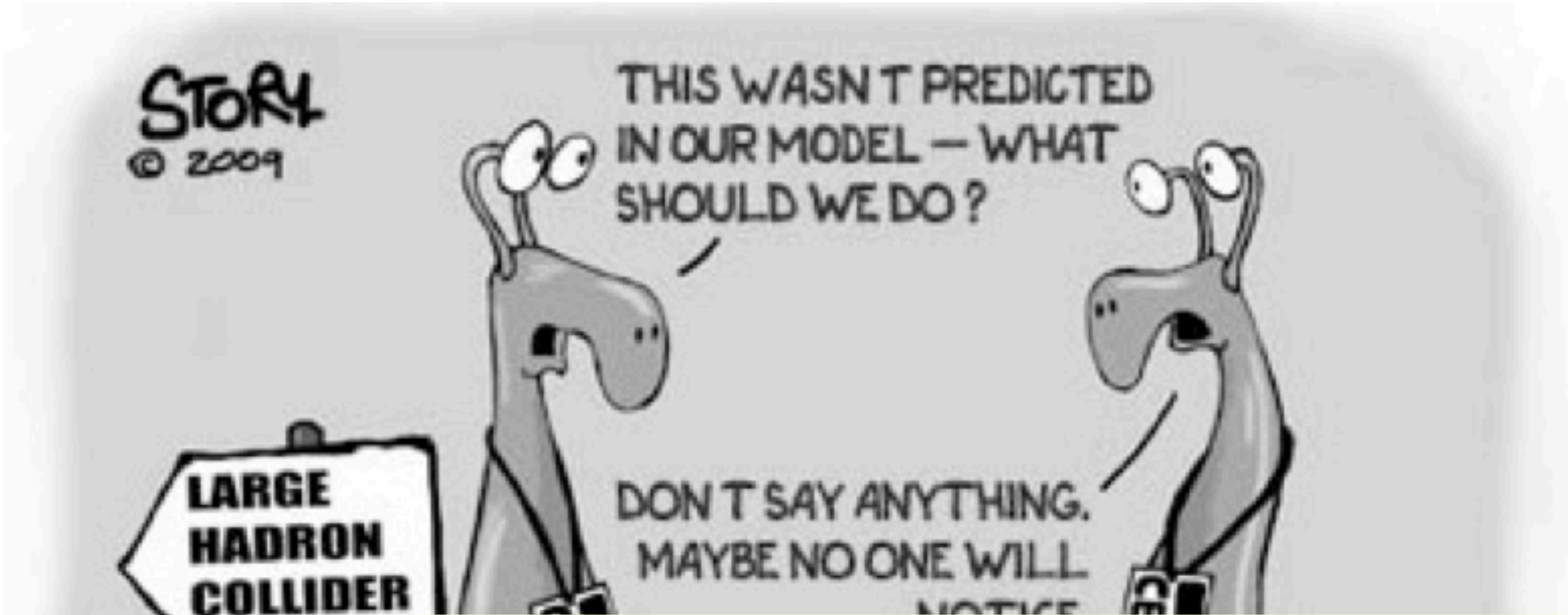
Conformal Extensions of the Standard Model

Manfred Lindner

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG



Very interesting lessons:

➔ SM (+neutrino masses) works perfectly
 ➔ triumph of concepts (QFT, symmetries, precision)
☺ Higgs discovered ←→ particle masses
☹ nothing else (so far…) ←→ ☺ quantum structure of SM
➔ For decades: many ideas for new physics…
➔ things may be different than expected:
 - neutrino masses, - DM, - DE … ➔ very exciting, but…
 ➔ experimental facts trigger (enforce!) new ideas
➔ Maybe it is time to re-think some aspects…

Look again carefully at the SM as a QFT

- **The SM itself (without embedding) is a QFT like QED**
  - infinities, renormalization ←→ δ*δ → only differences are calculable
  - SM itself is perfectly OK → many things unexplained…
- **Has (like QED) a triviality problem (Landau poles ←→ infinite λ)**
  - triviality = inconsistency → requires some scale Λ where the SM is embedded
  - 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

