Conformal and Electro-Weak Symmetry Breaking

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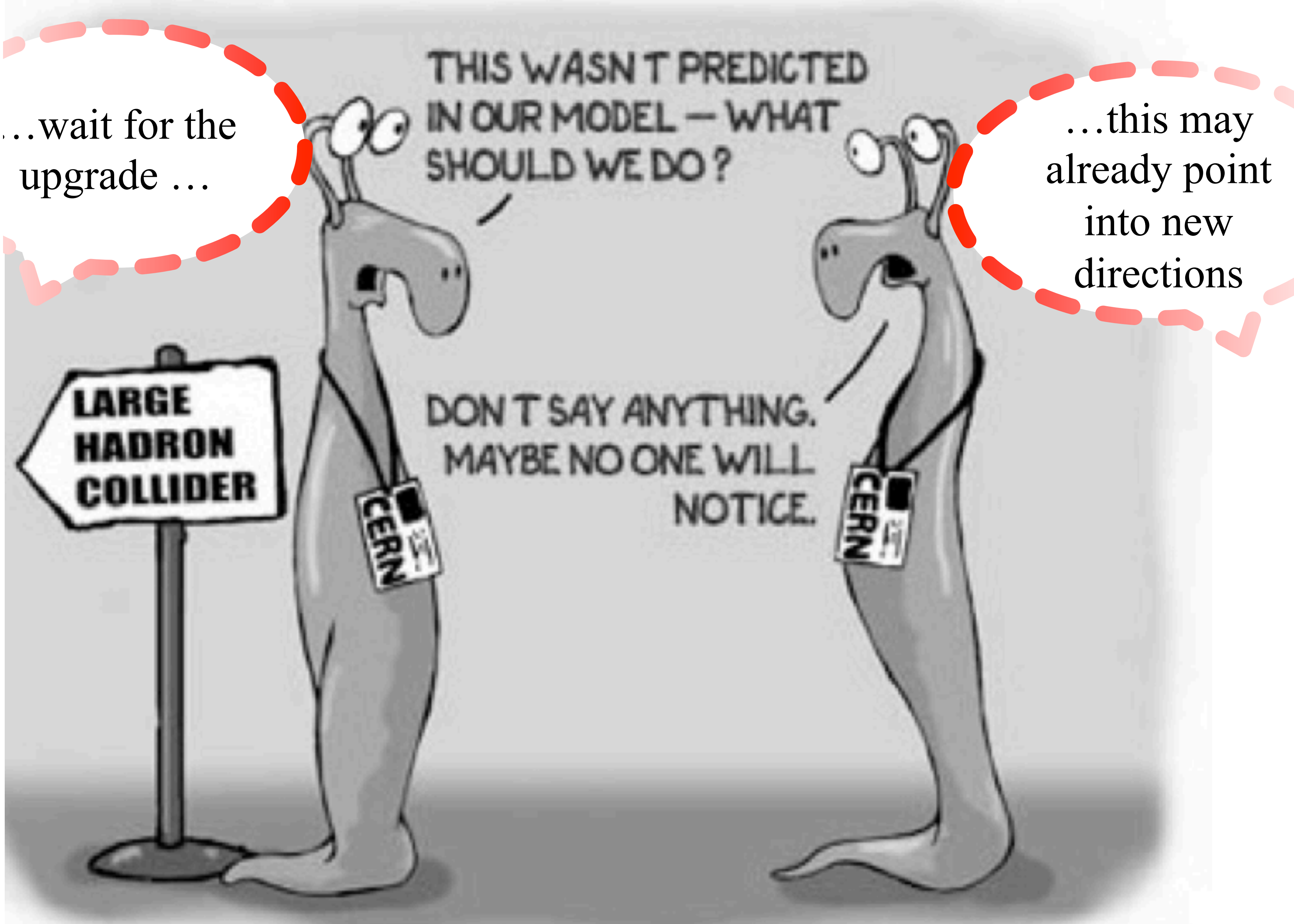

…wait for the upgrade …
THIS WASN T PREDICTED IN OUR MODEL — WHAT SHOULD WE DO ?
…this may already point into new directions
LARGE HADRON COLLIDER
CERN
DON T SAY ANYTHING. MAYBE NO ONE WILL NOTICE.
CERN

Look again carefully at the SM as QFT

- **The SM itself (without embedding) 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

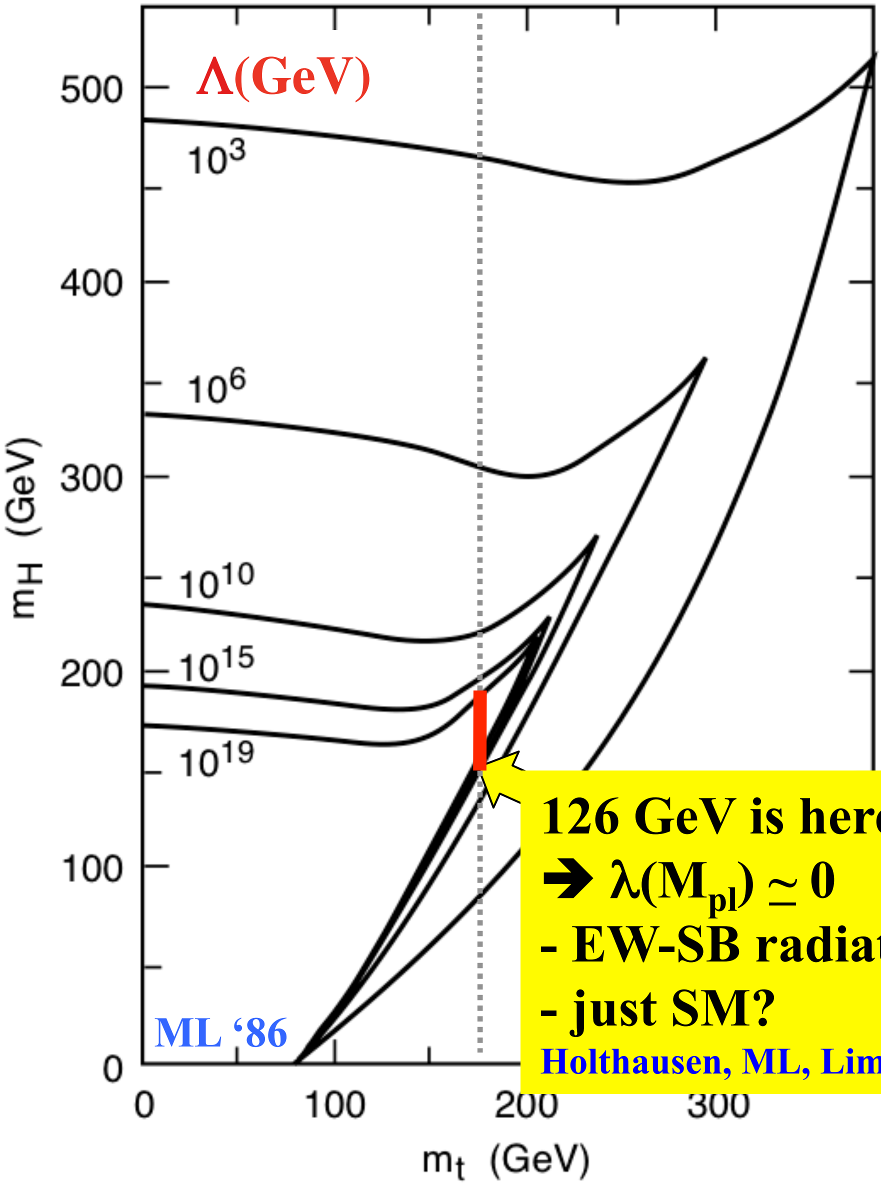
  ➔ requires some scale Λ where the SM is embedded

  ➔ the physics of this scale is unknown → explicit scale or effective
- **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 embedding):

