Vacuum (In)stability and the scale of New Physics

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Seminar im Graduiertenkolleg
"Mass and Symmetries after the Discovery of the Higgs Particle at the LHC"
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ROMA TRE
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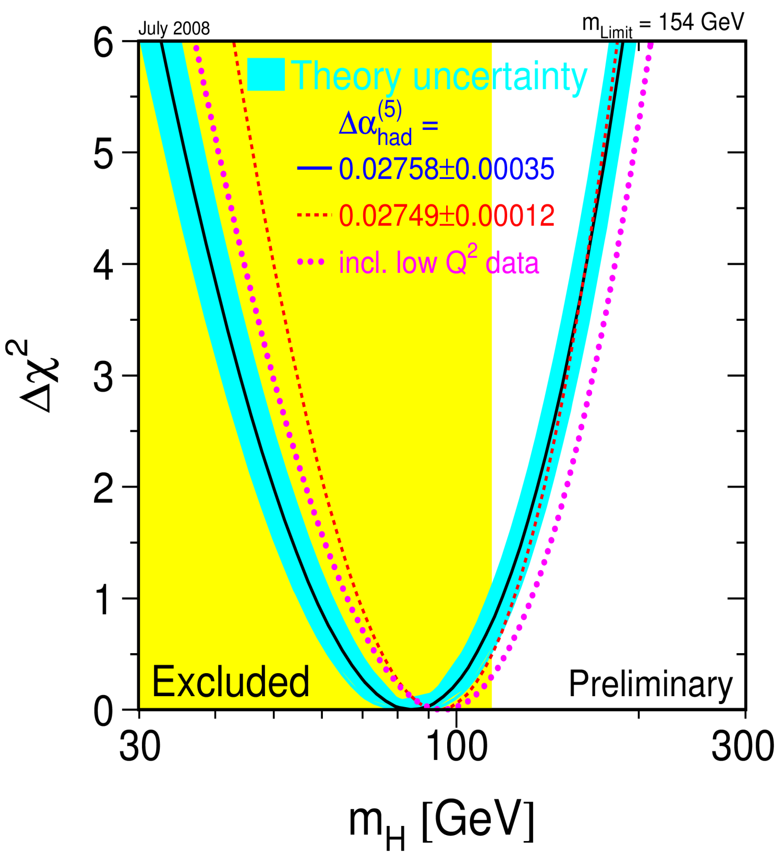
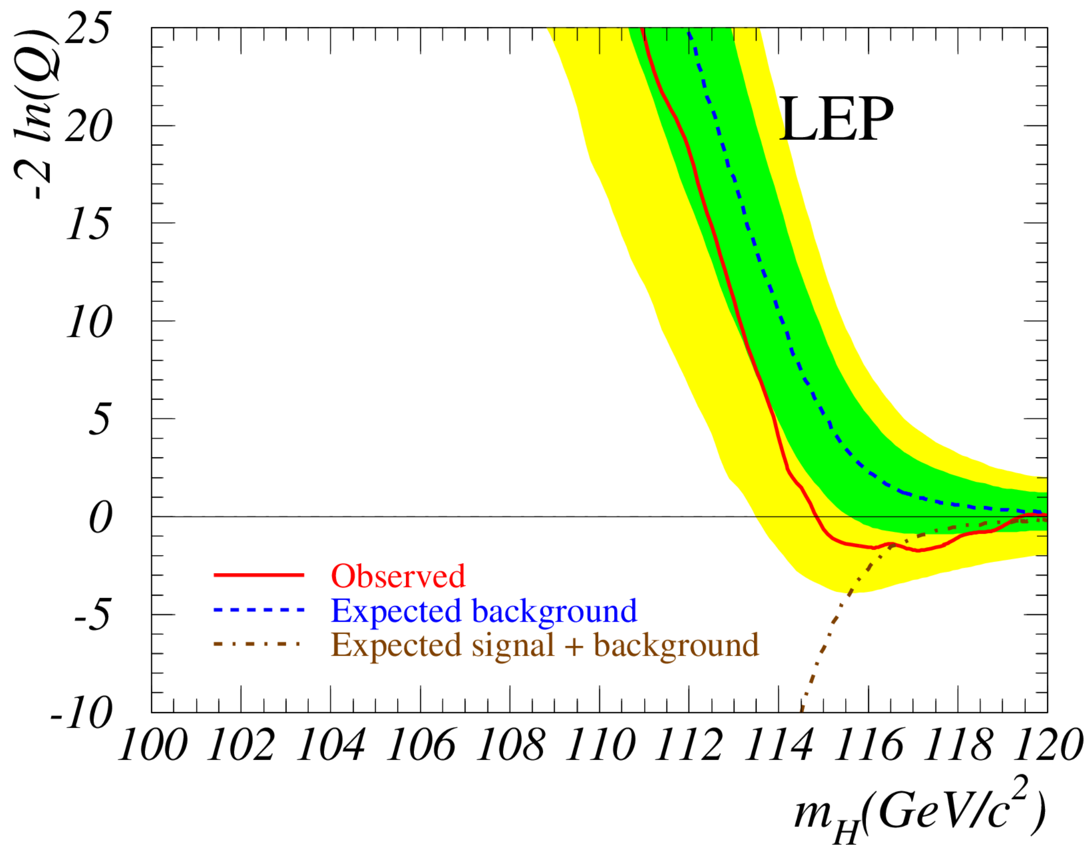
Outline

- Past and present informations on the Higgs boson
- Vacuum stability in the SM, the role of the top
- Minimal extensions of the SM that can stabilize the scalar potential
- Conclusions

Disclaimer: for this talk the di-photon events at 750 GeV do not exist.
If they are confirmed, (almost) all I am going to say in this seminar you can forget.

The past: LEP





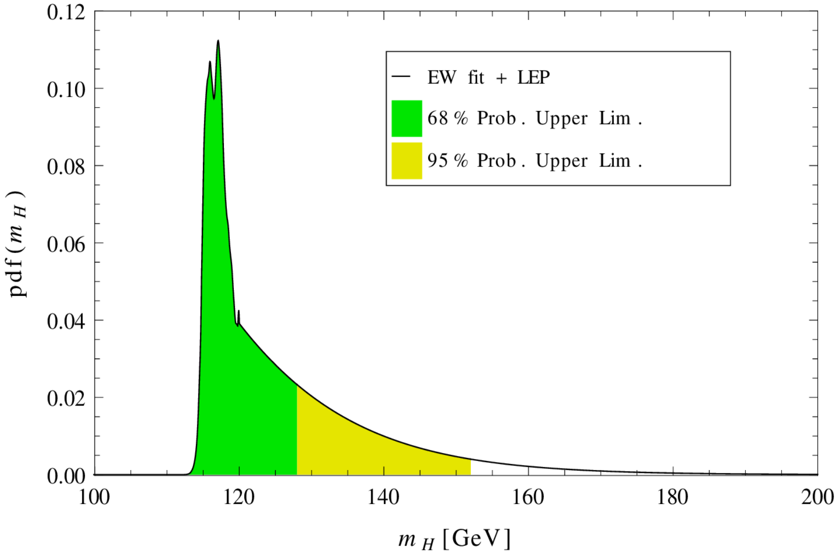
$$Q = \frac{\mathcal{L}(s+b)}{\mathcal{L}(b)}$$

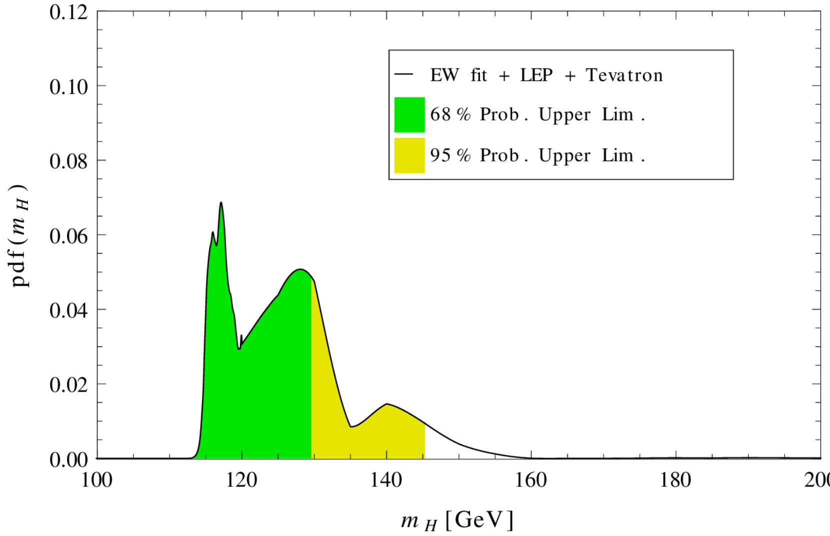
The past: LEP+ Tevatron

Combining direct and indirect information:

D'Agostini, G.D.1999

$$\mathrm{pdf}(M_h) \propto \frac{Q(M_h)e^{-(\chi^2/2)}}{M_h}$$

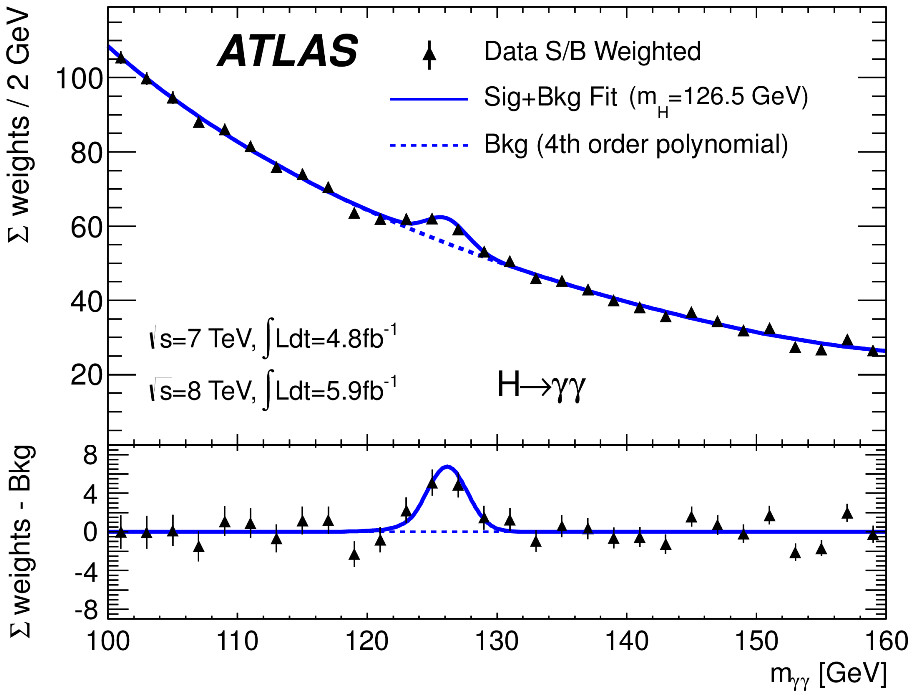


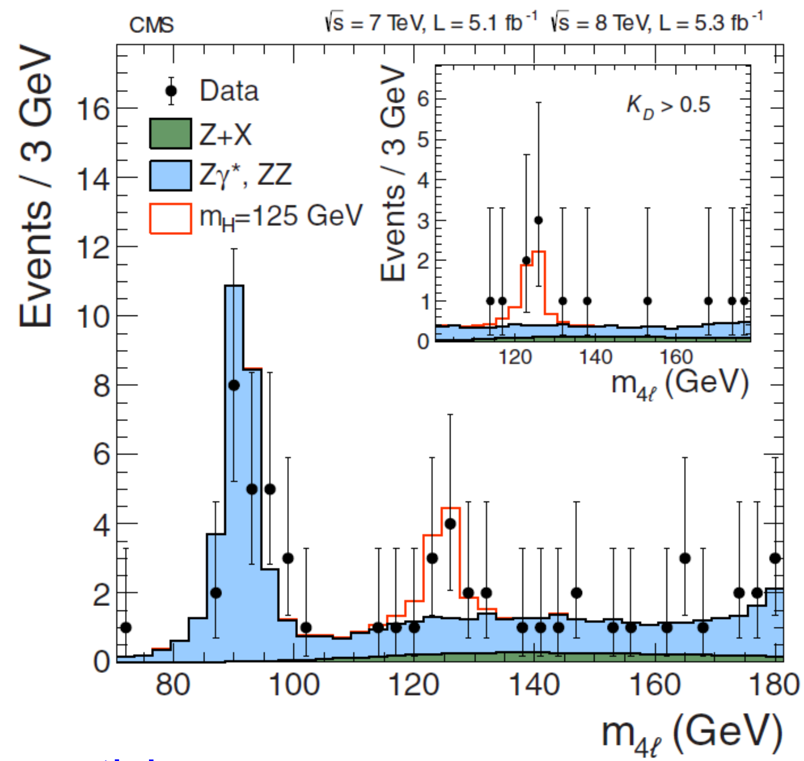


courtesy of S. Di Vita

The consistency of the (minimal) SM at the quantum level predicts a Higgs boson with mass between 110 and 160 GeV

