The BIG questions

Zuoz 2022

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Q: Will it rain on our excursion on Wednesday??

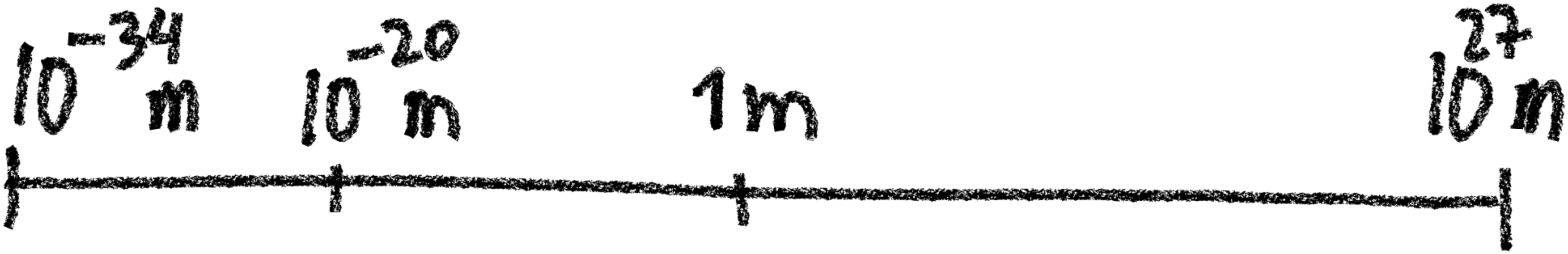
Q: who was so nice to put these in our rooms?

3 stories

- BSM physics & naturalness
- Dark matter
- H_0 crisis

Particle physics + Cosmology

shortest and longest distances



Particle physics + Cosmology

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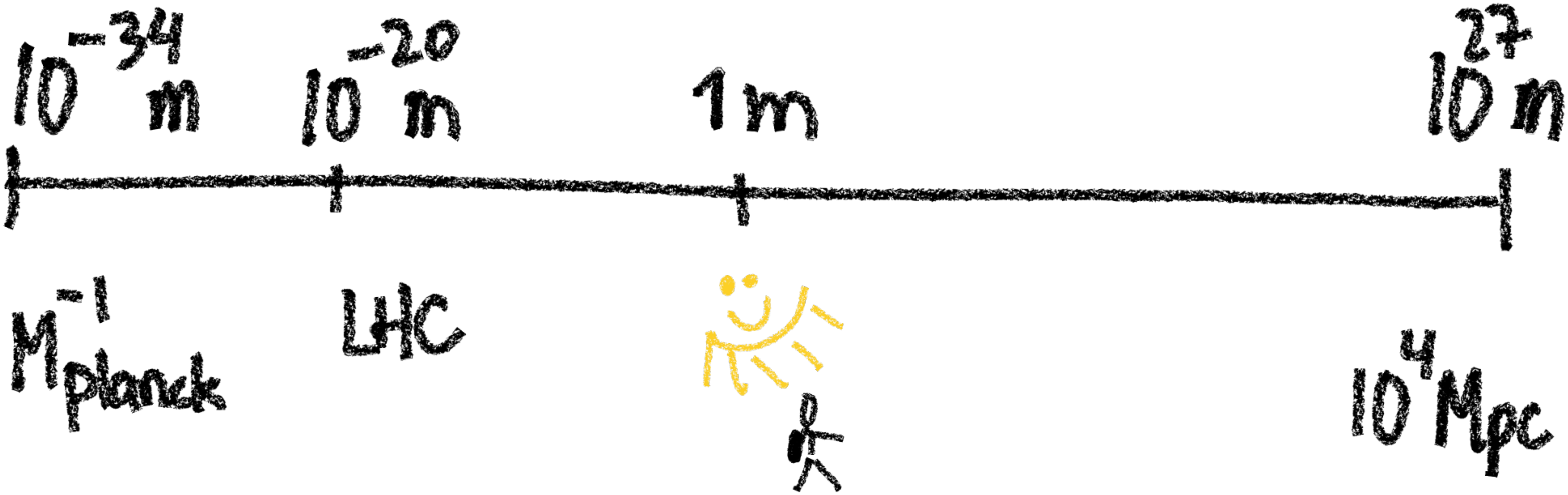
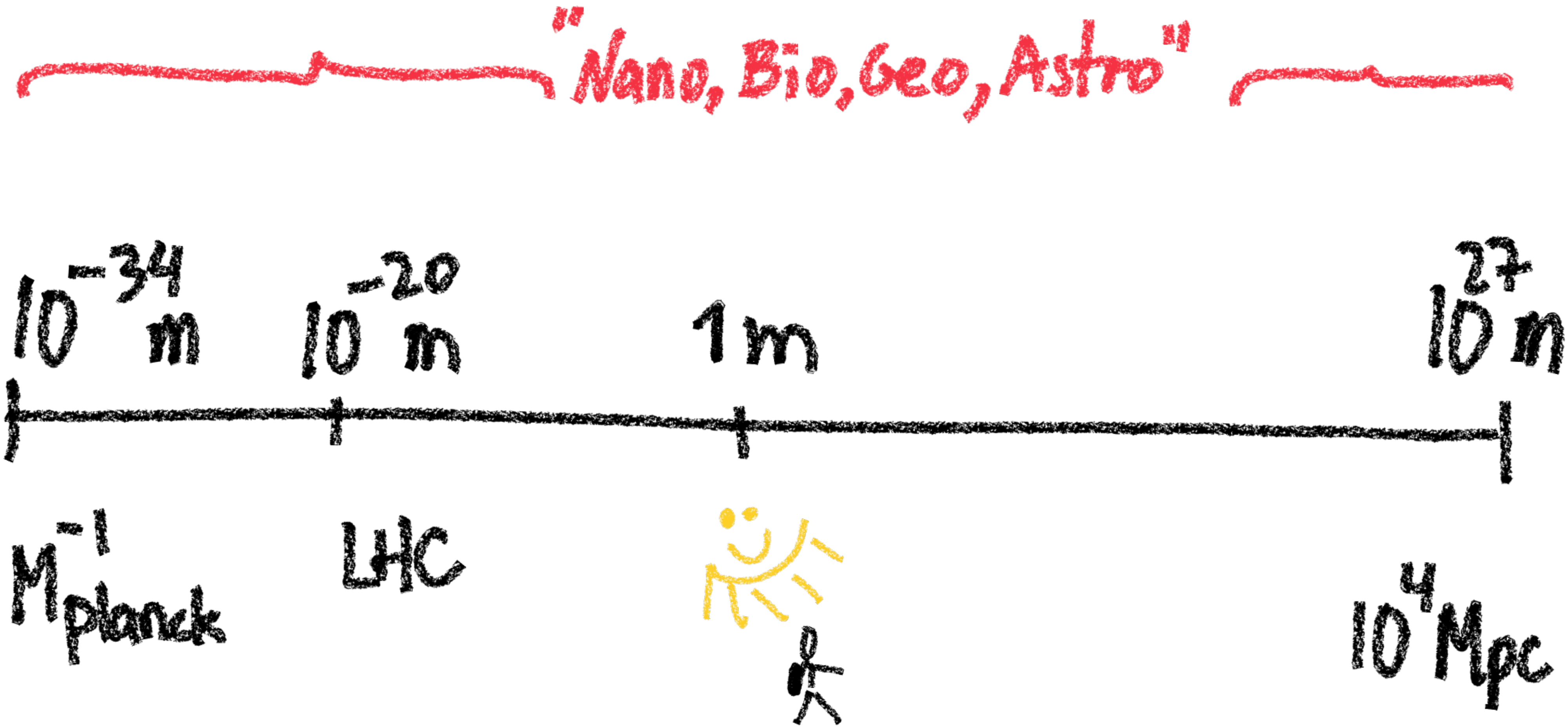


