What if the LHC finds nothing else?

Adam Smetana
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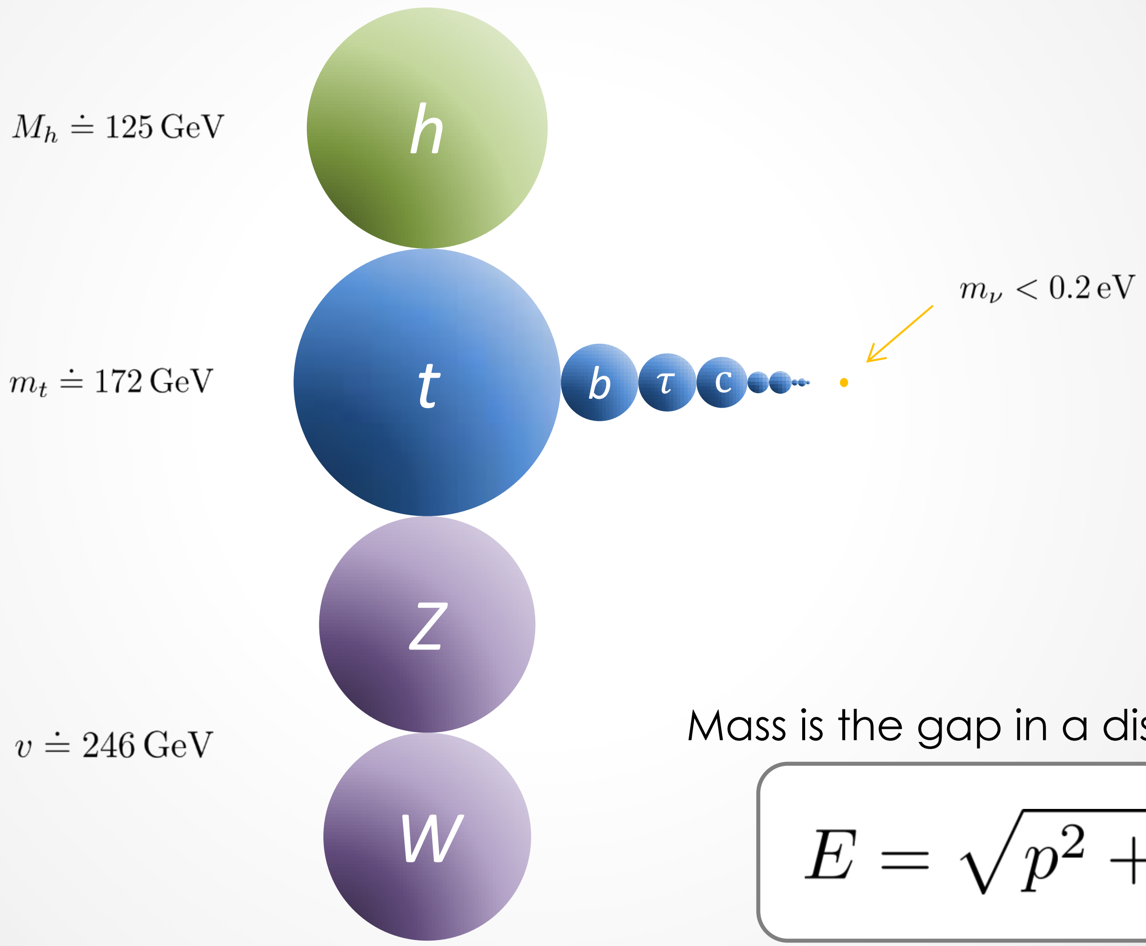
This is what we want to understand



Mass is the gap in a dispersion law.

$$E = \sqrt{p^2 + m^2}$$

Theory of elementary particles

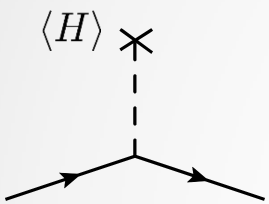
gauge symmetry $\{ \mathrm{SU}(3)_c \times \underbrace{\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y}_{\text{chiral symmetry}} \underbrace{\longrightarrow}_{\text{EW symmetry breaking}} \mathrm{SU}(3)_c \times \mathrm{U}(1)_{\mathrm{em}}$

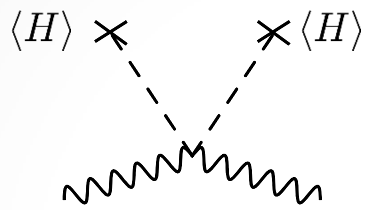
- **consistent renormalizable way to introduce gauge bosons** *g*, *W*, *Z*, γ
  predictivity, tree unitarity of amplitudes, ***massless gauge boson fields!***
- **Anderson-Englert-Higgs** (ABEGHHK) **mechanism:**
  gauge invariant way to get ***massive gauge boson particles!***
- **Higgs particle(s)** *tree unitarity of amplitudes*
- **fermion masses:**
  fermion fields are chiral thus massless, but as they are coupled to the EWSB, fermion particles are massive.

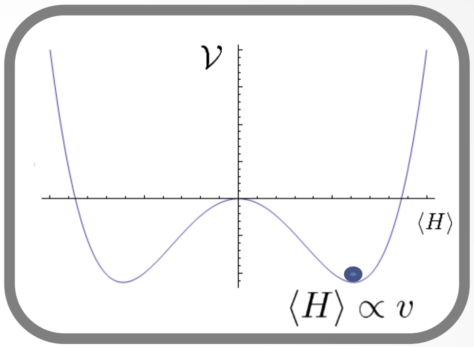
Standard Model of elementary particles

In the Standard Model, as the simplest way, we introduce elementary complex scalar doublet H:

$$\mathcal{V} = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

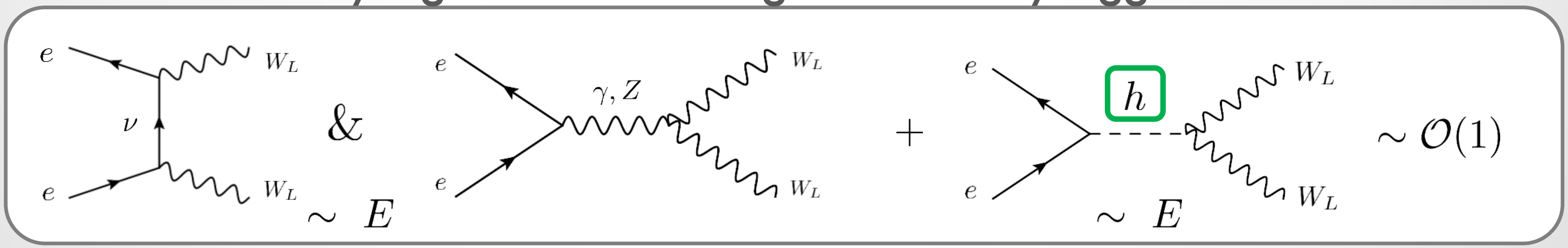






renormalizable Standard Model

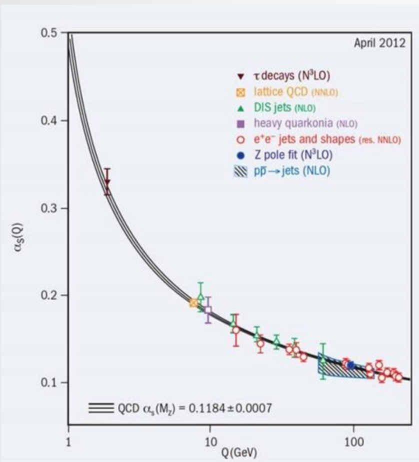
Tree-level unitarity is guaranteed bz single elementary Higgs boson