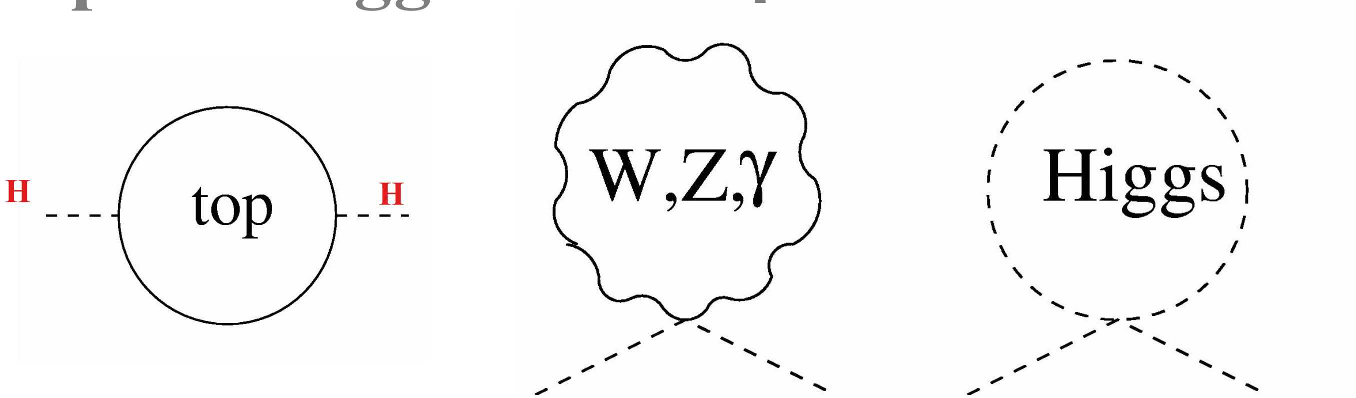
  → the physics at Λ is unknown → explicit scale or effective?
- **Another potential problem is vacuum instability (←→negative λ)**
  - does occur in SM for large top mass > 79 GeV → lower bounds on m_H

<u>The SM as QFT (without an embedding) works perfectly</u>:

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

The naïve Hierarchy Problem

- Loops ➔ Higgs mass depends on 'cutoff Λ'



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

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

*****OR*** one must explain:**

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

SM has not cutoff! ➔ Λ is embedding scale (form factor, heavy M)

The Neutrino Hierarchy Problem

There are generically two HPs:

1) why are scales vastly different

2) why do scales remain vastly different under quantum corrections

SM + an extra Higgs – see before

SM + Dirac neutrinos: no problem – just like SM

SM + Majorana neutrinos:

- two scales: VEV and the Majorana mass(es) M

➔ **generates a HP problem for large M even if y_ν is tiny**

$$\delta m_H^2 \simeq \frac{y_\nu^2}{16\pi^2} M^2 \qquad y_\nu^2 = M m_\nu / v^2$$

➔ $M \lesssim 10^7 - 10^8$ GeV

The Problem: Separation of explicit Scales

- Renormalizable QFT 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 (= portal) in addition to φ^4 and Φ^4
- Quantum corrections ~M^2 drives both masses to the (heavy) scale
  ➔ vastly different scalar scales are generically unstable

- **Since SM Higgs exists ➔ problem: embedding with a 2^{nd} scalar**
  - gauge extensions → must be broken…
  - GUTs → must be broken
  - even for SUSY GUTS → doublet-triplet splitting...
  - also for fashinable Higgs-portal scenarios...

Options:

- **no 2^{nd} Higgs** → just the SM → triviality → requires a new scale...
- **symmetry: SUSY, ...** ➔ conformal symmetry