Particle physics + Cosmology



largest fundamental particle mass

mass m

compton wavelength $\lambda = 1/m$

schwarzschild radius $r = G_N m$

want $r < \lambda$ (otherwise our particle is a classical black hole)

$$\Longrightarrow \quad m < \sqrt{G_N^{-1}} \equiv M_{\text{planck}}$$

Shortest distance

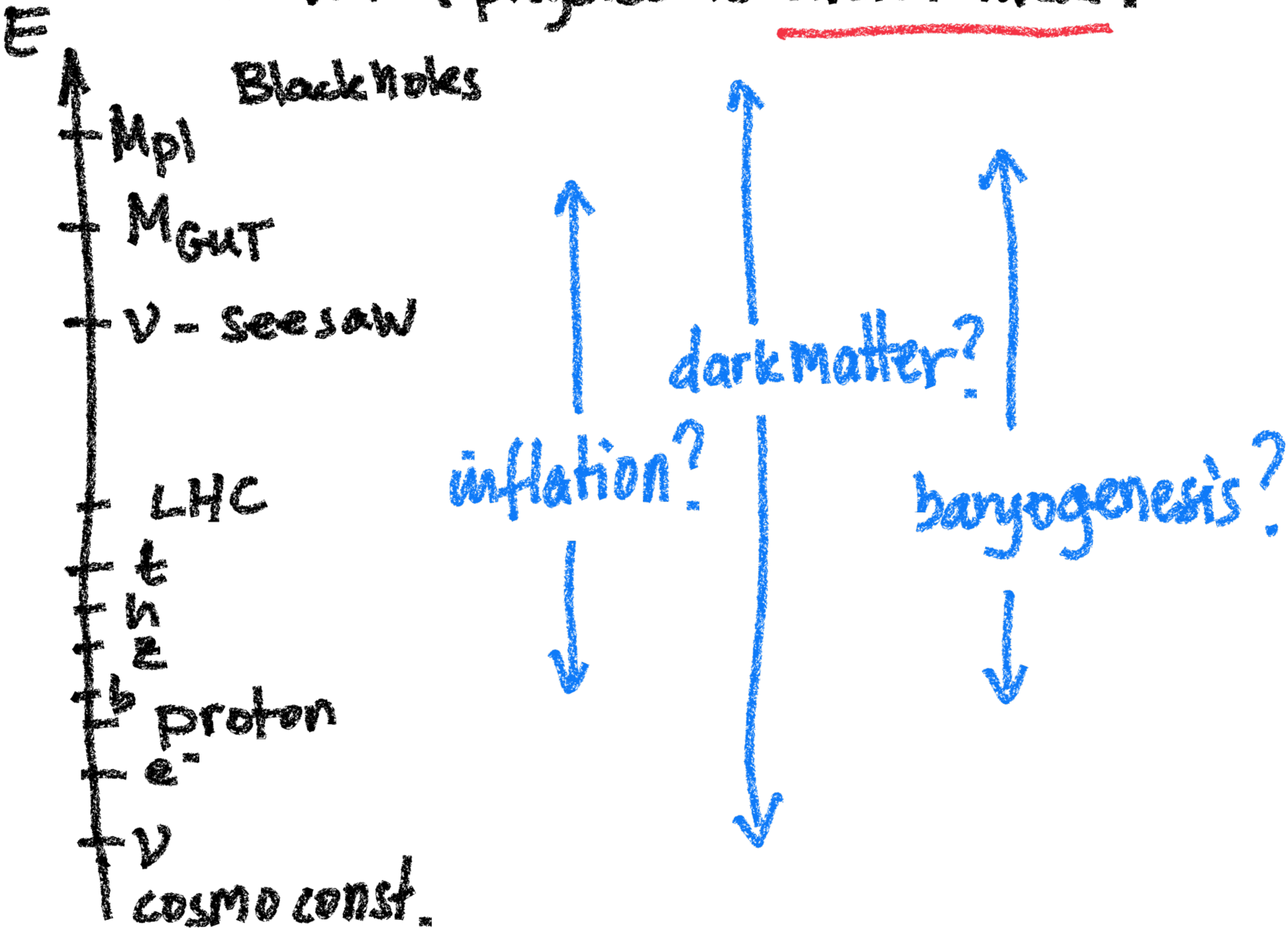
probe distance ℓ requires energy $E > 1/\ell$

