LEPP UNDERGRADS: Beyond the SM

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$\boxed{SM}$: Grown-up version

$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	u_R d_R	B $W^{1,2,3}$		γ Z W
$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	? e_R	g $h, H^0, H^\pm$		g h

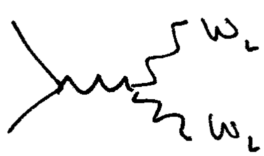
HIGGS : EW SYM BREAKING

- $B, W, H^0, H^\pm \longrightarrow \gamma, Z, W$
- $f_L + f_R \longrightarrow f$
- - - - x FEYNMAN RULE for h

TODAY : REASONS WHY WE EXPECT SOMETHING MORE.

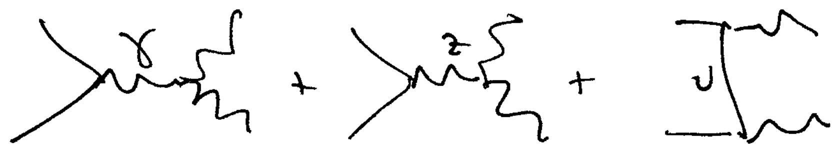
CAVEAT : maybe there is no Higgs? (maybe EW sym never existed?)

$\boxed{NO}$: must have something like the Higgs.



$\sim \frac{E}{M_W}$ } fact

WHAT HAPPENS @ Hi ENERGY?

IN SM : 

this is well behaved, even though each diagram $\sim E/M_W$.

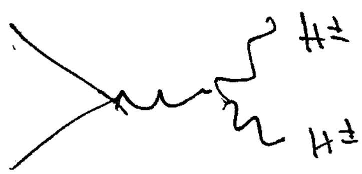
in principle, these are 3 separate sectors of the thy!

three diagrams must sum to be exactly cancelling!

EW Unification → all related.

MIRACLE? NO.
THE PROBLEM IS THAT MASSIVE SPIN-1 PARTICLES AREN'T WELL BEHAVED @ HI E.

BUT: @ Hi E the SM MASSIVE SPIN-1 PARTICLES ARE REALLY MASSLESS SPIN 1 + HIGGSES!



this IS well behaved

it just got mixed up in the above diagrams into pieces which individually misbehave.

"Unitarization of WW scattering"

So: ANY EXTENSION of SM MUST ~~SEE~~ INCLUDE HIGGS OR SOMETHING LIKE IT!

Problems of SM

① NEUTRINO MASS :

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \begin{matrix} + \ ? \\ + \ e_R \end{matrix} \begin{matrix} \longrightarrow \nu_{\text{massive}} \\ \longrightarrow e_{\text{massive}} \end{matrix}$$

because ν is neutral, it might be its own antipartner!

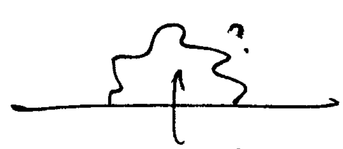
so OPTION 1 : $\nu_L \times \nu_R \times \nu_L$

or OPTION 2 : $\nu_L \times \text{anti-}\nu_L \times \nu_L$

we don't know.

further: why is m_ν so small?

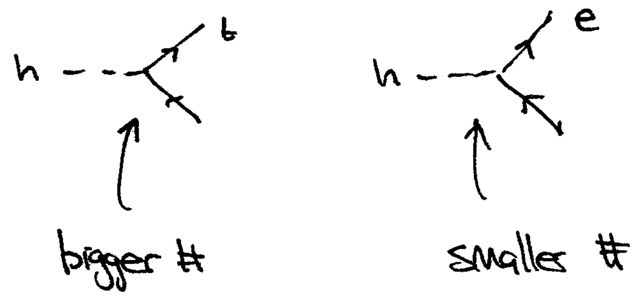
maybe it comes from some virtual loop?



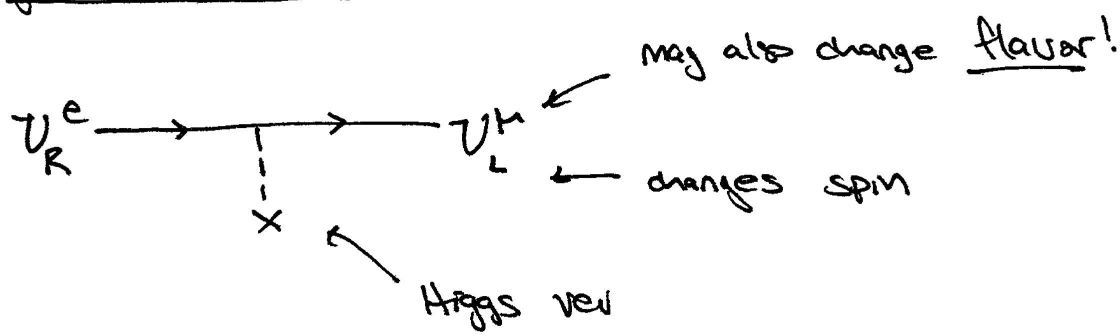
VERY HEAVY? 10^{15} GeV?

note: option 2 violates Lepton #!