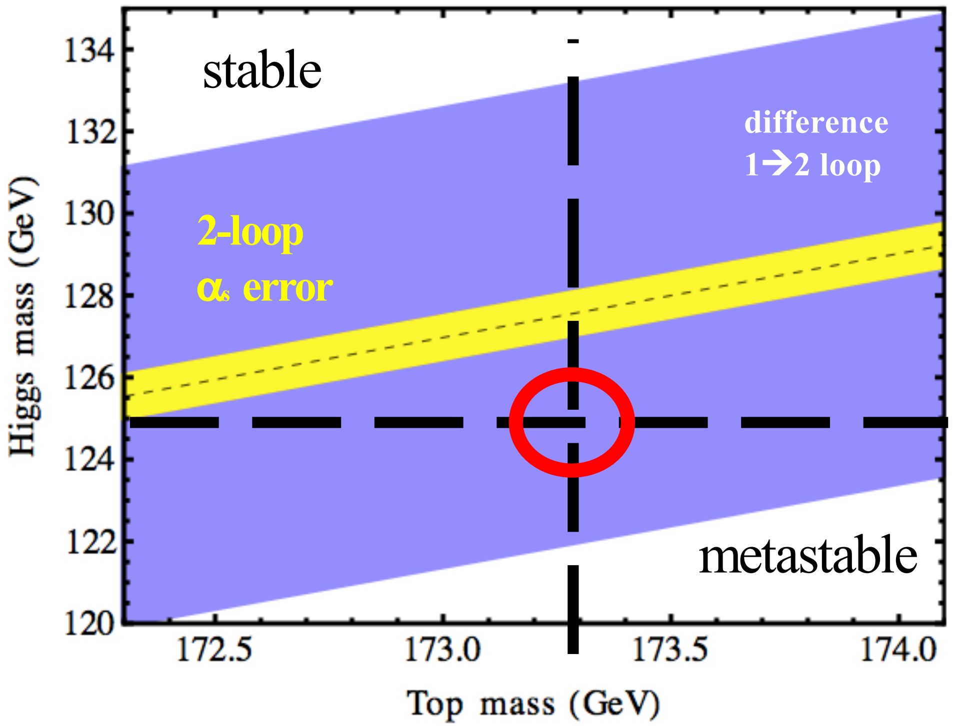
The main Idea

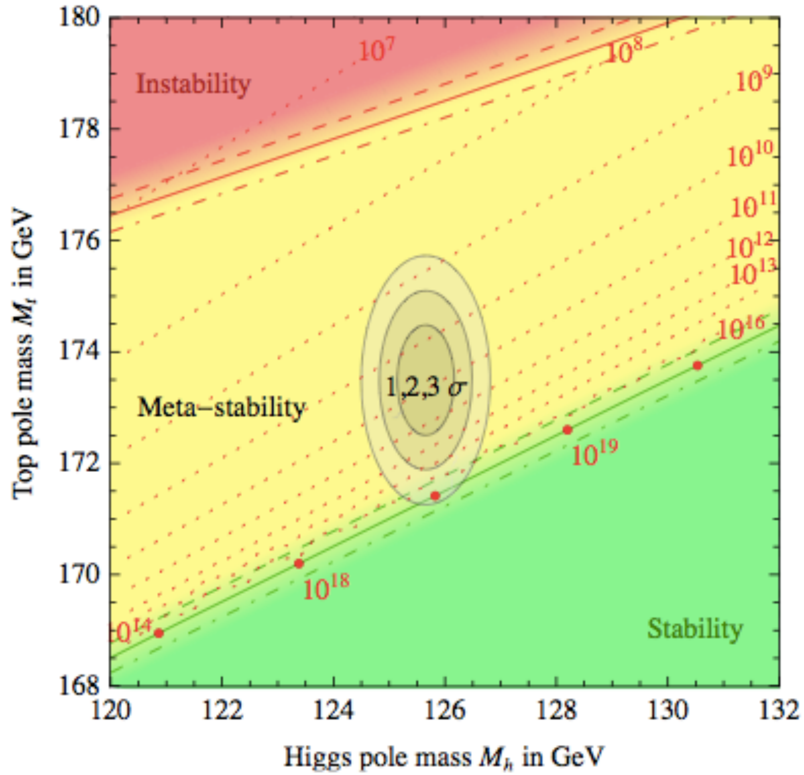
- **Do not introduce two or more fundamental scales**
- **Instead: No fundamental scale**
  ➔ theories with conformal or shift symmetry
- **Dynamical breaking of CS ➔ scale(s)**
- **Non-linear realization of CS:**
  ➔ naïve power counting ($\sim\Lambda^2$) misleading
  ➔ similar to gauge symmetry and vector boson masses

Anything pointing in that direction?

Is the Higgs Potential at M_{Planck} flat?

Holthausen, ML, Lim (2011) **Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia**





Experimental values point to metastability. Is it fully established?

➔ we need to include DM, neutrino masses, …? are all errors (EX+TH) fully included?

➔ be cautious about claiming that metastability is established

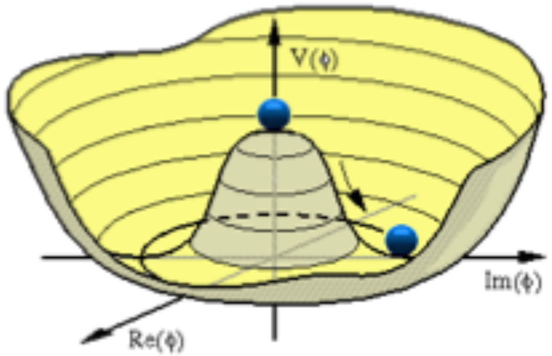
➔ May be a very important observation:

- remarkable relation between weak scale, m_t, couplings and M_{Planck} ←→ precision
- remarkable interplay between gauge, Higgs and top loops (log divergences – not Λ^2)

Is there a Message?

