Technical Naturalness, the SM & New Physics

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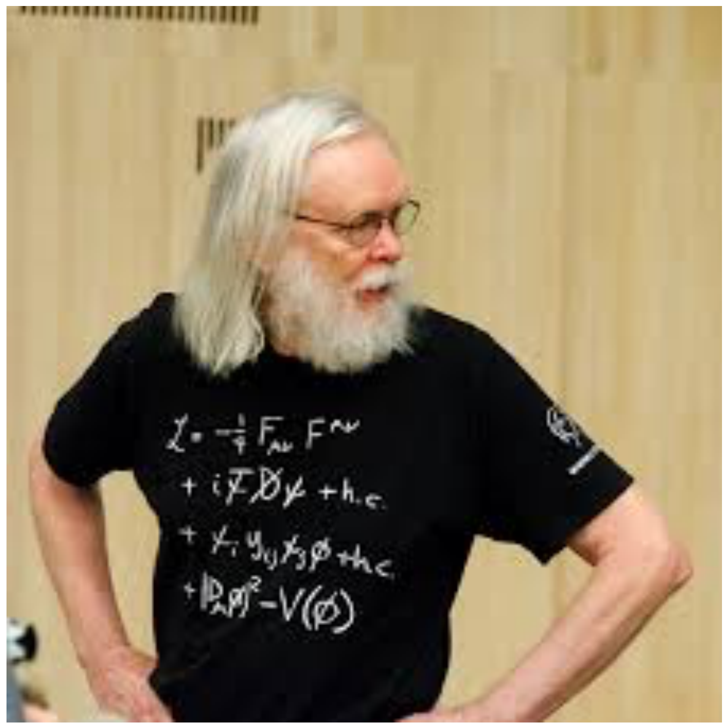
- technical naturalness
- BSM effective theory: Higgs physics
- relaxation

The Standard Model is now complete, ready for the t-shirt



Q: is the future of particle physics in the 3rd and 4th decimal place? i.e. is measuring the SM parameters more precisely all that is left to do?

Q: or are there hints in the SM that there is new physics to explore (experimentally)?

example: Fermi theory of weak interactions

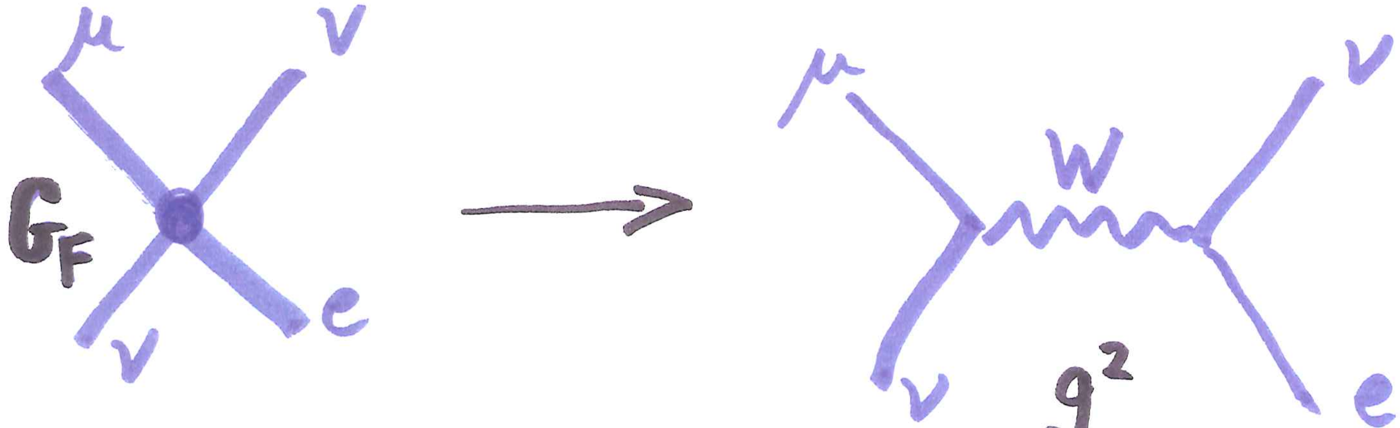
$$\frac{\bar{\mu}\,\gamma^\mu \nu \;\; \bar{\nu}\,\gamma_\mu e}{(250\ \mathrm{GeV})^2}$$

