Conformal Extensions of the Standard Model

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Scale invariance in particle physics and cosmology

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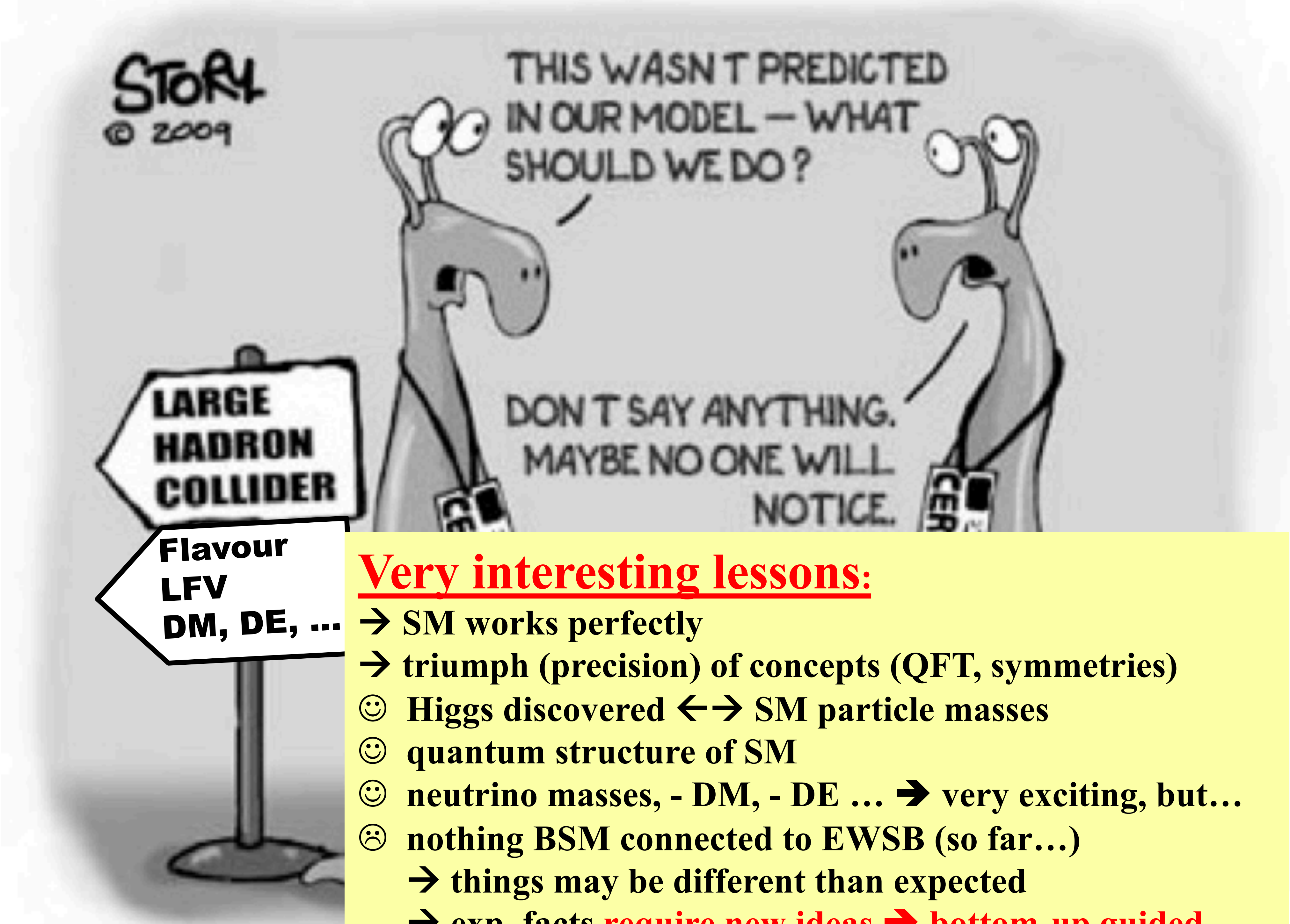