② <u>FLAVOR</u> why are there 3 generations?
why are they heavier?



{ <u>grown-up version</u> :



SO <u>FLAVOR</u> HAS TO DO W/ HOW THE HIGGS TALKS TO FERMIONS! good Q: why don't electrons oscillate? ⟶ ask Josh! }

(3) related to flavor: $\boxed{CP}$ ← antimatter

why is there more matter than antimatter?

FACT: LAWS of PHYSICS ARE NOT CP-INVARIANT

WHAT'S THE PROBLEM? SM does not seem to predict the right amount of CP violation.

↳ non-perturbative effects ("sphalerons, Θ angle")

related to: ≥ 3 flavors

(4) DARK MATTER ~ 20% of ENERGY of UNIVERSE

definitely not SM.

leading candidate: Weakly Int. Massive Particle (WIMP)

~~EARLY UNIVERSE LOTS of PARTICLE-ANTI-PARTICLE PAIRS~~

~~EXPANSION UNIVERSE COOLS PULLS PARTICLES APART~~

LOTS of EVIDENCE FOR A NEW PARTICLE!

if it interacts ~ weak force ⇒ M ~ 100s GeV

↳ SAME SCALE AS EWSB! COINCIDENCE?!

Maybe...

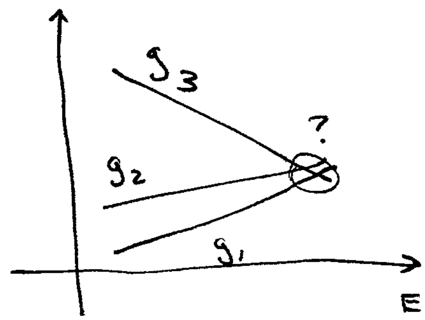
5

UNIFICATION

EM + (W,Z) → ELECTROWEAK → Grand unification

QCD → Grand unification

this is usually accompanied by a picture:



$g_1 \leftrightarrow B$

$g_2 \leftrightarrow W$

$g_3 \leftrightarrow g$

coupling "constants" ↔ strength of force

CHANGE w/ LENGTH SCALE

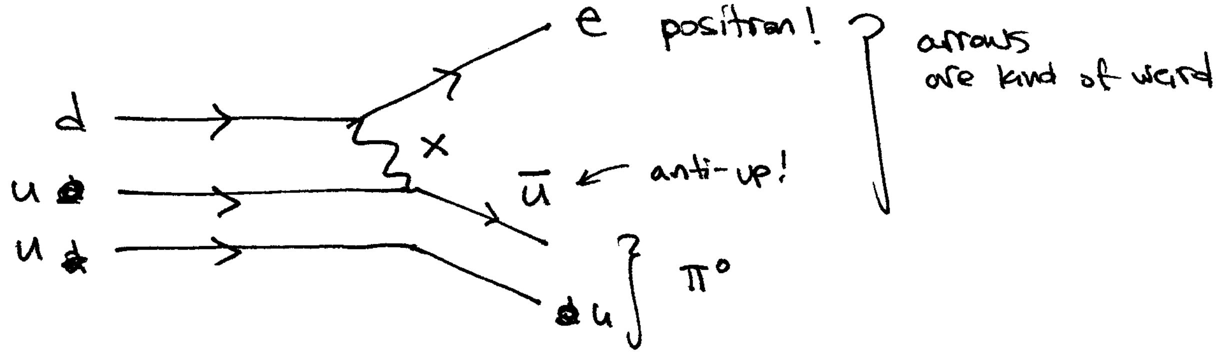
↪ vacuum polariz by virtual particles

BUT TRUE UNIF. ALSO MEANS

$$\begin{pmatrix}\nu\\ e\end{pmatrix} \begin{pmatrix}u\\ d\end{pmatrix} \longrightarrow \begin{pmatrix}\nu\\ e\\ u\\ d\\ \vdots\end{pmatrix}$$

} some force particle w/ > 4 charges can convert between these!

