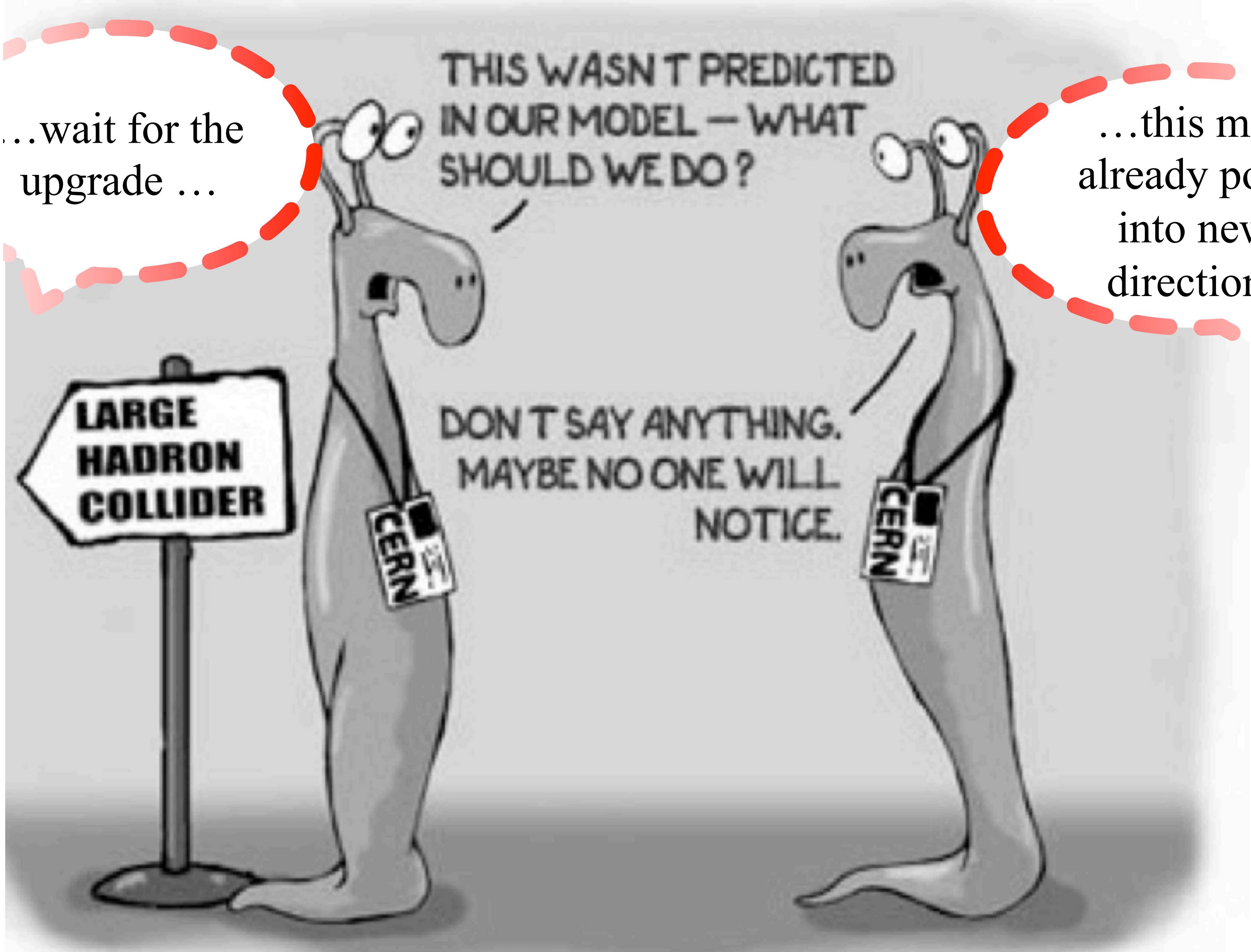
Neutrino Masses and Conformal Electro-Weak Symmetry Breaking

Manfred Lindner

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG

…wait for the upgrade …



…this may already point into new directions

Look very careful at the SM as QFT

- **The SM itself (without embeding) is a QFT like QED**
  - infinities, renormalization ➔ only differences are calculable
  - SM itself is perfectly OK ➔ many things unexplained…
- **Has (like QED) a triviality problem (Landau poles ←→ infinite λ)**
  - running $U(1)_Y$ coupling (pole well beyond Planck scale… - like in QED)
  - running Higgs / top coupling → upper bounds on m_H and m_t

