Scale Invariance and Electro-Weak Symmetry Breaking

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The SM: A Synergy of Concepts - d=4 QFT

QED	→ QCD	→ SM
$U(1)_{em}$	$SU(3)_C$	$SU(3)_C \times SU(2)_L \times U(1)_Y$

Physics: concepts (variables) ⊕ equations / principles
initial conditions → predictions

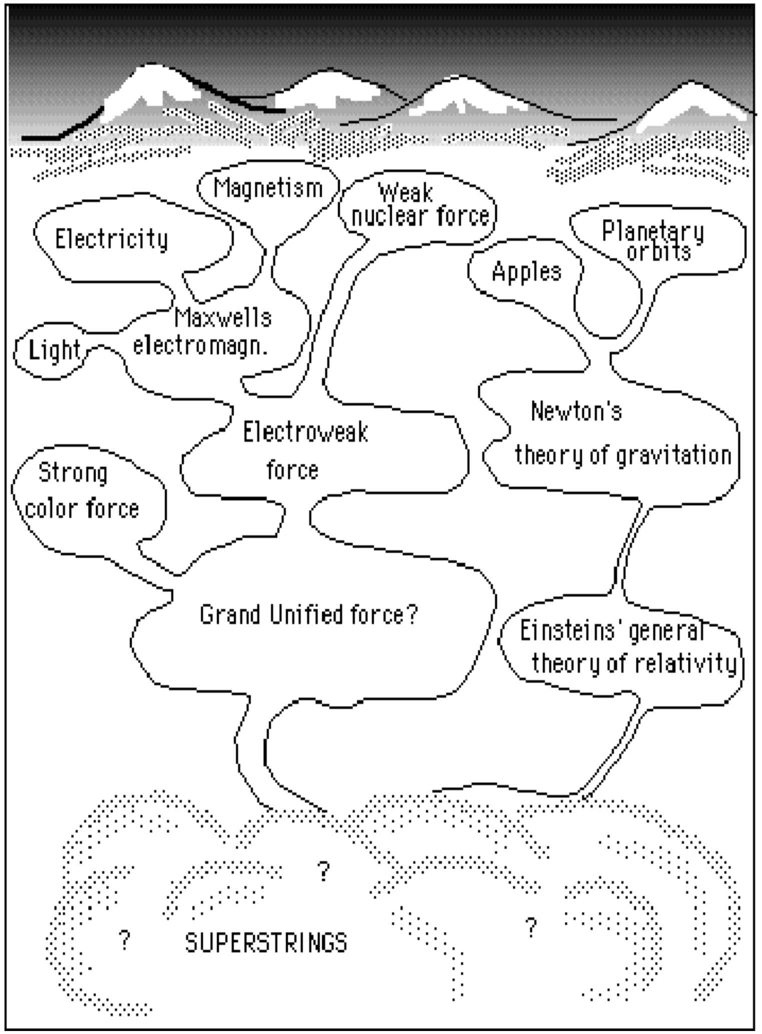
electrodynamics
relativity — QED
quantum mech.
strong force → QCD — SM — SM+
weak decays + Higgs, χ-ral
+ neutrino masses
+ dark matter … → ?
+ … ?

territory of speculation:
LR? TC? …?
SUSY? GUTs? TOE?
extra d.?

gravity — weak scale <<<< M_{planck}

Note: GR non-renormalizable… maybe good: QFT's cannot explain scales→other concepts

Reasons to go Beyond the Standard Model

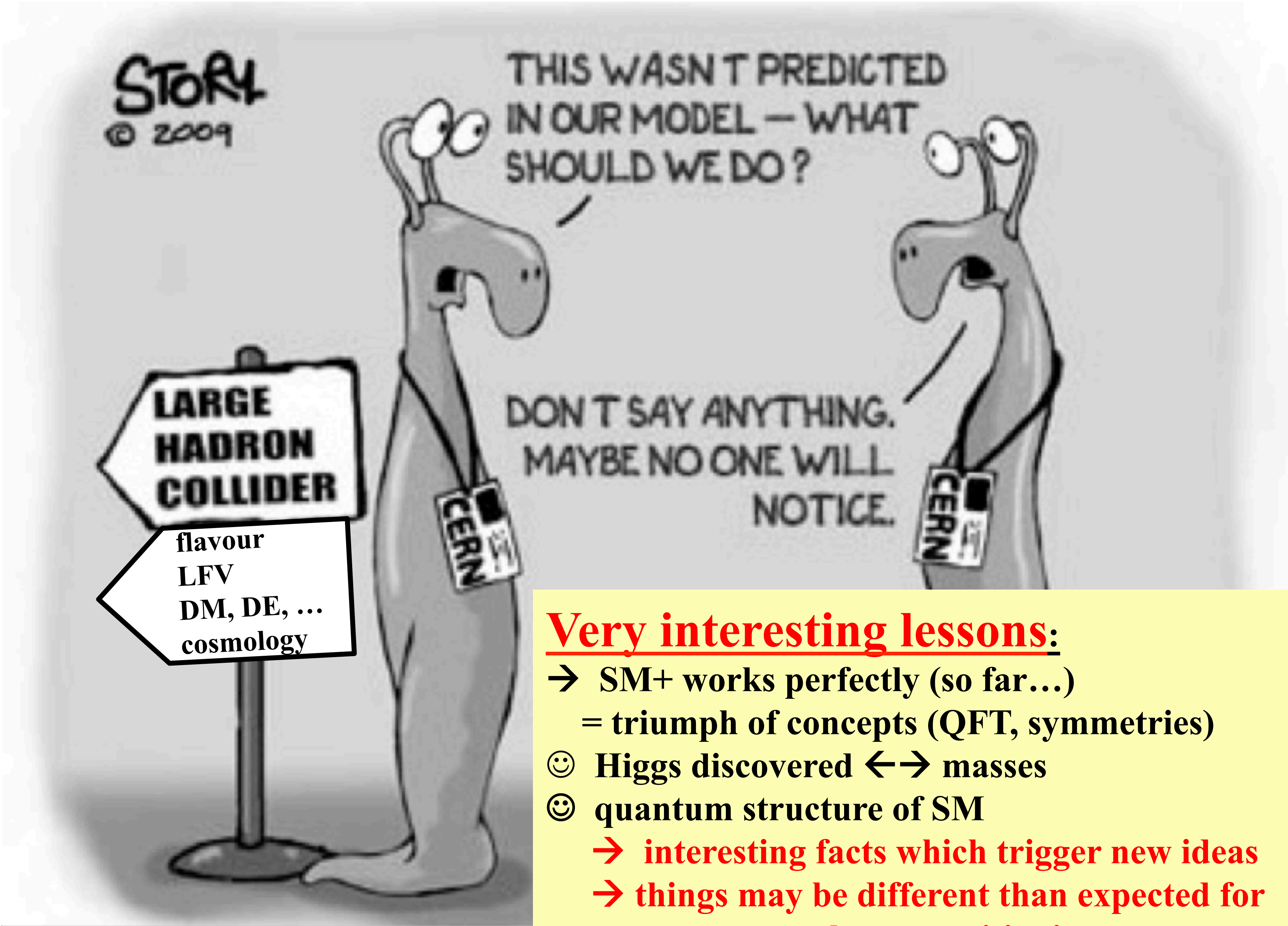


Theoretical:

