Hierarchies and conformal UV Completions

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The Standard Model and beyond

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

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

➔ **excellent agreement of theory and experiment**

Theoretical problems:

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

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

Hierarchy Problems

Emerge from scalars upon embedding / connecting to other vastly different scales

Solutions within d=4 QFT:

➔ **an additional symmetry**
- supersymmetry, other: conformal

➔ **a low lying scale where the scalar sector is composite**
- technicolor, other composite ideas

} **both:** Goldstone Bosons

Experiment:

Neither SUSY nor TeV-ish compositeness observed (so far)

➔ **little hierarchy problem (LHP)** ←→ BSM scale is too far away...

➔ **amplifies the old hierarchy problem (HP)**

Must solve LHP and HP ➔ LHP first

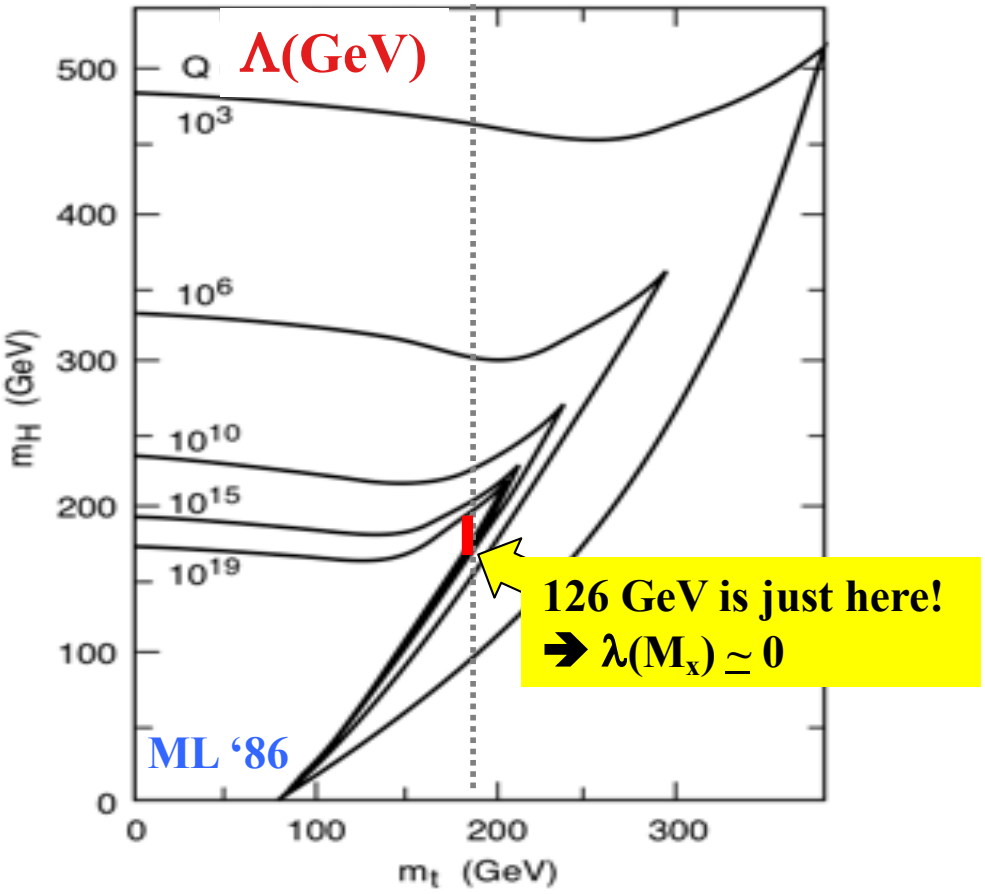
➔ **symmetry: all scalars dof (including the Higgs particle) GBs or PGBs**
- problem: GB decay constant ←→ Λ
- relaxed in little Higgs models ←→ natural explanation of LHP

