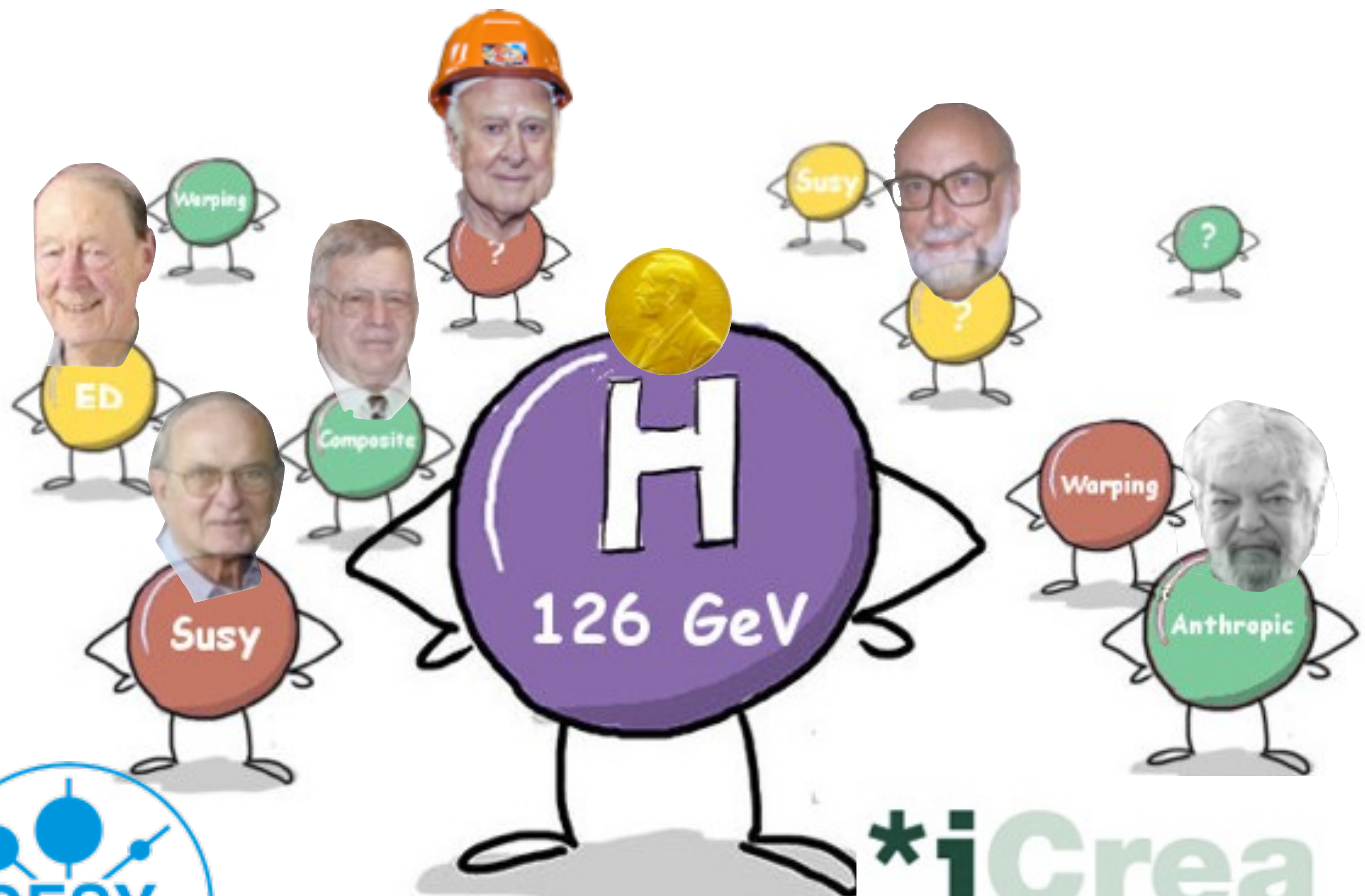
Beyond the Standard Model

CERN summer student lectures 2015



Lecture 3/5

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INSTITUCIÓ CATALANA DE RECERCA I ESTUDIS AVANÇATS

Outline

- Monday
  - general introduction, units
- Tuesday
  - Higgs physics as a door to BSM
- Wednesday
  - Higgs and Naturalness: small and large numbers in a quantum world
- Thursday
  - grand unification, proton decay
  - supersymmetry
  - extra dimensions
- Friday
  - cosmological interplay

Higgs and Flavor

In SM, the Yukawa interactions are the only source of the fermion masses

$$y_{ij}\bar{f}_{L_i}Hf_{R_j} = \frac{y_{ij}v}{\sqrt{2}}\bar{f}_{L_i}f_{R_j} + \frac{y_{ij}}{\sqrt{2}}h\bar{f}_{L_i}f_{R_j}$$

mass ↗ ↖ higgs-fermion interactions

both matrices are simultaneously diagonalizable

⇩ ⇩ ⇩

no tree-level Flavor Changing Current induced by the Higgs

Not true anymore if the SM fermions mix with vector-like partners $^{(*)}$ or for non-SM Yukawa

$$y_{ij}\left(1+c_{ij}\frac{|H|^2}{f^2}\right)\bar{f}_{L_i}Hf_{R_j} = \frac{y_{ij}v}{\sqrt{2}}\left(1+c_{ij}\frac{v^2}{2f^2}\right)\bar{f}_{L_i}f_{R_j} + \left(1+3c_{ij}\frac{v^2}{2f^2}\right)\frac{y_{ij}}{\sqrt{2}}h\bar{f}_{L_i}f_{R_j}$$

Look for SM forbidden Flavor Violating decays $h \to \mu\tau$ and $t \to hc$

- weak indirect constrained by flavor data (e.g. $\mu \to e\gamma$): BR<10%
- ATLAS and CMS have the sensitivity to set bounds O(1%)
- ILC/CLIC/FCC-ee can certainly do much better