SM does not exist without cutoff
(triviality, vacuum stability)
Gauge hierarchy problem
Gauge unification, charge quantization
Strong CP problem
Unification with gravity
Global symmetries & GR anomalies
Why: 3 generations, representations, d=4, many parameters

Experimental facts:

- Electro weak scale << Planck scale
- Gauge couplings almost unify
- Neutrinos masses & large mixings
- Flavour: Patterns of masses & mixings
- Baryon asymmetry of the Universe
- Dark Matter
- Inflation
- Dark Energy



Very interesting lessons:

→ SM+ works perfectly (so far…)
= triumph of concepts (QFT, symmetries)

☺ Higgs discovered ←→ masses

☺ quantum structure of SM

→ interesting facts which trigger new ideas

→ things may be different than expected for many years, but as exciting!

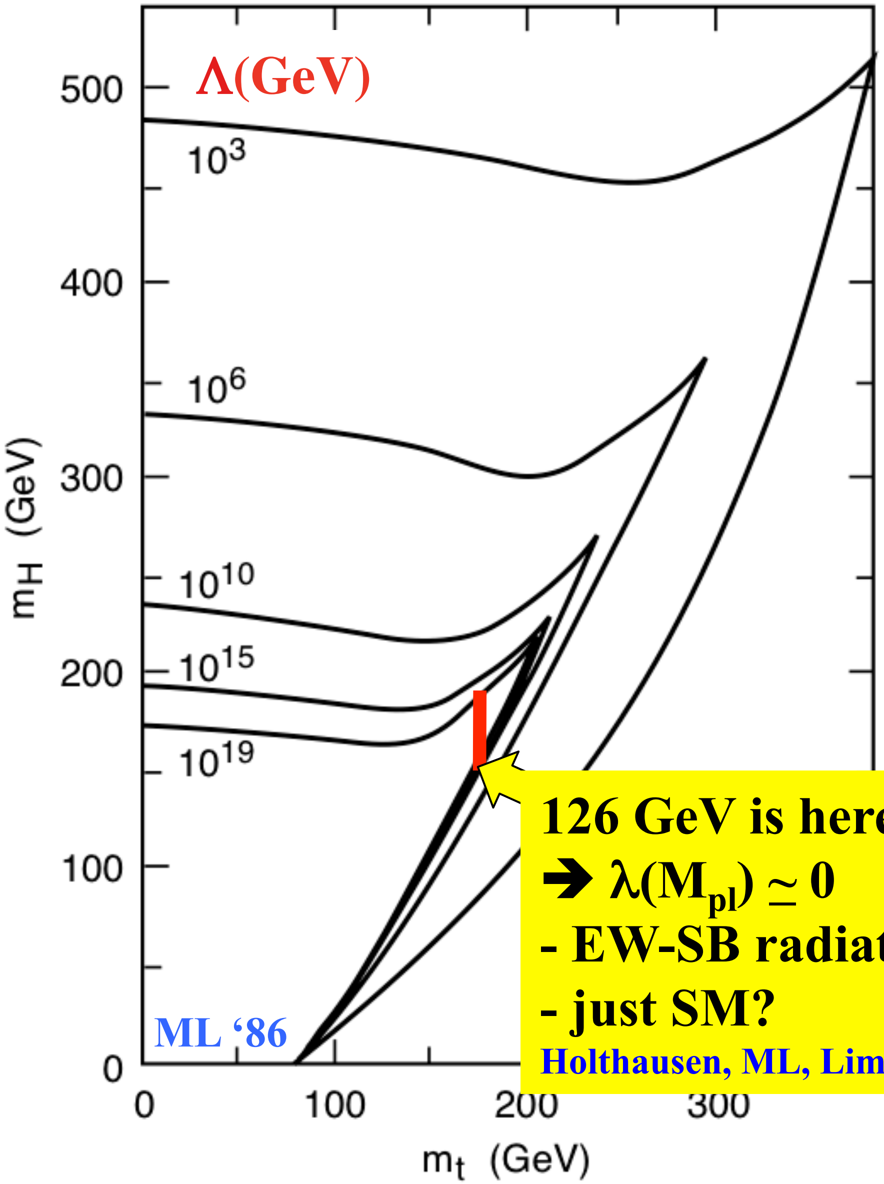
Look very careful at the SM as QFT

- **The SM itself (without embedding) is a QFT like QED**
  - infinities, renormalization ➔ only differences are calculable
  - perfectly OK ➔ many things unexplained…
- **It has (like QED) a triviality problem (Landau poles)**
  - running U(1) coupling (pole well beyond Planck scale…)
  - running Higgs coupling → upper bounds on m_H
  - ➔ requires some scale Λ where the SM is embedded
  - ➔ the physics of this scale is unknown
  - ➔ does not hurt SM QFT-calculations @ 0,1,2,.. Loops
- **Another potential problem is vacuum instability (negative λ)**
  - does occur in SM for large top mass > 79 GeV ➔ lower bounds on m_H