concentrated energy has b.h. horizon $r = G_N E$

to not form a b.h. we must have

$$r < \ell \quad \Longrightarrow \quad \ell > \sqrt{G_N} \equiv \ell_{planck}$$

Fundamental physics is hierarchical !



What generates these hierarchies?

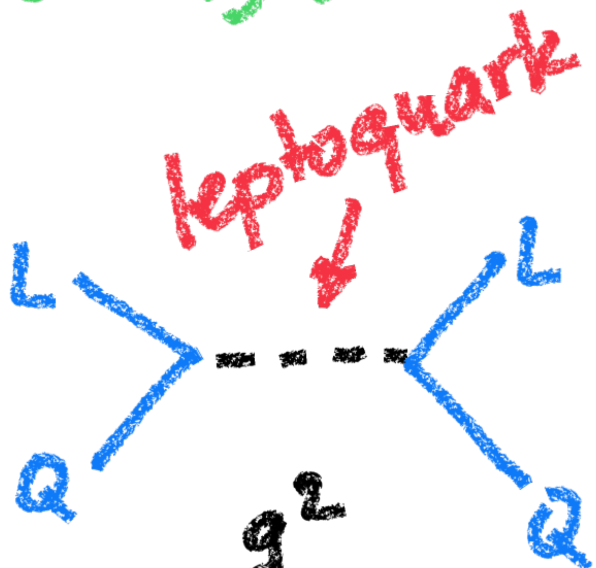
- $m_p \sim \Lambda_{QCD} \sim M_{pl}\, e^{-\int \frac{d\alpha}{\beta(\alpha)}}$

  dimensional transmutation!

- m_{weak}? don't know, hierarchy problem

Strategy: write effective Lagrangian with high scale physics integrated out

e.g.



$$\frac{g^2}{p^2 - M^2}$$

$$\xrightarrow{p \ll M}$$

$$\frac{g^2}{M^2} \equiv \frac{1}{\Lambda^2}$$

write all allowed couplings of SM fields and measure coefficients in experiments systematically... order terms by mass dimension