<u>Very interesting lessons</u>:

- → SM works perfectly
- → triumph (precision) of concepts (QFT, symmetries)
- ☺ Higgs discovered ←→ SM particle masses
- ☺ quantum structure of SM
- ☺ neutrino masses, - DM, - DE … ➔ very exciting, but…
- ☹ nothing BSM connected to EWSB (so far…)
  - → things may be different than expected
  - → exp. facts require new ideas ➔ bottom-up guided

Look again carefully at the SM as a QFT

- **The SM itself (without embedding) is a 4d 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**

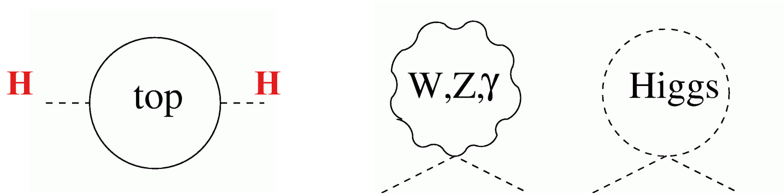
<u>The SM as QFT (without an embedding) works perfectly:</u>

- a hard cutoff Λ and the sensitivity towards Λ has no meaning
- renormalizable, calculable … - just like QED
- BUT: an embedding is required ←→ triviality…

SM Hierarchy Problems

1) why are scales vastly different
2) why do scales remain vastly different under quantum corrections

- **Loops ➔ Higgs mass depends on 'cutoff Λ'**



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

$\simeq O(\Lambda^2/4\pi^2)$

$m_H \leq 200$ GeV requires Λ ~ TeV ➔ new physics ➔ embedding at Λ ~ TeV
OR explain how m_H be O(100 GeV) if Λ is huge ?

- **SM + Dirac neutrinos:** no problem – just like SM
- **SM + Majorana ν's:** ➔ two scales: VEV and the Majorana mass(es) M

➔ $\delta m_H^2 \simeq \frac{y_\nu^2}{16\pi^2} M^2$ with $y_\nu^2 = M m_\nu / v^2$ ➔ $M \lesssim 10^7 - 10^8$ GeV

➔ generates a HP problem for large M even if y_ν is tiny ←➔ leptogenesis?

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 $\sim M^2$ drives both masses to the (heavy) scale
  ➔ **vastly different explicit 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 = no explicit scales!**

The main Idea

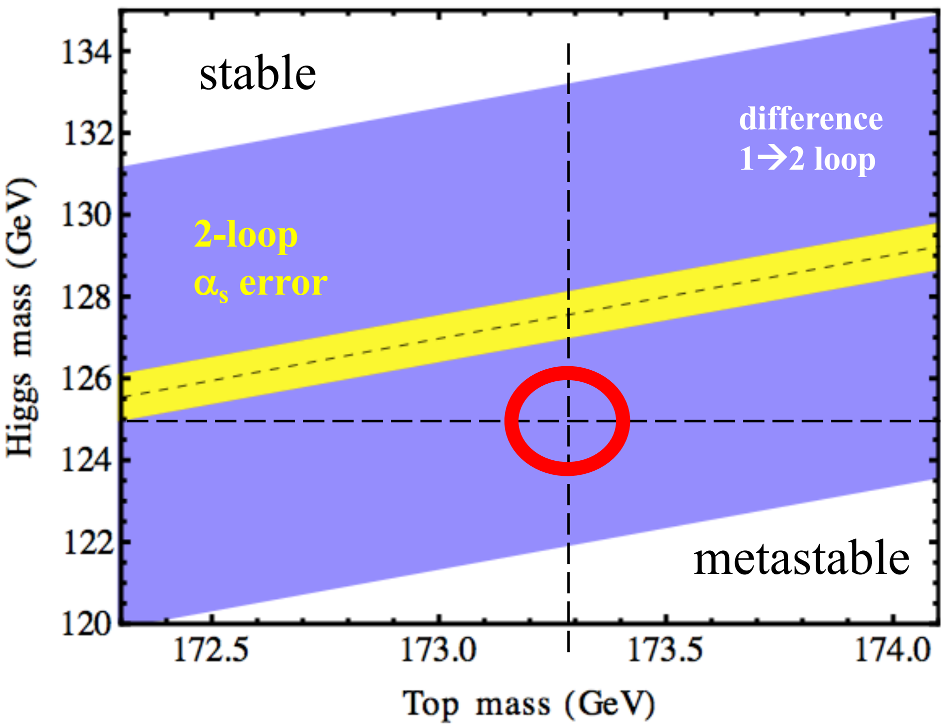
- **Do not introduce any fundamental (explicit) scales**
  ➔ theories with conformal or shift symmetry
- **Dynamical breaking of CS ➔ Coleman Weinberg V_{eff}**
  ➔ scale(s) by dimensional transmutation
  ➔ Non-linear realization of CS:
  - naïve power counting ($\sim\Lambda^2$) misleading
  - similar to gauge symmetry and vector boson masses
- **An UV complete theory should have UV fixedpoints to avoid conformal anomalies**

