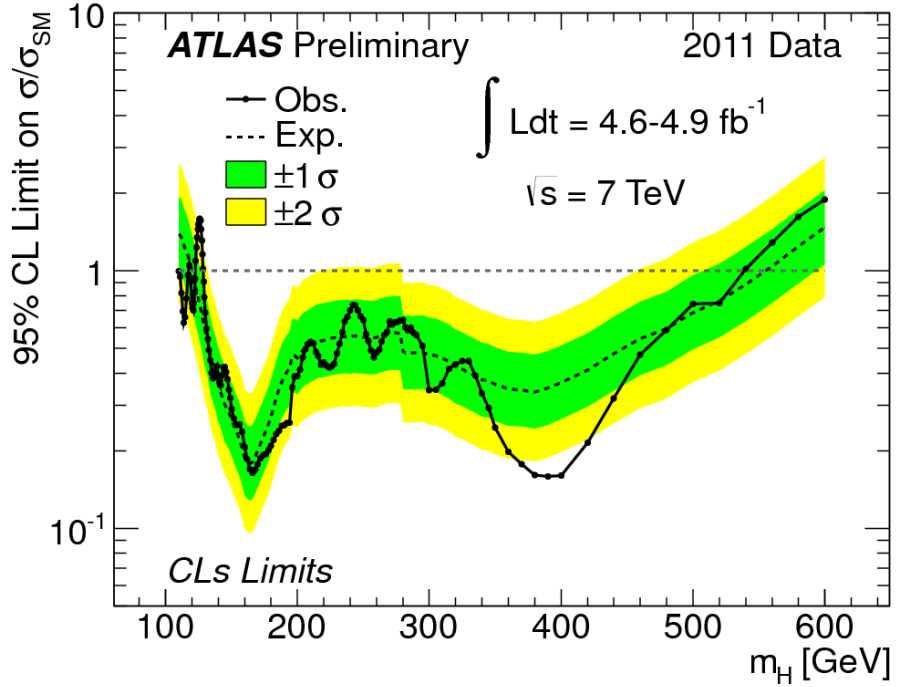
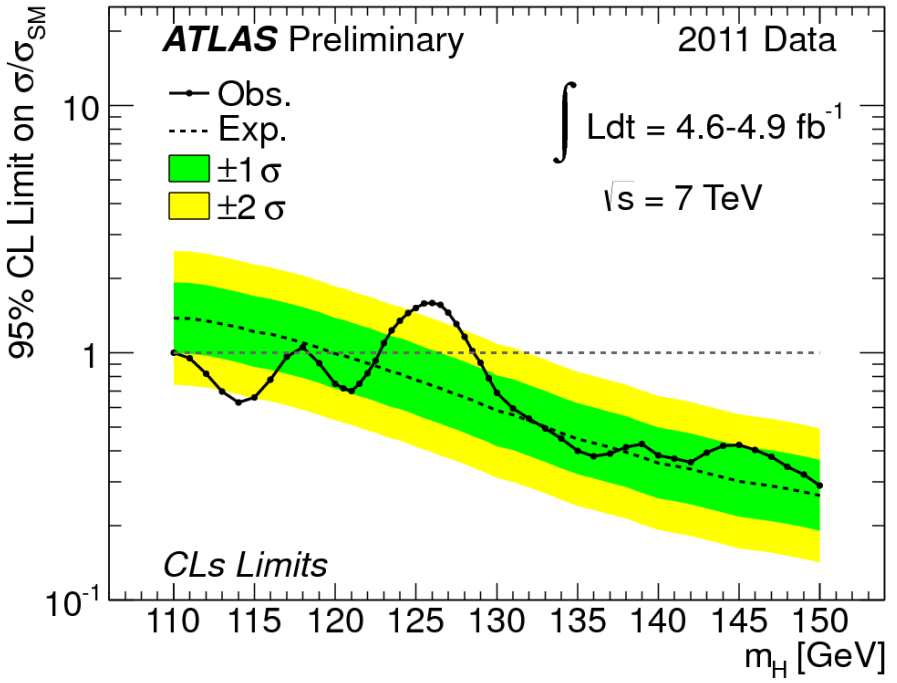
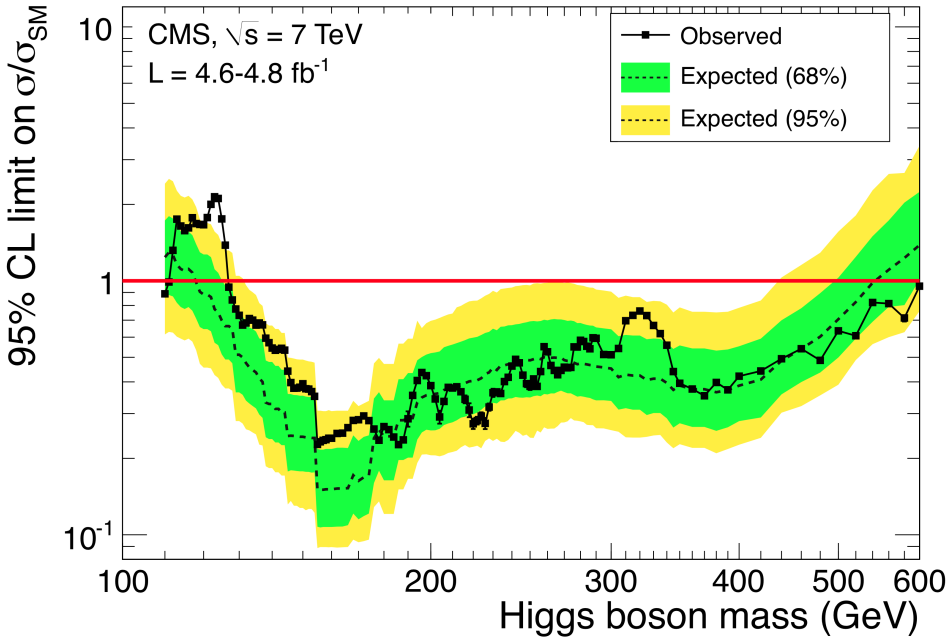
Concluding remarks (on the Higgs boson)

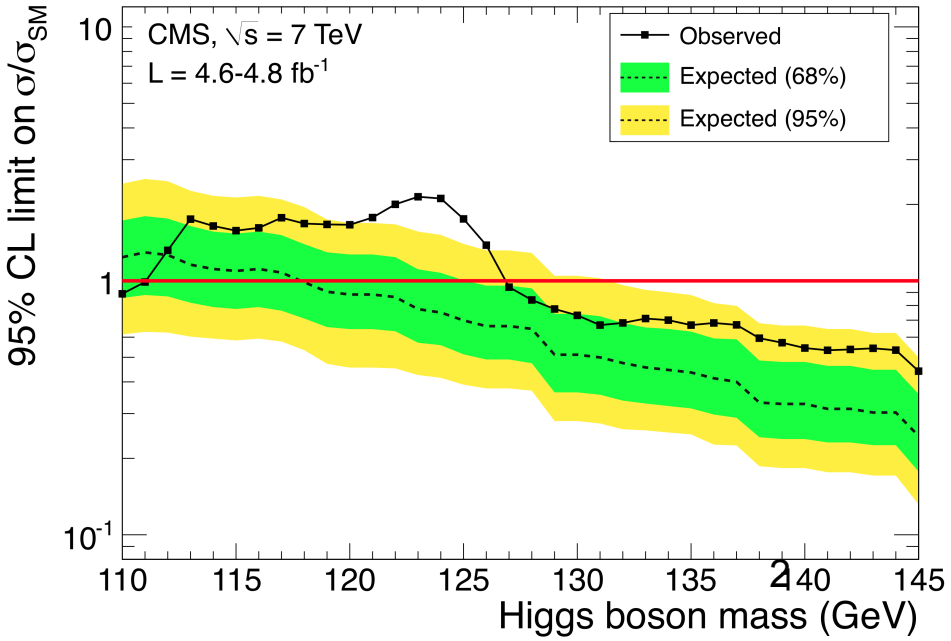
G.F. Giudice

What do we learn from this?









The phenomenon ~~of~~ EW has 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

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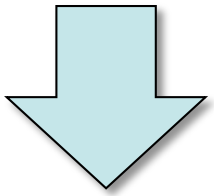

propagating particles do not share the full symmetry of interactions (spontaneous symmetry breaking)

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

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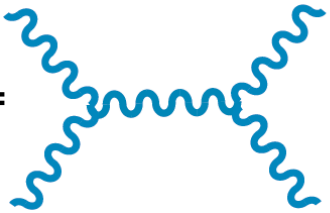
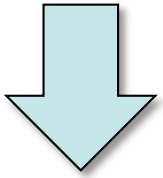
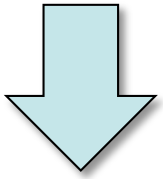
Even before Dec 13, 2011 theorists knew that this could not be the full story

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

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?

What is the phenomenon?

Simplest answer:
one real scalar field h

(π^a, h) form a complete SU_2 doublet

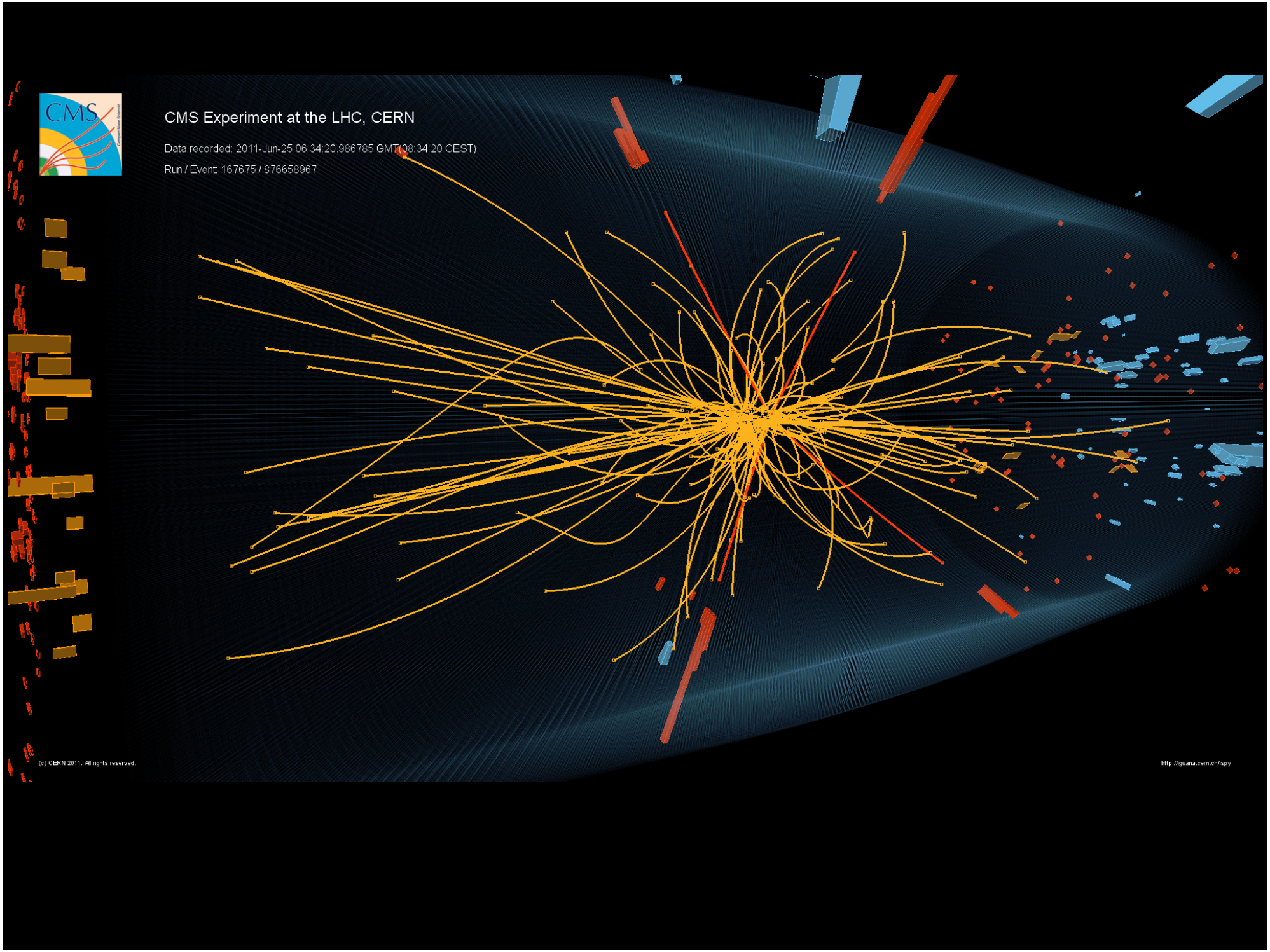
¾ of the Higgs have already been found;
the LHC should discover the rest