- $\lambda(M_{Planck}) \simeq 0$? ➔ remarkable log cancellations
  M_{planck}, M_{weak}, gauge, Higgs & Yukawa couplings are unrelated

- remember: μ is the only single scale of the SM ➔ special role
  ➔ if in addition $\mu^2 = 0$ ➔ $V(M_{Planck}) \simeq \sim 0$
  ➔ flat Mexican hat (<1%) at the Planck scale!



➔

➔ **conformal (or shift) symmetry as solution to the HP**

➔ **combined conformal & EW symmetry breaking**

- conceptual issues
- realizations

Generic Questions

- **Isn't the Planck-scale spoiling things (explicit scale, cut-off, …)?**
  ➔ renormalizable QFTs (SM) don't have cut-offs
  - explicit scales in embeddings act like a cut-off
  - important: no cutoff if the emebedding has no explicit scale

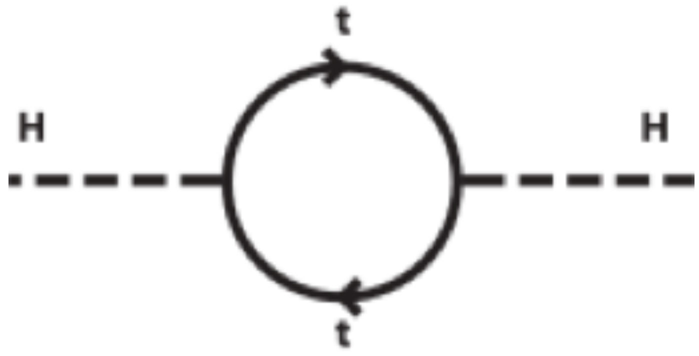
  ➔ non-linear realization of conformal symmetry… ➔ ~conformal gravity…
  ➔ protected by conformal symmetry up to conformal anomaly
  ➔ some mechanism that generates M_{Planck} by dimensional transmutation
  ➔ working assumption: M_{Planck} somehow generated in a conformal setting

- **Are M_{planck} and M_{weak} connected?**
  ➔ maybe …
  ➔ here assumed to be independently generated scales

- **UV: ultimate solution should be asymptotically safe** ➔ UV-FPs…

- **Conceptual change for scale setting:**
  So far a rollover of scale generation: SM ➔ BSM ➔ GUT ➔ gravity (M_{Planck})
  Here: only relative scales – absolute scale is meaningless

Non-linear Realization of Conformal Symmetry



Non-linear realization of conformal symmetry:

→ protection by conformal symmetry
→ naïve power counting invalid
→ similar to vector boson masses
→ only log sensitivity
←→ conformal anomaly
←→ β-functions

- **Avoids hierarchy problem, even though there is the the conformal anomaly - only logs ←→ β-functions**
- **Dimensional transmutation of conformal theories by log running like in QCD**
  → scalar QCD: scalars can condense and set scales like fermions
  → also for massless scalar QCD: **scale generation; no hierarchy**

Why the minimalistic SM does not work

Minimalistic version: → "SM-"

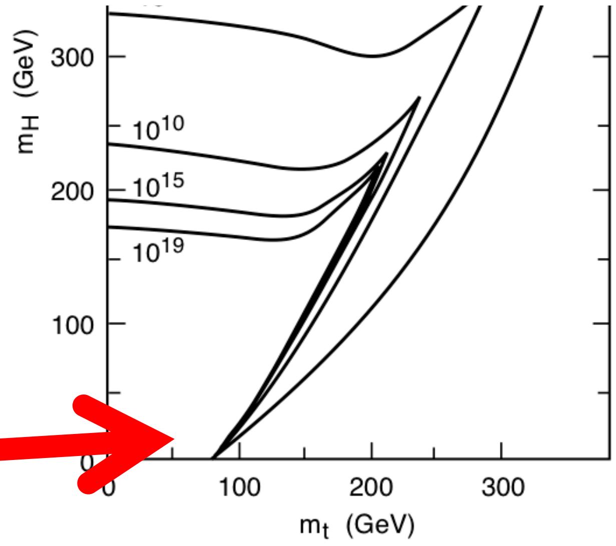
SM + with $\mu = 0$ ←→ CS

Coleman Weinberg: effective potential

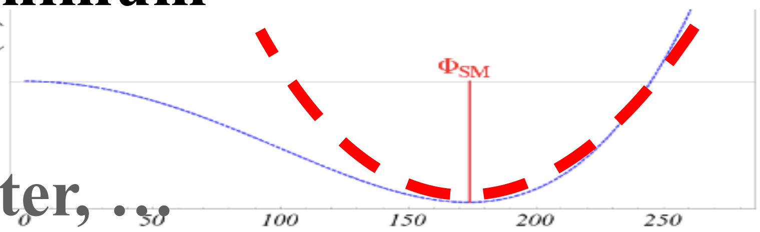
→ CS breaking (dimensional transmutation)