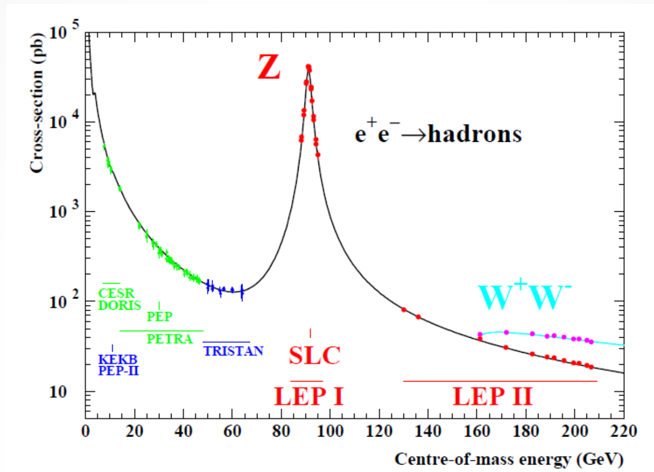


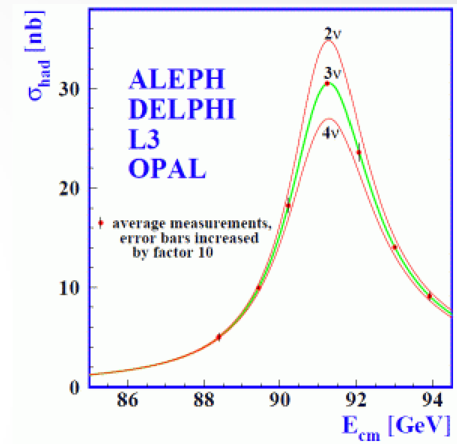
Success of the Standard Model

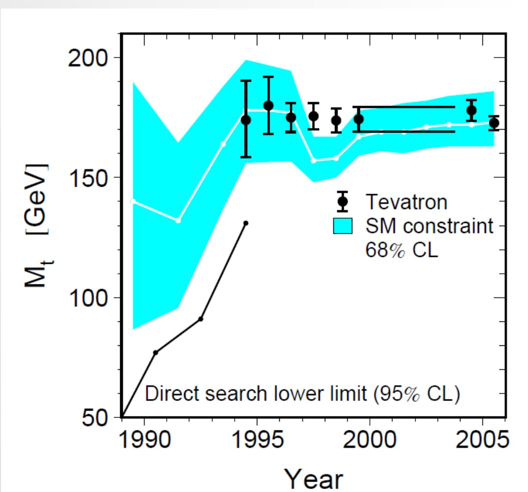
The renormalizable Standard Model works very well…

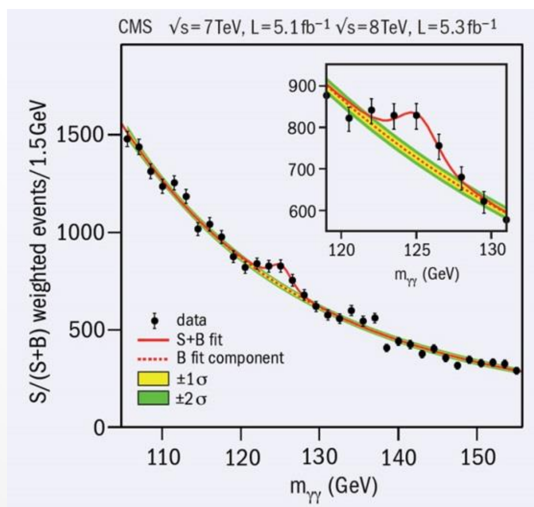
- no mismatch between **collider experimental data** and **the SM predictions**

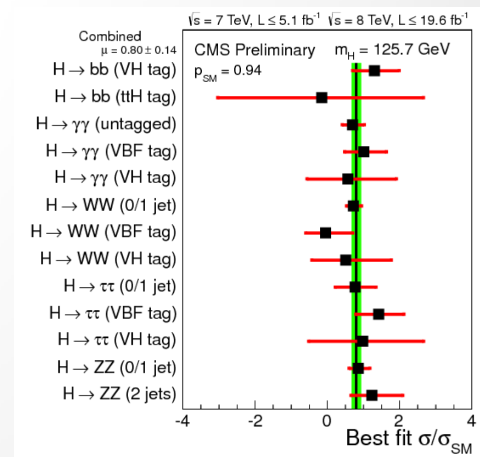












Why to go beyond the Standard Model

phenomenology

But the SM does not work for every observed phenomena.

- neutrinos oscilate → **neutrinos are not massless**
- we see **more than SM** in **extra-terrestrial observations**
  - Baryon asymmetry of the Universe,
  - Dark matter,
  - Dark energy

There are other hints which support going beyond SM, e.g.:

- reactor neutrino anomaly
- large scale structure formation

} sterile neutrinos?

Why to go beyond the Standard Model

theory

Flavor is just parametrized in the SM

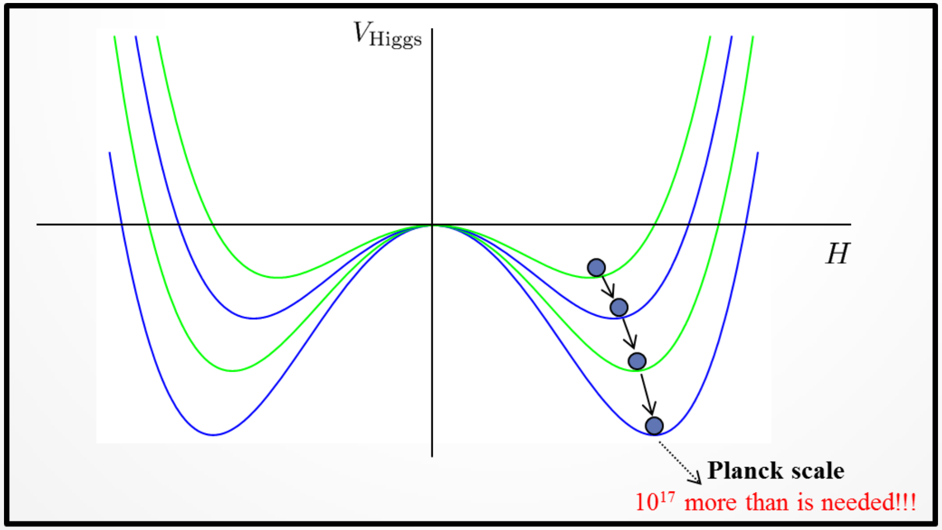
There is one-to-one correspondence between Yukawa parameters and femion mass matrices.

