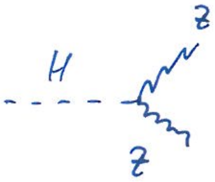
3-12-14

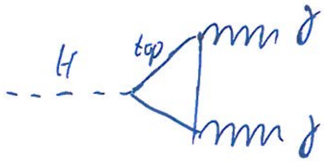
Recap.: •) $\phi \sim 2_{L,1}$ with mass $\lesssim$ few 100 GeV

seems to make sense; plus: needed for consistency

•) measured / detected @LHC (July 2012)

most important channels: 



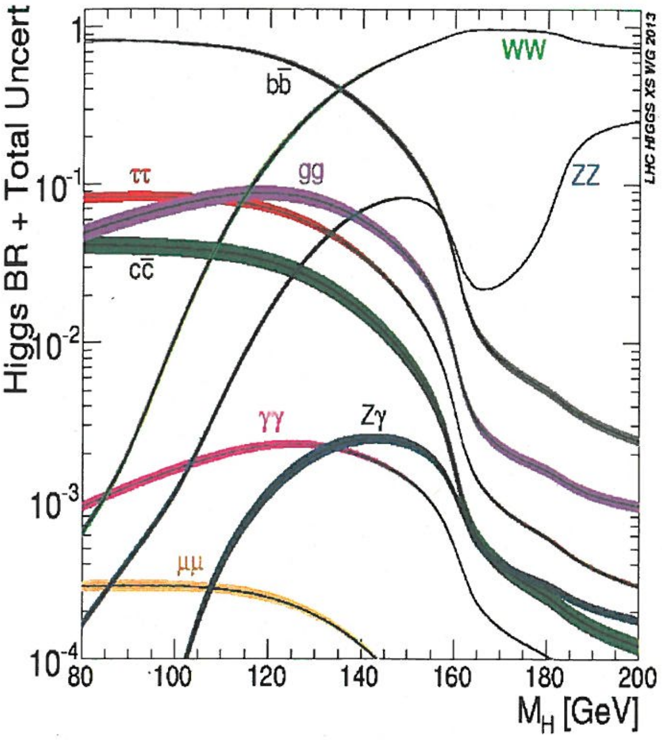


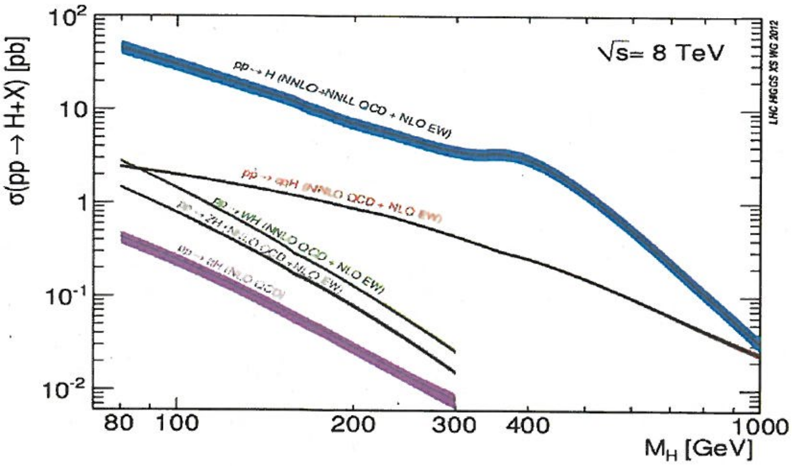
$$m_h \simeq 125.36 \pm \underset{\text{stat}}{0.37} \pm \underset{\text{sys}}{0.18} \text{ GeV}$$