SM as QFT: A hard cutoff and the sensitivity towards Λ has no meaning

⇔ The SM is a renormalizable QFT just like QED

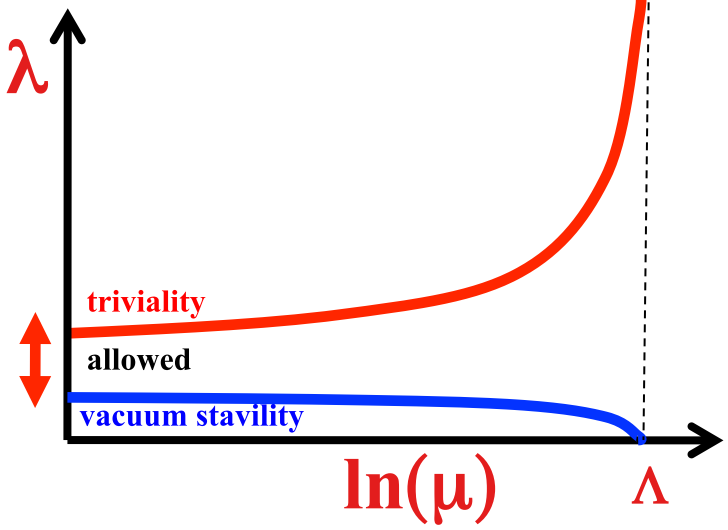
Triviality and Vacuum Stability



126 GeV is here!
➔ $\lambda(M_{pl}) \simeq 0$
- EW-SB radiative
- just SM?
Holthausen, ML, Lim (2011)

126 GeV < m_H < 174 GeV

SM does not exist w/o embedding
- U(1) copling , Higgs self-coupling



➔ RGE arguments seem to work
➔ we need some embedding

The allowed Range ⇔ Experiment

$$m_{\min} = [126.3 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 1.5]\ \mathrm{GeV}$$

$$m_{\max} = [173.5 + \frac{m_t - 171.2}{2.1} \times 1.1 - \frac{\alpha_s - 0.1176}{0.002} \times 0.3]\ \mathrm{GeV}$$

➔ **interesting experimental cases (for $\Lambda = M_{Planck}$):**

1) m_H < ca. 126 GeV ➔ instability ➔ new physics (or disaster)

2) 126 GeV – 135 GeV perfect: SM + MSSM range, …

3) 135 GeV – 157 GeV perfect: SM , non-minimal SUSY, …

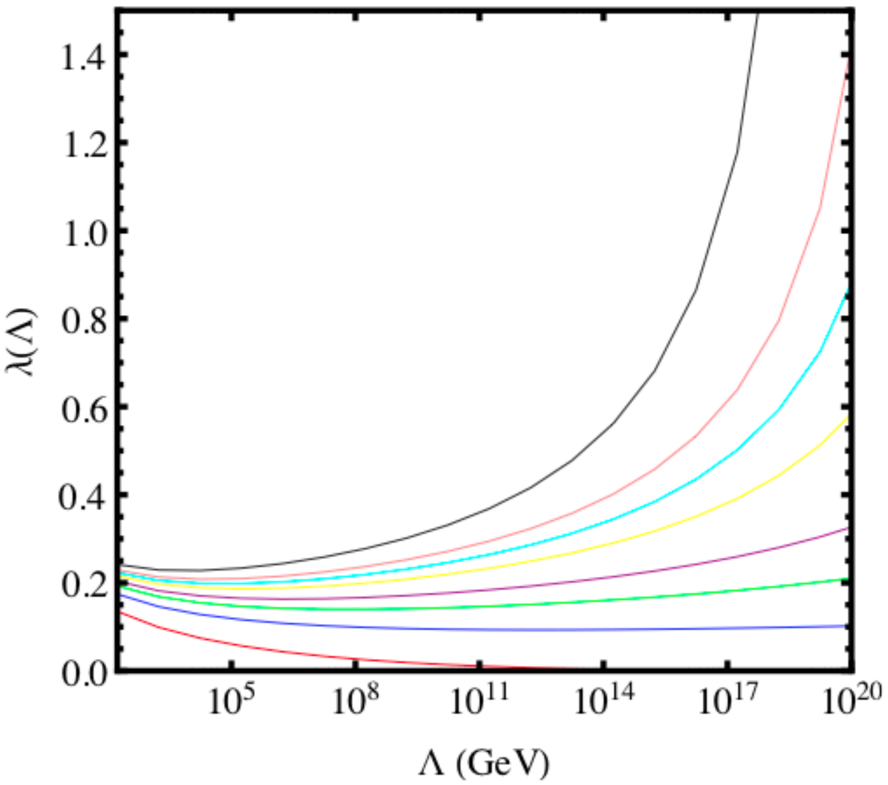
4) above 157 GeV – BSM

➔ **Remarkable aspects:**

- **SM parameters ⇔ quantum corrections over large scales**
- **we seem to be very precisely at the transition between 1) and 2)**

A special Value of λ at M_{planck} ?

ML '86



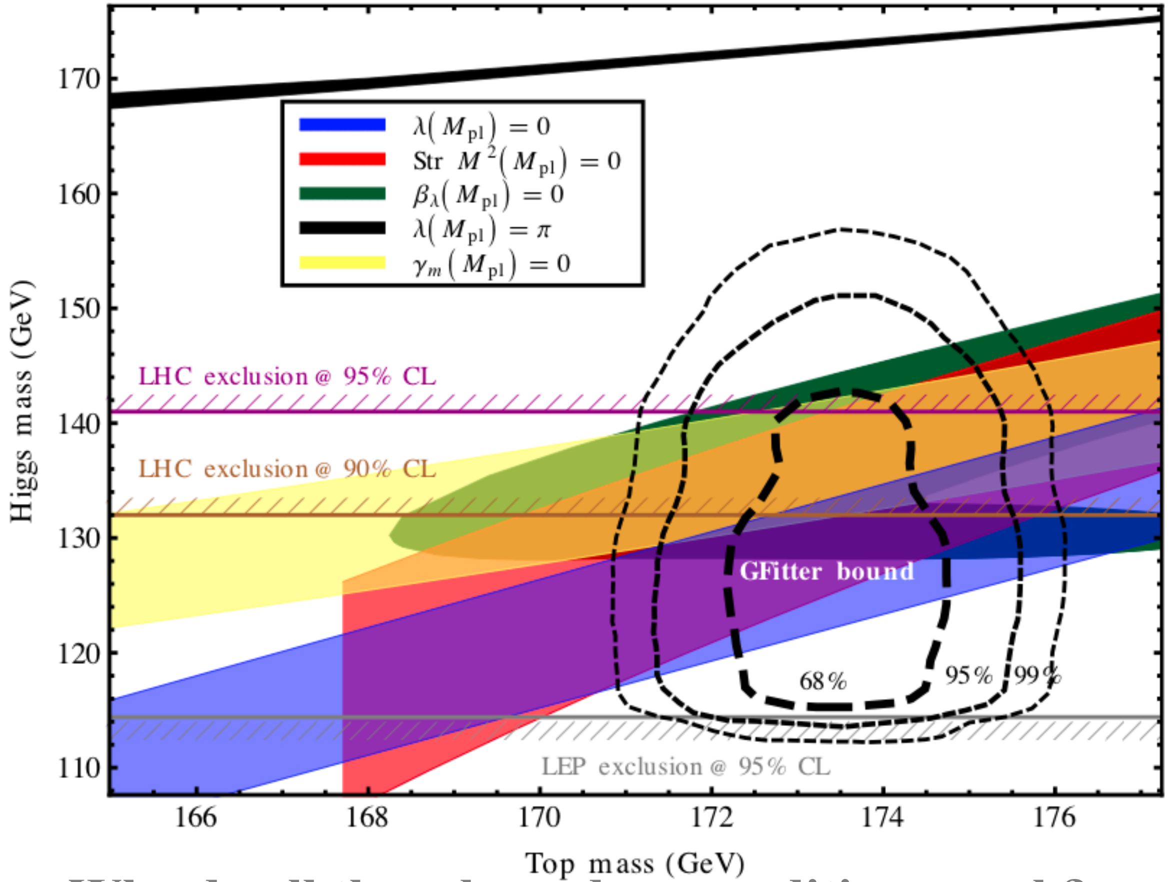
downward flow of RG trajectories
➔ IR QFP ➔ random λ flows to m_H > 150 GeV
➔ $m_H \simeq$ 126 GeV flows to tiny values at M_{Planck}…

