Lessons from LHC8

G.F. Giudice

INTERNATIONAL WORKSHOP ON
DISCOVERY PHYSICS AT THE LHC
DECEMBER 3 – 7, 2012
KRUGER, SOUTH AFRICA

Lessons from LHC8

- LHC is working marvellously
- Excellent performance of the experiments
- A SM-like Higgs boson has been discovered
- No sign of new physics

Higgs discovery:

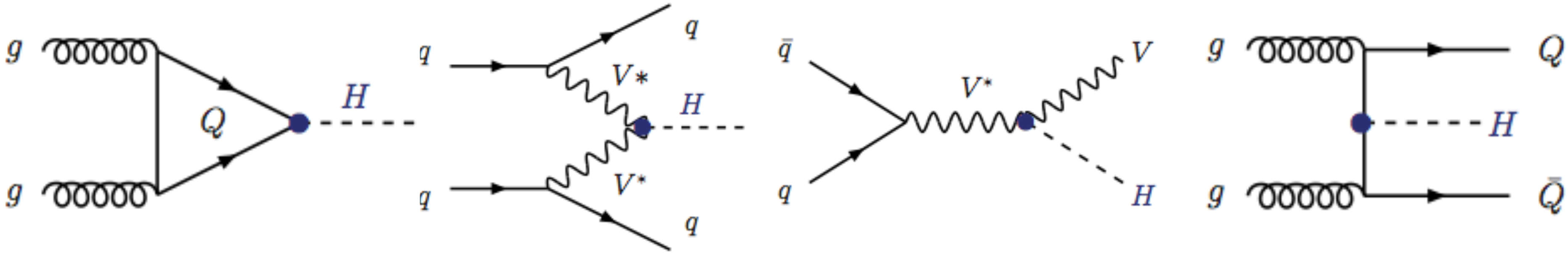
Is the particle related to EW breaking?

Decay into $\gamma\ \gamma$ ➔

- not a fermion
- not spin one (spin 2?)

$m_H = 126$ GeV ➔

- difficult for discovery
- a dream for exp'ts

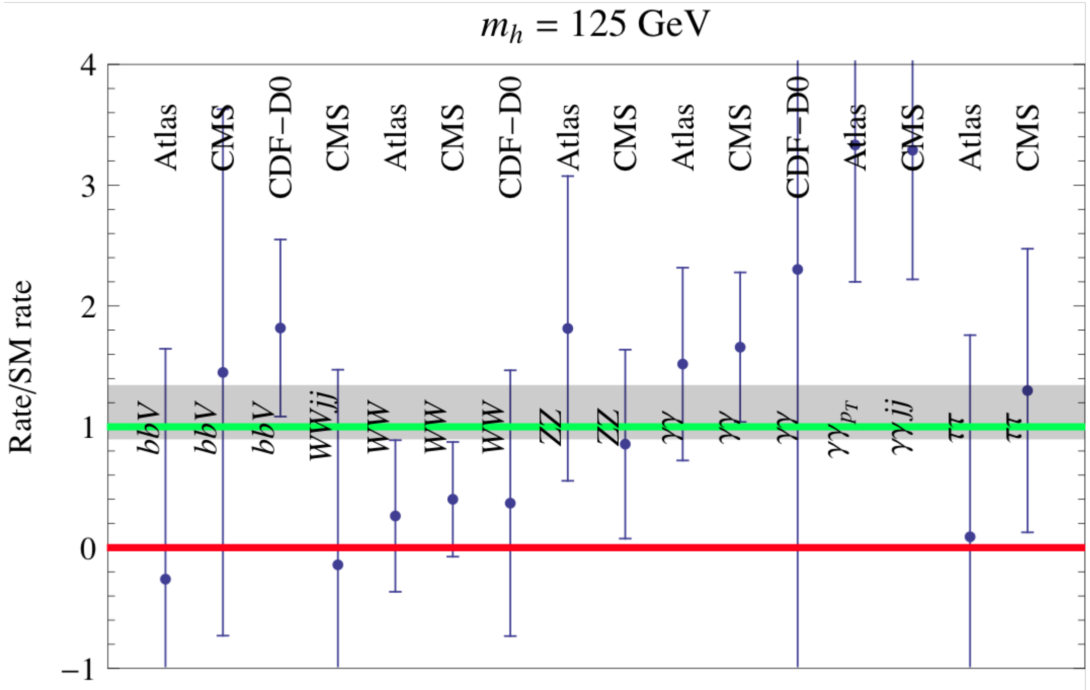


√s	gg	VBF	WH	ZH	ttH
7 TeV	15 pb	1.2 pb	0.6 pb	0.3 pb	0.08 pb
8 TeV	19 pb	1.6 pb	0.7 pb	0.4 pb	0.1 pb
14 TeV	50 pb	4.2 pb	1.5 pb	0.9 pb	0.6 pb

m_H [GeV]	bb %	WW %	gg %	ττ %	ZZ %	cc %	γγ %	Zγ %	μμ %	Γ [MeV]
125	58	21	8.6	6.3	2.6	2.9	0.23	0.15	0.022	4.1
126	56	23	8.5	6.1	2.9	2.8	0.23	0.16	0.021	4.1

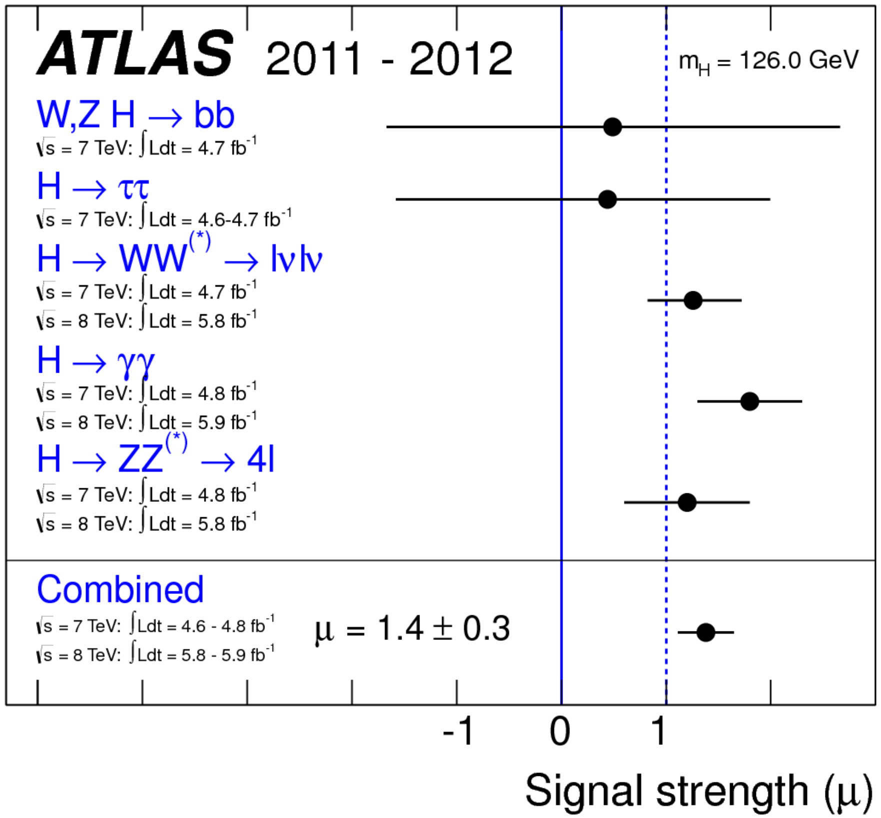
- All decay modes can be measured except cc.
- Test of H couplings: b, W, Z, g, γ, t, τ, μ, γZ, invisible.
- Rich program in H studies can nail H properties.

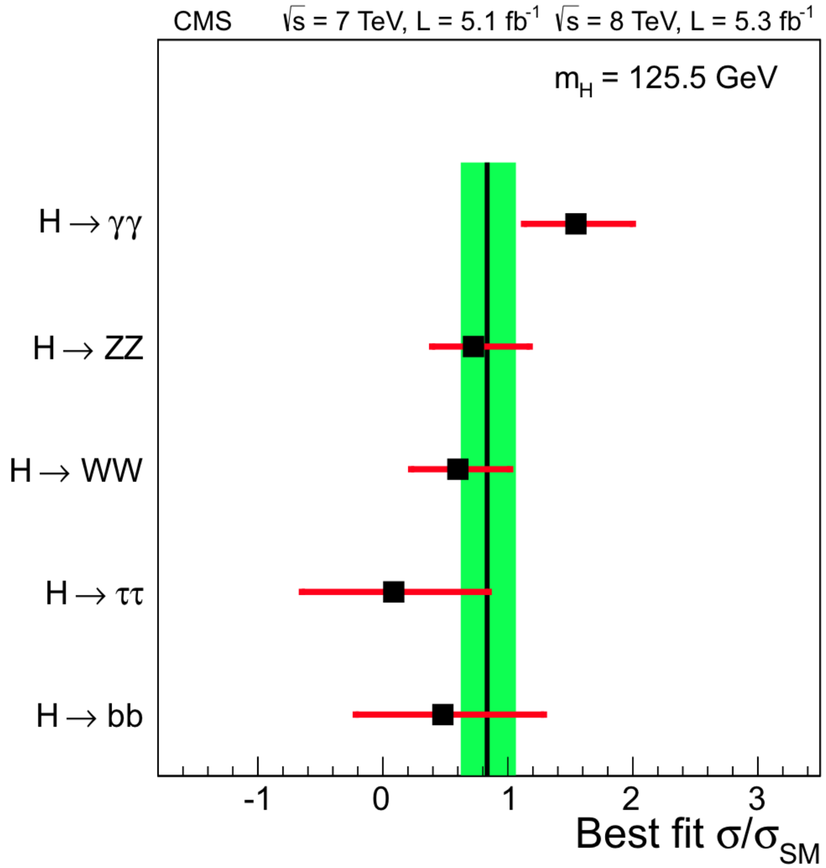
Winter 2011: overall agreement with the SM



- High $\Gamma(H \to \gamma\gamma)$??
- Low $\Gamma(H \to WW)/\Gamma(H \to ZZ)$?
- Low $\Gamma(H \to \tau\tau)$?

