Conformal Extensions of the Standard Model

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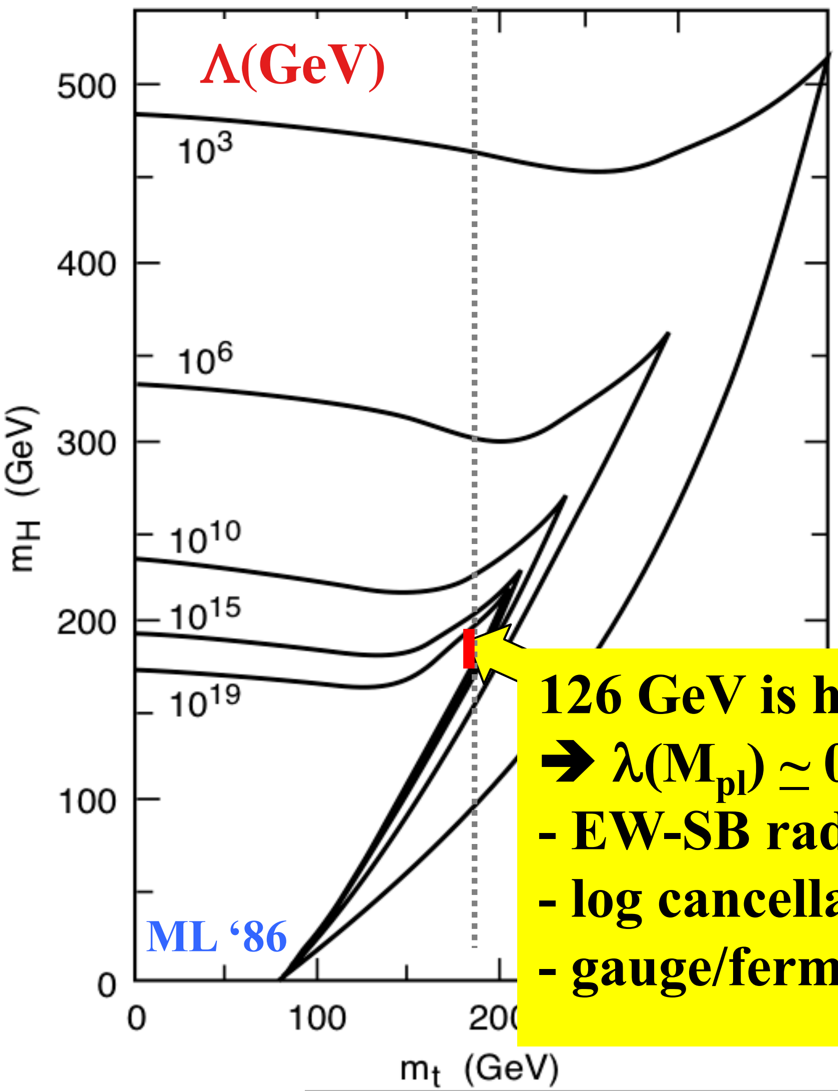
WARSAW OCHOTA CAMPUS

The SM: A true Success Story

➔ SM is a renormalizable QFT like QED w/o hierarchy problem

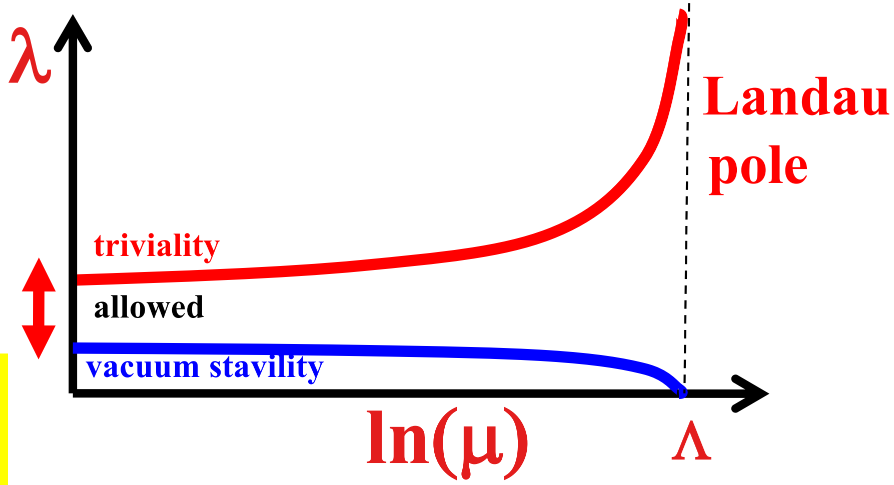
➔ Cutoff "Λ" has no meaning ➔ triviality, vacuum stability