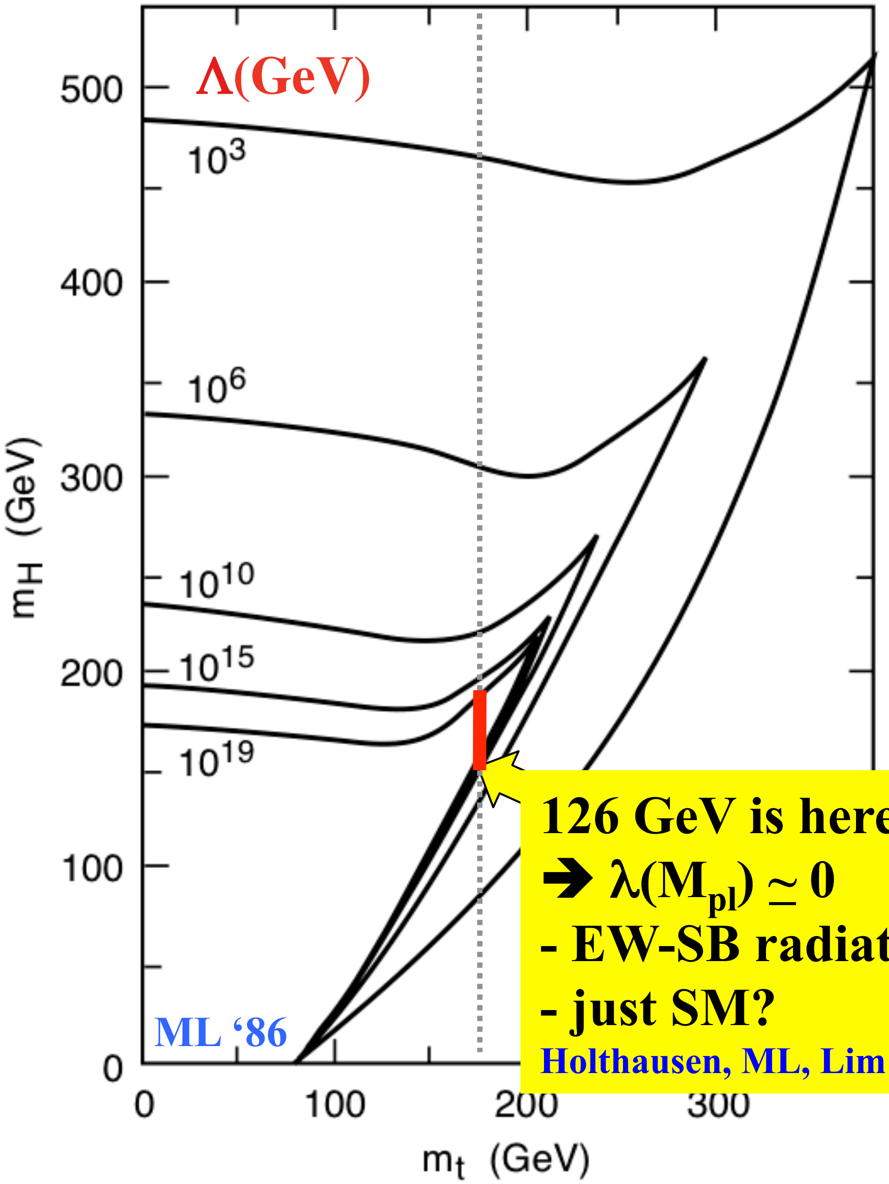
  ➔ requires some scale Λ where the SM is embedded

  ➔ the physics of this scale is unknown
- **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 (without an embeding):

- a hard cutoff Λ and the sensitivity towards Λ has no meaning
- renormalizable, calculable … - just like QED

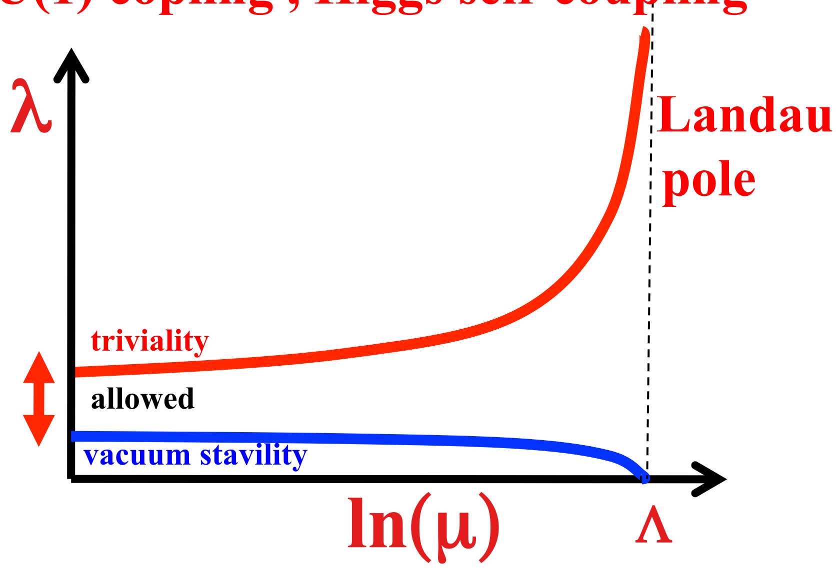
SM:Triviality and Vacuum Stability Bounds