Anything pointing in that direction?

Is the Higgs Potential at M_{Planck} flat?

Holthausen, ML, Lim

12 Dec 2011



Elias-Miro, Espinosa, Giudice, Isidori, Riotto, Strumia

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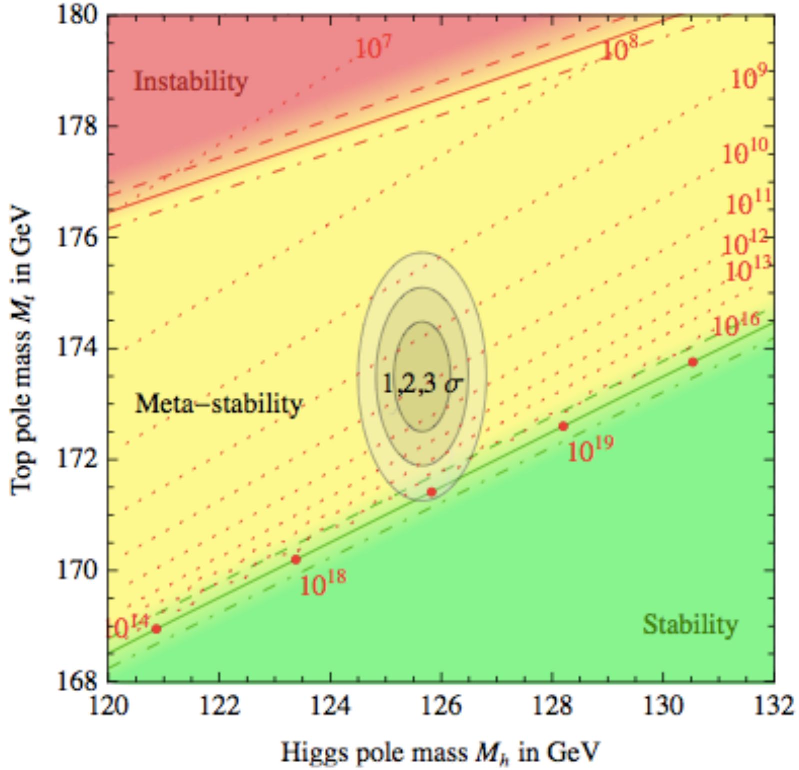


Experimental values point to metastability. Is it fully established?

➔ 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:

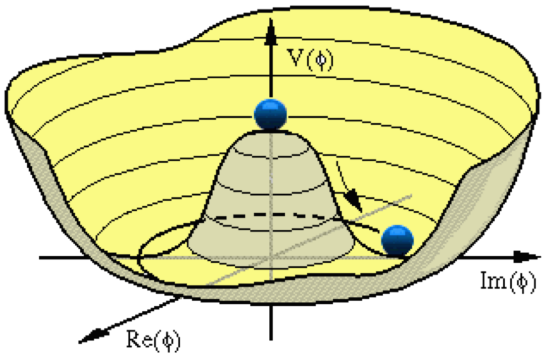
- remarkable relation between weak scale, m_t, couplings and M_{Planck} ←→ precision

- 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 ↔ CA~ β-fcts.
  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 $\mu^2 = 0$ → $V(M_{Planck}) \simeq 0$
  → flat Mexican hat (<1%) at the Planck scale!