was incomplete,

predicted non-unitary

scattering for $E_{CM} \gg 250\,\mathrm{GeV}$

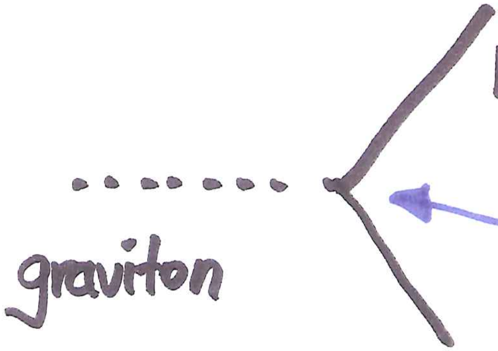
weak interactions



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

lesson: "downstairs" masses are a sign of new physics

any such signs in the SM ?



$$G_N^{1/2} \sim \frac{1}{M_{planck}}$$

$\Longrightarrow$ expect (must have!) new physics at the Planck scale.

any other hint?

let's do some dimensional analysis $\hbar = c = 1$

$$e^{iS} = e^{i\int d^4x\, \mathcal{L}(\phi, \psi)}$$

Locality: can expand $\mathcal{L}$ in power series in ϕ, ψ, ∂_μ

$$\mathcal{L} = c_0 M^4 + c_2 M^2 H^\dagger H + M \mathcal{L}_3 + \mathcal{L}_4 + \frac{\mathcal{L}_5}{M} + \frac{\mathcal{L}_6}{M^2} + \cdots$$

mass dimensions: $[\partial_\mu] = 1 \quad [\mathcal{L}] = 4$

$[\phi] = 1 \quad [\psi] = 3/2$

$[M] = 1 \longleftarrow$ some UV mass scale

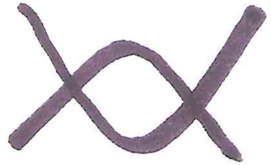
Examine dimensionless couplings first $\mathcal{L}_4$

$$\mathcal{L}_4^{toy} \sim (\partial\phi)^2 + \lambda^2\phi^4 + \bar{\psi}\not{\partial}\psi + \lambda_t \phi\bar{\psi}\psi$$

What is the theoretically natural/expected size for the couplings λ, λ_t ?

(at the weak scale)

an upper bound - strong coupling

Amplitude $(2\to 2) \sim$  $+$  $+ \dots$

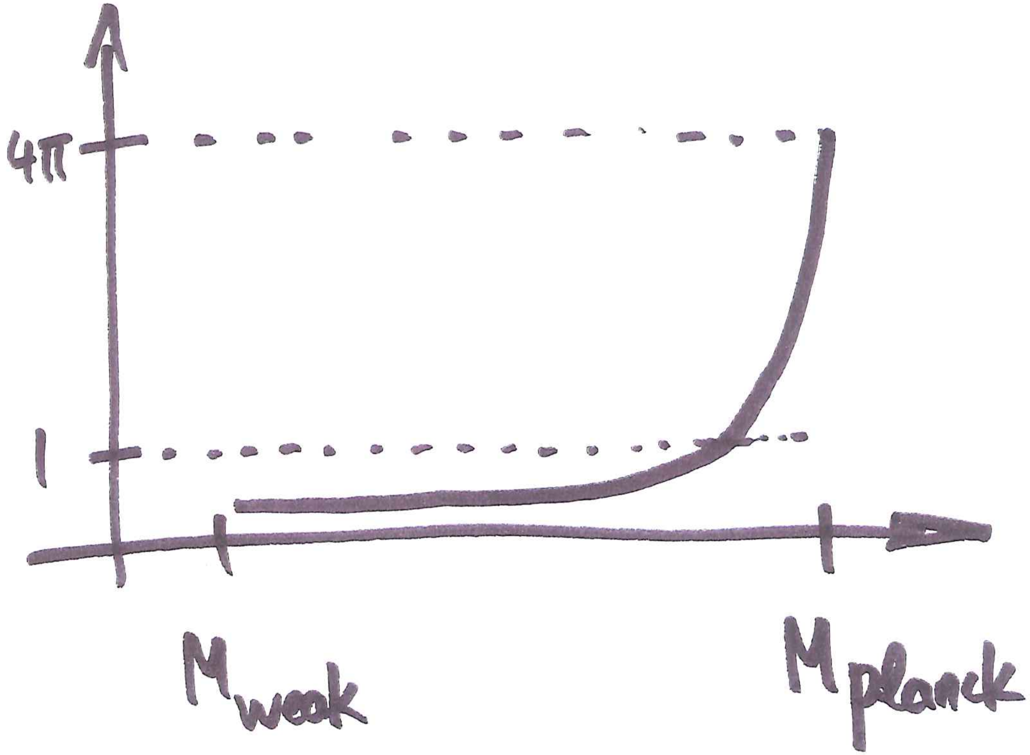
$$\sim \lambda^2 \left(1 + \frac{\lambda^2}{16\pi^2} + \dots \right)$$