Holthausen, ML Lim (2011)
Different conceivable special conditions:

- Vacuum stability
  $\lambda(M_{pl}) = 0$ [7–12]
- vanishing of the beta function of λ
  $\beta_\lambda(M_{pl}) = 0$ [9, 10]
- the Veltman condition [13–15] $\mathrm{Str}\mathcal{M}^2 = 0$,

$$\delta m^2 = \frac{\Lambda^2}{32\pi^2 v^2}\mathrm{Str}\mathcal{M}^2$$
$$= \frac{1}{32\pi^2}\left(\frac{9}{4}g_2^2 + \frac{3}{4}g_1^2 + 6\lambda - 6\lambda_t^2\right)\Lambda^2$$

- vanishing anomalous dimension of the Higgs mass parameter
  $\gamma_m(M_{pl}) = 0,\ m(M_{pl}) \neq 0$



$m_H < 150$ GeV
➔ random $\lambda = O(1)$ excluded

- **Why do all these boundary conditions work?**
  - suppression factors compared to random choice = O(1)
  - $\lambda = F(\lambda, g_i^2, \ldots)$ ➔ loop factors $1/16\pi^2$
  - top loops ➔ fermion loops ➔ factors of (-1)

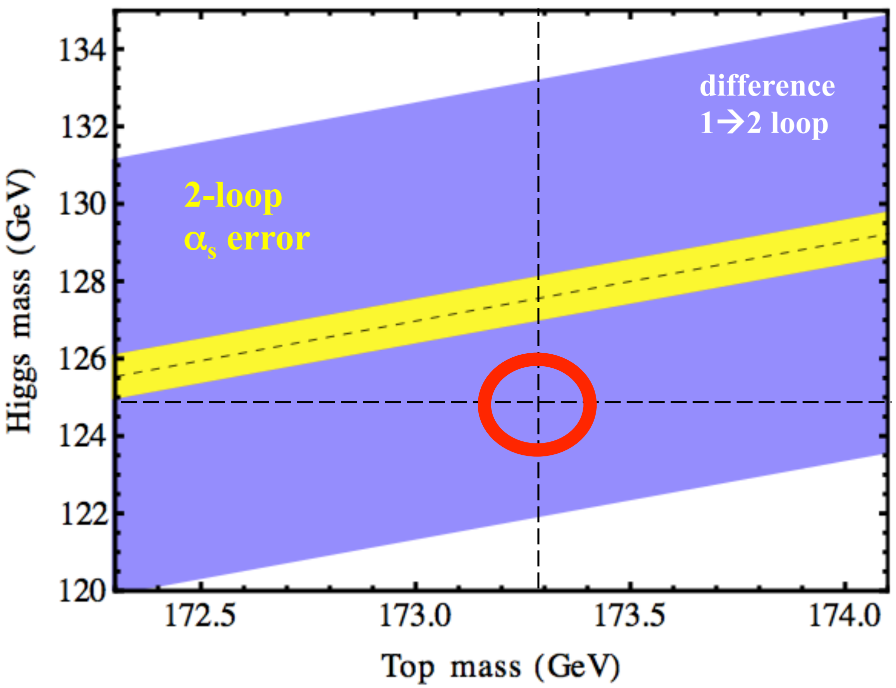
➔ any scenario which 'predicts' a suppressed (small/tiny) λ at M_{Planck} is OK

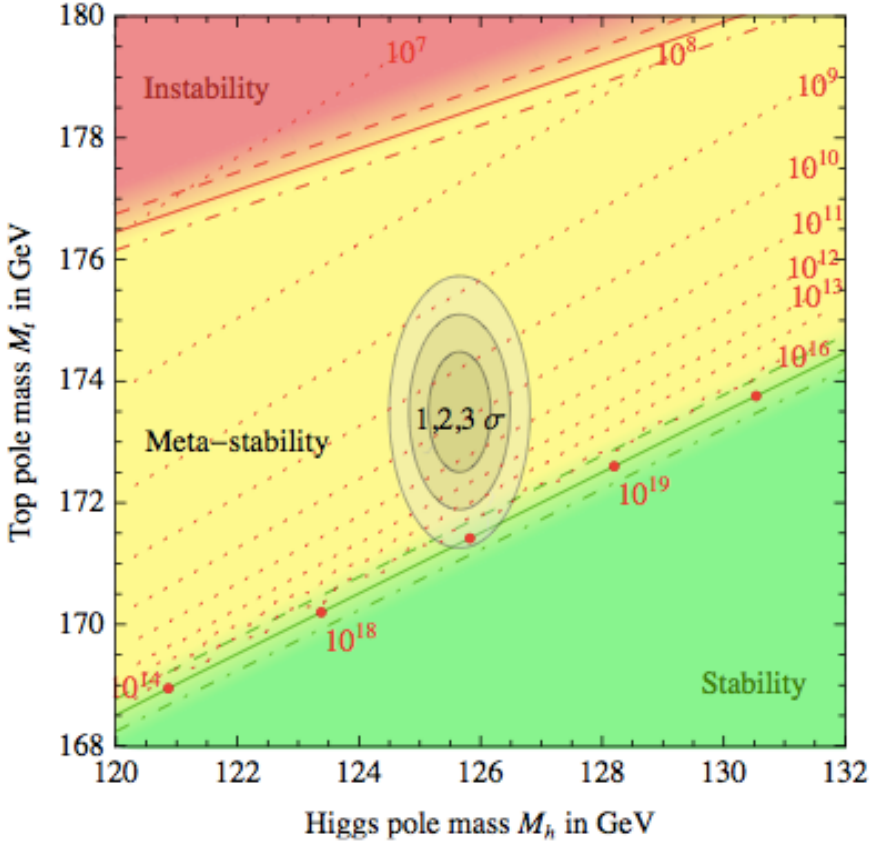
➔ more precision ➔ selects options ; e.g. $\gamma_m = 0$ now ruled out

Is the Higgs Potential at M_{Planck} flat?