126 GeV is here!
- ➔ $\lambda(M_{pl}) \simeq 0$
- EW-SB radiative
- log cancellations
- gauge/fermion/scalar

126 GeV < m_H < 174 GeV

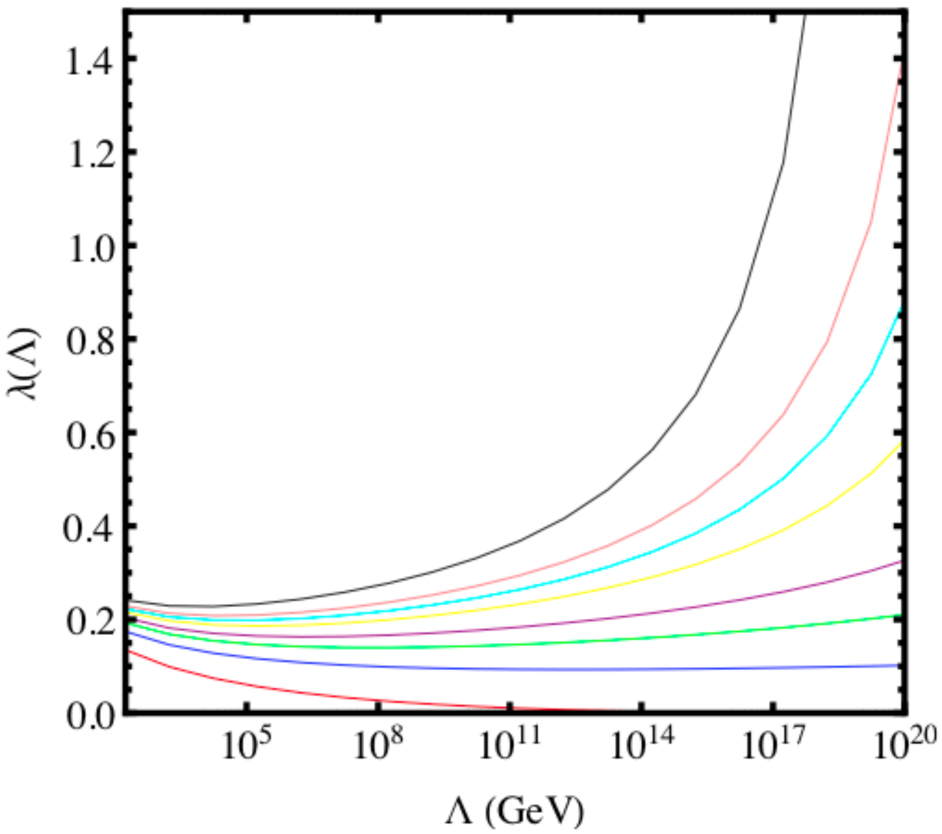
SM does not exist w/o embeding
- U(1) copling , Higgs self-coupling



➔ RGE arguments seem to work
➔ but we need some embedding

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:

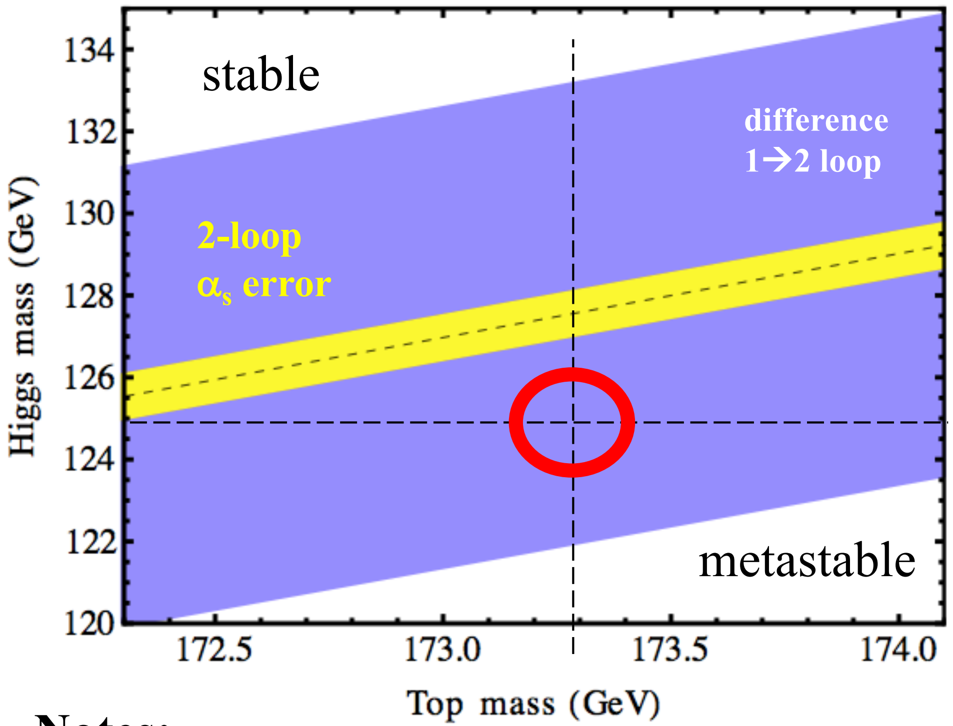
- Vacuum stability
  $\lambda(M_{pl}) = 0$ [7–12]
- vanishing of the beta function of λ
  $\beta_\lambda(M_{pl}) = 0$ [9, 10]
- the Veltman condition [13–15] $\mathrm{Str}\mathcal{M}^2 = 0$,

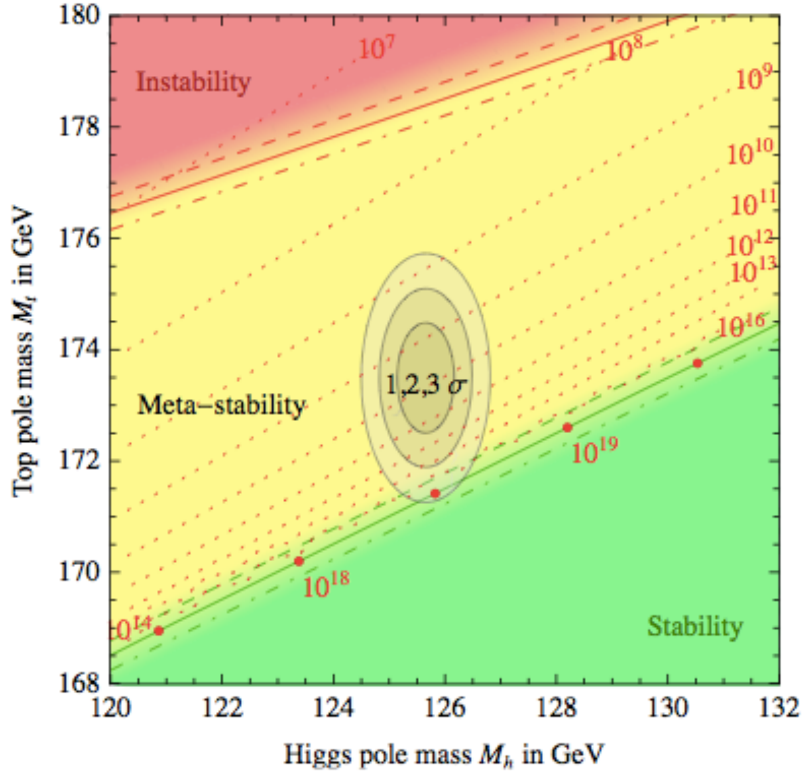
$$\delta m^2 = \frac{\Lambda^2}{32\pi^2 v^2}\mathrm{Str}\mathcal{M}^2 = \frac{1}{32\pi^2}\left(\frac{9}{4}g_2^2 + \frac{3}{4}g_1^2 + 6\lambda - 6\lambda_t^2\right)\Lambda^2$$

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

Is the Higgs Potential at M_{Planck} flat?