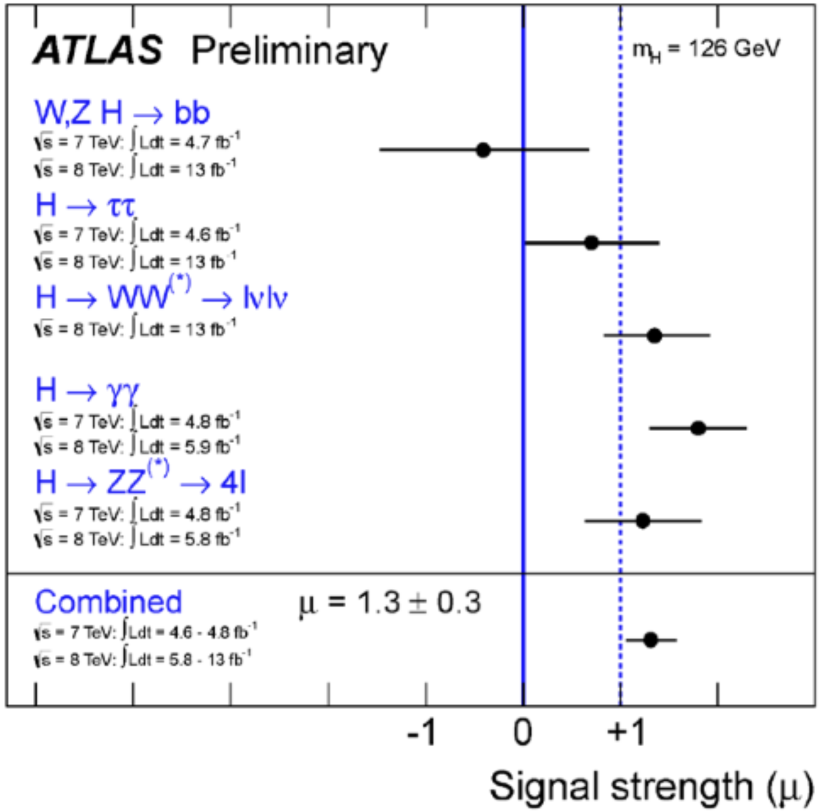
Summer 2012: impressive agreement with the SM





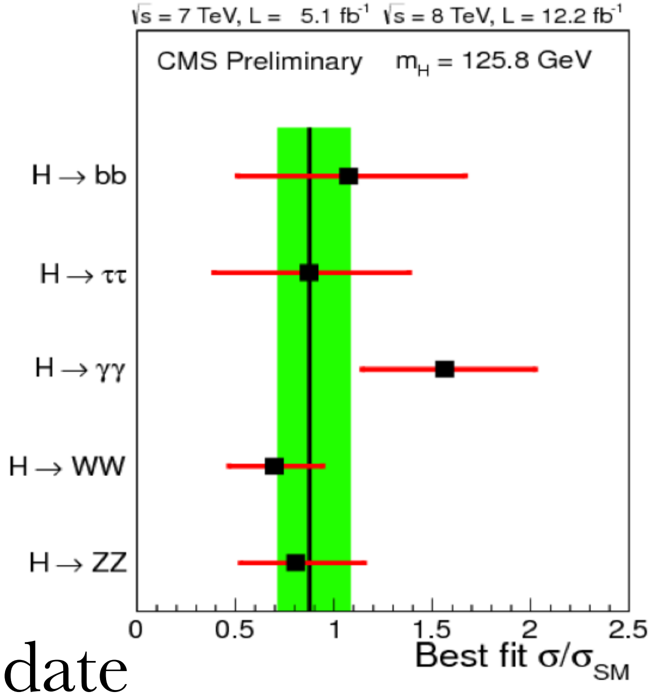
- High $\Gamma(H \to \gamma\gamma)$??
- ~~Low $\Gamma(H \to WW)/\Gamma(H \to ZZ)$?~~
- Low $\Gamma(H \to \tau\tau)$?

November 2012: disappointing agreement with the SM



$$m_H = 126.0 \pm 0.4_{\text{stat}} \pm 0.4_{\text{syst}} \quad \text{(ATLAS)}$$

$$m_H = 125.8 \pm 0.4_{\text{stat}} \pm 0.4_{\text{syst}} \quad \text{(CMS)}$$



- High $\Gamma(H \to \gamma\gamma)$?? ✗ ← no update
- ~~Low $\Gamma(H \to WW)/\Gamma(H \to ZZ)$?~~
- ~~Low $\Gamma(H \to \tau\tau)$?~~

What have we learned?

The phenomenon of ~~EW~~ had already been established before LHC

Experimental evidence for

- gauge structure also in TGC (γWW, ZWW)
- W and Z longitudinal polarizations
- masses of W, Z, quarks

propagating particles do not share the full symmetry of interactions

(spontaneous symmetry breaking)

Every phenomenon (before Dec 13, 2011) could be described by

$$L = -\frac{1}{4}\mathrm{Tr}\, F_{\mu\nu}F^{\mu\nu} + i\bar{f}\gamma^{\mu}D_{\mu}f$$

kinetic + interactions

$$+\frac{v^2}{4}\mathrm{Tr}\left(D_{\mu}\Sigma\right)^{+}D^{\mu}\Sigma - \frac{v}{\sqrt{2}}\bar{f}_L\Sigma\lambda_f f_R + \mathrm{h.c.}$$

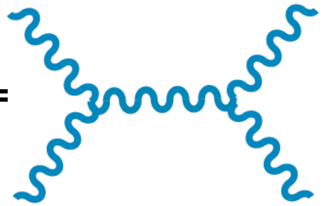
masses + long. pol.

$$\Sigma = \exp\left(\frac{iT^a\pi^a}{v}\right)$$

π^a longitudinal polarizations of W and Z

$v = 246$ GeV

Even before Dec 13, 2011 theorists knew that this could not be the full story

$A(\pi\pi \to \pi\pi) =$  $+$  $\propto \left(\frac{E}{4\pi v}\right)^2$

Loss of perturbative unitarity at $E \approx 4\pi\, v \approx 3$ TeV

New phenomena in the TeV region

Guaranteed discovery at the LHC!

What is the phenomenon?

Simplest answer:
one real scalar field h

(π^a, h) form a complete SU_2 doublet

The LHC discovered the missing ¼

THE SEMINAL PAPERS

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
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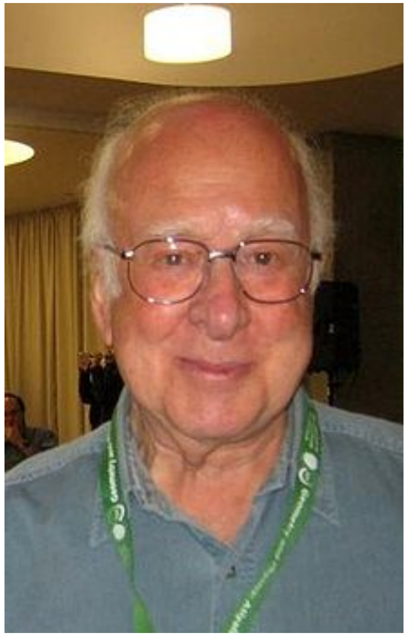
It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons.[8] It is to be