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

$126\ \text{GeV} < m_H < 174\ \text{GeV}$

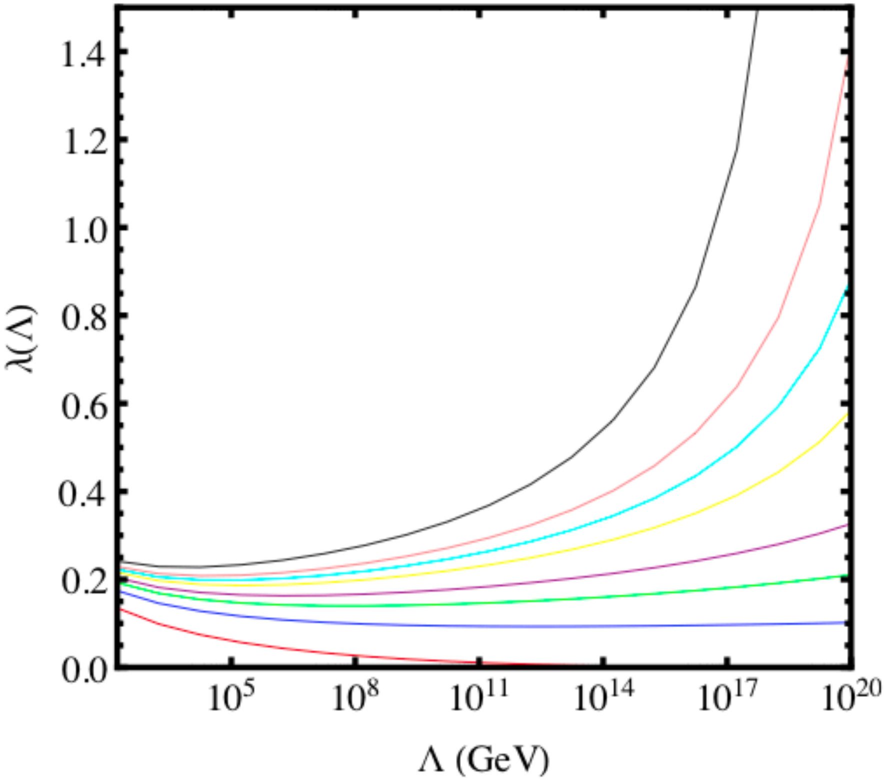
SM does not exist w/o embeding
- U(1) copling , Higgs self-coupling



- **➔ RGE arguments seem to work**
- **➔ we need some embeding**
- **⇔ no BSM physics observed!**
- **➔ just a SM Higgs**

A special Value of λ at M_{planck} ?

ML '86



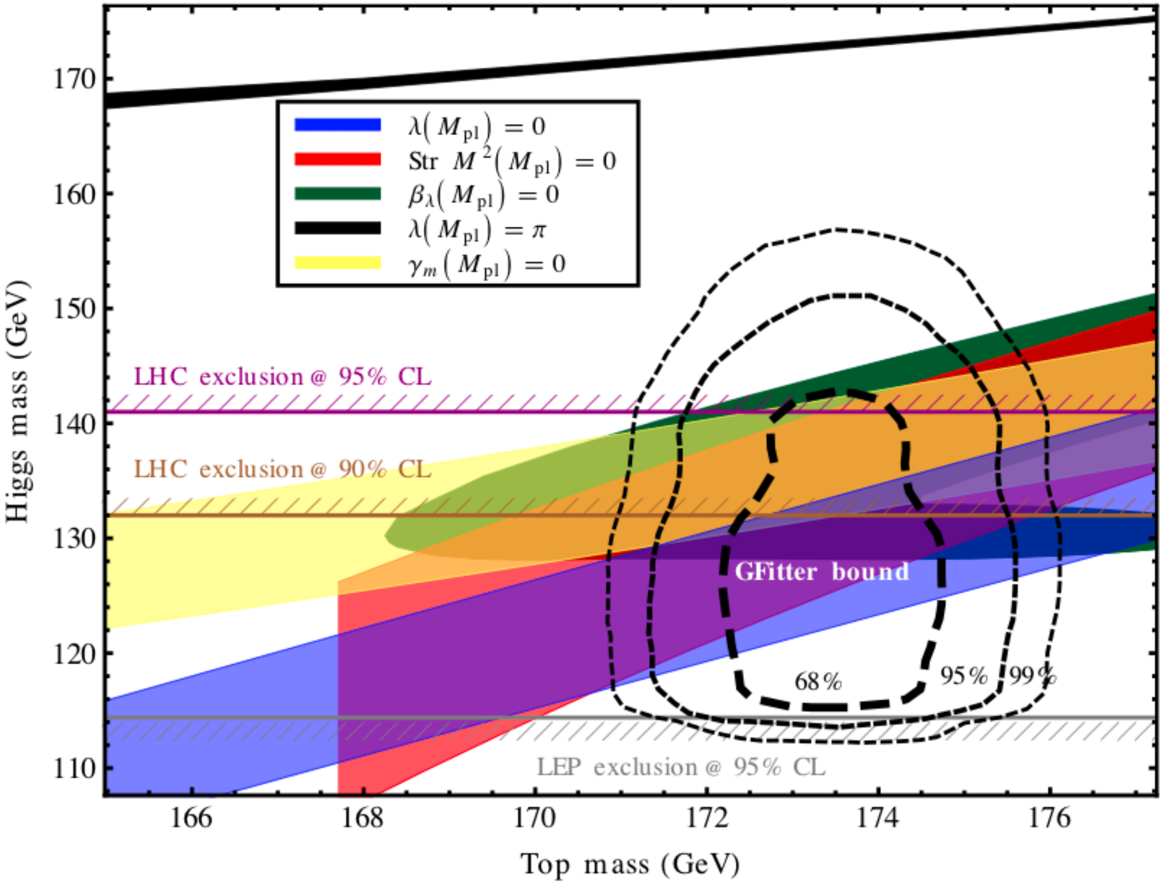
downward flow of RG trajectories
➔ IR QFP ➔ random λ flows to m_H > 150 GeV
➔ $m_H \simeq$ 126 GeV flows to tiny values at M_{Planck}…

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)