LHC 4th of July 2012 news





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

Today: ATLAS +CMS Higgs mass combination

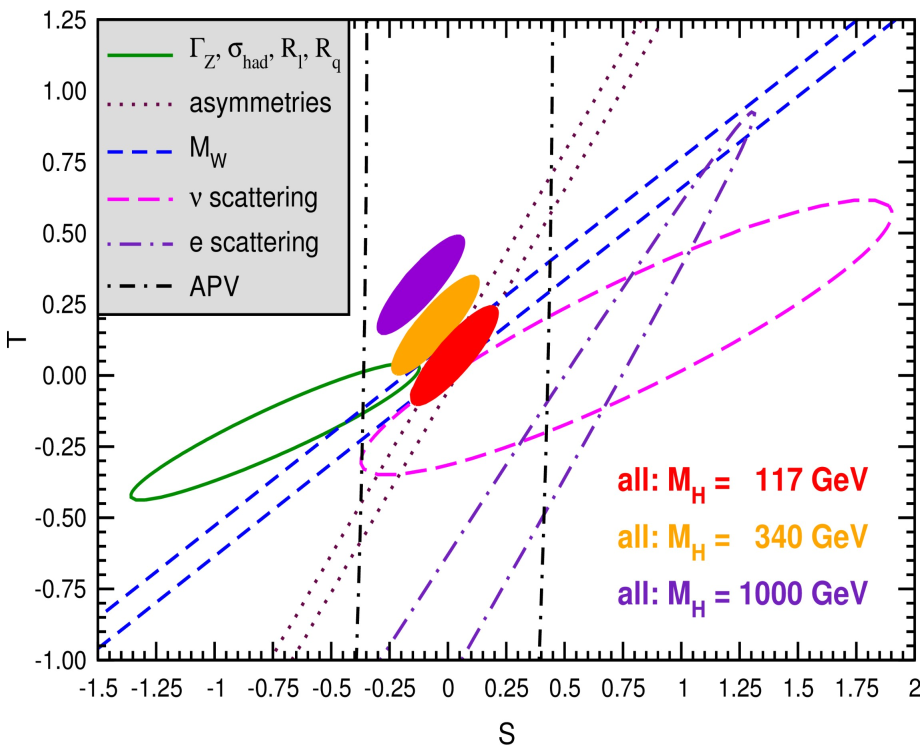
$$m_H = 125.09 \pm 0.21\,(stat) \pm 0.11\,(syst)\ \mathrm{GeV}$$

$$\frac{\delta m_H}{m_H} \sim 1.9 \times 10^{-3}$$

SM is constrained

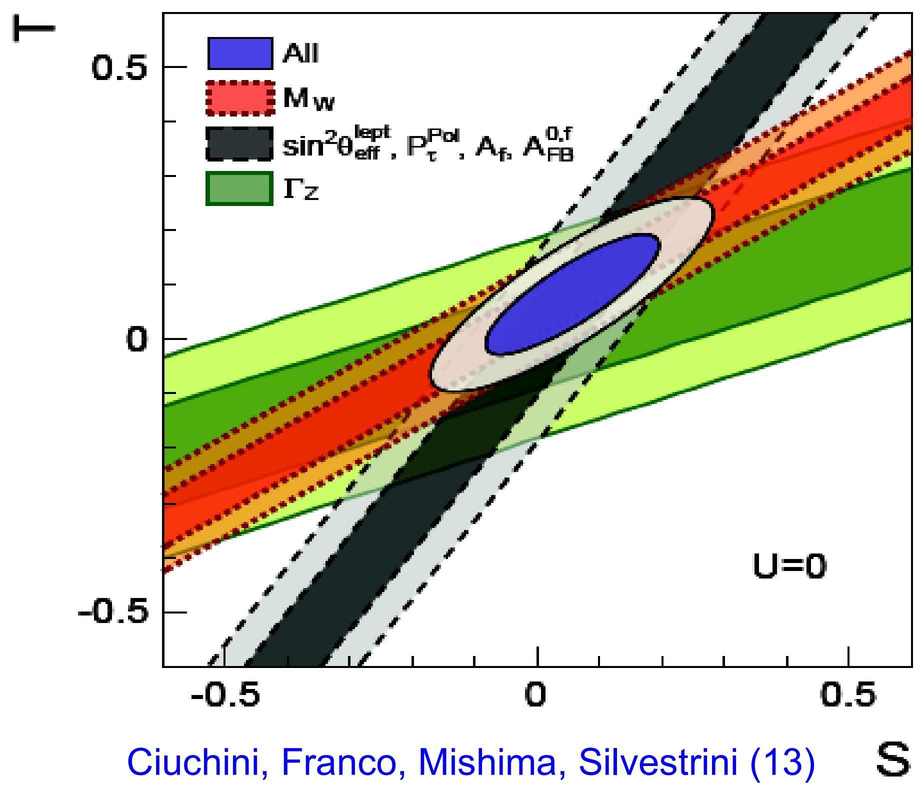
At the time of LEP we could envisage specific type of NP (extra Z, isosplitted (s)fermios, light sleptons etc.) that could allow a heavy Higgs in the EW fit ("conspiracy argument"). With the discovery of the Higgs boson, this is not any more possible

before



P.D.G. (11)

after



Ciuchini, Franco, Mishima, Silvestrini (13)

NP (if there) seems to be of the decoupling type at a high scale

SM as an effective theory?

The (M)SM, i.e. the GWS model, does not address several facts:

- neutrino masses
- a candidate for dark matter
- baryogenesis
- …….

Do we have an argument that ensure us that the SM is not a consistent theory up to M_{Pl} and therefore we are forced to see it as an effective theory, that represents the low-energy limit of a more fundamental theory that will show up at a scale $\Lambda <$ M_{Pl}?

$$V(\phi) = -\frac{m^2}{2}\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

sensitivity to NP
$\delta m^2 \sim \Lambda^2$

Vacuum instability (λ<0)
inconsistency of the model at large energy

No sign of NP at LHC

$M_H \sim 125$ GeV

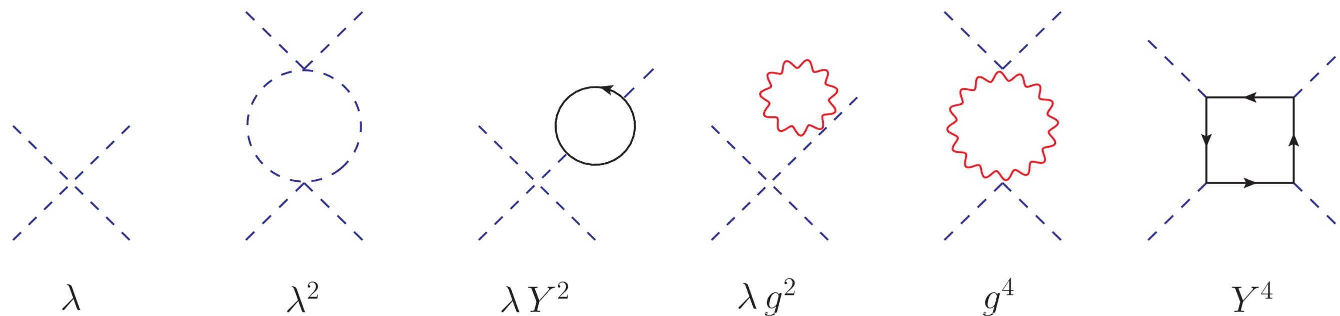
Vacuum Stability bound

Quantum corrections to the classical Higgs potential can modify its shape

$$V^{class}(\phi) = -\frac{1}{2}m^2\phi^2 + \lambda\phi^4 \longrightarrow V^{\rm eff} \approx -\frac{1}{2}m^2(\mu)\phi^2(\mu) + \lambda(\mu)\phi^4(\mu) \sim \lambda(\mu)\phi^4(\mu)$$

$\phi \sim \mu \gg v$

λ runs



$$\frac{d\lambda}{d\ln\mu} = \frac{1}{16\pi^2}\left[+24\lambda^2 + \lambda\left(4N_cY_t - 9g^2 - 3g'^2\right) \underbrace{-2N_cY_t^4 + \frac{9}{8}g^4 + \frac{3}{8}g'^4 + \frac{3}{4}g^2g'^2}_{\text{B<0 at the weak scale}} + \ldots\right]$$

First case: λ~0 (M_H~0)

$$V^{1l}_{eff} = -\frac{1}{2}m^2(M)\phi^2 + \lambda(M)\phi^4 + \frac{B}{32\pi^2}\phi^4\ln\frac{\phi^2}{M^2}$$

If B were constant at large values of Φ the potential would become negative and unbounded. But B runs

Various possibilities:

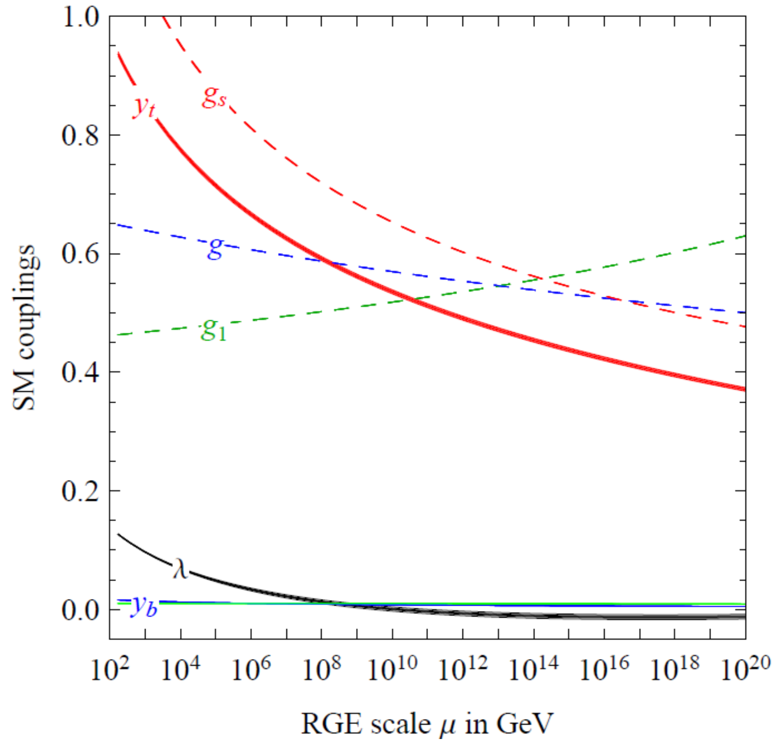
B is negative at the weak scale but not large enough to make B negative at a large scale such that the potential can become negative.

SM vacuum is stable

B is very negative at the weak scale and stays negative till the Planck scale

SM vacuum is unstable

N.P. should appear below the Planck scale to rescue our lives



B is sufficient negative at the weak scale that the potential will become negative at a certain scale. However, increasing more the scale B turns positive. The potential develops a second deeper minimum at a large scale

SM is unstable, but ….

