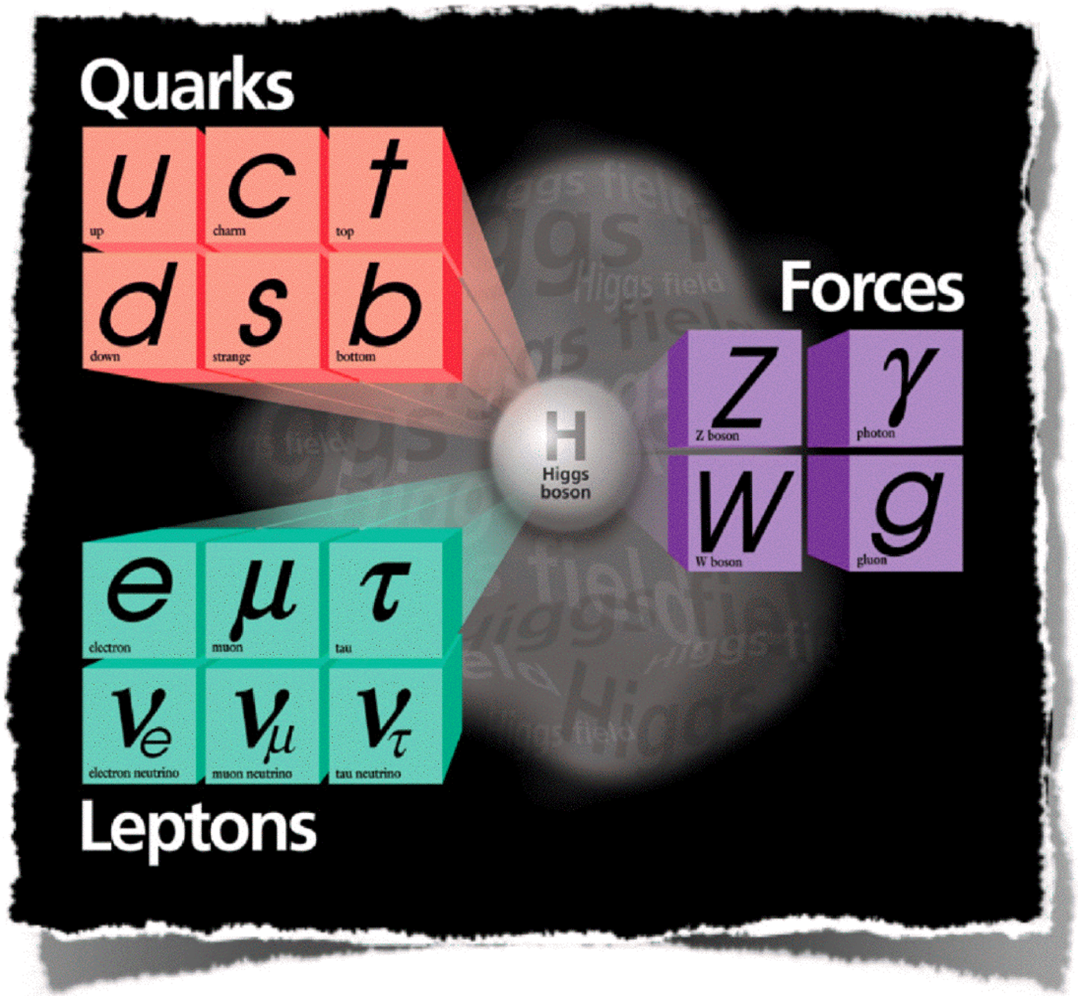
Standard Model

General Relativity

However, we know the SM cannot be the end of the story and that we are left with very intriguing un-answered fundamental questions.

To understand what we can (and cannot) expect from the LHC run-2 (and beyond), the first key point is to give a closer (*critical*) look to the SM...

A brief look to the SM



A brief look to the SM

The SM is a remarkably simple theory based on two very different sectors:

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

- *Natural*
- Experimentally tested with high accuracy
- Stable with respect to quantum correction (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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- *Ad hoc*
- Necessary to describe data [*clear indication of a non-invariant vacuum*] weakly tested in its dynamical form
- Not stable with respect to quantum corrections
- Origin of the flavor structure of the model [*and of all the problems of the model...*]

A brief look to the SM

The SM is a remarkably simple theory based on two very different sectors:

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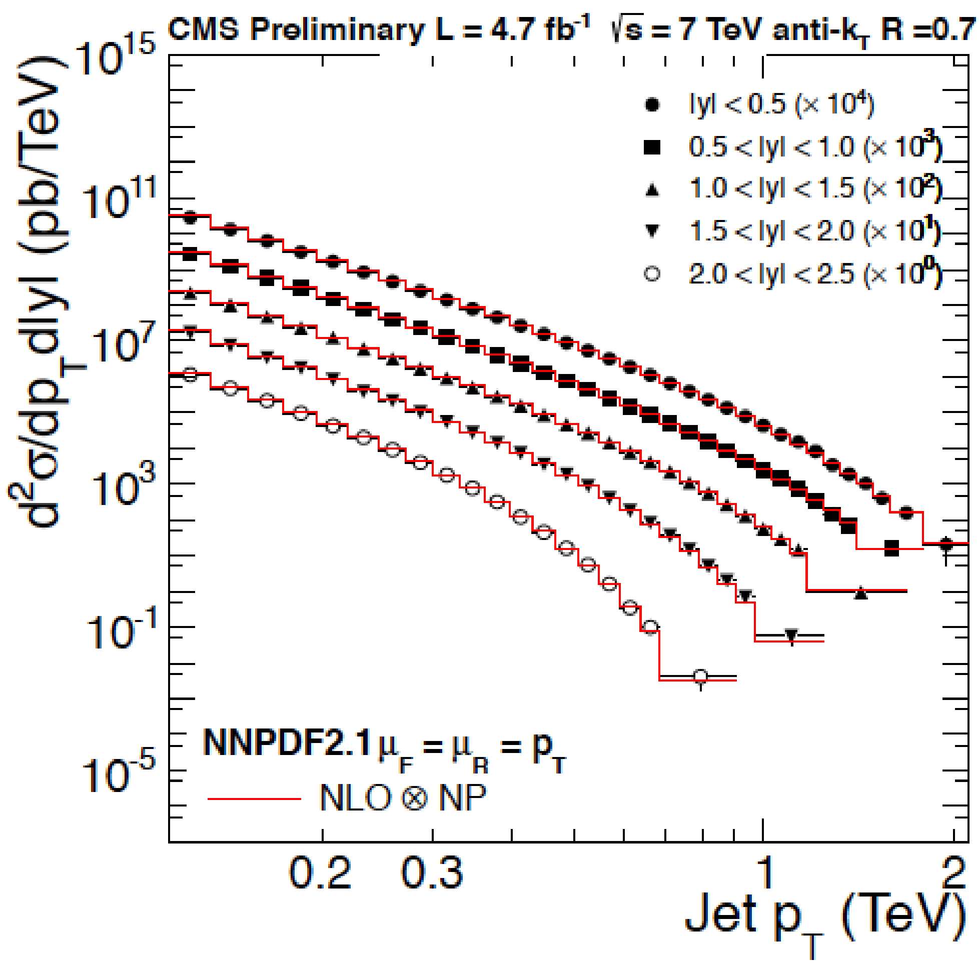
Elegant & stable, but also a bit boring...

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

The SM gauge sector:

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



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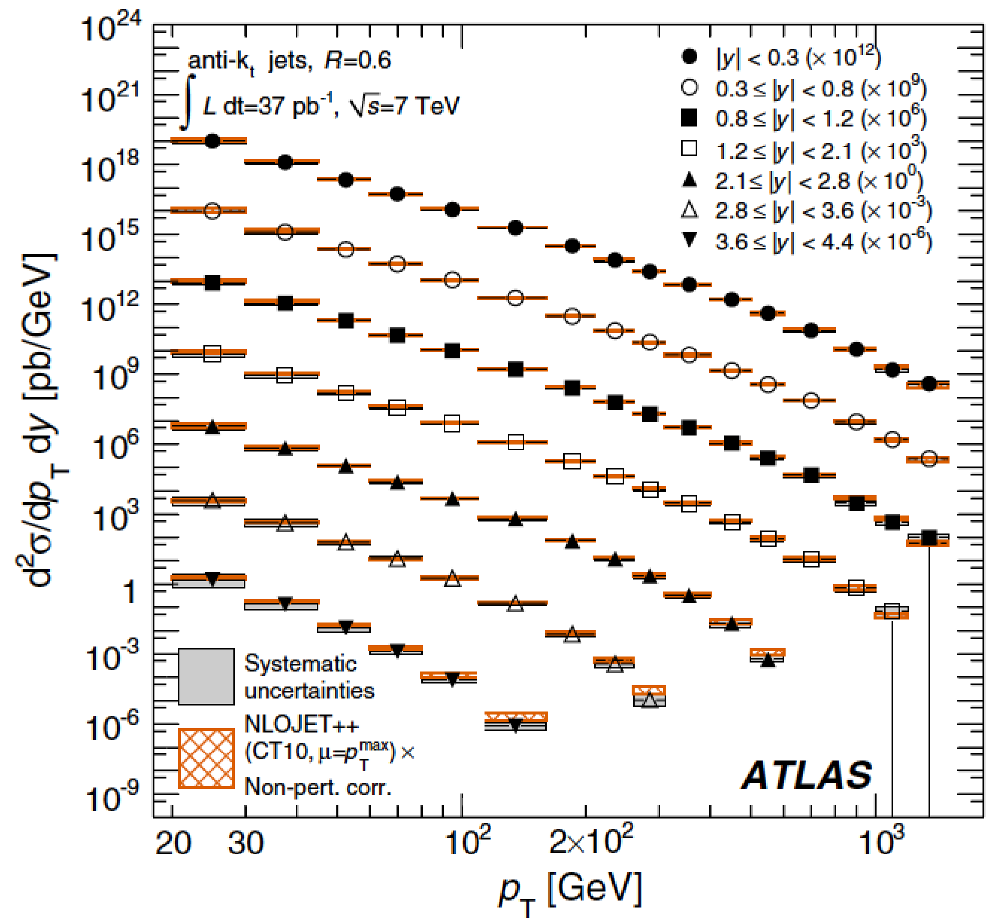

The SM gauge sector:

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

The requirement of local-gauge-invariance (symmetry principle) severely restricts the form of the Lagrangian

The number and the self-interactions on the gauge fields are completely specified by the choice of the gauge group:

A (subjective) measure of the "naturalness" of the theory is offered by the values of the gauge coupling constants just above the weak scale:

$SU(3)_c \times SU(2)_L \times U(1)_Y$ Unbroken symmetry (above e.w. scale)

$[T,T_3]$ $[Y]$

$\downarrow$

$SU(3)_c \times U(1)_Q$ low-energy symmetry

$[Q=T_3+Y]$

	E ~ 200 GeV
g_3	~ 1.2
g_2	~ 0.6
g_1	~ 0.3

The SM gauge sector:

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

basic matter family [3 replica]

The fermion part of the Lagrangian has more "freedom": number of fermions + quantum numbers not specified

$[Q=T_3+Y]$

basic matter family [3 replica]	$SU(3)_c$	$SU(2)_L$	Y	Q
$Q_L = \begin{bmatrix} u_L \\ d_L \end{bmatrix}$	3	2	+1/6	+2/3 -1/3
u_R	3	1	+2/3	+2/3
d_R	3	1	-1/3	-1/3
$L_L = \begin{bmatrix} \nu_L \\ e_L \end{bmatrix}$	1	2	-1/2	0 -1
e_R	1	0	-1	-1

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Everything is "natural" also here but for one key point: *Why the U(1) charge is quantized?"* → strong indication of a deeper layer with unified gauge group

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N.B.: a RH neutrino is something very special since it would be completely "neutral" under G_{SM}

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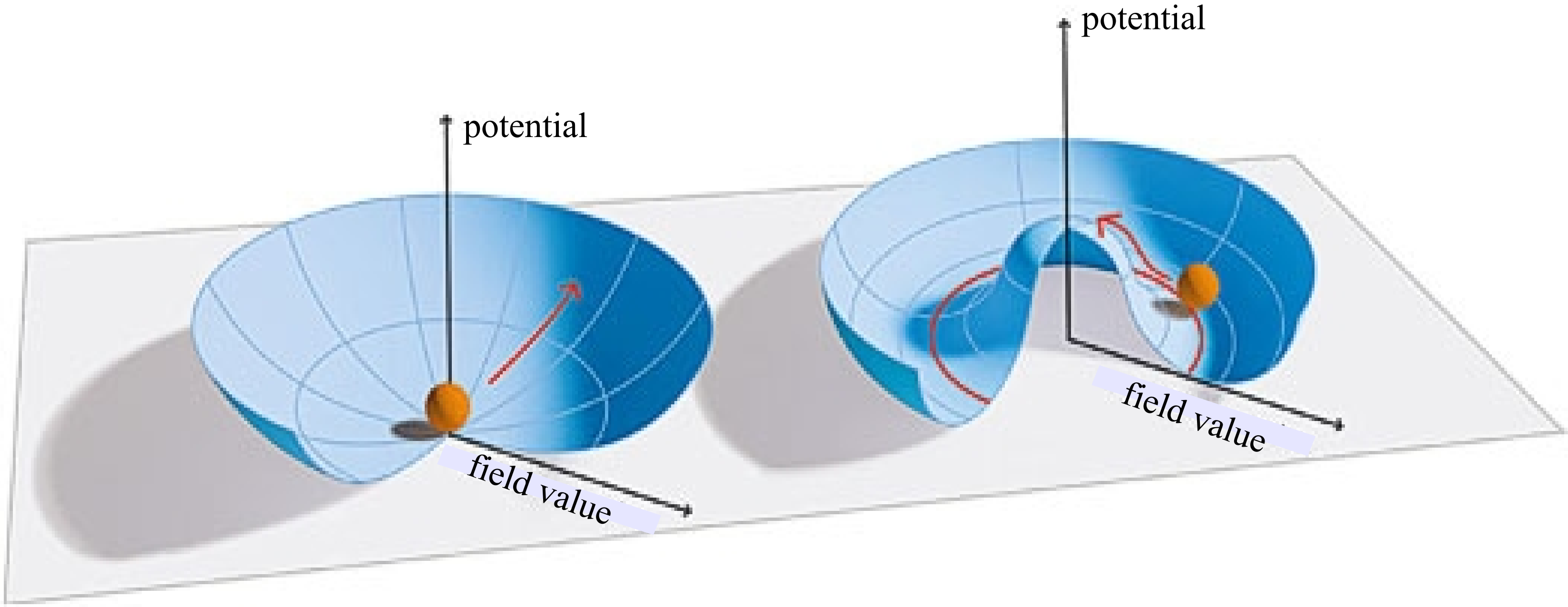
ν_R	1	1	0	0

The Higgs sector (a first look):

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.