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia

Holthausen, ML, Lim





Notes:

- remarkable relation between weak scale, m_t, couplings and M_{Planck} ←→ precision
- strong cancellations between Higgs and top loops
  → very sensitive to exact value and error of m_H, m_t, $\alpha_s = 0.1184(7)$
- higher orders, thresholds (low, high), … → important: watch central values & errors

Interpretations of special Conditions: E.g. $\lambda(M_{Planck}) = 0$

$\lambda\phi^4$ → 0 at the Planck scale → **no Higgs self-interaction (V is flat)**
→ m_H at low E radiatively generated - value related to m_t and g_i
→ **SM emdedded directly into gravity …!?**

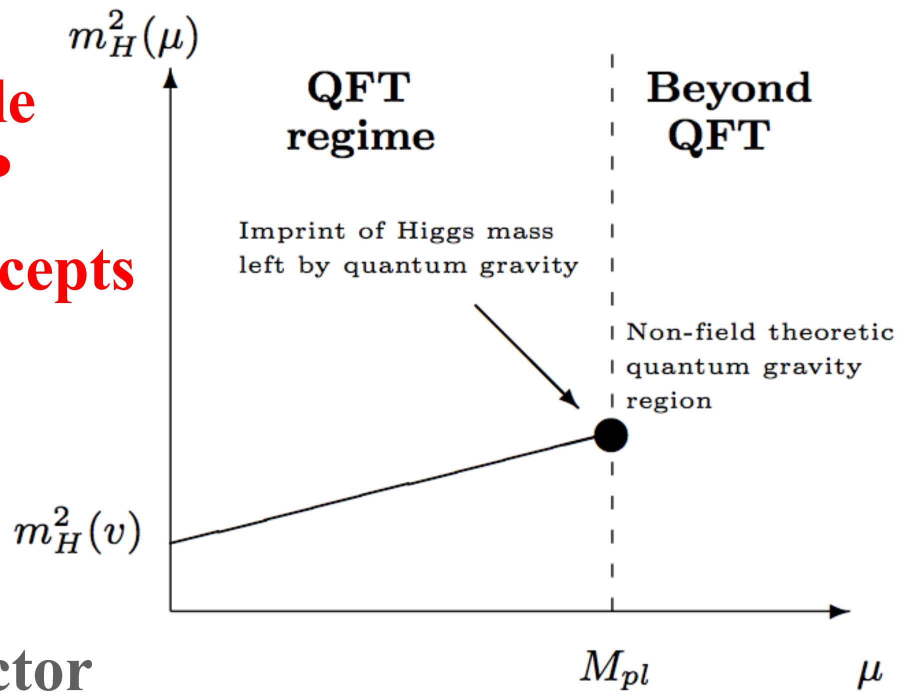
- **What about the hierarchy problem?**
  → GR is different: Non-renormalizable!
  → requires new concepts beyond QFT/gauge theories: … ?
  → BAD: We have no facts which concepts are realized by nature
  → **Two GOOD aspects:**

1) QFTs cannot explain absolute masses and couplings
- **QFT embeddings = shifting the problem only to the next level**
  → **new concepts beyond QFT might explain absolute values**

2) Asymmetry SM←→Planck scale may allow new solutions of the HP

→ **new non-QFT Planck-scale concepts could have mechanism which explain hierarchies**

→ **lost in effective theory = SM**

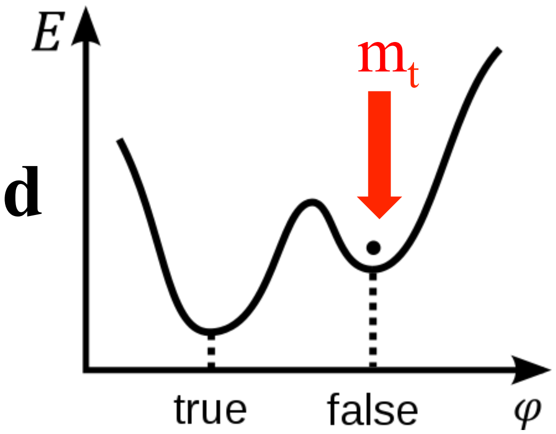


Anaology: Type II superconductor
Ginzburg-Landau effective QFT ←→ BCS theory

$$E \approx \alpha|\phi|^2 + \beta|\phi|^4 + \ldots$$ **←→ α, β, dynamical details lost**

➔ Important consequence of this scenario:
no intermediate QFT scales ←→ hierarchy problem back
(separation of two scalars unnatural in QFT)

What if the SM were metastable?



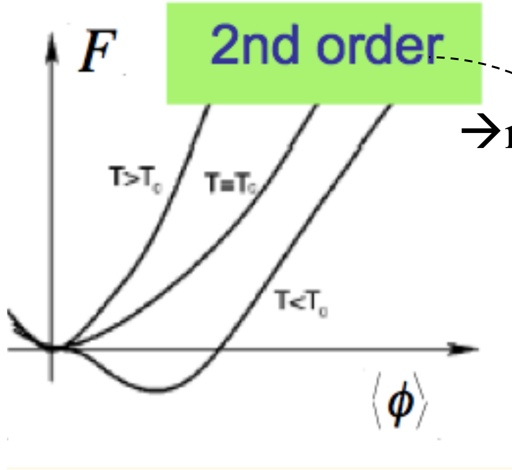
➔ **for large m_t the Higgs potential has two minima. If m_t > stability bound**

- **EW (false, required, local, metastable)**
- **"true" (deeper, global minimum)**

- 1^{st} bubble of true vacuum in U grows (surface vs. volume)
- mechanisms producing a 1^{st} bubble in the Universe: $r \sim 1/m_H$
  ➔ random collission of high energy cosmic rays
  ➔ metastability (slightly negative λ) is OK (yellow region)
- do other (faster) mechanisms exist?
  ➔ maybe some intelligent form of life did already collide somewhere particles to form a critical bubble…?

The dynamics of metastability:

- the bubble discussion ignores thermal cool-down, i.e. how/why we ended up in the (metastable) EW vacuum
- calculate thermal evolution of fluctuations and of field expectation value in cooling Universe ➔ Langevin eqs.