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

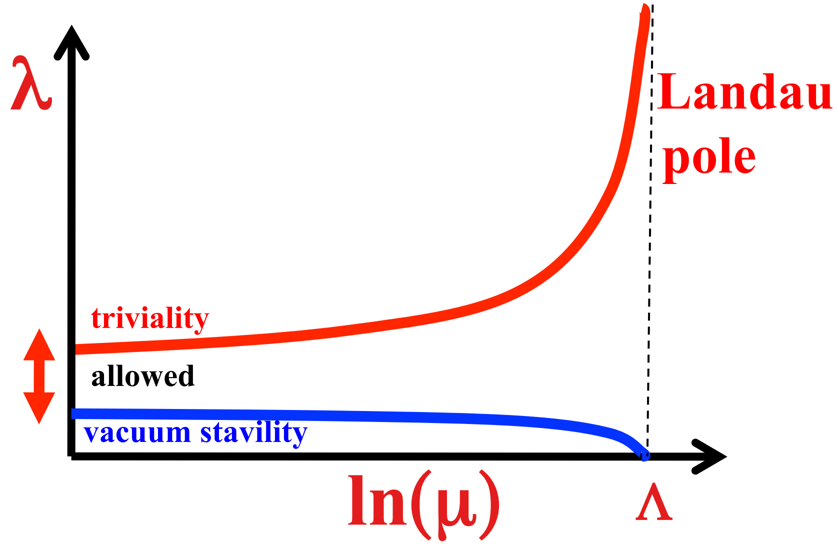
SM:Triviality and Vacuum Stability Bounds



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

126 GeV < m_H < 174 GeV

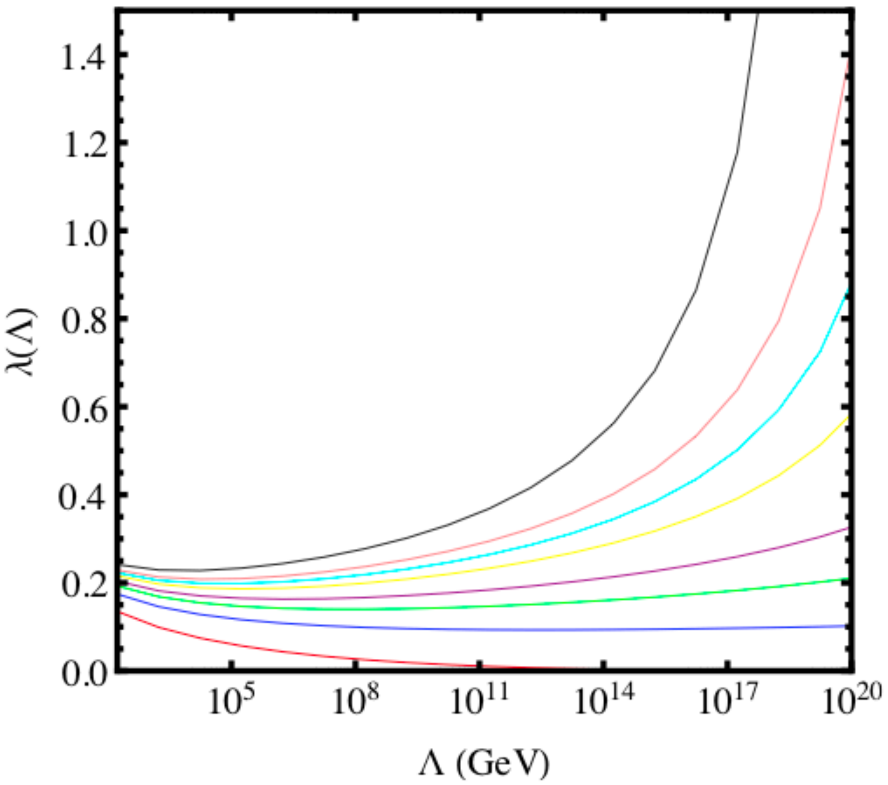
SM does not exist w/o embeding
- U(1) copling , Higgs self-coupling



➔ 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}…

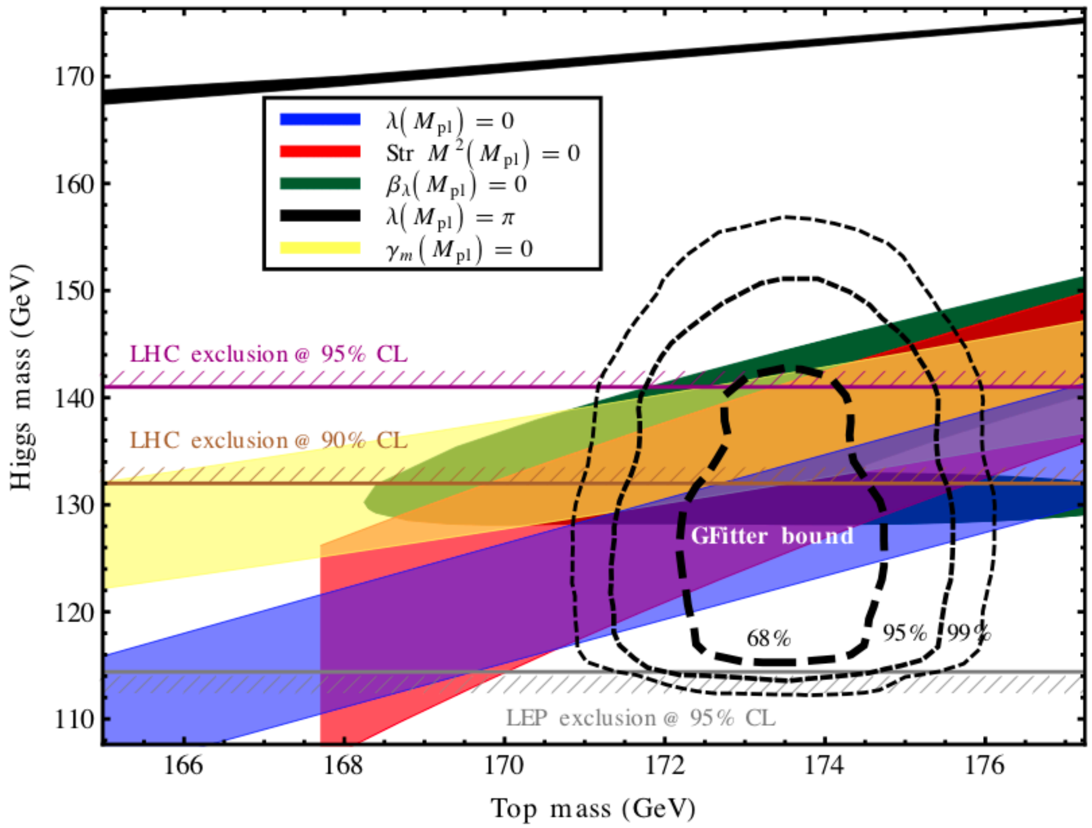
Holthausen, ML Lim (2011)

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

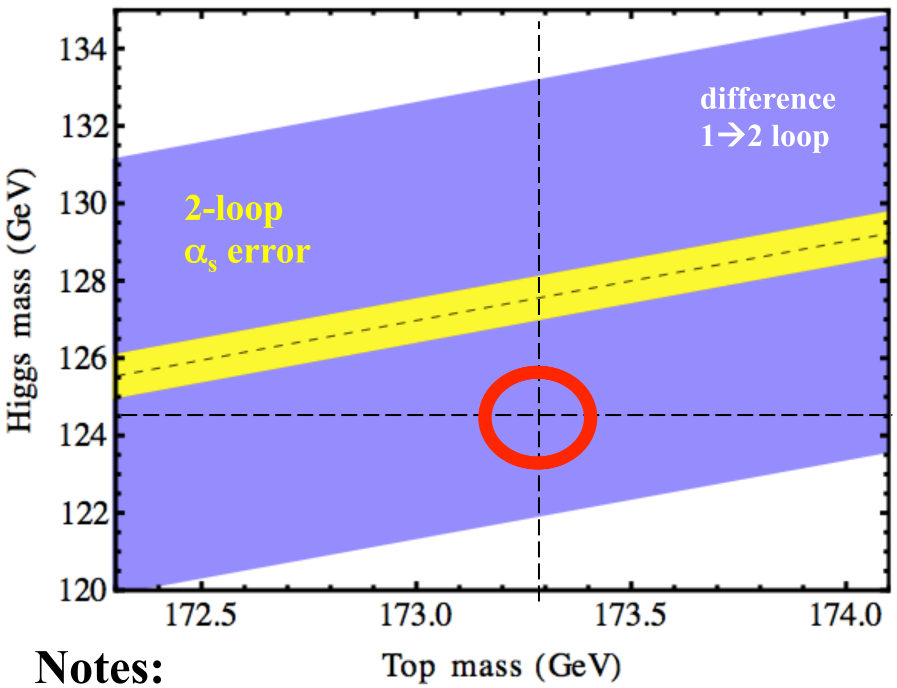
➔ more precision → selects options ; e.g. $\gamma_m = 0$ now ruled out