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

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

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:

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

The situation has substantially changed in 2012 with the observation of the 4^{th} degree of freedom of the Higgs field (or its *massive excitation*):

$$\lambda_{(\rm tree)} = \tfrac{1}{2}\, m_h^2 / v^2 \approx 0.13 \qquad\qquad \mu^2_{(\rm tree)} = \tfrac{1}{2}\, m_h^2$$

The Higgs sector (a first look):

Most of the "disturbing" (*but interesting*...) features of the SM are associated to the structure (and the various couplings) appearing in the Higgs potential:

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

vacuum instability

possible <u>internal inconsistency</u> of the model ($\lambda < 0$) at large energies

Hierarchy problem

(*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 ?)

flavor problem

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

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$$V(\phi) = V_0 - \mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2 + Y^{ij} \psi_L^{\,i} \psi_R^{\,j} \phi + \dots$$

additional non-renormalizable terms in this series could provide "ad hoc" explanations for ν masses & dark matter

Cosmological constant prob.

vacuum instability

possible internal inconsistency of the model ($\lambda < 0$) at large energies

Hierarchy problem

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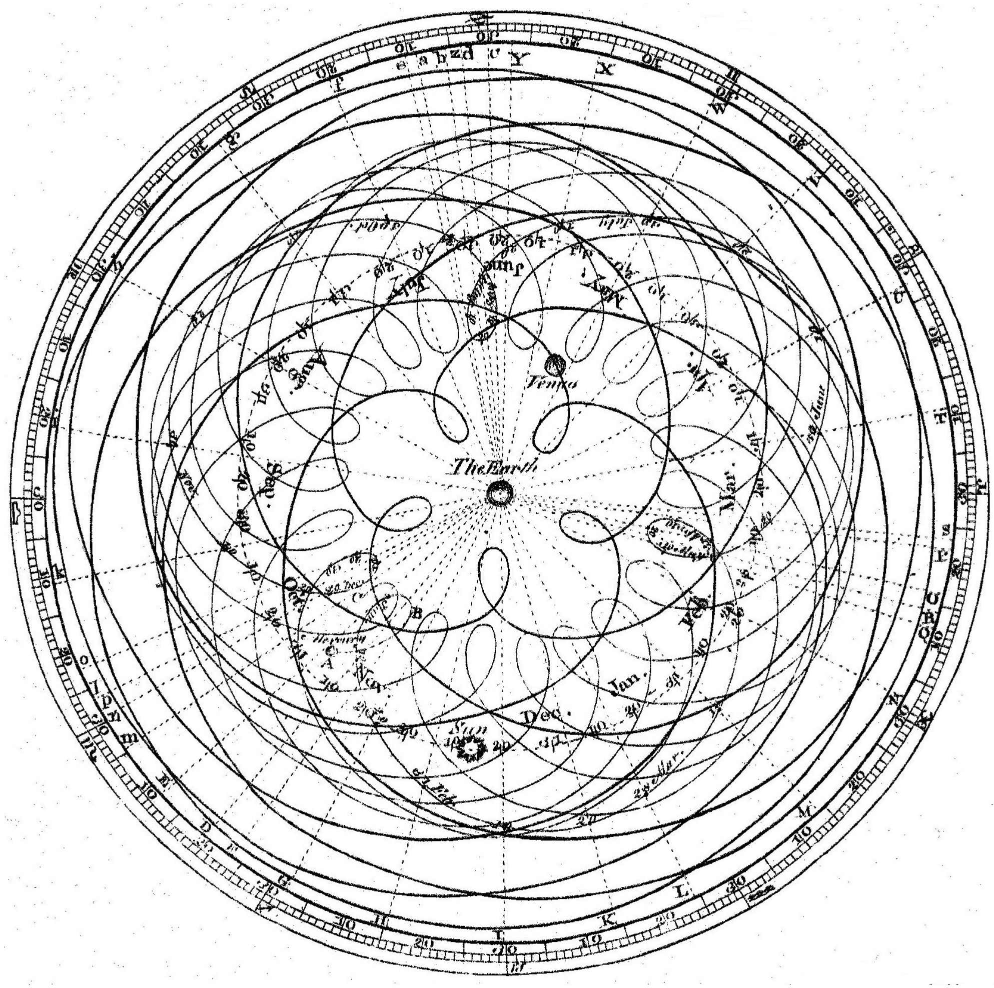
additional non-renormalizable terms in this series could provide "ad hoc" explanations for ν masses & dark matter

↓

The SM is likely to be only and *effective theory*, or the low-energy limit of a more fundamental theory, with new degrees of freedom above the electroweak scale ($v \sim 246$ GeV).

The SM as an effective theory



The SM as an effective theory

The modern point of view on the SM Lagrangian is that is only the low-energy limit of a more complete theory, or an effective theory.

New degrees of freedom are expected at a scale Λ above the electroweak scale.

$$\mathscr{L}_{\mathrm{eff}} = \mathscr{L}_{\mathrm{gauge}}(A_a, \psi_i) + \mathscr{L}_{\mathrm{Higgs}}(\phi, A_a, \psi_i) + \text{“heavy fields”}$$

$\mathscr{L}_{\mathrm{SM}}$ = renormalizable part of $\mathscr{L}_{\mathrm{eff}}$

All possible operators with $d \leq 4$,
compatible with the gauge symmetry,
depending only on the “light fields” of the system

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The concept of *effective* QFT allows us to give a more general meaning to the concept (request) of “renormalizability” in QFT

⬇

No fundamental distinction between renormalizable & non-renormalizable QFTs (once we consider them both as effective QFTs)

Some general remarks on effective QFT

The concept of *effective* QFT allows us to give a more general meaning to the concept (request) of "renormalizability" in QFT:

$$S = \int \mathscr{L}\, d^4 x \quad = \text{ adimensional number (setting } \hbar\text{=1)}$$

All terms in the Lagrangian must have d=4.

This defines the canonical dimensions of the fields, starting from their kinetic terms:

Scalar field: $\partial_\mu\phi\, \partial^\mu\phi \longrightarrow d[\phi] = 1$

Fermion field: $\bar{\psi}\, \partial_\mu\psi \longrightarrow d[\psi] = 3/2$

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$d < 4$ $\quad m_\phi^2\, \phi^2, \quad m_\psi\, \overline{\psi}\, \psi, \ldots$

$d = 4$ $\quad g\, A_\mu\, \overline{\psi}\, \gamma_\mu \psi, \quad \lambda\, \phi^4, \ldots$

$d > 4$ $\quad \frac{1}{\Lambda^2}\, (\overline{\psi}\, \gamma_\mu \psi)^2, \quad \frac{1}{\Lambda^2}\, \phi^6, \ldots$

Some general remarks on effective QFT

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$$S = \int \mathscr{L} \, d^4 x$$

Contributions to scattering amplitudes:

d < 4 $\quad m_\phi^{\,2}\, \phi^2, \quad m_\psi \, \overline{\psi}\, \psi, \ldots \longrightarrow \quad \dfrac{m_\phi^{\,2}}{E^2} \quad \dfrac{m_\psi}{E}$

dominant in the IR

d=4 $\quad g\, A_\mu \overline{\psi} \gamma_\mu \psi, \quad \lambda\, \phi^4, \ldots \longrightarrow \quad g(E), \quad \lambda(E)$

potentially relevant at all energies

d > 4 $\quad \dfrac{1}{\Lambda^2} (\overline{\psi} \gamma_\mu \psi)^2, \quad \dfrac{1}{\Lambda^2} \phi^6, \ldots \longrightarrow \quad \dfrac{E^2}{\Lambda^2}$

irrelevant at low energies,
but bad UV behavior

Some general remarks on effective QFT

The concept of *effective* QFT allows us to give a more general meaning to the concept (request) of "renormalizability" in QFT:

To define an effective QFT we need to define three basic ingredients:

I. The nature of the "light fields", or the nature of the degrees of freedom we can directly excite in the validity regime of the theory [e.g. the SM fields]

II. The symmetries of the theory [e.g. the SU(3)×SU(2)×U(1) gauge symmetry]

III. The validity regime of the theory [typically an UV cut-off]

In general, the most general Lagrangian compatible with I & II contains and infinite set of operators; however, there is a finite number of operators with a given canonical dimension → at low-energies we can focus only on a finite sets of operators given terms of high dimension given small contributions

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↙ ↘

"renormalizable" EFTs [e.g. SM]
No clear indication about the validity range of the theory

"non-renormalizable" EFTs [e.g. Fermi theory, CHPT, ...]
Clear indication about the maximal validity range of the theory

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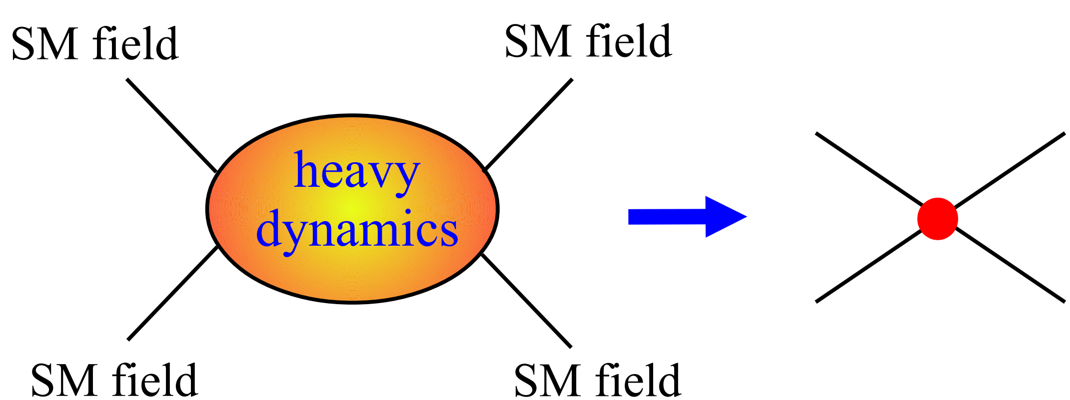
New degrees of freedom are expected at a scale Λ above the electroweak scale.

$$\mathscr{L}_{\mathrm{eff}} = \mathscr{L}_{\mathrm{gauge}}(A_a, \psi_i) + \mathscr{L}_{\mathrm{Higgs}}(\phi, A_a, \psi_i) + \Sigma \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

$\mathscr{L}_{\mathrm{SM}}$ = renormalizable part of $\mathscr{L}_{\mathrm{eff}}$

Operators of $d \geq 5$ containing SM fields only
(compatible with the SM gauge symmetry)

This is the most general parameterization of the new (heavy) degrees of freedom, as long as we do not have enough energy to directly produce them.