Hunt the Higgs

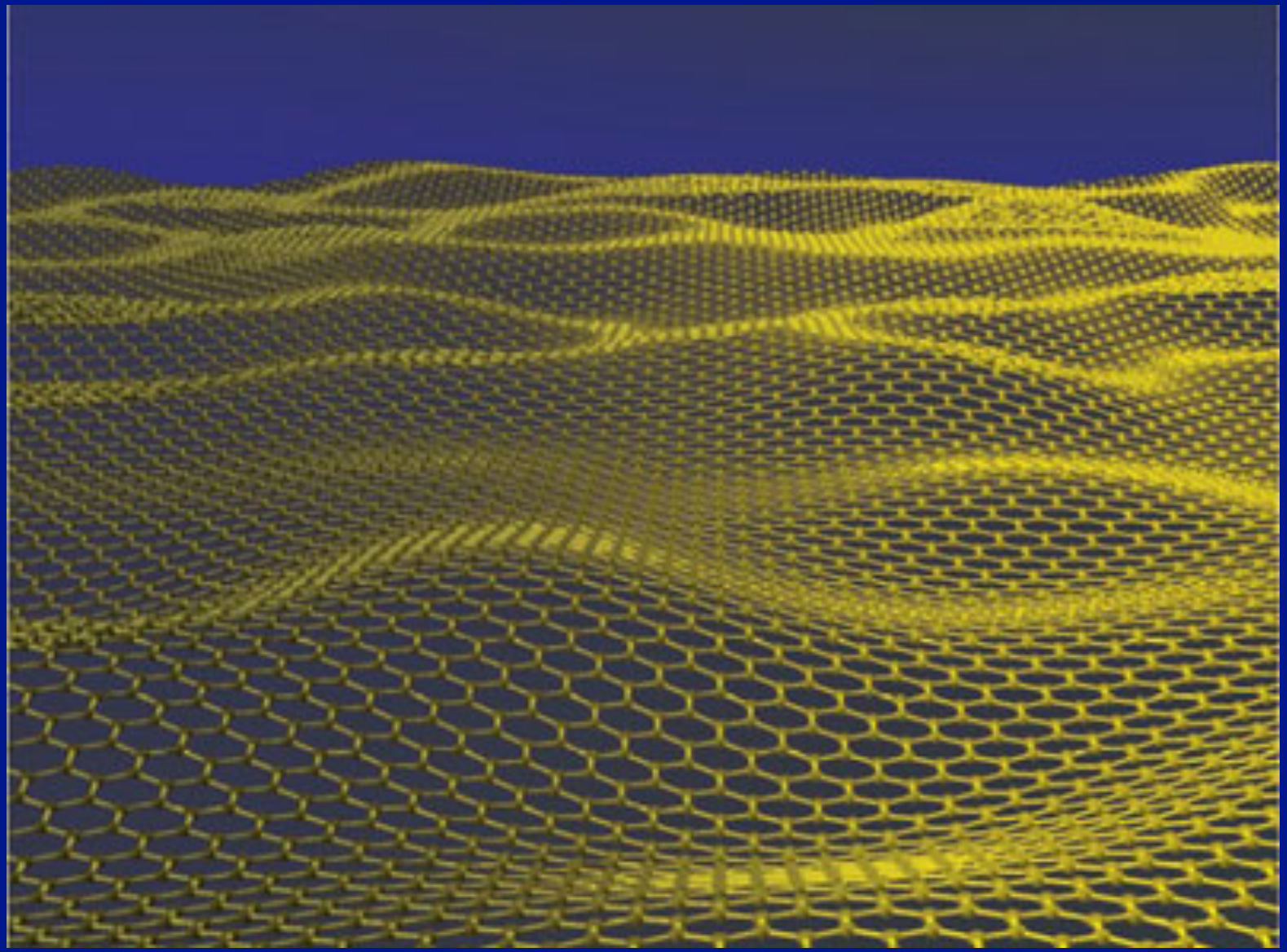
A game of chance and tactics for all ages.

Based on the fundamental particles and forces of nature.

No need for any previous knowledge of Particle Physics!


CMS Experiment at the LHC, CERN
Data recorded: 2011-Jun-25 06:34:20.986785 GMT(08:34:20 CEST)
Run / Event: 167675 / 876658967
(c) CERN 2011. All rights reserved.
http://iguana.cern.ch/ispy

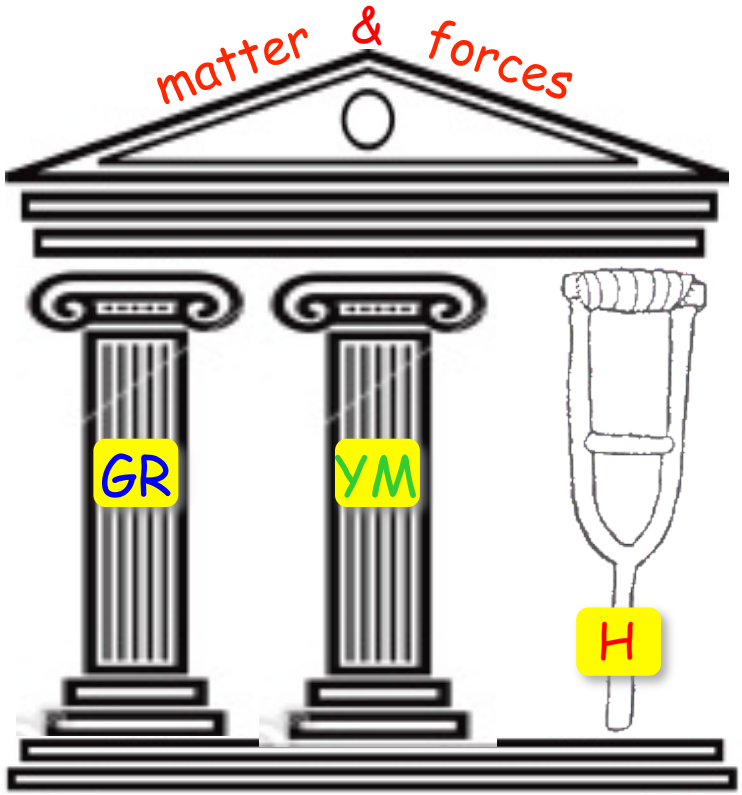
At 10^{-10} seconds after the Big Bang...



Finding the Higgs will be a key discovery

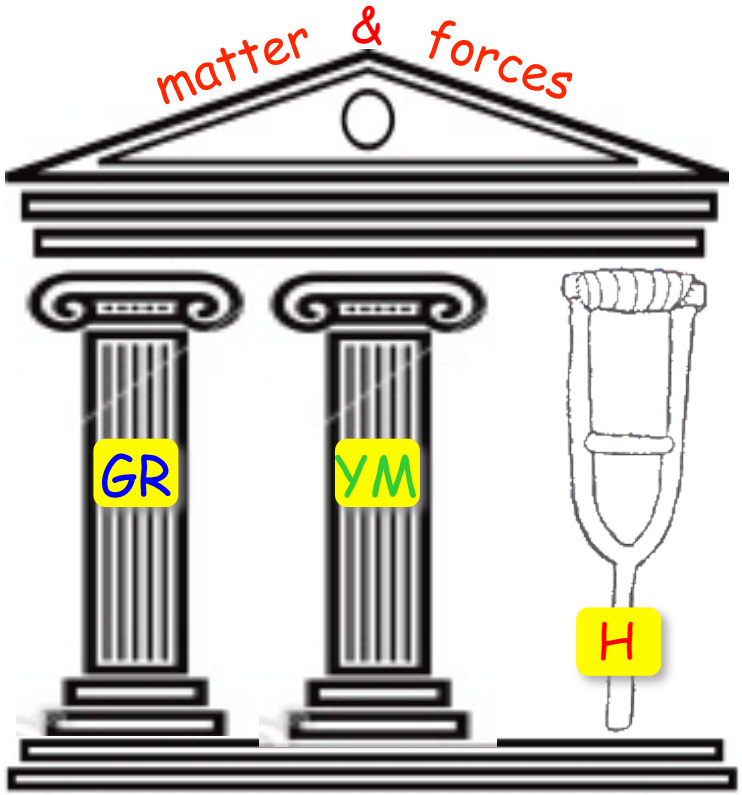
- Identify the origin of a fundamental scale
- A new guise of the gauge principle
- A new force of nature
- Indirect information from Higgs mass and couplings

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



GR + YM

- Structure determined by gauge symmetry
- Few free parameters
- Experimentally tested