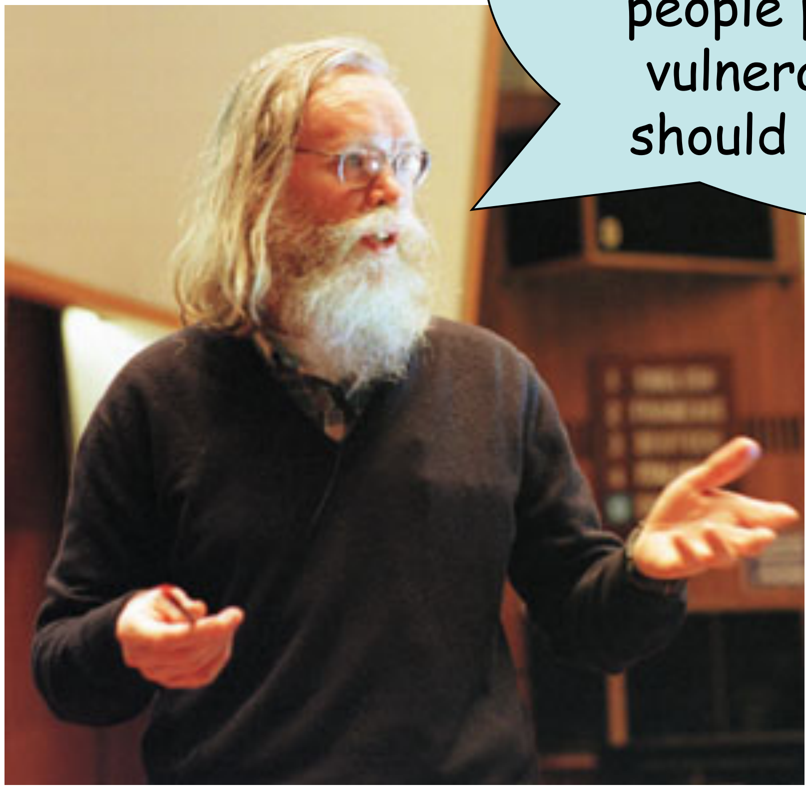


1. **The Assignment Of Particles To Multiplets Of Chiral Su(3) X Su(3). Peter W. Higgs (North Carolina U.). Jun 1966. 4 pp. PRINT-66-713.**
2. **Spontaneous Symmetry Breakdown without Massless Bosons.Peter W. Higgs (North Carolina U.). May 1966. 8 pp. Published in Phys.Rev. 145 (1966) 1156 - Cited by 1522 records**
3. **Integration of Secondary Constraints in Quantized General Relativity.Peter W. Higgs (Imperial Coll., London). Nov 1958. 2 pp. Published in Phys.Rev.Lett. 1 (1958) 373-374, Erratum-ibid. 3 (1959) 66 - Cited by 46 records**
4. **Broken symmetries, massless particles and gauge fields.Peter W. Higgs (Edinburgh U.). Sep 1964. 2 pp. Published in Phys.Lett. 12 (1964) 132 - Cited by 1980 records**
5. **Broken Symmetries and the Masses of Gauge Bosons.Peter W. Higgs (Edinburgh U.). Oct 1964. 2 pp. Published in Phys.Rev.Lett. 13 (1964) 508 - Cited by 1639 records**
6. **Dynamical Symmetries In A Spherical Geometry. 1.Peter W. Higgs (Edinburgh U.). Oct 1978. 24 pp. PRINT-78-0990 (EDINBURGH). Published in J.Phys.A A12 (1979) 309 - Cited by 134 records**

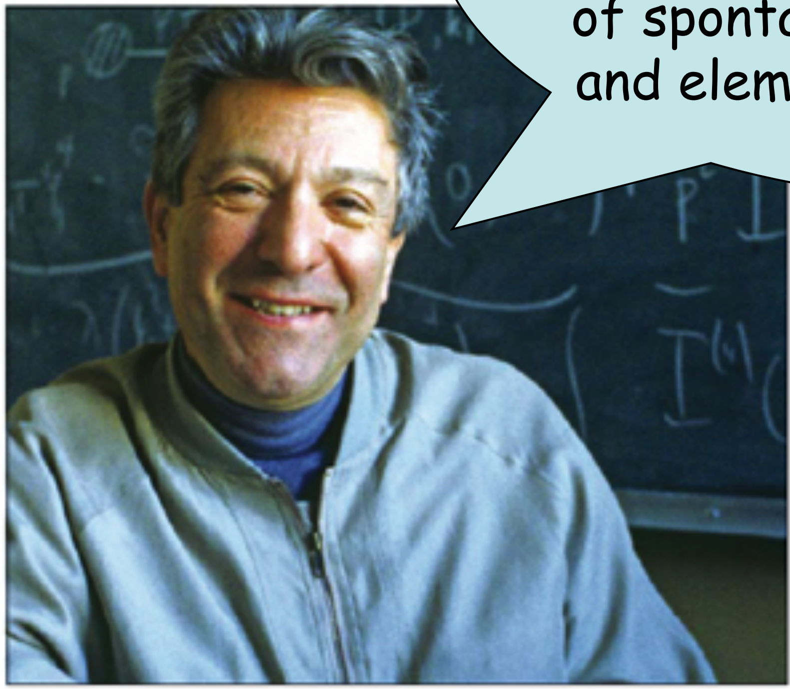
A fundamental discovery

- Identify the origin of a fundamental scale
- A new guise of the gauge principle
- Structure of space-time vacuum (new ether?)
- A new force of nature

We do not wish to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.



Ellis Gaillard Nanopoulos (1976)



Several people believe, and I share this view, that the Higgs scheme is a convenient parametrization of our ignorance concerning the dynamics of spontaneous symmetry breaking and elementary scalar particles do not exist

Iliopoulos, Einstein Symposium (1979)

It seems to me that the problem No.1 of high energy physics are scalar particles. The search for these particles is extremely important mainly because of their vital role in symmetry breaking.

Okun, Lepton-Photon (1981)

The Higgs boson looks like a toy model.

It is almost incredible that the toy model is just right.

Most physicists believe that the Higgs cannot be the end of the story.

Almost all the problems of the SM originate from Higgs interactions

$$L = \left(h_{ij}\overline{\psi}_i\psi_j H + \text{h.c.}\right) - \lambda|H|^4 + \mu^2|H|^2 - \Lambda^4$$

Flavor puzzle

Stability of the potential

Hierarchy problem

Cosmological constant problem

Just because the 5th force is not a gauge force...

Two fundamental questions:

1) What is the 5^{th} force?
2) Is the Higgs natural?

1) What is the 5^{th} force?

- Is it weak or strong?
- Is it a gauge force?
- Is it associated with a fundamental scalar?

Measurements of Higgs couplings!

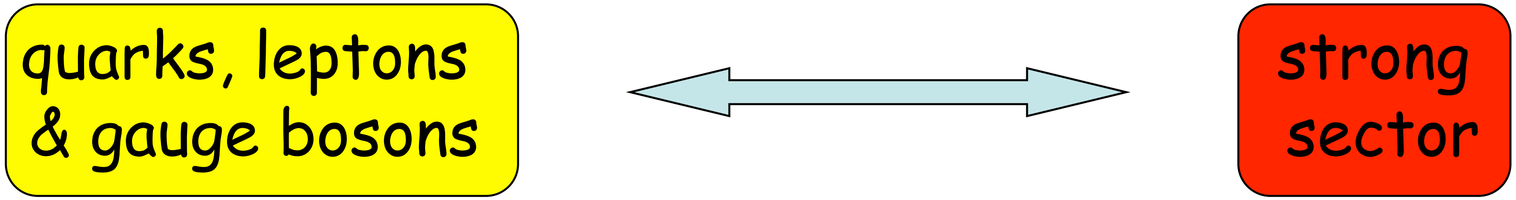
$$L = -\frac{1}{4}\mathrm{Tr}\,F_{\mu\nu}F^{\mu\nu} + i\bar{f}\gamma^{\mu}D_{\mu}f + \frac{v^2}{4}\mathrm{Tr}\left(D_{\mu}\Sigma\right)^{+}D^{\mu}\Sigma\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}+\ldots\right)$$

$$-\frac{v}{\sqrt{2}}\bar{f}_L\Sigma\lambda_f f_R\left(1+c\frac{h}{v}+\ldots\right)+\mathrm{h.c.}$$

$$\Sigma = \exp\left(\frac{iT^a\pi^a}{v}\right)$$

$$\text{In SM}: \; a = b = c = 1$$

Composite Higgs



Communicate via gauge (g_a)
and (proto)-Yukawa (λ_i)