Other case: B ~ 0, M_H large

$$V_{eff}^{1l} \sim \lambda(M)\phi^4 + \frac{3\lambda^2}{4\pi^2}\phi^4 \ln\frac{\phi^2}{M^2} \Rightarrow V_{eff}^{RGE} = \frac{\lambda\phi^4}{1 - \frac{3\lambda}{4\pi^2}\ln\frac{\phi^2}{M^2}}$$

Landau pole

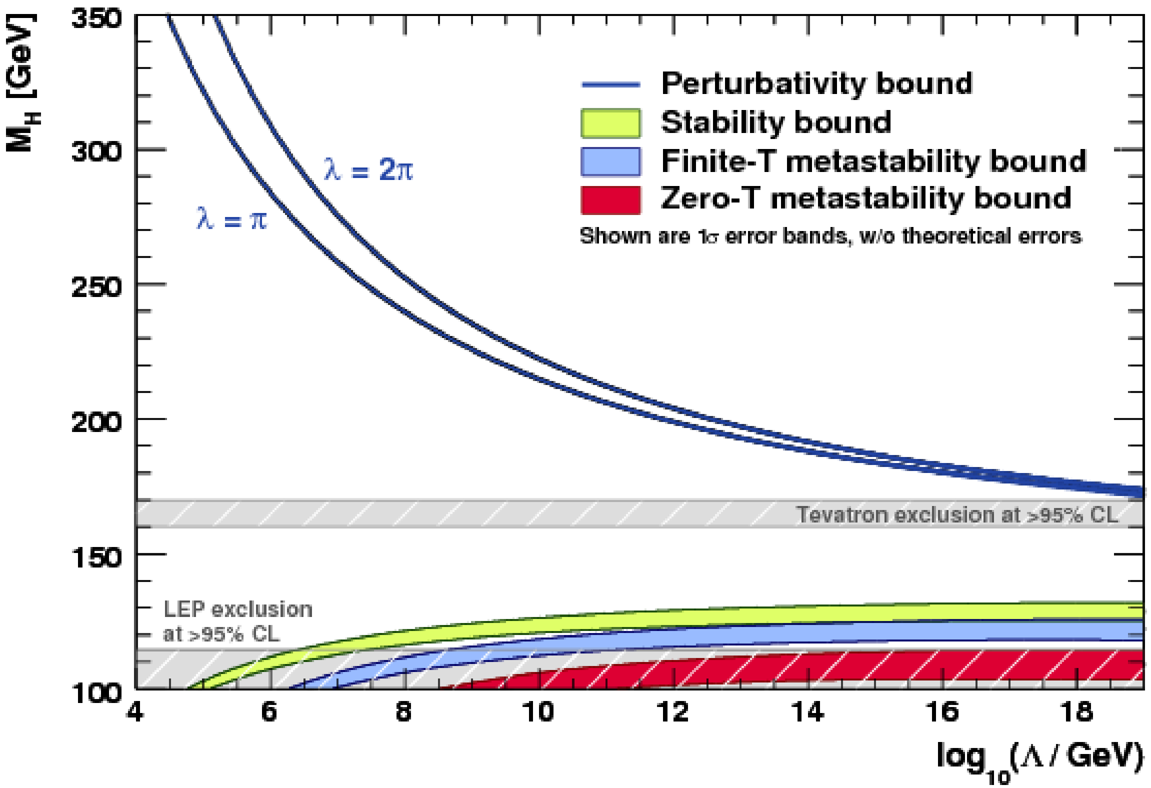
At large Φ perturbativity is lost

Which values of the Higgs mass ensure vacuum stability and perburbativity up to the Planck scale ?

Given the initial values for the couplings obtained from the experimental results we look for:

Vacuum stability → V_{eff} =0 (~ λ =0)

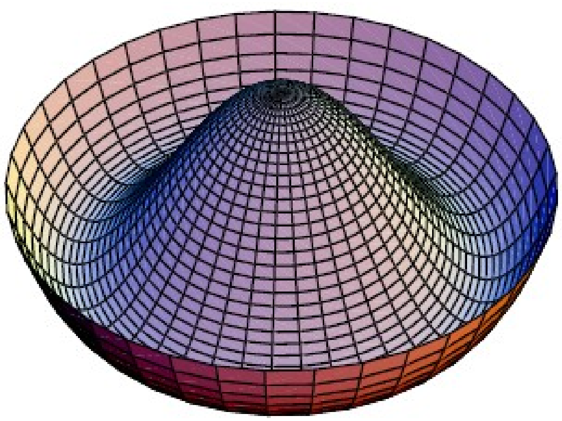
Perturbativity → when λ becomes large



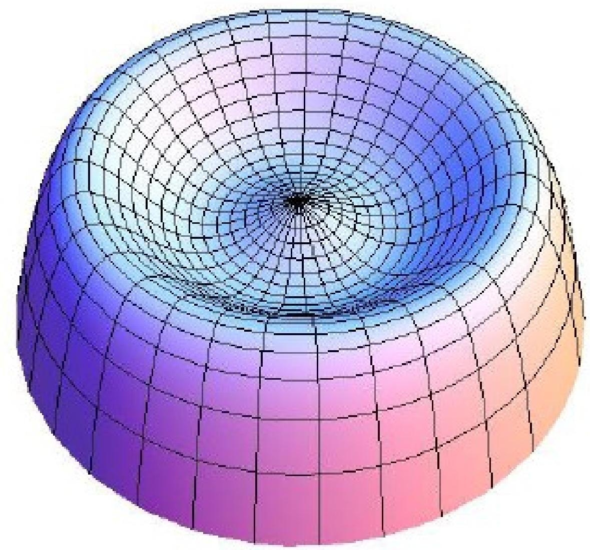
Ellis et al. 09

M_H ~ 125 GeV: $-Y_t^4$ wins: $\lambda(M_t)$ ~ 0.13 runs towards smaller values and can eventually become negative. If so the potential is either unbounded from below or can develop a second (deeper) minimun at large field values

Illustrative



$\rightarrow$

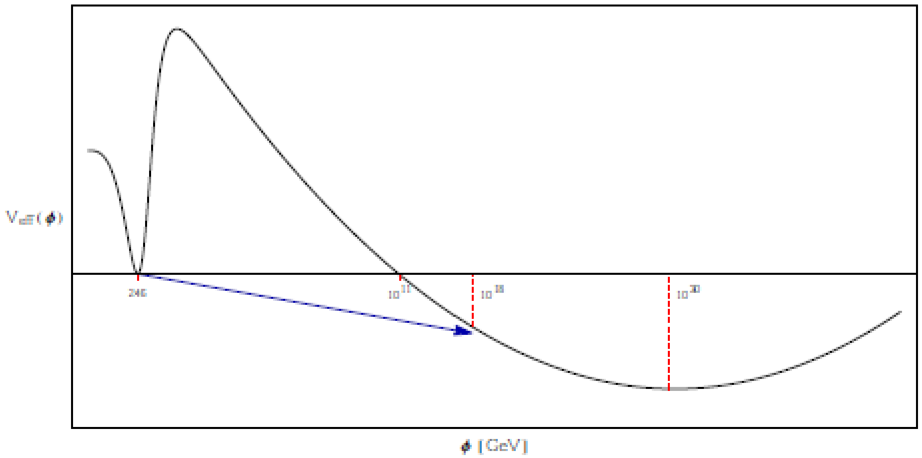


If your mexican hat turns out to be a dog bowl you have a problem...

from A. Strumia

The problem

There is a transition probability between the false and true vacua



It is really a problem ?

It is a problem that must be cured via the appearance of New Physics at a scale below that where the potential become unstable ONLY if the transition probability is smaller than the life of the universe.

Metastability condition: if λ becomes negative provided it remains small in absolute magnitude the SM vacuum is unstable but sufficiently long-lived compared to the age of the Universe

If our vacuum is only a local minimum of the potential, quantum tunneling towards the true minimum can happen. Bubbles of true vacuum can form in the false vacuum and possibly expand throughout the universe converting false vacuum to true. These bubbles are nothing but the solution of the e.o.m. that interpolate between the two vacua (bounces)

Coleman 79

The bounces h(r) are characterized by a size $R = \Lambda_B^{-1}$

$$h(r) = \sqrt{\frac{8}{|\lambda|}}\frac{R}{r^2+R^2}, \qquad r = |\vec{x}|^2 + \tau^2$$

Transition probability $p \sim \frac{\tau_U^4}{R^4} e^{-S[h]}, \quad S[h] = \int d^4x \left[\frac{1}{2}\partial_\mu h \partial_\mu h + V(h)\right] = \frac{8\pi^2}{3|\lambda|}$

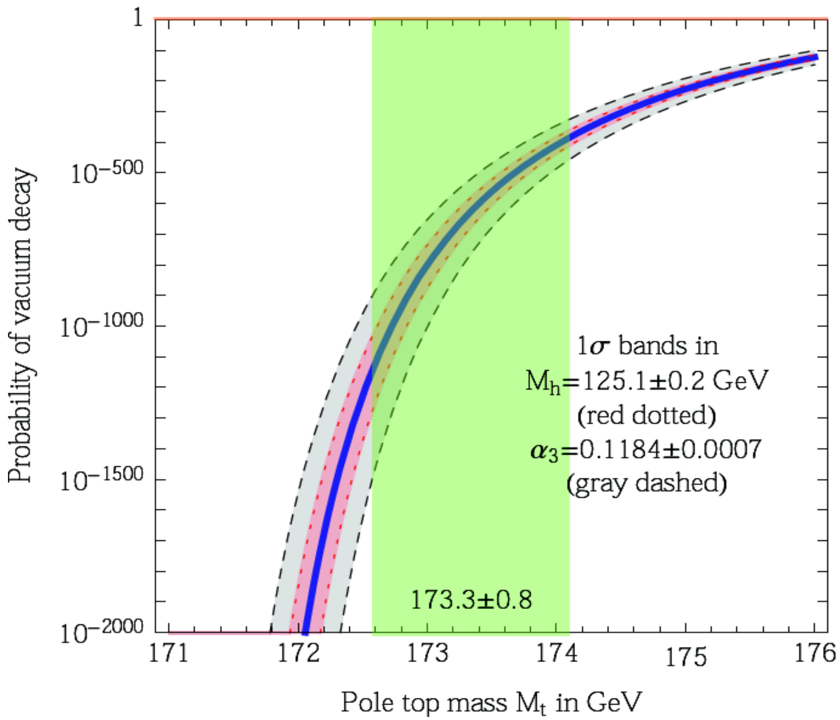
S is the action of the bounce of size R

Tunneling is dominated by the bounce of size R such that $\lambda(\Lambda_B)$ is minimized, i.e. $\beta_\lambda(\Lambda_B) = 0$.

Isidori, Ridolfi, Strumia (01)

$$\mathrm{p} \sim \tau_U^4 \Lambda_B^4 e^{-\frac{8\pi^2}{3|\lambda(\Lambda_B)|}} \sim \left(\frac{e^{140}}{M_{Pl}}\Lambda_B\right)^4 e^{-\frac{2600}{|\lambda/0.01|}} \qquad (\Lambda_B/M_{Pl} \sim 10^{-\mathcal{O}(1)})$$

wins if λ less ~ 0.05



What matters for p is the scale Λ_B (that happen to be close to M_{pl}) not Λ_I where V_{eff} < v~0

Caveat: unknown Planckian dynamics could affect the tunneling rate.

Branchina, Messina (13)

Toy model: $V(h) = \frac{\lambda}{4}h^4 + \frac{\lambda_6}{6M^2}h^6 + \frac{\lambda_8}{8M^4}h^8$ $\quad M > \Lambda_B^{SM}$

$\lambda_6 > 0$, $\lambda_8 > 0$, $p = p_{SM}$;

$\lambda_6 < 0$, $\lambda_8 > 0$, $p \gg p_{SM}$, $\tau \sim 10^{-\mathcal{O}(100)}\tau_U$

New Physics modifies the ground state of the theory, generating a new deep minimum around the scale M, a new bounce with $\Lambda_B \sim M$ is present

"Physics in the deep UV cannot improve on stability"

Di Luzio, Isidori, Ridolfi (15)

Vacuum stability analyses

Long history, back to the middle seventies

Linde (76); Weinberg (76); Cabibbo, Maiani, Parisi, Petronzio (79); Hung (79); Lindner (86); Sher(89) ....

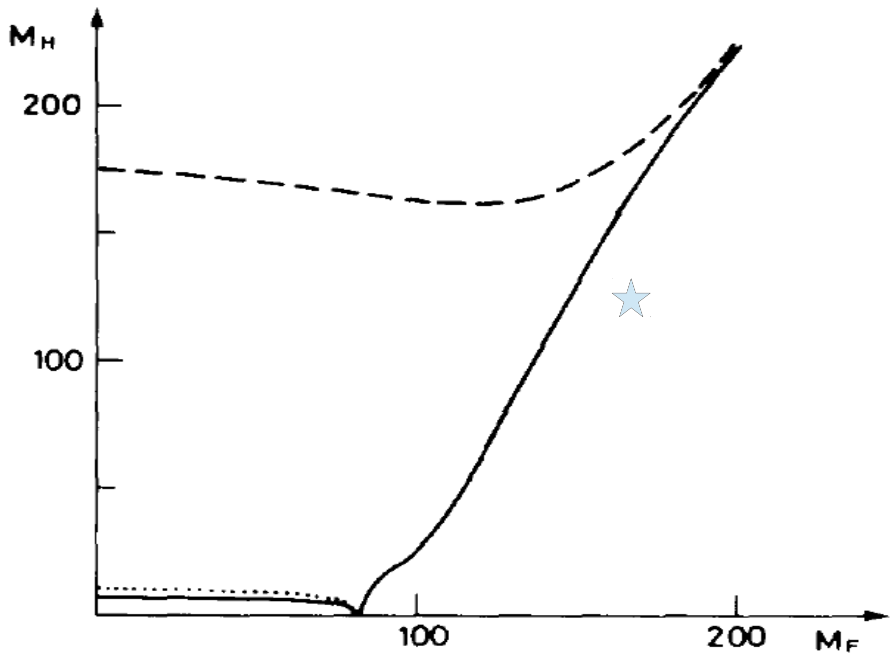


Fig. 1. Bounds on the mass of the Higgs boson (m_H) as a function of the top quark mass (M_f) in the case of three generations. We have taken $\sin^2\theta_W = 0.2$. The dashed line and the full line represent the upper and the lower bound, respectively. The dotted line is the prediction of the massless theory. The curves end in correspondence to the upper bound on M_f, eq. (4.2).

