the HIERARCHY PROBLEM :

LAST TIME: RENORMALIZABILITY

↳ LOOP DIAGRAMS INTRODUCE POTENTIAL "UV SENSITIVITY"

details of UV PHYSICS

$\int d^4k \sim \Lambda^n$

UV ENERGY SCALE ↝ $1/\Lambda$ SHORT DISTANCE MICROPHYSICS

QUESTION: why are particles light?

↳ REALLY A PROBLEM for HIGGS

$\sim \int d^4k \; y^2 \frac{k^2}{(k^2 - m_\psi^2)^2} \sim \Lambda^2$?!

(y's from FERMION) HIERARCHY PROBLEM

trace over indices (spin) → $\frac{Tr\left[\not{k}(k_\mu \sigma^\mu + m_\psi)^2 \not{k}\right]}{(k^2 - m_\psi^2)^2}$

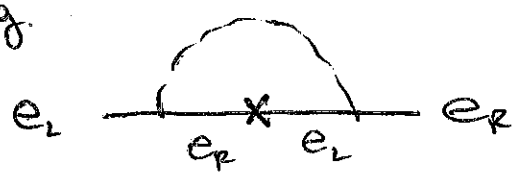
MASS of HIGGS GETS HUGE QUANTUM CORRECTIONS!
IF Λ is QUANTUM GRAV SCALE: $\Lambda \sim 10^{19}$ GeV!

What about other PARTICLES?

↳ no. they WANT to be MASSLESS

HIGGS (vev) BREAKS SYMMETRIES ⇒ PERMIT A MASS → ANY MASS HAS TO BE $\propto v/\sqrt{2}$

eg.



actually 2 different internal lines

$$\sim \int d^4k \, \frac{1}{k^2}\left(\frac{1}{k}\right)^2 \sim \log \Lambda$$

↑ HIGGS ↑ 2 FERMIONS

MUCH SOFTER DIVERGENCE

can be absorbed into our definition of mass

eg $M^{OBS} = M^{(0)} + \underbrace{\frac{y^2}{4\pi}}_{\text{estimate}} \log \Lambda/M^{OBS}$

even if $\Lambda \sim 10^{25}$ GeV this is an $O(10)$ #

CAN BE $O(1/100)$

→ "CHIRAL SYM" PROTECTS MASS
↳ $\frac{v}{\sqrt{2}}$ needed to GIVE DIRAC MASS

eg. GAUGE BOSONS : GAUGE INVARIANCE

$M_Z^2 \sim \frac{v^2}{2}$

BECAUSE $v/\sqrt{2}$ IS ORDER PARAM OF EWSB.

IF $v/\sqrt{2} \to 0$, $SU(2)\times U(1)$ IS RESTORED. then

$B_\mu \to B_\mu + \partial_\mu \theta(x)$ IS A SYMMETRY

& $M_B^2 B^2$ IS PROHIBITED.

↳ so in $v \to 0$ limit, $M_Z^2 \to 0$.

or: in limit where $v/\sqrt{2} = 0$, no diagram contributes to GAUGE BOSON MASS.

So we have a puzzle: why is HIGGS LIGHT?!

on the one hand, it must be:

① we observed it: $m_H = 125$ GeV (comparable to $v/\sqrt{2}$)

② the $WW \to WW$ scattering amplitude becomes non-perturbative @ ~ TeV if no HIGGS.

↳ so something crazy would have been seen @ LHC if there were no HIGGS.