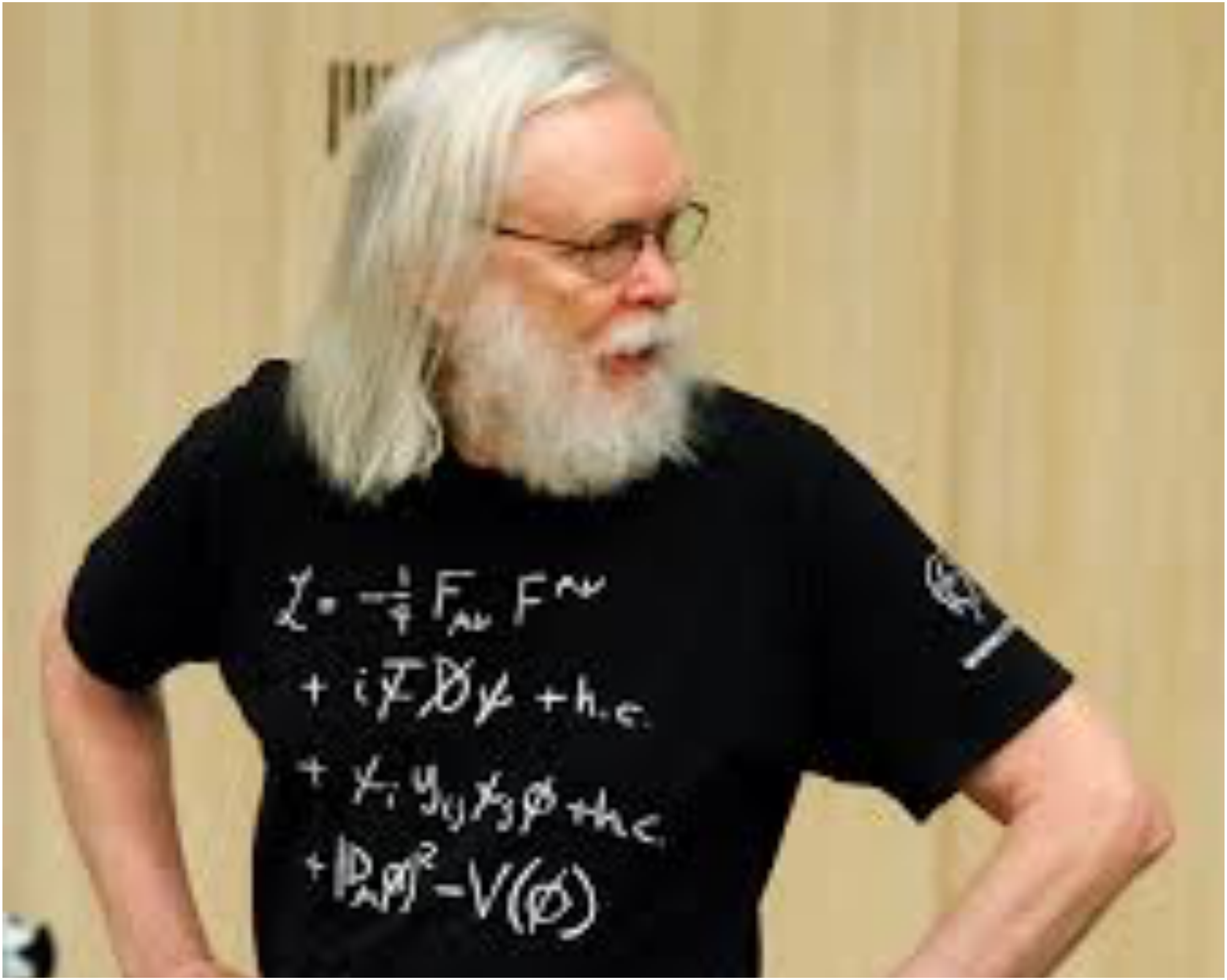
$$\mathcal{L}_{eff} = \Lambda^4 + \Lambda^2 H^\dagger H + \underbrace{\lambda (H^\dagger H)^2 + \mathcal{L}^{SM}_{kinetic} + \mathcal{L}^{SM}_{Yukawa}}_{\text{dim 4, coefficients dimensionless}} \leftarrow \text{the SM}$$

dim 5 $\quad + \dfrac{(L_L H)^2}{\Lambda}$

dim 6 $\begin{cases} + \dfrac{H^\dagger D_\mu H H^\dagger D^\mu H}{\Lambda^2} + \dfrac{H^\dagger D_\mu H \, \bar{e}_R \gamma^\mu e_R}{\Lambda^2} + \dfrac{H^\dagger \sigma^a H \, W^a_{\mu\nu} B^{\mu\nu}}{\Lambda^2} \\ + \dfrac{H^\dagger H \, B_{\mu\nu} B^{\mu\nu}}{\Lambda^2} + \dfrac{H^\dagger H \, W^a_{\mu\nu} W_a^{\mu\nu}}{\Lambda^2} + \dots \end{cases}$

>80 more at dimension 6

$+$ dim > 6


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

Example:

$$\frac{H^\dagger D_\mu H \, H^\dagger D^\mu H}{\Lambda^2}$$

$\partial_\mu + igZ_\mu$ $\qquad$ $v+h$

four Higgs scattering! 

but also ... $\underbrace{g^2 v^2}_{m_Z^2} \dfrac{v^2}{\Lambda^2} Z_\mu Z^\mu$ ... a Z mass correction

$$\frac{\delta m_Z^2}{m_Z^2} \simeq \frac{v^2}{\Lambda^2} \qquad v = 246 \text{ GeV}$$

no shift in W-mass $\Rightarrow$ $m_W = m_Z \cos\theta$ violated

$$\frac{\delta m_Z^2}{m_Z^2} = \frac{v^2}{\Lambda^2}$$

Experimental precision: $\frac{\delta m_W}{m_W} \sim 2.4 \cdot 10^{-4}$

$$\Longrightarrow \frac{v^2}{2\Lambda^2} \lesssim 2.4 \cdot 10^{-4}$$

$$\Longrightarrow \Lambda \gtrsim v \cdot 46 \approx 11 \text{ TeV}$$

indirect precision test probes 11 TeV!

$\Big\{$ $\Lambda = \frac{M'}{g'}$, "typical" Z' $g' \sim 1/2$, $1/4$ dropped in calculation

$\Rightarrow M_{Z'} \gtrsim 3$ TeV similar to direct limits $\Big\}$

$\mathcal{L}_{eff}$ has ∞ number of undetermined coefficients

- useful as expansion $\frac{\partial_\mu \partial^\mu}{\Lambda^2} \to \frac{P^2}{\Lambda^2} \ll 1$
- also $\frac{v^2}{\Lambda^2}$
    - δm_Z
    - $\frac{H^\dagger D_\mu H \, \bar{e}_R \gamma^\mu e_R}{\Lambda^2} \to g \frac{v^2}{\Lambda^2} \bar{e}_R Z_\mu \gamma^\mu e_R$

$$\frac{\delta g}{g} \sim \frac{v^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim \text{few TeV} \quad \text{(LEP)}$$

back to Effective SM

$$\mathcal{L}_{eff} = \Lambda^4 + \Lambda^2 H^\dagger H + \mathcal{L}_4 + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \dots$$

- expansion in $1/\Lambda$, valid when $p, m_{SM}, v \ll \Lambda$
- $\Lambda \sim$ scale of NP
- coefficients free parameters, determined by experiment.