→

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

→ **combined conformal & EW symmetry breaking**

- conceptual issues
- minimal realizations ↔ SM seems to know about high scales → bottom-up
  ↔ many new d.o.f. (fields, big reps.) ~ UV-instabilities

Generic Questions

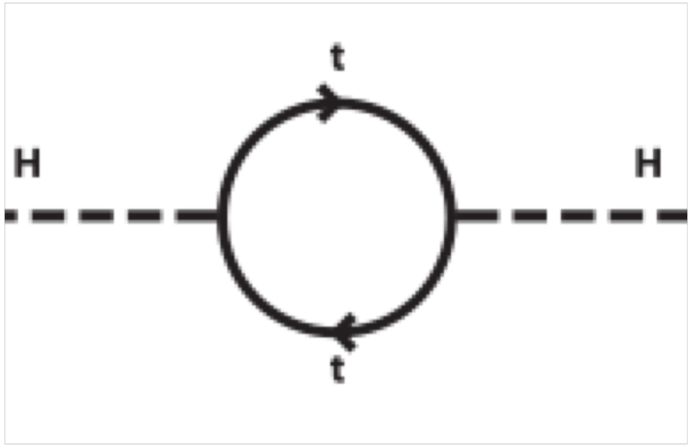
- **Isn't the Planck-scale spoiling things (explicit scale, cut-off, …)?**
  ➔ non-linear realization of conformal symmetry…
    ➔ ~conformal gravity…
  ➔ protected by conformal symmetry up to conformal anomaly
  ➔ generate M_{Planck} by dimensional transmutation
  ➔ for now assumption: M_{Planck} somehow generated in a conformal setting

- **Are M_{planck} and M_{weak} connected?**
  ➔ 1st part: assumed to be independently generated scales
  ➔ later more…

- **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})
  Now ➔ only relative scales – absolute scale is meaningless
  Could solve both HPs ⬌ scale is a quantum effect
  Fully consistent realization ➔ now new concept for scale setting required

Non-linear Realization of Conformal Symmetry



SB of conformal symmetry
→ naïve power counting invalid
→ similar to Higgs mech. vs. explicit M_V
→ only log sensitivity
←→ conformal anomaly ←→ UV-FP
←→ 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

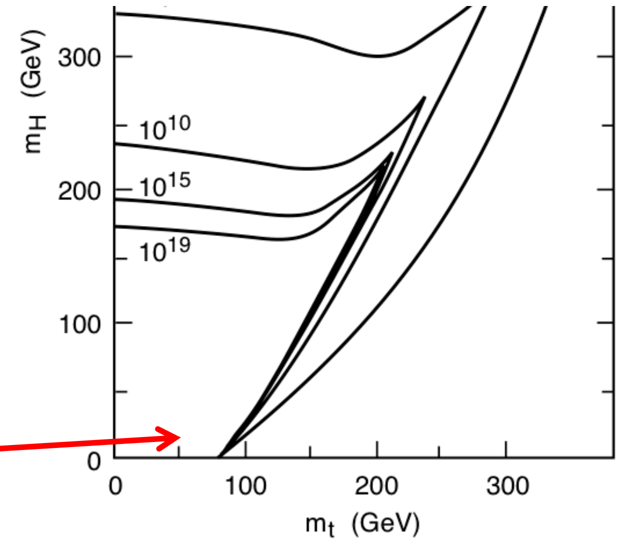
Minimalistic version: → "SM-"