for $\lambda \gtrsim 4\pi$ loops are as important as trees

$\Rightarrow$ strong coupling, $\mathcal{L}_4$ useless $\Rightarrow$ $\lambda < 4\pi$

Couplings run: λ

Strong couplings run fast



unless we happen to be near strong coupling

expect $\quad \lambda \lesssim \mathcal{O}(1)$

in the SM, biggest couplings @ M_{weak}

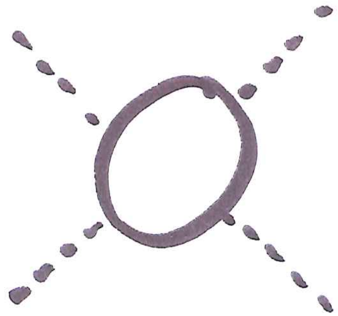
$$\lambda_t \approx 1 \qquad \lambda_H \approx 1/3$$

$$g_s \approx 1 \quad g \approx 0.6 \quad g' \approx 0.4$$

very consistent with natural expectation,

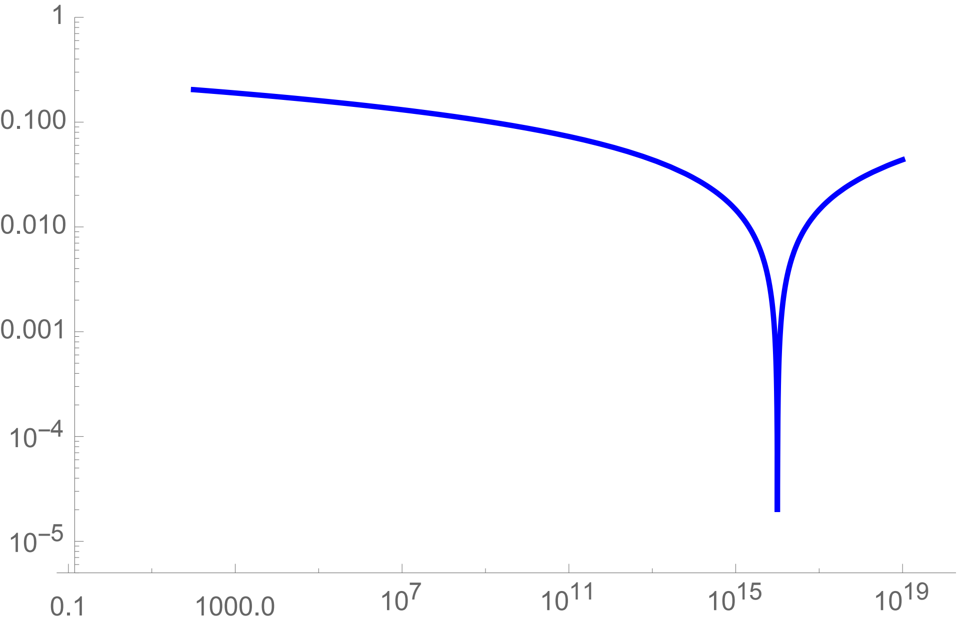
no evidence for strong coupling nearby (i.e. < 10 TeV) is there also a natural <u>lower</u> bound?

top loop correction to λ_H:



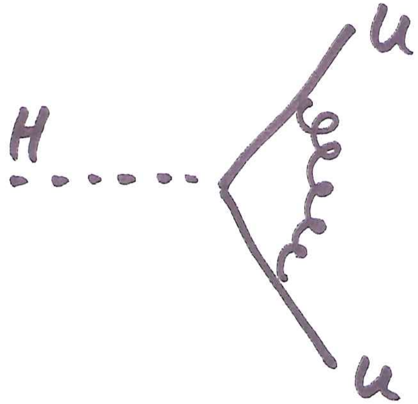
$$\delta \lambda_H^2 \sim \frac{\lambda_t^4}{16\pi^2} \log\left(\frac{\mu_1}{\mu_2}\right)$$

$$\Longrightarrow \lambda_H \gtrsim \frac{\lambda_t^2}{4\pi} \sqrt{\log}$$ unless there is a cancelation.


1
0.100
0.010
0.001
10^−4
10^−5
0.1
1000.0
10^7
10^11
10^15
10^19

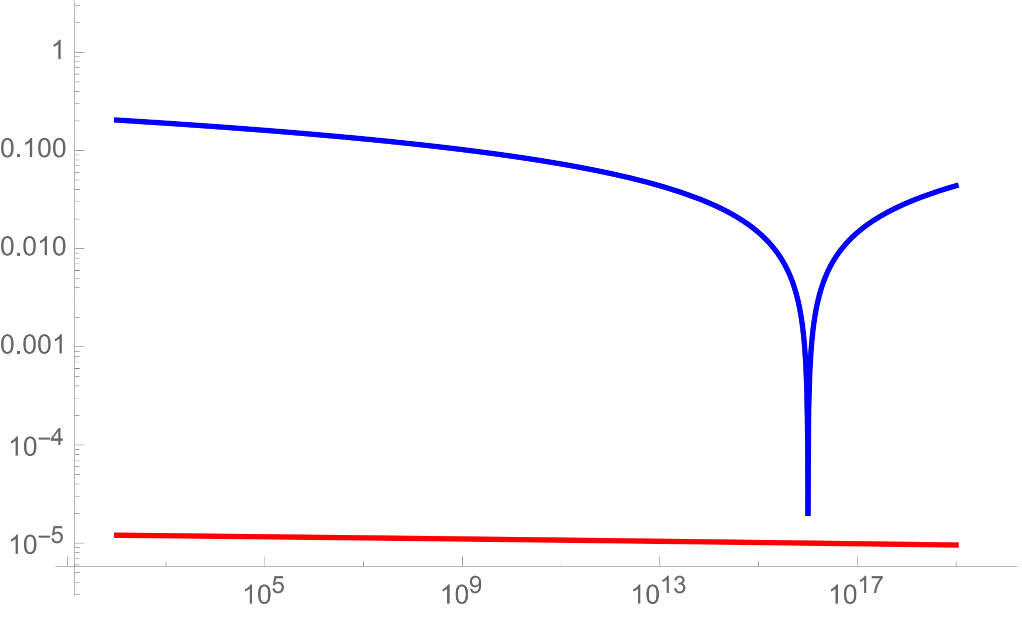
what about $\lambda_u \sim 10^{-5}$?

loop corrections to λ_u



$$\delta\lambda_u \sim \lambda_u \frac{g_s^2}{16\pi^2} \log\left(\frac{\mu_1}{\mu_2}\right)$$

small, because proportional to λ_u


1
0.100
0.010
0.001
10^{-4}
10^{-5}
10^{5}
10^{9}
10^{13}
10^{17}

How are the two cases different?

Technical Naturalness: ('t Hooft)	a coupling is technically natural if setting it to zero leads to a new symmetry of the theory

example λ_u:

$\lambda_u \, Q H U^c$ symmetry $U^c \to e^{i\theta} U^c$

only broken by λ_u

$\Longrightarrow$ any diagram which generates the coupling λ_u must be proportional to λ_u