  If UV physics known, calculate coeffs in terms of UV parameters

Assume a non-zero coeff in $\mathcal{L}_6$ measured $\Rightarrow \Lambda$ known

$\Rightarrow$ guarantee of new physics

$$\Lambda \sim \frac{M}{g} \Rightarrow M \sim g\Lambda \leq 4\pi\Lambda$$ upper bound !

- Historical example: muon decay

$$\frac{1}{\Lambda^2} \sim \frac{1}{(200\,\mathrm{GeV})^2}$$

Nature was nice: $M_W = 80\,\mathrm{GeV}$, $g < 1$

current situation:

- neutrino mass $(LH)^2/\Lambda$ $\qquad m_\nu \sim \frac{v^2}{\Lambda} \sim 0.1\,\text{eV}$

$$\Rightarrow \Lambda \sim 10^{14}\,\text{GeV} \quad \Rightarrow M \lesssim 10^{15}\,\text{GeV}$$

(or neutrino is Dirac $LH\nu_R$)

- gravity $\quad g_{\mu\nu} \frac{\partial^\mu H^\dagger \partial^\nu H}{M_{pl}}$ $\qquad \Lambda \sim M_{pl}$ $\qquad$ new physics @ M_{pl}

graviton

- B physics $R_{K^{(*)}}$?? $\qquad \Lambda \approx 30\,\text{TeV}$

$\Rightarrow$ currently no <u>direct</u> evidence for a low NP scale :(

<u>indirect</u>? Naturalness

Naive Naturalness

contributions to $\mathcal{L}_{eff}$ from NP at mass scale Λ

$$\mathcal{L} \sim c_4 \Lambda^4 + c_2 \Lambda^2 H^\dagger H + c_{01} \begin{pmatrix} t \\ b \end{pmatrix}_L H t_R + c_{02} \begin{pmatrix} \nu \\ e \end{pmatrix}_L \hat{H} e_R + \dots$$

$$+ \dots \quad + c_{-21} \frac{(H^\dagger D_\mu D)^2}{\Lambda^2} + \dots$$

with Λ scale of NP, c_i numbers of order 1 ?

Note if there are multiple NP scales Λ then

c_{-2} terms dominated by the lowest scale

c_2, c_4 " " " " highest "

c_0 contributions from all scales

Experimental values?

- c_{-2} no solid evidence for NP nearby
- c_0 $\lambda_H \sim g_1 \sim g_2 \sim g_3 \sim \lambda_{top} \sim O(1)$ ← natural

$$\left.\begin{array}{l} \lambda_b \sim \lambda_c \sim \lambda_\tau \sim 10^{-2} \\ \lambda_s \sim \lambda_\mu \sim 10^{-3} \\ \lambda_u \sim \lambda_d \sim 10^{-5} \qquad \lambda_e \sim 10^{-6} \end{array}\right\} \text{unnatural "flavor problem"}$$

$\theta_{QCD} F_{\mu\nu} \tilde{F}^{\mu\nu}$ $\theta < 10^{-10}$ ← strong CP problem

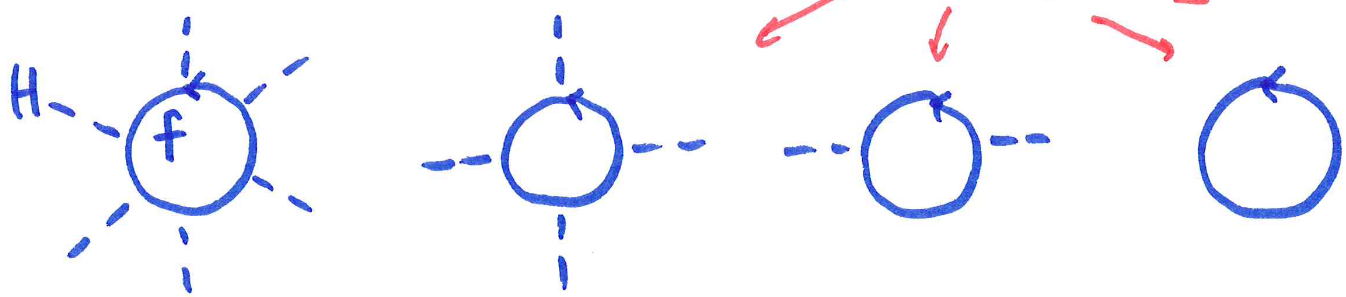
- c_2 $m_H^2 H^+ H$ $m_H \ll \Lambda \sim M_{pe}$ ← EW hierarchy problem
- c_4 $c_4 \Lambda^4 \sim 10^{-120} M_{pe}^4$ ← CC problem

C_2 & C_4 most interesting because sensitive to highest scales, most problematic! are they actually generated?