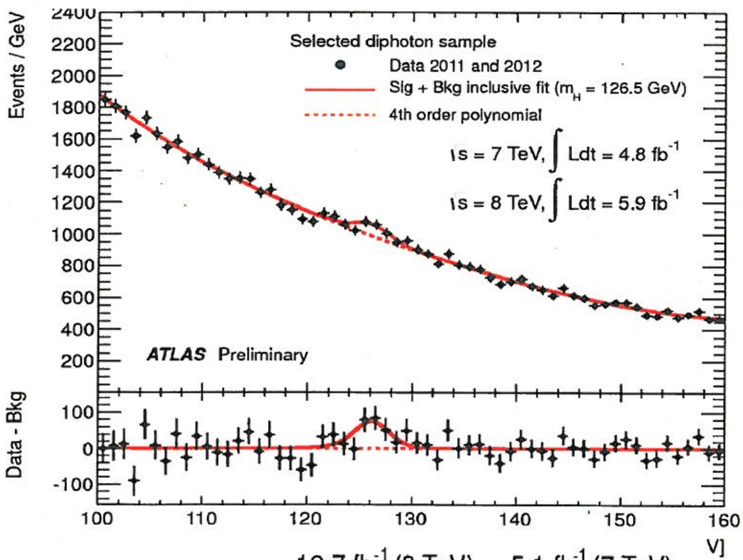
$$\Gamma_{pred} = 4.21 \times 10^{-3} \text{ GeV} \Rightarrow \tau = 1.56 \times 10^{-22} \text{ s}$$

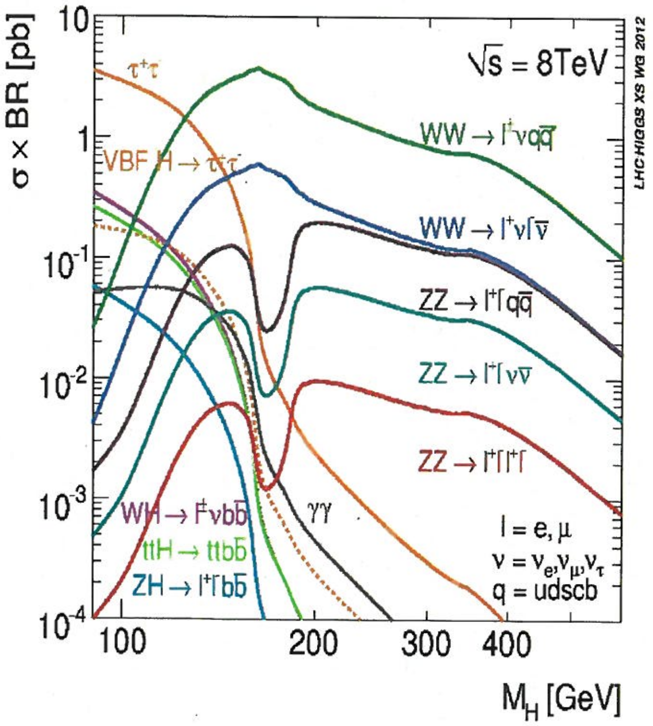
(some) experimental aspects → sheet with BR, σ, $\sigma \times BR$, etc.

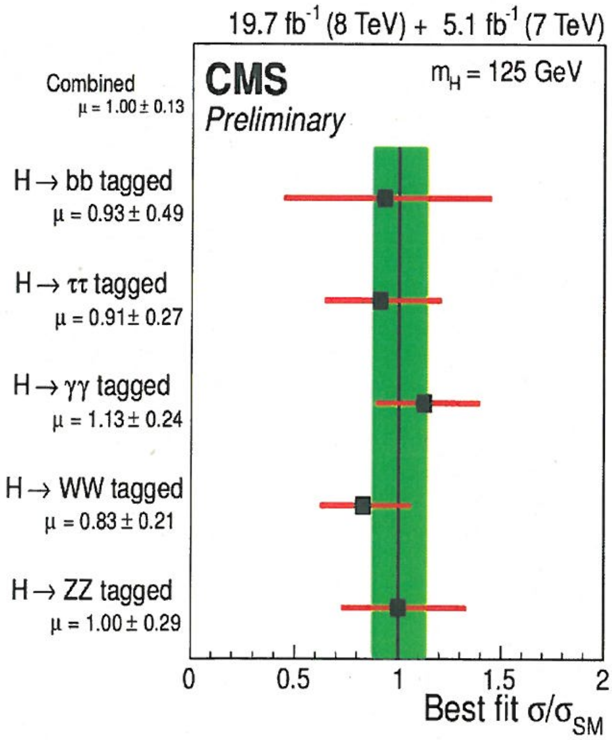
today: extrapolation of Higgs to higher E