Neutrino masses

A clear evidence of a non-vanishing term in the series of higher-dim. ops. (so far the only one...) comes from *neutrino masses*:

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{gauge}}(A_a, \psi_i) + \mathscr{L}_{\text{Higgs}}(\phi, A_a, \psi_i) + \Sigma \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

Neutrino masses are well described by *the only d=5 term allowed by the SM gauge symmetry.*

$$\frac{g_\nu^{ij}}{\Lambda} (L_L^{T\,i} \sigma_2 \phi)(L_L^j \sigma_2 \phi^T)$$

$$(m_\nu)^{ij} = \frac{g_\nu^{ij} v^2}{\Lambda}$$

$$v = \langle \phi \rangle$$

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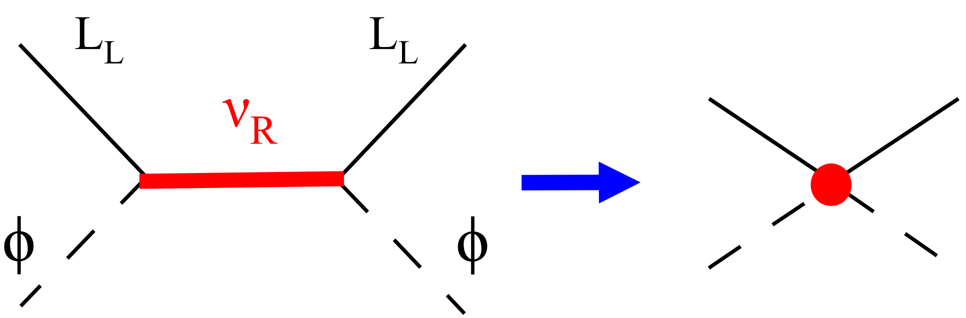
$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_{\rm a}, \psi_{\rm i}) + \mathscr{L}_{\rm Higgs}(\phi, A_{\rm a}, \psi_{\rm i}) + \sum \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_{\rm a}, \psi_{\rm i})$$

Possible dynamical origin of this d=5 ops.:

$$\frac{g_\nu^{\,ij}}{\Lambda}\,(L_L^{T\,i}\,\sigma_2\,\phi)(L_L^{j}\,\sigma_2\,\phi^T)$$



$$(m_\nu)^{ij} = \frac{g_\nu^{\,ij}\, v^2}{\Lambda}$$

In this case (see-saw mechanism):
$$\frac{g_\nu}{\Lambda} = \frac{Y_\nu^T Y_\nu}{M_R}$$

$$v = \langle \phi \rangle$$

Neutrino masses

A clear evidence of a non-vanishing term in the series of higher-dim. ops. (so far the only one...) comes from *neutrino masses*:

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi, A_a, \psi_i) + \Sigma \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

$$\frac{g_\nu^{ij}}{\Lambda} (L_L^{T\,i} \sigma_2 \phi)(L_L^j \sigma_2 \phi^T)$$

$$(m_\nu)^{ij} = \frac{g_\nu^{ij}\, v^2}{\Lambda}$$

$$v = \langle \phi \rangle$$

The smallness of m_ν seems to point toward a very high value of Λ (*that fits well with the idea of an underlying GUT at very high energies*):

$$\frac{O(1) \times (246 \text{ GeV})^2}{10^{15} \text{ TeV}} \sim 0.06 \text{ eV}$$

$$0.3 \text{ eV} \lesssim m_\nu^{\max} \lesssim 0.04 \text{ eV}$$

(cosmological bounds) (atmospheric oscillations)

Neutrino masses

A clear evidence of a non-vanishing term in the series of higher-dim. ops. (so far the only one...) comes from *neutrino masses*:

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi, A_a, \psi_i) + \Sigma \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

The smallness of m_ν seems to point toward a very high value of Λ

$$\frac{g_\nu^{ij}}{\Lambda_{LN}} (L_L^{T\,i} \sigma_2 \phi)(L_L^j \sigma_2 \phi^T)$$

However, this d=5 ops. violates lepton number, which is a global symmetry of the SM → *the high value of Λ may be related to the breaking of LN*.

$$(m_\nu)^{ij} = \frac{g_\nu^{ij}\, v^2}{\Lambda_{LN}}$$

We can expect lower values of Λ for effective operators that do not violate any of the symmetries of the SM Lagrangian

$$v = \langle \phi \rangle$$

Neutrino masses and "naturalness"

A clear evidence of a non-vanishing term in the series of higher-dim. ops. (so far the only one...) comes from *neutrino masses*:

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi, A_a, \psi_i) + \Sigma \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

$$\mu^2 \ \phi^+\phi \xrightarrow[\text{corrections}]{\text{quantum}} \Lambda^2 \ \phi^+\phi$$

$$\left[\mu^2_{\rm (tree)} = \tfrac{1}{2} m_h^2\right]$$

Indeed an indication of a much lower value of Λ comes from *the only d=2 term in this Lagrangian*, namely from the Higgs sector:

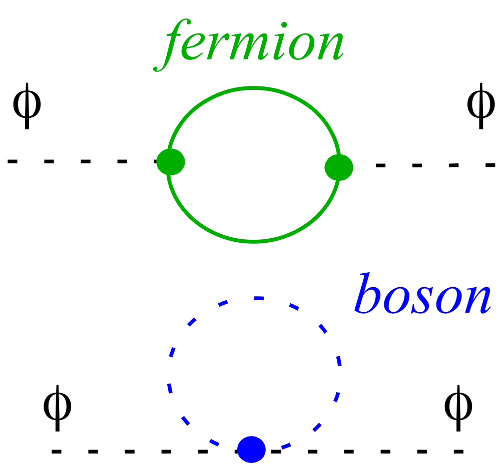
If the effective theory is *"natural"* we should expect some new degrees of freedom (respecting SM symmetries and coupled to the Higgs sector) not far from the TeV scale to stabilize the Higgs mass term.

Neutrino masses and "naturalness"

If the effective theory is *"natural"* we should expect some new degrees of freedom (respecting SM symmetries and coupled to the Higgs sector) not far from the TeV scale to stabilize the Higgs mass term.

$$\mu^2\ \phi^+\phi \xrightarrow[\text{corrections}]{\text{quantum}} \Lambda^2\ \phi^+\phi$$

N.B.: the quadratic sensitivity of the Higgs mass from the cut-off is not a pure "technical" issue: it implies a quadratic sensitivity to the the new degrees of freedom (*if we assume there is something else beyond the SM, such e.g. RH neutrinos*):



$$\longrightarrow\quad \Delta m_H^2 \sim \Sigma_b\, c_b M_b^2 - \Sigma_f\, c_f M_f^2$$

If $\Lambda \gg m_h$, either m_h is "fine-tuned" or the NP does not couple to the Higgs sector

Neutrino masses and "naturalness"

If the effective theory is *"natural"* we should expect some new degrees of freedom (respecting SM symmetries and coupled to the Higgs sector) not far from the TeV scale to stabilize the Higgs mass term.

$$\mu^2 \ \phi^+ \phi \ \xrightarrow[\text{corrections}]{\text{quantum}} \ \Lambda^2 \ \phi^+ \phi$$

N.B.: the quadratic sensitivity of the Higgs mass from the cut-off is not a pure "technical" issue: it implies a quadratic sensitivity to the the new degrees of freedom

N.B. (II): a "warning" that the naturalness argument should be taken with some care comes from the cosmological constant

$$V_0 + \mu^2 \ \phi^+ \phi \ \xrightarrow[\text{corrections}]{\text{quantum}} \ \Lambda^4 + \Lambda^2 \ \phi^+ \phi$$

"exp"

$\sim (0.002\ \text{eV})^4$ $\sim (100\ \text{MeV})^2$

The key questions of particle physics

The modern point of view on the SM Lagrangian is that is only the low-energy limit of a more complete theory, or an effective theory.

New degrees of freedom are expected at a scale Λ above the electroweak scale.

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi, A_a, \psi_i) + \Sigma \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

Two key questions of particle physics today:

- Which is the energy scale of New Physics (*or the value of* Λ) → High-energy searches [*the high-energy frontier*]
- Which is the symmetry structure of the new degrees of freedom (*or the structure of the* c_n) → High-precision measurements [*the high-intensity frontier*]

The key questions of particle physics

More precisely, on both "frontiers" we have two independent sets of questions, a *"difficult one"* and a *"more pragmatic one"*:

- *What determines the Higgs mass term (or the Fermi scale)?*
- *Is there anything else beyond the SM Higgs at the TeV scale?*

High-energy searches
[*the high-energy frontier*]

- *What determines the observed pattern of masses and mixing angles of quarks and leptons?*
- *Which are the sources of flavor symmetry breaking accessible at low energies?*
[Is there anything else beside SM Yukawa couplings & neutrino mass matrix?]

High-precision measurements
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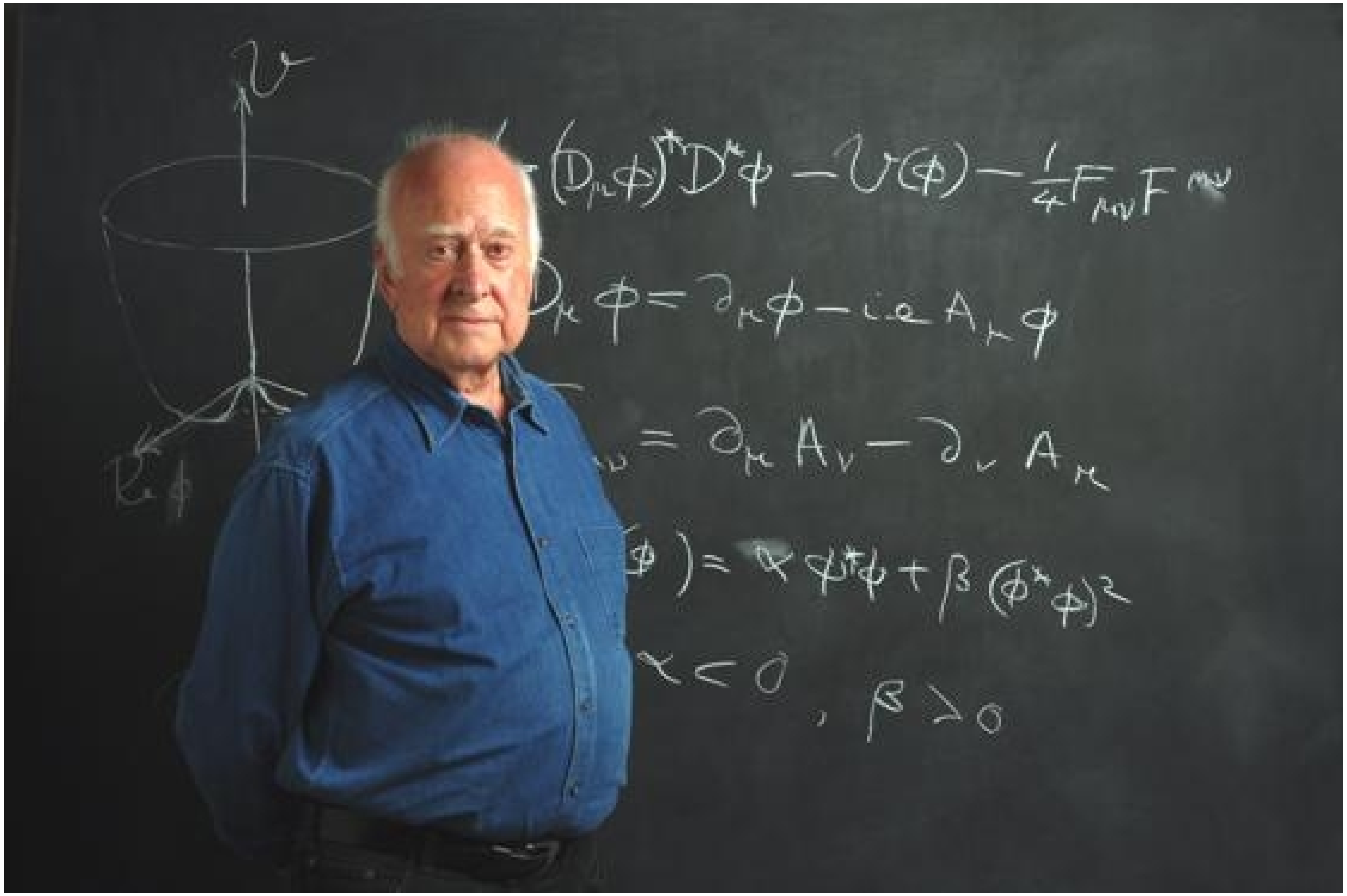
High-precision measurements
[*the high-intensity frontier*]

A closer look to the Higgs sector



Consistency with e.w. precision tests

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 and flavor symmetries that we observe in nature.