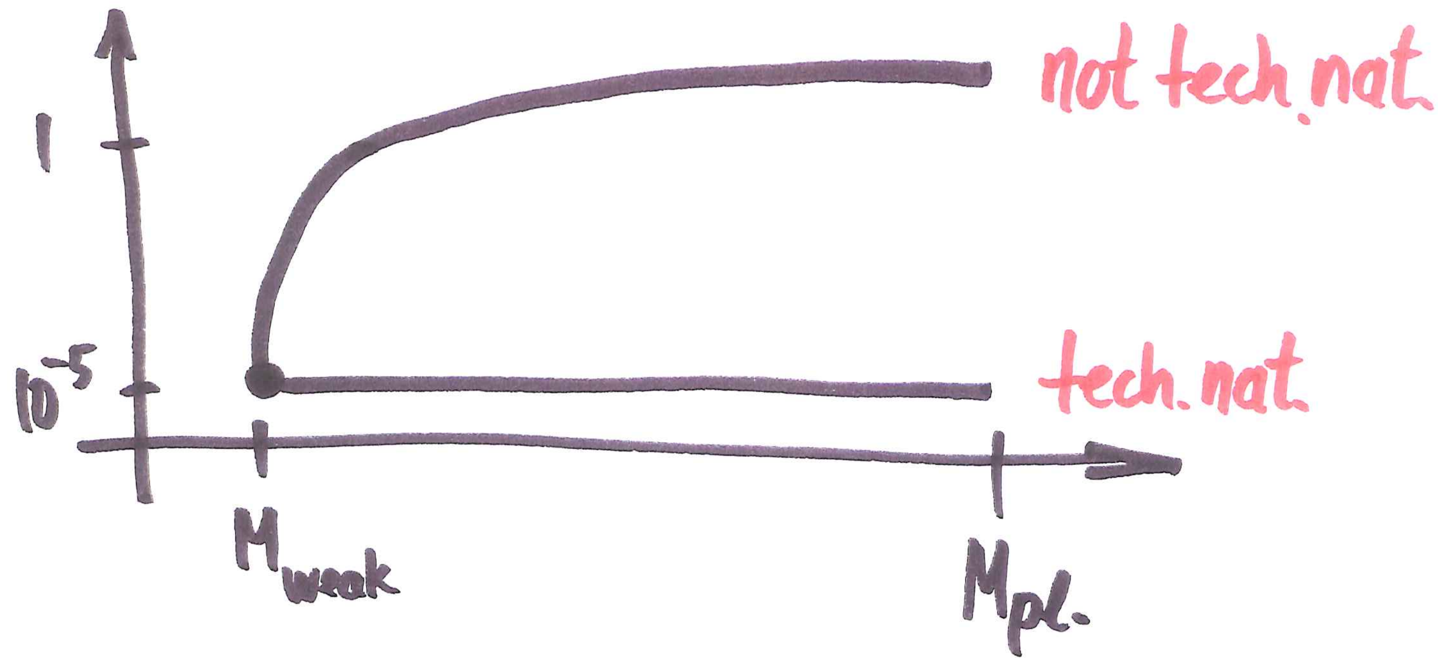
technically natural.

$$\lambda\,(H^{+}H)^{2}$$

does not break any symmetry that isn't broken elsewhere in the Lagrangian

=> not technically natural

Small couplings are "strange" either way but there is an important difference



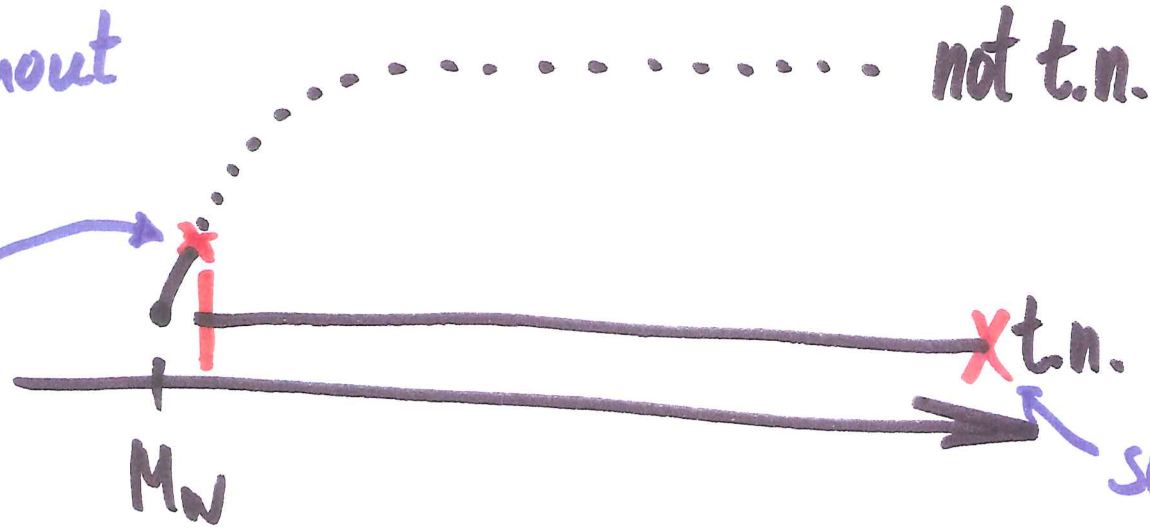
a different question:

t.n. why is λ so small?

not t.n. why is λ so small exactly at M_{weak}?

for a technically natural coupling the mechanism which explains smallness can be in the far UV

in the case without tech. nat. the mechanism must be in the IR



some UV mechanism, not accessible

$\Rightarrow$ accessible to experiment!

a coupling which is not tech. nat. is good news for experiment.

in $\mathcal{L}_4^{SM}$ all* couplings are tech. nat.

☹ no sign of N.P. nearby.

λ_{quarks}, $\lambda_{leptons}$ chiral symmetry

g_s, g, g' gauge symmetry

$\lambda_{Higgs} \sim 0.1$ no new symmetry in $\lambda_H \to 0$ limit but λ_H has natural size in SM

$\delta\lambda_{Higgs} \sim 0.1$

the rest of the SM Lagrangian ...

$$\underbrace{c_0 M^4}_{\text{cosmo const.}} + \underbrace{c_2 M^2 H^\dagger H}_{\text{Higgs mass term}} + \mathcal{L}_4 + \underbrace{\frac{\mathcal{L}_5}{M} + \frac{\mathcal{L}_6}{M^2}}_{\text{tomorrow}} + \dots$$

expected size of c_i ? $c_i \sim O(1)$ not tech. nat

$\lesssim O(1)$ tech. nat

M is the UV scale at which $\mathcal{L}$ is determined is $m^2 H^\dagger H$ tech. nat ?

symmetry: $H \to H + \text{const}$ can forbid $m^2 H^\dagger H$

but: broken badly by other couplings $\lambda_t Q H u^c$

$\lambda^2 H^4$

$g^2 W_\mu W^\mu H^2$

$\vdots$

$\Rightarrow$ not tech. nat. $\Rightarrow$ $m \ll M$ requires N.P. nearby

Sorry: Let's study this in detail because it's important and people get it wrong

example, free fields:

$$(\partial\phi)^2 - m^2\phi^2 + \bar{\psi}\not{\partial}\psi + M\bar{\psi}\psi \qquad M \gg m$$

m is tech. nat. symmetry: $\phi \to \phi + \text{const.}$

shift symmetry only broken by m.

$\Rightarrow$ if $m \ll M$ by some UV mechanism it remains small. (obvious!)

interactions:

$$(\partial\phi)^2 - m^2\phi^2 + \bar{\psi}\not{\partial}\psi + M\bar{\psi}\psi + \lambda\phi\bar{\psi}\psi$$

λ breaks $\phi \to \phi + \text{const}$ symmetry $\Rightarrow$ m not tech. nat.

$$\delta m^2 \sim \cdots\bigcirc\cdots \sim \frac{\lambda^2}{16\pi^2}\left(\cancel{\Lambda^2} + M^2\right) \sim \left(\frac{\lambda M}{4\pi}\right)^2 \mathrm{Log}$$

renormalization

$= 0$ in $\overline{MS}$.