SM + with $\mu = 0$ ↔ CS

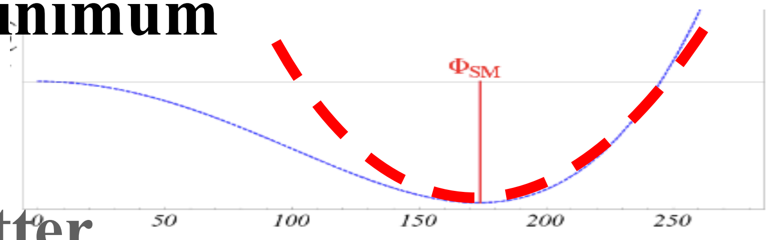
Coleman Weinberg: effective potential

→ 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**
  → scale set by running couplings
- **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 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 $\ln(\Lambda)$

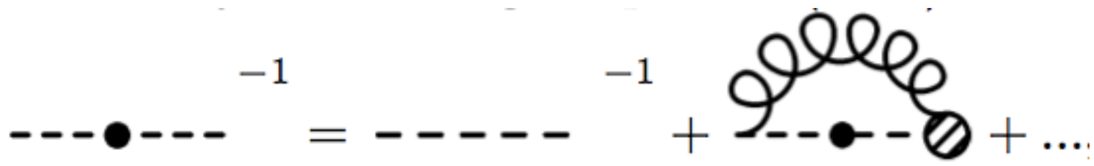
→ implies a TeV-ish condensate for φ to obtain $<\Phi> = 246$ GeV

- 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

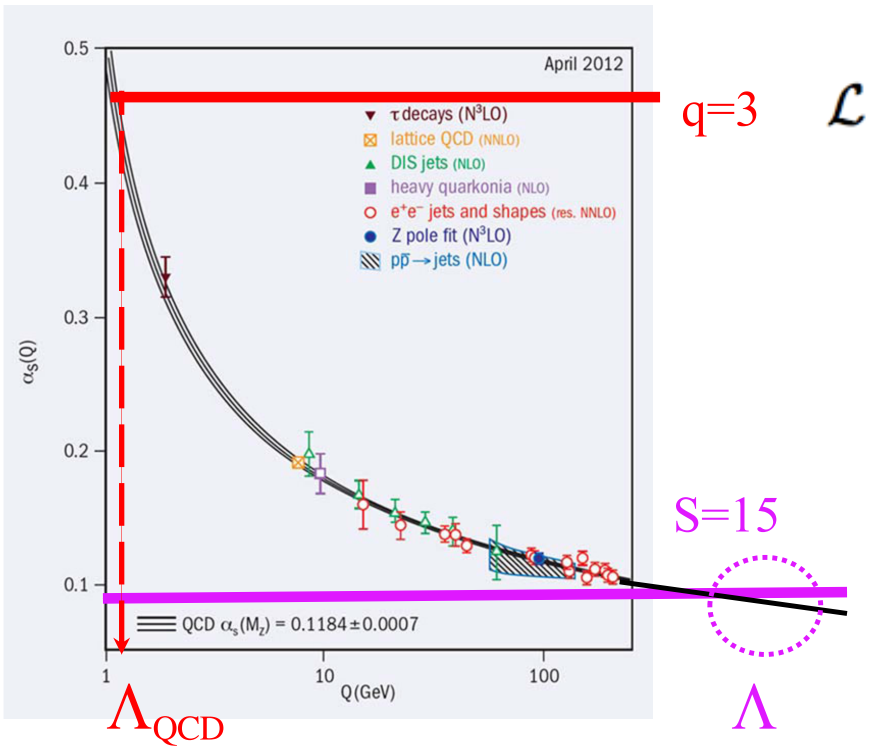
J. Kubo, K.S. Lim, ML New scalar representation S → QCD gap equation:



→ $C_2(S)\alpha(\Lambda) \gtrsim X$

$C_2(\Lambda)$ increases with larger representations

←→ condensation for smaller values of running α



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

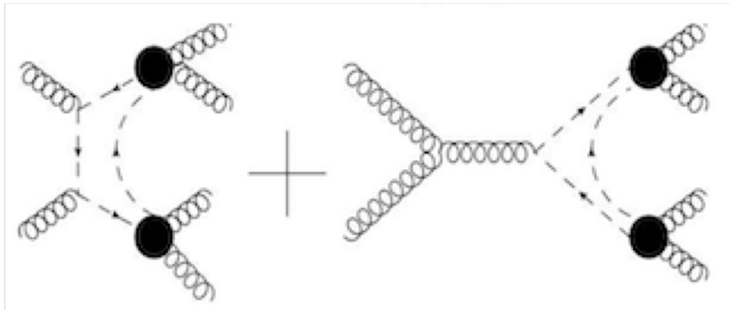
$$\lambda_{HS} \langle S^\dagger S \rangle H^\dagger H \to \lambda_{HS} \Lambda^2 H^\dagger H$$

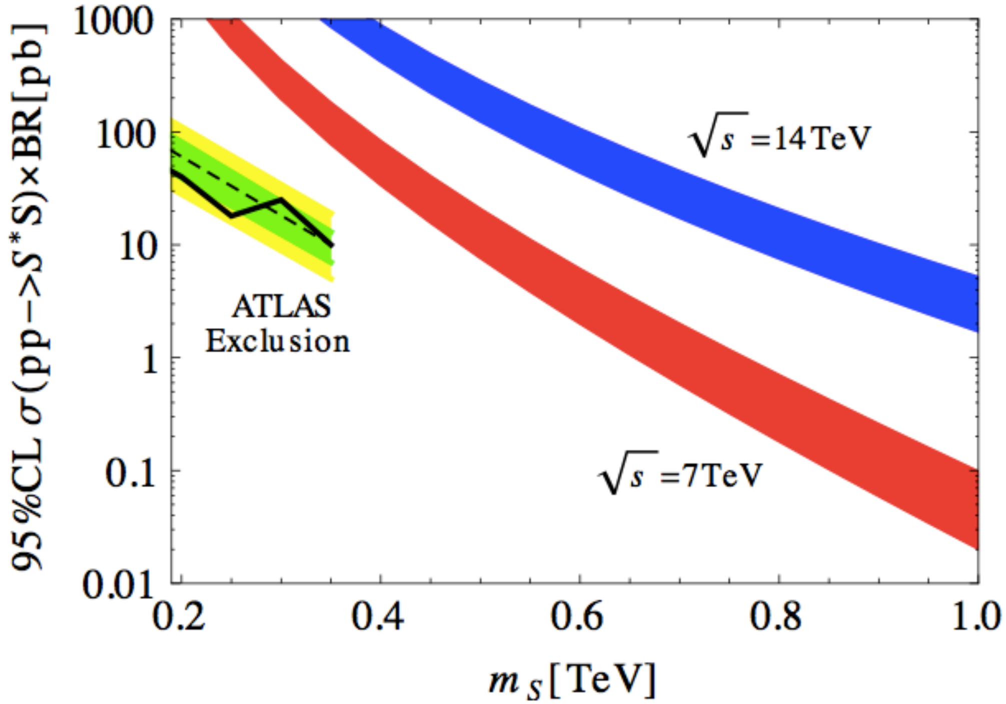
$$m_h^2 = 2\lambda_{HS}\Lambda^2 \qquad \frac{\lambda_h}{\lambda_{HS}} = \frac{\Lambda^2}{v^2}$$

Phenomenology

TeV-ish hidden sector ←→ may show up at LHC

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





Drawback of this scenario:

- large representations appear less attractive
- Tend to lead to instabilities at high energy

   → cannot run all the way…

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

→ **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}

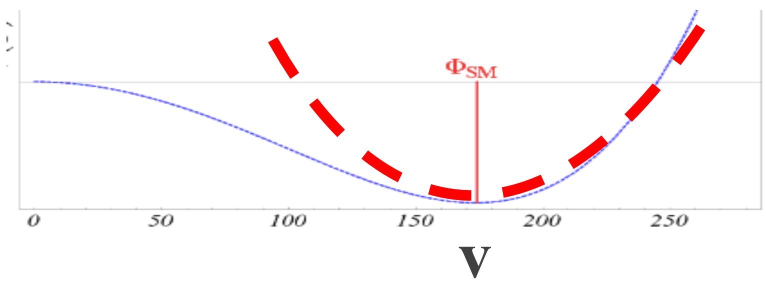
➔ Gildner-Weinberg formalism (RG improvement of flat directions)