→ 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
- **DSB for weak coupling ←→ CS= phase boundary**
- **Reason for $m_H \ll v$: 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 scalar portal $\lambda_{mix}(\varphi^+\varphi)(\Phi^+\Phi)$ 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 $\ln(\Lambda)$

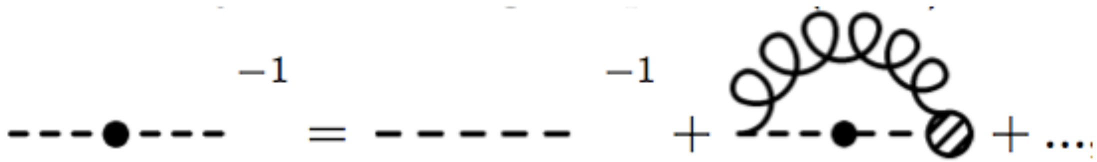
→ implies a TeV-ish condensate for φ to obtain $<\Phi> = 246$ GeV

- 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!

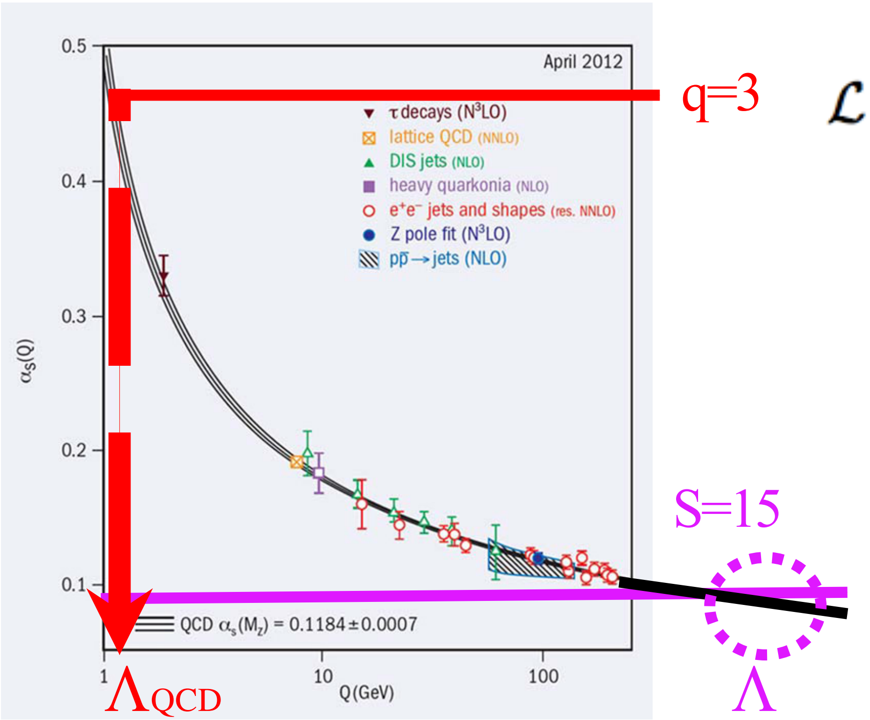
Rather minimalistic: SM + QCD Scalar S

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

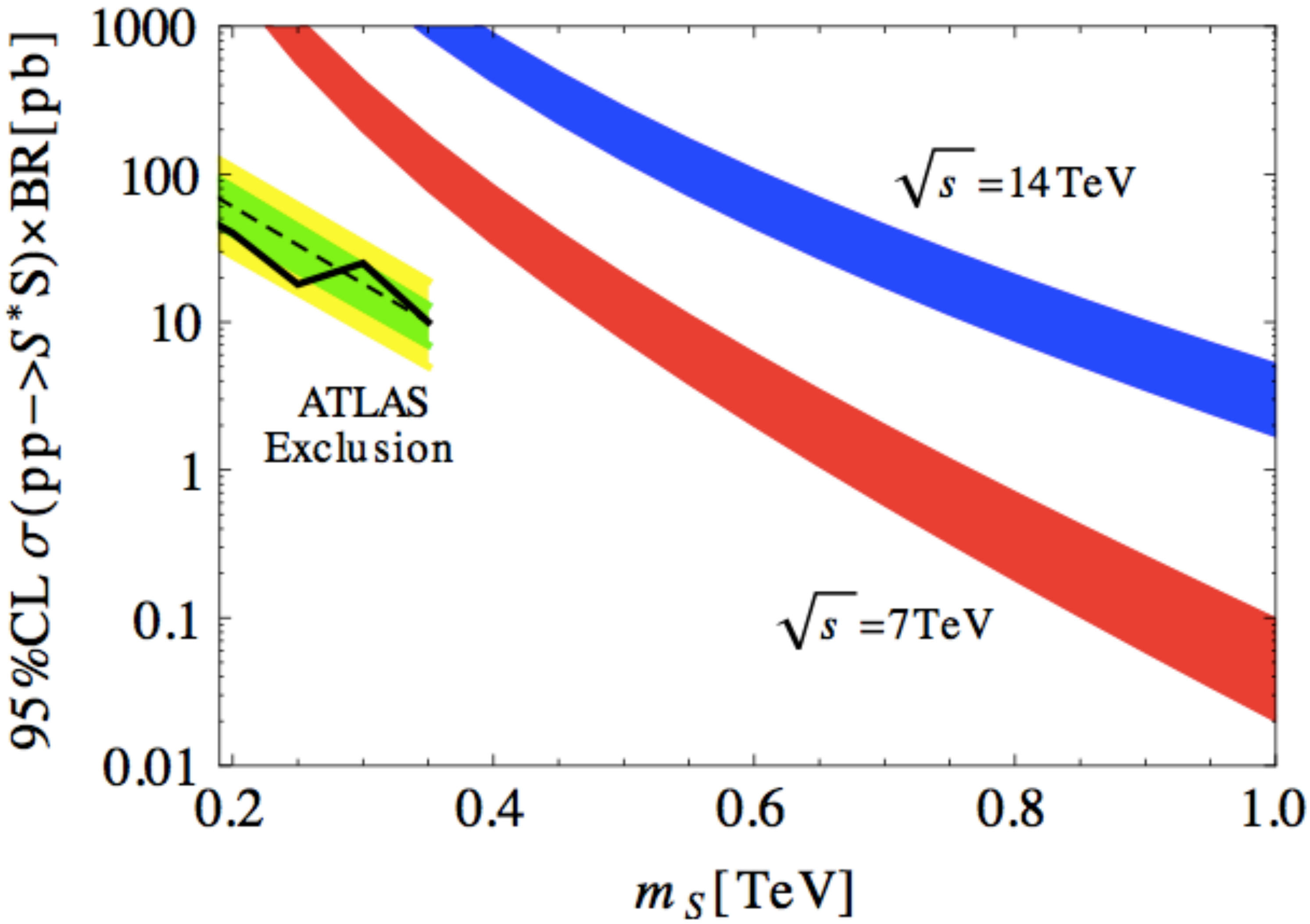