EWSB is just parametrized in the SM

- **Hierarchy problem** – v.e.v. of Higgs is quadratically divergent

$$v^2 \propto \mu^2\,, \qquad \delta v^2 \propto \Lambda^2$$

Scale of new physics



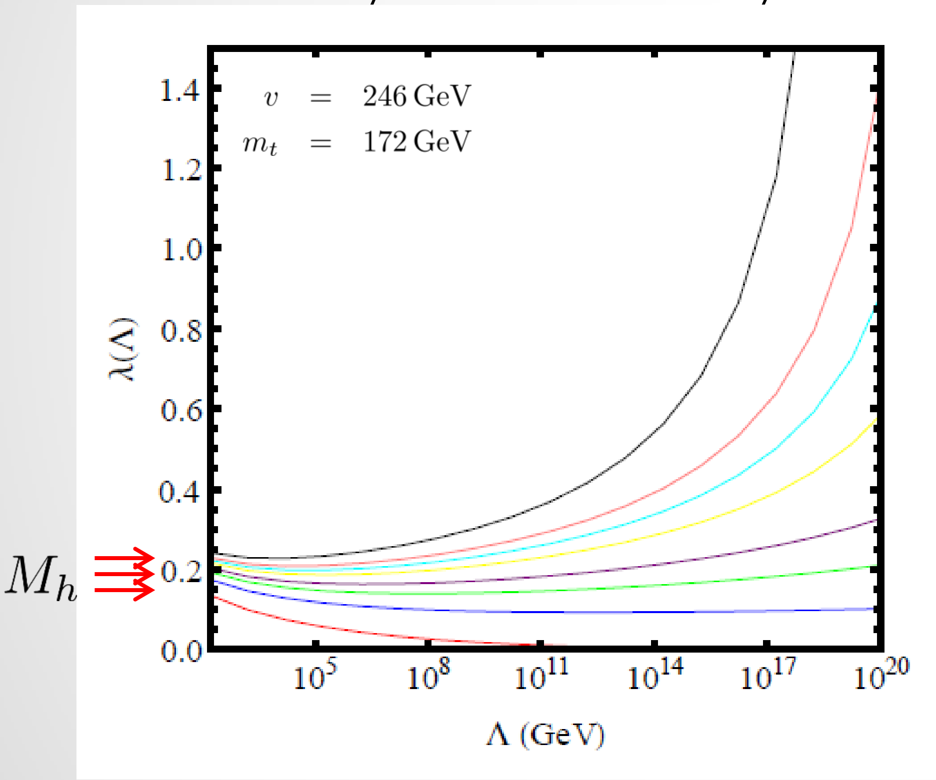
Other problems are: strong CP problem, missing quantum theory of gravity

Why to go beyond the Standard Model

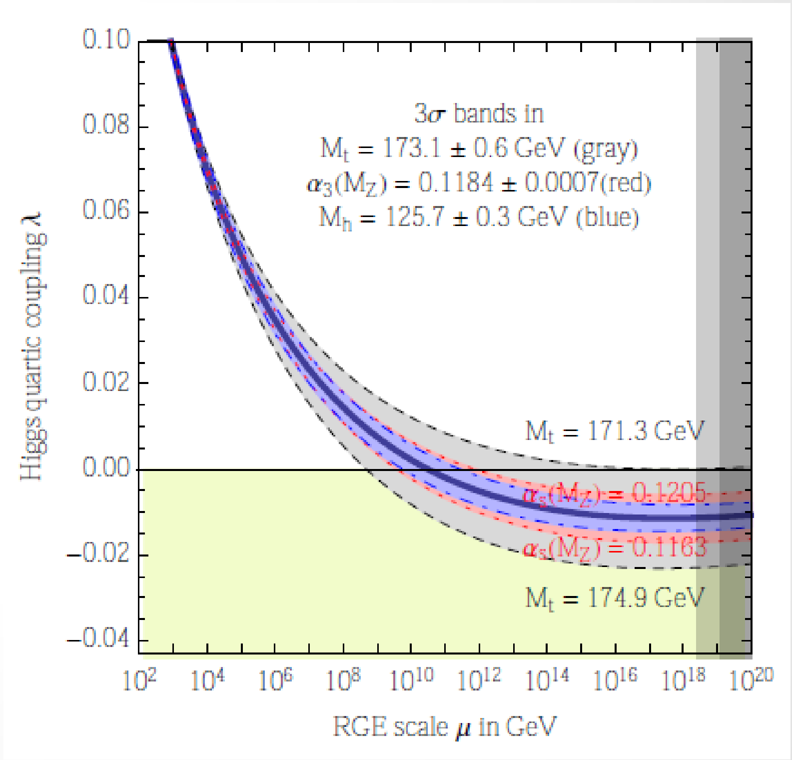
theory

The Higgs potential may be unstable below the Planck scale!

triviality & vacuum stability



vacuum stability after Higgs



RGE: $16\pi^2 \frac{d}{dt}\lambda = 12\lambda^2 - 12y_t^4$

Superconductivity

We know similar situation.

Meisner effect: photons are massive in the bulk of superconductor.

$$\mathrm{U}(1)_{\mathrm{em}}$$

is spontaneously broken.

Ginzburg—Landau theory describes it by complex order parameter field,

Thermodynamic free energy

$$F \supset \alpha|\phi|^2 + \frac{\beta}{2}|\phi|^4 + \frac{1}{2m_e}|(-i\hbar\nabla - 2e\mathbf{A})\phi|^2$$

which can develop nonzero value $|\phi|^2 = -\frac{\alpha}{\beta} \overset{\text{if}}{>} 0$

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PHENOMENOLOGICAL DESCRIPTION

which can develop nonzero value $|\phi|^2 = -\frac{\alpha}{\beta} \overset{\text{if}}{>} 0$

Bardeen—Cooper—Schrieffer theory: $\phi \sim \psi^e_{\mathbf{k}}\psi^e_{-\mathbf{k}}$

electrons acquire a gap

$$E = \sqrt{\epsilon^2_{\mathbf{k}} + |\Delta|^2}$$

Standard Model

Electroweak symmetry breaking: W, Z bosons are massive.

$$\mathrm{U}(1)_Y \times \mathrm{SU}(2)_L$$

is spontaneously broken.