- 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 $\otimes$ hidden SU(3)$_H$ Gauge Sector

Holthausen, Kubo, Lim, ML

- hidden SU(3)$_H$:

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

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

- SM coupled by S via a Higgs portal:

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

- no scalar mass terms
- use similarity to QCD, use NJL approximation, …
- χ–ral symmetry breaking in hidden sector: SU(3)$_L$xSU(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

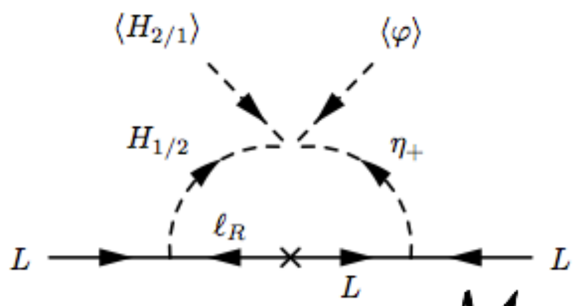
➔ wide range of sterile masses ➔ including pseudo-Dirac case

➔ suppressed $0\nu\beta\beta$

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

→ suitable scalars required
→ no explicit masses: all via Yukawa couplings
→ different numerical expectations ←→ could easily explain keV masses

Radiative masses



$\mathcal{M} = m_L$ 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

Another Example: Inverse Seesaw

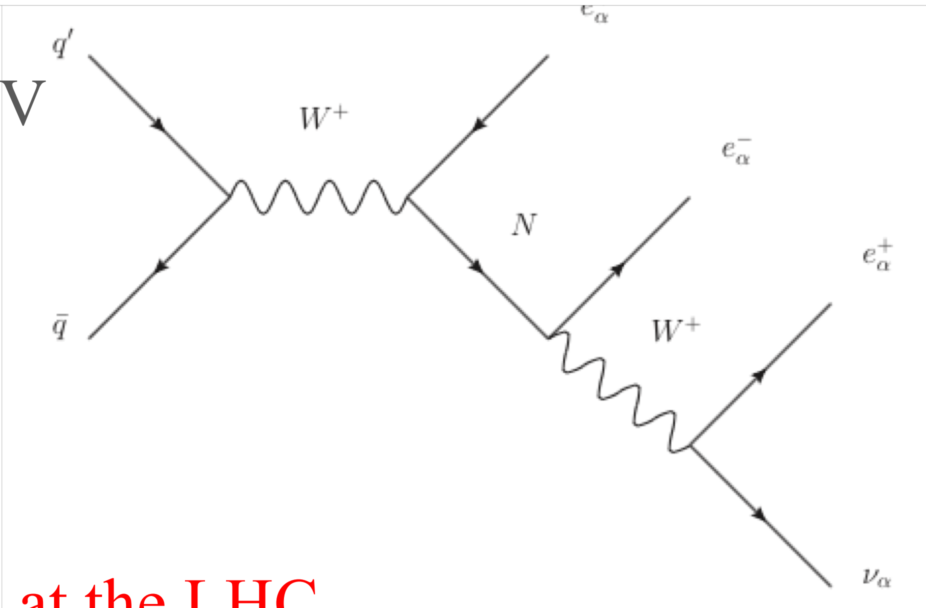
$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$

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 ➔

Conformal Symmetry & Dark Matter

Different natural and viable options:

1) eV, **keV = DM**, TeV, … sterile ν mass easily possible
   ←→ not so easy in standard see-saw's

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…)

The Planck Scale from CS Breaking

➔ dynamically generated from conformal gravity ⊗ SU(N)
- condensate via SU(N) helper field – similar to → Donoghue, Menezes, ...