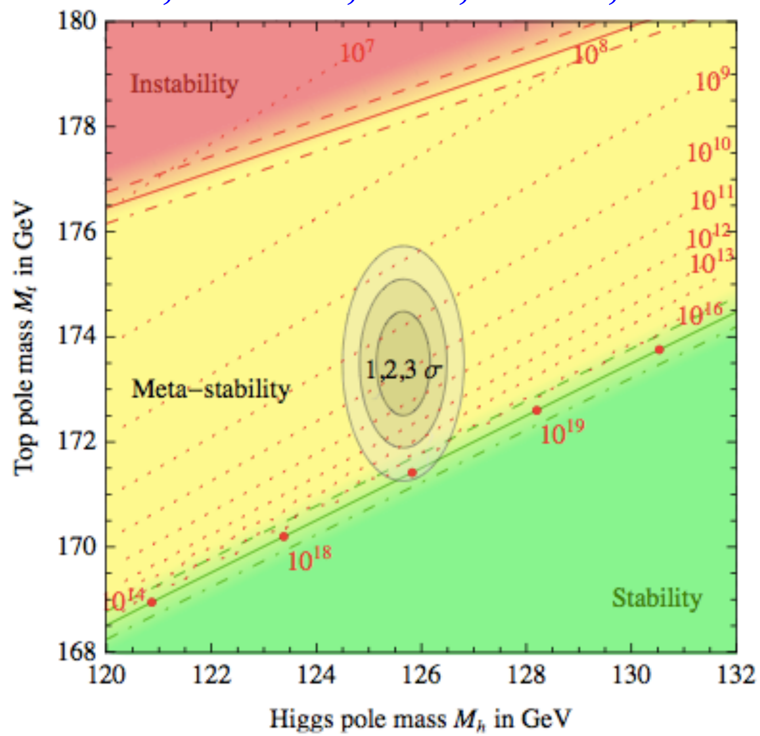
➔ Planck scale boundary conditions seem to fit to experiment…!!!

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: DM, m_ν … axions, …Planck scale thresholds… SM+ ←→ $\lambda = 0$

→ top mass errors: data ←→ LO-MC → translation of m_{pole} → MS bar

→ be cautious about metastability

→ IS THERE A MESSAGE IN : $\lambda(M_{planck}) \simeq 0$? ; and what if also $m^2 = 0$?

➔ Re-thinking Naturalness…

think about / discuss / understand old or new modified basic concepts …

… before you write down specific models

… before you complicate things (confuse yourself…) by technical steps (like a lattice, Λ, …) which are unphysical

… and/or before you start to discuss non-perturbative stuff

➔ new concepts ➔ new symmetries ➔ ???

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 / related to gravity …!?

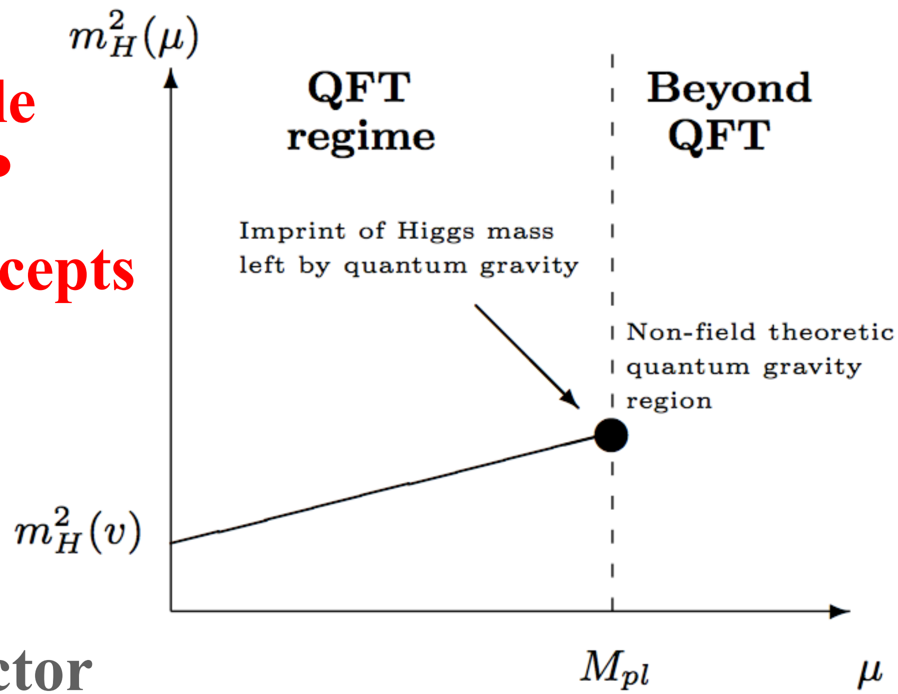
- **What about the hierarchy problem?**
  → GR is different: Non-renormalizable!
  → requires new concepts beyond QFT/gauge theories: … ?
  → BAD: We have no facts which concepts are realized by nature
  → Two GOOD aspects:

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

$$E \approx \alpha|\phi|^2 + \beta|\phi|^4 + \dots$$ ←→ **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.**

Within known Concepts: Symmetry…

The Hierarchy Problem: Not Λ → two explicit scalar Scales

- 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: <u>maybe CS still forbids Λ^2 divergences</u>
- → CS breaking ←→ β-functions ←→ $\ln(\Lambda)$ divergences
- → anomaly induced spontaneous EWSB

NOTE: asymmetric logic! The fact the dimensional regularization kills a Λ^2 dependence is well known. Argument goes the other way!

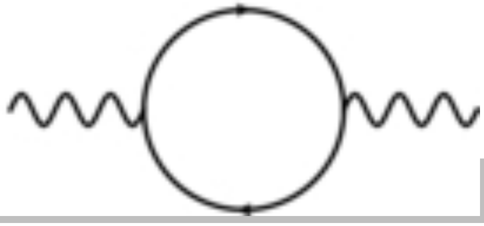
Looking at it in different Ways…

- **Basics of QFT: Renormalization ←→ commutator**
  - [Φ(X),Π(y)] ~ δ^3(x-y) ➔ ~~delta funtion~~ ➔ distribution
  - freedom to define δ*δ ➔ renormalization ←→ counterterms
  - along come technicalities: lattice, Λ, Pauli-Villars, MS-bar, …
- **Reminder: Technicalities do not establish physical existence!**
- **Nice examples → BPHZ-renormalization**
- **Symmetries are essential!**

Question: Is gauge symmetry spoiled by discovering massive gauge bosons? ➔ NO ←→ Higgs mechanism

➔ non-linear realization of the underlying symmetry

➔ important consequence: naïve power counting is wrong



Gauge invariance ➔ only log sensitivity

Versions of QCD…

- **QCD with massless (chrial) fermions**
  - ➔ gauge + conformal symmetry
  - ➔ dimensional transmutation ➔ Λ_{QCD}
  - ➔ reference scale ; everything else is scale ratios
  - ➔ no Λ^2 sensitivity – there is no other physical scale!
  - ➔ **no hierarchy problem**

Question:Do fundamental theories require absolute scales?

Why not everything in relative terms?