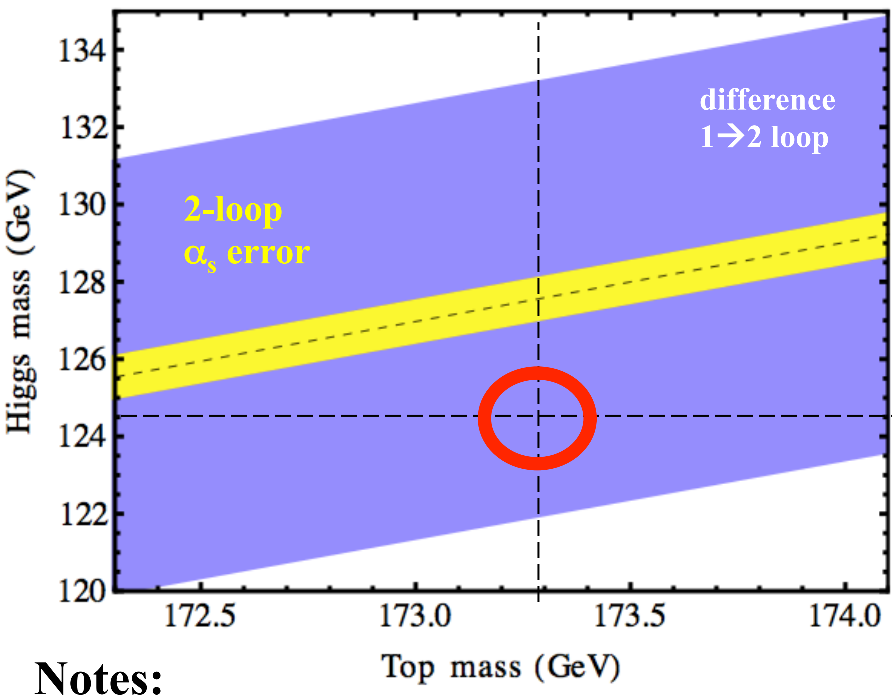
➔ scenarios 'predicting' sufficiently suppressed (small/tiny) λ at M_{planck} are OK

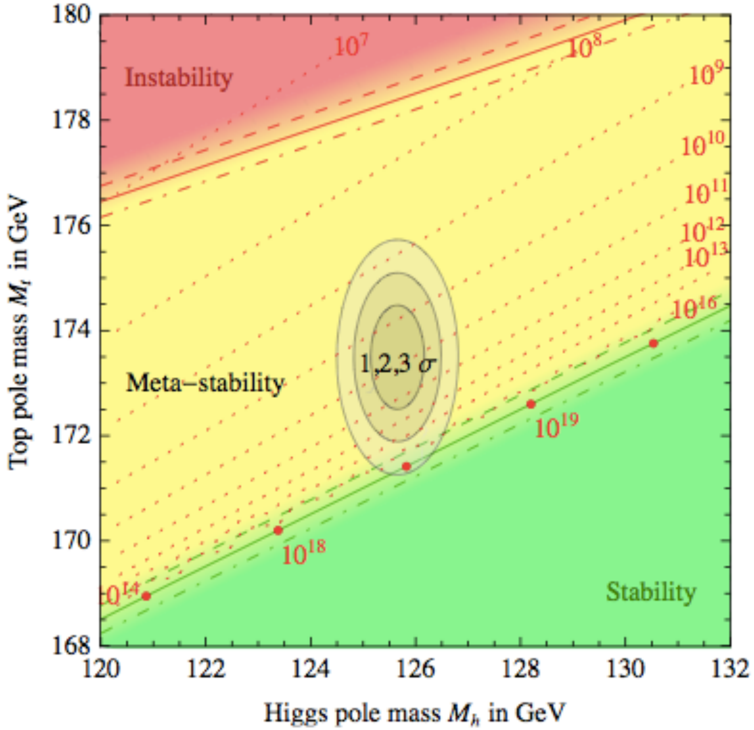
➔ more precision → selects options ; e.g. $\gamma_m = 0$ now ruled out

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, $\alpha_s = 0.1184(7)$ → currently 1.8σ in m_t
- other physics, … Planck scale thresholds… Lalak, Lewicki, Olszewski,

→ important: watch central values & errors → important: new physics ←→ DM, m_ν

→ what if the SM were metastable…? → 1st bubble… → thermal history…

Interpretating 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 radiativly generated - value related to m_t and g_i
→ SM emdeded directly into gravity …!?