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





Notes:

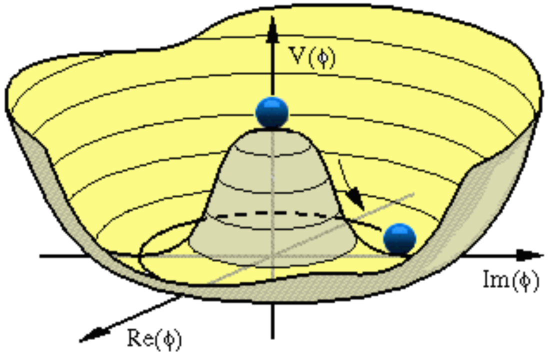
- remarkable relation between weak scale, m_t, couplings and M_{Planck} ←→ precision
- strong cancellations between Higgs and top loops
  → very sensitive to exact value and error of m_H, m_t, $\alpha_s = 0.1184(7)$ → currently 1.8σ in m_t
- other physics: DM, m_ν … axions, …Planck scale thresholds… SM+ ←→ $\lambda = 0$

→ top mass errors: data ←→ LO-MC → translation of m_{pole} → MS bar
→ be cautious about claiming that metastability is established
→ and we need to include DM, neutrino masses, …

Is there a Message?

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

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



➔

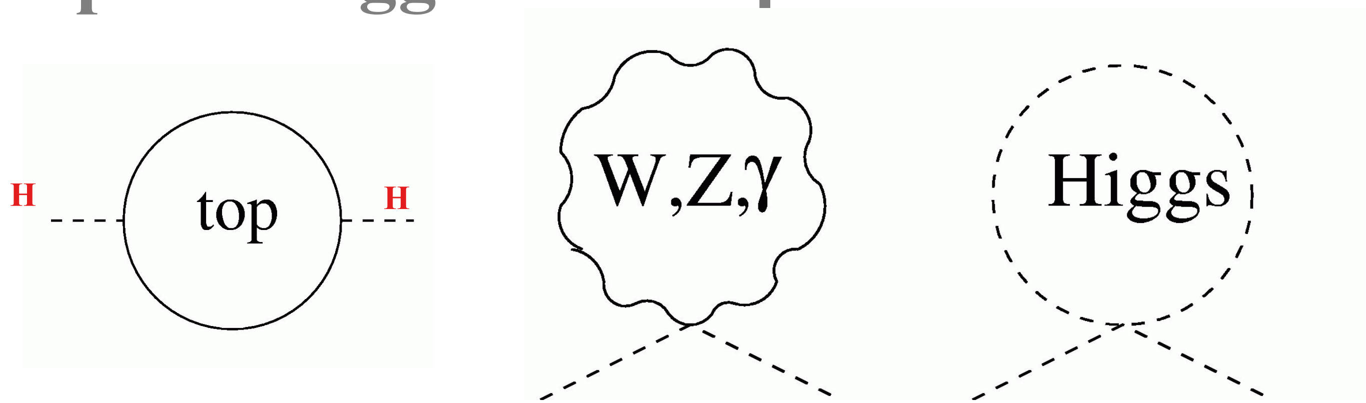
➔ conformal (or shift) symmetry as solution to the HP

➔ combined conformal & EW symmetry breaking

➔ realizations; implications for neutrino masses and DM

The naïve Hierarchy Problem

- Loops ➔ Higgs mass depends on '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*** one must explain:**

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

BUT: What does Λ mean? For SM? Renormalizable embeddings?

Λ ⇔ new Physics

- 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 (= portal)
- Quantum corrections ~M^2 drive 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**
- **some symmetry: SUSY, ...?**

Λ and conformal Symmetry

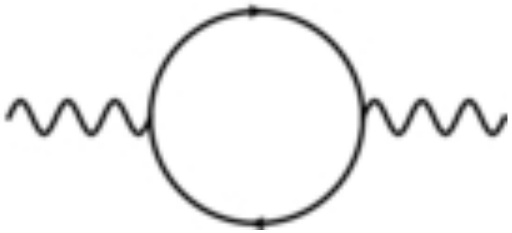
- **Basics of QFT: Renormalization ←→ commutator**
  - $[\Phi(X),\Pi(y)] \sim \delta^3(x\text{-}y)$ ➔ ~~delta funtion~~ ➔ distribution
  - freedom to define δ*δ ➔ renormalization ←➔ counter-terms
  - along come technicalities: lattice, Λ, Pauli-Villars, MS-bar, …
- **Reminder: Technicalities do not establish physical existence!**

➔ Symmetries are essential!