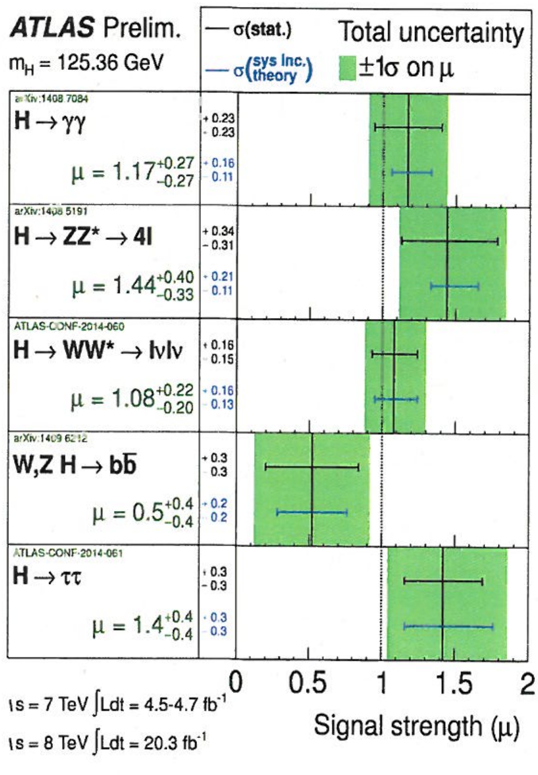

Higgs BR + Total Uncert
LHC HIGGS XS WG 2013
WW
bb̄
ττ
gg
ZZ
cc̄
γγ
Zγ
μμ
M_H [GeV]


σ(pp → H+X) [pb]
√s= 8 TeV
LHC HIGGS XS WG 2012
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → ttH (NLO QCD)
M_H [GeV]

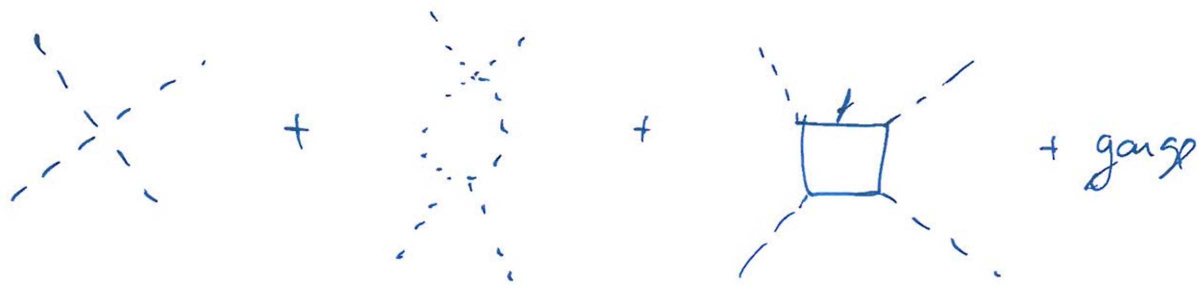

Events / GeV
Selected diphoton sample
Data 2011 and 2012
Sig + Bkg inclusive fit (m_H = 126.5 GeV)
4th order polynomial
√s = 7 TeV, ∫ Ldt = 4.8 fb⁻¹
√s = 8 TeV, ∫ Ldt = 5.9 fb⁻¹
ATLAS Preliminary
Data - Bkg