Blankenburg, Ellis, Isidori '12

Harnik et al '12
Davidson, Verdier '12
CMS-PAS-HIG-2014-005

$^{(*)}$ e.g. Buras, Grojean, Pokorski, Ziegler '11

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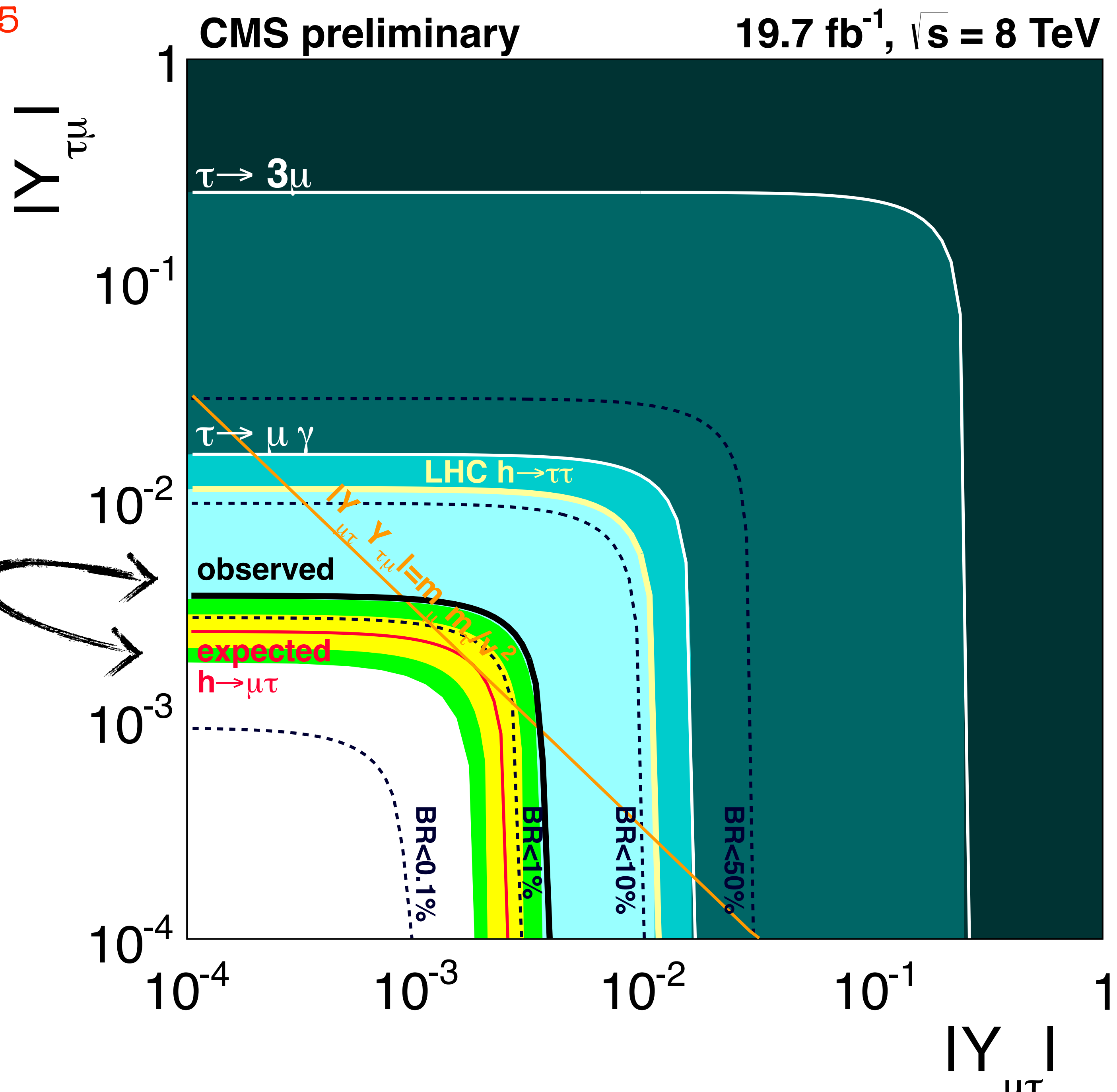
CMS-PAS-HIG-2014-005



by the way:
2.3σ excess!

Off-diagonal Higgs couplings can reveal the origin of flavor

The interesting models of flavor ($Y_{ij} \approx \sqrt{(m_i m_j/v^2)}$) start being probed by the experimental data

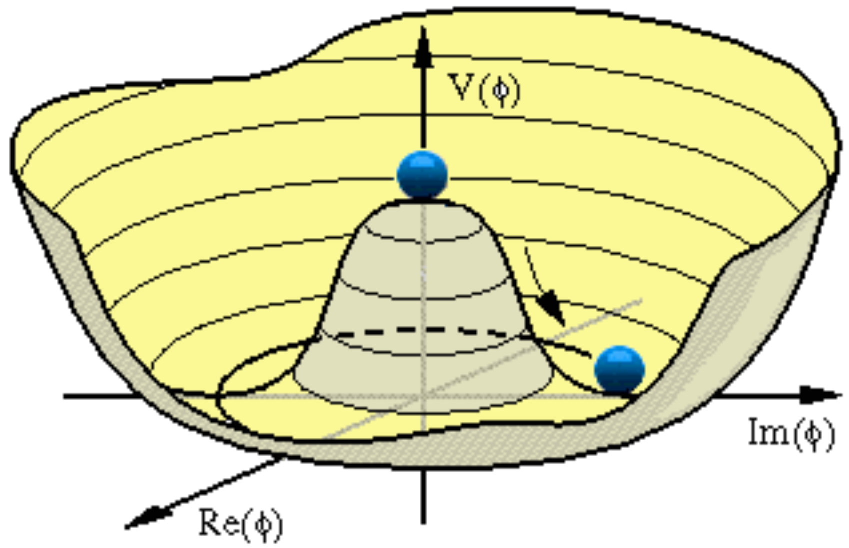
HEP with a Higgs boson

"If you don't have the ball, you cannot score"

Now with the Higgs boson in their feets,
particle physicists can... play as well as Barça players

Profound change in paradigm:
missing SM particle ⇨ tool to explore SM and venture into physics landscape beyond

Higgs and EW vacuum Stability

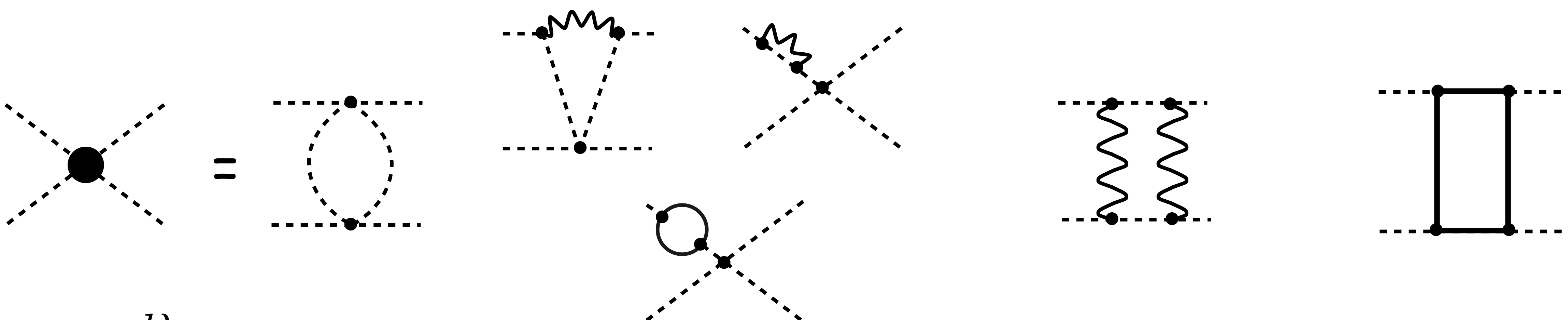


$$V(h) = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4$$

vev: $v^2 = \mu^2/\lambda$ mass: $m_H^2 = 2\lambda v^2$

the vacuum is not empty even classically $(\hbar \to 0)$

How is Quantum Mechanics changing the picture?