Strong sector characterized by m_ρ mass of resonances
g_ρ coupling of resonances

Take λ_l, $g_a << g_\rho < 4\pi$

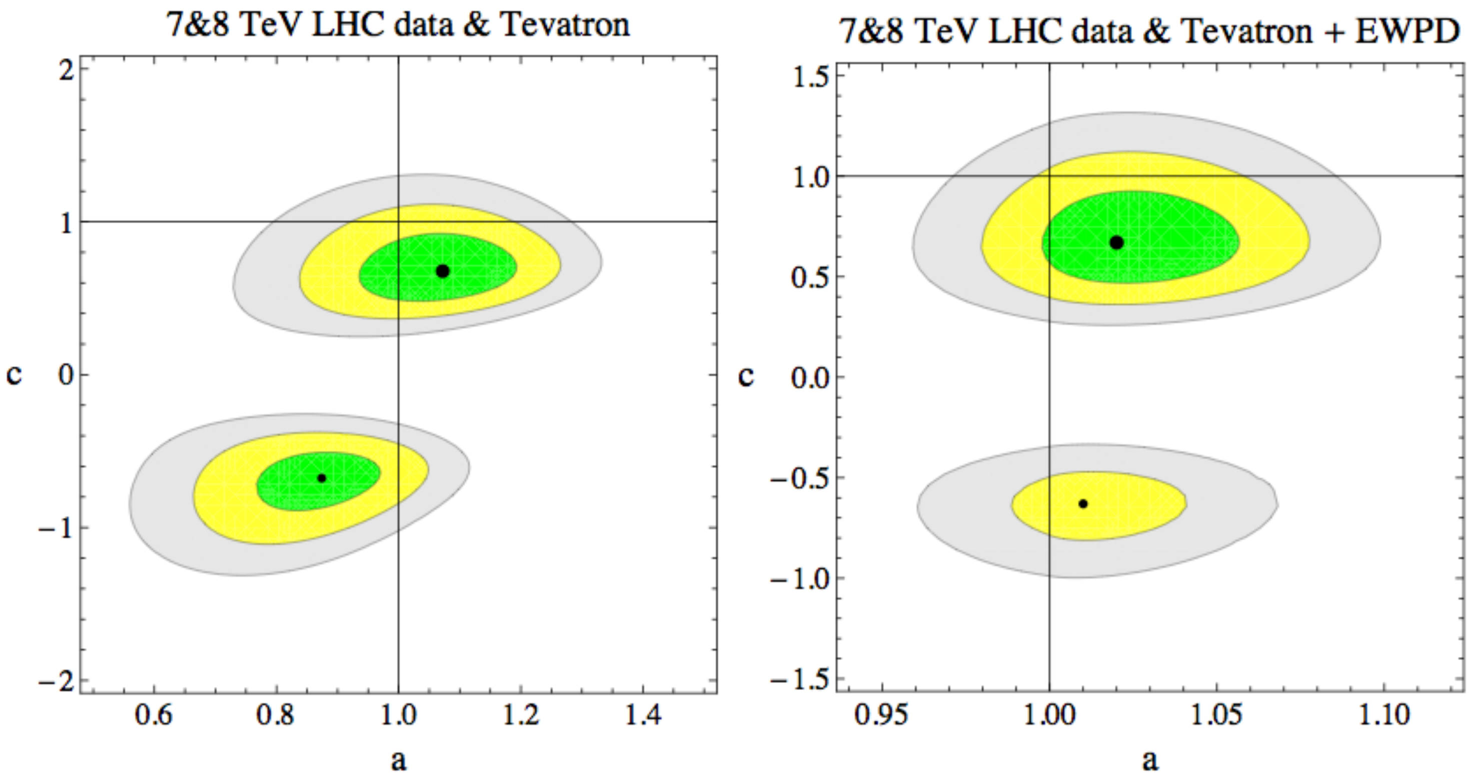
In the limit λ_l, $g_a = 0$, strong sector contains
Higgs as Goldstone bosons

Ex. $H = SU(3)/SU(2)\times U(1)$ or $H = SO(5)/SO(4)$

σ-model with $f = m_\rho \,/\, g_\rho$

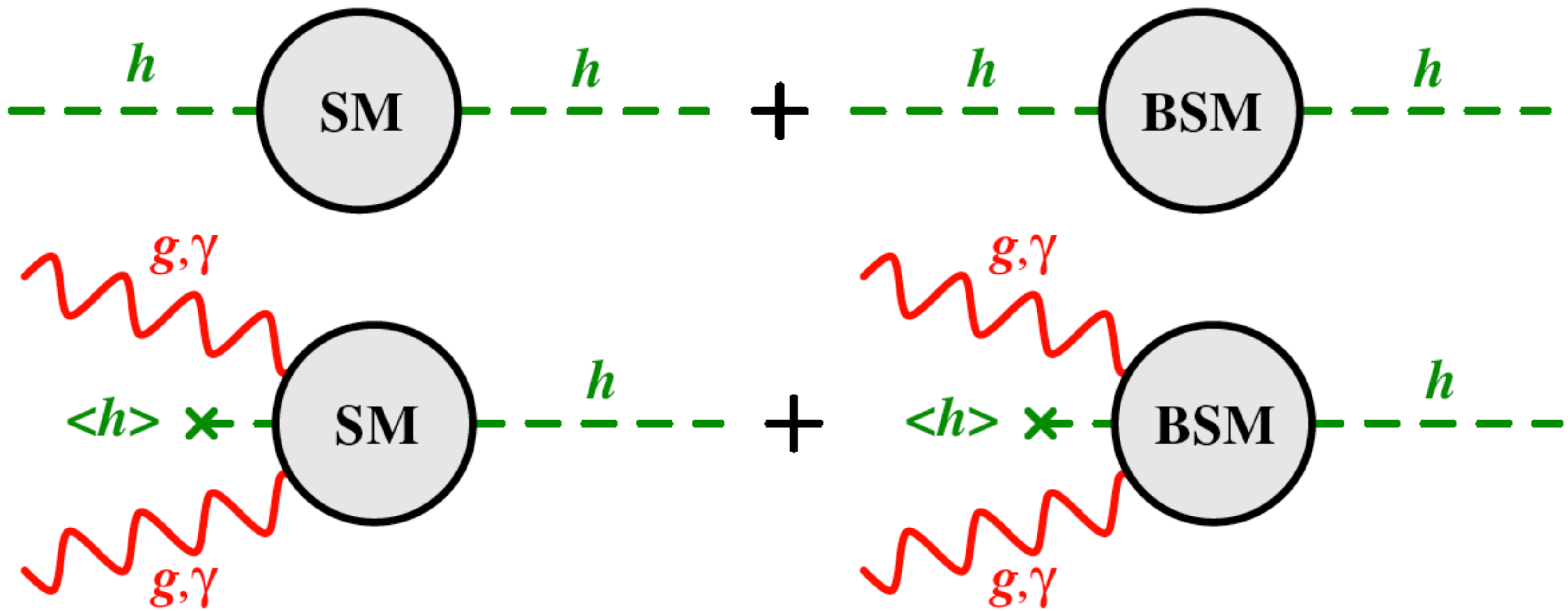
In composite Higgs: $a \approx b \approx c = 1 + O(v^2/f^2)$

where $4\pi f$ is the scale of compositeness



Espinosa et al.

In weakly-interacting BSM (like SUSY), deviations are expected in γ and g couplings. The more natural the Higgs is, the more its properties deviate from SM.



$$\frac{\Gamma(h \leftrightarrow gg)}{\Gamma(h \leftrightarrow gg)_{\rm SM}} = (1 + \Delta_t)^2 \ , \qquad \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\rm SM}} = (1 - 0.28 \ \Delta_t)^2 \ ,$$

$$\Delta_t \approx \frac{m_t^2}{4} \left[\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2} - \frac{A_t^2}{m_{\tilde{t}}^4} \right]$$

$$\frac{\delta \Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\rm SM}} \approx \left(\frac{500 \text{ GeV}}{m_{\tilde{t}}} \right)^2 2\%$$

A posteriori: deviations in Higgs BR larger than 10% are rather special.

CMS projection

Scenario 1: systematics as in 2012
Scenario 2: theory syst. scaled by a factor ½, other systematics scaled by 1/√L

Coupling	Uncertainty (%)			
	300 fb^{-1}		3000 fb^{-1}	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

	250/350 GeV	500 GeV†	3 TeV
g_{Hbb}	1.6/1.4 %	?	2 %
g_{Hcc}	4/3 %	2 %	2 %
$g_{H\tau\tau}$	3*/3 %	2.5 %	?
g_{HWW}	4/3 %	1.4 %	< 2 %
$g_{H\mu\mu}$	–/–	–	7.5 %
$\frac{g_{HWW}}{g_{HZZ}}$	?/?	?	< 1 %*
g_{Htt}	–/–	15 %	?

LC

[1210.0202]

2) Is the Higgs natural?

- Naturalness is not an idle theoretical concept

- Its importance goes beyond ~~EW~~, and it will influence the strategy for future directions in particle physics

- Naturalness is linked to the use of EFT
- EFT is the tool to implement the intuitive notion of separation of scales
- We build stacks of EFT
- At each stage we have discovered simpler laws and larger symmetries
- We can use the naturalness criterion to infer the energy scale of the next layer

Naturalness at work:

1. classical electron self-energy

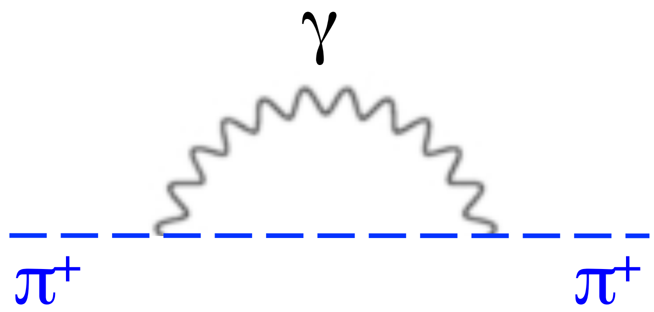
electrostatic energy: $E \approx \frac{\alpha}{r} < m_e c^2 \Rightarrow \Lambda < \frac{m_e}{\alpha} \approx 70 \text{ MeV}$

magnetic energy: $E \approx \frac{\mu^2}{r^3}, \mu = \frac{e\hbar}{2m_e c} < m_e c^2 \Rightarrow \Lambda < \frac{m_e}{\alpha^{1/3}} \approx 3 \text{ MeV}$

(spinning sphere)