σ × BR [pb]
√s = 8TeV
LHC HIGGS XS WG 2012
τ⁺τ
VBF H → τ⁺τ⁻
WW → l⁺νqq̄
WW → l⁺νl⁻ν̄
ZZ → l⁺l⁻qq̄
ZZ → l⁺l⁻νν̄
ZZ → l⁺l⁻l⁺l⁻
WH → l±νbb̄
ttH → ttbb̄
ZH → l⁺l⁻bb̄
γγ
l = e, μ
ν = ν_e,ν_μ,ν_τ
q = udscb
M_H [GeV]


19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)
CMS
Preliminary
m_H = 125 GeV
Combined
μ = 1.00 ± 0.13
H → bb tagged
μ = 0.93 ± 0.49
H → ττ tagged
μ = 0.91 ± 0.27
H → γγ tagged
μ = 1.13 ± 0.24
H → WW tagged
μ = 0.83 ± 0.21
H → ZZ tagged
μ = 1.00 ± 0.29
Best fit σ/σ_SM


ATLAS Prelim.
m_H = 125.36 GeV
σ(stat.)
σ(sys inc. theory)
Total uncertainty
±1σ on μ
H → γγ
μ = 1.17 +0.27 −0.27
H → ZZ* → 4l
μ = 1.44 +0.40 −0.33
H → WW* → lνlν
μ = 1.08 +0.22 −0.20
W,Z H → bb̄
μ = 0.5 +0.4 −0.4
H → ττ
μ = 1.4 +0.4 −0.4
√s = 7 TeV ∫Ldt = 4.5-4.7 fb⁻¹
√s = 8 TeV ∫Ldt = 20.3 fb⁻¹
Signal strength (μ)

•) RG-Analysis of Higgs



$\Rightarrow \lambda = \lambda(Q^2) = f(\lambda, g, g', m_t/v) \quad \Rightarrow$ top-quark gives largest fermion-contribution

$$16\pi^2 \frac{d\lambda}{d\log Q^2} = 12\lambda^2 + 6\lambda Y_t^2 - 3Y_t^4 - \frac{3}{2}\lambda(3g'^2 + g^2) + \frac{3}{16}(2g'^4 + (g'+g)^2)$$

•) large λ

$$\frac{d\lambda}{d\log Q^2} = \frac{3}{4\pi^2}\lambda \quad : \lambda \nearrow \text{ for } Q^2 \nearrow$$

$$\Rightarrow \lambda(Q^2) = \frac{\lambda(\mu^2)}{1 - \frac{3}{4\pi^2}\lambda(\mu^2)\log Q^2/\mu^2}$$

choose $\mu^2 = v^2$ as start

denominator $= 0$ for $Q = v \exp\left\{\frac{2\pi^2}{3\lambda(v^2)}\right\}$

$$= v \exp\left\{\frac{4\pi^2 v^2}{3 m_h^2}\right\}$$

Landau-pole only avoidable for $\lambda = 0 \Rightarrow$ „triviality bound"

$\Leftrightarrow \lambda(\text{low energy}) \overset{!}{<} \lambda_{max} \Rightarrow m_h < m_h^{max}$

•) small λ

$$\frac{d\lambda}{d\log Q^2} = -\frac{3}{16\pi^2} y_t^4$$: $\lambda \downarrow$ for $Q^2 \nearrow$

(top Yukawa)

$$\Rightarrow \lambda(Q^2) = \lambda(v^2) - \frac{3 y_t^4}{16\pi^2} \log Q^2/v^2$$ (starting value $\lambda(v^2) = m_h^2/2v^2$)

when is $\lambda(Q^2) = 0$?

$$\lambda(v^2) = \frac{3}{16\pi^2} y_t^4 \log Q^2/v^2$$; $y_t = \frac{\sqrt{2}\, m_t}{v}$

$$\Rightarrow m_h = \frac{3 m_t^4}{2\pi^2 v^2} \log Q^2/v^2$$

$m_h = 126$ GeV ; $m_t = 173$ GeV

$$\Rightarrow Q = \exp\left\{ \frac{m_h^2 \pi^2 v^2}{3 m_t^4} \right\} v \simeq 10^5 \text{ GeV}$$