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

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

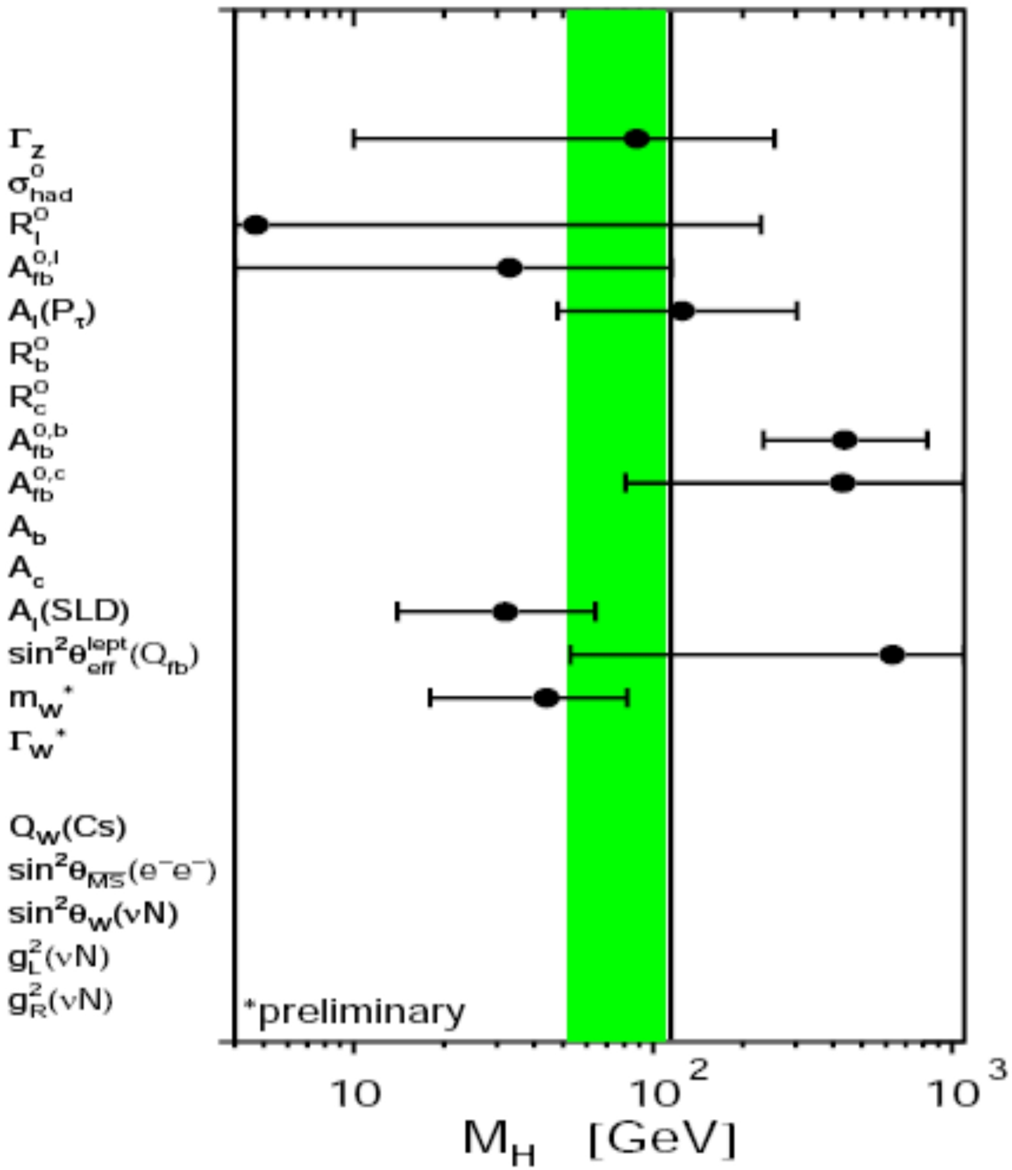
$$\boxed{\lambda_{(tree)} = \tfrac{1}{2}\, m_h^2 / v^2 \approx 0.13} \qquad \boxed{\mu^2_{(tree)} = \tfrac{1}{2}\, m_h^2}$$

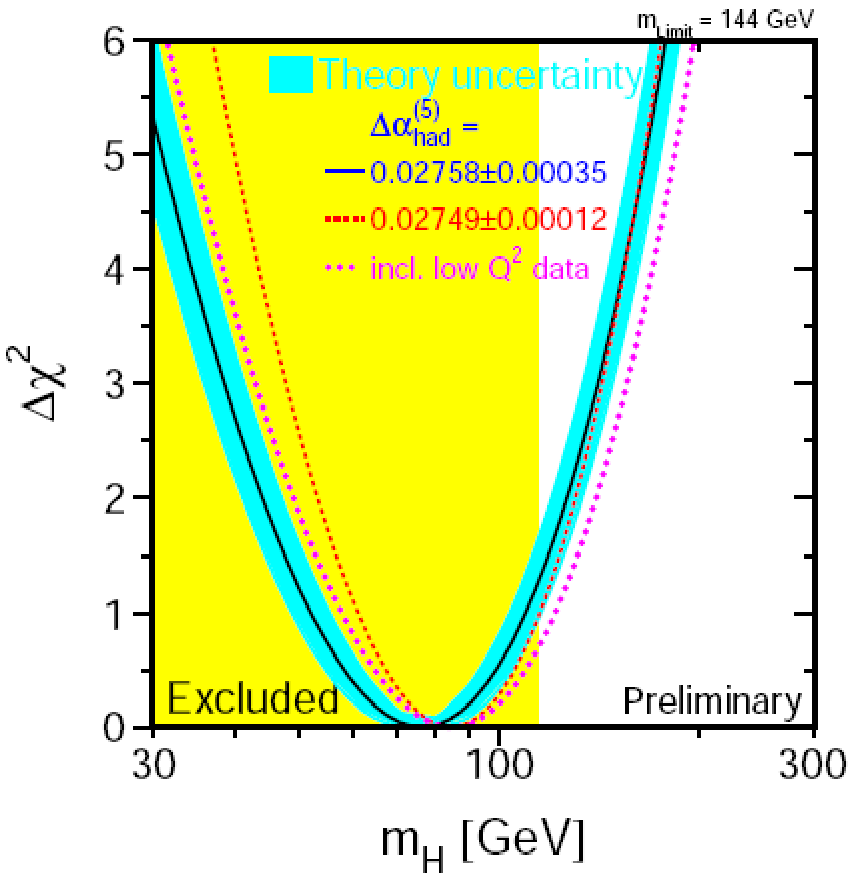
$$v = \langle\phi^+\phi\rangle^{1/2} \sim 246 \text{ GeV} \quad [\, m_W = \tfrac{1}{2}\, g\, v \,]$$

Even before the Higgs discovery, some information about the Higgs mass was already present in the EWP tests $\rightarrow$ the consistency between this indirect information and the observed value of m_h carries an important message

Consistency with e.w. precision tests

The indirect (logarithmic) sensitivity on m_h was derived by a series of EWPO





[LEP-EWWG '07]

Consistency with e.w. precision tests

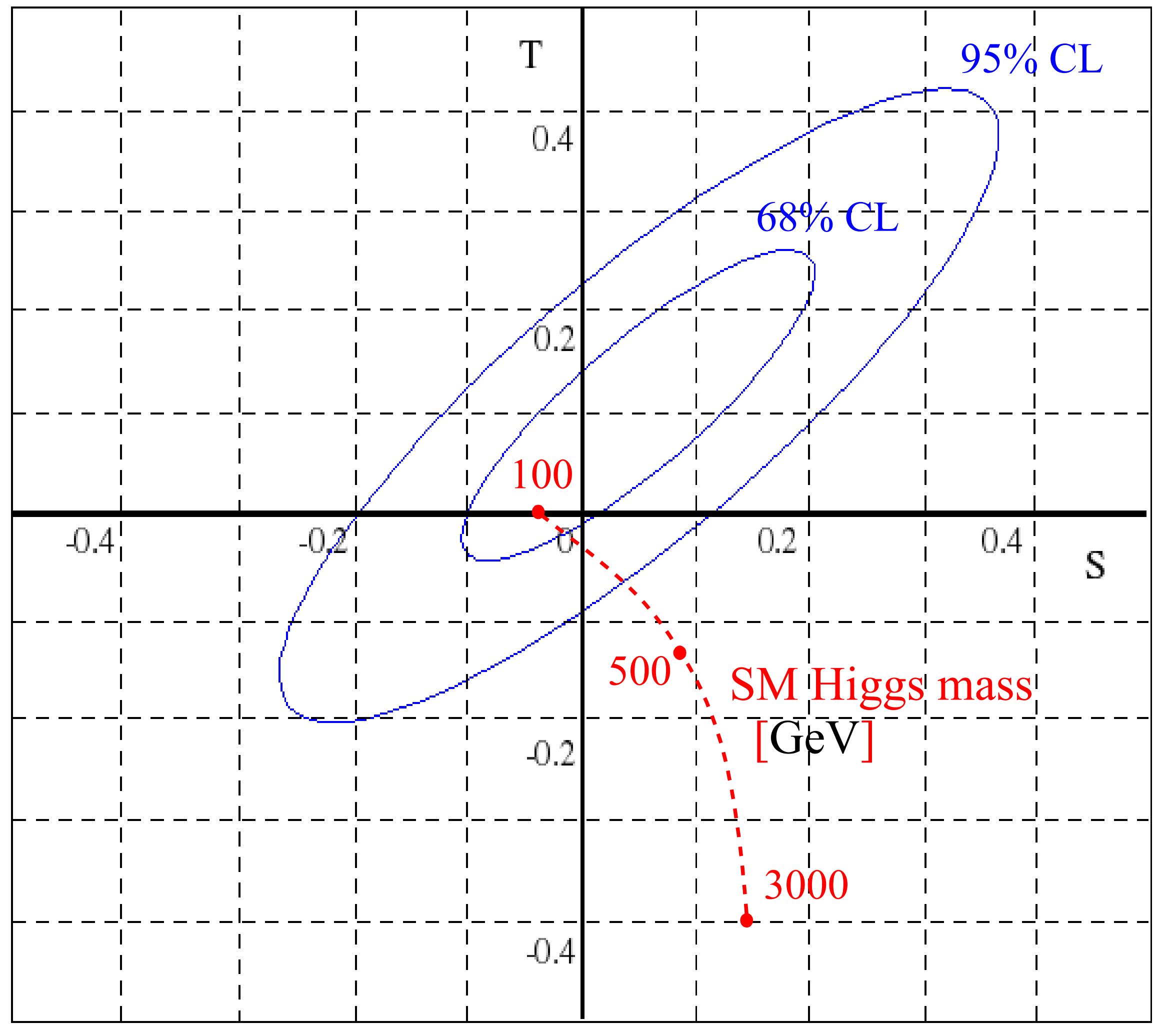
The indirect (logarithmic) sensitivity on m_h was derived by a series of EWPO

Despite the mild sensitivity of each observable, the overall indication for a light Higgs was quite strong:

Leading *oblique parameters* from EWPO

$$T = \frac{\Pi_{33}(0) - \Pi_{WW}(0)}{m_W^2}$$

$$S = \frac{g}{g'} \frac{d\,\Pi_{30}(q^2)}{dq^2}\Bigg|_{q^2=0}$$



Consistency with e.w. precision tests

The indirect (logarithmic) sensitivity on m_h was derived by a series of EWPO
Despite the mild sensitivity of each observable, the overall indication for a light Higgs was quite strong:

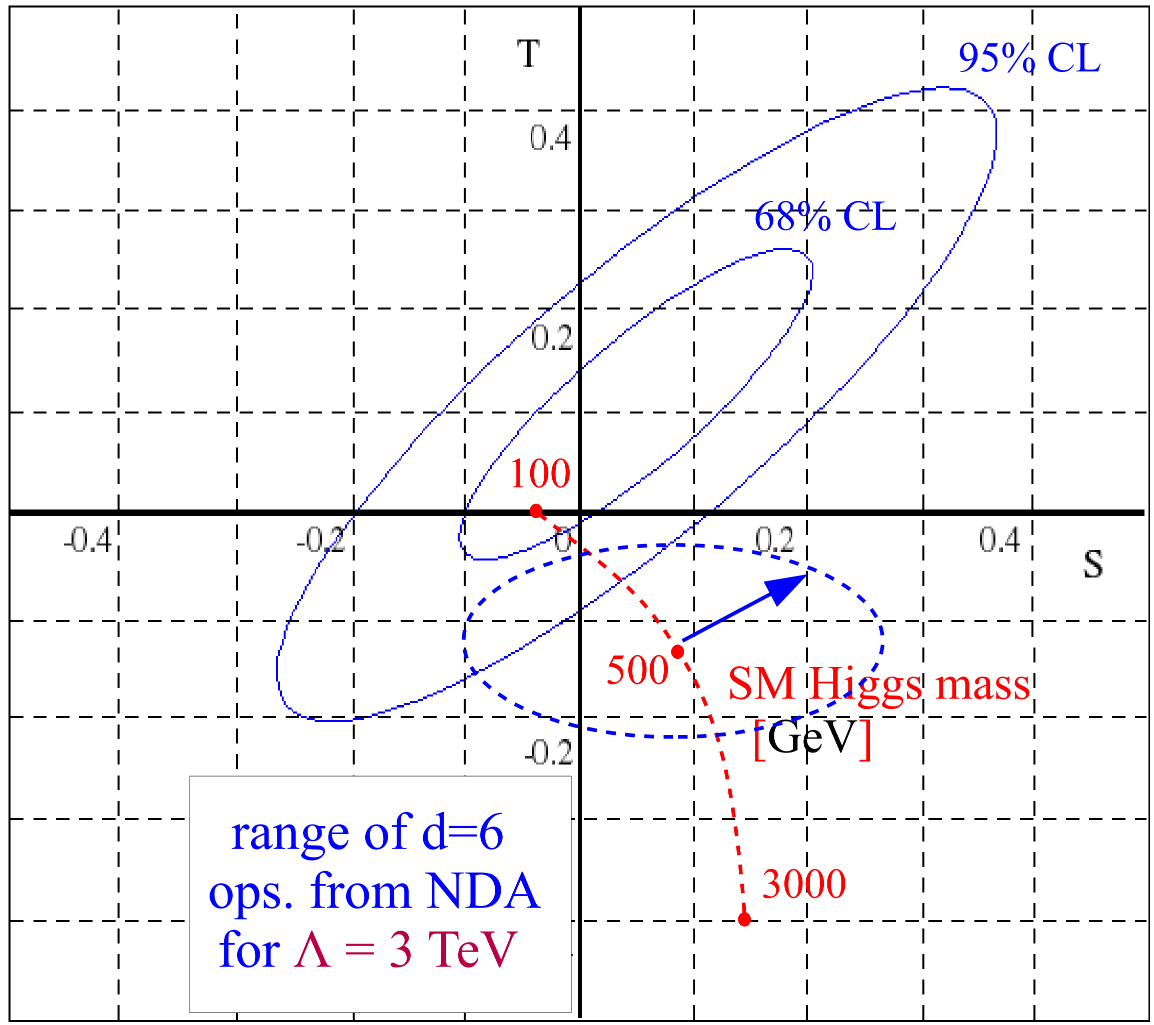
An inconsistency between direct & indirect det. of m_h would have been a clear indication of NP close to the e.w. scale:

$$\Delta S,\, \Delta T \sim \frac{v^2}{\Lambda^2}$$

direct $m_h \neq$ indirect m_h

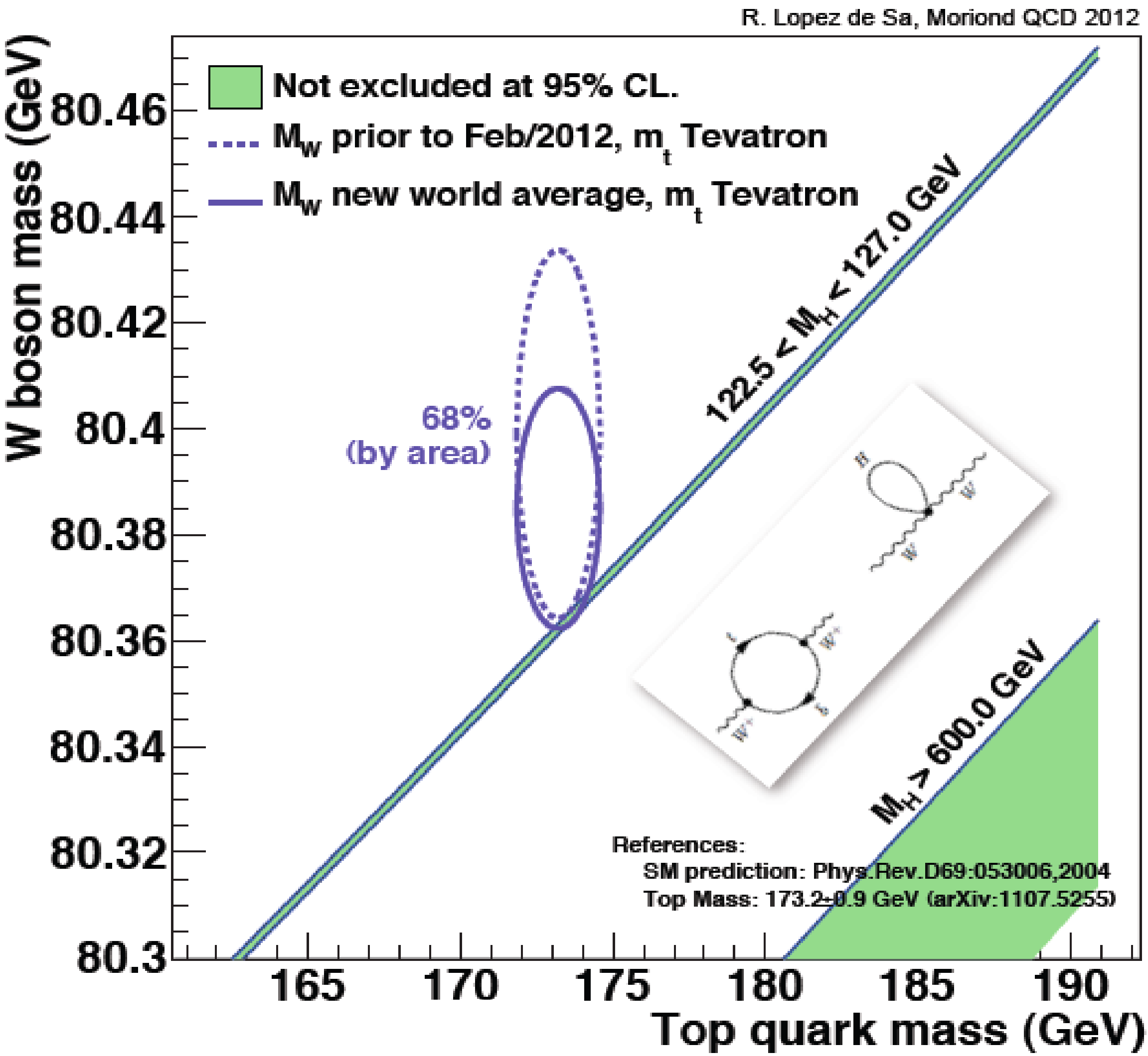
↓ *unambiguous indication*

NP close to the TeV scale



Consistency with e.w. precision tests

Updated plot on EWP constrains just before the Higgs discovery (winter 2012):



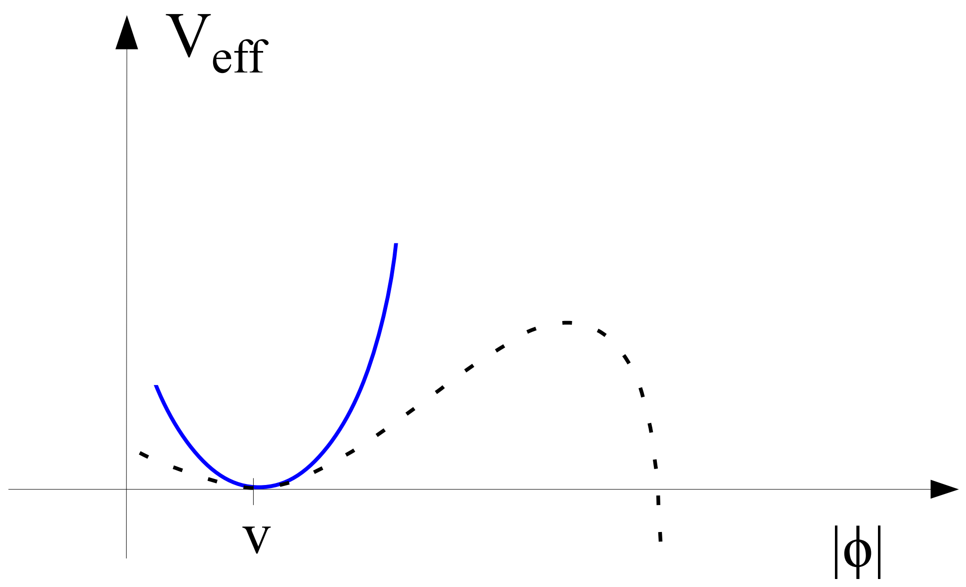
direct $m_h \sim$ indirect m_h

NP close to the TeV scale

The consistency of direct & indirect constrains on m_h does not allow to exclude NP, but it indicates that (up to conspiracies) the theory has a *minimal* & *weakly coupled* structure around the TeV scale, as in the SM.

The high-energy behavior of the potential

In principle, an unambiguous indication for the existence of physics beyond the SM could have been obtained by the high-energy behavior of the Higgs potential:



The high-energy behavior of the potential

In principle, an unambiguous indication for the existence of physics beyond the SM could have been obtained by the high-energy behavior of the Higgs potential:

At the classical level:

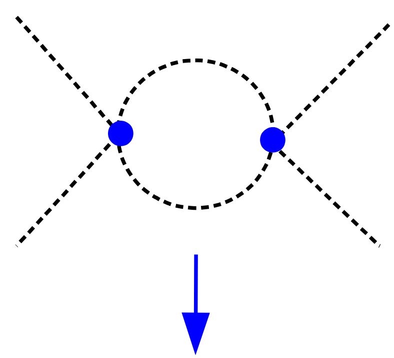
$$V_{\text{clas.}}(\phi) = \lambda \times (|\phi|^2 - v^2)^2$$

At the quantum level, at large field values:

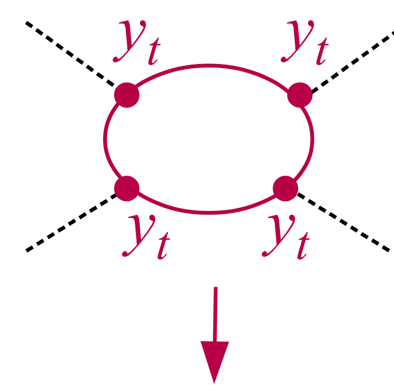
$$V_{\text{eff}}(\,|\phi| \gg v\,) \approx \lambda(|\phi|) \times |\phi|^4 + O(v^2|\phi|^2)$$

Higgs self-coupling
evaluated at high energies

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



increasing λ
at large energies



decreasing λ
at large energies

The high-energy behavior of the potential

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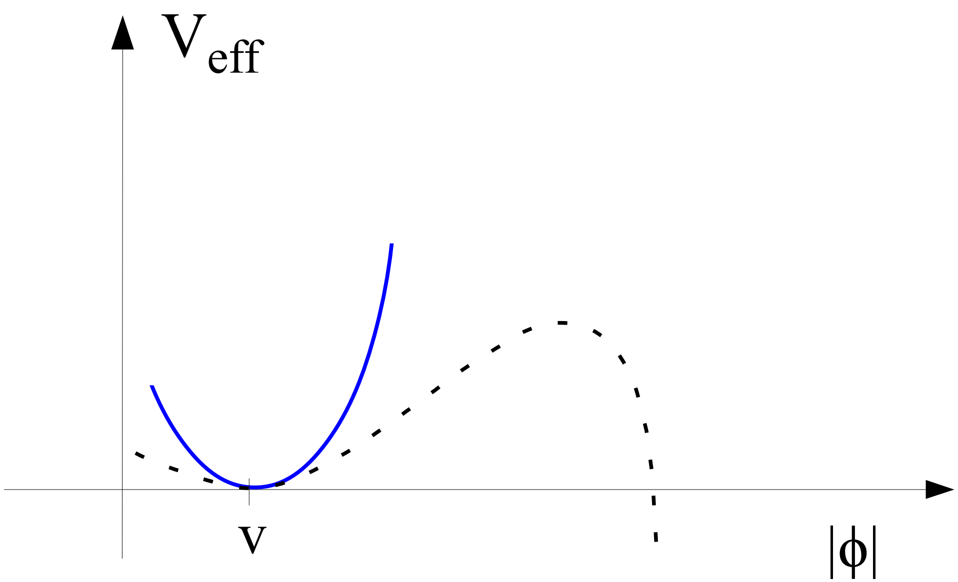
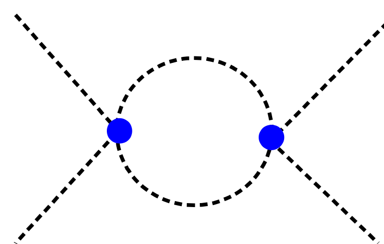
$$V_{eff}(\ |\phi| \gg v\ ) \approx \lambda(|\phi|) \times |\phi|^4 + O(v^2|\phi|^2)$$