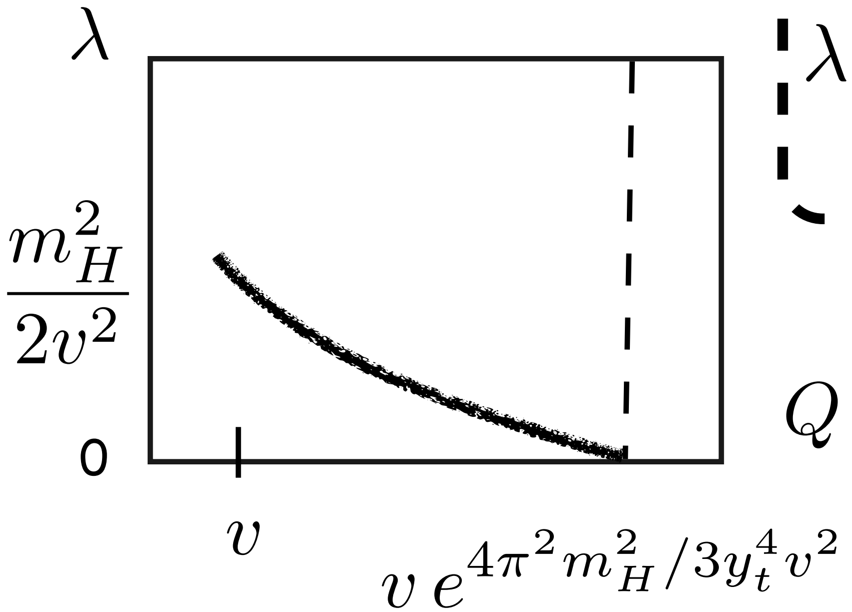
$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - 6y_t^4 +$$ Higher loops Small Yukawa

Higgs and EW vacuum Stability

Small mass (y_t dominated RGE)

$$\lambda(Q) = \lambda_0 - \frac{\frac{3}{8\pi^2} y_0^4 \ln \frac{Q}{Q_0}}{1 - \frac{9}{16\pi^2} y_0^2 \ln \frac{Q}{Q_0}}$$

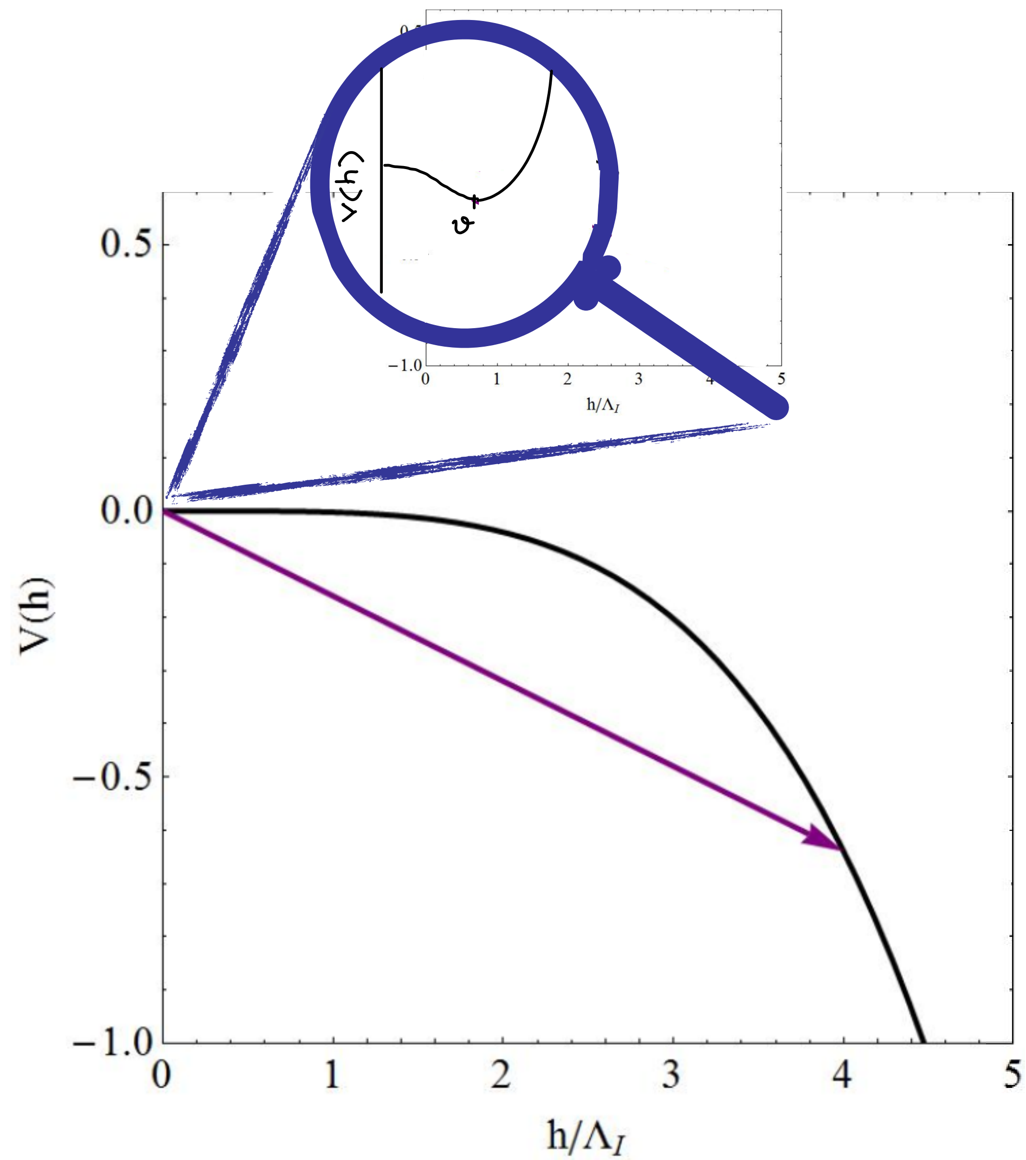
Linde '76, '80
Weinberg '76
Maini et al '78, '79
Politzer, Wolfram '79
Lindner '86
+...