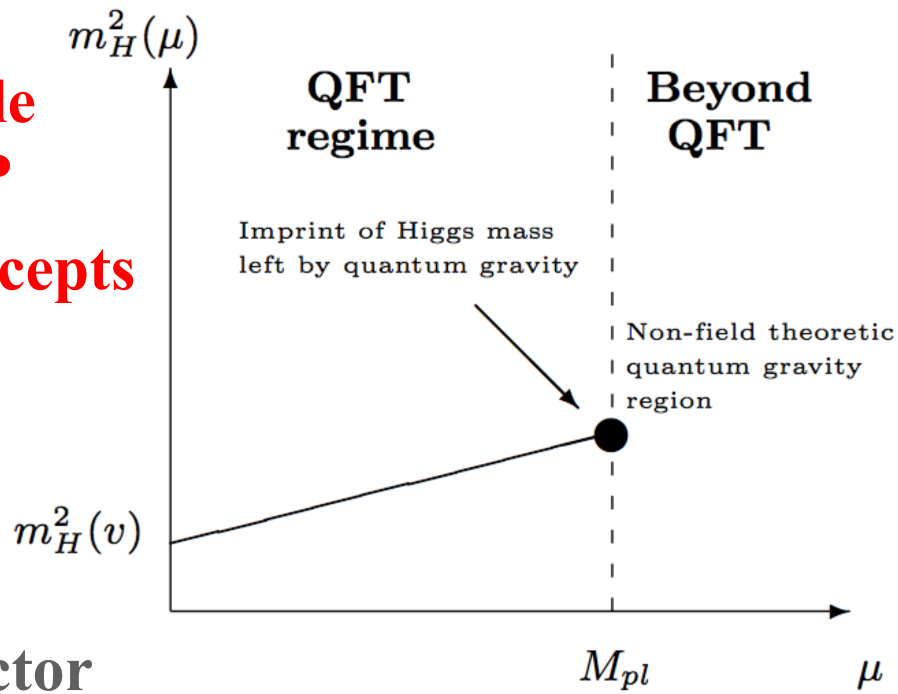
- What about the hierarchy problem?
  → GR is different: Non-renormalizable!
  → requires new concepts beyond QFT/gauge theories: … ?
  → BAD: We have no facts which concepts are realized by nature
  → Two GOOD aspects:

1) QFTs cannot explain absolute masses and couplings
   - QFT embedings = 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**

➔ **The hierarchy problem may be an artefact of the bottom-up QFT perspective. New concepts beyond QFT at the Planck-scale could explain things top-down.**

Embeding the SM

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

What kind of embeding? → two options:

1) some new concept beyond d=4 QFT ←→ $\lambda(M_{Planck})=0$ above
2) some d=4 QFT

2nd route ←→ <u>work over many years</u>
- add representations
- extended gauge groups with and without GUTs
- include SUSY: MSSM, NMSSM, …, SUSY GUTs
- hidden (gauge) sectors, mirror symmetry, …

→ Must face the gauge hierarchy problem

The Hierarchy Problem: What is "Λ"

- Renormalizable QFTs with two scalars φ , Φ with masses m, M and a mass 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 (=since) the SM Higgs field exists

➔ problem: embeding with a 2nd scalar with much larger mass

➔ usual solutions:

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

→ **LHC !**

b) is usually SUSY, but SUSY & gauge unification = SUSY GUT →
→ doublet-triplet splitting problem → hierarchy problem back

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 (CA): Quantum effects explicitly break CS**

  existence of CA → CS preserving regularization does not exist
  - dimensional regularization is close to CS and gives only $\ln(\Lambda)$
  - cutoff reg. → Λ^2 terms; violates CS badly → Ward Identity

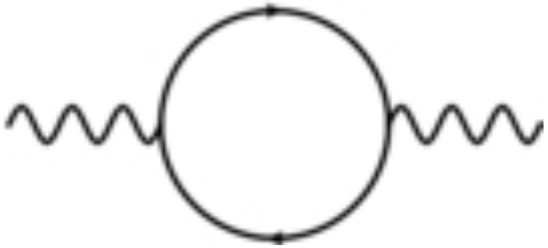
Bardeen: maybe CS still forbids Λ^2 divergences

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

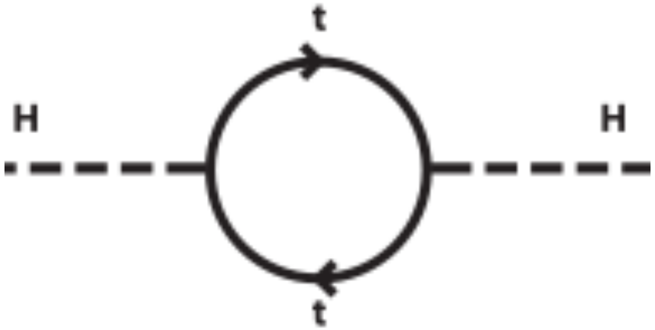
→ anomaly induced spontaneous EWSB

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

Implications



Gauge invariance ➔ only log sensitivity



Relics of conformal symmetry ➔ only log sensitivity

- **With CS there no hierarchy problem, even though it has anomaly**
- **Dimensional transmutation due to log running like in QCD**

  ➔ scalars can condense and set scales like fermions

  ➔ use this in Coleman Weinberg effective potential calculations

  ←→ most attractive channels (MAC) ←→ β-functions

Why the minimalistic SM does not work

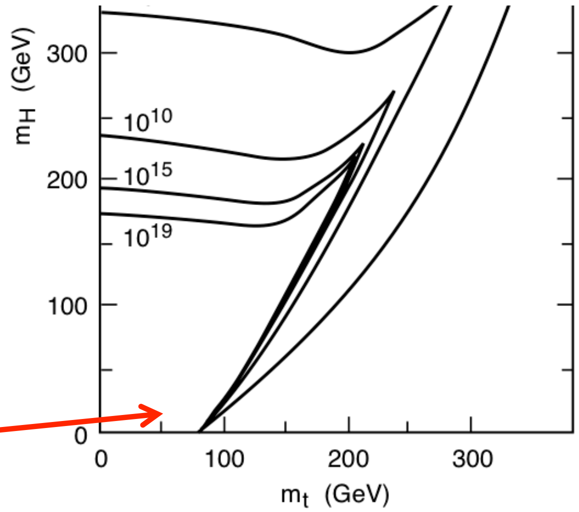
Minimalistic:

SM + 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

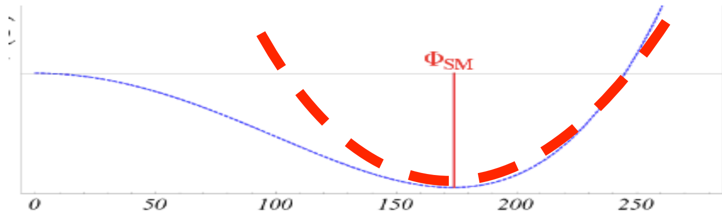


This would conceptually realize the idea, but:

Higgs too light and the idea does not work for $m_t > 79$ GeV

Reason for $m_H << v$: V_{eff} flat around minimum

←→ m_H ~ loop factor ~ $1/16\pi^2$



AND: We need neutrino masses, dark matter, …

Realizing the Idea via Higgs Portals

- SM scalar 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 of $\langle\varphi^{+}\varphi\rangle$ produces $\lambda_{mix}\langle\varphi^{+}\varphi\rangle(\Phi^{+}\Phi) = \mu^2(\Phi^{+}\Phi)$
→ effective mass term for Φ

- CS anomalous … → breaking → only $\ln(\Lambda)$

→ implies a TeV-ish condensate for φ to obtain $\langle\Phi\rangle = 246$ GeV

- Model building possibilities / phenomenological aspects:
  - φ could be an effective field of some hidden sector DSB
  - further particles could exist in hidden sector; e.g. confining…
  - extra hidden U(1) potentially problematic ←→ U(1) mixing
  - avoid Yukawas which couple visible and hidden sector

→ phenomenology safe due to Higgs portal, but there is TeV-ish new physics!

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

→ **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}

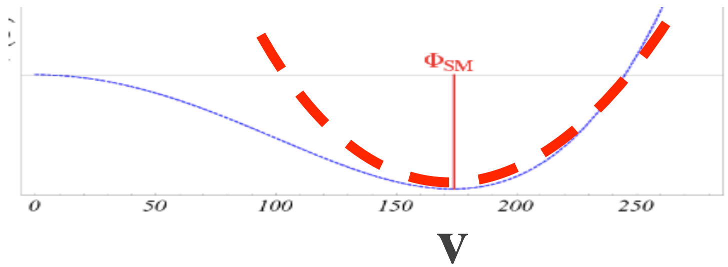
➔ Gildner-Weinberg formalism (RG improvement of flat directions)

- 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 $\sim 1/16\pi^2$

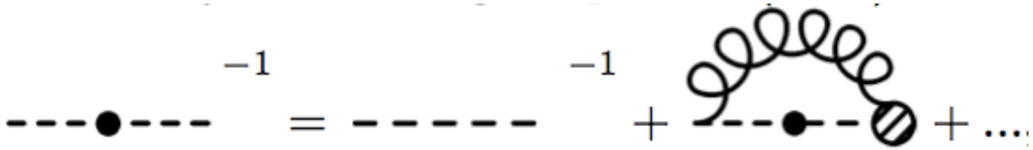
  ➔ generic feature ➔ predictions
- everything works nicely…



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

Rather minimalistic: SM + QCD Scalar S

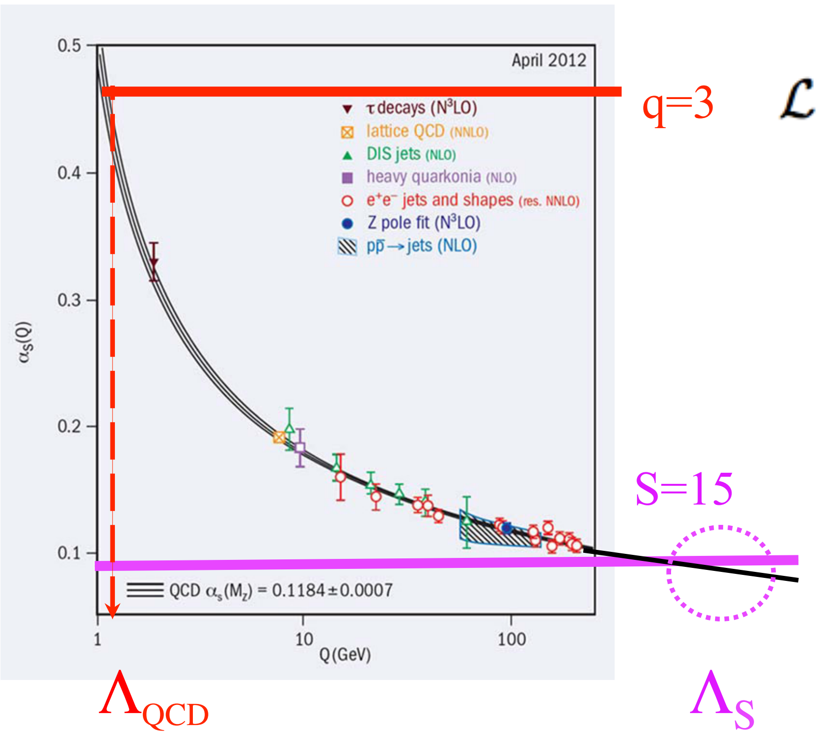
J. Kubo, K.S. Lim, ML New scalar representation S → QCD gap equation:



→ $C_2(S)\alpha(\Lambda) \gtrsim X$

$C_2(\Lambda)$ increases with larger representations

↔ condensation for smaller values of running α



$$\mathcal{L} = \mathcal{L}_{\mathrm{SM},m^2\to 0} + (D_{\mu,ij}S_j)^\dagger (D^\mu_{ik} S_k) + \lambda_{HS} H^\dagger H S^\dagger S - \lambda_{1_i} \left[\bar{\boldsymbol{S}} \times \boldsymbol{S} \times \bar{\boldsymbol{S}} \times \boldsymbol{S}\right]_{\mathbf{1}_i}$$

$$\lambda_{HS}\langle S^\dagger S\rangle H^\dagger H \to \lambda_{HS}\Lambda^2 H^\dagger H$$

$$m_h^2 = 2\lambda_{HS}\Lambda^2 \qquad \frac{\lambda_h}{\lambda_{HS}} = \frac{\Lambda^2}{v^2}$$

Phenomenology

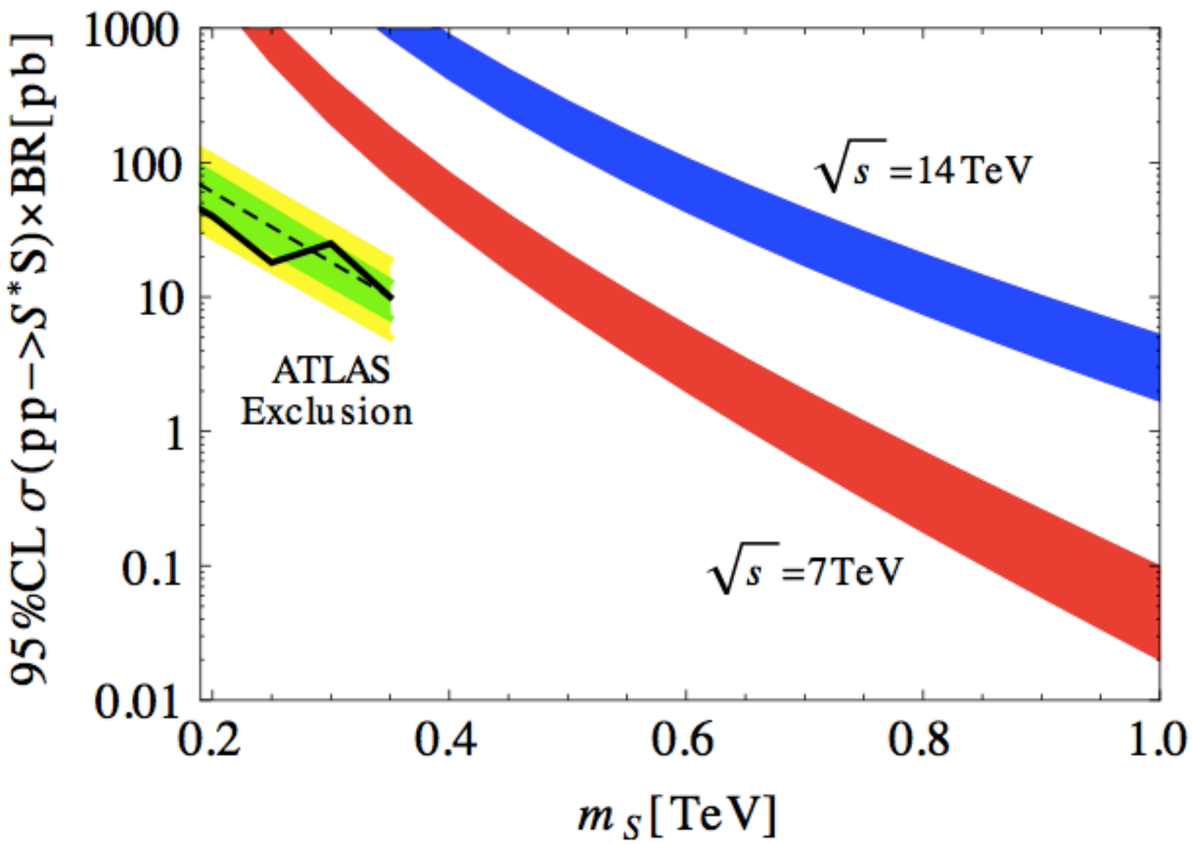


Figure 3. The S pair production cross section from gluon fusion channel is calculated for different value of m_S. The 95% confidence level exclusion limit on $\sigma \times$BR for $\sqrt{s} = 7$ TeV by ATLAS is plotted. We assume 100% BR of $\langle S^\dagger S \rangle$ into two jets.

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 a hidden sector

Hambye, Strumia, Ko, Carone, Ramos, Holthausen, Kubo, Lim, ML

SM embedded into larger symmetry (CW-type LR)

Holthausen, ML, M. Schmidt

SM + colored scalar which condenses at TeV scale

Kubo, Lim, ML

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

Further Comments

- **Having a new (hidden) sector ➔ not surprisingly DM**
- **… or keV-ish sterile neutrios as warm DM …**

- **Question: Isn't the Planck-Scale spoiling things?**
  ➔ conformal gravity = non-linear realization
  see e.g. 1403.4226 by A. Salvio and A. Strumia ➔ `Agravity'
  or K. Hamada, 1109.6109, 0811.1647, 0907.3969

- **Question: What about inflation**
  see e.g. 1405.3987 by K. Kannike, A. Racioppi, M. Raidal