Cabibbo, Maiani, Parisi, Petronzio (79);

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NNLO

- Two-loop effective potential
  (complete) Ford, Jack, Jones 92,97; Martin (02)

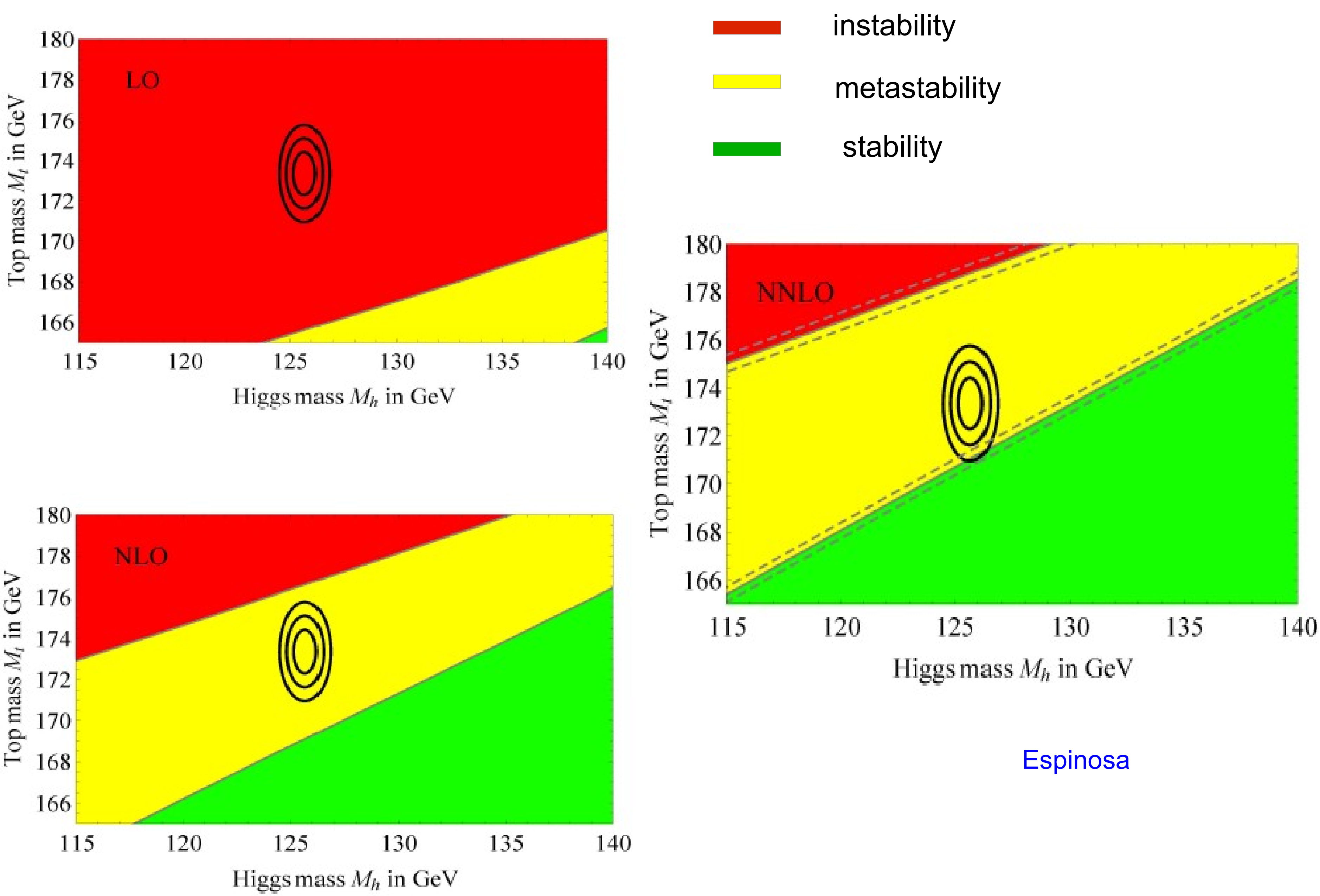
- Three-loop beta functions

gauge	Mihaila, Salomon, Steinhauser (12)
g_3 (NNLO)	v. Ritbergen, Vermaseren, Larin (97); Czakon (05)
Yukawa, Higgs	Chetyrkin, Zoller (12, 13,); Bednyakov et al. (13)

- Two-loop threshold corrections at the weak scale

y_t:	g_3 (NNLO)	Chetyrkin, Steinhauser (00); Melnikov, v. Ritbergen (00)
	gauge x QCD	Bezrukov, Kalmykov, Kniehl, Shaposhnikov (12)
	α_W^2	Buttazzo,Giardino, Giudice, Sala, Salvio, Strumia, G.D. (13)
λ:	Yuk x QCD,	Bezrukov et al. (12), Di Vita et al. (12)
	SM gaugeless	Di Vita, Elias-Miro, Espinosa, Giudice, Isisodri, Strumia, G.D. (12)
	Full SM	Buttazzo,Giardino, Giudice, Sala, Salvio, Strumia, G.D. (13)
g_2, g_Y	Full SM	Buttazzo,Giardino, Giudice, Sala, Salvio, Strumia, G.D. (13)
		Kniehl, Pikelner, Veretin (15)

Dominant theory uncertainty on the Higgs mass value that ensures vacuum stability comes from the threshold corrections at the weak scale


instability
metastability
stability
LO
NLO
NNLO
Top mass M_t in GeV
Higgs mass M_h in GeV
180
178
176
174
172
170
168
166
115
120
125
130
135
140

Espinosa

NNLO Calculation

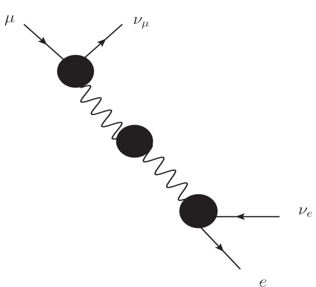
λ(μ) in terms of G_μ, $\alpha_s(M_Z)$, M_h, M_t, M_z, M_w (pole masses)

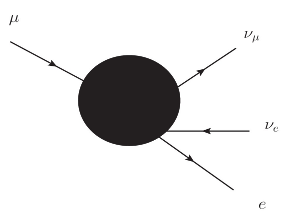
$$\lambda(\mu) = \frac{G_\mu}{\sqrt{2}} M_h^2 - \delta\lambda^{(1)}(\mu) - \delta\lambda^{(2)}(\mu)$$

Sirlin, Zucchini (86)

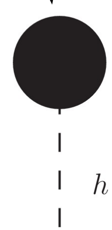
$$\frac{G_\mu}{\sqrt{2}} = \frac{1}{2v_0^2}(1+\Delta r_0)$$

$$\delta\lambda^{(2)}(\mu) = \frac{G_\mu}{\sqrt{2}} M_h^2 \left\{ -\frac{\Delta r_0^{(1)}}{M_h^2}\left[M_h^2 \Delta r_0^{(1)} + \frac{3\,T^{(1)}}{2\,v_{\rm ren}} + \mathrm{Re}\,\Pi_{hh}^{(1)}(M_h^2)\right] + \Delta r_0^{(2)} + \frac{1}{M_h^2}\left[\frac{T^{(2)}}{v_{\rm ren}} + \mathrm{Re}\,\Pi_{hh}^{(2)}(M_h^2)\right]\right\}_{\rm fin} + \Delta_\lambda$$

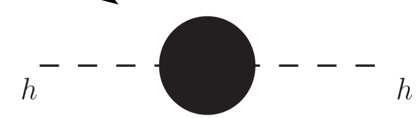




analytical



analytical

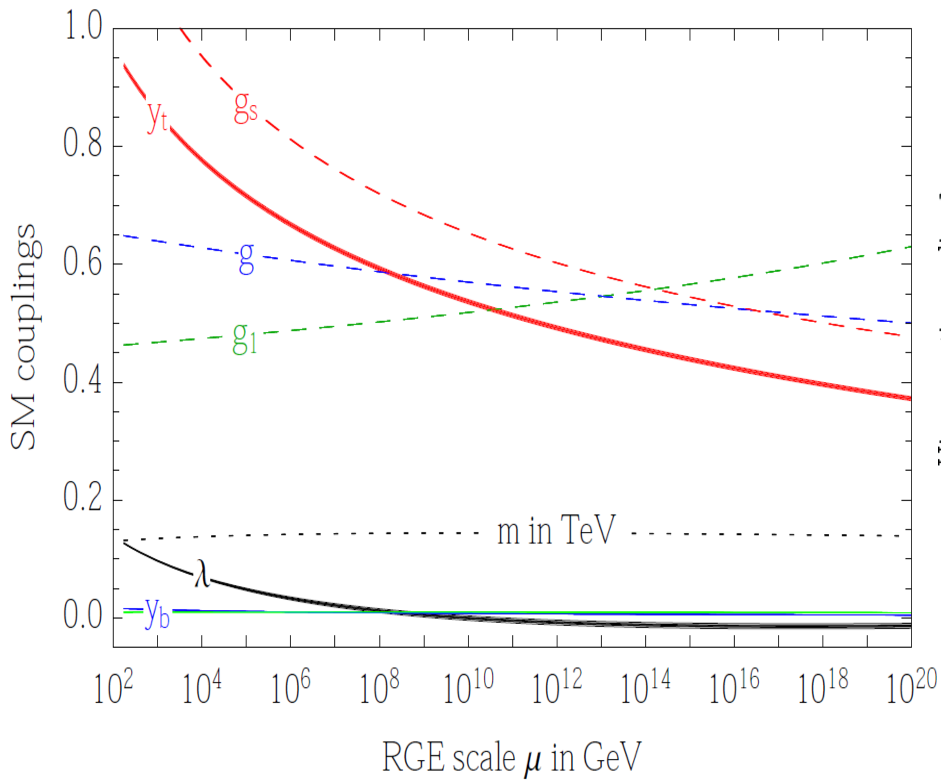


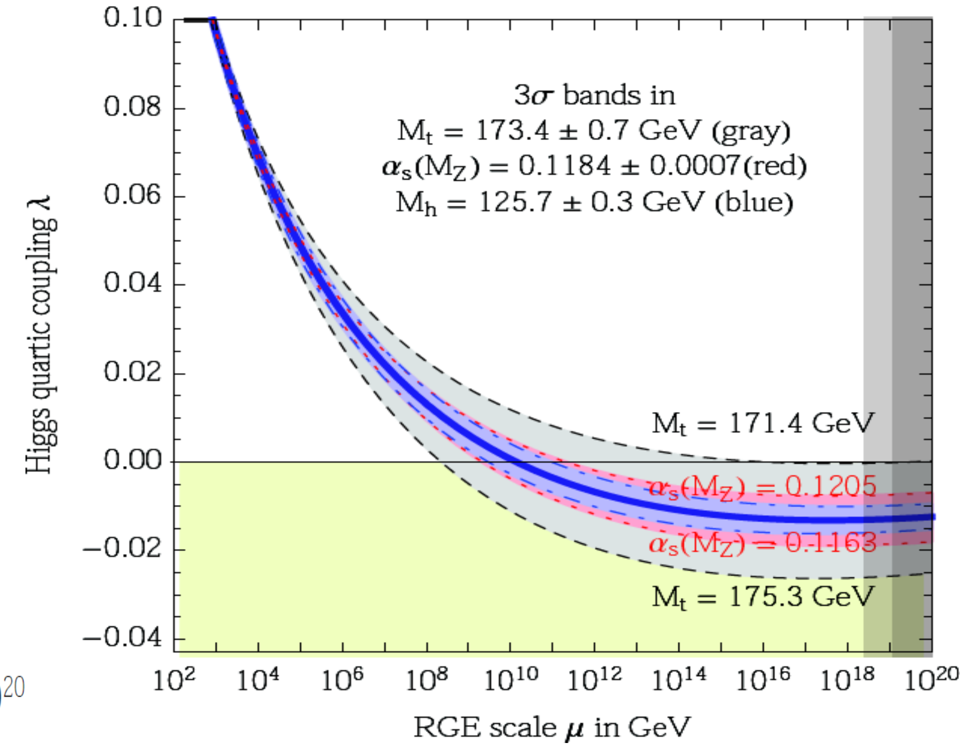
numerical,
Martin's loop functions

Martin (02,03)

$$\delta\lambda^{(2)}_{SM}(\mu = M_t) = -\frac{9.545}{(4\pi)^4}, \qquad \delta\lambda^{(2)}_{G.L.}(\mu = M_t) = -\frac{9.605}{(4\pi)^4}$$

$$\lambda(\mu = M_t) = 0.12709 + 0.00206\left(\frac{M_h}{\rm GeV} - 125.66\right) - 0.00004\left(\frac{M_t}{\rm GeV} - 173.15\right) \pm 0.00035_{\rm th}$$