$\lambda < 0$ ⇛ potential unbounded from below

$$\Lambda \leq v\, e^{4\pi^2 m_H^2/3y_t^4 v^2}$$

New physics should appear before that point to restore stability



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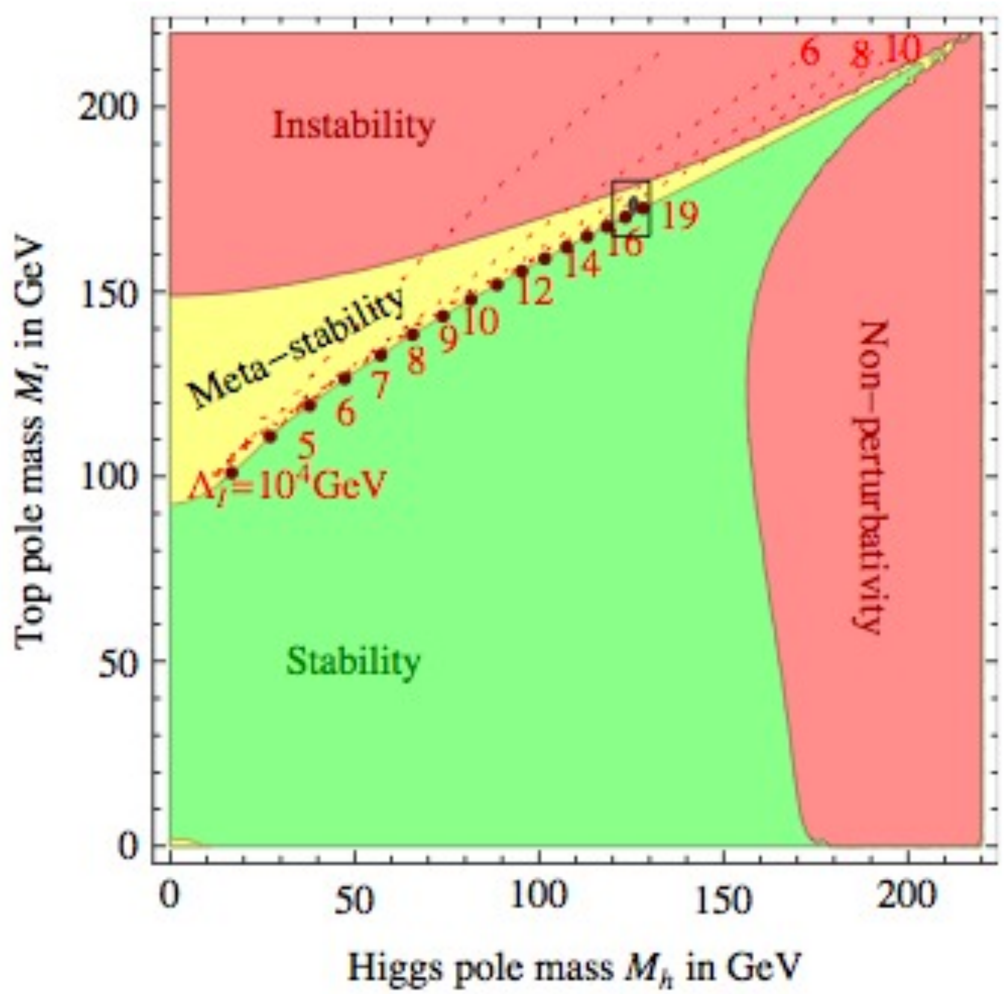
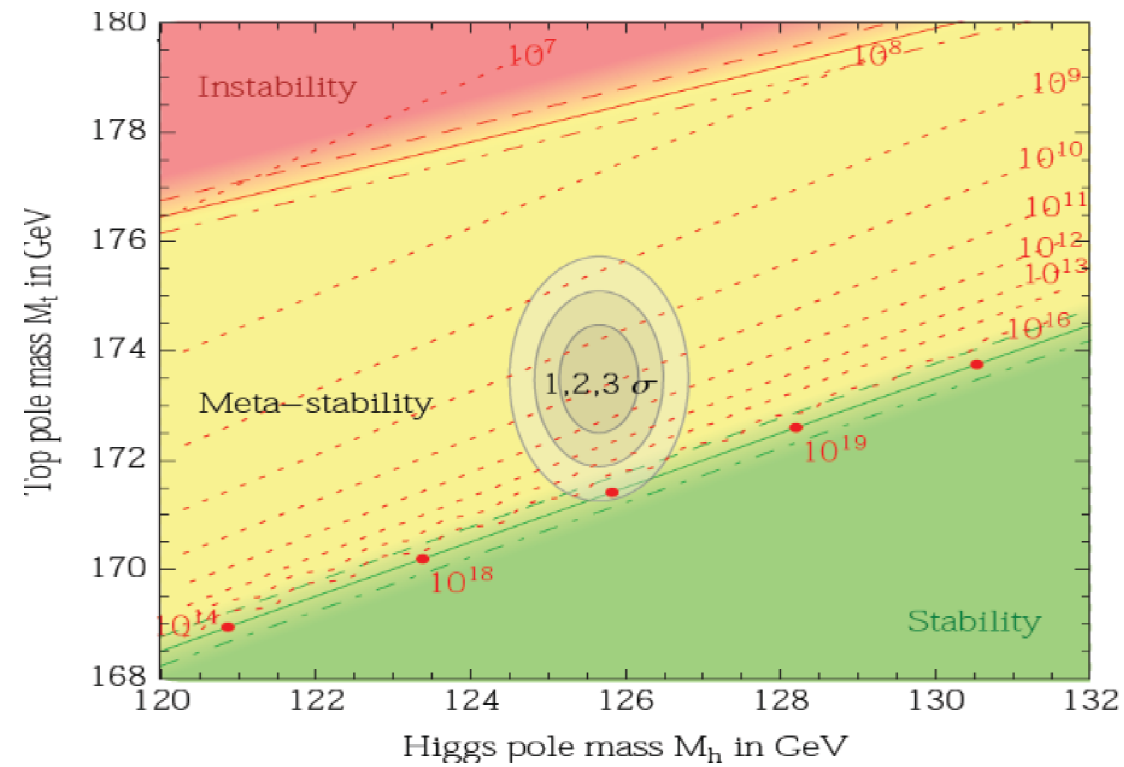
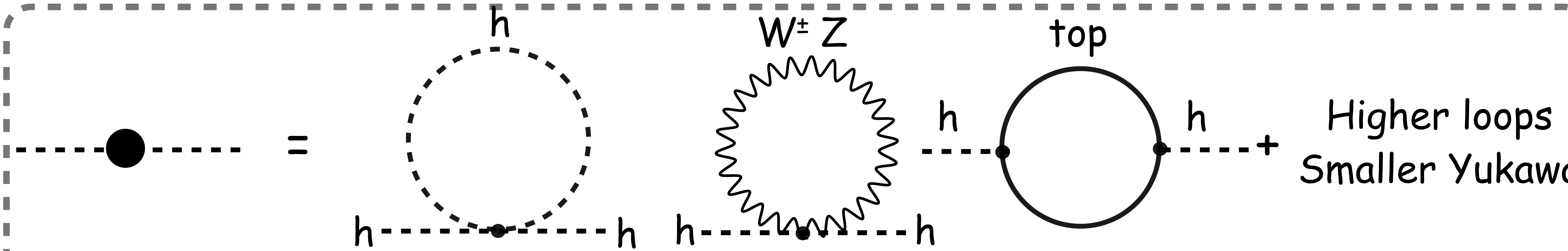




Buttazzo et al '13

Quantum Instability of the Higgs Mass

so far we looked only at the RG evolution of the Higgs quartic coupling (dimensionless parameter). The Higgs mass has a totally different behavior: it is highly dependent on the UV physics, which leads to the so called hierarchy problem



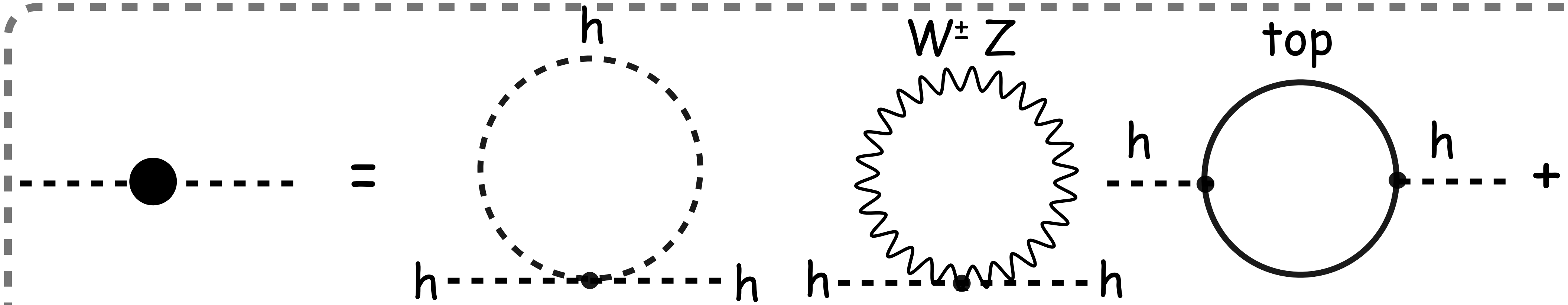
$$\int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m^2} \propto \Lambda^2 \qquad \int \frac{d^4k}{(2\pi)^4}\frac{k^2}{(k^2-m^2)^2} \propto \Lambda^2$$