Conformal Symmetry & Neutrino Masses

ML, S. Schmidt , J. Smirnov; arXiv:1405.6204

- No explicit scale ➔ no explicit (Dirac or Majorana) mass term
  ➔ only Yukawa couplings ⊗ generic scales
- Enlarge the Standard Model field spectrum
  like in 0706.1829 - R. Foot, A. Kobakhidze, K.L. McDonald, R. Volkas
- Consider direct product groups: SM ⊗ HS
- Two scales: CS breaking scale at O(TeV) + EW scale

➔ spectrum of Yukawa couplings ⊗ TeV or EW scale
➔ many possibilities

Examples

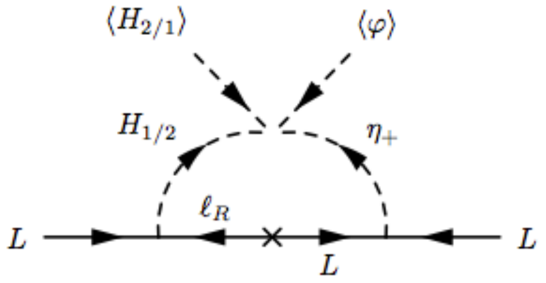
$$\mathcal{M} = \begin{pmatrix} 0 & y_D\langle H\rangle \\ y_D^T\langle H\rangle & y_M\langle\phi\rangle \end{pmatrix}$$

Yukawa seesaw:
SM + ν_R + singlet

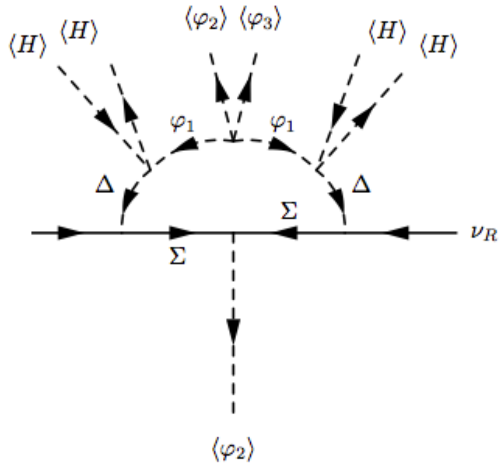
$$\langle\phi\rangle \approx \text{TeV}$$
$$\langle H\rangle \approx 1/4\,\text{TeV}$$

➔ **generically expect a TeV seesaw**
BUT: y_M might be tiny
➔ **wide range of sterile masses** ➔ **includes pseudo-Dirac case**

Radiative masses



Potential: $V = \lambda_L \eta H_1^\dagger H_2\,\varphi + h.c. + \ldots$



Potential: $V = \lambda\varphi_1 H^T i\sigma_2 \boldsymbol{\Delta}^\dagger \tilde{H} + \lambda'\varphi_1^2\varphi_2\varphi_3 + h.c. + \ldots$

$$\mathcal{M} = m_L$$

or

$$\mathcal{M} = \begin{pmatrix} \mu_1 & y_D\langle H\rangle \\ y_D^T\langle H\rangle & \mu_2 \end{pmatrix}$$

➔**pseudo-Dirac case**

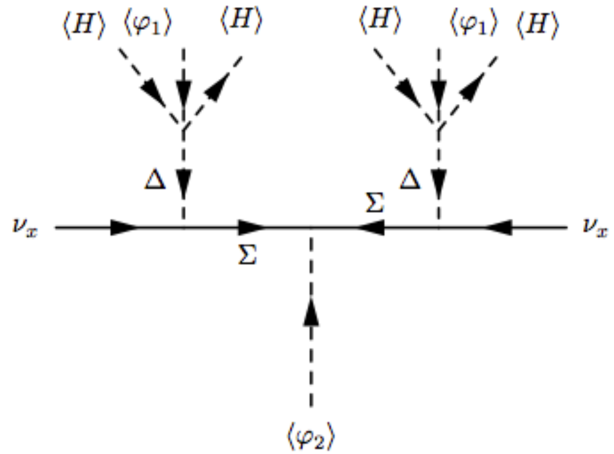
More Examples: Inverse Seesaw

Seesaw & LNV

$$\nu_R \;:\; (1_{SU(2)}, 0_Y, 0_{HS})$$
$$\nu_x \;:\; (1_{SU(2)}, 0_Y, n_{HS})$$

$$\mathcal{M} = \begin{pmatrix} 0 & y_D\langle H\rangle & 0 \\ y_D^T\langle H\rangle & 0 & y_{Rx}\langle\phi\rangle \\ 0 & y_{Rx}^T\langle\phi\rangle & \mu \end{pmatrix}$$

$$\epsilon = \frac{1}{2} y_D^\dagger (y_{Rx}^{-1})^* (y_{Rx}^{-1})^T y_D \cdot \frac{\langle H\rangle^2}{\langle\phi\rangle^2}$$
$$\langle\phi\rangle > \langle H\rangle \text{ and } m_\nu \approx \mu\,\epsilon$$



μ is suppressed (LNV) natural scale keV

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**

- $\lambda(M_{Planck}) = 0$? ←→ **precise value for m_t**
- Embedings into QFTs with classical conformal symmetry
  - SM: Coleman Weinberg effective potential – excluded
  - extended versions → work!

→ implications for Higgs couplings, dark matter, …

→ implications for neutrino masses

→ **testable consequences @ LHC, DM search, neutrinos**