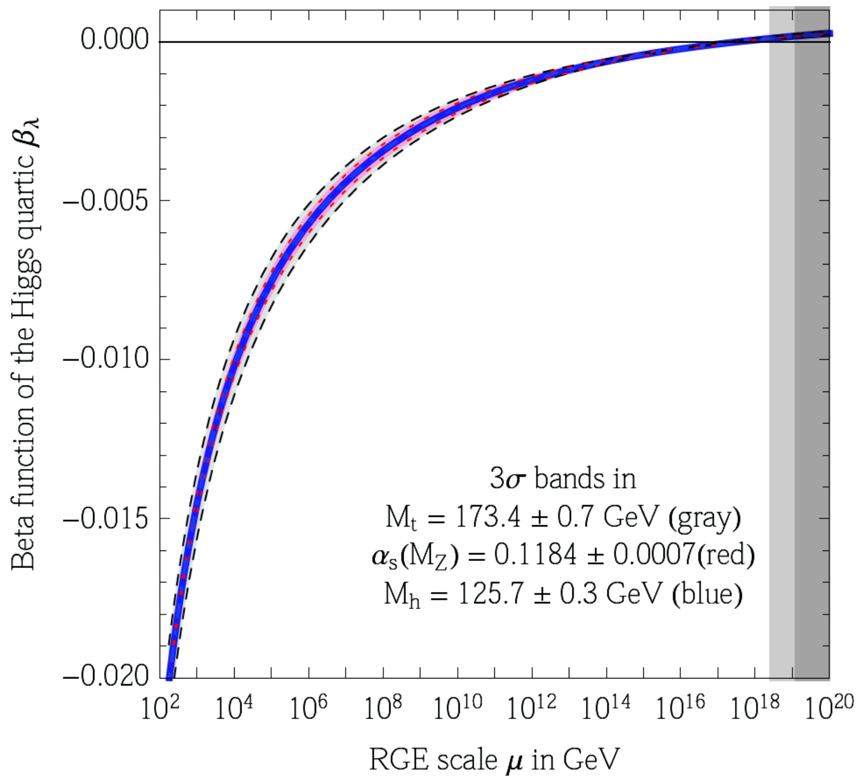
$\lambda(M_{Pl}) > 0$ or $\lambda(M_{Pl}) < 0$ depends on the assumed value of M_t ($\rightarrow Y_t(\mu_W)$)

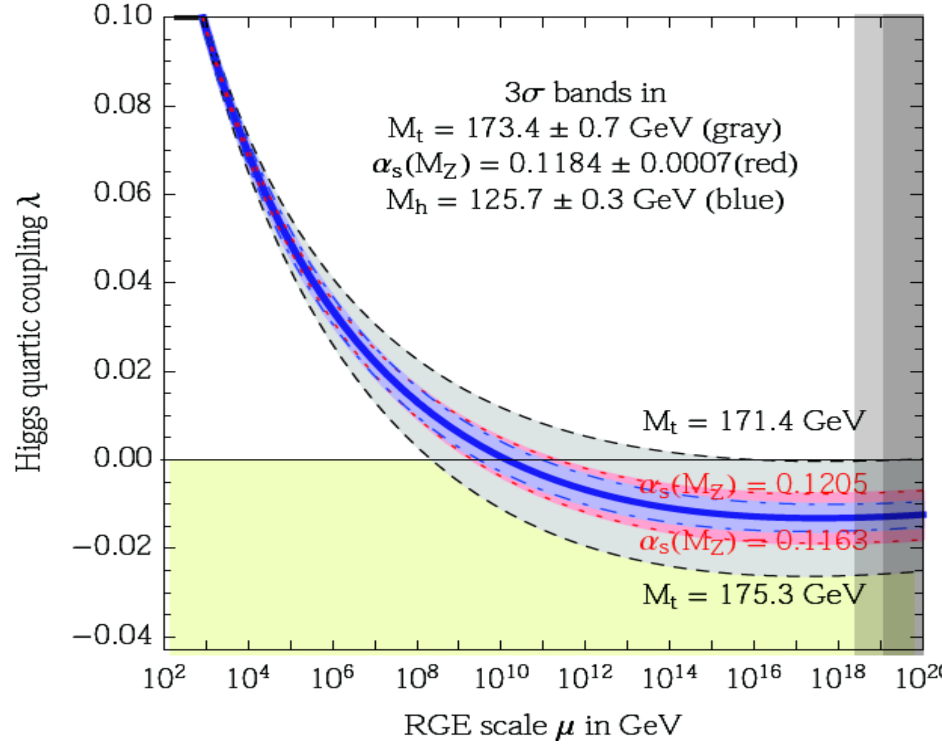
λ never becomes too negative at M_{pl}. Both λ and β_λ are very close to zero around M_{pl}

$$\lambda(M_{Pl.}) = -0.0128 + 0.0010\left(\frac{M_h - 125.66\,\text{GeV}}{0.34\,\text{GeV}}\right) - 0.0043\left(\frac{M_t - 173.35\,\text{GeV}}{0.65\,\text{GeV}}\right) + 0.0018\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right)$$

All analyses agree with this result, no one is claiming stability for
$M_t = 173.4$ GeV $\rightarrow$ $M_t^{\overline{MS}}(M_t) = 163.3\ \text{GeV}$ $\lambda < 0$ at $\Lambda \sim 10^{10}$-10^{11} GeV

Stability requires $Y_t(M_t) = 0.927$, present value (including 3 loop QCD) $Y_t(M_t) = 0.937$
difference as large as the full (QCD + EW) two-loop contribution





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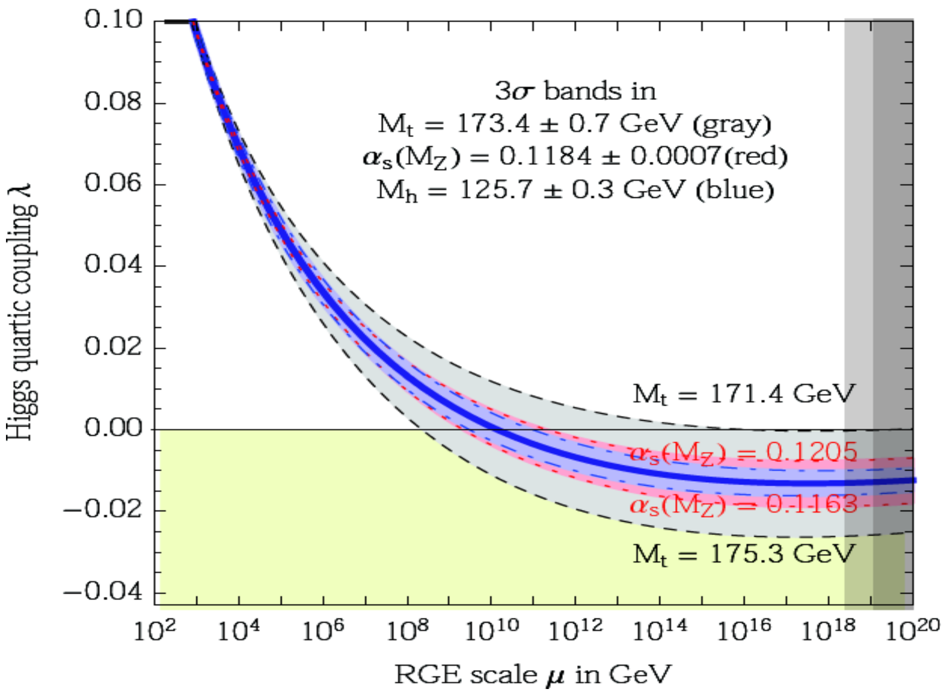
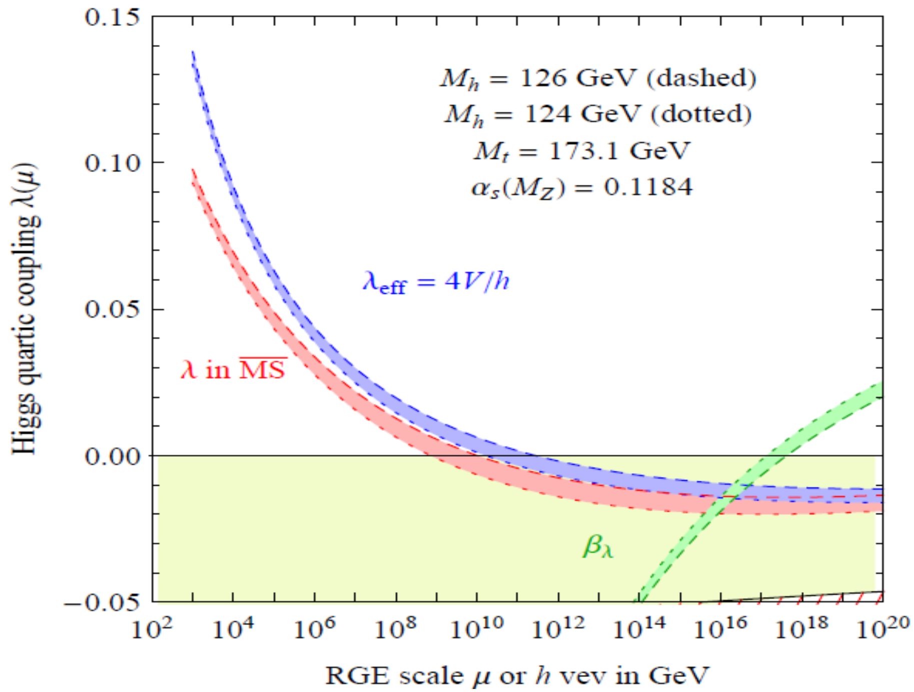




Refined analysis with V_{eff} gives the same outcome.

For the present central values of the experimental inputs stability is not achived in the SM.

To achieve stability:

$$M_h > \left[129.6 + 1.3\left(\frac{M_t - 173.35\,\mathrm{GeV}}{0.65\,\mathrm{GeV}}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 0.3_{\mathrm{pert.}} \pm 0.6_{\mathrm{non-pert.}}\right]\ \mathrm{GeV}$$

$$M_t < (171.36 \pm 0.15_{\mathrm{pert.}} \pm 0.30_{\mathrm{non-pert.}} \pm 0.25_{\alpha_s} \pm 0.17_{M_h})\ \mathrm{GeV}$$

Buttazzo et al. (13)

$$M_h > \left[129.40 \pm 0.58 + 2.26\left(\frac{M_t - 173.34\,\mathrm{GeV}}{1.12\,\mathrm{GeV}}\right)\right]\ \mathrm{GeV}$$

$$M_t < \left[171.22 \pm 0.28 + 0.12\left(\frac{M_h - 125.14\,\mathrm{GeV}}{0.24\,\mathrm{GeV}}\right)\right]\ \mathrm{GeV}$$

Andreassen, Frost, Schwartz (14)

$$M_t < (171.54 \pm 0.30^{+0.26}_{-0.41})\ \mathrm{GeV}$$

Bednyakov et al. (15)

Top pole vs. MC mass

Analysis is done in terms of the pole top mass identified with the Tevatron-LHC number.

Monte Carlo are used to reconstruct the top mass M_t^{MC} from its decays products.
Modeling of the event that contain jets, missing energy and initial state radiation is required.
M_t^{MC} is obtained via a comparison of data with MC (template or matrix element methods).

In MC top propagator is written: $\dfrac{1}{\not{p} - M_t^{MC}}$

$$M_t = M_t^{MC} + \Delta, \qquad \delta M_t^{MC} = \pm 0.76 \text{ GeV},$$

Few issues:

- How solid is $\delta M_t^{MC} = \pm 0.76$ GeV ? CR is under control?

- How far can we go with $M_t = M_t^{MC} + \Delta$? Pole mass is ambiguous by an amount $\mathcal{O}(\Lambda_{QCD})$ due to its IR sensitivity in the top self-energy (renormalon). Do we need to use of a better theoretically defined mass (short-distance) ?
  How well we control $M_t^{MC} \to M_t^{SD}$?