Trees? No $\quad \dfrac{1}{p^2-M^2} \to \dfrac{1}{M^2} + \dfrac{p^2}{M^4} + \cdots$

Loops? Yes

after regulating and subtracting cut-off



$$\frac{\lambda^6}{16\pi^2}\frac{(H^\dagger H)^3}{M^2} \qquad \frac{\lambda^4}{16\pi^2}\log M/\Lambda\,(H^\dagger H)^2 \qquad \frac{\lambda^2}{16\pi^2}M^2 H^\dagger H \qquad \frac{1}{16\pi^2}M^4$$

$$C_{-2} \qquad C_0 \qquad C_2 \qquad C_4$$

- ignore $c_4 \Lambda^4$ $\longrightarrow$ anthropics? (Weinberg)

- $m_H^2 H^\dagger H$ contributions from any NP with coupling to H

$$\sum_{NP} \#_i \frac{\lambda_i^2}{16\pi^2} M_i^2 \sim \text{largest scale in theory } M_{pl}^2$$

$$m_H^2 = m_{H,\text{bare}}^2 + \sum \# \frac{\lambda^2}{16\pi^2} M^2 \overset{\text{exp.}}{=} (125\,\text{GeV})^2$$

$\Rightarrow$ extreme fine-tuning (conspiracy)

Solutions ?

- ignore the problem

- Higgs is composite at scales above m_H

Hydrogen is a scalar, it's mass is not renormalized by UV physics

- symmetries, technical naturalness

Symmetries → technical naturalness

idea: $$- - \text{NP} - - = \sum \#_i \frac{\lambda_i^2}{16\pi^2}\left(M_i^2 - (M_i^2 + \delta M_i^2)\right)$$

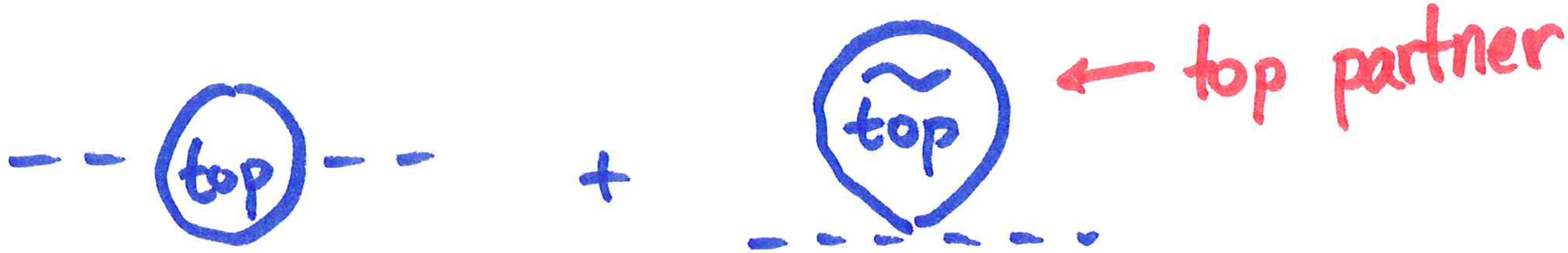
partners related by symmetry

$$\approx \sum \text{''}\, \delta M_i^2$$

natural if $\delta M_i \lesssim \frac{4\pi}{\lambda_i} m_{Higgs}$

⇒ predict partners with relations between couplings & masses

most important example ($\lambda_{top} \approx 1$)



$$m_{\widetilde{top}} \lesssim 4\pi \, m_{Higgs} \approx \text{TeV}$$

Aside ... why are there no large NP contributions to the electron mass?

SM: e_R, $\begin{pmatrix} \nu \\ e \end{pmatrix}_L$ $\quad \overset{e}{—}$ (NP) $\overset{e}{—}$?

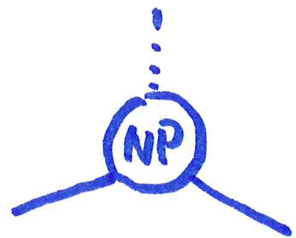
Dirac $\quad m_{uv}\, e_R^+ e_L$ $\quad$ not gauge invariant

Majorana $\quad m_{uv}\, e_R e_R$ $\quad$ " $\quad$ "

$\quad e_R^+ e_R$ $\quad$ not Lorentz invariant

e^- mass requires Higgs doublet

$$\lambda_e \begin{pmatrix}\nu\\ e\end{pmatrix}_L^\dagger H\, e_R \;\Rightarrow\; m_e = \overset{10^{-6}}{\lambda_e}\, v$$

1. λ_e dimensionless (c_0) $\Rightarrow$ 

$\propto \log(m_{UV})$

at worst

2. λ_e is "technically natural" in SM

't Hooft: small parameter is technically natural if setting it to zero leads to a new symmetry of $\mathcal{L}$.

e^- chiral symmetry

$e_R \to e^{i\theta} e_R$, all other fields invariant

check: $e_R^\dagger \not{D} e_R$ invariant $\qquad \lambda_e \begin{pmatrix}\nu \\ e\end{pmatrix}_L^\dagger H e_R$ not invariant

λ_e is only parameter which breaks e_R chiral symmetry

$\Rightarrow$ if all other couplings in $\mathcal{L}_{SM} + \mathcal{L}_{NP}$ preserve c.s.

then any loop correction to λ_e is proportional to λ_e

$\Rightarrow$ at worst $\quad \delta\lambda_e \sim \lambda_e \frac{g^2}{16\pi^2} \log \frac{M_{UV}}{M_{weak}} \lesssim \lambda_e$ technical naturalness

e^- lessons :

1. e^--mass forbidden in SM, λ_e is dimensionless

   $\Rightarrow$ not dominated by highest scales

2. λ_e is protected by chiral symmetry $e_R \to e^{i\theta} e_R$

   "technically natural".

