Hierarchies and conformal UV Completions

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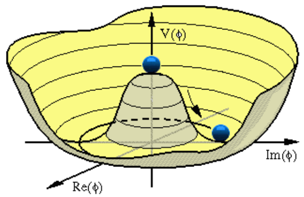
The Success of the Standard Model

The SM is the endpoint of a very successful development: d=4 renormalizable gauge theory

QED $\Rightarrow$	QCD $\Rightarrow$	SM
$U(1)_{em} \Rightarrow$	$SU(3)_c \Rightarrow$	$SU(3)_c \times SU(2)_L \times U(1)_Y$

new ingredient:
Higgs = fundamental scalar
➔ spontaneous symmetry breaking



based on QFT in 4d, symmetries & quantum effects
➔ excellent agreement of theory and experiment
➔ known deficiencies ... ➔ BSM!

Exper. facts, hints, problems:

- Electro-weak scale ≪ Planck scale
- Gauge couplings almost unify
- Neutrino masses & large mixings
- Flavour: Patterns of masses & mixings
- Baryon asymmetry of the Universe
- Dark Matter
- Dark Energy

Theoretical problems:

SM does not exist without cutoff
(triviality, vacuum stability)
Gauge hierarchy problem – became worse
Gauge unification &charge quantization
Strong CP problem
Unification with gravity
3 generations, reps., d=4, many parameters

Standard Model Hierarchy Problems

The (old) hierarchy problem: quantum stability of scales

- SM with a cutoff $\Lambda \gg M_H$

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

- big quantum corrections **pull M_H to Λ ➔ problem!**
- SM is renomalizable, no cutoff ➔ no problem!
  Λ ←➔ **new physics (= embedding, typically more scales)**

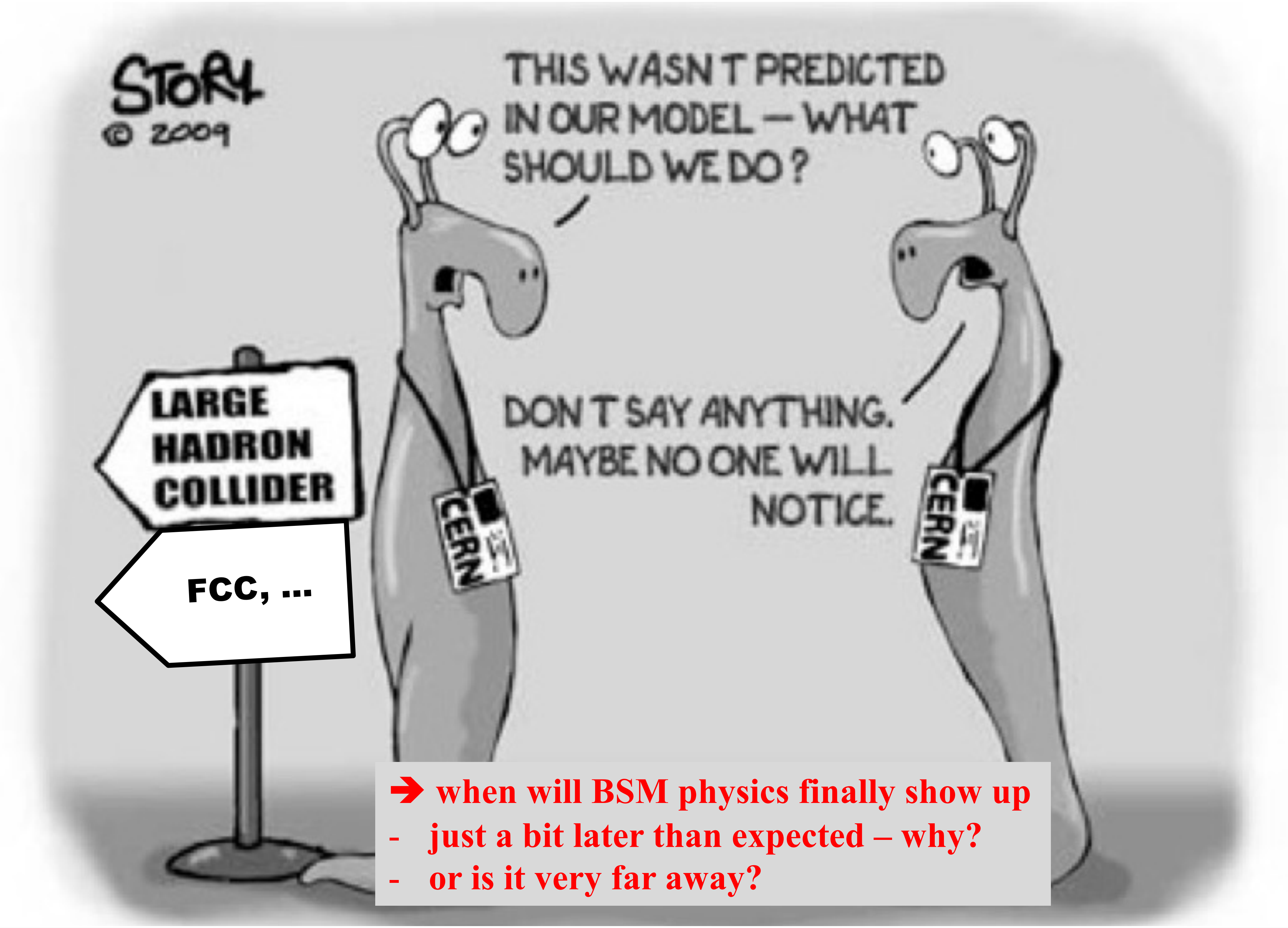
The (new) little hierarchy problem: (so far) nothing showed up