$\lambda(\text{low energy}) > \lambda_{min} \Rightarrow m_h > m_h^{min}$

„vacuum stability bound"

[λ must be > 0 to have a minimum in V;

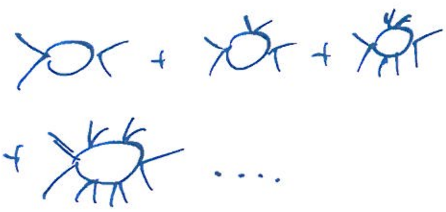
$\leftrightarrow$ V bounded from below!]

otherwise theory not defined!

the larger ϕ, the more negative the Hamiltonian

•) the story doesn't end here ... further corrections:

e.g. $V_{eff} \propto -y_t^4 \phi^4 \ln \frac{g^2\phi^2}{\mu^2}$ from summing up:

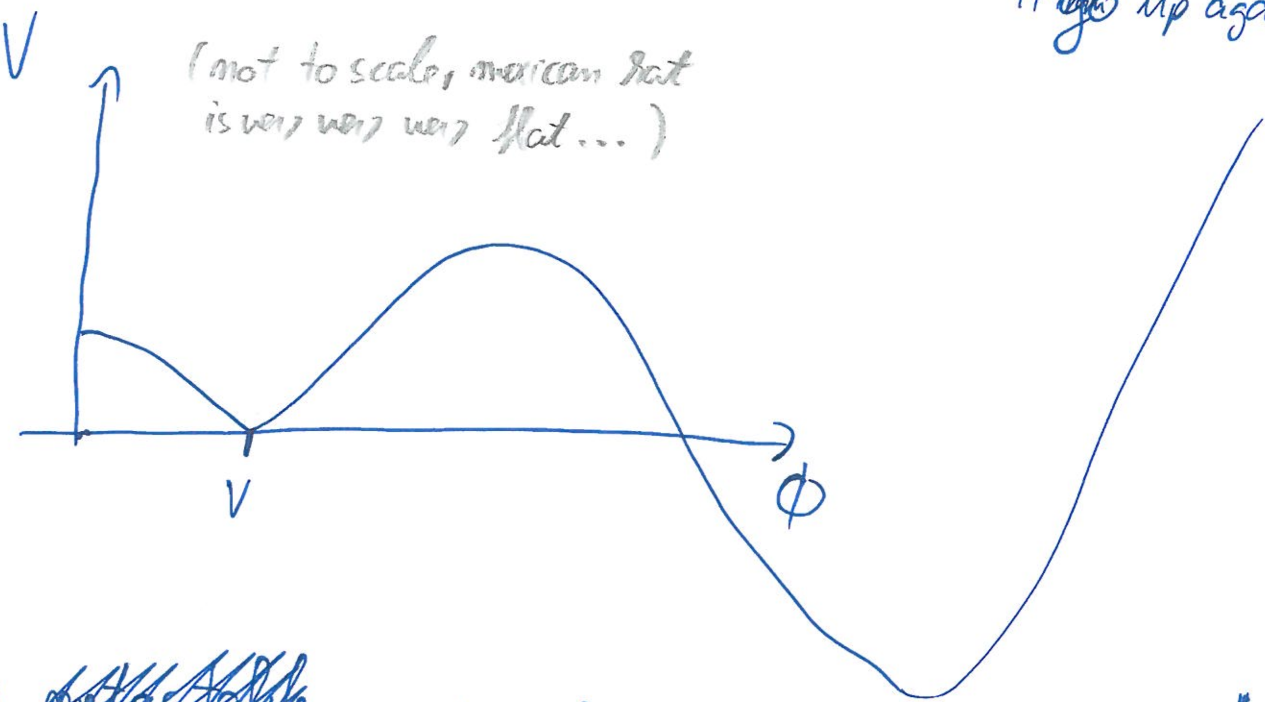


[if no quadratic term in V: conformal symmetry!
→ minimum generated by V_{eff}!
"dimensional transmutation" (↔ f_π in QCD)
gives too small Higgs mass in SM...]
Coleman-Weinberg

at large ϕ-values: V dominated by $\lambda_{eff}\,\phi^4$

becomes > 0 again:
$y_t \Downarrow$, gauge couplings make it go up again

(not to scale)