IMMEDIATE PROBLEM:



PROTON DECAYS! (& fairly quickly)

cf. PROTON LIFETIME $> 10^{32}$ <u>years</u>

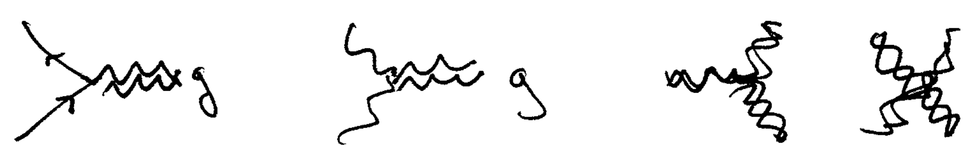
↳ SUGGESTS $m_X >$ REALLY HEAVY

(this is why Baryon # cons. is important)

(6) <u>GRAVITY</u>: what if we wanted to be even more ambitious? unify particle physics w/ gravity?

<u>MYTH</u>: CANNOT WRITE A QUANTUM THY of GRAVITY.

<u>false</u>:



all fermions all gauge self interactions

there it is. quantum gravity.

<u>but</u>: this theory breaks down in the same way that SM w/o higgs breaks down.

⟺ VERY HARD TO WRITE DOWN A <u>FUNDAMENTAL</u> THEORY of QUANTUM GRAVITY.

An easier way to see this:

short distances ⟷ high energy

... but this means that @ very short distances & very high energies ... HIGH ENERGY DENSITY

⇒ GRAVITY PREDICTS <u>BLACK HOLES</u>!
QFT has a hard time describing these.
⟹ see Nima Arkani-Hamed's 3RD messenger lecture!

<u>LEADING CANDIDATE</u>: STRING THEORY
↳ see talk by Paul McGuirk

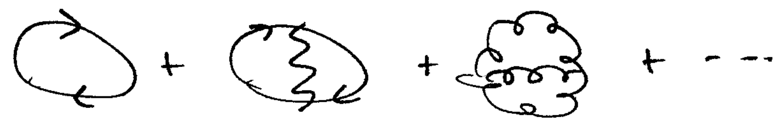
$\boxed{\text{BUT}}$: all this is very far away from any kind of experimental verification.

(7) <u>Cosmology</u> many topics here
↳ Yuhsin will discuss a few

<u>eg</u>. Baryogenesis: where did all of our baryons come from?

<u>also</u>: cosmological constant ⟷ vacuum energy

<u>QFT</u>:

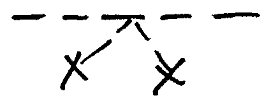


↳ PREDICTION FOR COSMOLOGICAL CONSTANT
... $\sim M_{Pl}^4$, 10^{120} too large!!

<u>also</u>: inflation ⟷ ∃ "inflaton" field which makes this happen.

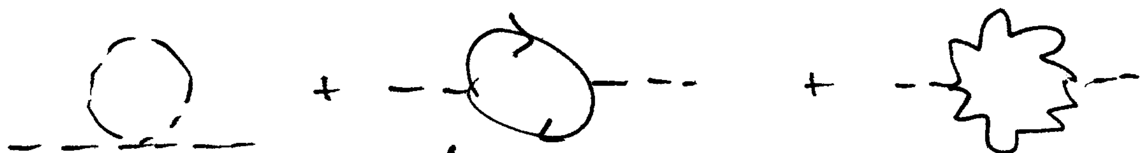
"fine tuning problem"

⑧ The Hierarchy Problem

the Higgs mass:  $\sim$ 125 GeV?

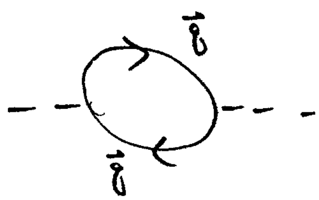
AS WE SAID EARLIER, SOMETHING HIGGSY @ 100's of GeV
→ required for WW scattering to make sense.

but then we also have:



esp. top quark

EACH OF THESE IS AN INFINITE SUM (INTEGRAL!)

eg. 

sum over all internal momenta!!
⟹ end up w/ $M^2 \sim (\infty \text{ GeV})^2$

By the way: why is  A MASS?

imagine going to rest frame. this is the "self energy" of the particle.

n.b: technically, not all of this is mass...

Looks like Higgs mass <u>diverges</u>!!