New physics (positron) at $m_e < \Lambda$

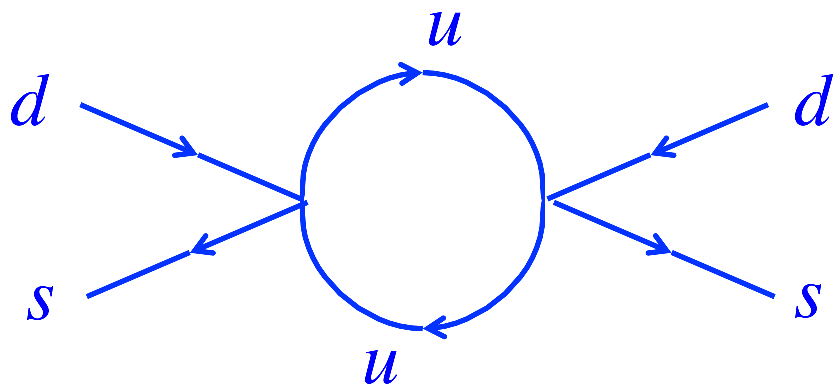
Naturalness at work:
2. QED contribution to pion mass difference



$$\frac{3\alpha}{4\pi}\Lambda^2 < M_{\pi^+}^2 - M_{\pi^0}^2 \Rightarrow \Lambda < 850 \text{ MeV}$$

New physics (hadrons) at $M_\rho < \Lambda$ ($M_\rho = 770$ MeV)

Naturalness at work:
3. Neutral kaon mass difference



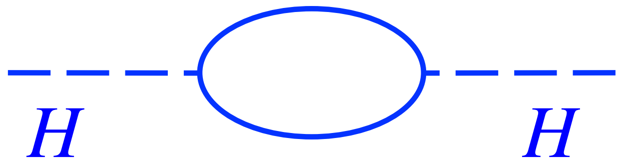
Effective theory at M_K:

$$\frac{G_F^2 f_K^2}{6\pi^2}\sin^2\theta_c\Lambda^2 < \frac{M_{K_L^0} - M_{K_S^0}}{M_{K_L^0}} \Rightarrow \Lambda < 2\text{ GeV}$$

New physics (charm) at $m_c < \Lambda$ $(m_c = 1.2\text{ GeV})$

Naturalness at work ?

The weak scale



$$\delta m_h^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2\right)\Lambda^2 < m_h^2 \Rightarrow \Lambda < 500 \text{ GeV}$$

Where is new physics?

- Around the corner?
- Mild tuning?
- Failure of effective theory approach?

Indications for a failure of EFT?

- Dark energy
  Where is new physics? $\Lambda_{CC} = 2.4 \times 10^{-3}$ eV

- Holography, gauge-gravity duality, AdS-CFT correspondence: a single Lagrangian cannot encompass the physical content of the theory?

- IR/UV connection

Connection between smallest and largest distances?

Largest scale = Hubble length H^{-1} = 10^{26} m

Smallest scale = Planck length M_P^{-1} = 10^{-35} m

$$\Lambda_{CC} = \sqrt{H\,M_P} = 5 \times 10^{-3}\ \text{eV}$$

$$\Lambda_{Weak} = \sqrt{\Lambda_{CC}\,M_P} = 5\ \text{TeV}$$

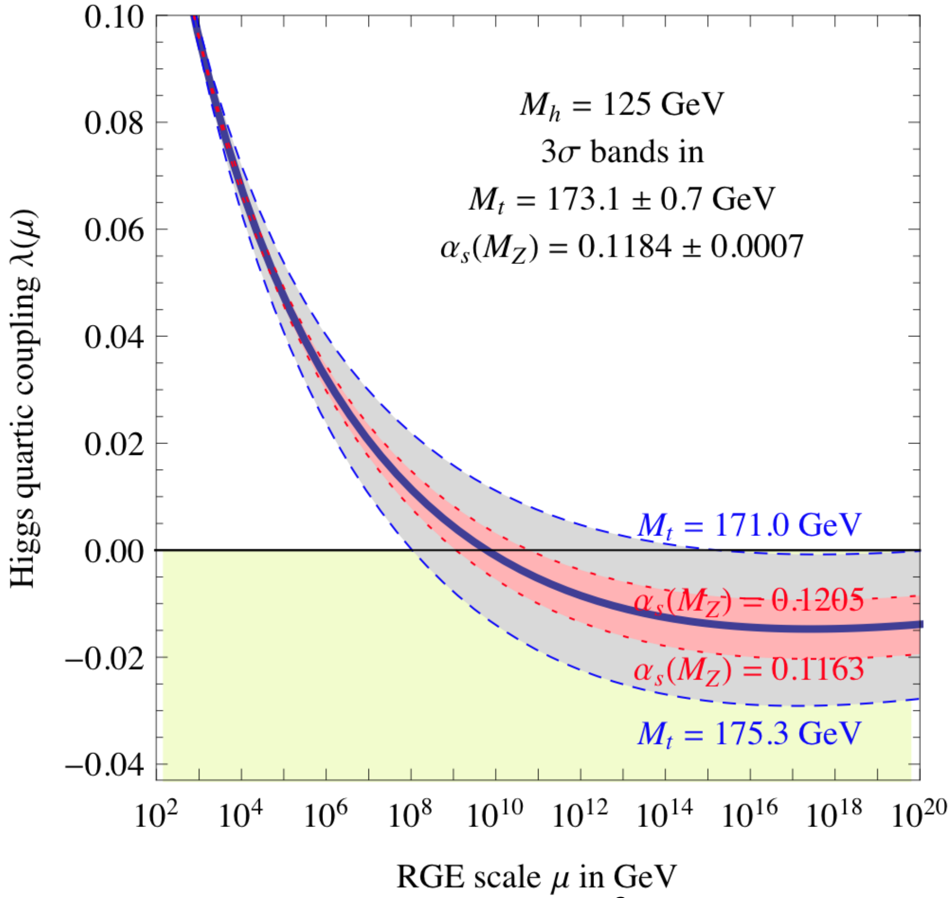
An effective theory will never be able
to catch an IR/UV connection

Another possibility: the multiverse

• Anthropic arguments may play a role in selecting the PDF of the universes
• This is the most convincing explanation of the CC so far
• If true, some questions that we thought as fundamental are just the result of environmental conditions

• Physics is confronting a crossroad: naturalness of unnaturalness?
• Far-reaching consequences for physics

What did we learn from the Higgs mass measurement?



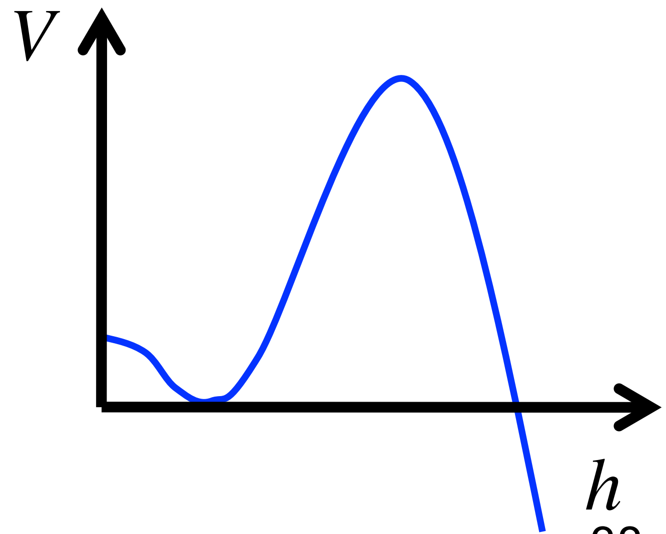
Extrapolate the SM up to very high energies