Standard Model describes it by complex Higgs field,

$$\mathcal{L} \supset \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + D^\mu H^\dagger D_\mu H$$

which develops nonzero v.e.v. $H^\dagger H = -\frac{\mu^2}{2\lambda} \overset{\text{if}}{>} 0$

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PHENOMENOLOGICAL DESCRIPTION?

which develops nonzero v.e.v. $H^\dagger H = -\frac{\mu^2}{2\lambda} \overset{\text{if}}{>} 0$

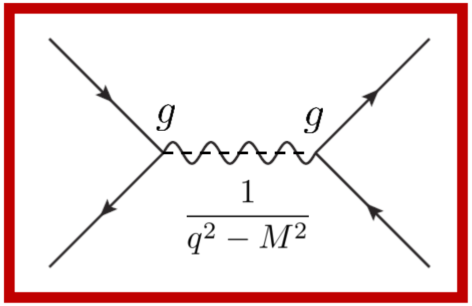
Dynamical EWSB: $H \sim \bar{\Psi}\Psi$

e.g. (E)TC

$$E = \sqrt{\mathbf{p}^2 + m^2}$$

New dynamics

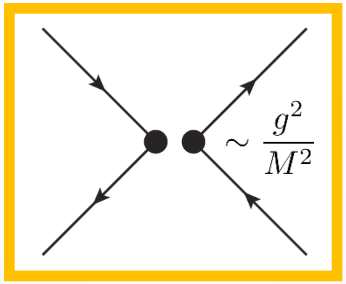
Renormalizable underlying model characterized by a scale $\Lambda^2 \sim M^2$



For example

Effective low-energy description:

$$q^2 \ll M^2 \sim \Lambda^2 < \Lambda^2_{\text{Planck}}$$



$$\equiv G\mathcal{O}_{d=6} = G(\bar{f}f)^2$$

For example

Standard Model as the effective theory

$$\mathcal{L}^{\rm SM}_{\rm eff.} = \mathcal{L}^{\rm SM} + \mathcal{L}^{\rm SM}_{d=5} + \mathcal{L}^{\rm SM}_{d=6} + \ldots$$

$$\mathcal{L}^{\rm SM}_{d=5} = \frac{c_\nu}{\Lambda}(\overline{L^c_L}\mathrm{i}\sigma_a H)(H\mathrm{i}\sigma_a L_L)$$ ← **only 1** Weinberg operator

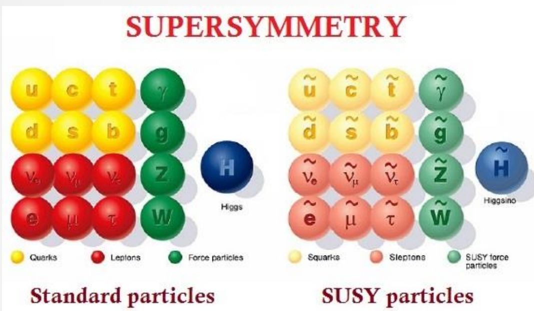
$$\mathcal{L}^{\rm SM}_{d=6} = \frac{c^{(3)\ell}_{LL}}{\Lambda^2}(\bar{L}_L\sigma_a\gamma_\mu L_L)(\bar{L}_L\sigma_a\gamma^\mu L_L) + \ldots$$ ← 59(64) independent operators

Scale of new physics

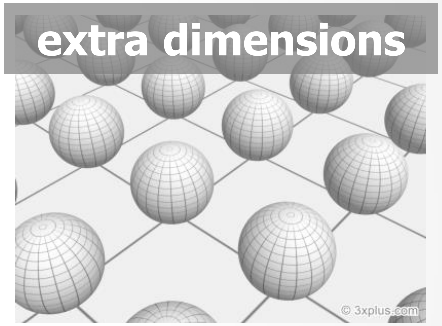
Many mainstream beyond-Standard models install the new physics at the scale within the reach of current colliders…

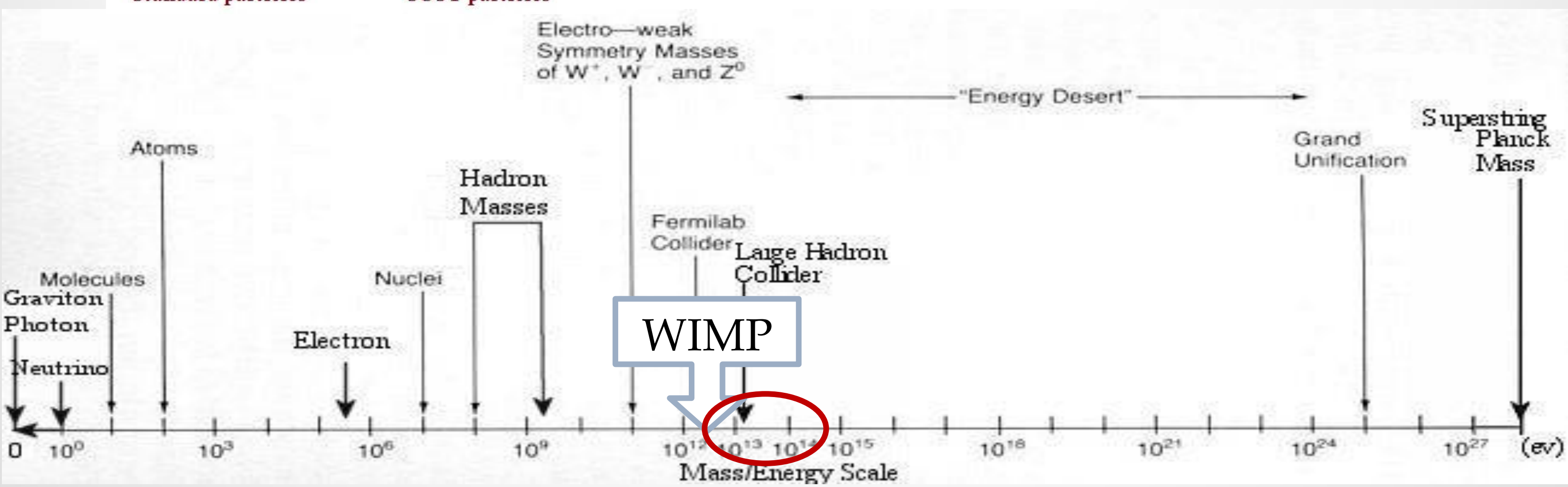
...mainly for two reasons:

- ✓ to **avoid** the hierarchy problem
- ✓ to see spectacular signs of the new physics



technicolor

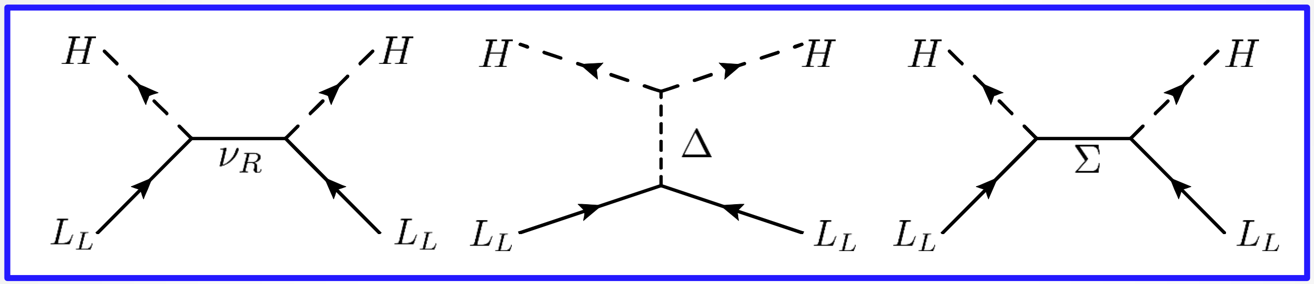




Dimension-5 Weinberg operator

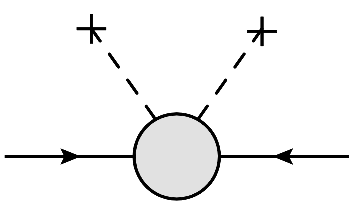
$$\mathcal{L}_{d=5}^{\mathrm{SM}} = \frac{c_\nu}{\Lambda}(\overline{L_L^c}\mathrm{i}\sigma_a H)(\tilde{H}^T\mathrm{i}\sigma_a L)$$

Due to the exchange of heavy particle of the new dynamics.