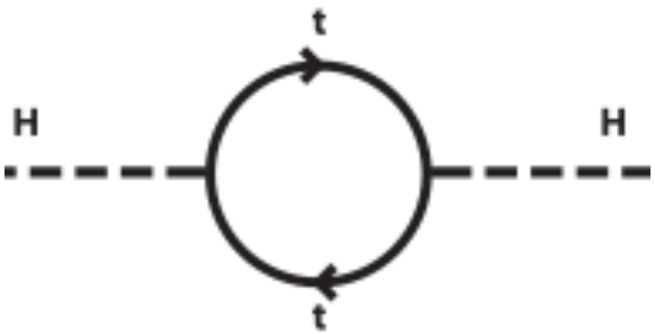
Don't blame a theory on scale problems which you invented (a lattice, a cutoff, …)

Important: The conformal anomaly

⇔ dimensional transmutation ⇔ β-fcts. ⇔ logs

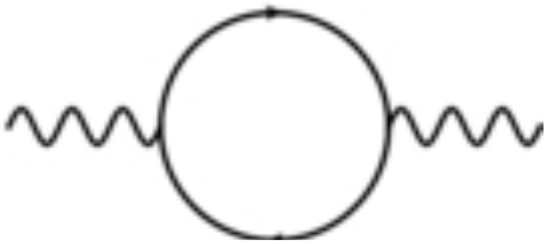
Now massless scalar QCD…

- Massless scalar instead of chiral fermions
- Gauge and conformal symmetry
- Technically there seems to be a Λ^2 divergence
  ➔ but this has no meaning since (if) there is no other explicit physical scale
- Dimensional transmutation ; ➔ Λ_{QCD}
  ➔ reference scale ; everything else is scale ratios
  ➔ conformal anomaly ➔ β-fcts. ➔ only logs

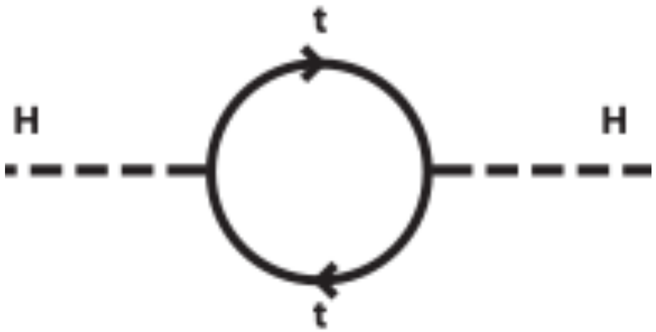


Relict of conformal symmetry
➔ only log sensitivity

Implications



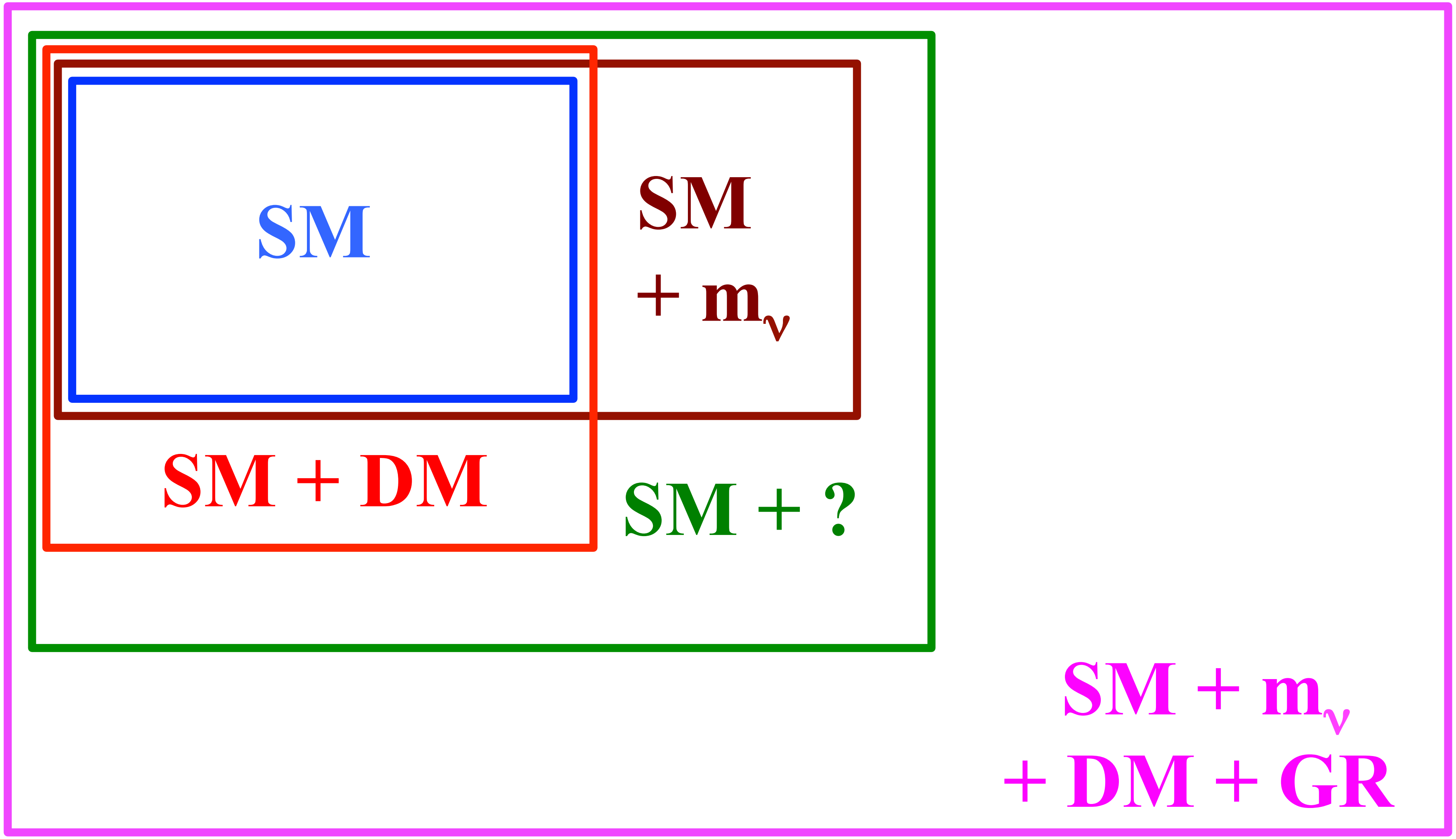
Gauge invariance ➔ only log sensitivity



If conformal symmetry is realized in a non-linear way ➔ protective relic of conformal symmetry ➔ only log sensitivity

- No hierarchy problem, even though there is the the conformal 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

Implementing the Ideas at different Levels



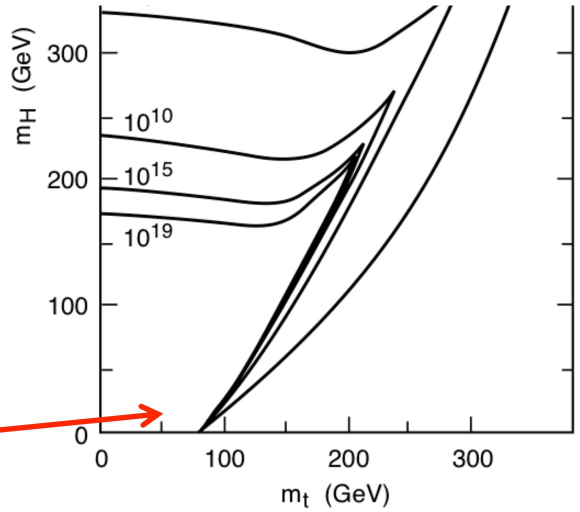
➔ **at all levels: non-linear realization of conformal symmetry**

Further general Comments

- New (hidden) sector ⇔ DM, neutrino masses, …
- Question: Isn't the Planck-Scale spoiling things?
  ➔ non-linear realization… ➔ conformal gravity…
  ideas: see e.g. 1403.4226 by A. Salvio and A. Strumia
  K. Hamada, 1109.6109, 0811.1647, 0907.3969, …
- Question: What about inflation?
  see e.g. 1405.3987 by K. Kannike, A. Racioppi, M. Raidal
  or 1308.6338 by V. Khoze
- What about unification …
- UV stability: ultimate solution should be asymptotically safe (have UV-FPs) … → U(1) from non-abelian group
- Justifying classical scale invariance ➔ …

Open points… but let's play with the idea

Why the minimalistic SM does not work



Minimalistic:

SM + choose $\mu = 0$ ←→ CS

Coleman Weinberg: effective potential

➔ CS breaking (dimensional transmutation)

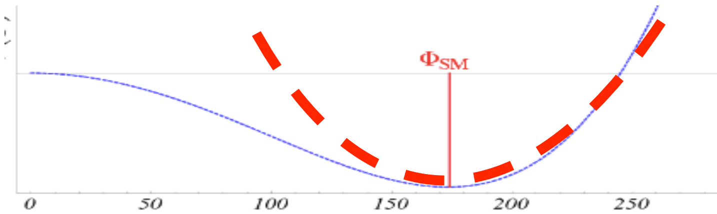
➔ induces for $m_t < 79$ GeV
a Higgs mass $m_H = 8.9$ GeV

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

←→ $m_H \sim$ loop factor $\sim 1/16\pi^2$



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 $<\varphi^+\varphi>$ produces $\lambda_{mix}<\varphi^+\varphi>(\Phi^+\Phi) = \mu^2(\Phi^+\Phi)$
→ effective mass term for Φ