$$\mathcal{L} = \mathcal{L}_{\mathrm{SM},m^2\to 0} + (D_{\mu,ij}S_j)^\dagger (D^\mu_{ik}S_k) + \lambda_{HS} H^\dagger H S^\dagger S - \lambda_{1_i}\left[\bar{\boldsymbol{S}} \times \boldsymbol{S} \times \bar{\boldsymbol{S}} \times \boldsymbol{S}\right]_{1_i}$$

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

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

Phenomenology



S pair production cross section from gluon fusion (assumed: 100% BR into two jets)

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

→ **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}

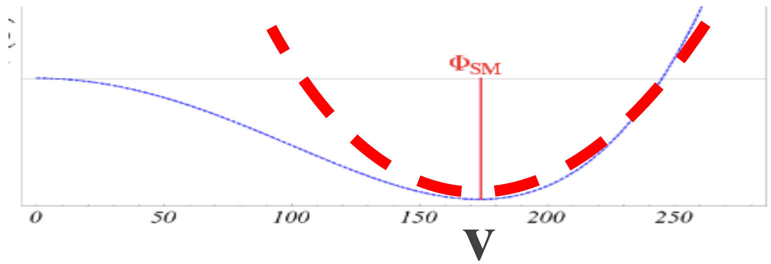
➔ Gildner-Weinberg formalism (RG improvement of flat directions)

- anomaly breaks CS
- spontaneous breaking of parity, Z_4, LR and EW symmetry
- m_H << 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…?