- **Λ = scale of some (composite) dynamics:** condensates generate GBs, PGBs:

  $\mathcal{L}_{\text{kin}} = f^2\, \partial_\mu \Sigma^\dagger \partial^\mu \Sigma$ → radiative: M_W, potential:

$$\mu^2 = c\frac{g^2}{16\pi^2}\Lambda^2 \sim cg^2 f^2, \quad \lambda = c'\frac{g^2}{f^2}\frac{1}{16\pi^2}\Lambda^2 \sim c'g^2$$

- f = 200-300 GeV ←→ correct EW scale (M_W) ➔**Λ at most 3 TeV ←➔ LHC**



➔ when will BSM physics finally show up
- just a bit later than expected – why?
- or is it very far away?

The Problem: Two or more Scalars (Scales)

- SM has just one scale $<\Phi> = v$ → all masses ~v, no problem
- **simplest case:** scalars φ , Φ with masses m, M and **$m \ll M$**
- $\varphi^+\varphi$ and $\Phi^+\Phi$ are singlets → **portal term** $\lambda_{mix}(\varphi^+\varphi)(\Phi^+\Phi)$
- quantum corrections ~ M^2 drive m to the (heavy) scale M
  → vastly different explicit scalar scales are generically unstable

SM embeddings need SSB ←→ more scalars

- gauge extensions: LR, PS, GUTs → must be broken…
- even for SUSY GUTS → doublet-triplet splitting...
- also for fashionable Higgs-portal scenarios...

→ generic conflict between BSM indications and more scales

Mitigating Hierarchy Problems

central issue: scalar portals: $\lambda_p H^+ H \Phi^+ \Phi$ with $\lambda_p = \mathcal{O}(1)$

➔ quantum corrections: $\delta(m_H)^2 \sim (M_\Phi)^2$ ➔ $m_H \ll M_\Phi$ is a fine-tuning

in general a sum of contributions: **$\delta(m_H)^2$ = sum of diagrams $\sim \Lambda^2$**

postulate: $\delta M_H^2 = \frac{\Lambda^2}{32\pi^2 V^2}\left(6M_W^2 + 3M_Z^2 + 3M_H^2 - 12M_t^2\right) = 0$ Veltman condition

...but there is no reason (symmetry, mechanism) for this relation...