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

→ implies a TeV-ish condensate for φ to obtain $<\Phi> = 246$ 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 $\mathcal{P}$	$\mathbb{Z}_4$	$\mathrm{Spin}(1,3) \times (\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R) \times (\mathrm{SU}(3)_C \times \mathrm{U}(1)_{B-L})$
$\mathbb{L}_{1,2,3} = \begin{pmatrix} L_L \\ -\mathrm{i}L_R \end{pmatrix}$	$P\mathbb{P}\mathbb{L}(t,-x)$	$L_R \to \mathrm{i}L_R$	$\left[\left(\tfrac{1}{2},\underline{0}\right)(\underline{2},\underline{1}) + \left(\underline{0},\tfrac{1}{2}\right)(\underline{1},\underline{2})\right](\underline{1},-1)$
$\mathbb{Q}_{1,2,3} = \begin{pmatrix} Q_L \\ -\mathrm{i}Q_R \end{pmatrix}$	$P\mathbb{P}\mathbb{Q}(t,-x)$	$Q_R \to -\mathrm{i}Q_R$	$\left[\left(\tfrac{1}{2},\underline{0}\right)(\underline{2},\underline{1}) + \left(\underline{0},\tfrac{1}{2}\right)(\underline{1},\underline{2})\right](\underline{3},\tfrac{1}{3})$
$\Phi = \begin{pmatrix} 0 & \Phi \\ -\tilde{\Phi}^\dagger & 0 \end{pmatrix}$	$\mathbb{P}\Phi^\dagger\mathbb{P}(t,-x)$	$\Phi \to \mathrm{i}\Phi$	$(\underline{0},\underline{0})(\underline{2},\underline{2})(\underline{1},0)$
$\Psi = \begin{pmatrix} \chi_L \\ -\mathrm{i}\chi_R \end{pmatrix}$	$\mathbb{P}\Psi(t,-x)$	$\chi_R \to -\mathrm{i}\chi_R$	$(\underline{0},\underline{0})\left[(\underline{2},\underline{1}) + (\underline{1},\underline{2})\right](\underline{1},-1)$

→ **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}

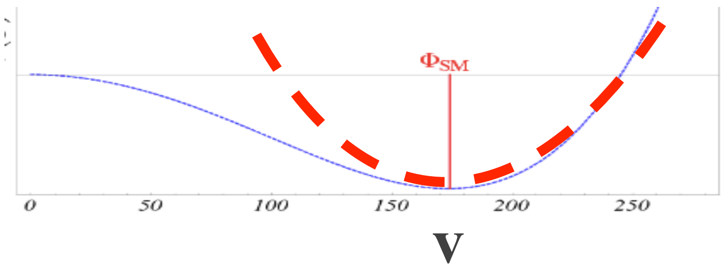
➔ Gildner-Weinberg formalism (RG improvement of flat directions)

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

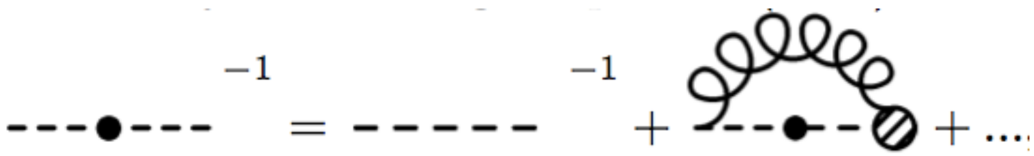
  → generic feature → predictions
- everything works nicely…



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

Rather minimalistic: SM + QCD Scalar S

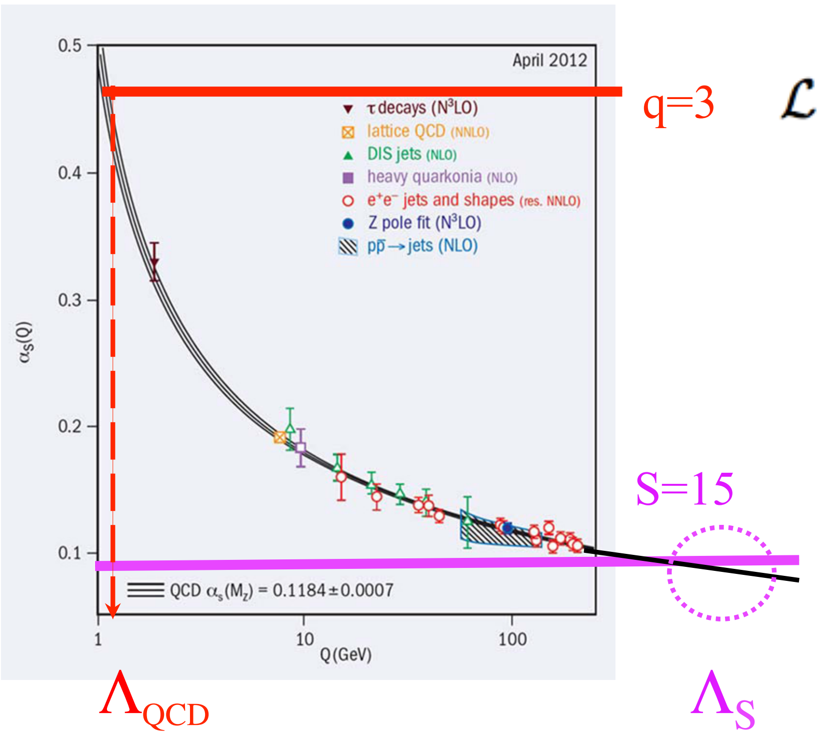
J. Kubo, K.S. Lim, ML New scalar representation S → QCD gap equation:



→ $C_2(S)\alpha(\Lambda) \gtrsim X$

$C_2(\Lambda)$ 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

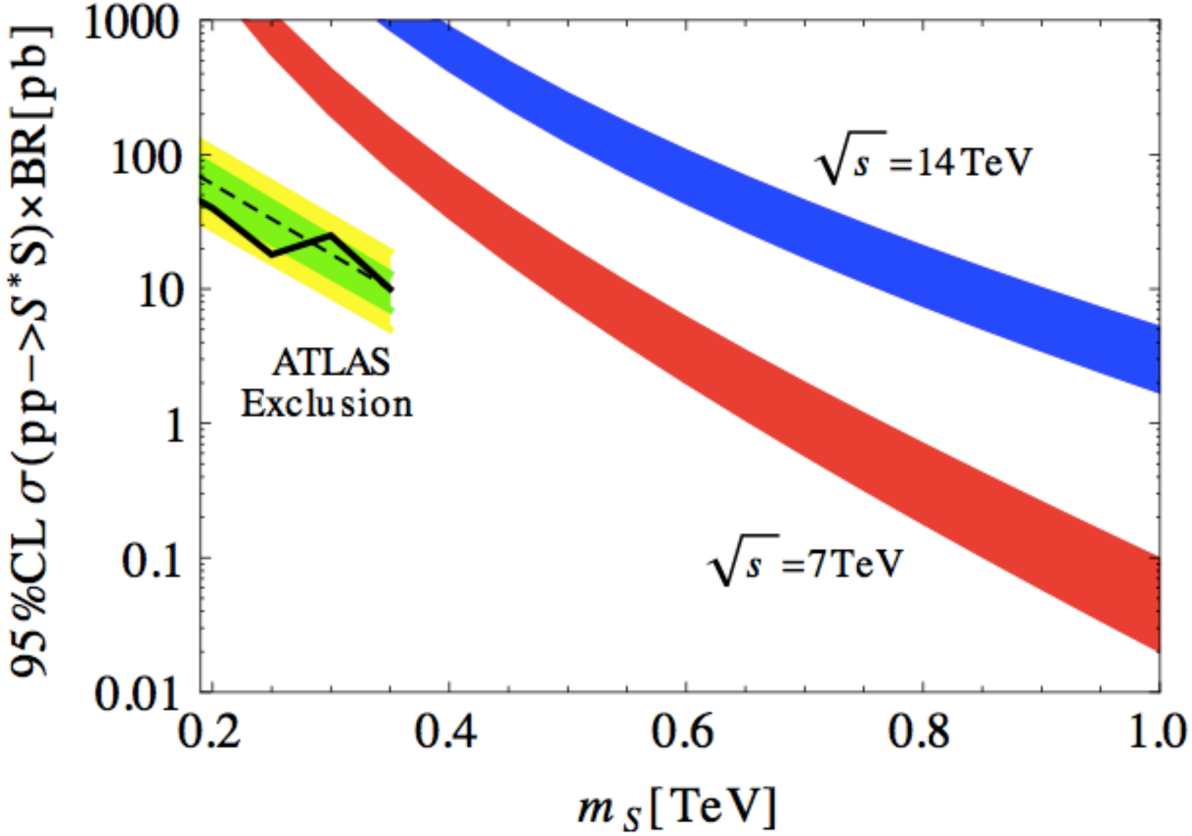


Figure 3. The S pair production cross section from gluon fusion channel is calculated for different value of m_S. The 95% confidence level exclusion limit on $\sigma \times$BR for $\sqrt{s} = 7$ TeV by ATLAS is plotted. We assume 100% BR of $\langle S^\dagger S \rangle$ into two jets.