SM ⊗ hidden $SU(3)_H$ Gauge Sector

Holthausen, Kubo, Lim, ML

- hidden $SU(3)_H$:

$$\mathcal{L}_H = -\frac{1}{2}\mathrm{Tr}\ F^2 + \mathrm{Tr}\ \bar{\psi}(i\gamma^\mu D_\mu - yS)\psi$$

gauge fields ; $\psi = 3_H$ with $SU(3)_F$; **S = real singlet scalar**

- SM coupled by S via a Higgs portal:

$$V_{SM+S} = \lambda_H (H^\dagger H)^2 + \frac{1}{4}\lambda_S S^4 - \frac{1}{2}\lambda_{HS} S^2 (H^\dagger H)$$

- no scalar mass terms
- use similarity to QCD, use NJL approximation, …
- χ–ral symmetry breaking in hidden sector:
  $SU(3)_L x SU(3)_R$ → $SU(3)_V$ → **generation of TeV scale**

→ **transferred into the SM sector through the singlet S**

→ **dark pions are PGBs: naturally stable → DM**

Realizing the Idea: Specific Realizations

SM + extra singlet: Φ, φ

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

SM ⊗ $SU(N)_H$ with new N-plet in a hidden sector

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

SM embedded into larger symmetry (CW-type LR)

Holthausen, ML, M. Schmidt

SM + QCD colored scalar which condenses at TeV scale

Kubo, Lim, ML

SM ⊗ [$SU(2)_X$ ⊗ $U(1)_X$]

Altmannshofer, Bardeen, Bauer, Carena, Lykken

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

Conformal Symmetry & Neutrino Masses

ML, S. Schmidt and J.Smirnov

- 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) + induced EW scale

Important consequence for fermion mass terms:
→ spectrum of Yukawa couplings ⊗ TeV or EW scale
→ interesting consequences ←→ Majorana mass terms are no longer expected at the generic L-breaking scale → anywhere

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

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

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

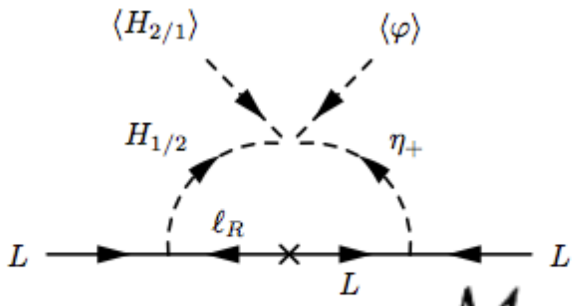
➔ generically expect a TeV seesaw

BUT: y_M can be tiny

➔ wide range of sterile masses ➔ including pseudo-Dirac case

➔ suppressed $0\nu\beta\beta$

Radiative masses



$$\mathcal{M} = m_L \quad \text{or}$$

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

➔pseudo-Dirac case

The punch line:
all usual neutrino mass terms can be generated

→ suitable scalars
→ no explicit masses
all via Yukawa couplings
→ different numerical expectations

Another Example: Inverse Seesaw

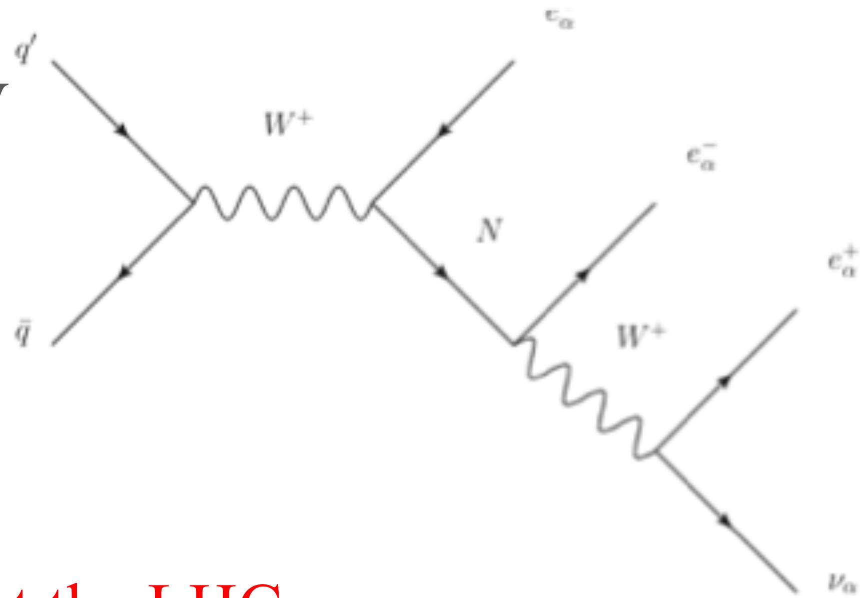
$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$