$\Rightarrow$ $m \lesssim \frac{\lambda}{4\pi} M$ not natural

how about scale invariance symmetry?

$$\phi \to s\,\phi(sx)$$
$$\psi \to s^{3/2}\,\psi(sx)$$

equivalent to

$$\phi \to s\,\phi(x)$$
$$\psi \to s^{3/2}\,\psi(x)$$
$$d^4x \to \frac{1}{s^4}\,d^4x$$
$$\partial \to s\,\partial$$

$$\int d^4x \;\; \underbrace{(\partial\phi)^2}_{\text{inv.}} - \underbrace{m^2\phi^2}_{1/s^2} + \underbrace{\lambda\phi\bar\psi\psi}_{\text{inv.}} + \underbrace{\bar\psi\not\partial\psi}_{\text{inv.}} + \underbrace{M\bar\psi\psi}_{1/s}$$

$m^2=0$ not a new symmetry because of M

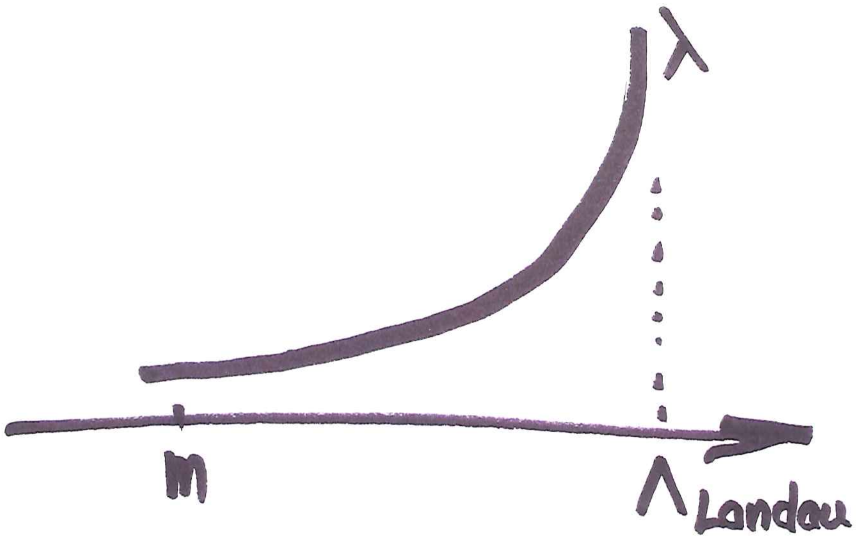
what if $M=0$? $\quad (\partial\phi)^2 - m^2\phi^2 + \lambda\phi\bar{\Psi}\Psi + \bar{\Psi}\partial\!\!\!/\Psi$

$\qquad\qquad\qquad\qquad\quad$ inv. $\quad 1/s^2 \quad$ inv. $\quad$ inv.

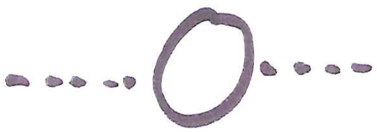
"looks" OK. $m^2 \to 0$ enhanced symmetry in classical theory

in QFT: $\lambda(\mu/M)$ runs $\Rightarrow$ breaks scale invariance

$m \ll \Lambda$ not natural



How do I see that in a calculation?

 $\sim \frac{\lambda^2}{16\pi^2} \cancel{\Lambda^2_{\text{cutoff}}} = 0$

$= 0$ in $\overline{MS}$

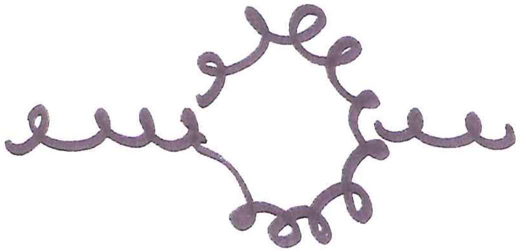
to all orders in pert. theory

a wrong calculation! theory changes at Λ_{Landau}

$\Rightarrow$ not correct to integrate $\int_0^\infty d^{4-\varepsilon}p \, \frac{1}{p^2} = 0$

calculation must include non-perturbative physics

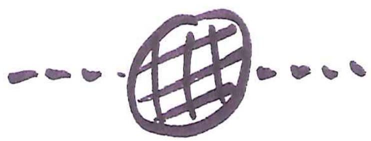
example QCD:



gluon massless to all orders

correct answer: non-perturbative physics removes gluons

$$m_G \sim \Lambda_{QCD}$$

in our toy: $\delta m^2 \sim$  $\sim \Lambda^2_{\text{Landau}}$

non-perturb.

Summary: really need scale invariant QFT for a small scalar mass to be technically natural.

but then m is the only scale in the theory and naturalness is obvious!