⇒ ~~metastable~~ ⇒ tunneling in true minimum!

if $\tau > T_{universe}$: metastable

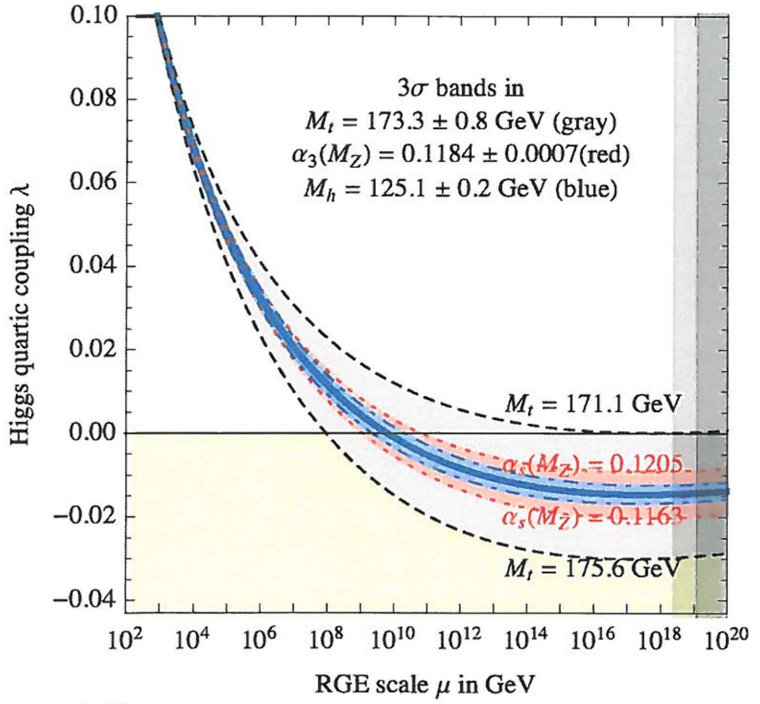
$\tau < T_{universe}$: instable (bad!)

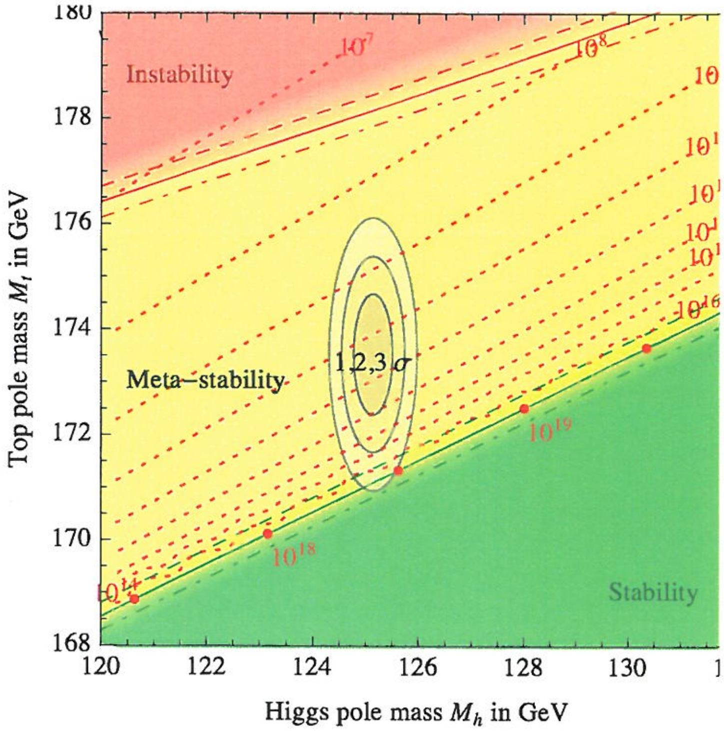
stable for $m_h > 129.6\ \text{GeV} + 2(m_t - 173.35\ \text{GeV}) - \frac{\alpha_s(m_Z) - 0.1184}{0.0014} \pm 0.3$G