Weisskopf '39
't hooft '79

$$\delta m_H^2 = \left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)\frac{3G_F\Lambda^2}{8\sqrt{2}\pi^2}$$

$$m_H^2 \sim m_0^2 - (115\ \text{GeV})^2\left(\frac{\Lambda}{700\ \text{GeV}}\right)^2$$

Quantum Instability of the Higgs Mass

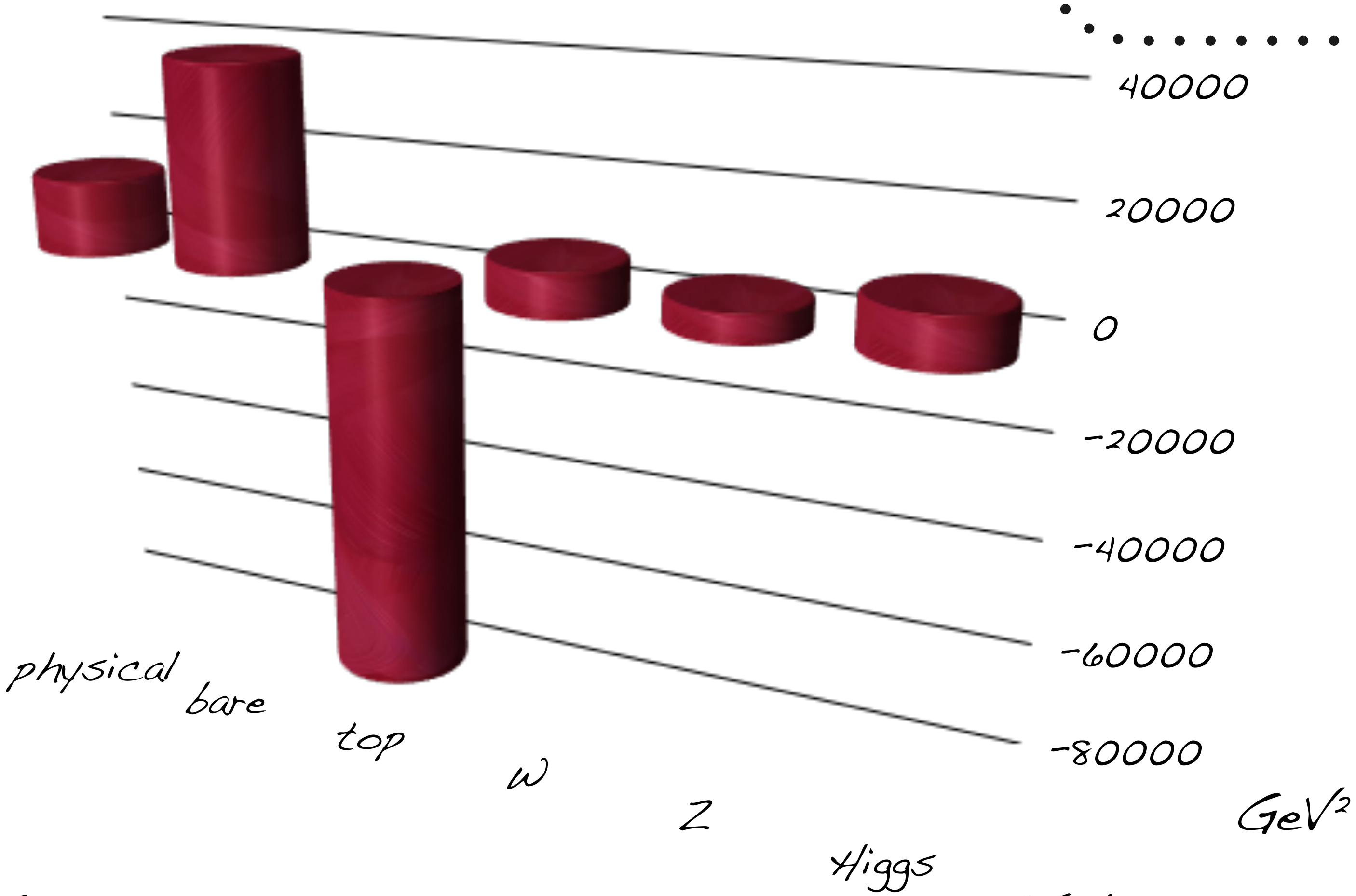


Higher loops
Smaller Yukawa

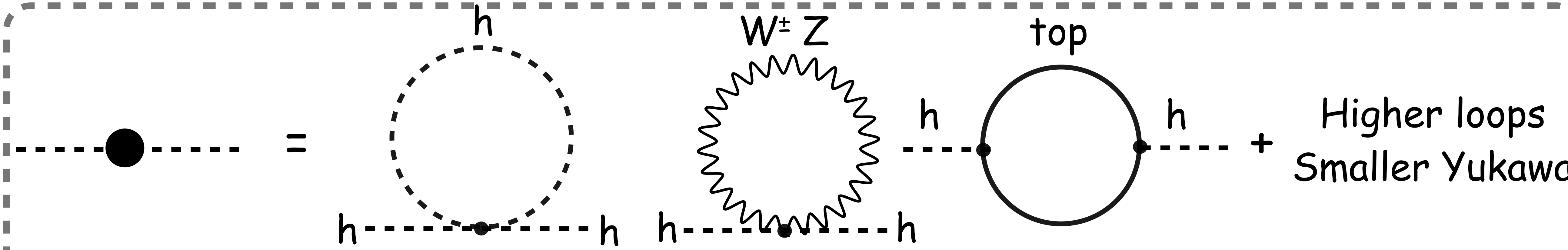
$$\int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m^2} \propto \Lambda^2 \qquad \int \frac{d^4k}{(2\pi)^4}\frac{k^2}{(k^2-m^2)^2} \propto \Lambda^2$$

$$m_H^2 \sim m_0^2 - (115\ \text{GeV})^2 \left(\frac{\Lambda}{700\ \text{GeV}}\right)^2$$