Definition of M_t

Ambiguity in the top pole mass

$$\mathrm{M}_t = M_t^{\overline{MS}} \times \left[1 + c_1 \frac{\alpha_s}{\pi} + c_2 \left(\frac{\alpha_s}{\pi}\right)^2 + c_3 \left(\frac{\alpha_s}{\pi}\right)^3 + \left(\frac{\alpha_s}{\pi}\right)^4 + \ldots\right]$$

$$= M_t^{\overline{MS}} \times [1 + 0.046 + 0.010 + 0.003 + 0.001 + \ldots]$$

Marquad, A. Smirnov, V. Smirnov, Steinhauser (15)

$$\delta M_t \sim \mathcal{O}(0.001 \times M_t^{\overline{MS}}) \approx \mathcal{O}(200\,\mathrm{MeV})$$

From truncation of the series

$$M_t^{\overline{MS},3l} - M_t^{\overline{MS},4l} \approx \mathcal{O}(300\,\mathrm{MeV})$$

$$\delta M_t \approx \mathcal{O}(100\,\mathrm{MeV})$$

From the estimate of the renormalon

Nason (15)

M_t^{MC} is interpreted as M_t within the intrinsic ambiguity in the definition of M_t

$\Delta \sim O(\Lambda_{QCD})$ ~250-500 MeV

Mangano (13),

To go below ~300 MeV in δM_t a better theoretically defined mass is needed

Alternative: use observables thet do not require a threshold mass:

ex. total production cross section $\sigma(t\bar{t} + X)$

$$M_t^{\overline{MS}}(M_t) = 162.3 \pm 2.3\,\mathrm{GeV} \rightarrow M_t = 171.2 \pm 2.4\,\mathrm{GeV}$$

Moch, (14)

Caution

Fermion masses are parameters of the QCD Lagrangian, not of the EW one.
The Yukawa (and gauge) couplings are the parameters of the EW Lagrangian.
The vacuum is not a parameter of the EW Lagrangian.

$\overline{MS}$ masses are gauge invariant objects in QCD, not in EW, Yukawas are.
A $\overline{MS}$ mass in the EW theory has not a unique definition (RGE is not unique).
It depends upon the definition of the vacuum:

- Minimum of the tree-level potential

  $\rightarrow M_t^{\overline{MS}}$ g.i. but large EW corrections in the relation pole-$\overline{MS}$ mass (~ M_t^4)

  But direct extraction of $M_t^{\overline{MS}}$ requires EW correction

  Jegerlehner, Kalmykov, Kniehl, (12)

- Minimum of the radiatively corrected potential

  $\rightarrow M_t^{\overline{MS}}$ not g.i. (problem? $\overline{MS}$ mass is not a physical quantity)

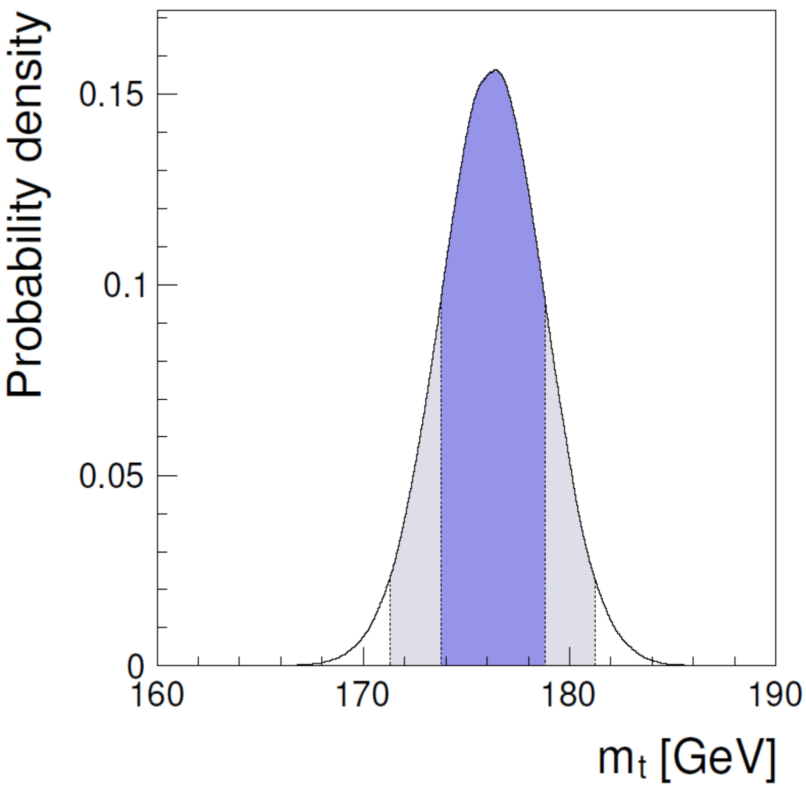
  no large EW corrections in the relation pole-$\overline{MS}$ mass

RGEs are written in terms of $\overline{MS}$ gauge, Yukawa and λ couplings not in terms of masses.

N.B. The top pole mass is the same object that enters in the EW fit

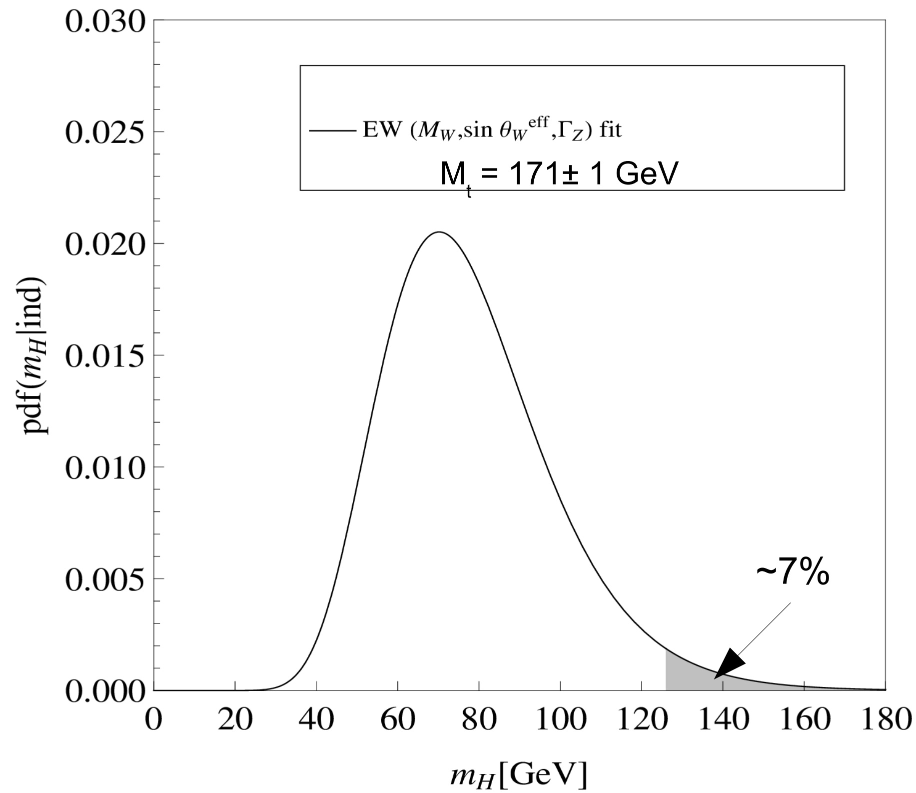
Is M_t ~ 171 GeV compatibile?

Indirect determination of M_t



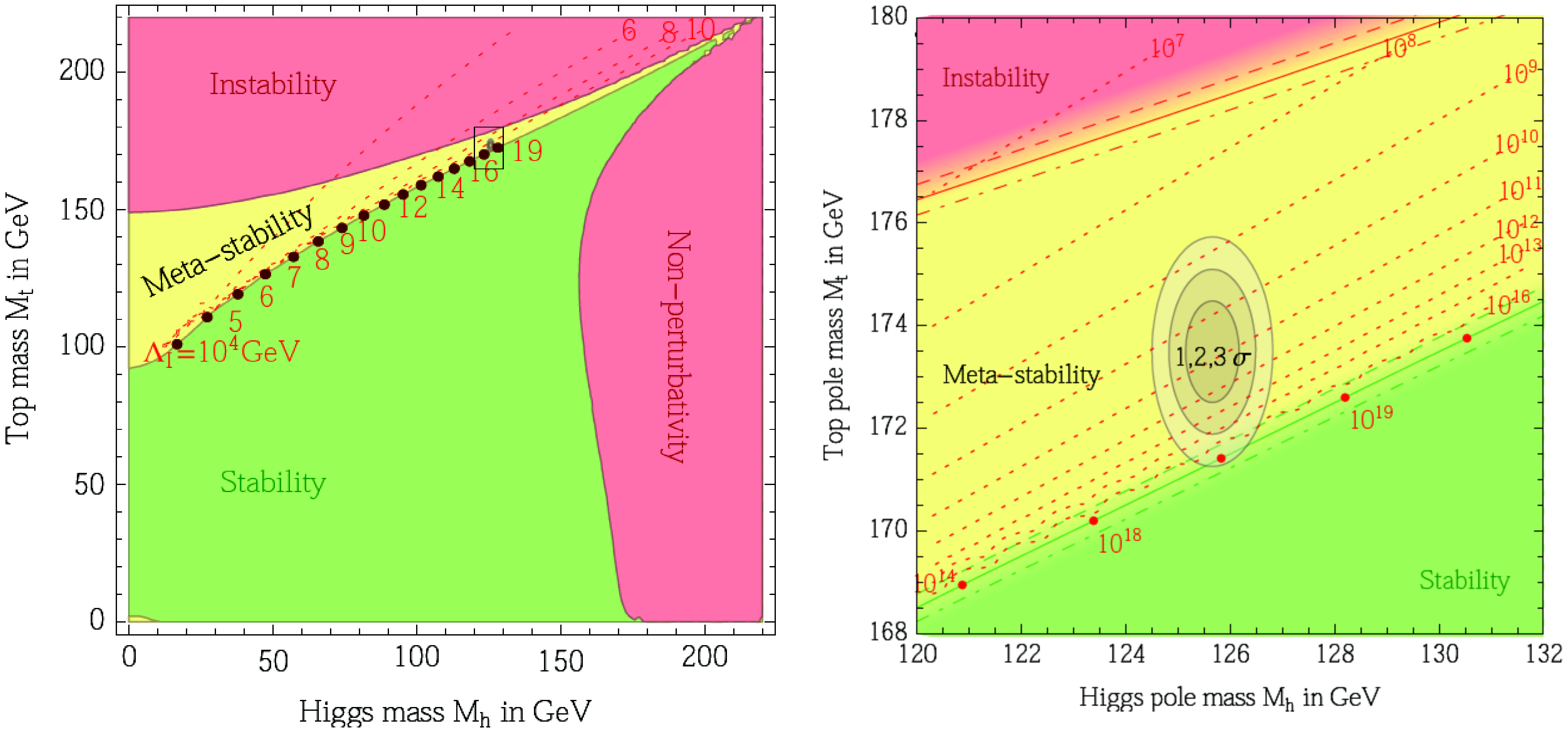
Ciuchini, Franco, Mishima, Silvestrini (13)