GR + YM

- Structure determined by gauge symmetry
- Few free parameters
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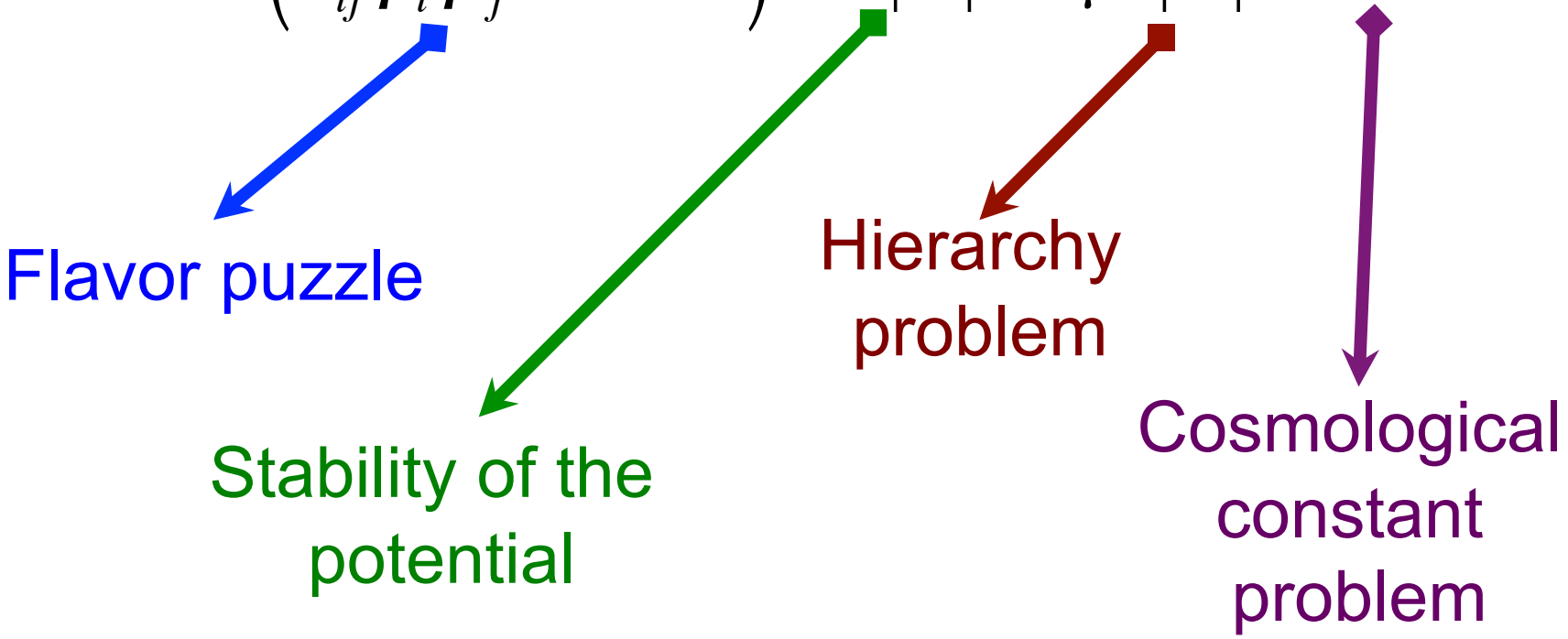
Higgs

- The structure is not determined by pure symmetry principles
- The mechanism is unable to predict the values of quark and lepton masses
- The field value is very sensitive to quantum fluctuations

Courtesy of C. Grojean & A. Weiler

Almost all the problems of the SM originate from Higgs interactions

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



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

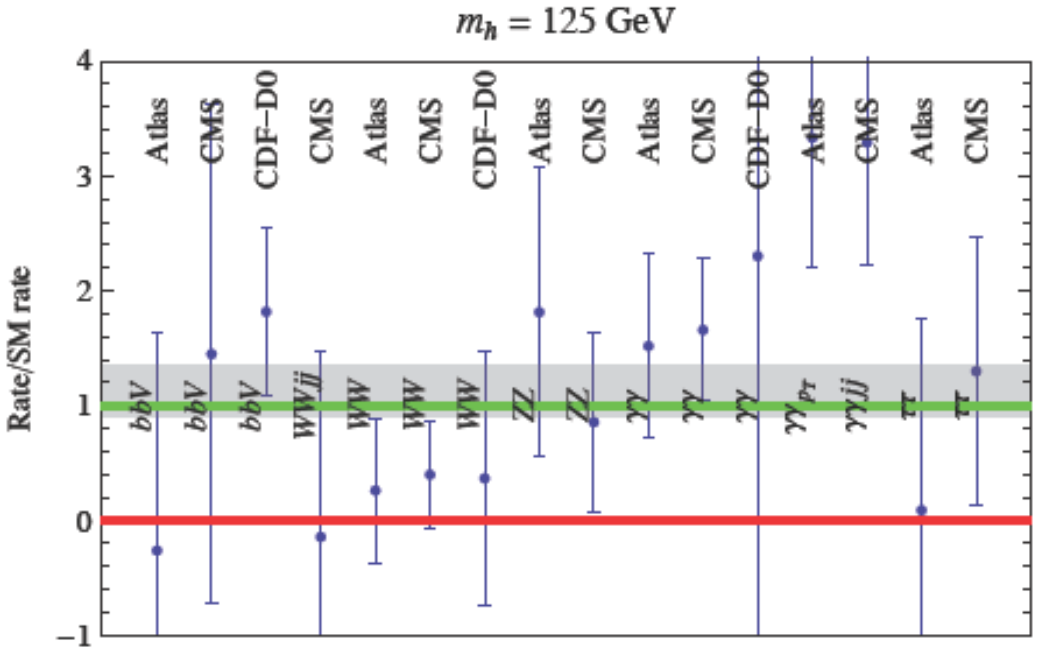
What do we learn from Higgs searches?

Two fundamental questions

1) What is the 5th force?

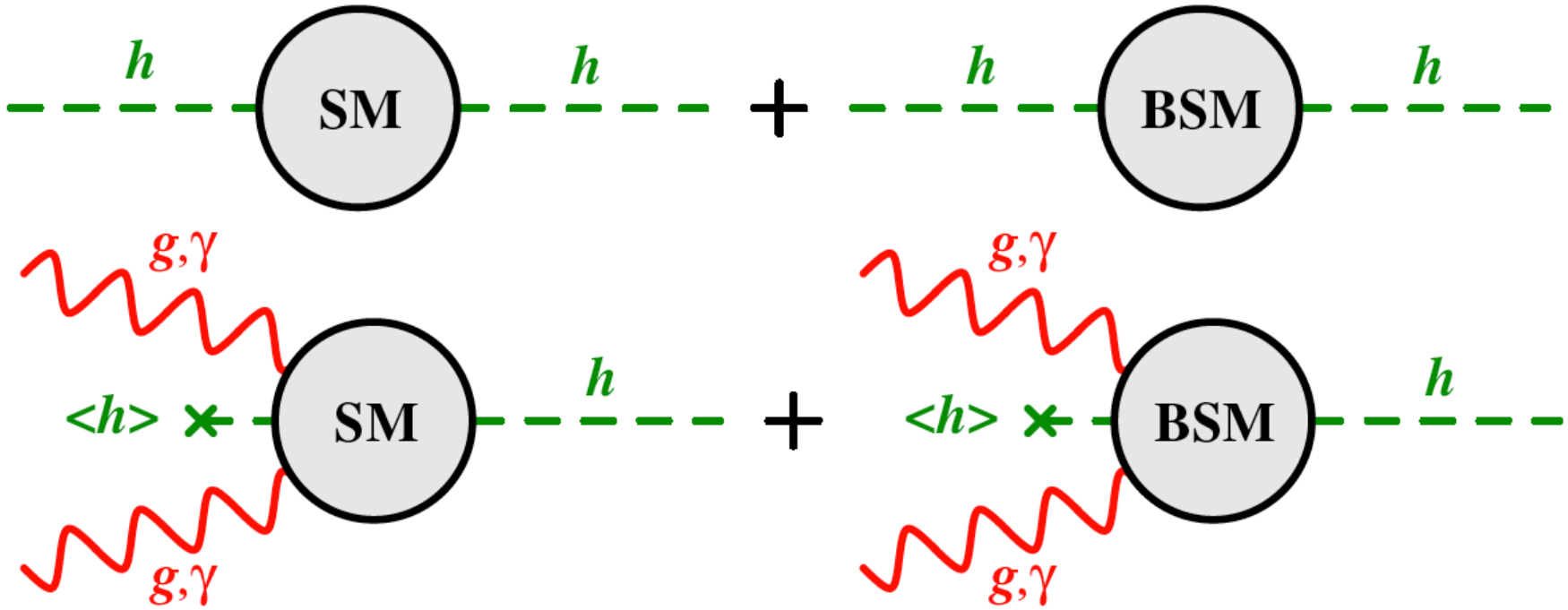
- Is it weak or strong?
- Is it a gauge force?
- Is it associated with a fundamental scalar?

Measurements of Higgs couplings!



The new S-T parameter space of precision measurements
(but deviations could be large!)

The more natural the Higgs is, the more its properties deviate from SM



Natural supersymmetry $\Rightarrow \tilde{m}_t \approx m_t \Rightarrow O(1)$ effects in hgg and $h\gamma\gamma$

Technicolor $\Rightarrow O(1)$ effects in the Higgs

Composite Higgs $\Rightarrow$ effects in Higgs couplings $O\left(v^2/f^2\right)$,

where $4\pi f$ is the compositeness scale

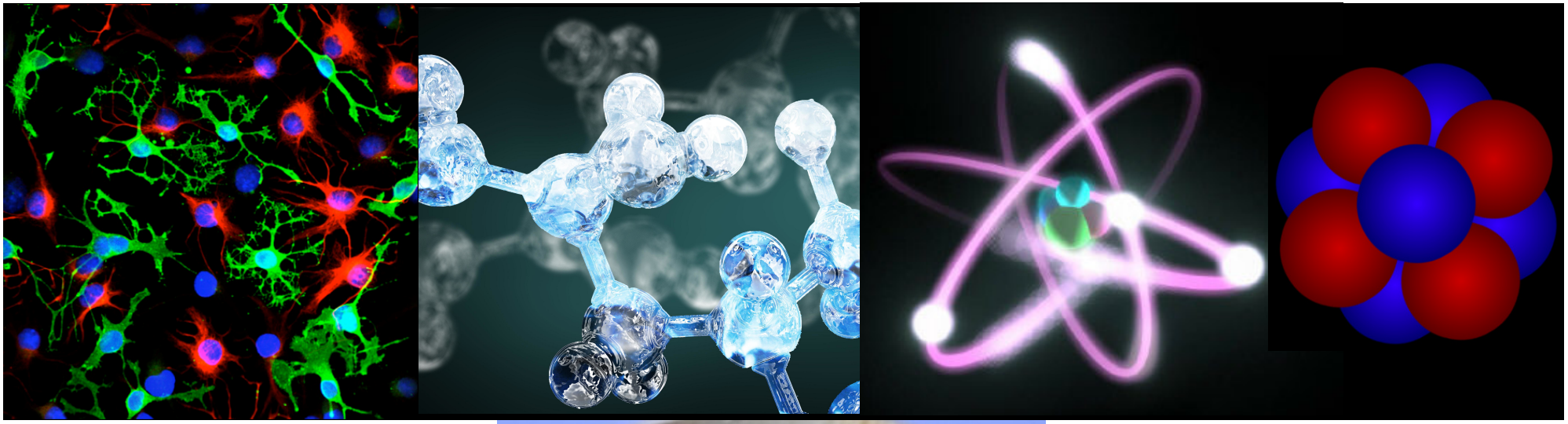
Measuring the Higgs couplings is the way to probe the 5th force and may be the first way for new physics to show up

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 ⇦⇨ Effective field theory



Naturalness at work:
1. classical electron self-energy

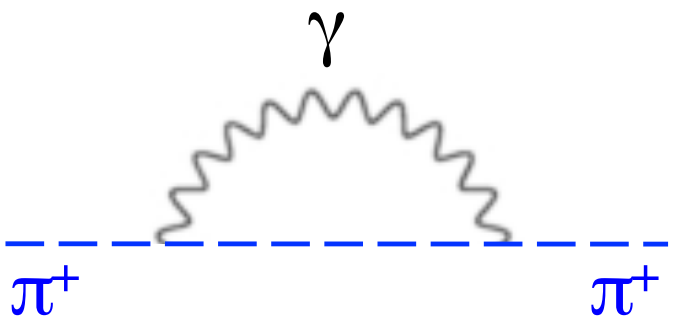
electrostatic energy : $E \approx \frac{\alpha}{r} < m_e c^2 \Rightarrow \Lambda < \frac{m_e}{\alpha} \approx 70\ \text{MeV}$