$\Lambda = 1$ TeV



Quantum Instability of the Higgs Mass



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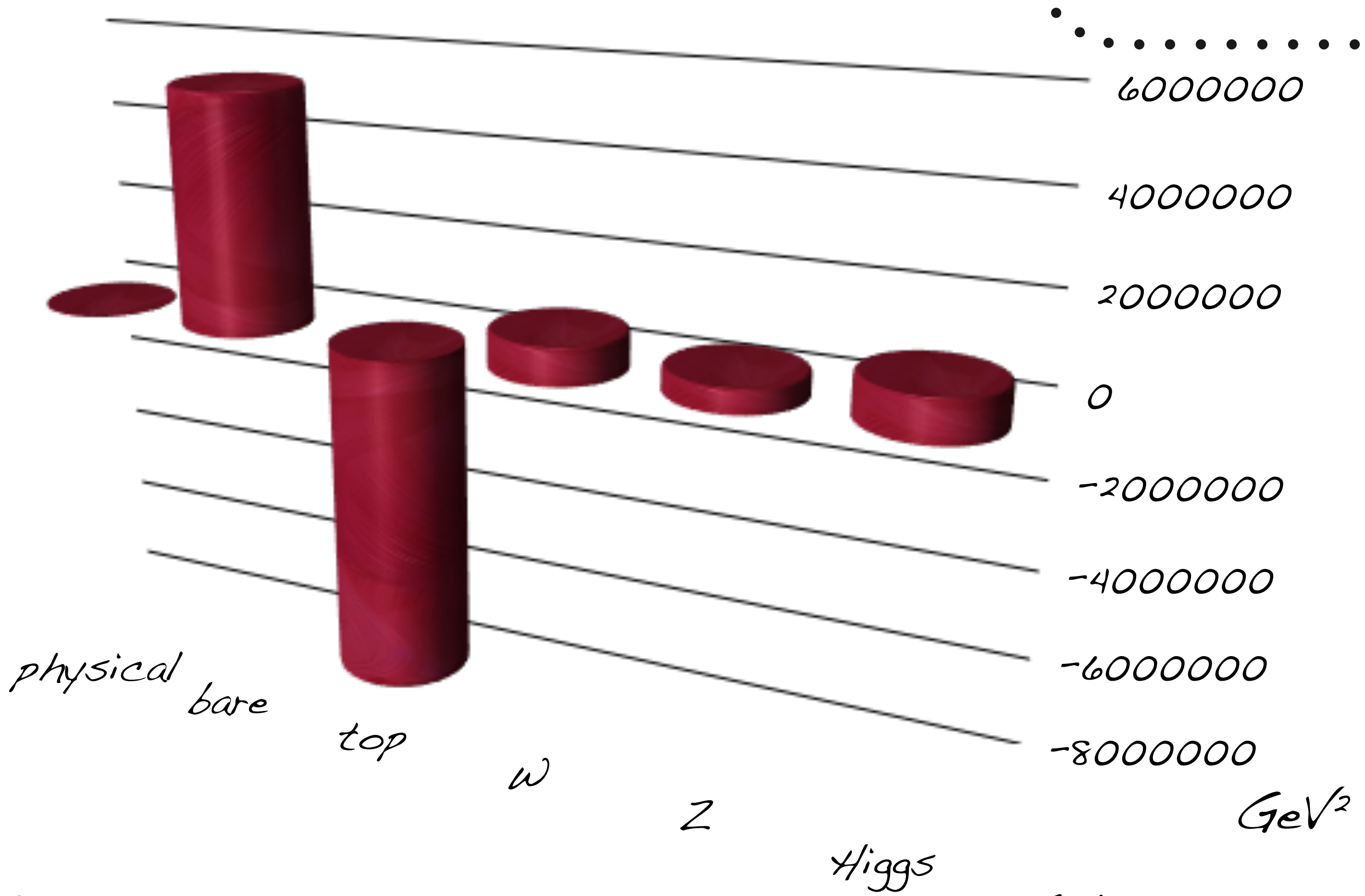
$$m_H^2 \sim m_0^2 - (115\ \text{GeV})^2 \left(\frac{\Lambda}{700\ \text{GeV}}\right)^2$$

$\Lambda = 10$ TeV



How to Stabilize the Higgs Potential

Goldstone's Theorem

spontaneously broken global symmetry ⇨ massless scalar

... but the Higgs has sizable non-derivative couplings

The spin trick

a particle of spin s: 2s+1 polarization states

...with the only exception of a particle moving at the speed of light

... fewer polarization states

Spin 1 Gauge invariance ⟶ no longitudinal polarization ↘ m=0

Spin 1/2 Chiral symmetry ⟶ only one helicity ↗ m=0

... but the Higgs is a spin 0 particle

Naturalness principle

Following the arguments of Wilson, 't Hooft (and others):
only small numbers associated to the breaking of a symmetry survive quantum corrections

Field	Symmetry as $m \to 0$	Implication
Spin-1/2 $m\Psi\bar{\Psi}$	$\Psi \to e^{i\theta}\Psi$ $\bar{\Psi} \to e^{-i\theta}\bar{\Psi}$ (chiral symmetry)	$\delta m \propto m$ **Natural!**
Spin-1 $m^2 A_\mu A^\mu$	$A_\mu \to A_\mu + \partial_\mu \alpha$ (gauge invariance)	$\delta m \propto m$ **Natural!**

courtesy to N. Craig @ Blois '15

The Higgs mass in the SM doesn't break any (quantum*) symmetry

* it does break classical scale invariance, as the running of the gauge couplings does too!

Naturalness principle @ work

Following the arguments of Wilson, 't Hooft (and others):
only small numbers associated to the breaking of a symmetry survive quantum corrections

Beautiful examples of naturalness to understand the need of "new" physics

see for instance Giudice '13 (and refs. therein) for an account

- the need of the positron to screen the electron self-energy: $\Lambda < m_e/\alpha_{\text{em}}$
- the rho meson to cutoff the EM contribution to the charged pion mass: $\Lambda < \delta m_\pi^2/\alpha_{\text{em}}$
- the kaon mass difference regulated by the charm quark: $\Lambda^2 < \frac{\delta m_K}{m_K} \frac{6\pi^2}{G_F^2 f_K^2 \sin^2\theta_C}$
- the light Higgs boson to screen the EW corrections to gauge bosons self-energies
- ...
- New physics at the weak scale to cancel the UV sensitivity of the Higgs mass?

Playing with cracks: The way forward

Small numbers are not necessarily theoretically inconsistent
but they require some conspiracy at different scales

Better to find an explanation with new degrees of freedom that cancel the sensitivity to the details of the physics at high-energy