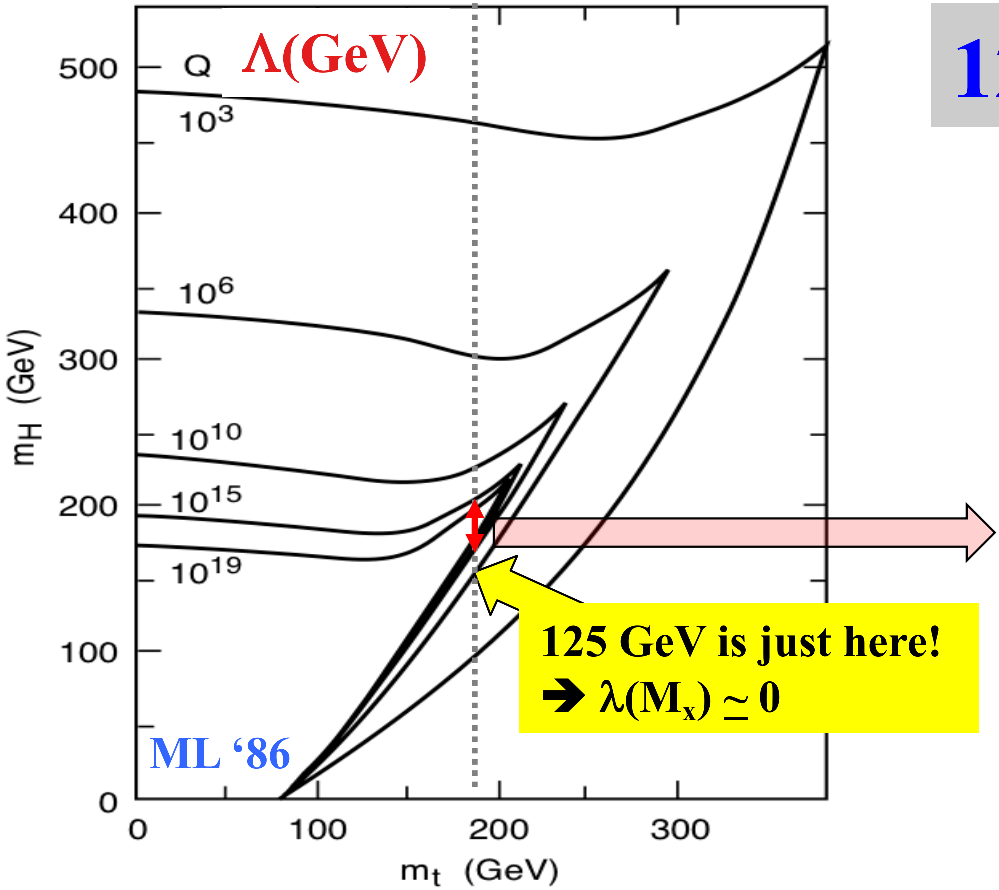
➔ potential directions:

a) supersymmetry (superpartners)
b) loop suppression ←→ $1/16\pi^2$, accidental symmetries, composite Φ
c) unsuppressed portals to dark sectors (invisible BSM)
d) a natural explanation for a very tiny $\lambda_p \ll 1$ (at quantum level)
conformal: $G = G_1 * G_2$ + orthogonal representations + ...

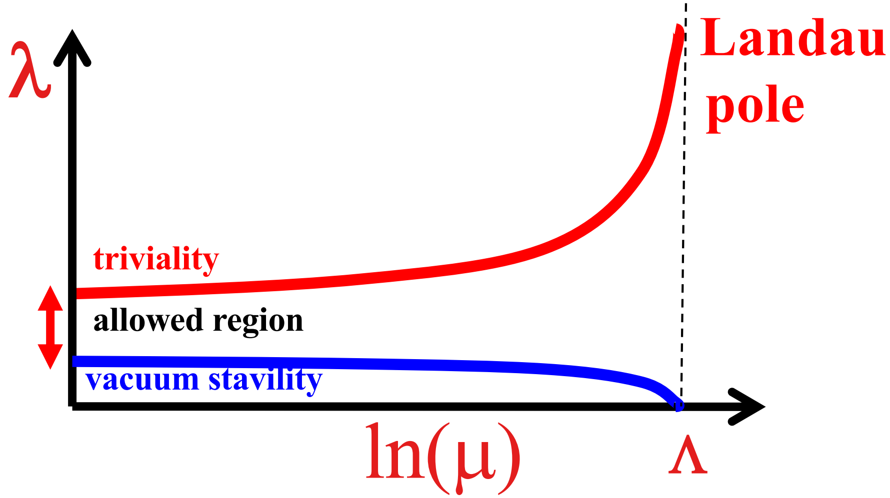
Experimental Observations

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

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



126 GeV $< m_H <$ 174 GeV



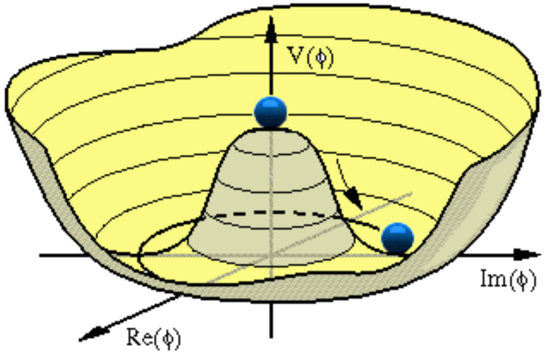
➔ SM quantum corrections OK over large scals distances