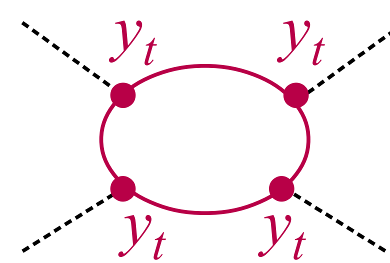


A too-light m_h could imply an unstable Higgs potential → need for NP



increasing λ at large energies

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

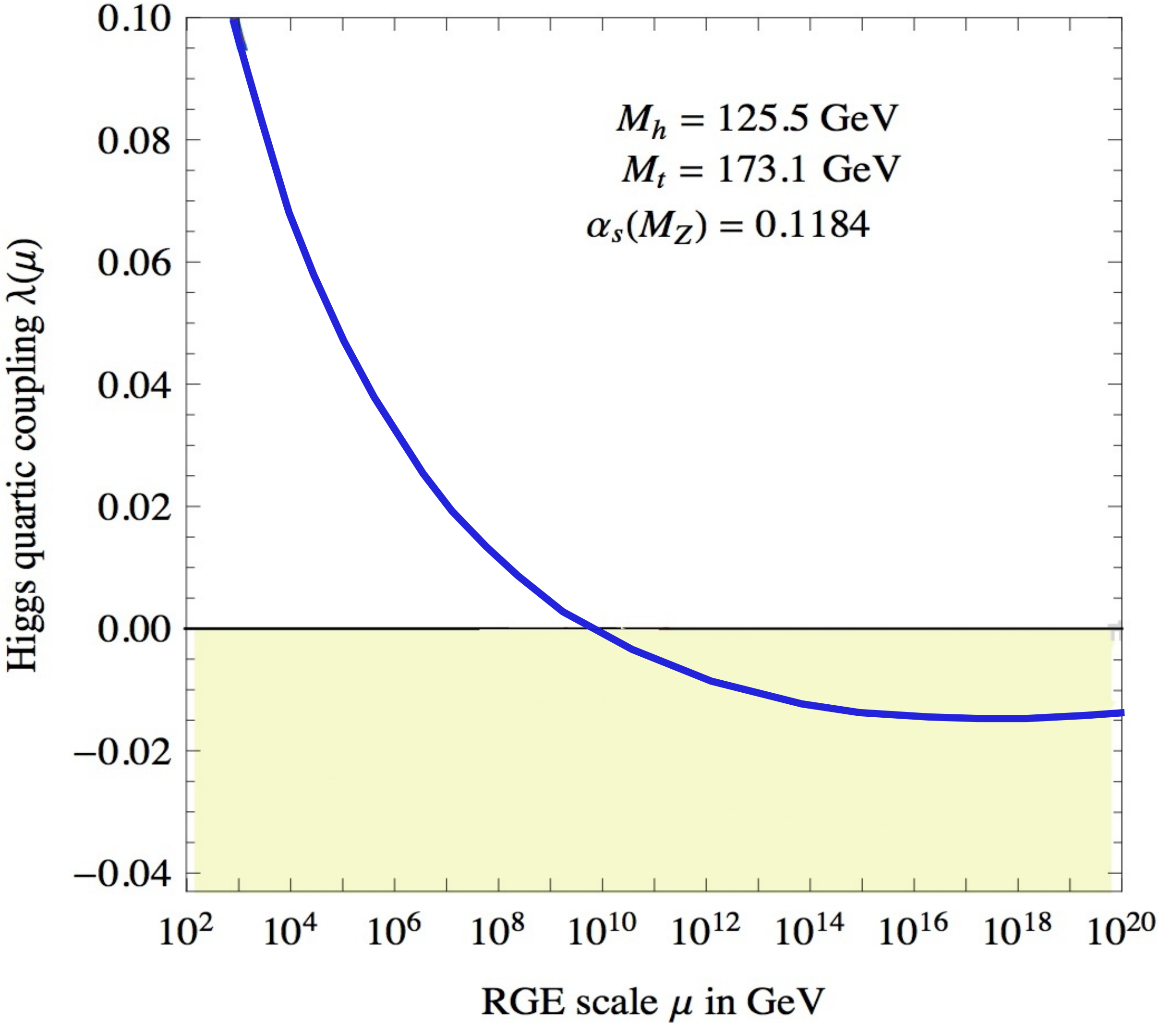


decreasing λ at large energies

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

The high-energy behavior of the potential

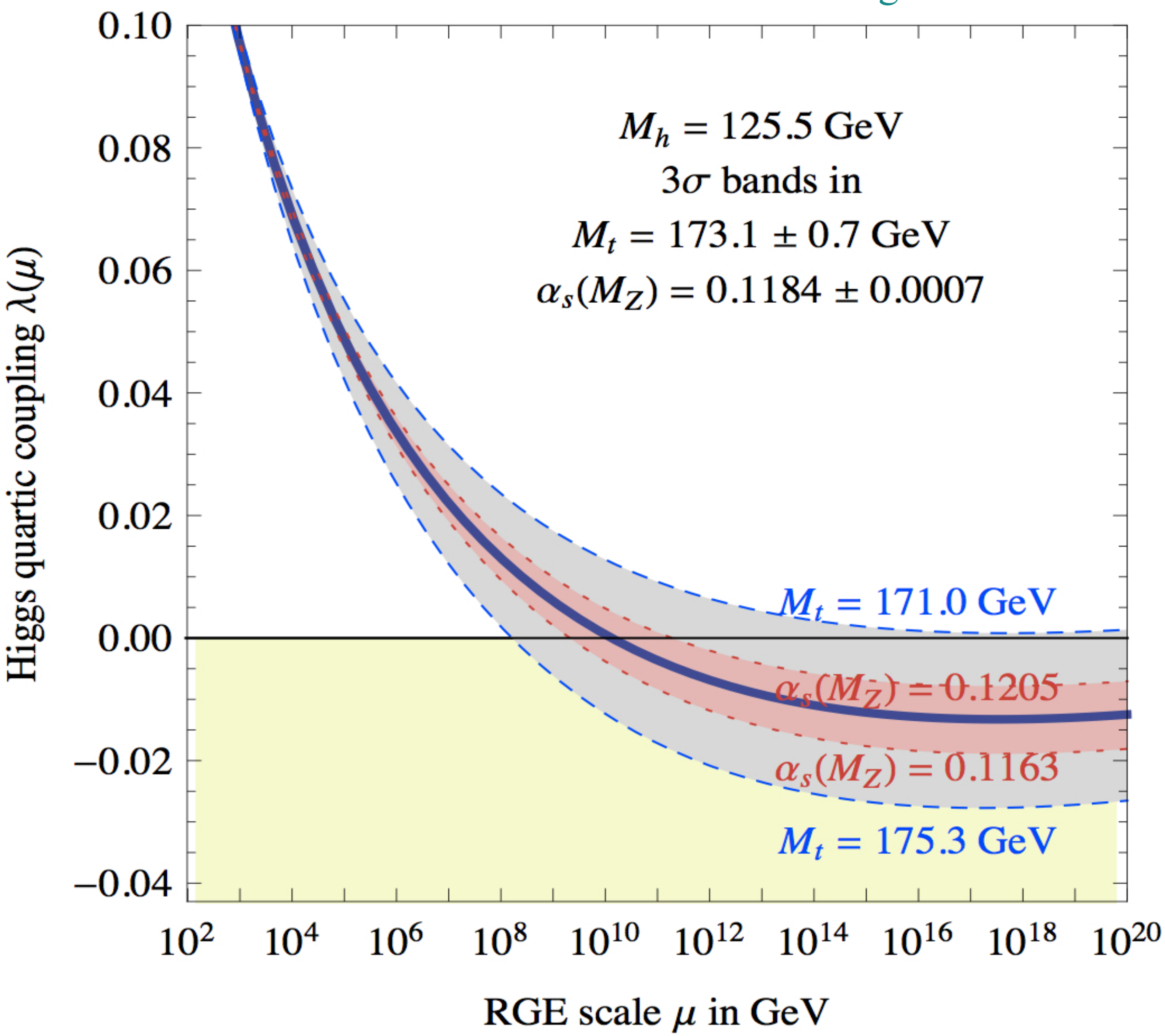
This is indeed what happens for $m_h \approx 125$ GeV and $m_t \approx 173$ GeV !



The high-energy behavior of the potential

This is indeed what happens for $m_h \approx 125$ GeV and $m_t \approx 173$ GeV ...

Degrassi *et al.* '12



...however, unfortunately (?) this is <u>not enough</u> to unambiguously claim the need of NP:

- The present error on m_t does not allow us to exclude at more than 3σ that $\lambda > 0$ up to M_{Planck}

- Even for the central values of m_h and m_t, the Higgs potential remains <u>sufficiently metastable</u>

The high-energy behavior of the potential

The metastability condition: even if the potential has a second deeper minimum, the model is consistent with observations (= no need for NP) if the lifetime of the (unstable) e.w. minimum is longer than the age of the Universe

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

▶ *The high-energy behavior of the potential*

The metastability condition: even if the potential has a second deeper minimum, the model is consistent with observations (= no need for NP) if the lifetime of the (unstable) e.w. minimum is longer than the age of the Universe

The e.w. minimum is destabilized by:

Quantum fluctuations (at T=0)

computable in a model-independent way

⬇

Most conservative bound

Thermal fluctuations

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

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

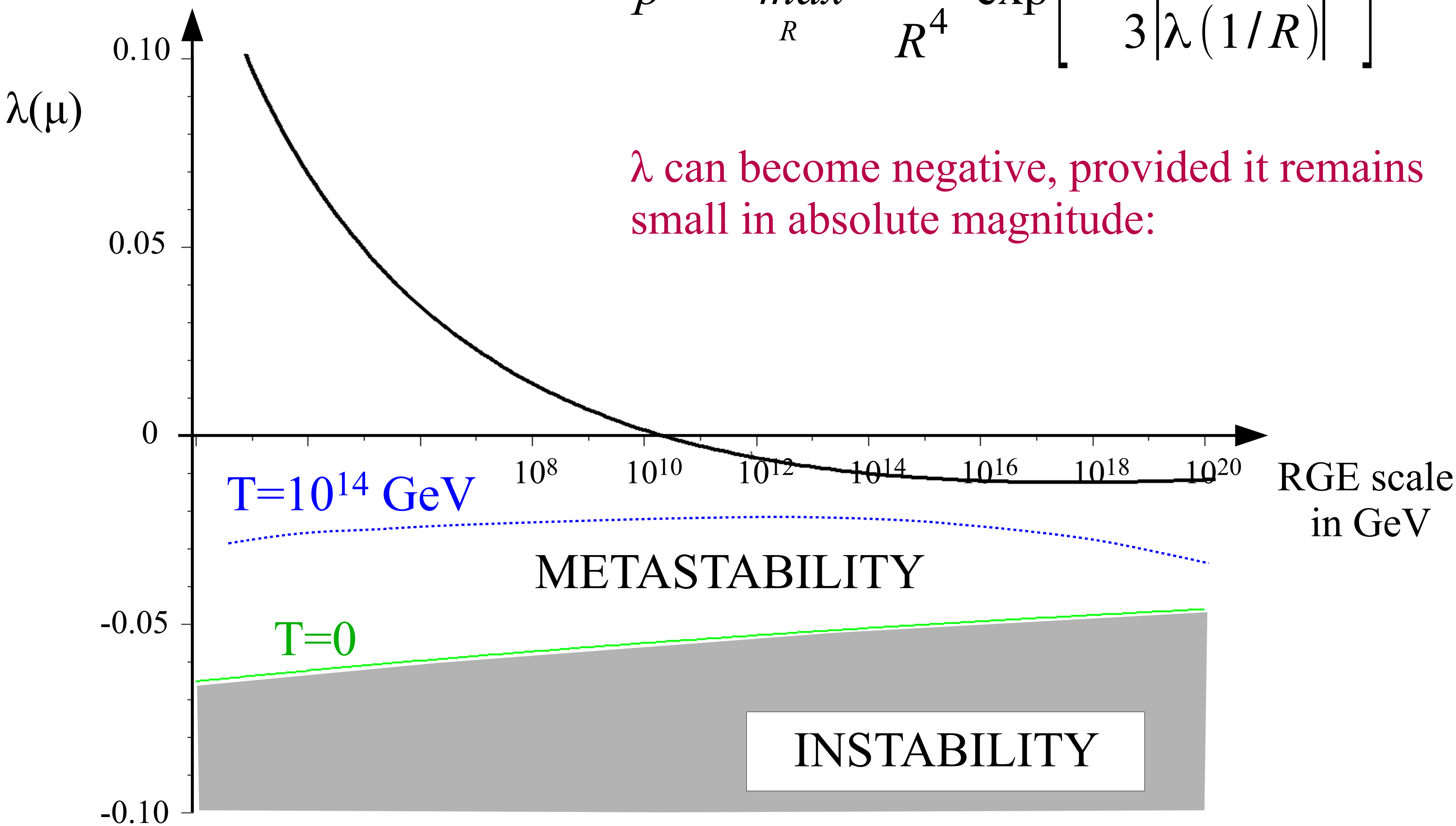
The tunneling is dominated by "bounces" of size R, such that $\lambda(1/R)$ reaches its minimum value: λ can become negative, provided it remains small in magnitude.