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 $m_e < \Lambda$

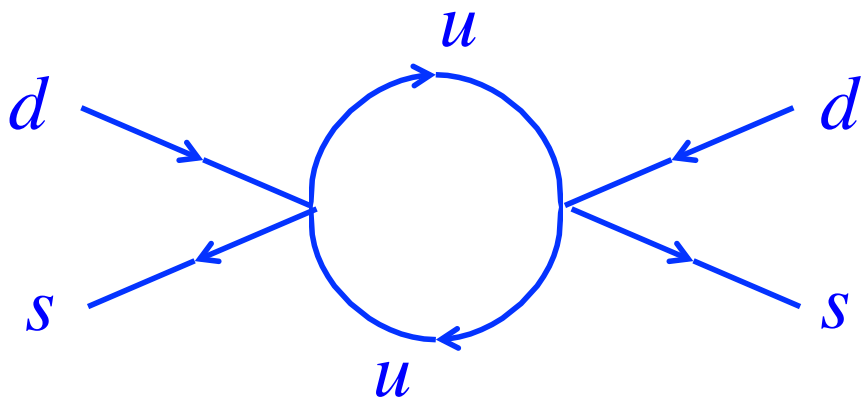
Naturalness at work:
2. QED contribution to pion mass difference



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

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

Naturalness at work:
3. Neutral kaon mass difference



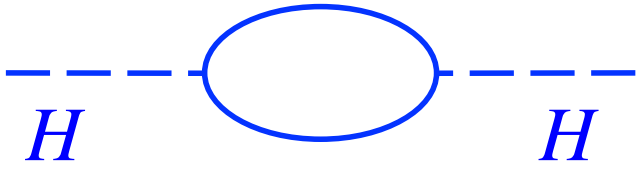
Effective theory at M_K:

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

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

Naturalness at work ?

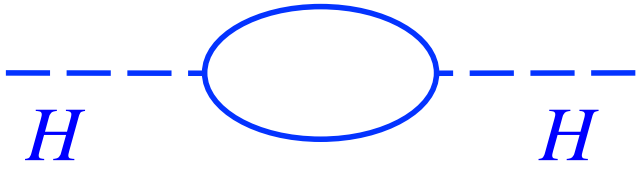
The weak scale



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

Naturalness at work ?

The weak scale



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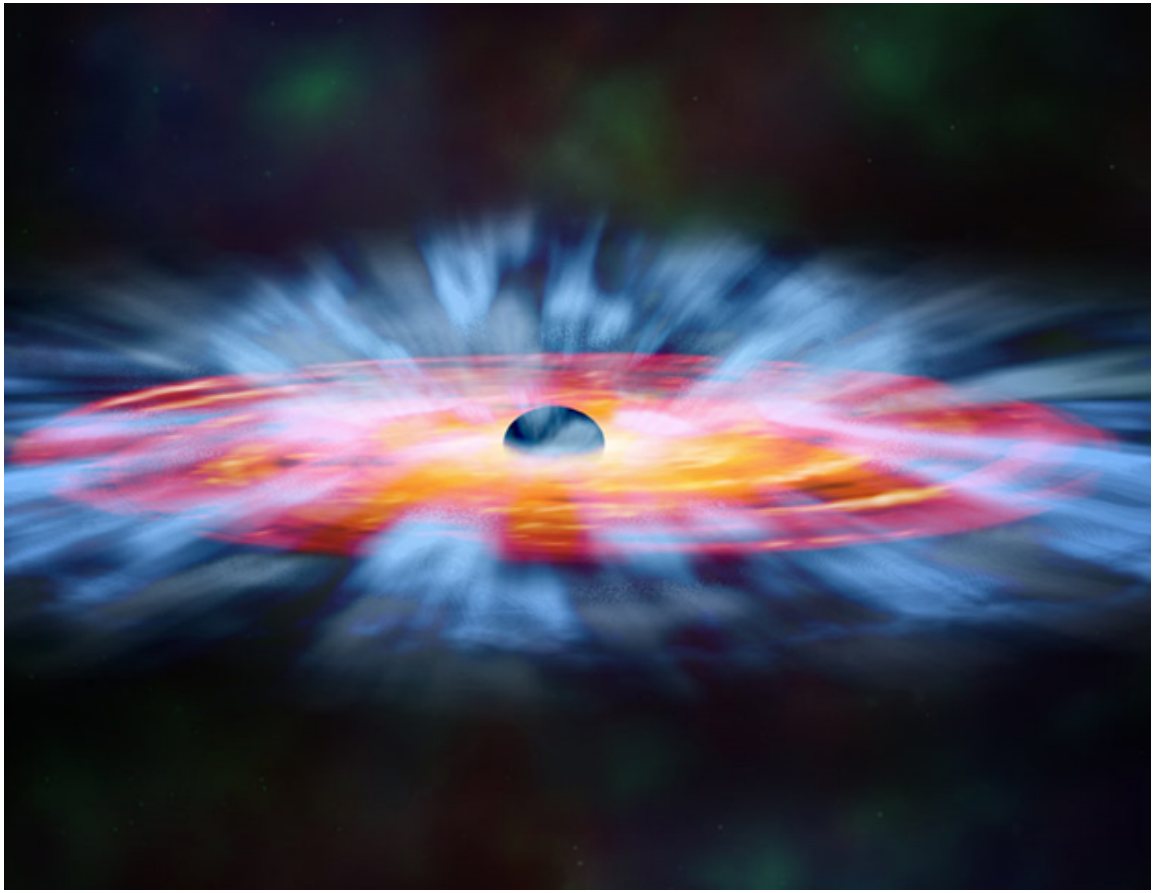
Where is new physics?

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

Is dark energy already evidence for a failure of effective field theories?

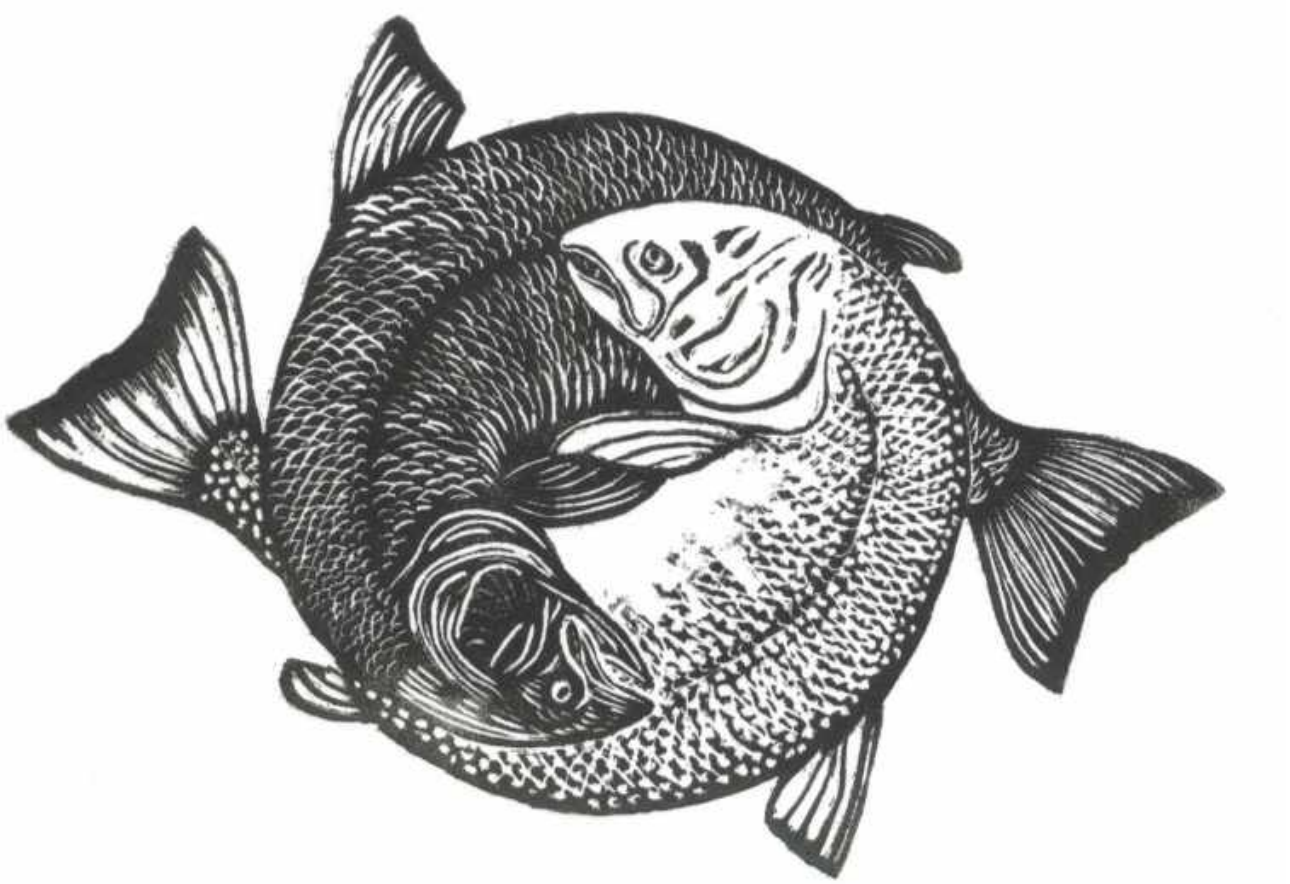
$$\Lambda_{CC} = 2.4 \times 10^{-3}\ \text{eV}$$

Where is new physics?



Is gauge-gravity duality already evidence for a failure of effective field theories?

A single Lagrangian cannot encompass the physical content of the theory



Connection between smallest and largest distances?