Important observation:

- **a remarkable relation between the weak scale, m_t, m_H, gauge couplings and Λ**
- **connected to log divergences – not to quadartic divergences ←→ HP?**

Is there a Message?

- $\lambda(M_X) \simeq 0$? ➔ remarkable log cancellations of unrelated parameters
- **remember: μ is the only single scale of the SM ➔ special role**
- if in addition $\mu^2 = 0$ ➔ $V(M_X) \simeq 0$ ➔ **C-SM with no scale at all**
  ➔ Mexican hat becomes flat due to conspiring quantum effects



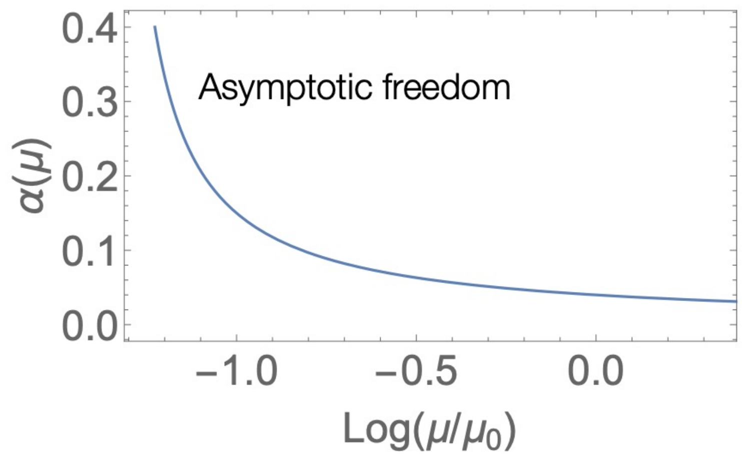
➔

- alternatively: All scalar and Yukawa couplings dissolve
  i.e. composite scalars ➔ potential dissolves (no metastability issues)

- **In both cases tempting:**
  LE broken conformal (or shift) symmetry ←➔ HP?

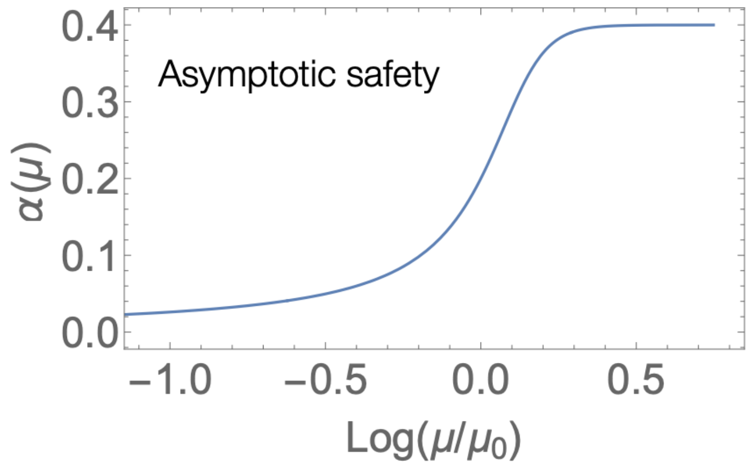
UV-Completion & Conformal Symmetry

Successful theories should have a meaningful UV-completion
➔ vanishing β-functions (UV fixedpoints) ←→ restored scale symmetry



Interacting UV-fixedpoint ➔

← trivial fixedpoint



Interacting UV-fixedpoints:

- scalar and Yukawa couplings tend to have Landau poles, instability...
- all couplings... requires carefully selected particle content ➔ explanation?

Trivial fixedpoints:

- no fundamental scalars
- no Yukawa couplings
- asymptotically free non-abelian gauge theories w/o scalars ➔ easy

Higgs Portals to Hidden Sectors

- **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

- **no CA… → breaking only ln(Λ)**

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

- **<u>Many model building possibilities / phenomenological aspects:</u>**
  - 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 →suppressed TeV-ish BSM physics!