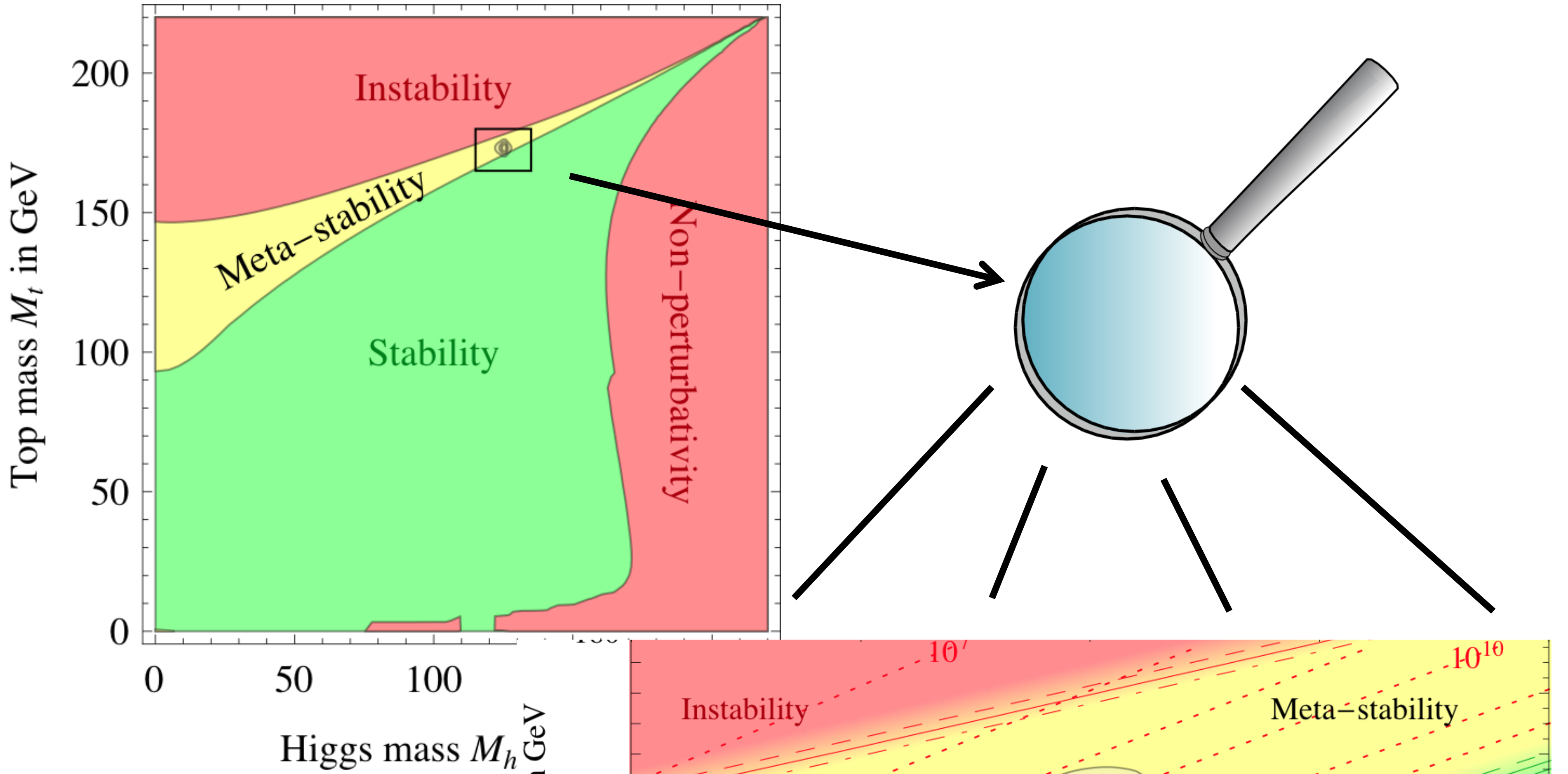
↑Higgs mass

↓Top quark mass

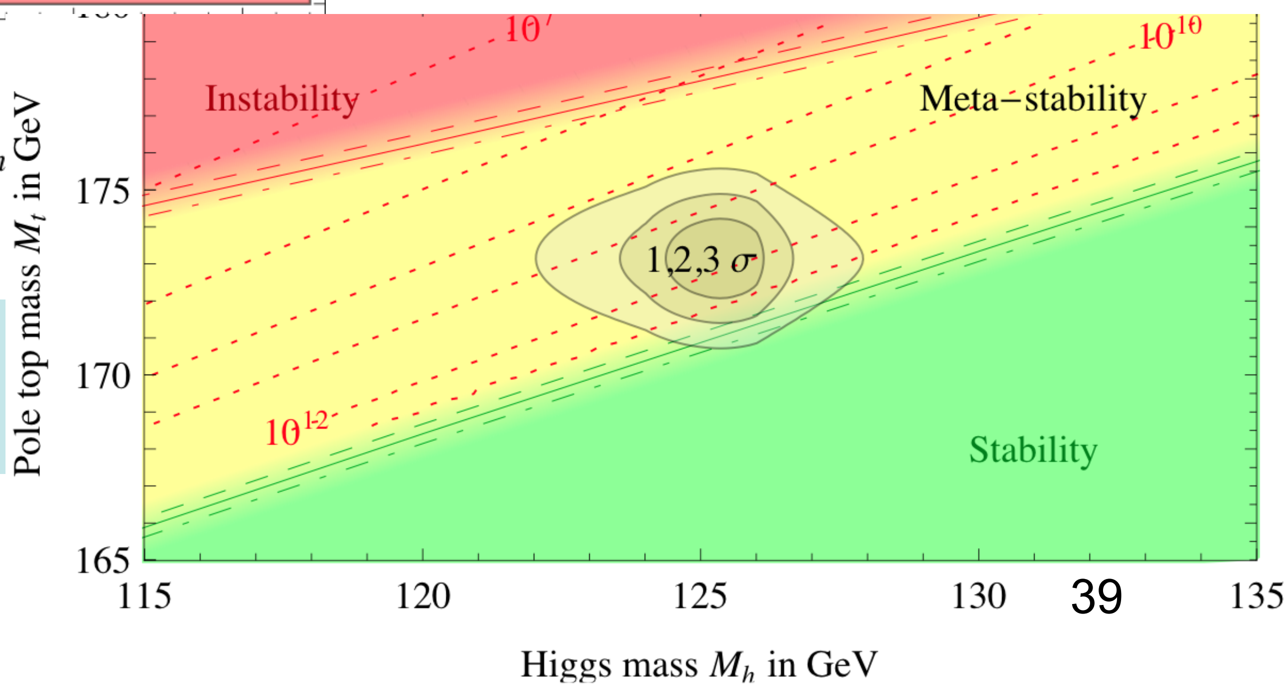
$$V = \frac{\lambda}{4}\left(h^2 - v^2\right)^2$$