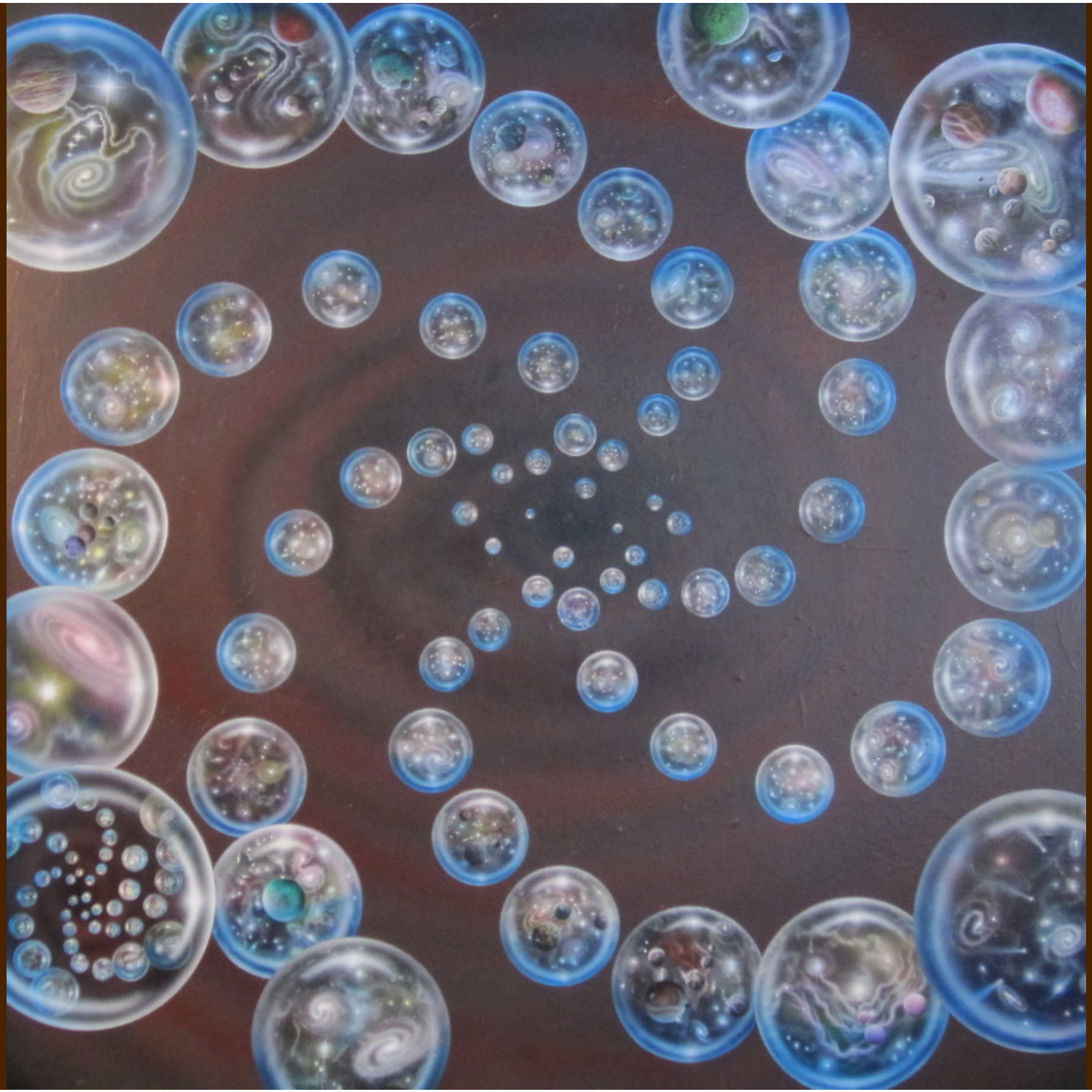
Largest scale = Hubble length H^{-1} = 10^{26} m

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

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

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

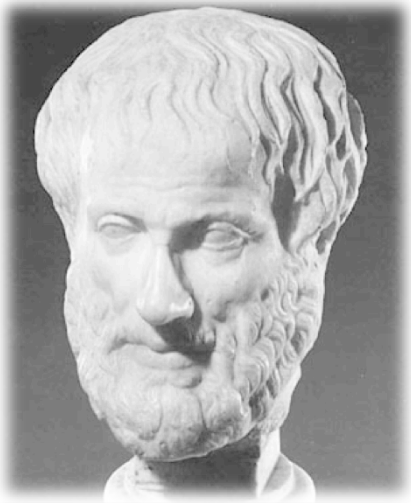
An effective theory will never be able to catch an IR/UV connection




EFT SYMMETRY
UNIFICATION
MULTIVERSE
IR/UV CONNECTION
NO LAGRANGIAN

Establishing the fate of Higgs naturalness has far-reaching consequences for particle physics

The LHC will give us the answer



Natural Higgs accompanied by new physics

➔ Symmetry & unification

SM Higgs

➔ ???

ASSUMPTION: SM + Higgs (with mass 125-126 GeV)

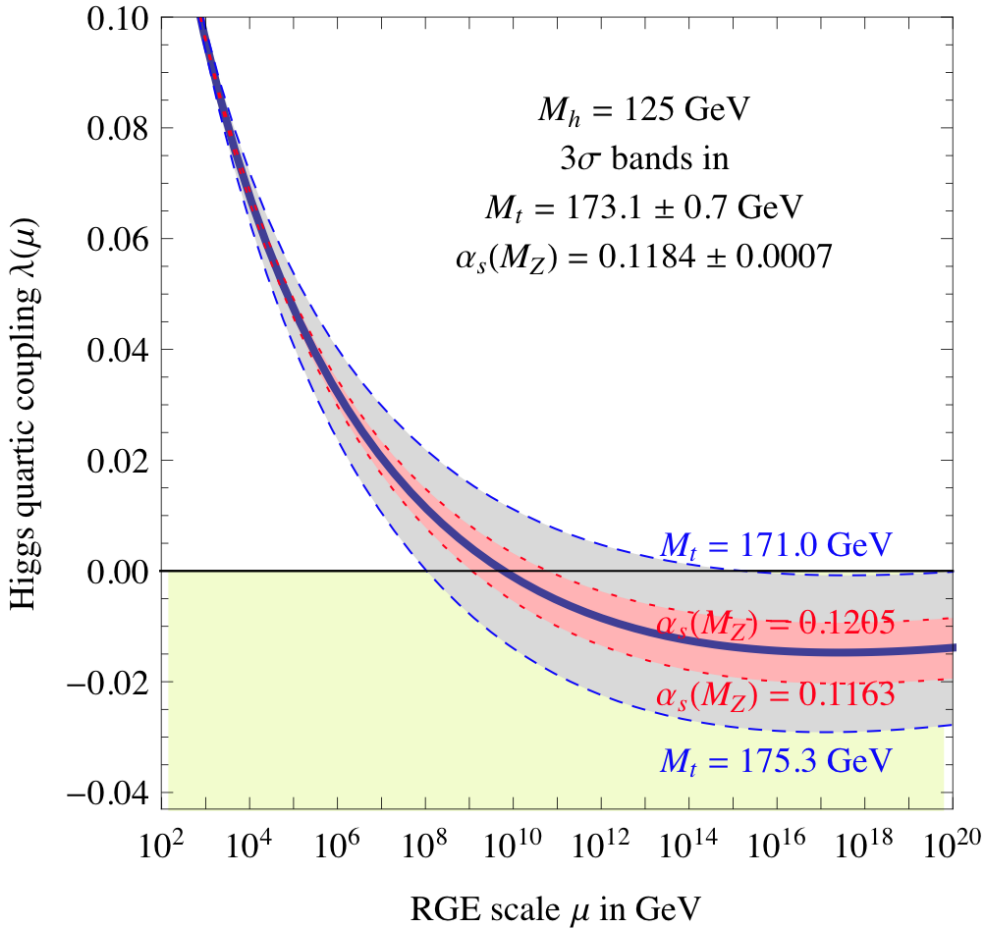
ASSUMPTION: SM + Higgs (with mass 125-126 GeV)

What do we learn if the Higgs mass is 125 GeV?

Do we live on the verge of a cosmic catastophe?

When the universe was 10^{-10} second old, it underwent a phase transition.

Is a new phase transition going to happen?