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:

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

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

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

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

Many more Models along this Direction

SM + extra singlet or doublet: Φ, φ
Nicolai, Meissner Farzinnia, He, Ren, Foot, Kobakhidze, Volkas, Hill, …

Minimal B-L extension: $SU(3)c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ Iso, Okada, Orikasa

SM + high rep. QCD scalar: J. Kubo, K.S. Lim, ML

Minimal LR-model: $SU(3)c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ Holthausen, ML, Schmidt

SM $\otimes$ $SU(N)_H$ with new N-plet in a hidden sector
Ko, Carone, Ramos, Holthausen, Kubo, Lim, ML, Hambye, Strumia , …

SM + QCD colored scalar which condenses at TeV scale Kubo, Lim, ML

SM $\otimes$ [$SU(2)_X \otimes U(1)_X$]
Altmannshofer, Bardeen, Bauer, Carena, Lykken

… more ...

Since SM- does not work ➔ more ➔ observable effects:
- Higgs & other scalars (singlet, hidden sector, …) → little hierarchy is natural
- dark matter candidates ←→ hidden sectors & Higgs portals
- consequences for neutrino masses, ...

Conformal Little Higgs

conformal little Higgs: **Ahmed, ML, Saake, 2309.07845, PRD 109.075041**

1) All scalars (including Higgs) are GBs or PGBs

→ scale **$\Lambda \simeq$ 10 TeV little Higgs model**

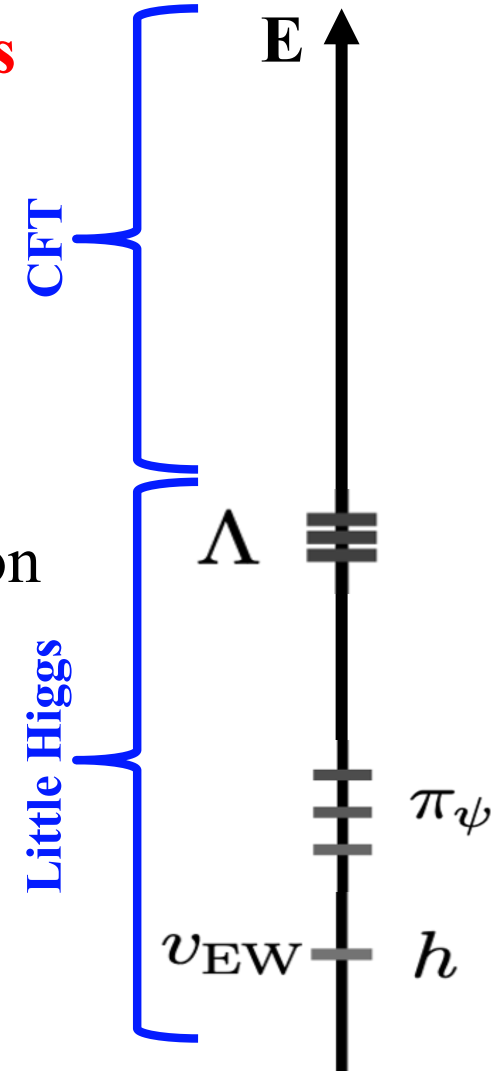
→ symmetry explanation of the LHP

→ all λ's and Yukawa couplings dissolve at Λ

2) conformal non-abelian UV completion

→ Λ becomes scale of a dimensional transmutation

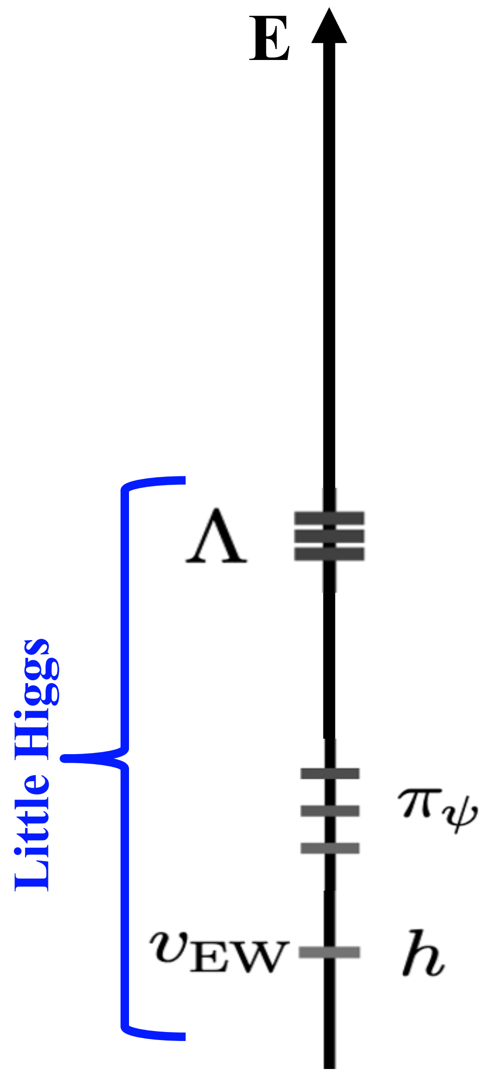
→ no new scalars or scales ←→ HP



Remarks:

- realized for SM, but works for extended Higgs sectors
- can be combined with neutrino masses, DM, BAU, ...
- gravity – comments if time allows

A little Higgs reminder



Λ = scale of some (composite) dynamics

- condensates generate GBs, PGBs

  $\mathcal{L}_{\rm kin} = f^2\, \partial_\mu \Sigma^\dagger \partial^\mu \Sigma$ → radiative: M_W, potential:

$$\mu^2 = c \frac{g^2}{16\pi^2} \Lambda^2 \sim c g^2 f^2, \quad \lambda = c' \frac{g^2}{f^2} \frac{1}{16\pi^2} \Lambda^2 \sim c' g^2$$

- f = 200-300 GeV ←→ correct EW scale (M_W)

  → Λ at most 2-3 TeV: exp. excluded operators

  → spectrum may contain lower lying states?

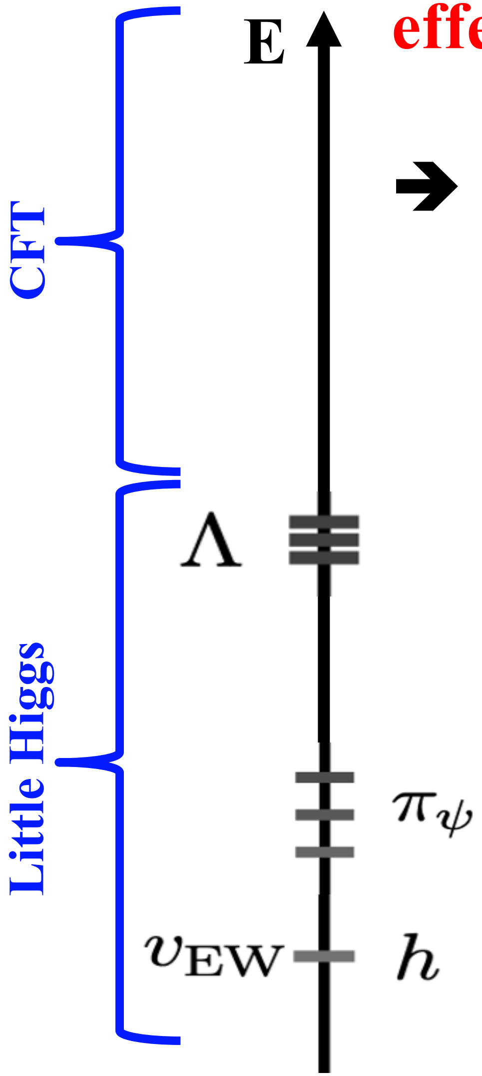
  c.f. techni-ρ in technicolor → S parameter...