Humbert, ML, J. Smirnov

	H	ϕ_1	ϕ_2	L	ν_R	N_R	N_L
$U(1)_X$	0	1	2	0	0	1	1
Lepton Number	0	0	0	1	1	0	0
$U(1)_Y$	1	0	0	-1	0	0	0
$SU(2)_L$	2	1	1	2	1	1	1

$$\mathcal{M} = \begin{pmatrix} 0 & y_D \langle H \rangle & 0 & 0 \\ y_D \langle H \rangle & 0 & y_1 \langle \phi_1 \rangle & \tilde{y}_1 \langle \phi_1 \rangle \\ 0 & y_1 \langle \phi_1 \rangle & y_2 \langle \phi_2 \rangle & 0 \\ 0 & \tilde{y}_1 \langle \phi_1 \rangle & 0 & \tilde{y}_2 \langle \phi_2 \rangle \end{pmatrix}$$

➔ light eV "active" neutrino(s)
➔ two pseudo-Dirac neutrinos; m ~ TeV
➔ sterile state with μ ≈ keV



➔tiny non-unitarty of PMNS matrix
➔tiny lepton universality violation
➔suppressed 0νββ decay ←!
➔lepton flavour violation
➔tri-lepton production could show up at the LHC
➔keV neutrinos as warm dark matter →

More flexible Neutrino Mass Spectra

3   0 … N   3x3 matrix   3xN   NxN

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

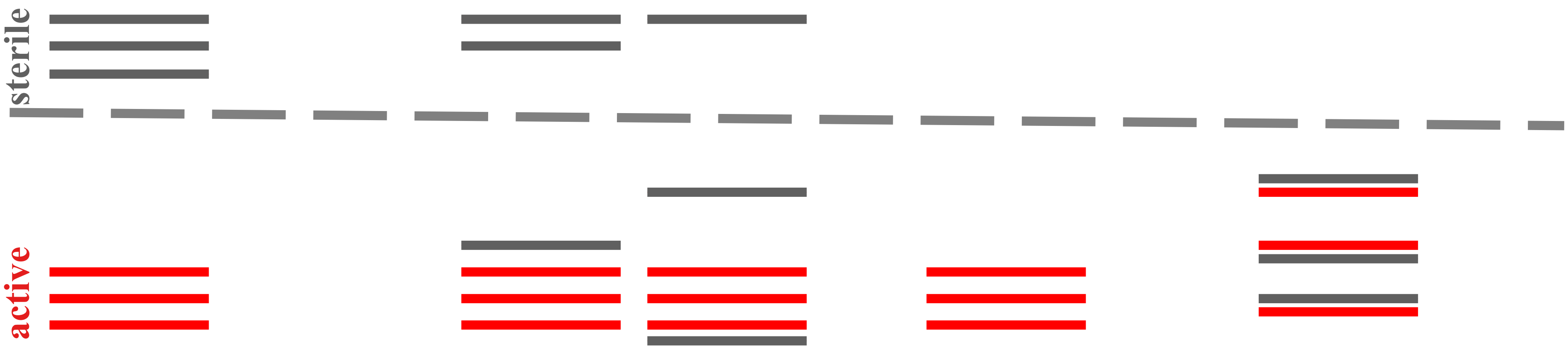
Usually:

M_L tiny or 0, M_R heavy
→ see-saw & variants
light sterile: F-symmetries…

Now:

M_L, M_R may have any value:
➔ 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 = ε pseudo Dirac



Conformal Symmetry & Dark Matter

Different natural and viable options:

1) A keV sterile neutrino is in all cases easily possible

2) New particles which are fundamental or composite DM candidates:
   - hidden sector pseudo-Goldstone-bosons
   - stable color neutral bound states from new QCD representations

➔ some look like WIMPs
➔ others are extremely weakly coupled (via Higgs portal)
➔ or even coupled to QCD (threshold suppressed…)

Summary

- **SM works (so far) perfectly**
  - be a bit more patient: new physics around the corner…
  - maybe it is time to re-consider some things…

- **The old hierarchy problem…? No new physics observed**
  $\lambda(M_{Planck}) = 0$? ←→ **precise value for m_t → is there a message?**

→ Embedings into QFTs with conformal symmetry

→ combined conformal & electro-weak symmetry breaking

→ implications for BSM phenomenology

→ implications for Higgs couplings, dark matter, …

→ implications for neutrino masses

→ testable consequences: @LHC, dark matter, neutrinos