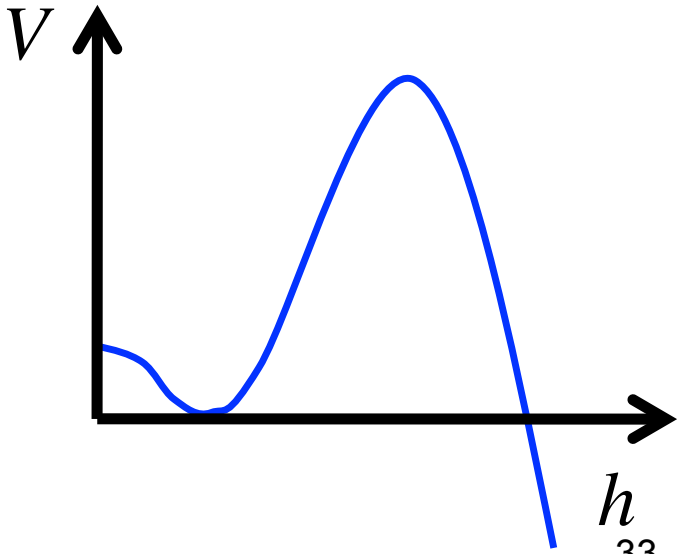


Extrapolate the SM up to very high energies

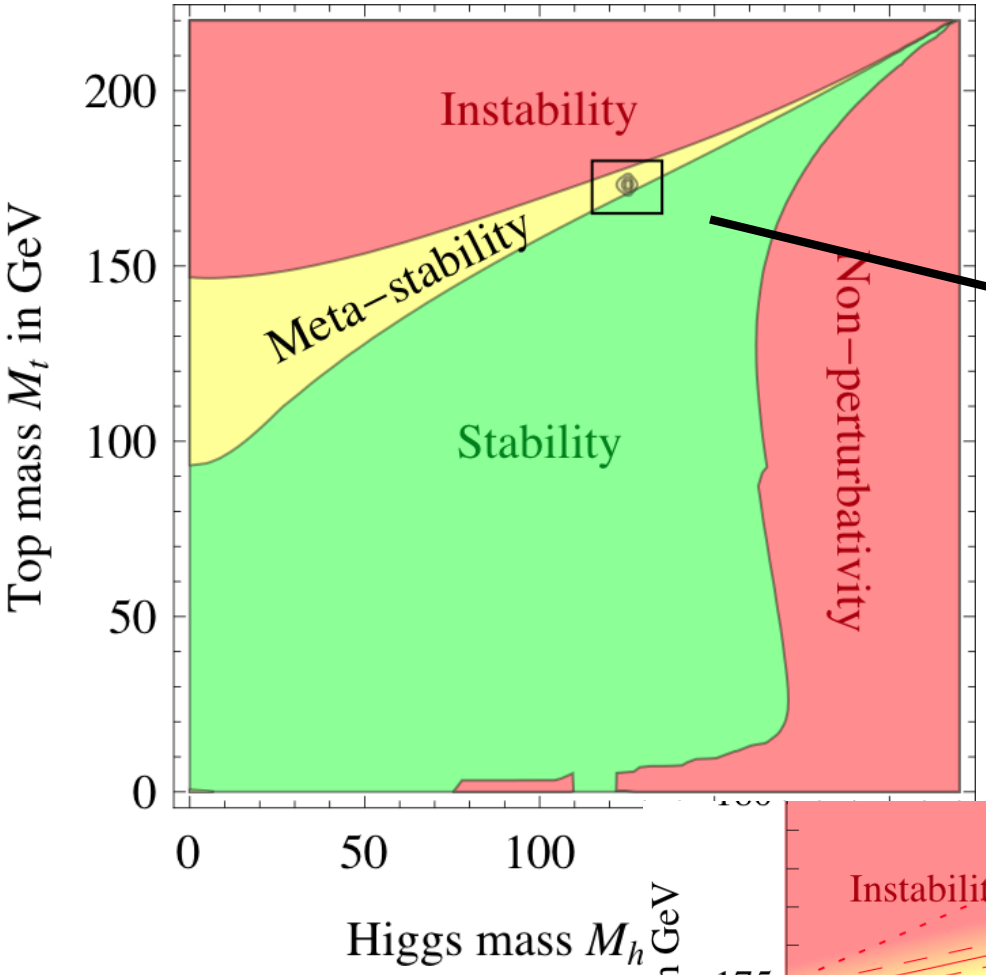
⬆Higgs mass

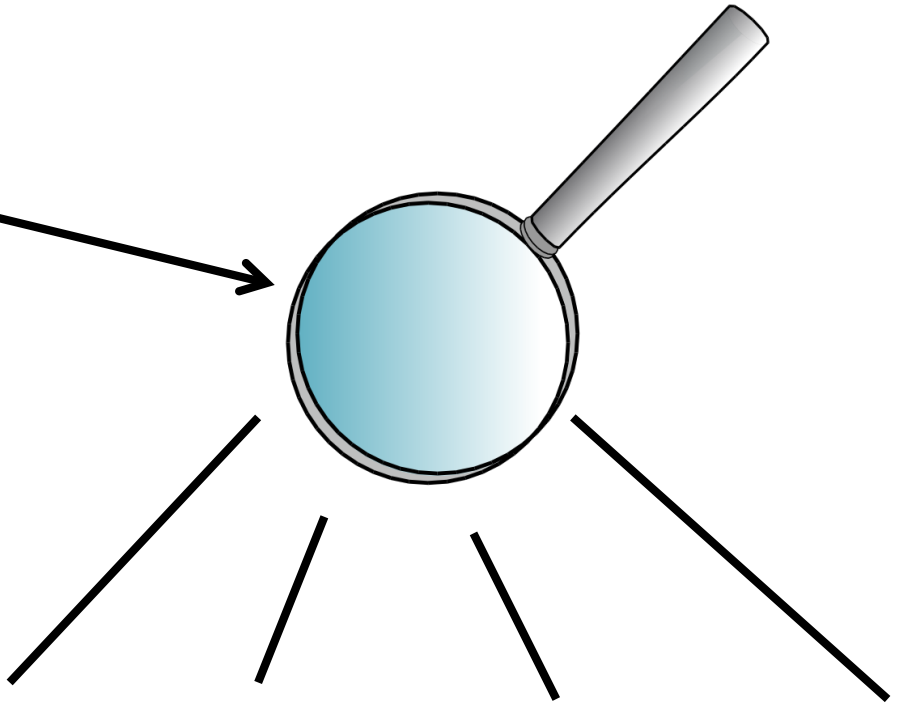
⬇Top quark mass

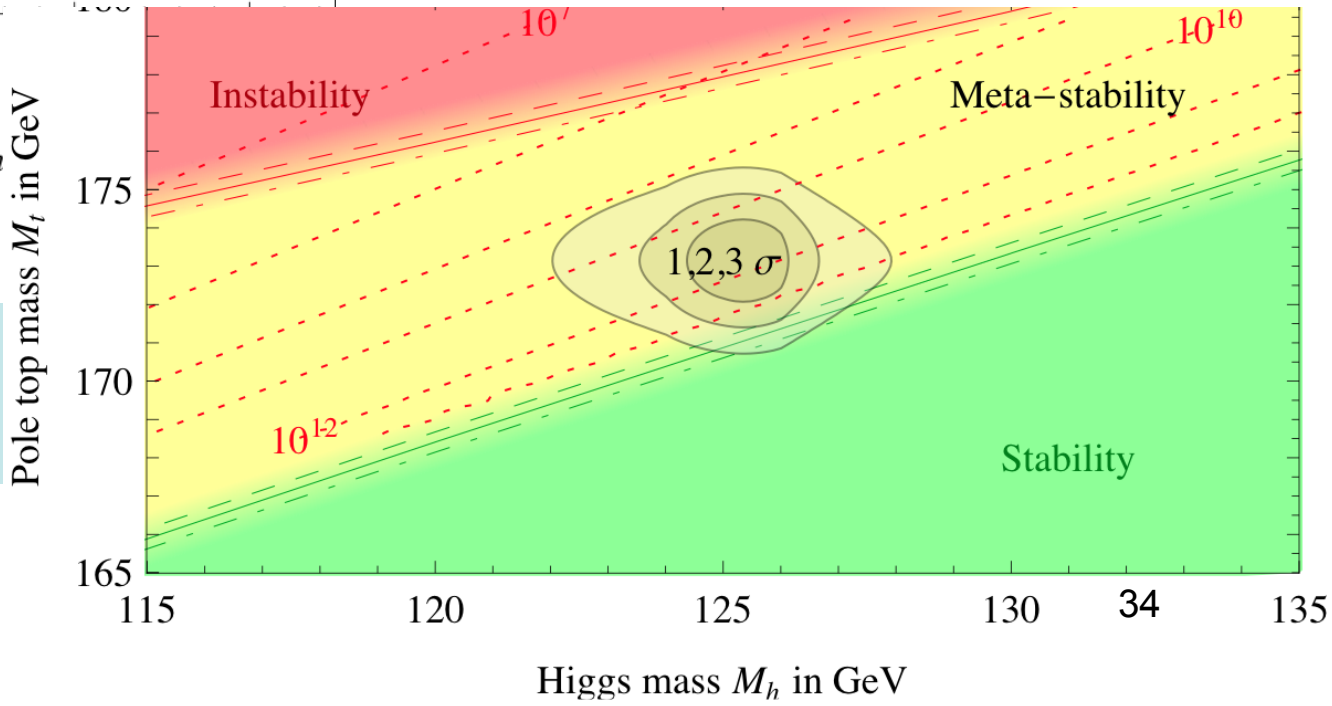
$$V = \frac{\lambda}{4}\left(h^2 - v^2\right)^2$$