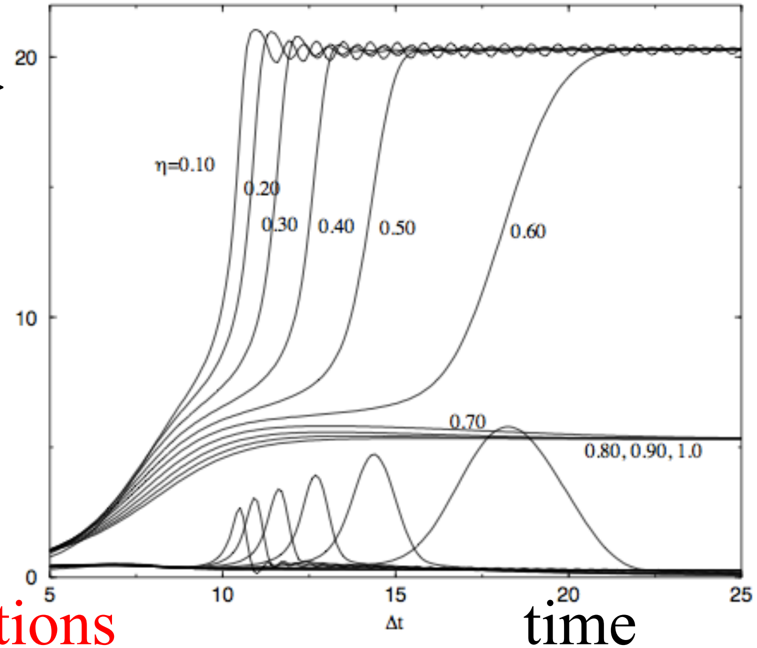


→metastability

➔ does the fluctuating field fall into EW or global (wrong) vacuum?

Bergerhoff, ML, Weiser

<φ>



time

The answer depends on exact parameters:
- correct vacuum ➔ bubble discussion…
- wrong vacuum ➔ always instable!

➔ SM metastability potentially dangerous
➔ or avoid it: embedding into…
➔ importance of precise m_H, m_t determinations

Embedding the SM

Remember: The SM does not exist without some embedding triviality/vacuum stab. ➔ scale Λ required ➔ cannot be ignored!

Embedding into which concept? ➔ two options:

1) some new concept beyond d=4 QFT
2) some d=4 QFT

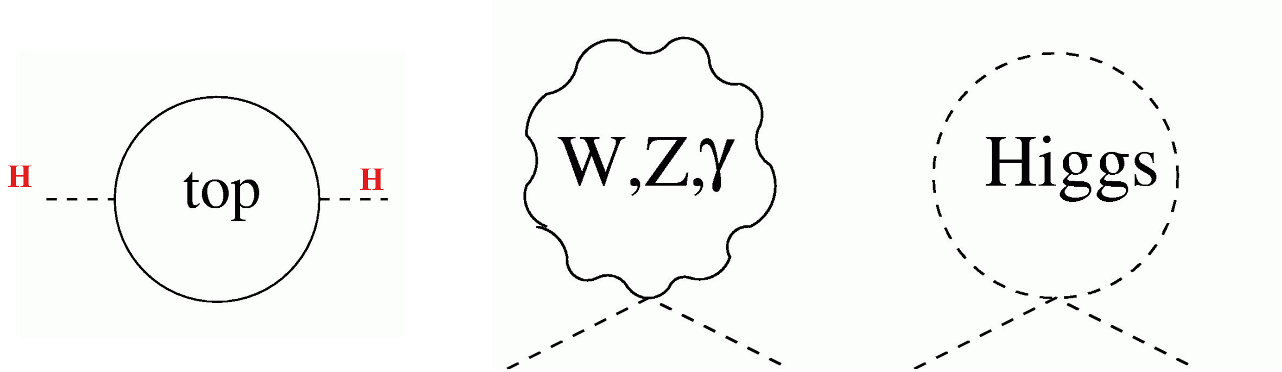
The $\lambda(M_{Planck})=0$ scenario above was along route #1
Most work over many years was along route #2:

- add representations
- extended gauge groups with and without GUTs
- include SUSY: MSSM, NMSSM, …, SUSY GUTs
- hidden (gauge) sectors, mirror symmetry, …

➔ runs into the gauge hierarchy problem

The naïve Hierarchy Problem

- Naive version: Higgs mass grows with cutoff scale Λ



$$\delta M_H^2 = \frac{\Lambda^2}{32\pi^2 V^2}\left(6M_W^2 + 3M_Z^2 + 3M_H^2 - 12M_t^2\right) \simeq O(\Lambda^2/4\pi^2)$$

$m_H \leq 200$ GeV requires Λ ~ TeV → new physics at TeV scale

*****OR***: you must explain →**

How can m_H be O(100 GeV) if Λ is huge ?

BUT: What does Λ mean for a renormalizable theory?