➔ more symmetry + no scale ➔ power counting renormalizable

J. Kubo,ML, K. Schmitz, M. Yamada ➔ see talk with more details by M. Yamada

$$S_{\rm C} = \int d^4x \sqrt{-g} \left[-\hat{\beta}\, S^\dagger S\, R + \hat{\gamma}\, R^2 - \frac{1}{2} {\rm Tr}\, F^2 + \right.$$
$$\left. + g^{\mu\nu} (D_\mu S)^\dagger D_\nu S - \hat{\lambda} (S^\dagger S)^2 + a\, R_{\mu\nu} R^{\mu\nu} + b\, R_{\mu\nu\alpha\beta} R^{\mu\nu\alpha\beta} \right]$$

R = Ricci curvature scalar, $R_{\mu\nu}$ = Ricci tensor, $R_{\mu\nu\alpha\beta}$ = Riemann tensor

F = field-strength tensor of the SU(N_c) gauge theory ; S = complex scalar in fund. rep. ➔ N_c

➔ most general diffeomorphism invariance, gauge invariance, and global scale invariance

Condensation in SU(N_c) gauge sector: ⟨S^+S⟩ ➔ Planck mass ➔ normal GR

➔ $M_{\rm planck} = 2\,\beta\, f_0 = \frac{N_c \beta}{16\pi^2} (2\,\lambda\, f_0) \left(1 + 2\,\ln \frac{2\,\lambda\, f_0}{\Lambda^2}\right)$ with $f_0 = \langle S^+S \rangle$

ghost? ➔ don‘t quantize GR, but after condensation normal gravity ➔ best of both worlds?

➔ Dilaton-scalaron inflation ➔ fits data very well!

Scale dependence: EW vs. Planck Scale

- **Assume:**
  - SM scale generated by some TeV-ish conformal extension
  - Planck scale generation by conformal gravity ⊗ scalar QCD

➔ Do we understand the hierarchy between EW and Planck scale?

$$V = \lambda_1 (\mathbf{H}^\dagger \mathbf{H})^2 + \underbrace{\lambda_2 (\mathbf{H}^\dagger \mathbf{H})(\mathbf{\Phi}^\dagger \mathbf{\Phi})}_{\text{portal coupling}} + \lambda_3 (\mathbf{\Phi}^\dagger \mathbf{\Phi})^2$$

➔ Does λ_2 portal lead to the usual hierarchy problem? ➔ Ideas:

- a tiny λ_2 ⟷ additive RGE evolution...
- composite Higgs & loop generation of portal term
- sequential breaking by RG running ➔ `CW tumbling'

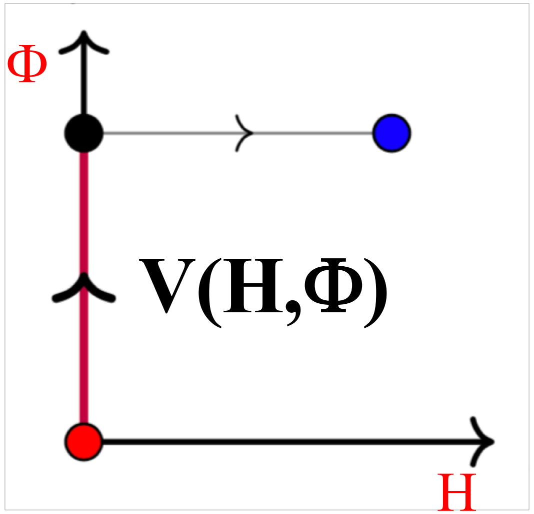
$m^2 = 0$ is boundary broken/unbroken

➔ SSB for tiny attractive force

➔ if $<\Phi^+\Phi>$ condenses first (stronger coupling)

➔ portal can induce $m^2 > 0$ for H ➔ shifts SSB boundary

➔ 2nd SSB by log running of couplings



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?**
  → SM 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

- **Planck scale generation by gauge induced breaking of conformal GR**
  → very nice phenomenology: inflation…
  → consistent quantum gravity: renormalizablity?, ghost?
  ←→ normal GR from a theory with more symmetry
  → stabilizing large scale hierarchies…