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

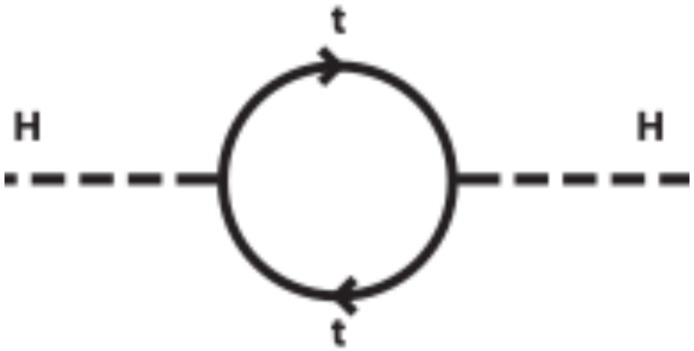
➔ non-linear realization of the underlying symmetry

➔ important consequence: naïve power counting is wrong



Gauge invariance ➔ only log sensitivity

Non-linear Realization of Conformal Symmetry



If conformal symmetry is realized in a non-linear way:
➔ protective relic of conformal symmetry
➔ only log sensitivity
←→ conformal anomaly ←→ β-functions

- **No hierarchy problem, even though there is the the conformal anomaly - only logs ←→ β-functions**
- **Dimensional transmutation by log running like in QCD**
  ➔ scalar QCD: scalars can condense and set scales like fermions
  ➔ also for massless scalar QCD: **no scale ➔ scale ; no hierarchy**
  ➔ use this in Coleman Weinberg effective potential calculations
  ←→ most attractive channels (MAC) ←→ β-functions

Implementing the idea…

Why the minimalistic SM does not work

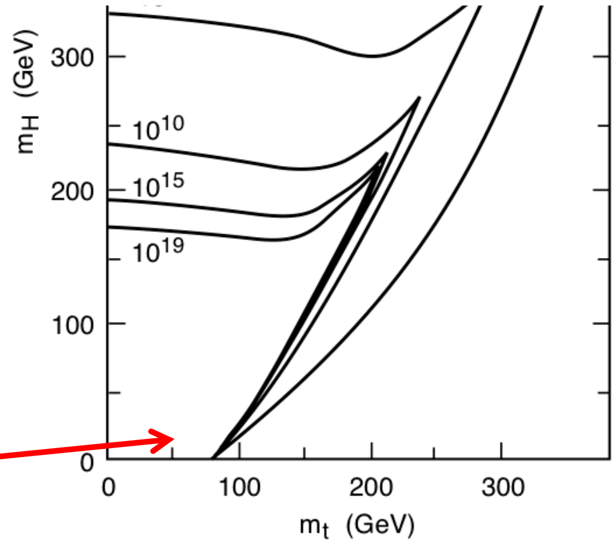
Minimalistic version: → SM-

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

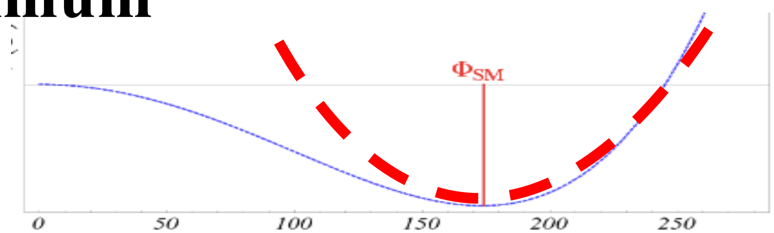


This would conceptually realize the idea, but:

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

Reason for $m_H \ll v$: 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 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 $\ln(\Lambda)$

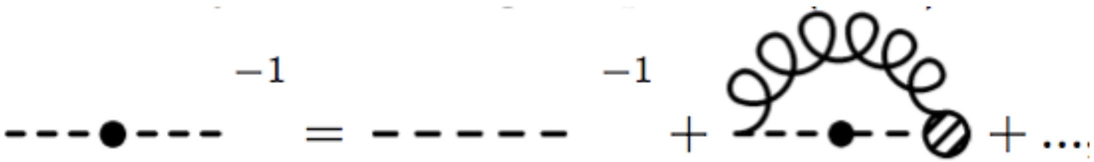
→ implies a TeV-ish condensate for φ to obtain $<\Phi> = 246$ GeV

- 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!