Realizing the Idea: Examples for 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

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

SM embedded into larger symmetry (CW-type LR)

Holthausen, ML, M. Schmidt

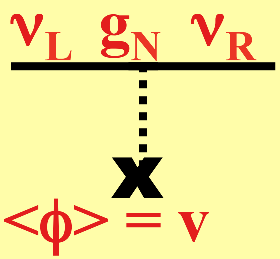
SM + colored scalar which condenses at TeV scale

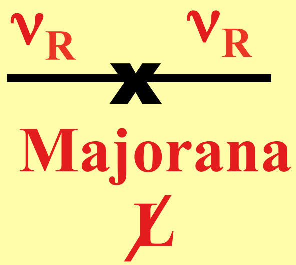
Kubo, Lim, ML

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

Neutrino Masses = New Physics...

Simplest possibility: add 3 right handed neutrino fields





$$\rightarrow \begin{pmatrix} \bar{\nu}_L & \bar{\nu}^c_R \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu^c_L \\ \nu_R \end{pmatrix}$$

like quarks and charged leptons → Dirac mass terms (including NMS mixing)

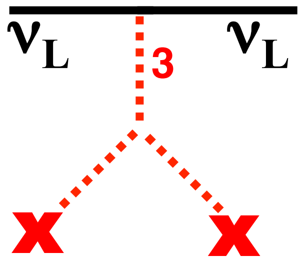
New ingredients:
1) Majorana mass (explicit)
2) lepton number violation

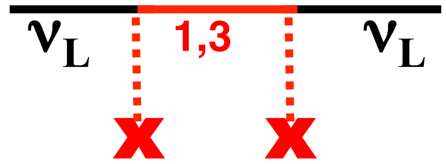
6x6 block mass matrix block diagonalization M_R heavy → 3 light ν's

NEW ingredients, 9 parameters → SM+

Are right-handed neutrinos established?

New scalar tripelts (3_L) or fermionic 1_L ro 3_L





➔ left-handed Majorana mass term:

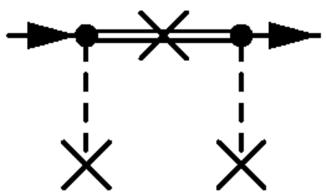
➔ $M_L \overline{L} L^c$

Both ν_R and new singlets / triplets:

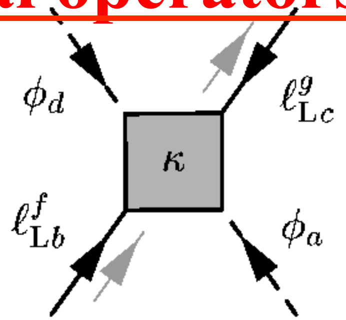
➔ see-saw type II, III

$$m_\nu = M_L - m_D M_R^{-1} m_D^T$$

Higher dimensional operators: d=5, …



$\Rightarrow$

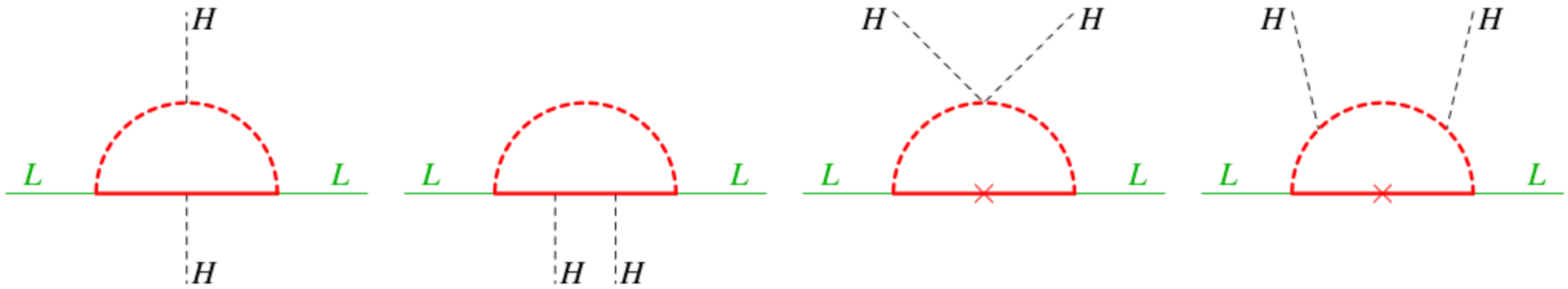


$\Leftrightarrow$

$$\mathcal{L}_{mass} = \kappa \cdot \overline{\nu}^C_L \nu_L \Phi^T \Phi$$

➔ $M_L \overline{L} L^c$

Radiative neutrino mass generation



SUSY, extra dimensions, …

➔ inspiring options, many questions, connections to LFV, LHC, ...
  ➔ SM+ ➔ can/may solve two of the SM problems:
   - Leptogenesis as explanation of BAU
   - keV sterile neutrinos as excellent warm dark matter candidate

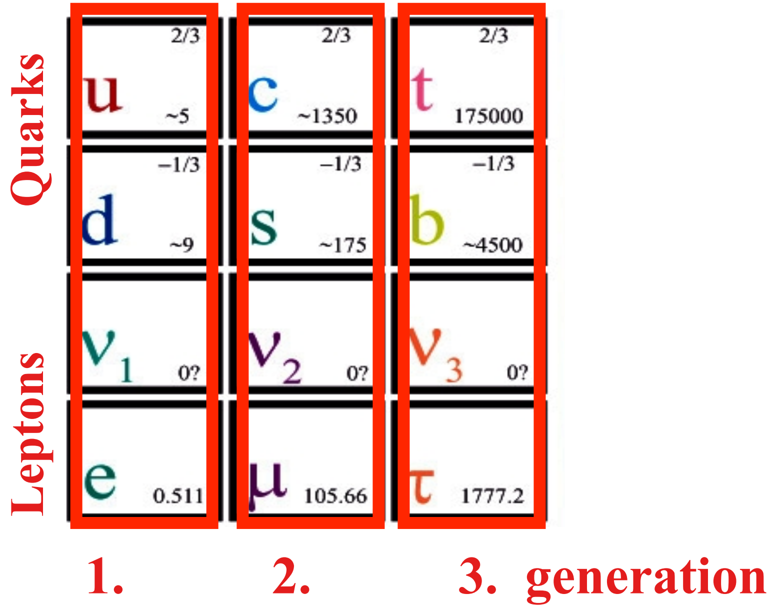
➔ progress:
  - new experimental results ...waiting...
  - theoretical guidance ...guessing...