- Quantum tunneling
- Thermal tunneling

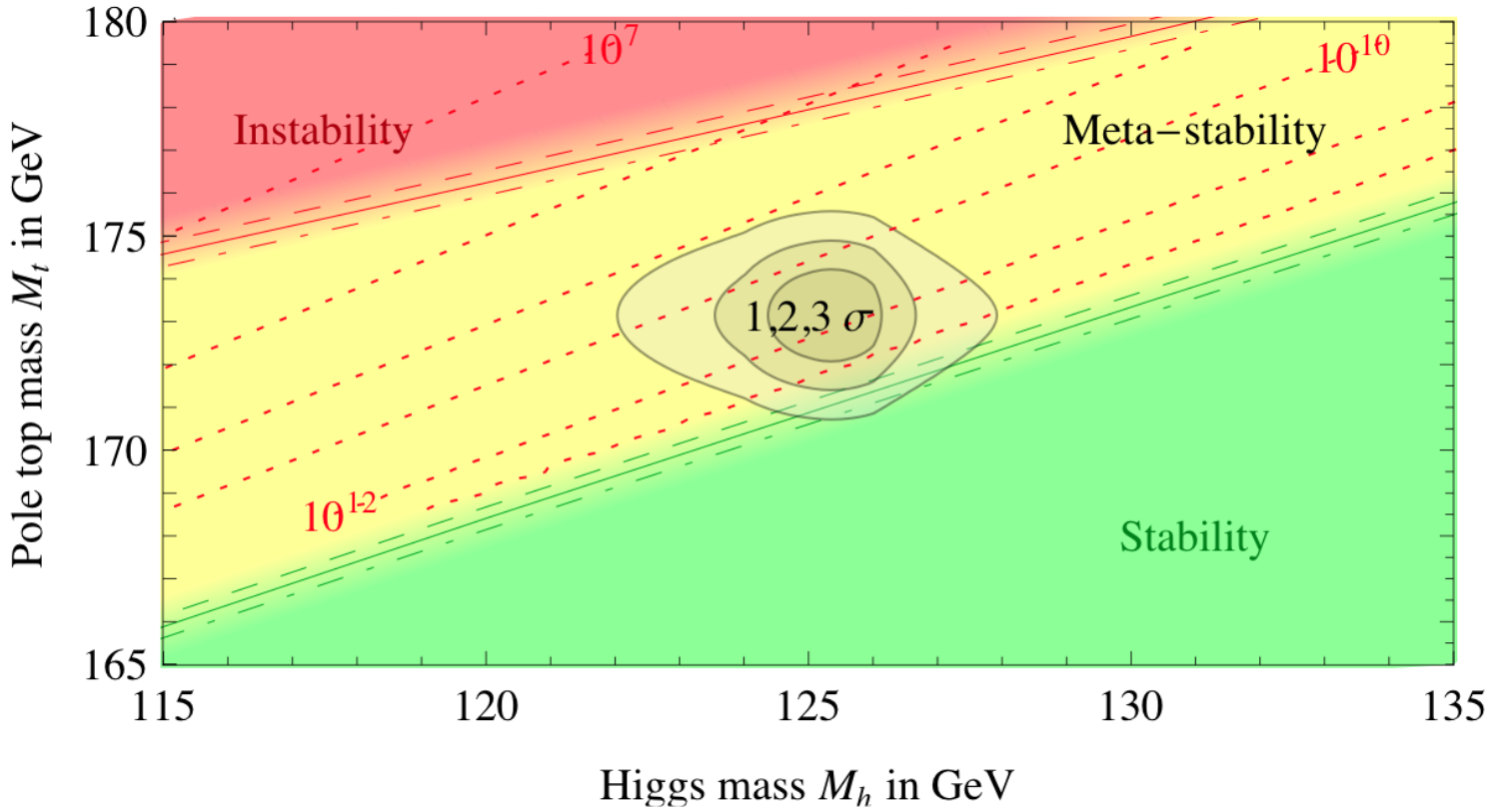






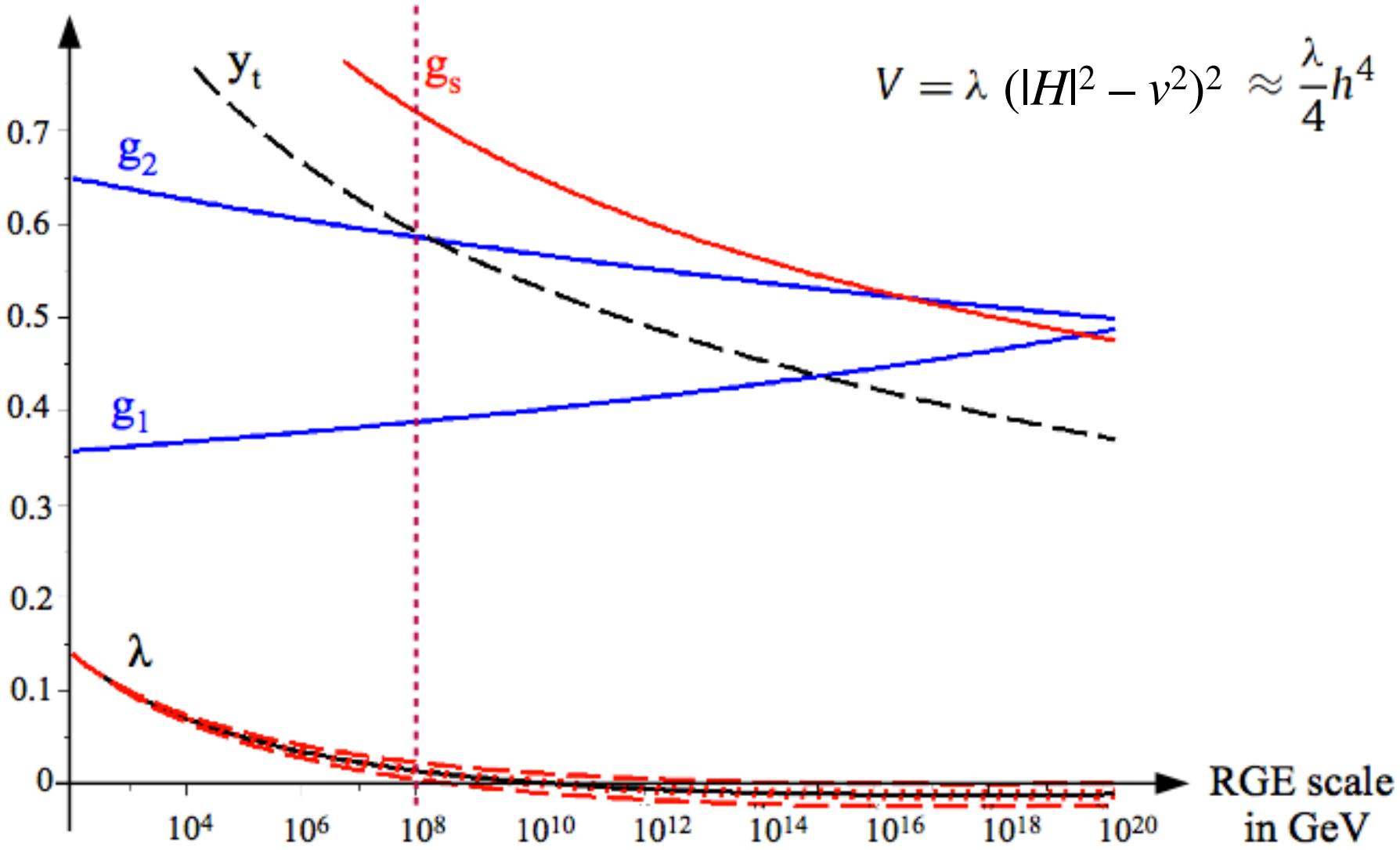
We seem to live near a critical condition

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

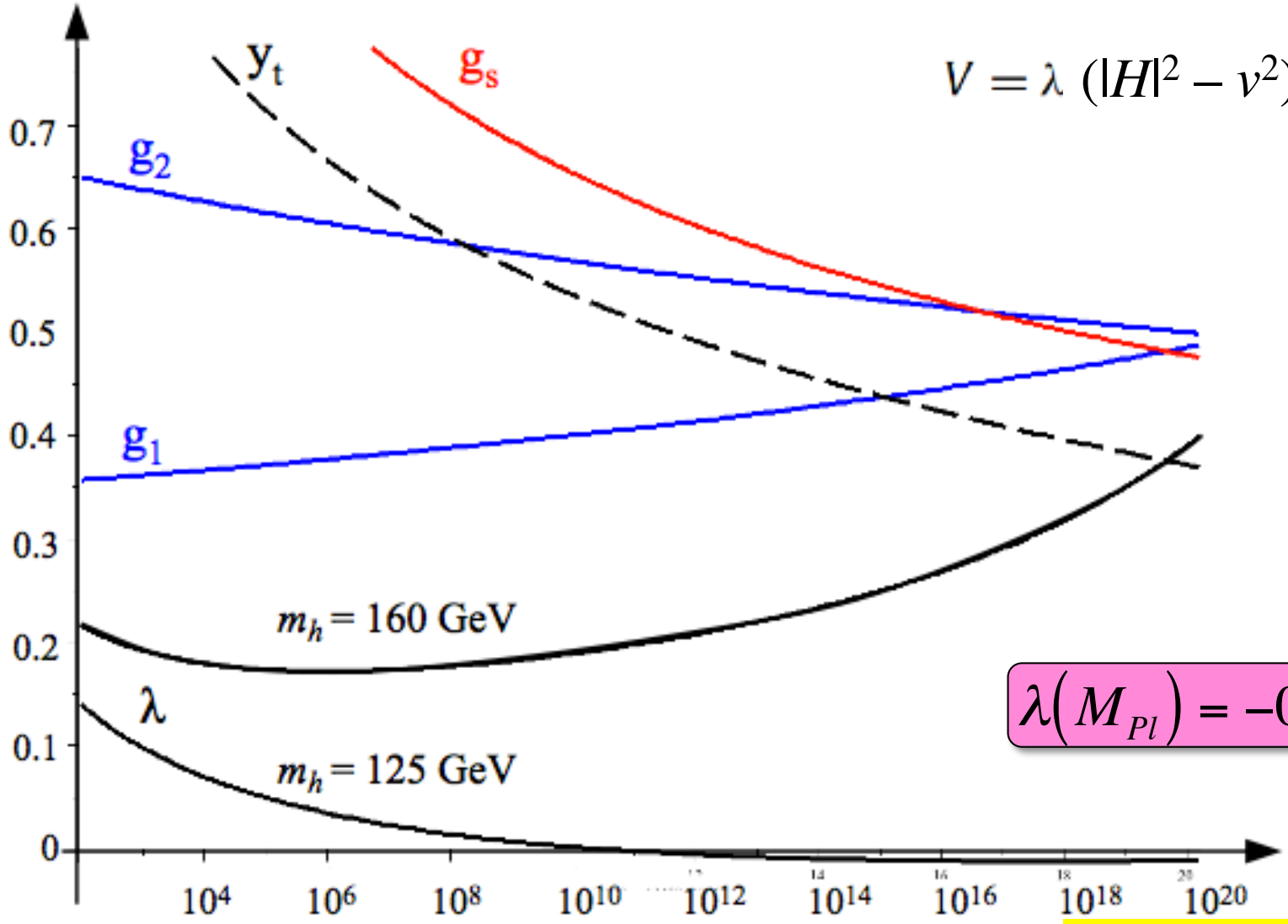


Stability condition:

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



λ and β_λ nearly vanish at high energies?



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

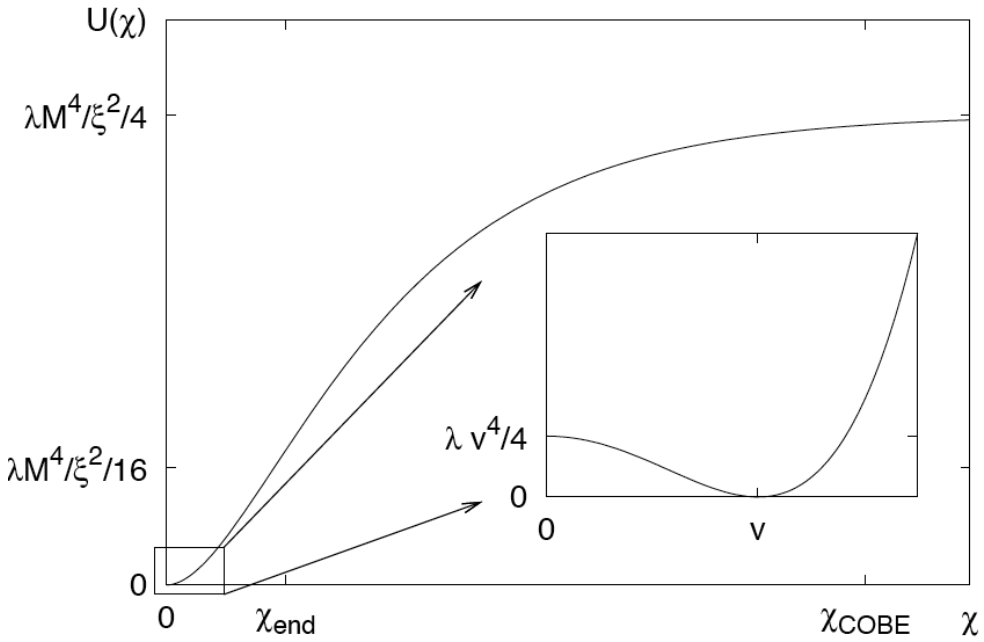
$$\lambda(M_{Pl}) = -0.014 \pm 0.006$$

Difficulty for Higgs inflation (besides other conceptual problems)

HIGGS INFLATION

Non-minimal gravitational coupling flattens potential

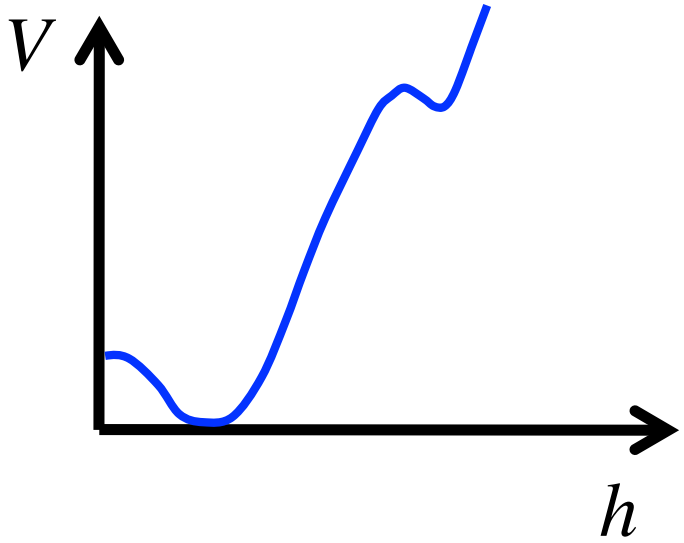
$\xi\,|H|^2\,R$



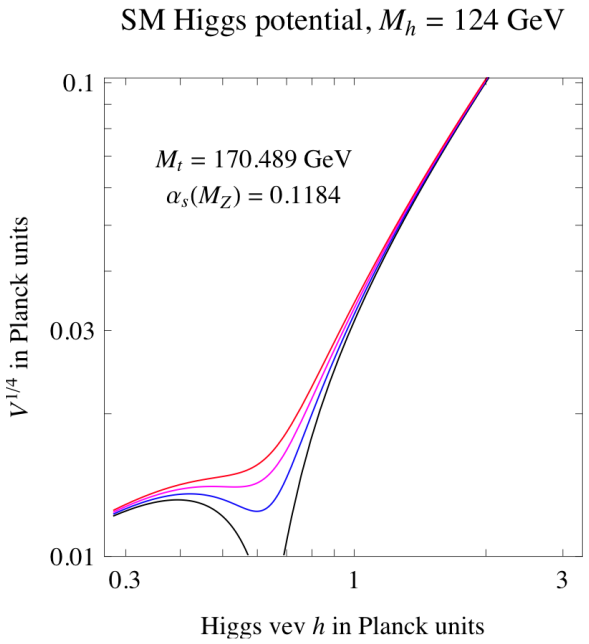
Perturbative unitarity violated below inflationary scale