- Quantum tunneling
- Thermal tunneling

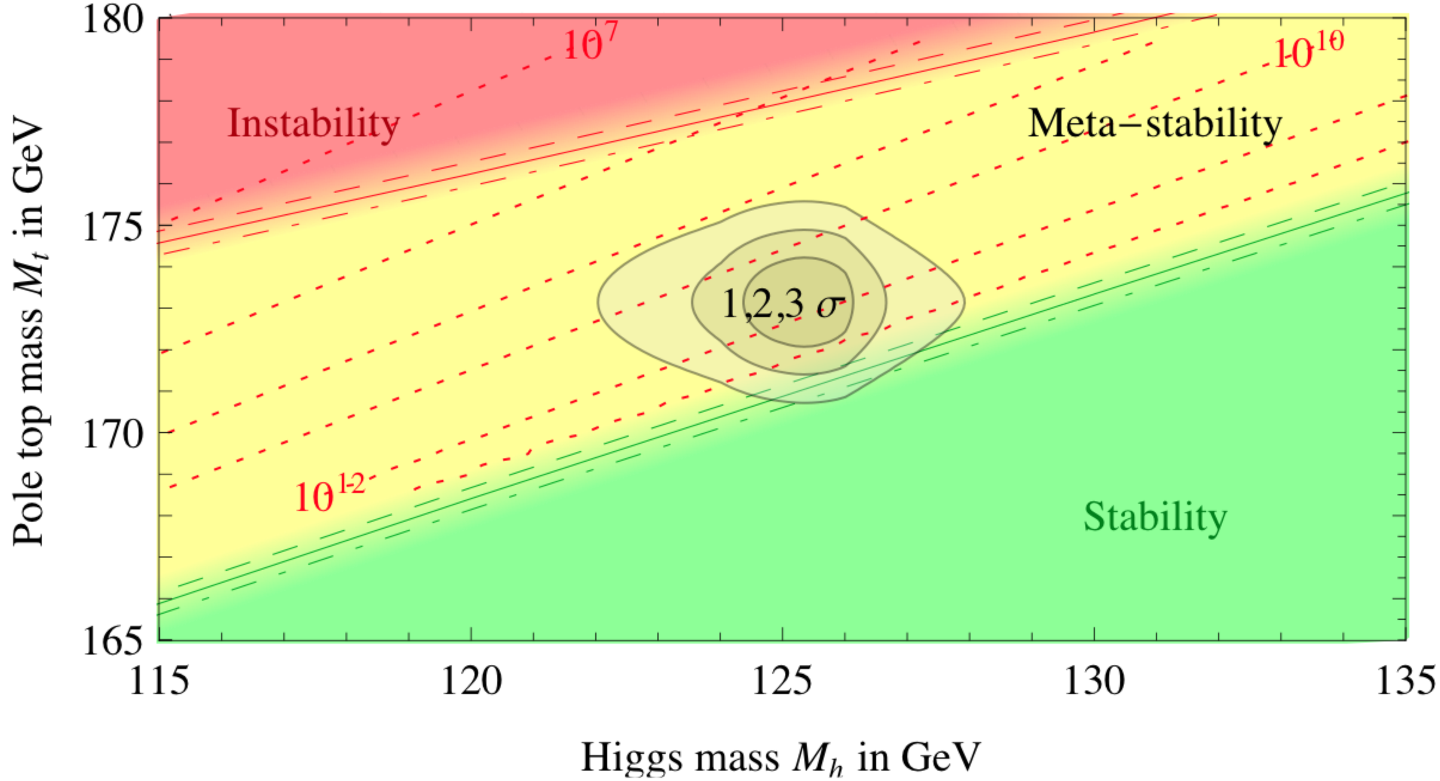




We seem to live near a critical condition

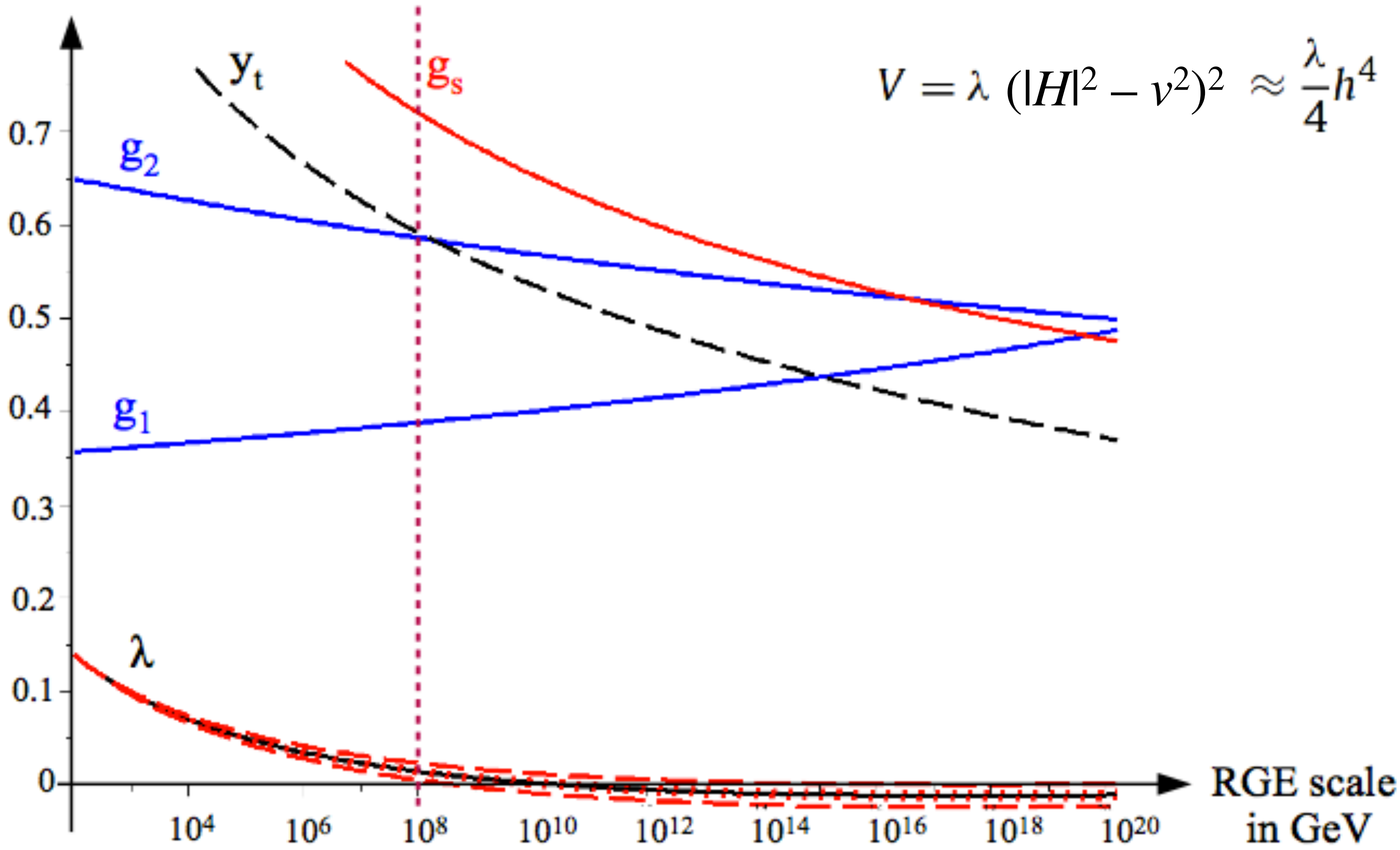


Precise determinations of M_h and M_t are necessary to establish the fate of our universe

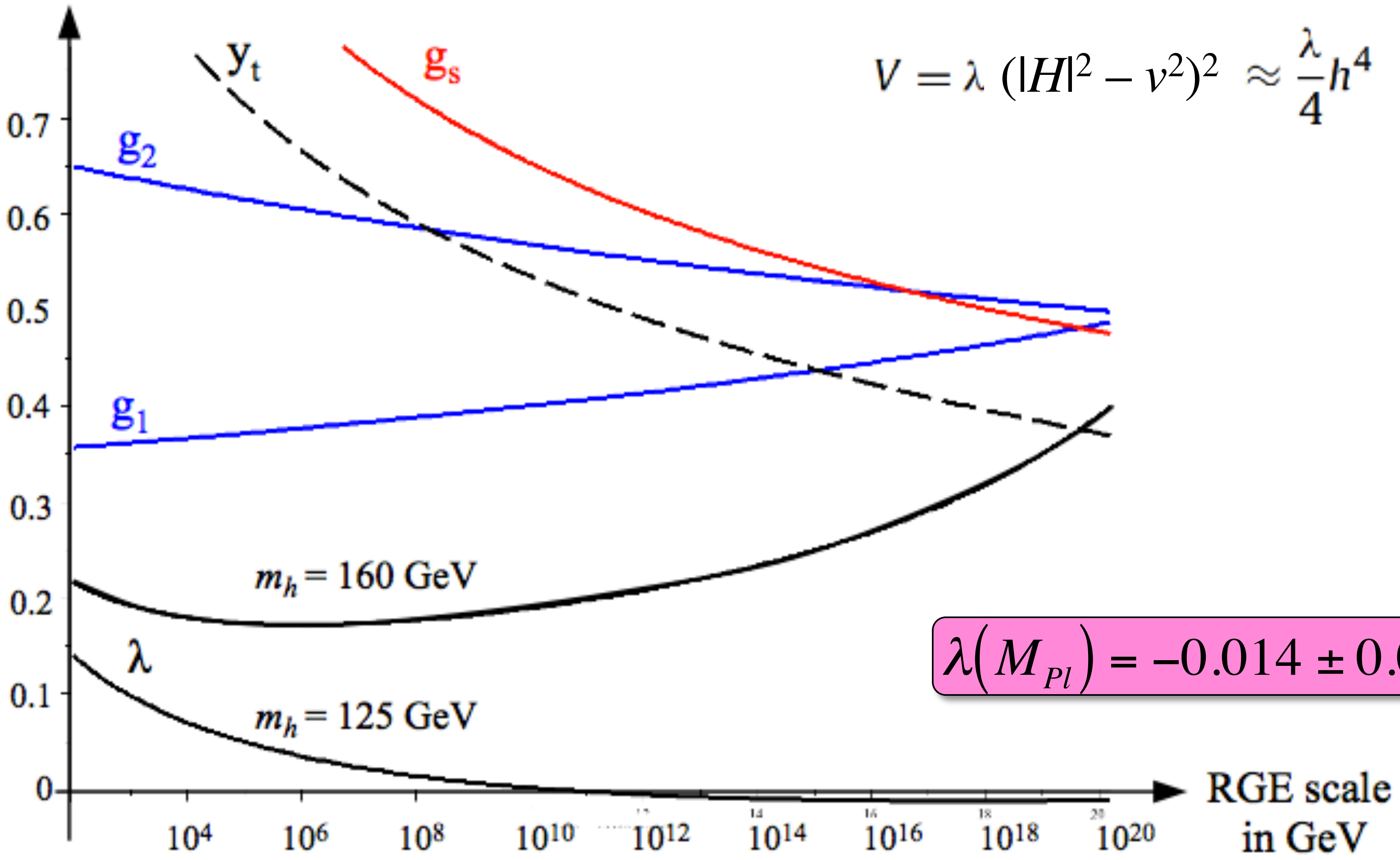


Stability condition:

$$M_h\ [\text{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\text{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\text{th}}$$



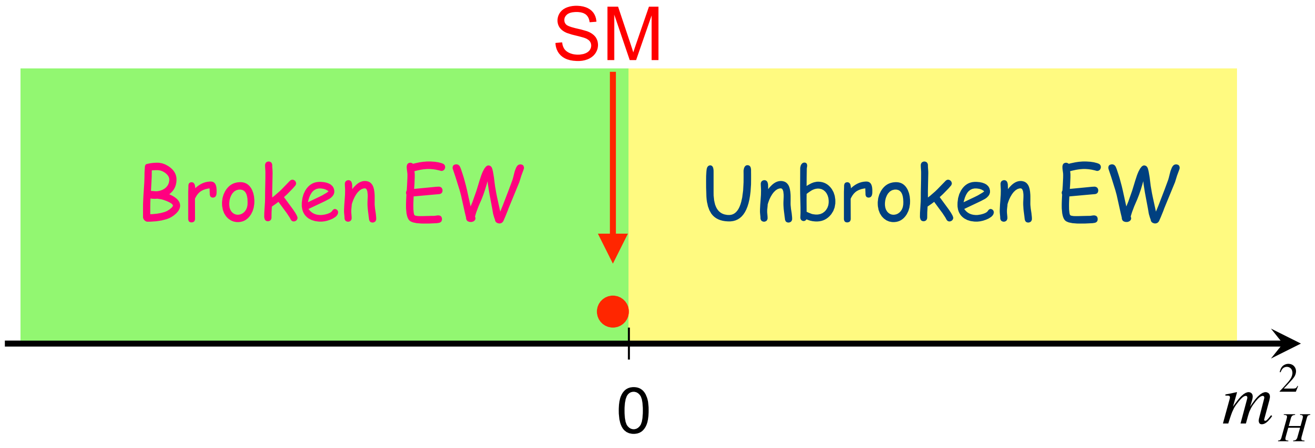
λ and β_λ nearly vanish at high energies?