Indirect determination of M_h



courtesy of S. Di Vita

SM phase diagram

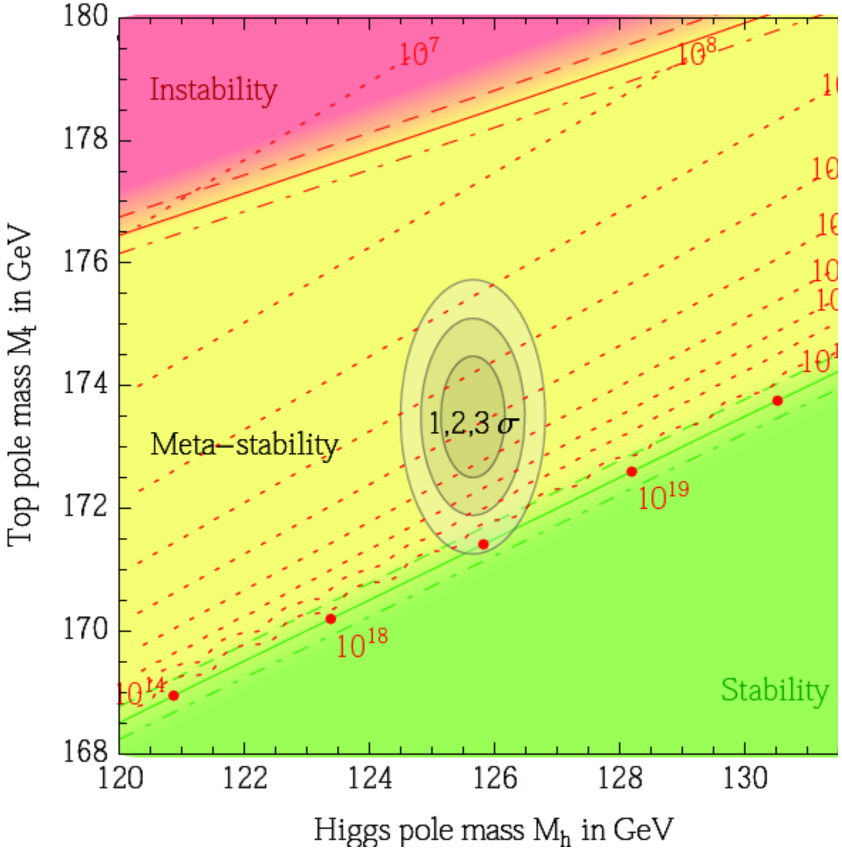


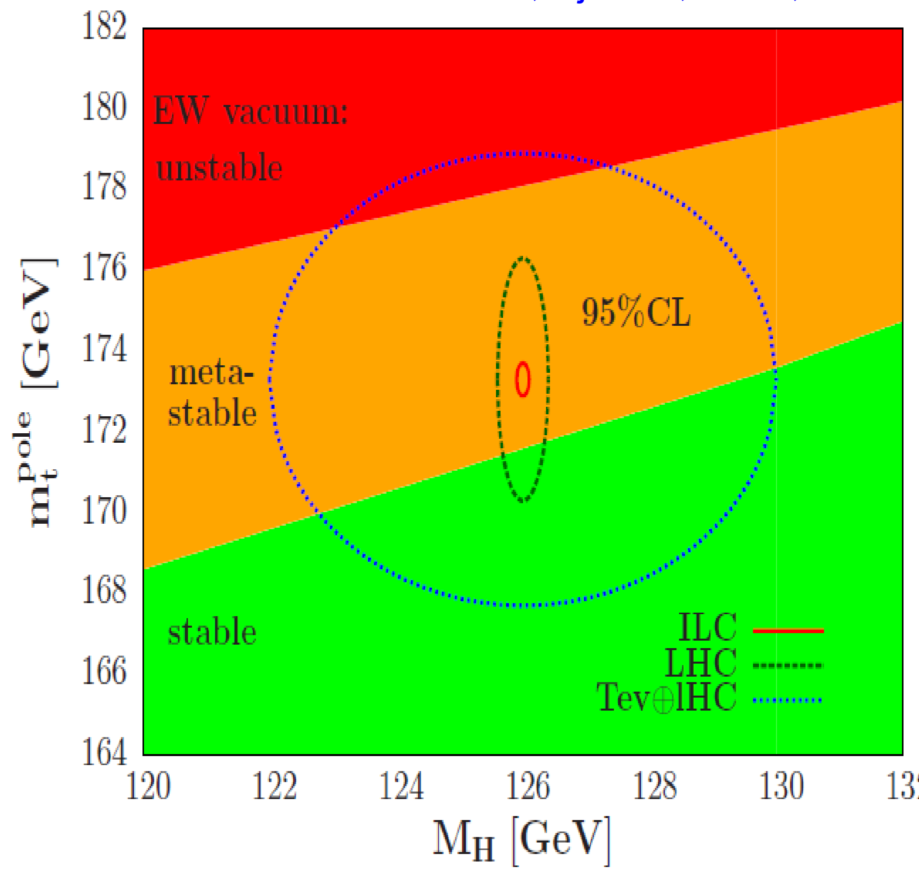
If we trust a “reasonable” error on the top mass then

We live in a metastable universe close to the border with the stability region.

SM phase diagram

Alekhin, Djouadi, Moch, 12



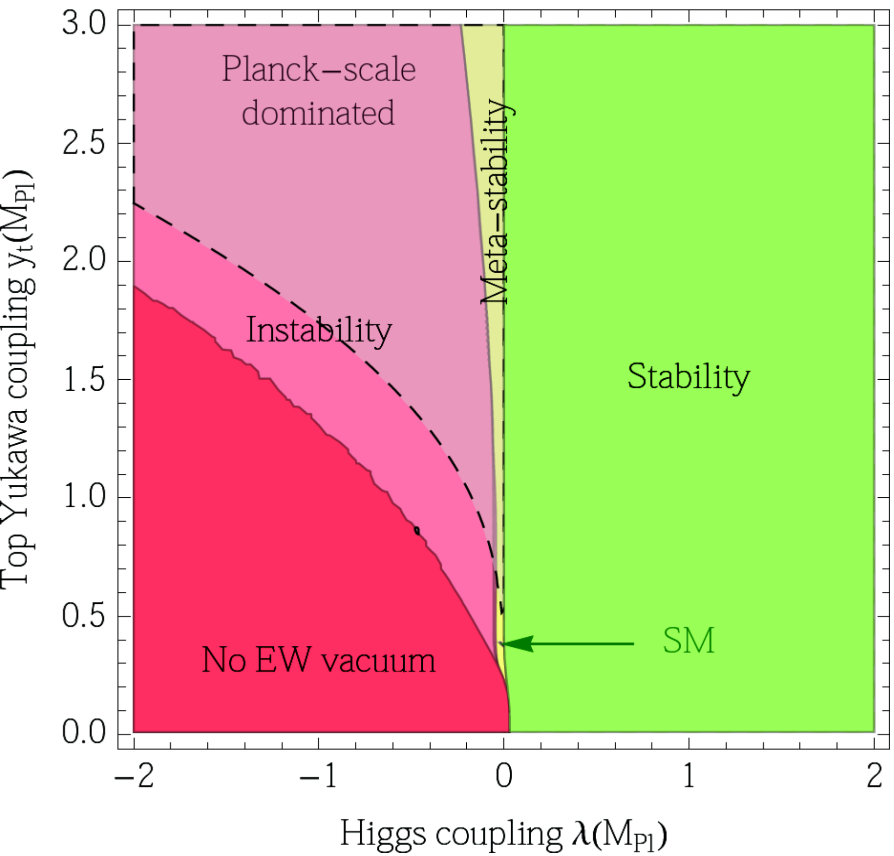


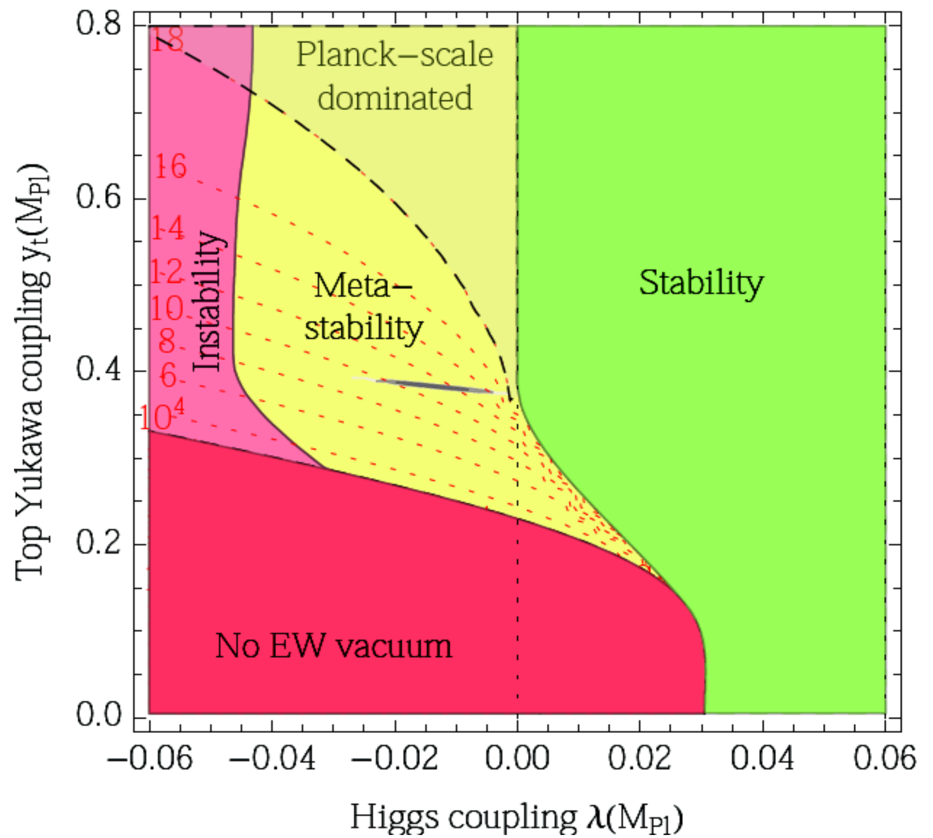
If we do not trust a “reasonable” error on the top mass and use

$$\delta M_t^{\overline{MS}} = \pm 2.7 \text{ GeV}$$

You can make a propaganda plot for ILC although it is true that only ILC will be able to say the definite word on the metastability-stability options

Near criticality





$\lambda(M_{Pl})$ and $y_t(M_{Pl})$ almost at the minimum of the funnel

An accident or deep meaning?

Obviously Planck scale Physics can change this picture but this does not change the right question to ask:

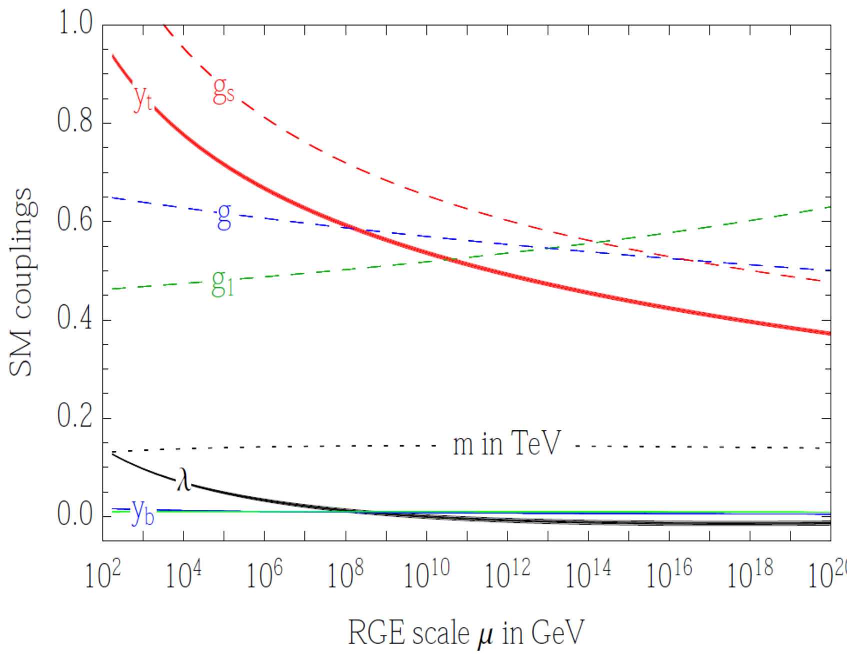
Is this picture suggesting something?