- **little Higgs:** f can be O(TeV) → Λ = 5-10 TeV

$$\mu^2 \sim \frac{g^2}{16\pi^2} f^2 \log \frac{\Lambda^2}{f^2} \sim \frac{g^2}{8\pi^2} f^2 \log(4\pi)$$

- important: *all* scalar dof are GBs or PGBs
- lower lying bound states more remote

Conformal UV Completion



Idea: Make the little Higgs model to be the effective theory of a conformal completion

➔ **Suitable conformal theory:**

- no fundamental scalars, no scales, χ-ral fermions
- non-abelian gauge group → asymptotically free
  - → trivial UV fixepoint
  - → β=0 ←→ no conformal anomaly
  - → IR dimensional transmutation like χ-ral QCD
- condensation → **effective little Higgs model**
- dynamical transmutation no y's or λ's beyond Λ
  - ➔ no Λ^2 corrections

Conformal Little Higgs Models

Ahmed, ML, Saake, arXiv: 2309.07845, PRD 109.075041

Exemplification for ``bested little Higgs'' model:

➔ UV completion without introducing any elementary/fundamental scalars

- confining non-abelian gauge symmetry SU(N_c) - we take $N_c = 2$
- new fermions:
  → ``technifermions''
  four light flavors

	$SU(N_c)$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$\tilde{\psi} \equiv \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$	$\square$	$\mathbf{1}$	$\square$	0
$\psi' \equiv \begin{pmatrix} \psi_3 \\ \psi_4 \end{pmatrix}$	$\square$	$\mathbf{1}$	$\mathbf{1}$ $\mathbf{1}$	$-\frac{1}{2}$ $+\frac{1}{2}$
$\chi \times N_m$	$\square$	$\mathbf{1}$	$\mathbf{1}$	0

- $SU(2)_L \subset SU(4)_L$ and the custodial group $SU(2)_L' \subset SU(4)_L$, respectively
- conjugate fields transform under the subgroups of $SU(4)_R$
- global symmetry breaking coset $SU(4)_L \times SU(4)_R / SU(4)_V$
- condensation ➔ flavor symmetry breaking

The Higgs Sector

- condensation ➔ 15 Goldstone bosons
- transform under the custodial symmetry SO(4) ≃ $SU(2)_L \times SU(2)_R \subset$ SU(4)V as $15_{SU(4)V} = (2,2)+(2,2)+(3,1)+(1,3)+(1,1)$
- Goldstone matrix: $$U = \exp\left[i\Pi/\sqrt{2}f\right]$$
- where $$\Pi = \begin{pmatrix} \sigma^a \Delta_1^a + \eta/\sqrt{2} & -i\Phi_H \\ i\Phi_H^\dagger & \sigma^a \Delta_2^a - \eta/\sqrt{2} \end{pmatrix}$$
- with bi-doublet $$\Phi_H \equiv \left(\widetilde{H}_1 + i\widetilde{H}_2, \quad H_1 + iH_2\right); \quad \widetilde{H}_i \equiv i\sigma_2 H_i^*$$

  where H_i are Higgs doublets under SU(2)L
- and the triplets $$\sigma^a \Delta^a = \begin{pmatrix} \Delta^0 & \sqrt{2}\Delta^+ \\ \sqrt{2}\Delta^- & -\Delta^0 \end{pmatrix}$$

Including the Planck Scale

The Planck Scale from CS Breaking

Conformal Gravity (C-GR):

- more symmetry ➔ power counting renormalizable
- C-GR may have a ghost ➔ ...
- spontaneous generation of M_{Pl} ➔ Einstein-Hilbert gravity
- most economic and simple way:

$$\frac{\xi_S}{2} S^2 R \rightarrow \frac{\xi_S}{2} \langle S \rangle^2 R \rightarrow \frac{M_{Pl}^2}{2} R$$

$$M_{Pl} = \sqrt{\xi_S} \langle S \rangle$$

Brans+Dicke,’61; Fujii,’74; Englert+Truffin+Grastmans,’76; Minkowsky,’77;......

Idea: Generate M_{Planck} from conformal gravity ⊗ SU(N)

➔ gauge assisted condensate via SU(N) field ➔ M_{Planck} = effective scale

Kubo, ML, Schmitz, Yamada similar ideas: **Donoghue, Menezes, ...**

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

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

➔ **dimensional transmutation:** ⟨S^+S⟩ ➔ effective Planck mass

$$M_{\text{planck}} = 2\beta f_0 = \frac{N_c \beta}{16\pi^2} (2\lambda f_0) \left(1 + 2 \ln \frac{2\lambda f_0}{\Lambda^2}\right) \quad \text{with} \quad f_0 = <S^+S>$$

➔ Effectively normal gravity with a dynamically generated M_{Planck}

What about the portal of S with the SM scalar Φ? ➔ **effective S + gravity suppresses portal**

de Boer, Kubo, ML, Reinig to appear soon...