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

$$\lambda\left(M_{Pl}\right) = -0.014 \pm 0.006$$

A problem of criticality: $V(H) = -m_H^2 |H|^2 + \lambda |H|^4$



Why is nature so close to the critical line?

Symmetry?
- Supersymmetry: $m_H{}^2 = 0$
- Goldstone boson: $\lambda = 0$

Do we live near a critical condition because of dynamics or because of statistics in the multiverse?

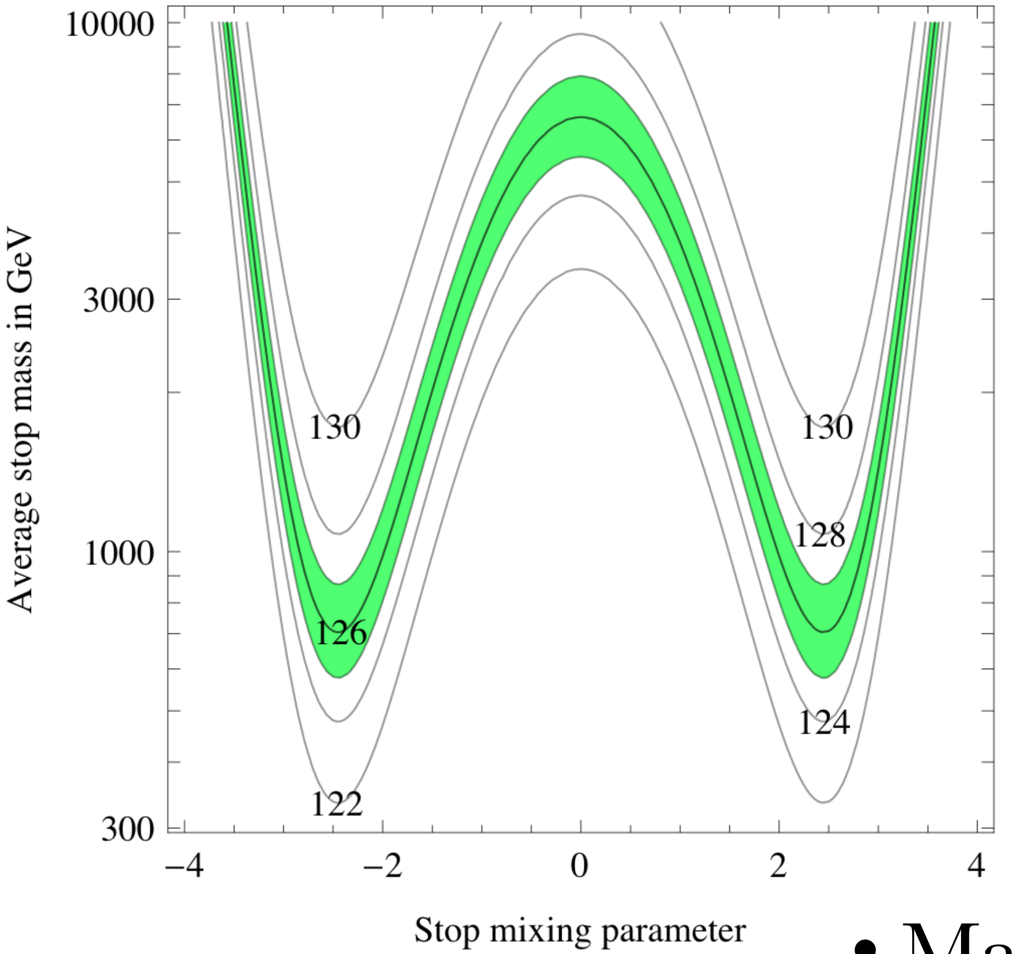
Higgs mass is a crucial parameter for many BSM theories

$m_h \approx 126$ GeV can be accomodated in composite models, but it gives no indication in favor of compositeness

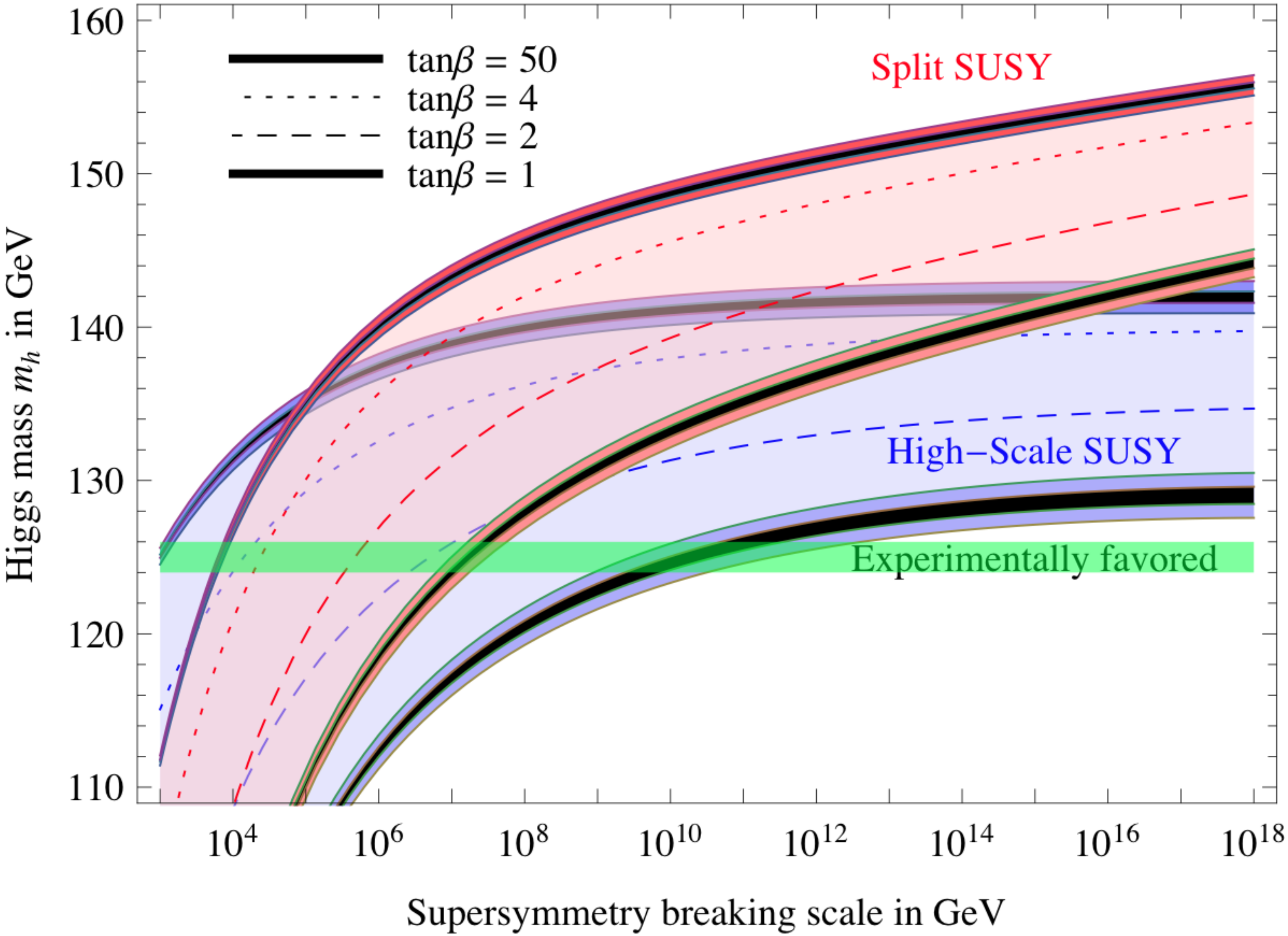
$$\begin{cases} m_h < 120 \text{ GeV} & \text{OK for natural susy} \\ m_h > 130 \text{ GeV} & \text{NO minimal susy} \end{cases}$$

In susy, $m_h \approx 126$ GeV can be reached, but only for extreme parameters

- Natural setups (where parameters are correlated) are ruled out (e.g. simple gauge mediation)
- The idea of low-energy susy is still alive



- Maximal mixing?
- NMSSM?
- New gauge groups?
- New vector-like fermions?



- $m_h \approx 126$ GeV rules out grossly split susy, but mildly split susy is OK
- Anomaly mediation with $M_{\tilde{g}} = O(\text{TeV}), \quad \tilde{m} \approx 4\pi M_{\tilde{g}} = O(10\ \text{TeV})$
- Susy broken at Planck mass is ruled out

CONCLUSIONS

Higgs searches address fundamental issues:
1) What is the 5th force?
2) Is the Higgs natural?

The answers will define future directions of our field

We have discovered how EW is broken, but not solved the mystery

The most puzzling (and surprising) message is criticality
Numerical coincidence or deep meaning?