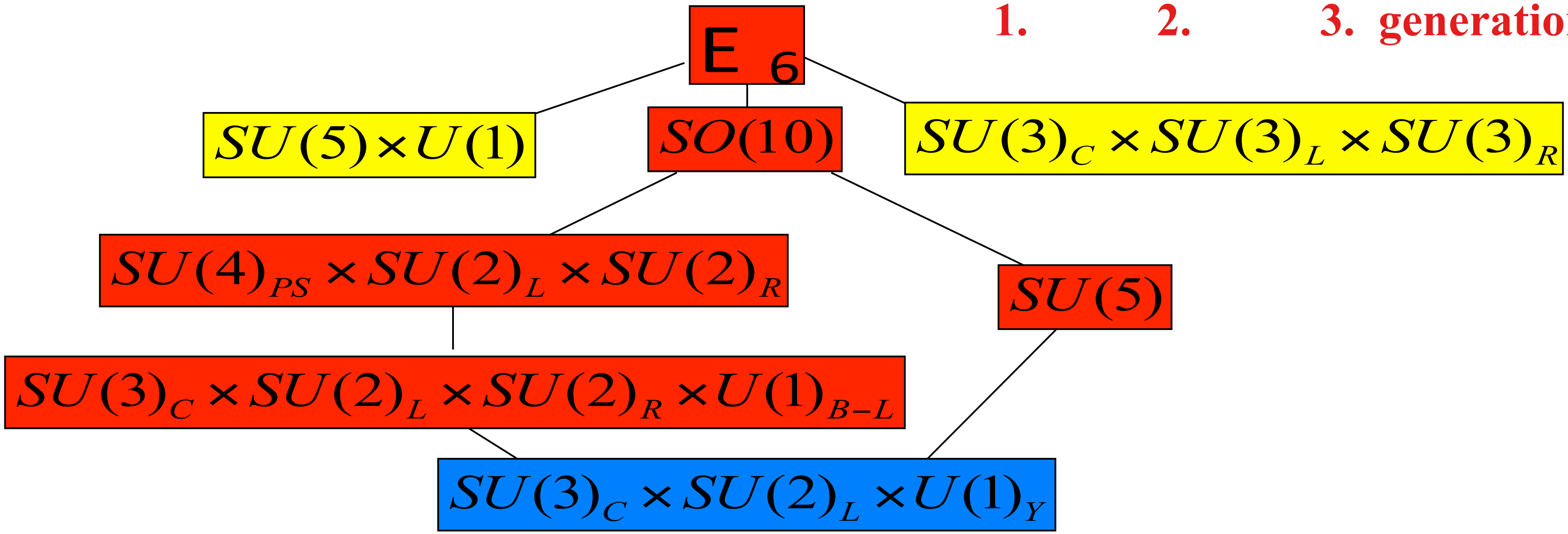
Guidance by the larger Picture: GUTs

Gauge unification suggests GUTs

Ingredients:

- unified gauge group
- unified particle multiplets ⇔ ν_R
  - ➔ Q,L Yukawa couplings connected
  - ….
  - ➔ proton decay , …
- generations are just copies



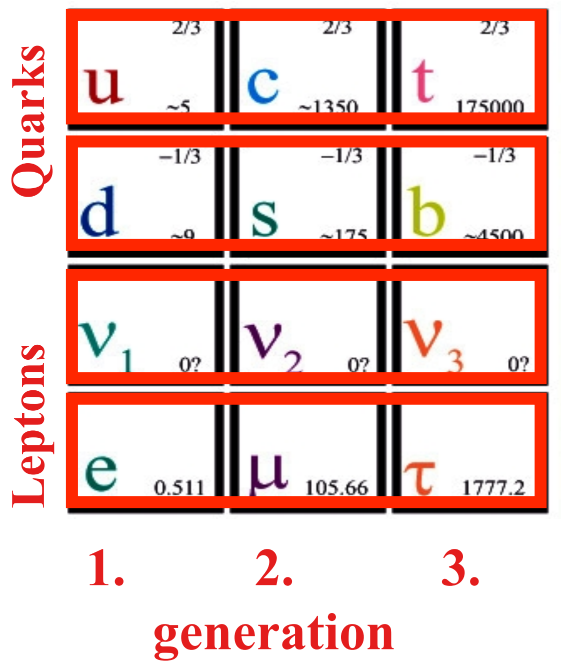


Flavour Unification

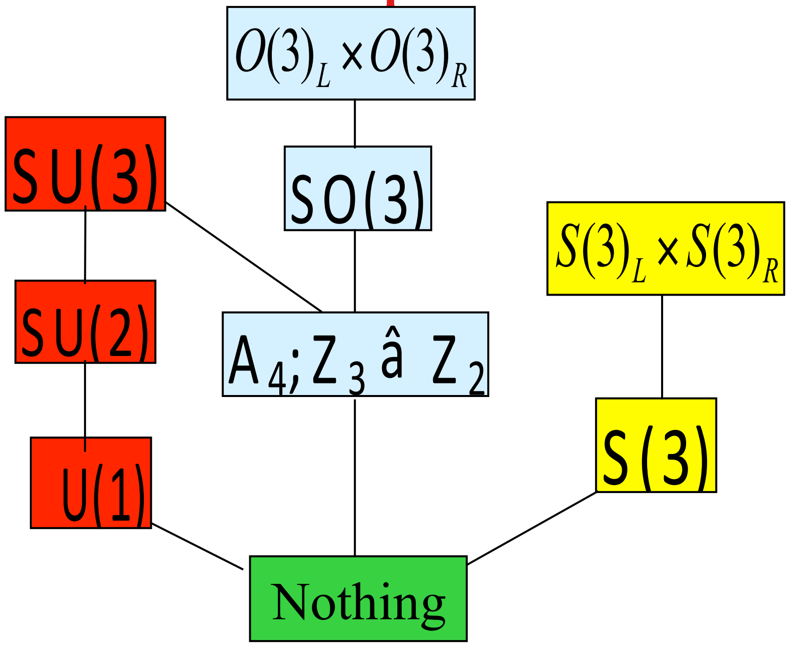
- so far **no understanding of flavour, 3 generations**
- apparant regularities in quark and lepton parameters

➔ flavour symmetries (finite number for limited rank)

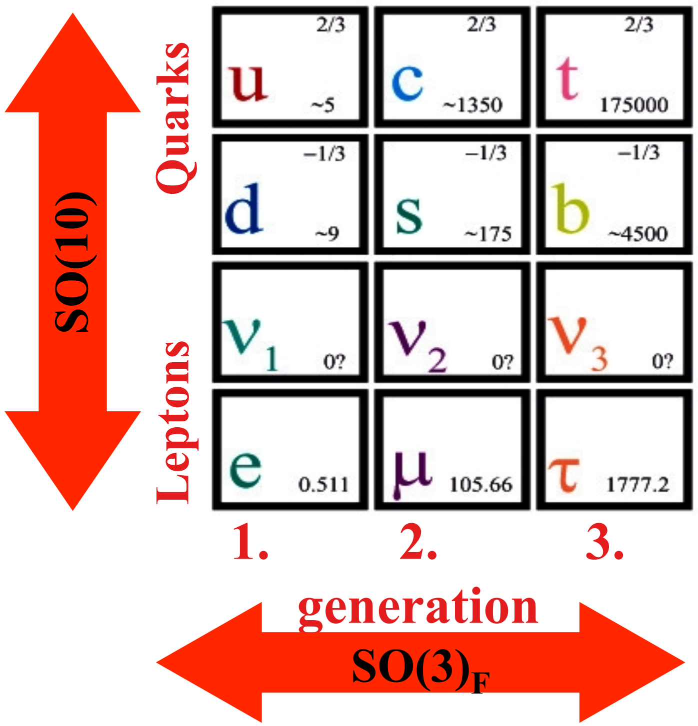
➔ **symmetry** not texture zeros



Examples:



GUT & Flavour Unification



➔ GUT group x flavour group

example: SO(10) x $SU(3)_F$

- SSB of $SU(3)_F$ between Λ_{GUT} and Λ_{Planck}
- all flavour Goldstone Bosons eaten
- discrete sub-groups survive ⟵➔SSB
  e.g. Z2, S3, D5, A4, ...
  ➔ structures in flavour space
  ➔ compare with data

➔ aim: distinguish models by future precision and learn about the origin of flavour

➔ reality so far: many models get killed by data (see e.g. θ_{13}…)

Hints / Arguments / … for Sterile Neutrinos

Particle Physics: LSND,Gallium, MiniBooNE, reactor anomaly, …

CMB: N_ν = 3.3 $\pm$ 0.27 → extra eV-ish ν's possible **PLANCK 2013**

BBN: N_ν = 3-4 → possible e.g. Coc

Astrophysics: keV-ish sterile neutrinos could explain pulsar kicks

Kusenko, Segre, Mocioiu, Pascoli, Fuller et al., Biermann & Kusenko, Stasielak et al., Loewenstein et al., Dodelson, Widrow, Dolgov, …

Dark matter: **keV sterile neutrinos are excellent WDM**

claims

Asaka, Blanchet, Shaposhnikov, … ML, Bezrukov, Hettmanperger

Sterile ν's and improved EW fits: **TeV-ish ν's improve χ^2**

Akhmedov, Kartavtsev, ML, Michaels and J. Smirnov

Most likely not all true, but one is enough:

VERY IMPORTANT IMPLICATIONS → new direct experiments

Options for Neutrino Mass Spectra

3x3 matrix

3 — 0 … N — 3xN — NxN

$$\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} M_L & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