Type-I Type-II Type-III

Seesaw and Majorana neutrinos are predicted by effective Standard Model

$m_\nu =$  $\propto c_\nu \frac{v^2}{\Lambda}$

- Majorana neutrinos
- Lepton number violation
- CP violation

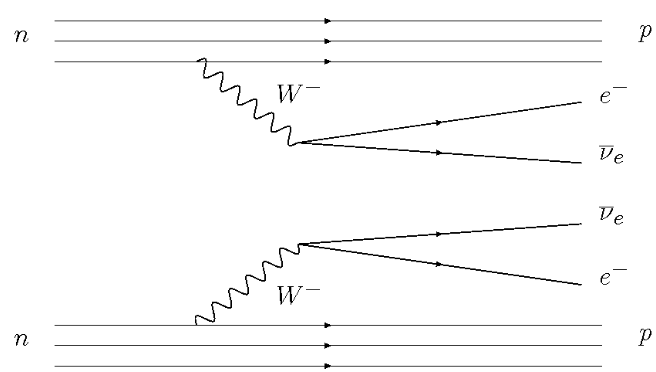
- **0νββ**
- leptogenesis

Compare with charged fermions

$m_f = y_f v$

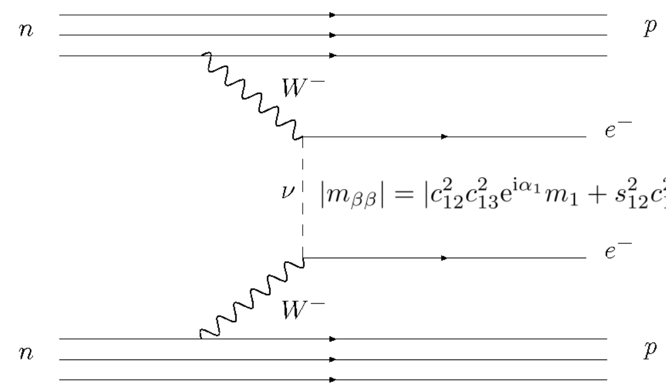
Tiny neutrino masses suggest huge Λ!

0νββ and cosmology



allowed in the renormalizable SM

ΔL=0

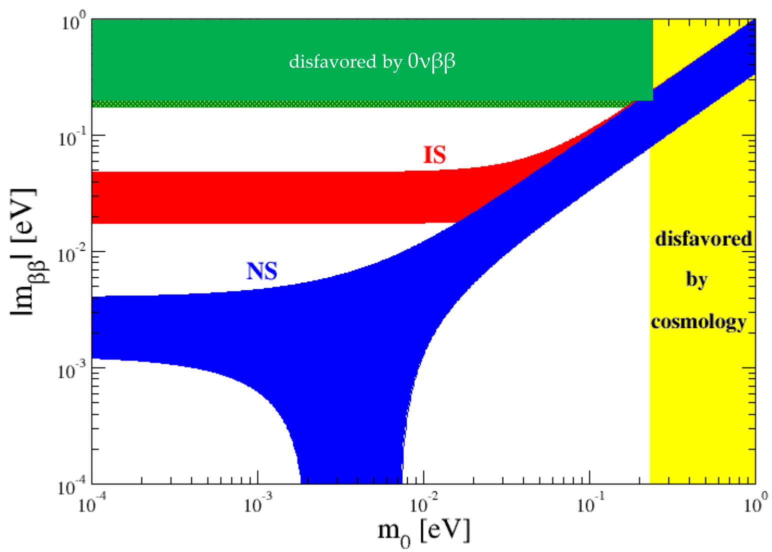


$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 e^{i\alpha_1} m_1 + s_{12}^2 c_{13}^2 e^{i\alpha_2} m_2 + s_{13}^2 m_3|$$

forbidden in the renormalizable SM

predicted by the effective SM

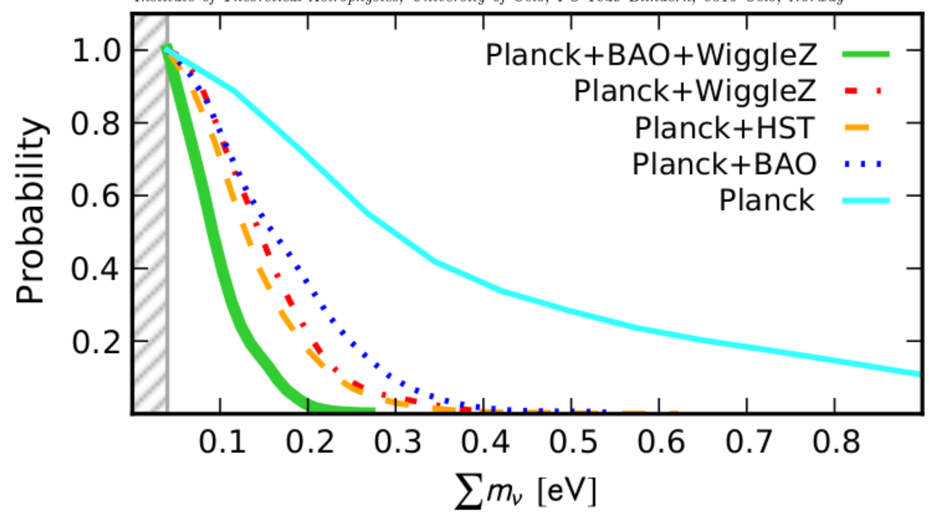
ΔL=2



Combining Planck with Large Scale Structure gives strong neutrino mass constraint

Signe Riemer-Sørensen,[1,2,*] David Parkinson,[1] and Tamara M. Davis[1]

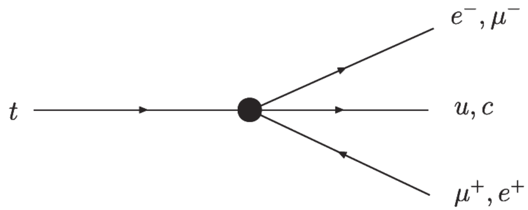
[1] *School of Mathematics and Physics, University of Queensland, Brisbane, QLD 4072, Australia*
[2] *Institute of Theoretical Astrophysics, University of Oslo, PO 1029 Blindern, 0315 Oslo, Norway*