Rather minimalistic: SM + QCD Scalar S

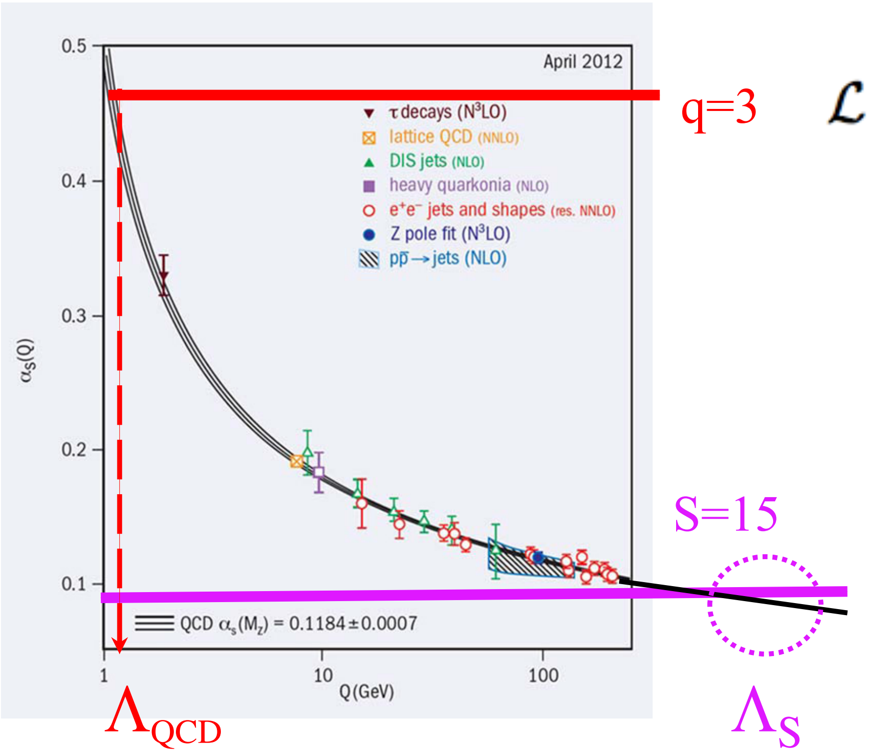
J. Kubo, K.S. Lim, ML New scalar representation S → QCD gap equation:



→ $C_2(S)\alpha(\Lambda) \gtrsim X$

$C_2(\Lambda)$ 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

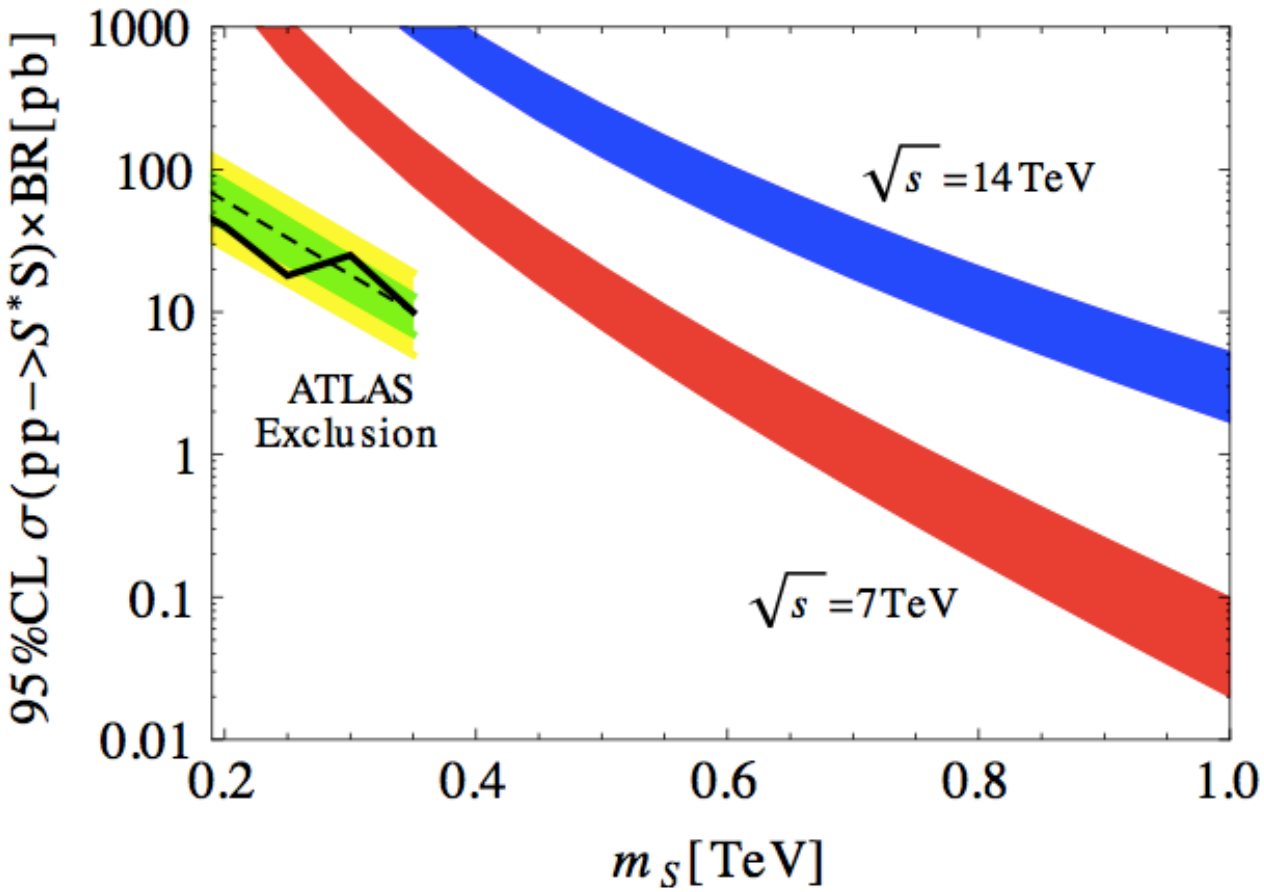


Figure 3. The S pair production cross section from gluon fusion channel is calculated for different value of m_S. The 95% confidence level exclusion limit on $\sigma \times \mathrm{BR}$ for $\sqrt{s} = 7$ TeV by ATLAS is plotted. We assume 100% BR of $\langle S^\dagger S \rangle$ into two jets.

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) ≃ Spin(4) → representations)

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

- → **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}

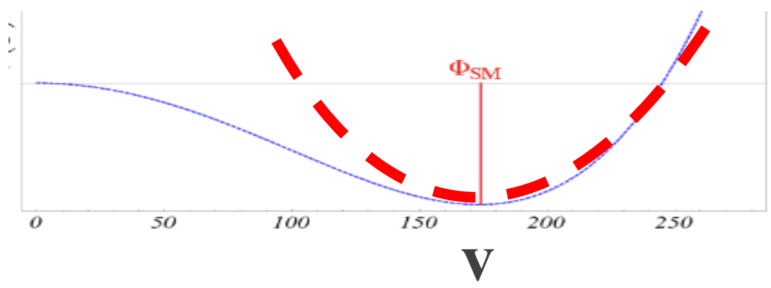
➔ Gildner-Weinberg formalism (RG improvement of flat directions)

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

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

- 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 + extra SU(N) 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

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

Comments / Expectations / Questions

- New (hidden) sector ←→ DM, neutrino masses, … !
- Question: Isn't the Planck-Scale spoiling things (cut-off)?
  → non-linear realization… → conformal gravity…
  ideas: see e.g. A. Salvio and A. Strumia, … ? K. Hamada, …
  → some mechanism to generate M_{Planck} by dimensional transmutation
- Are M_{planck} and M_{weak} connected? → not necessary
- Question: What about inflation?
  see e.g. K. Kannike, A. Racioppi, M. Raidal, V. Khoze
- What about unification … → no – or $M_{Planck} = M_{GUT}$
- UV: ultimate solution should be asymptotically safe (UV-FPs) …
  → see talk by others; UV-FPs ←→ conformal? Here: FP=0… >0...?
- Justifying classical scale invariance
  → cancel the conformal anomaly
  → nature of space time & observables…