A side Story: The Veltman Condition

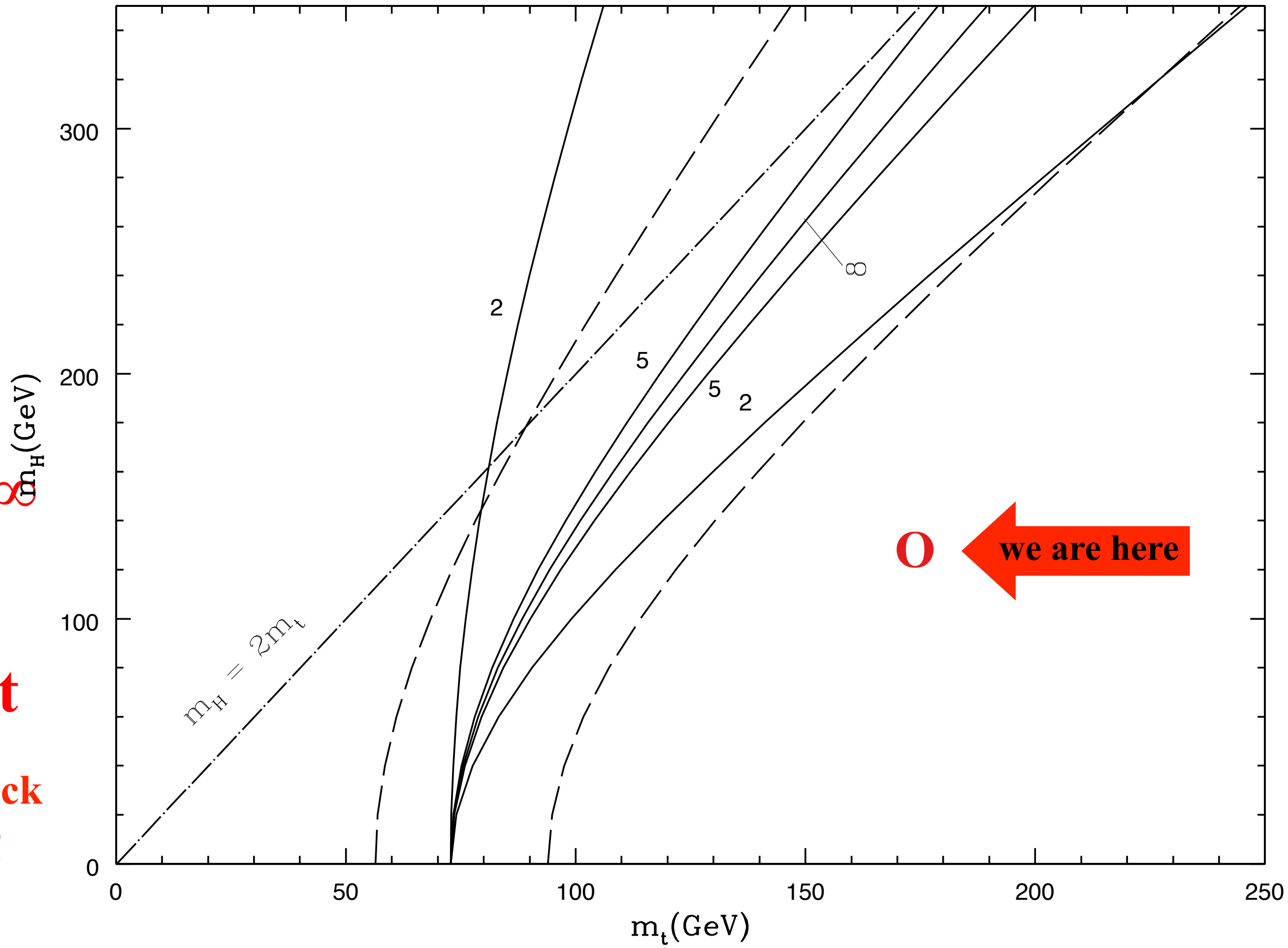
- The relation $$\delta M_H^2 = \frac{\Lambda^2}{32\pi^2 V^2}\left(6M_W^2 + 3M_Z^2 + 3M_H^2 - 12M_t^2\right)$$

Allows for

- exact cancellation
  if *rhs* is zero
- partial cancellation
  if $\delta m_H^2 < m_H^2$

➔ Λ = 2 TeV, 5 TeV, ∞

➔ not fulfilled
➔ not a RG invariant
BUT: OK @ M_{Planck}
➔ scheme dependent
…meaning of Λ… ?



The Hierarchy Problem: Specify Λ

- Renormalizable QFTs with two scalars φ , Φ with masses m, M and a hierarchy **m << M**
- These scalars must interact since $\varphi^+\varphi$ and $\Phi^+\Phi$ are singlets
  → $\lambda_{mix}(\varphi^+\varphi)(\Phi^+\Phi)$ **must exist** in addition to φ^4 and Φ^4
- **Quantum corrections ~M^2 drive both masses to the (heavy) scale**
  → two vastly different scalar scales are generically unstable

Therefore: If the SM Higgs field exists

→ problem: embedding with a 2nd scalar with much larger mass

→ solutions:

a) new scale @TeV
b) protective symmetry (SUSY) @TeV

→ LHC !

Remark: SUSY & gauge unification → SUSY GUT →
→ doublet-triplet splitting problem → hierarchy problem back

SM Embedding Directions

Recap.: Embedding options (and some examples) **at scale Λ**

1) some new concept beyond d=4 QFT

extra dimensions @TeV , $\lambda(M_{Planck})=0$, …

2) some d=4 QFT

a) new scale @TeV

LR symmetry, Z', composite, …

b) protective symmetry @TeV

SUSY: MSSM, …

BUT: no new physics @TeV observed???

BUT: Maybe there is another way out: **conformal symmetry (CS)**

The SM has almost CS

$$V(\Phi^+\Phi) = -\cancel{\mu}^2\Phi^+\Phi + \underbrace{\frac{\lambda}{2}}_{\simeq 0\ @\ M_{Planck}}\left(\Phi^+\Phi\right)^2$$

Conformal Symmetry as Protective Symmetry

- Exact (unbroken) CS

➔ absence of Λ^2 and $\ln(\Lambda)$ divergences

➔ no preferred scale and therefore no scale problems

- Conformal anomaly: Quantum effects break CS

➔ explicit breaking of CS ➔ anomaly induced spontaneous EWSB

➔ CS breaking ←→ β-functions ←→ $\ln(\Lambda)$ divergences

➔ <u>BUT: maybe CS still forbids Λ^2 divergences</u> **Bardeen**

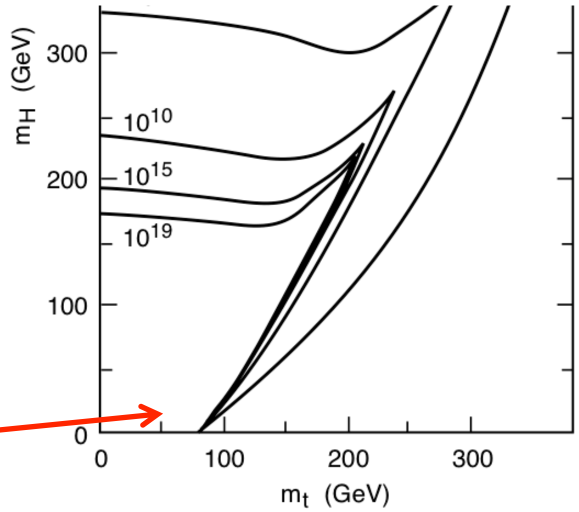
Conformal anomaly → no symmetry preserving regularization

- cutoff ➔ Λ^2 terms but violates CS explicitly → Ward Identity

- dimensional regularization gives no Λ^2 terms – only $\ln(\Lambda)$

IMPORTANT CONSEQUENCE: The conformal limit of the SM (or extensions) may have no hierarchy problem!