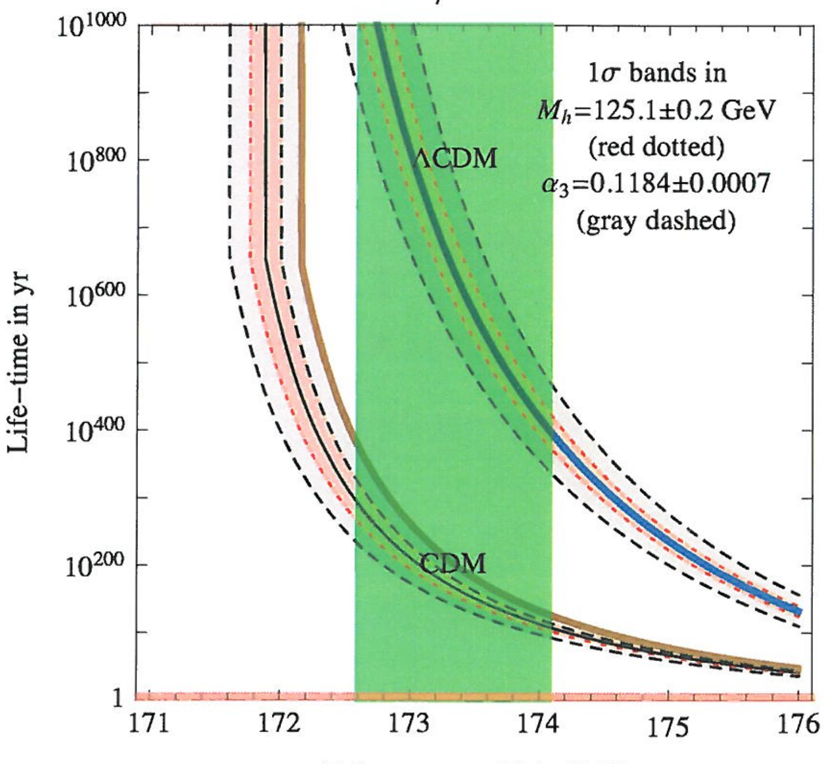
„Vacuum decay":

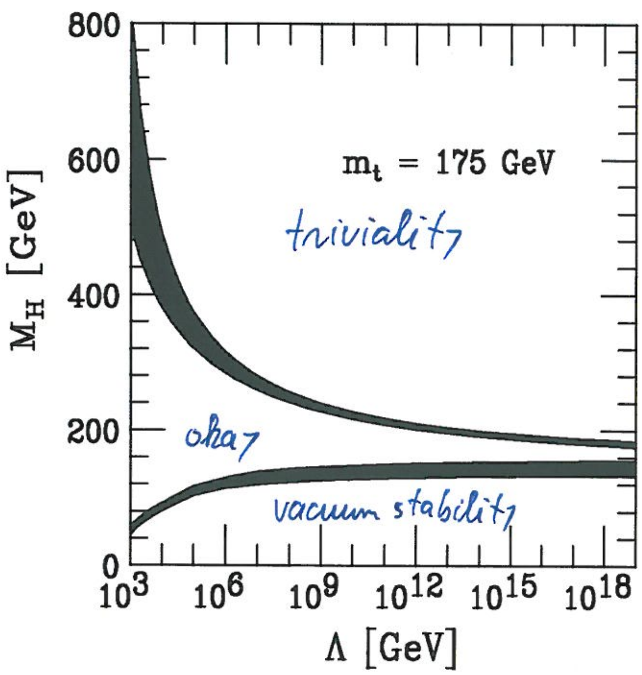
-) quantum tunneling (depends on cosmolog. past and future ...)
-) „classical transition" via bubble formation; radius R;
  surface costs energy: R^2
  volume produces energy $-R^3$

-) experimental question (value of m_t, α_s)
-) new physics coupling to SM modifies all calculations!
-) stretching all parameters to corners of parameter space: $\lambda(M_{Pl}) = 0$ is possible
  (boundary conditions from e.g. Quantum Gravity?)