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

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

<u>Yukawa seesaw:</u>

SM + ν_R + singlet

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

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

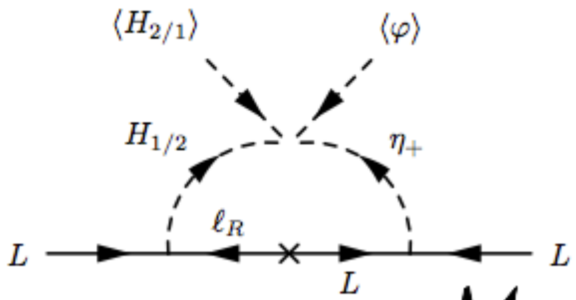
➔ generically expect a TeV seesaw

BUT: y_M might be tiny

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

➔ suppressed $0\nu\beta\beta$

<u>Radiative masses</u>



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

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

➔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

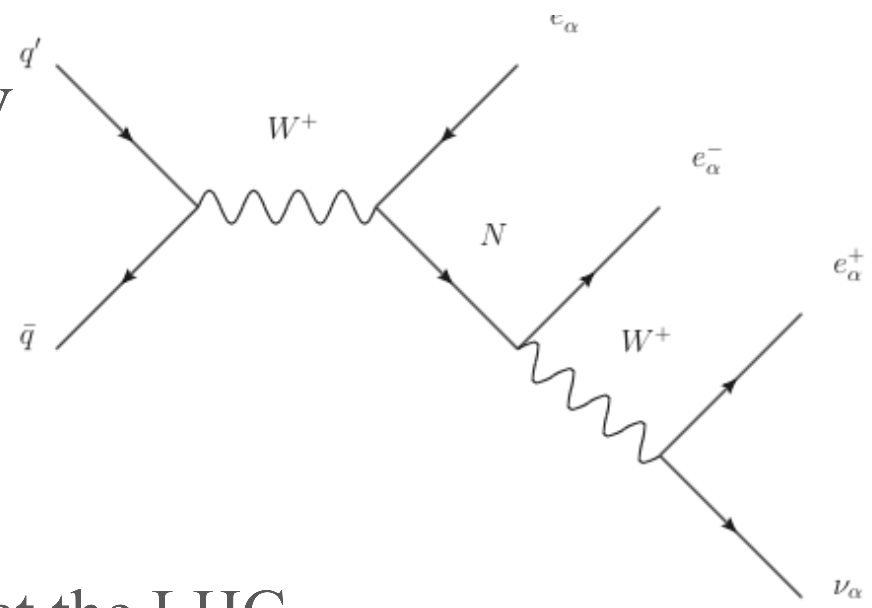
$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$

P. 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 ➔

Implications for Neutrino Mass Spectra

3 — 0 … N — 3x3 matrix — 3xN — NxN

$$\begin{pmatrix} \overline{\nu}_L & \overline{\nu}^c_R \end{pmatrix} \begin{pmatrix} M_L & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu^c_L \\ \nu_R \end{pmatrix}$$

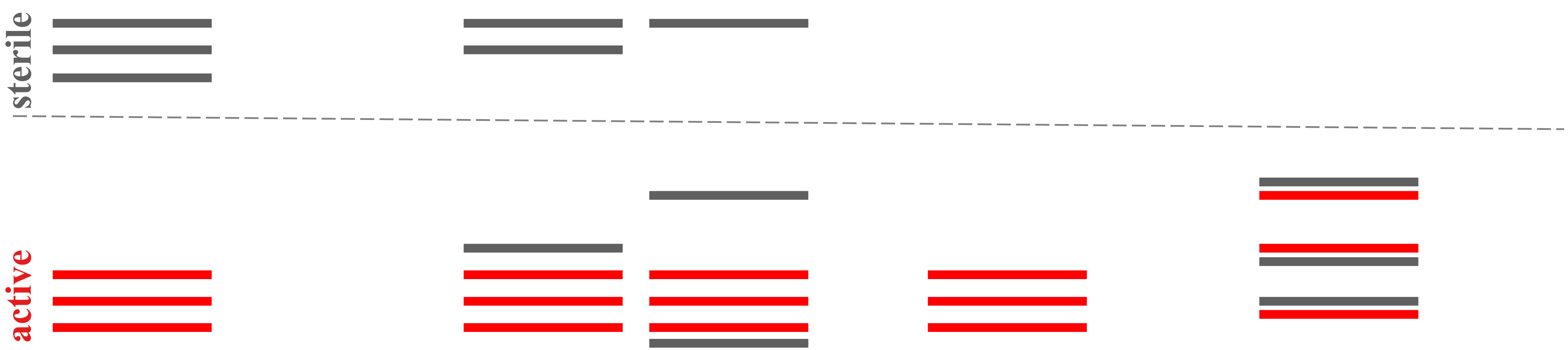
Usually:

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	$M_L = M_R = \varepsilon$ pseudo Dirac



Conformal Symmetry & Dark Matter

Different quite natural 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 (with threshold suppression)

Summary

- **SM works perfectly; (so far) no signs of new physics**

- **The standard hierarchy problem suggests TeV scale physics … which did (so far…) not show up**

- **The old problem: …the hierarchy problem …**

  $\lambda(M_{Planck}) = 0$? ←→ **precise value for m_t**

  → **is there a message?**

→ 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, dark matter, neutrinos**