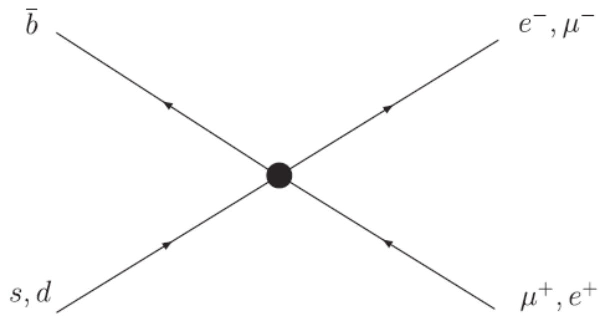
Dimension-6 operators

For example: flavor-violating four-fermion interactions

$$t \to u(c)e^{\pm}\mu^{\mp}$$

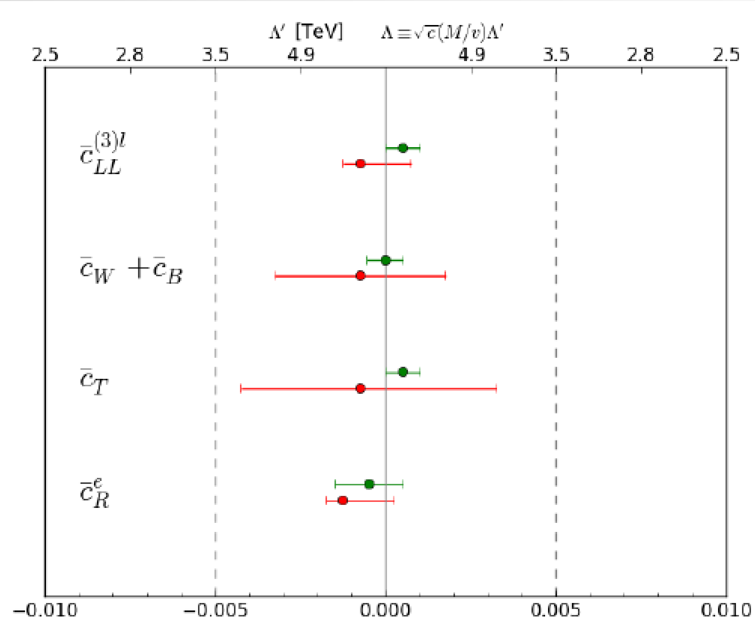


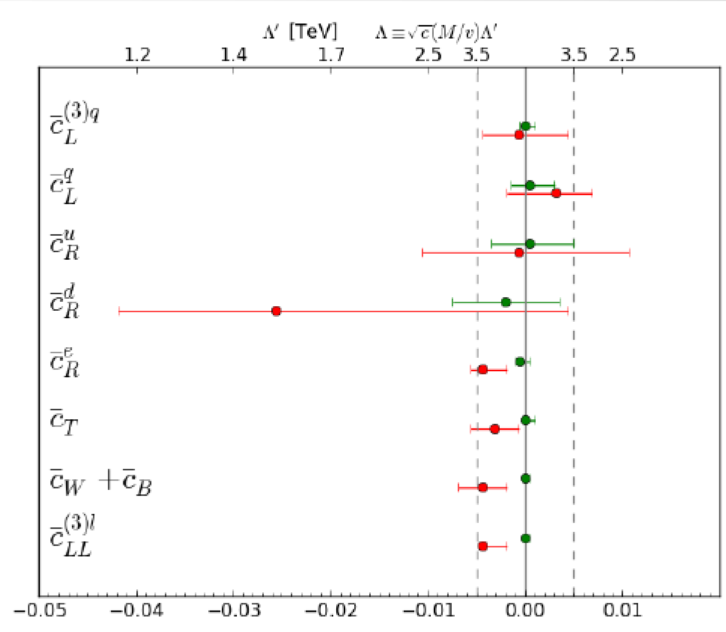
$$B_s \to e^{\pm}\mu^{\mp}$$



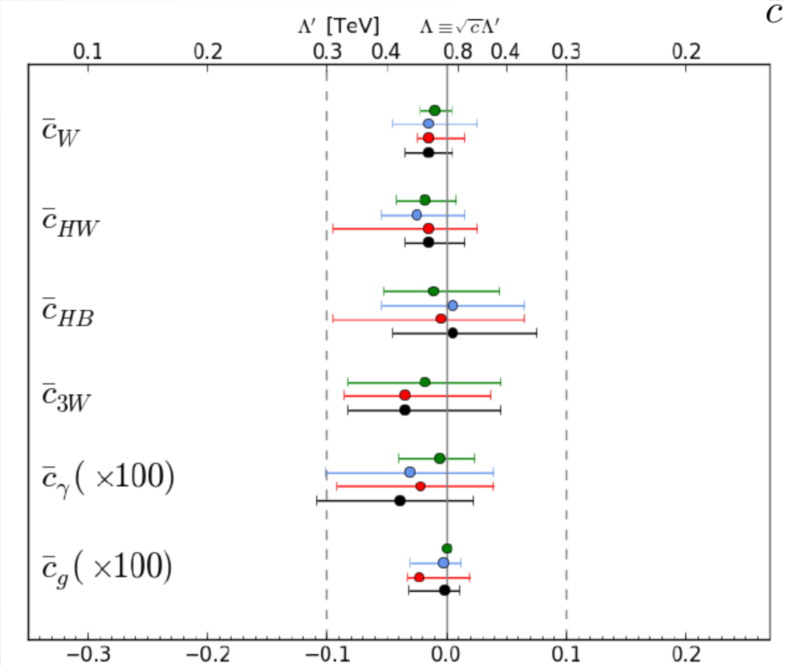
These processes pushes Λ to higher values!

$$\Lambda > \mathcal{O}(10\,\mathrm{GeV})$$





$$\bar{c} \equiv \frac{v^2}{\Lambda^2} c$$



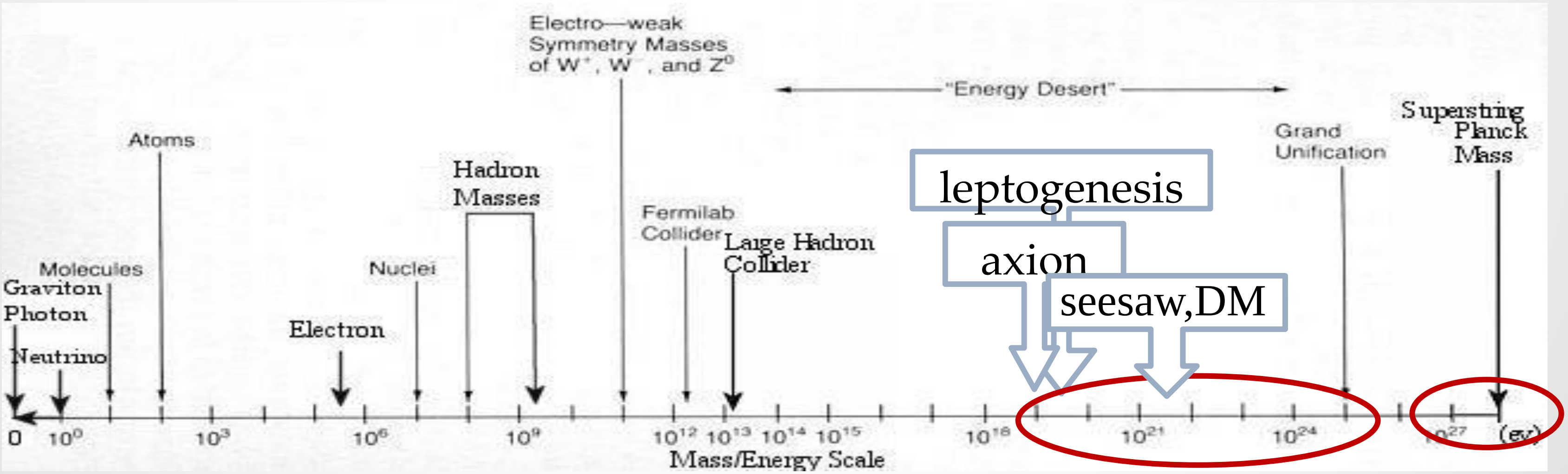
The Effective Standard Model after LHC Run I