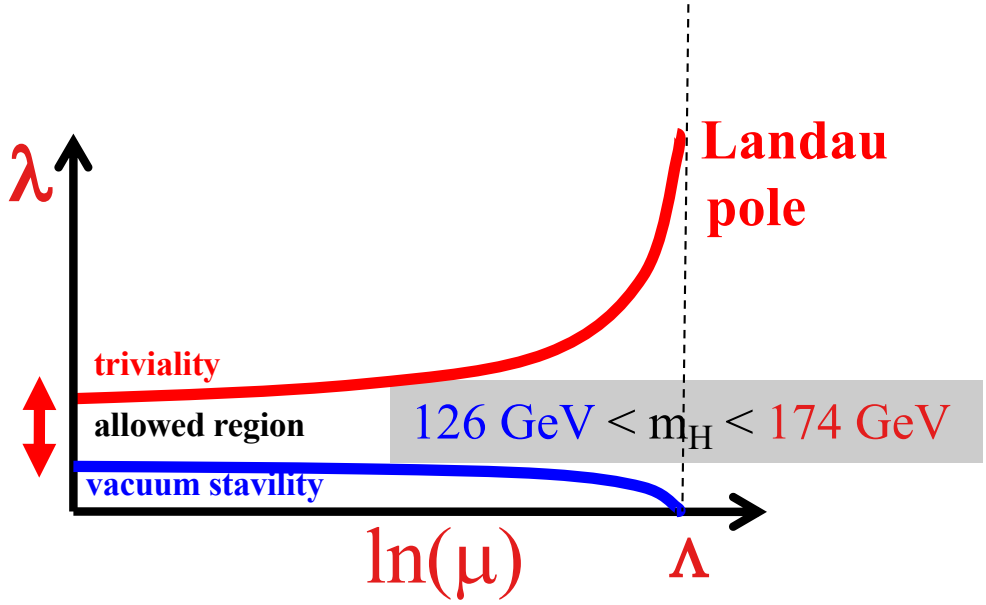
BUT: These models have scalars and scales ➔ only shifting problems?

Another experimentally driven Observation

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

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





➔ SM quantum corrections OK over large scale distances

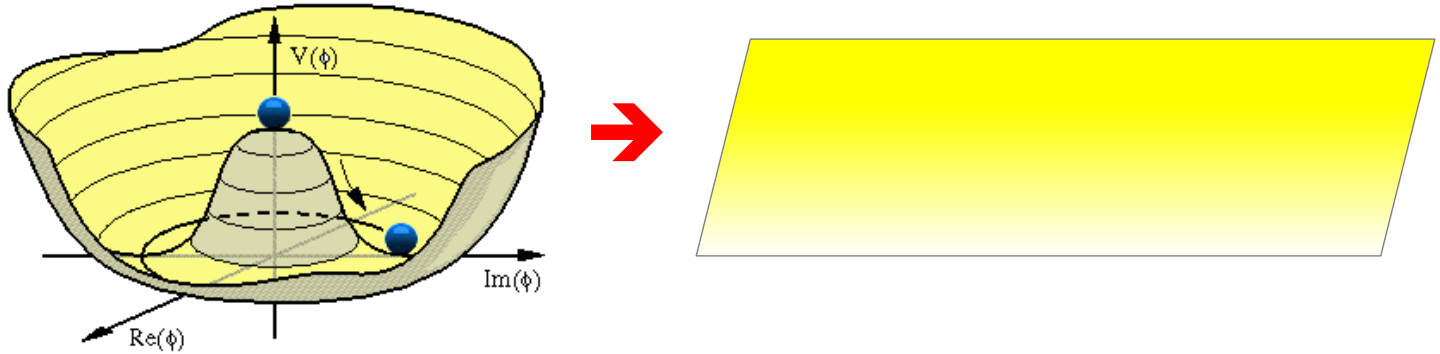
Interesting observation:

- 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
- **remember: μ is the only single scale of the SM ➔ special role**
- if in addition $\mu^2 = 0$ ➔ $V(M_X) \simeq 0$
  ➔ Mexican hat becomes flat due to conspiring quantum effects

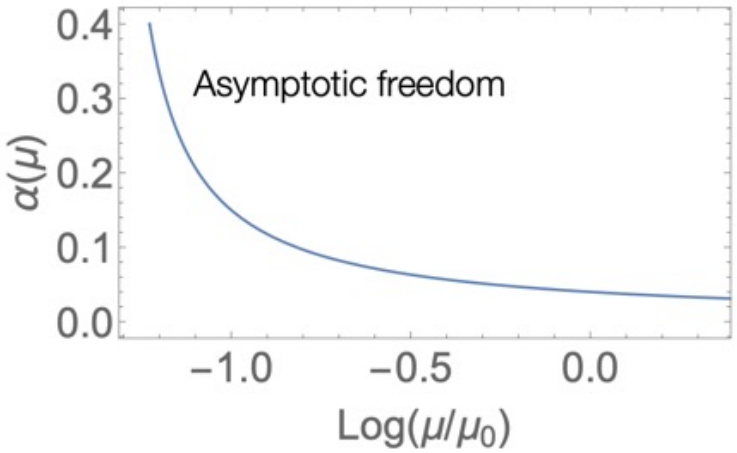


- alternatively: All scalar and Yukawa couplings dissolve
  i.e. composite scalars ➔ potential dissolves (no metastability issues)