$\Rightarrow$ $\lambda_e \sim 10^{-6}$ is preserved by NP corrections

$\Rightarrow$ $\lambda_e \sim 10^{-6}$ might be determined in far UV ☹ for LHC

is m_H^2 "technically natural"? (in the SM)

$m_H^2 H^\dagger H$ Lorentz + gauge + "chiral" invariant

$H \to e^{i\theta} H$

$\Rightarrow$ no enhancement when $m_H^2 \to 0$

$\Rightarrow$ Higgs mass not protected when SM coupled to physics at large scales

$\delta m_H^2 (\cdots\text{O}\cdots) \propto m_{UV}^2$

can we extend the SM to make m_H^2 technically natural?

i.e. extend SM such that $m_H^2 \to 0$ gives rise to a new symmetry.

[one example: SUSY $\quad$ SM $\to$ MSSM

$m_H^2 \to 0$ restores SUSY.]

Little Higgs theories (shift symmetry)

Aside γ: how is the photon mass protected?

$$m_\gamma^2 A_\mu A^\mu \quad \text{not gauge invariant} \quad A_\mu \to A_\mu + \partial_\mu \theta$$

$\Rightarrow$ $m_\gamma^2 = 0$ is technically natural because shift symmetry appears when $m_\gamma \to 0$.

check: photon couplings $\bar{\psi}(\partial_\mu + iA_\mu)\gamma^\mu \psi$ are invariant

$$\psi \to e^{-i\theta}\psi \,, \quad A_\mu \to A_\mu + \partial_\mu \theta$$

extend the SM to implement shift symmetry

$$H \to H + \xi$$ constant

- $m_H^2 H^\dagger H$ not invariant
- also forbids $\begin{pmatrix} t \\ b \end{pmatrix}_L^\dagger H\, t_R$

only $\partial_\mu H$ couplings allowed. Scalars with shift symmetry arise as Nambu Goldstone bosons from spontaneous breaking of global symmetries

Simplest little Higgs

implement a global symmetry into the SM such that top yukawa is allowed but H is pseudo-NGB such that m_H^2 is technically natural.

simplest example $SU(3)_{global} \to SU(2)$

little Higgs example in 5 steps ...

Cohen: hep-ph/0105239
Review: hep-ph/0502182

1. Scalar field theory with SU(3) (global)

triplet $\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix}$

3x3 Hermitian

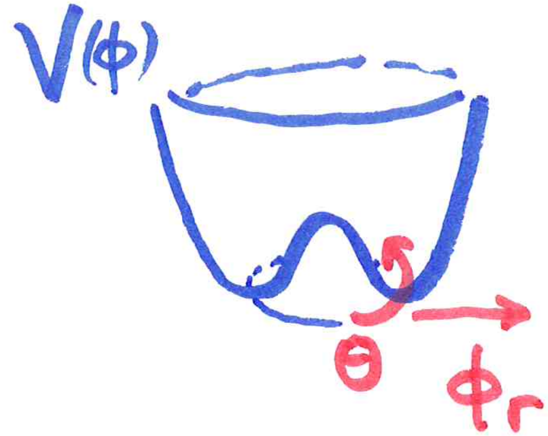
SU(3): $\phi \to U\phi \equiv e^{i\xi}\phi \quad , \quad \xi = \xi^a T^a$

$$\phi^\dagger\phi \to \phi^\dagger \underbrace{U^\dagger U}_{=1} \phi \quad \text{invariant!}$$

$\Rightarrow \mathcal{L} = \partial_\mu\phi^\dagger\partial^\mu\phi - V(\phi^\dagger\phi)$ is SU(3) invariant

2. spontaneous breaking, Nambu Goldstone bosons

$$V(\phi^\dagger\phi) = \lambda\left(\phi^\dagger\phi - f^2\right)^2$$



$$\Rightarrow \langle\phi^\dagger\phi\rangle = f^2 \quad \text{or} \quad \langle\phi\rangle = \begin{pmatrix}0\\0\\f\end{pmatrix} \Big\} \; \text{SU(2) unbroken}$$

"polar" coordinates: $$\phi = e^{i\theta/f}\begin{pmatrix}0\\0\\f+\phi_r\end{pmatrix}$$

massless heavy

SU(3): $$\phi \to e^{i\xi}\, e^{i\theta/f}\begin{pmatrix}0\\0\\f\end{pmatrix} \Rightarrow \theta \to \theta + \xi$$

If $\mathcal{L}$ preserves SU(3), then $\theta \to \theta + \xi$ is symmetry.

$\Rightarrow$ no $m^2\theta^2$ mass!

3. Where is the Higgs doublet H ?

$$\phi = e^{i\theta/f}\begin{pmatrix}0\\0\\f\end{pmatrix} \qquad \theta = \left(\begin{array}{cc|c} 0 & 0 & \\ 0 & 0 & H \\ \hline \multicolumn{2}{c|}{H^\dagger} & \theta_0 \end{array}\right) \longleftarrow \text{there}$$

$$\phi \approx \begin{pmatrix}0\\0\\f\end{pmatrix} + i\begin{pmatrix}H\\0\end{pmatrix} + \ldots \longleftarrow \text{doublet under unbroken } SU(2)$$

$\longrightarrow SU(2)_{weak}$!

$$\partial_\mu\phi^\dagger\partial^\mu\phi \longrightarrow \partial_\mu H^\dagger\partial^\mu H + \ldots$$

$$V(\phi^\dagger\phi) \longrightarrow H \text{ independent}$$

$\Longrightarrow$ theory of "Higgs" doublet with no mass, no potential.
a Nambu Goldstone boson.