See: xxx.lanl.gov/abs/1307.3536

•) Hierarchy problem

Embedding of SM in larger theory, cutoff Λ

$$m_{fermion} = m^0_{fermion}\left(1 + c \log \Lambda/\mu\right)$$

- •) multiplicative
- •) $m_f \to 0$ for $m_f^0 = 0$
- •) logarithmic

$$\boxed{m_h^2 = (m_h^0)^2 + \frac{3}{8\pi^2 v^2}\left(4m_t^2 - 2m_W^2 - 4m_Z^2 - m_h^2\right)\Lambda^2}$$

- •) quadratic !
- •) want $\Delta m_h \lesssim m_h^0$ „ natural theory"

$\Rightarrow$ fine-tuning : if $\Lambda = M_{Pl} = \sqrt{\frac{1}{G_N}}$

$$\underbrace{m_h^2}_{(10^2\,\mathrm{GeV})^2} = (m_h^0)^2 + 10^{37}\,\mathrm{GeV}^2$$

$\Rightarrow$ $\boxed{10^{-33} \text{ fine-tuning}}$

☹

Solutions:

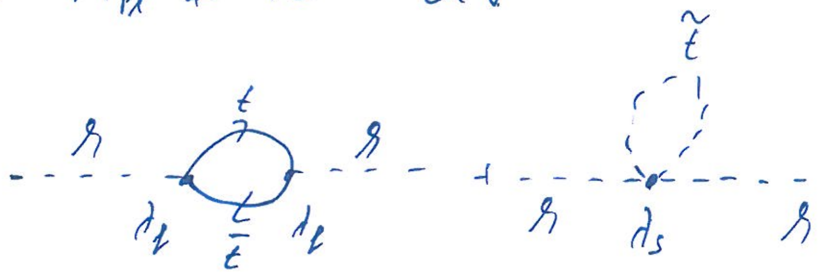
- $4 m_t^2 - 2 m_W^2 - 4 m_Z^2 - m_h^2 = 0$ (Veltman condition)

  $\rightarrow$ at electroweak scale : $m_h = 314$ GeV ↯

  ($\rightarrow$ works at Planck scale ...)

- Extra dimensions : $M_{Pl} \neq 10^{19}$ GeV

- Supersymmetry



scalar partner of top : „stop"

$$\Delta m_h^2 \propto (-\lambda_t^2 + \lambda_s)\,\Lambda^2$$

$= 0$ for exact SUSY $m_t = m_{\tilde{t}}$

must be broken : $\Delta m_h^2 \simeq \frac{1}{16\pi^2}\, m_{SUSY}^2 \log \Lambda / m_{SUSY}$

(must be zero for $m_{SUSY} = 0$
and should be $\propto \Lambda^2$ or $\ln \Lambda / m_{SUSY}$)

to have $\Delta m_h^2 \lesssim 10^2$ GeV :

new particles at 10^3 GeV ....

•) avoid scalar particles!

Recall: pions (scalar...) formed by condensates of u, d quarks; <u>dynamical symmetry breaking</u> ($\alpha_s \nearrow$, confinement)

→ $\pi^{\pm}, \pi^0$ have quantum numbers of Goldstone-bosons that are eaten by gauge bosons.

→ $m_{W,Z} \simeq g f_\pi$ with $f_\pi \simeq 100$ MeV

too small (but included in calculations of EW precision observables)

→ introduce new interaction and fermions with $f_{\pi'} = v$

„<u>Technicolor</u>" $SU(N_{TC})$

⇒ Higgs mechanism, but no Higgs particle

⇒ Fermion masses?

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for all this Higgs-stuff and more, see the write-up of Tilman Plehn's LHC lectures from his homepage