Theoretical inconsistencies

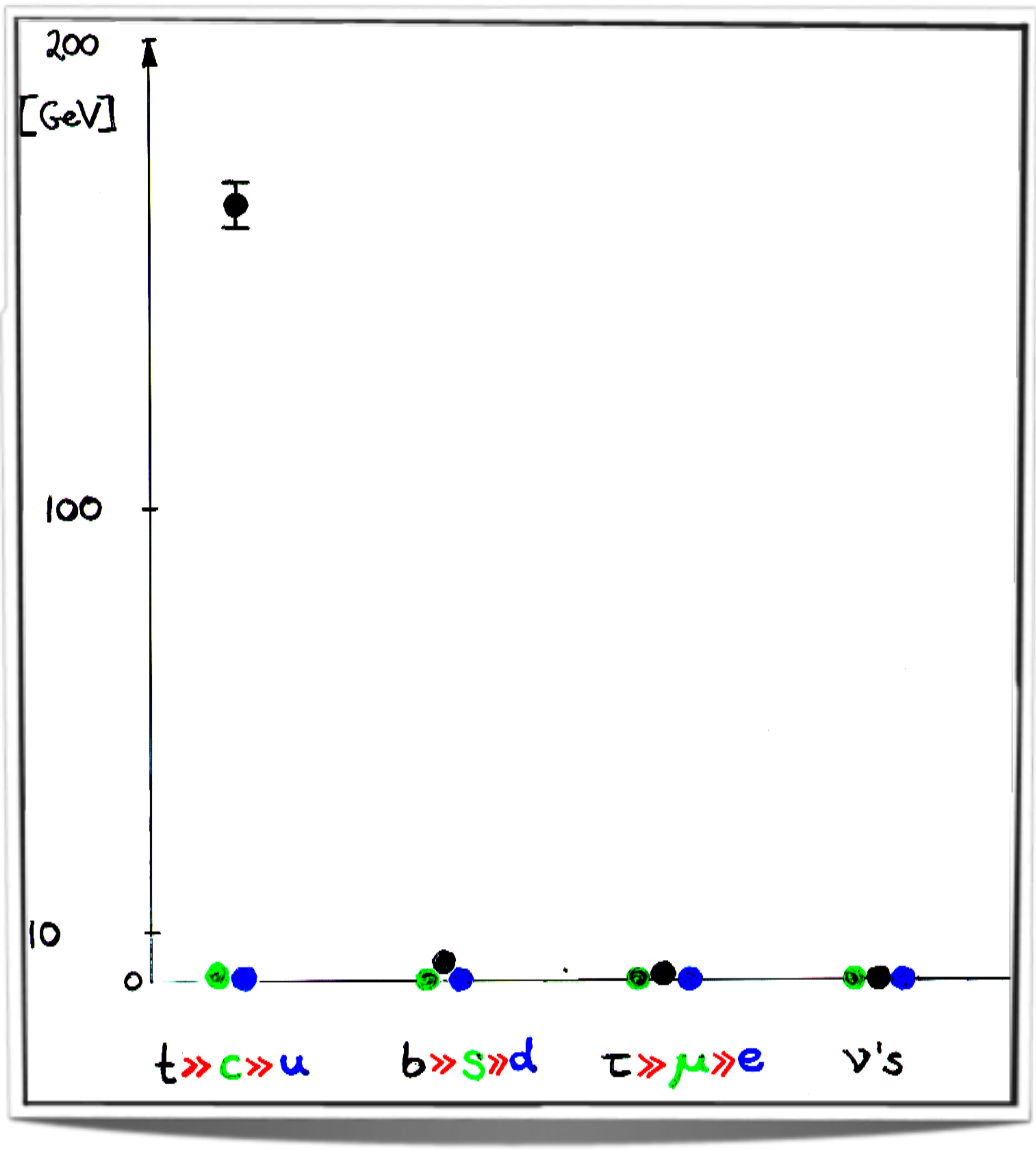
- ✳ 4 Fermi interactions to describe muon decay
  $\mathcal{A} \sim G_{\mathcal{F}} E^2$ ➢ W boson
- ✳ $W_L W_L$ scattering
  $\mathcal{A} \sim E^2/v^2$ ➢ H boson

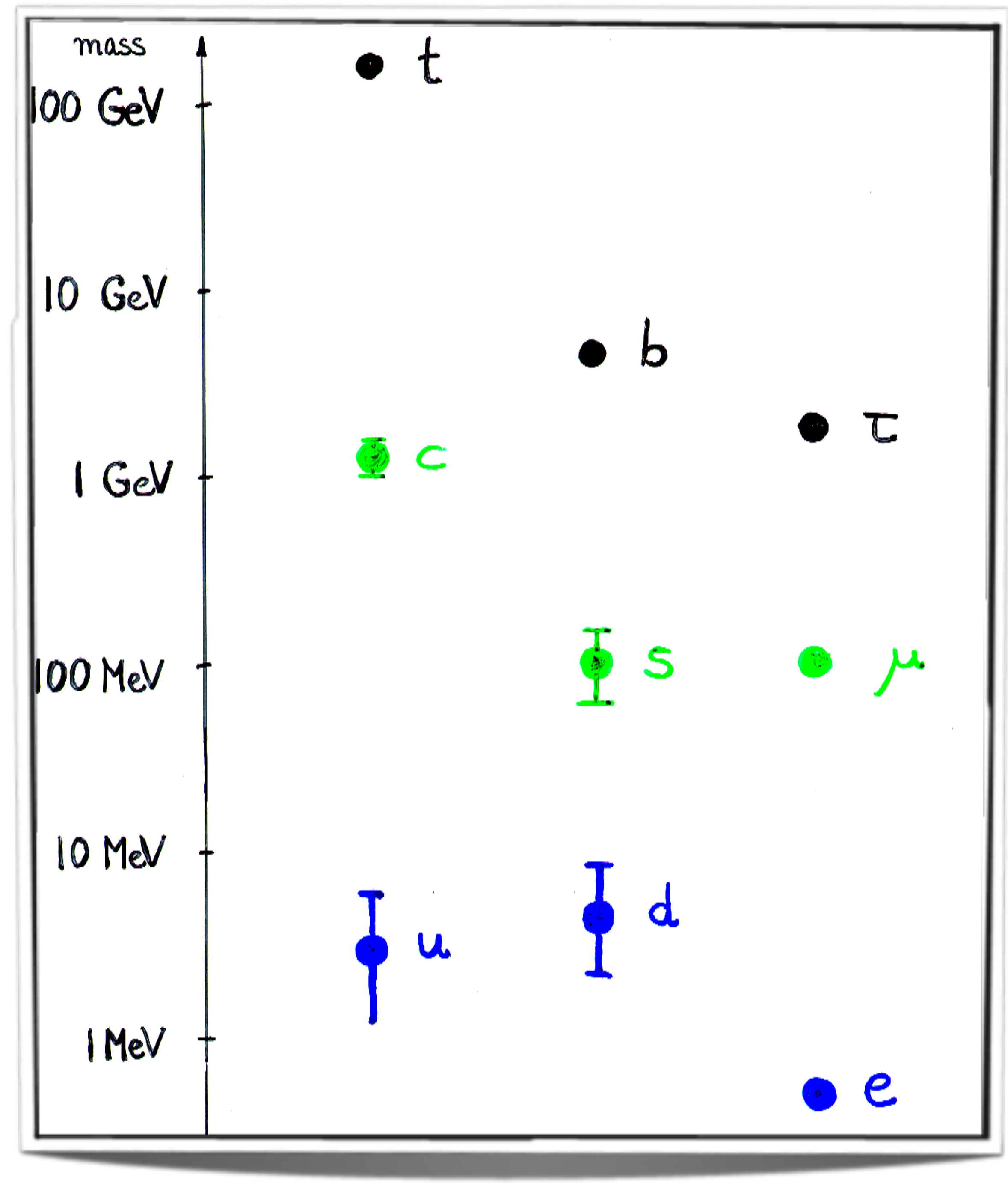
Naturalness arguments

- ✳ positron
- ✳ rho
- ✳ charm quark
- ✳ susy?

Small Numbers in a Quantum World

the mass spectrum of the fermions is intriguing





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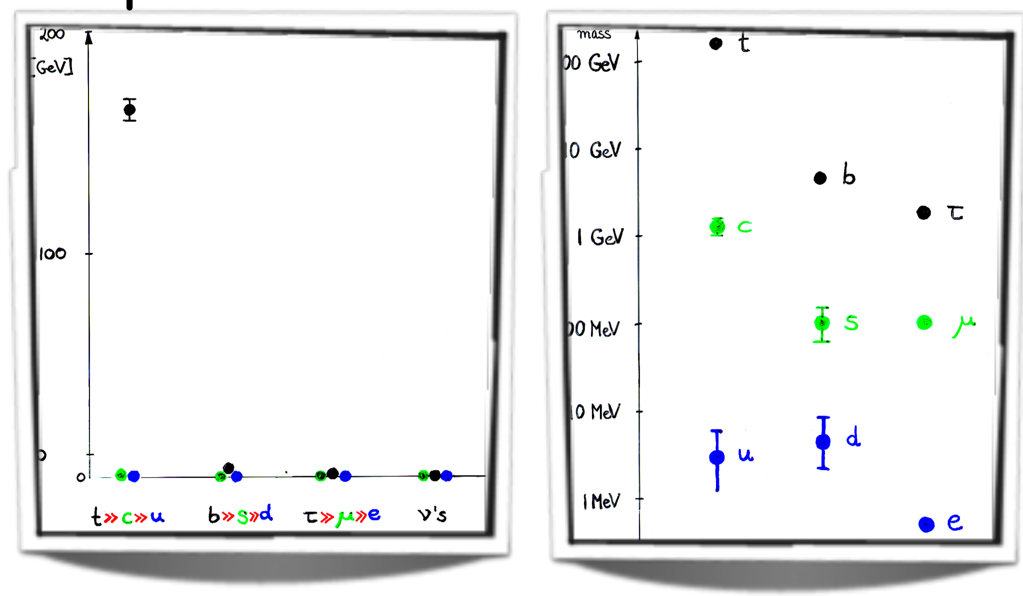