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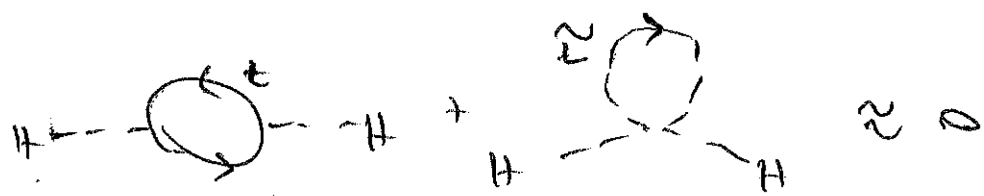
3 common solutions:

1. SUSY. FORCE ⟷ MATTER
(BOSON) ⟷ (FERMION)

why? iN SUSY LIMIT, MASSES PROHIBITED.
↳ inherit "chiral sym" PROTECTION of FERMIONS

SUSY is not exact, but maybe we live in a vacuum where it is spontaneously broken.



implications: double the # of particles
→ look for THEM

2. EXTRA DIMENSIONS

↑ many variants. We'll discuss one.

MAYBE the QUANTUM GRAVITY SCALE is LOWER than WE THINK.

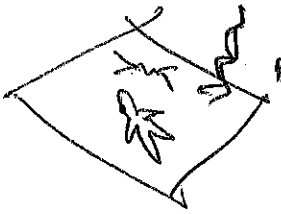
↳ weakness of GRAV ↔ HIGH SCALE

$$G_N \sim \frac{1}{M_{Pl}^2}$$

↑ this is small, because this is large

↑ using $\Lambda \sim M_{Pl}$.

MAYBE WE LIVE ON (3+1)dim MEMBRANE



STANDARD MODEL

BUT GRAVITY KNOWS ABOUT A LARGER SPACE

↑ GRAVITY "LEAKS" INTO EXTRA DIMENSIONS

↑ eg GAUSS' LAW, BUT WITH MORE DIRECTIONS.

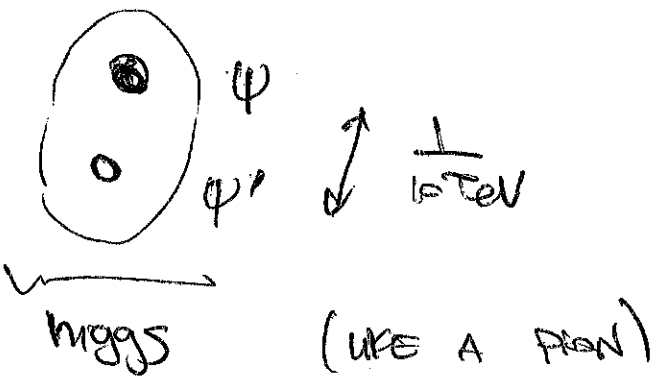
implications: BLACK HOLES GET MESSED UP

IF XD IS COMPACT, KK GRAVITONS

3. COMPOSITENESS

maybe HIGGS IS NOT FUNDAMENTAL.

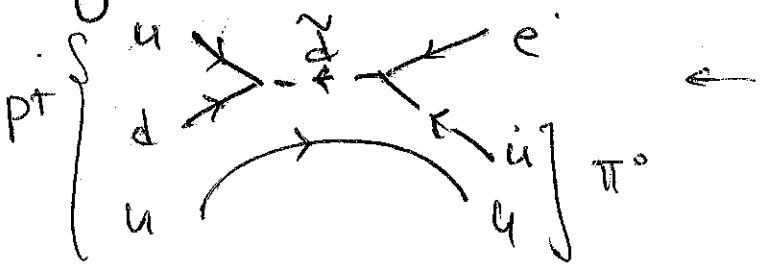
↳ eg @ some $\Lambda \sim 10$ TeV $\ll M_{Pl}$, we resolve that it is a bound state:



implications: new particles (other BOUND states)
Higgs decays get weird.

INTERESTING BYPRODUCT:
none of these solutions work 'out of the box' → need to fix some things that do not agree w/ experiment

eg PROHIBIT INTERACTIONS THAT LEAD TO PROTON DECAY



← R PARITY: PROHIBIT VERTICES W/ ONLY ONE SUPER-PARTNER

If you impose a PARITY & have new charged stuff, then the lightest PARITY-odd particle is stable.

↳ cannot decay bc no lighter particles to decay to that can carry the CHARGE

... so PREDICT lots of this stuff sitting around in the universe...