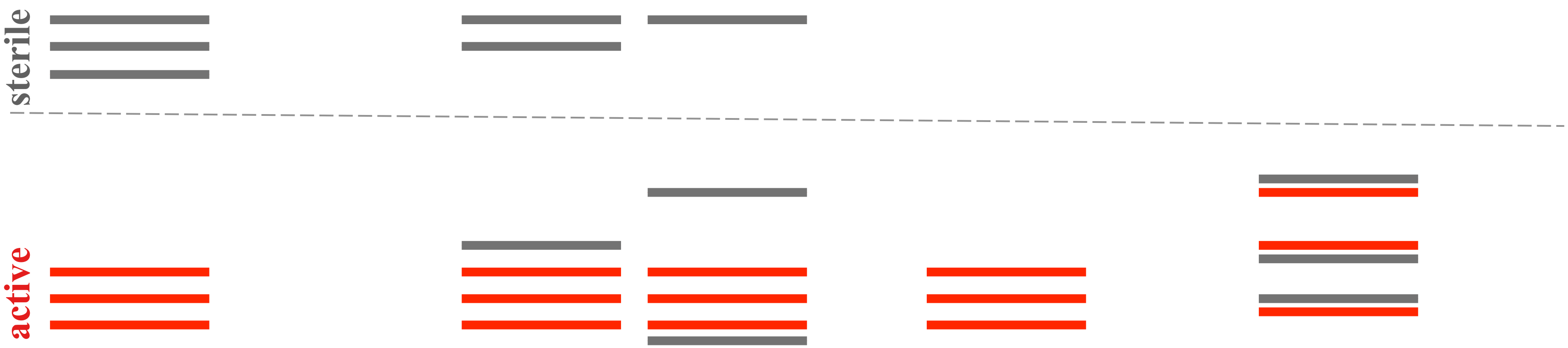
M_L, m_D, M_R may have almost any form / values:

- zeros (symmetries)
- 0 + tiny corrections
- scales: M_W, M_{GUT}, …

➔ diagonalization: 3+N EV

➔ 3x3 active almost unitary

$M_L=0$, $m_D = M_W$, M_R=high: see-saw	M_R singular singular-SS	$M_L = M_R = 0$ Dirac	$M_L = M_R = \varepsilon$ pseudo Dirac



Conformal Symmetry & Neutrino Masses

ML, S. Schmidt and 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

$$\langle\phi\rangle \approx \text{TeV}$$

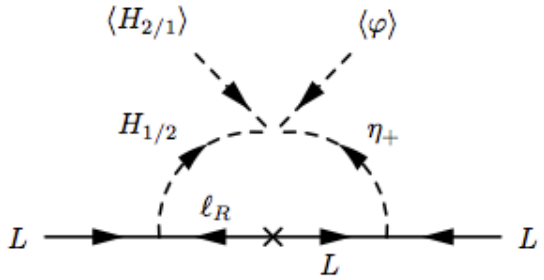
$$\langle H\rangle \approx 1/4\,\text{TeV}$$

➔ **generically expect a TeV seesaw**

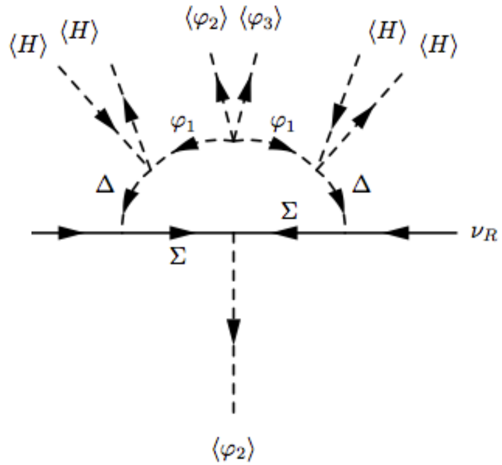
BUT: y_M might be tiny

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

$$\mathcal{M} = m_L$$

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**

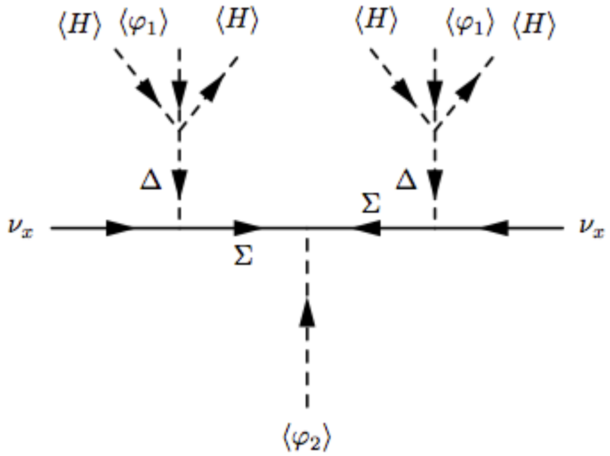
More Examples: Inverse Seesaw

Seesaw & LNV

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

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

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

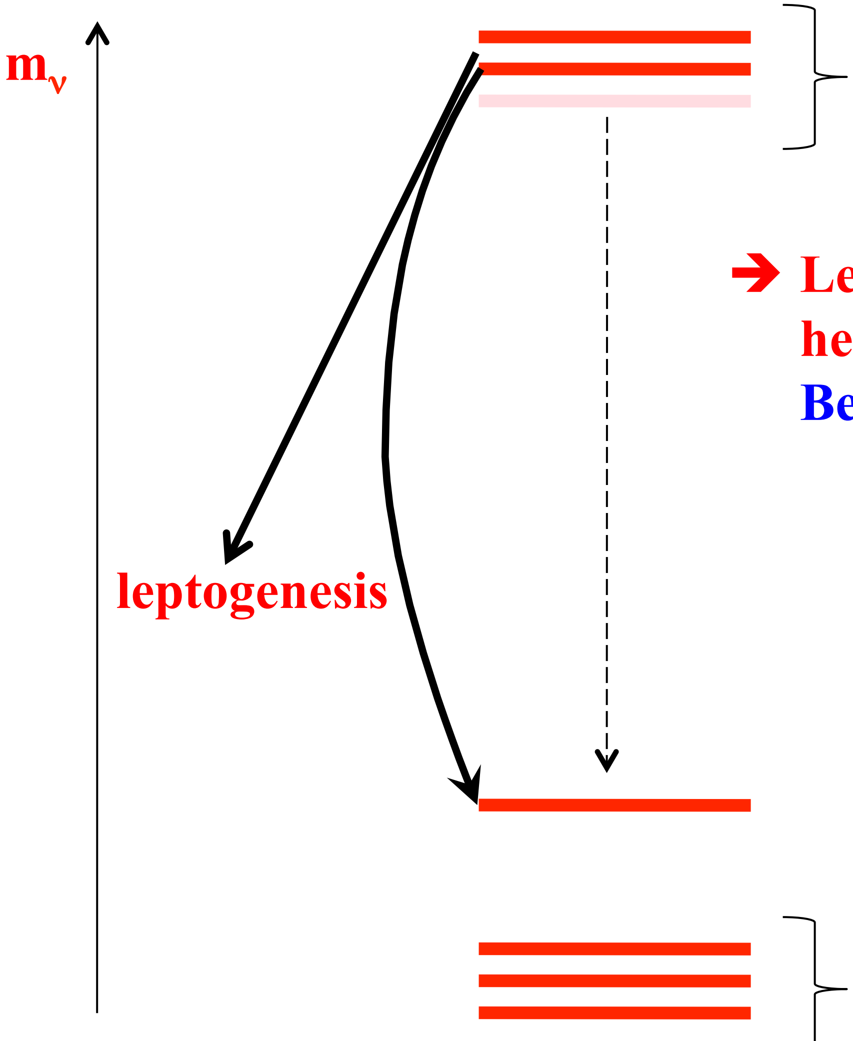


μ is suppressed (LNV) natural scale keV

The punch line:
- all usual neutrino mass terms can be generated
- No explicit masses→ all via Yukawa couplings→ different numerical expectations

➔ More Flexible Neutrino Mass Spectrum

…see-saw spectrum may be rather different than usual. E.g. …



heavy sterile neutrinos typ. $\geq 10^{13}$ GeV

➔ Leptogenesis from the decay of two remaining heavy sterile neutrinos works perfectly!
Bezrukov, Kartavtsev, ML

one light sterile neutrino $\simeq$ keV = DM

light active neutrinos < eV

Summary

- **SM (+m_ν+DM) 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