but this spectrum is stable under radiative corrections

$\delta m_e \propto m_e$ if the electron mass is small, it will remain small in a quantum world

the origin of this intriguing spectrum might come from dynamics at much higher scales that will never be explored at colliders

When a small number is "protected" by a symmetry, quantum corrections won't affect it and we can safely postpone the question "why is it small?" to higher energy scales
The Higgs mass is a priori not protected and its "smallness" requires an explanation now!

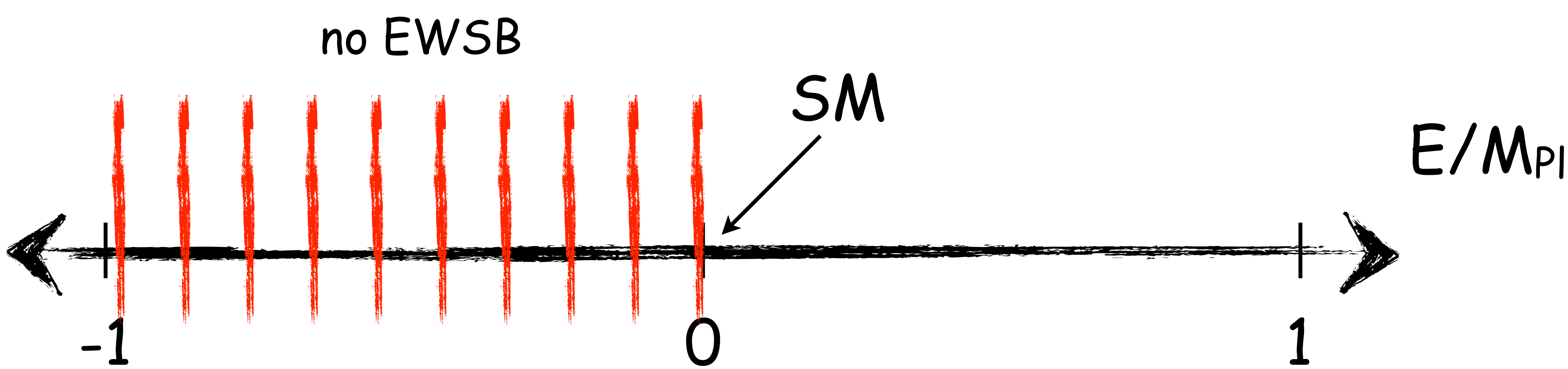
The Higgs, as a fundamental scalar field, is the worm inside the SM

Higgs & Naturalness

The last unknown parameter of the SM has been measured

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$

$$\mu \approx 88.8\,\mathrm{GeV} \qquad \lambda \approx 0.13$$



Why $m_H/M_{Pl} \sim 10^{-16}$? Why m_H so close to the critical boundary?

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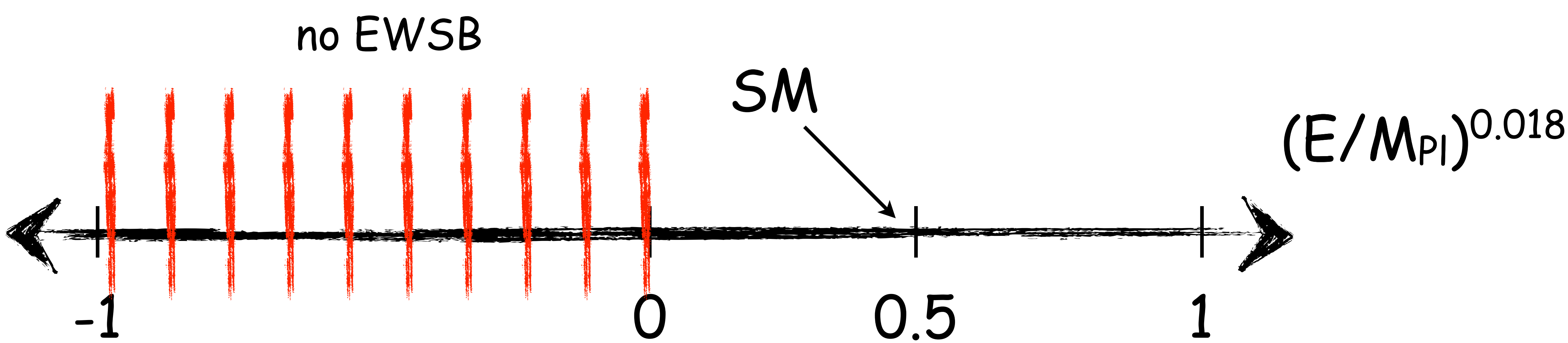

Why m_H/M_{Pl}~10^{-16}? Why m_H so close to the critical boundary?

Change the metric? e.g. $d=(E/M_{Pl})^{0.018}$

Higgs self-couplings and Naturalness

In the SM, $|H|^2$ is the only relevant operator
and it is the source of the hierarchy/naturalness/fine-tuning problem
It presence has never been tested!

Reconstructing the Higgs potential before EW symmetry breaking
from measurements around the vacuum is difficult in general
but we can easily test gross features, like the presence of the relevant operator

SM

$$V = -\mu^2 |H|^2 + \lambda |H|^4 \quad \Rightarrow \quad V(h) = \frac{1}{2} m_h^2 h^2 + \frac{1}{6} \frac{3 m_h^2}{v} h^3 + \ldots$$

EWSB W/O H^2

$$V = -\lambda |H|^4 + \frac{1}{\Lambda^2} |H|^6 \quad \Rightarrow \quad V(h) = \frac{1}{2} m_h^2 h^2 + \frac{1}{6} \frac{7 m_h^2}{v} h^3 + \ldots$$

200% correction
to SM prediction
+
allows 1st phase transition

Symmetries to Stabilize a Scalar Potential

Supersymmetry

fermion ~ boson

Higher Dimensional Lorentz invariance

$\Lleftarrow$ gauge-Higgs unification models

[Manton '79, Fairlie 79, Hosotani '83 +...]

$$A_\mu \sim A_5$$

4D spin 1 4D spin 0

These symmetries cannot be exact symmetry of the Nature. They have to be broken. We want to look for a soft breaking in order to preserve the stabilization of the weak scale.

EWSB might be unnatural

nothing to say but the usual words:

- cosmological constant problem...
- multiverse...
- landscape of vacua...
- laws of physics are environmental...
- anthropic solution...
- end of reductionism...

will be tested to an unprecedented level (10^{-4})