Realizing this Idea



Minimalistic: The Standard Model

choose $\mu = 0$ ←→ CS

Coleman Weinberg: effective potential

→ CS breaking (dimensional transmutation)

→ induces for $m_t < 79$ GeV
a Higgs mass $m_H = 8.9$ GeV

This would conceptually realize the idea, but:
Higgs too light and the idea does not work for $m_t > 79$ GeV

→ Other realizations:

A) SM singlets

B) embeddings of the SM gauge group into larger groups

C) orthogonal (hidden) sectors

Realizing this Idea: Left-Right Extension

M. Holthausen, ML, M. Schmidt

Radiative SB in conformal LR-extension of SM

(use isomorphism SU(2) × SU(2) $\simeq$ Spin(4) → representations)

particle	parity $\mathcal{P}$	$\mathbb{Z}_4$	$\mathrm{Spin}(1,3) \times (\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R) \times (\mathrm{SU}(3)_C \times \mathrm{U}(1)_{B-L})$
$\mathbb{L}_{1,2,3} = \begin{pmatrix} L_L \\ -\mathrm{i}L_R \end{pmatrix}$	$P\mathbb{P}\mathbb{L}(t,-x)$	$L_R \to \mathrm{i}L_R$	$\left[\left(\tfrac{1}{2},\underline{0}\right)(\underline{2},\underline{1}) + \left(\underline{0},\tfrac{1}{2}\right)(\underline{1},\underline{2})\right](\underline{1},-1)$
$\mathbb{Q}_{1,2,3} = \begin{pmatrix} Q_L \\ -\mathrm{i}Q_R \end{pmatrix}$	$P\mathbb{P}\mathbb{Q}(t,-x)$	$Q_R \to -\mathrm{i}Q_R$	$\left[\left(\tfrac{1}{2},\underline{0}\right)(\underline{2},\underline{1}) + \left(\underline{0},\tfrac{1}{2}\right)(\underline{1},\underline{2})\right](\underline{3},\tfrac{1}{3})$
$\Phi = \begin{pmatrix} 0 & \Phi \\ -\tilde{\Phi}^\dagger & 0 \end{pmatrix}$	$\mathbb{P}\Phi^\dagger\mathbb{P}(t,-x)$	$\Phi \to \mathrm{i}\Phi$	$(\underline{0},\underline{0})(\underline{2},\underline{2})(\underline{1},0)$
$\Psi = \begin{pmatrix} \chi_L \\ -\mathrm{i}\chi_R \end{pmatrix}$	$\mathbb{P}\Psi(t,-x)$	$\chi_R \to -\mathrm{i}\chi_R$	$(\underline{0},\underline{0})\left[(\underline{2},\underline{1}) + (\underline{1},\underline{2})\right](\underline{1},-1)$

→ **the usual fermions, one bi-doublet, two doublets**

→ **a Z_4 symmetry**

→ **no scalar mass terms ←→ CS**

➔ Most general gauge and scale invariant potential respecting Z4

$$\mathcal{V}(\Phi,\Psi) = \frac{\kappa_1}{2}\left(\overline{\Psi}\Psi\right)^2 + \frac{\kappa_2}{2}\left(\overline{\Psi}\Gamma\Psi\right)^2 + \lambda_1\left(\mathrm{tr}\Phi^\dagger\Phi\right)^2 + \lambda_2\left(\mathrm{tr}\Phi\Phi + \mathrm{tr}\Phi^\dagger\Phi^\dagger\right)^2 + \lambda_3\left(\mathrm{tr}\Phi\Phi - \mathrm{tr}\Phi^\dagger\Phi^\dagger\right)^2 + \beta_1\,\overline{\Psi}\Psi\mathrm{tr}\Phi^\dagger\Phi + f_1\,\overline{\Psi}\Gamma[\Phi^\dagger,\Phi]\Psi\,,$$

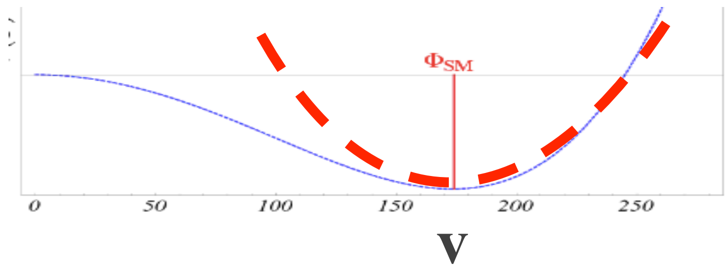
➔ calculate V_{eff}

➔ Gildner-Weinberg formalism (RG improvement of flat directions)

- anomaly breaks CS
- spontaneous breaking of parity, Z_4, LR and EW symmetry
- $m_H \ll v$; typically suppressed by 1-2 orders of magnitude

  Reason: V_{eff} flat around minimum

  ←→ $m_H \sim$ loop factor $\sim 1/16\pi^2$
- everything works nicely…



➔ requires moderate parameter adjustment for the separation of the LR and EW scale… PGB…?

More Scalars + Conformal Symmetry

- SM scalars Φ plus some new scalar φ (or more scalars)
- CS → no scalar mass terms
- the scalars interact: $\lambda_{mix}(\varphi^+\varphi)(\Phi^+\Phi)$ must exist
  ➔ a condensate in the φ direction can lead to $\langle\varphi^+\varphi\rangle > 0$
  λ_{mix} ➔ effective mass term for Φ

- CS anomalous … → broken by quantum effects → only $\ln(\Lambda)$

- Note that this opens many other possibilities:
  - φ could be an effective field of some hidden sector DSB
  - further particles could exist in hidden sector; e.g. confining…
  - extra U(1) potentially problematic ←→ U(1) mixing
  - avoid Yukawas which couple visible and hidden sector
  → phenomenologically safe since NP comes only via portal

Realizing the Idea: Other Directions

SM + extra singlet: Φ, φ

Nicolai, Meissner
Farzinnia, He, Ren
Foot, Kobakhidze, Volkas

SM + extra SU(N) with new N-plet in hidden sector

Ko
Carone, Ramos
Holthausen, Kubo, Lim, ML (to appear…)
…

SM + …

…

Since the SM-only version does not work ➔ observable effects:
- Higgs coupling to other scalars (singlet, hidden sector, …)
- dark matter candidates ←→ hidden sectors & Higgs portals
- consequences for neutrino masses

Summary

- **SM works perfectly – no signs of new physics**
- **The standard hierarchy problem suggests TeV scale physics … which did (so far…) not show up**
- **Revisit how the hierarchy problem may be solved**

- Embedding into new concepts beyond QFT at M_{planck}
  ←→ might be connected to $\lambda(M_{Planck}) = 0$?
- Embeddings into QFTs with classical conformal symmetry
  → SM: Coleman Weinberg effective potential – excluded
  → extended versions: singlets, SM=subgroup, hidden sectors
  → implications for Higgs couplings, dark matter, neutrinos
    ➔ testable consequences @ LHC, DM search, neutrinos