The high-energy behavior of the potential

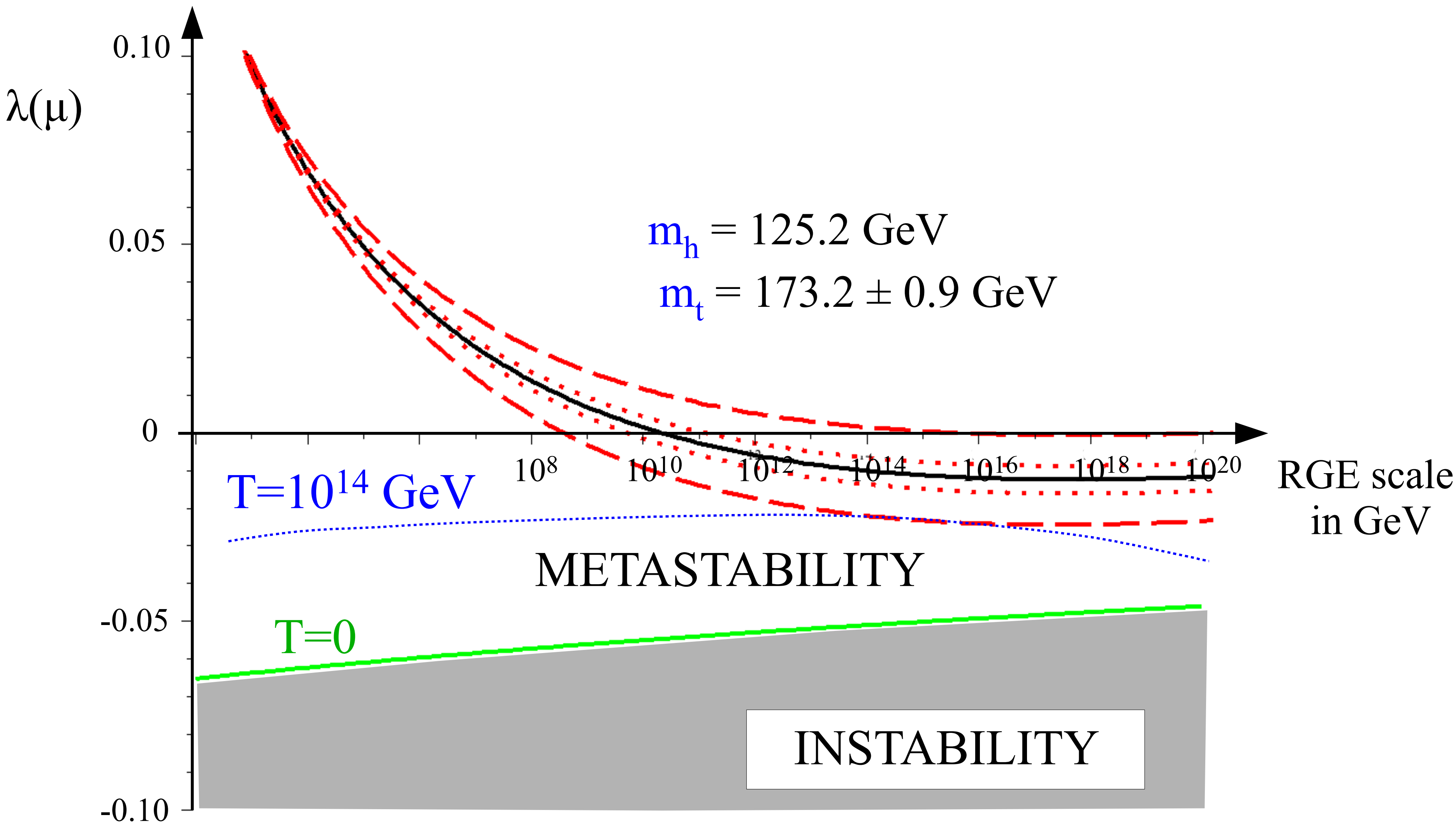
The metastability condition

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

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



Key message: For the values of m_h and m_{top} determined by experiments, the SM vacuum is likely to be unstable but it certainly sufficiently long-lived, compared to the age of the Universe → no need of NP below M_{Planck}



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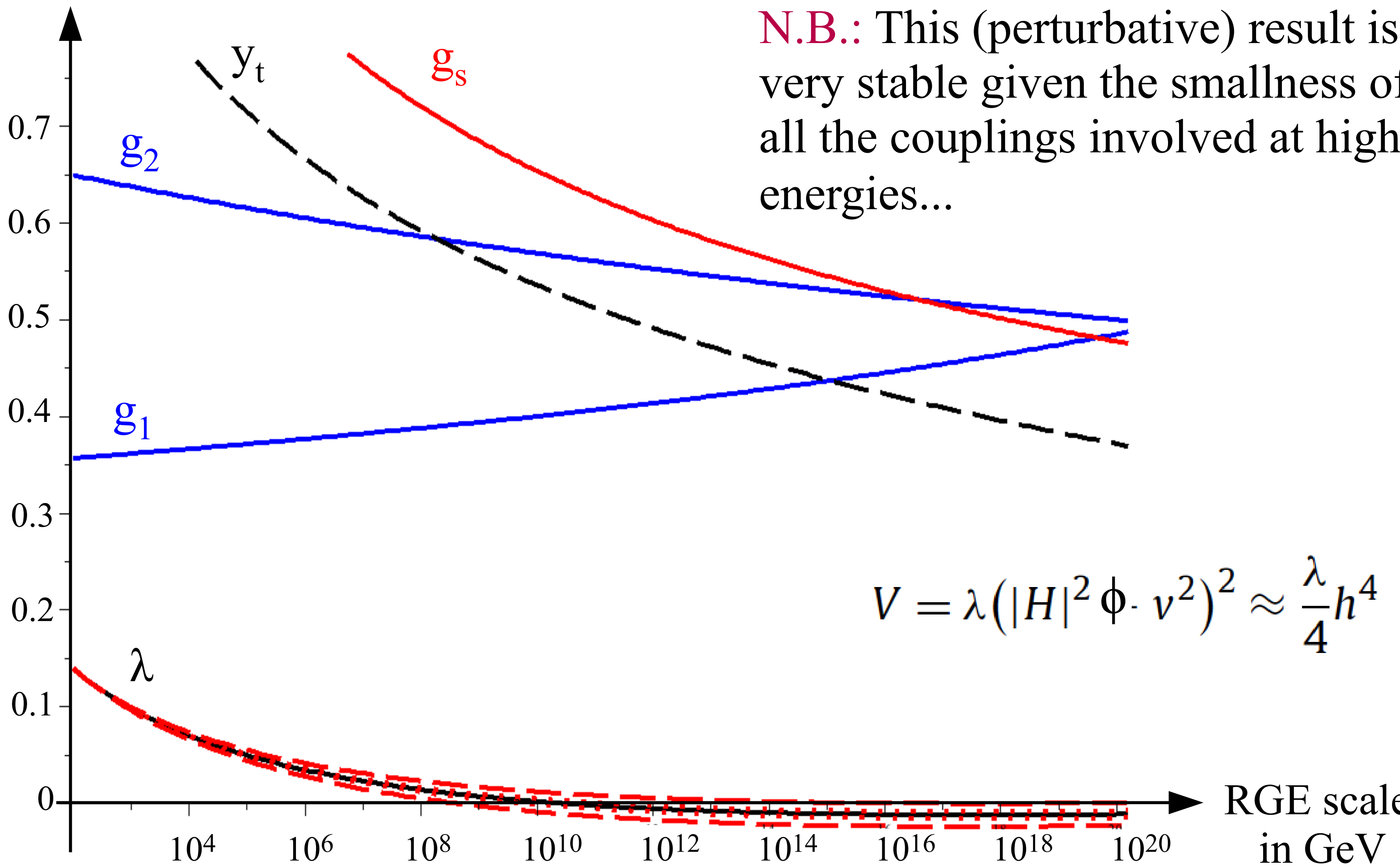
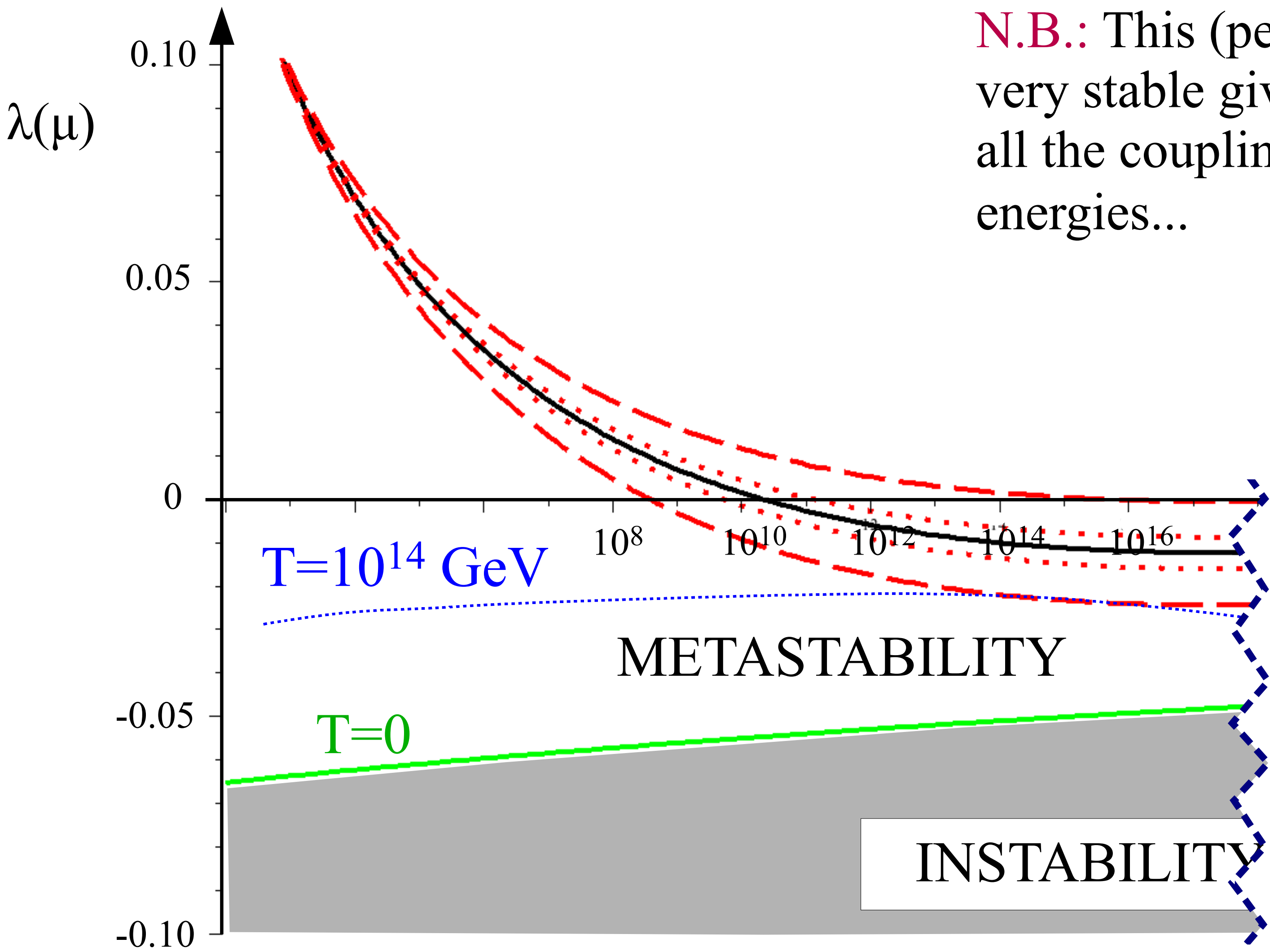


N.B.: This (perturbative) result is very stable given the smallness of all the couplings involved at high energies...

$$V = \lambda\left(|H|^2 - v^2\right)^2 \approx \frac{\lambda}{4}h^4$$

Key message: For the values of m_h and m_{top} determined by experiments, the SM vacuum is likely to be unstable but it is certainly sufficiently long-lived, compared to the age of the Universe → no need of NP below M_{Planck}



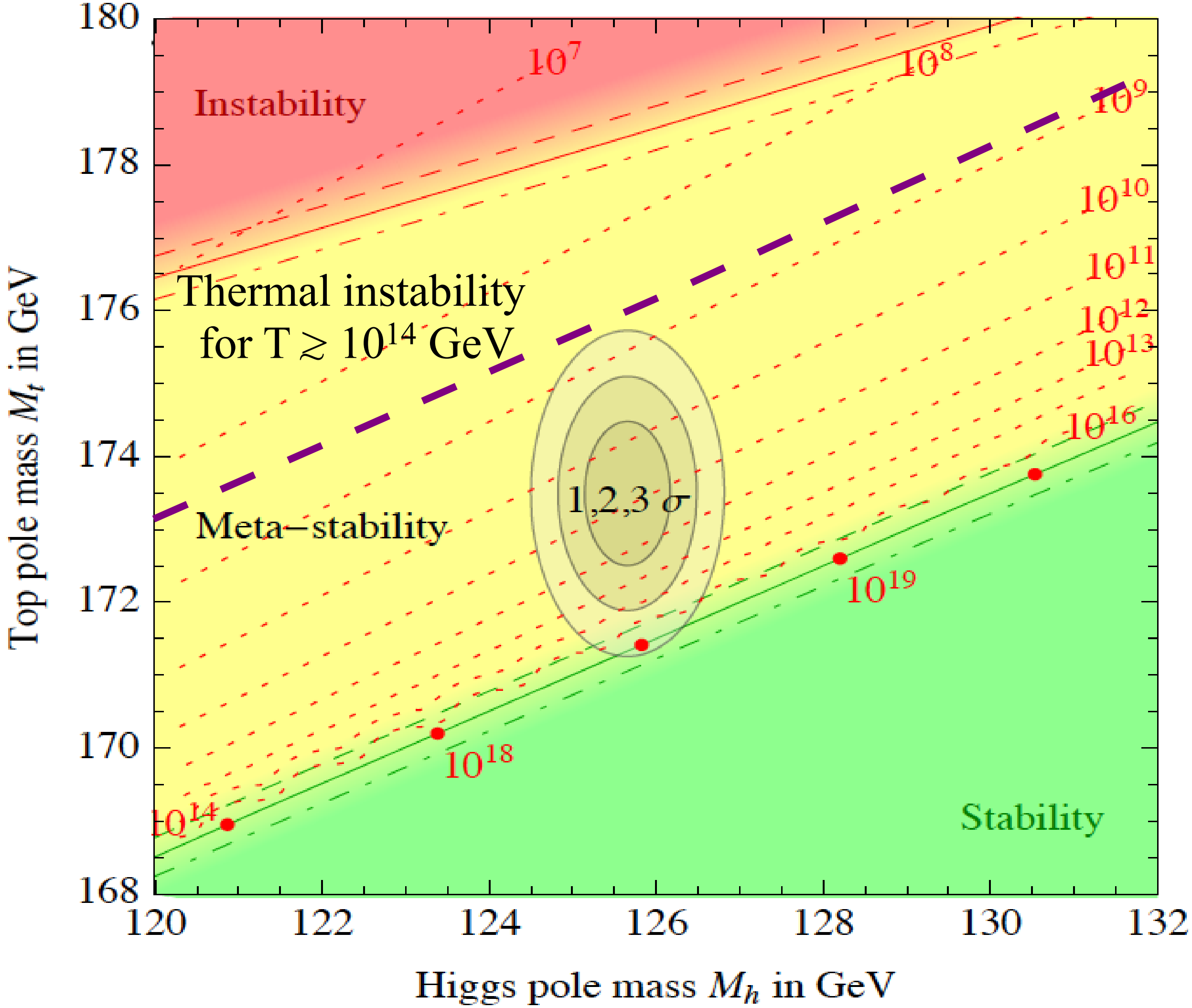
N.B.: This (perturbative) result is very stable given the smallness of all the couplings involved at high energies...