John Ellis[1,2], Verónica Sanz[3] and Tevong You[1]

[1] *Theoretical Particle Physics and Cosmology Group, Physics Department, King's College London, London WC2R 2LS, UK*
[2] *TH Division, Physics Department, CERN, CH-1211 Geneva 23, Switzerland*
[3] *Department of Physics and Astronomy, University of Sussex, Brighton BN1 9QH, UK*

Maybe we should rather *accept* the existence of huge hierarchy between *electroweak* and *new dymamics*…

… and *explain* it rather than *avoid* it!



Two interesting approaches

From the teoretical point of view there is **no strict necessity** to have the new physics at the TeV scale.

- GUT theories *accept* the hierarchy, but they *do not explain* it, just parametrize it.

We like two approaches based on a dynamical (mass) scale generation as the explanation for the hierarchy

(in the analogy with QCD)

- **fermion condensation models**
- **scale invariant models**

- scale invariant quantum gravity embedding?? Agravity??

Shaposhnikov 2013, Lindner 2013 Salvio & Strumia 2014

QCD – a prototype of a fundamental theory

assuming chiral limit

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4}G^2 + \bar{\psi}(\mathrm{i}\partial\!\!\!/ + g_{\rm s} A\!\!\!/)\psi$$

- **classically scale invariant theory** – no scale in Lagrangian
- dimensional transmutation

$$\alpha_{\rm s}(q^2) \equiv \frac{g_{\rm s}^2(q^2)}{4\pi} \simeq \frac{4\pi}{b \ln q^2/\Lambda_{\rm QCD}^2}$$

$$g_{\rm s} \longrightarrow \Lambda_{\rm QCD}$$

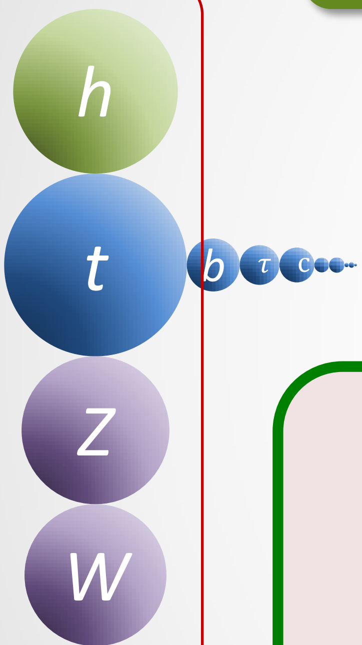
- **all masses in the QCD spectrum are proportional to athe single scale** $\Lambda_{\rm QCD}$

- nice features: $\Lambda_{\rm QCD} = \mathrm{e}^{-4\pi/b\alpha_{\rm s}(\Lambda_{\rm Planck})}\Lambda_{\rm Planck}$

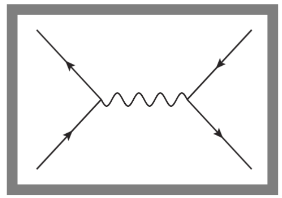
  no Landau pole

Fermion condensation approach

of the same order of magnitude



new dynamics between quarks and leptons



$$m_t \propto \langle \bar{t}t \rangle\,, \quad m_b \propto \langle \bar{b}b \rangle\,, \quad m_c \propto \langle \bar{c}c \rangle\,, \;\ldots$$

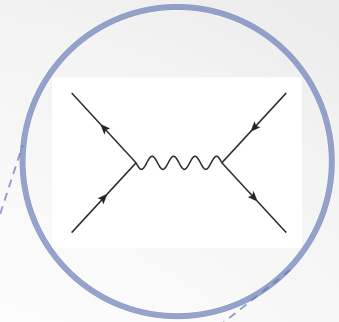
$$m_\tau \propto \langle \bar{\tau}\tau \rangle\,, \quad m_\mu \propto \langle \bar{\mu}\mu \rangle\,, \;\ldots$$

$$v \;\sim\; \langle \bar{t}t \rangle\,,\, \langle \bar{b}b \rangle\,,\, \ldots\,,\, \langle \bar{\tau}\tau \rangle\,,\, \ldots$$

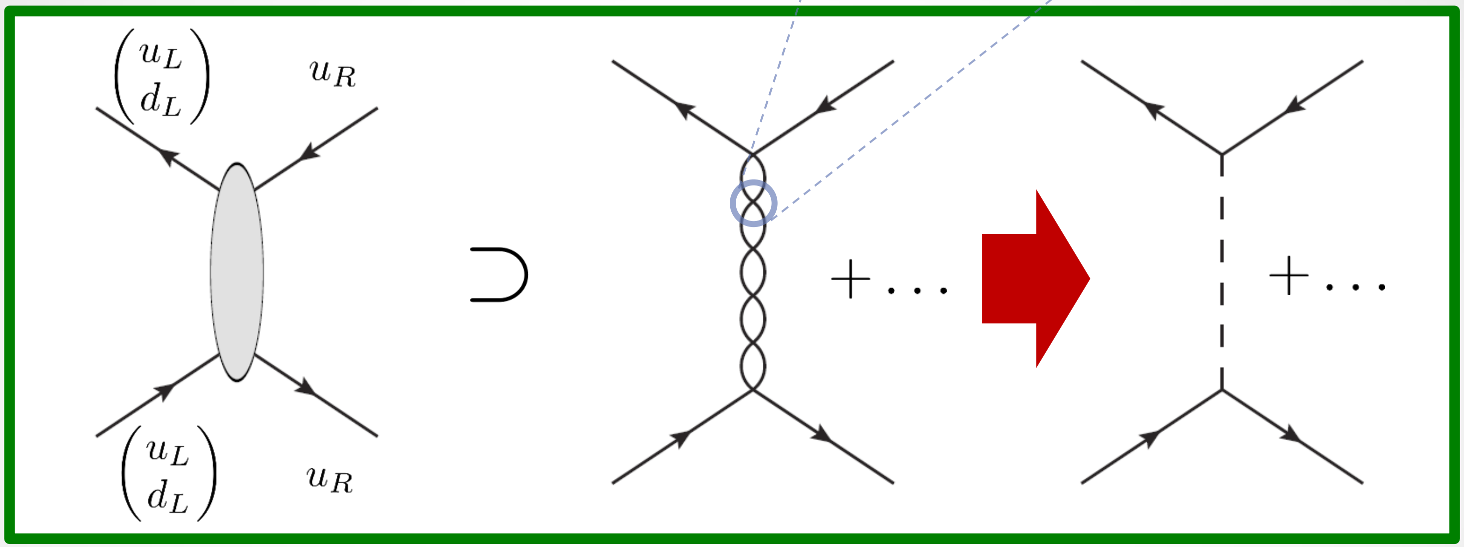
in **complete** analogy with superconductivity