4. SU(3) and the top Yukawa coupling

top yukawa: $\lambda \begin{pmatrix} t \\ b \end{pmatrix}_L^\dagger H\, t_R$

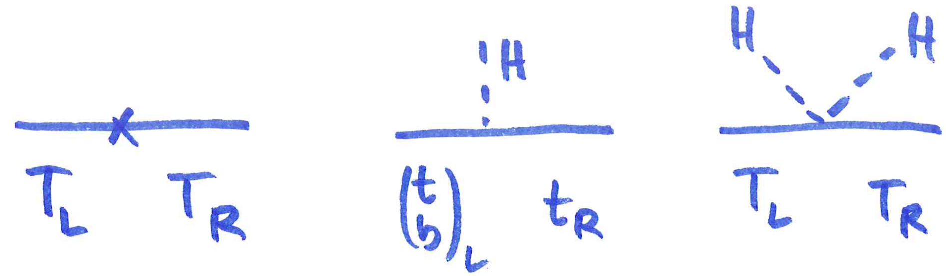
want SU(3): $\lambda \begin{pmatrix} t \\ b \\ T \end{pmatrix}_L^\dagger \phi\, t_{R_1} + \tilde{f}\, T_L^\dagger t_{R_2}$

breaks SU(3) "softly"

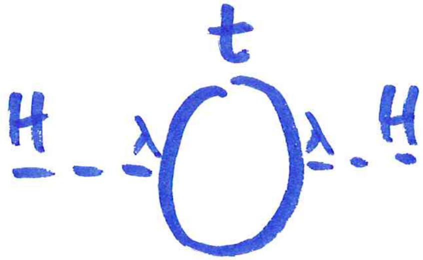
expanding...

$$\phi = \begin{pmatrix} \\ \\ f \end{pmatrix} + i\begin{pmatrix} H \\ 0 \end{pmatrix} - \frac{1}{2}\begin{pmatrix} 0 \\ 0 \\ \frac{H^\dagger H}{f} \end{pmatrix} + \dots$$

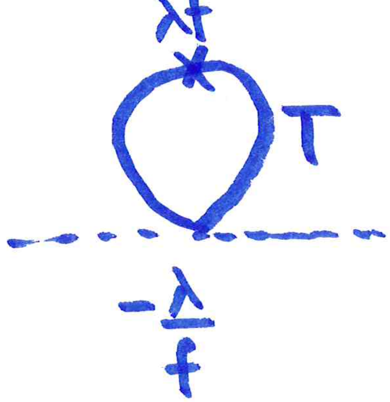
$$\lambda f \underset{\substack{\uparrow \\ \text{T-mass}}}{T_L^\dagger}\big(\underbrace{t_{R_1} + t_{R_2}}_{T_R}\big) + i\underset{\substack{\uparrow \\ \lambda_t}}{\lambda \begin{pmatrix} t \\ b \end{pmatrix}_L^\dagger} H\, \underset{\substack{\uparrow \\ T_R,\, t_R}}{t_{R_1}} - \frac{1}{2}\lambda \frac{H^\dagger H}{f} T_L^\dagger t_{R_1} \dots$$



5. Higgs mass corrections from top + T



$$\sim \frac{\lambda^2}{16\pi^2}\left(\Lambda^2 + m_t^2\right)$$



$$\sim -\frac{\lambda^2}{16\pi^2}\left(\Lambda^2 + m_T^2\right)$$

$$\delta m_H^2 = -6\,\frac{\lambda_t^2}{16\pi^2}\left(m_T^2 - m_t^2\right)$$

$\Rightarrow$ natural for $m_T \sim \lambda f \lesssim \frac{4\pi}{\sqrt{6}}\, m_h \sim \text{TeV}$

A full little Higgs theory has

$$m_H^2 \sim m_{H_{bare}}^2 - \frac{\lambda_t}{16\pi^2}\left(\overset{T}{m_T^2} - \overset{t}{m_t^2}\right) + \frac{g^2}{16\pi^2}\left(\overset{W'}{m_{W'}^2} - \overset{W}{m_W^2}\right) + \frac{\lambda^2}{16\pi^2}\left(\overset{H'}{m_{H'}^2} - \overset{H}{m_H^2}\right) \cdots$$

partners with biggest couplings give biggest corrections

$\Rightarrow$ need to be lightest

10% tuning $\Rightarrow$ $\left.\begin{array}{l} m_T \lesssim \text{TeV} \\ m_{W'} \lesssim 2\,\text{TeV} \end{array}\right\}$ already ruled out by LHC

$m_{H'} \lesssim 5\,\text{TeV}$

SM effective Lagrangian

$$\mathcal{L} \sim \Lambda^2 H^\dagger H + \ldots \lambda_e \begin{pmatrix} \nu \\ e \end{pmatrix}_L^\dagger H e_R + \ldots \frac{\mathcal{L}_6}{\Lambda^2} + \ldots$$

not natural for $m_H^2 \ll M_{NP}$

$\Rightarrow$ NP must be "close by" ($\sim$TeV)

unnaturally small couplings $\lambda_e \sim 10^{-6}$ are technically natural

$\Rightarrow$ NP corrections $\delta\lambda_e \propto \lambda_e$, small

probe NP with precision measurements