Dilaton-Scalaron Inflation

Effective Jordan-frame Lagrangian:

$$\frac{\mathcal{L}^J_{\text{eff}}}{\sqrt{-g_J}} = -\frac{1}{2} B(\chi)\, M^2_{\text{Pl}}\, R_J + G(\chi)\, R_J^2 + \frac{1}{2} g_J^{\mu\nu} \partial_\mu \chi\, \partial_\nu \chi - U(\chi)$$ ➔ auxiliary field Ψ ➔

$$\frac{\mathcal{L}^J_{\text{eff}}}{\sqrt{-g_J}} = -\left[\frac{1}{2} B(\chi)\, M^2_{\text{Pl}} - 2\, G(\chi)\, \psi\right] R_J + \frac{1}{2} g_J^{\mu\nu} \partial_\mu \chi\, \partial_\nu \chi - U(\chi) - G(\chi)\, \psi^2$$

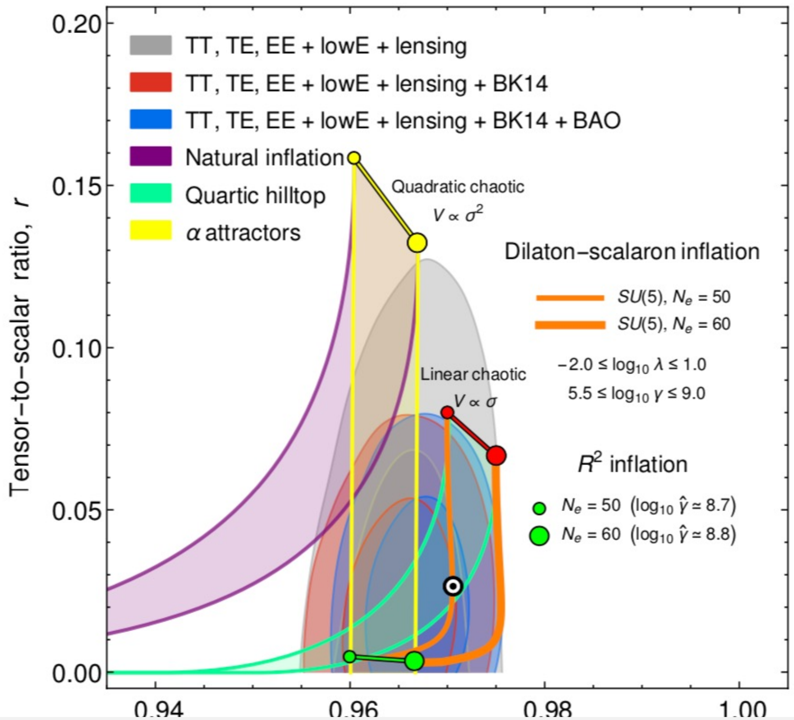
Weyl rescaling: $g_{\mu\nu} = \Omega^2\, g^J_{\mu\nu}$ $\qquad \Omega^2 = e^{\Phi(\phi)}\,, \qquad \Phi(\phi) = \dfrac{\sqrt{2}\,\phi}{\sqrt{3}\, M_{\text{Pl}}}$

Einstein-frame scalar potential:

$$V(\chi, \phi) = e^{-2\,\Phi(\phi)} \left[U(\chi) + \frac{M^4_{\text{Pl}}}{16\, G(\chi)} \left(B(\chi) - e^{\Phi(\phi)} \right)^2 \right]$$

➔ Slow role inflation

➔ fits data very well!



Conclusions

- **The Standard Model**
  → works perfectly – no problems besides triviality, metastability
  → list of unanswered questions / problems ←→ BSM
  → lots of progress: DM, ν's, GR waves, ... + many new ideas
  → hierarchy problem worsened due to the little hierarchy problem
  → remarkable coincidence of parameters: flat Higgs potential @HE

- **Conformal portals to dark sectors**
  → dimensional transmutation in dark sector + portal O(1) → SM

- **Conformal little Higgs**
  → a natural explanation of LHP: all scalar dof are GBs or PGBs
  → conformal UV completion: avoid to reintroduce problems (fund. scalars)
  → non-abelian gauge theory with fermions, gauge bosons and no scale
  ➔ dimensional transmutation at multi Tev-ish Λ

- **Including the Planck scale**
  → conformal gravity with dimensional transmutation