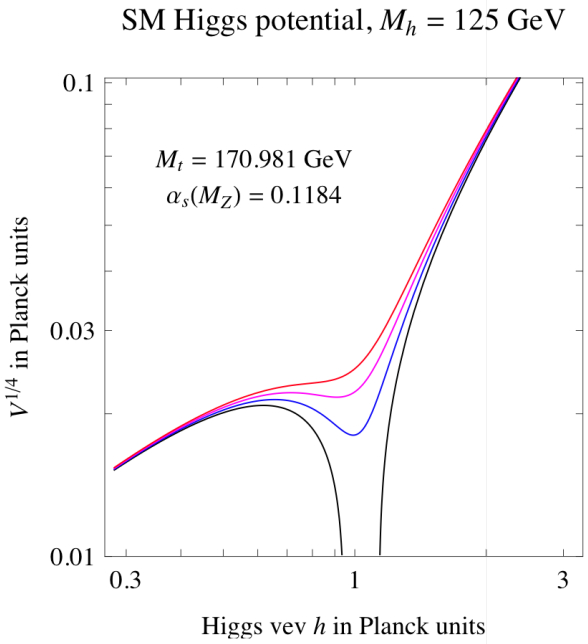
Higgs must be in the stability region: $m_t < 171$ GeV

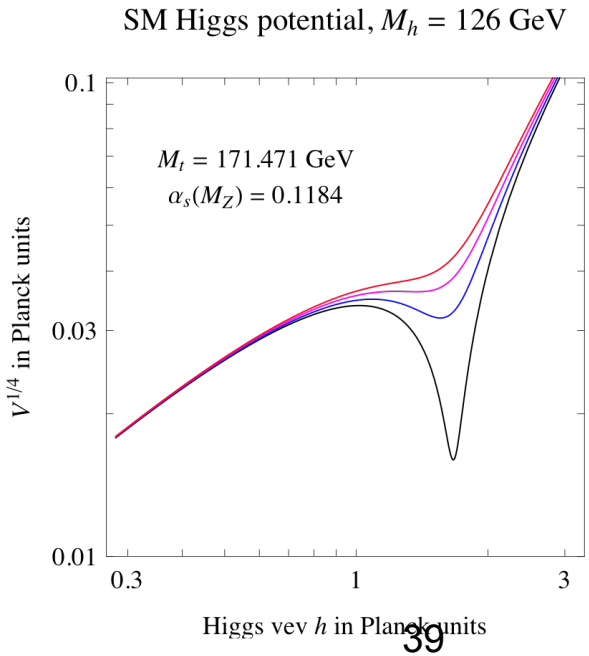
HIGGS INFLATION



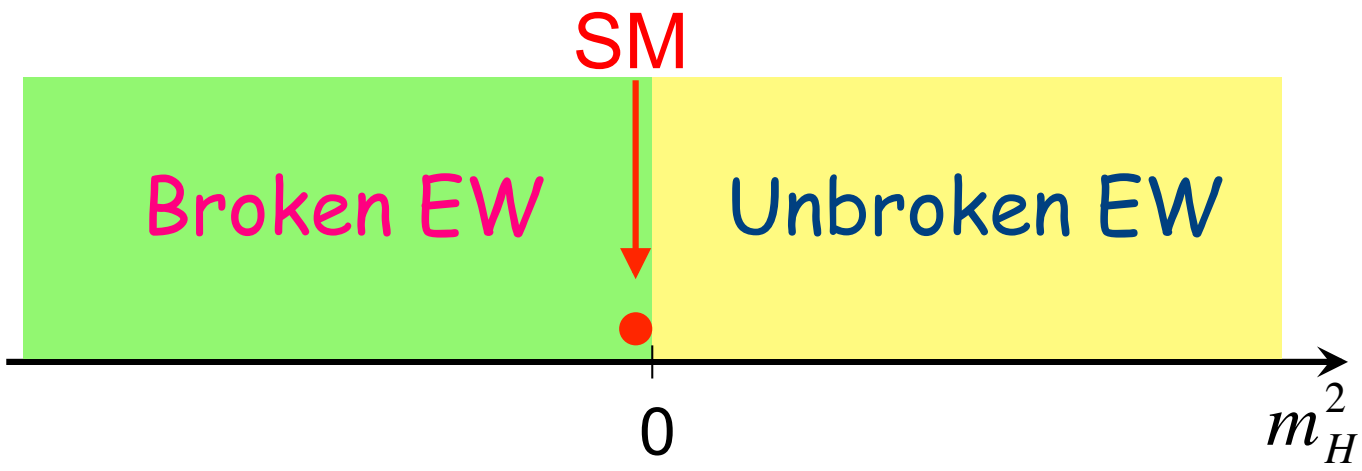
New scalars to exit inflation
(why not adding an inflaton?)







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?

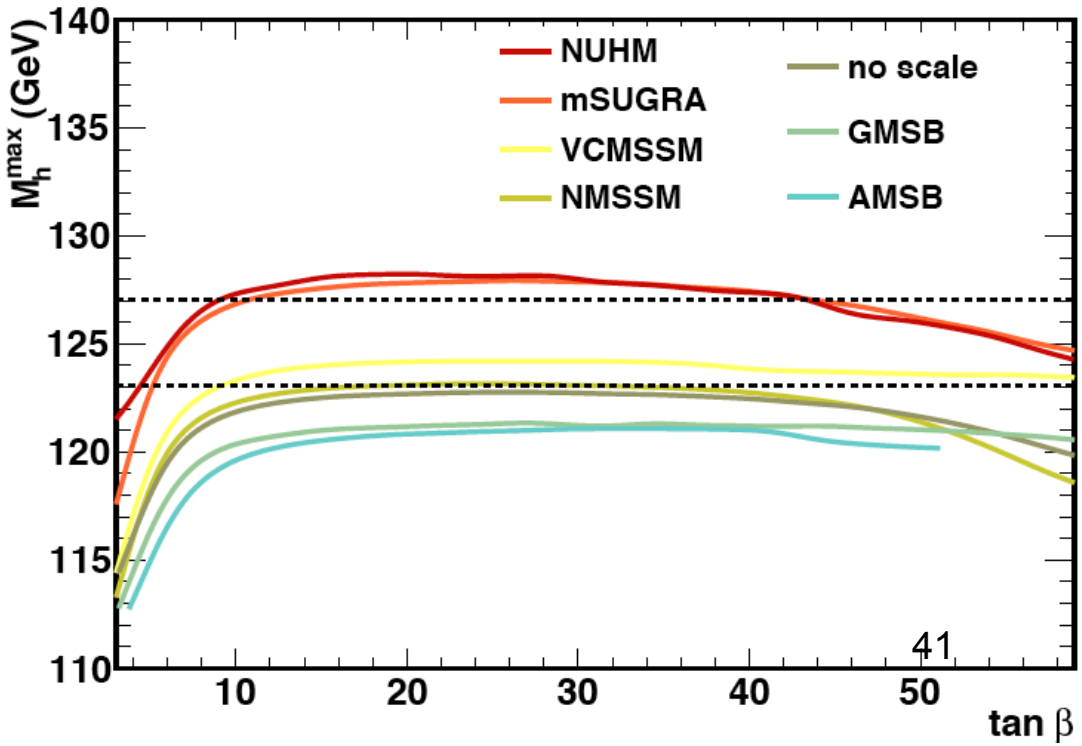
Higgs mass is a critical parameter for many BSM theories

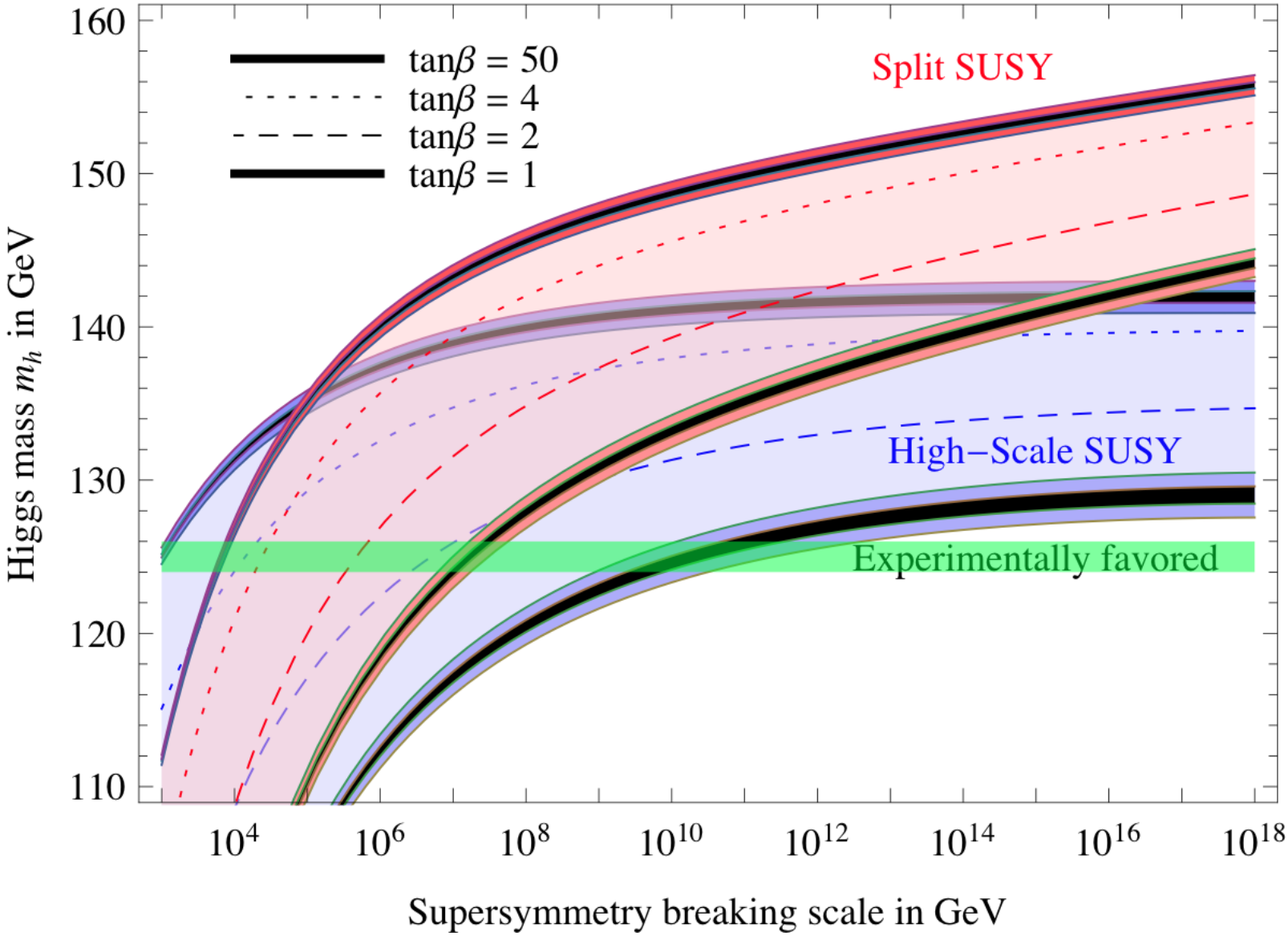
$m_h < 120$ GeV OK for natural susy

$m_h > 130$ GeV NO minimal susy

In susy, $m_h \approx 125$ GeV can be reached, but only for extreme parameters

- Enough to exclude some natural setups
- The idea of low-energy susy is still alive





- $m_h \approx 125$ 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 lie in precision measurements of Higgs mass and couplings

The answers will define future directions of our field

Important consequences for BSM theories

The most puzzling (and surprising) message is criticality

Numerical coincidence or deep meaning?