The mass term in the Higgs potential

$$V(\phi) = -\frac{m^2}{2}\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

In the SM m^2 renormalizes multiplicative
it stays basically flat till M_{Pl}

No NP, no jumps because no new
particle thresholds



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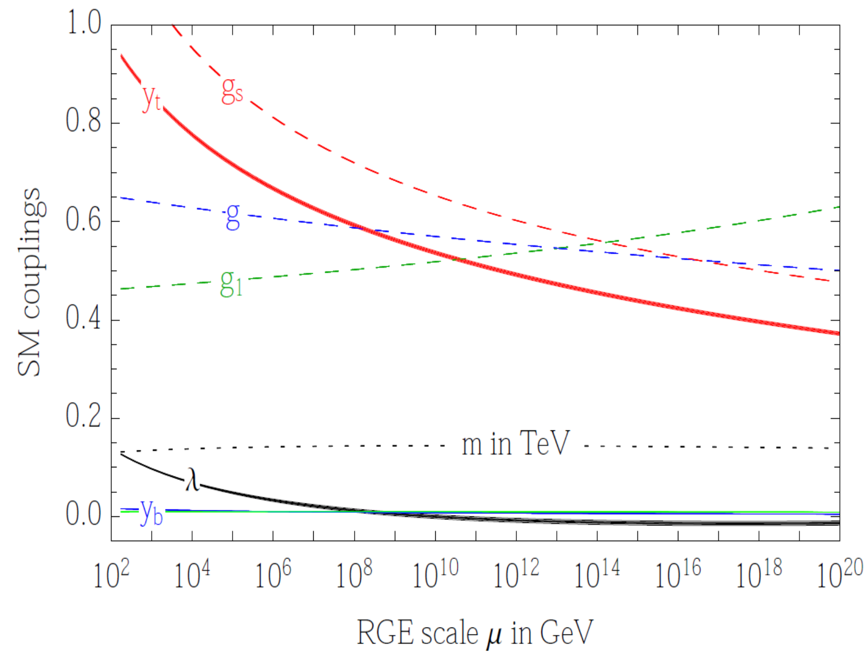

Effective theory approach:
SM is not the end of the story

$$\delta M_h^2 \sim \frac{3G_\mu}{4\sqrt{2}\pi^2}(-2M_W^2 - M_Z^2 - M_h^2 + 4M_t^2)\Lambda_{NP}^2 \sim \left(\frac{\Lambda_{NP}}{500\ \mathrm{GeV}}\right)^2 M_h^2$$

The LHC probing of Λ_{NP} is up to now negative

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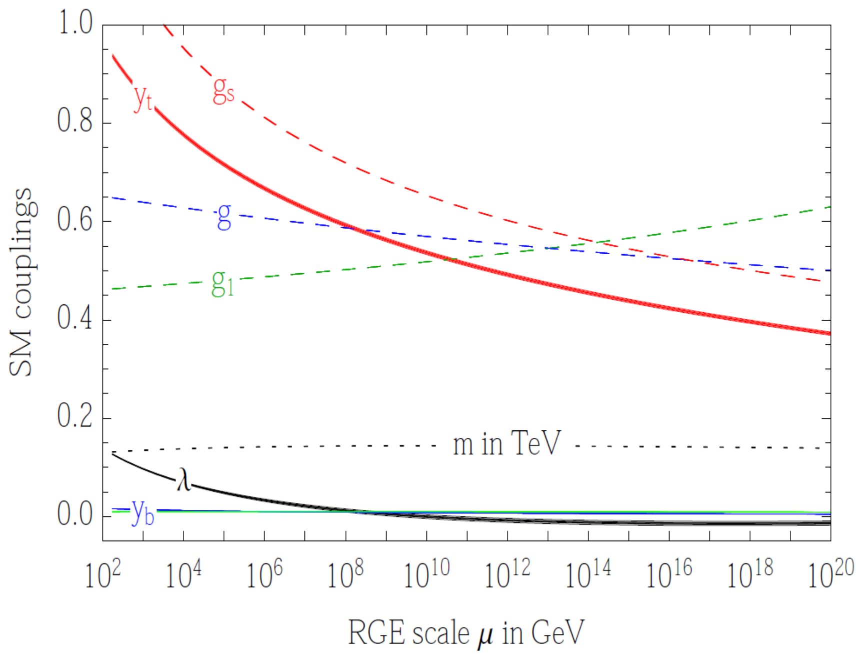

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The LHC probing of Λ_{NP} is up to now negative

Gordian knot solution: no Λ_{NP} no problem

But we have $\Lambda_{NP} = M_{Pl}$

Do we understand gravity enough well to be sure that
$$\delta m^2 \propto M_{Pl}^2$$

Why not $m^2(M_{Pl}) \approx 0$

Stabilising the electroweak vacuum

Simplest model: SM + a complex singlet scalar

$$V_0(H,S) = m^2|H|^2 + \lambda|H|^4 + \lambda_{SH}|H|^2|S|^2 + m_S^2|S|^2 + \lambda_S|S|^4$$

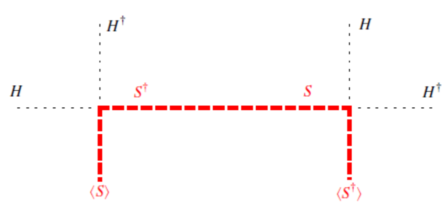
portal

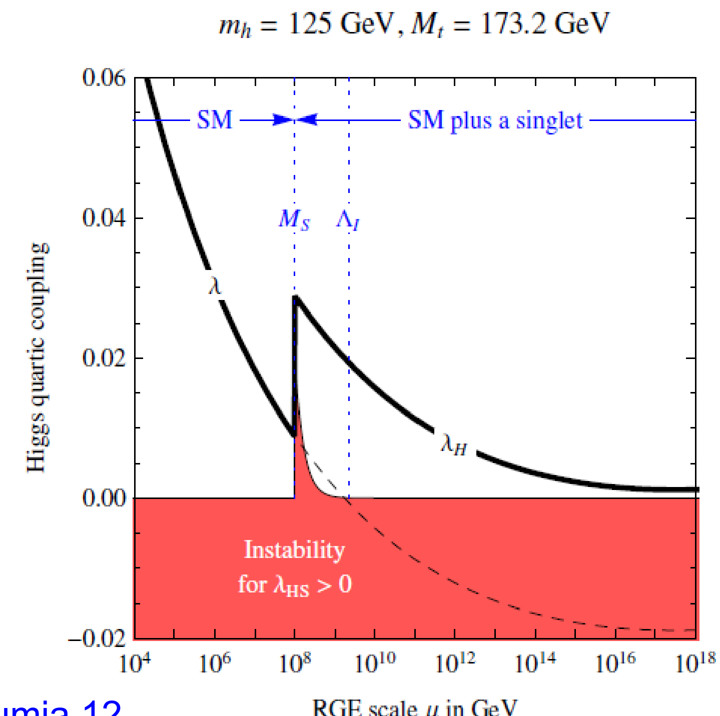
Effect of the portal is to increase the vacuum stability adding a positive contribution to β_λ

$$\beta_\lambda = \beta_\lambda^{SM} + 2\lambda_{SH}^2$$

Many models that differ by:
i) m_S obtained via a vev?
ii) mass scale of S roughly the same as the H or much larger?

If m_S obtained via a vev and $m_S >> v$
threshold effect can stabilize the vacuum





Elias-Miro', Espinosa, Giudice, Lee, Strumia 12

Conclusions

- SM is quite OK
- M_h−125 GeV is a very intriguing value.
- The SM potential is at the “border” of the stability region.
  The exact value of the top mass plays the central role between the full stability or metastability (preferred) options.
- All the analyses based on $\lambda > 0$ up to M_{pl} are assuming $M_t \sim 171$ GeV, a value not preferred by the EW fit
- Model-independent conclusion about the scale of NP cannot be derived.
  λ is small at high energy: NP (if exists) should have a *weakly interacting* Higgs particle
- λ and β_λ are very close to zero around the Planck mass:
  deep meaning or coincidence?
- Minimal extensions of the SM can stabilize the potential

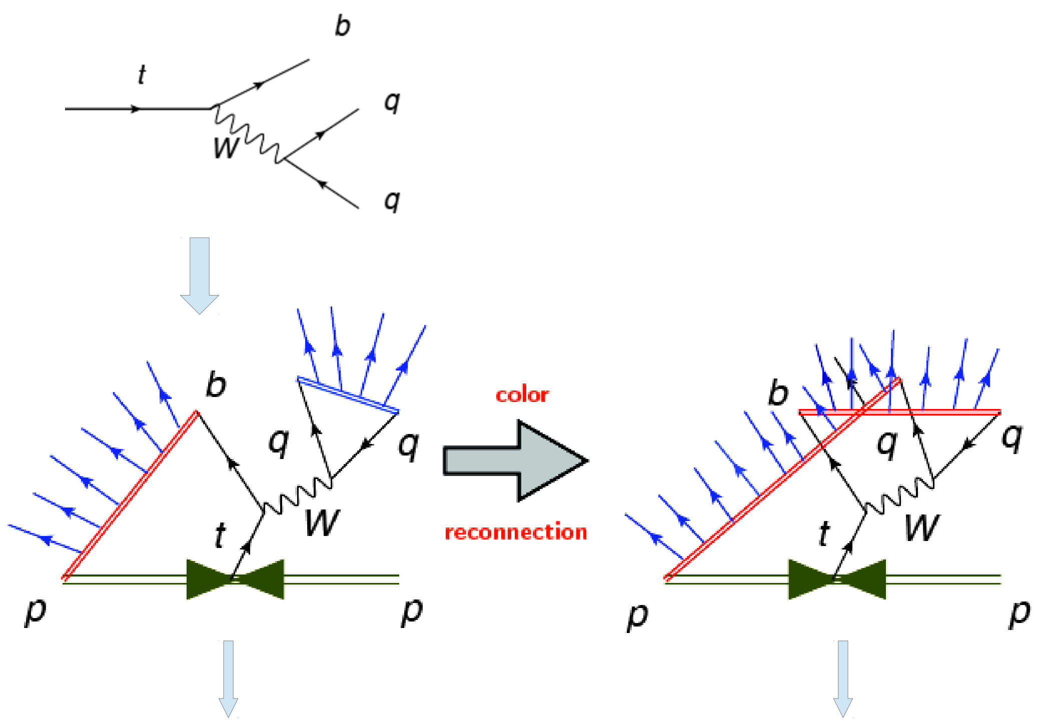
Backup slides

Parametric uncertainties: $\delta M_t^{MC} = \pm 0.76$ GeV,

I will discuss only the color reconnection issue: in δM_t^{MC} error due to CR is 310 MeV (40 %)

pp event description:
Hard subprocess → Parton Shower (W decay product are CC)
→ colorless combination of partons (strings) → hadrons

CR affects the reconstruction of the top system



$$M_t^2 = (P_b + P_{j1} + P_{j2})^2 \qquad M_t^2 \neq (P_b + P_{j1} + P_{j2})^2$$

Estimate of the CR uncertainty: $\Delta M_t = M_t(\text{CR}) - M_t(\text{no CR})$

Obviously it depends on how CR is modeled in the generator (Pythia version) and on the validation of the modeling.

Summary

The situation so far...

- until recently very few measurements to constrain CR in top events
- $m_{top}(\text{CR})$ - $m_{top}(\text{no CR})$ probably underestimates the uncertainty
  (at least when using the default Pythia8 model)

Our work...

- new CR models developed and tuned to data
- a realistic estimate for the top mass uncertainty is of the order of 500 MeV
- observables to constrain/exclude CR models with existing LHC data

S. Argyropoulos

(Frascati topical workshop "Top mass: challenges in definition and determination" 6-8 May 2015)

Short-distance mass: any mass not affected by the renormalon ambiguity.
To define it one has to remove the IR sensitivity from the self-energy. This imply the introduction of a IR scale R where the removal is performed, with M_t^{SD} (R=0)= M_t .
(Ex. $\overline{\text{MS}}$-mass, MSR-mass, Potential subt. mass)

$M_t^{MS}(M_t)$ is a SD mass but not a threshold mass $\longrightarrow$ $$\frac{1}{\not{p} - M_t^{\overline{MS}} - \Sigma^{\text{fin}}}$$
very different from M_t^{MC}

One can construct a SD-threshold mass: ex. M_t^{MSR} (R)

$$M_t^{MC} = M_t^{MSR}(3^{+6}_{-2}\,\text{GeV}) = M_t^{MSR}(3\,\text{GeV})^{+0.32}_{-0.62}$$

Hoang, Stewart (08)

$$M_t^{MC} \xrightarrow[\sim 1\text{ GeV}]{} M_t^{SD}(\Gamma_t) \xrightarrow[\sim 0.5\text{ GeV}]{} M_t$$

Moch, (14)

$m_S \sim v$

S mixes with H: rate H→ diboson smaller than in the SM

- If λ_{SH} <0 the vev of S can generate the negative mass term needed for EWSB via the portal.

- Scale invariant model (m=0, mS=0) can be constructed.

Ex:

$$V_0(H,S) = \lambda|H|^4 + \lambda_{SH}|H|^2|S|^2 + \lambda_S|S|^4 + \lambda'_S(S^4 + (S^\dagger)^4) + \lambda''_S|S|^2(S^2 + (S^\dagger)^2) + \lambda'_{SH}|H|^2(S^2 + (S^\dagger)^2)$$

Ishiwata, (12); Frazinnia, He, Ren (13); Gabrielli et al (13)

The vev of S can be generate radiatively a la Coleman-Weinberg, which then causes EWSB. We obtain a relatively light CP-even boson, η (pseudo Goldstone boson of scale symmetry) that mixes with the 125 GeV Higgs and a heavier CP-odd boson, χ, that can be interpreted as a dark matter candidate. Via the vev of S a Majorana mass term for the neutrino can be constructed.

But

- Scalar couplings have the tendency to grow towards a Landau Pole
- η is light (300-500 GeV) in the LHC run 1 range
- Mixing of H with η is experimentally constrained (especially by ATLAS)