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

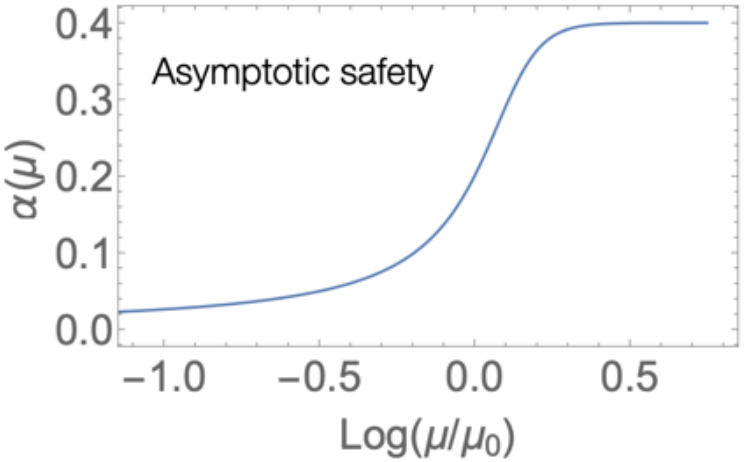
Conformal Symmetry & UV-Completion

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...
- requires carefully selected particle content ➔ explanation?

Trivial fixedpoints:

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

Little Higgs + conformal UV Completion

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

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

→ scale **$\Lambda \sim$ multi TeV little Higgs model**

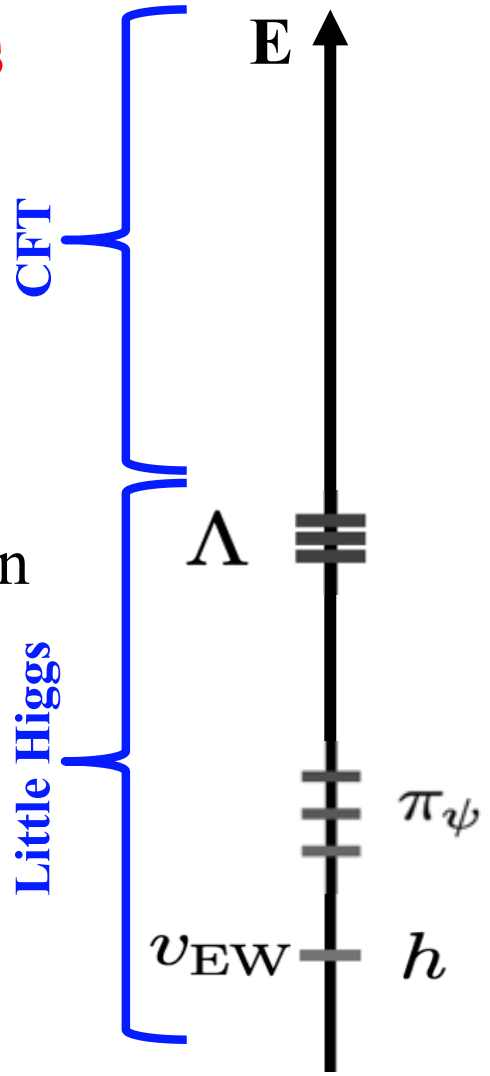
→ symmetry explanation of the LHP

→ 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

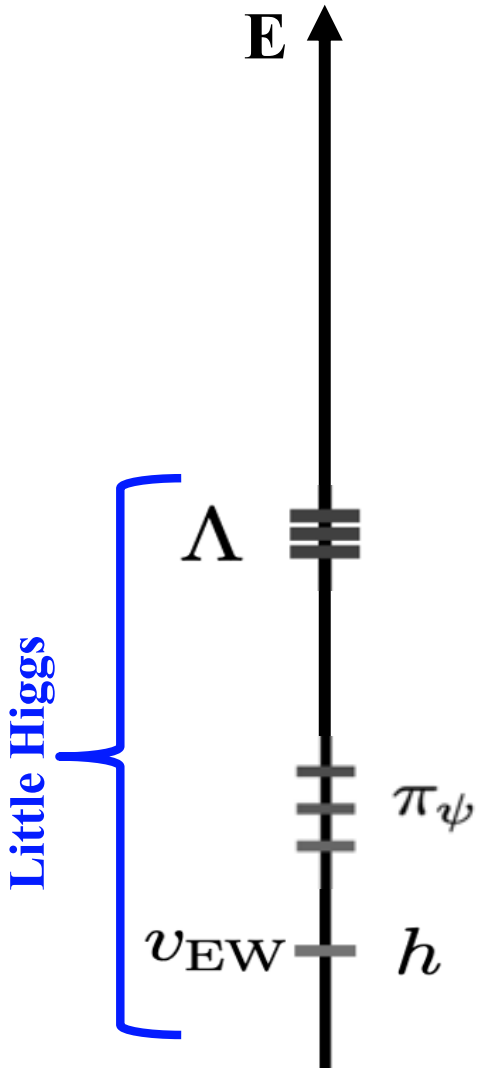


Remarks:

- 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 compositeness dynamics



- condensates generate GBs, PGBs

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

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

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

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

  → spectrum may contain lower lying states?

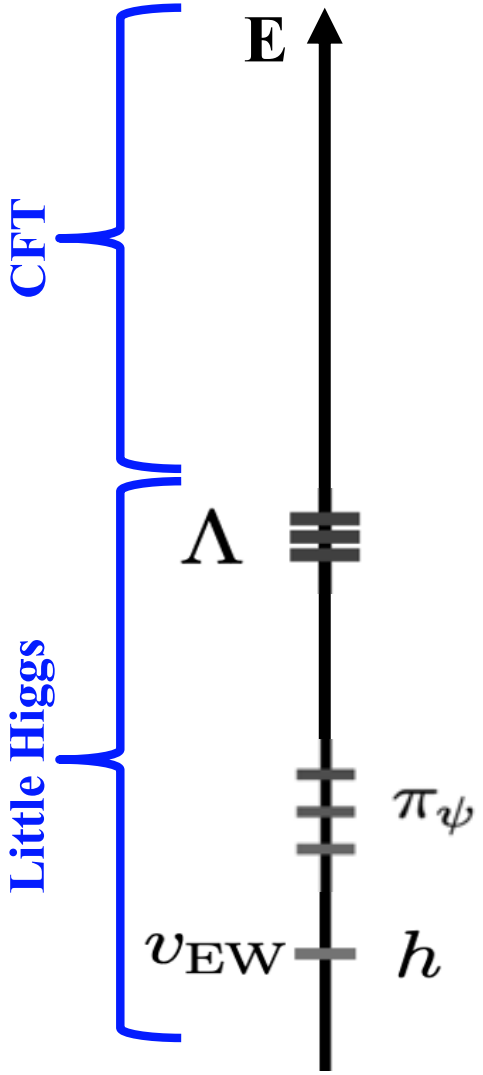
  c.f. techni-ρ in technicolor → S parameter...

- **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



Suitable conformal theory:

- no fundamental scalars, no scales, χ-ral fermions
- non-abelian gauge group → asymptotically free
  → trivial UV fixepoint
  → $\beta=0$ ←→ no conformal anomaly
  → IR dimensional transmutation like χ-ral QCD
- condensation → **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 $$\sigma^a \Delta^a = \begin{pmatrix} \Delta^0 & \sqrt{2}\Delta^+ \\ \sqrt{2}\Delta^- & -\Delta^0 \end{pmatrix}$$

Phenomenology

- conformal symmetry is broken at $\Lambda \sim O(5)$ TeV by fermion condensate
  → spontaneous breaking of a global symmetries
  → no quadartic divergences in analogy to χ-ral QCD

- Higgs and partners emerge as pseudo-Goldstone Bosons
- low-energy phenomenology closely resembles ``bestest Little Higgs'' model
  →little hierarchy between SM and Λ explained by Little Higgs dynamics
- H_1 corresponds to the SM Higgs doublet
- H_2, scalar triplet Δ_1 and singlet η → substantial masses O(1) TeV
- heavy gauge boson partners W' and Z' → O(1) TeV
- fermionic top-partners have masses at the scale f

  → promising for future LHC runs

- The lightest stable neutral composite scalar can be a DM candidate.
- ...

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 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
    - ➔ GBs and PGBs explain scalar physics at EW scale
  - → generic mechanism – exemplified for ``bested little Higgs''

- **Not covered:**
  phenomenological implications, neutrino physics, dark matter, …
  combination with gravity (conformal gravity+breaking; inflation, ghosts?)