→ No infinities in physics... appearance of infinity is a sign that our description of physics is failing.

high momentum ⟷ high energy (⟷ short distance)

so @ some scale, SM breaks down
eg definitely by M_{Pl}.
(b/c maybe <u>QFT</u> breaks down there!)

suppose $m_H^2 \sim (M_{Pl})^2$ ... finite -- but too heavy!

↳ maybe the coefficients of THESE #'s:

<u>MIRACULOUSLY</u> CANCEL s.t. $m_H^2 \sim (125\ \text{GeV})^2$?

↑
UNLIKE WW scattering, no reason for this!

So: we are looking for a <u>REASON</u> for Higgs to be light.

Two approaches:

BOTH EXTEND SPACETIME!

"weakly coupled"

"strongly couplet"

SUSY

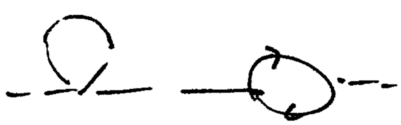
XD ↔ compositeness

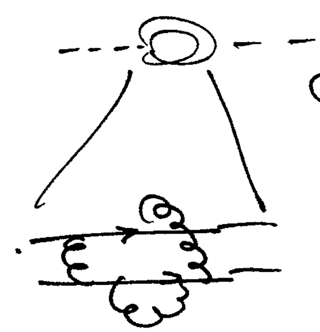
extra quantum dimension

extra space dimension

every SM particle has a PARTNER w/ DIFFERENT SPIN

every SM PARTICLE has a tower of resonances (bound states)

→ RELATES 



@ some length scale, higgs stops behaving like higgs!.

LOOKS LIKE PAIR of fermions.

ANALOG TO ANTIPARTICLES

Jack, next theory lecture

Yuhsin, in 2 weeks.

SUSY names

$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$ u_R d_R

$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ e_R $\longrightarrow$ $\tilde{q}$ & $\tilde{\ell}$ SQUARKS & SLEPTONS

q $\longrightarrow$ $\tilde{q}$

$\gamma, W^\pm, Z$ or B, W, $\longrightarrow$ GAUGINOS → PHOTINO, etc. → BINO, WINO,

→ neutralinos & charginos

g $\longrightarrow$ GLUINO

h_u, h_d $\Longrightarrow$ Higgsinos

two!

(actually, five...) → $H_u = \begin{pmatrix} \tilde{h} + \tilde{H}^0 \\ \tilde{H}^\pm \end{pmatrix}$ → feeds W, Z

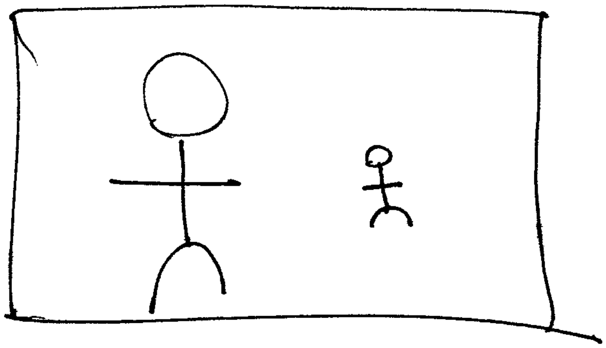
$H_d = \begin{pmatrix} \tilde{h} + \tilde{H}^0 \\ \tilde{H}^\pm \end{pmatrix}$

Roughly: $\gamma \, q \, q \Rightarrow W \, \tilde{q} \, \tilde{q}$, $\tilde{W} \, \tilde{q} \, q$

Rule: change two to superpartners

↑ conserve angular momentum.

Holographic Principle



What is this?

a) big guy + little guy

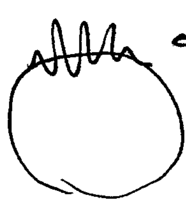
b) close guy + far guy w/rt XD

RECALL: QCD is hard to describe w/ feynman diagrams

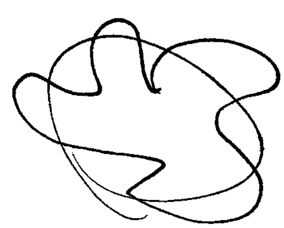
↳ STRONGLY COUPLED

↳ forms bound states w/ tower of masses

But I can also do feynman diagrams in extra dimensions. eg suppose extra "circle" dimension



← PARTICLE ON A LARGE XD.



← PARTICLE ON SMALL XD

← "HIGHER KK #" OR HIGHER MASS "BOUND STATE"