… but we cannot trust the estimate of the tunneling rate too close to M_{Pl}

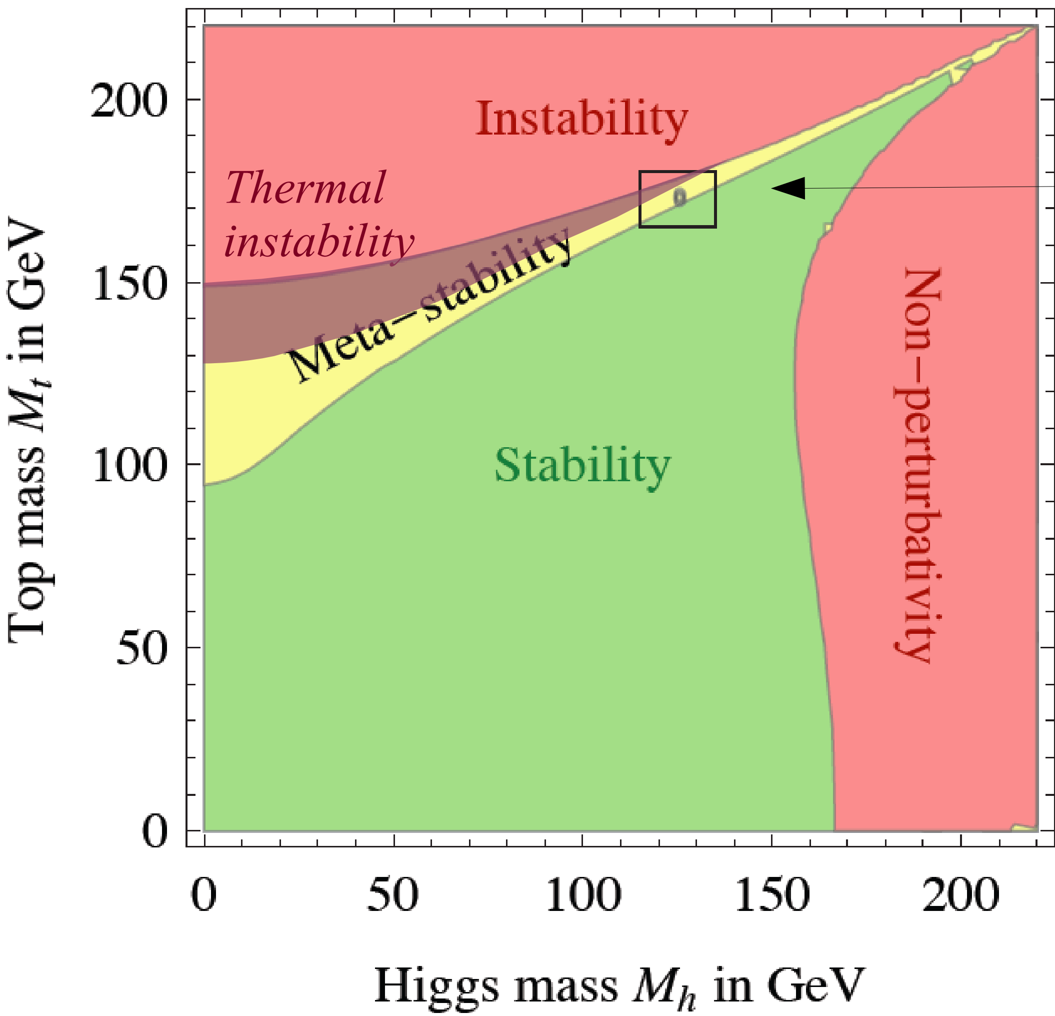
The "near-criticality" condition

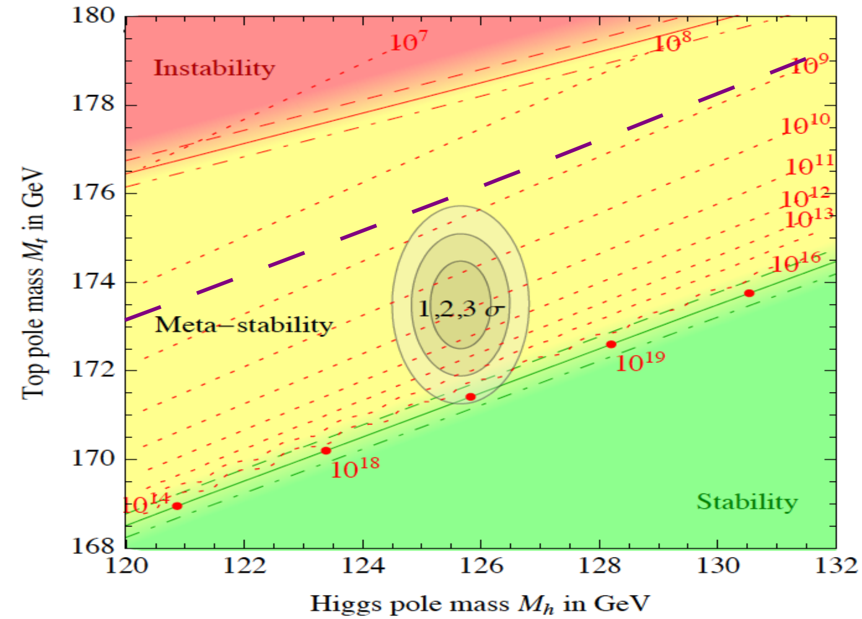
We can look at the metastability condition as a relation between the possible allowed values of m_h and m_{top}

Degrassi et al. '12, Buttazzo *et al.* '13



The "near-criticality" condition



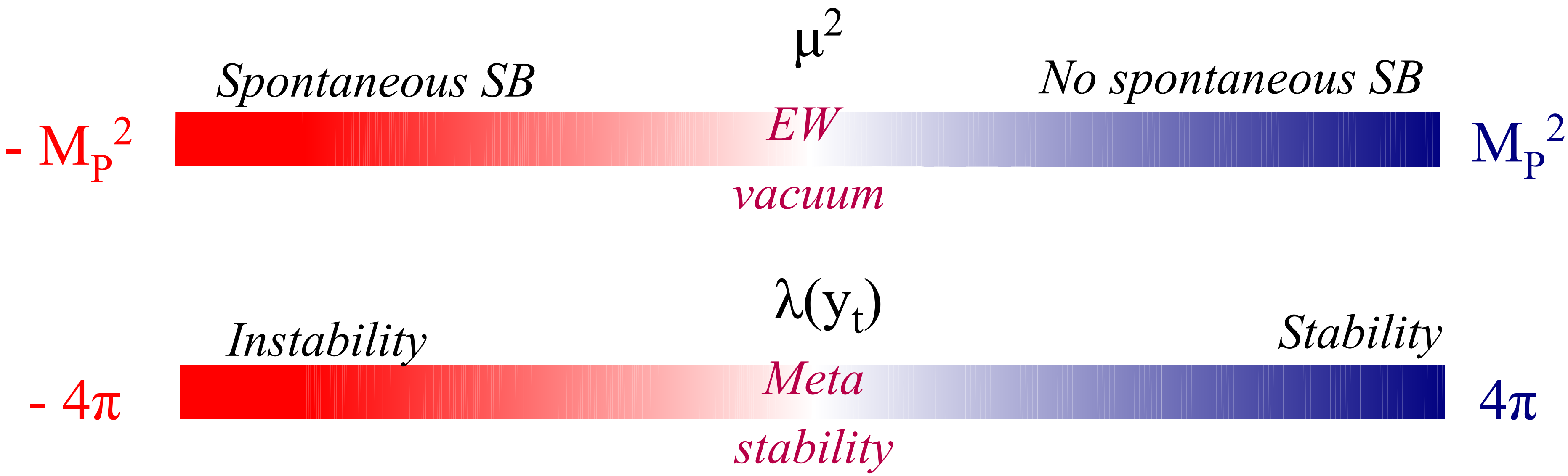


Looking at the plane from a more distant perspective, it appears more clearly that "we live" in a quite "peculiar" region...

The "near-criticality" condition

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

$$V(\phi) = -\mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2 + y_t \bar{\psi}\psi\phi$$



The "near-criticality" condition

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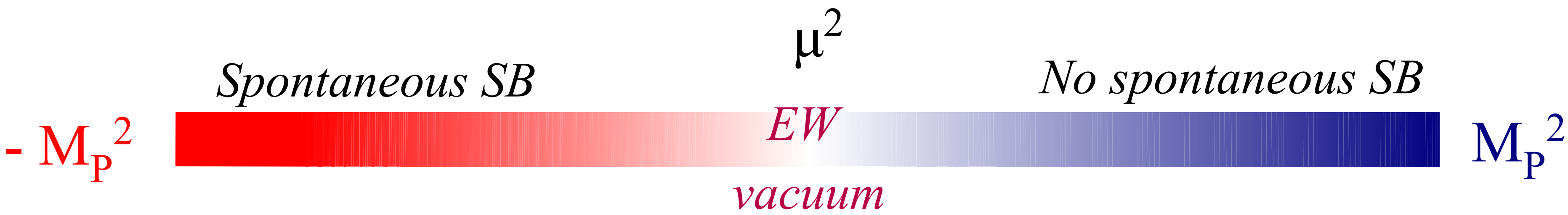
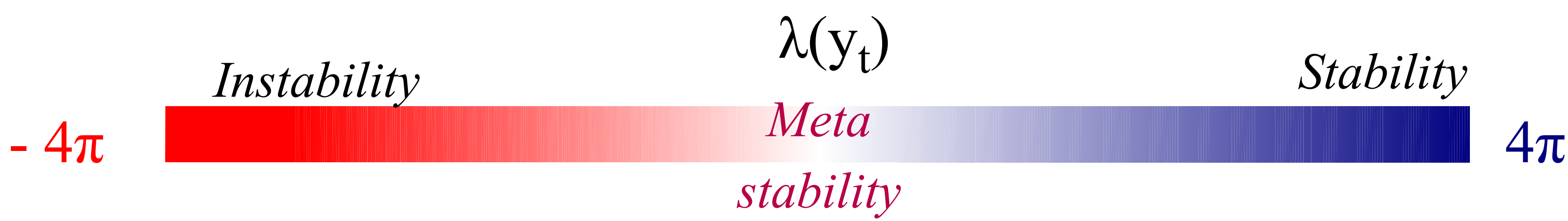
$$V(\phi) = V_0 - \mu^2 \phi^+\phi + \lambda\,(\phi^+\phi)^2 + y_t \overline{\psi}\psi\phi$$





and if we consider also the cosmological constant, we have a 3rd tuned parameter

Is it the indication of some statistical phenomenon occurring at high energies ["multiverse" + "anthropic selection"]...?

Or it is nothing but a "coincidence"?

Back to the key questions of particle physics

More precisely, on both "frontiers" we have two independent sets of questions, a *"difficult one"* and a *"more pragmatic one"*:

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High-energy searches
[*the high-energy frontier*]

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High-precision measurements
[*the high-intensity frontier*]

Back to the key questions of particle physics

The "difficult questions" are equivalent to ask: *what determines the parameters of the Higgs potential.*

Two main roads:

The anthropic principle
"*Darwinism in physics...*"

New symmetries (& new dynamics)
"*The Galilean way...*"

Back to the key questions of particle physics

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The anthropic principle	New symmetries (& new dynamics)
“*Darwinism in physics...*”	“*The Galilean way...*”

Basic idea:

- The “free parameters” of the SM are unpredictable dynamical variables that can change giving rise to <u>different universes</u>.
- The presently measured values of such couplings are what they are, because only for such values... *...we can be there to measure them!*

▶ Back to the key questions of particle physics

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"*Darwinism in physics...*"

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- The presently measured values of such couplings are what they are, because only for such values...
...we can be there to measure them!

⬇

The leading couplings in the Higgs potential seems to be compatible with this idea...

...but this does not mean we should stop searching for "falsifiable explanations" !

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"*Darwinism in physics...*"

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New symmetries (& new dynamics)

"*The Galilean way...*"

So far, the identification of universal symmetry principles has been the main road to understand, simplify, and predict, natural phenomena.

It is not obvious that we can find a "symmetrical/dynamical" explanation for all the SM parameters, but maybe for most of them. And we should not forget we have clear clues of new symmetries [U(1) *charges* + *ν-masses* → *GUT*]

Worth trying → testable consequences