[Ho82]
[KiMu85]
[Na88]
[MiYa89]
[BaHiLi89]

Composite Higgs field



Full process



composite scalars:
Nambu—Goldstone bosons, Higgs boson

$$\bar{u}_R q_L = \bar{u}_R \begin{pmatrix} u_L \\ d_L \end{pmatrix} \implies H_u \sim \begin{pmatrix} \bar{u}_R u_L \\ \bar{u}_R d_L \end{pmatrix}$$

Top-quark and neutrino condensation

We assume that …

… out of all electroweakly charged fermions, both **top-quark and neutrinos** contribute **significantly** to the electroweak scale by their Dirac masses and the corresponding condensates.

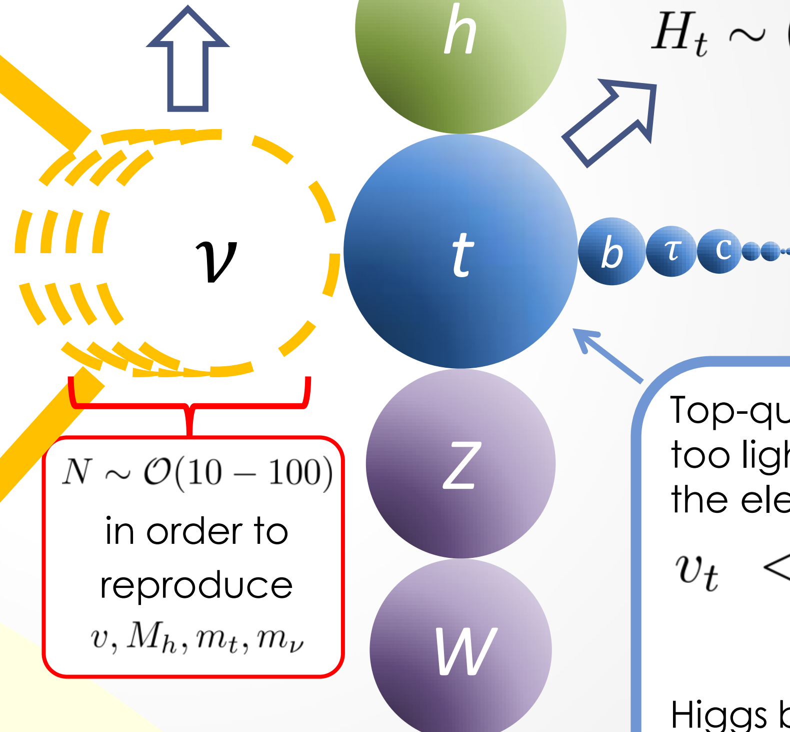
$$m \approx -\frac{m_D^2}{M_R} \sim 0.1\,\mathrm{eV}$$

$$H_\nu \sim (\bar{\nu}_R \ell_L)$$

$$H_t \sim (\bar{t}_R q_L)$$

The seesaw mechanism

$$(\bar{\nu}_L \;\; \bar{\nu}^c_R) \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \bar{\nu}^c_L \\ \bar{\nu}_R \end{pmatrix}$$



$N \sim \mathcal{O}(10-100)$ in order to reproduce v, M_h, m_t, m_ν

$$M \approx M_R \sim 10^{14}\,\mathrm{GeV}$$

Top-quark alone is too light to saturate the electroweak scale.

$$v_t < 0.68 v$$

$$\Lambda < \Lambda_{\mathrm{Planck}}$$

Higgs boson comes out too heavy.

Scale invariant extension of the Standard Model

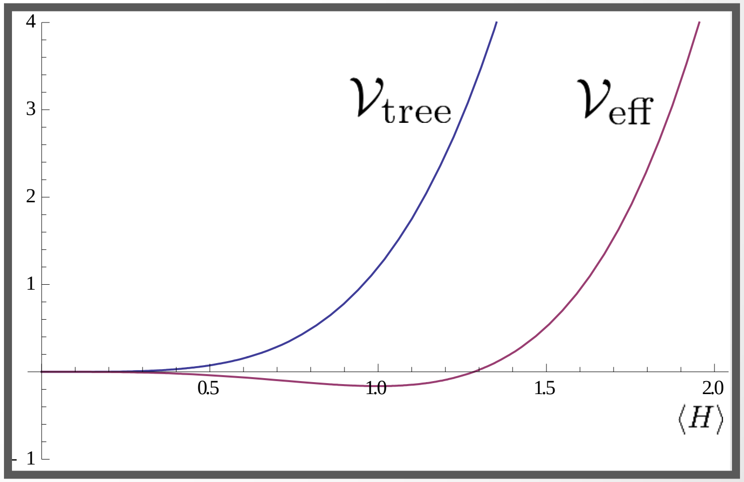
Bardeen 1995

$$\mathcal{L} = \mathcal{L}_{\rm SM}(\mu = 0) \supset -\cancel{\mu^2 H^\dagger H} + \lambda(H^\dagger H)^2$$

The fundamental theory behind SM may be the classically scale invariant theory.

- no scale in the Lagrangian
- only logarithmic divergences
- Mass scale is generated by radiative corrections via **dimensional transmutation**.
- weakly coupled theory – everything is under control.

Coleman, Weinberg 1973



pseudo-NG boson of broken scale invariance = **scalon** **Higgs?**

Scale invariant models beyond the Standard Model

Direct scale invariant SM (Higgs=scalon) **does not work**

- large top-quark mass destabilizes the effective potential
- smaller top-quark mass would lead to small Higgs mass

More bosonic d.o.f. are needed to stabilize the eff. potential

$$\mathcal{L}(H,\phi,\nu_R) = -\frac{\lambda_1}{4}(H^\dagger H)^2 - \frac{\lambda_2}{2}(H^\dagger H)(\phi^\dagger \phi) - \frac{\lambda_3}{4}(\phi^\dagger\phi)^2 + \phi\bar{\nu}_R Y \nu_R^c + \text{h.c.}$$

- hidden sector – Dark Matter candidates, dynamical origin of singlet neutrino masses M_R

What if the LHC finds nothing else?

For theory it would be **no disaster rather challenge**.

For experiment it would probably mean to go in the direction of:

- **Precision measurements** of Standard Model processes
  (Higgs properties, flavor violation,…)
- **Cosmology**
  (particle content of the Universe,…)
- **Neutrino physics**
  (CP and lepton number violation, neutrino mass scale)